Gaussian entanglement and beyond in atmospheric channels

Martin Bohmann

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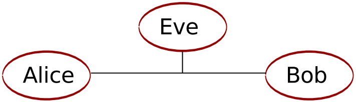
Why quantum optics in the atmosphere?

The question can be answered in two parts:

1. **Quantum part:**
    - Secure data communication with the aid of quantum physics
    - Quantum key distribution



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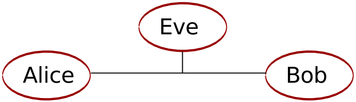
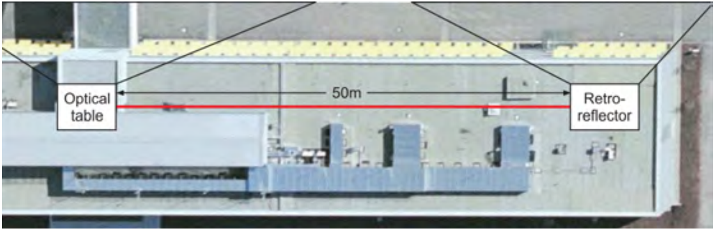


2. **Atmosphere part:**
    - Optical fibers are limited due to losses ($\sim$ 100km)
    - Flexible global communication possible

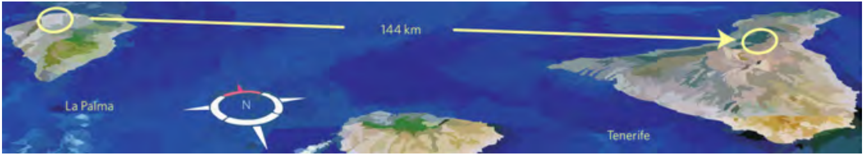
From rooftops to satellites



| references

D. Elser *et al.*, New J. Phys. **11**, 045014 (2009) **[1]**

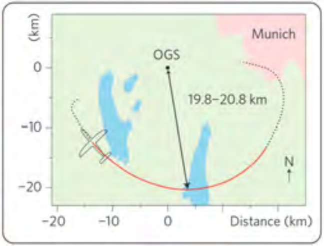
From rooftops to satellites



| references

A. Fedrizzi *et al.*, Nature Phys. **5**, 389 (2009) **[2]**

From rooftops to satellites



| references

S. Nauerth *et al.*, Nature Phot. **7**, 382 (2013) **[3]**

From rooftops to satellites

| references

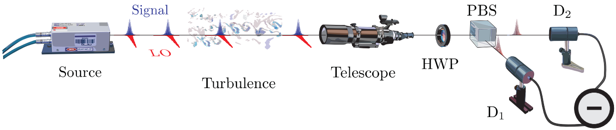
J. Wang et al., Nature Phot. **7**, 387 (2013) **[4]**

Outline

- ♣ Introduction
- ♠ Gaussian entanglement
- ♥ Higher-order moments
- ♦ Simulating atmospheric channels
- ♣ Summary and outlook

Basic example

Example: homodyne detection for atmosphere channels[1,2]



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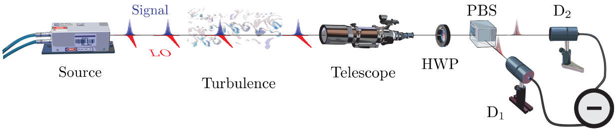
Example: homodyne detection for atmosphere channels[1,2]

$P_{\text{in}}(\alpha)$



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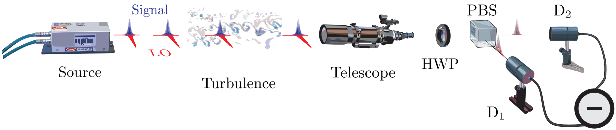

$\mathcal{P}(\eta)$

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Basic example

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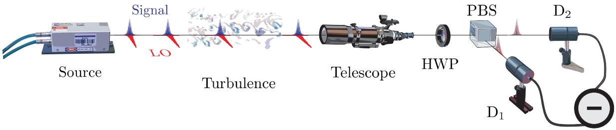
$P_{\mathrm{in}}(\alpha)$ $P_{\mathrm{out}}(\alpha)$



