



Engineering two-photon wavefunction and exchange statistics in a semiconductor chip

Shaping frequency entanglement and particle statistics on-chip



Motivation

Entangled Photons

easy transmission
robust to decoherence^[1]
variety of encoding d.o.f.



Energy-Time Entanglement

high-dimensional
robust propagation
easy to handle



Shaping of the JSA

clock-synchronisation^[2]
heralded sources^[3]
quantum simulations^[4]

$$|\psi\rangle = \iint d\omega_s d\omega_i \text{JSA}(\omega_s, \omega_i) \hat{a}_s^\dagger(\omega_s) \hat{a}_i^\dagger(\omega_i) |0, 0\rangle_{s,i}$$

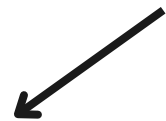


Aim of the Paper

Shaping the Joint Spectral Amplitude by post manipulation inevitably reduces brightness and integrability



Is it possible to control both frequency correlations and exchange symmetry at the generation stage?



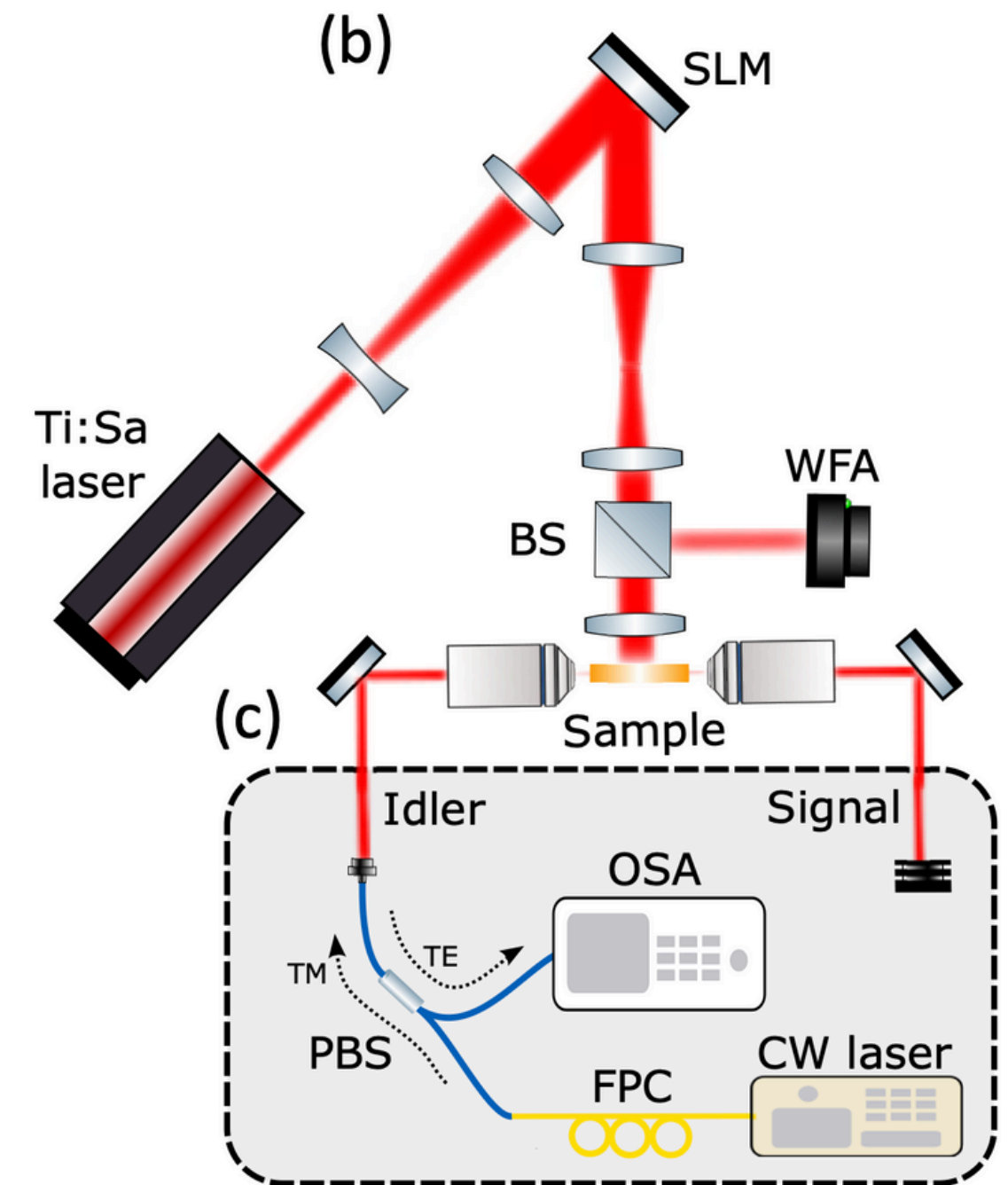
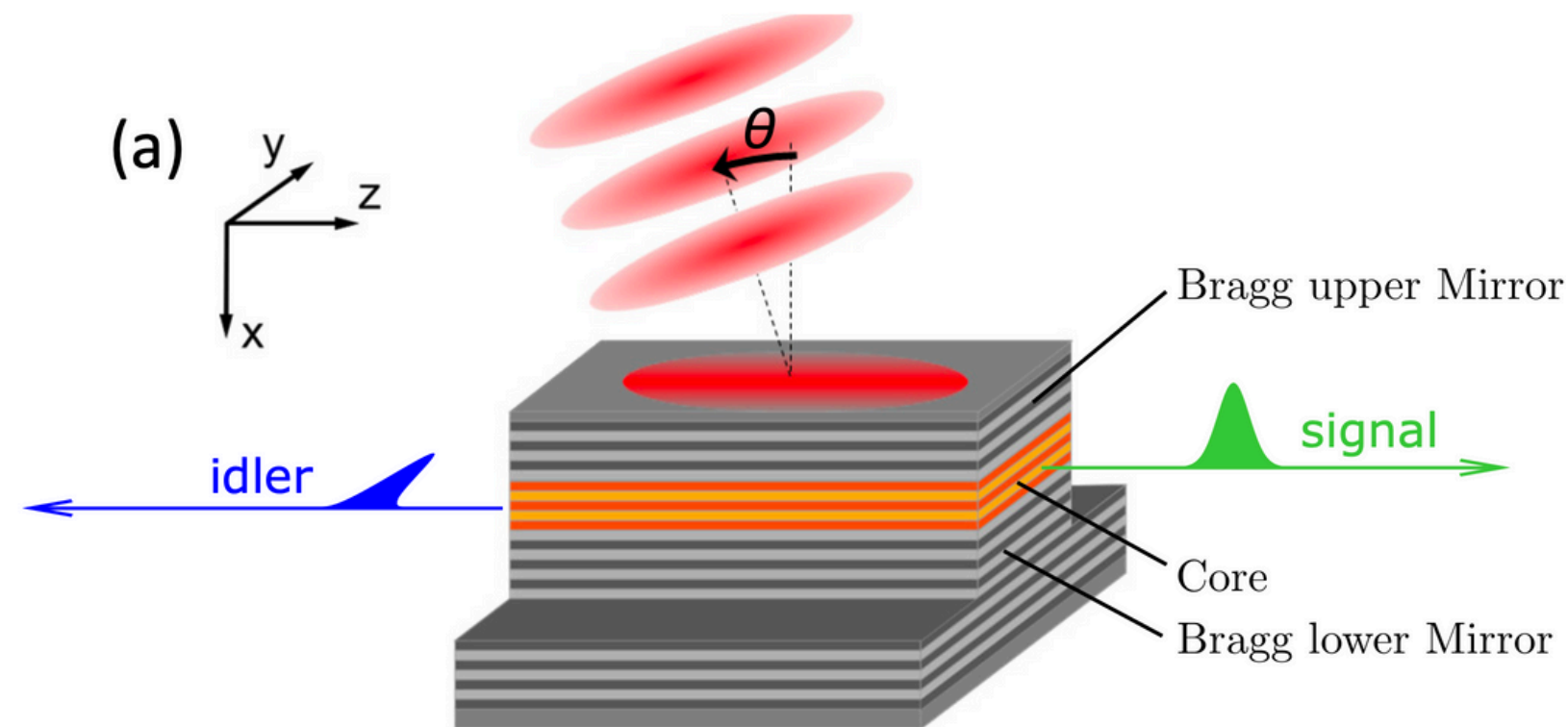
1) Frequency Correlation
pump waist
pump spectrum



