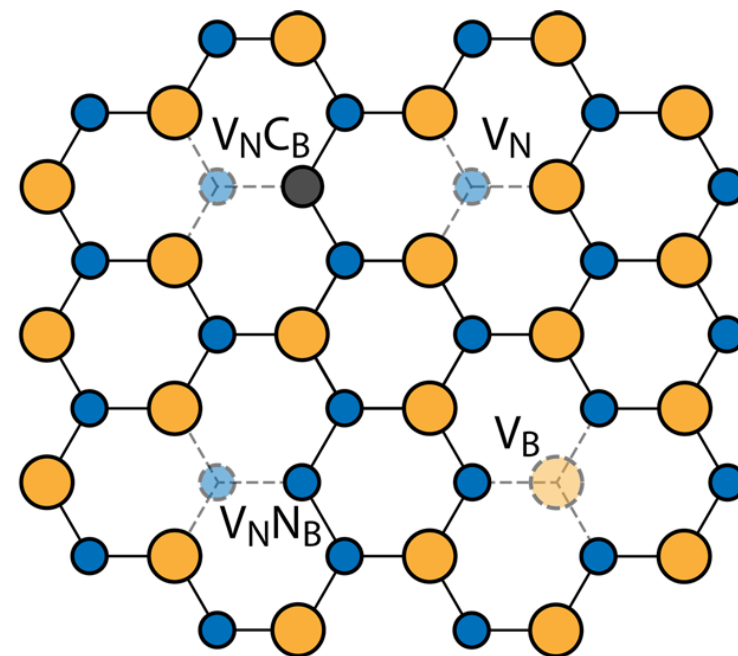


Quantum Technologies

with
Color Centers in hBN

Mehdi Abdi

Theoretical Quantum Optics and
Quantum Technologies



Outline

Introduction

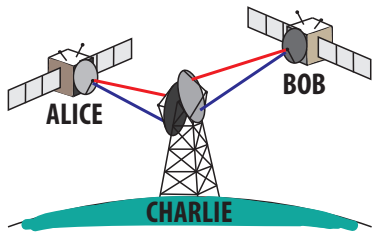
Hybrid Quantum Devices

hBN Color Centers

Vibrating Emitters

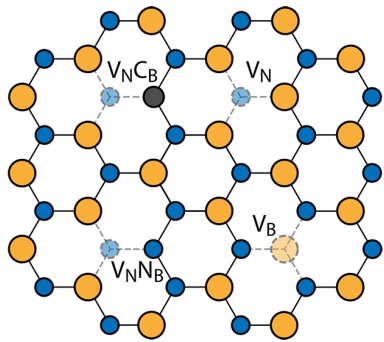
Sensing and Simulation

Outline



Introduction

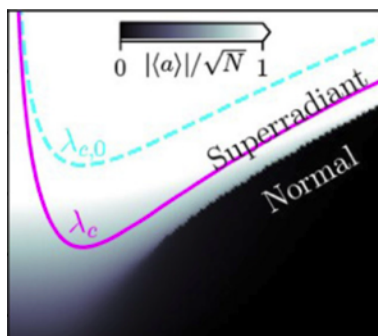
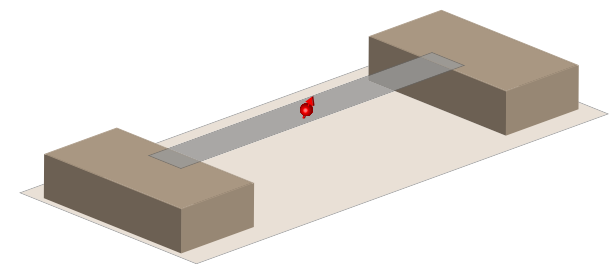
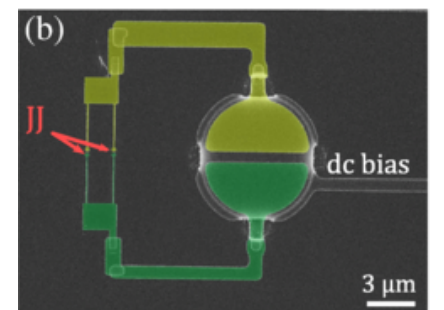
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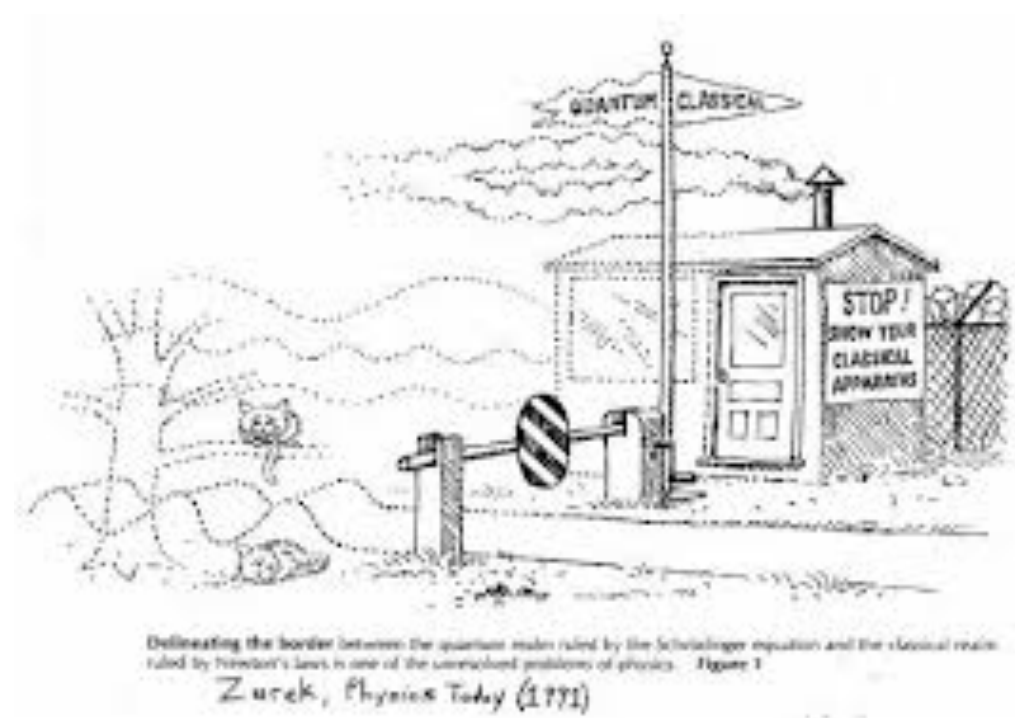
Quantum Mechanics

Foundational

- Collapse models
- Classical—Quantum borderline

Technological

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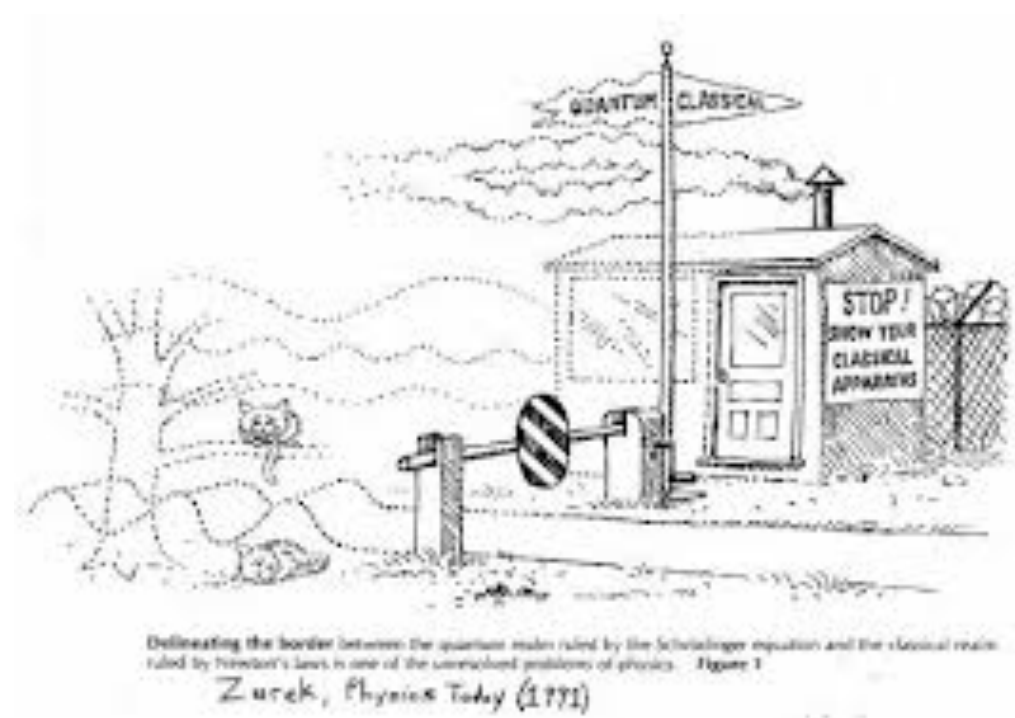
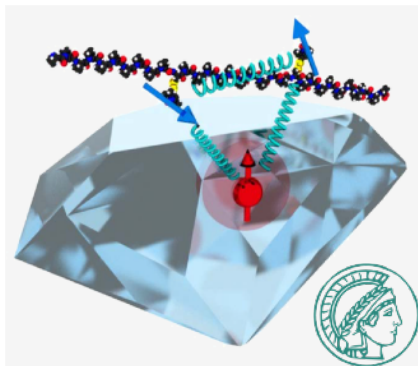
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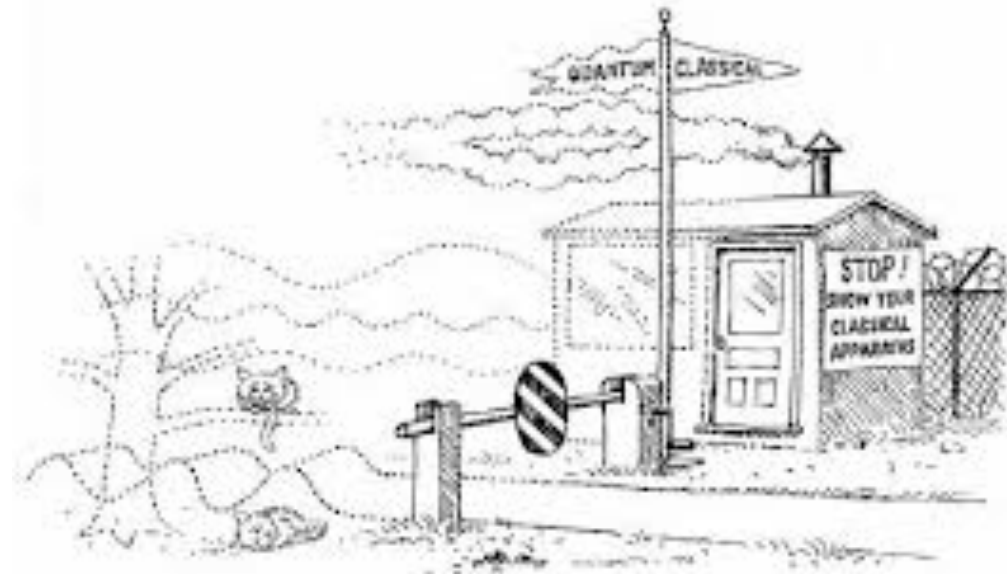
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Foundational

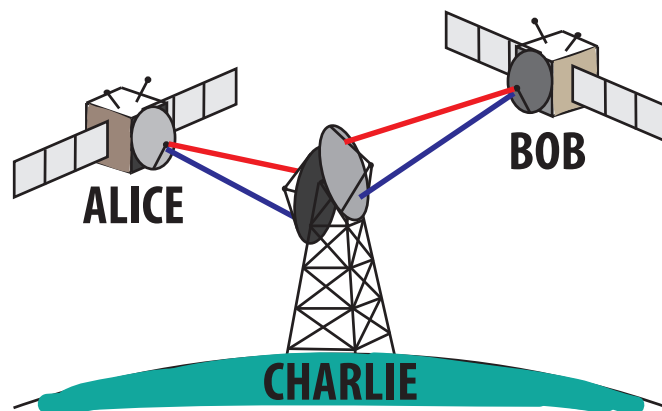
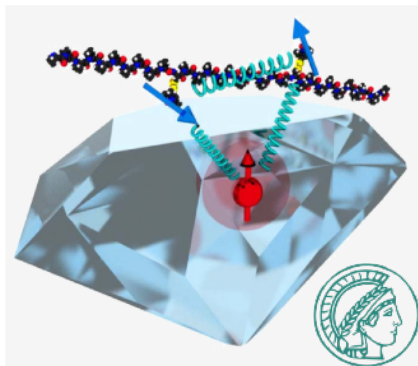
- Collapse models
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Technological

- Sensing
- Communication
-
-



Delineating the border between the quantum realm ruled by the Schrödinger equation and the classical realm ruled by Newton's laws is one of the unsolved problems of physics. Figure 1
Zurek, *Physics Today* (1991)



Schäfer-Nolte et al., *Phys. Rev. Lett.* (2014)
Greif et al., *Science* (2013)

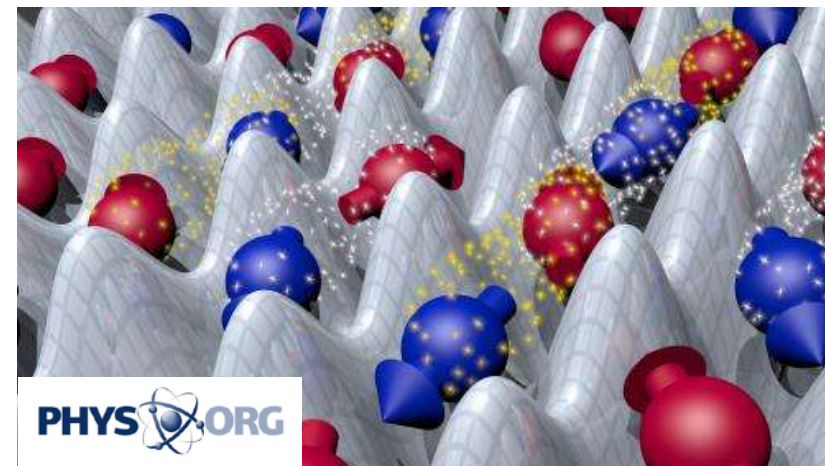
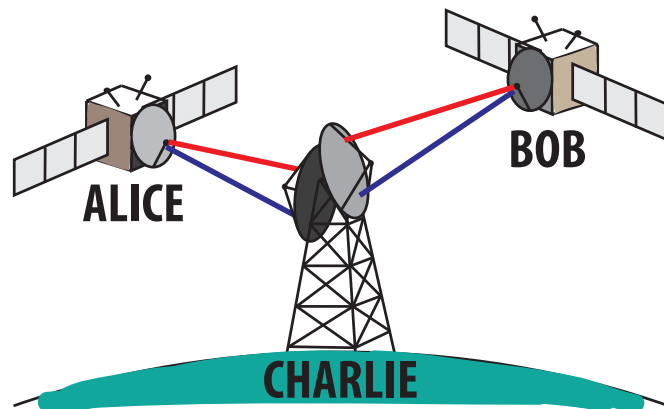
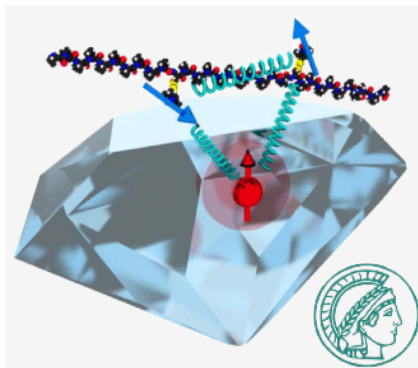
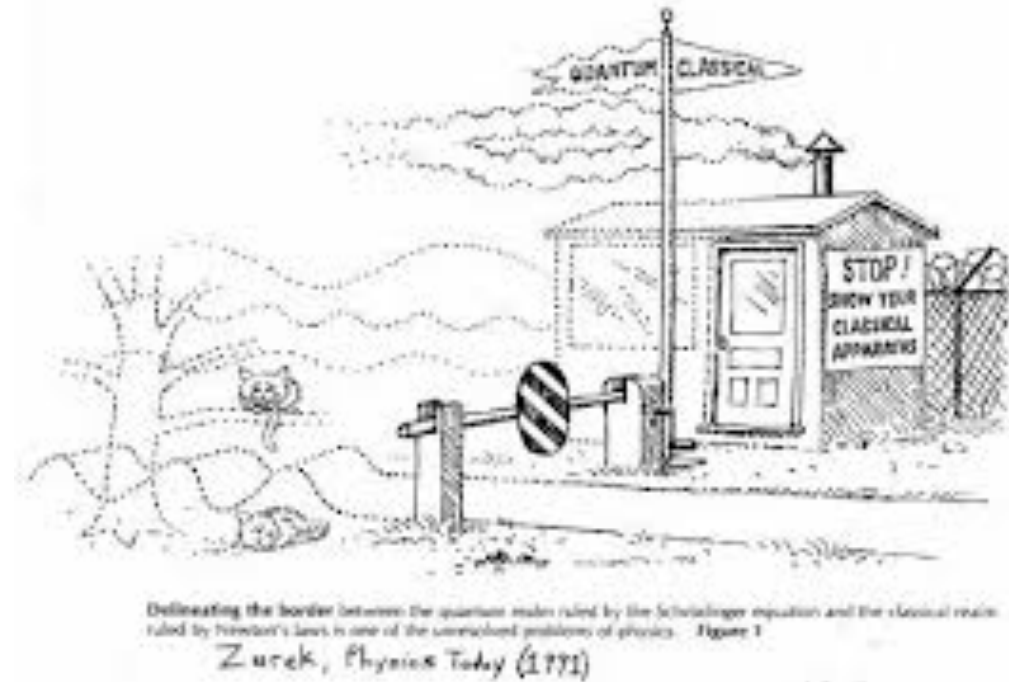
Quantum Mechanics

