

Title: Colloquium - Resonant light scattering from few-level quantum systems - from textbook physics to unexpected results

Speakers: Kai Mueller

Collection/Series: Waterloo-Munich Joint Workshop

Subject: Quantum Information

Date: October 02, 2024 - 2:00 PM

URL: <https://pirsa.org/24100058>

Abstract:

- * Introduction to resonant light matter interaction (coherent and incoherent scattering, Rabi oscillations, Mollow triplets)
- * Origin of antibunching in resonance fluorescence (L. Hanschke et al. Phys. Rev. Lett. 125, 170402 (2020))
- * Doubly-dressed Mollow triplets (C. Gustin et al. Phys. Rev. Research 3, 013044 (2021))
- * Dynamic Mollow triplets from Janes-Cummins systems (K. Fischer et al. Nature Photonics 10, 163-166 (2016))
- * Dynamic Mollow triplets from two-level systems (K. Boos et al. arXiv:2305.15827 (2023) - accepted at PRL)

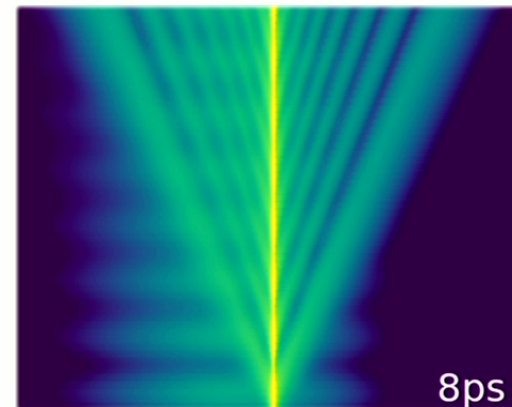
Resonant light scattering from few-level quantum systems – from textbook physics to unexpected results

Kai Müller

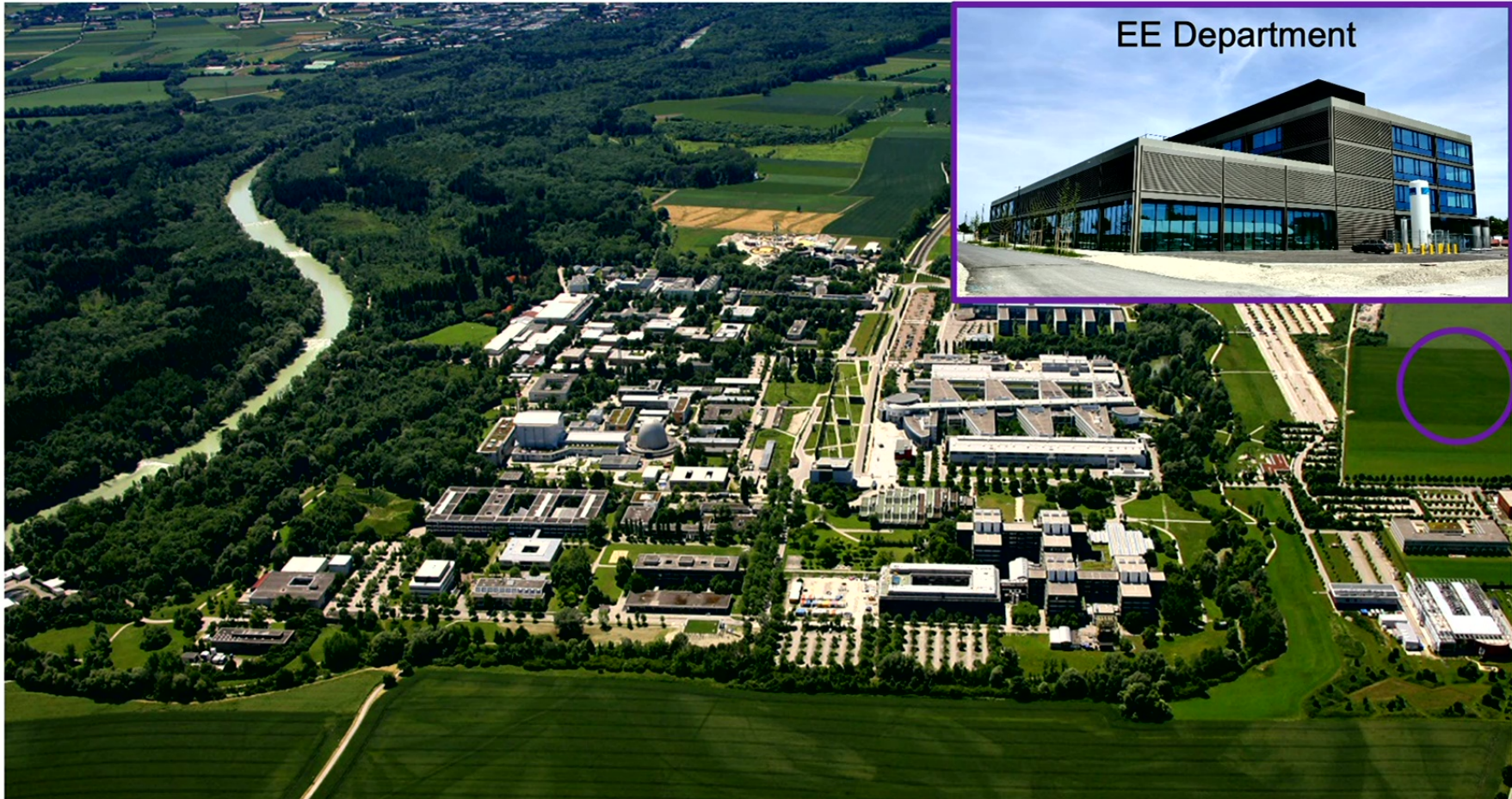
Technical University of Munich

Quantum Electronics and
Computer Engineering (QEC)

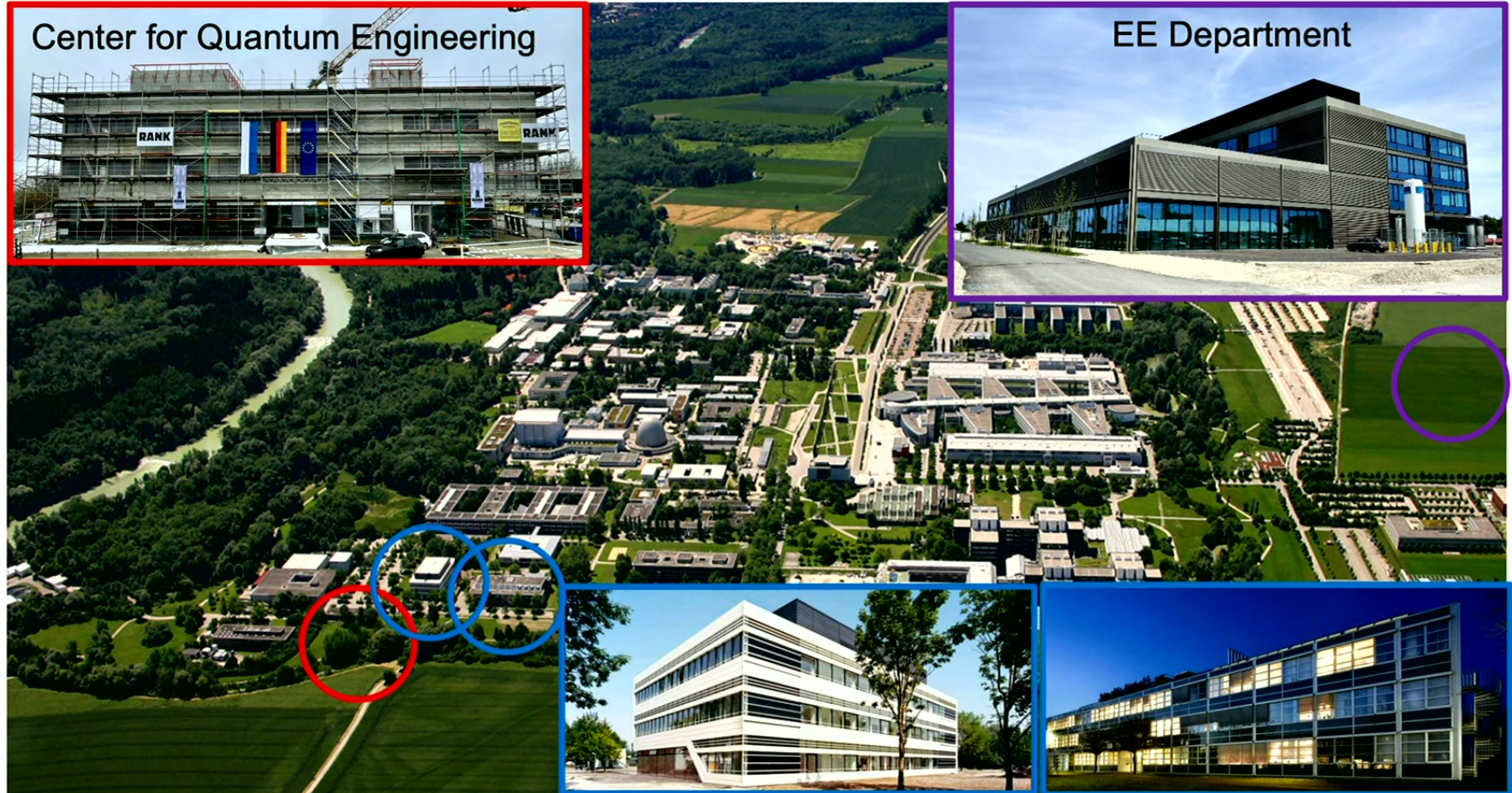
kai.mueller@tum.de



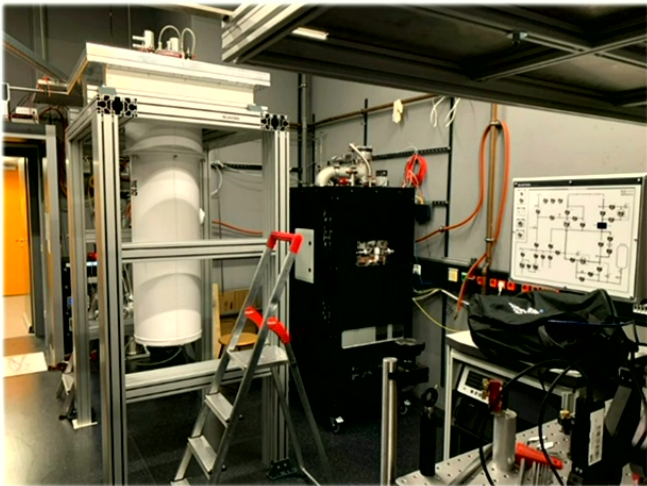
QEC group @TUM



QEC group @TUM



QEC group: Laboratories

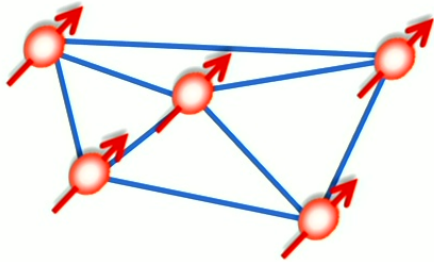


Cryostats:

- 1x Bluefors LD-400 with vector magnet
- 2x Attocube attodry 2100 with vector magnet
- 1x Qinu Sionludi-L mK cryostat
- 1x Kiutra MR-3 mK cryostat
- 2x Attocube attodry 800
- 1x Attocube attodry 800xs
- 2x Attocube CMC
- Multiple dipstick cryostats

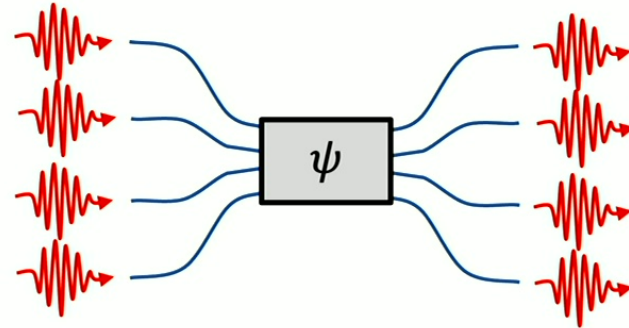
Photonic Quantum Technologies

Quantum Communication



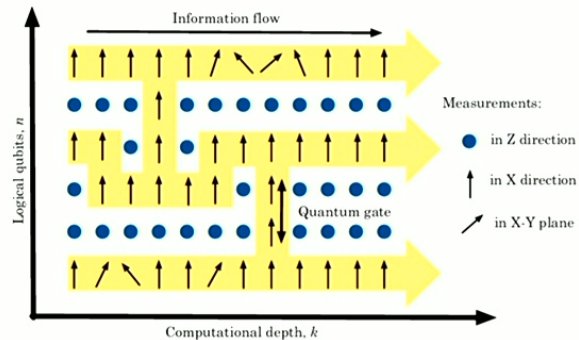
A. S. Holevo et al., *Problems of Information Transmission* 9, 177–183 (1973)

