# In the Name of God

# Quantum spectroscopy by photons that have not touched the sample

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Quantum phenomena do not occur in a Hilbert space. They occur in a laboratory.

A. Peres

# Topics:

- Nonlinear quantum optics:

  Metrology beyond the quantum standard limit.

- Spontaneous Parametric Down Conversion (SPDC).
- Quantum Imaging:

  Induced coherence without induced emission.

- IR Quantum Spectroscopy with visible light.
- Discussion.

Metrology beyond the quantum standard limit.

## Inquiry: precise phase measurement

Quantum Standard Limit

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Shot Noise Limit (SNL)

$$\Delta\phi_{min} = \frac{\Delta M}{dM/d\phi}$$

## Metrology beyond the quantum standard limit.

## Inquiry: precise phase measurement

For homodyne detection of a coherent state in an SU(2) interferometer we have:

$$\Delta M = \sqrt{\langle \hat{n} \rangle} \; ; \; \frac{dM}{d\phi} = \langle \hat{n} \rangle$$

$$\Rightarrow \quad \Delta\phi_{min} = \frac{1}{\sqrt{\langle \hat{n} \rangle}} \leftarrow \text{SNL}$$

We can pass SNL by Using Squeezed state instead:

$$\Delta\phi_{min} = e^{R} / \sqrt{\langle \hat{n} \rangle} \; ; \; R < 0$$

Metrology beyond the quantum standard limit.

# Inquiry: precise phase measurement

We can improve the resolution of phase measurement by using single photon in interferometer:

Single photon $\Rightarrow \begin{cases} \Delta M = 1 \\ dM/d\phi = \langle \hat{n} \rangle \end{cases} \Rightarrow \Delta\phi_{min} = \dfrac{1}{\langle \hat{n} \rangle}$,

Heisenberg limit

$\Delta\phi \Delta n \geq 1 \Rightarrow \Delta\phi_{min} = \dfrac{1}{\langle \hat{n} \rangle}$

$\Delta n_{max} = \langle \hat{n} \rangle$

# Metrology beyond the quantum standard limit.

## Inquiry: precise phase measurement

Also, using entangled NOON states in interferometer can help us to reach Heisenberg limit.

$$|NOON\rangle = \frac{1}{\sqrt{2}}\left(|N0\rangle + |0N\rangle\right)$$

$$\Delta\phi_{min} = 1/N$$

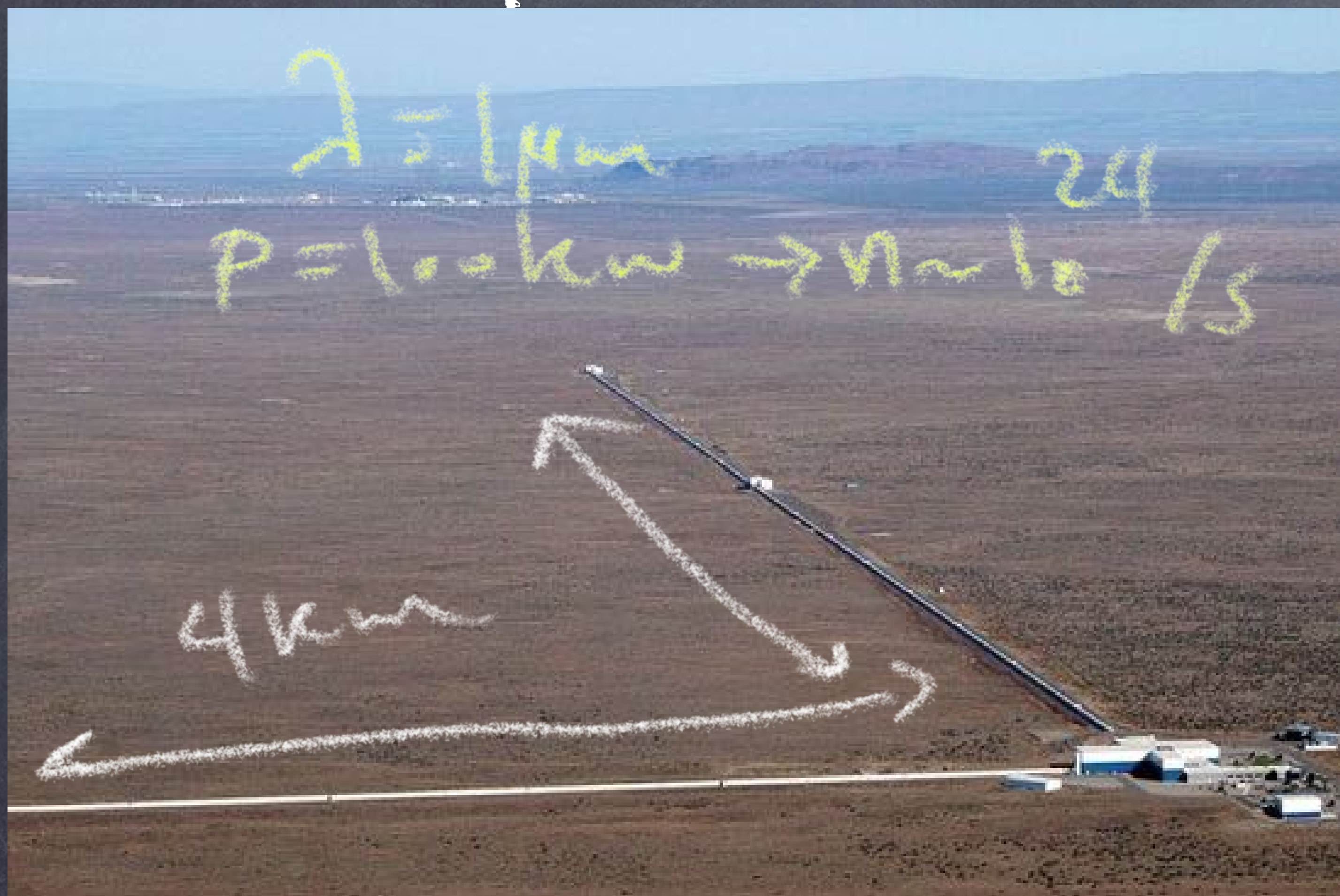
$$\lambda^{D}_{NOON} = \frac{\lambda^{D}_{single\ photon}}{N} \Rightarrow \text{Super photon}$$