2) Exchange Symmetry
pump phase

The Device

Non-Linear Crystal illuminated by a pulsed laser source
Generation of two entangled counter-propagating photons



Source: (a)-(b) Ducci et al., Phys. Rev. A 102, 033508 (2020)



Theoretical backbone

Photons pairs generation requires conservation of energy and momentum

$$\omega_p = \omega_i + \omega_s \qquad k_p(n_p) = k_i(n_i) + k_s(n_s)$$

The JSA can be factorised as^[5]

$$\text{JSA}(\omega_s, \omega_i) = \underbrace{\phi_{\text{spectral}}(\omega_s + \omega_i)}_{\text{energy conservation}} \underbrace{\phi_{\text{PM}}(\omega_s - \omega_i)}_{\text{phase-matching}}$$

Where

$$\phi_{\text{PM}}(\omega_s - \omega_i) = \int_{-L/2}^{L/2} dz \underbrace{\mathcal{A}_p(z)}_{\substack{\text{pump spatial} \\ \text{profile}}} e^{-i(k_{\text{deg}} + (\omega_s - \omega_i)/v_g)z}$$

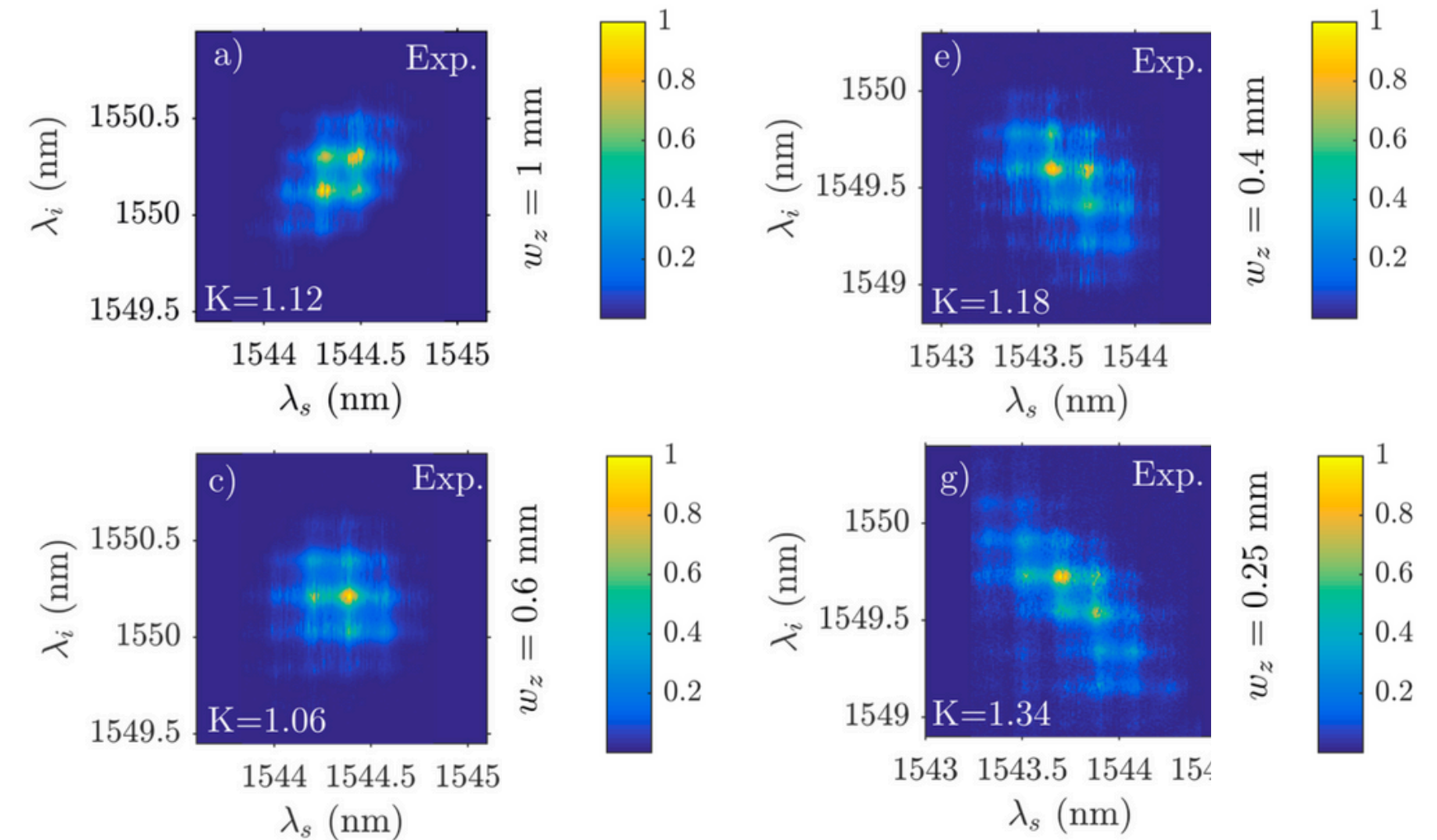


I. Frequency Correlations

Use a Gaussian pump, with adjustable waist (w) to control spatial profile

$$\mathcal{A}_p(z) = e^{-z^2/w^2} e^{ikz}$$

We can effectively control frequency correlations between photons





The pump has Gaussian spatial profile and sech frequency profile

- frequency profile → affects energy conservation (“diagonal”)
- spatial profile → affects phase matching (“anti-diagonal”)

