DTU Physics
Department of Physics

DTU

Investigation and exploitation of squeezed states

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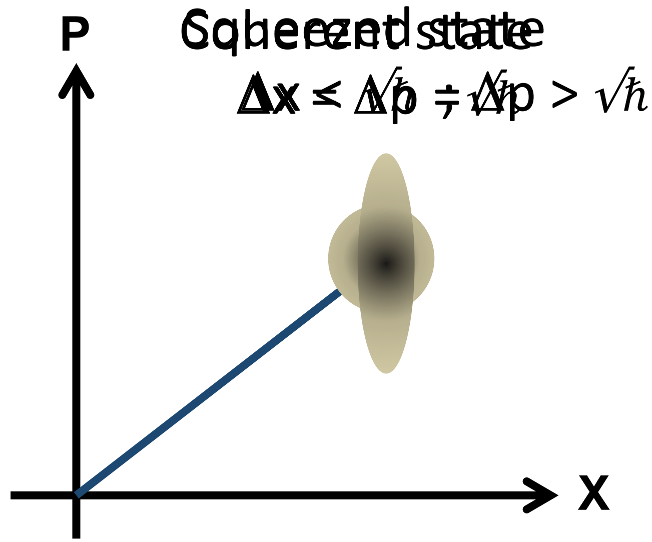
Recent collaborations: C. Marquardt, G. Leuchs, C. Muller, M. Paris, R. Filip, V. Usenko, M. Jezek

Squeezed states

Quadrature eigenstate

$$\left| x \right\rangle$$



Photon number squeezing
Polarization squeezing (spin squeezing)
OAM squeezing

Impacting physics

- Quantum sensing
- Fundamental tests
- Quantum information processing

One talk two topics

- Investigating squeezed states in its polarization manifolds
- Squeezed vacuum for ab-initio phase estimation

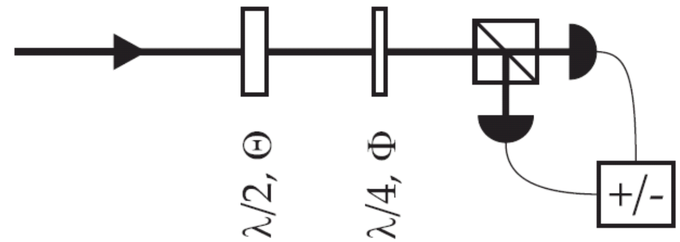
Stokes parameters

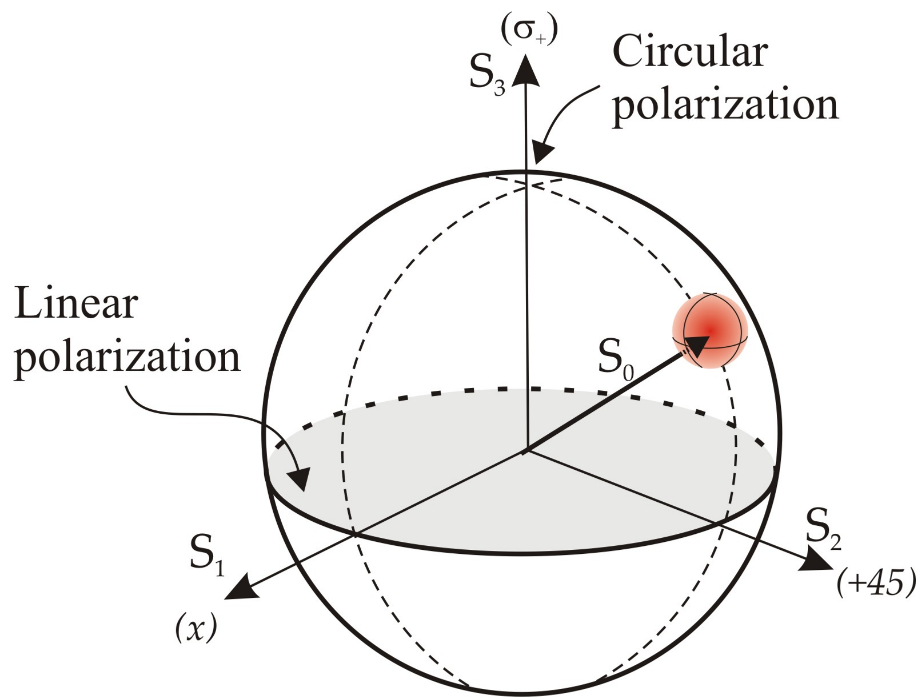
$$\hat{J}_0 = \frac{1}{2}(\hat{a}_H^\dagger \hat{a}_H + \hat{a}_V^\dagger \hat{a}_V)$$

$$\hat{J}_1 = \frac{1}{2}(\hat{a}_H^\dagger \hat{a}_V + \hat{a}_V^\dagger \hat{a}_H)$$

$$\hat{J}_2 = \frac{i}{2}(\hat{a}_H \hat{a}_V^\dagger - \hat{a}_H^\dagger \hat{a}_V)$$

$$\hat{J}_3 = \frac{1}{2}(\hat{a}_H^\dagger \hat{a}_H - \hat{a}_V^\dagger \hat{a}_V)$$





Polarization Squeezing:

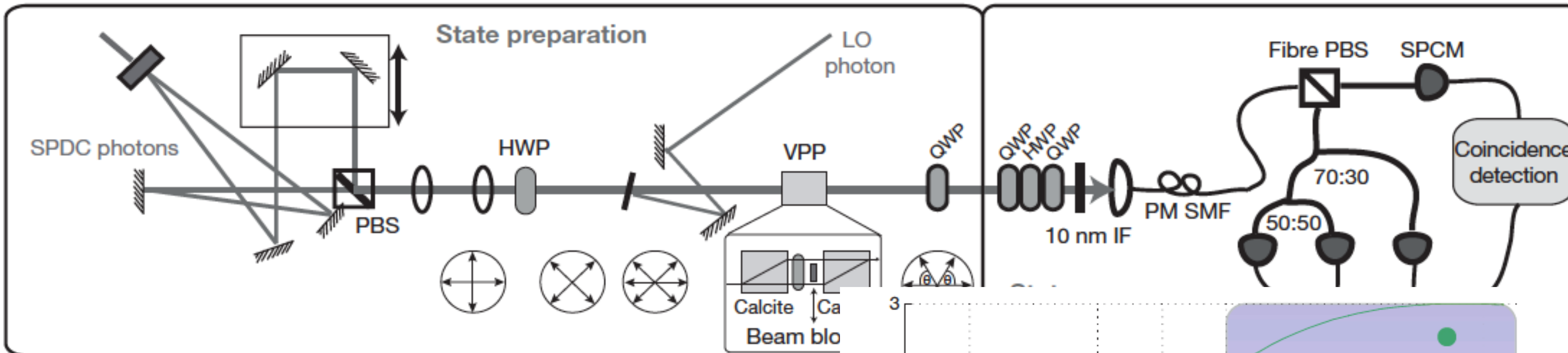
$$\frac{\Delta^2(\hat{J}_{min})}{\langle \hat{J}_0 \rangle} < 1$$

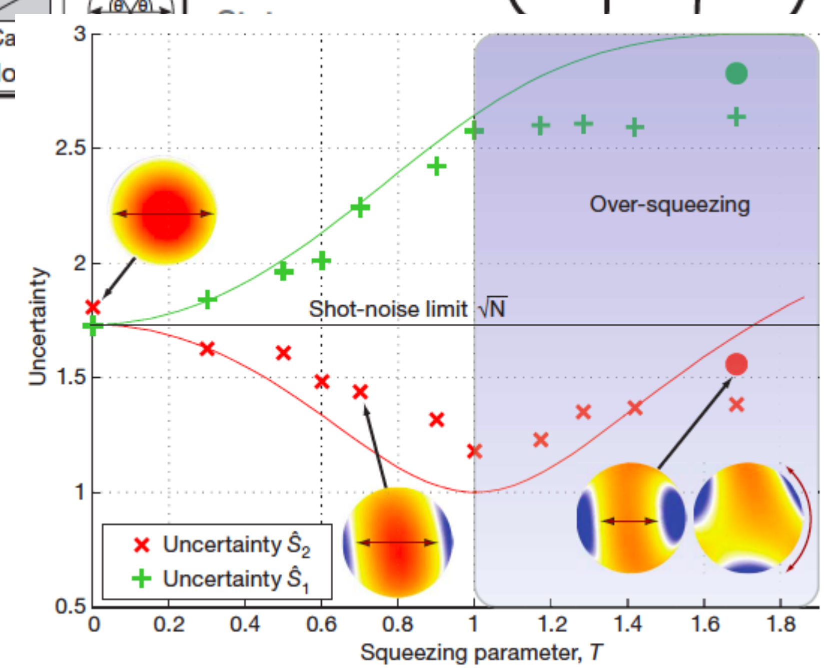
Two different regimes of polarization squezing

Regime I

- Squeezing of states with a definite number of photons.

