Quantum metrology through spectral measurements in quantum optics

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arXiv > quant-ph > arXiv:2509.04300

Quantum Physics

[Submitted on 4 Sep 2025]

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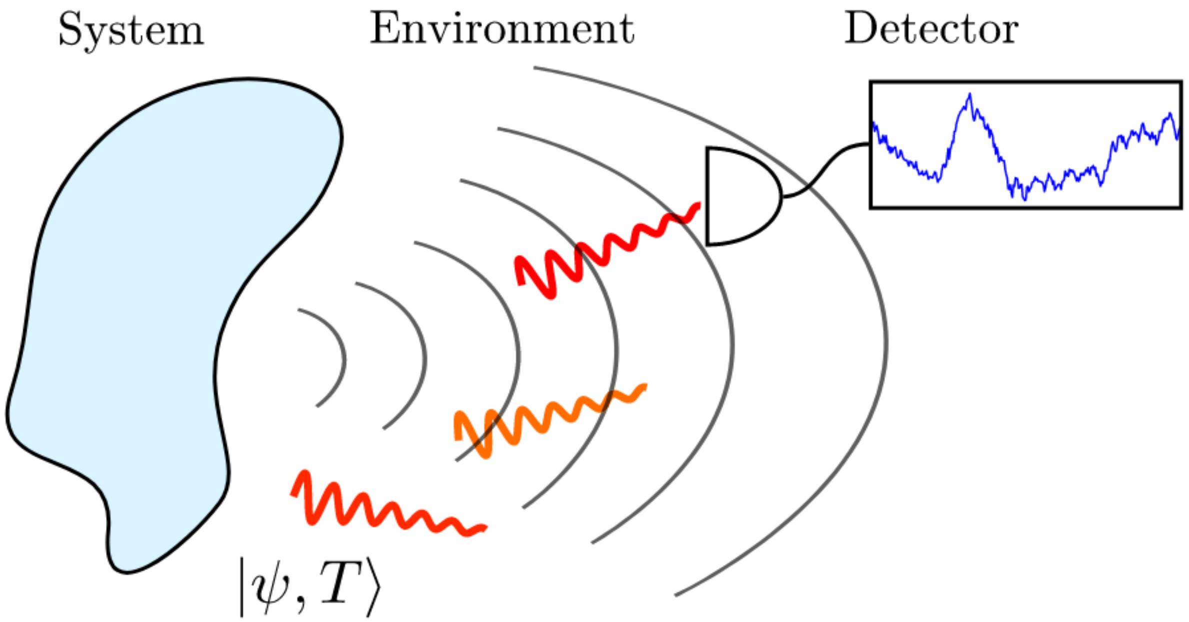
Parameter estimation in open quantum systems

Continuously monitored open quantum systems are emerging as promising platforms for quantum metrology:

Setup
- Sensor is coupled to an environment (driven-dissipative scenario)
- Radiation into environment is **continuously monitored**.

Task
- Estimate unknown parameters that govern the dynamics of the sensor

Relevance
- Metrology with non isolated systems
- Metrology of time-varying signals
- Magnetometry, spectroscopy, fluorescence microscopy…
- Device characterization



PRL **112,** 170401 (2014) PHYSICAL REVIEW LETTERS week ending 2 MAY 2014

Fisher Information and the Quantum Cramér-Rao Sensitivity Limit of Continuous Measurements

Søren Gammelmark and Klaus Mølmer*
Department of Physics and Astronomy, Aarhus University, Ny Munkegade 120, DK-8000 Aarhus C, Denmark
(Received 22 October 2013; published 28 April 2014)

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IOP Publishing Journal of Physics A: Mathematical and Theo
J. Phys. A: Math. Theor. 48 (2015) 365301 (27pp) doi:10.1088/1751-8113/48/36/3

Fisher informations and local asymptotic normality for continuous-time quantum Markov processes

Catalin Catana[1], Luc Bouten[2] and Mădălin Guţă[1]

PHYSICAL REVIEW X 13, 031012 (2023)

Efficient Information Retrieval for Sensing via Continuous Measurement

Dayou Yang, Susana F. Huelga, and Martin B. Plenio
Institut für Theoretische Physik and IQST, Universität Ulm, Albert-Einstein-Allee 11, D-89069 Ulm, Germany

Adaptive measurement filter: efficient strategy for optimal estimation of quantum Markov chains

Alfred Godley and Mădălin Guţă

PHYSICAL REVIEW LETTERS 132, 050801 (2

Continuous Sensing and Parameter Estimation with the Boundary Time Crystal

Albert Cabot,[1,*] Federico Carollo,[1] and Igor Lesanovsky[1,2,3]
[1]*Institut für Theoretische Physik, Eberhard Karls Universität Tübingen, Auf der Morgenstelle 14, 72076 Tübingen, Germany*
[2]*School of Physics and Astronomy, University of Nottingham, Nottingham, NG7 2RD, United Kingdom*
[3]*Centre for the Mathematics and Theoretical Physics of Quantum Non-Equilibrium Systems, University of Nottingham, Nottingham, NG7 2RD, United Kingdom*

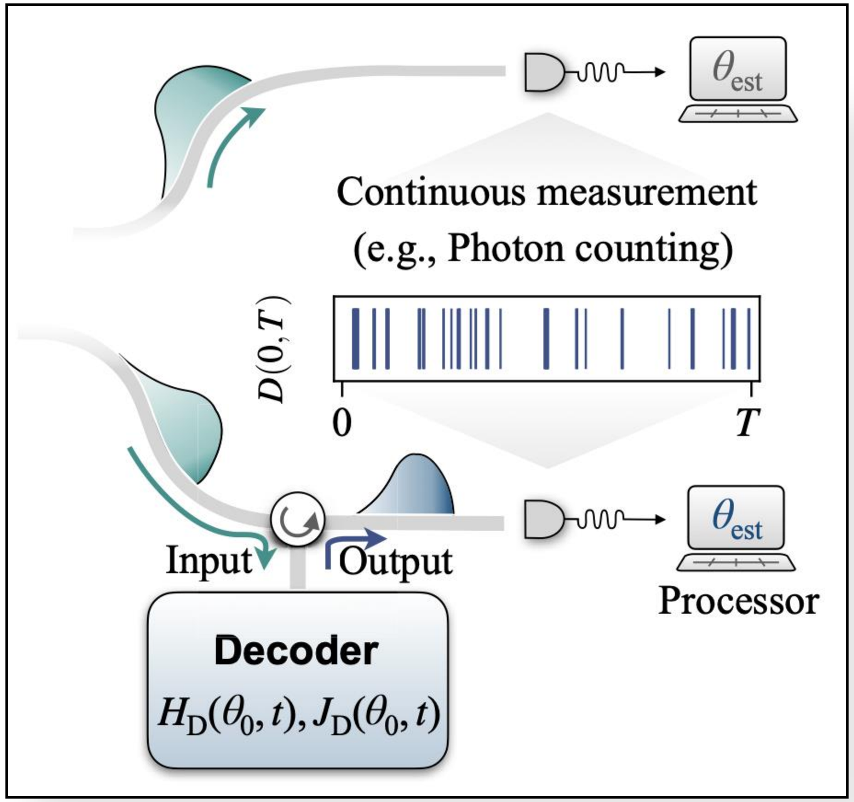
Parameter estimation in open quantum systems

Challenge: Information retrieval

Design measurement strategies that efficiently **extracts the full information content**

↓ **Proposal**

Incorporate ancillary systems that interact with the system and **extract information from the radiated field**.



Efficient Information Retrieval for Sensing via Continuous Measurement.
D. Yang, S.F. Huelga, and M. B. Plenio; PRX 13, 031012.

Our proposal: Frequency-filtering for metrology

To **analyze the properties of the emitted light** from a given quantum source, **we capture the radiation** by **selecting modes** from the output.

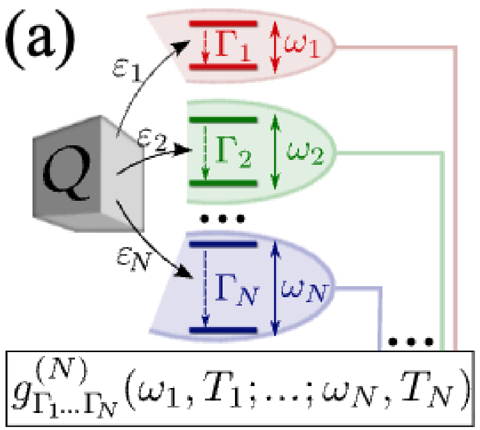
Theoretical descriptions of filtered light:

- **Elena del Valle's method** (sensor method)

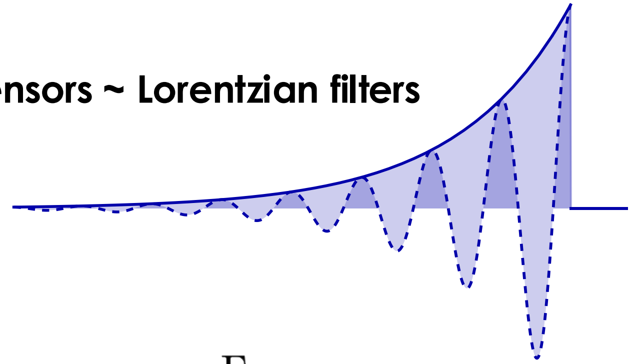
PRL **109**, 183601 (2012) PHYSICAL REVIEW LETTERS week ending 2 NOVEMBER 2012

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]
[1]*Physik Department, Technische Universität München, James-Franck-Straße, 85748 Garching, Germany*
[2]*Física Teórica de la Materia Condensada, Universidad Autónoma de Madrid, 28049 Madrid, Spain*
[3]*Walter Schottky Institut, Technische Universität München, Am Coulombwall 3, 85748 Garching, Germany*
(Received 2 April 2012; published 31 October 2012)



Sensors ~ Lorentzian filters



$$v(t)[t_0;\omega;\Gamma] = \frac{\Gamma}{2} e^{(t-t_0)(i\omega+\Gamma/2)}\theta(t_0 - t)$$