Foundational

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Technological

- Sensing
- Communication
- Simulation
-

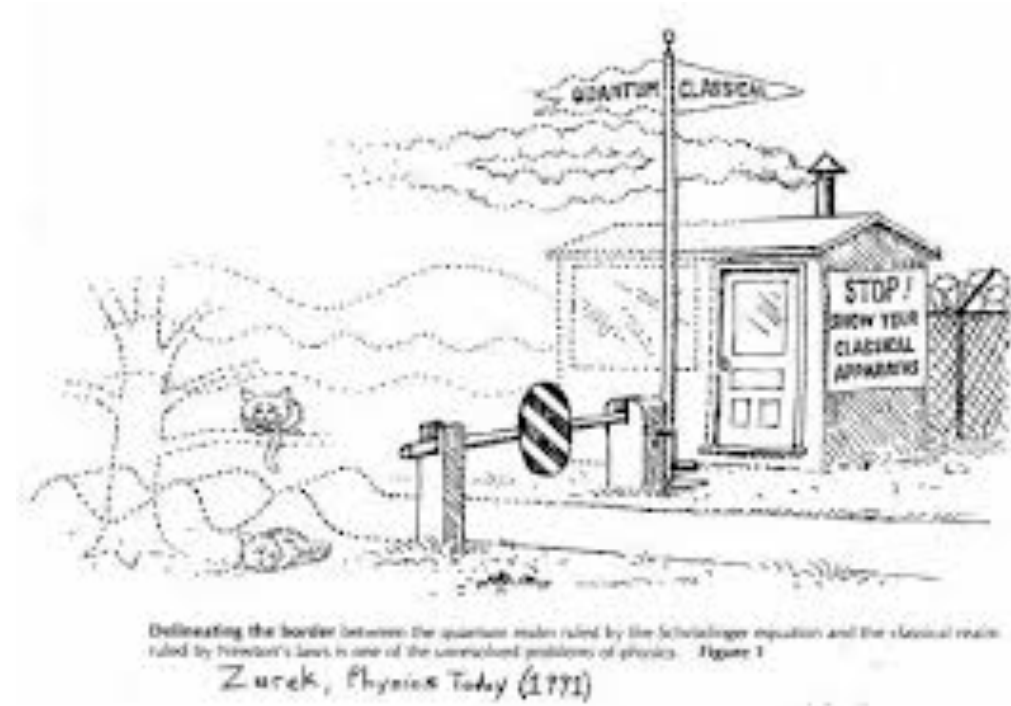


Schäfer-Nolte et al., *Phys. Rev. Lett.* (2014)
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Quantum Mechanics

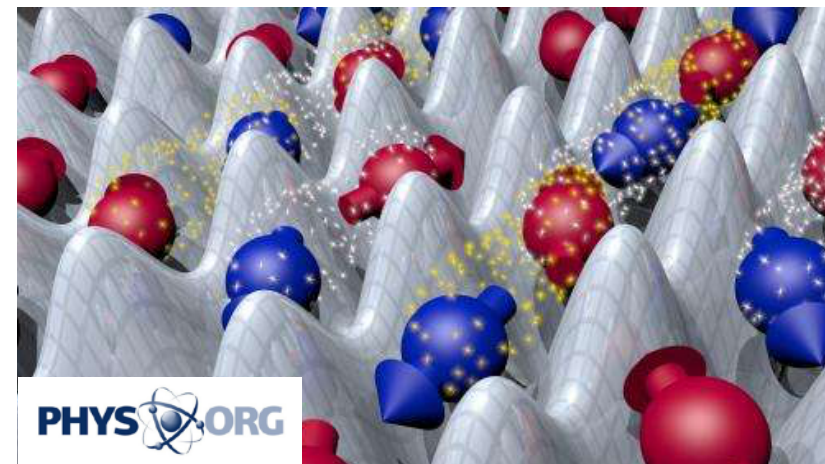
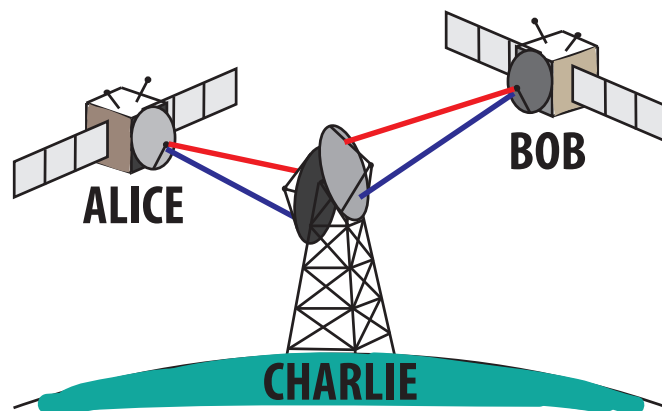
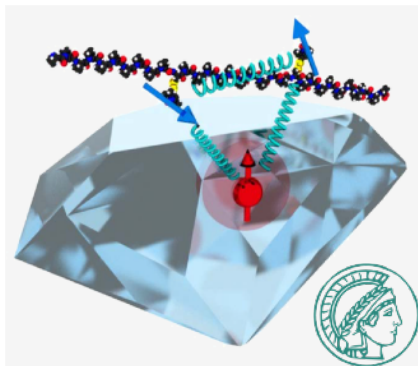
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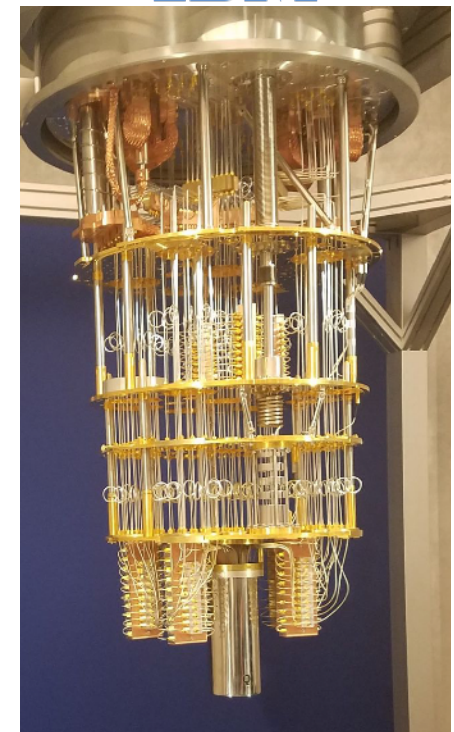


Technological

- Sensing
- Communication
- Simulation
- Computation



IBM



Schäfer-Nolte et al., *Phys. Rev. Lett.* (2014)
Greif et al., *Science* (2013)

Photons?

What photons truly are?

- Particle 
- Wave 

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Hanbury-Brown and Twiss (HBT) Experiment

- Spontaneous emission
- Number states



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$$\hat{a}^\dagger \hat{a} |n\rangle = n |n\rangle$$

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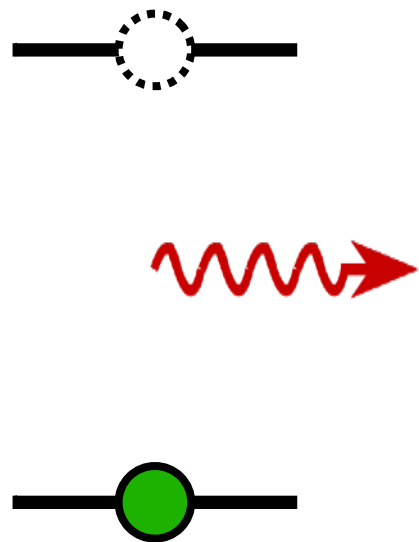
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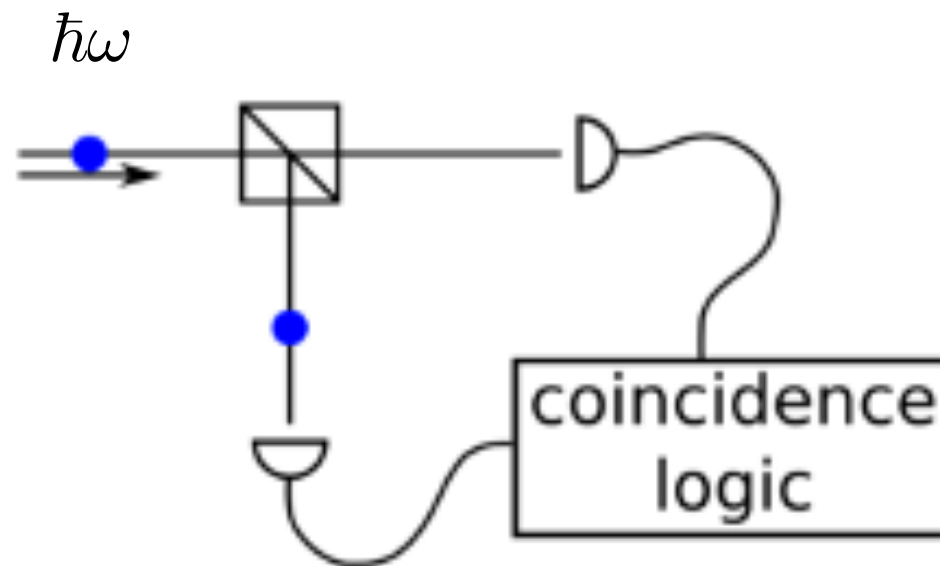
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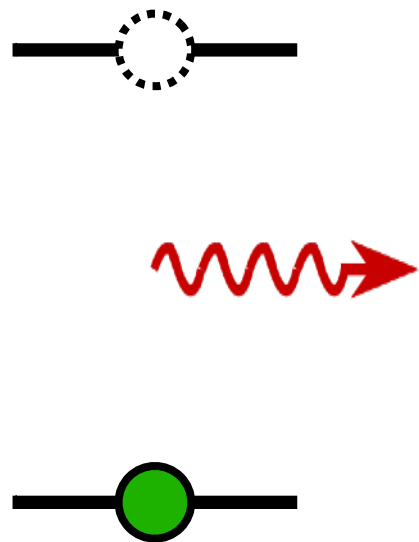
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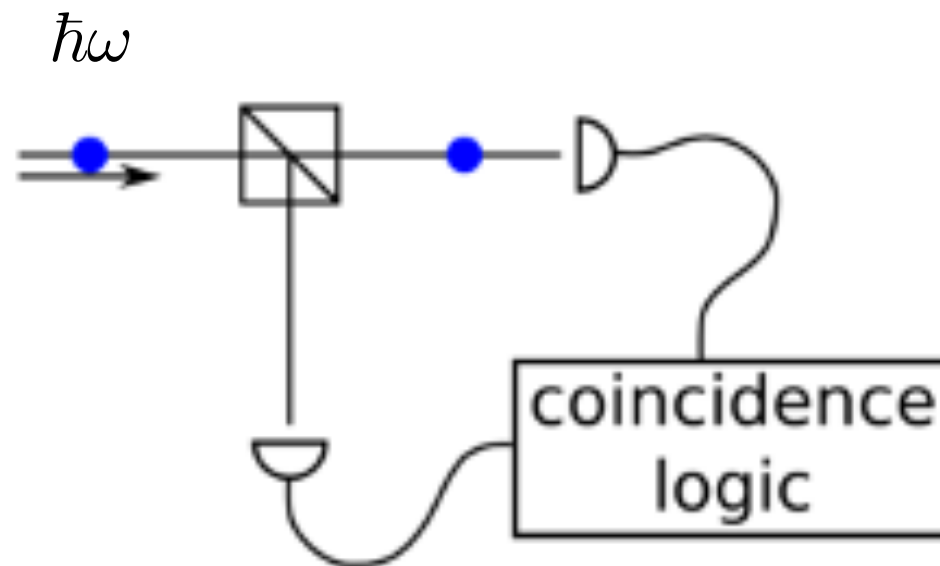
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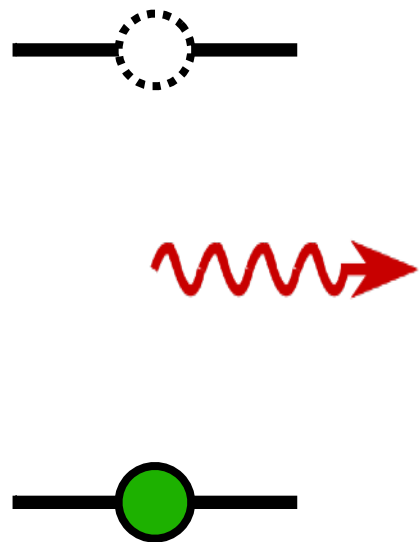
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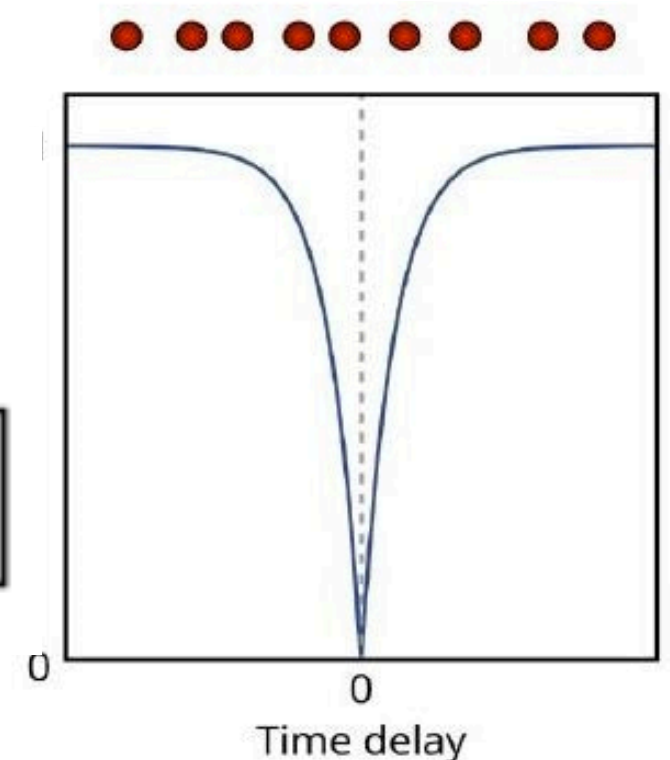
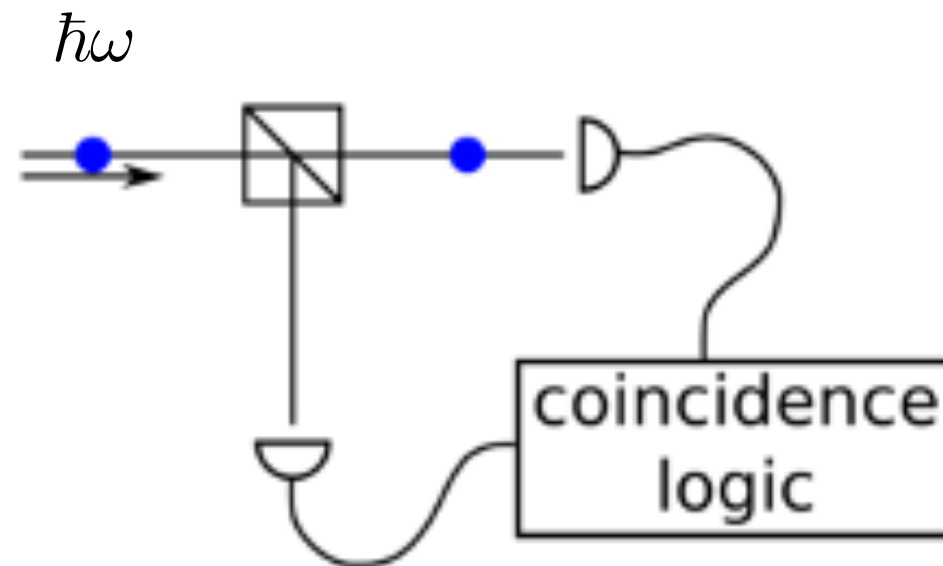
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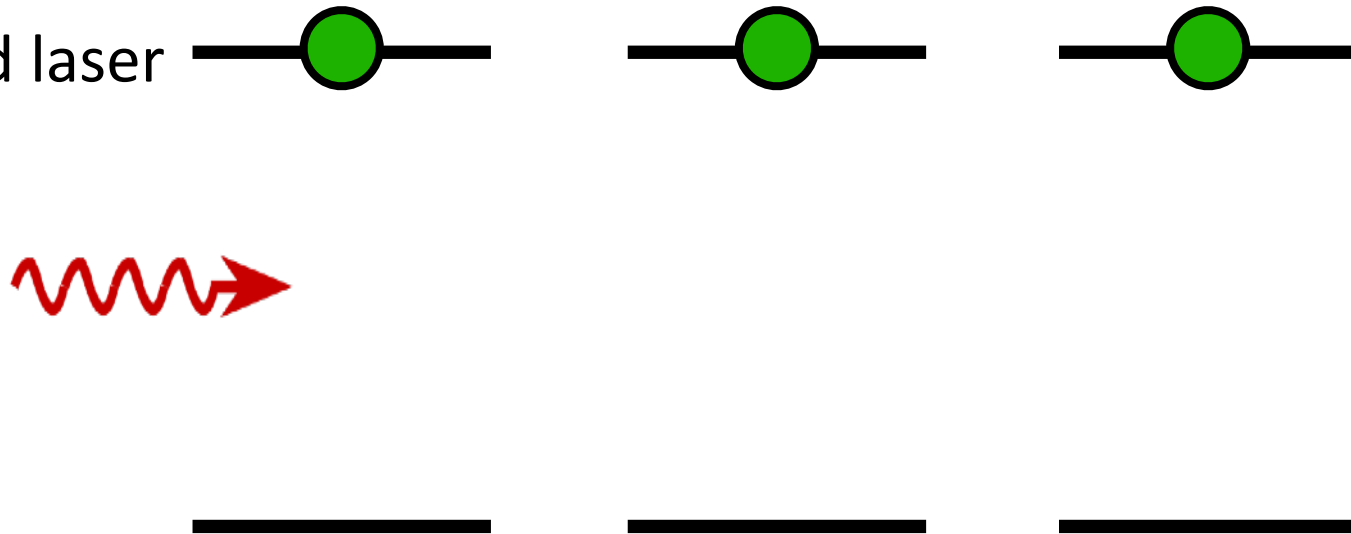
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Photons?