Example: three-photon state



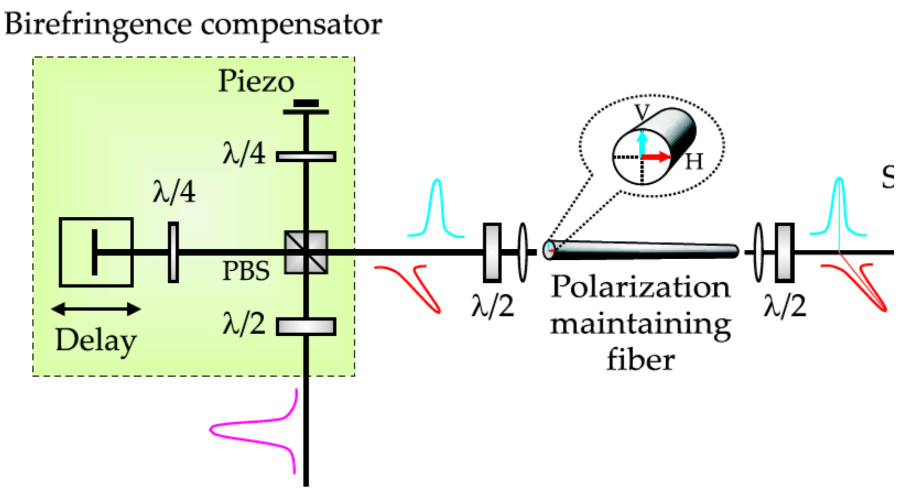


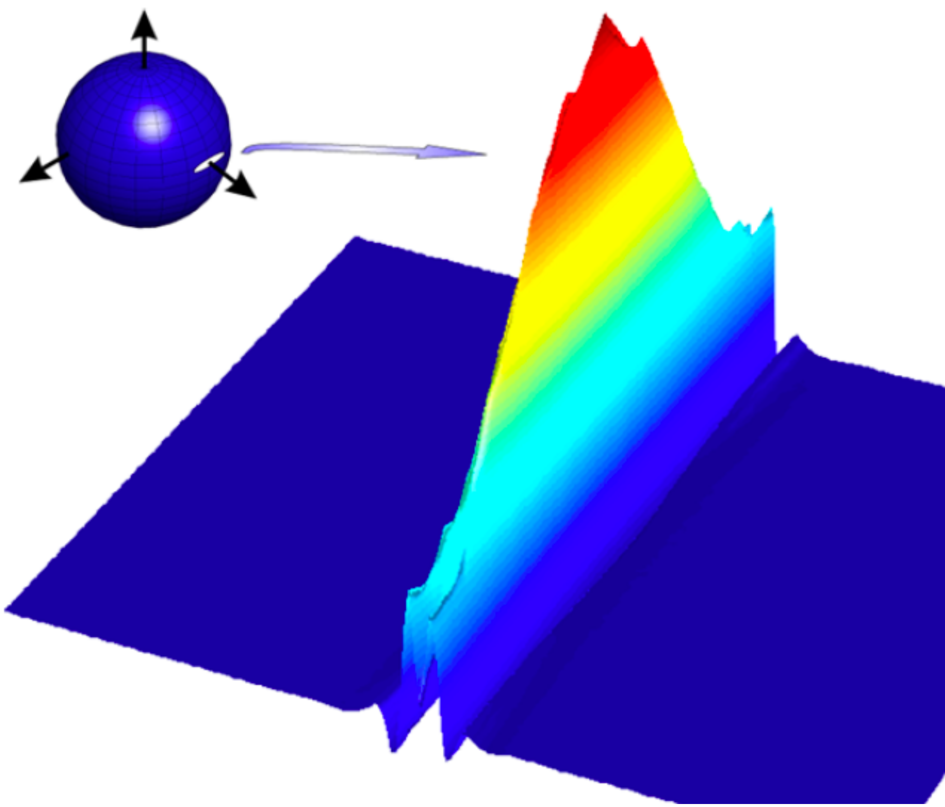
Shalm et al Nature 457, 67 (2009)

Regime II:

Squeezing of states with an indefinite number of photons.

Example: displaced squeezed vacuum state





C. Marquardt et al, PRL 99, 220401 (2007)

How are these regimes connected?

Photons are like spins

$$\left|n_H, n_V\right\rangle \rightarrow \left|j, m\right\rangle$$ (common eigenstate of J^2 and J_3)

$$j = \left(n_H + n_V\right)/2, \quad m = \left(n_H - n_V\right)/2$$

Example: two-photon state $j = 1, \quad m = -1, 0, 1$

$$\left\{\left|2,0\right\rangle, \left|1,1\right\rangle, \left|0,2\right\rangle\right\}$$

$$\left|\psi_1\right\rangle = a\left|2,0\right\rangle + b\left|1,1\right\rangle + c\left|0,2\right\rangle$$

Atomic coherent and squeezed states in the 2-photon manifold

Another example: 3-photon state

$$j = 3/2, \quad m = -3/2, -1/2, 1/2, 3/2$$

$$\left\{ \left|3,0\right\rangle, \left|2,1\right\rangle, \left|1,2\right\rangle, \left|0,3\right\rangle \right\}$$

$$\left|\psi_{3/2}\right\rangle = a\left|0,3\right\rangle + b\left|1,2\right\rangle + c\left|2,1\right\rangle + d\left|3,0\right\rangle$$

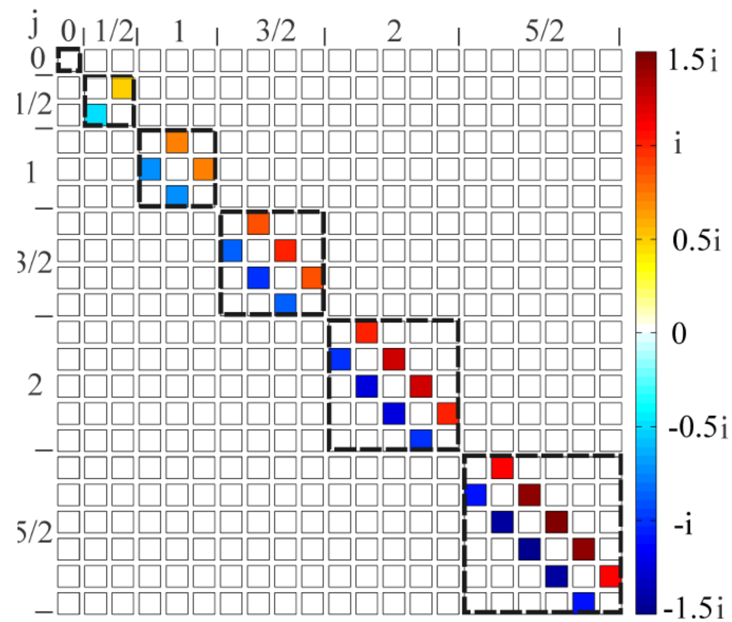
Atomic coherent and squeezed states in the 3-photon manifold

and so on for j=2,5/2,3…

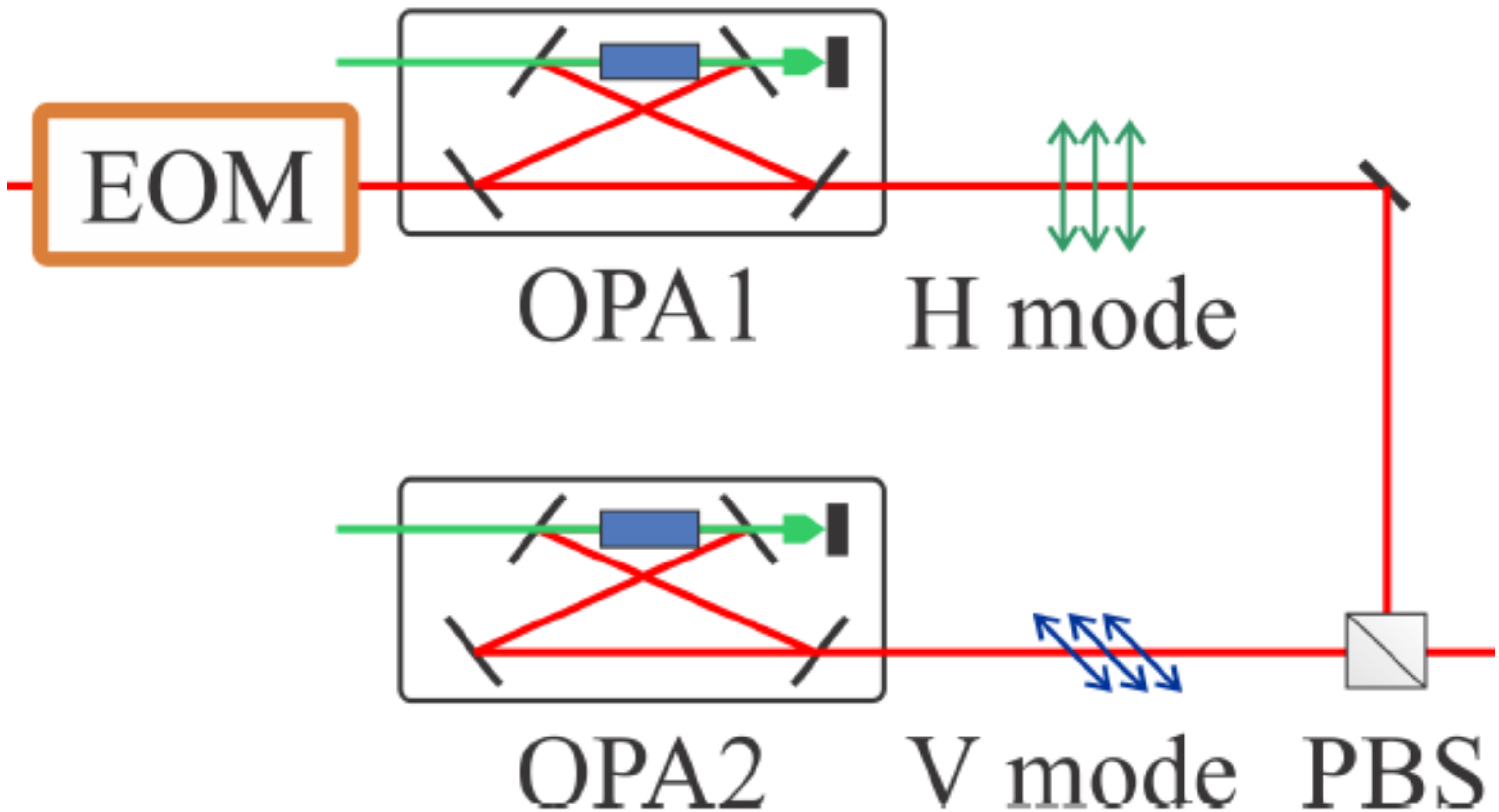
For states with indefinite photon numbers

$$\hat{\rho}_{pol} = \bigoplus_{j=0}^{\infty} \hat{\rho}^{(j)} = \sum_{j=0}^{\infty} \sum_{m,m'=-j}^{j} \rho^{(j)}_{m\,m'} |j, m\rangle\langle j, m'|$$