Quantum Simulation



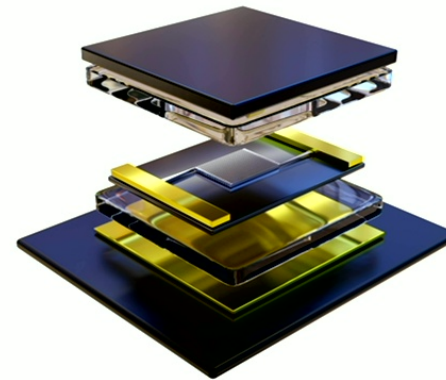
S. Aaronson et al., *Theory of Computing*. 9: 143–252 (2013)

Quantum Computing



R. Raussendorf et al., *Phys. Rev. Lett.* 86, 5188 (2001)

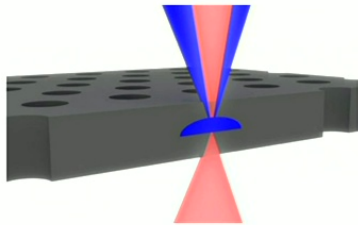
Quantum Sensing



QEC group: Research activities

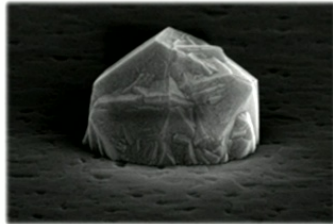
Building blocks

Quantum light sources



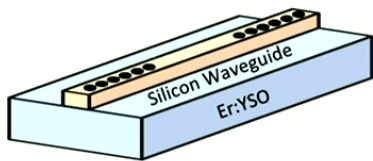
Quantum dots

Spin-photon interfaces



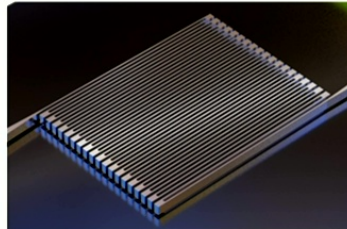
Color centers

Quantum memories



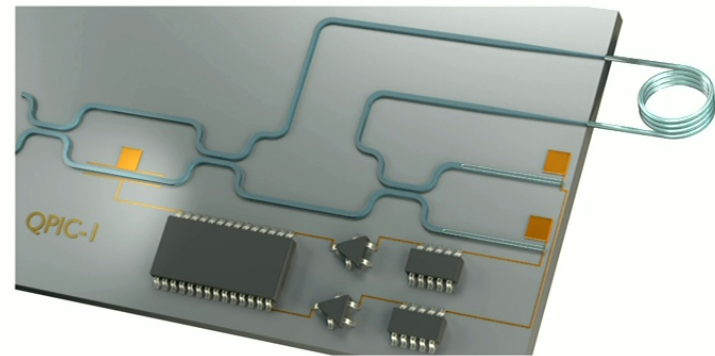
Rare-earth ions

Single-photon detectors

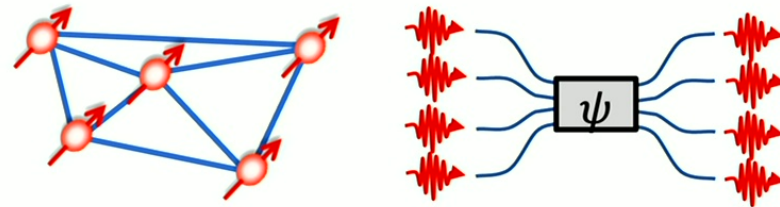


Superconducting films

Integrated photonics and devices

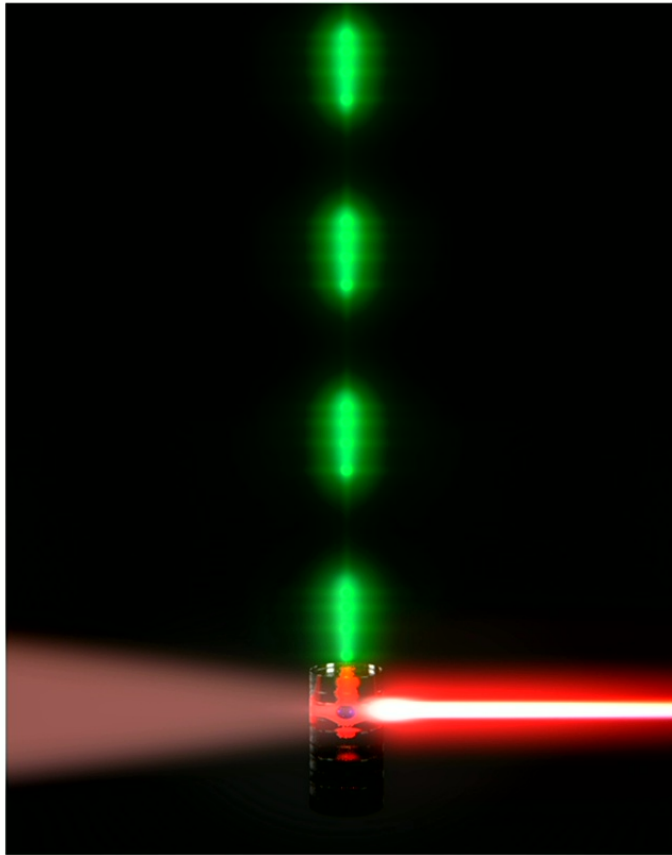


Demonstrator experiments



Quantum communication, Quantum computation
Quantum simulation, Quantum sensing

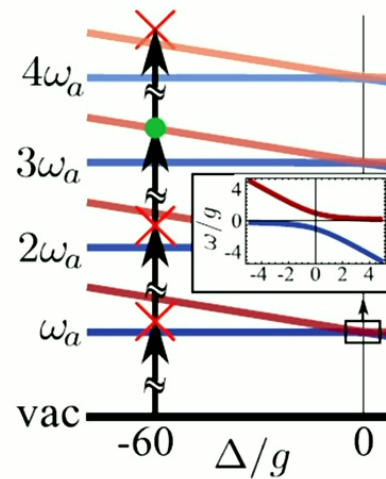
Everybody needs a hobby



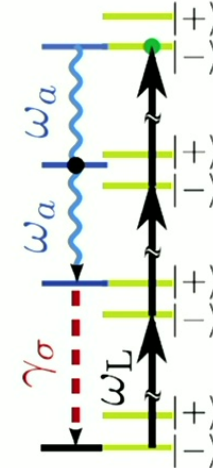
Emitters of N -photon bundles

C. Sánchez Muñoz¹, E. del Valle¹, A. González Tudela², K. Müller^{3,4}, S. Lichtmannecker³, M. Kaniber³, C. Tejedor¹, J. J. Finley³ and F. P. Laussy^{1*}

Jaynes-Cummings ladder

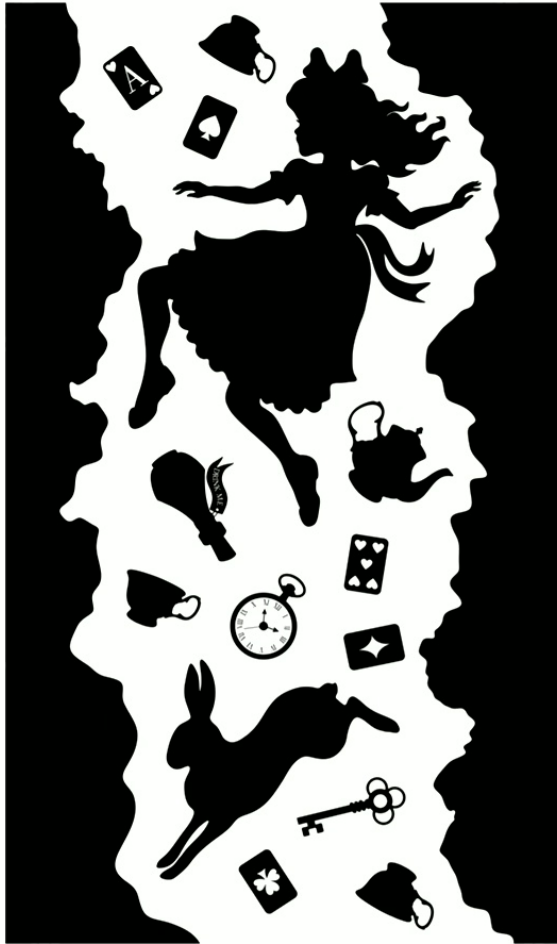


Mollow ladder



C. Sánchez Muñoz et al. *Nature Photonics* 8, 550-555 (2014)

Falling down the rabbit hole



2013-2014 – N-photon bundles from strongly coupled JC systems

C. Sánchez Muñoz et al. Nature Photonics 8, 550-555 (2014)

2014-2016 – Single photons from strongly coupled JC systems

K. Müller et al. Phys. Rev. X 5, 031006 (2015)

K. Müller et al. Phys. Rev. Lett. 114, 233601 (2015)

K.A. Fischer et al. Nature Photonics 10, 163 (2016),

K. Mueller et al. Optica 3, 931-936 (2016)

2017 – Two-photon pulses from 2-LS

K.A. Fischer et al. Nature Physics 13, 649–654 (2017)

2018-2022 – Single photons from 2-LS and 4-LS

L. Hanschke et al. npj Quantum Information 4, 43 (2018)

E. Schöll et al. Physical Review Letters 125, 233605 (2020)

F. Sbresny et al. Physical Review Letters 128, 093603 (2022)

2020-2024 – Resonantly driven 2-LS

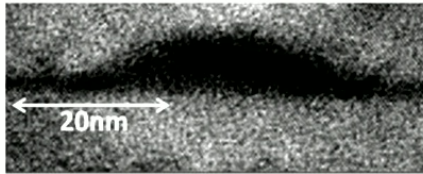
L. Hanschke et al. Physical Review Letters 125, 170402 (2020)

C. Gustin et al., Physical Review Research 3, 013044 (2021)

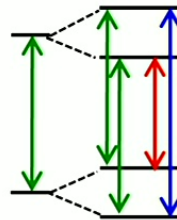
K. Boos et al. Physical Review Letters 132, 053602 (2024)

Overview

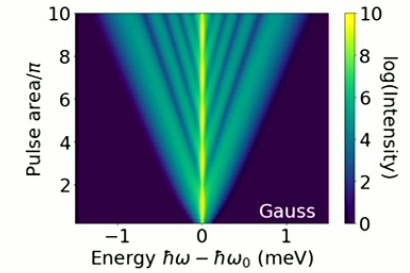
QD quantum optics



CW Mollow Triplets

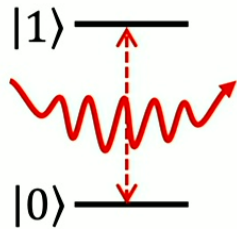


Dynamic Mollow triplets



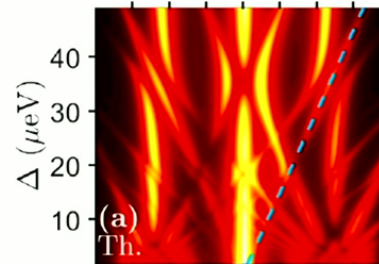
K. Boos et al.
Physical Review Letters 132,
053602 (2024)

Origin of Antibunching



L. Hanschke et al.
Physical Review Letters 125,
170402 (2020)

Double-dressed Mollow



C. Gustin et al.
Physical Review Research 3,
013044 (2021)

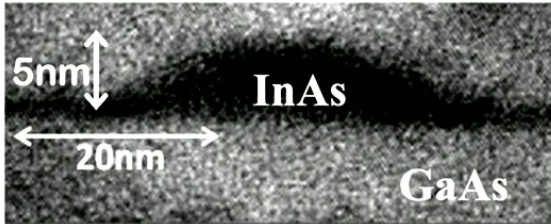
... from JC-Systems



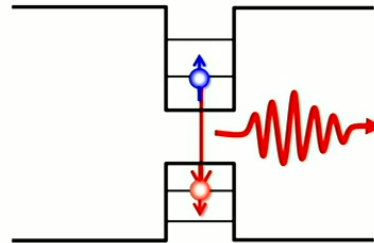
K.A. Fischer et al. Nature
Photonics 10, 163–166
(2016)