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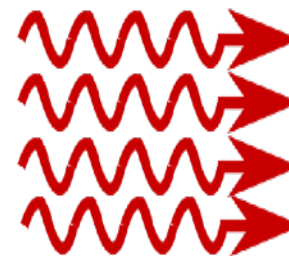
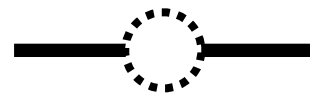
- Stimulated emission
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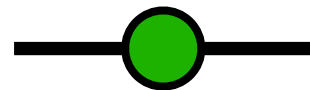
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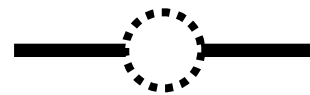
$$\hat{a}|\alpha\rangle = \alpha|\alpha\rangle$$



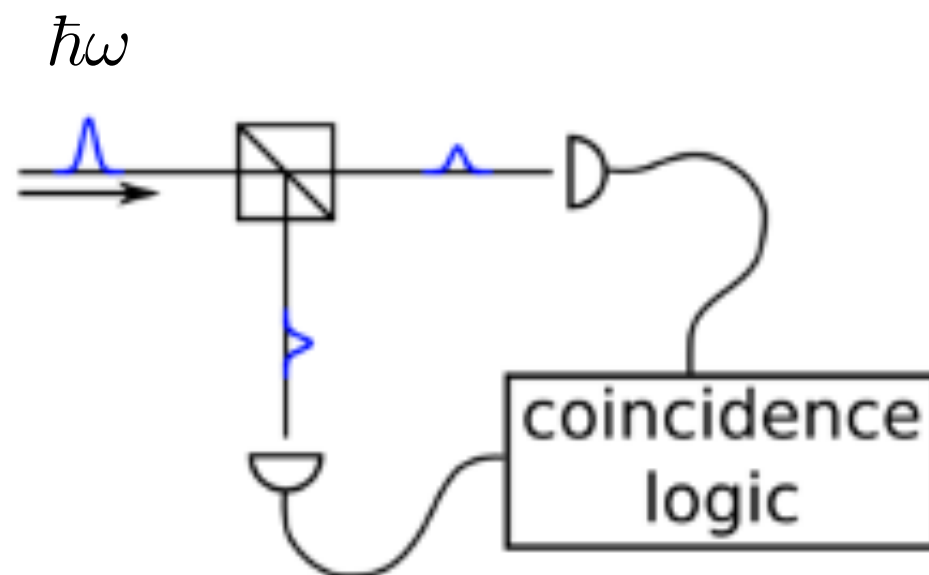
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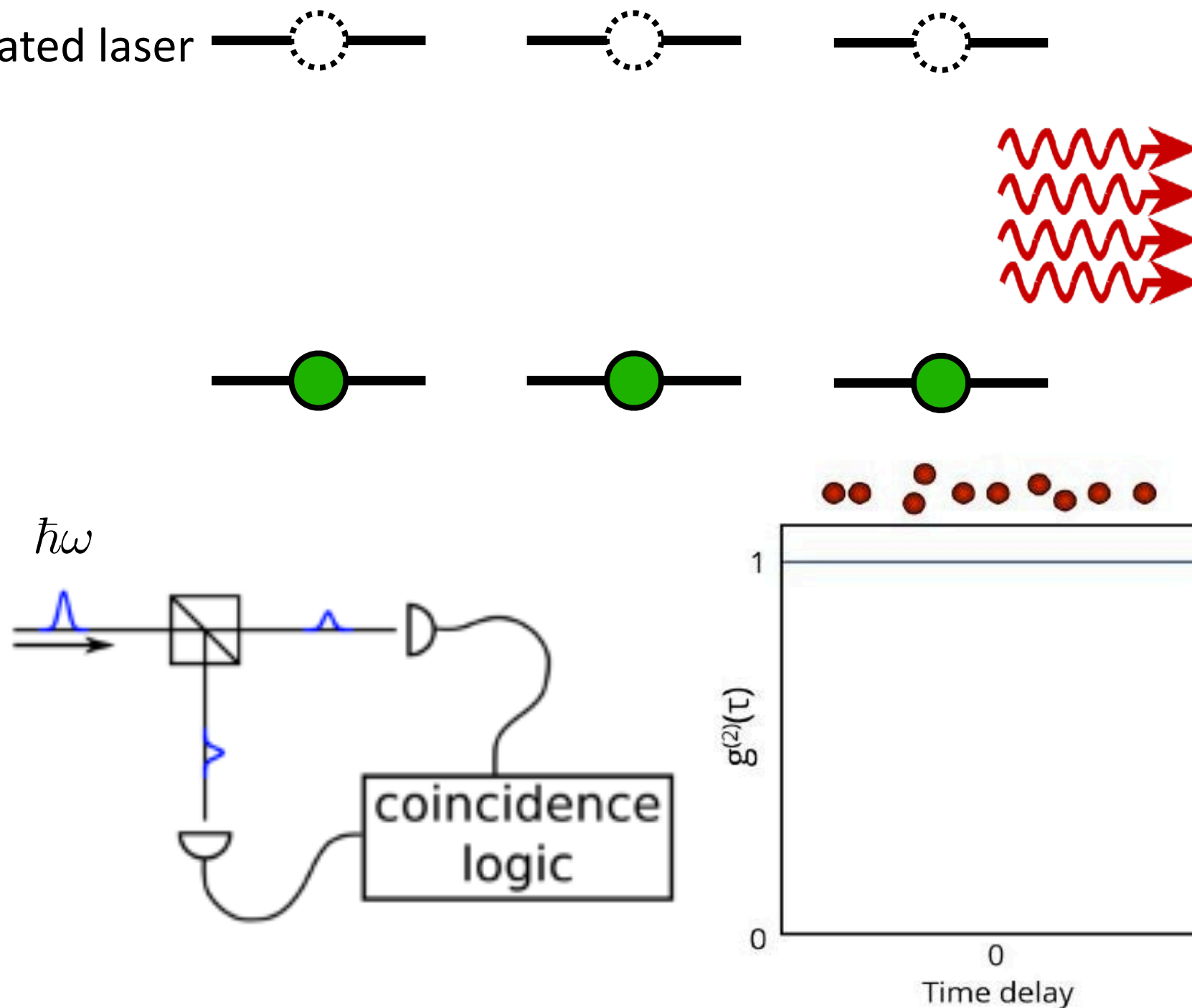
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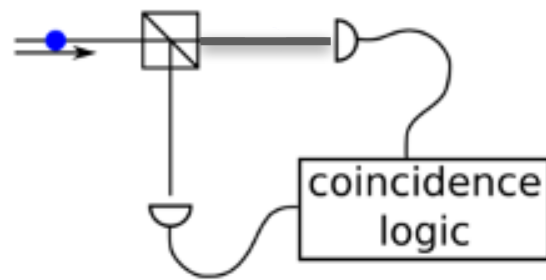


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Are Single Photons Particles?

Hong, Ou, and Mandel (HOM)