$\Downarrow$

to Lithography

to Imaging

# For example: LIGO Interferometer:




$$\Delta\phi = k\,\Delta x$$

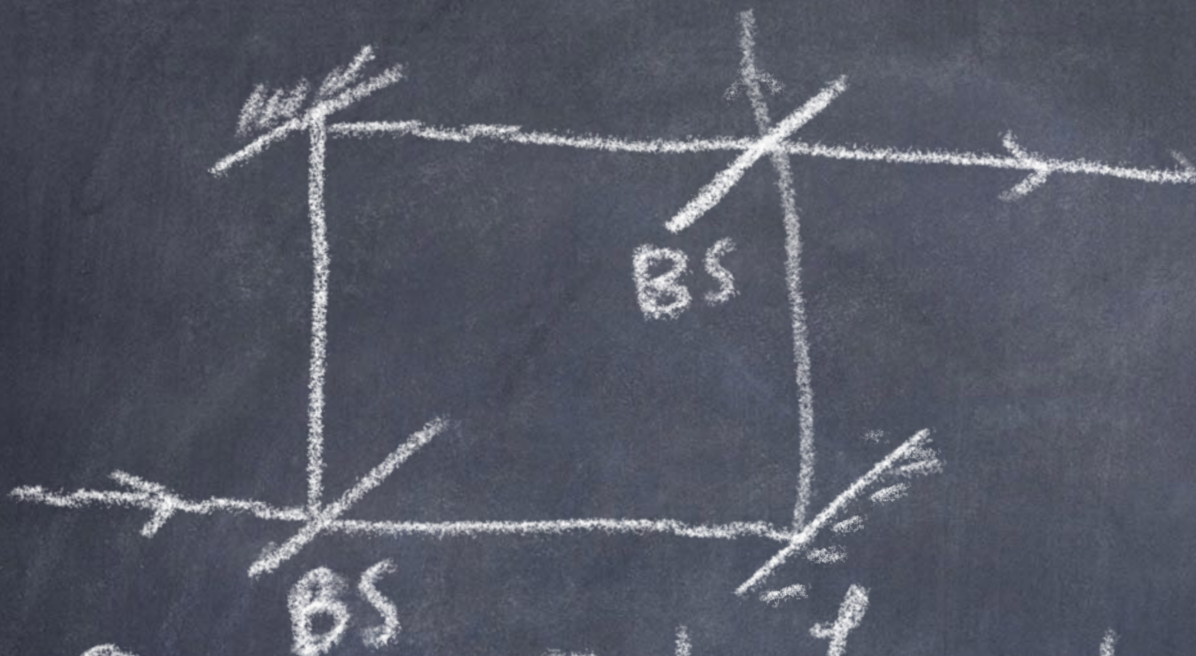
$$\Delta x = \frac{\Delta\phi}{k} = \frac{\lambda\Delta\phi}{2\pi}$$

$$\Delta x_{min} = \frac{\lambda\Delta\phi_{min}}{2\pi}$$

coherent state $\rightarrow \Delta x_{min} = \dfrac{\lambda}{2\pi\sqrt{\langle \hat{n}\rangle}} \sim 10^{-19}\,m$

