HUNTING FOR PHOTON CORRELATIONS

EXPLORING NEW LANDSCAPES OF FREQUENCY-FILTERED PHOTON CORRELATIONS

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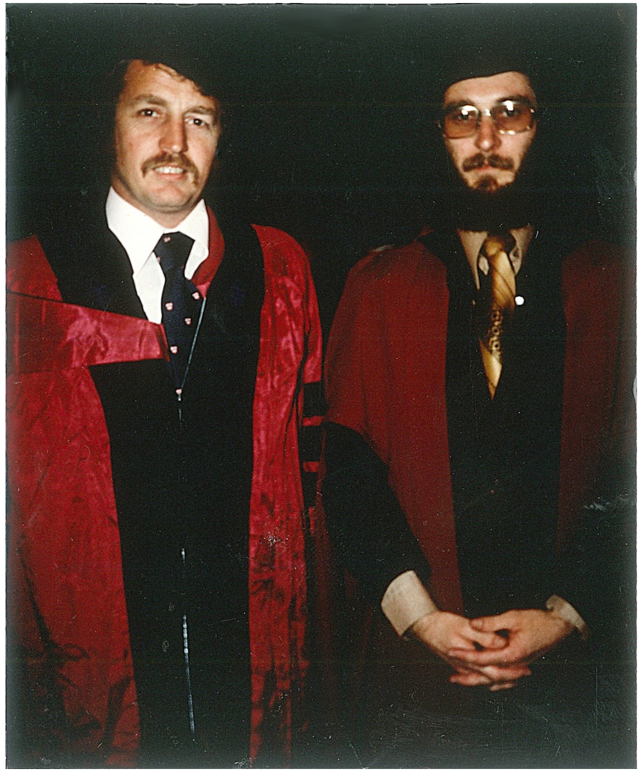
ANTIBUNCHING – A QUANTUM EFFECT



Proposal for the measurement of the resonant Stark effect by photon correlation techniques

H J Carmichael† and D F Walls
School of Science, University of Waikato, Hamilton, New Zealand

Received 8 December 1975

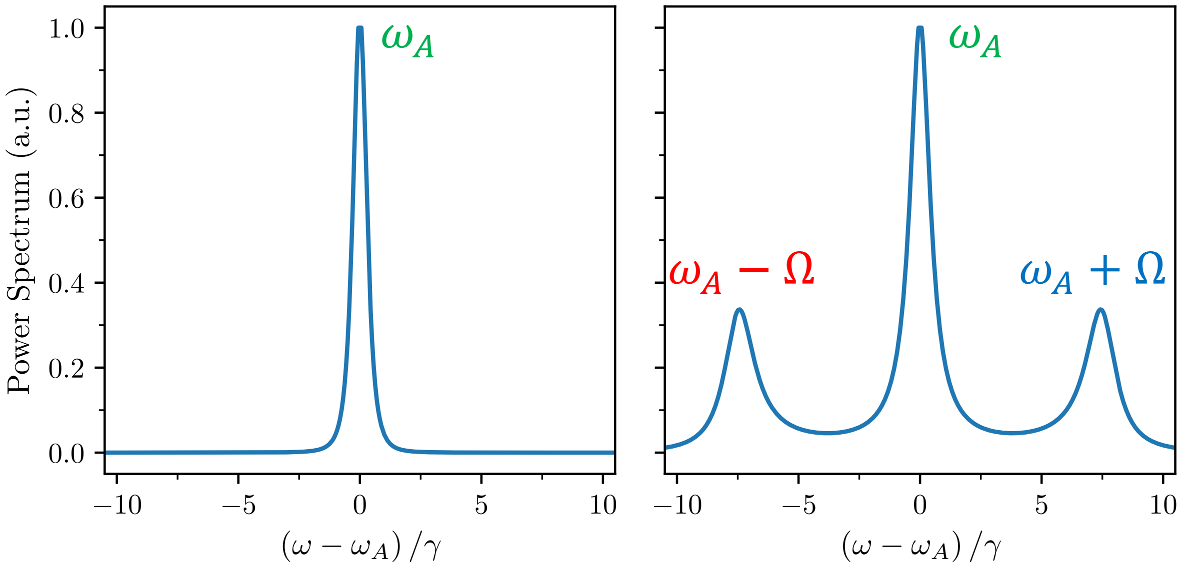
- Second-order correlation function:

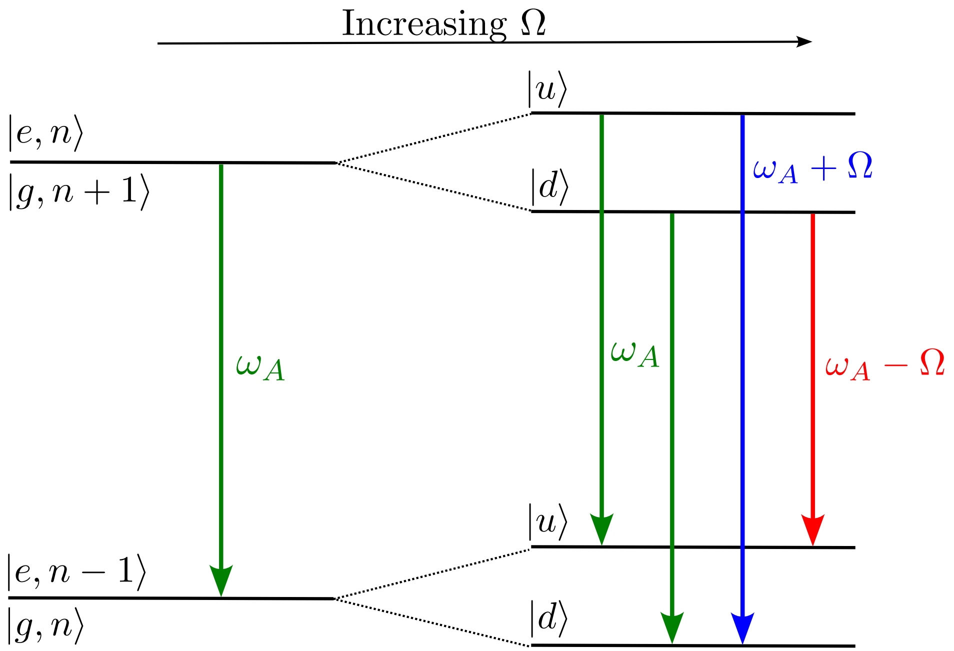
$$g^{(2)}(\tau) = \frac{\langle \sigma_+(0)\sigma_+\sigma_-(\tau)\sigma_-(0)\rangle_{ss}}{\langle \sigma_+\sigma_-\rangle_{ss}^2}$$

- $g^{(2)}(0) = 0$: antibunching / single-photons
- $g^{(2)}(0) = 1$: uncorrelated / random
- $g^{(2)}(0) > 1$: bunching / multi-photons

J. Phys. B: At. Mol. Phys. 9, L43 (1976)

THE MOLLOW TRIPLET





Power Spectrum of Light Scattered by Two-Level Systems

B. R. Mollow*
National Aeronautics and Space Administration, Electronics Research Center, Cambridge, Massachusetts

(Received 2 September 1969)

Dressed-atom description of resonance fluorescence and absorption spectra of a multi-level atom in an intense laser beam

Claude Cohen-Tannoudji and Serge Reynaud
Laboratoire de Spectroscopie Hertzienne, Ecole Normale Supérieure et Collège de France, 24 rue Lhomond, 75231 Paris Cedex 05, France

Received 22 June 1976, in final form 23 September 1976

FREQUENCY FILTERING

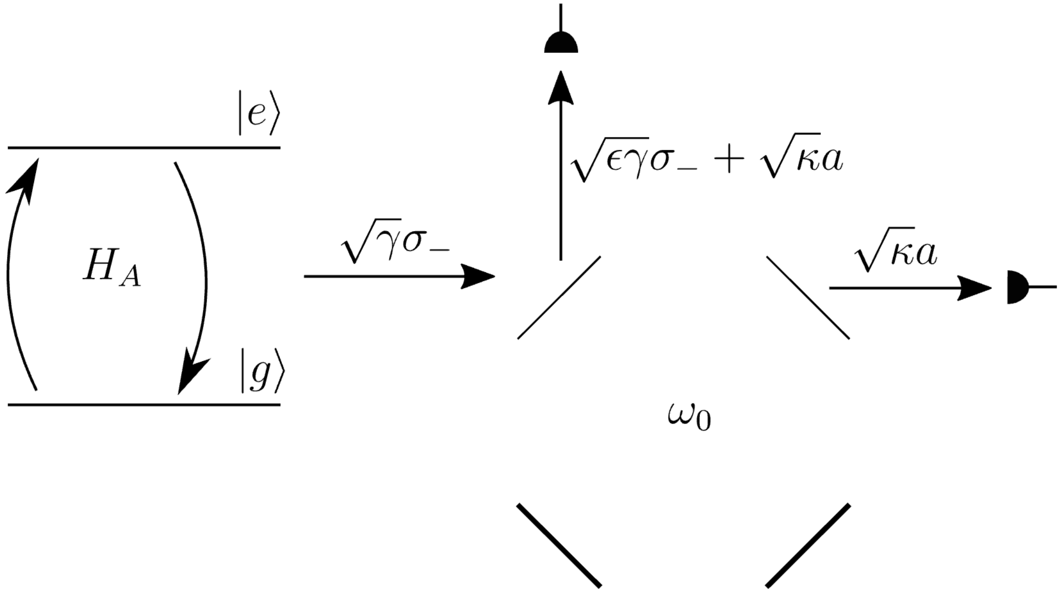
Detector atom approach – PRL **109**, 183601 (2012).

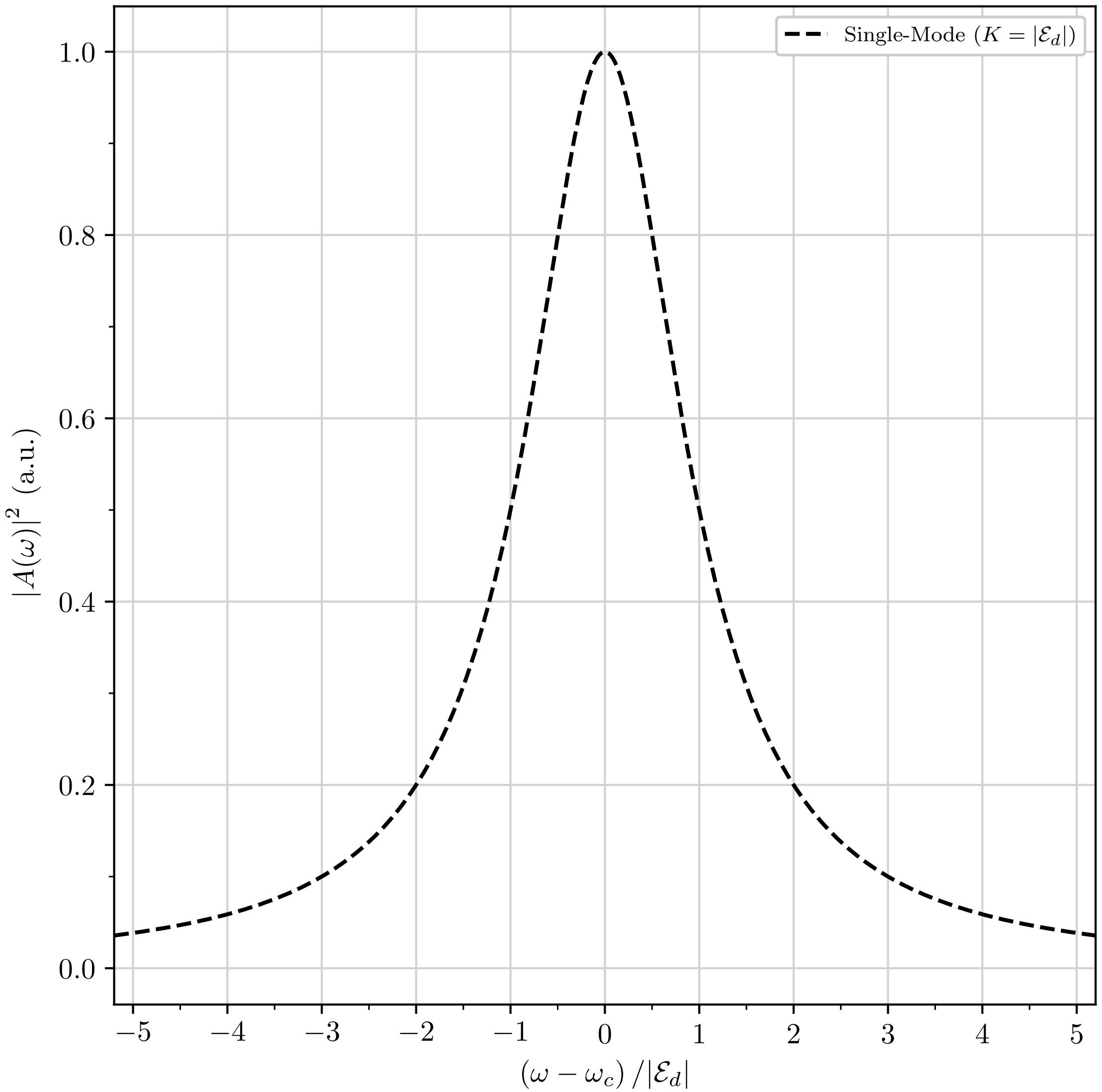
PRL **109,** 183601 (2012) PHYSICAL REVIEW LETTERS week ending 2 NOVEMBER 2012