We can simulate how spatial profile would affect the JSA

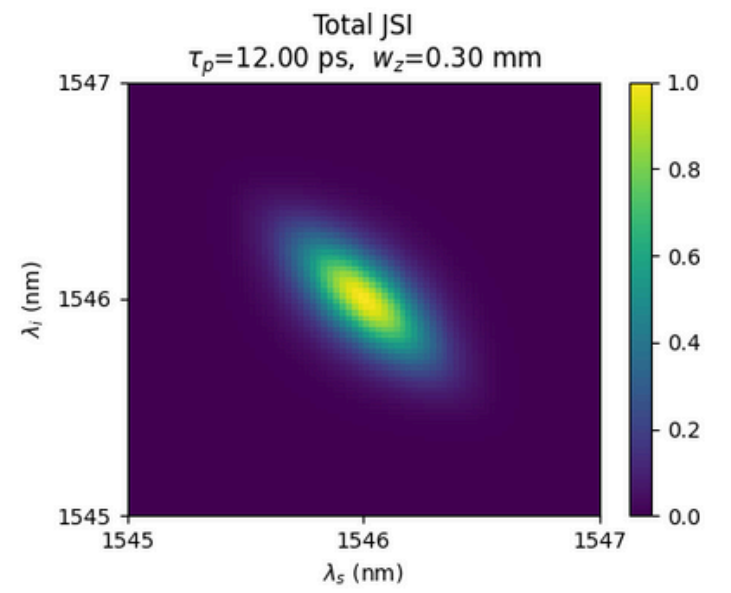
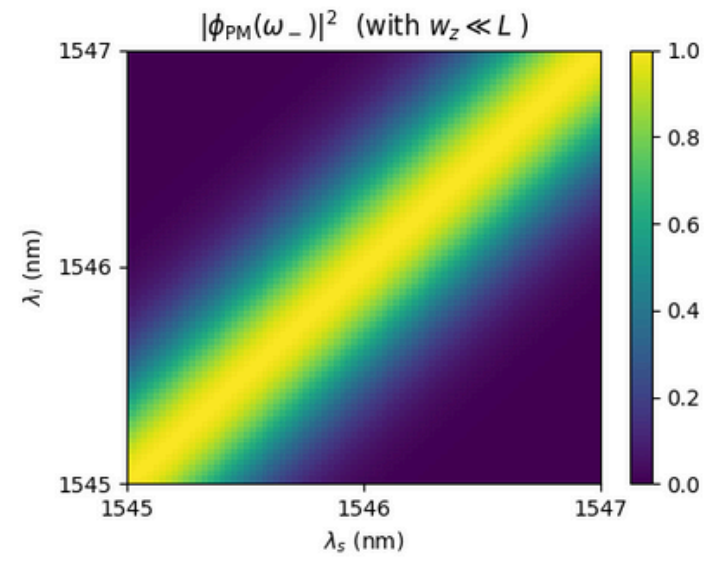
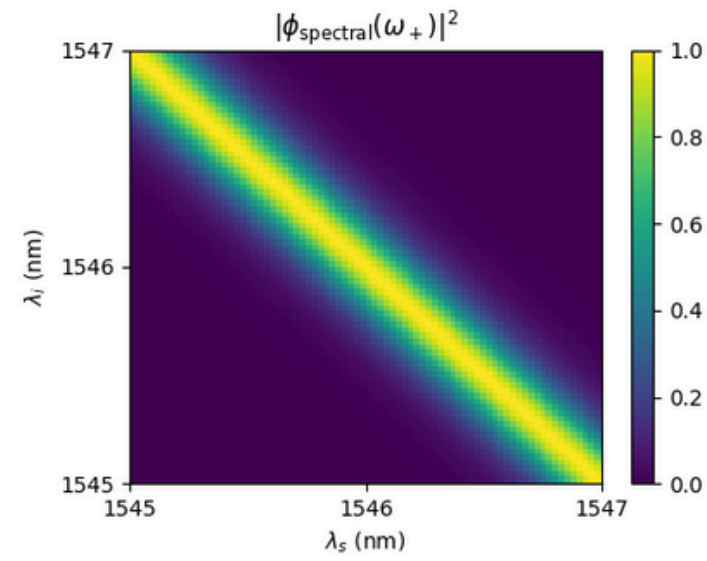
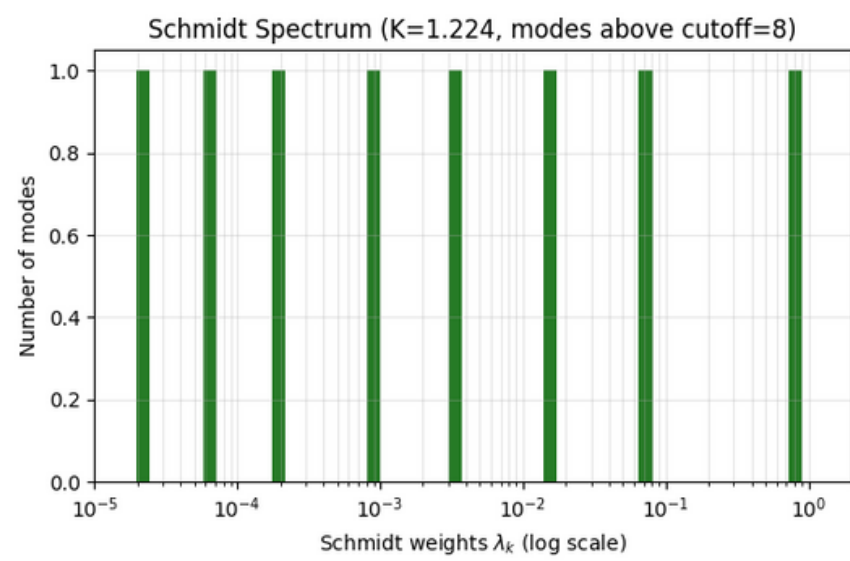
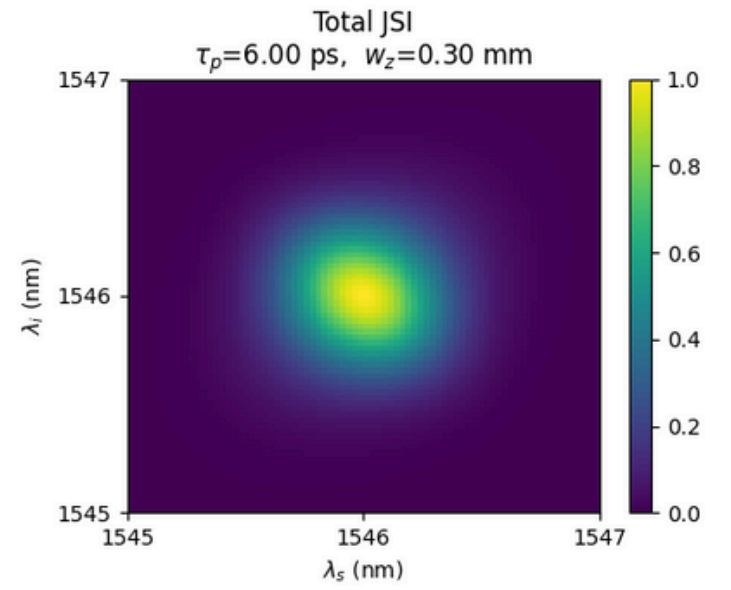
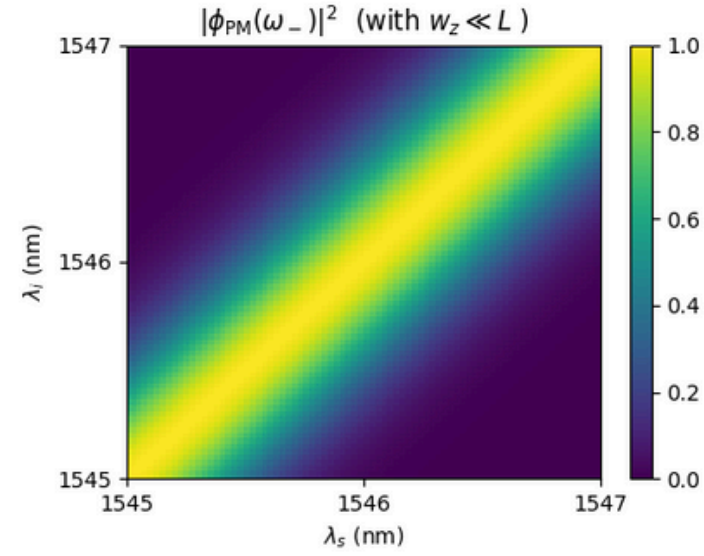