Single photon state $= \Delta x_{min} = \dfrac{\lambda}{2\pi\langle \hat{n}\rangle} \sim 10^{-31}\,m$

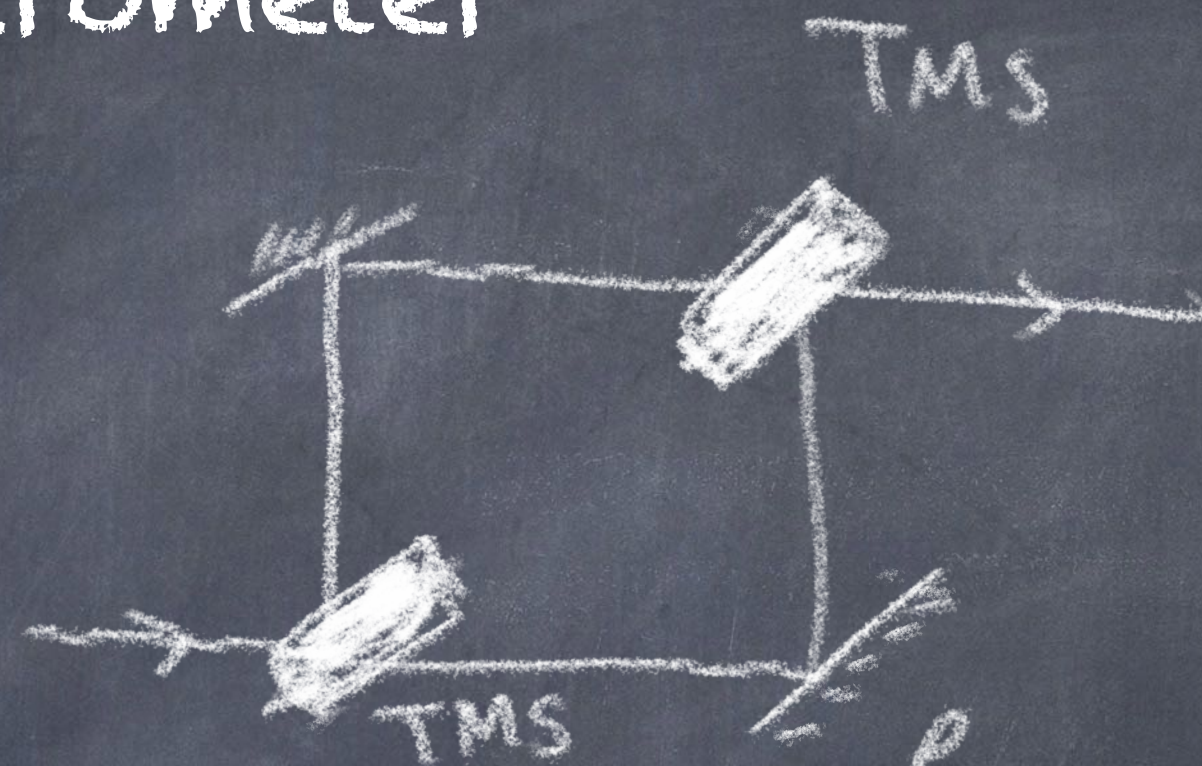
# Non-linear Interferometer




SU(2)-Interferometer

$\downarrow$

$$\mathcal{H}_{in} = g\,\hat{a}_1^\dagger \hat{a}_2 + H.c.$$