Theory of Frequency-Filtered and Time-Resolved *N*-Photon Correlations

E. del Valle,[1,*] A. Gonzalez-Tudela,[2] F. P. Laussy,[2,3] C. Tejedor,[2] and M. J. Hartmann[1]

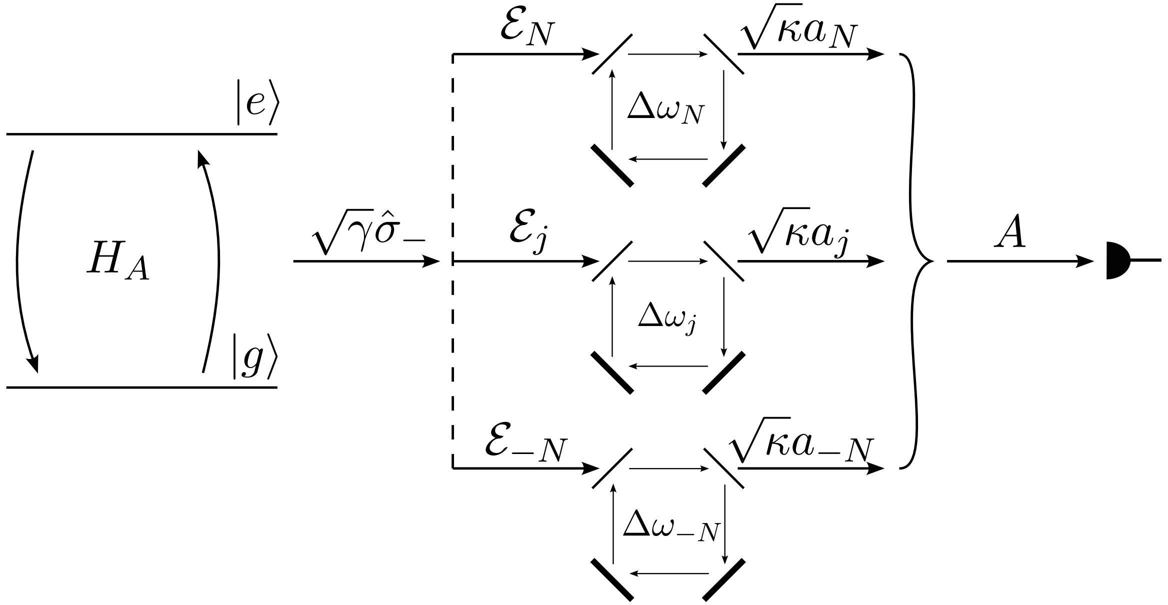
Single-mode cavity filters

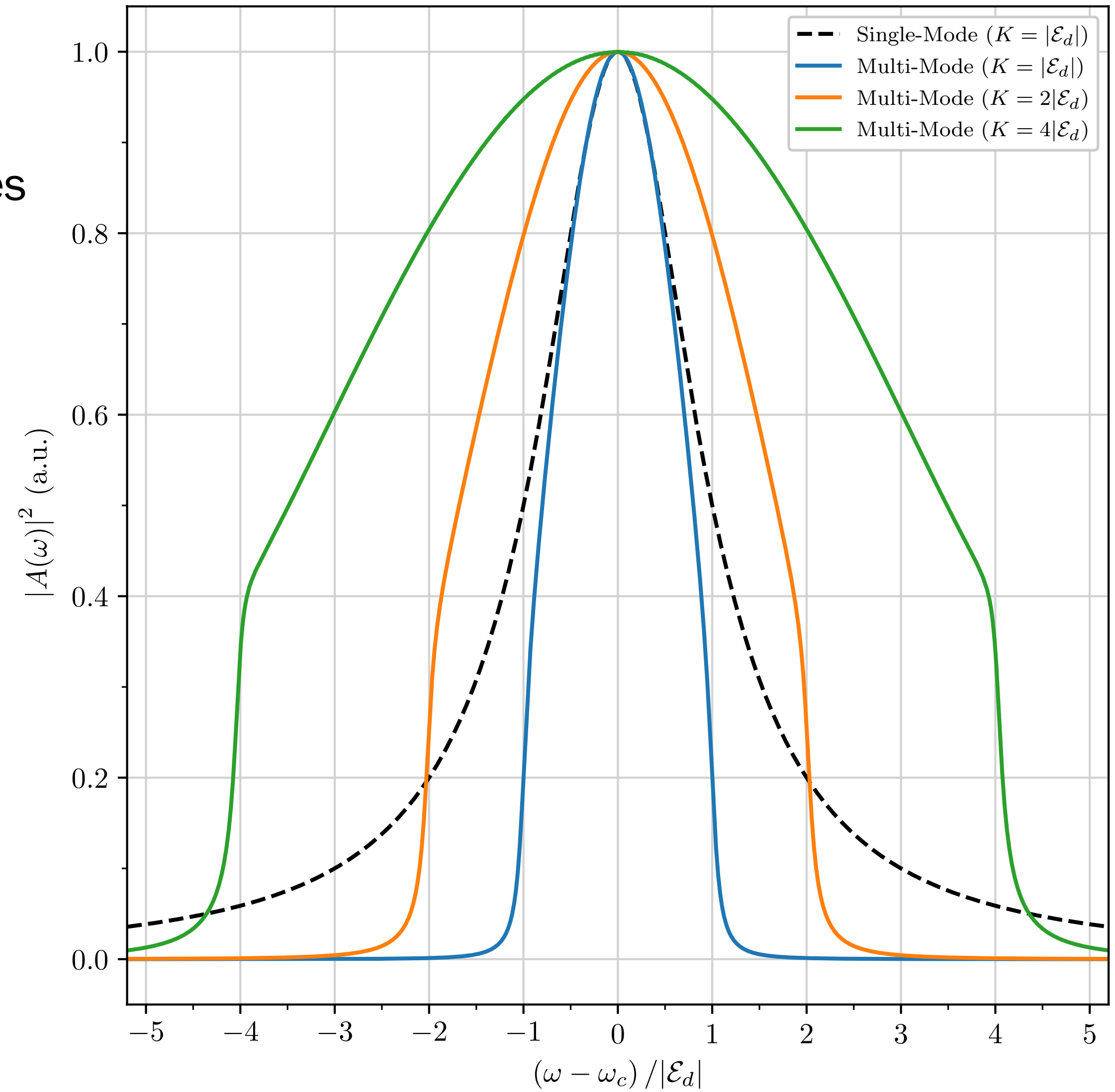




THE MULTI-MODE ARRAY FILTER

- Cascade fluorescence into an *array* of single-mode cavities
- Sharper frequency response cut-off
- NO back-action of filter on atom
- Larger bandwidth = faster (better) temporal response

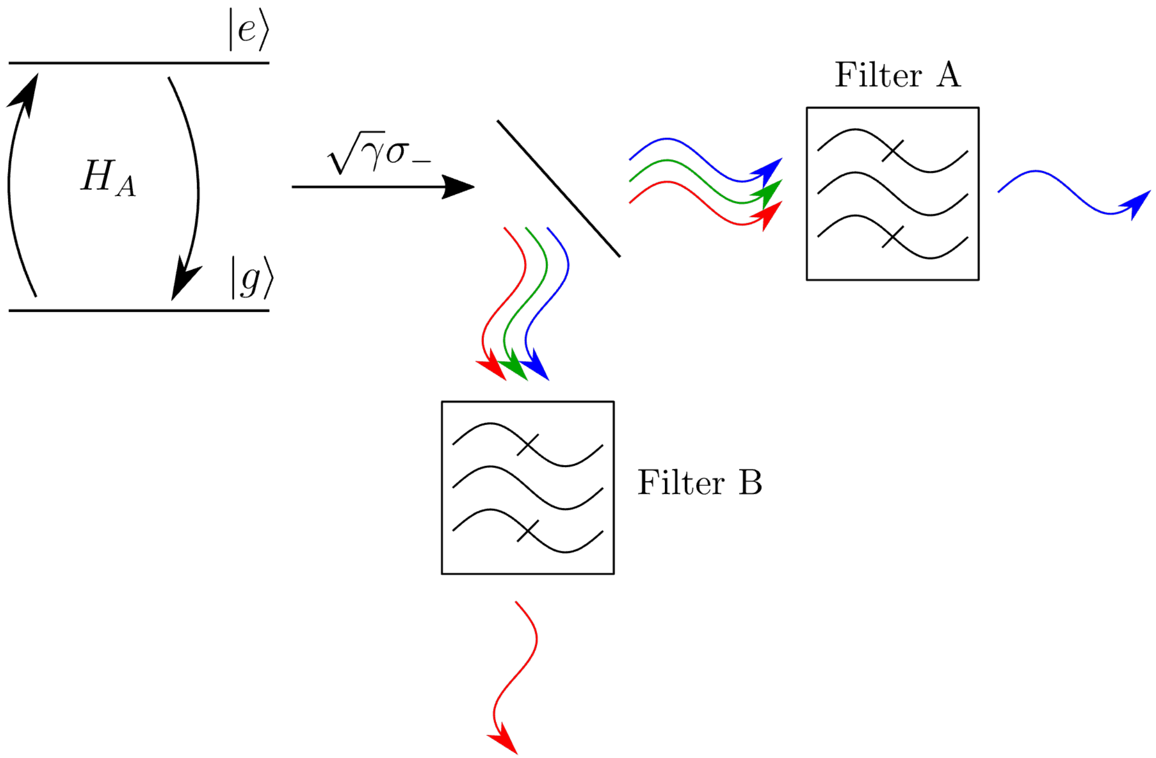




THE MULTI-MODE ARRAY FILTER

Master equation

$$
\begin{aligned}
\frac{\mathrm{d}\rho}{\mathrm{d}t} = & -i\frac{\Omega}{2}[\sigma_+ + \sigma_-, \rho] + \frac{\gamma}{2}\Lambda(\sigma_-)\rho \\
& - i\sum_{j=-N}^{N}\Delta\omega_j^{(a)} a_j^\dagger a_j + \frac{\kappa}{2}\sum_{j=-N}^{N}\Lambda(a_j)\rho \\
& - \sum_{j=-N}^{N}\mathcal{E}_j\left(a_j^\dagger\sigma_-\rho - \sigma_-\rho a_j^\dagger\right) - \sum_{j=-N}^{N}\mathcal{E}_j^*\left(\rho\sigma_+ a_j - a_j\rho\sigma_+\right) \\
& - i\sum_{j=-N}^{N}\Delta\omega_j^{(b)} b_j^\dagger b_j + \frac{\kappa}{2}\sum_{j=-N}^{N}\Lambda(b_j)\rho \\
& - \sum_{j=-N}^{N}\mathcal{E}_j\left(b_j^\dagger\sigma_-\rho - \sigma_-\rho b_j^\dagger\right) - \sum_{j=-N}^{N}\mathcal{E}_j^*\left(\rho\sigma_+ b_j - b_j\rho\sigma_+\right)
\end{aligned}
$$



$$\Lambda(X)\bullet = 2X\bullet X^\dagger - X^\dagger X\bullet - \bullet X^\dagger X$$

THE MULTI-MODE ARRAY FILTER

Master equation

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = \boxed{-i\frac{\Omega}{2}[\sigma_+ + \sigma_-, \rho] + \frac{\gamma}{2}\Lambda(\sigma_-)\rho}$$