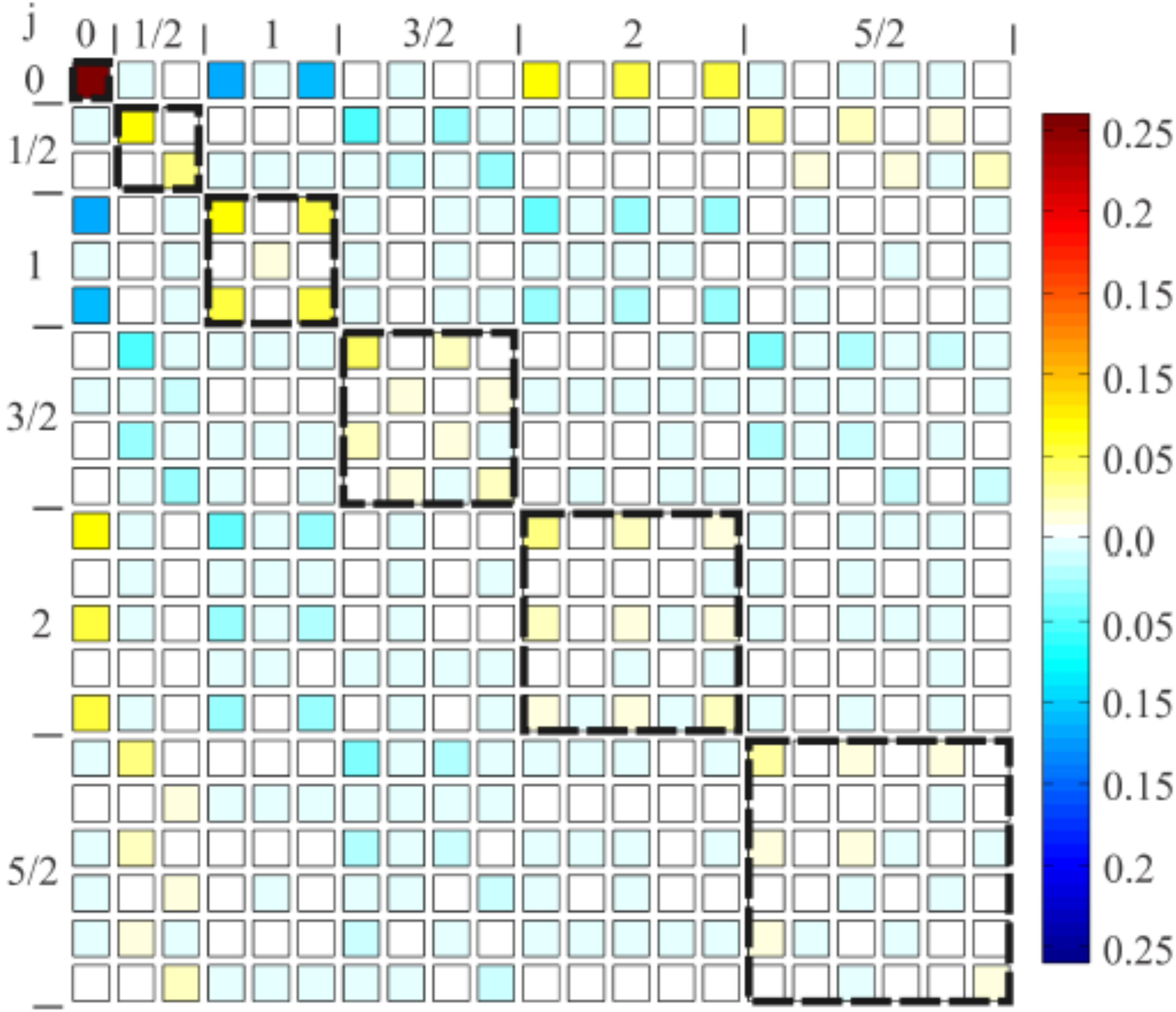
Moments of Stokes parameters independent on the coherences between the different manifolds.

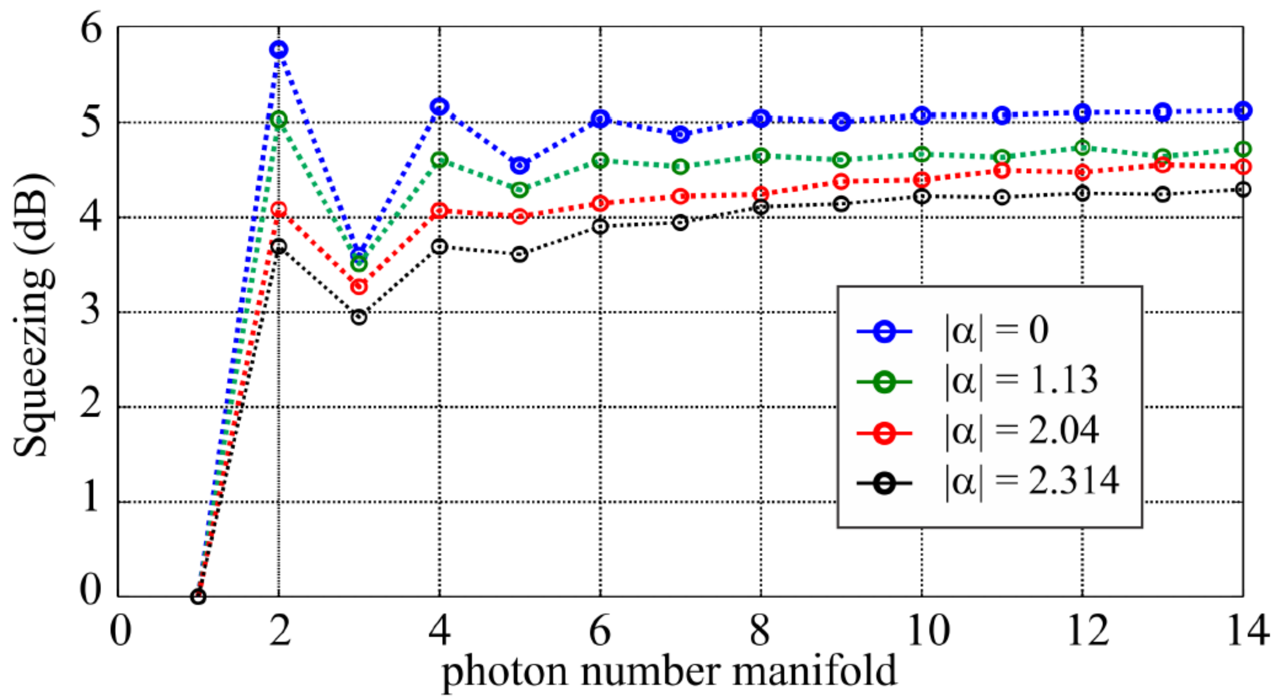


Preparation



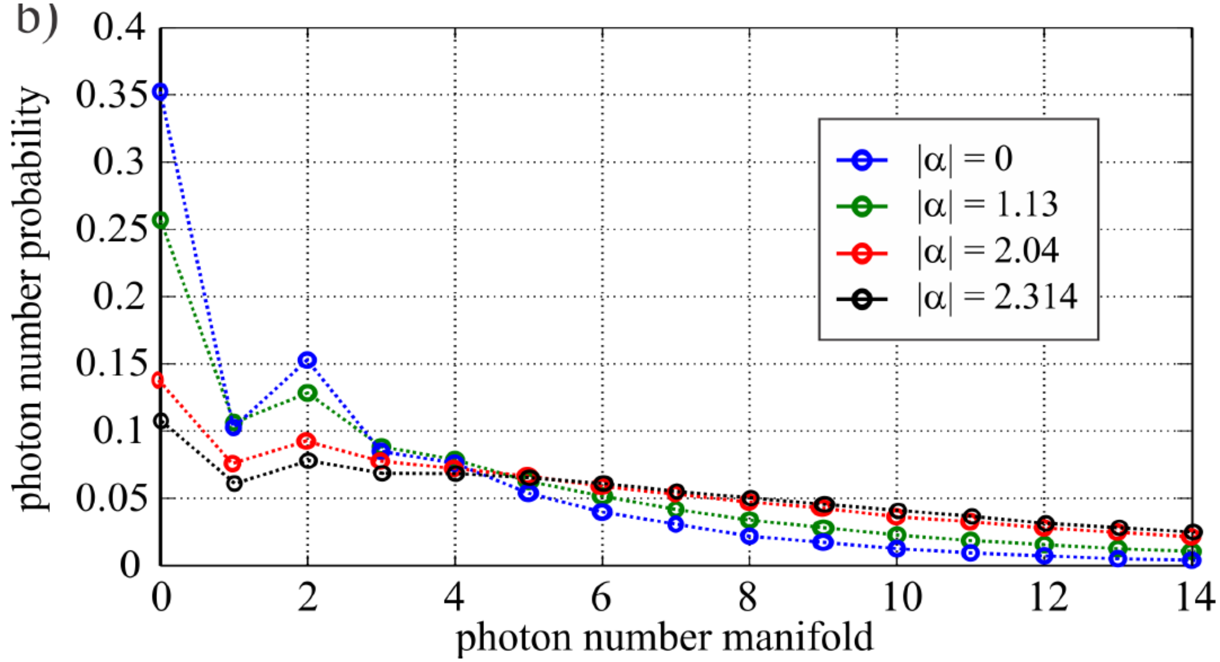
Density matrix





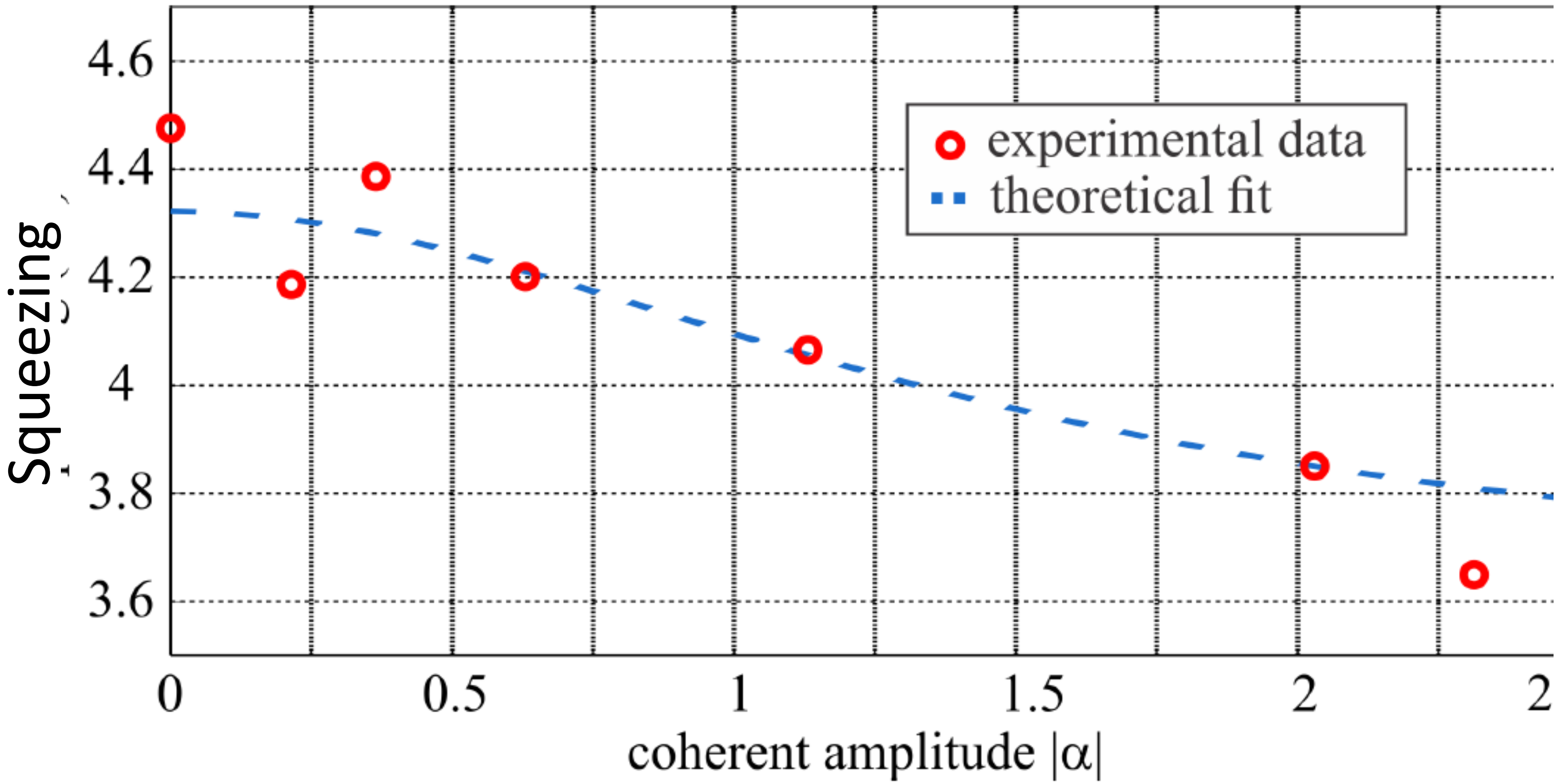
Squeezing (dB)
photon number manifold
|α| = 0
|α| = 1.13
|α| = 2.04
|α| = 2.314

b)