SU(1,1)-Interferometer

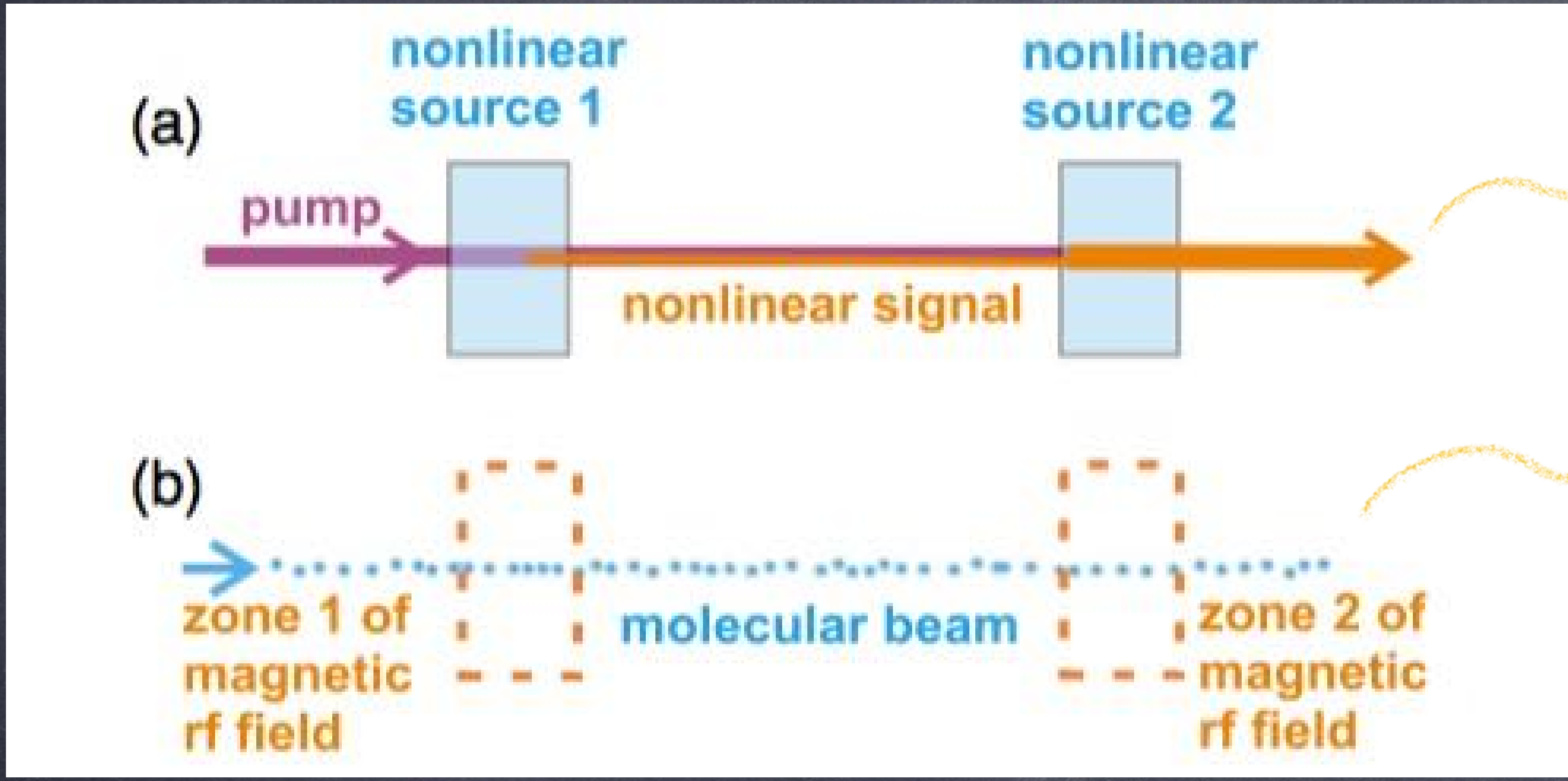
$\downarrow$

$$\mathcal{H}_{in} = g\,\hat{a}_s^\dagger \hat{a}_i^\dagger + H.c.$$

BS ≡ Beam splitter

TMS ≡ Two-Mode Squeezer

# Nonlinear Interferometer:



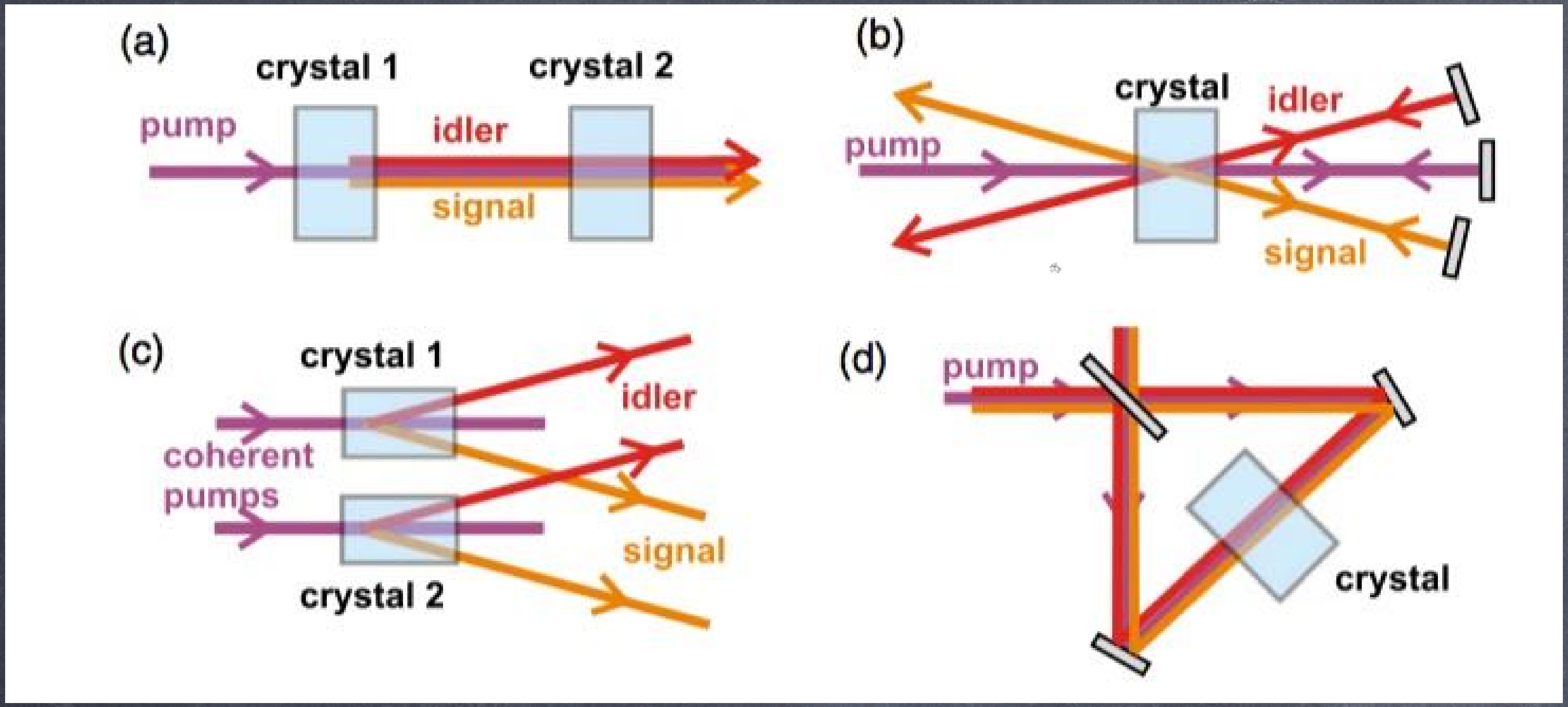