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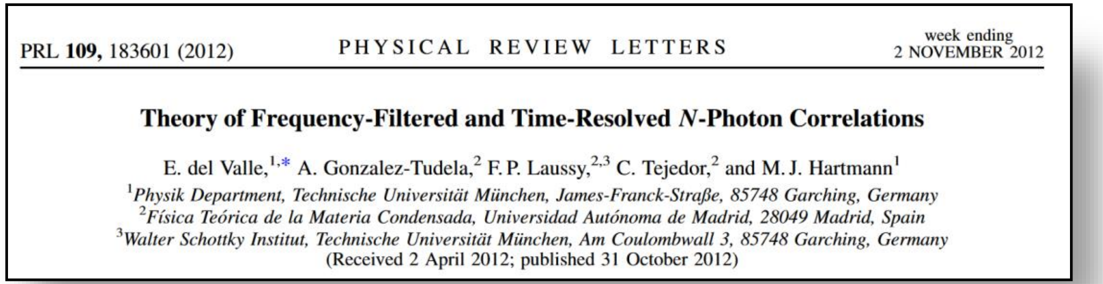
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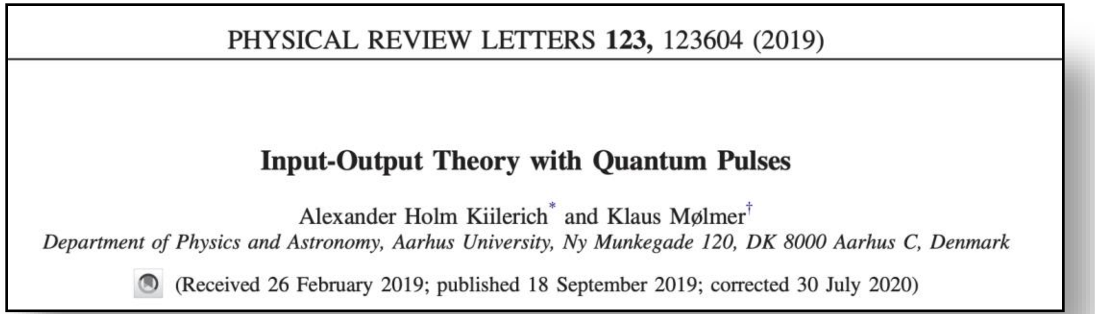
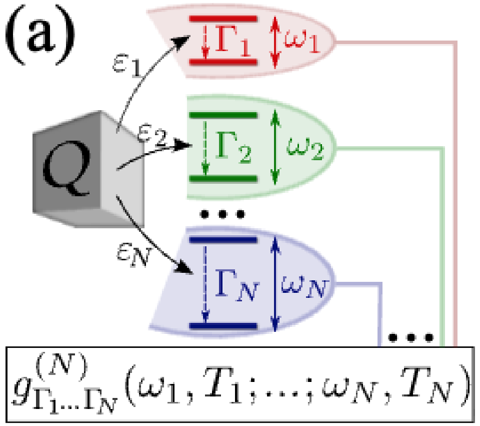
(Received 2 April 2012; published 31 October 2012)

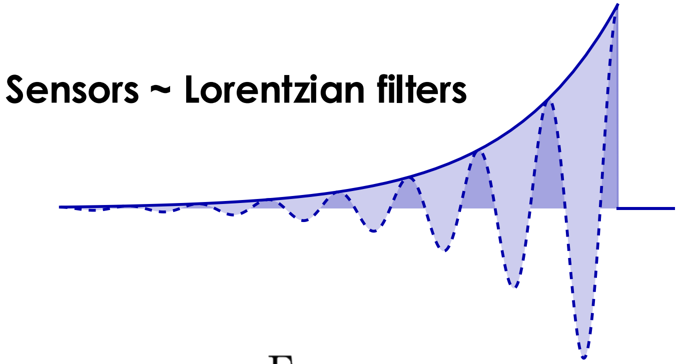
- **Klaus Mølmer's method** (quantum pulses)


PHYSICAL REVIEW LETTERS **123**, 123604 (2019)

Input-Output Theory with Quantum Pulses

Alexander Holm Kiilerich[*] and Klaus Mølmer[†]
Department of Physics and Astronomy, Aarhus University, Ny Munkegade 120, DK 8000 Aarhus C, Denmark
(Received 26 February 2019; published 18 September 2019; corrected 30 July 2020)





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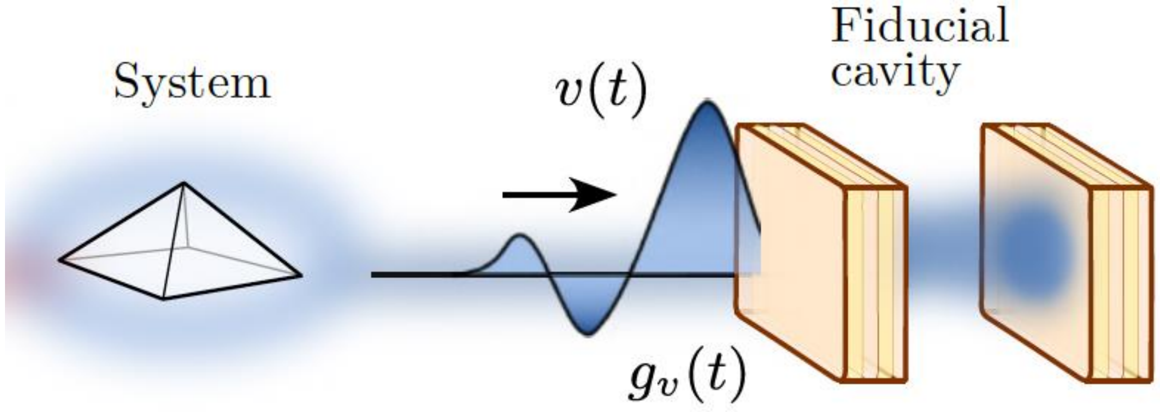
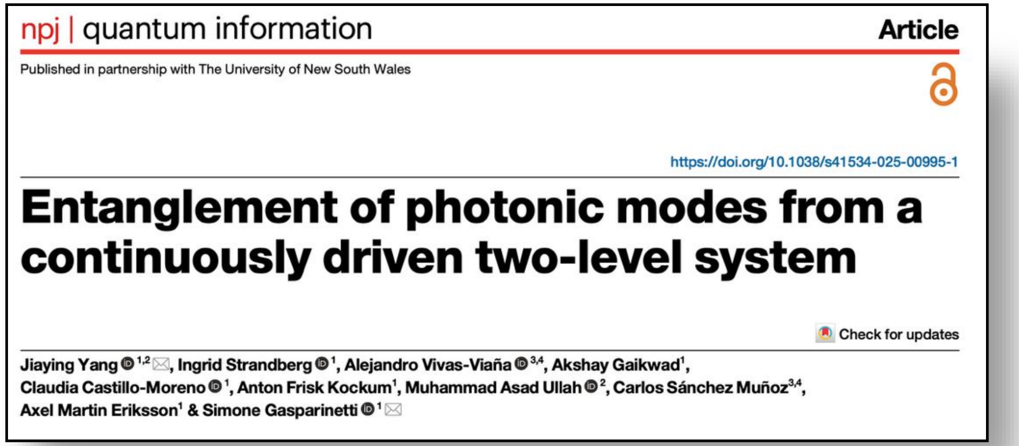


Quantum state of the fiducial cavity

=

Quantum state of the filtered mode

Experiment in SC: reconstructing entangled state



npj | quantum information — Article

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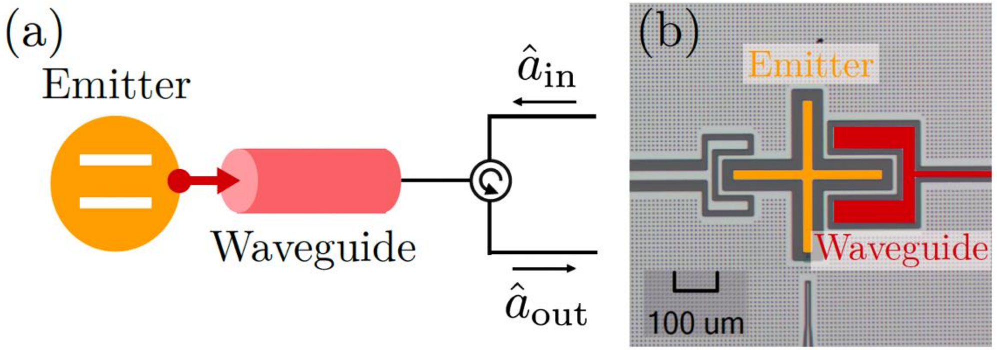
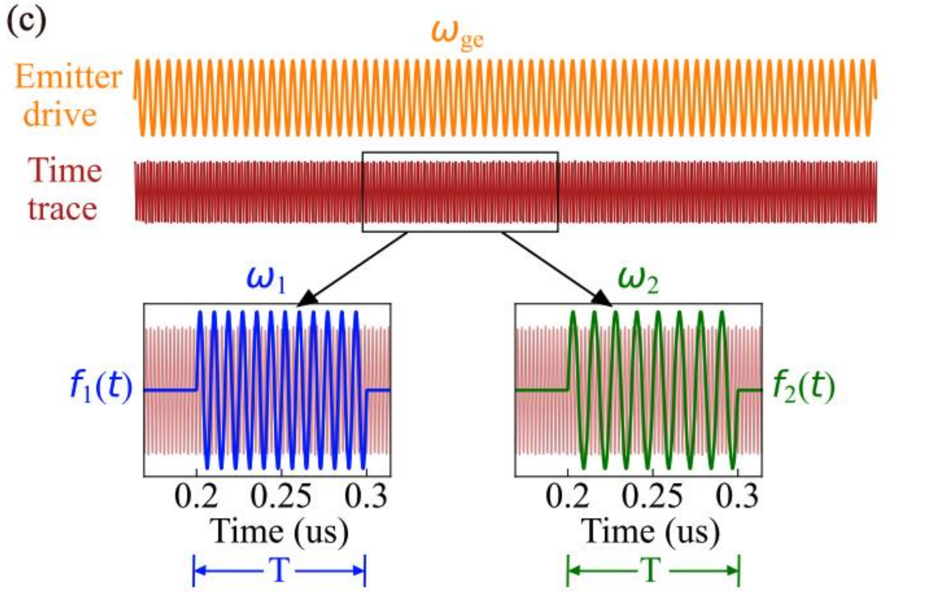
https://doi.org/10.1038/s41534-025-00995-1