InAs/GaAs quantum dots

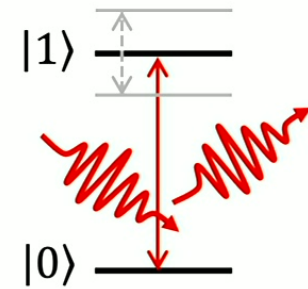
3D confinement for electrons and holes



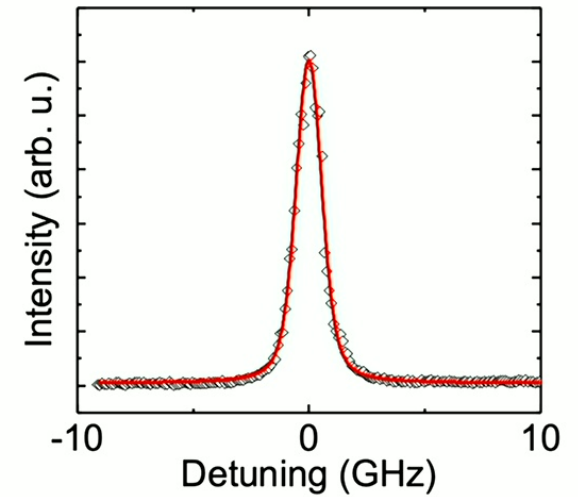
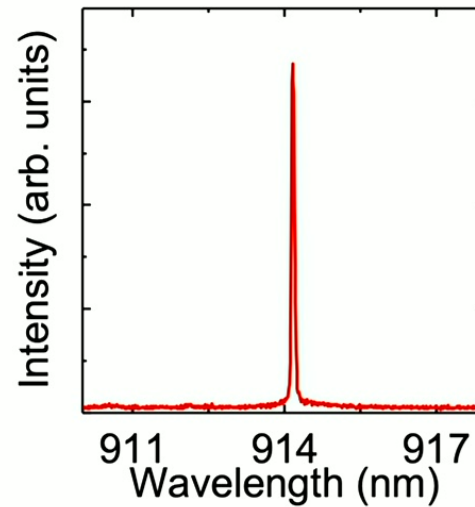
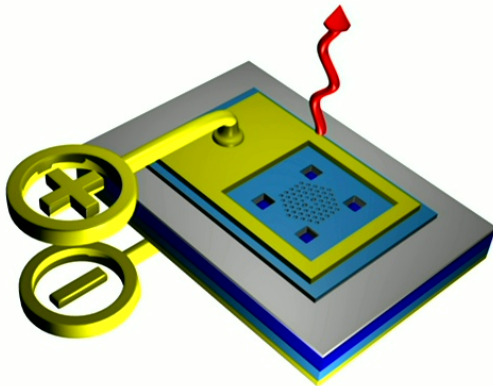
Strong interband transitions



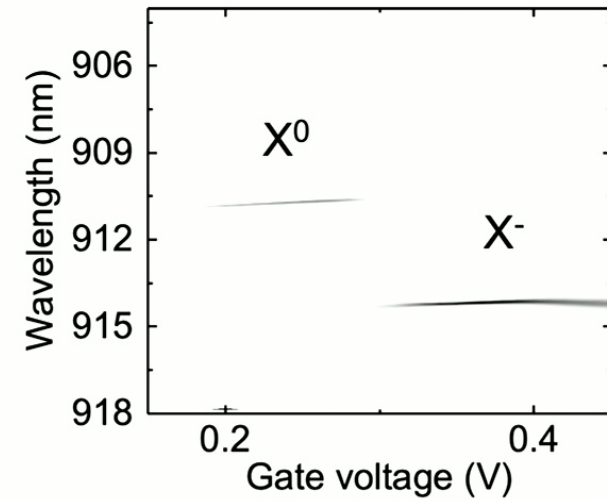
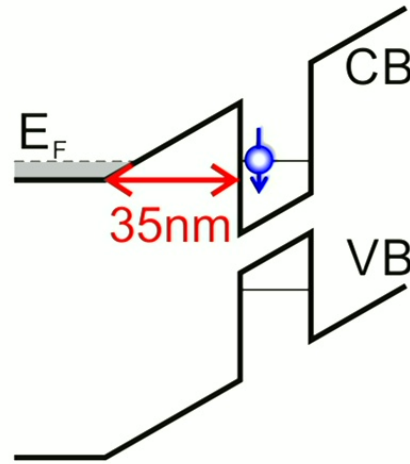
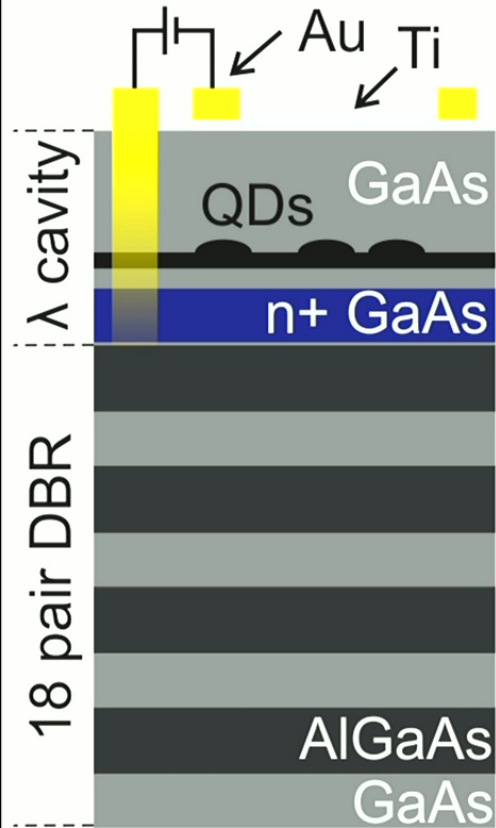
Transform-limited linewidth



Opto-electronic integration



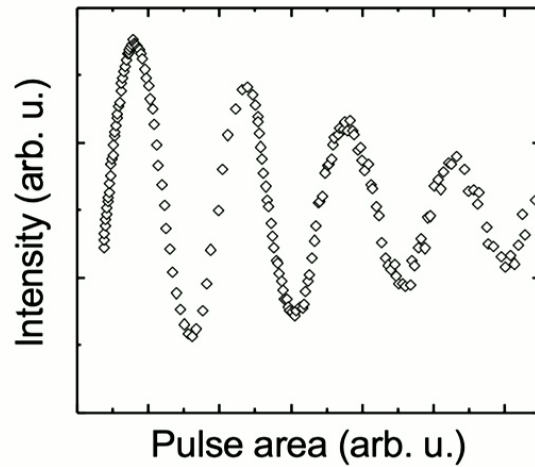
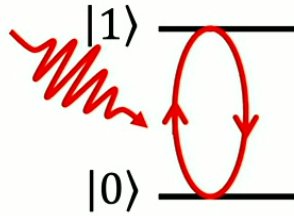
Quantum dot devices



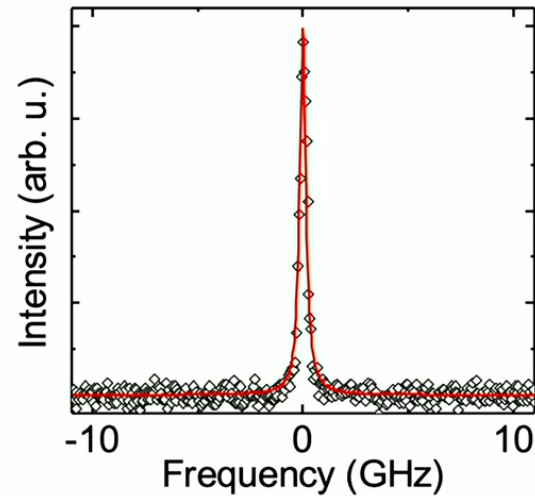
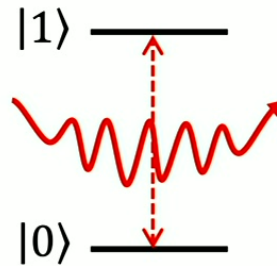
- DBR enhances photon collection efficiency
- Diode structure allows for control charge status

QD quantum optics

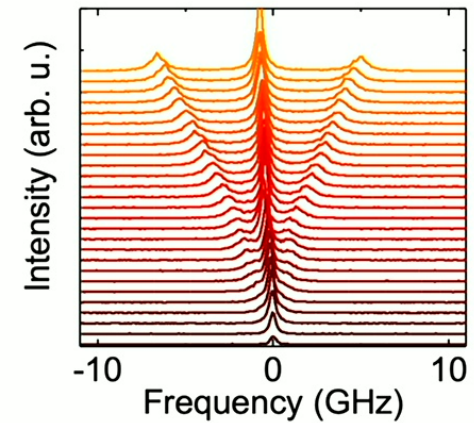
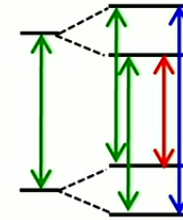
Rabi oscillations



Coherent scattering



Mollow triplets



Sub-natural linewidth and antibunching ?

APPLIED PHYSICS LETTERS **99**, 261904 (2011)

Ultra-coherent single photon source

H. S. Nguyen,¹ G. Sallen,^{1,a)} C. Voisin,¹ Ph. Roussignol,¹ C. Diederichs,^{1,b)}
and G. Cassabois^{1,2,3}

¹Laboratoire Pierre Aigrain, Ecole Normale Supérieure, CNRS (UMR 8551), Université P. et M. Curie,
Université D. Diderot, 24, rue Lhomond, 75231 Paris Cedex 05, France

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³CNRS, Laboratoire Charles Coulomb UMR 5221, F-34095 Montpellier, France

(Received 5 October 2011; accepted 2 December 2011; published online 28 December 2011)

PRL **108**, 093602 (2012)

PHYSICAL REVIEW LETTERS

week ending
2 MARCH 2012

Subnatural Linewidth Single Photons from a Quantum Dot

Clemens Matthiesen,^{1,*} Anthony Nickolas Vamivakas,^{1,2} and Mete Atatüre^{1,†}

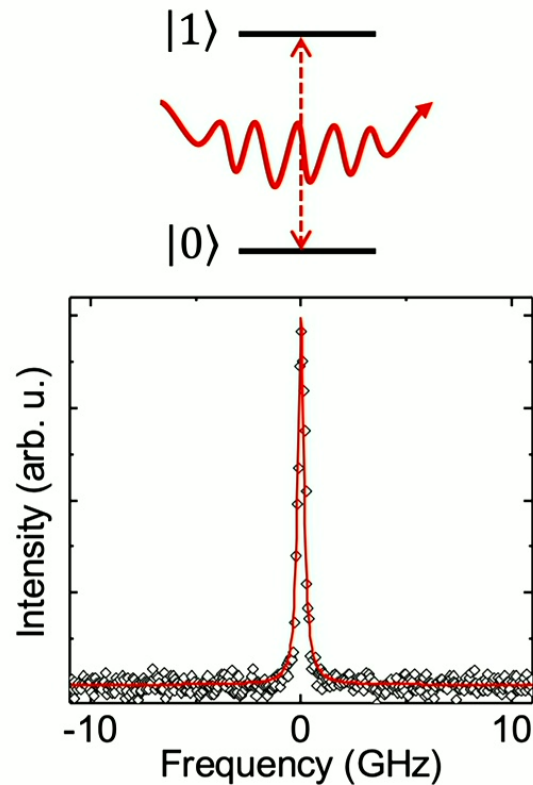
¹Cavendish Laboratory, University of Cambridge, JJ Thomson Avenue, Cambridge CB3 0HE, United Kingdom

²Institute of Optics, University of Rochester, 275 Hutchison Road, Rochester, New York 14627-0186, USA

(Received 15 September 2011; revised manuscript received 13 February 2012; published 28 February 2012)

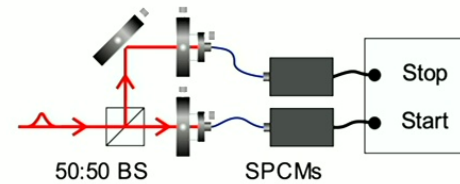
Sub-natural linewidth and antibunching ?

