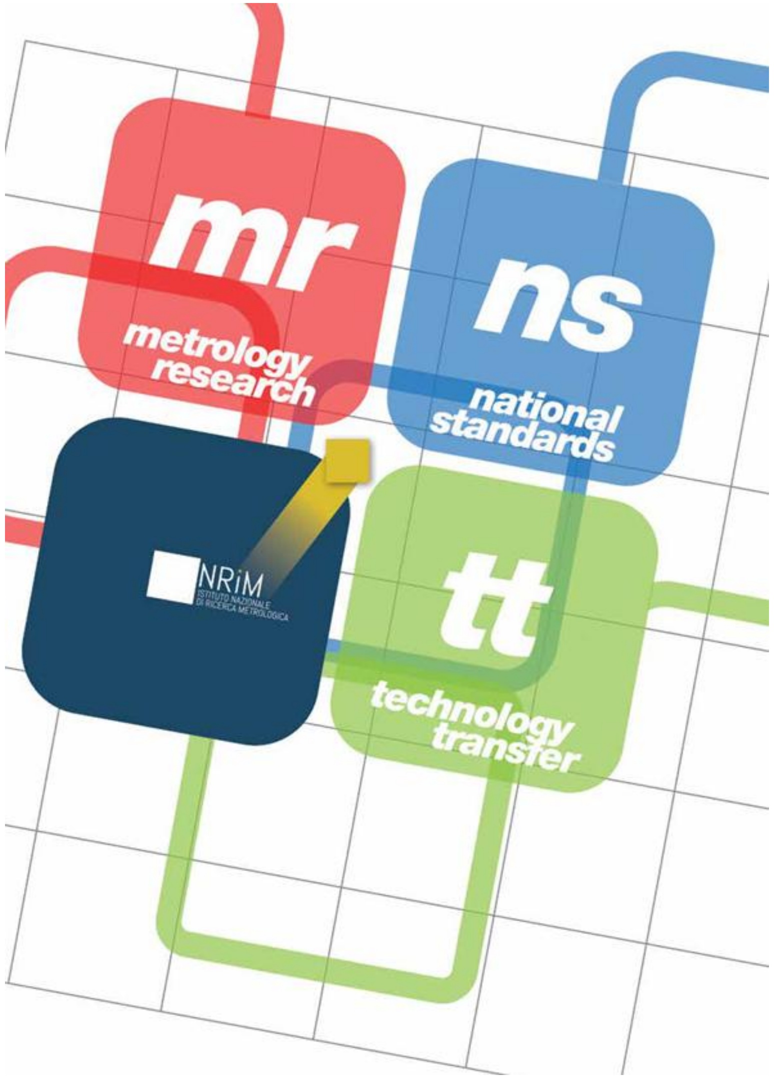
Programmable Cluster State with Josephson Metamaterials

Superconducting Devices for Quantum Optics

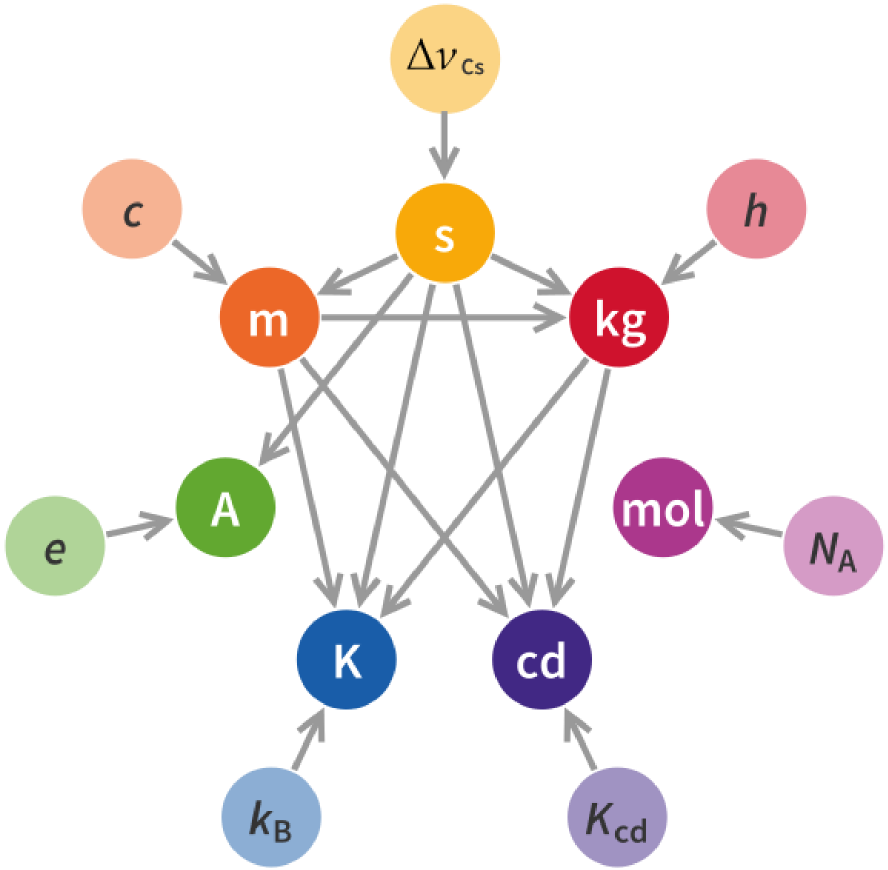
ECT* - Trento 8 October 2025

Emanuele ENRICO (e.enrico@inrim.it)

INRiM - Introduction

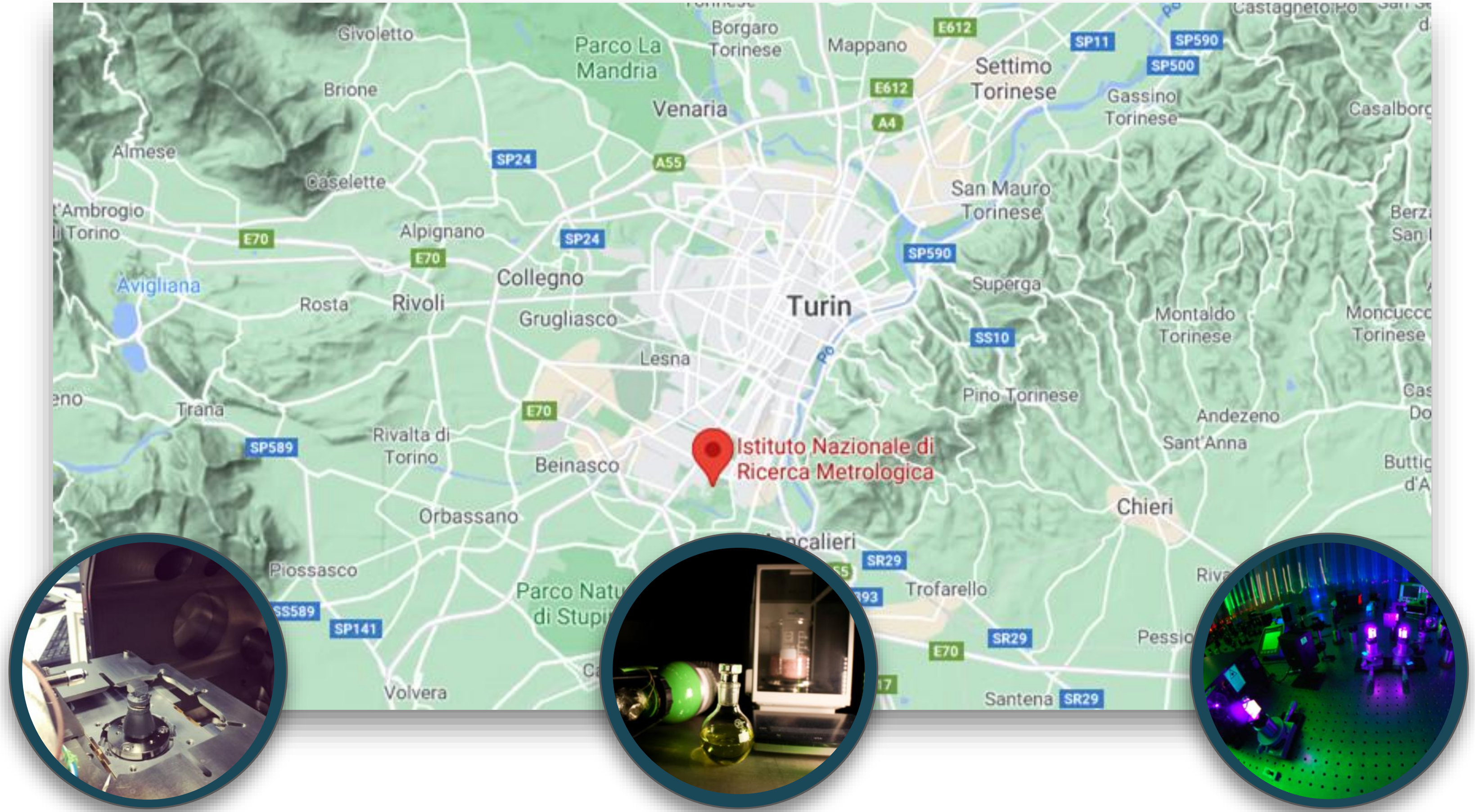


New SI



INRiM
ISTITUTO NAZIONALE
DI RICERCA METROLOGICA

INRiM - Divisions

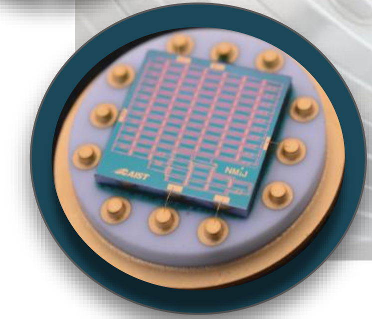


Advanced materials metrology and life science

Applied metrology and engineering

Quantum metrology and nano technologies

Quantum Electronics - NanoTech

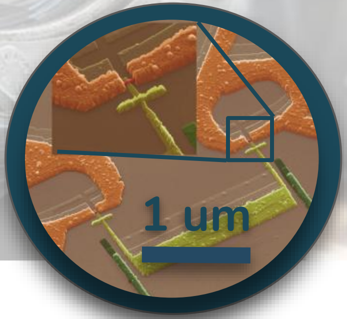


Quantum Hall Array
Resistance Standard

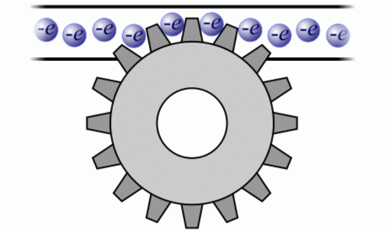
$R_H = R_K/i$

with $R_K = h/e^2$

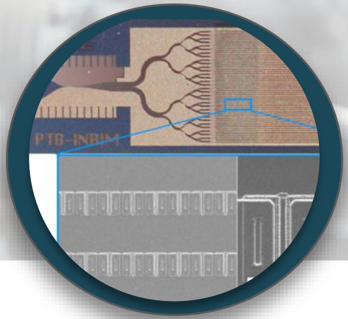
and $i = 1, 2, 3, 4, \ldots$



Quantized-charge transport
DC current standard



$I=nef$

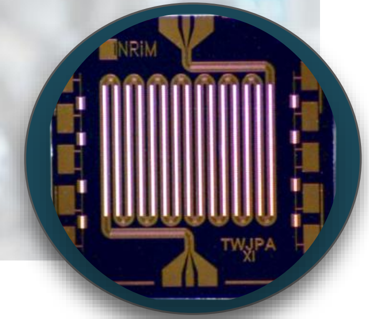


Josephson
Voltage Standard

$V_J = n\, K_J\, f$

with $K_J = h/2e$

and $k = 1, 2, 3, 4, \ldots$



Microwave photonics

ν	1 GHz →20 GHz
$\lambda=c/\nu$	300 cm →15 cm
$E=h/\nu$	4 μeV→80 μeV
$T=E/k_B$	50 mK→1K

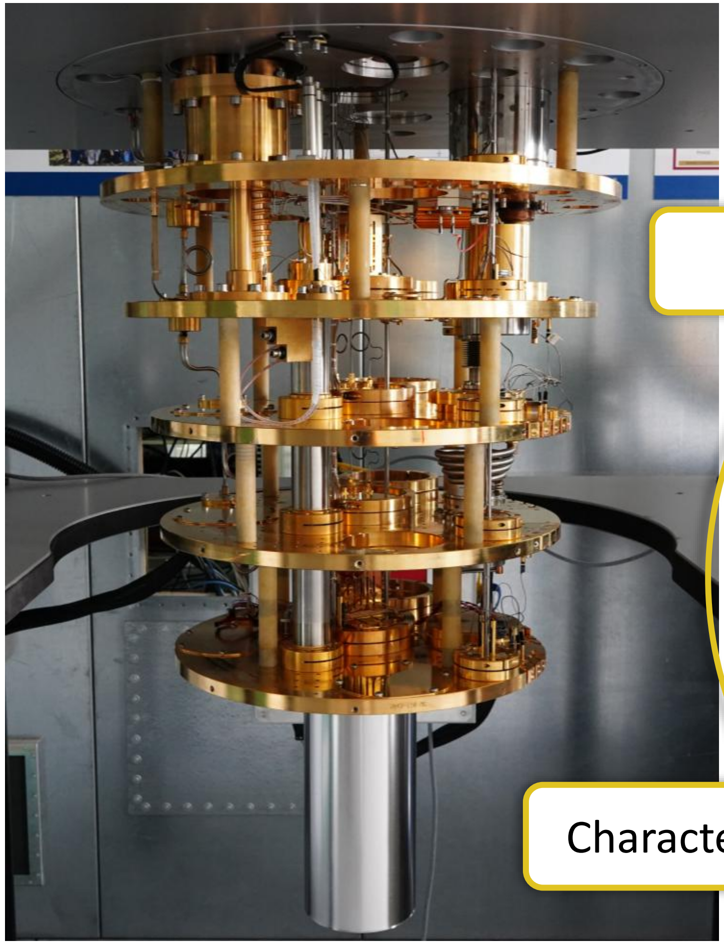
INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

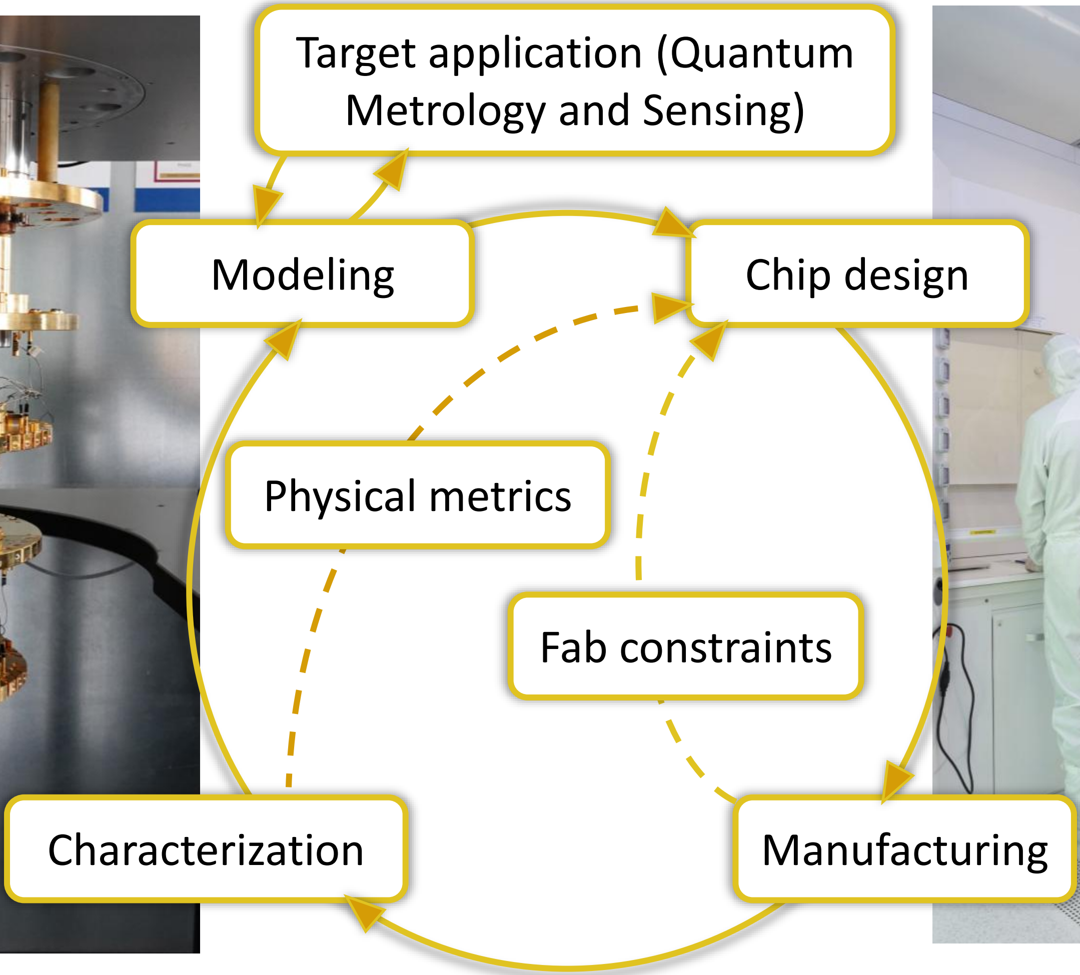
Superconducting Quantum Electronics

- Researchers
  - Emanuele ENRICO (PI)
  - Luca FASOLO
  - Luca OBERTO
  - Luca CALLEGARO
- PhD Students
  - **Alessandro ALOCCO (PoliTO)**
  - Andrea CELOTTO (PoliTO)
  - Emanuele PALUMBO (PoliTO)
  - Bernardo GALVANO (UniPA)
- Master/Bachelor students
  - Fabrizio BISOGNO (UniTO)
  - Tommaso SABBADINI (PoliTO)
- CleanRoom Technician
  - Start on July