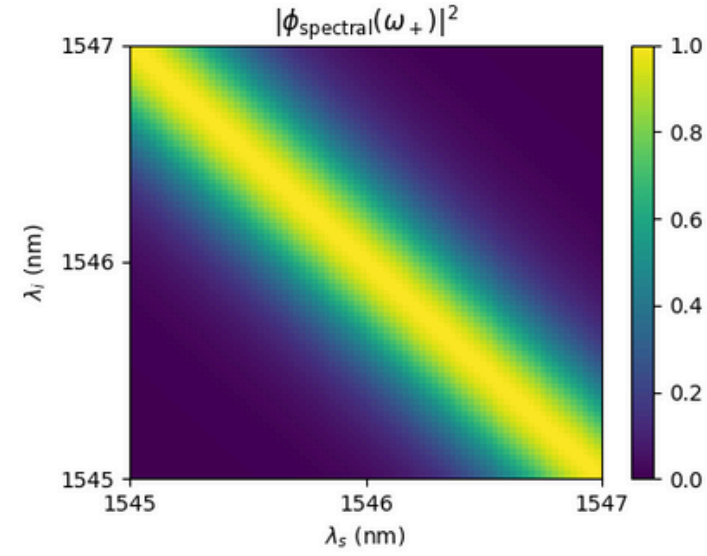
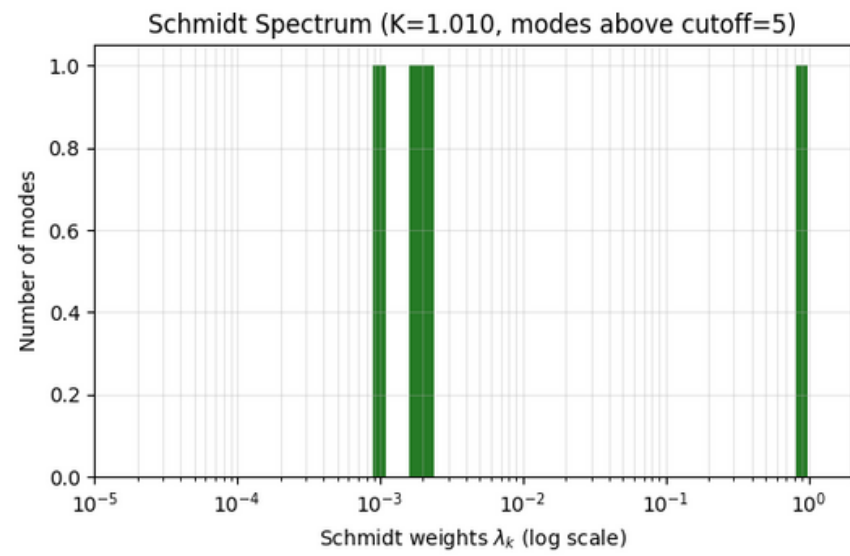
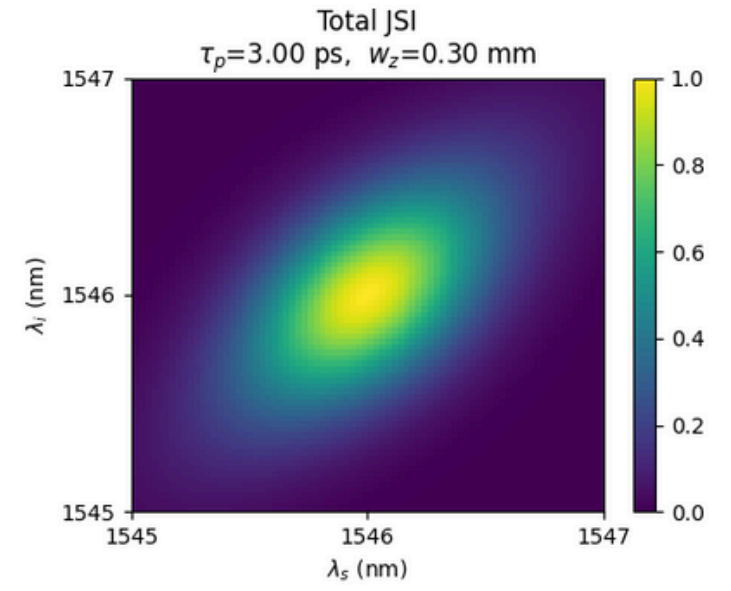
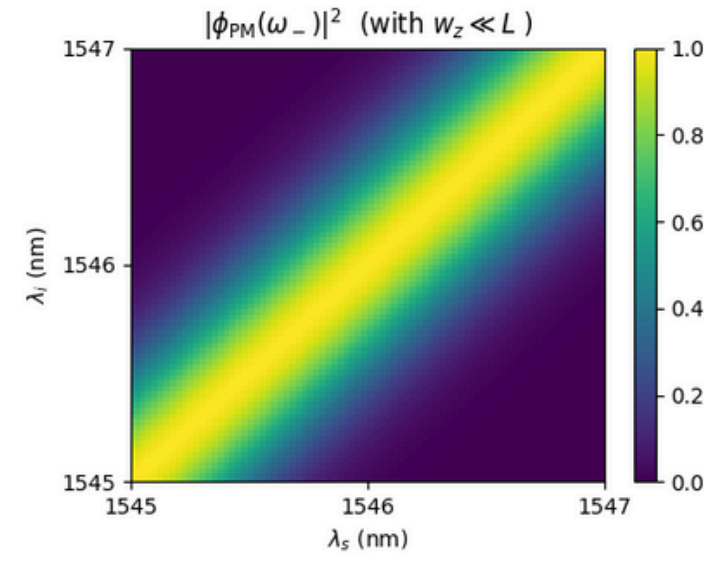
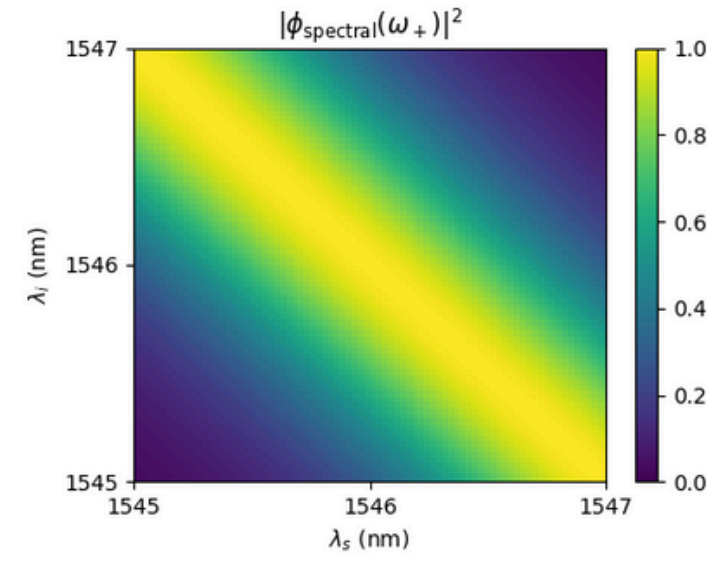
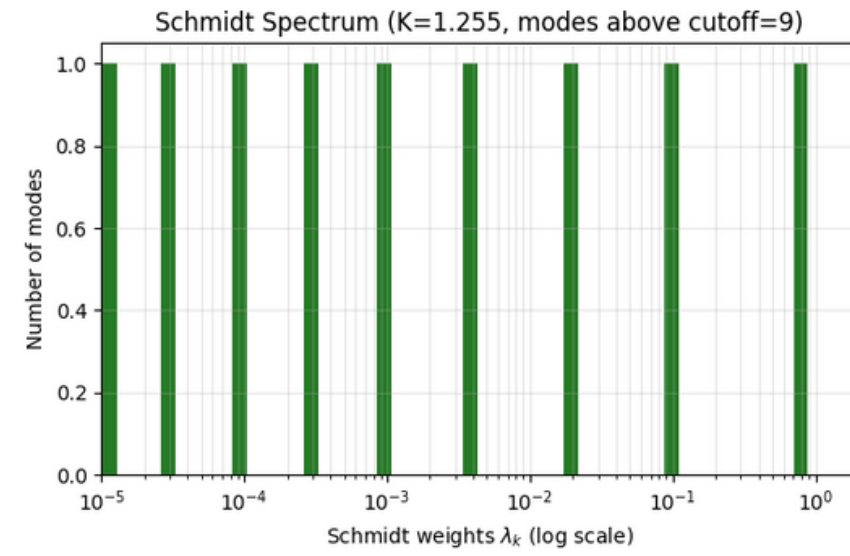
To verify the entanglement of the state we estimate numerically the Schmidt Number (K)^[6]