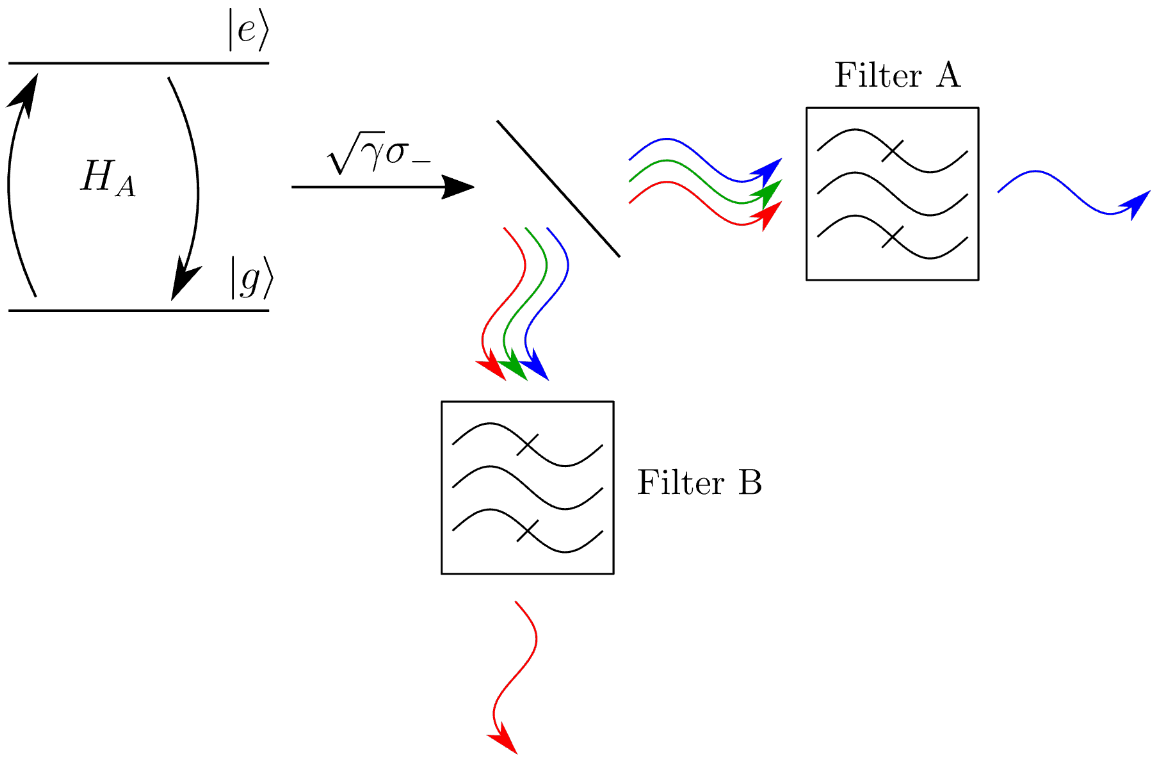
Driven atom

$$- i \sum_{j=-N}^{N} \Delta\omega_j^{(a)} a_j^\dagger a_j + \frac{\kappa}{2} \sum_{j=-N}^{N} \Lambda(a_j)\rho$$

$$- \sum_{j=-N}^{N} \mathcal{E}_j \left(a_j^\dagger \sigma_- \rho - \sigma_- \rho a_j^\dagger \right) - \sum_{j=-N}^{N} \mathcal{E}_j^* \left(\rho\sigma_+ a_j - a_j \rho \sigma_+ \right)$$

$$- i \sum_{j=-N}^{N} \Delta\omega_j^{(b)} b_j^\dagger b_j + \frac{\kappa}{2} \sum_{j=-N}^{N} \Lambda(b_j)\rho$$

$$- \sum_{j=-N}^{N} \mathcal{E}_j \left(b_j^\dagger \sigma_- \rho - \sigma_- \rho b_j^\dagger \right) - \sum_{j=-N}^{N} \mathcal{E}_j^* \left(\rho\sigma_+ b_j - b_j \rho \sigma_+ \right)$$



$$\Lambda(X)\bullet = 2X \bullet X^\dagger - X^\dagger X \bullet - \bullet X^\dagger X$$

THE MULTI-MODE ARRAY FILTER

Master equation

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = -i\frac{\Omega}{2}[\sigma_{+} + \sigma_{-}, \rho] + \frac{\gamma}{2}\Lambda(\sigma_{-})\rho$$

Driven atom

$$- i \sum_{j=-N}^{N} \Delta\omega_{j}^{(a)} a_{j}^{\dagger} a_{j} + \frac{\kappa}{2} \sum_{j=-N}^{N} \Lambda(a_{j})\rho$$

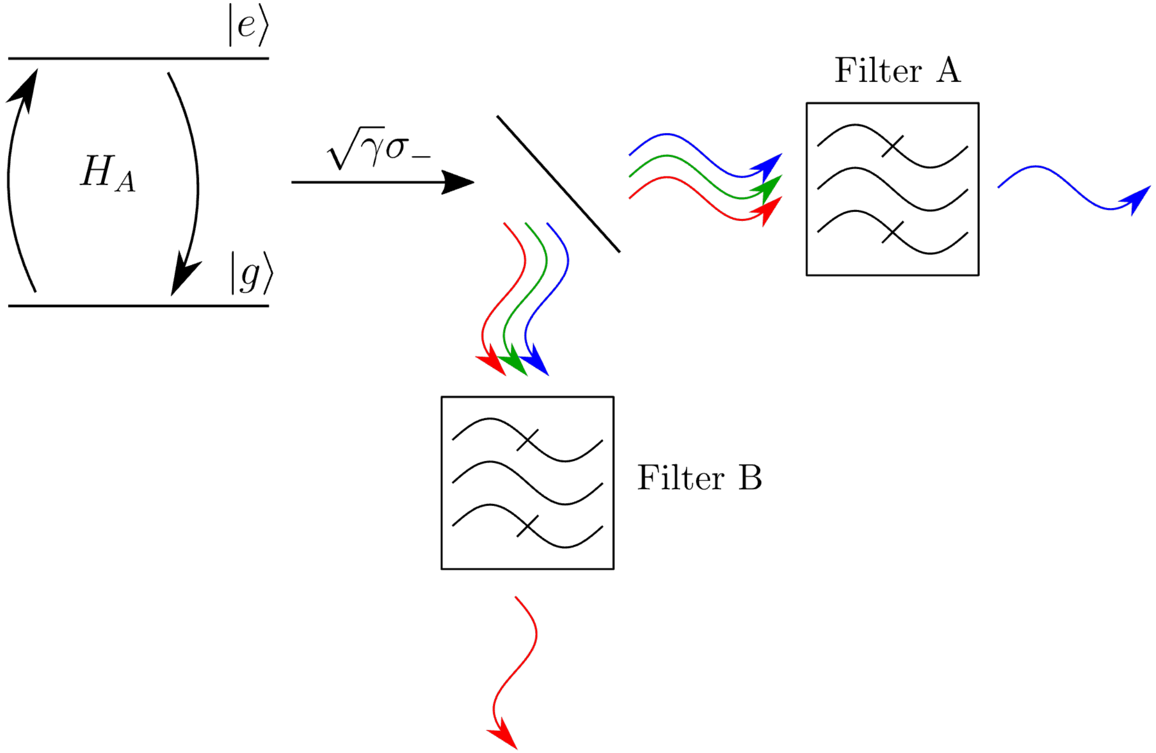
Array Filter A

$$- \sum_{j=-N}^{N} \mathcal{E}_{j} \left(a_{j}^{\dagger}\sigma_{-}\rho - \sigma_{-}\rho a_{j}^{\dagger} \right) - \sum_{j=-N}^{N} \mathcal{E}_{j}^{*} \left(\rho\sigma_{+} a_{j} - a_{j}\rho\sigma_{+} \right)$$

$$- i \sum_{j=-N}^{N} \Delta\omega_{j}^{(b)} b_{j}^{\dagger} b_{j} + \frac{\kappa}{2} \sum_{j=-N}^{N} \Lambda(b_{j})\rho$$

Array Filter B

$$- \sum_{j=-N}^{N} \mathcal{E}_{j} \left(b_{j}^{\dagger}\sigma_{-}\rho - \sigma_{-}\rho b_{j}^{\dagger} \right) - \sum_{j=-N}^{N} \mathcal{E}_{j}^{*} \left(\rho\sigma_{+} b_{j} - b_{j}\rho\sigma_{+} \right)$$



$$\Lambda(X)\bullet = 2X \bullet X^{\dagger} - X^{\dagger}X \bullet - \bullet X^{\dagger}X$$

THE MULTI-MODE ARRAY FILTER

Master equation

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = -i\frac{\Omega}{2}[\sigma_+ + \sigma_-, \rho] + \frac{\gamma}{2}\Lambda(\sigma_-)\rho$$

Driven atom

$$- i \sum_{j=-N}^{N} \Delta\omega_j^{(a)} a_j^\dagger a_j + \frac{\kappa}{2} \sum_{j=-N}^{N} \Lambda(a_j)\rho$$

Array Filter A

$$- \sum_{j=-N}^{N} \mathcal{E}_j \left(a_j^\dagger \sigma_- \rho - \sigma_- \rho a_j^\dagger \right) - \sum_{j=-N}^{N} \mathcal{E}_j^* \left(\rho \sigma_+ a_j - a_j \rho \sigma_+ \right)$$

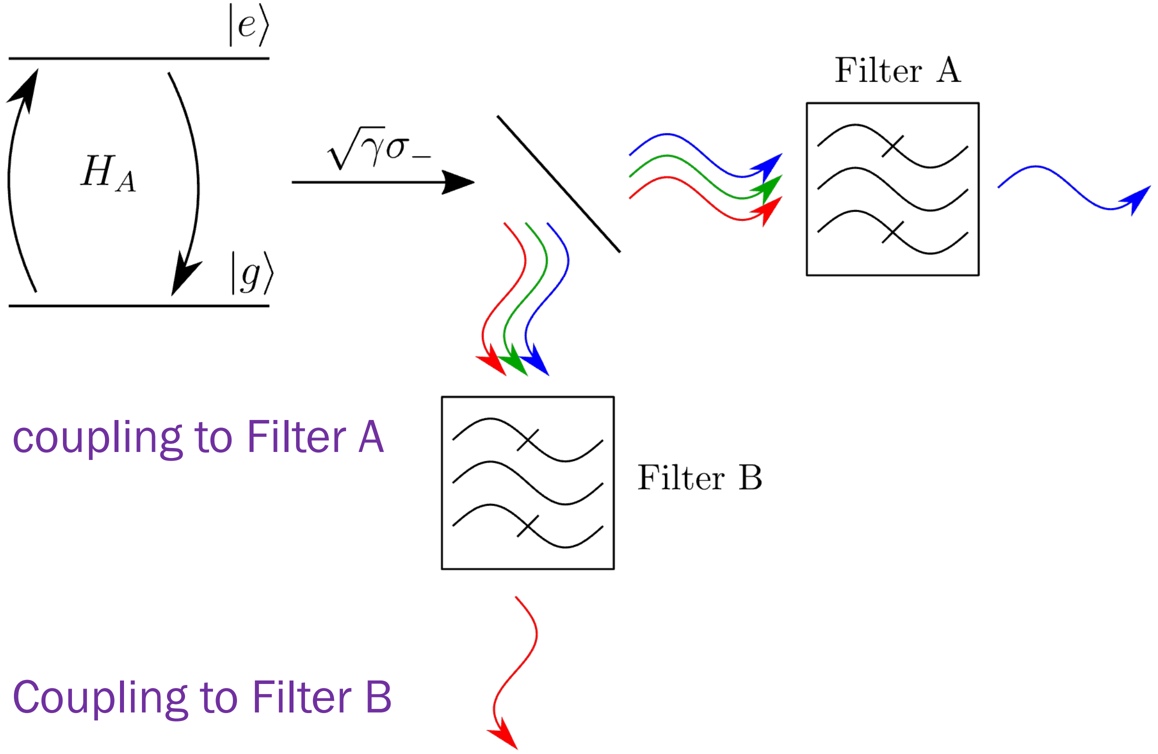
Cascaded coupling to Filter A

$$- i \sum_{j=-N}^{N} \Delta\omega_j^{(b)} b_j^\dagger b_j + \frac{\kappa}{2} \sum_{j=-N}^{N} \Lambda(b_j)\rho$$

