Unraveling two-photon entanglement via the squeezing spectrum of light traveling through nanofiber-coupled atoms

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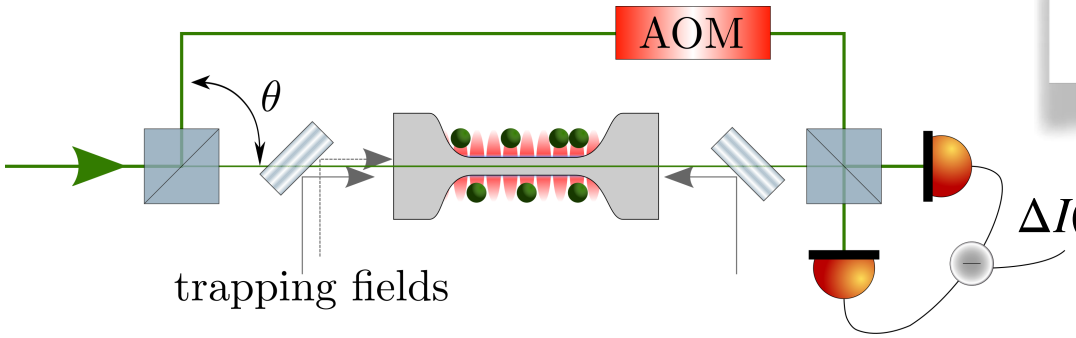
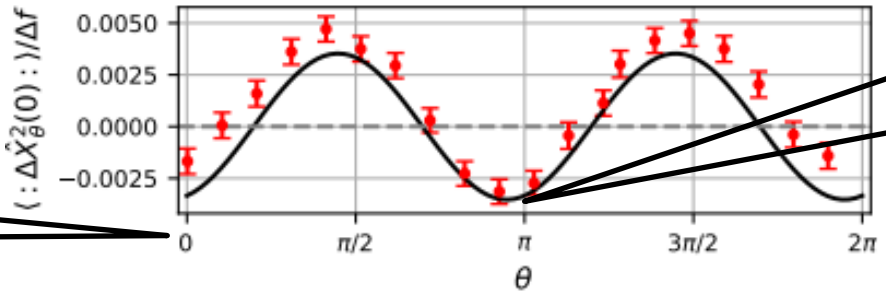


Hinney et al. 2020, arXiv:2010.09450

$$\Delta I(t) \propto X_\theta(t) \propto \hat{a}(t)e^{i\theta} + \hat{a}^\dagger(t)e^{-i\theta}$$

- Ensemble of laser cooled atoms coupled to evanescent field of a nanofiber
- 1D array of atoms in fiber guided dipole traps
- Probe atoms near-resonantly through nanofiber
- Balanced homodyne detection for squeezing measurement