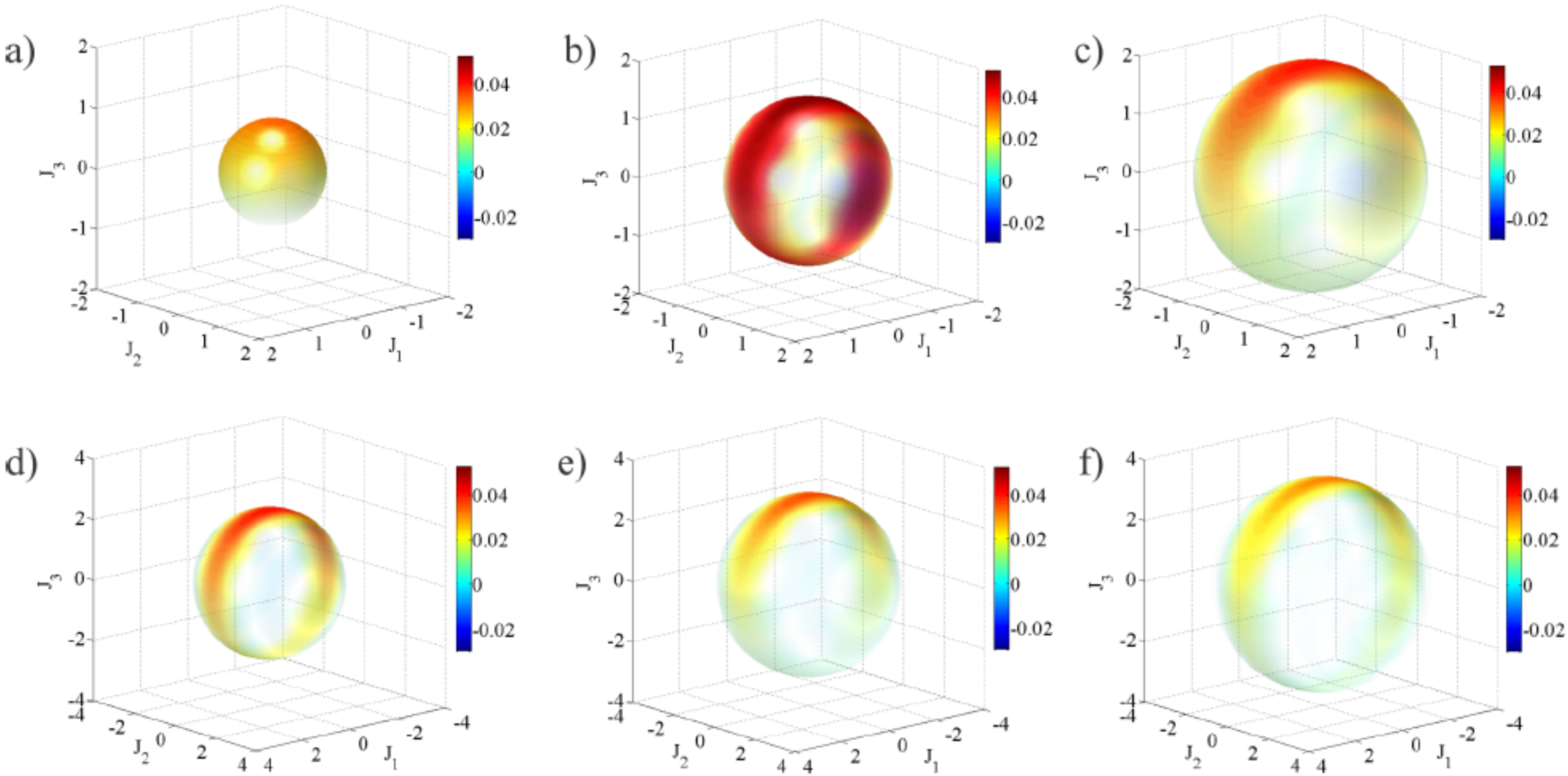


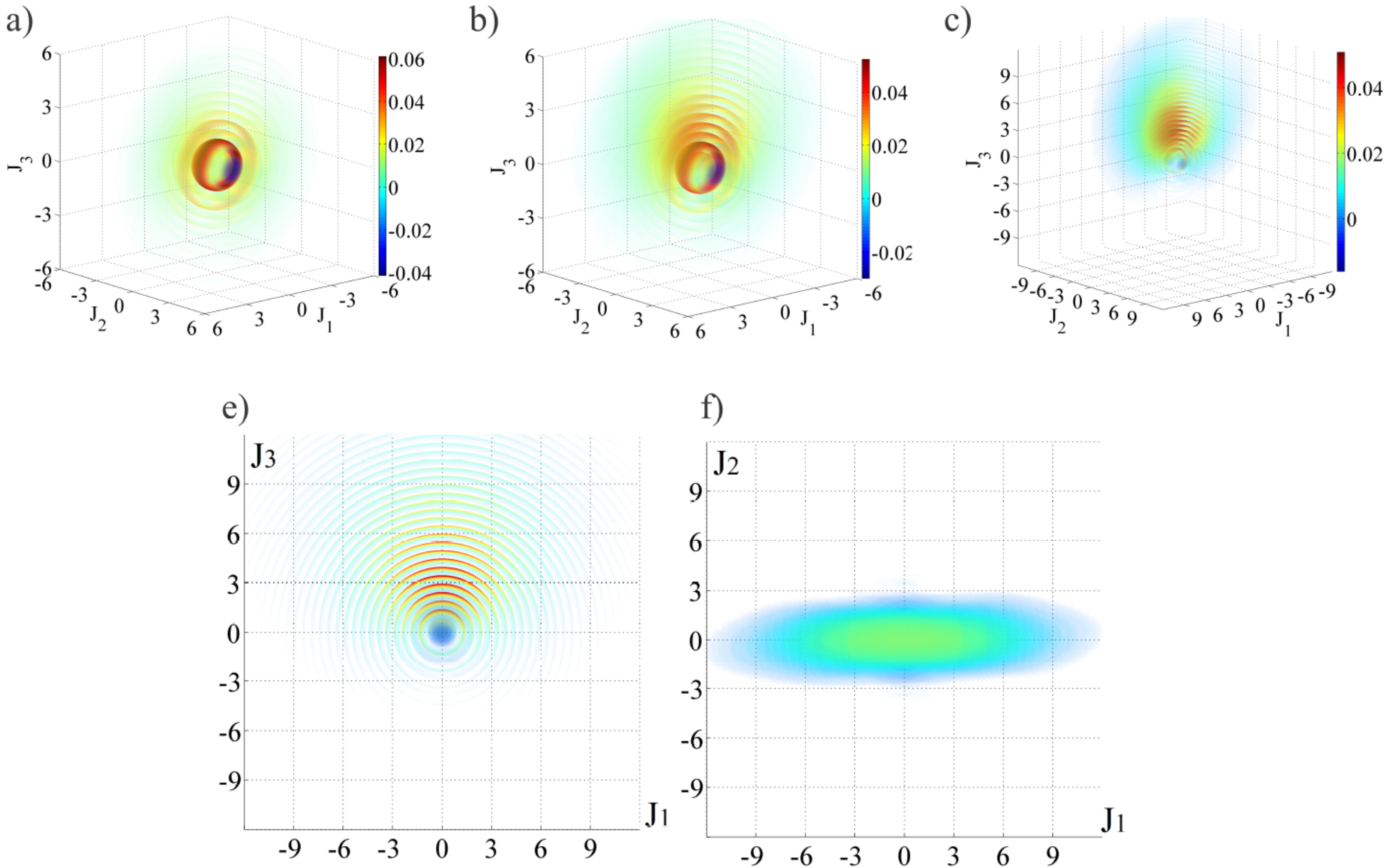
photon number probability
photon number manifold
|α| = 0
|α| = 1.13
|α| = 2.04
|α| = 2.314