Array Filter B

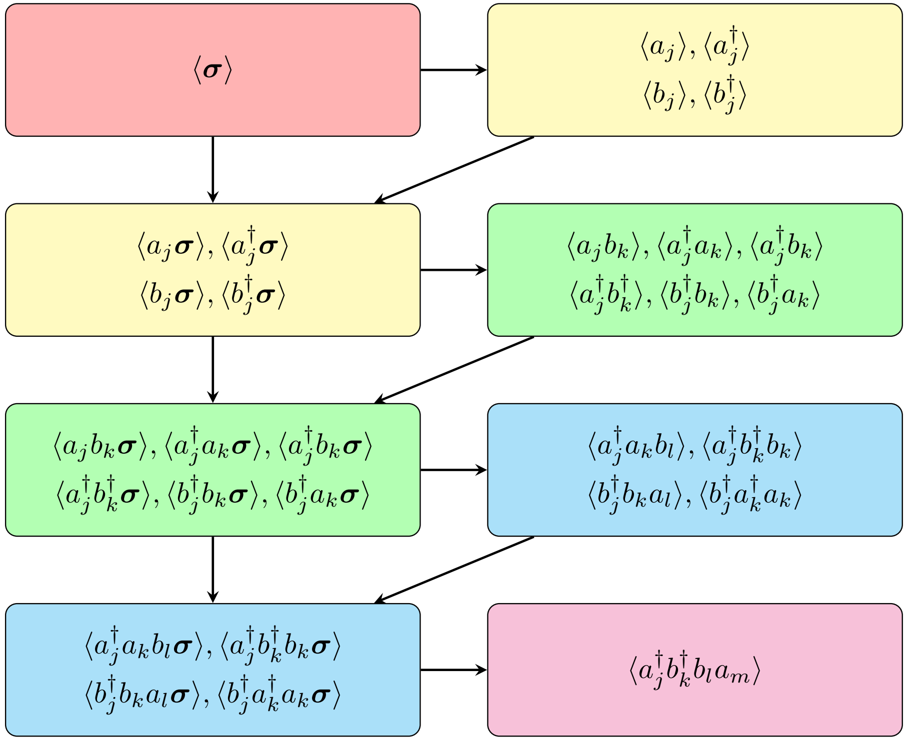
$$- \sum_{j=-N}^{N} \mathcal{E}_j \left(b_j^\dagger \sigma_- \rho - \sigma_- \rho b_j^\dagger \right) - \sum_{j=-N}^{N} \mathcal{E}_j^* \left(\rho \sigma_+ b_j - b_j \rho \sigma_+ \right)$$

Cascaded Coupling to Filter B



$$\Lambda(X)\bullet = 2X \bullet X^\dagger - X^\dagger X \bullet - \bullet X^\dagger X$$

THE MULTI-MODE ARRAY FILTER



- Frequency-filtered second-order correlation function:

$$g^{(2)}(\alpha, 0; \beta, \tau) = \frac{\langle A^\dagger(0) B^\dagger B(\tau) A(0) \rangle_{ss}}{\langle A^\dagger A \rangle_{ss} \langle B^\dagger B \rangle_{ss}}$$

- Collective mode annihilation operators

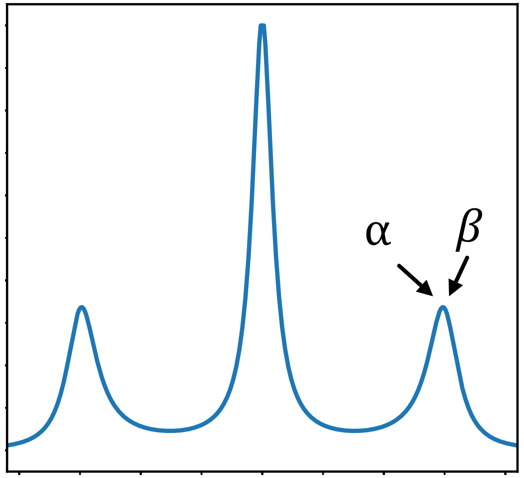
$$A = \sum_{j=-N}^{N} a_j, \quad B = \sum_{j=-N}^{N} b_j$$

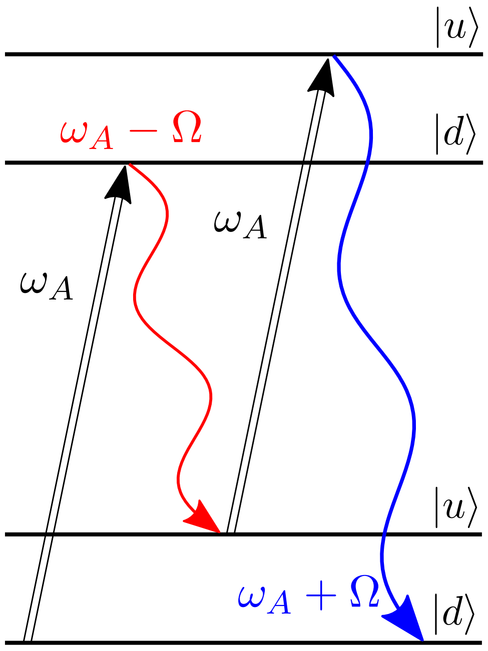
- Moment equations – efficient method for calculating

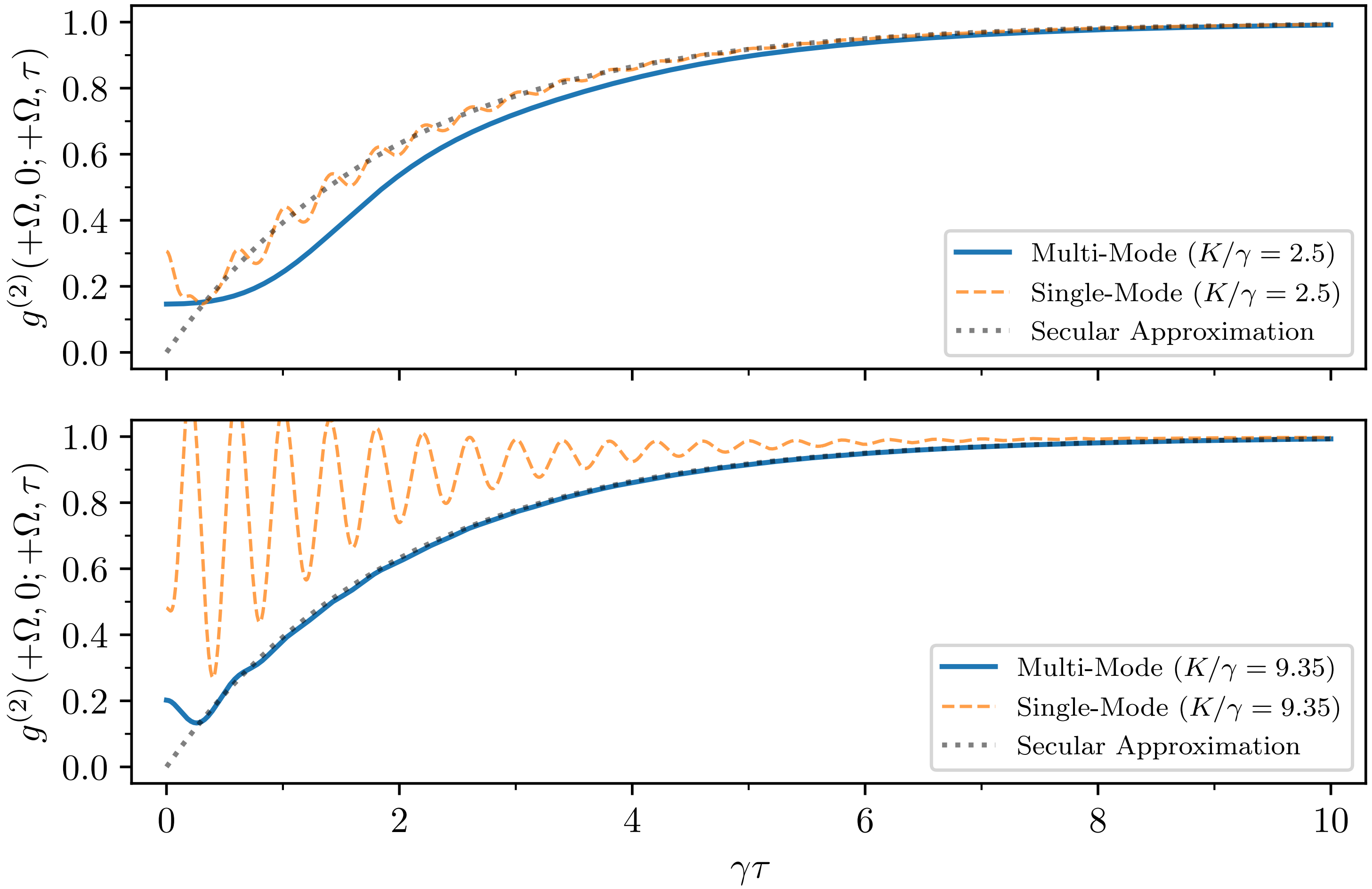
FREQUENCY-FILTERED AUTO-CORRELATIONS

- From secular approximation:

$$g^{(2)}(\pm\Omega, 0; \pm\Omega, \tau) = 1 - e^{-\frac{\gamma}{2}\tau}$$

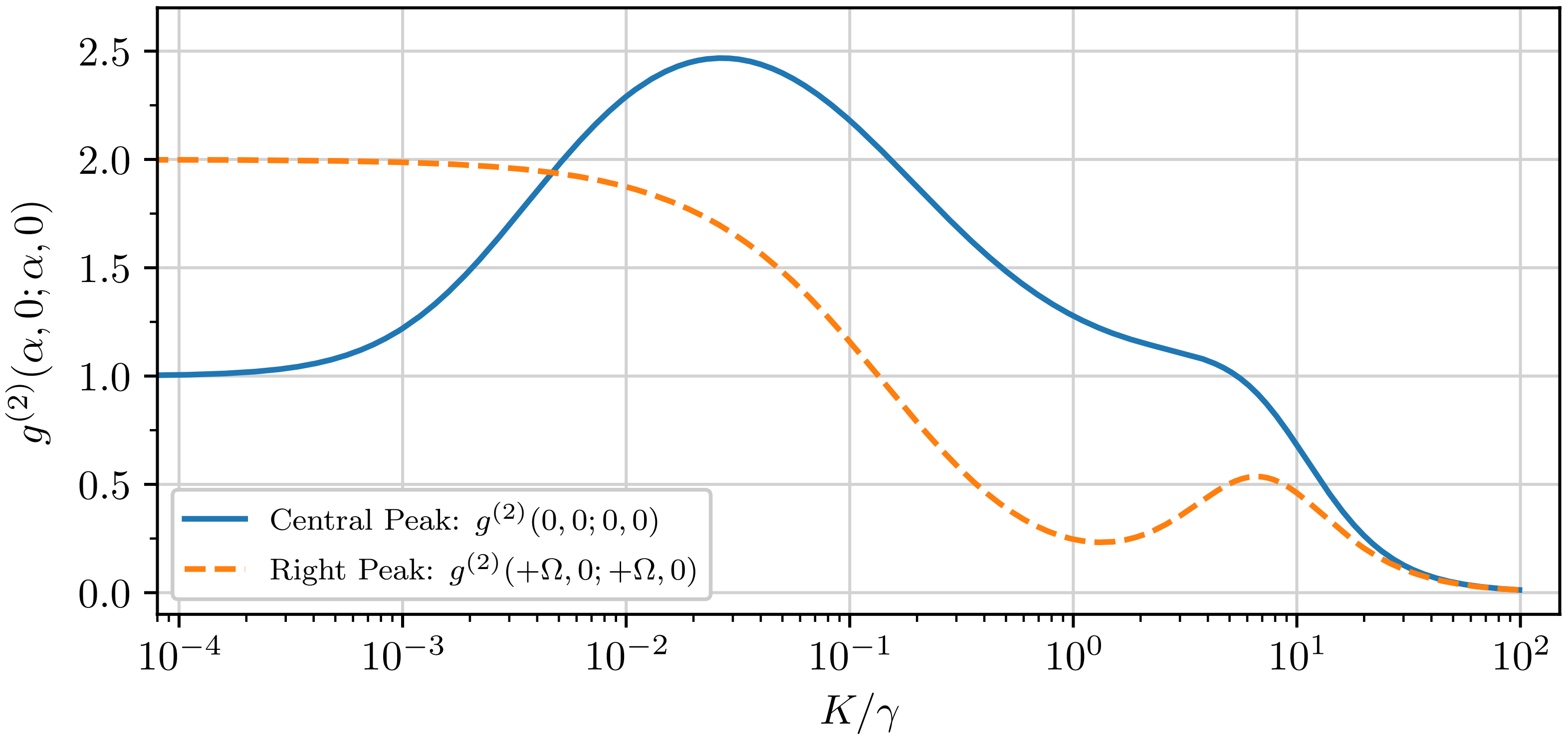






NARROW BANDWIDTHS – SINGLE-MODE

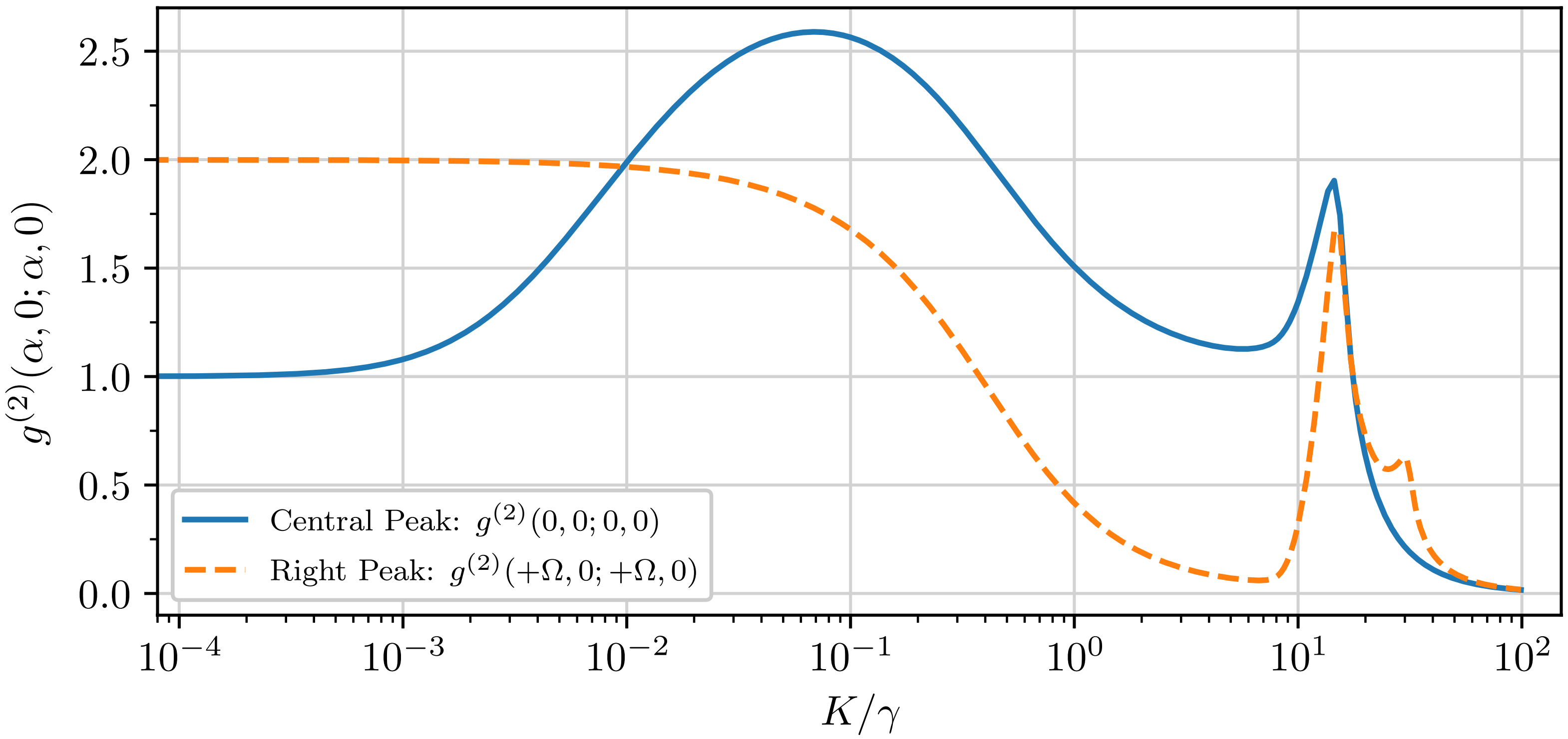
- What happens when we *decrease* the bandwidth?
- Large bandwidth = antibunching
- Vanishing bandwidth = uncorrelated (central peak), thermal (right peak)



Single-mode auto-correlations

NARROW BANDWIDTHS – MULTI-MODE

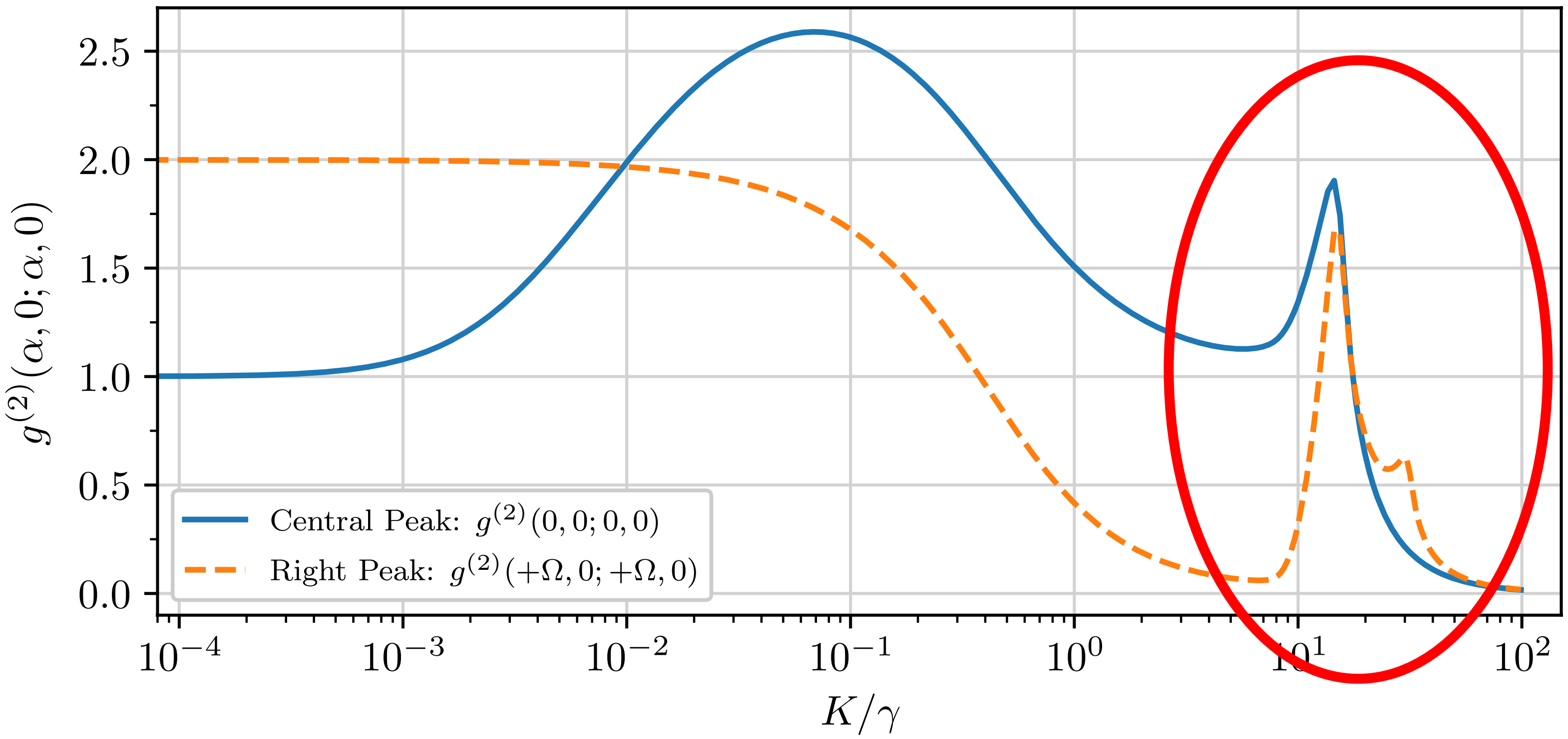
- Similar results to single-mode for extreme bandwidths
- Large bunching appearing when bandwidth is close to peak separation (K ≈ Ω)
- Only visible with improved frequency isolation of multi-mode array filter



Multi-mode auto-correlations

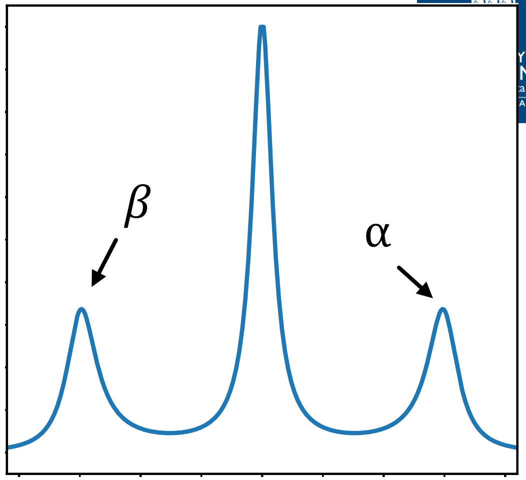
NARROW BANDWIDTHS – MULTI-MODE

- Similar results to single-mode for extreme bandwidths
- Large bunching appearing when bandwidth is close to peak separation ($K \approx \Omega$)
- Only visible with improved frequency isolation of multi-mode array filter