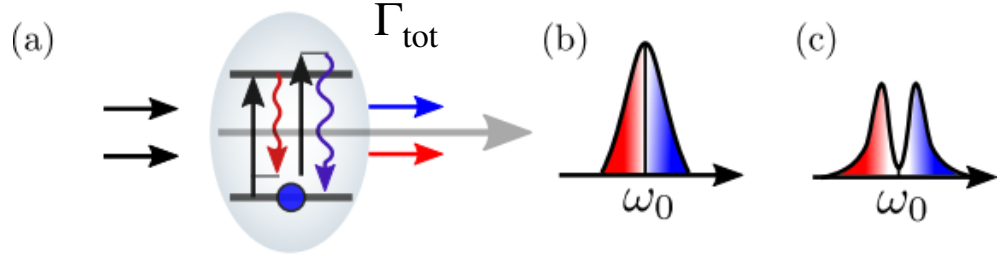


Amplitude squeezing

0.63% squeezing in $\Delta f = 21.5\,\mathrm{MHz}$

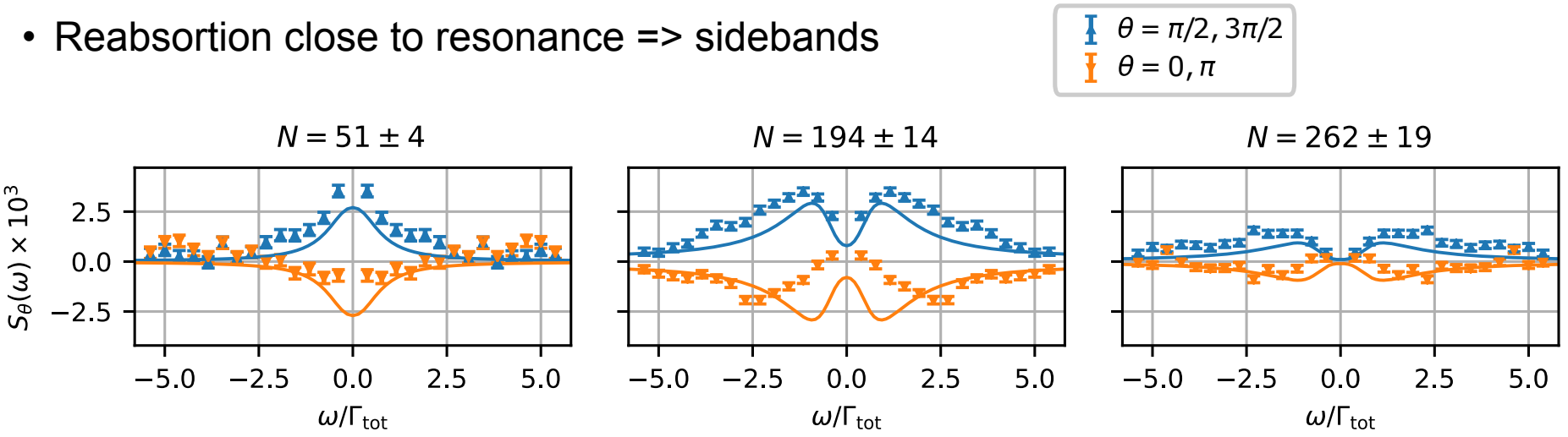
Squeezing spectrum

- Non-linear scattering
  - => Energy-time entangled photons



- Normally ordered squeezing spectrum: $S_\theta(\omega) = \int_{-\infty}^{\infty} d\tau \, \langle :\hat{X}_\theta(0)\hat{X}_\theta(\tau): \rangle e^{i\omega\tau}$
  - Coherent state $S_\theta(\omega) = 0$
  - Limit of zero noise $S_\theta(\omega) = -1/4$

- Reabsortion close to resonance => sidebands



- Theory: Scattering matrix formalism based on Bethe Ansatz solutions

Reconstructing the entangled part of the two-photon wavefunction

- Two-photon wavefunction consists of separable and entangled part

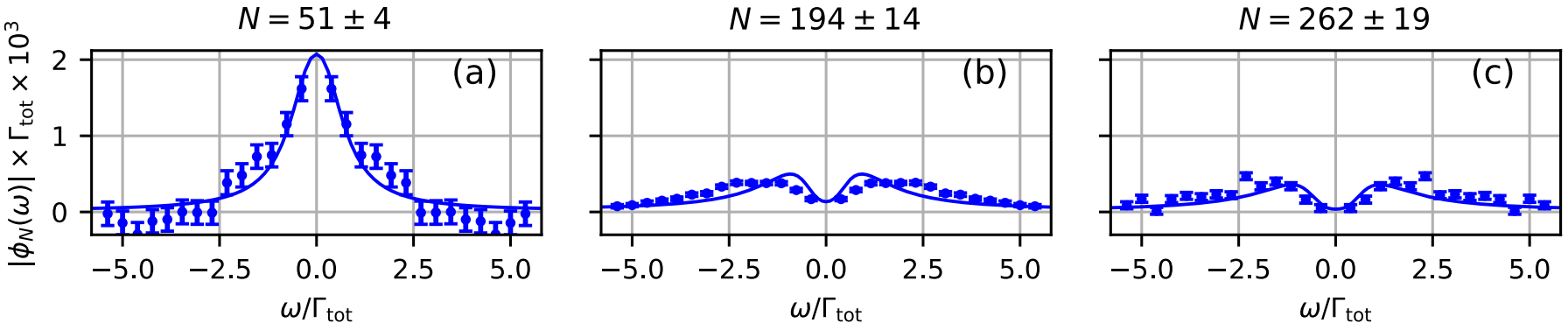
$$\psi_2(x_1, x_2) \propto t^{2N} - \phi_N(x_1 - x_2)$$

$$\phi_N(\omega) = \int \mathrm{d}\tau\, \phi_N(\tau) e^{i\omega\tau}$$

- Low saturation limit:
  - Squeezing is related entangled part of the wavefunction $\phi_N(\omega) = |\phi_N(\omega)|\, e^{i\varphi_N(\omega)}$

$$\boxed{S_\theta(\omega) \propto \cos\left[\theta + \varphi_N(\omega)\right] |\phi_N(\omega)|}$$