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Our workflow



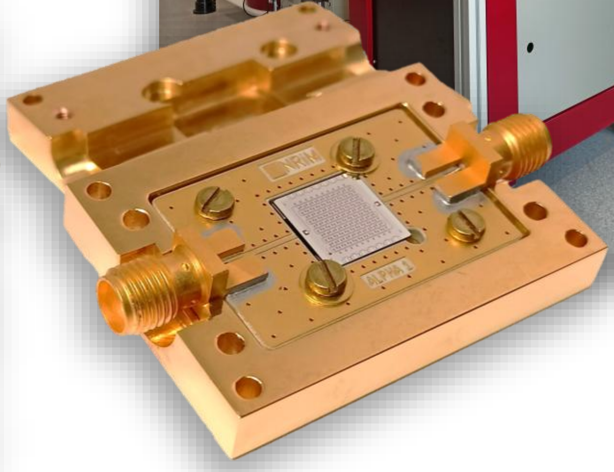


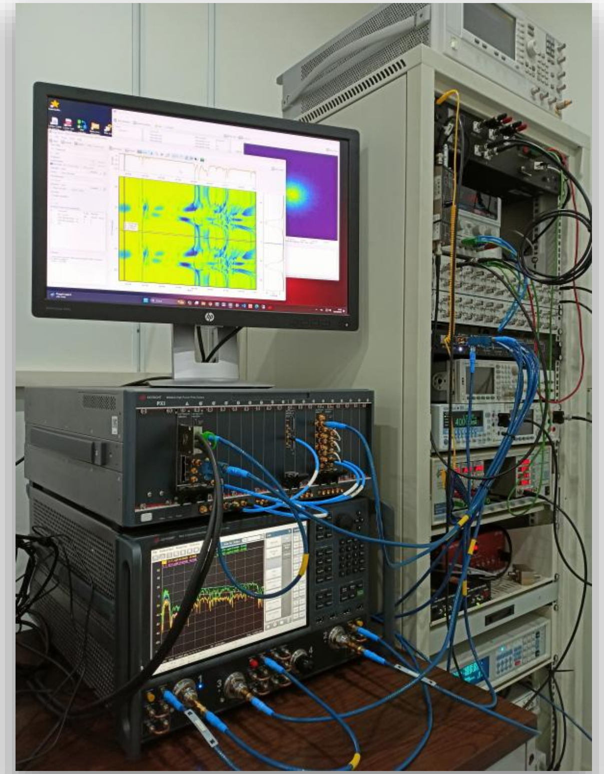
Quantum Circuit for Metrology laboratory
hosting a dilution refrigerator (T < 20 mK)

PiQuET Cleanroom facility

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Quantum Ciruits for Metrology Lab.





Dilution Refrigerator
- Leiden CF-CS110
- (400 µW @ 100 mK, BT < 20 mK)
- Warm insertable probe for RF
- µMetal(RT) and CryoPhy(BT) shields
- Warm insertable probe for QHE
- 9T magnet option

Shielded and thermally stable room
- Control electronics (DC+RF)
- CW (PNA-X) and pulsed protocols (QCS)

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Superconducting Devices for Quantum Optics

(with a metrological flavor)

INRiM
ISTITUTO NAZIONALE
DI RICERCA METROLOGICA

SPDC and Metrology – Quantum Adv.

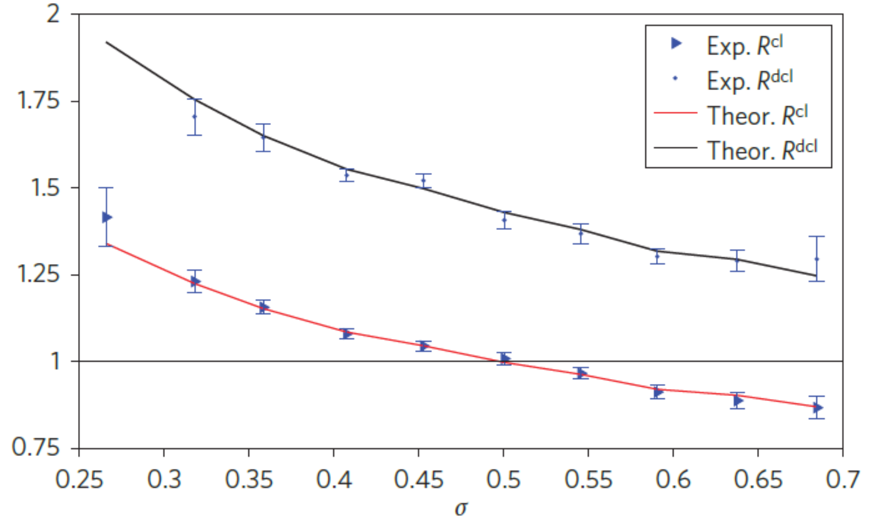
nature photonics

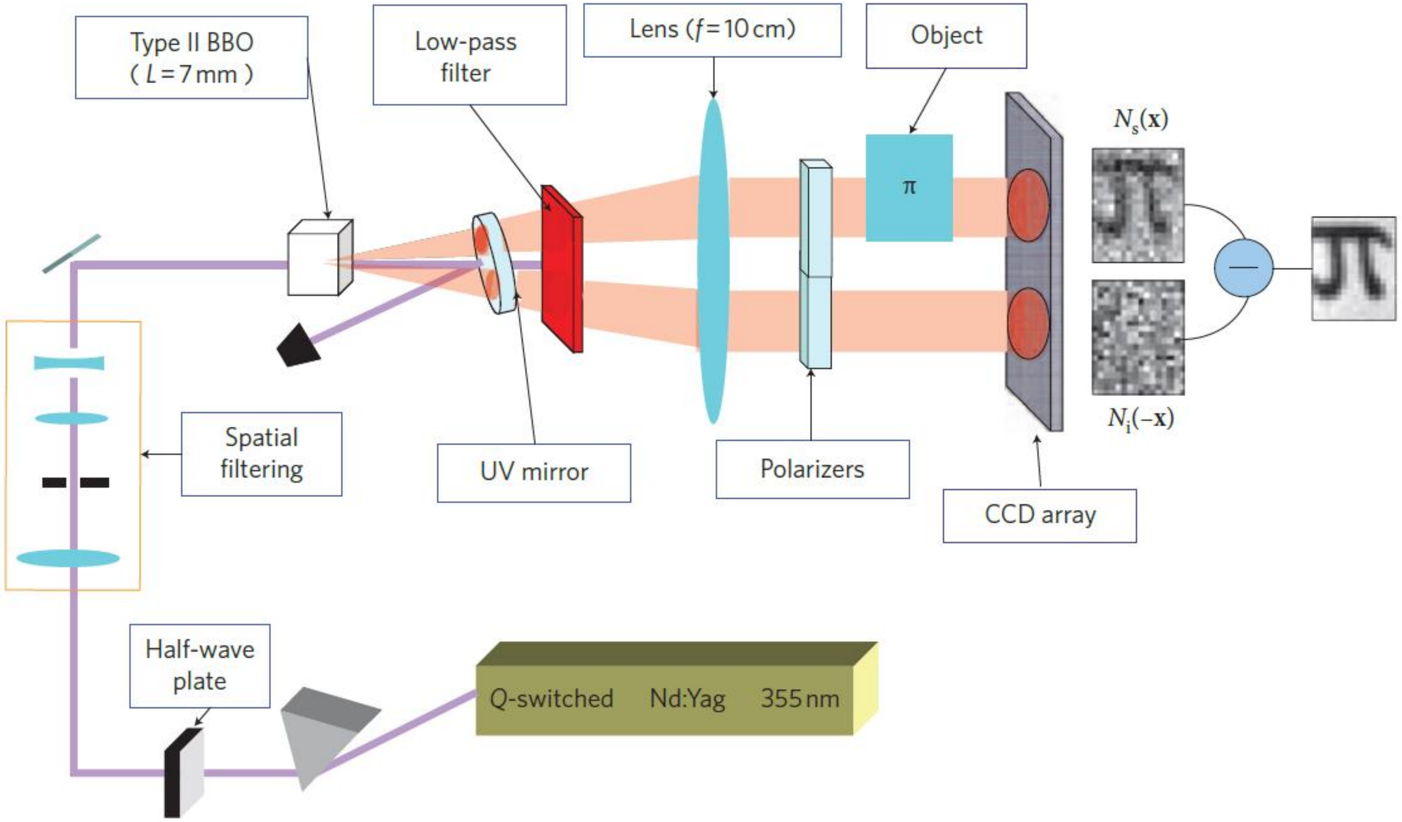
LETTERS

PUBLISHED ONLINE: 28 FEBRUARY 2010 | DOI: 10.1038/NPHOTON.2010.29

Experimental realization of sub-shot-noise quantum imaging

G. Brida, M. Genovese and I. Ruo Berchera*





Ratio R between the **signal-to-noise ratio in quantum imaging, and differential (dcl) and direct (cl) classical imaging**. R is plotted as a function of the degree of correlation

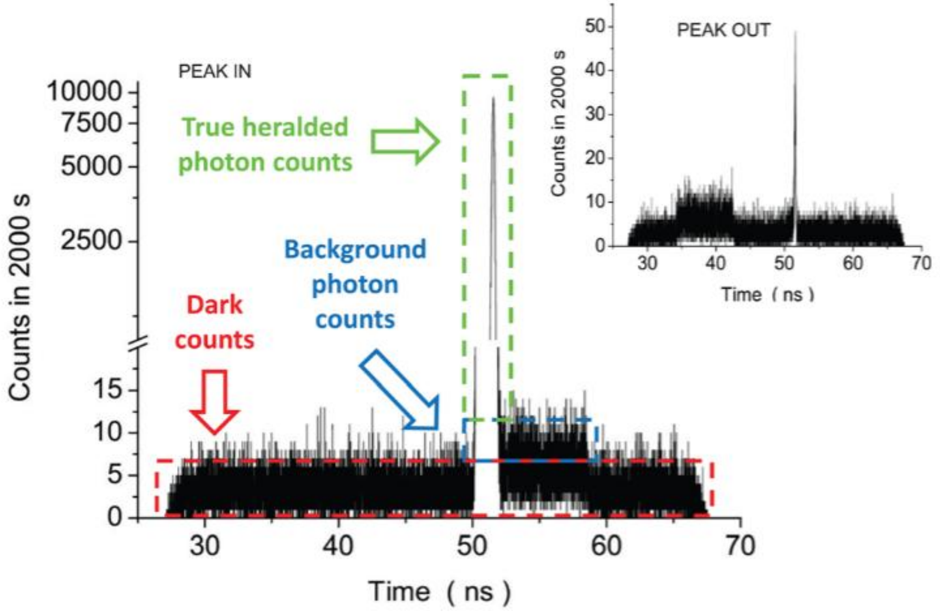
INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

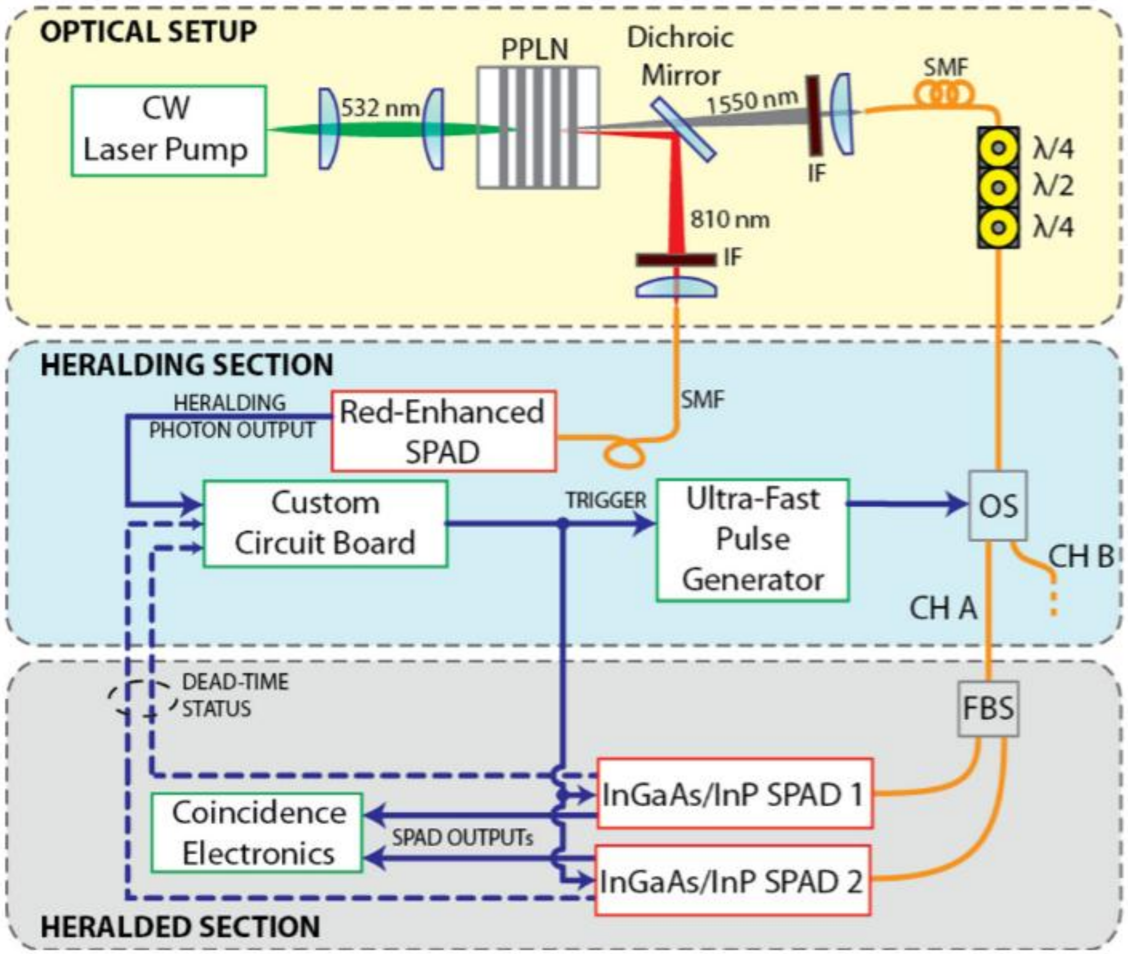
SPDC and Metrology – Counting

APPLIED PHYSICS LETTERS **101**, 221112 (2012)

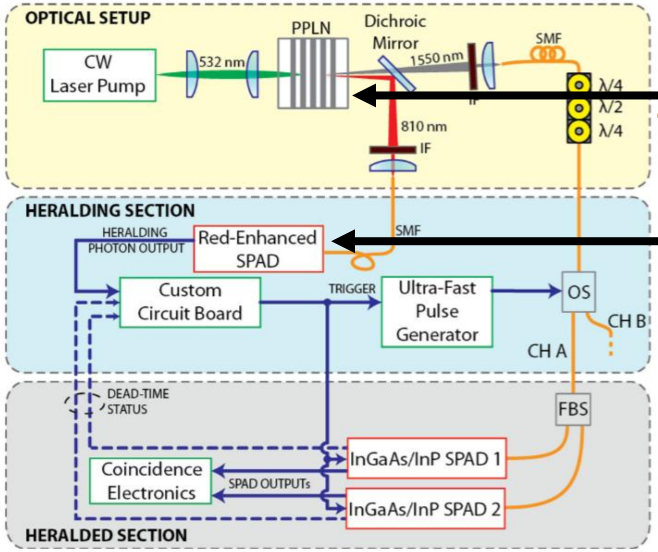
An extremely low-noise heralded single-photon source: A breakthrough for quantum technologies