non linear interferometer

Ramsey experiment

1966 → 1970

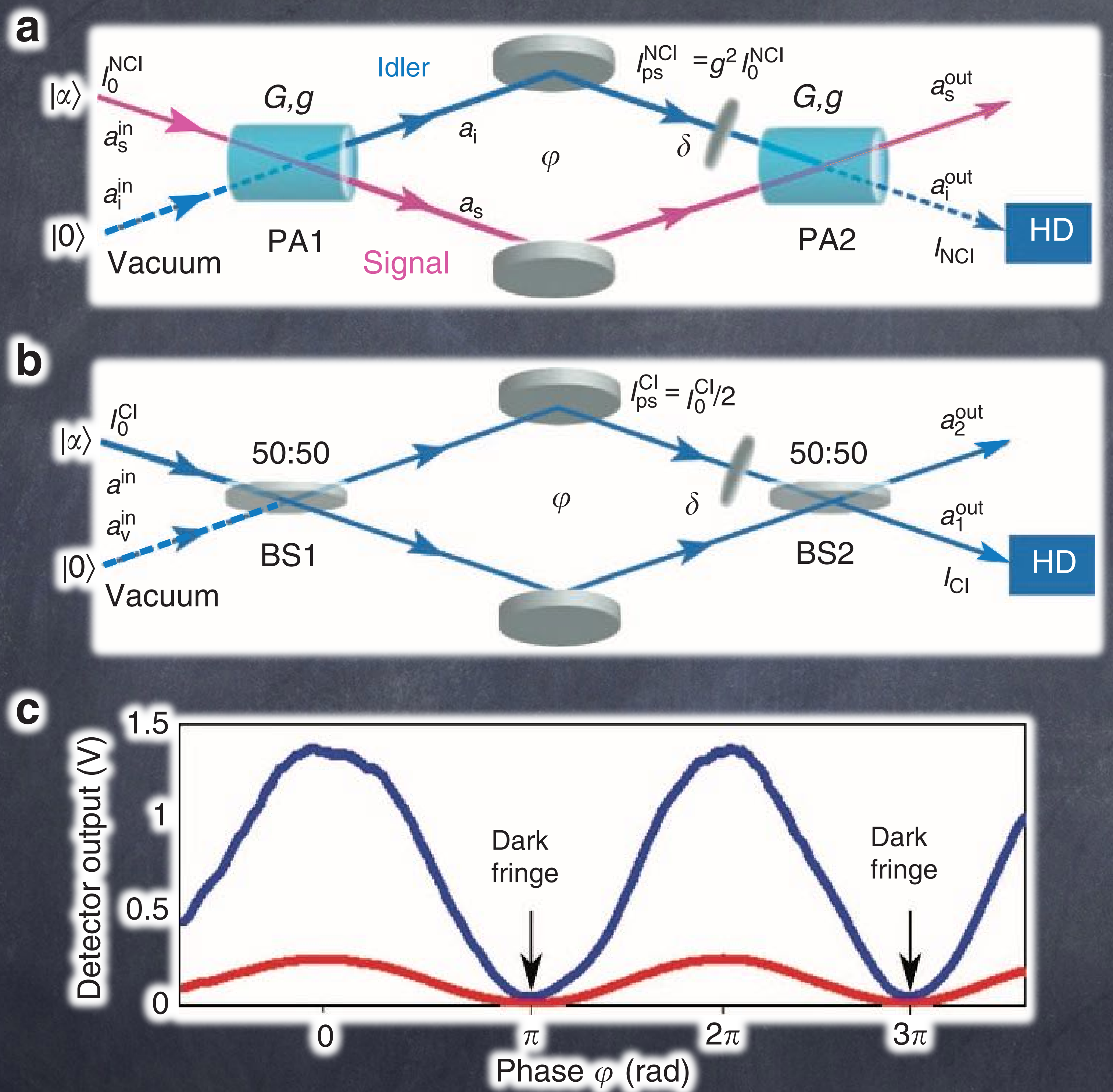
7/20

# SU(1,1) nonlinear Interferometers:




a) Mach-Zender Int.
b) Michelson Int.
c) Young Int.
d) Saganac Int.

# The fringe enhancement of SU(1,1) w.r.t. SU(2) Int.




Signal ↑