- Reconstruct two-photon wave function $\phi_N(\omega)$ vs. atom number ($\varphi_N(\omega) = 0$)

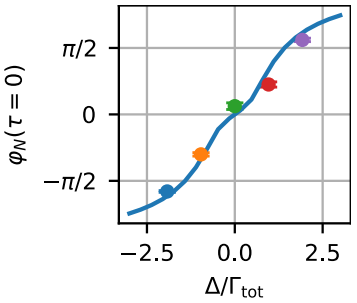


Reconstructing the entangled part of the two-photon wavefunction — detuned

Angle φ_N from fit of cosine-modulation

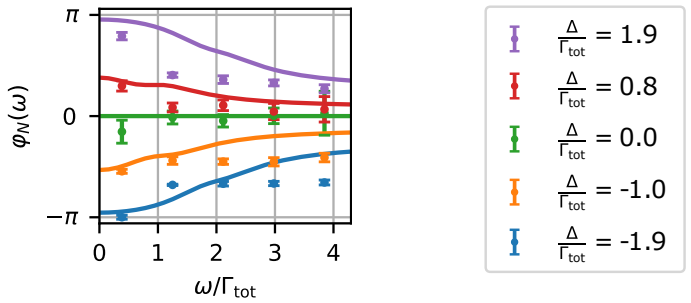
$S_\theta(\omega) \propto \cos\left(\theta + \varphi_N(\omega)\right) |\phi_N(\omega)|$

Integrated Phase: (Related to Squeezing phase)

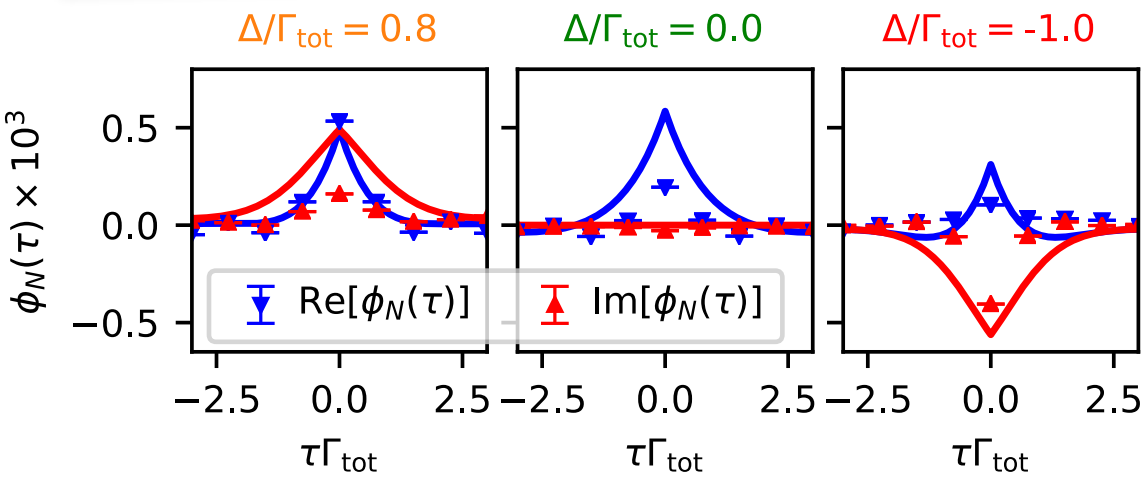


Δ: Probe detuning

Phase across the spectrum $\varphi_N(\omega)$



Reconstruction technique for entangled two-photon wavefunction $\phi(\tau)$



Time-dependent wavefunction:

$$\phi_N(\tau) = \frac{1}{2\pi}\int \mathrm{d}\tau\, \phi_N(\omega) e^{-i\omega\tau}$$