G. Brida,[1] I. P. Degiovanni,[1] M. Genovese,[1] F. Piacentini,[1] P. Traina,[1] A. Della Frera,[2] A. Tosi,[2] A. Bahgat Shehata,[2] C. Scarcella,[2] A. Gulinatti,[2] M. Ghioni,[2] S. V. Polyakov,[3] A. Migdall,[3] and A. Giudice[4]
[1]*Istituto Nazionale di Ricerca Metrologica-I.N.RI.M., Strada delle Cacce 91, 10135 Torino, Italy*
[2]*Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milano, Italy*
[3]*Joint Quantum Institute, University of Maryland, and National Institute of Standards and Technology, 100 Bureau Dr, Stop 8410, Gaithersburg, Maryland 20899, USA*
[4]*Micro Photon Devices Srl, Via Stradivari 4, 39100 Bolzano, Italy*





INRiM
ISTITUTO NAZIONALE DI RICERCA METROLOGICA



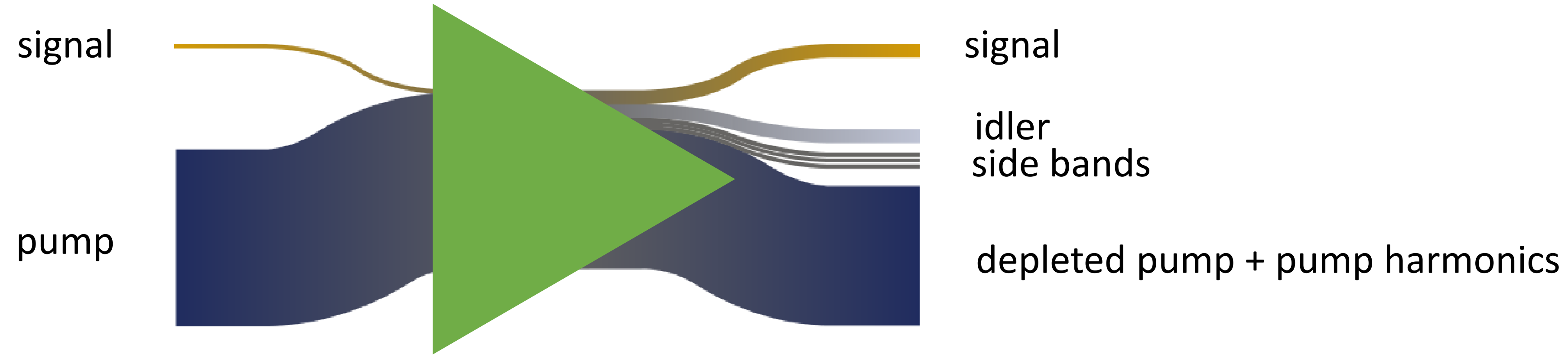
sources

detectors

Superconducting Devices for Quantum Optics

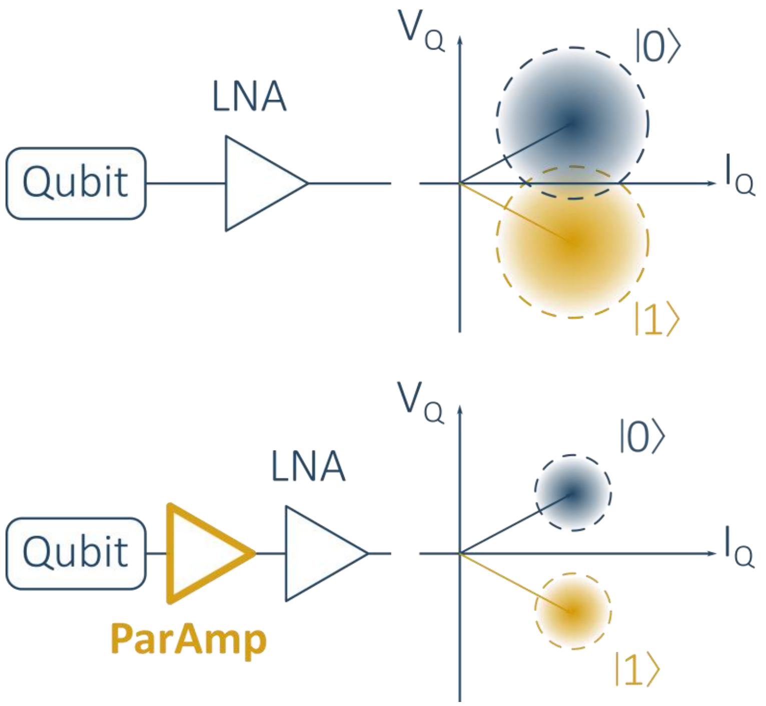
(with a **metrological** flavor)

Josephson Nonlinear Metamaterials

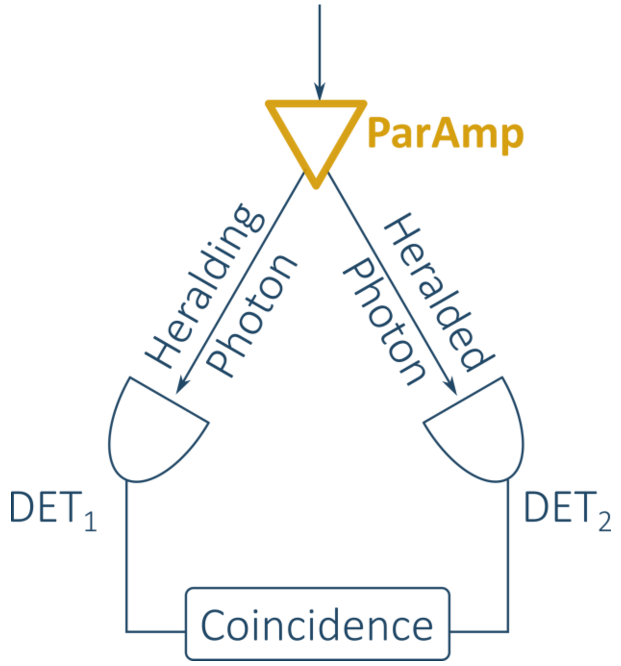


J-Metamaterials and Metrology

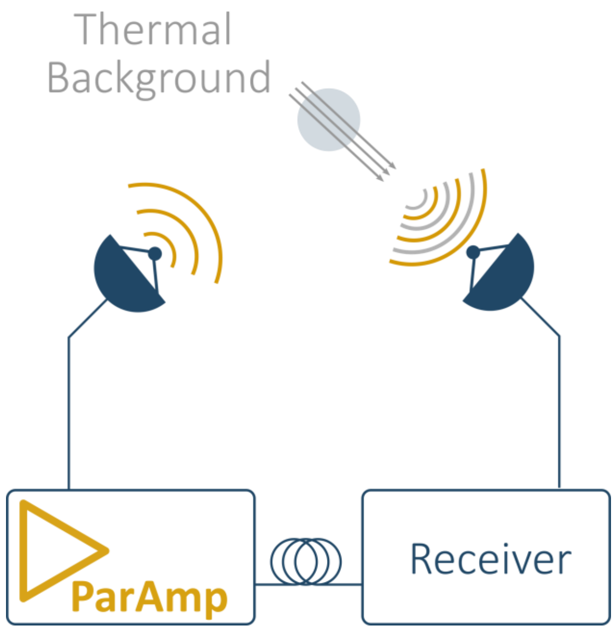
Improvement of readout of weak microwave signals with a **quantum limited amplifier**



Realization of **absolute calibration** technique of microwave **number resolved photon detectors**



Microwave **Quantum Illumination** to improve detection or sensing in noisy environments

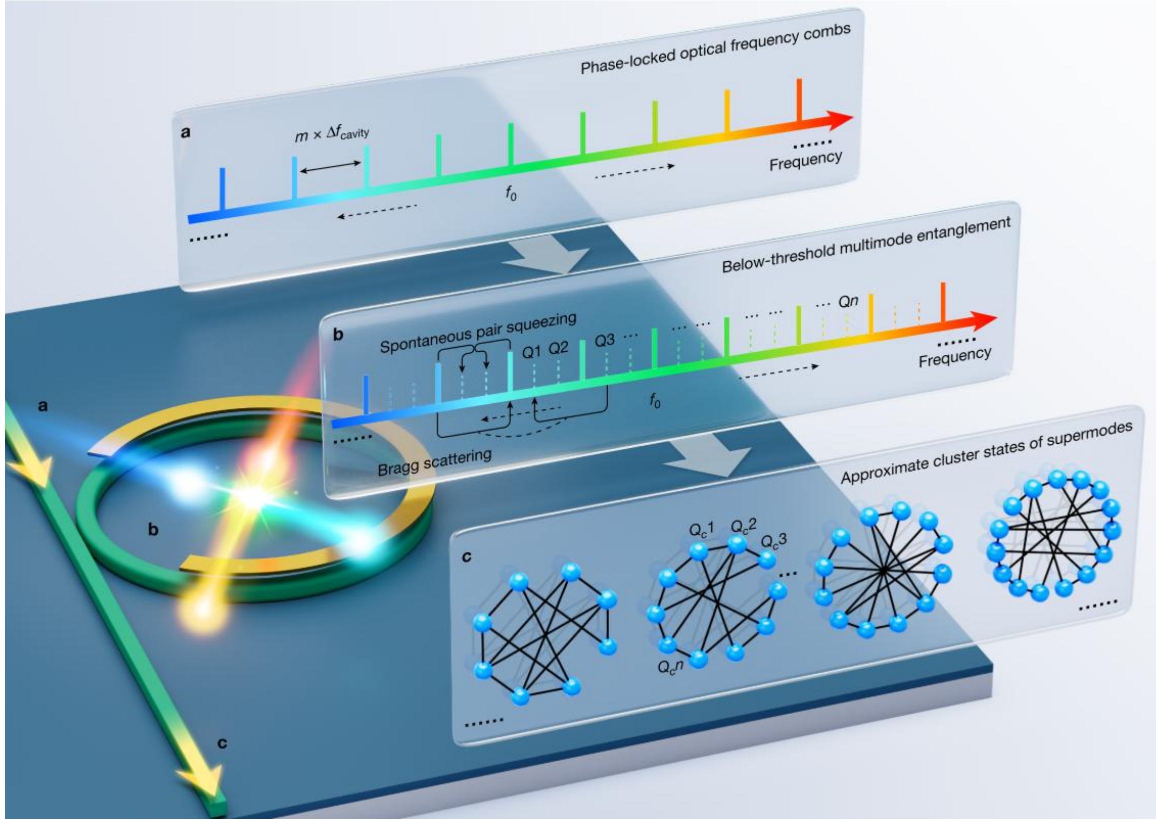


INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Cluster States - Overview

- Qubit Cluster States: Highly entangled states on discrete-variable systems (two-level qubits)
- CV Cluster States: Analogous entangled states in continuous-variable systems (e.g., squeezed light modes)

- Both serve as universal resources for measurement-based quantum computation (MBQC)
- Built via entangling operations on graph-like structures (e.g., controlled-Z for qubits, beam splitters + squeezing for CV)

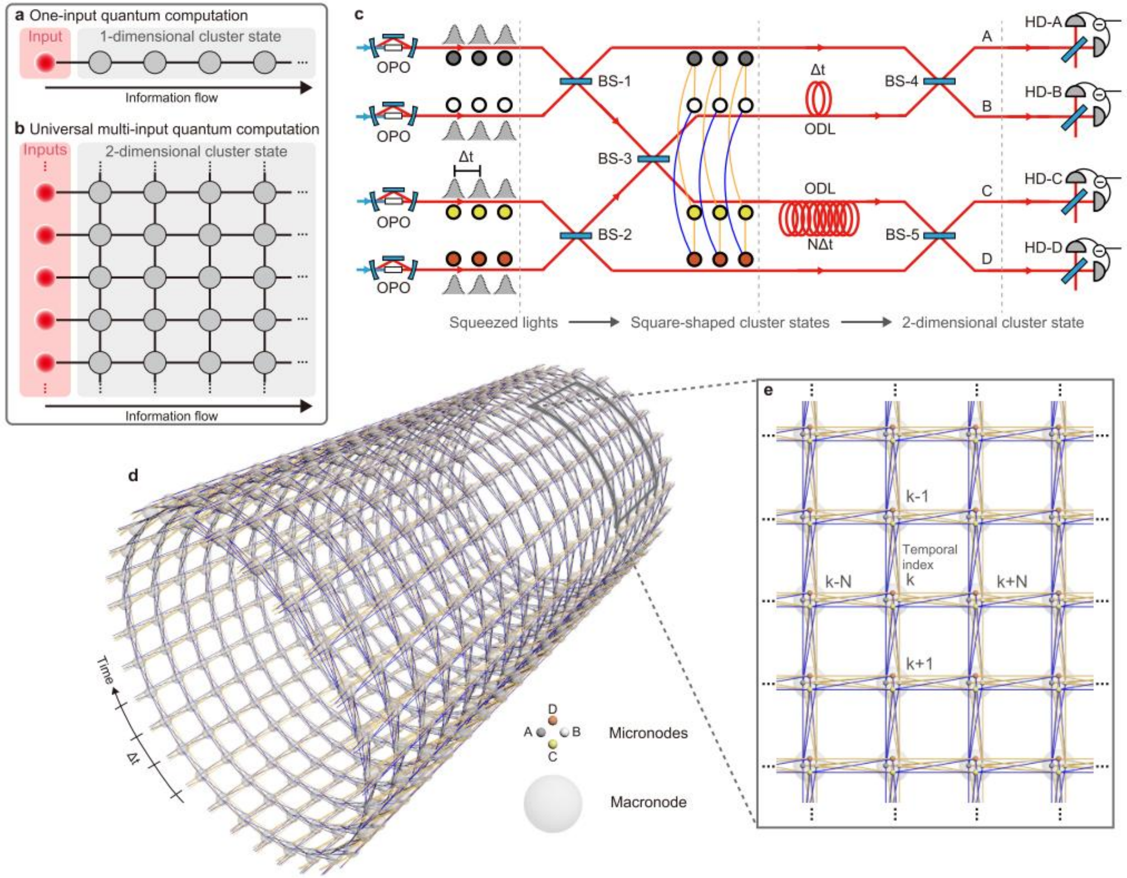


Jia, X., Zhai, C., Zhu, X. et al. Continuous-variable multipartite entanglement in an integrated microcomb. Nature 639, 329–336 (2025). https://doi.org/10.1038/s41586-025-08602-1

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Cluster States - Applications

- **MBQC**: Perform quantum algorithms via local measurements on a pre-prepared entangled state
- Quantum Communication: Enable one-way quantum repeaters and teleportation networks (qubit & CV)
- Quantum Simulation: Emulate complex many-body systems and quantum dynamics
- Quantum Error Correction: Foundation for topological codes (qubit) and bosonic codes (CV)
- **Quantum Sensing & Metrology**: Exploit multipartite entanglement for enhanced sensitivity (especially in CV systems)

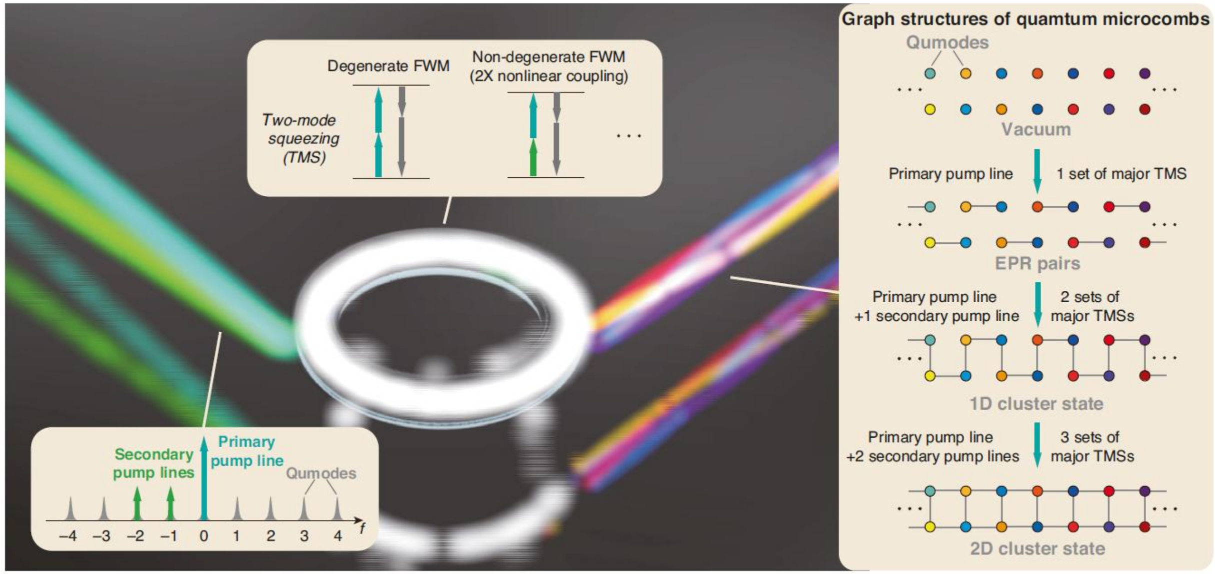


Warit Asavanant et al. ,Generation of time-domain-multiplexed two-dimensional cluster state. Science 366,373-376 (2019). DOI:10.1126/science.aay2645