Noise ↓

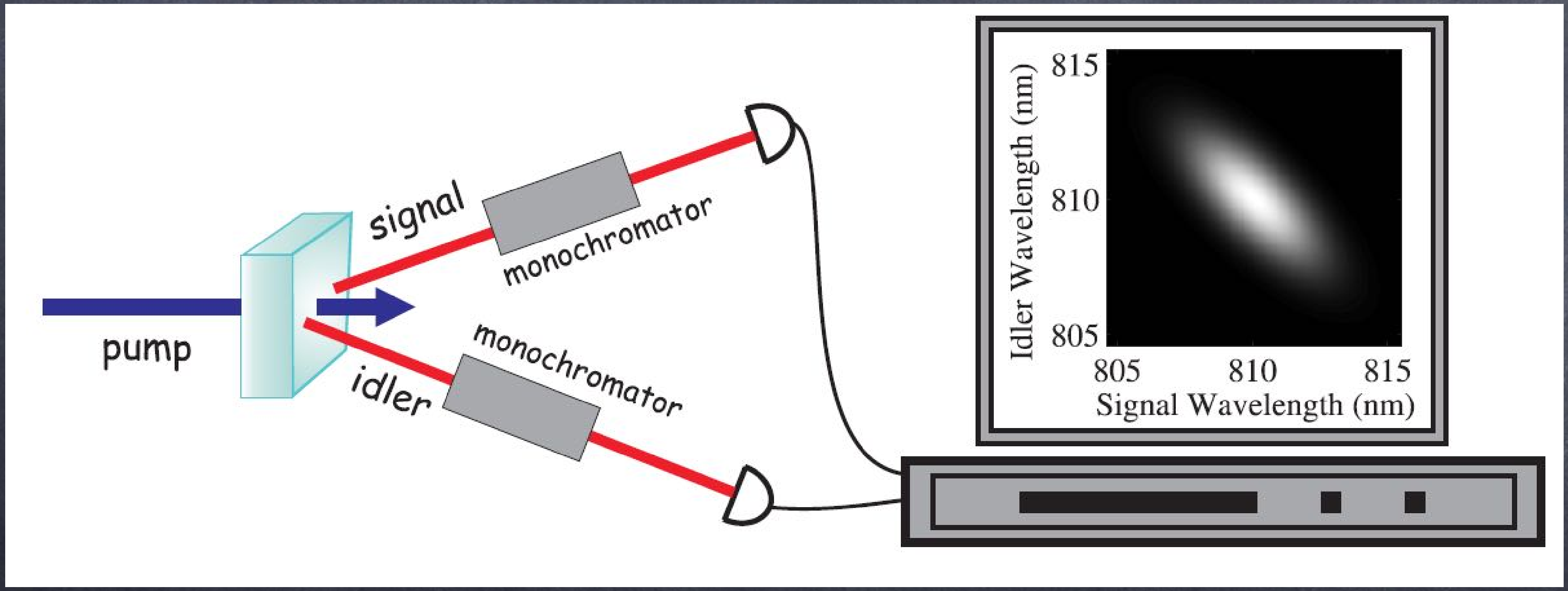
NATURE COMMUNICATIONS DOI: 10.1038/ncomms4049

Idea:

Using SPDC as two-mode squeezer in a non-linear interferometer, for the purpose of high precision phase measurement for Spectroscopy and characterization of optical component.