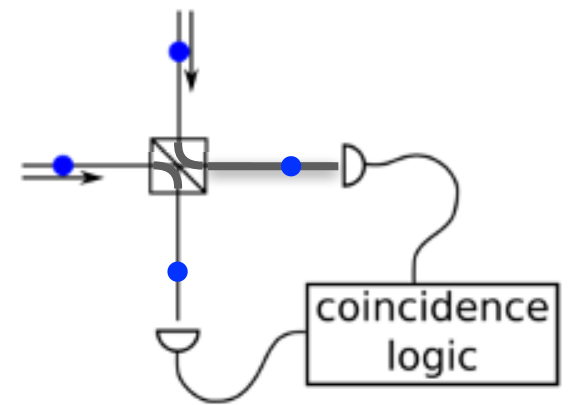
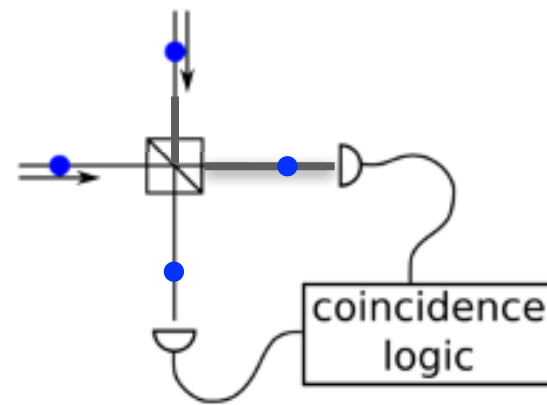
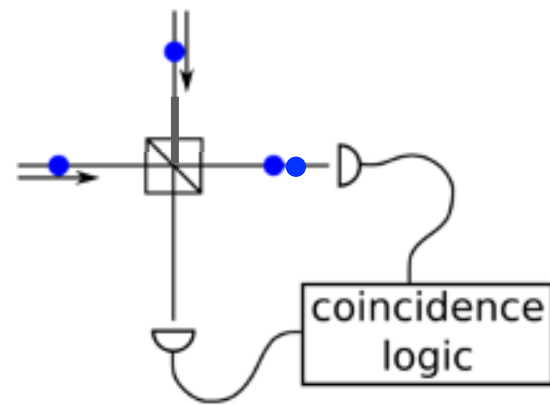
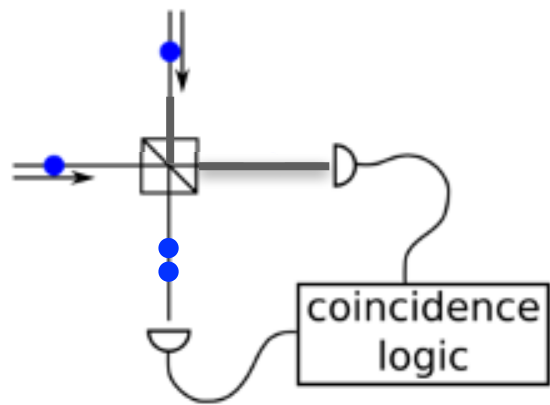
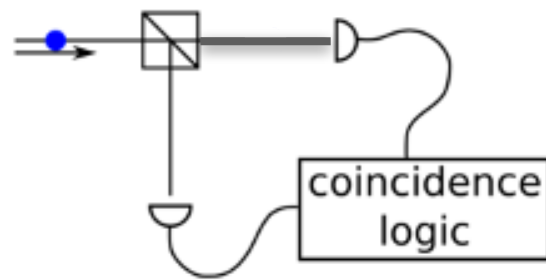
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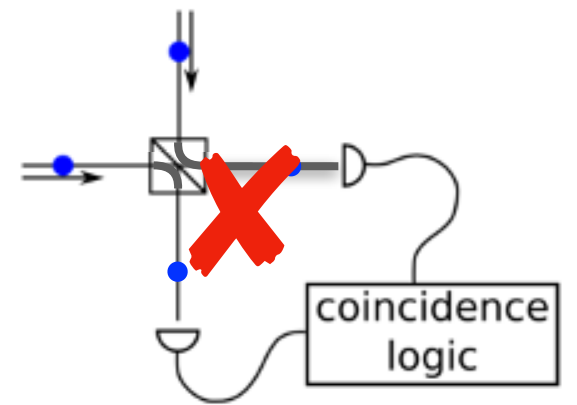
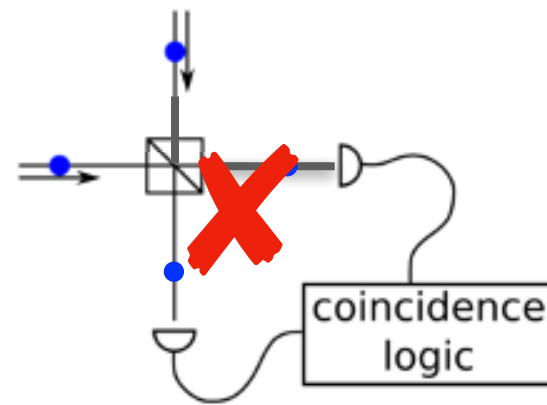
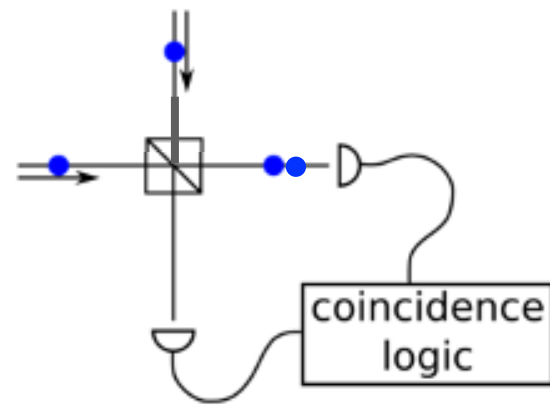
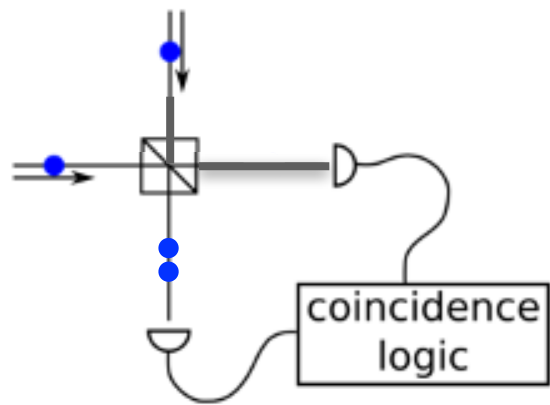
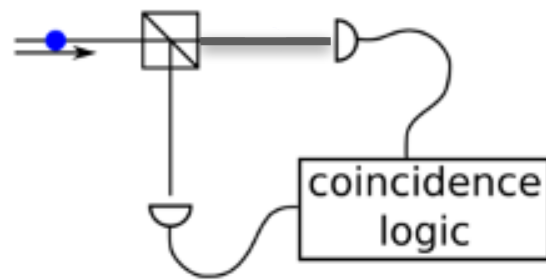
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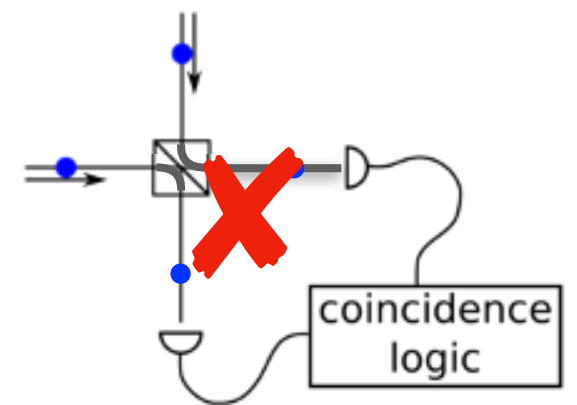
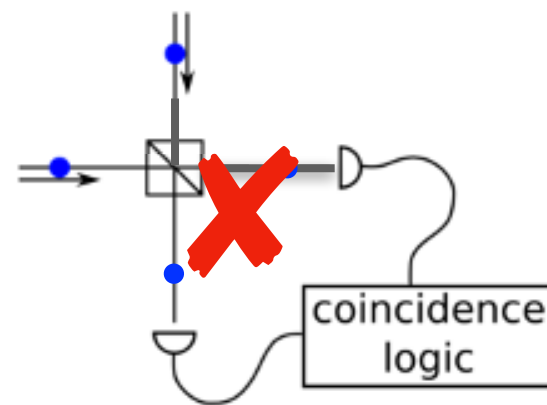
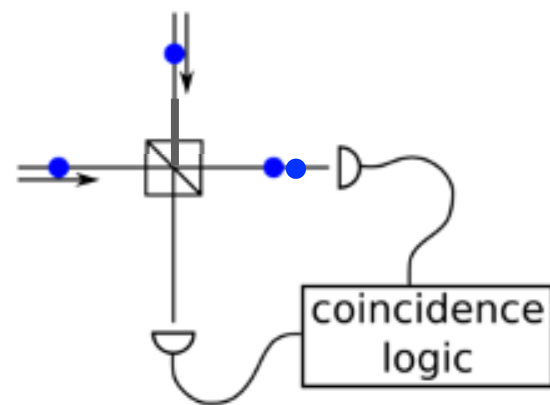
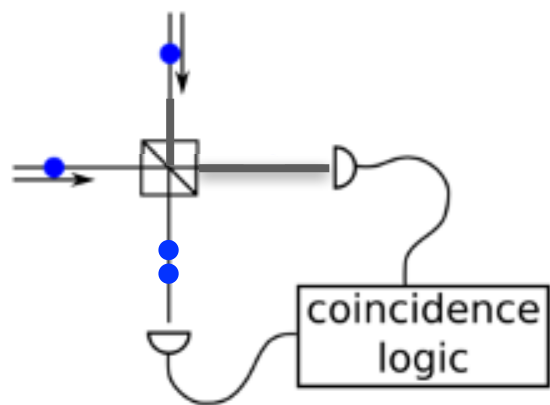
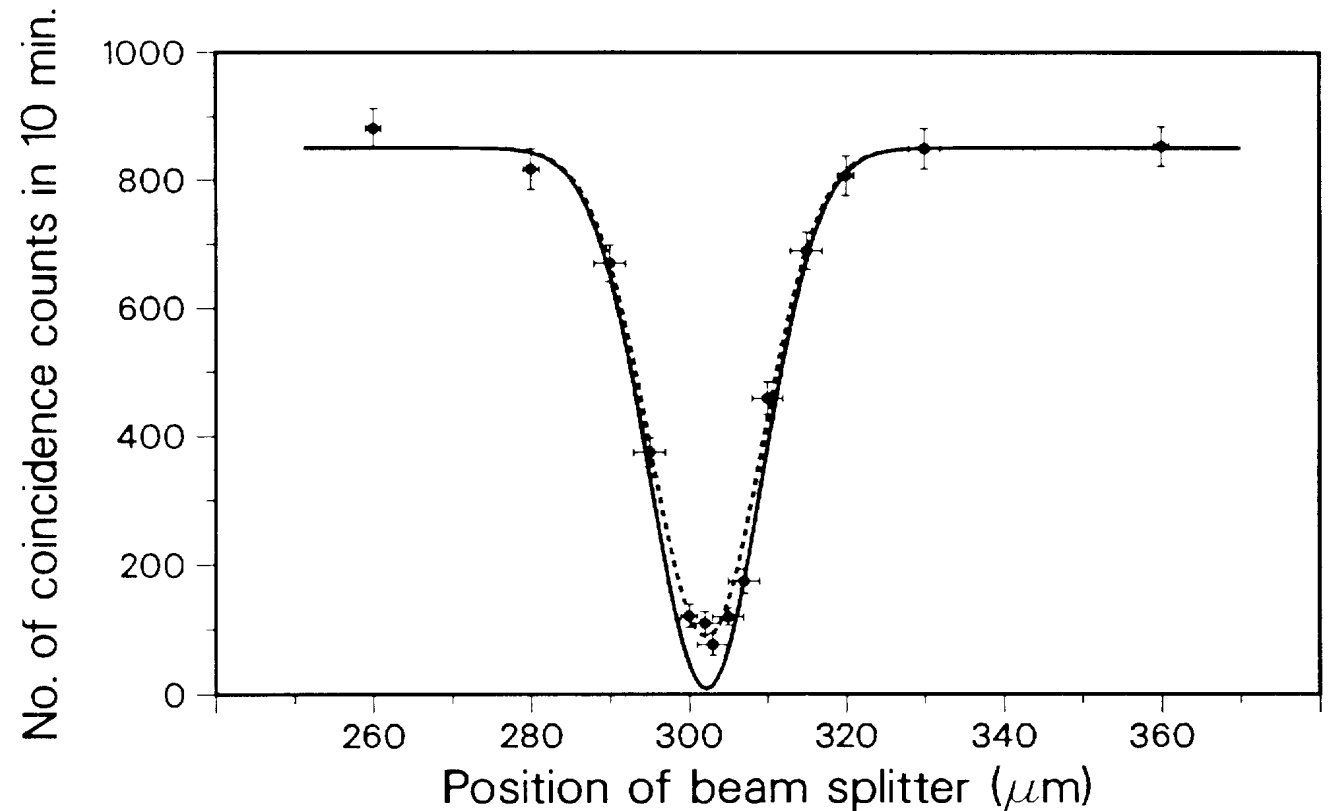
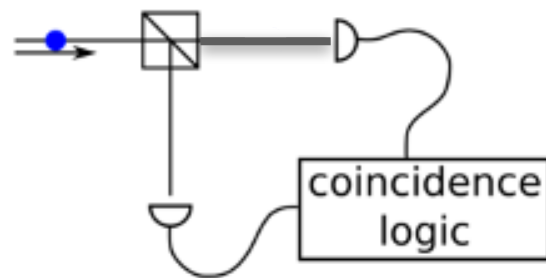
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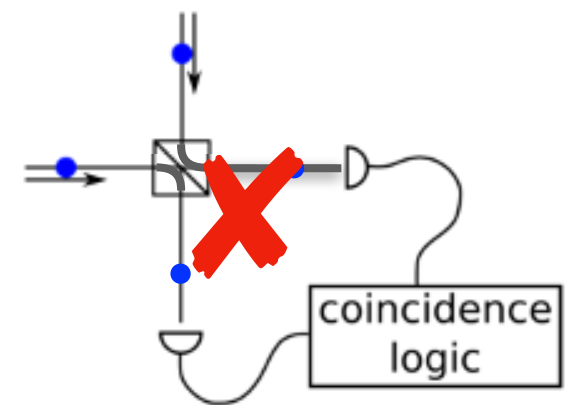
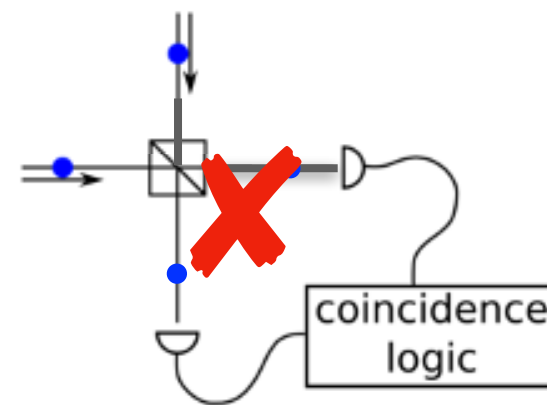
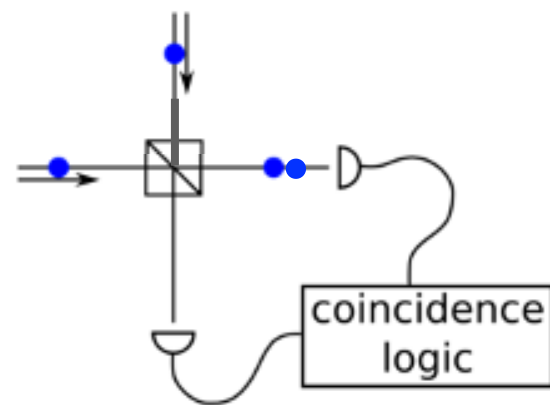
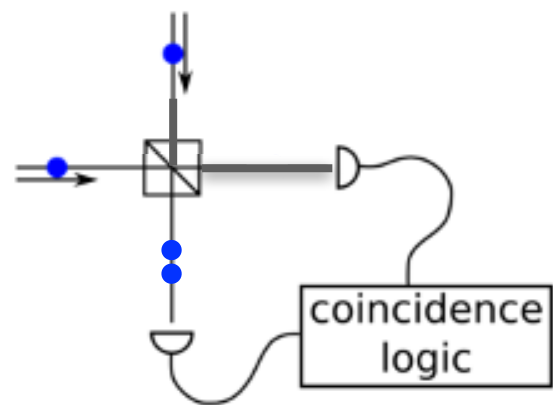
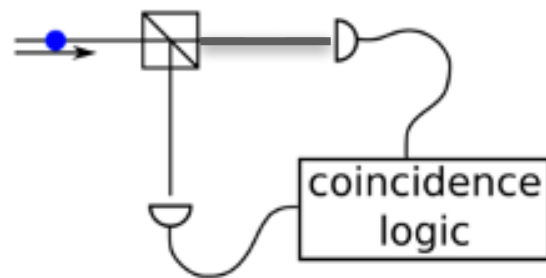
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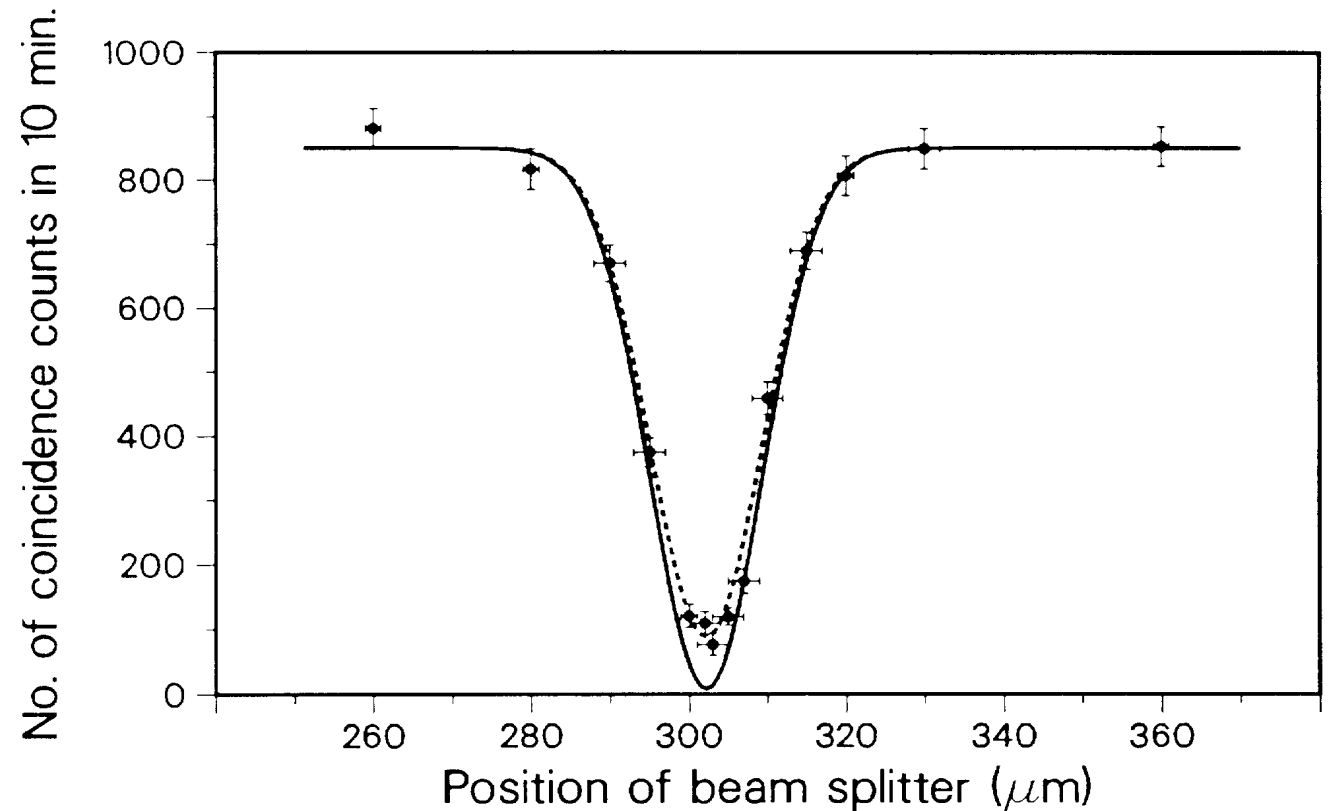
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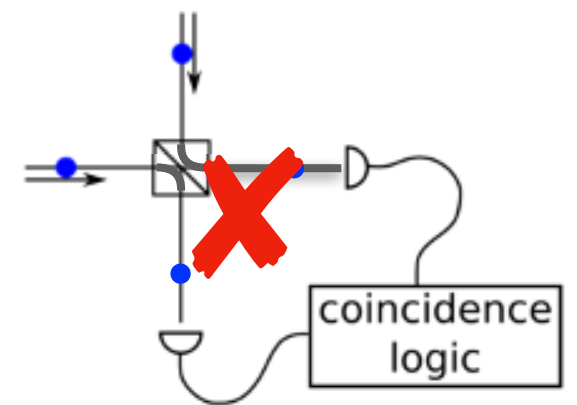
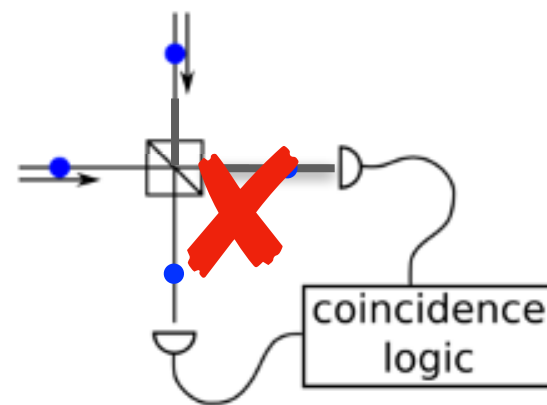
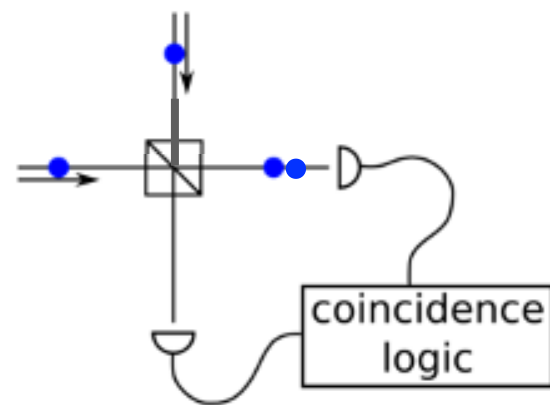
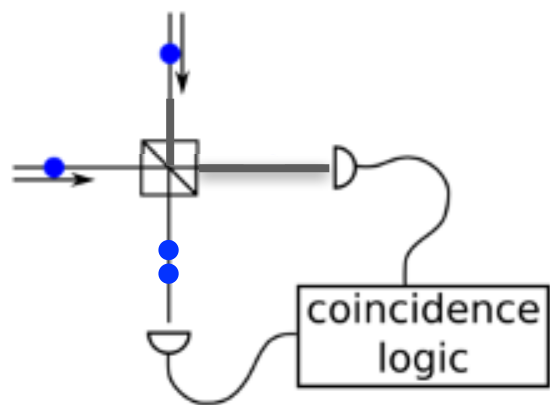
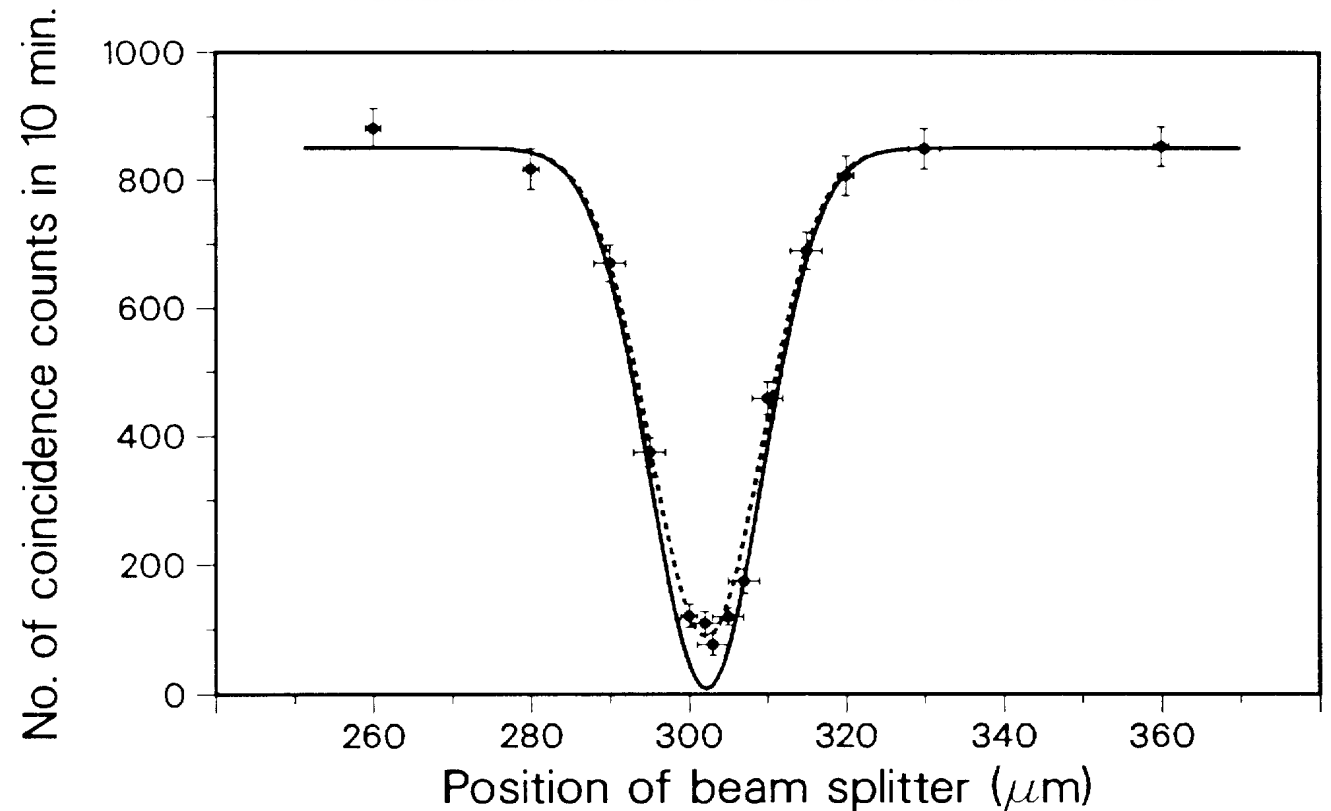
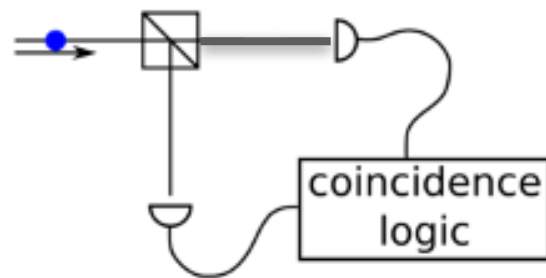
What is a photon, ontological?
We don't really know.