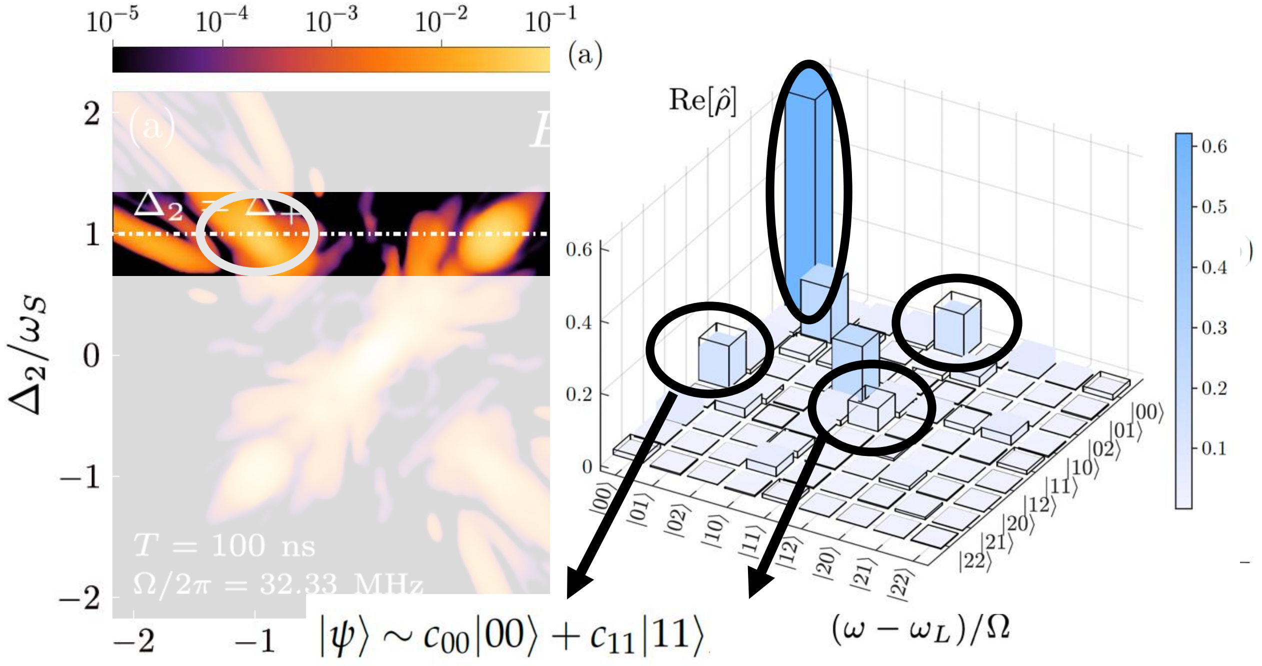
Entanglement of photonic modes from a continuously driven two-level system

Check for updates

Jiaying Yang[1,2], Ingrid Strandberg[1], Alejandro Vivas-Viaña[3,4], Akshay Gaikwad[1], Claudia Castillo-Moreno[1], Anton Frisk Kockum[1], Muhammad Asad Ullah[2], Carlos Sánchez Muñoz[3,4], Axel Martin Eriksson[1] & Simone Gasparinetti[1]







$|\psi\rangle \sim c_{00}|00\rangle + c_{11}|11\rangle$

(Two-mode squeezed entangled state)

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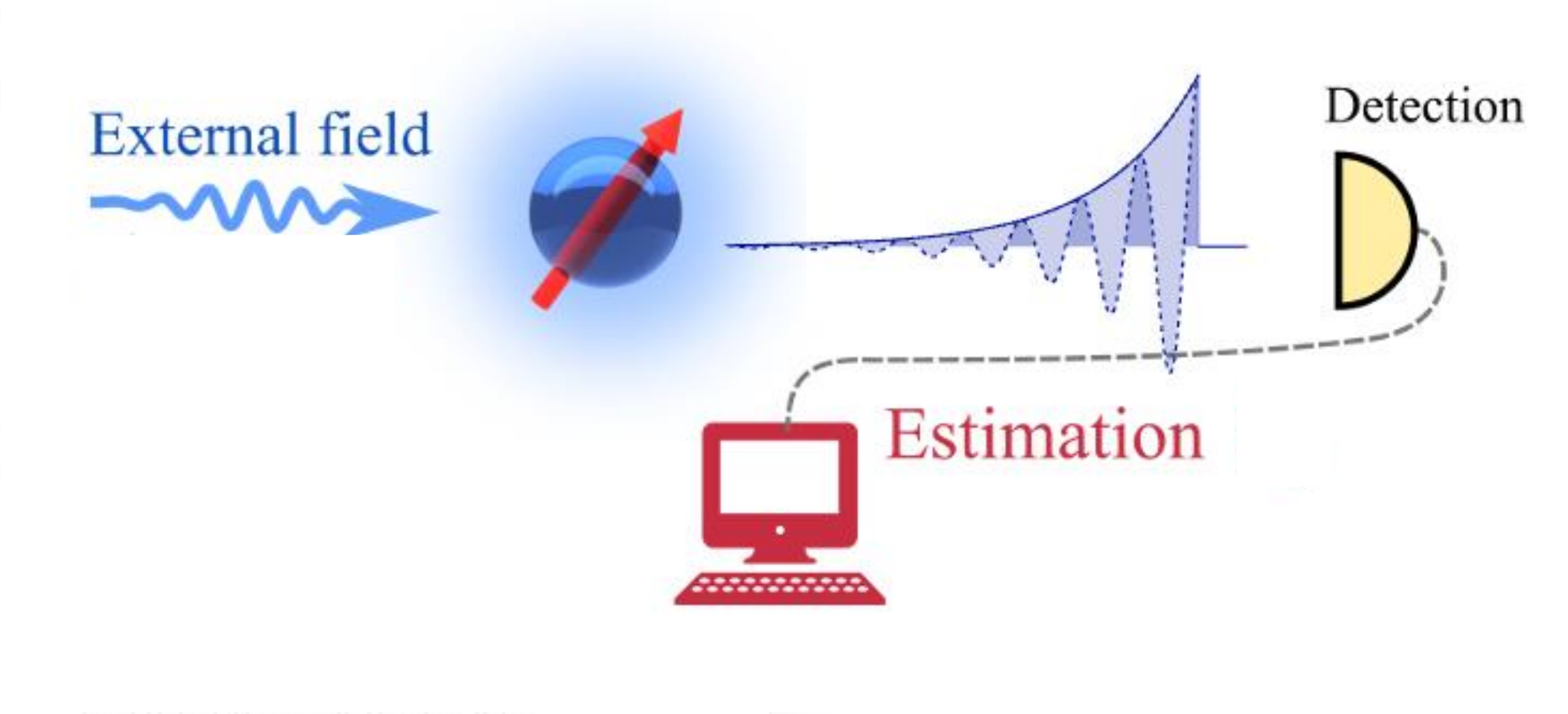
Theoreti



Sensors ~ Lorentzian filters

Quantum state of the fiducial cavity
=
Quantum state of the filtered mode

Frequency-filtering for metrology: Questions

- Metrological gain from **frequency** filtering?
- Metrological gain from **quantum fluctuations** within a filtered mode?
- Metrological gain from **quantum correlations** across different filtered modes?

Frequency-filtering for metrology: Questions

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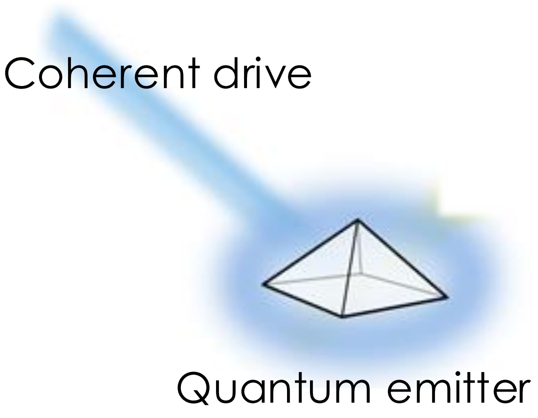
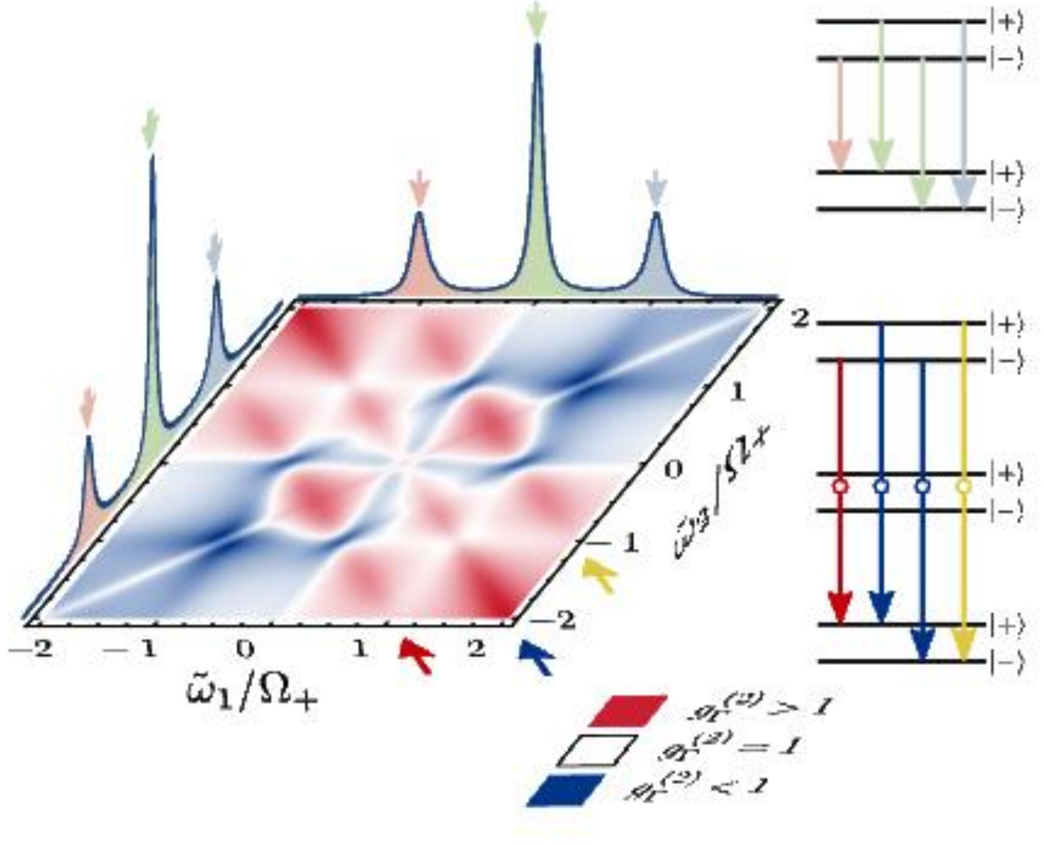
Model – Testbed of quantum optics: a coherently driven TLS