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

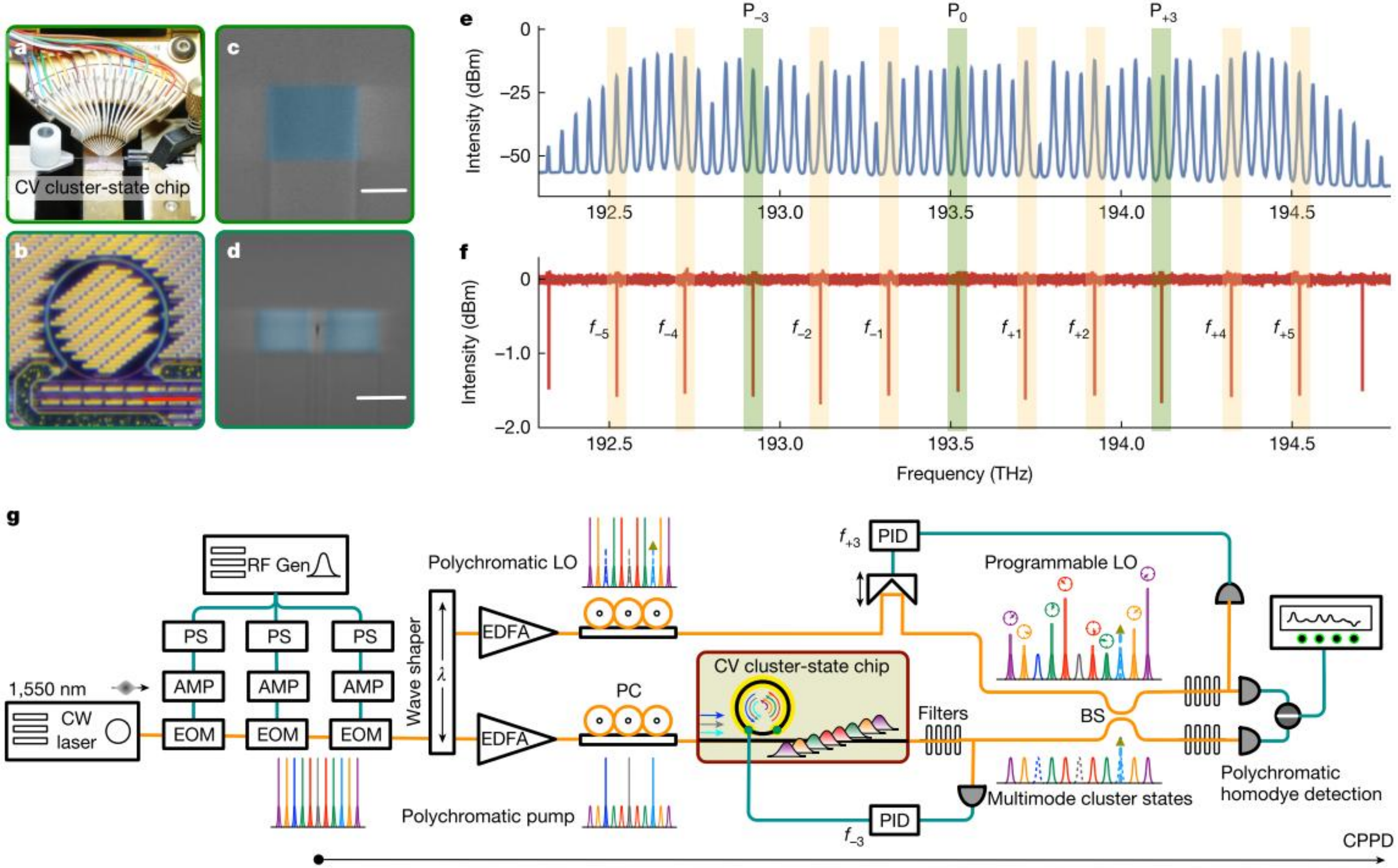
Cluster States – Advantages

- Decoupled Architecture: Prepare entanglement once, compute via measurements → simplifies control
- Parallelism: Many measurements can be performed simultaneously in spatial or temporal structures
- Scalability: CV cluster states can be generated in large scale (e.g., using optical frequency combs or time-domain multiplexing)
- Hardware Efficiency: Measurement-based protocols reduce gate complexity and hardware overhead
- Noise Robustness: Topological and fault-tolerant constructions possible for both qubit and CV implementations



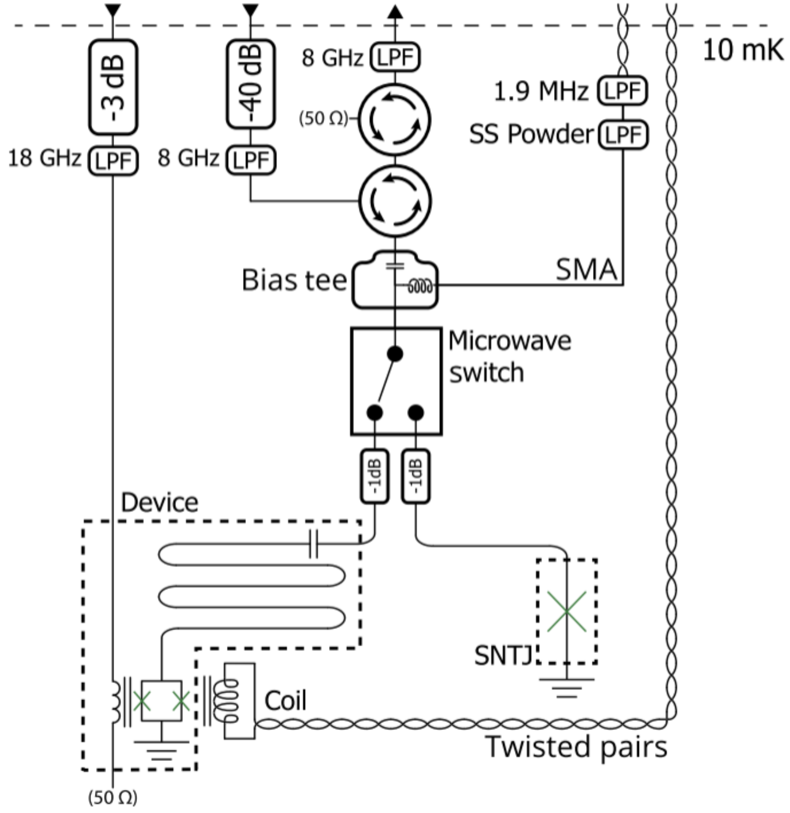
Wang, Z., Li, K., Wang, Y. et al. Large-scale cluster quantum microcombs. Light Sci Appl 14, 164 (2025). https://doi.org/10.1038/s41377-025-01812-2

Cluster States – Optics Regime

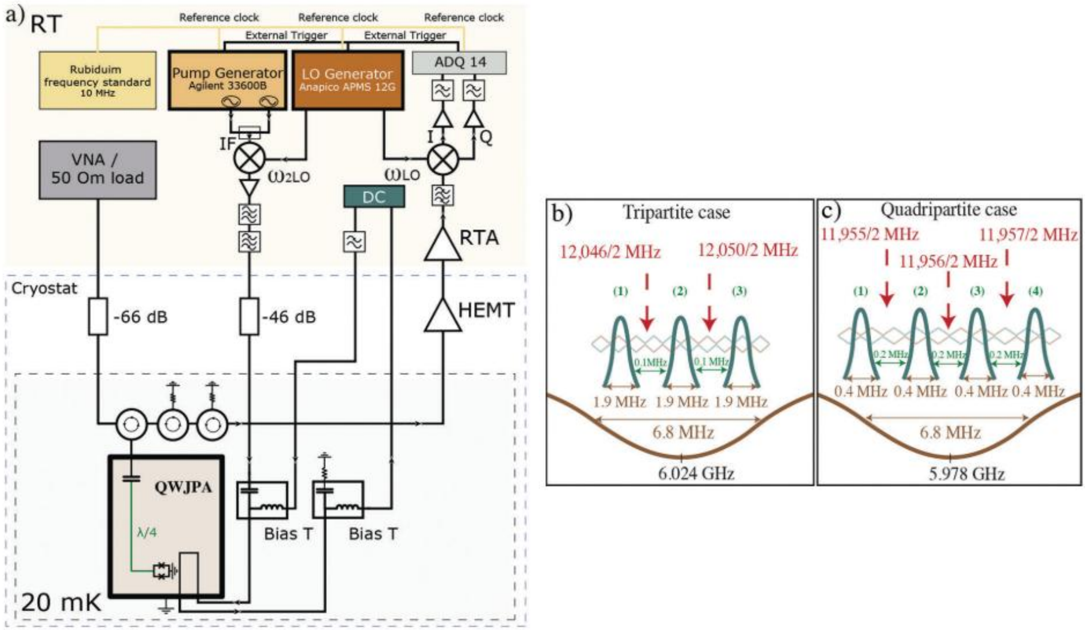


Jia, X., Zhai, C., Zhu, X. et al. Continuous-variable multipartite entanglement in an ***integrated microcomb****. Nature 639, 329–336 (2025). https://doi.org/10.1038/s41586-025-08602-1*

Cluster States – Microwave Regime



Sandbo Chang, C. W., Simoen, M., Aumentado, J., et.al. (2018). Generating Multimode Entangled Microwaves with a Superconducting Parametric Cavity. Physical Review Applied, 10(4). https://doi.org/10.1103/PhysRevApplied.10.044019



Petrovnin, K. V., Perelshtein, M. R., Korkalainen, T., Vesterinen, V., Lilja, I., Paraoanu, G. S., & Hakonen, P. J. (2023). Generation and Structuring of Multipartite Entanglement in a Josephson Parametric System. Advanced Quantum Technologies, 6(1). https://doi.org/10.1002/qute.202200031

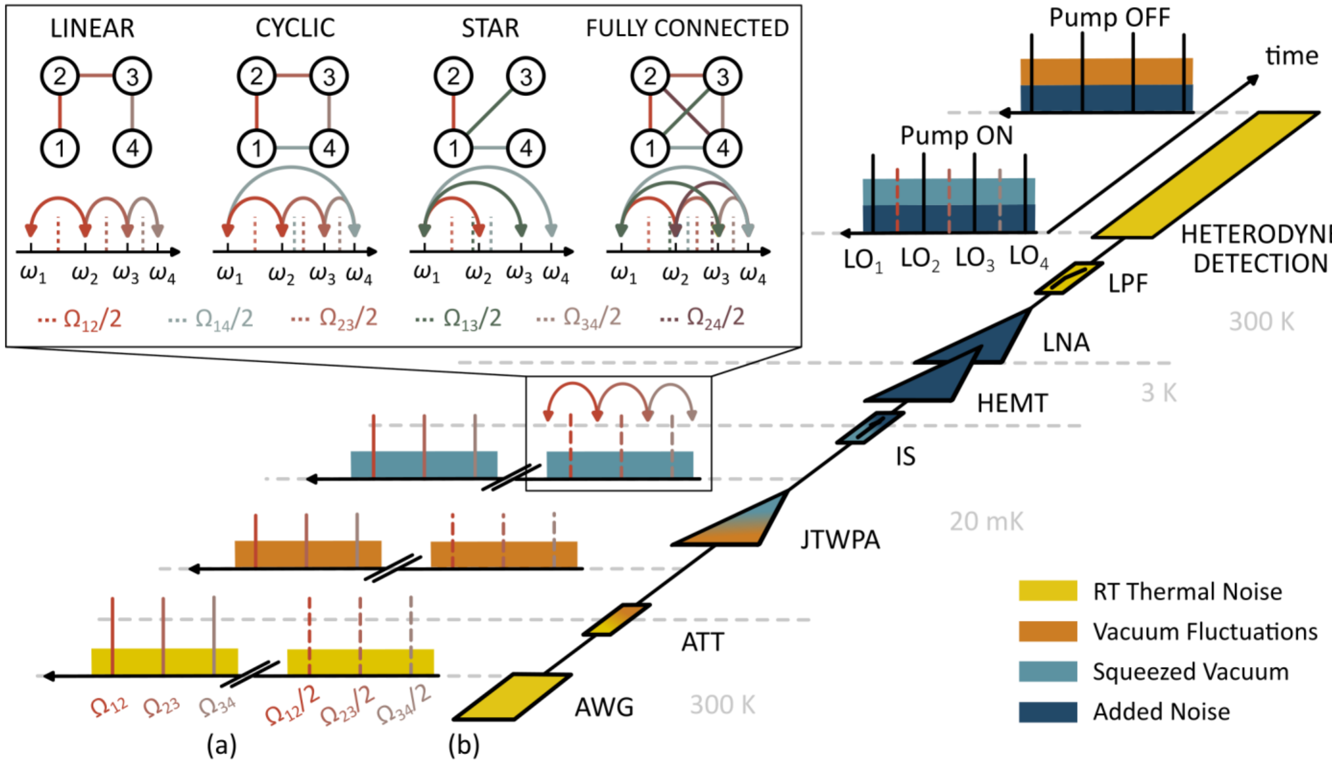
INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Programmable Microwave CS

(a) Multiple pump tones from an AWG drive the **JTWPA[1] into a three-wave mixing regime**, generating CV cluster states in the frequency domain.

(b) Experimental setup: broadband mode synthesis, cryogenic routing, and **multiplexed heterodyne detection** with noise rejection via **reference state protocol**.