Polarization of the entire state



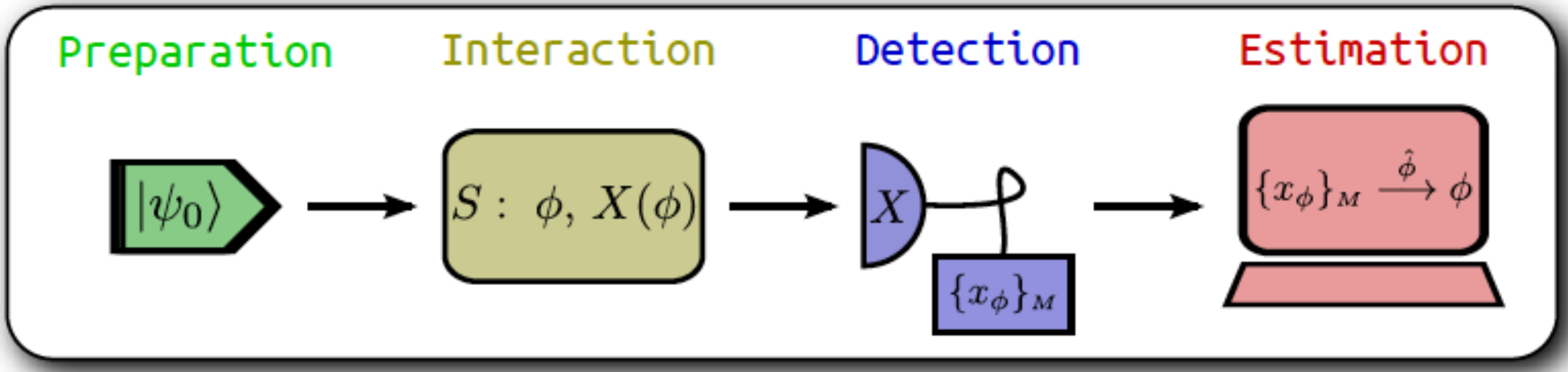
Photon number manifolds

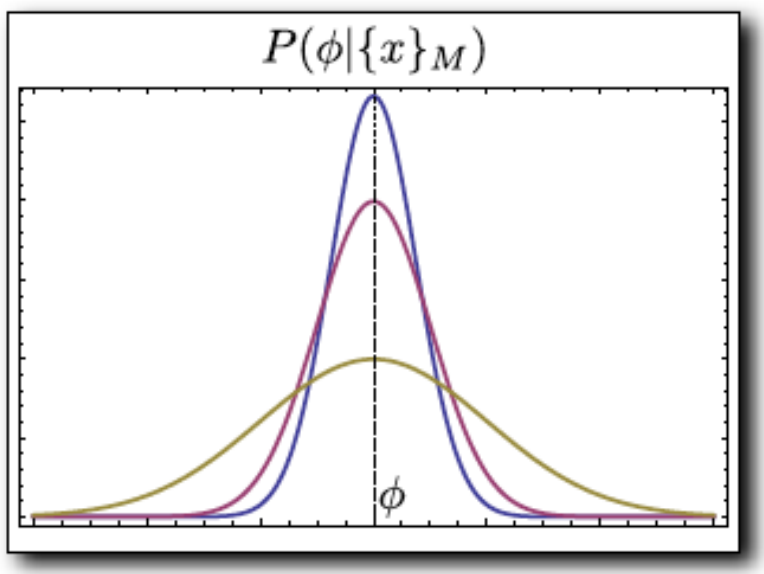



a)
b)
c)
e)
f)
J1
J2
J3
0.06
0.04
0.02
0
-0.02
-0.04

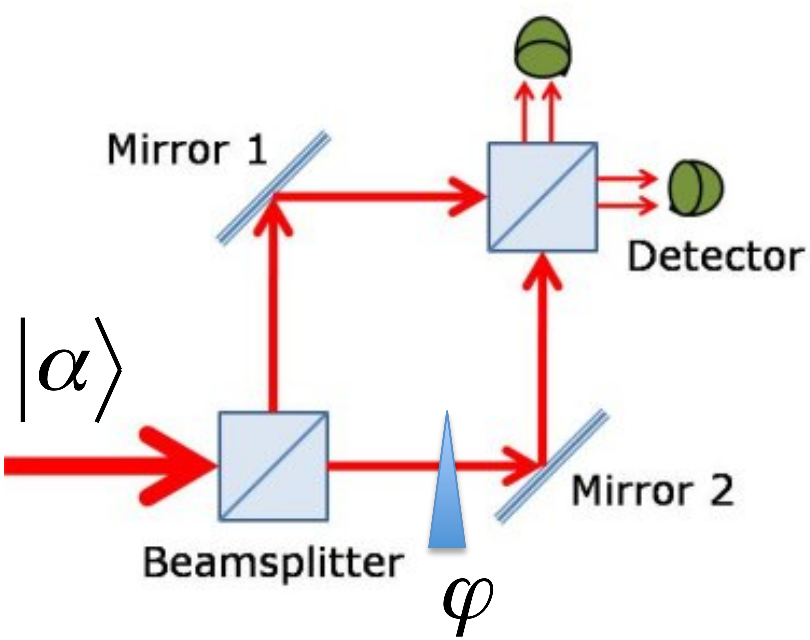
Ab initio phase estimation

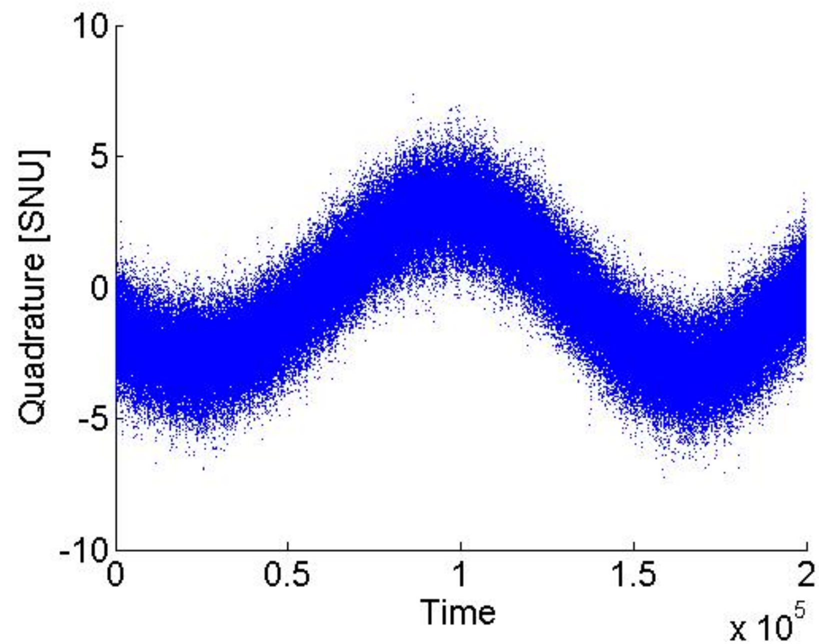
Quantum estimation theory





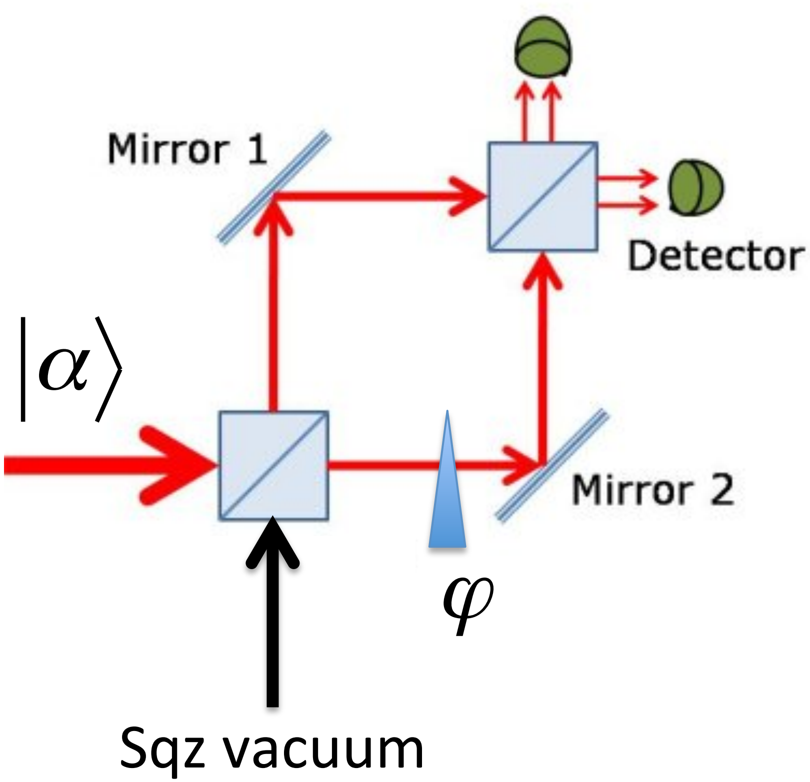
Example – the MZ interferometer





Sensitivity: $V(\varphi) = \frac{1}{NM}$

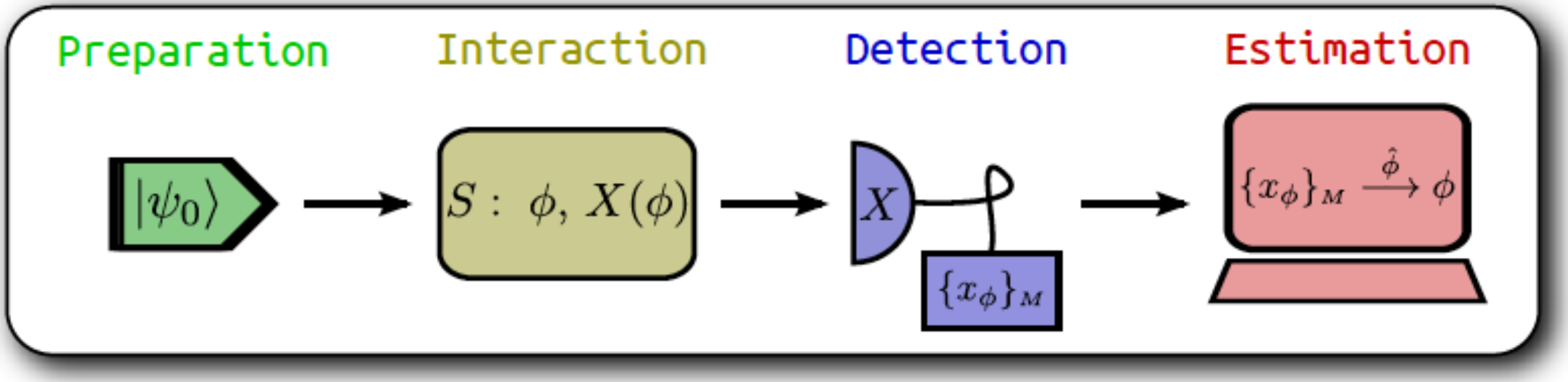
Using squeezed states

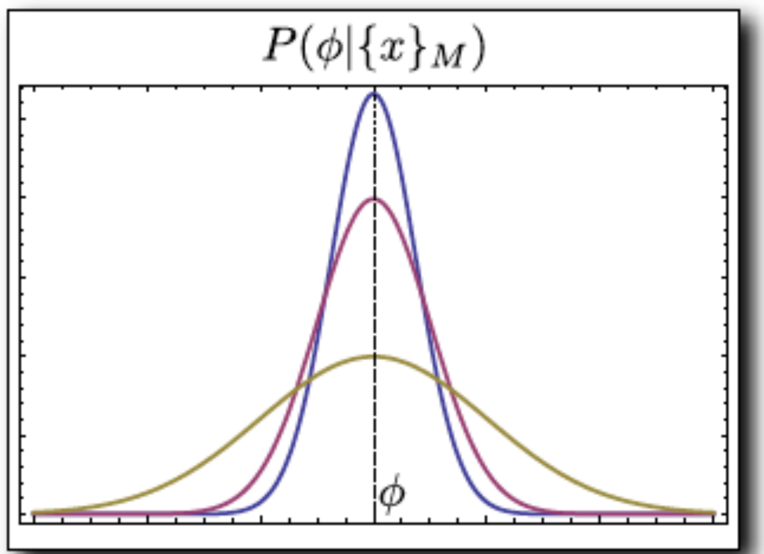


$$V(\varphi) = \frac{1}{NM} V_{sqz}$$

if the coherent state is very bright

Demonstrated at GEO600 and LIGO


Preparation
Interaction
Detection
Estimation
$|\psi_0\rangle$
$S:\ \phi,\ X(\phi)$
X
$\{x_\phi\}_M$
$\{x_\phi\}_M \xrightarrow{\hat{\phi}} \phi$