$$K = \frac{1}{\sum_m \lambda_m^2}$$

Where

$$\phi(\omega_s, \omega_i) = \sum_m \sqrt{\lambda_m} u_m(\omega_s) v_m(\omega_i)$$

With $\{u_n\}$ and $\{v_n\}$ orthonormal sets of functions in L_2



II. Exchange Symmetry

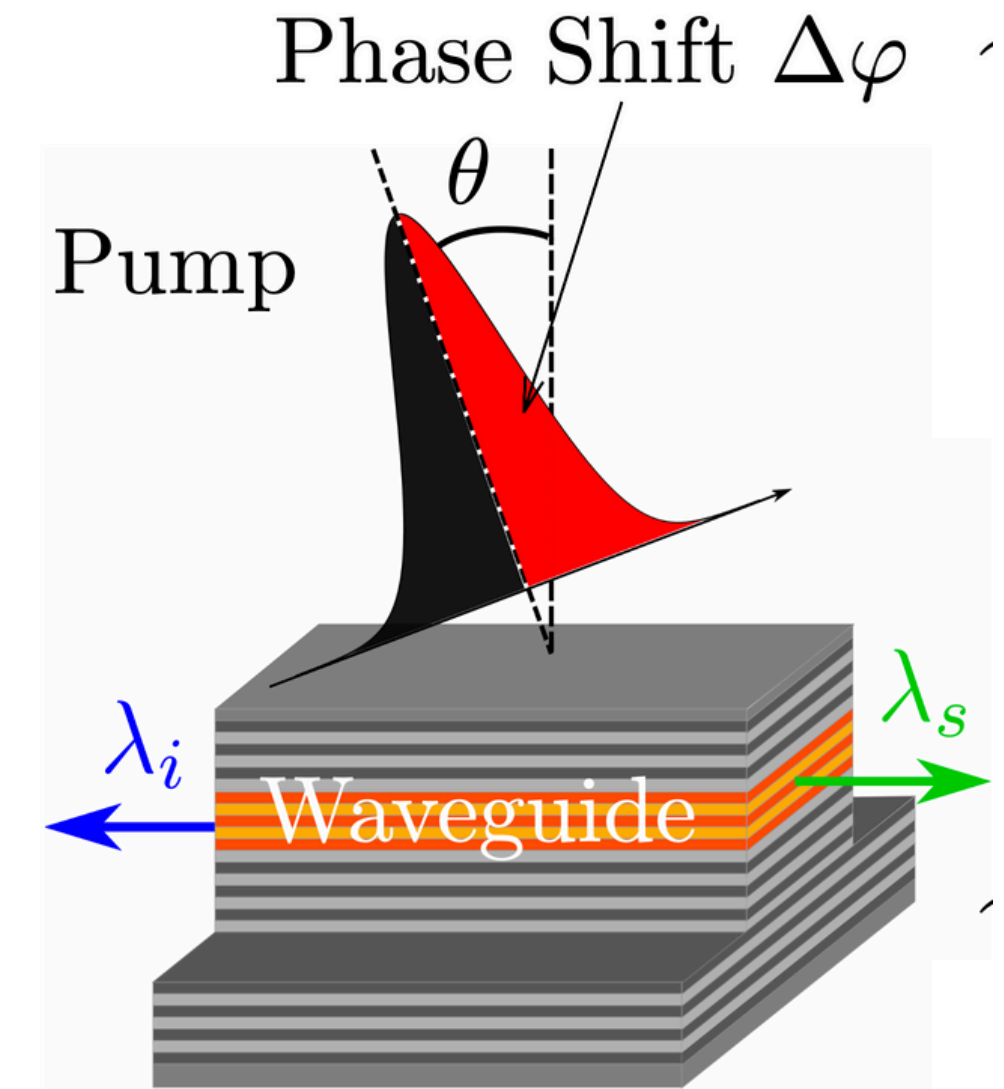
Controlled independently via phase-modulation of pump

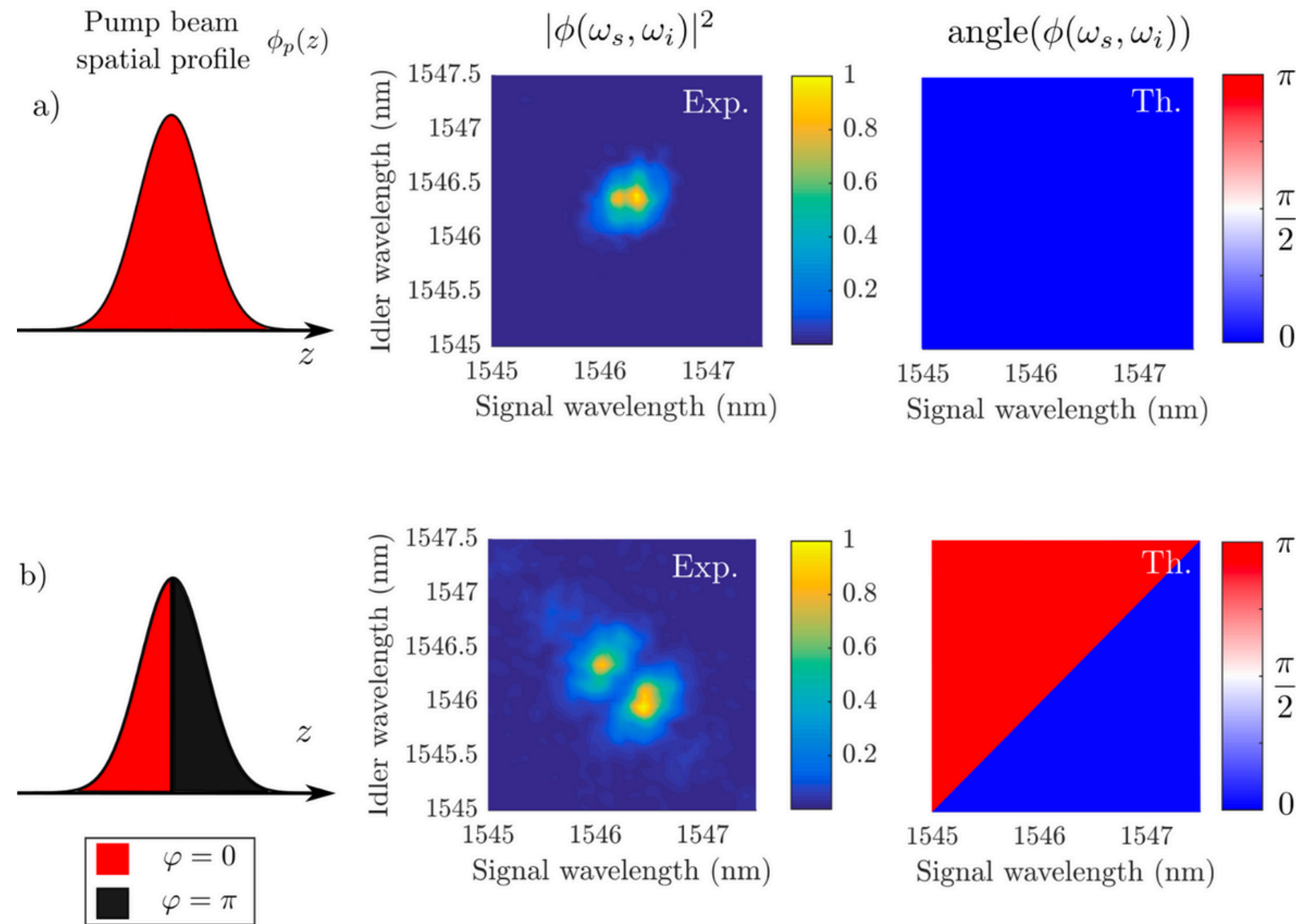
$$\mathcal{A}_p(z) = F(z)e^{-z^2/w^2}e^{ikz}$$

Where

$$\begin{cases} F(z) = 1 & \text{for } z < 0 \\ F(z) = e^{i\Delta\varphi} & \text{for } z > 0 \end{cases}$$