[1] VTT /Arctic TWPA from



MetSuperQ

EUROPEAN PARTNERSHIP

Co-funded by the European Union

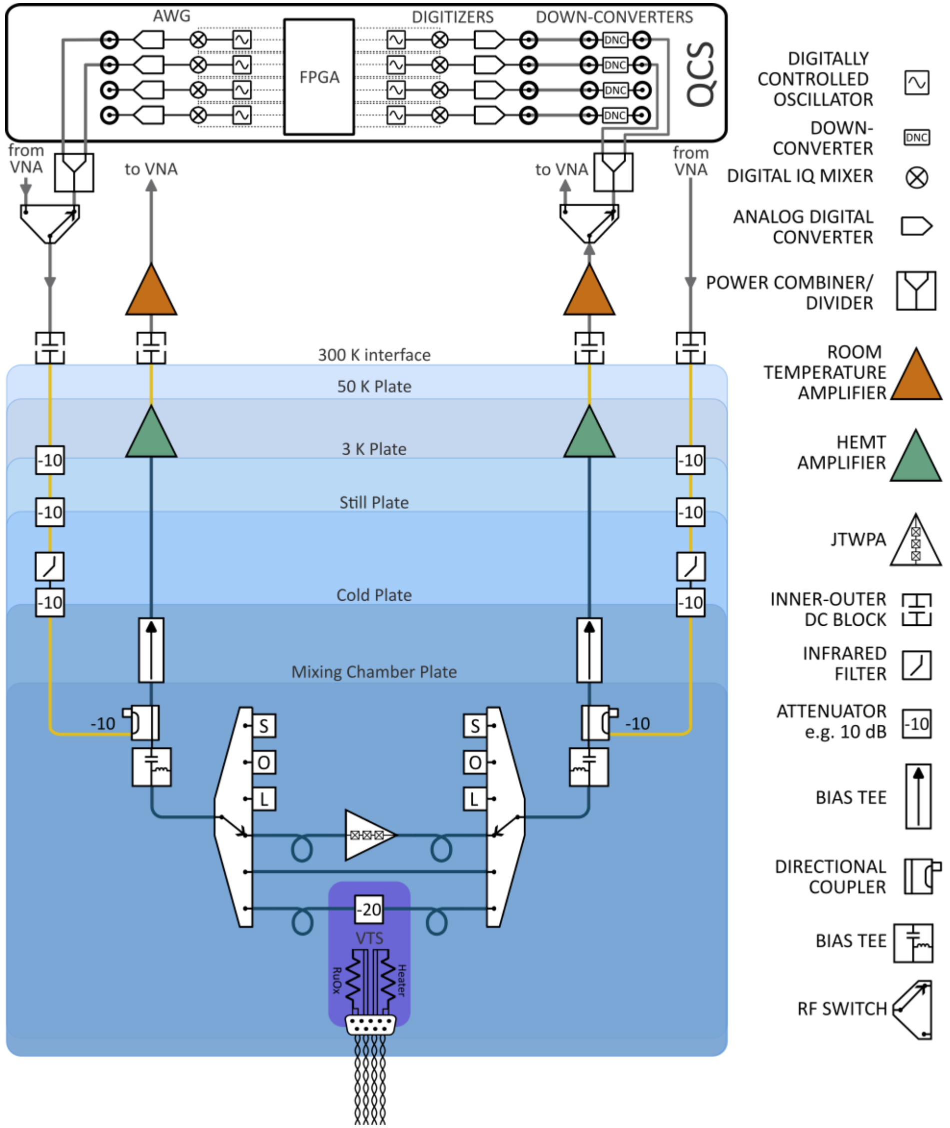
METROLOGY PARTNERSHIP

EURAMET

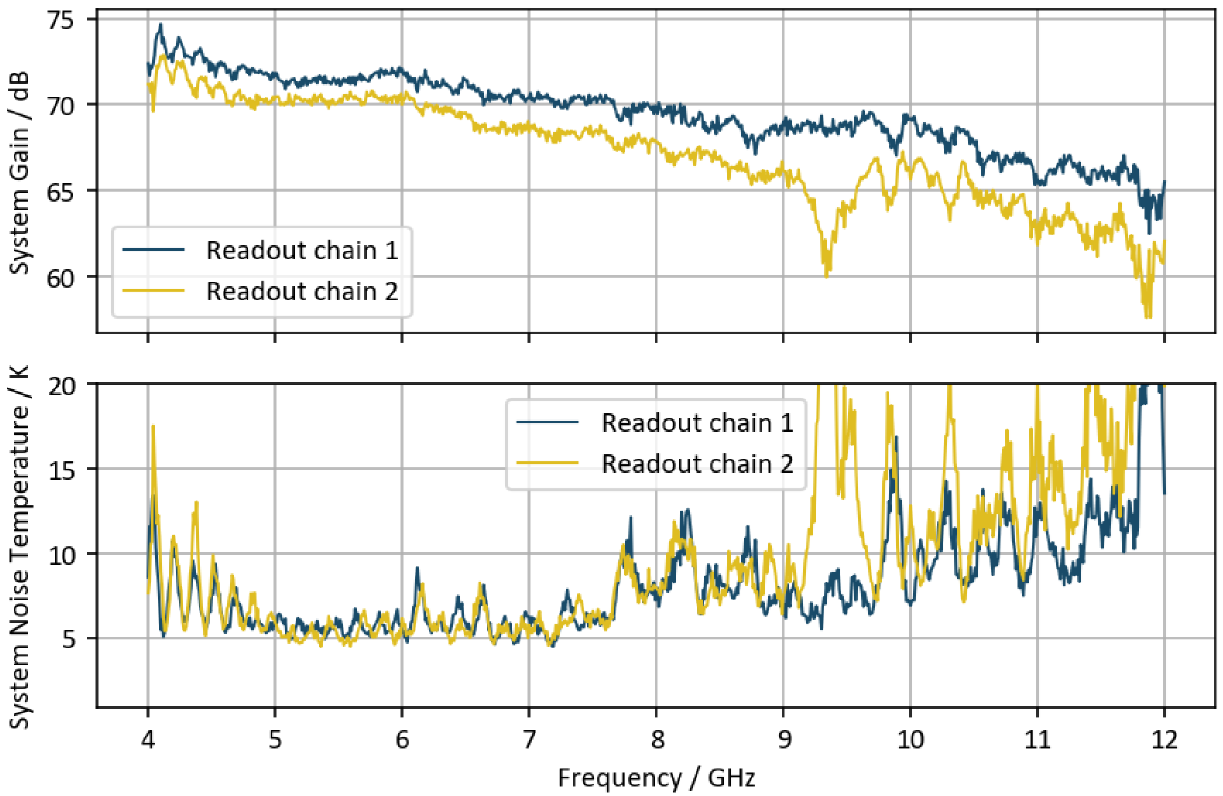
$$\hat{H}_{\text{eff}} = \sum_{k=1}^{n} \sum_{j \le l} \left(r_{jl}^{(k)} \hat{a}_j^\dagger \hat{a}_l^\dagger + r_{jl}^{(k)*} \hat{a}_j \hat{a}_l \right) \qquad r_{jl}^{(k)} = g_{jl}^{(k)} \alpha_k e^{-i\phi_k}$$

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Cryogenic setup and Plank spectroscopy

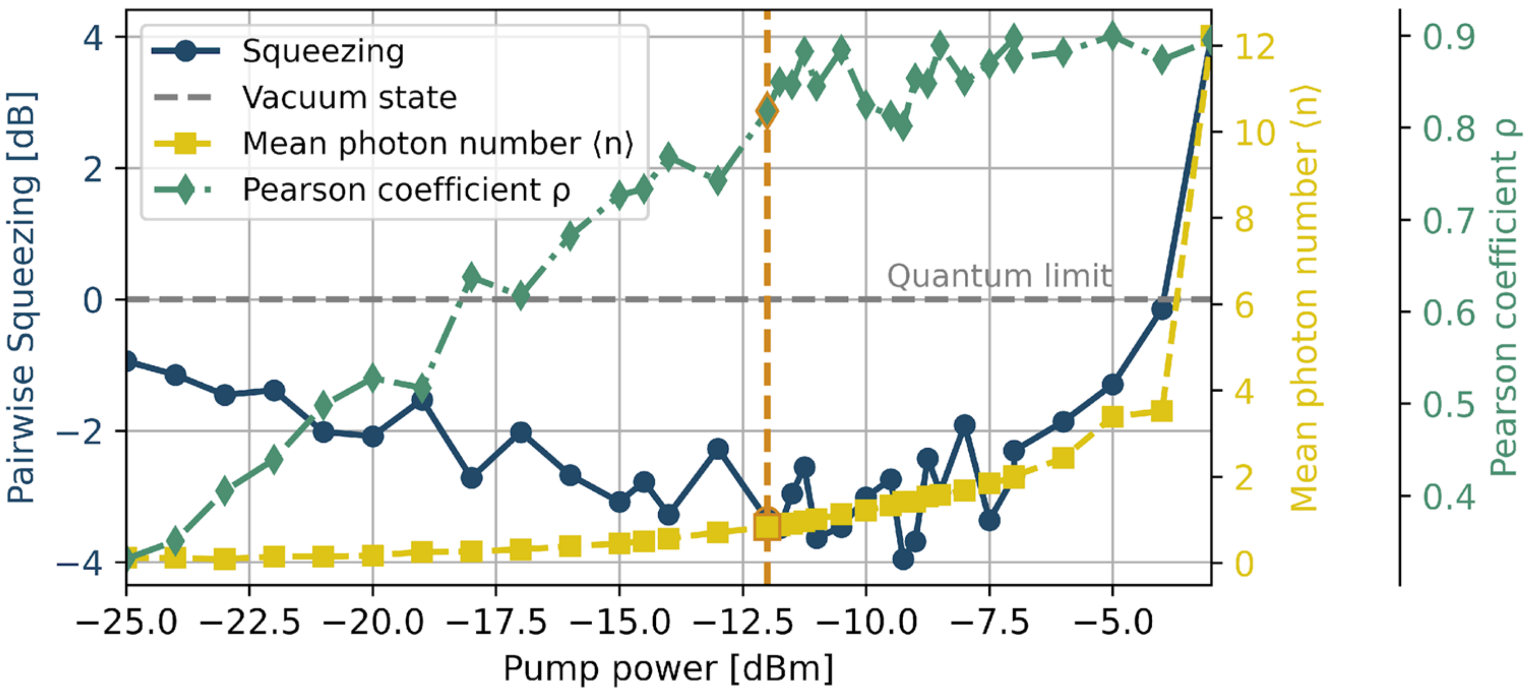


$$\frac{\langle I_j^2 + Q_j^2 \rangle}{Z_0 \tau_j^{-1}} = G_j \left[\frac{\hbar\omega_j}{2} \coth\left(\frac{\hbar\omega_j}{2k_B T_{VTS}} \right) + k_B T_{SYS,j} \right]$$



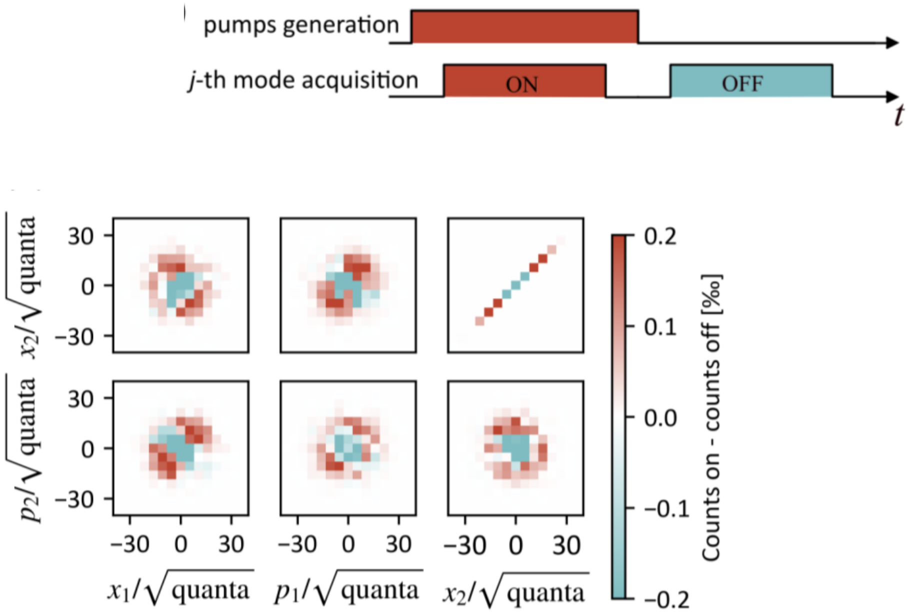
INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

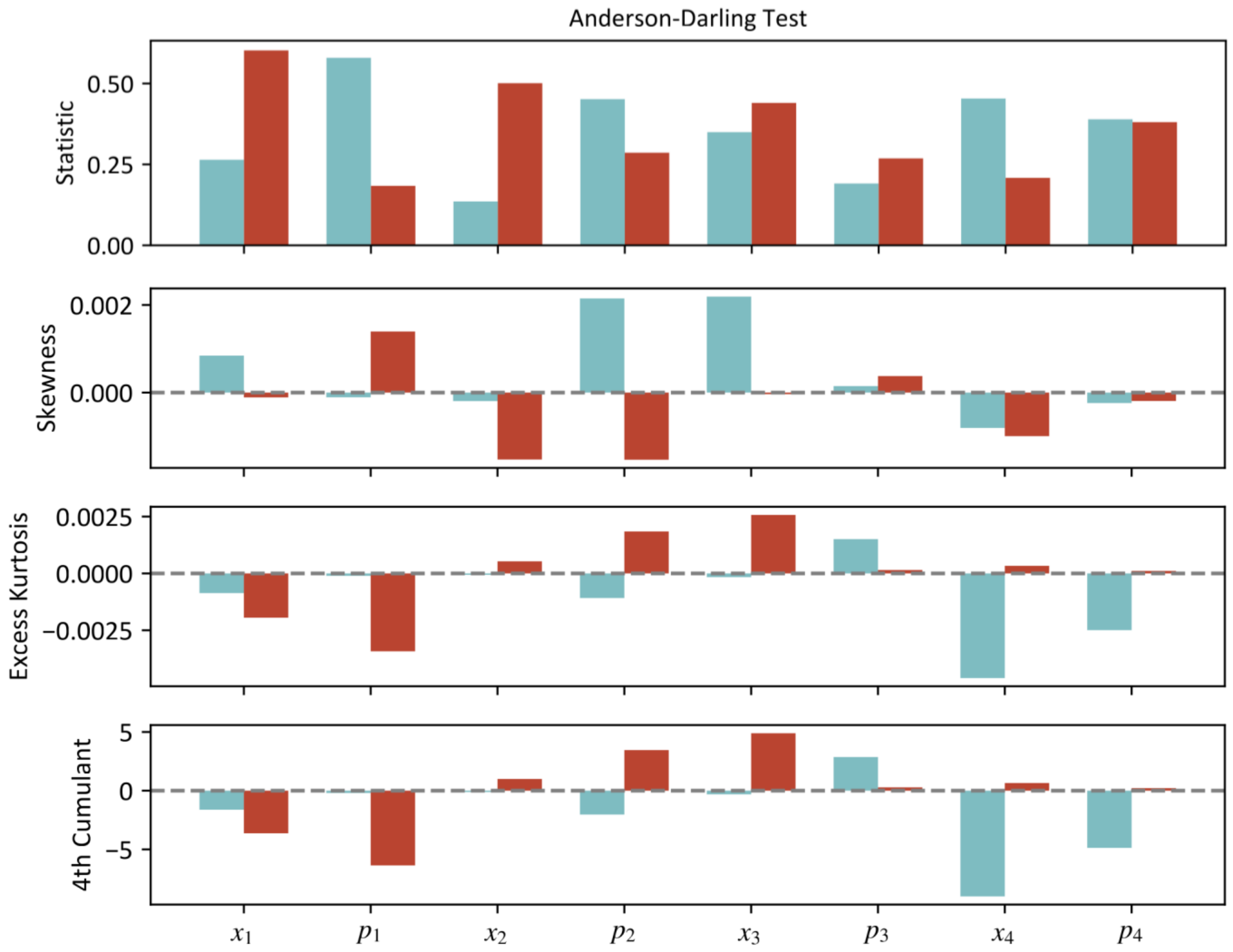
Single pump setup validation



INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

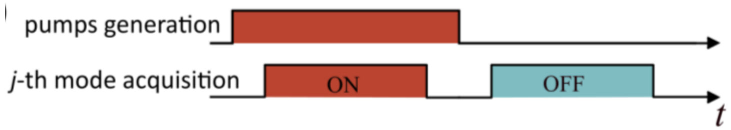
Gaussianity Validation

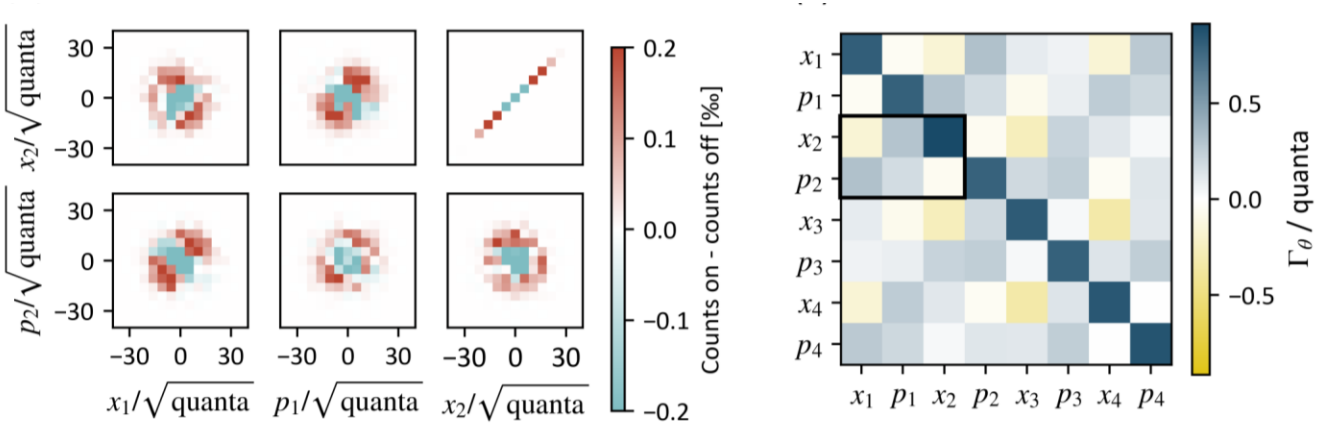




- **Standard normality tests,** namely the Shapiro–Wilk and Anderson–Darling tests.
- **Moment analysis up to fourth order**, including skewness, excess kurtosis, and fourth-order cumulants.

Covariance Matrix Reconstruction





$$i_j = \frac{I_j}{\sqrt{2G_j Z_0 \hbar\omega_j/2\tau^{-1}}}, \quad q_j = \frac{Q_j}{\sqrt{2G_j Z_0 \hbar\omega_j \tau^{-1}}}$$

$$\Gamma^{\text{exp}}_{j,l} = \frac{1}{2}\langle M_j M_l + M_l M_j\rangle - \langle M_j\rangle\langle M_l\rangle$$

$$M = (i_1, q_1, \ldots, i_m, q_m)^T$$

Measure output quadratures with pump OFF
→ **reference vacuum state**.

Measure with pump ON
→ signal (**CS**) + TWPA-added noise.