$P(\phi|\{x\}_M)$
ϕ

The Cramer-Rao bounds

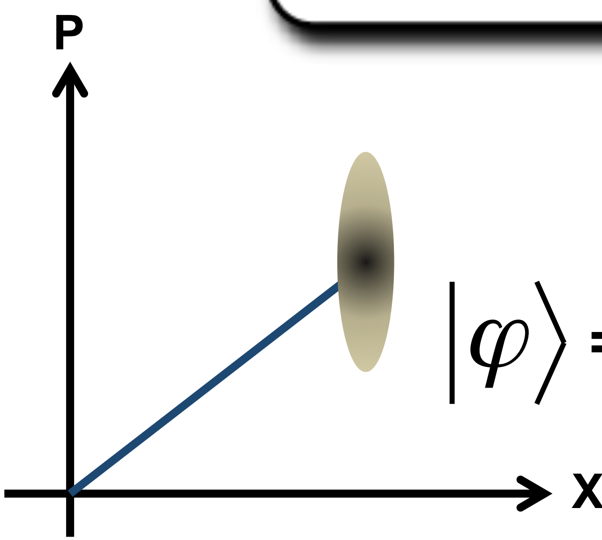
S.L. Braunstein and C.M. Caves, *Phys. Rev. Lett.* **72**, 3439-3443 (1994)

Cramér-Rao

Quantum Cramér-Rao

$$\mathrm{Var}[\hat{\phi}] \geq \frac{1}{M \cdot F(\phi)} \geq \frac{1}{M \cdot H}$$

$$H = \max_{\{\hat{\Pi}\}} [F(\phi)]$$

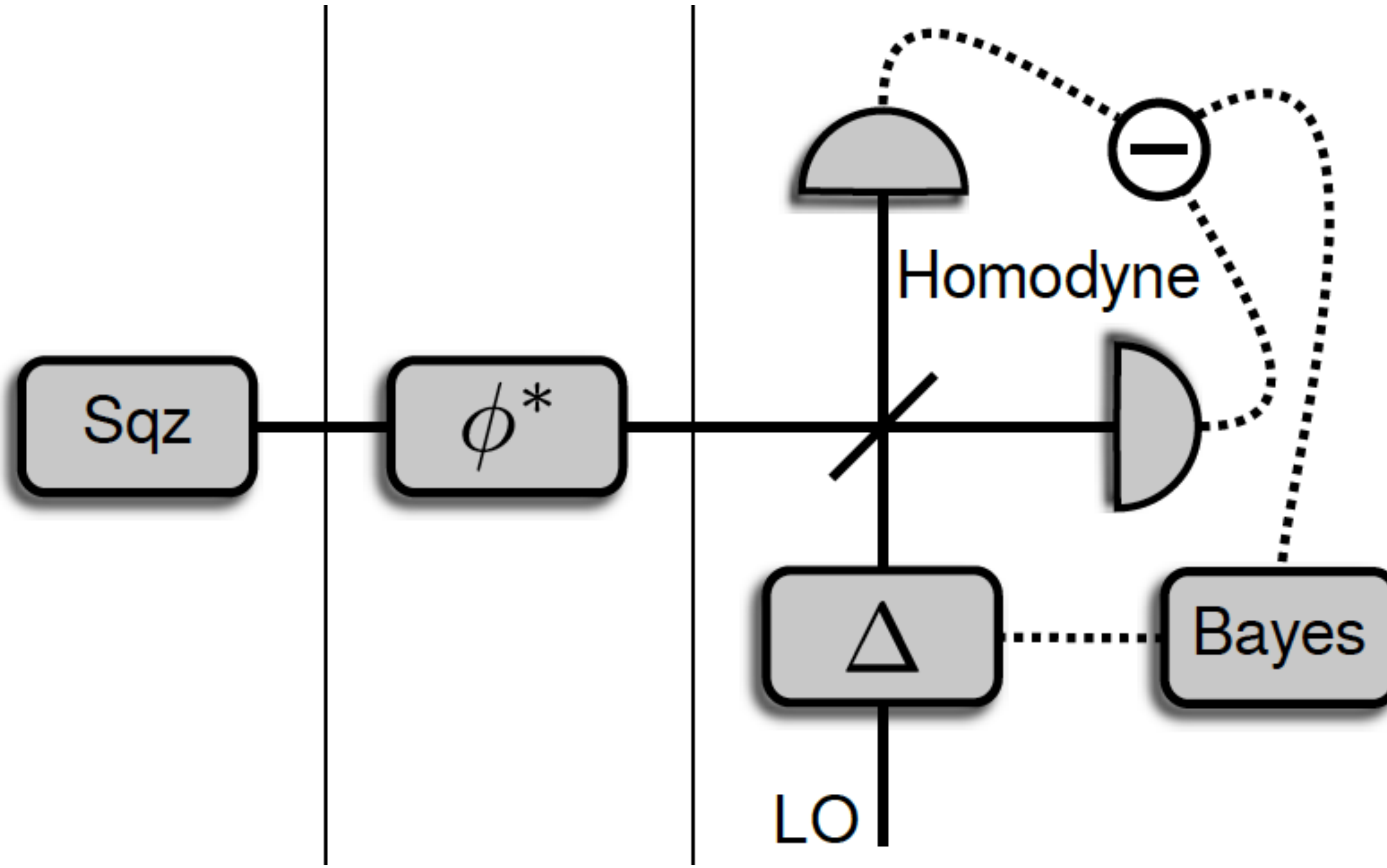


$$|\varphi\rangle = D(x,p)S(r)|0\rangle$$

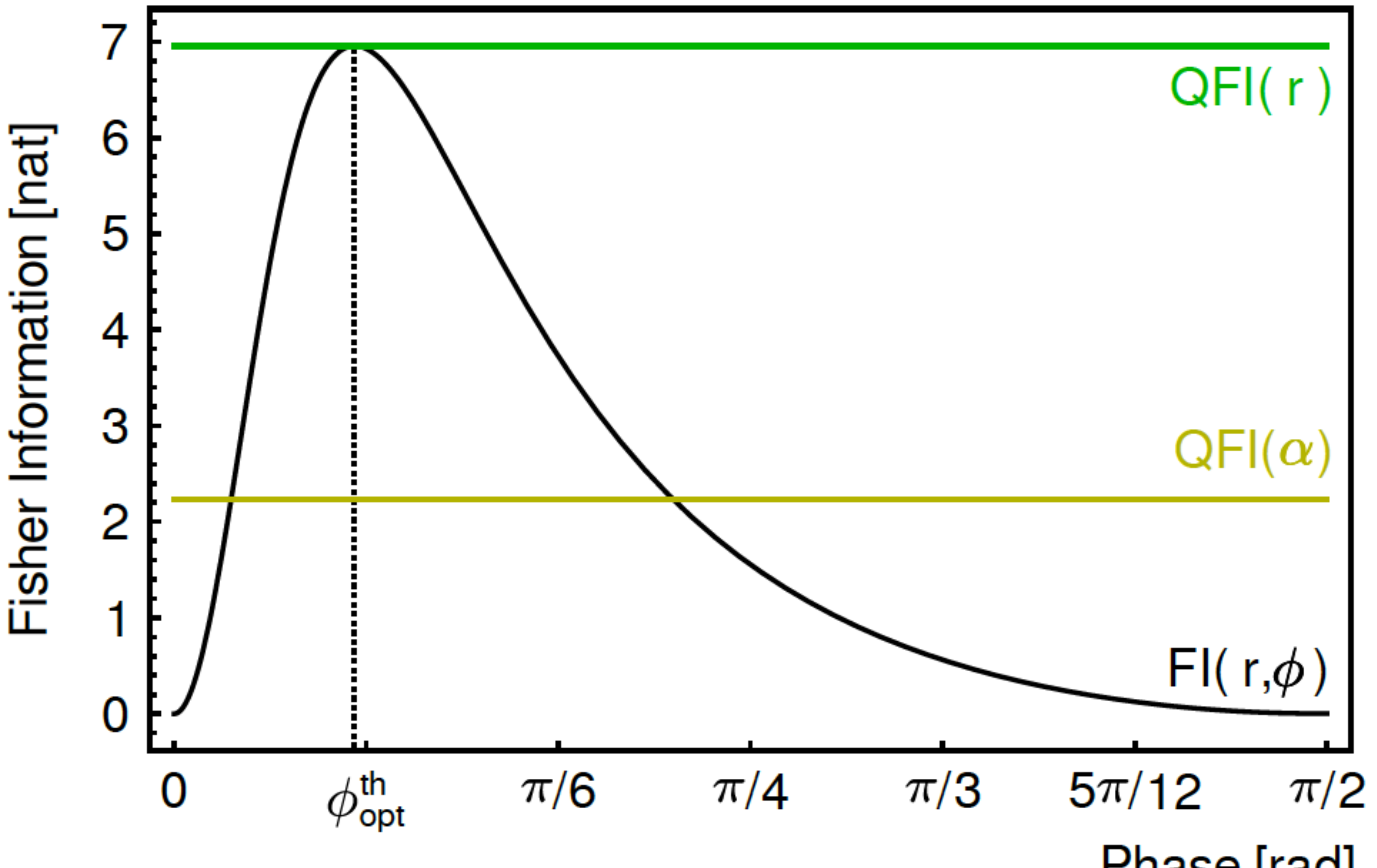
Optimized for pure squeezed vacuum states