Sub-natural linewidth

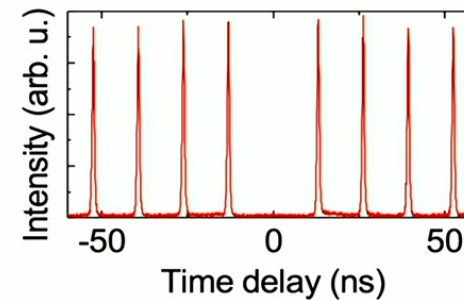


W. Heitler, *The Quantum Theory of Radiation*,
Oxford University Press (1954)

Antibunching

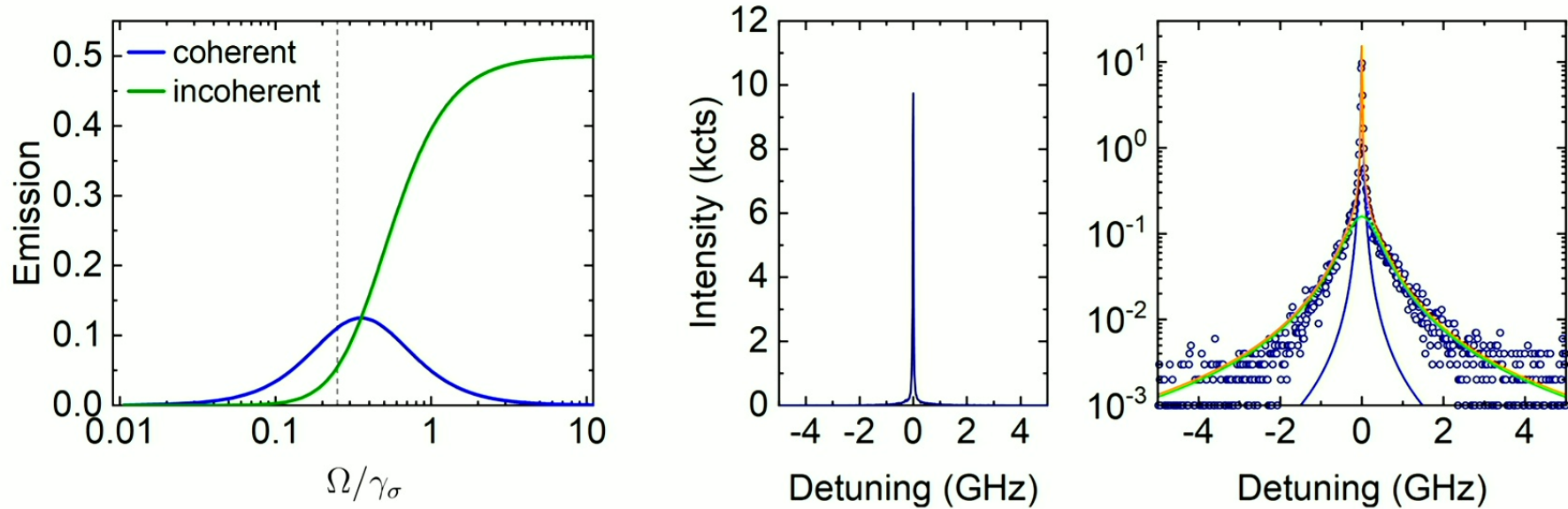


$$g^{(2)}(0) = \frac{\langle n(n-1) \rangle}{\langle n \rangle^2}$$



R. Glauber *Phys. Rev. Lett.* 10, 84 (1963)

Frequency filtering of resonant scattering

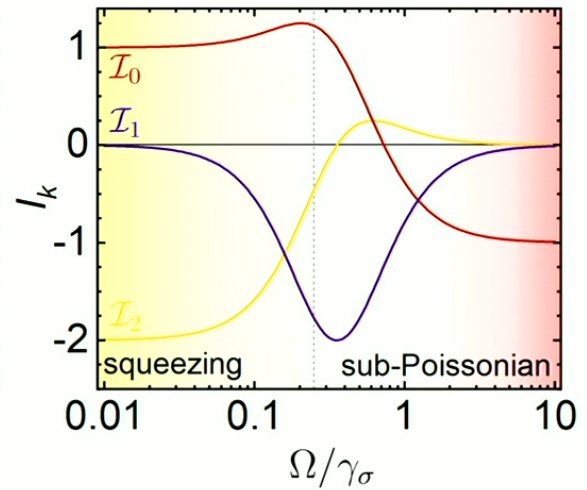
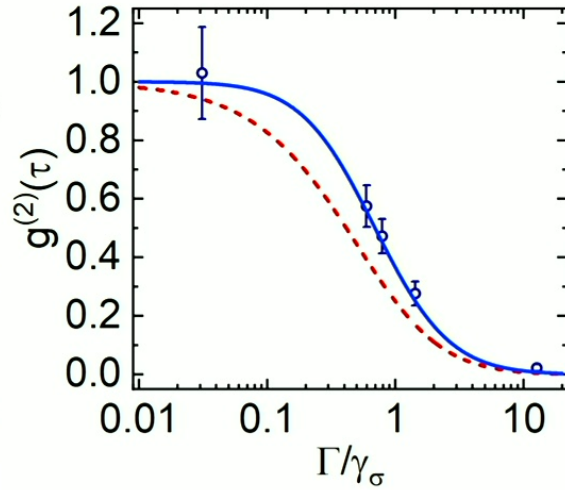
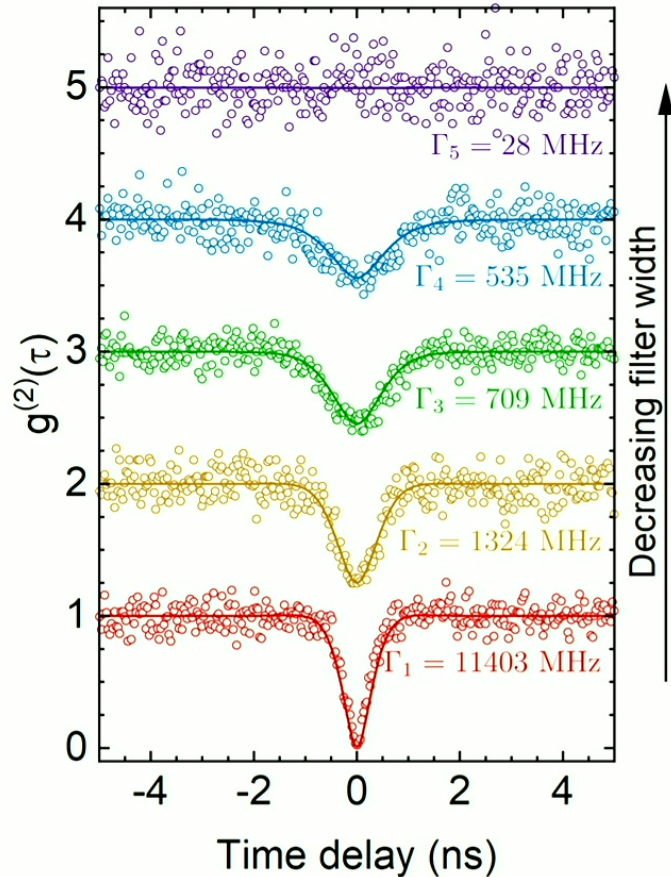


→ Resonance fluorescence consists of coherent and incoherent scattering

L. Hanschke et al. Physical Review Letters 125, 170402 (2020)

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Frequency filtering of resonant scattering

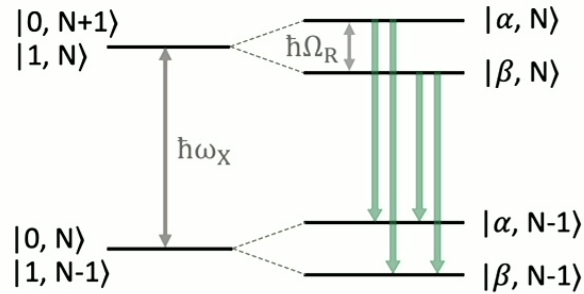


- Frequency filtering reduces the antibunching
- The origin of the antibunching for weak driving results from interference between coherent and incoherent scattering

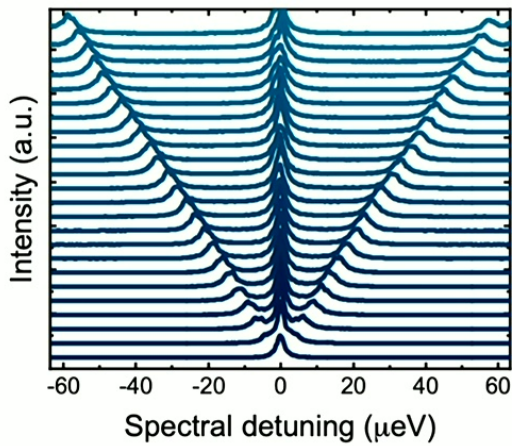
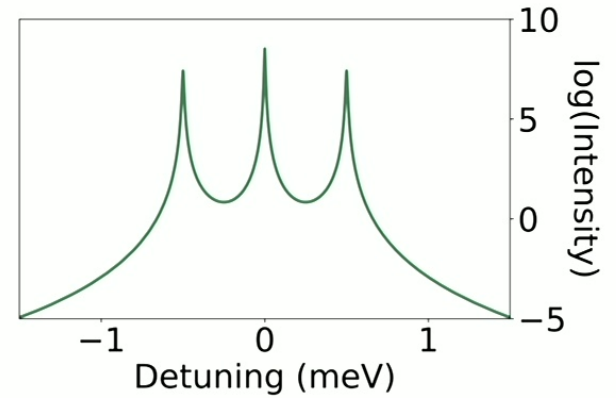
L. Hanschke et al. Physical Review Letters 125, 170402 (2020)

The Mollow Triplet

Two-level system
+
Resonant cw driving

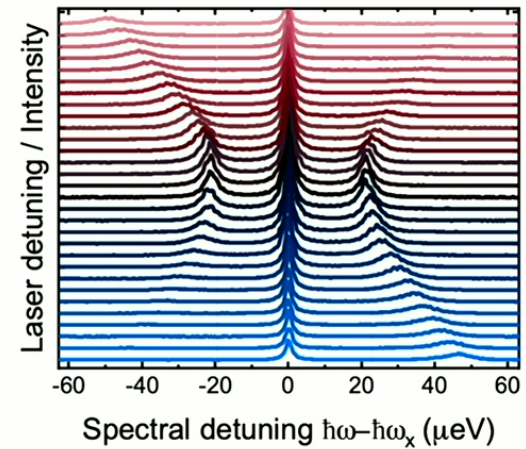


Dressed states

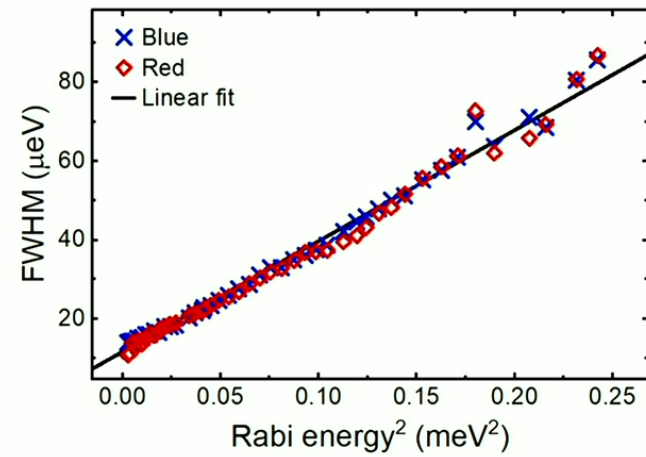
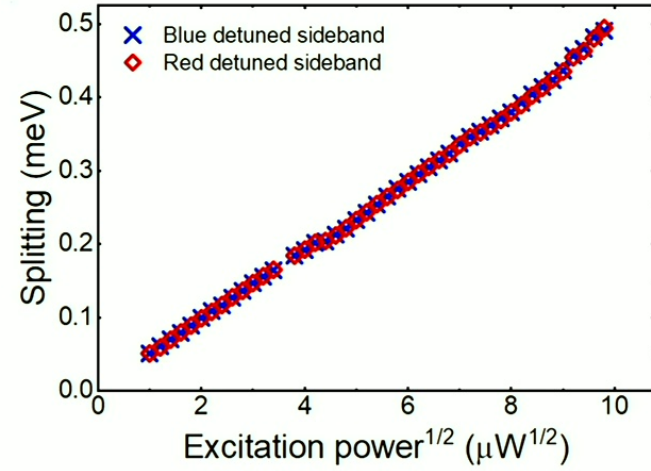
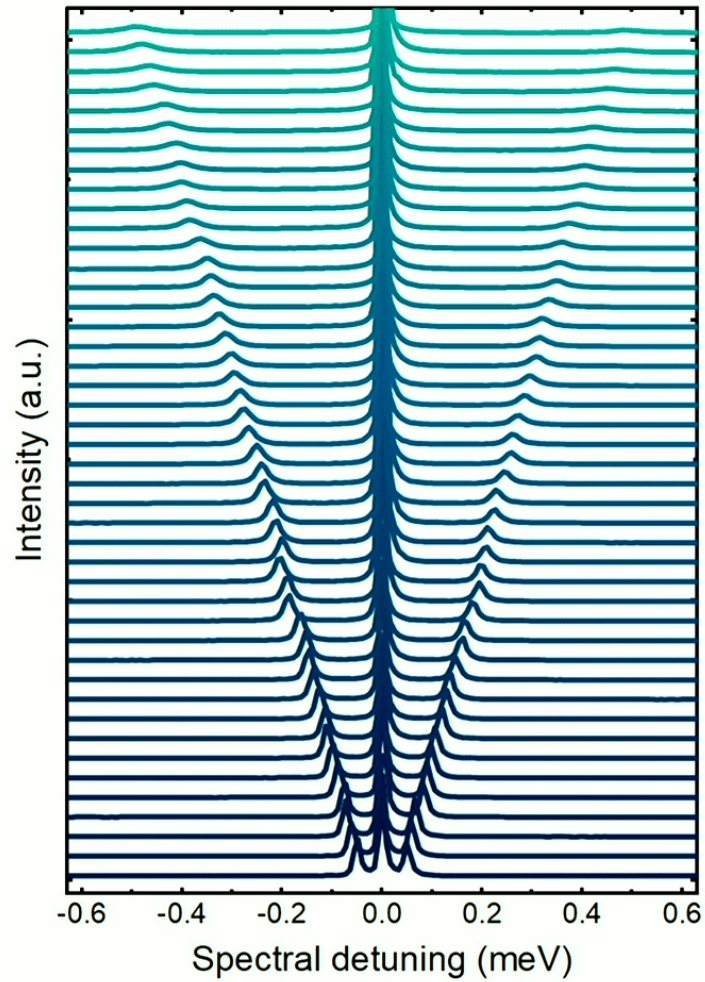