$\mathcal{P}(\eta)$

$$P_{\mathrm{out}}(\alpha) = \int_0^1 \mathrm{d}\eta\, \frac{1}{\eta} P_{\mathrm{in}}\left(\frac{\alpha}{\sqrt{\eta}}\right) \mathcal{P}(\eta), \qquad \eta = T^2 \in \mathbb{R}$$

| references

D. Elser et al., New J. Phys. **11**, 045014 (2009) [1]
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Two main tasks

$$P_{\text{out}}(\alpha) = \int_0^1 \mathrm{d}\eta \, \frac{1}{\eta} P_{\text{in}}\left(\frac{\alpha}{\sqrt{\eta}}\right) \mathcal{P}(\eta)$$

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Dr. Andrii Semenov

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Two main tasks

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Theory of the PDT

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Two main tasks

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Quantum effects in the atmosphere

Theory of the PDT

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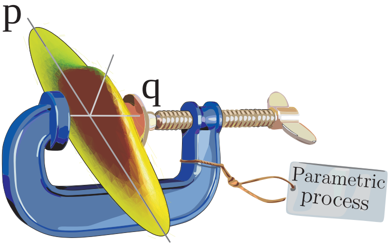
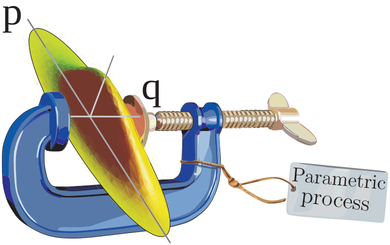
Quadrature squeezing



$$\left\langle \Delta\hat{q}^2 \right\rangle = \left\langle : \Delta\hat{q}^2 : \right\rangle + 1$$

$$\left\langle : \Delta\hat{q}^2 : \right\rangle < 1 \Rightarrow \text{squeezing}$$

Quadrature squeezing



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Input-output relation

$$\left\langle : \Delta\hat{q}^2 : \right\rangle_{\mathrm{out}} = \left\langle T^2 \right\rangle \left\langle : \Delta\hat{q}^2 : \right\rangle_{\mathrm{in}} + \left\langle \Delta T^2 \right\rangle \langle q \rangle_{\mathrm{in}}^2$$

standard attenuation — turbulence

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- ♥ Higher-order moments
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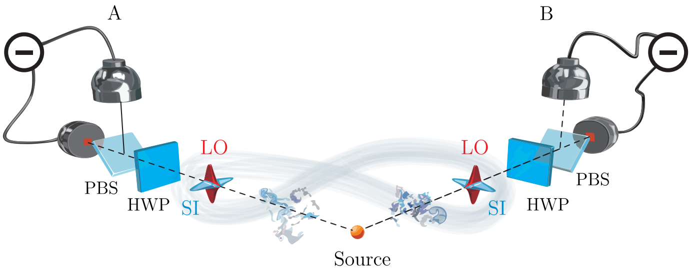
Gaussian entanglement in the atmosphere

Basic setup:



Gaussian entanglement criterion

Simon criterion[1] which can be written as[2]