Changing phase-shift affects directly JSA exchange-symmetry





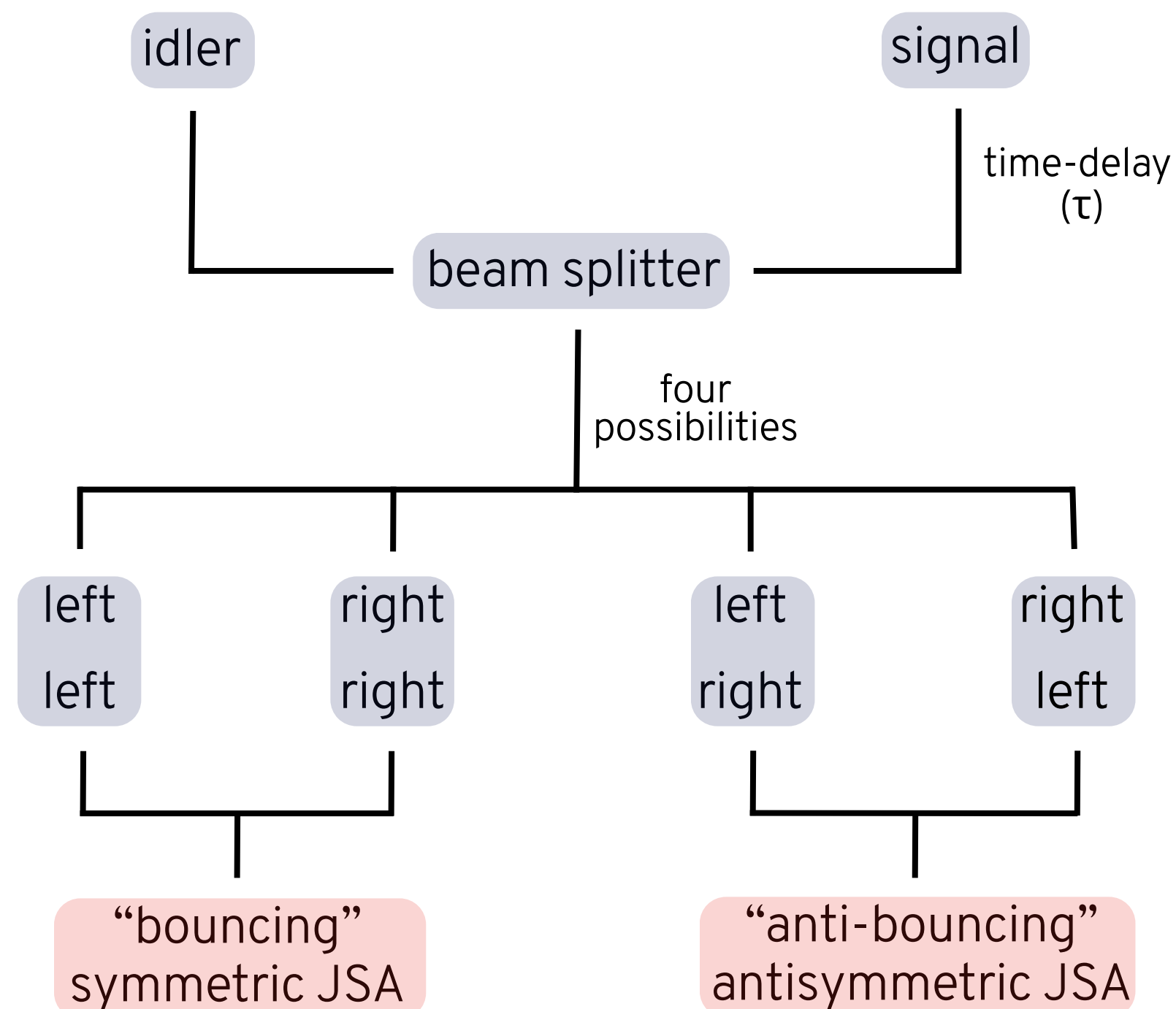
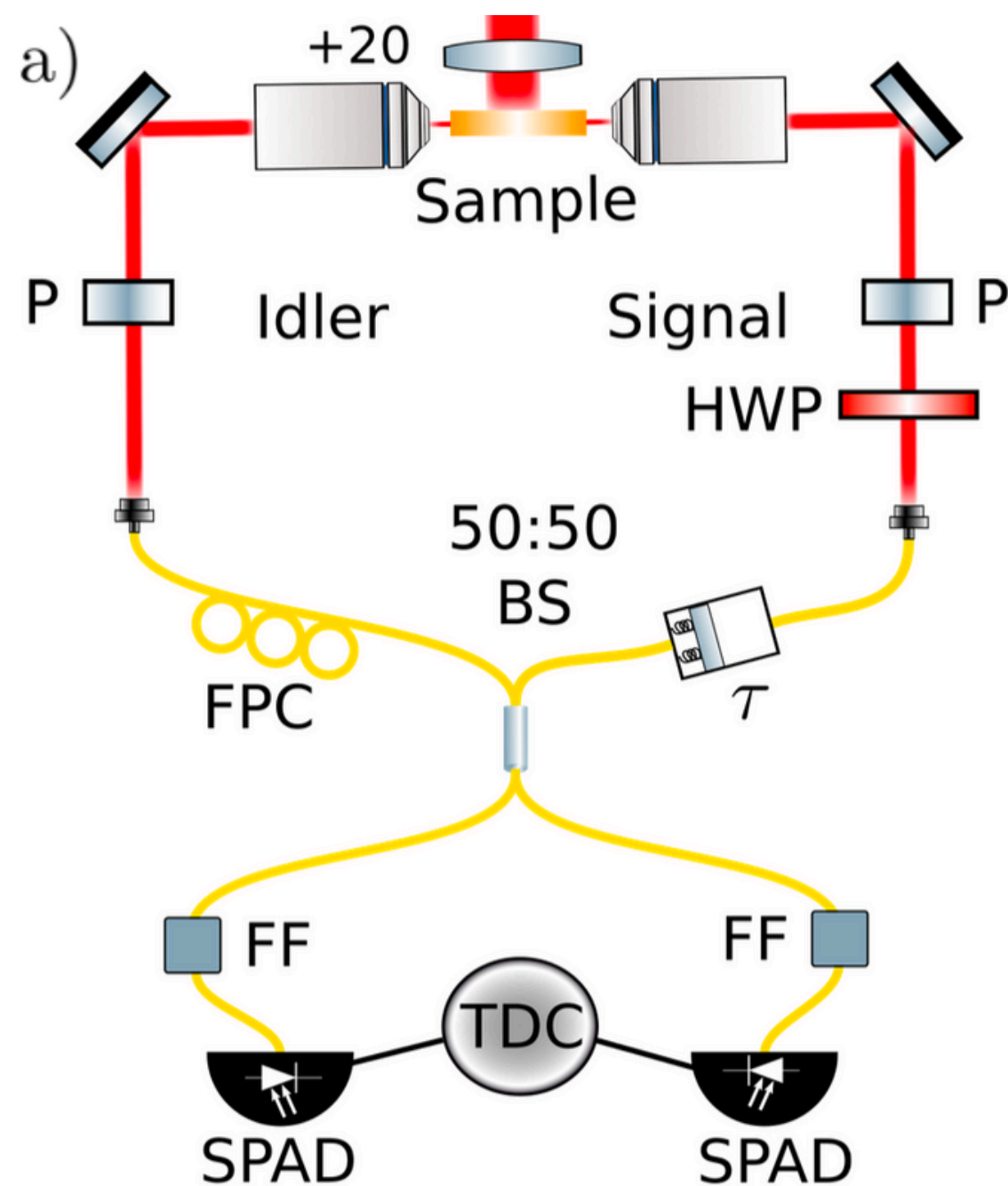
$\text{JSI}(\omega, \omega) = 0$ necessary
but not sufficient for
exchange-antisymmetry

JSI is not phase-
sensitive

how to probe
exchange symmetry?

Hong-Ou-Mandel
Interferometry^[7]