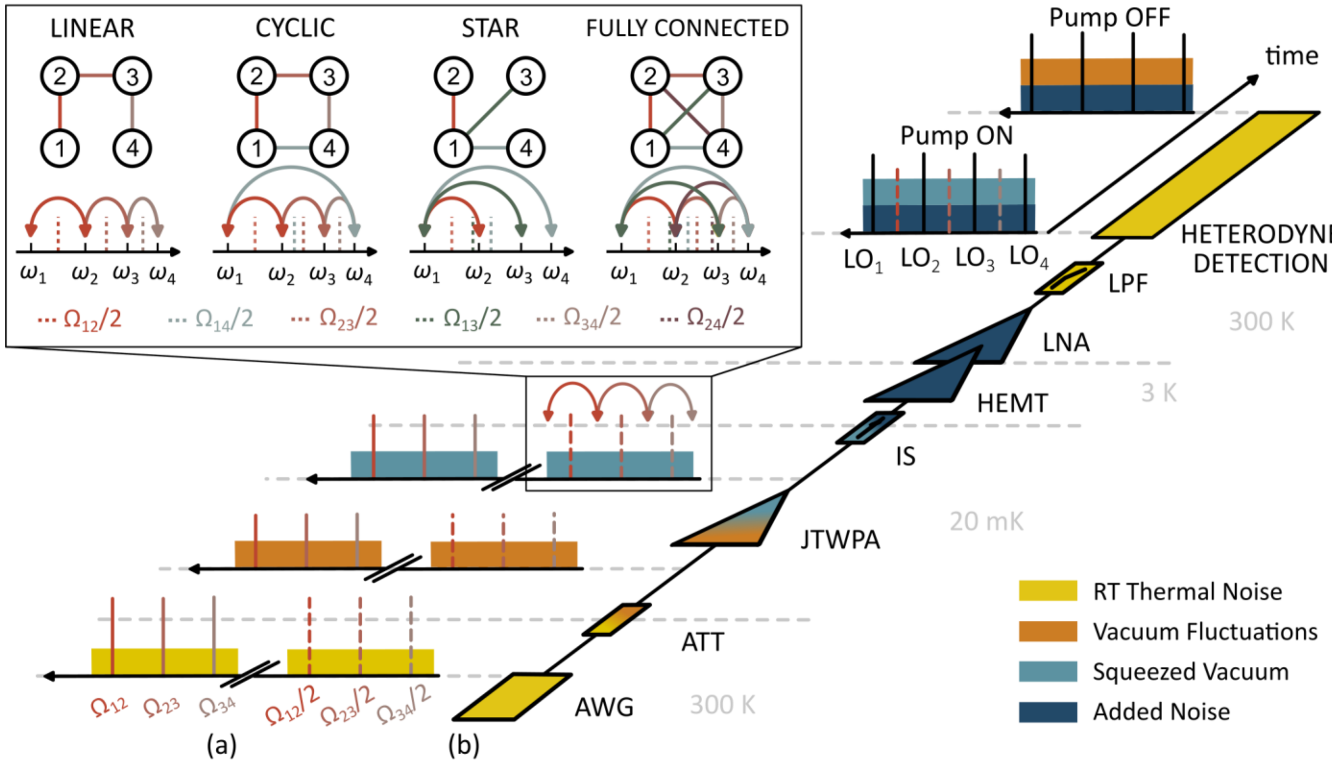
Comparing the two
→ reconstruction of the output covariance matrix, isolating the TWPA's effect (**amplification, squeezing, added noise**).

$$\boldsymbol{\Gamma}_\theta = (\boldsymbol{\Gamma}^{\text{exp}}_{\text{ON}} - \boldsymbol{\Gamma}^{\text{exp}}_{\text{OFF}}) + \boldsymbol{\sigma}^{\text{in}}$$

INRiM
ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Het. Det. with Unknown Phase Offsets

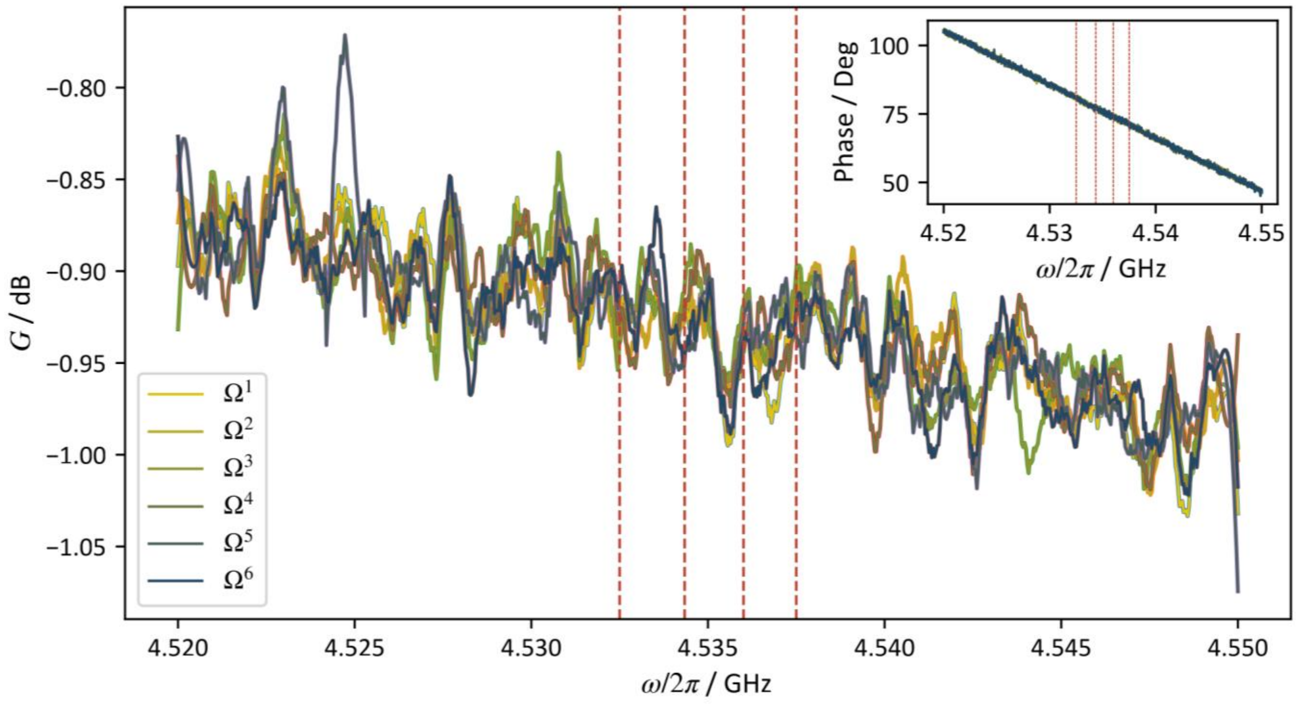
- LOs are **phase-locked** to the JTWPA pumps.
- Unknown **phase shifts arise** from setup components, cable dispersion, and group delays.
- These cause effective quadrature rotation across frequency.
- Covariance matrix affected.



$$\mathbf{\Gamma}_\theta = \mathbf{R}_\theta \cdot \mathbf{\Gamma} \cdot \mathbf{R}_\theta^{\mathrm{T}}, \qquad \boldsymbol{R}_\theta = \bigoplus_{j=1}^{m} \begin{pmatrix} \cos\theta_j & -\sin\theta_j \\ \sin\theta_j & \cos\theta_j \end{pmatrix}$$

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Assumptions & Squeezing Optimization



- Covariance matrix optimized **via local phase-space rotations** $R_j(\theta_j)$.
- Pumps phase-locked, frequencies close
  $\Rightarrow$ stable relative phase drift.
- Symmetric (almost flat) squeezing
  $\Rightarrow$ no need for local squeezing or shear.
- Restriction to orthogonal symplectic transforms **preserves entanglement structure**.

→ Goal: reorient squeezing axes to maximize observed two-mode correlations.

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Squeezing Optimization Procedure

- Optimization aims to maximize $p_j - x_l$ correlations over the **set of LO phases θ**.
- Define the **average covariance** function:

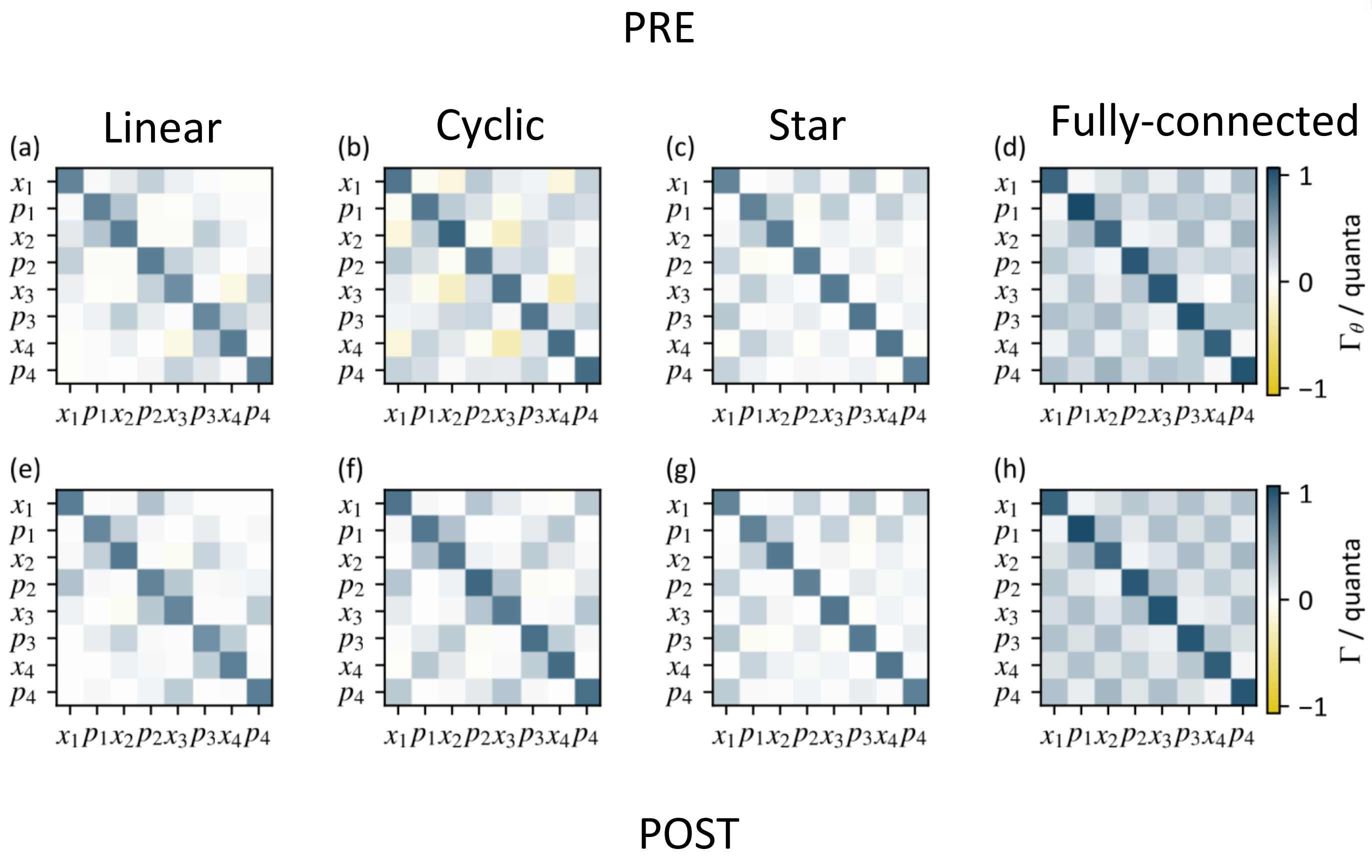
$$\mathscr{C}_{px}(\theta) = \frac{1}{m^2} \sum_{j=1}^{m} \sum_{l=1}^{m} \Gamma_{\theta, p_j, x_l}$$

- The optimal phase set θ_{opt} **maximizes** this correlation measure.

$$\theta_{\mathrm{opt}} = \arg\max_{\theta} \mathscr{C}_{px}(\theta)$$

- This identifies the **global quadrature basis** where the reconstructed covariance matrix Γ_θ best matches an ideal cluster state.

$$\Gamma = \mathbf{R}_{\theta_{\mathrm{opt}}}^{-1} \Gamma_\theta \left(\mathbf{R}_{\theta_{\mathrm{opt}}}^{-1} \right)^\top$$

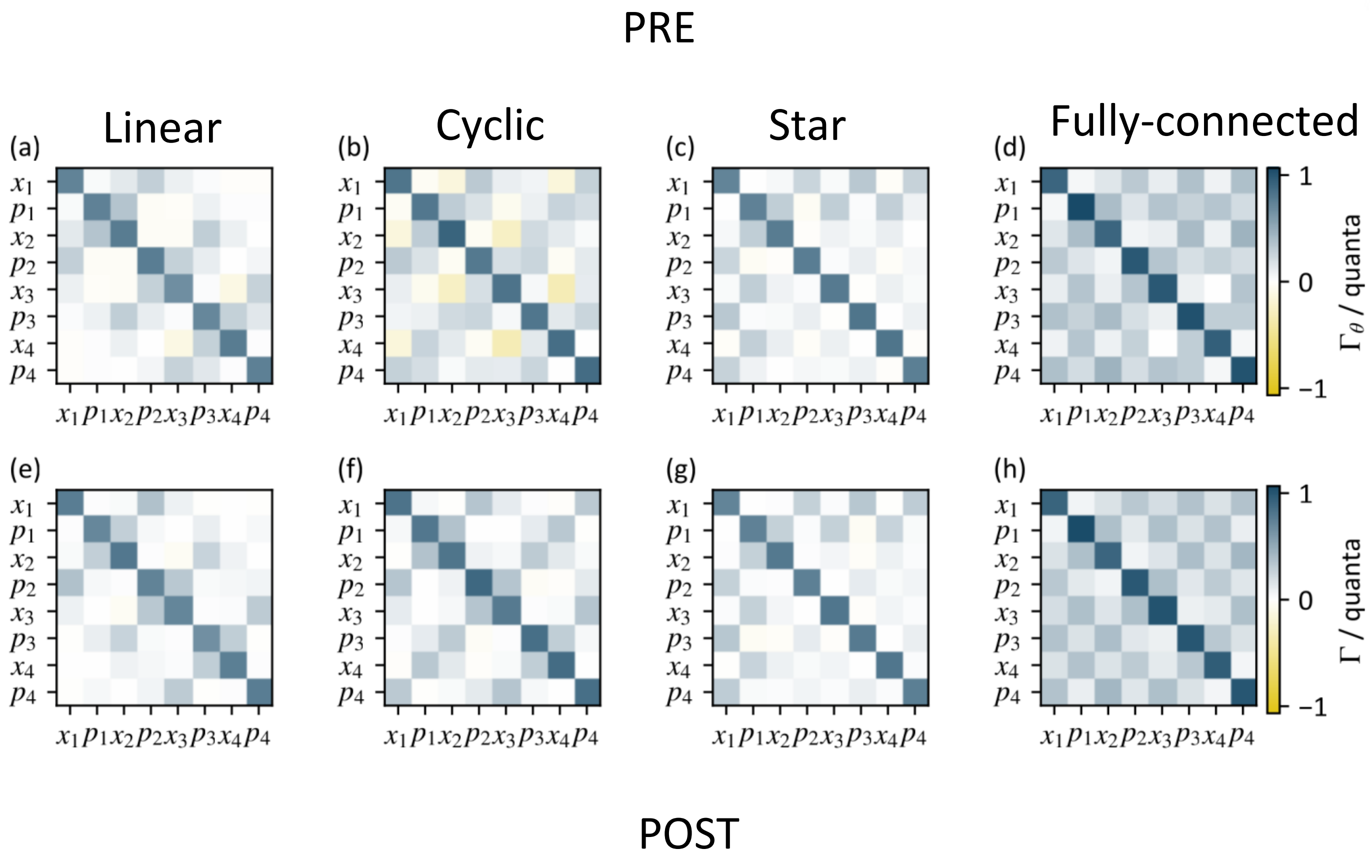


INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Squeezing Optimization Procedure