$$\mathcal{W} = \det V^{\mathrm{PT}} < 0,$$

with $$V = \begin{pmatrix} \langle \Delta\hat{a}^\dagger \Delta\hat{a} \rangle & \langle \Delta\hat{a}^{\dagger 2} \rangle & \langle \Delta\hat{a}^\dagger \Delta\hat{b} \rangle & \langle \Delta\hat{a}^\dagger \Delta\hat{b}^\dagger \rangle \\ \langle \Delta\hat{a}^2 \rangle & \langle \Delta\hat{a} \Delta\hat{a}^\dagger \rangle & \langle \Delta\hat{a} \Delta\hat{b} \rangle & \langle \Delta\hat{a} \Delta\hat{b}^\dagger \rangle \\ \langle \Delta\hat{a} \Delta\hat{b}^\dagger \rangle & \langle \Delta\hat{a}^\dagger \Delta\hat{b}^\dagger \rangle & \langle \Delta\hat{b}^\dagger \Delta\hat{b} \rangle & \langle \Delta\hat{b}^{\dagger 2} \rangle \\ \langle \Delta\hat{a} \Delta\hat{b} \rangle & \langle \Delta\hat{a}^\dagger \Delta\hat{b} \rangle & \langle \Delta\hat{b}^2 \rangle & \langle \Delta\hat{b} \Delta\hat{b}^\dagger \rangle \end{pmatrix} = \begin{pmatrix} A & C^\dagger \\ C & B \end{pmatrix}$$

| references

R. Simon, Phys. Rev. Lett. **84**, 2726 (2000) [1]
E. Shchukin and W. Vogel, Phys. Rev. Lett. **95**, 230502 (2005) [2]

Output condition[1]

The fluctuating losses transform the covariance matrix V into

$$V \mapsto V_{\mathrm{atm.}} = V_{\langle T_a^2\rangle,\langle T_b^2\rangle,\Gamma} + \begin{pmatrix} \vec{\mu}_a\vec{\mu}_a^\dagger & \Delta\Gamma\vec{\mu}_a\vec{\mu}_b^\dagger \\ \Delta\Gamma\vec{\mu}_b\vec{\mu}_a^\dagger & \vec{\mu}_b\vec{\mu}_b^\dagger \end{pmatrix}.$$

- displacement vectors $\vec{\mu}_a = \sqrt{\langle\Delta T_a^2\rangle}(\langle\hat{a}^\dagger\rangle, \langle\hat{a}\rangle)^{\mathrm{T}}$
- $V_{\mathrm{atm.}}$ are reduced due to Γ: $C \mapsto \Gamma C$ and $\Gamma \in [0, 1]$
- Constant losses lead only to scaling $V_{\mathrm{cl}} = T^2 V$

| references

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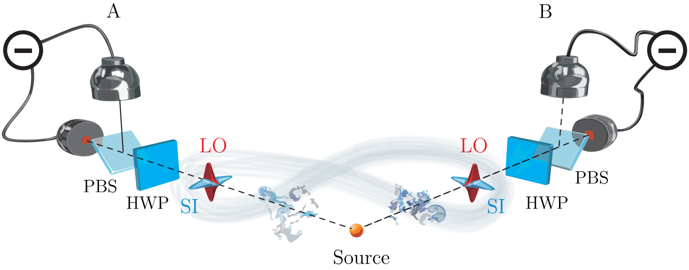
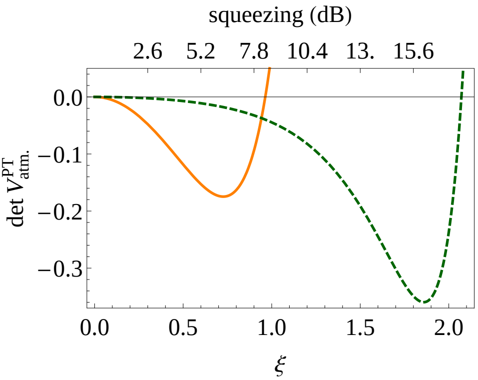


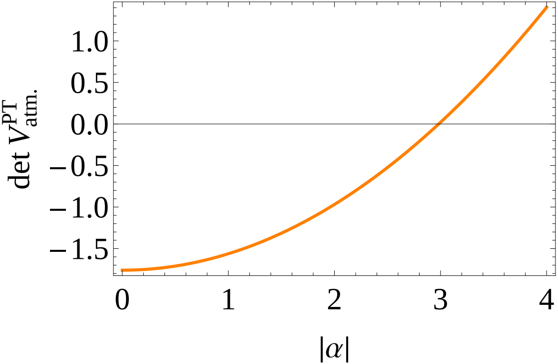
Now we consider uncorrelated loss ($T_a \neq T_b$)