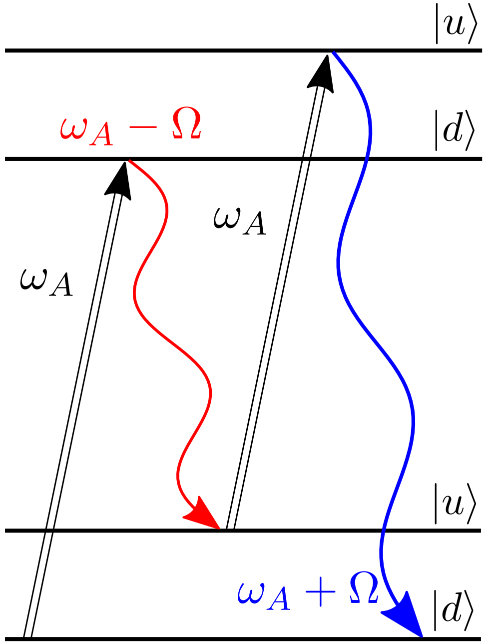


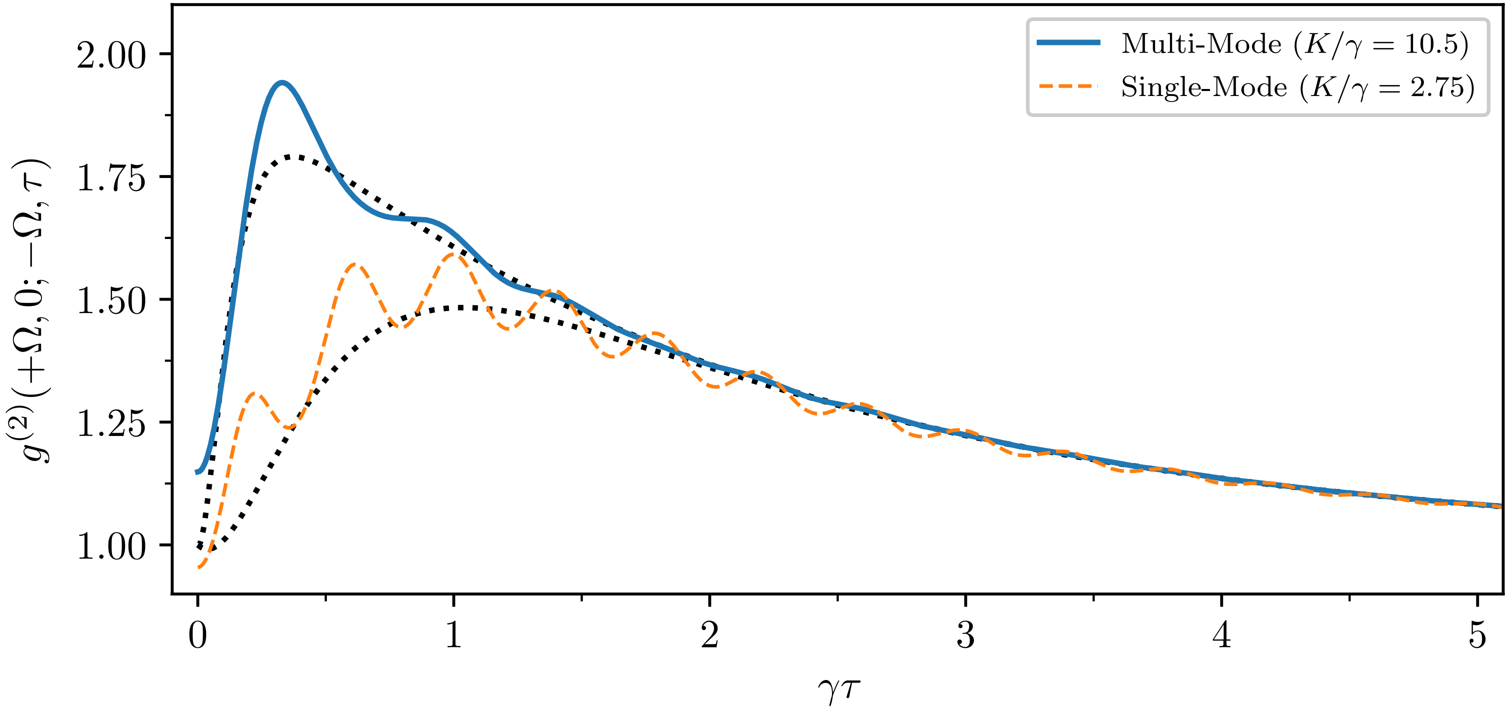
Multi-mode auto-correlations

FREQUENCY-FILTERED CROSS-CORRELATIONS

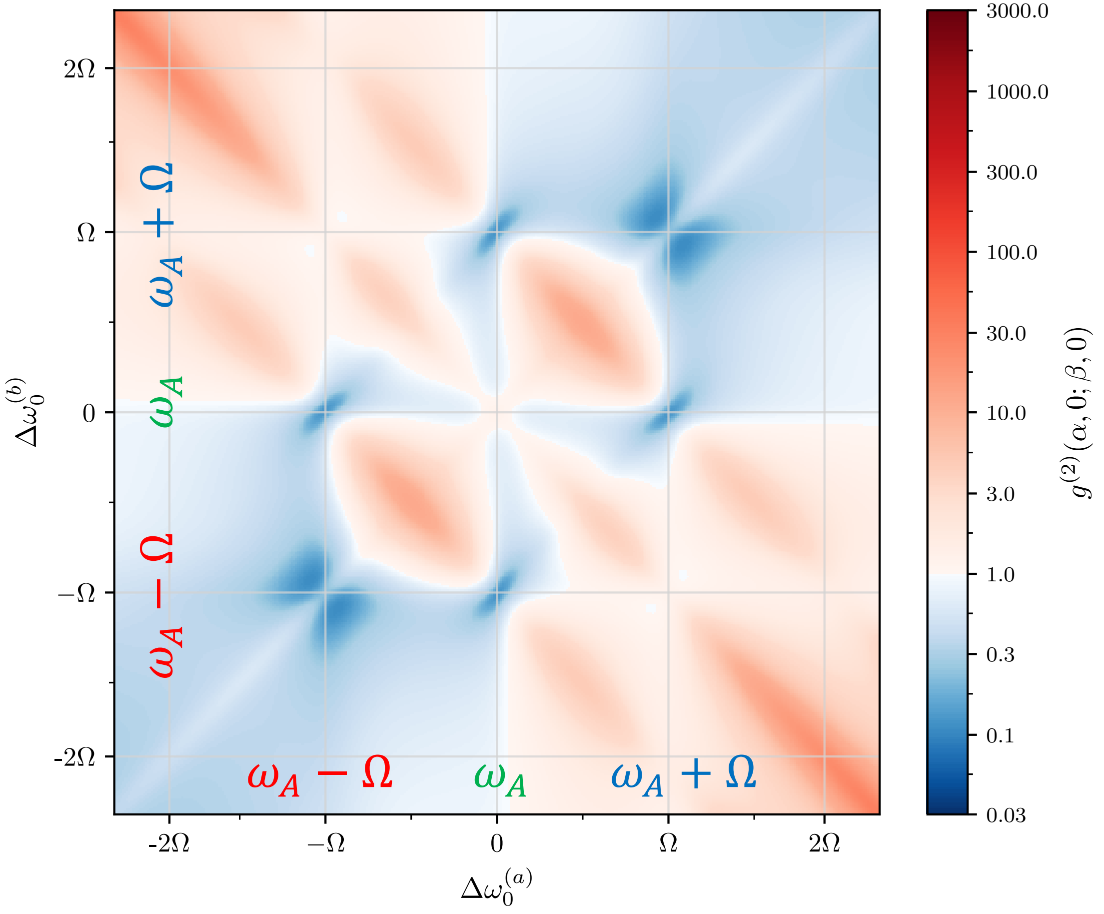


Approximate correlations from
PRL **67**, 2443 (1991) PRA **45**, 8045 (1992).





LANDSCAPES OF PHOTON CORRELATIONS

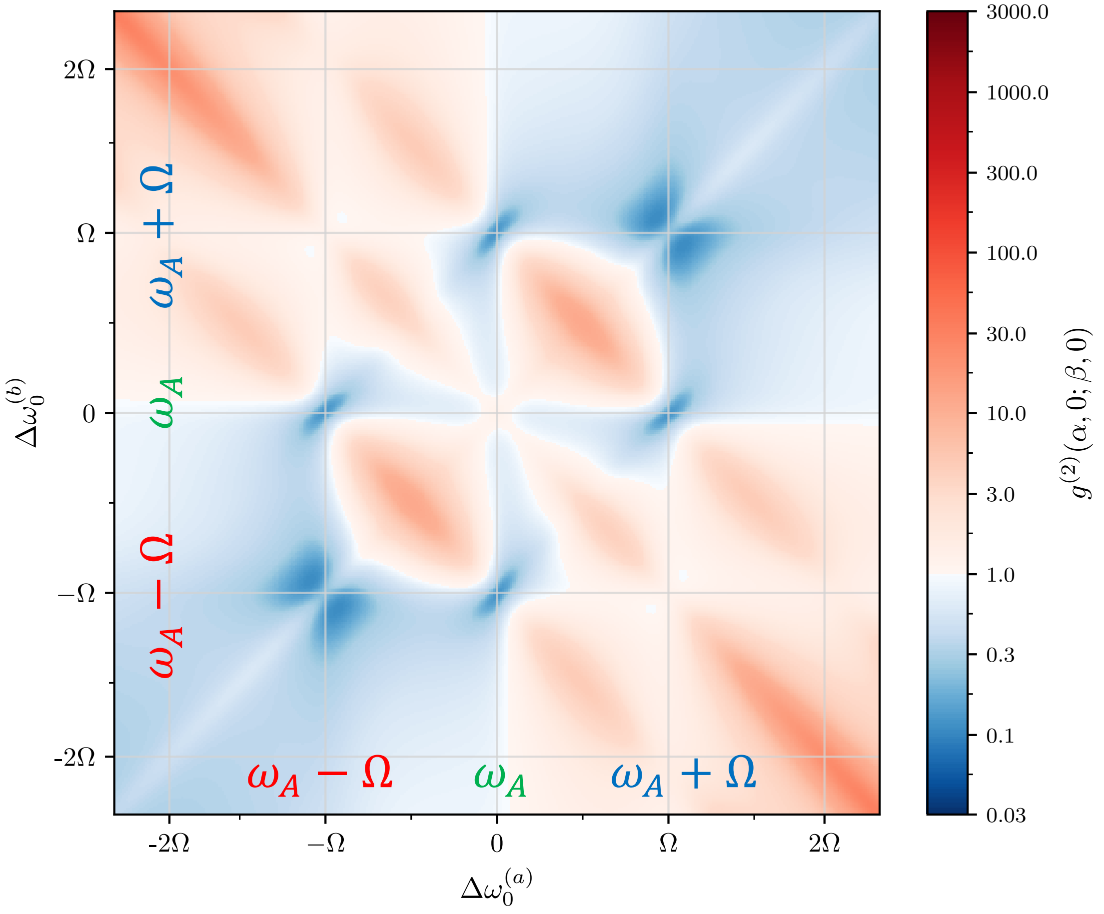


Reproduction of single-mode results from Laser Photons Rev. **11**, 170090 (2017)

Initial correlation values

- Red – correlated / bunching
- White – uncorrelated / random
- Blue – anti-correlated / antibunched

LANDSCAPES OF PHOTON CORRELATIONS



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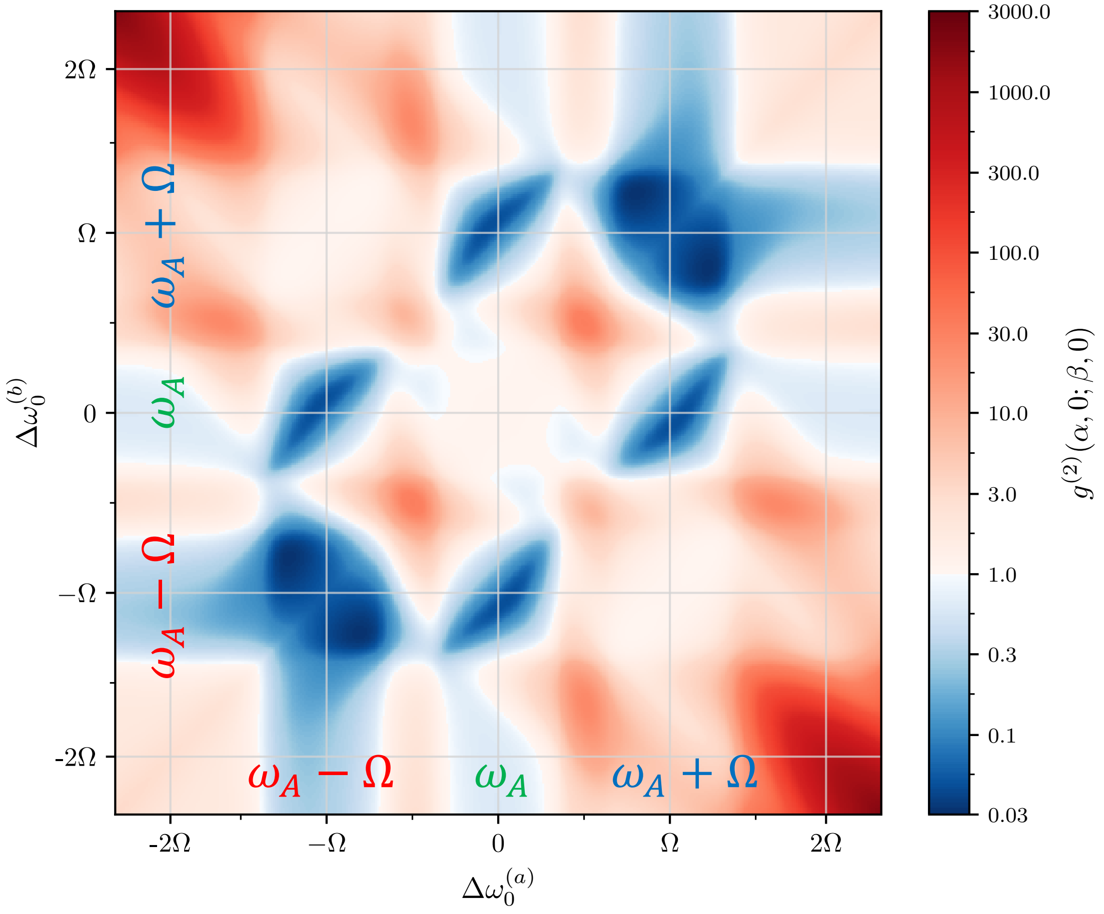
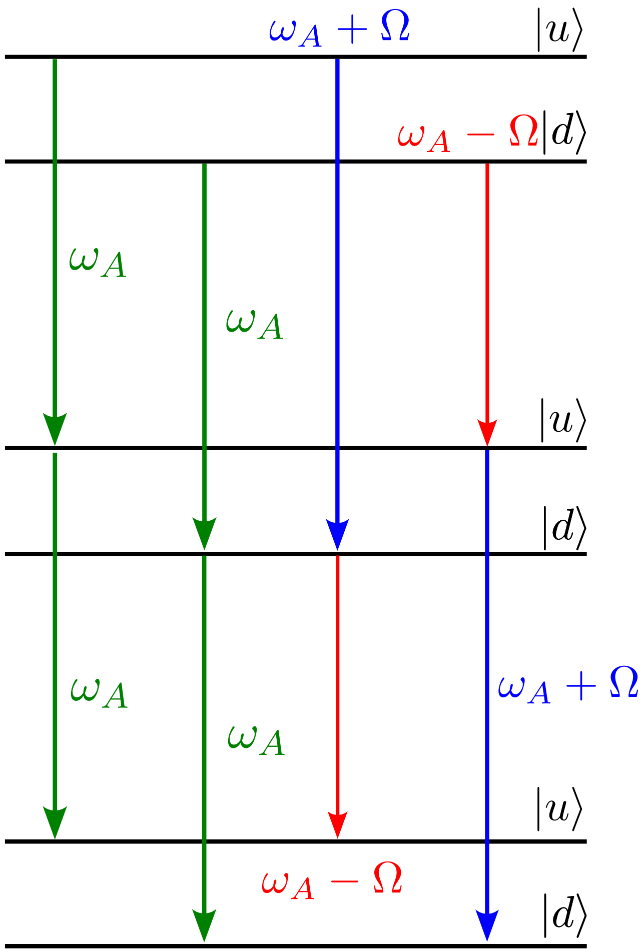
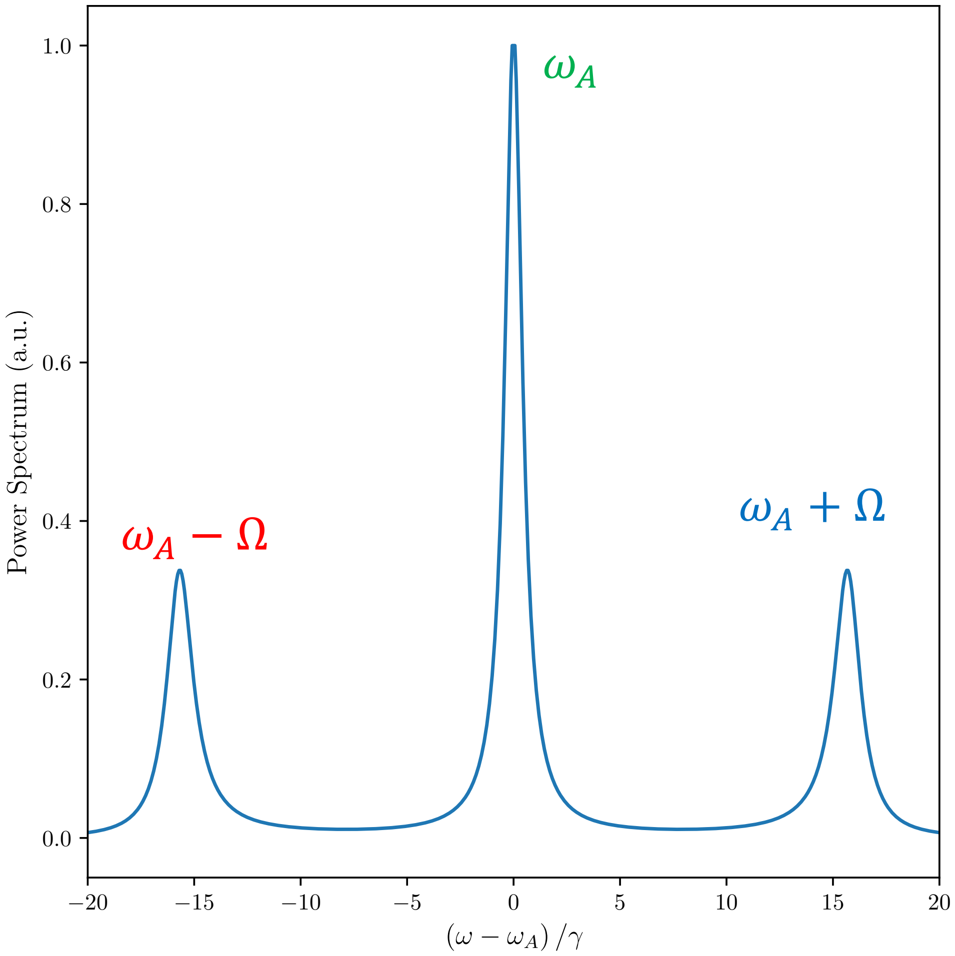