-> All energy should be put into squeezing

Basic setup



Only optimal for a specific phase

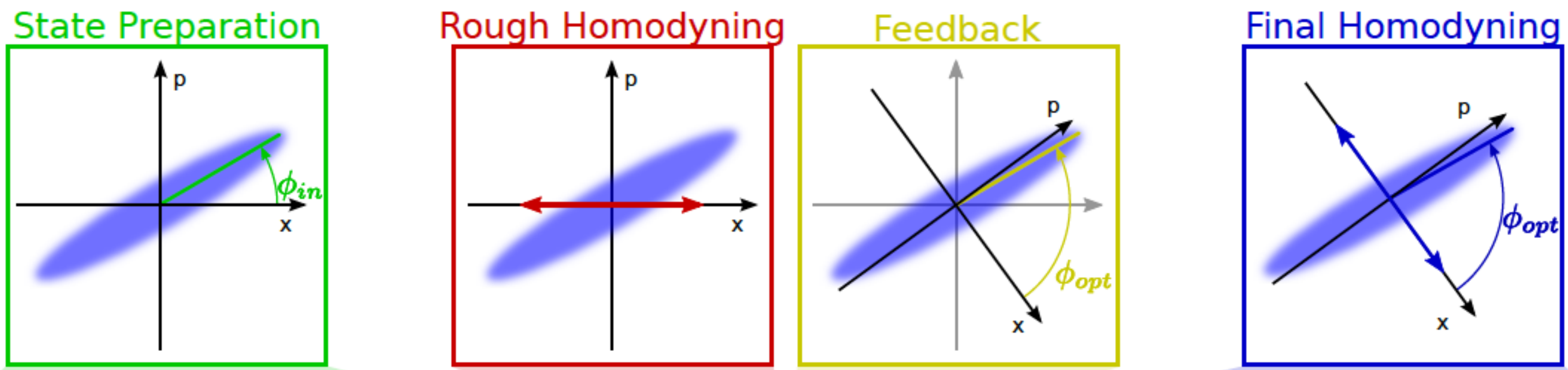


Baysian homodyne to estimate phase

$$P(x,\varphi) \rightarrow P\left(\varphi,\{x\}\right)$$

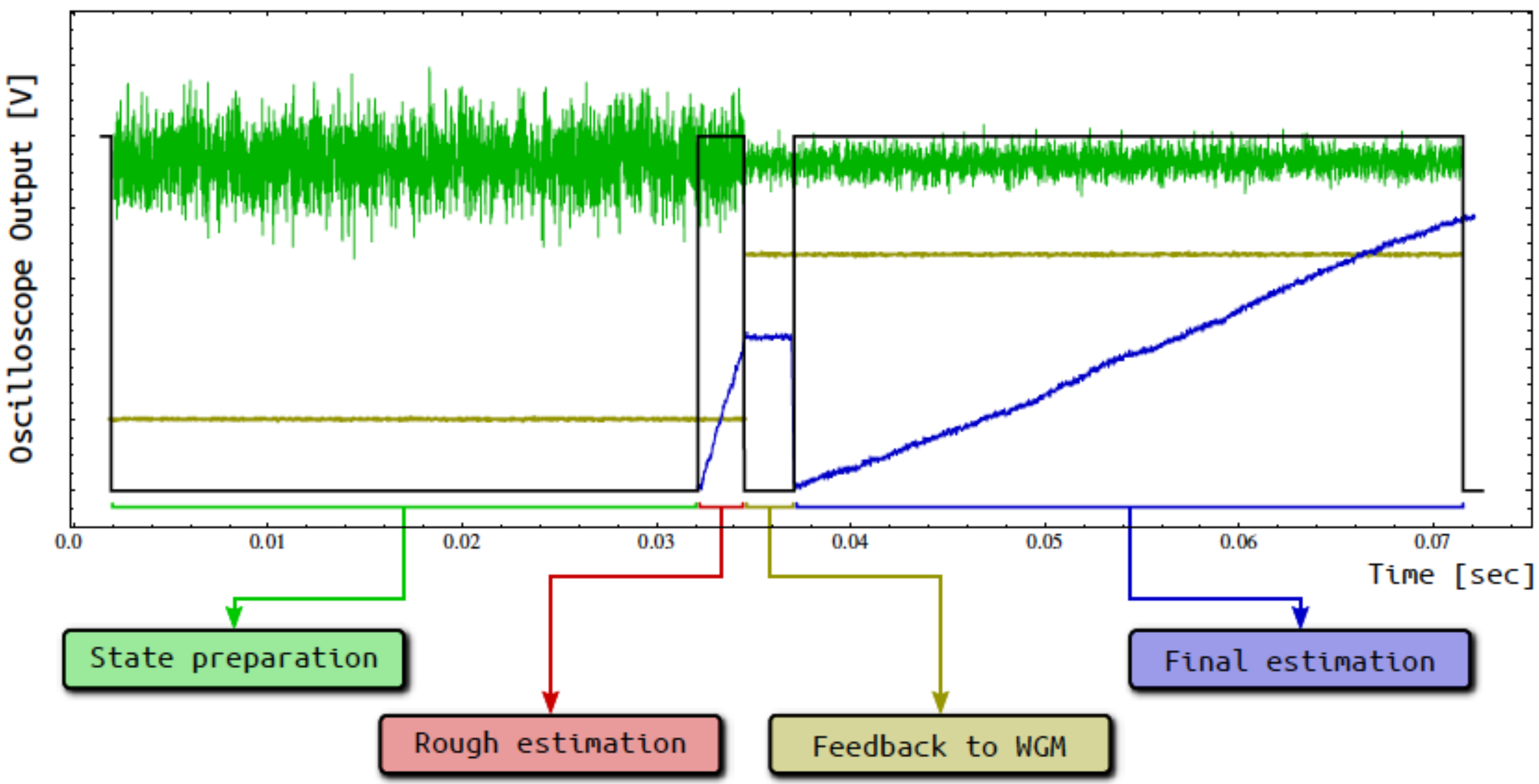
Strategy

1) Initial short quadrature measurement.
2) Rough estimate of the phase.
3) Adjust the local oscillator phase.
4) Final accurate estimate.

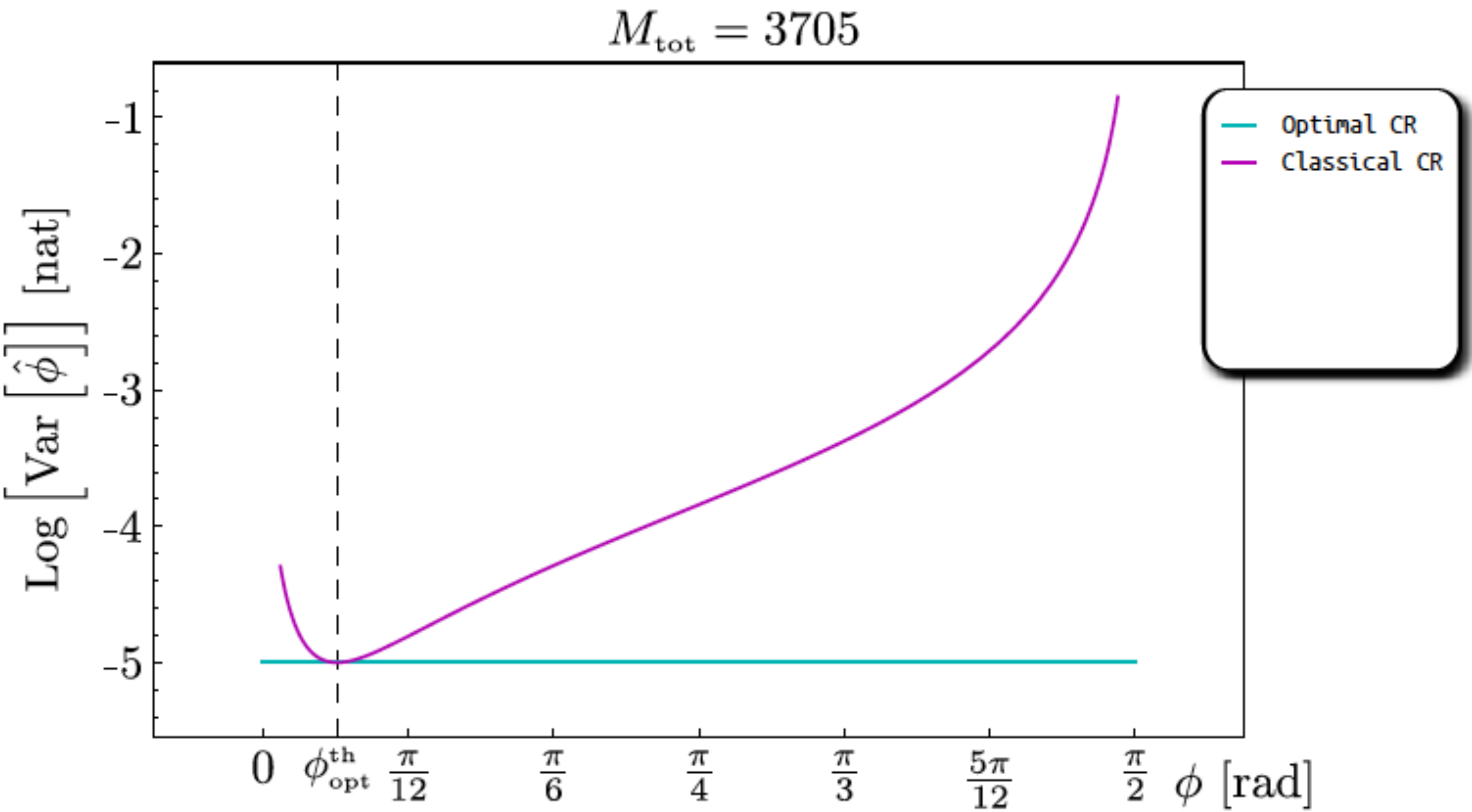


Monras Phys. Rev. A (2006); Olivares, Paris, J. Phys. B (2009)