Dependence on squeezing strength

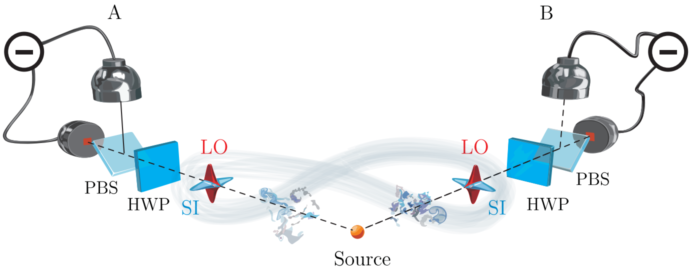


- Two-mode squeezed vacuum state in 144 km and 1.6 km free-space channel
- Strong squeezing leads to disentanglement

Dependence on coherent displacement



- Displaced two-mode squeezed vacuum state
- Displacement can lead to disentanglement

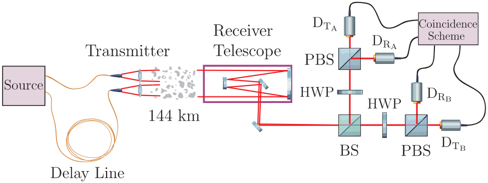


Now we consider correlated loss ($T_a = T_b$)

Correlated channels: $T_a = T_b$

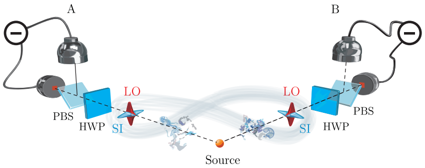
Copropagation

Discrete variables: A. Fedrizzi, R. Ursin, T. Herbst, M. Nespoli, R. Prevedel, T. Scheidl, F. Tiefenbacher, T. Jennewein, and A. Zeilinger, Nat. Phys. **5**, 389 (2009)]



Correlated channels: $T_a = T_b$

Adaptive correlations



1. Monitor both transmission coefficients T_a and T_b
2. Share this information via classical communication
3. Attenuate one channel to the level of the other $\Rightarrow$ $T_a = T_b$
4. Result: corresponds to deterministic loss

   Most Gaussian entanglement is preserved[2]

| references

M. B., A. A. Semenov, J. Sperling, and W. Vogel, Phys. Rev. A **94**, 010302(R) (2016). [1]
F. A. S. Barbosa *et al.*, Phys. Rev. A **84**, 052330 (2011). [2]

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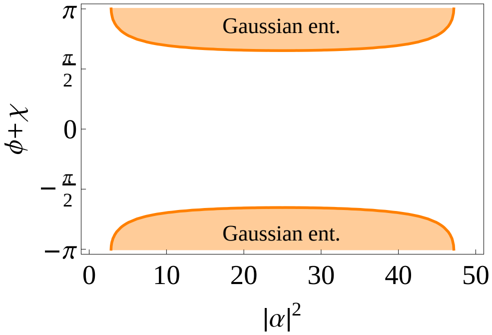

- Displaced two-mode squeezed vacuum state: $\langle \hat{a} \rangle = |\alpha| e^{i\phi}$ and $\langle \hat{b} \rangle = |\beta| e^{i\chi}$
- Plot: $|\alpha|^2 + |\beta|^2 = 50$, 144 km atmospheric channel
- Gaussian entanglement depends on displacement direction

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Moment criteria

Method: matrix of moments $M_{(\vec{p},\vec{q}),(\vec{r},\vec{s})} = \langle [\hat{\vec{a}}^{\dagger\vec{p}}\hat{\vec{a}}^{\vec{q}}]^{\dagger}[\hat{\vec{a}}^{\dagger\vec{r}}\hat{\vec{a}}^{\vec{s}}]\rangle$ [1,2]