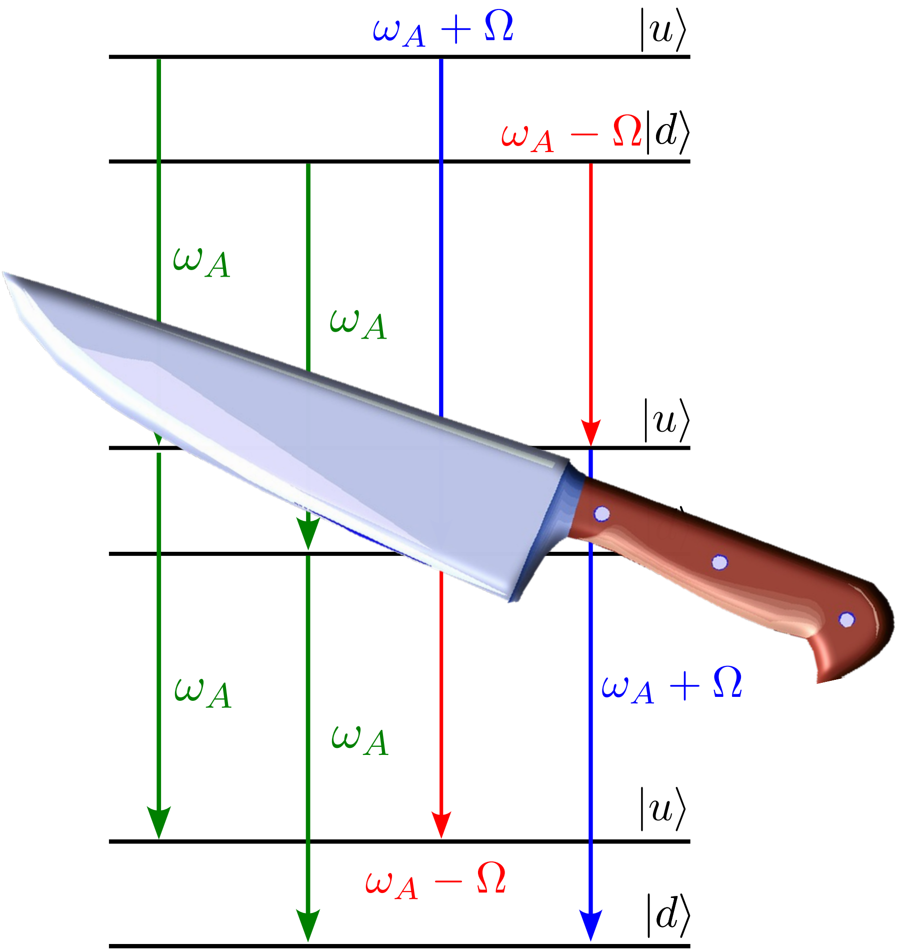
Multi-mode array filter

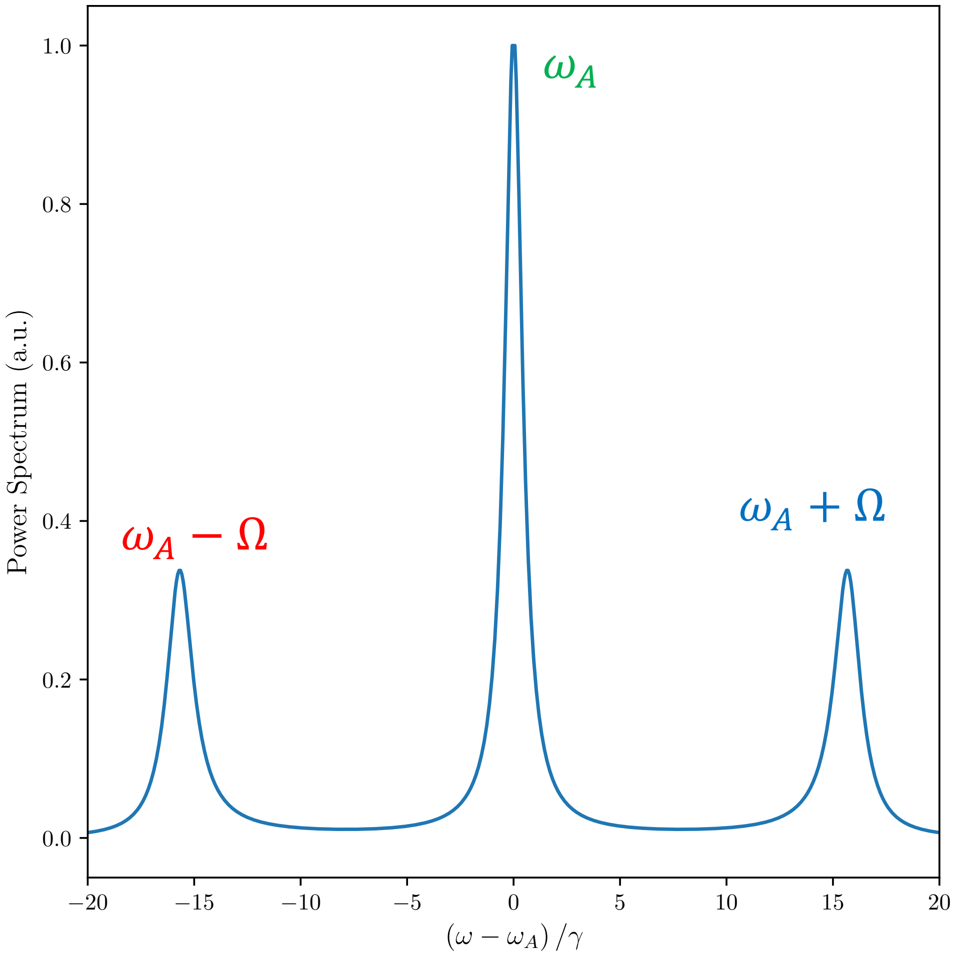
SIMULTANEOUS TWO-PHOTON DECAY





SIMULTANEOUS TWO-PHOTON DECAY





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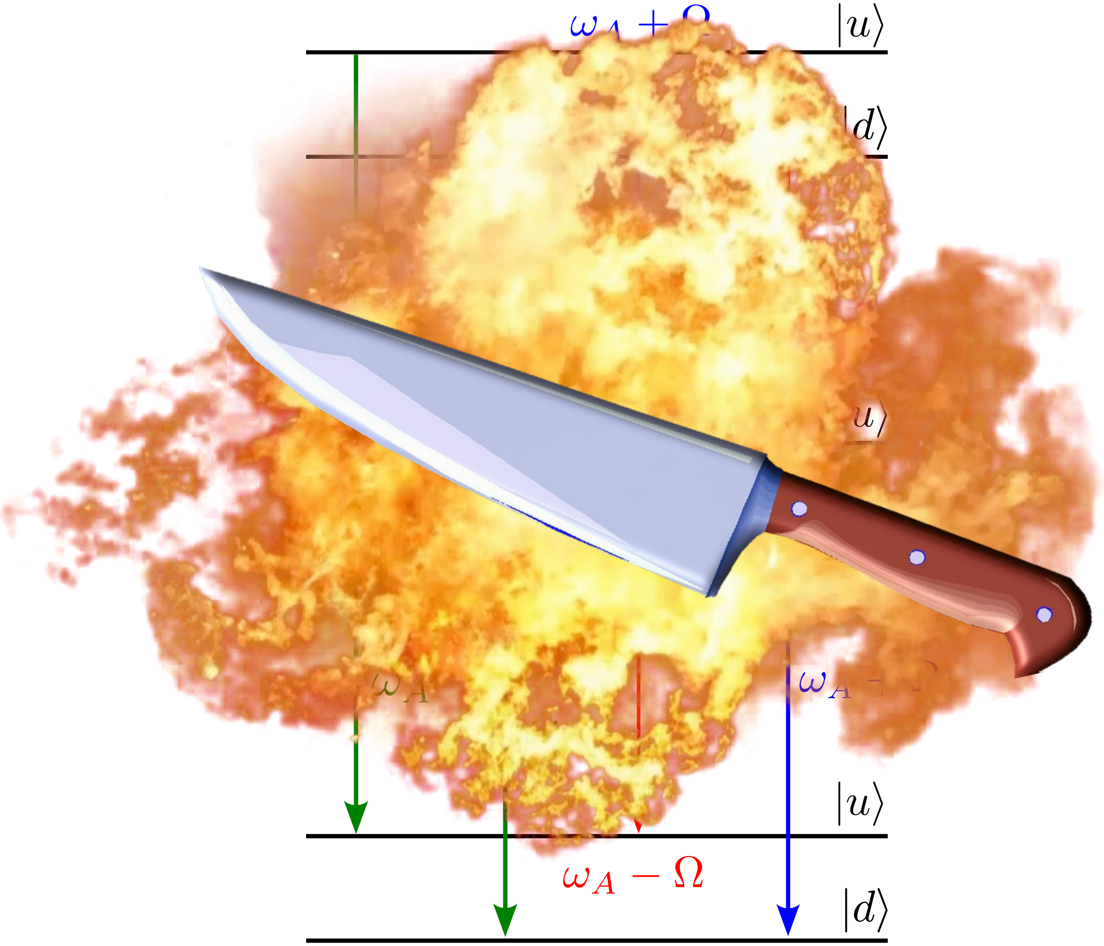