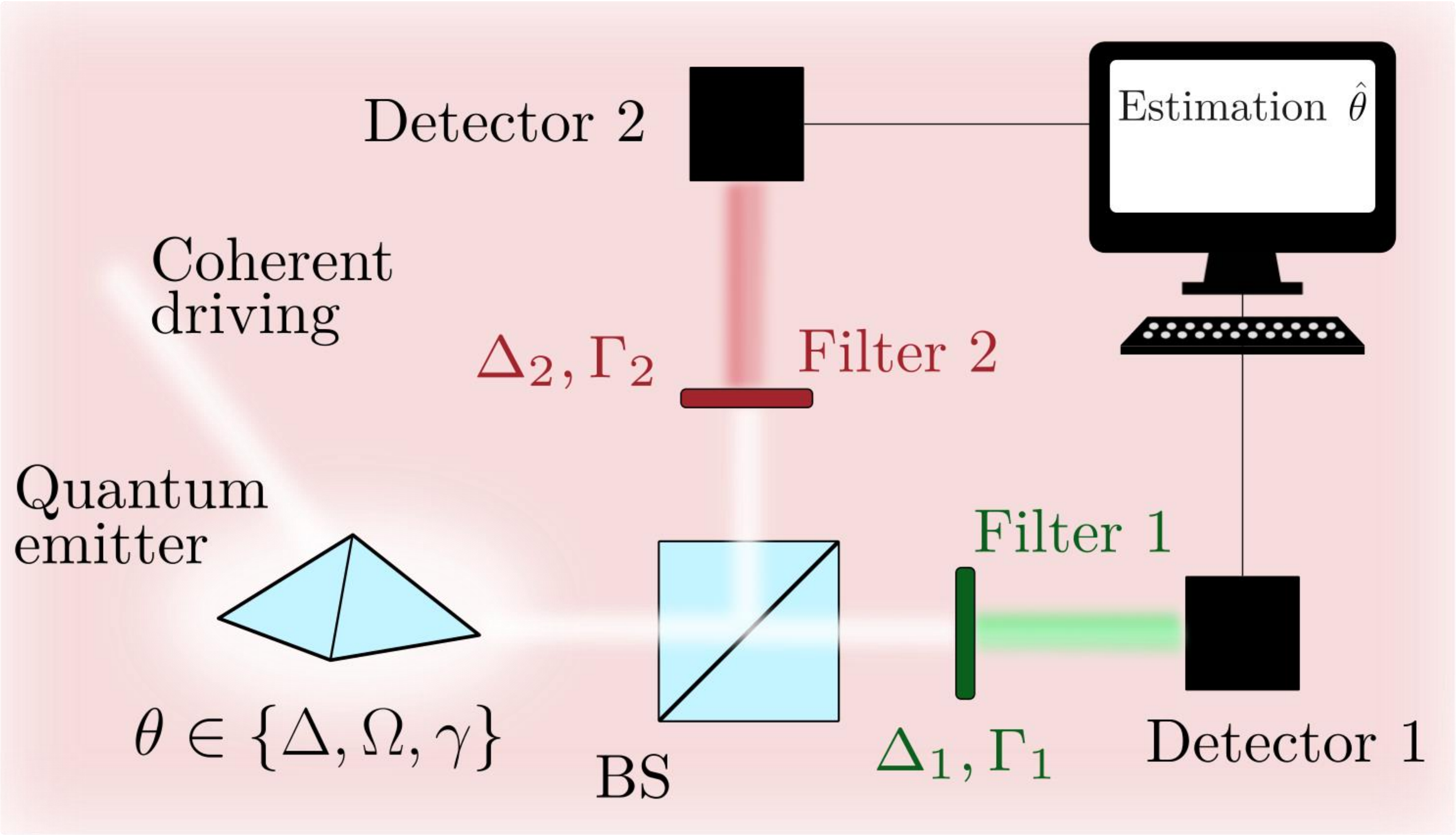
Master equation (rotating frame)

$$\hat{H}_\sigma = \Delta_\sigma \hat{\sigma}^\dagger \hat{\sigma} + (\tilde{\Omega}\hat{\sigma} + \tilde{\Omega}^* \hat{\sigma}^\dagger),$$
$$\frac{d\hat{\rho}}{dt} = -i[\hat{H}_\sigma, \hat{\rho}] + \frac{\gamma}{2}\mathcal{D}[\hat{\sigma}]\hat{\rho},$$

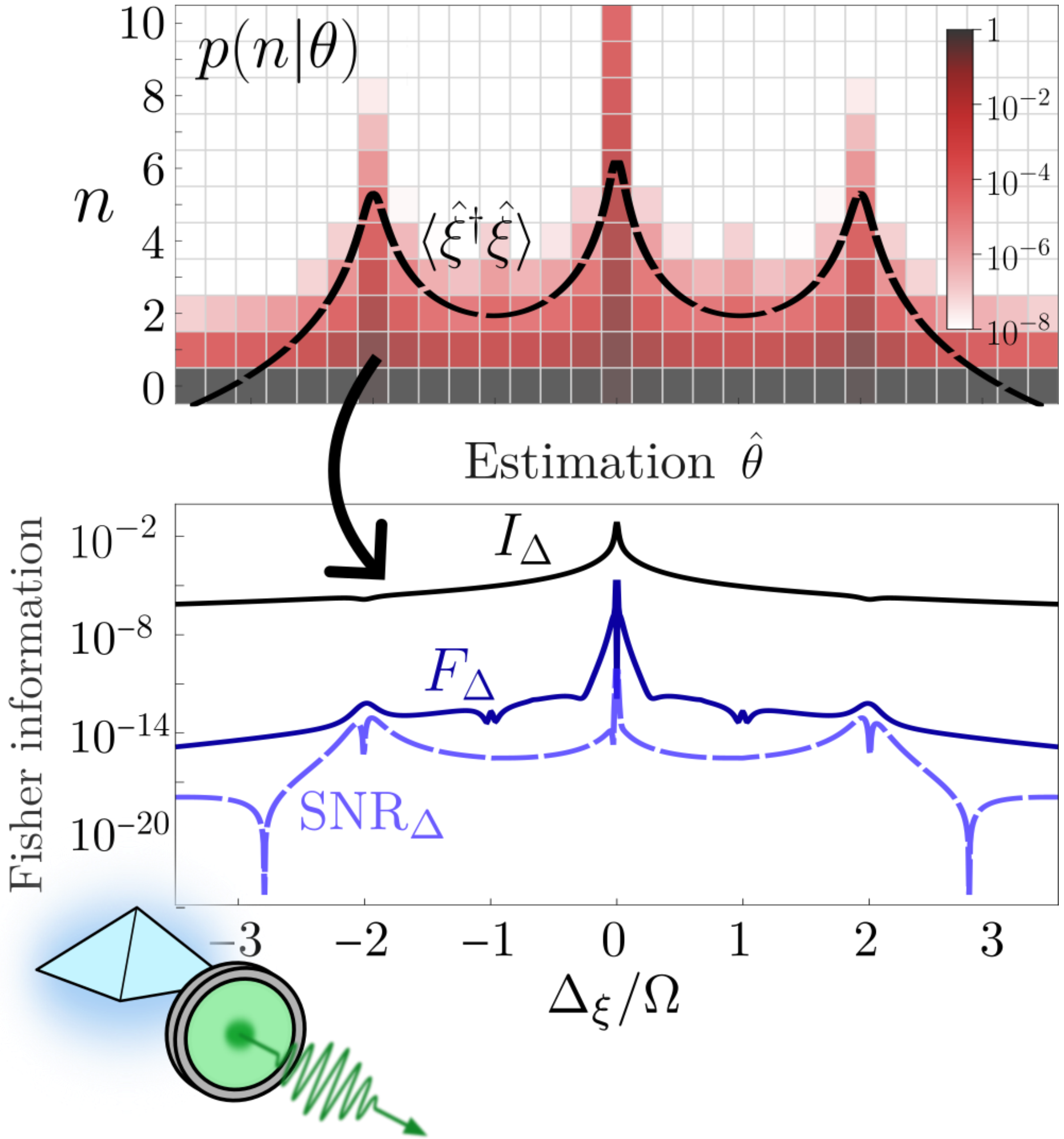


JC López Carreño, E del Valle, FP Laussy.
Photon correlations from the Mollow triplet.
Laser & Photonics Reviews 11 (5), 1700090 (2017)

Metrological setup



Metrological setup – one sensor



Observable: Photon counting

Figures of merit:

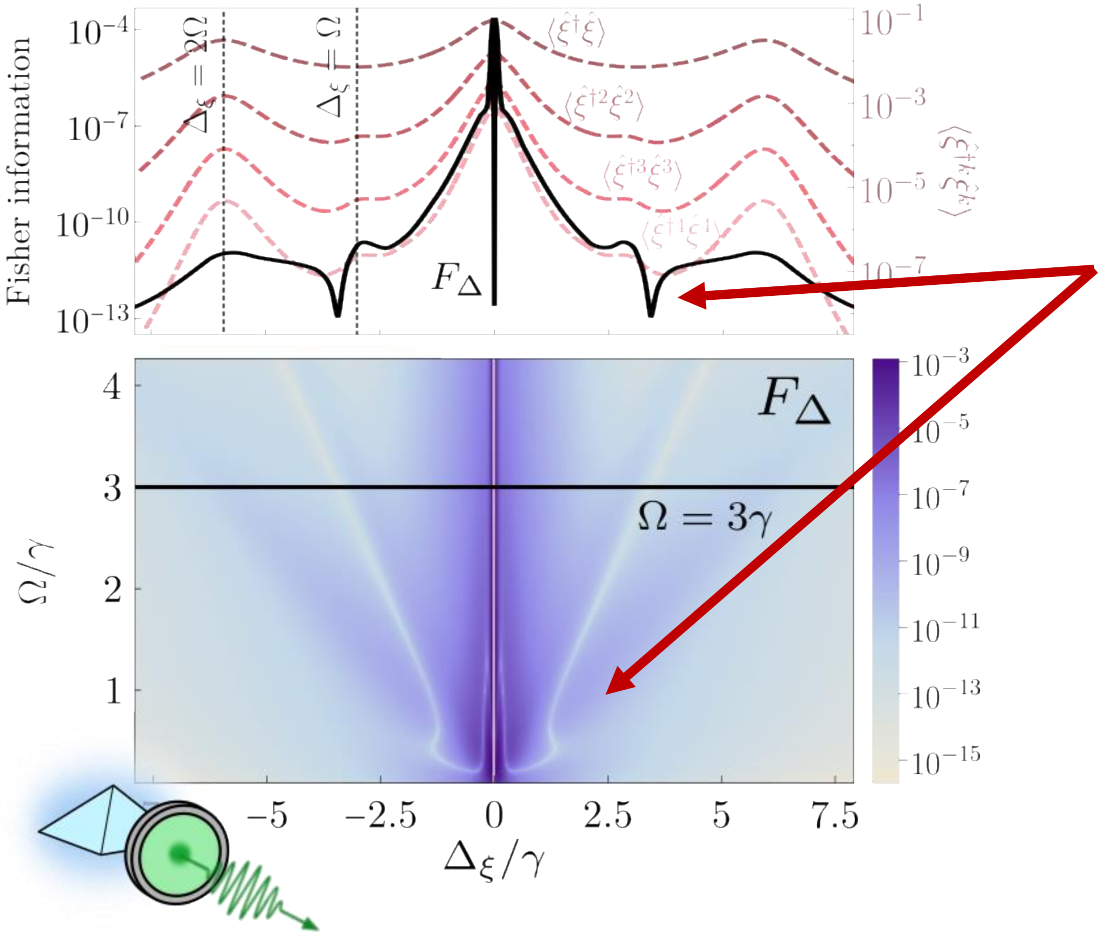
- Quantum Fisher information (QFI)
- Classical Fisher Information (FI)
- Signal-to-noise ratio (SNR)

Precision set by the Cramér-Rao Bound

$$\Delta^2\hat{\theta} \geq \frac{1}{M I_\theta} \geq \frac{1}{M F_\theta^{\vec{\alpha}}} \geq \frac{1}{M \mathrm{SNR}_\theta[\hat{O}]}$$

Frequency-resolved Fisher Information

Estimation of qubit-laser detuning, $\theta = \Delta$



Importance of selectively resolving the spectral components of radiation.

Frequency-resolved Fisher Information

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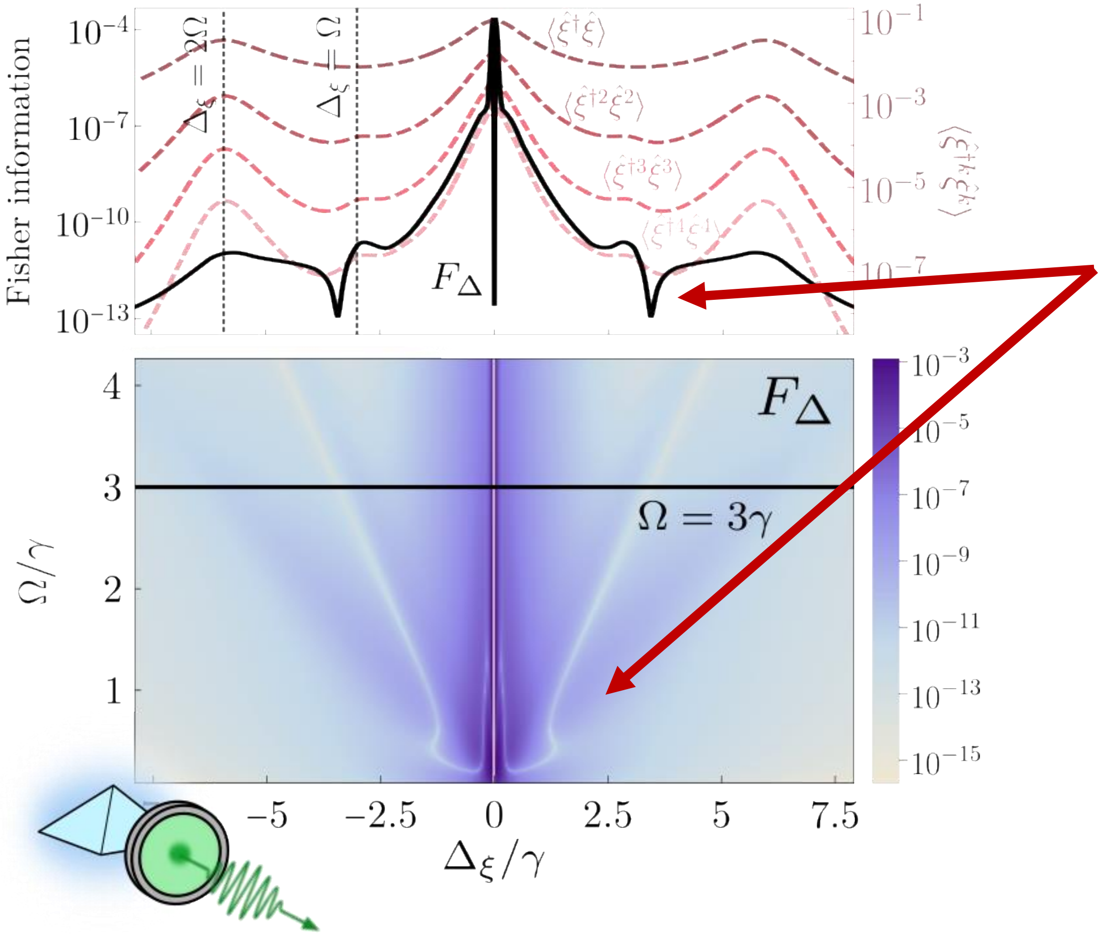

Importance of selectively resolving the spectral components of radiation.

$$F_\theta = \sum_n^{n_{\text{exc}}} \frac{\left[\sum_{k\geq n}^{n_{\text{exc}}} c_{n,k} \partial_\theta \langle \hat{\xi}^{\dagger k} \hat{\xi}^k \rangle\right]^2}{\sum_{k\geq n}^{n_{\text{exc}}} c_{n,k} \langle \hat{\xi}^{\dagger k} \hat{\xi}^k \rangle}$$

Nontrivial interplay of the derivatives of all higher-order correlators with respect to the parameter to be estimated

Frequency-filtering for metrology: Questions

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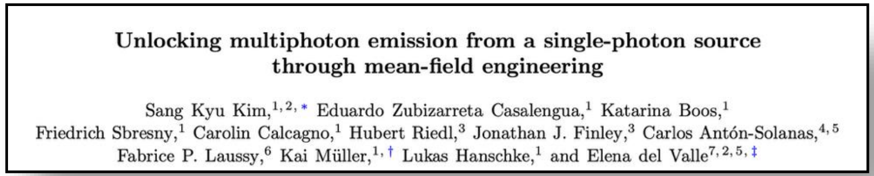
Mean-field engineering to improve sensitivity


Unlocking multiphoton emission from a single-photon source through mean-field engineering

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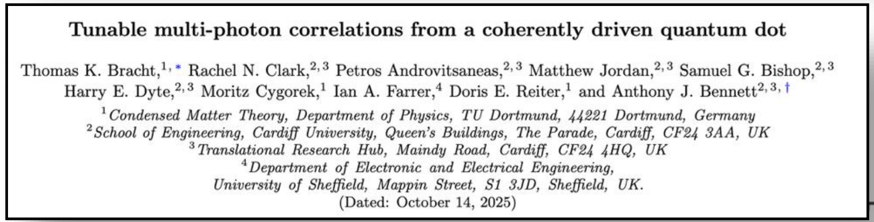
Tunable multi-photon correlations from a coherently driven quantum dot