Driving strength

Finite detuning

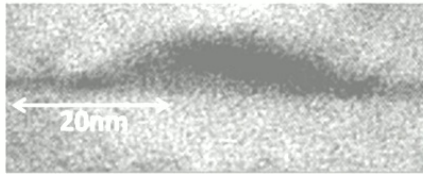


Strong dressing

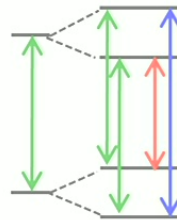


Overview

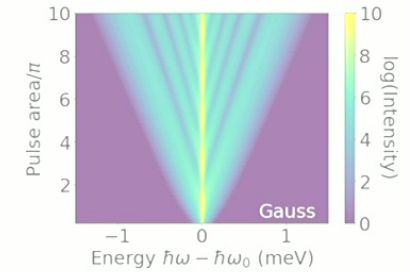
QD quantum optics



CW Mollow Triplets

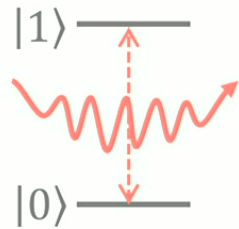


Dynamic Mollow triplets



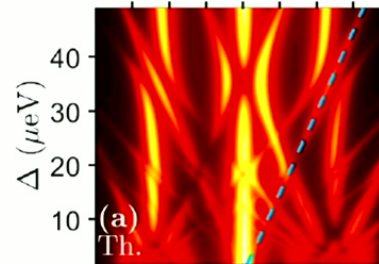
K. Boos et al.
Physical Review Letters 132,
053602 (2024)

Origin of Antibunching



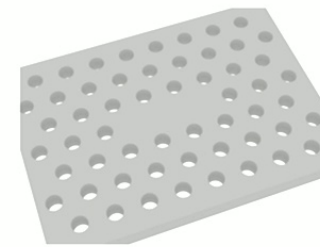
L. Hanschke et al.
Physical Review Letters 125,
170402 (2020)

Double-dressed Mollow



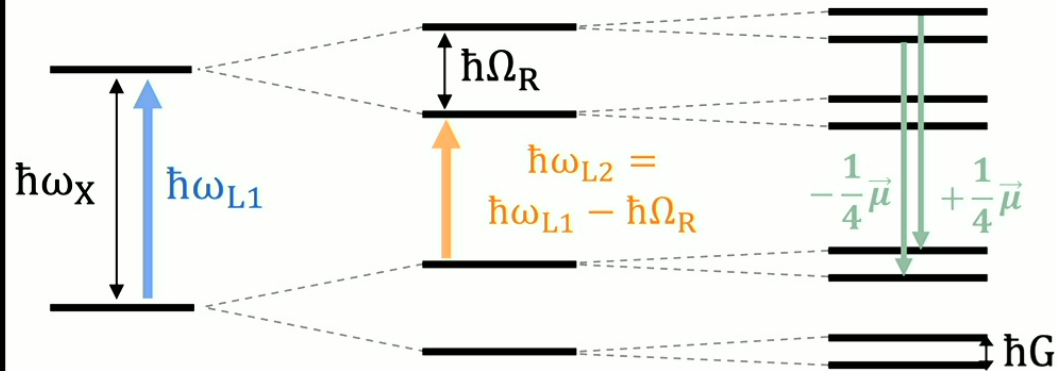
C. Gustin et al.
Physical Review Research 3,
013044 (2021)

... from JC-Systems



K.A. Fischer et al. Nature
Photonics 10, 163–166
(2016)

Dressing the dressed states



Two-level system

+ Driving laser

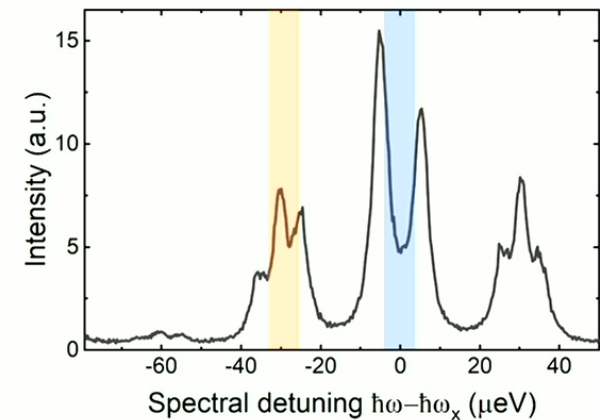
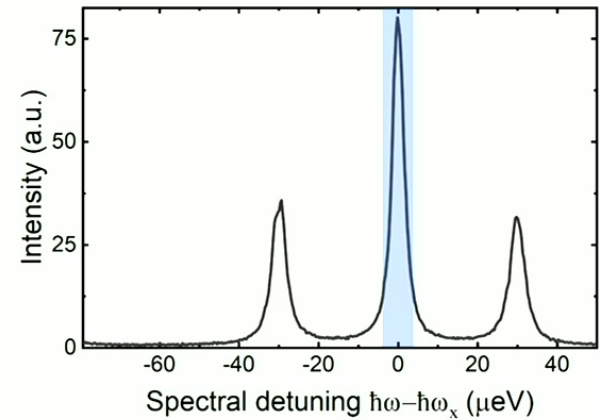


Dressed states

+ Coupling laser

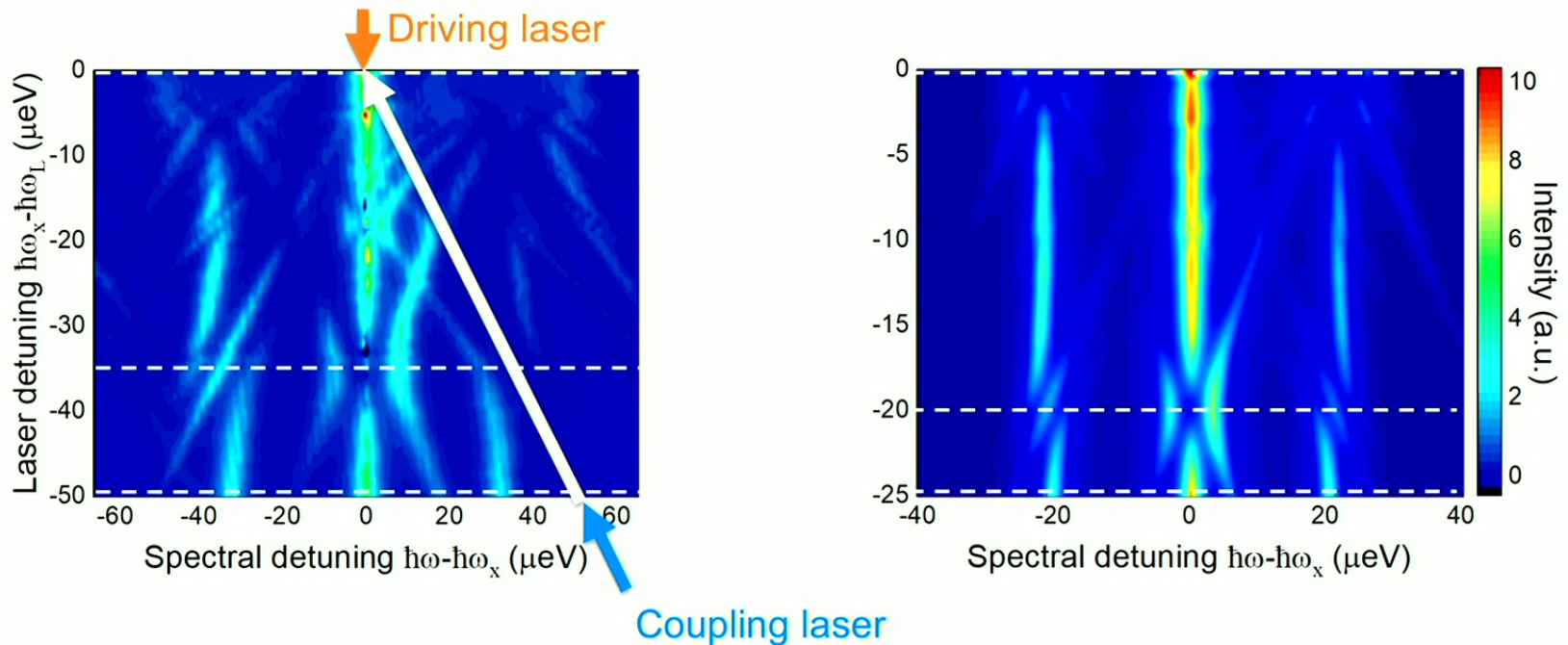


Doubly dressed states



C. Gustin et al., *Physical Review Research* 3, 013044 (2021)
 Related work: Y. He et al., *Phys. Rev. Lett.* 114, 097402 (2015)

Detuning-dependent dynamical suppression



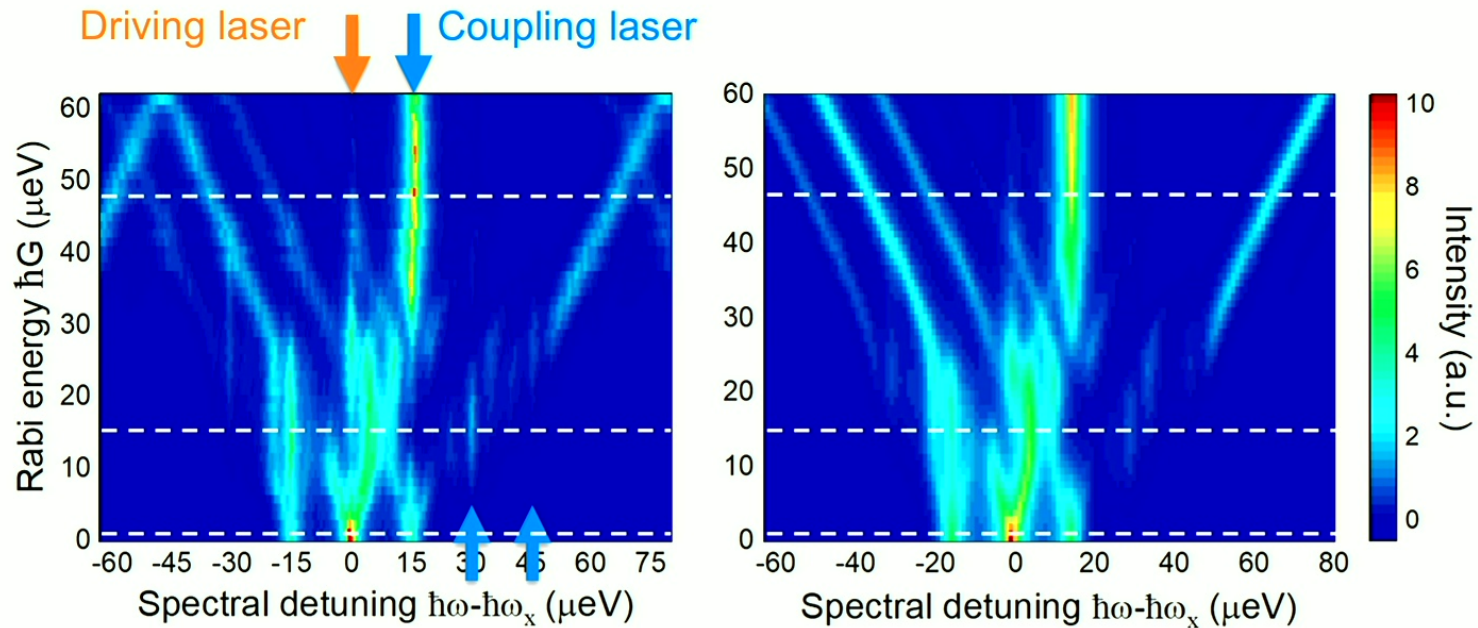
Quantum interference \rightarrow Suppression of central emission line

- At resonance with sideband $\hbar\omega_{L2} = \hbar\Omega_R$

C. Gustin et al., Physical Review Research 3, 013044 (2021)

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Power-dependent bichromatic excitation



- Higher order coupling \rightarrow triplets at $n \hbar\Omega_R$, $n = \pm 2, +3$
- Detuned Mollow triplet for large coupling laser power

C. Gustin et al., Physical Review Research 3, 013044 (2021)

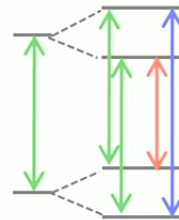
27

Overview

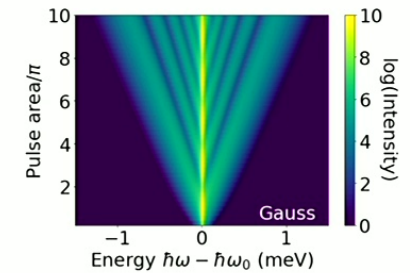
QD quantum optics



CW Mollow Triplets

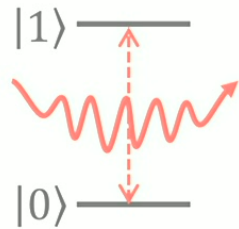


Dynamic Mollow triplets



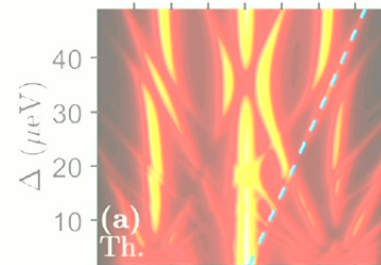
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053602 (2024)

Origin of Antibunching



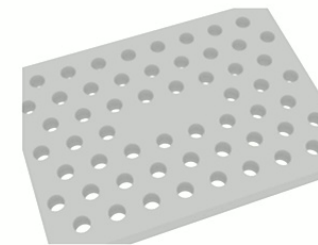
L. Hanschke et al.
Physical Review Letters 125,
170402 (2020)