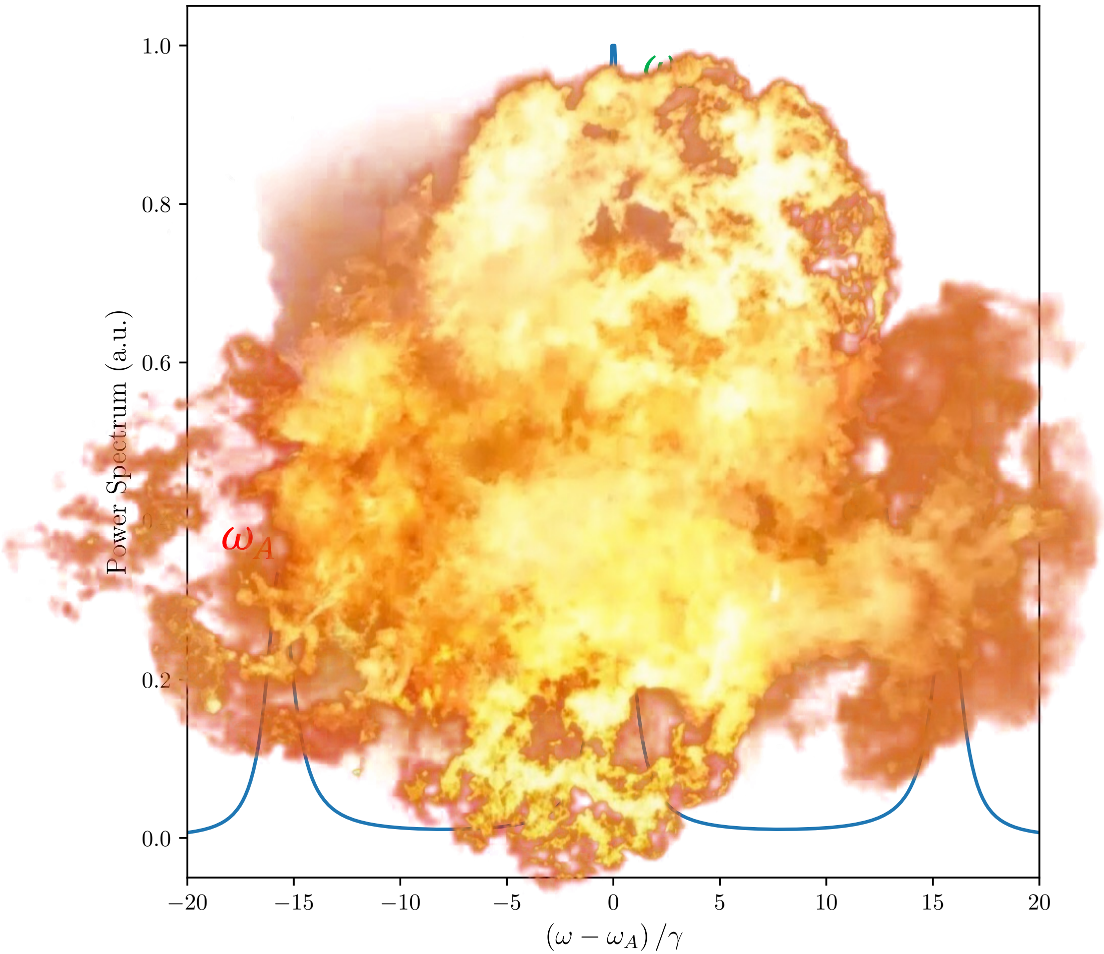

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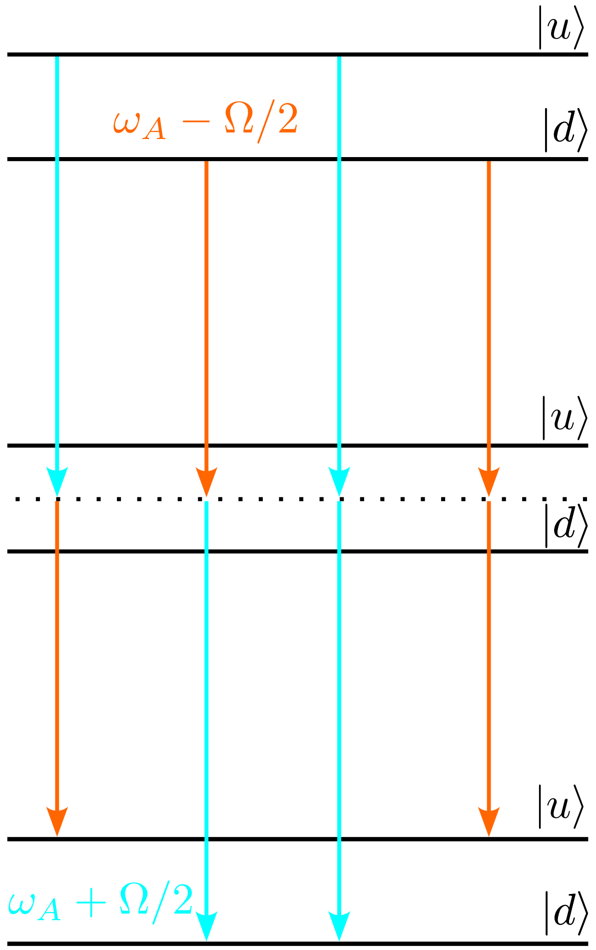

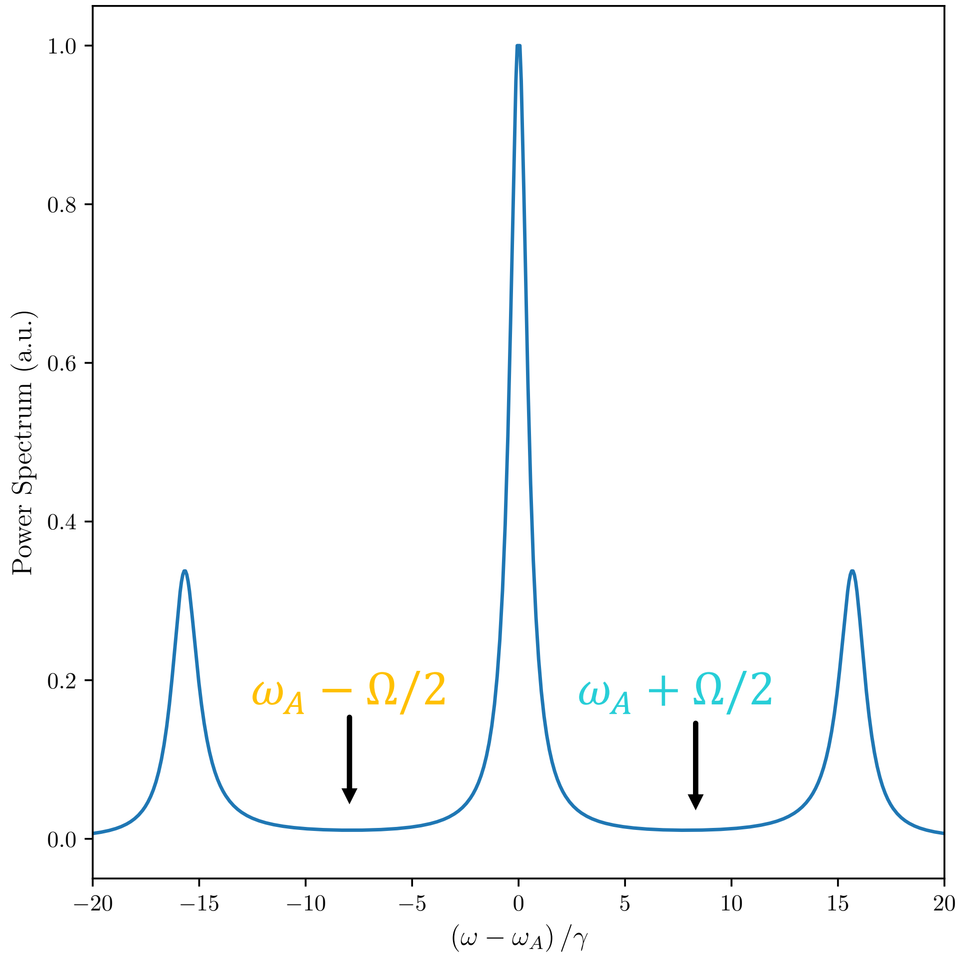

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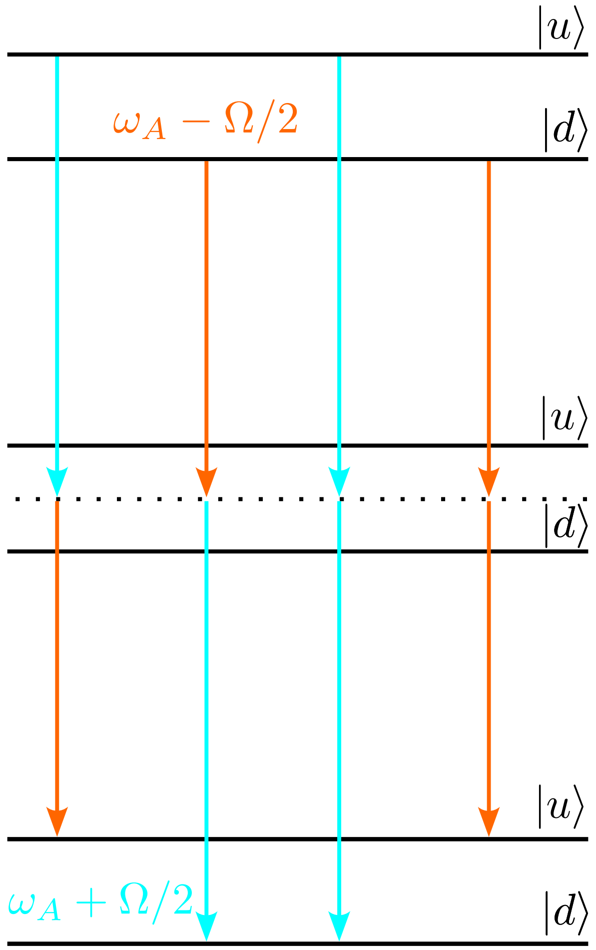

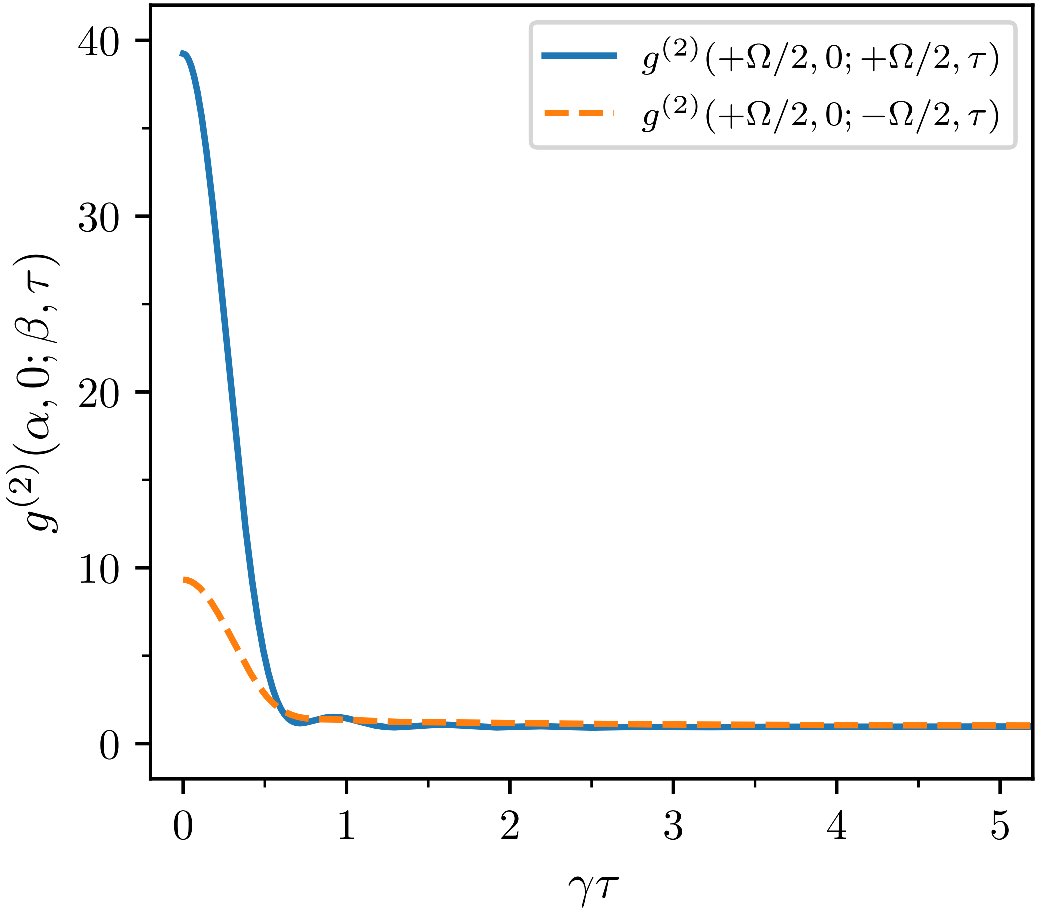

CONCLUSIONS

- Sharper frequency response can find for new regions of photon correlations
- A large system with an extremely efficient method of calculations
- *Probably* an experimental nightmare