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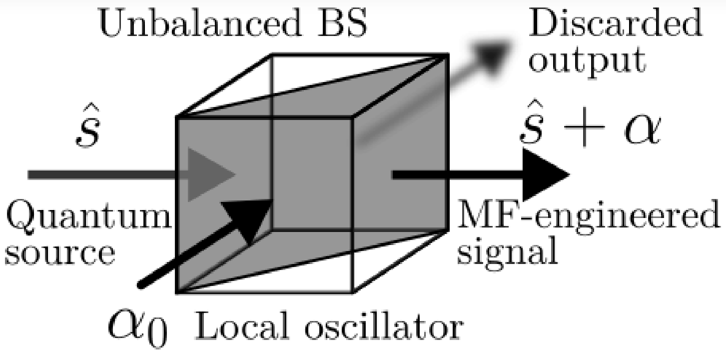
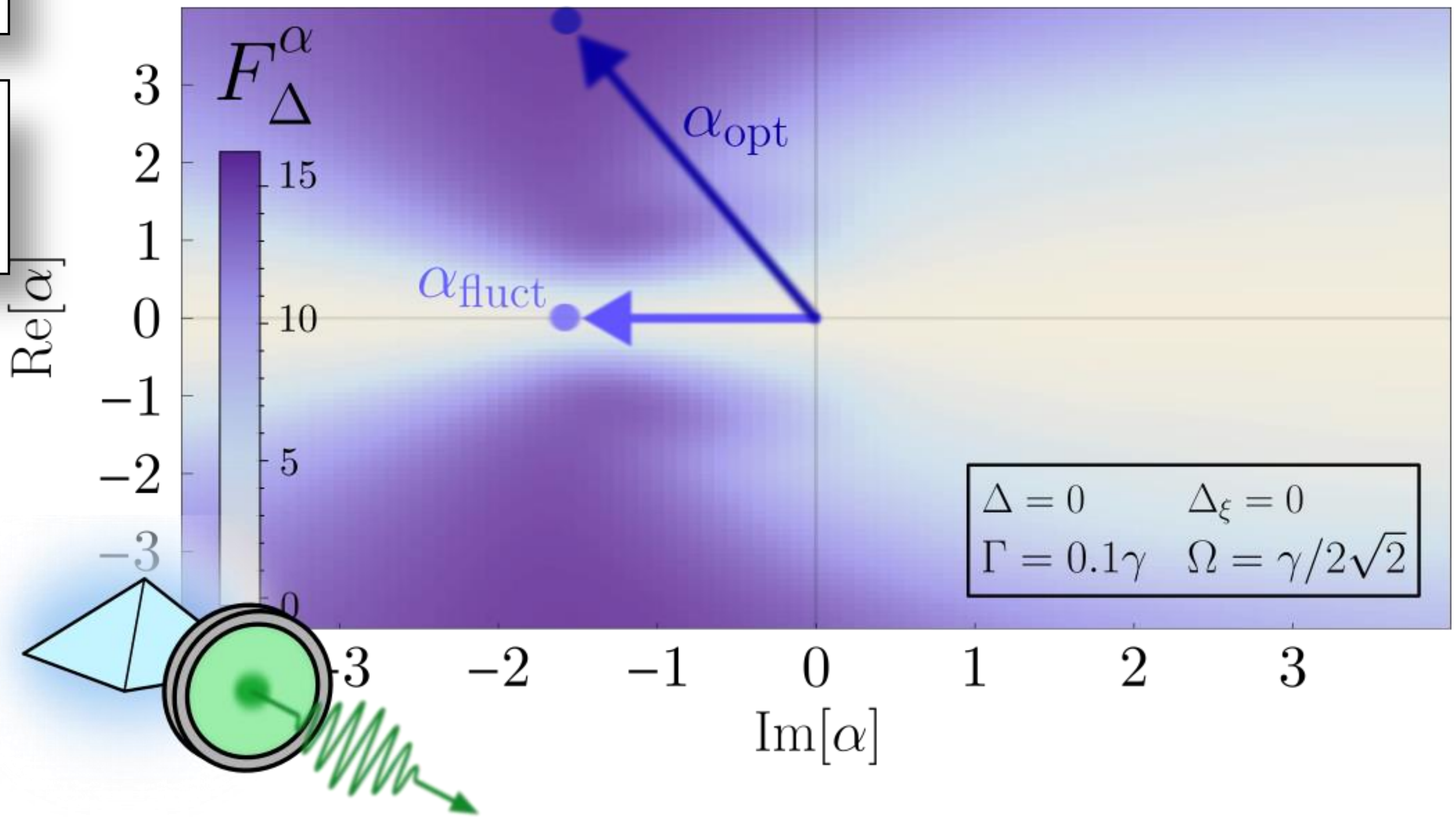
[1] *Condensed Matter Theory, Department of Physics, TU Dortmund, 44221 Dortmund, Germany*
[2] *School of Engineering, Cardiff University, Queen's Buildings, The Parade, Cardiff, CF24 3AA, UK*
[3] *Translational Research Hub, Maindy Road, Cardiff, CF24 4HQ, UK*
[4] *Department of Electronic and Electrical Engineering, University of Sheffield, Mappin Street, S1 3JD, Sheffield, UK.*

(Dated: October 14, 2025)





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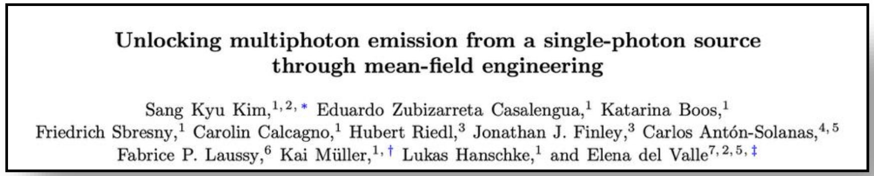

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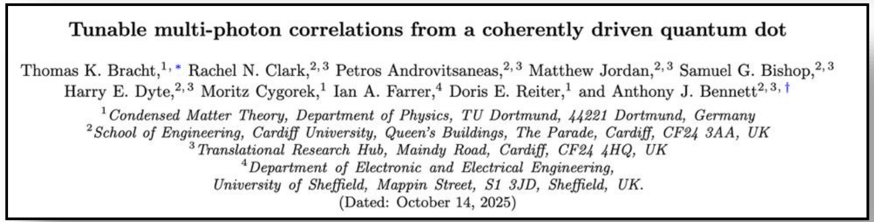

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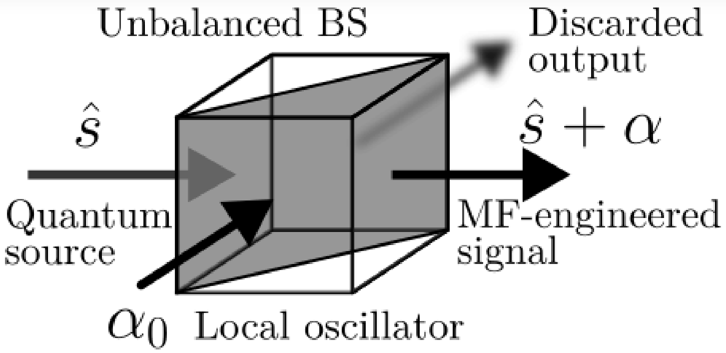