- Captures and **compensates unknown pump-induced phase shifts**

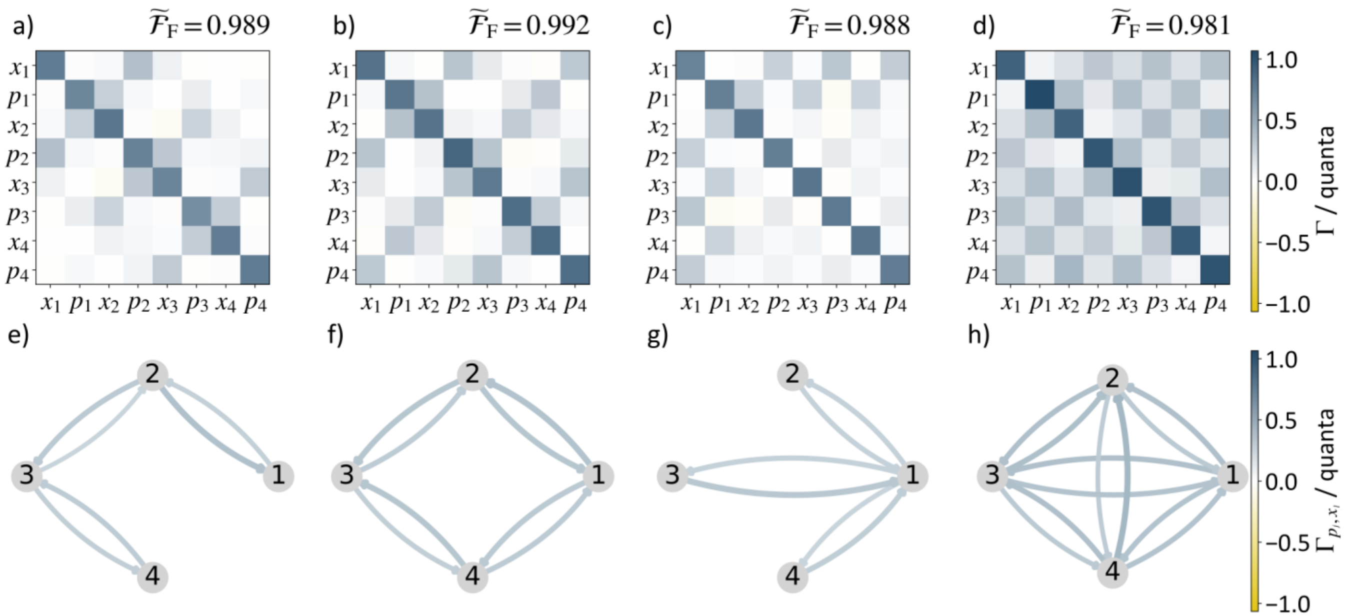
- Ensures **physically consistent phase alignment across modes**—key for coherent protocols (e.g. cluster states, error correction)



INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Squeezing Optimization Procedure

- Captures and **compensates unknown pump-induced phase shifts**
- Ensures **physically consistent phase alignment across modes**—key for coherent protocols (e.g. cluster states, error correction)
- The **optimal global quadrature basis** reveals maximal two-mode squeezing and **graph structure**

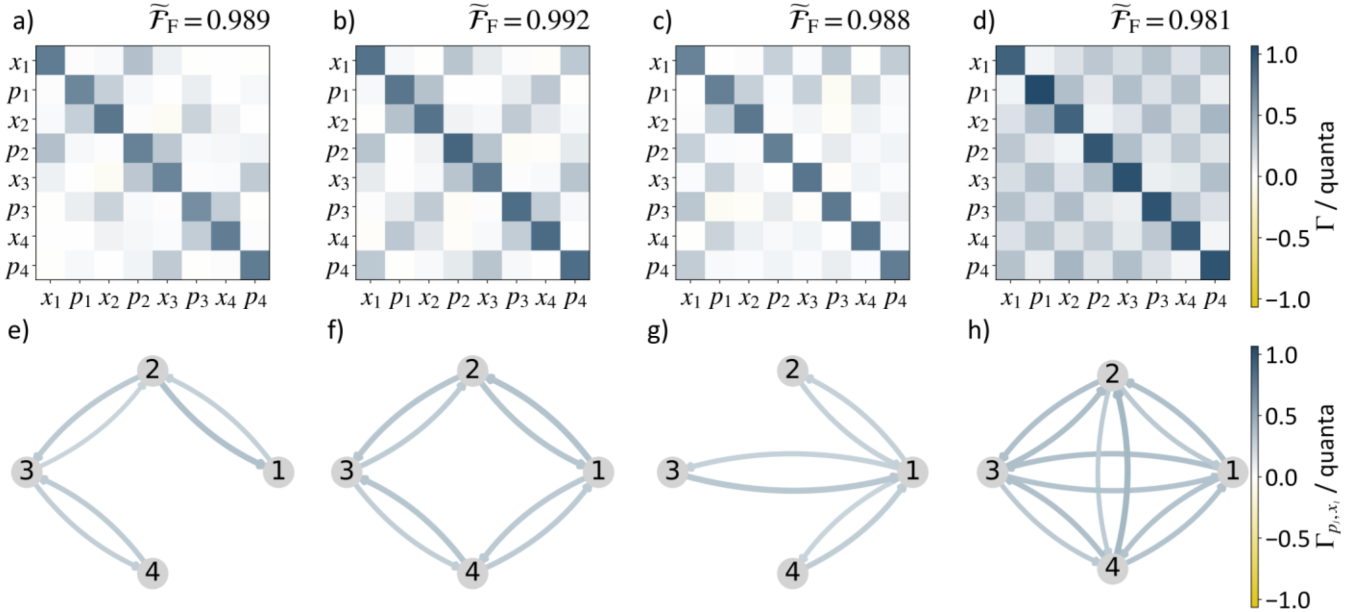


INRiM
ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Squeezing Optimization Procedure

Is there a trivial way to compare with the theory?

- Captures and **compensates unknown pump-induced phase shifts**
- Ensures **physically consistent phase alignment across modes**—key for coherent protocols (e.g. cluster states, error correction)
- The **optimal global quadrature basis** reveals maximal two-mode squeezing and **graph structure**



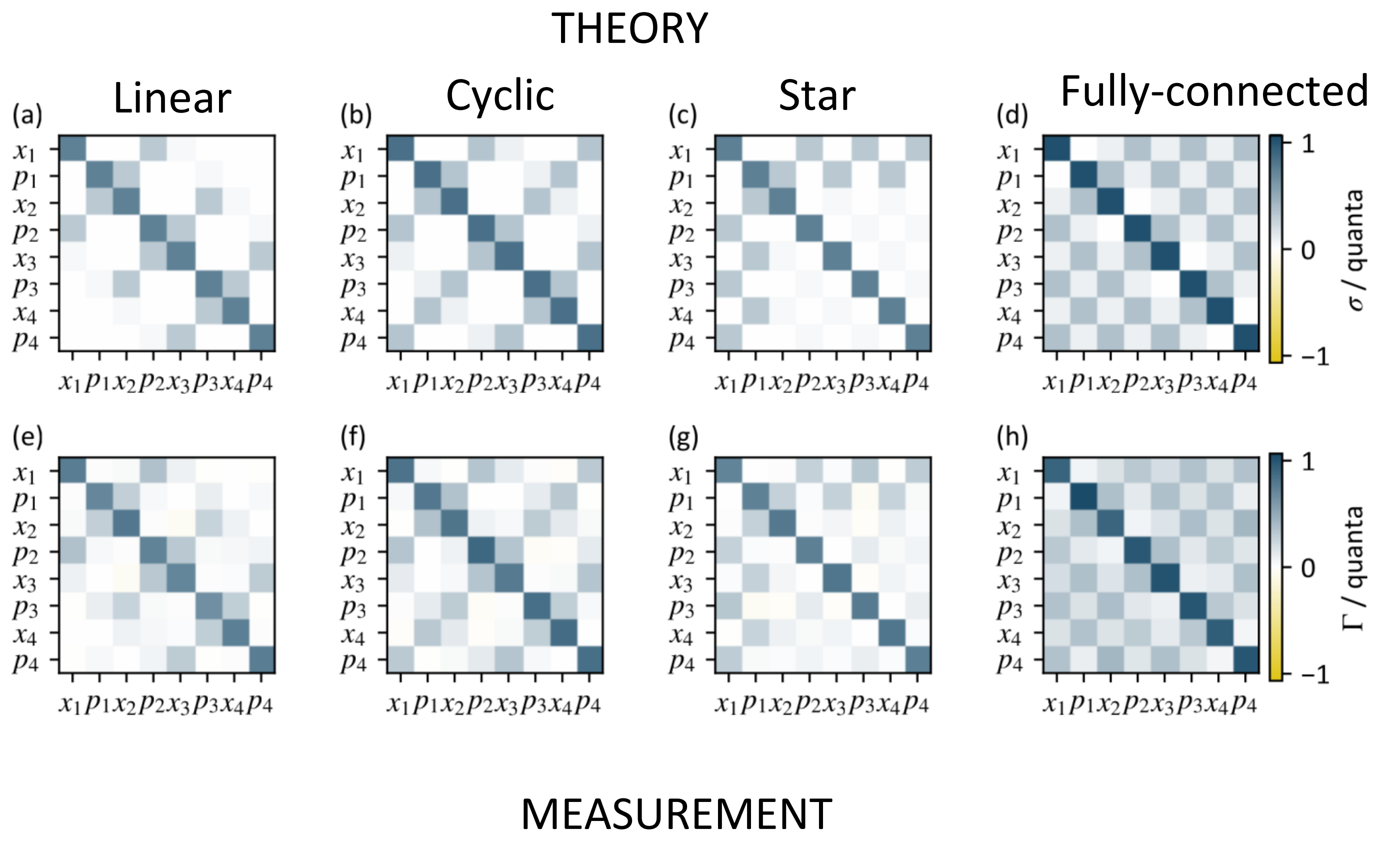
INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Comparison with Theory

- The reconstructed covariance matrix Γ is compared to its **theoretical model** σ

- The **Frobenius distance** quantifies the similarity between the two

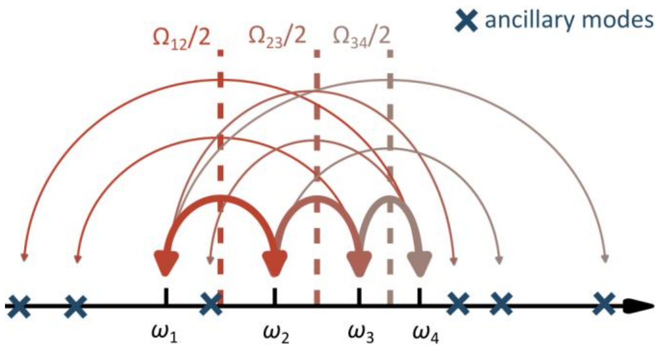
$$\widetilde{\mathscr{F}}_{\mathrm{F}}(\sigma,\Gamma) = \exp\left(-\frac{\|\sigma-\Gamma\|_{\mathrm{F}}^2}{\|\sigma\|_{\mathrm{F}}^2}\right)$$



Role of Ancillary Modes: e.g. Linear CS

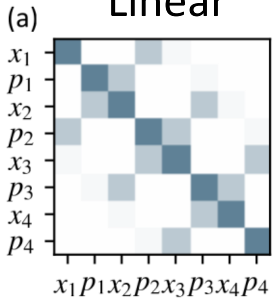
- **Principal modes**: 1−4 connected linearly via TMS links
  (1,2),(2,3),(3,4)

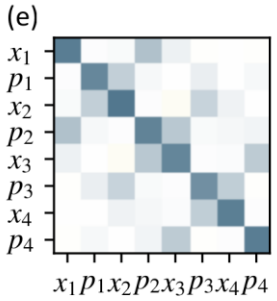
- **Ancillary modes**: 5−10, connected to the principal chain via TMS links:
  (1,5), (1,6), (2,7), (3,8), (4,9), (4,10).



THEORY

Linear





MEASUREMENT

Generalized input-output relations

$$\hat{a}_{\mathrm{out},i} = \sum_j \left(\mathbf{U}_{ij} a_i + \mathbf{V}_{ij} \hat{a}_j^\dagger \right)$$

Bogoliubov matrices

$$\mathbf{U} = \mathbb{I}_m + (\cosh|r| - 1) \cdot \mathrm{diag}(\mathbf{D}), \qquad \mathbf{V} = \sinh|r| \cdot \mathbf{A}$$

Covariance matrix within symplectic formalism

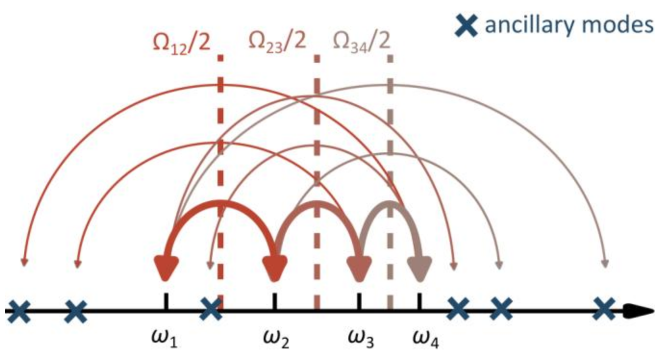
$$\boldsymbol{\sigma} = \frac{1}{2} \mathbf{S}_X \mathbf{S}_X^\top = \frac{1}{2} \begin{pmatrix} (\mathbf{U}+\mathbf{V})^2 & 0 \\ 0 & (\mathbf{U}-\mathbf{V})^2 \end{pmatrix}$$

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Role of Ancillary Modes: e.g. Linear CS

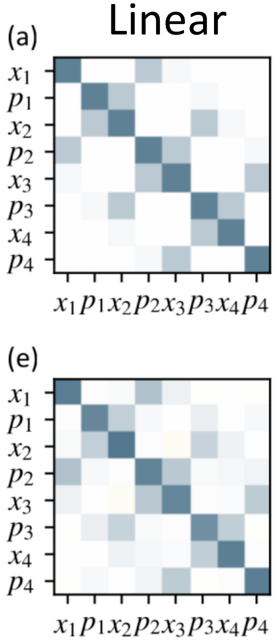
- **Principal modes**: 1−4 connected linearly via TMS links
  (1,2),(2,3),(3,4)

- **Ancillary modes**: 5−10, connected to the principal chain via TMS links:
  (1,5), (1,6), (2,7), (3,8), (4,9), (4,10).



THEORY

Linear



MEASUREMENT

Principal

Ancillary

$$\sigma_{\text{red}}^{(1:4)} = \begin{bmatrix} D & 0 & 0 & A & E & 0 & 0 & 0 \\ 0 & D & A & 0 & 0 & E & 0 & 0 \\ 0 & A & D & 0 & 0 & A & E & 0 \\ A & 0 & 0 & D & A & 0 & 0 & E \\ E & 0 & 0 & A & D & 0 & 0 & A \\ 0 & E & A & 0 & 0 & D & A & 0 \\ 0 & 0 & E & 0 & 0 & A & D & 0 \\ 0 & 0 & 0 & E & A & 0 & 0 & D \end{bmatrix}$$

…

…

$$D = -6\cosh(|r|) + 3\cosh(2|r|) + \frac{7}{2}$$
$$A = (3\cosh(|r|) - 2)\sinh(|r|),$$
$$E = \tfrac{1}{2}\sinh^2(|r|).$$

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Validation via Nullifier Measurements

- To verify multipartite entanglement and validate the cluster graph, we use **nullifier operators** based on the **adjacency matrix**.

$$\hat{\delta}_j = \hat{p}_j - \sum_{l=1}^{m} A_{jl}\,\hat{x}_l, \qquad j = 1,\dots,m$$

$$\hat{\boldsymbol{\delta}} = \mathbf{N}\cdot\hat{\boldsymbol{X}}, \qquad \text{with} \quad \mathbf{N} = (-\mathbf{A} \mid \mathbb{I}_m)$$

Nullifier covariance matrix

$$\boldsymbol{\Delta} = \mathbf{N}\boldsymbol{\sigma}\mathbf{N}^\top$$

Diagonal elements

$$\Delta_{jj} = \langle\hat{\delta}_j^2\rangle - \langle\hat{\delta}_j\rangle^2 = \mathrm{Var}(\hat{\delta}_j)$$

Validation via Nullifier Measurements

- To verify multipartite entanglement and validate the cluster graph, we use **nullifier operators** based on the **adjacency matrix**.

$$\hat{\delta}_j = \hat{p}_j - \sum_{l=1}^{m} A_{jl}\,\hat{x}_l, \qquad j = 1,\ldots,m$$

- In an **ideal** cluster state, **nullifiers vanish**; in practice, finite squeezing leads to small but nonzero variances.

$$\hat{\boldsymbol{\delta}} = \mathbf{N}\cdot\hat{\boldsymbol{X}}, \qquad \text{with} \quad \mathbf{N} = (-\mathbf{A} \mid \mathbb{I}_m)$$

Nullifier covariance matrix

$$\boldsymbol{\Delta} = \mathbf{N}\boldsymbol{\sigma}\mathbf{N}^{\top}$$

Diagonal elements

$$\Delta_{jj} = \langle\hat{\delta}_j^2\rangle - \langle\hat{\delta}_j\rangle^2 = \mathrm{Var}(\hat{\delta}_j)$$

Eg. 3-modes Cyclic cluster state

$$\mathbf{A} = \begin{pmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{pmatrix}$$

$$\hat{\delta}_1 = \hat{p}_1 - \hat{x}_2 - \hat{x}_3$$
$$\hat{\delta}_2 = \hat{p}_2 - \hat{x}_1 - \hat{x}_3$$
$$\hat{\delta}_3 = \hat{p}_3 - \hat{x}_1 - \hat{x}_2$$

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Validation via Nullifier Measurements

- To verify multipartite entanglement and validate the cluster graph, we use **nullifier operators** based on the **adjacency matrix**.