Double-dressed Mollow



C. Gustin et al.
Physical Review Research 3,
013044 (2021)

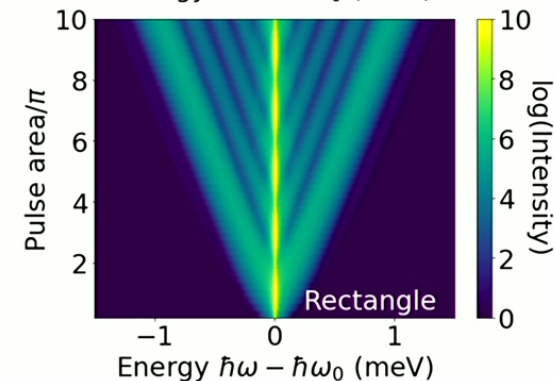
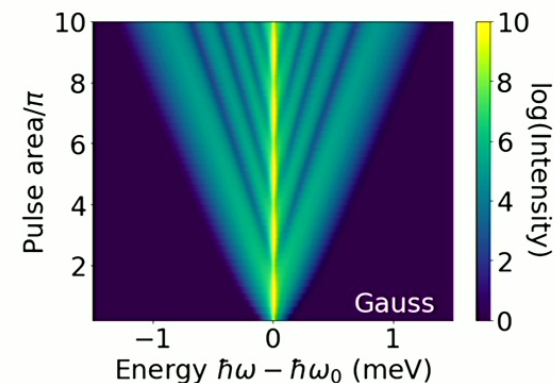
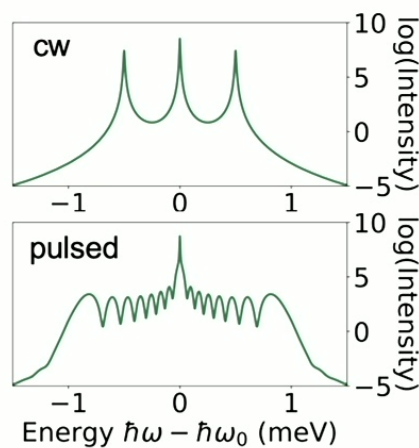
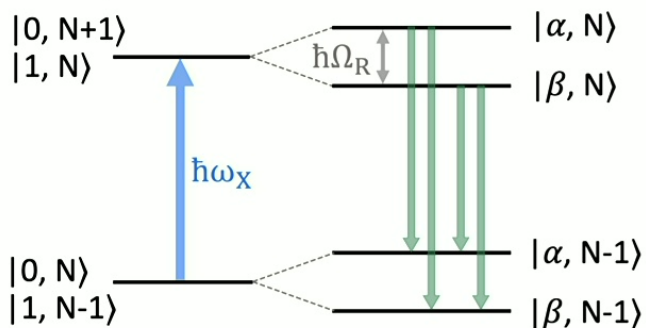
... from JC-Systems



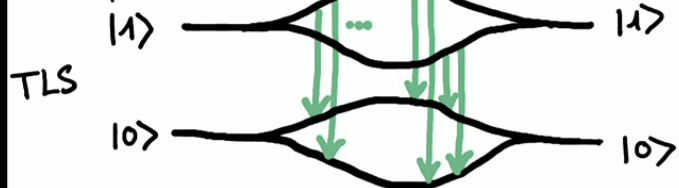
K.A. Fischer et al. Nature
Photonics 10, 163–166
(2016)

Dynamic Mollow Triplets

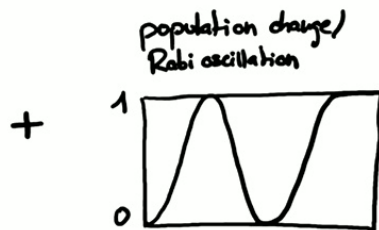
cw / at specific time t_x



time-dependent

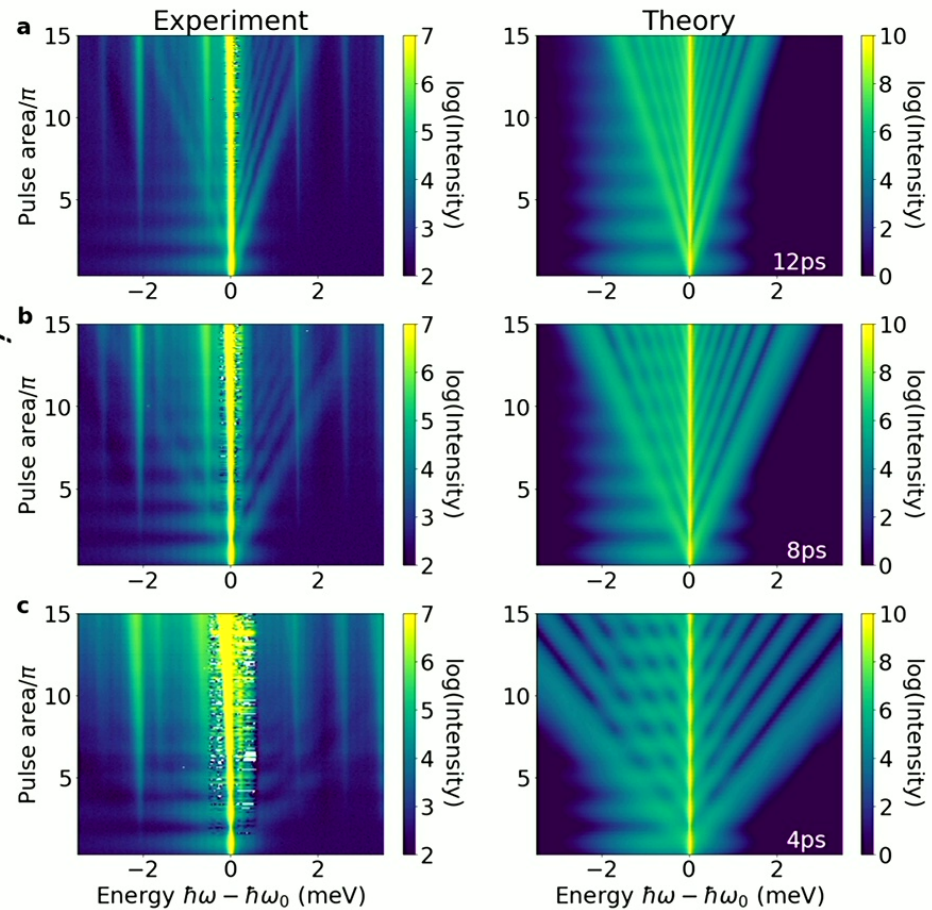
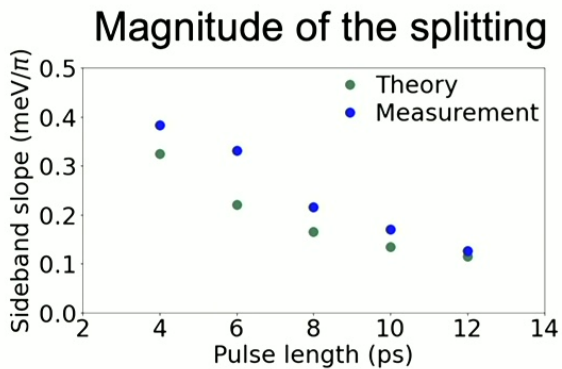
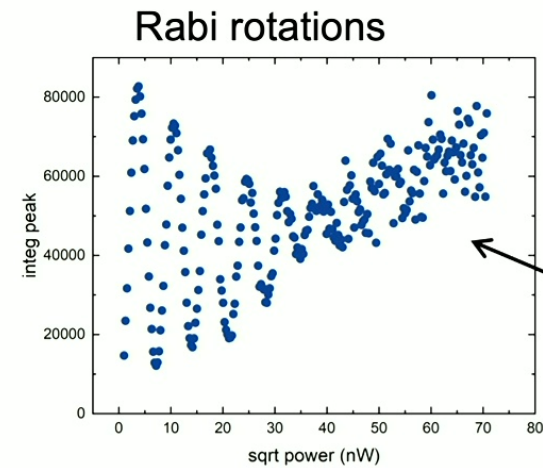


Pulse



K. Boos et al. *Physical Review Letters* 132, 053602 (2024)

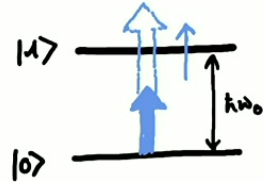
Dynamic Mollow Triplets from QDs



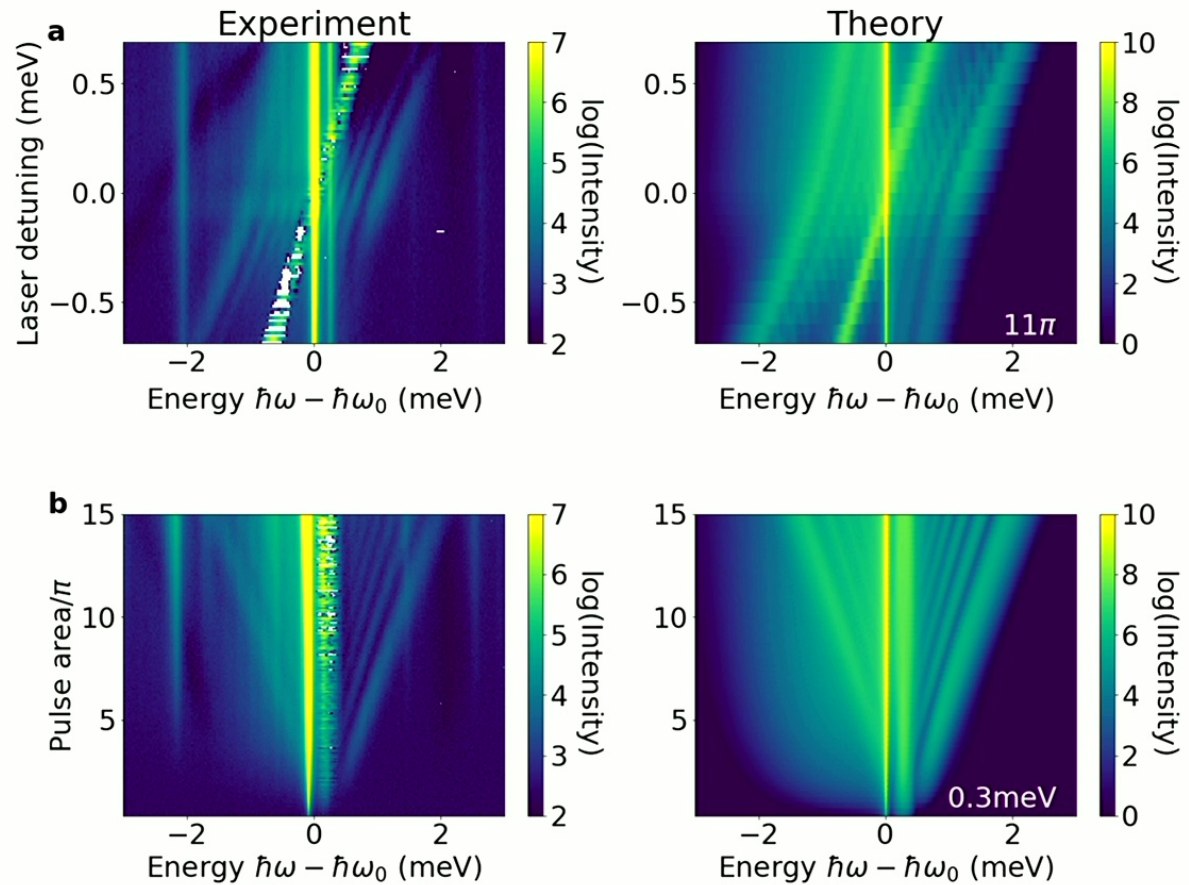
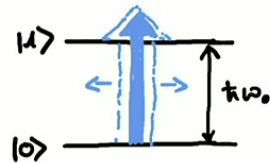
K. Boos et al. Physical Review Letters 132, 053602 (2024)

Finite detuning

Detuning the exc. pulse



Increasing Rabi energy with fixed detuning



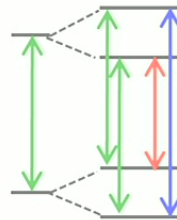
K. Boos et al. *Physical Review Letters* 132, 053602 (2024)

Overview

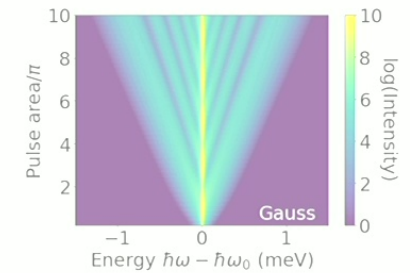
QD quantum optics



CW Mollow Triplets

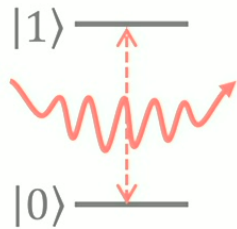


Dynamic Mollow triplets



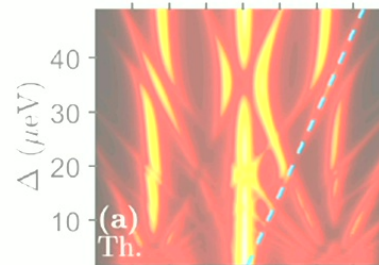
K. Boos et al.
Physical Review Letters 132,
053602 (2024)