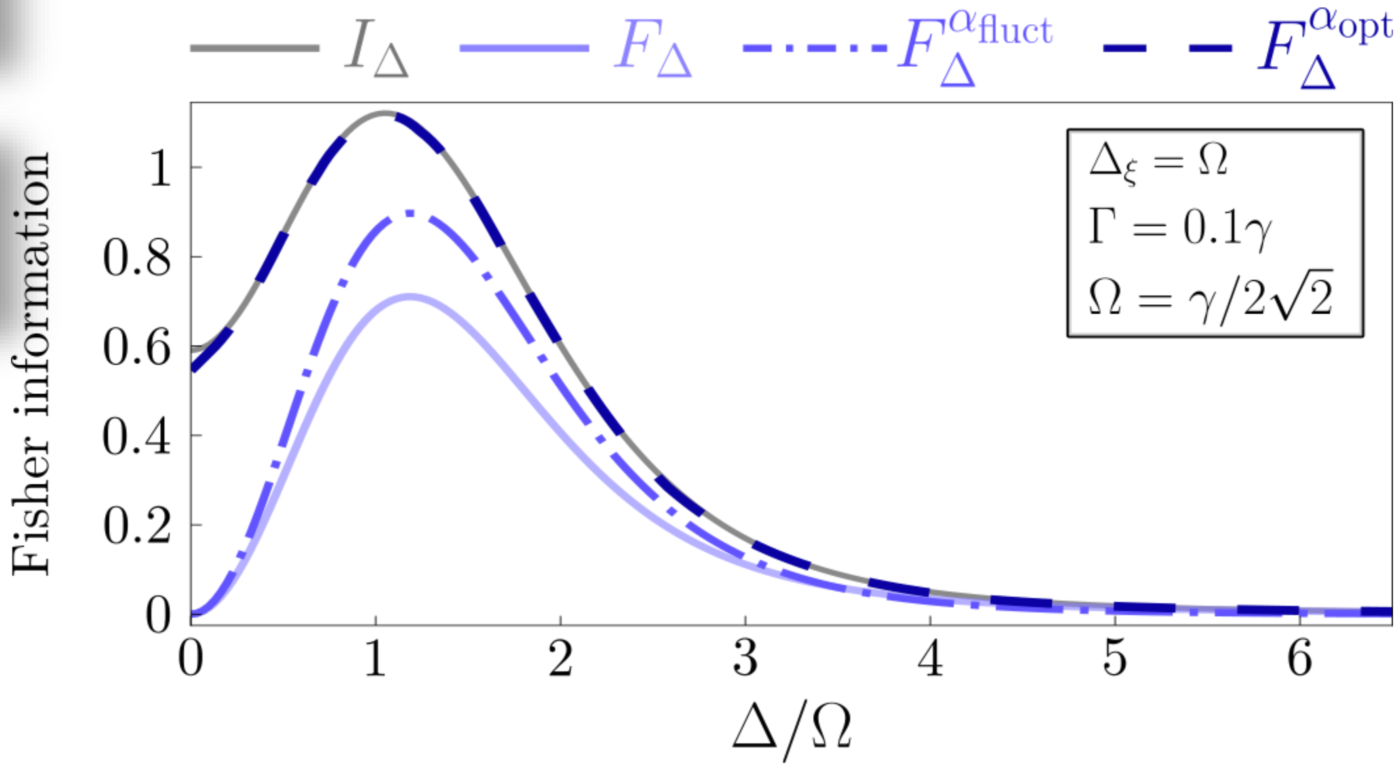

Mean-field engineering offers a route towards saturating the QFI

Frequency-filtering for metrology: Questions

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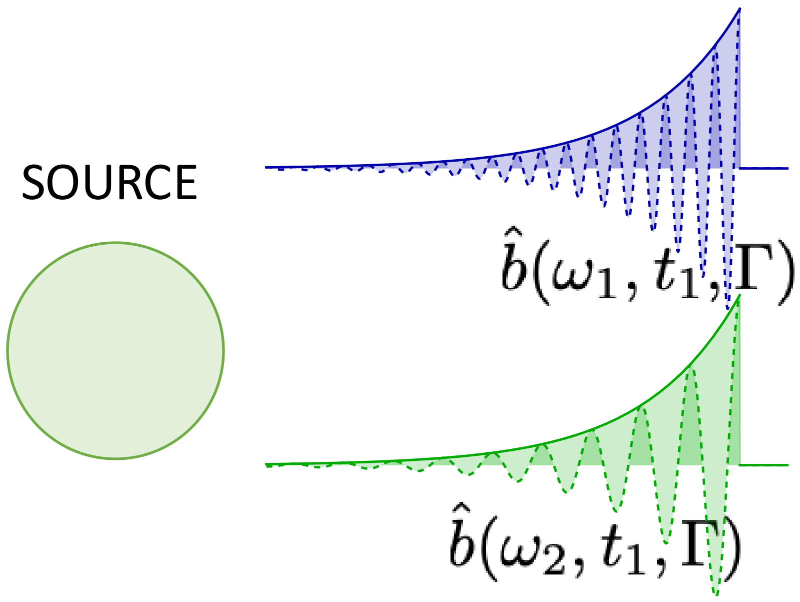
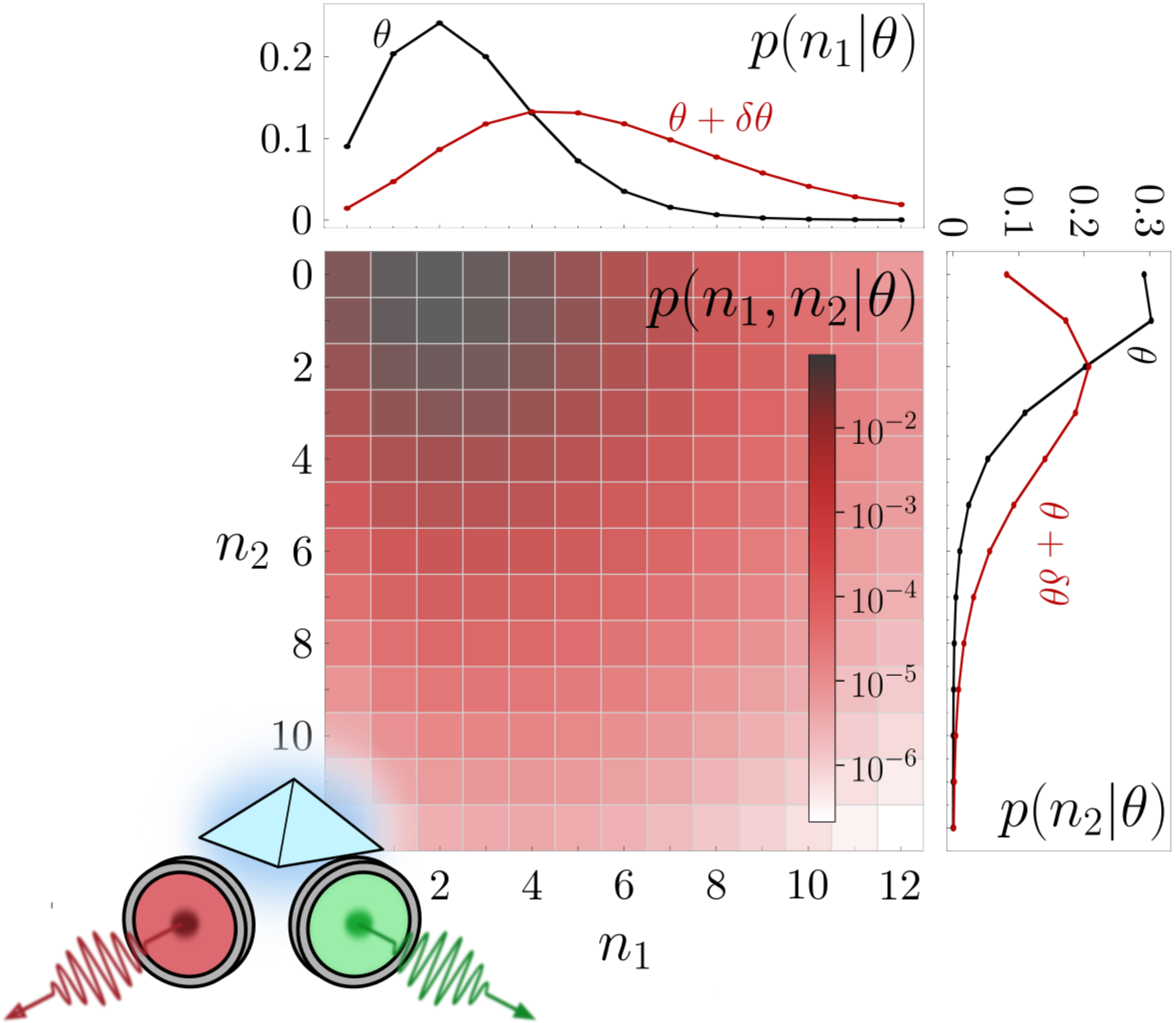
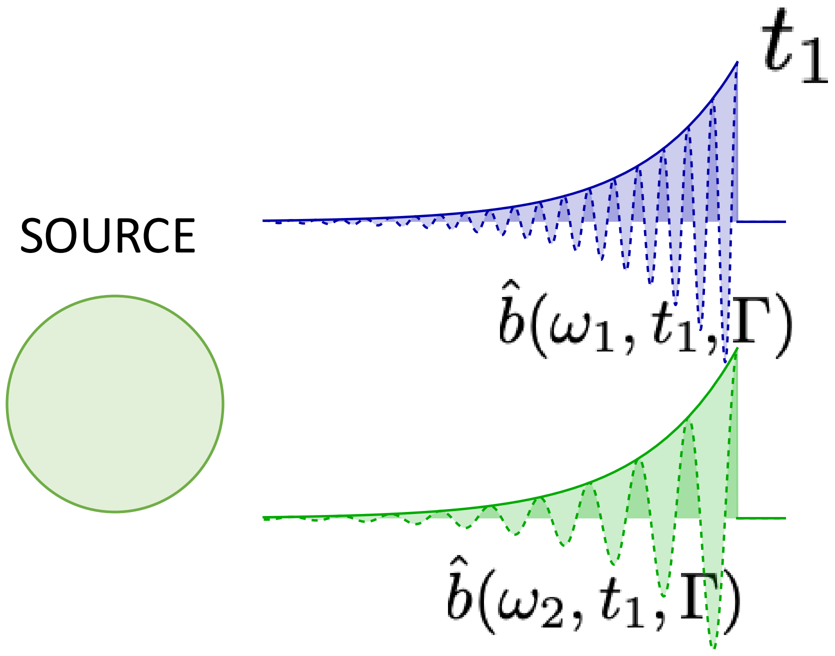
Metrological setup – two sensors