HOM as a Symmetry Probe

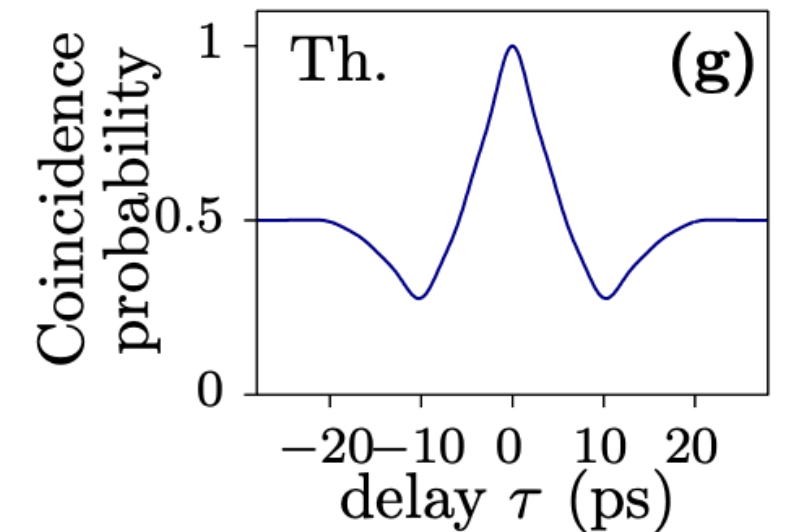
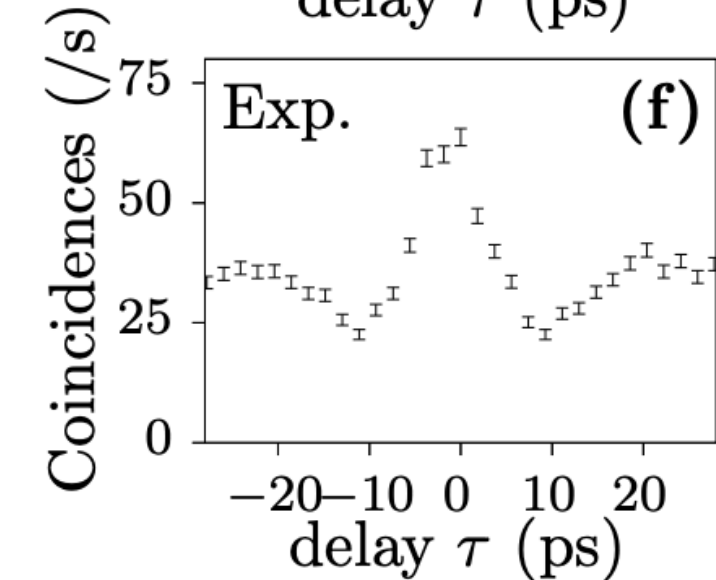
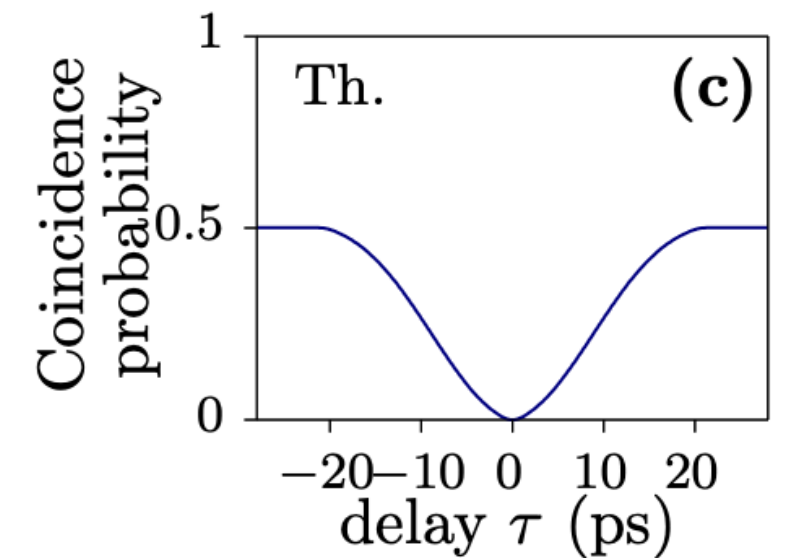
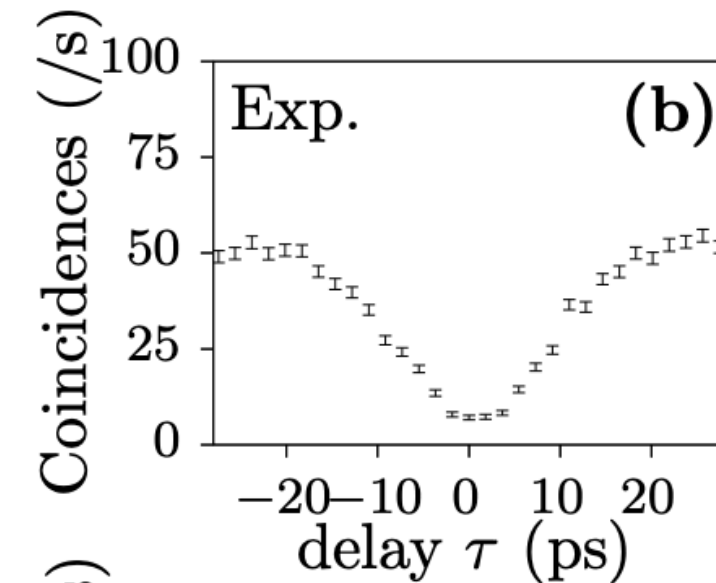
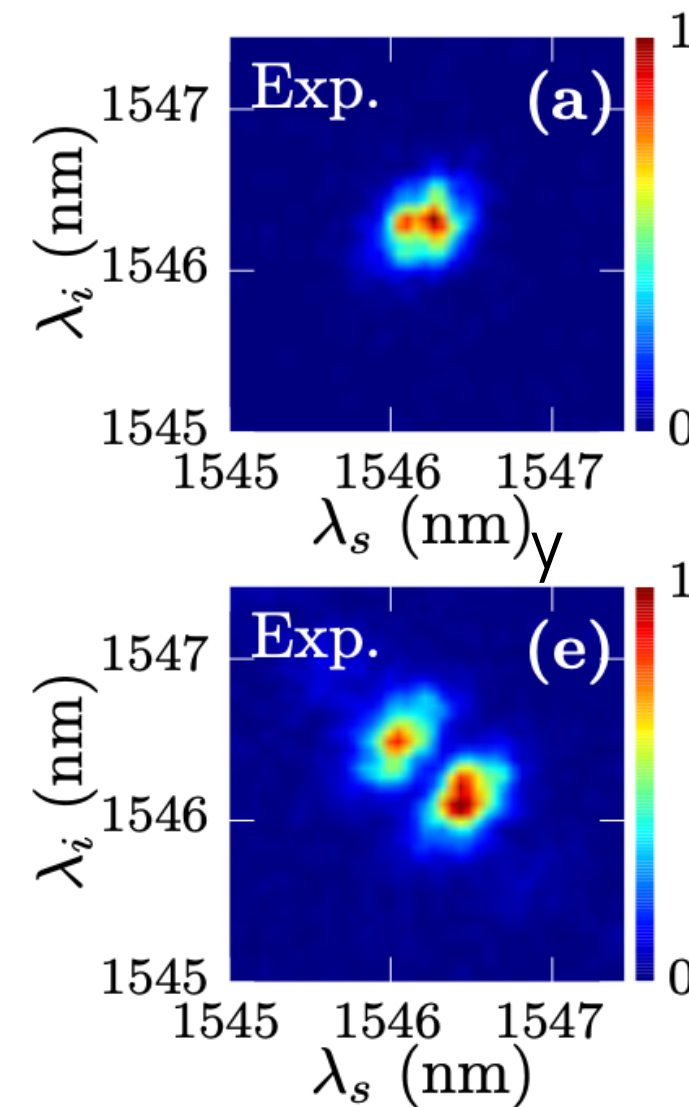




We measure are coincidence counts and JSI:

Gaussian pump-beam
symmetric state
“bouncing”

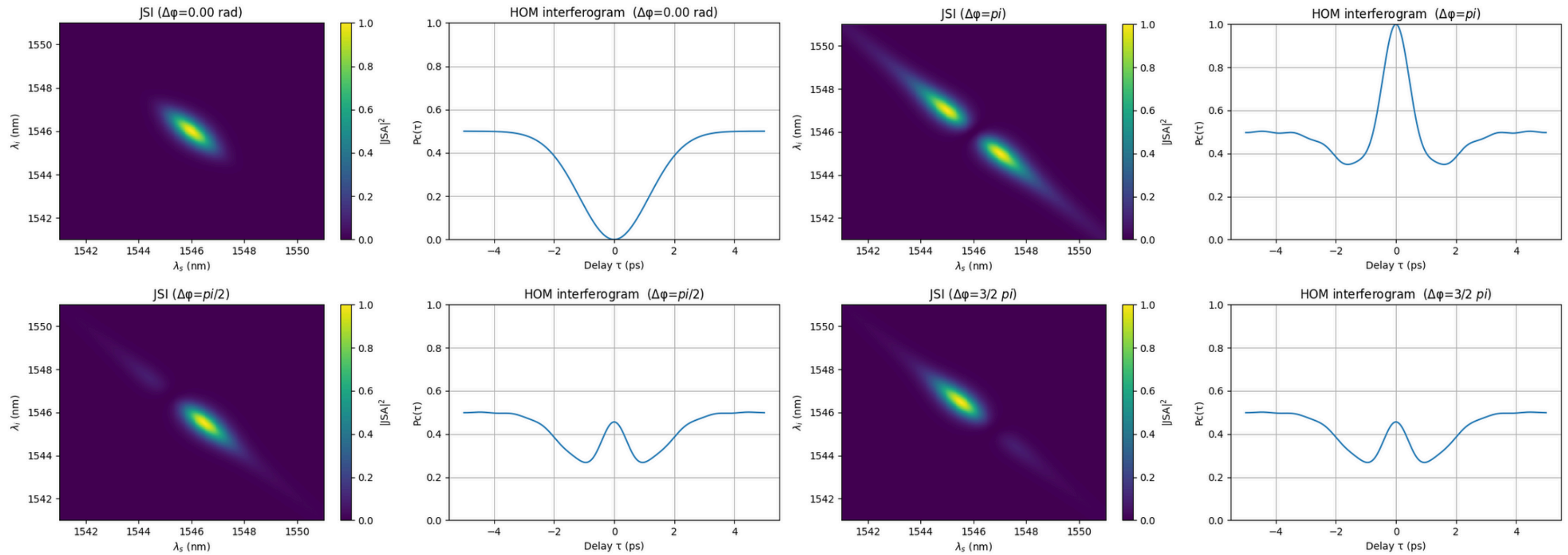
Gaussian pump-beam
antisymmetric state
“anti-bouncing”