# Spontaneouse Parametric Down-Conversion (SPDC)

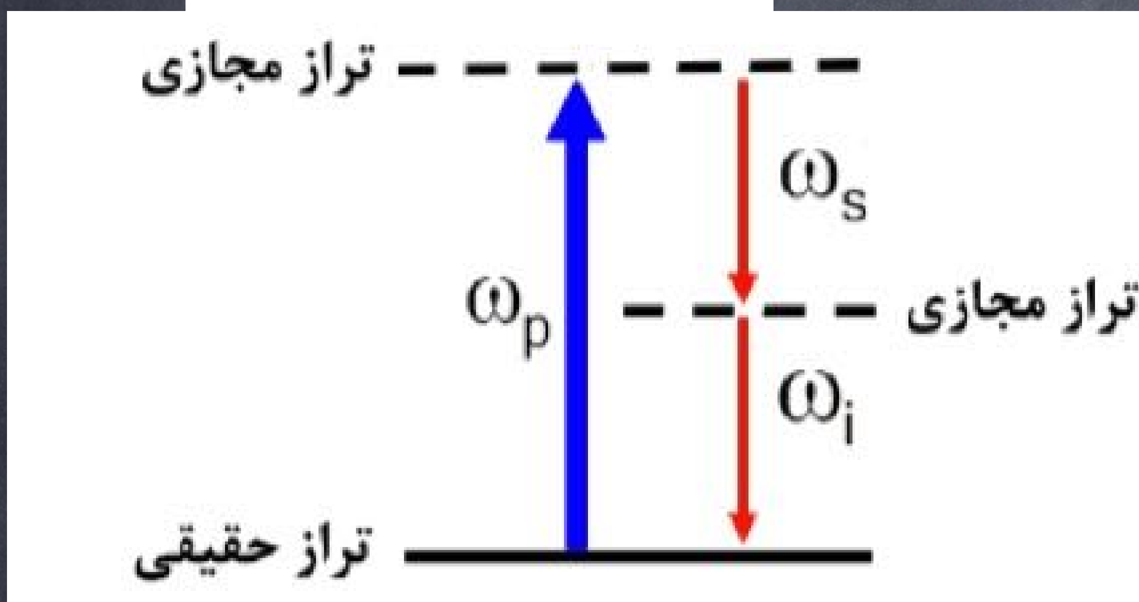
$$\mathbf{P} = \epsilon_0 \chi^{(1)} \mathbf{E} + \epsilon_0 \chi^{(2)} \mathbf{E}^2 + \epsilon_0 \chi^{(3)} \mathbf{E}^3 \ldots$$
$$= \epsilon_0 \sum_{n=1,2,3,\ldots} \chi^{(n)} \mathbf{E}^n,$$