Origin of Antibunching



L. Hanschke et al.
Physical Review Letters 125,
170402 (2020)

Double-dressed Mollow



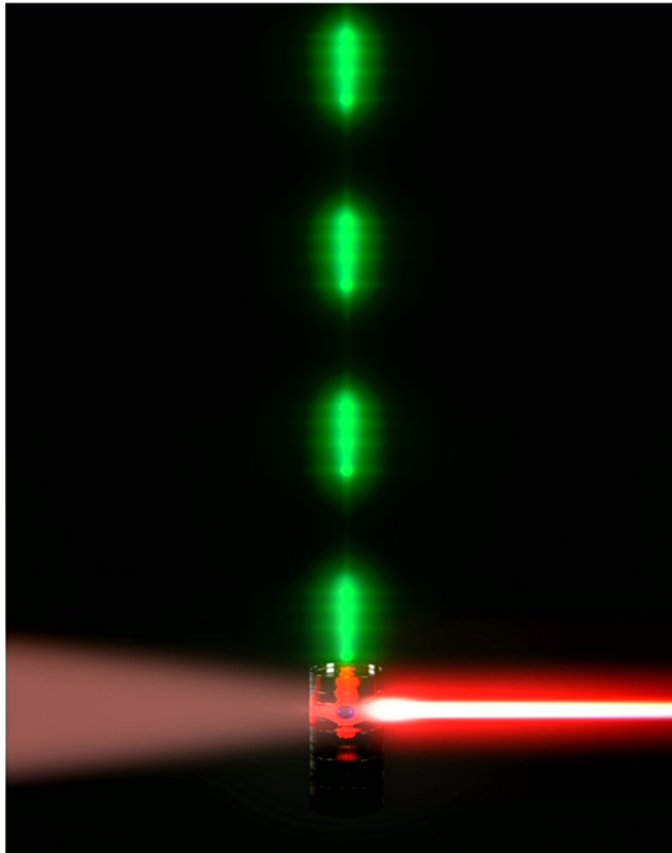
C. Gustin et al.
Physical Review Research 3,
013044 (2021)

... from JC-Systems



K.A. Fischer et al. Nature
Photonics 10, 163–166
(2016)

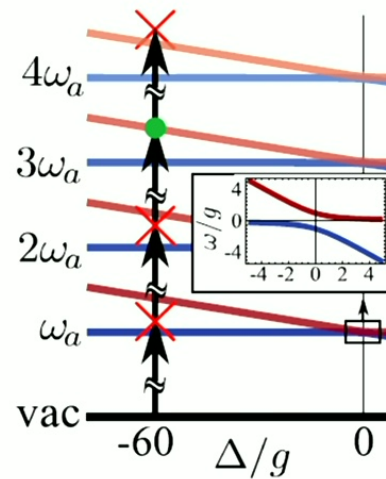
The bundler and the Mollow triplet



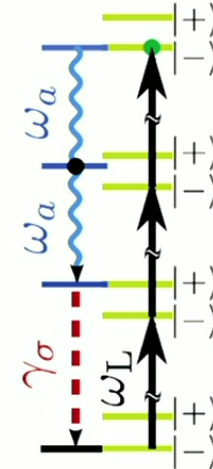
Emitters of N -photon bundles

C. Sánchez Muñoz¹, E. del Valle¹, A. González Tudela², K. Müller^{3,4}, S. Lichtmannecker³, M. Kaniber³, C. Tejedor¹, J. J. Finley³ and F. P. Laussy^{1*}

Jaynes-Cummings ladder

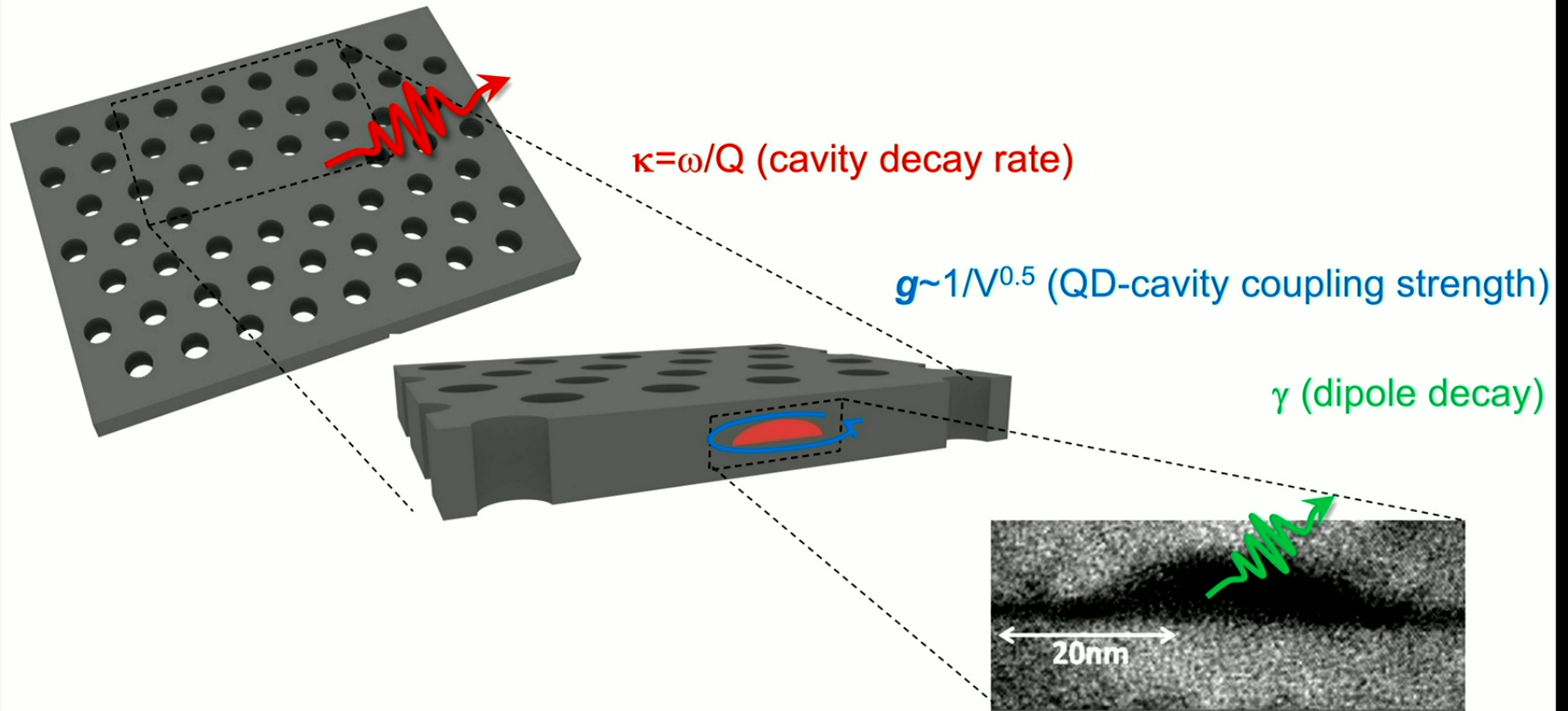


Mollow ladder



C. Sánchez Muñoz et al. *Nature Photonics* 8, 550-555 (2014)

JC-system

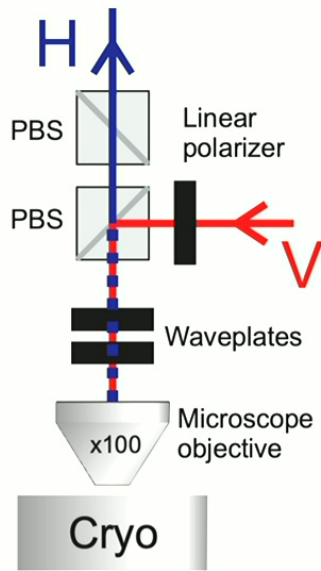


All rates in the GHz regime

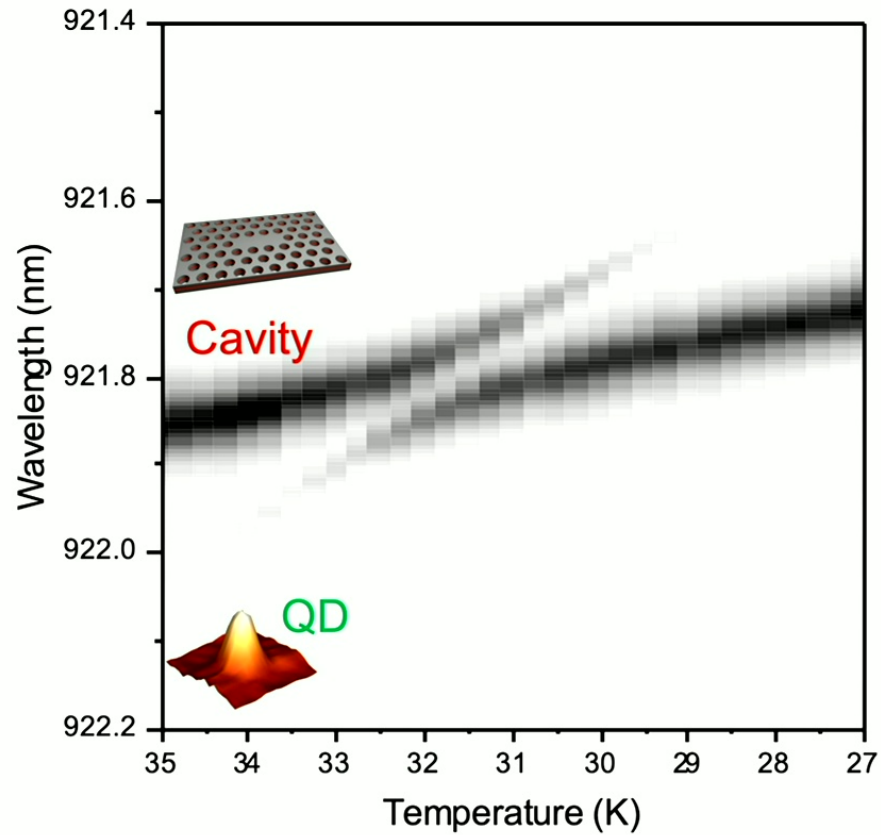
Strong coupling: g exceeds loss rates ($\kappa/2, \gamma/2$)

Observing strong coupling

Cross-polarized reflectivity:



Cavity at 45°



Coherent and incoherent scattering

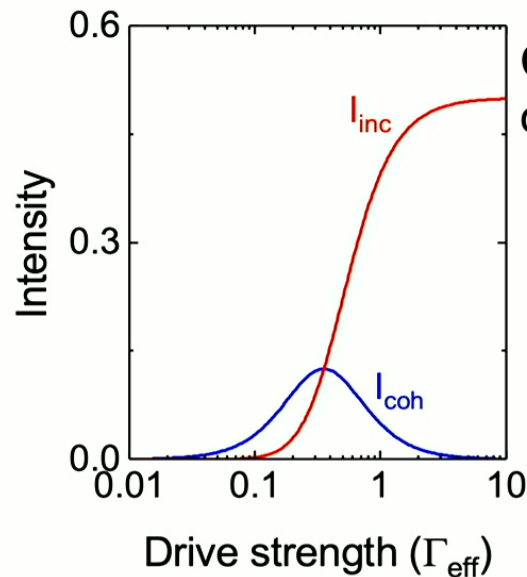
Coherent scattering

$$I_c \propto \langle a \rangle^2$$

Incoherent scattering

$$I_{inc} \propto \langle a^2 \rangle - \langle a \rangle^2$$

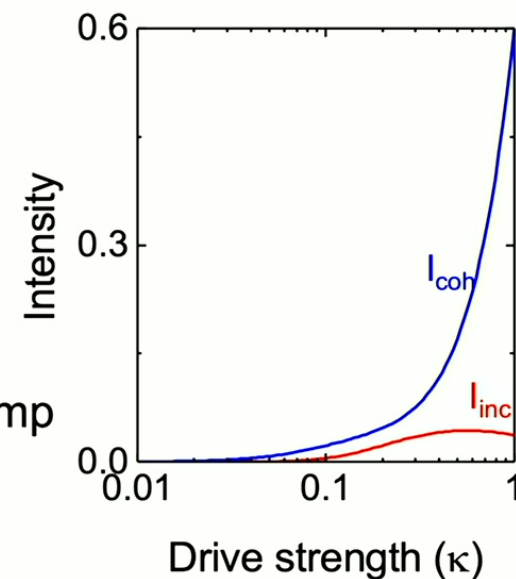
Two-level system



Coherent scattering
dominant for **weak** pump

Coherent scattering
dominant for **strong** pump

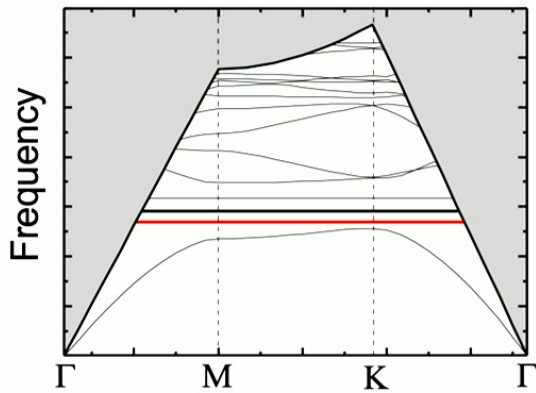
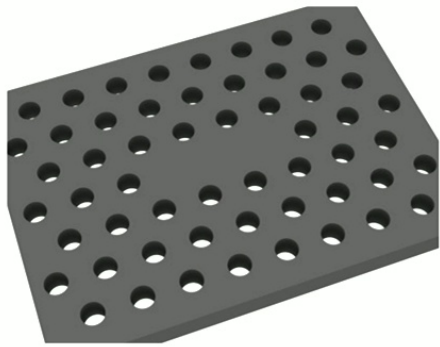
JC system