$$N_{(\vec{p},\vec{q}),(\vec{r},\vec{s})} < 0 \xleftarrow[\text{ordering}]{\text{normal}} M_{(\vec{p},\vec{q}),(\vec{r},\vec{s})} \xrightarrow[\text{transposition}]{\text{partial}} M^{\mathrm{PT}}_{(\vec{p},\vec{q}),(\vec{r},\vec{s})} < 0$$

nonclassicality

PT entanglement

| references

E. Shchukin, Th. Richter, and W. Vogel, Phys. Rev. A **71**, 011802(R) (2005) [1]
E. Shchukin and W. Vogel, Phys. Rev. Lett. **95**, 230502 (2005) [2]
M. Bohmann, J. Sperling, A. A. Semenov, and W. Vogel, Phys. Rev. A **95**, 012324 (2017) [2]

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Derivation of the input-output relation[3]

| **references**

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Amplitude squeezing

- Criterion for amplitude squeezing:

$$d = \begin{vmatrix} 1 & \langle \hat{a}^\dagger \rangle & \langle \hat{a} \rangle \\ \langle \hat{a} \rangle & \langle \hat{a}^\dagger \hat{a} \rangle & \langle \hat{a}^2 \rangle \\ \langle \hat{a}^\dagger \rangle & \langle \hat{a}^{\dagger 2} \rangle & \langle \hat{a}^\dagger \hat{a} \rangle \end{vmatrix} = \Bigg| \underbrace{\begin{matrix} \langle \Delta\hat{a}^\dagger \Delta\hat{a} \rangle & \langle (\Delta\hat{a})^2 \rangle \\ \langle (\Delta\hat{a}^\dagger)^2 \rangle & \langle \Delta\hat{a}^\dagger \Delta\hat{a} \rangle \end{matrix}}_{A} \Bigg| < 0$$

- Output condition:

$$d^{\mathrm{out}} = \langle T^2 \rangle^2 \left[d + \Gamma \left(\langle \hat{a}^\dagger \rangle, \langle \hat{a} \rangle \right) A \begin{pmatrix} \langle \hat{a} \rangle \\ \langle \hat{a}^\dagger \rangle \end{pmatrix} \right] < 0$$

with $\Gamma = 1 - \frac{\langle T \rangle^2}{\langle T^2 \rangle}$

$\Rightarrow$ strong dependency on the coherent displacement

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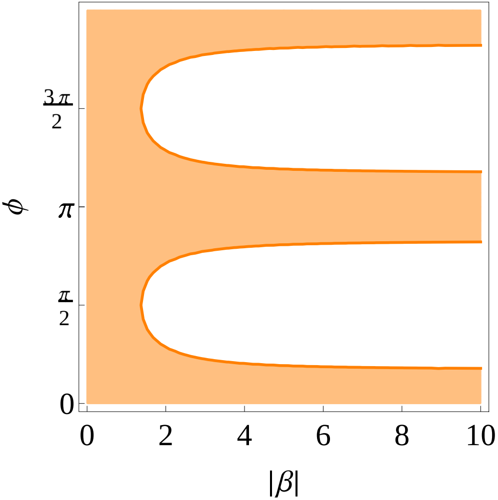

Higher-order entanglement

- Example of a higher-order criterion:

$$S = \begin{vmatrix} 1 & \langle \hat{a}\hat{b}^\dagger \rangle \\ \langle \hat{a}^\dagger \hat{b} \rangle & \langle \hat{a}^\dagger \hat{a} \hat{b}^\dagger \hat{b} \rangle. \end{vmatrix} \overset{\text{ent.}}{<} 0$$

- Output condition:

$$S^{\mathrm{out}} = \langle T_a^2 T_b^2 \rangle \left[S + \Gamma_{ab} |\langle \hat{a}\hat{b}^\dagger \rangle|^2 \right]$$

with $\Gamma_{ab} = \frac{\langle T_a^2 T_b^2 \rangle - \langle T_a T_b \rangle^2}{\langle T_a^2 T_b^2 \rangle}$ and $\Gamma_{ab} \in [0, 1]$

- Is non-Gaussian entanglement more or less robust?