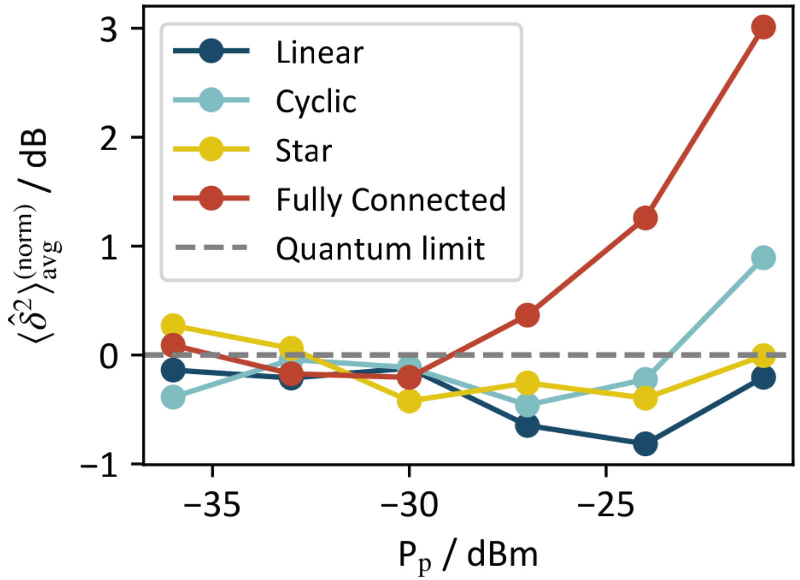
$$\hat{\delta}_j = \hat{p}_j - \sum_{l=1}^{m} A_{jl}\,\hat{x}_l, \qquad j = 1, \ldots, m$$

- In an **ideal** cluster state, **nullifiers vanish**; in practice, finite squeezing leads to small but nonzero variances.

- A state is identified as a cluster state if all **nullifier variances** are below the shot noise level (vacuum limit).

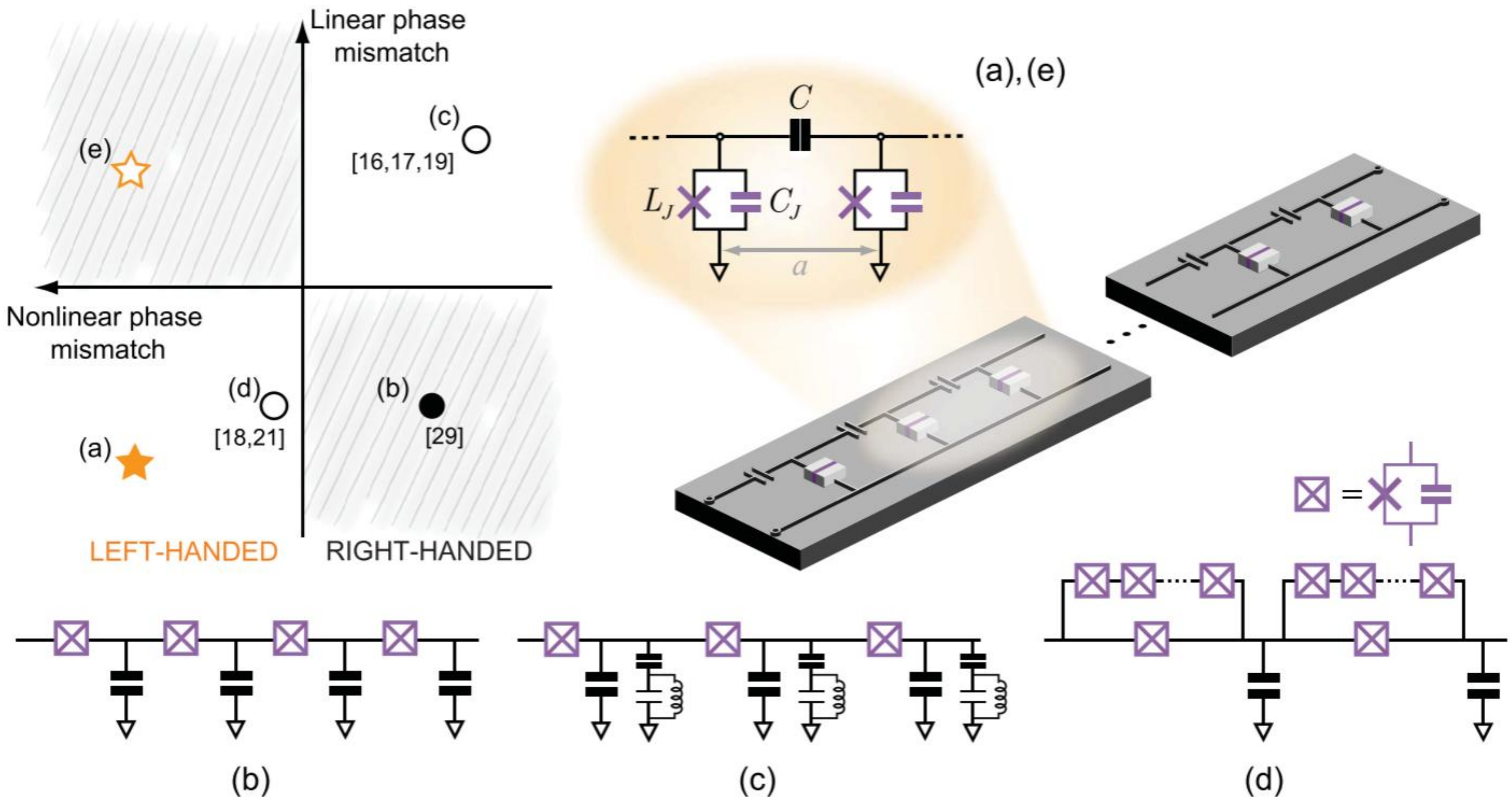
$$\langle \hat{\delta}_j^2 \rangle = \langle \hat{p}_j^2 \rangle + \sum_l A_{jl}^2 \langle \hat{x}_l^2 \rangle = \frac{1}{2}\left(1 + \sum_l A_{jl}^2\right)$$

$$\langle \hat{\delta}^2 \rangle_{\text{avg}}^{(\text{norm})} = \frac{1}{m} \sum_{j=1}^{m} \frac{2\Delta_{jj}}{1 + \sum_l A_{jl}^2}$$



INRiM
ISTITUTO NAZIONALE
DI RICERCA METROLOGICA

Squeezing-Gain trade-off



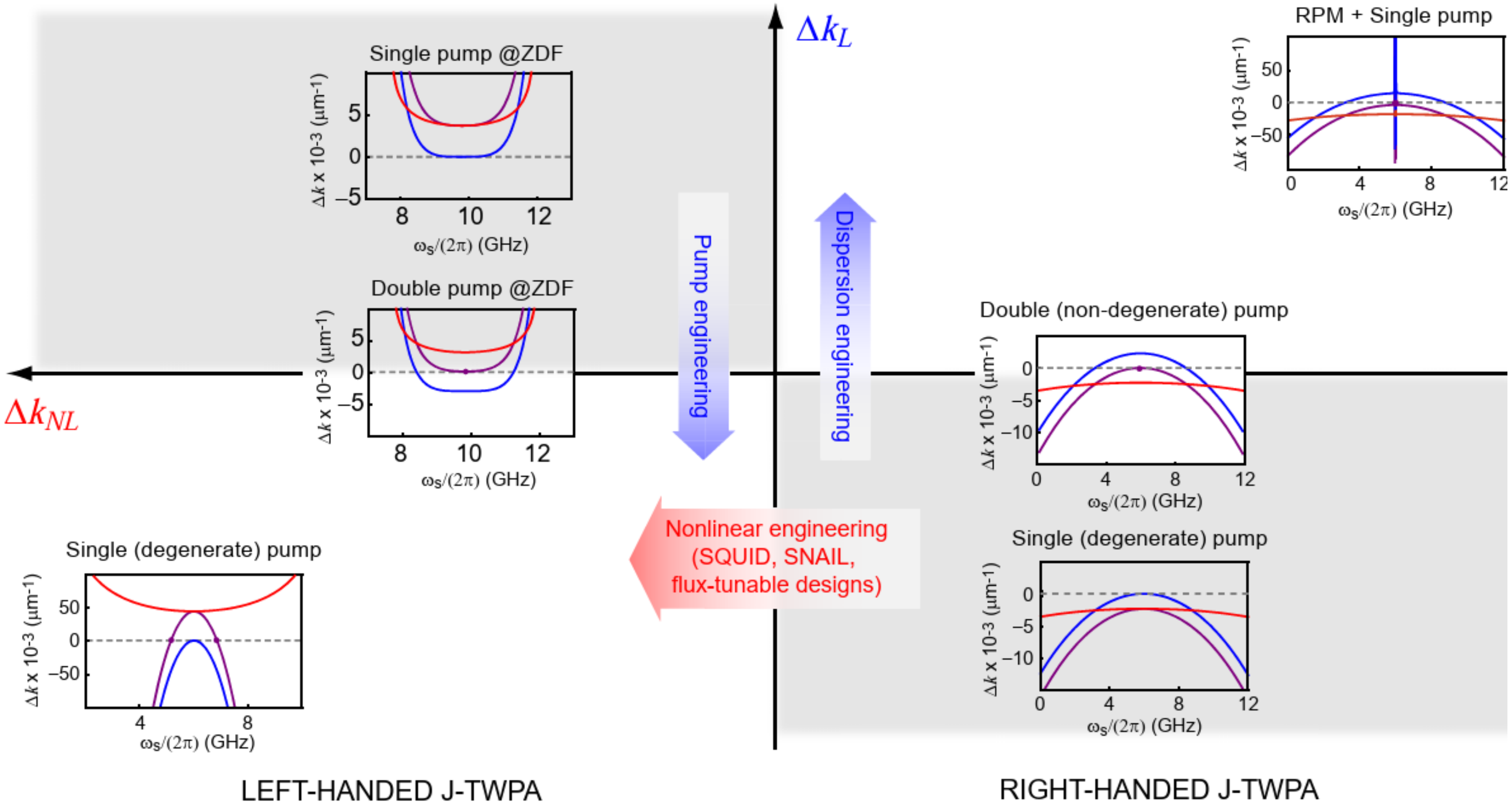
Kow, C., Podolskiy, V., & Kamal, A. (2024). Self phase-matched broadband amplification with a ***left-handed Josephson transmission line****. http://arxiv.org/abs/2201.04660*

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Squeezing-Gain trade-off

Recall on the squeezing parameter

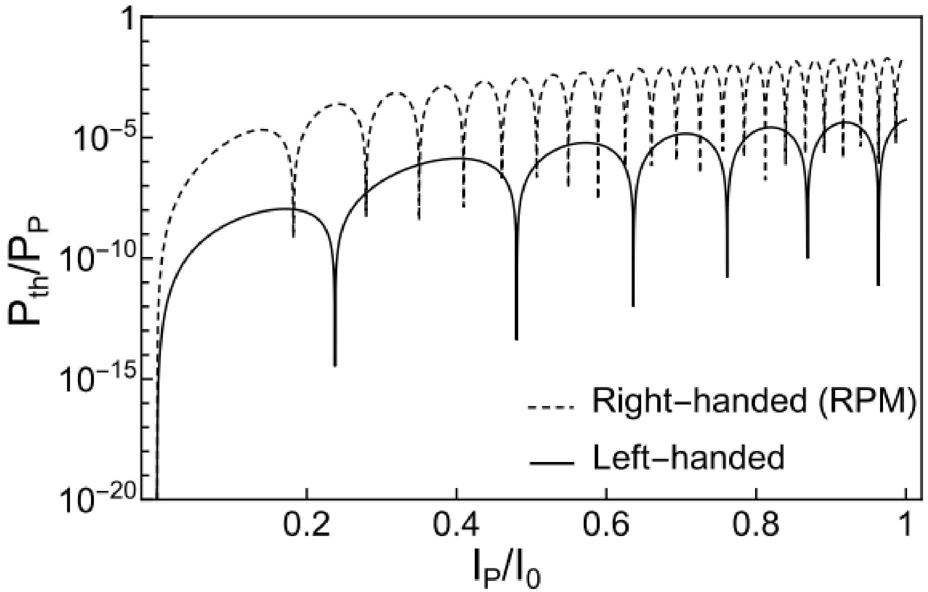
$$r_{jl}^{(k)} = g_{jl}^{(k)} \alpha_k e^{-i\phi_k}$$



*Kow, C., Podolskiy, V., & Kamal, A. (2024). Self phase-matched broadband amplification with a **left-handed Josephson transmission line**. http://arxiv.org/abs/2201.04660*

Squeezing-Gain trade-off

Pump harmonics (and relative sidebands) dilute entanglement over multiple modes and increase complexity



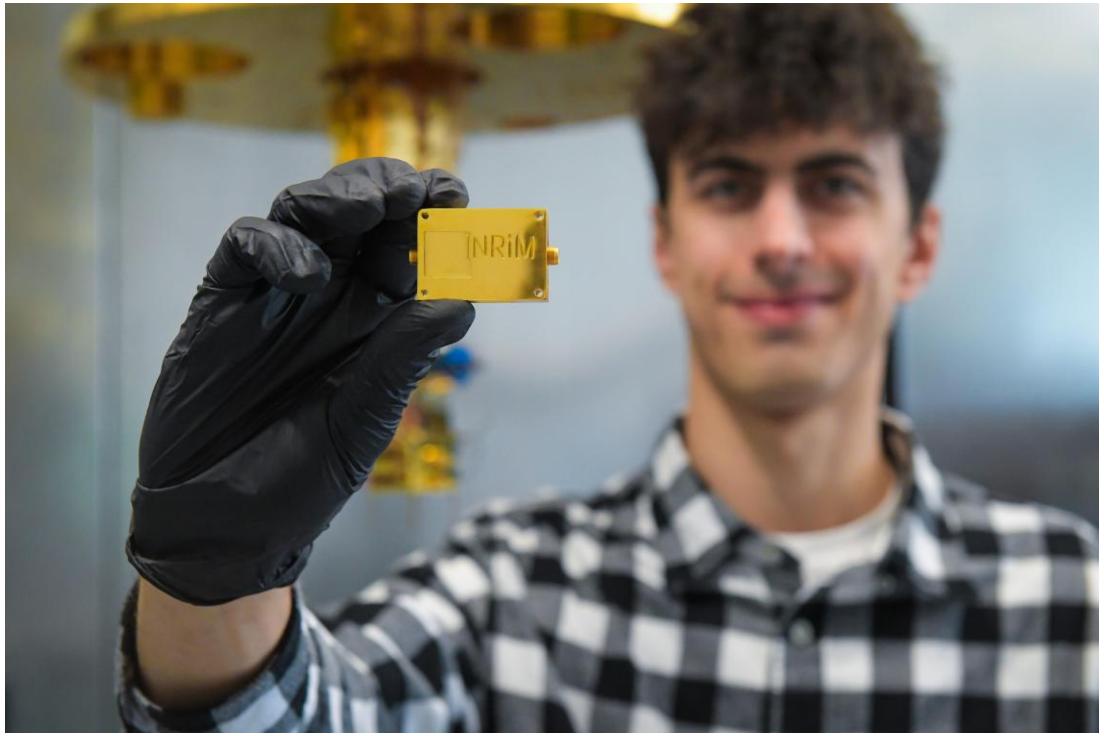
Kow, C., Podolskiy, V., & Kamal, A. (2024). Self phase-matched broadband amplification with a ***left-handed Josephson transmission line****. http://arxiv.org/abs/2201.04660*

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Conclusions and Perspectives

- We demonstrate a reconfigurable, scalable platform for generating continuous-variable cluster states using programmable pump engineering in a superconducting **Josephson Travelling Wave Parametric Amplifier**.
- Our method **leverages the frequency domain** to create large entangled graphs with **minimal hardware overhead**.
- Graph structure and entanglement are **validated via nullifier** measurements and **covariance-based reconstruction**.
- This approach bridges optical CV techniques and microwave superconducting hardware, enabling hardware-efficient measurement-based quantum computation.
- Future integration with **LH-TWPAs and feedback** could enable quantum algorithm execution.

INRiM
ISTITUTO NAZIONALE
DI RICERCA METROLOGICA



Thanks for your attention!

INRiM
ISTITUTO NAZIONALE
DI RICERCA METROLOGICA

Acknowledgments

MetSuperQ

EUROPEAN PARTNERSHIP
Co-funded by the European Union

METROLOGY PARTNERSHIP
EURAMET

IMiSS
Microwave Squeezing with Superconducting (meta) materials

HORIZON EUROPE

Funded by the European Union

CalQuStates

Finanziato dall'Unione europea
NextGenerationEU

MUR

Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

INRiM
ISTITUTO NAZIONALE DI RICERCA METROLOGICA