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Boson Sampling, Quantum Supremacy

Color Centers

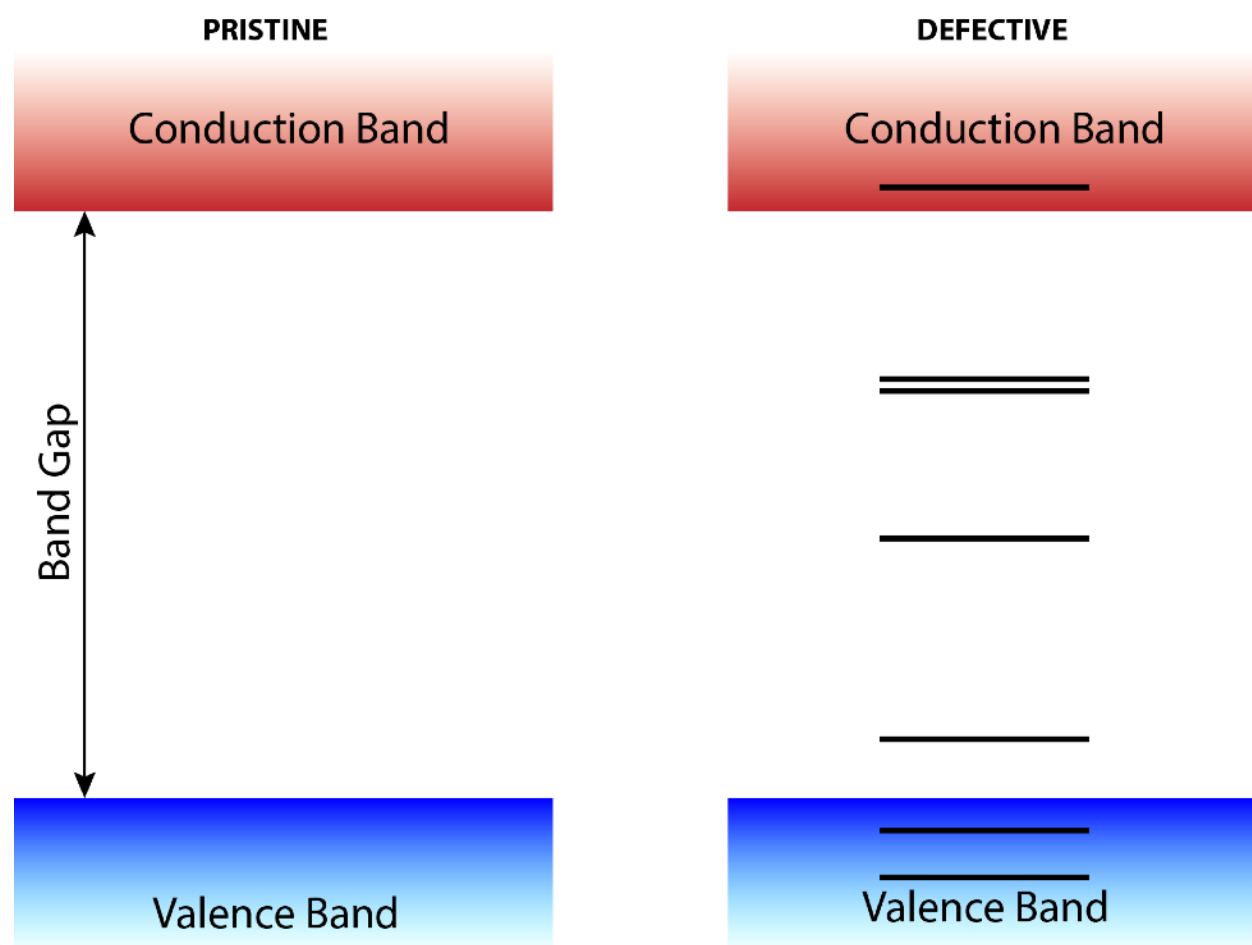
Insulators and Defects

- Large bandgap (Optical transitions)
- Localized defect (Spatial and Energy)
- Partial occupation by electrons

Color Centers

Insulators and Defects

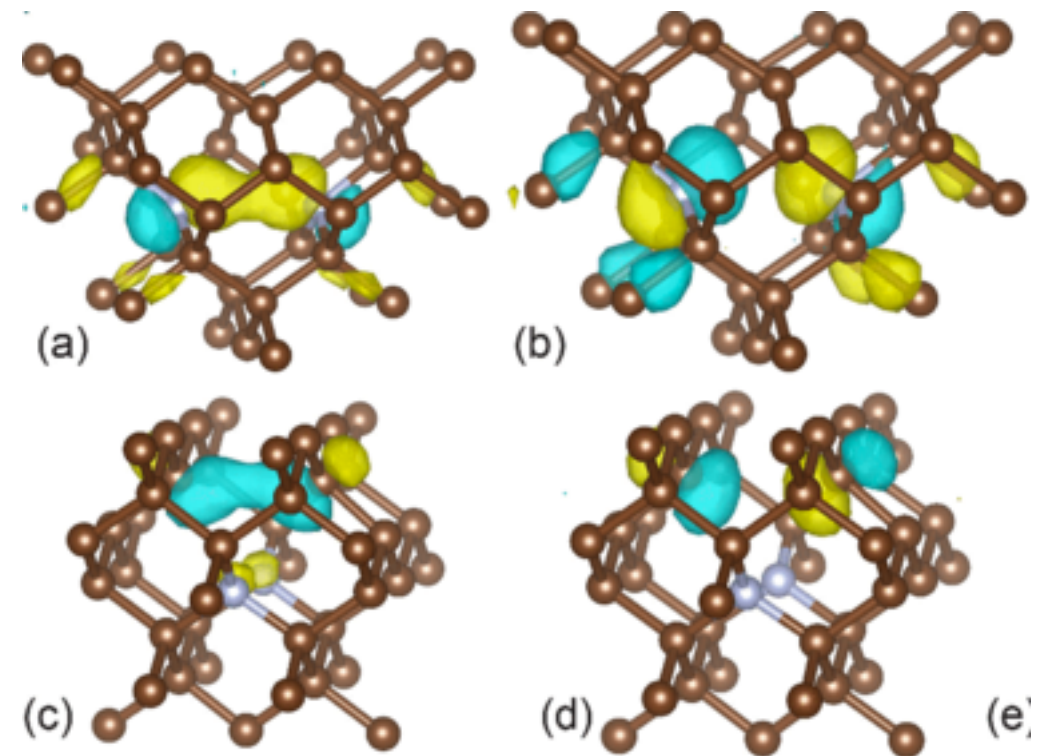
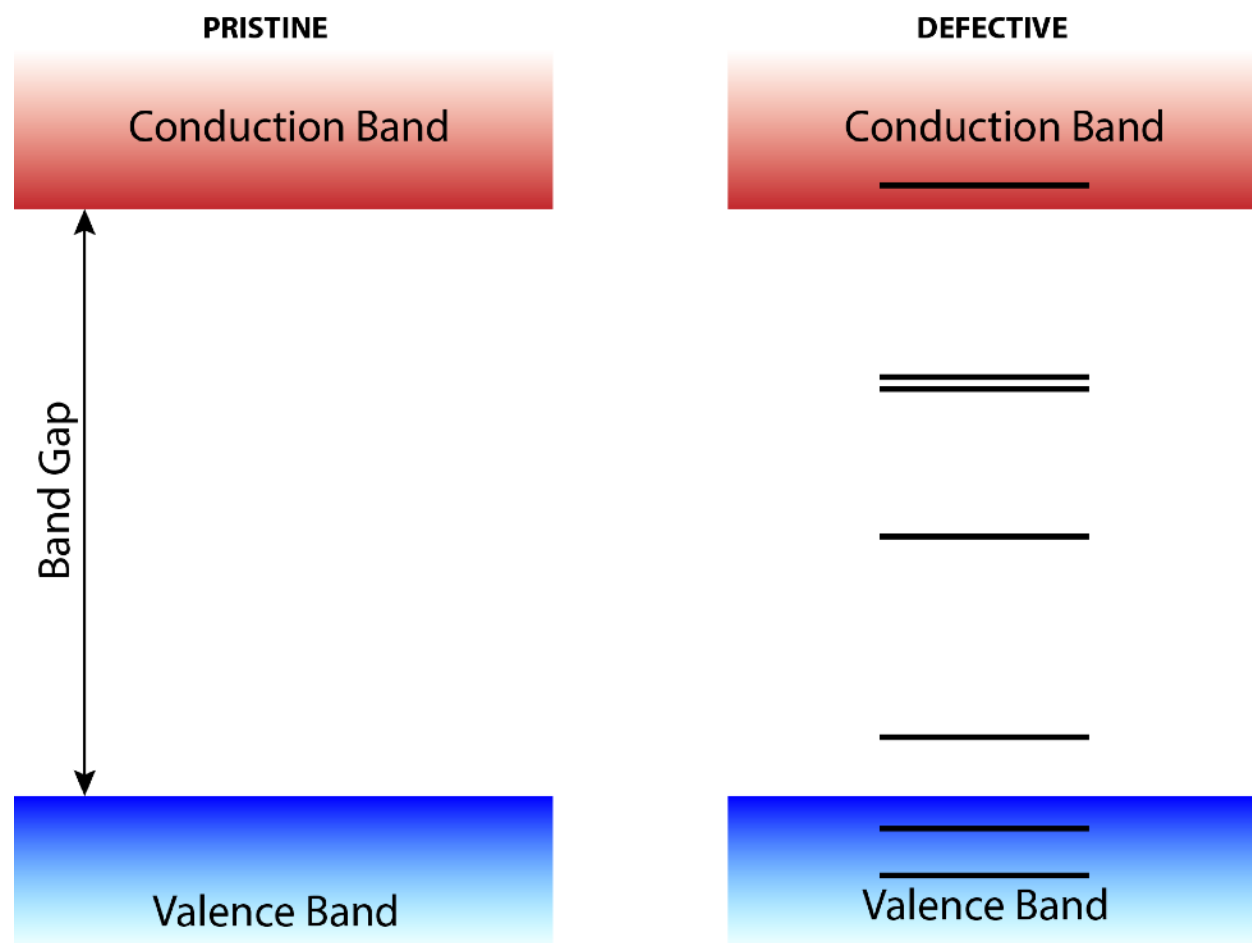
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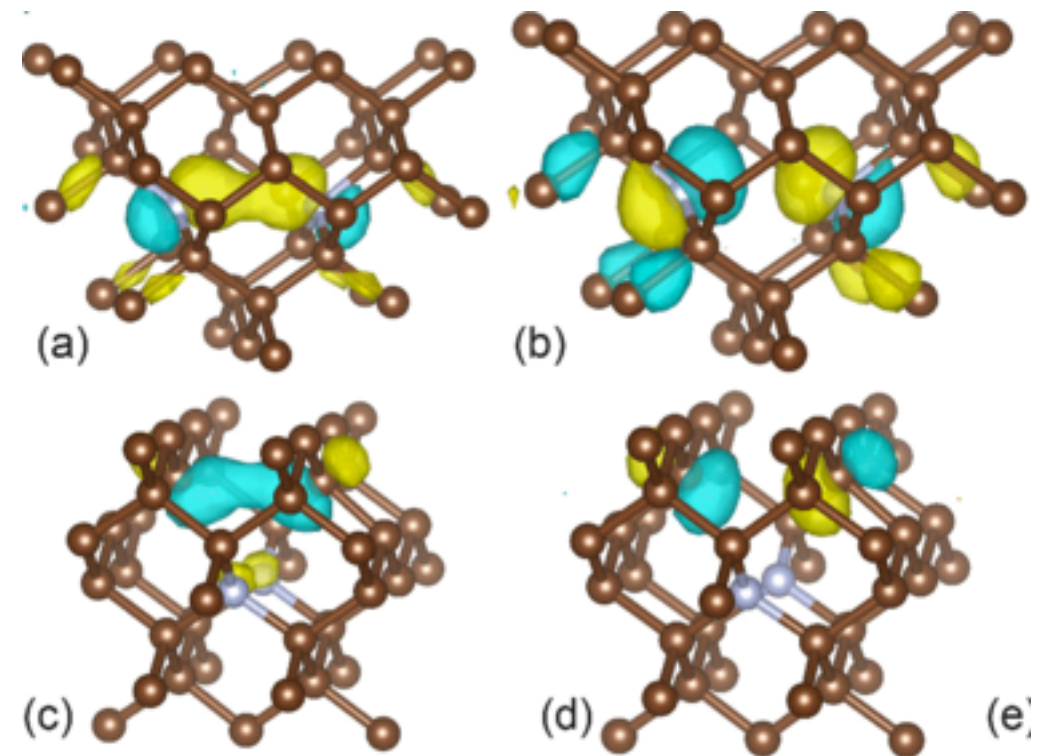
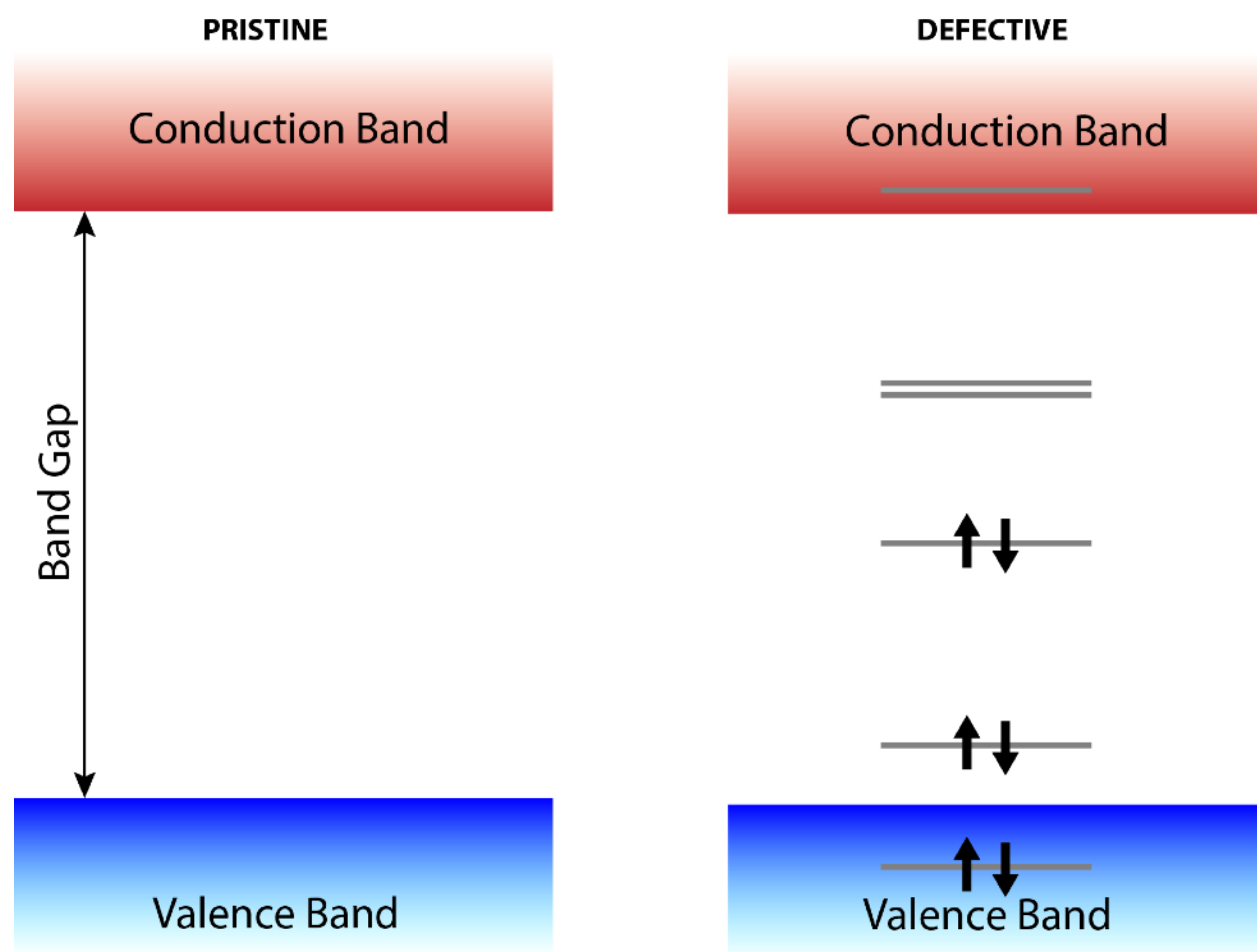
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Color Centers

Diamond Color Centers

- Pristine diamond is transparent
- Different colors



Actual colors may vary due to individual computer screen color settings.

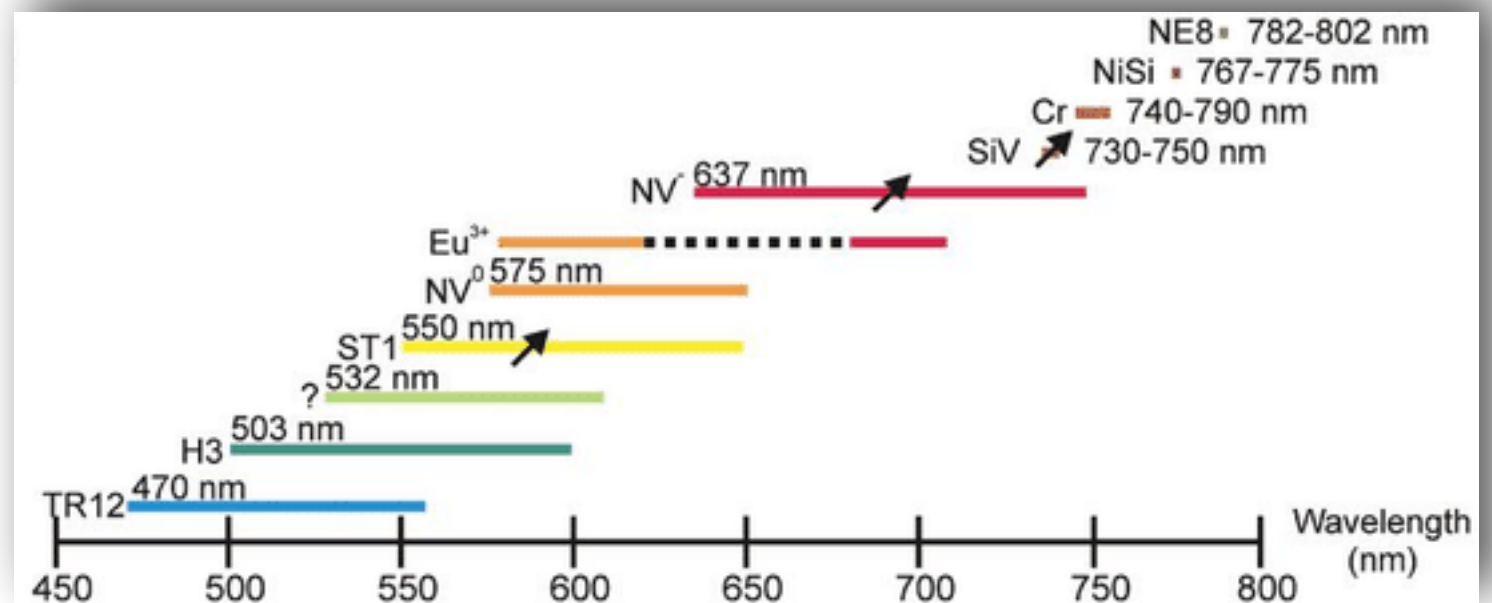
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Aharonovich and Neu, Adv. Opt. Mat. (2014)

Could One Do Quantum Technologies With PhoNons?