Data acquisition and processing

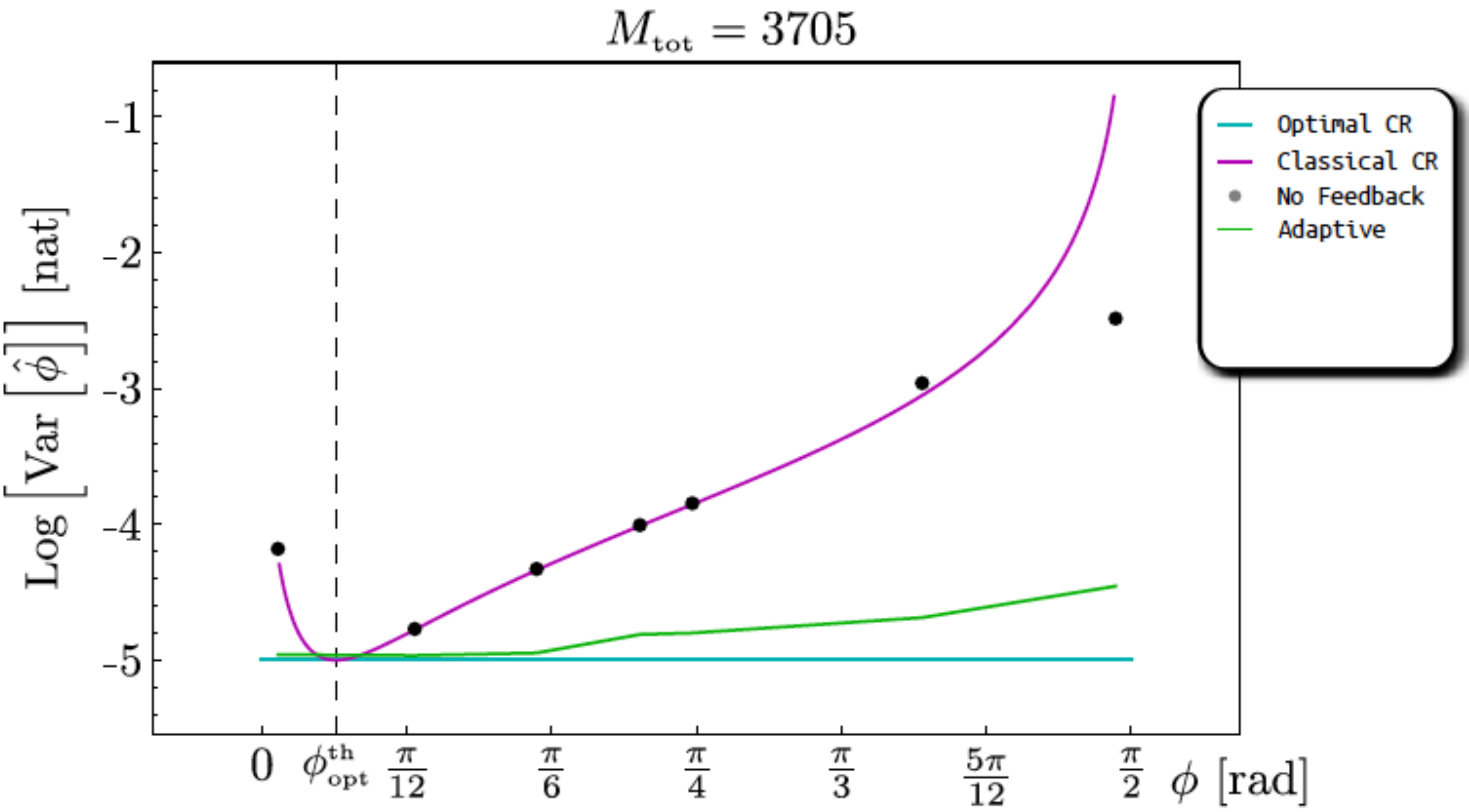


Results



Squeezing: -5.69 ± 0.07 [dB]
Antisqueezing: $+11.83 \pm 0.09$ [dB]
Squeezing strength: 1.008 ± 0.005 [nat]
Thermalization: 0.51 ± 0.01 [nat]
Probe energy: 3.30 ± 0.07 [nat]

Results



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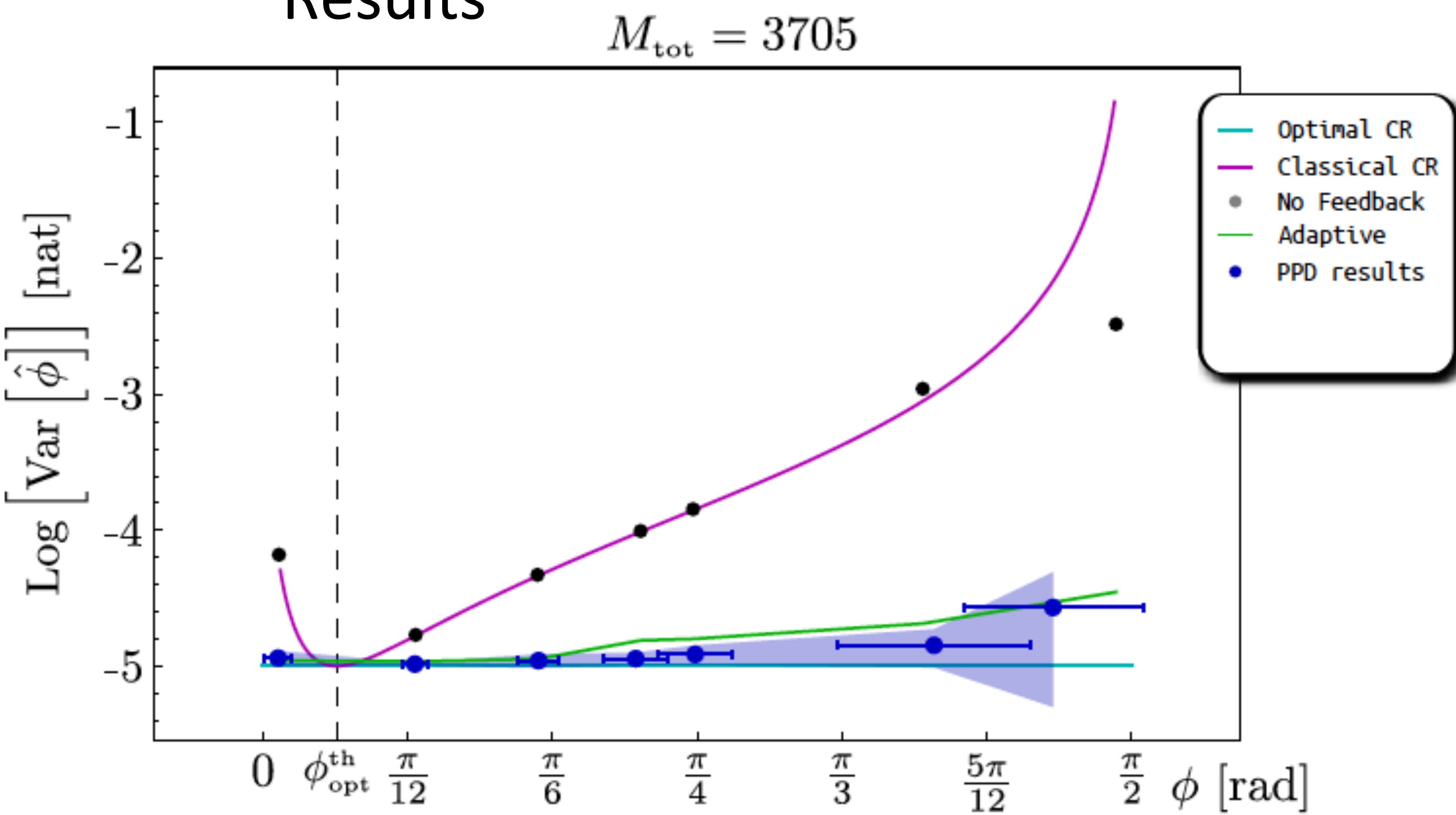

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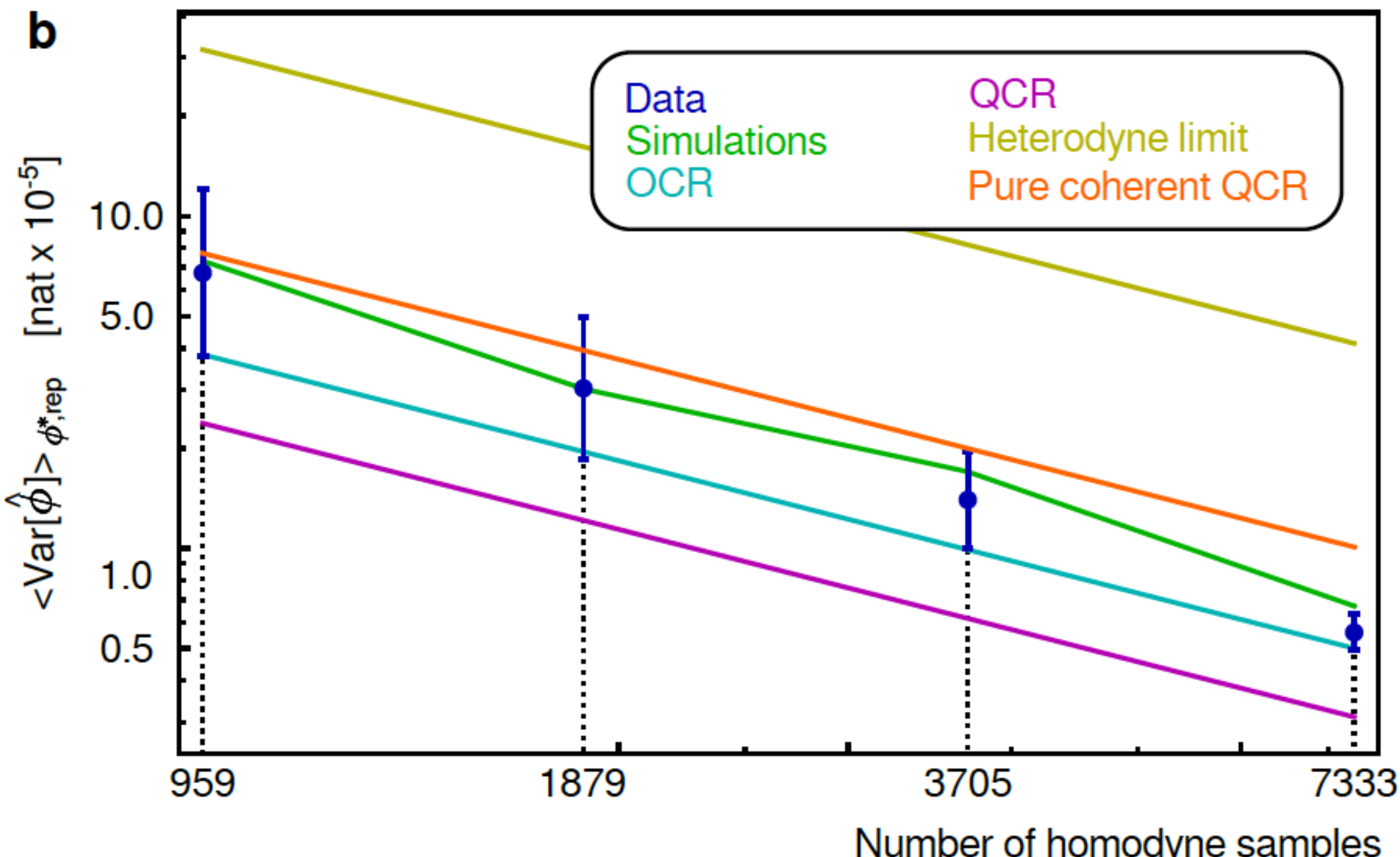
A. Berni, T. Gehring, B. Madsen, V. Händchen, M. Paris and ULA, Arxiv 1503.01365 (2015)

Results



A. Berni, T. Gehring, B. Madsen, V. Händchen, M. Paris and ULA, Arxiv 1503.01365 (2015)

Conclusion

Polarization squeezing of the photon number manifolds of quadrature squeezed light

Real time, deterministic and ab-initio phase estimation beyond the standard quantum limit

7th Summer School on

Quantum and Nonlinear Optics

7th - 13th June 2015 at Sørup Herregaard/Denmark

Topics
- Quantum, nonlinear and integrated optics
- Mechanical quantum oscillators
- Light-matter interfaces
- Quantum metrology
- Quantum information

Invited lecturers
- Konrad Banaszek / Warsaw University
- Darrick Chang / ICFO
- Martin van Exter / Leiden Univ.
- Fedor Jelezko / Ulm Univ.
- Marko Lončar / Harvard Univ.
- Morgan Mitchell / ICFO
- Martin Plenio / Ulm Univ.
- Mike Raymer / Oregon Univ.
- Andreas Reiserer / Delft Univ.
- Ian Walmsley / Oxford Univ.

Further information and registration
- http://bit.ly/qnlo2015

Organizing commitee
- Ulrik L. Andersen, DTU
- Anders S. Sørensen, NBI
- Peter Lodahl, NBI
- Karsten Rottwitt, DTU
- Jesper Mørk, DTU
- Christoph Marquardt, MPI for the Science of Light
- Alexander Huck, DTU

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