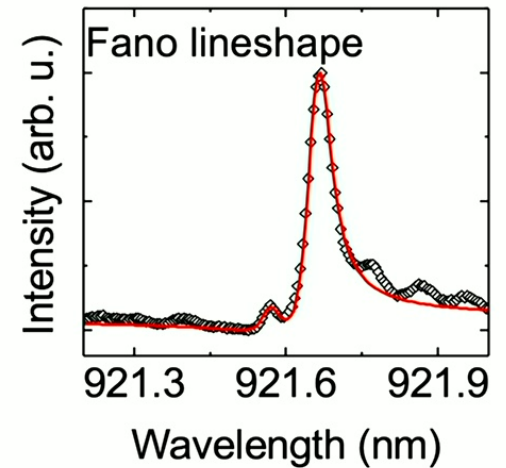
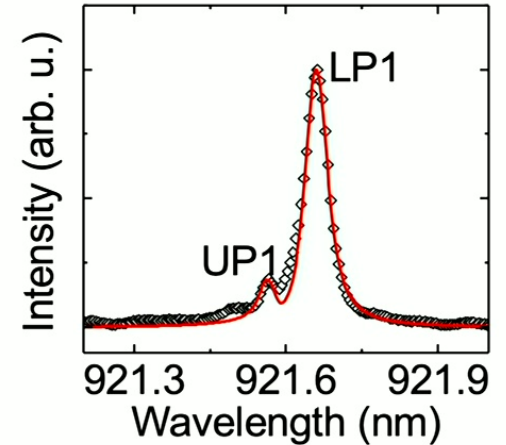
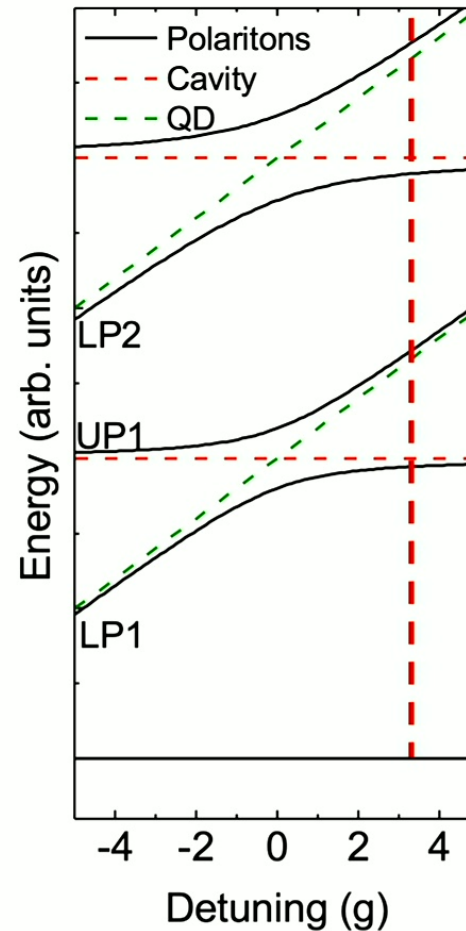
K.A. Fischer et al. Phys. Rev. Applied 7, 044002 (2017)

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Self-homodyne suppression



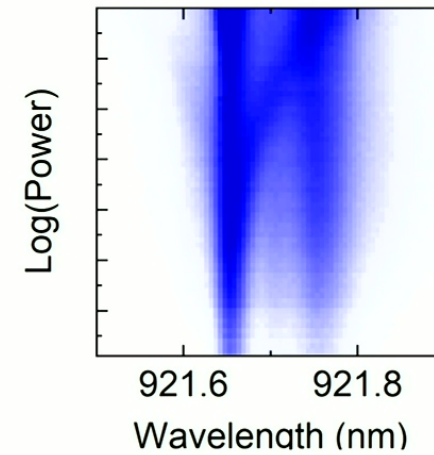
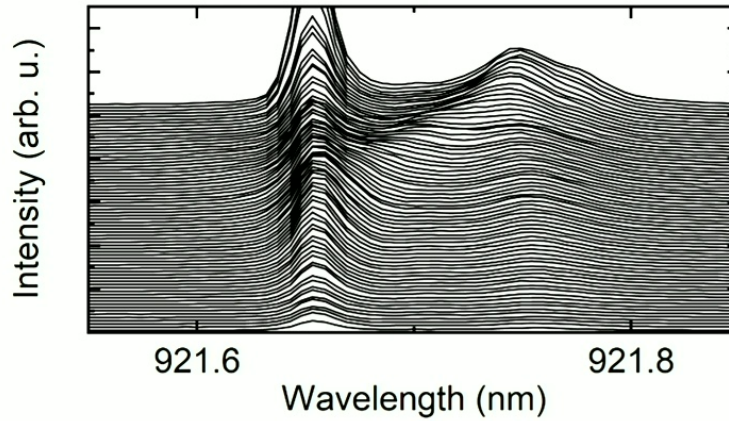
Photonic crystal cavities are more than single mode resonators!



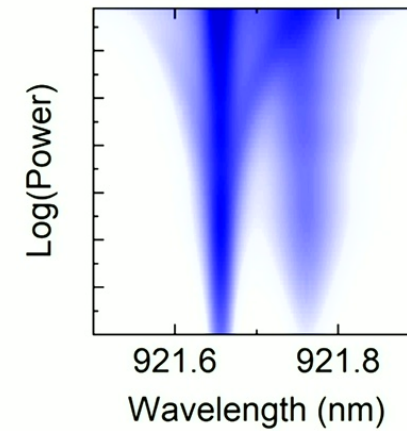
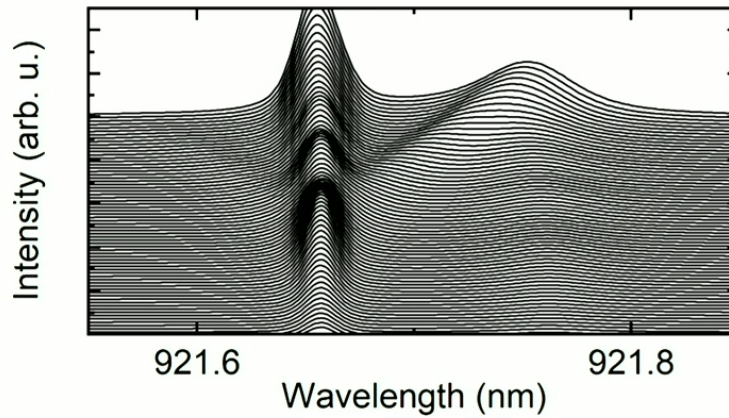
K.A. Fischer et al. Nature Photonics 10, 163–166 (2016)

Dynamic Mollow from JC-system

Experiment



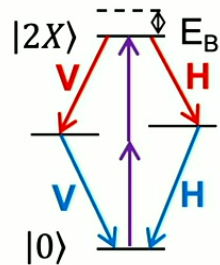
Simulation



K.A. Fischer et al. Nature Photonics 10, 163–166 (2016)

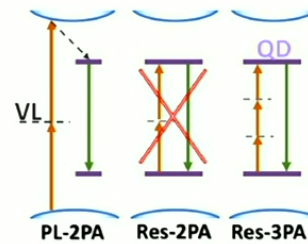
Other recent results

Cascaded emission



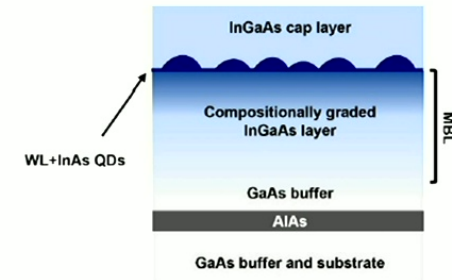
L. Hanschke et al. *npj Quantum Info* 4, 43 (2018)
 E. Schöll et al. *Phys. Rev. Lett.* 125, 233605 (2020)

3-Photon excitation



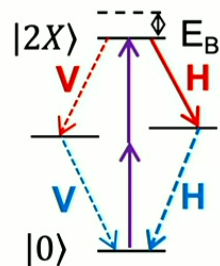
V. Villafane et al. *Physical Review Letters* 130, 083602 (2023)

Telecom QDs



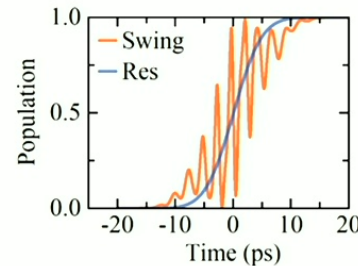
B. Scaparra et al., *Materials for Quantum Technology* 3, 035004 (2023)

Stimulated generation



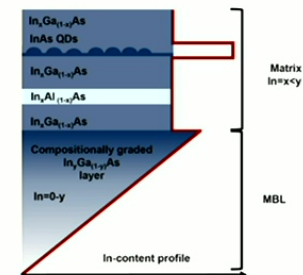
F. Sbresny et al. *Physical Review Letters* 128, 093603 (2022)

Swing-up excitation



K. Boos et al. *Advanced Quantum Technologies*, 2300359 (2024)

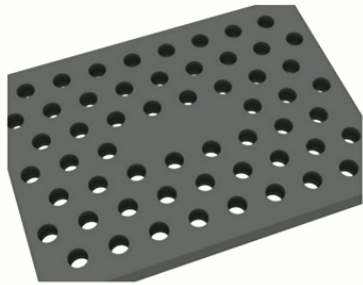
Virtual substrates



B. Scaparra et al. *arXiv:2407.12619* (2024)

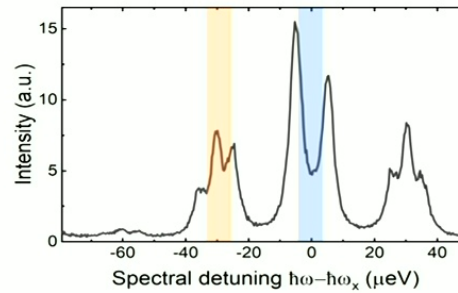
Summary

Dynamic Mollow triplets from JC-Systems



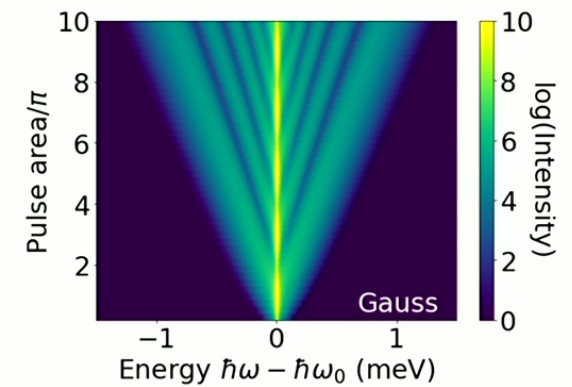
K.A. Fischer et al. Nature Photonics 10, 163–166 (2016)

Dressing dressed states



C. Gustin et al., Physical Review Research 3, 013044 (2021)

Dynamic Mollow triplets from TLS



K. Boos et al. Physical Review Letters 132, 053602 (2024)



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MCQST

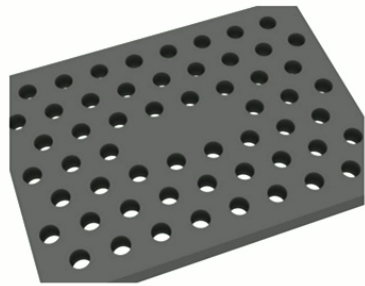
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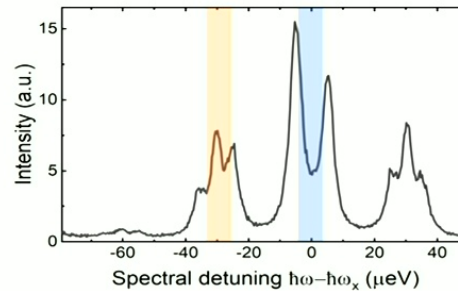
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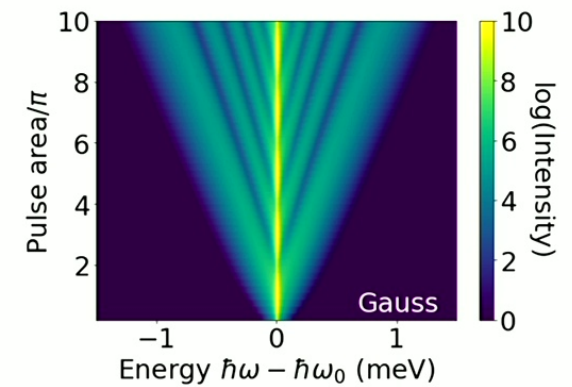
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Thank you very much for your attention!



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