MPQ

WMI

TUM

Hybrid Devices

Superconducting Circuit

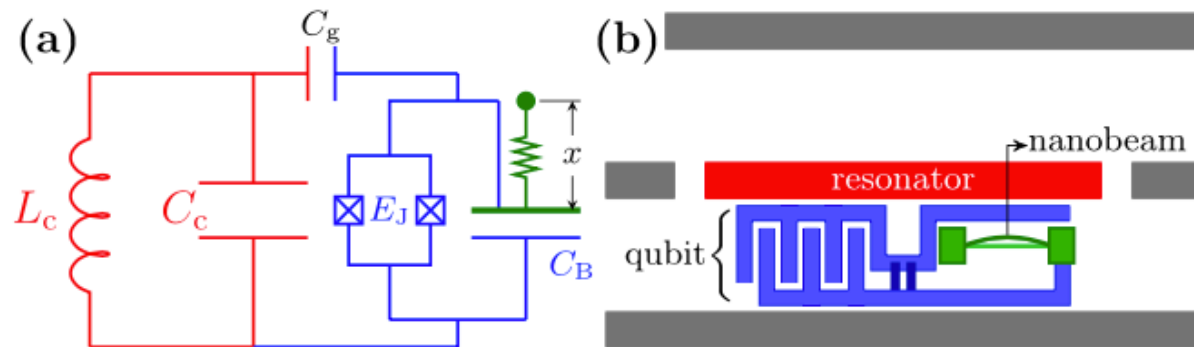
- Polariton-Phonon
- Nonclassical states
- Mechanical Fock



Hybrid Devices

Superconducting Circuit

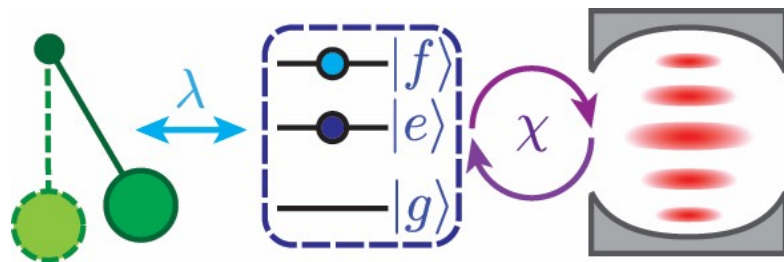
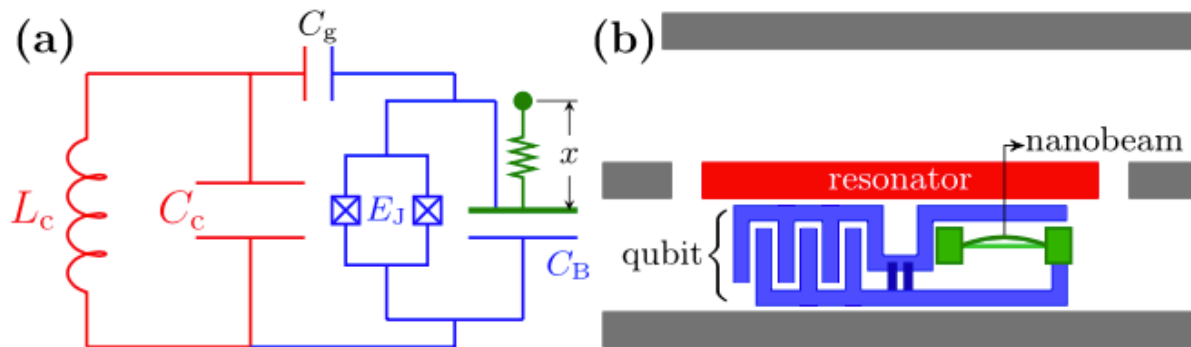
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Hybrid Devices

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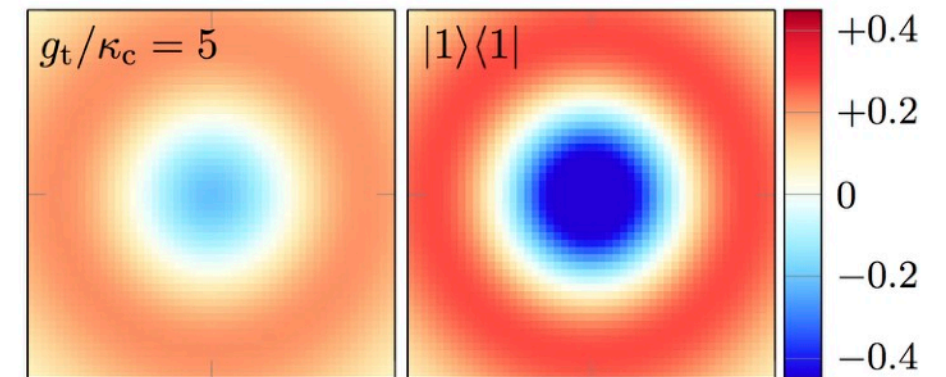
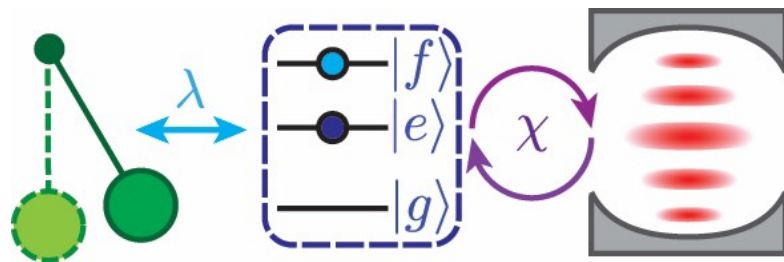
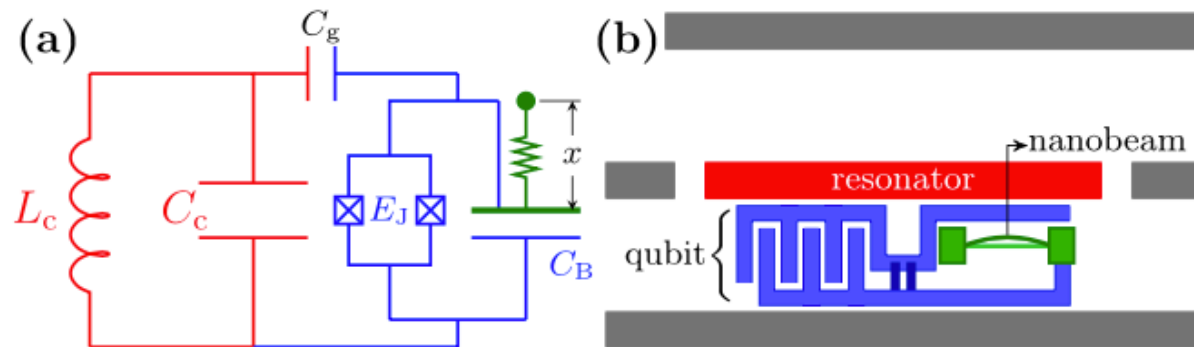
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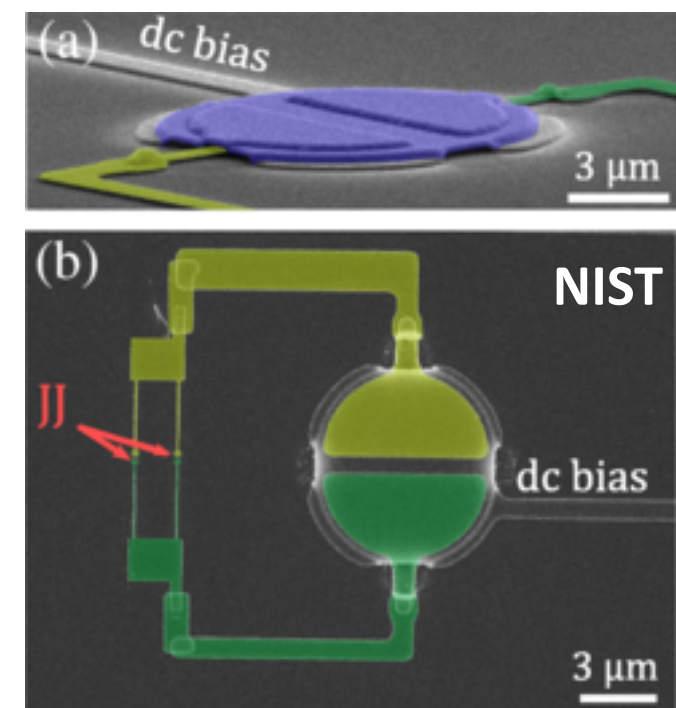
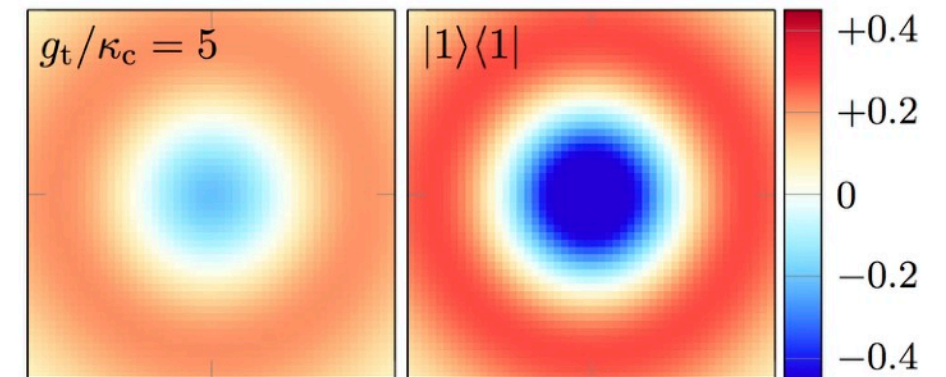
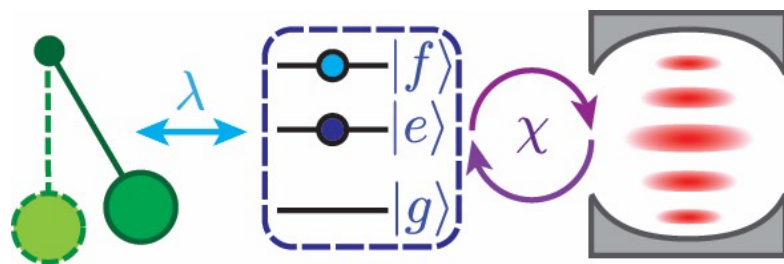
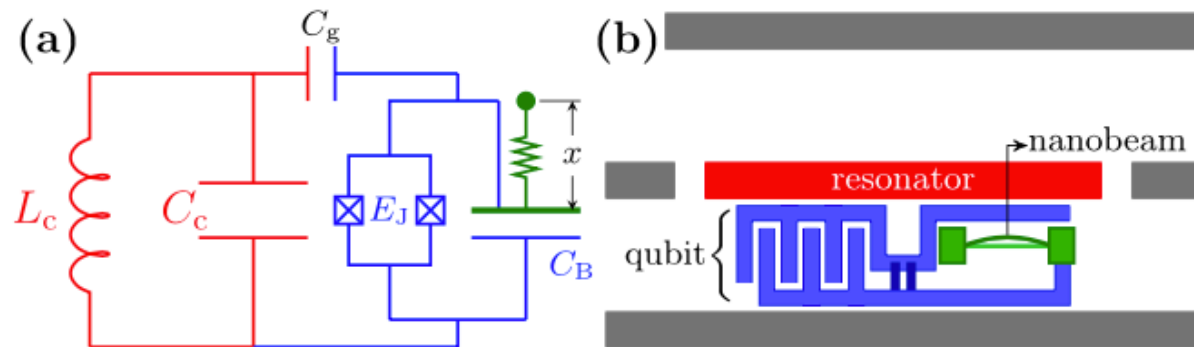
- Polariton-Phonon
- Nonclassical states
- Mechanical Fock



Hybrid Devices

Superconducting Circuit

- Polariton-Phonon
- Nonclassical states
- Mechanical Fock



Motional Hybridization

Varieties

- Bulk Acoustic Resonator
- Strings
- Bats
- Surface Acoustic Resonator
- Graphene

Pirkkalainen et al., *Nature* (2013)

Yeo et al., *Nat. Nanotechnol.* (2013)

Gustafsson et al., *Science* (2014)

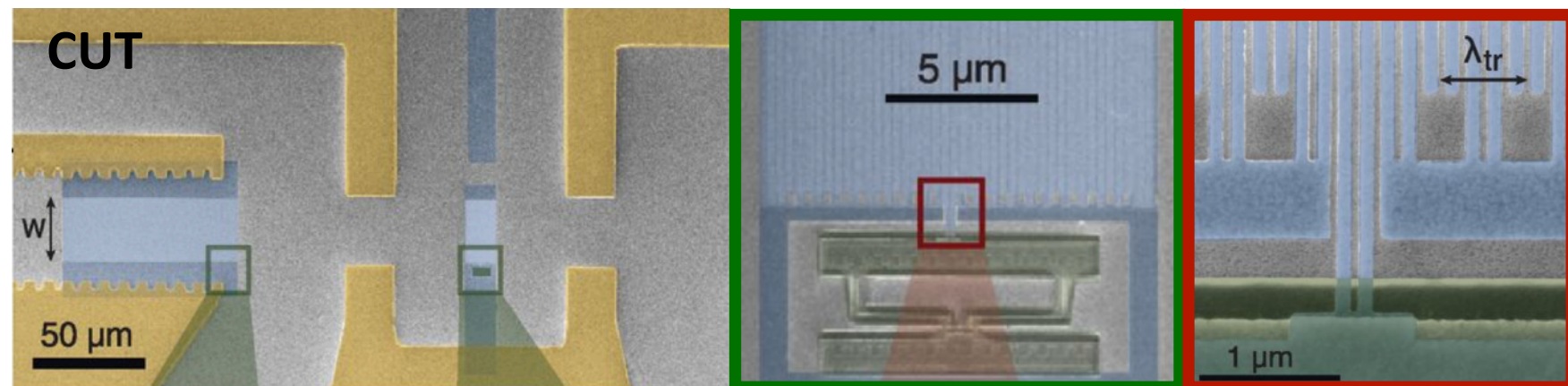
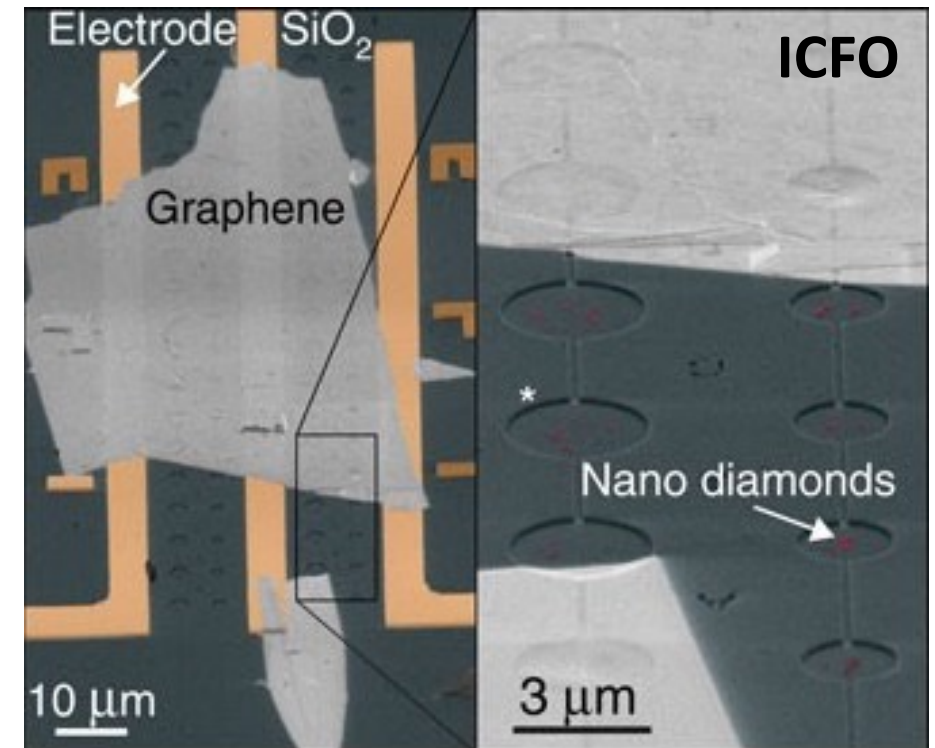
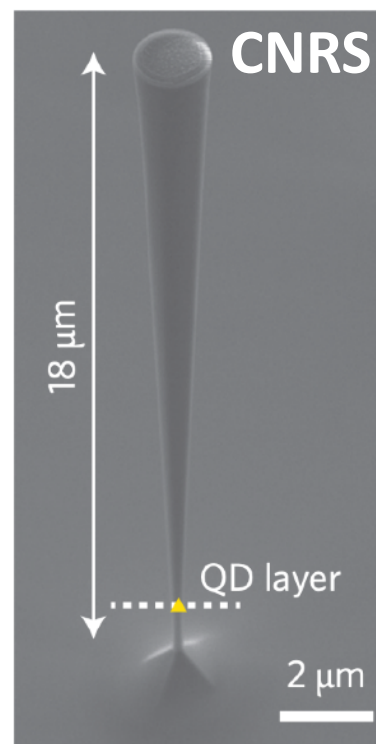
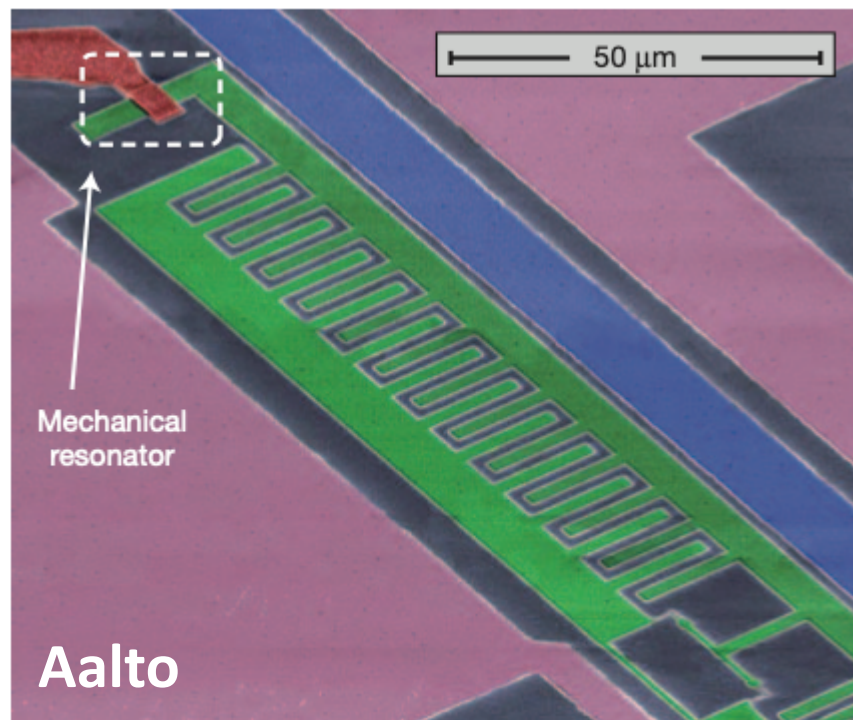
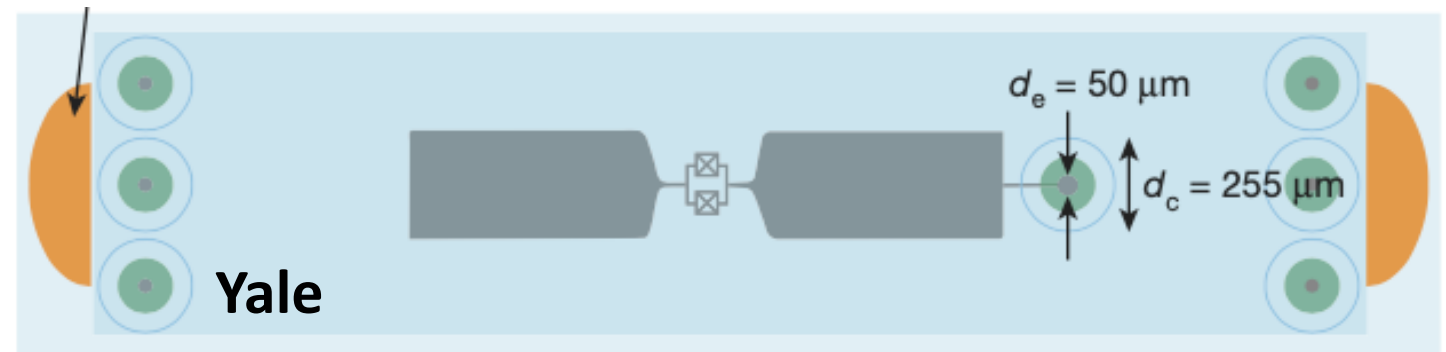
Reserbat-Plantey et al., *Nat. Commun.* (2016)