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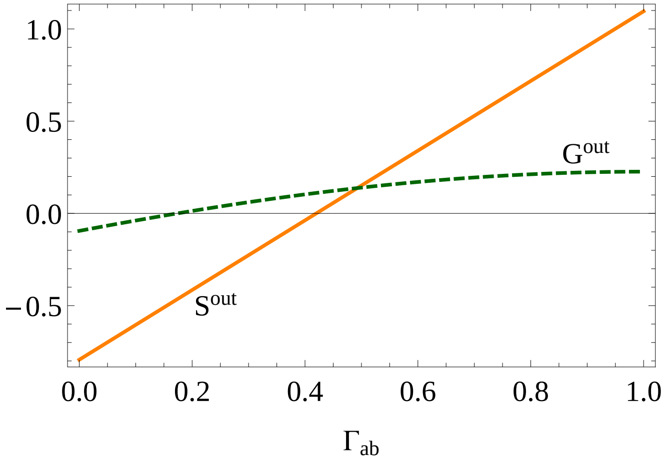
Higher-order entanglement

State: $|\Psi^-\rangle = \mathcal{N}(\alpha)\big(|\alpha\rangle \otimes |\alpha\rangle - |-\alpha\rangle \otimes |-\alpha\rangle\big)$



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Idea[1]

- Aim: testing atmospheric channels in the lab
- Measure with different constant attentions η_k
- Allows to approximate the atmospheric transmission distribution

$$\tilde{\mathcal{P}}(Y=\eta_k)=\mathcal{P}(\eta_k)\left[\sum_{j=0}^{n}\mathcal{P}(\eta_j)\right]^{-1}.$$

- Measurement results

$$x^{\text{atm.}}=\sum_{j=0}^{n}\tilde{\mathcal{P}}(\eta_j)x_j.$$

| references

M. Bohmann, R. Kruse, J. Sperling, C. Silberhorn, and W. Vogel, Phys. Rev. A **95**, 063801 (2017). [1]

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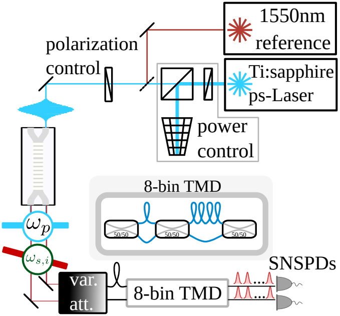
Implementation



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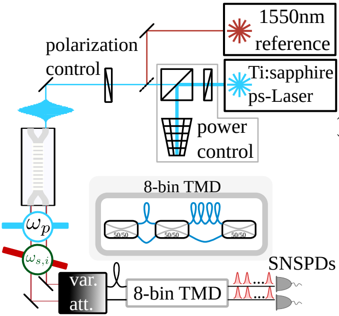

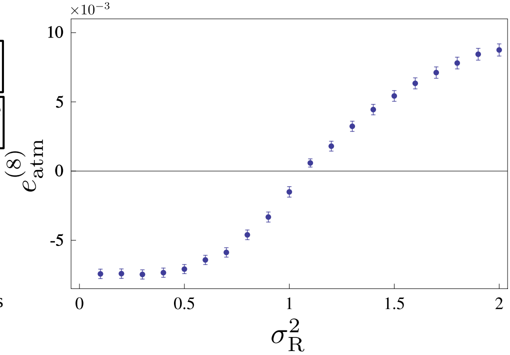

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Outline

- ♣ Introduction
- ♠ Gaussian entanglement
- ♥ Higher-order moments
- ♦ Simulating atmospheric channels
- ♣ Summary and outlook

Conclusion

- Full treatment of Gaussian entanglement in the atmosphere
- Dependence on squeezing and coherent displacements
- Preserving Gaussian entanglement with adoptive channel correlation
- Generalization to nonclassicality and PT entanglement testing
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How do our results relate to

- Quantum key distribution[1]
- Entanglement and squeezing distillation[2]
- Quantum teleportation[3]
- Sensing the atmosphere

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Thank you for your attention!