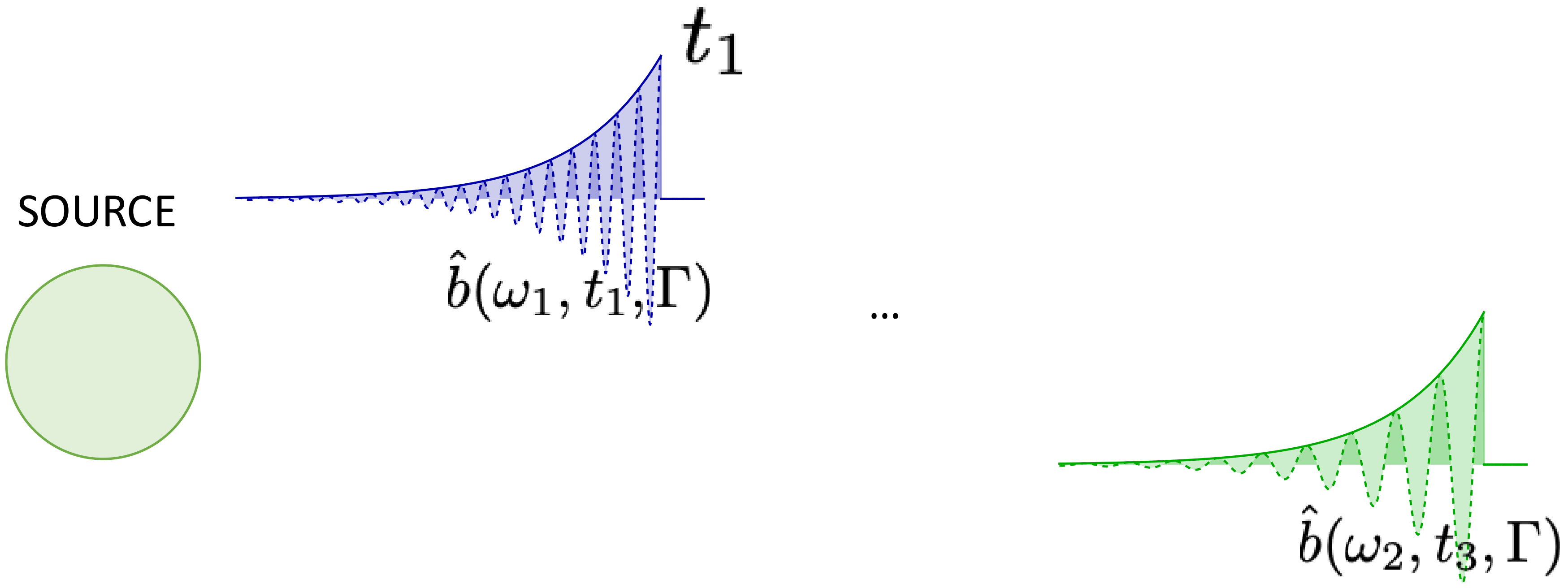
Correlated vs Independent Fisher



Simultaneous detection:
Coincidence measurements

$F \qquad p(n_1, n_2)$

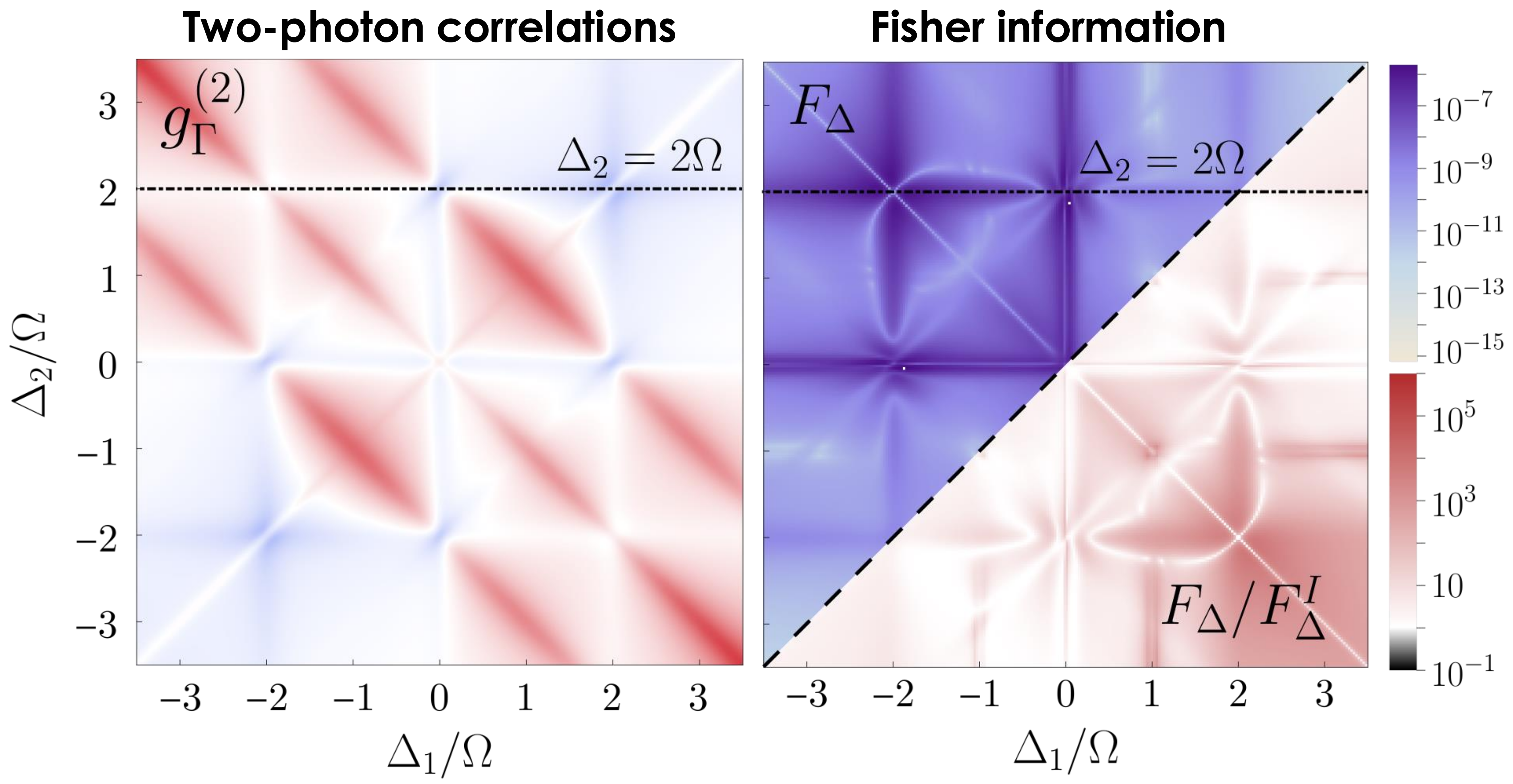
Correlated vs Independent Fisher



Independent detection (e.g. sequential):
Factorized distribution

$$F_I \qquad p(n_1)p(n_2)$$

Two-mode Fisher information



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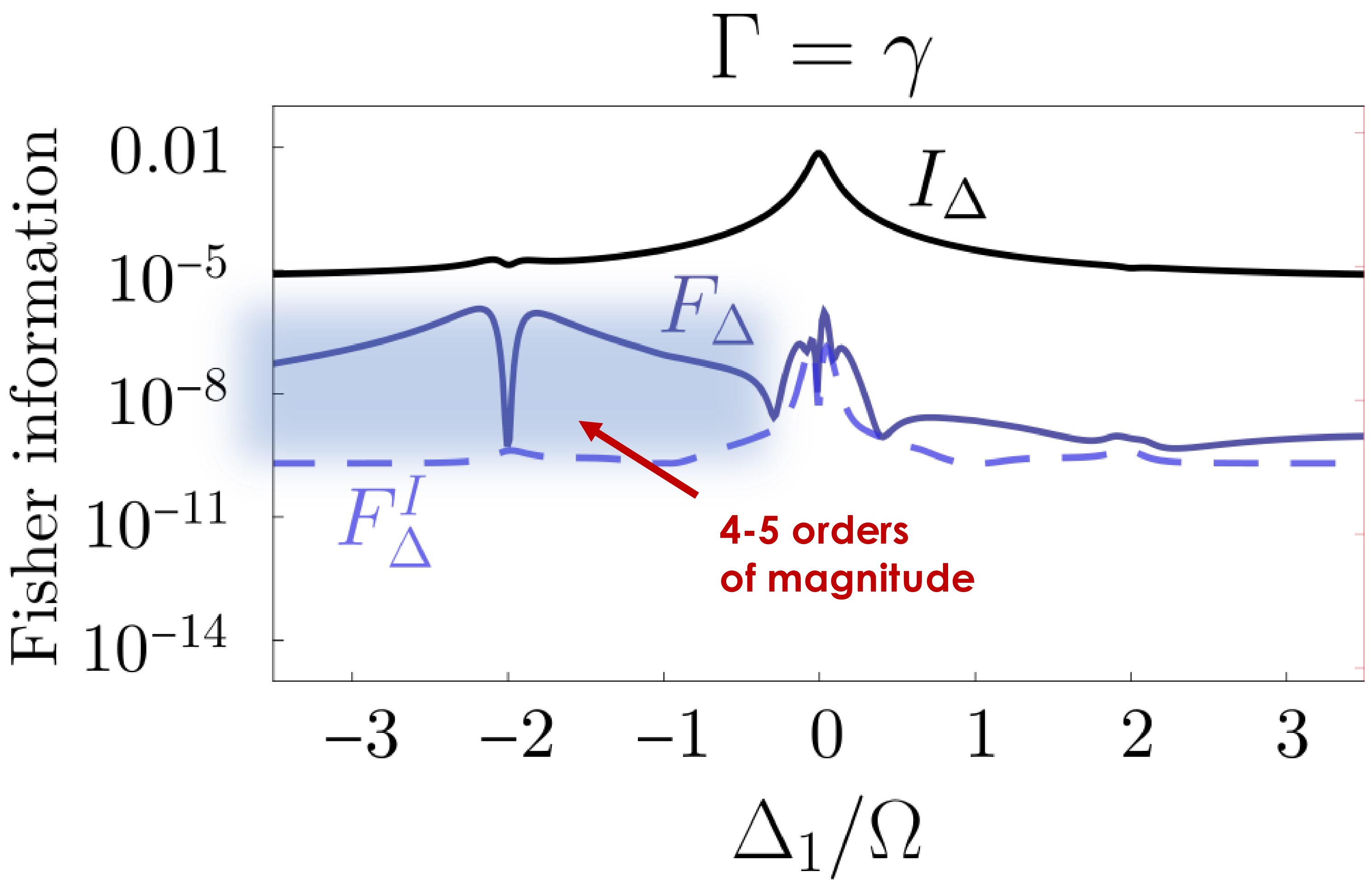
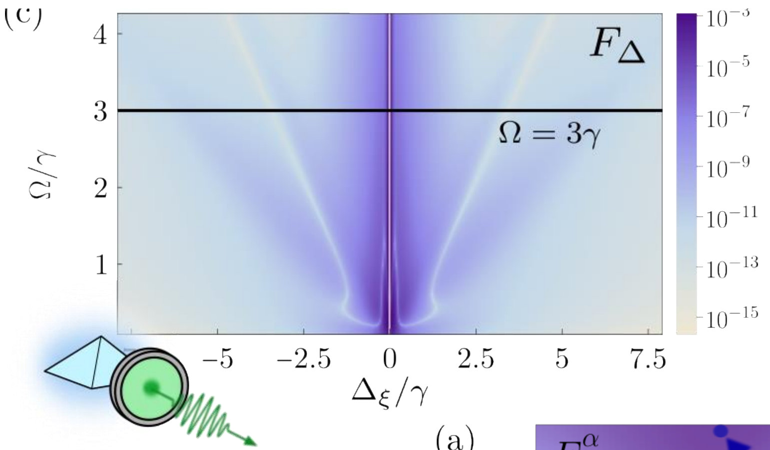
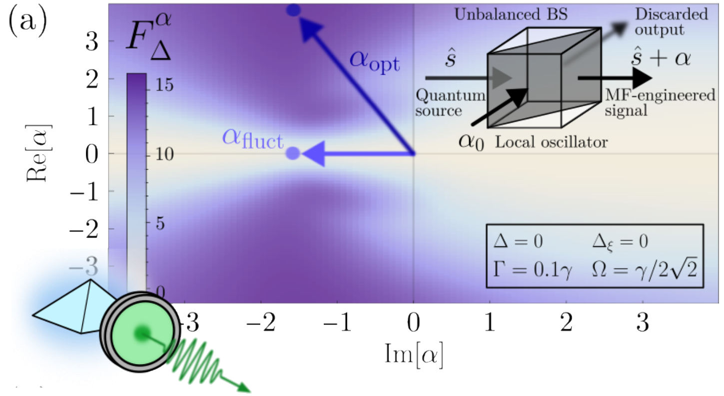


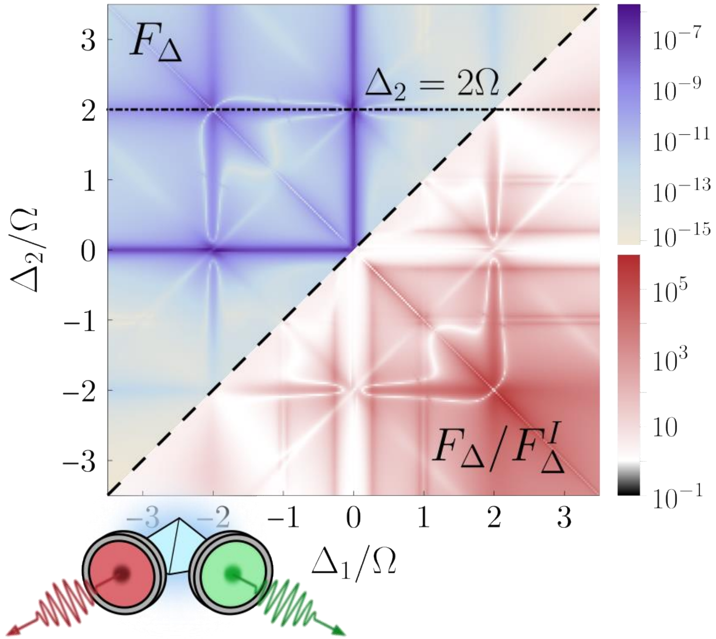
Conclusions



→ Framework to study **metrology with frequency-resolved modes** of the output of an open quantum system.

→ **Filtering and counting coincidences** improve precisión..





→ **Mean-field engineering** technique: by appropriately tuning the displacement, the CFI can saturates the quantum Fisher information

→ **Photon-photon correlations** can significantly enhance estimation precision.

Outlook

→ Extend to **more complex systems** (nonlinear cavity QED, critical dynamics ,…).

→ Explore the role of **higher-order correlations** beyond second order.

→ Develop **inference** protocols (e.g. Bayesian).

Acknowledgements

Dr. Carlos Sánchez Muñoz

Thank you for your attention!

arXiv > quant-ph > arXiv:2509.04300

Quantum Physics

[Submitted on 4 Sep 2025]

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Check the arxiv!