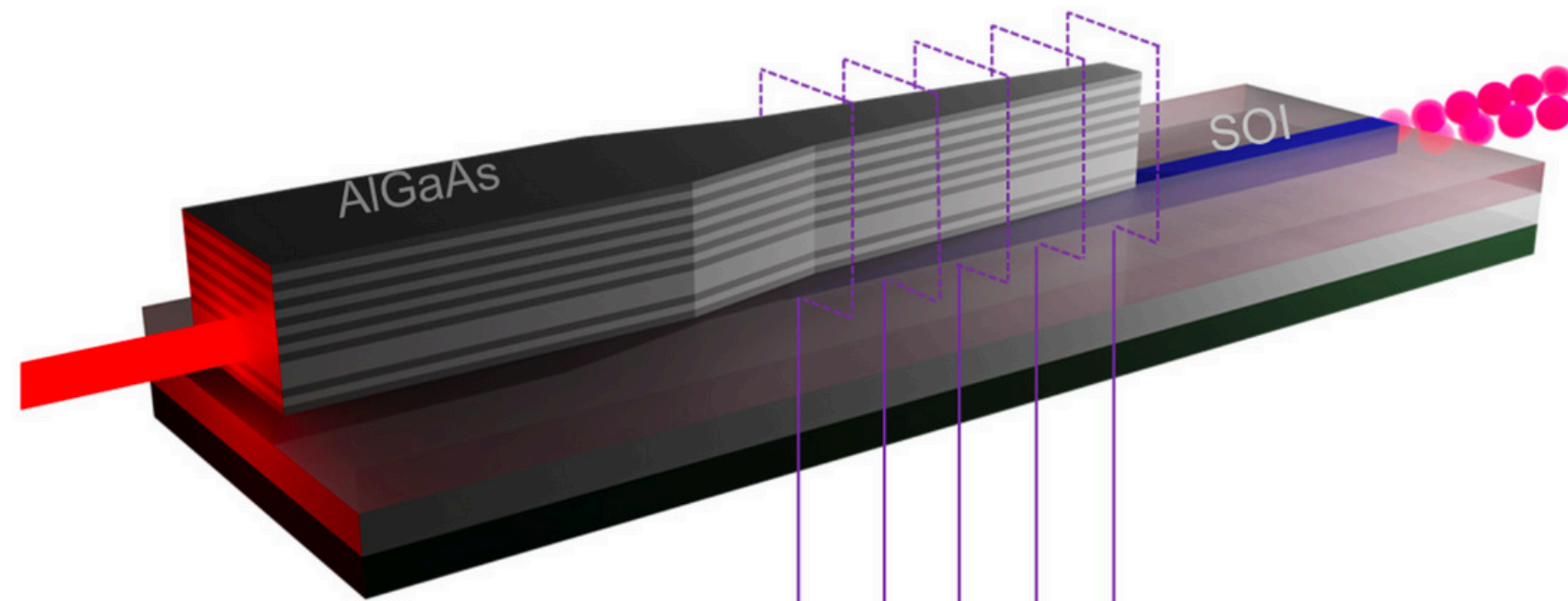
Time-delay tunes indistinguishability of the two photons



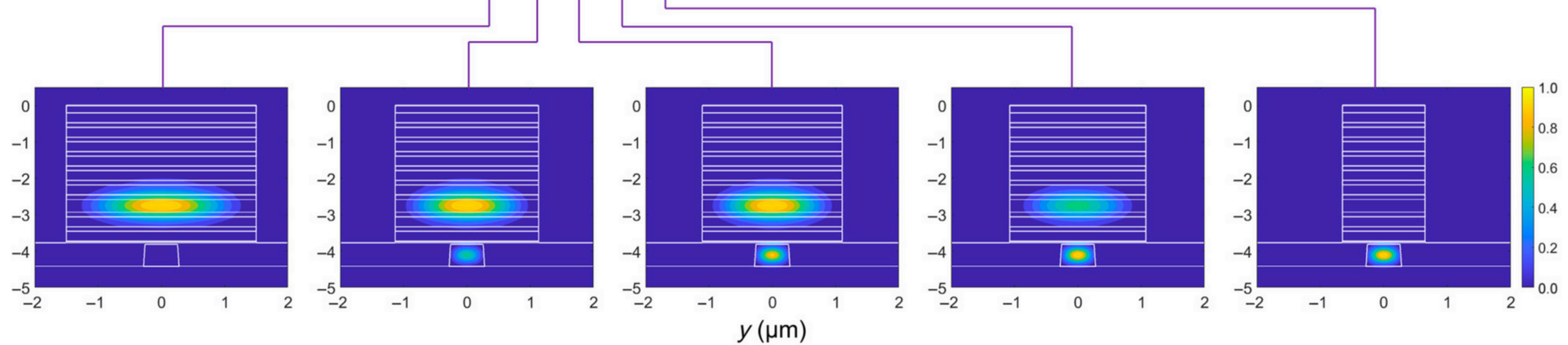
Can we introduce a different phase-shift?



A Glimpse Into the Future



...towards a fully integrated quantum photonic processors



Source: (a)-(c), (e)-(g) Ducci et al., Phys. Rev. A 102, 033508 (2020)

References

Main references

Ducci, S. et al., Phys. Rev. Research 2, 023169 (2020)

“Engineering two-photon wavefunction and exchange statistics in a semiconductor chip”

→ Main paper, core experimental and conceptual framework

Francesconi, S., PhD Thesis, Université de Paris (2020)

“On-chip generation of high-dimensional entangled states of light”

→ full theoretical development, derivations, extensions, and context

Cited in text

[1] I. Walmsley, Science 348, 525 (2015)

[2] V. Giovannetti, S. Lloyd, and L. Maccone, Nature 412, 417 (2001)





- [3] P. J. Mosley, J. S. Lundeen, B. J. Smith, P. Wasylczyk, A. B. U'Ren, C. Silberhorn, and I. A. Walmsley, Phys. Rev. Lett. 100, 133601 (2008).
- [4] A. Crespi, R. Osellame, R. Ramponi, D. J. Brod, E. F. Galvao, N. Spagnolo, C. Vitelli, E. Maiorino, P. Mataloni, and F. Sciarrino, Nature Photonics 7, 545 (2013)
- [5] G. Boucher, T. Douce, D. Bresteau, S. P. Walborn, A. Keller, T. Coudreau, S. Ducci, and P. Milman, Phys. Rev. A 92, 023804 (2015).
- [6] C. K. Law, I. A. Walmsley, and J. H. Eberly, “Continuous frequency entanglement: Effective finite hilbert space and entropy control”, Physical Review Letters 84, 5304–5307 (2000)
- [7] C. K. Hong, Z. Y. Ou, and L. Mandel, “Measurement of Subpicosecond Time Intervals between Two Photons by Interference”, 59, 2044–2046 (1987) (cit. on pp. 101, 120, 124).