Chu et al., *Nature* (2018)

Motional Hybridization

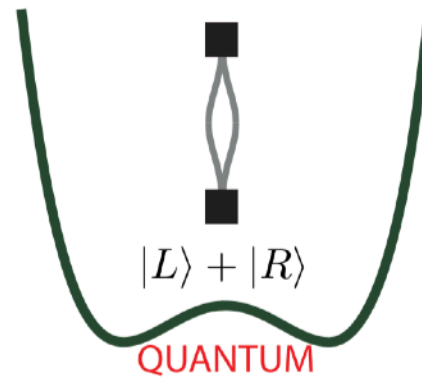
Varieties

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Pirkkalainen et al., *Nature* (2013)
 Yeo et al., *Nat. Nanotechnol.* (2013)
 Gustafsson et al., *Science* (2014)
 Reserbat-Plantey et al., *Nat. Commun.* (2016)
 Chu et al., *Nature* (2018)

Graphene Cat State

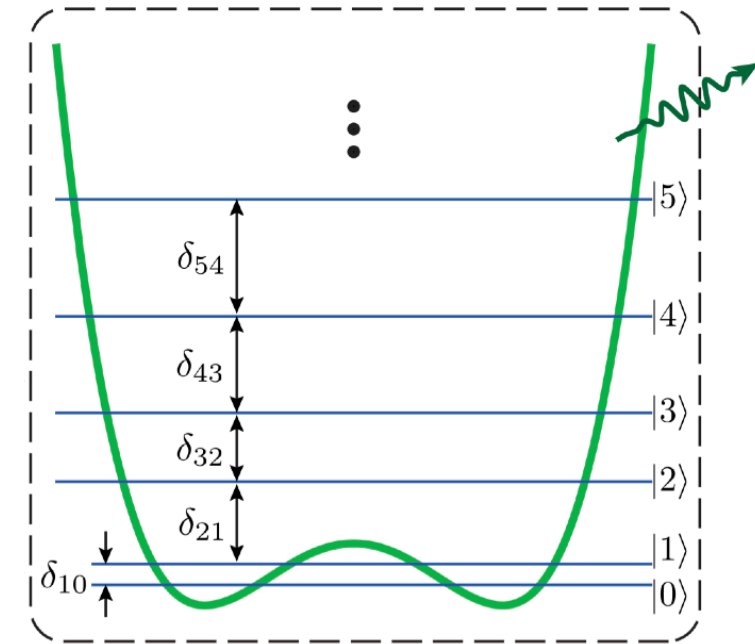
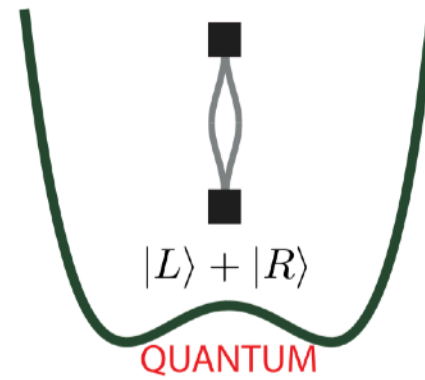


Singh et al., *Nat. Nanotechnol.* (2014)

Weber et al., *Nano Lett.* (2014)

MA et al., *Phys. Rev. Lett.* (2016)

Graphene Cat State

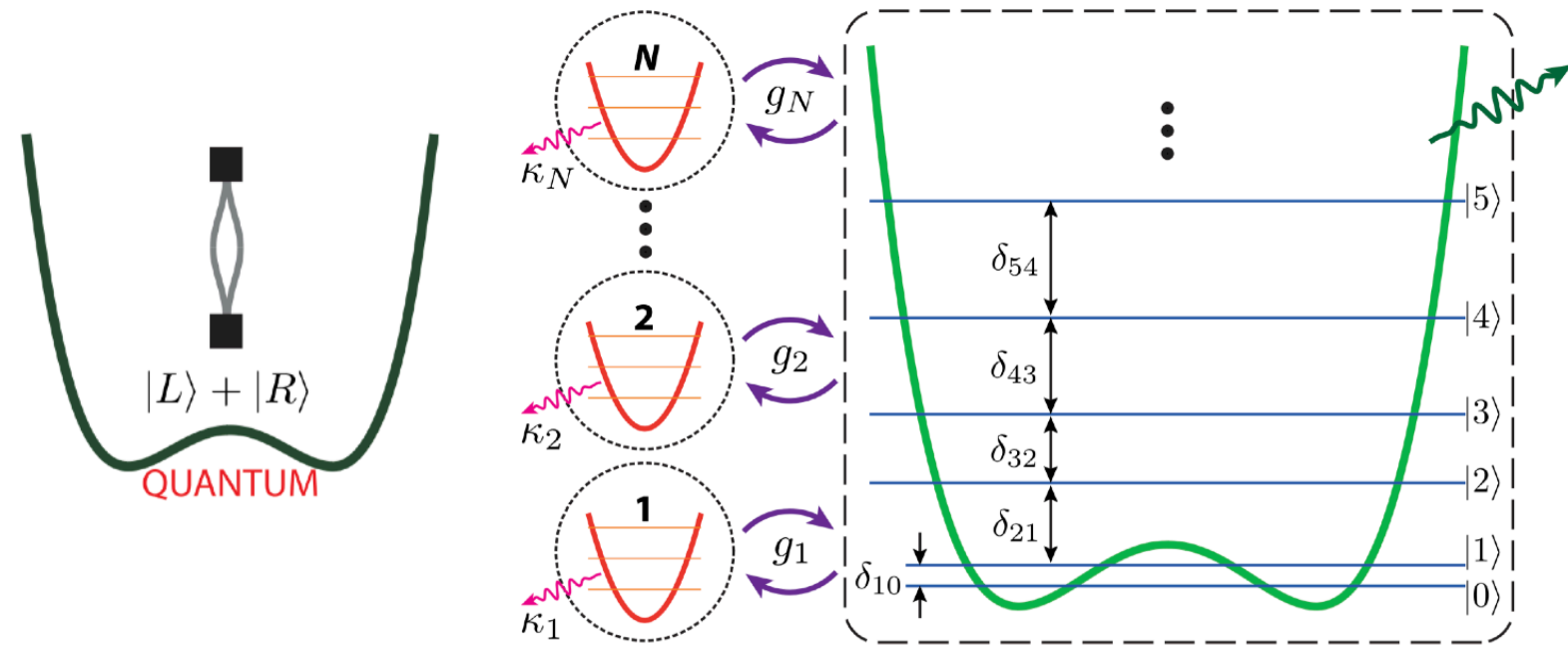


Singh et al., *Nat. Nanotechnol.* (2014)

Weber et al., *Nano Lett.* (2014)

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Graphene Cat State

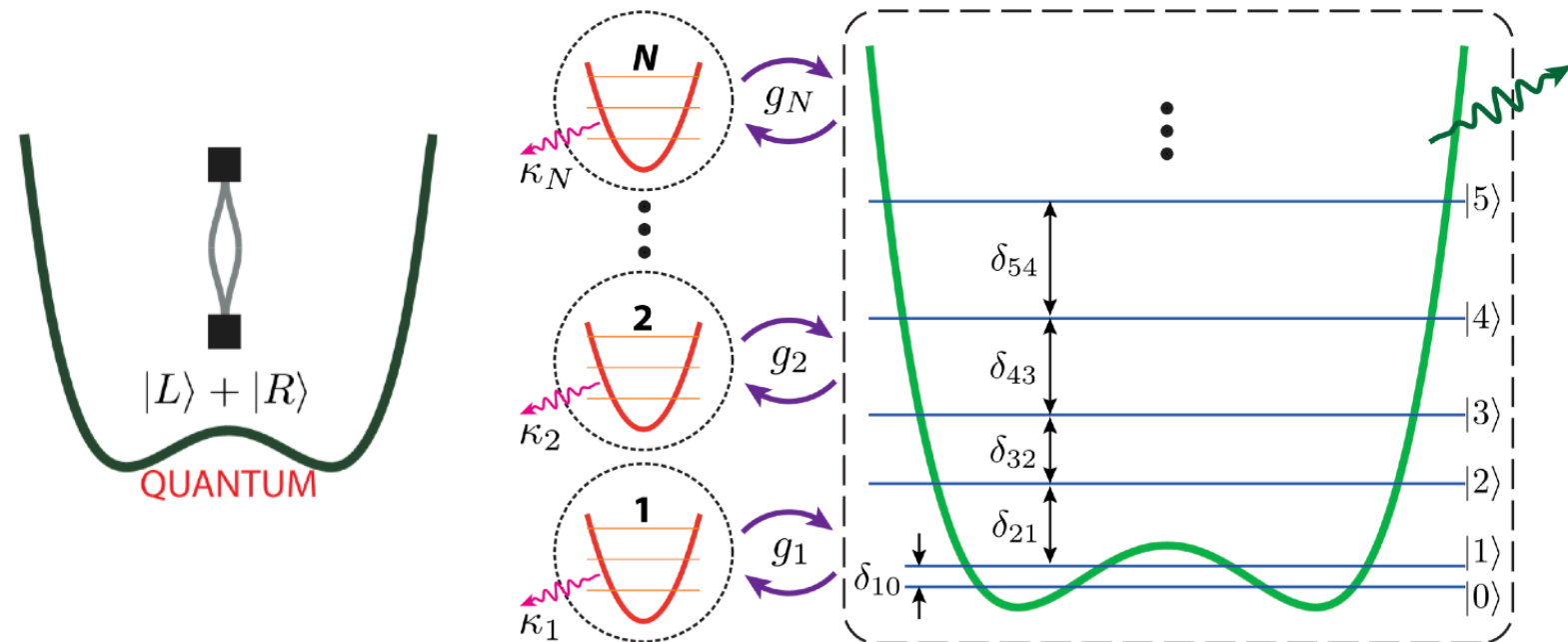
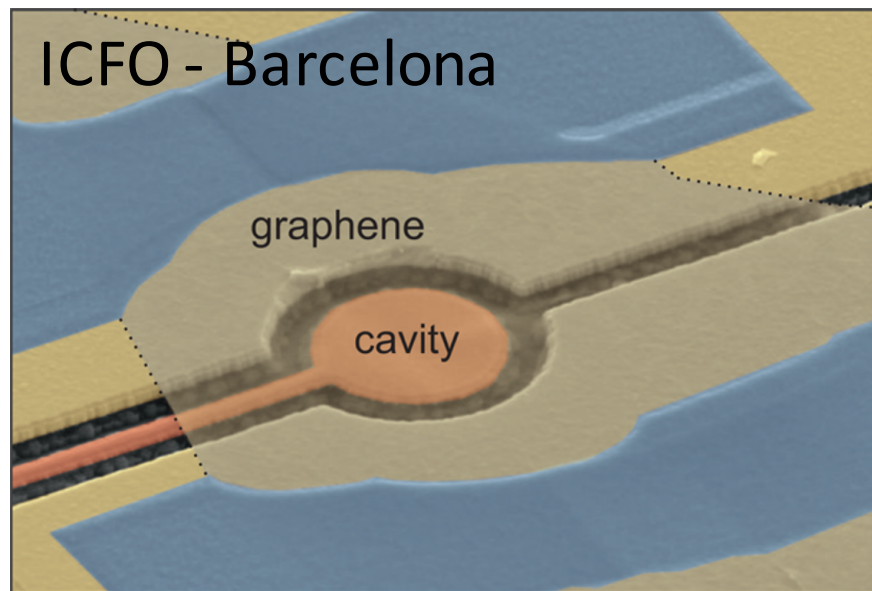
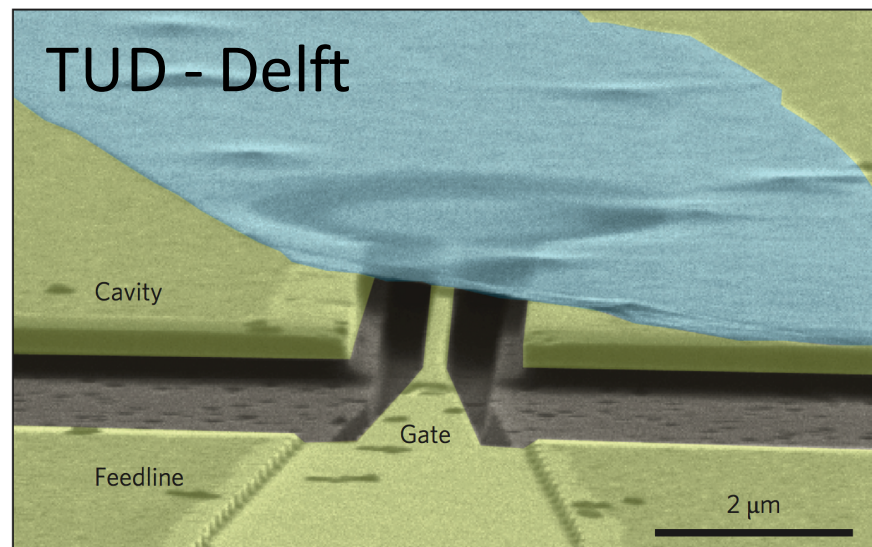


Singh et al., *Nat. Nanotechnol.* (2014)

Weber et al., *Nano Lett.* (2014)

MA et al., *Phys. Rev. Lett.* (2016)

Graphene Cat State

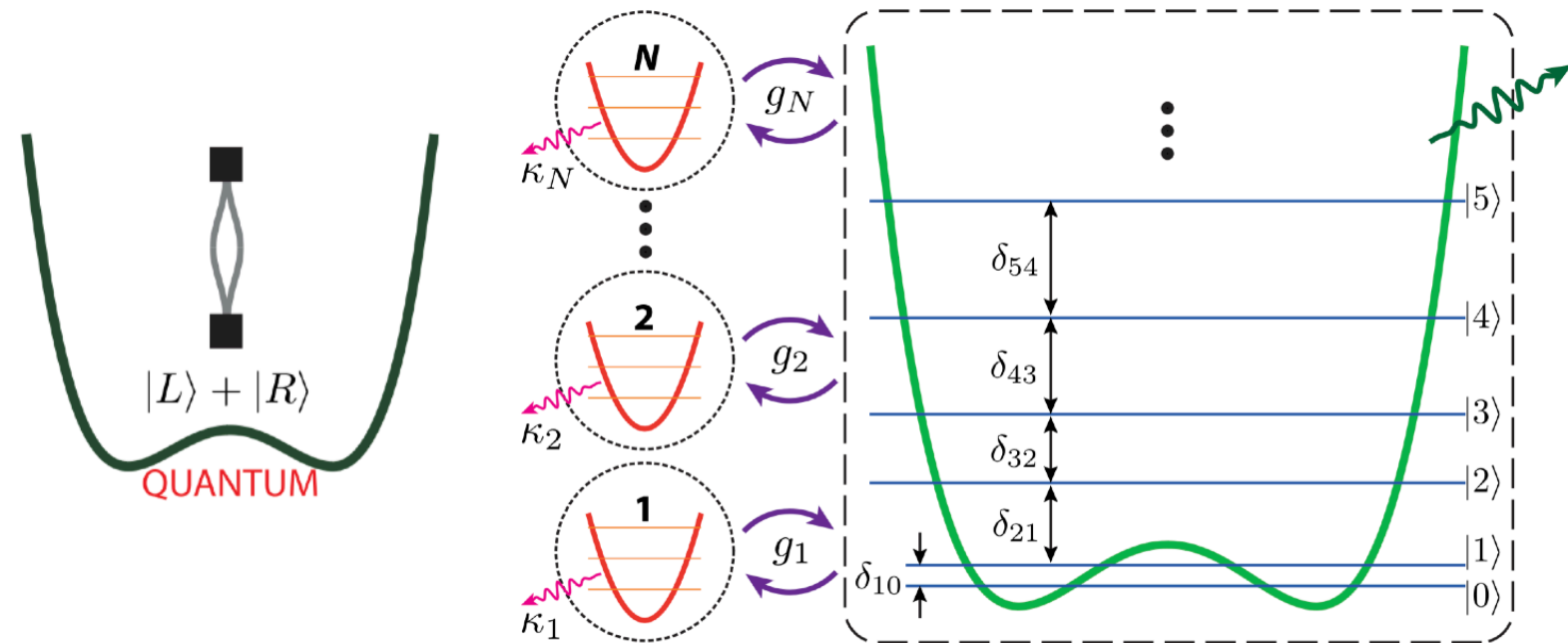
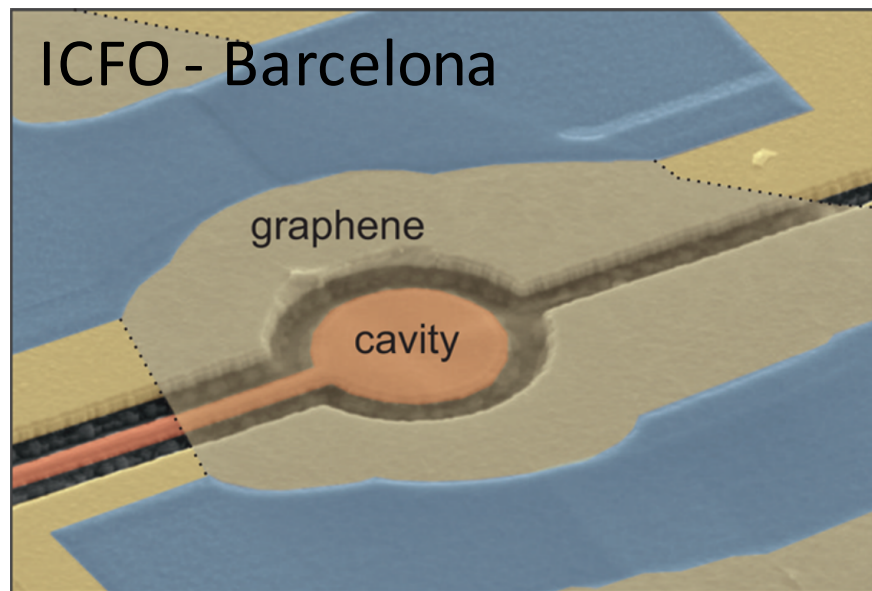
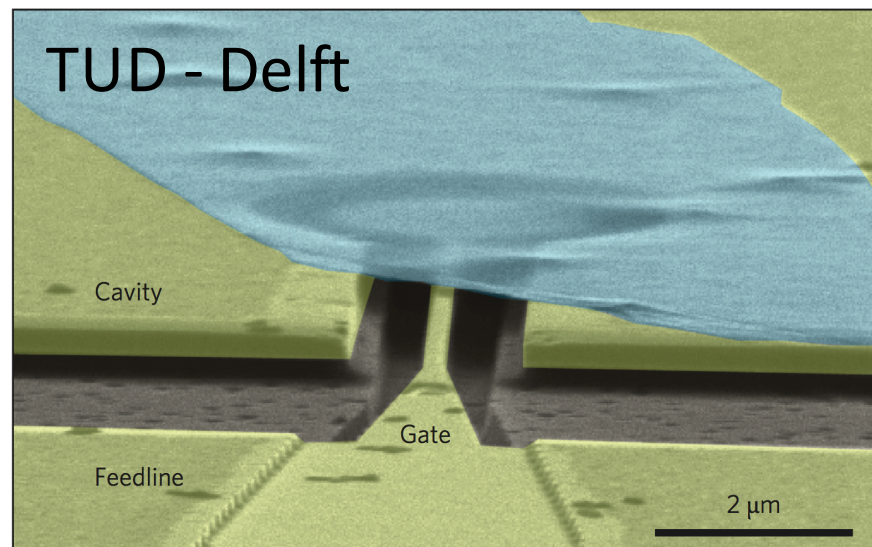


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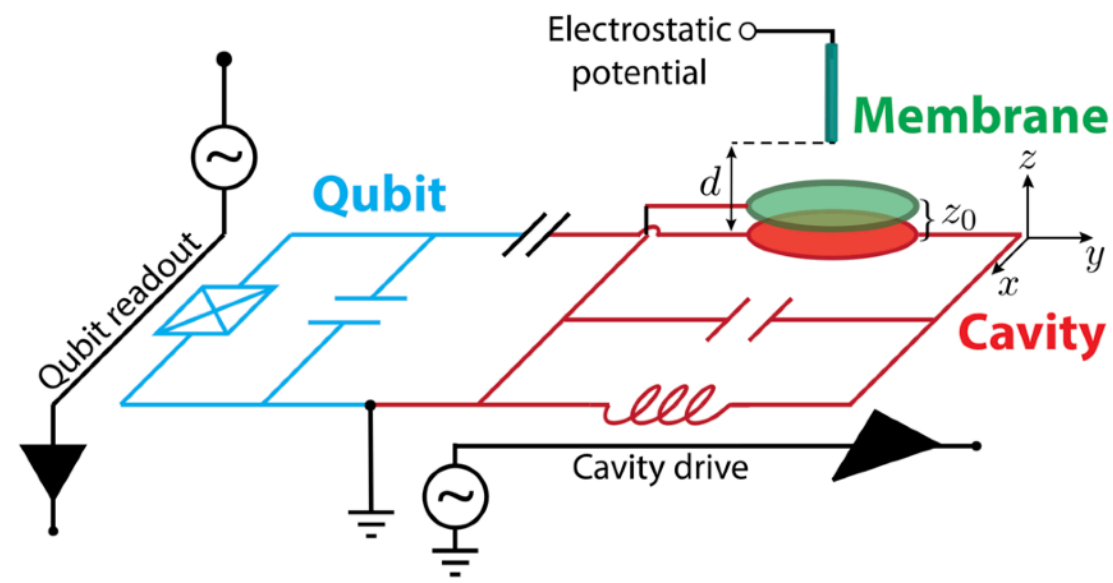
Superconducting Circuits



Graphene

- high Coherence
- microwave
- strong Coupling to qubits
- nonlinearity

- high Quality
- flexural modes



Singh et al., *Nat. Nanotechnol.* (2014)

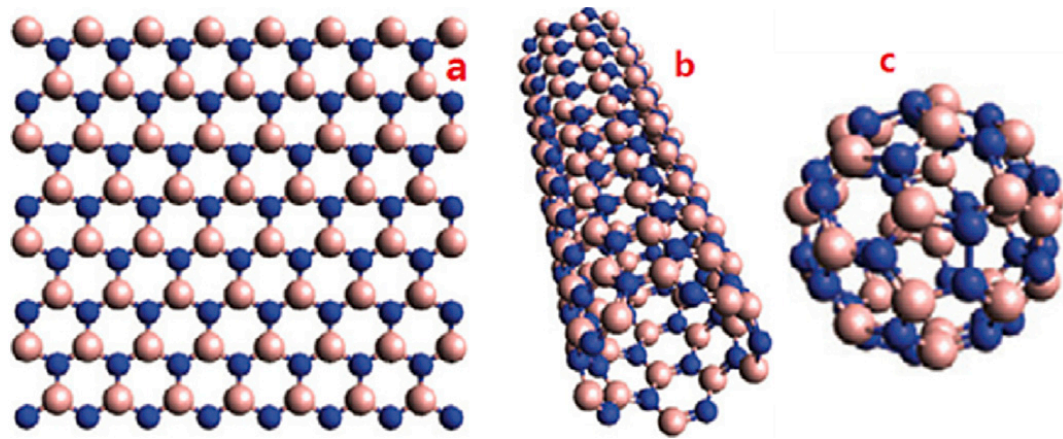
Weber et al., *Nano Lett.* (2014)

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Single-Photon Emitters in h-BN

hexagonal Boron Nitride

- Van der Waals
- Wide band gap (≈ 6.0 eV)
- Host for color centers



Wang et al., *Mat. Tod. Phys.* (2017)

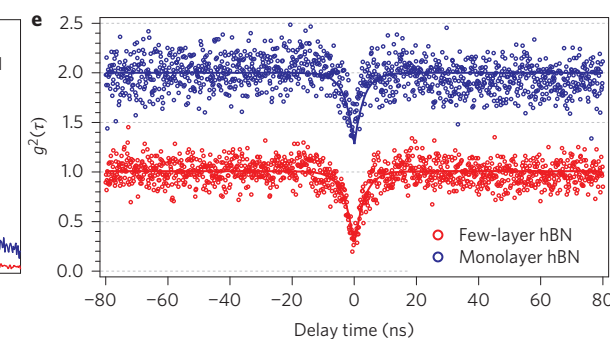
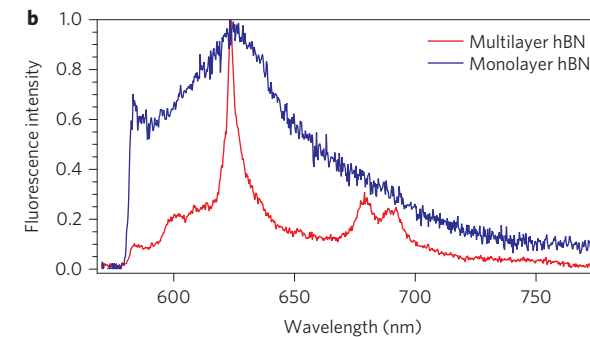
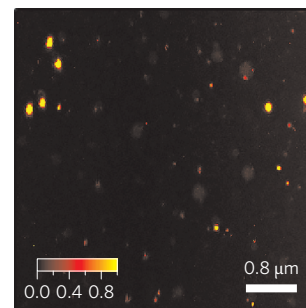
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nanotechnology

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Quantum emission from hexagonal boron nitride monolayers

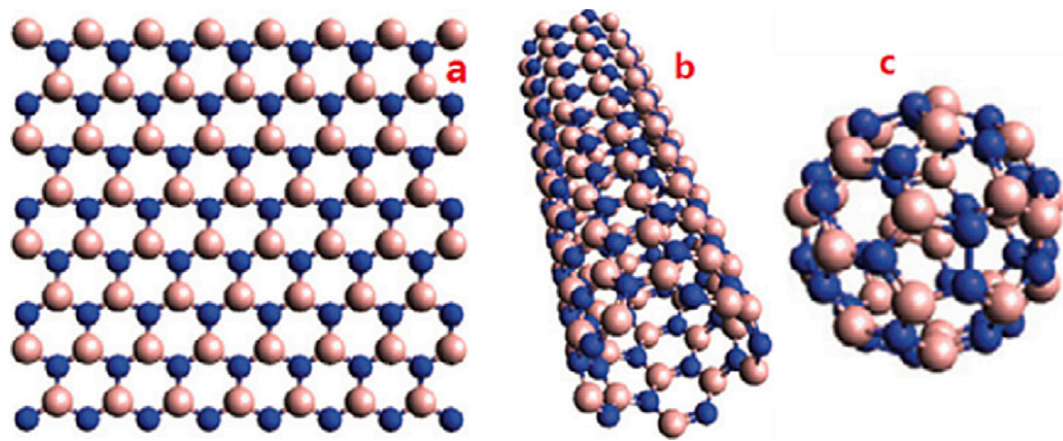
Toan Trong Tran, Kerem Bray, Michael J. Ford, Milos Toth* and Igor Aharonovich*



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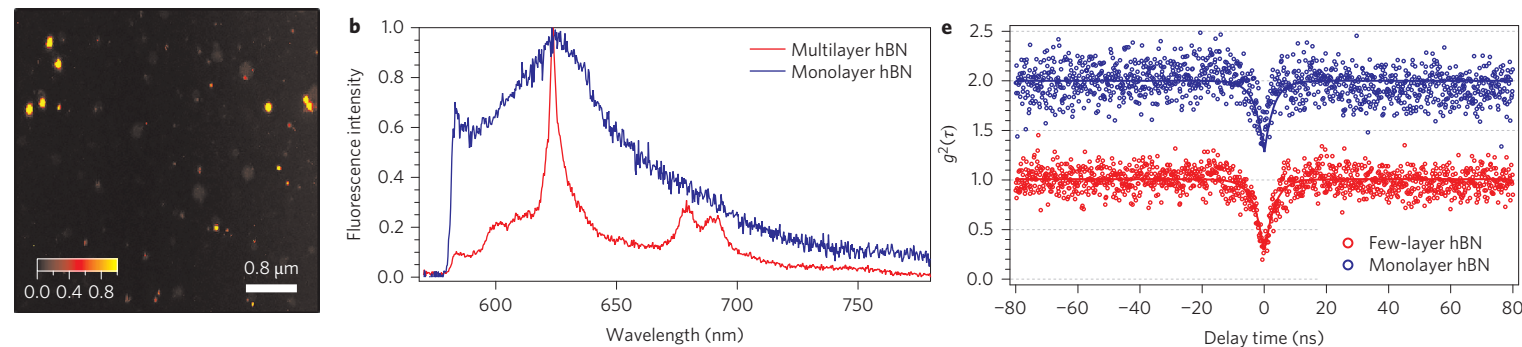
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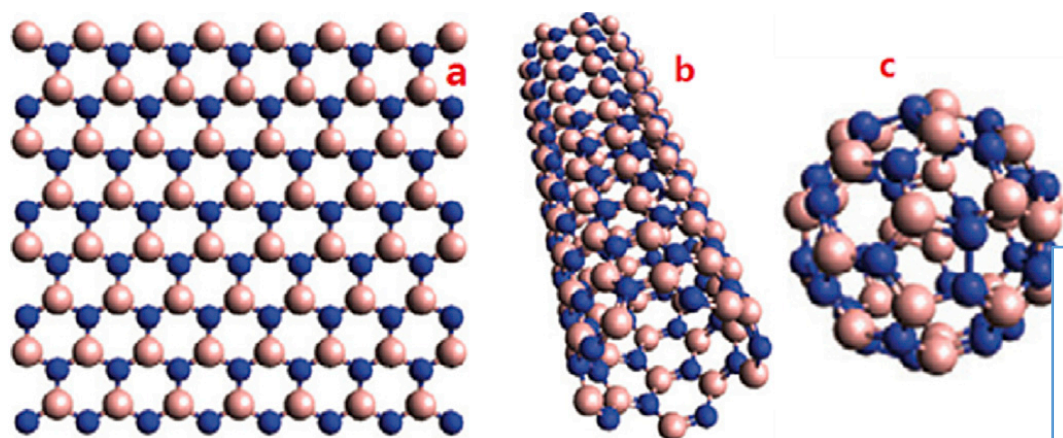
SPEs

- Ultra-bright
- Stable
- Localized
- Room Temperature

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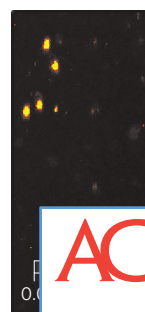
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agonal

e Luo,[†]

Menon,^{*,†,‡}

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Emission from Boron Nitride

Lobo,[†] Gabriele Grosso,[‡]
and Milos Toth^{*,†}

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Structural Attributes and Photodynamics of Visible Spectrum Quantum Emitters in Hexagonal Boron Nitride

Nathan Chejanovsky,^{†,‡} Mohammad Rezai,[†] Federico Paolucci,[‡] Youngwook Kim,[‡] Torsten Rendler,[†] Wafa Rouabeh,[‡] Felipe Fávaro de Oliveira,[†] Patrick Herlinger,[‡] Andrej Denisenko,[†] Sen Yang,[†] Ilja Gerhardt,^{†,‡} Amit Finkler,^{*,†} Jurgen H. Smet,[‡] and Jörg Wrachtrup^{†,‡}

Summary and Outlook

Summary

- hBN color centers
- Phonons
- Various coupling mechanisms
- Quantum sensing
- Quantum simulation

Other works & Outlook

- Simulation with Nuclear spins
- Sensing with Nuclear spins
- Further characterizations