# Frequency and Phase Matching in SPDC

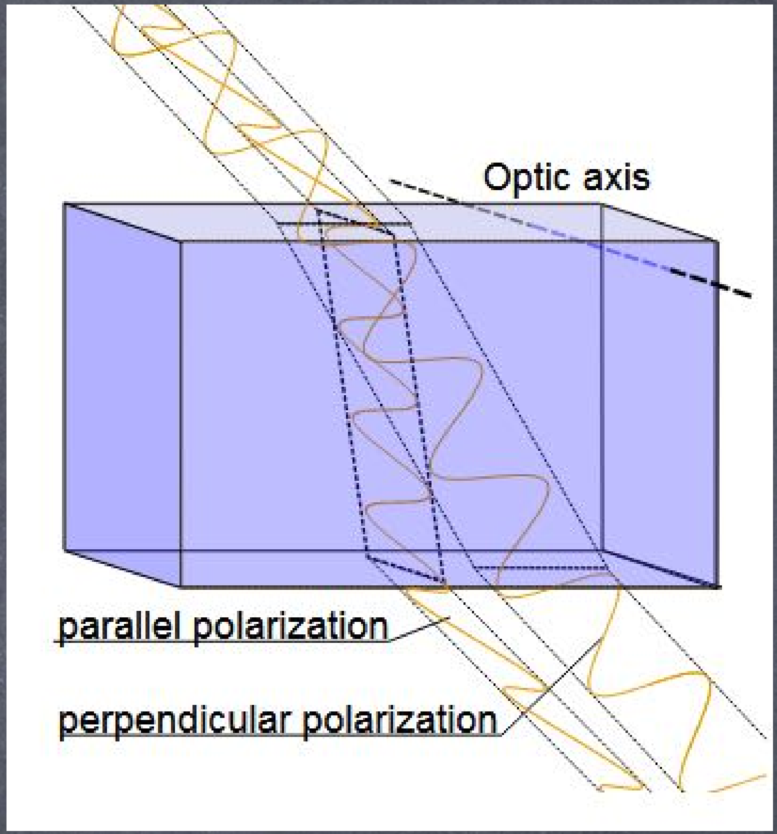
$$\omega_p = \omega_s + \omega_i$$

$$\vec{k}_p = \vec{k}_s + \vec{k}_i$$

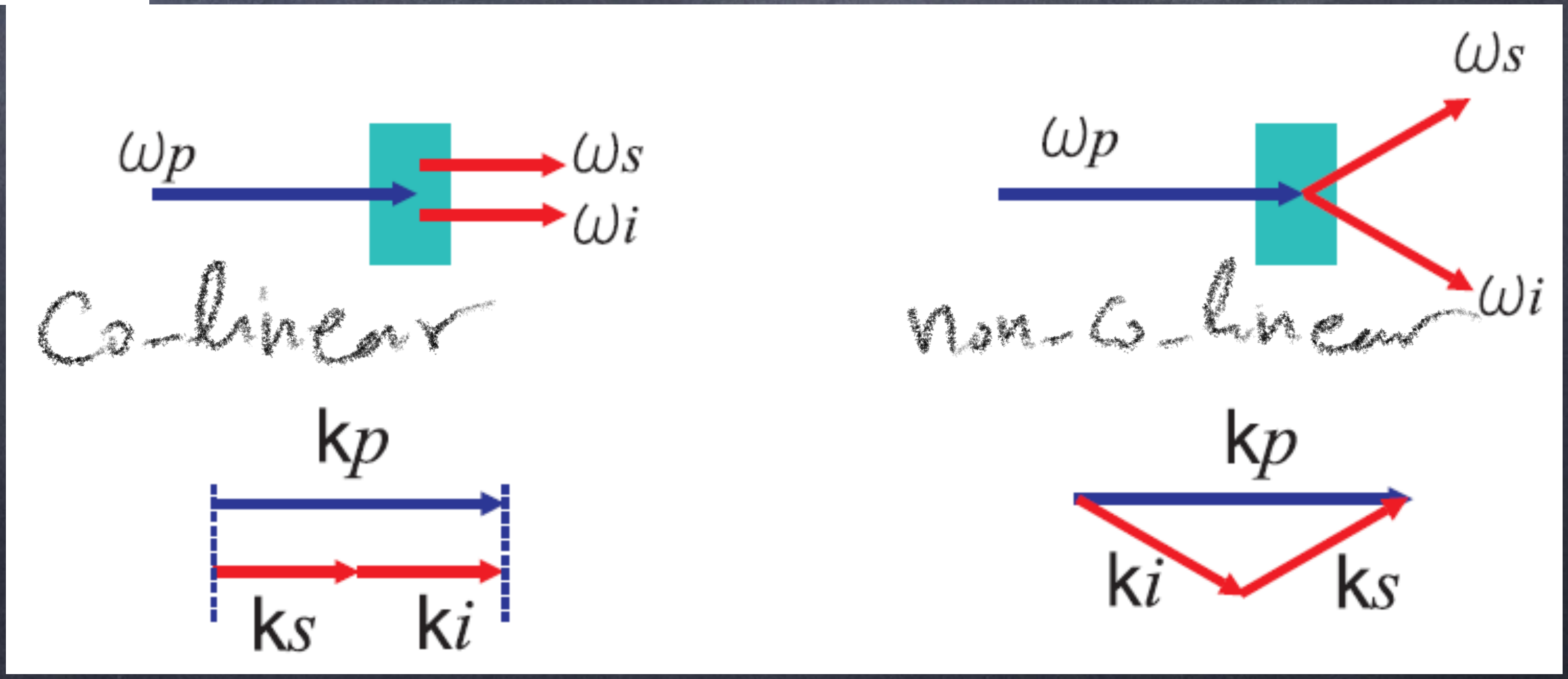



phase mismatch

$$\vec{\Delta k} = \vec{k}_p - \vec{k}_i - \vec{k}_s$$

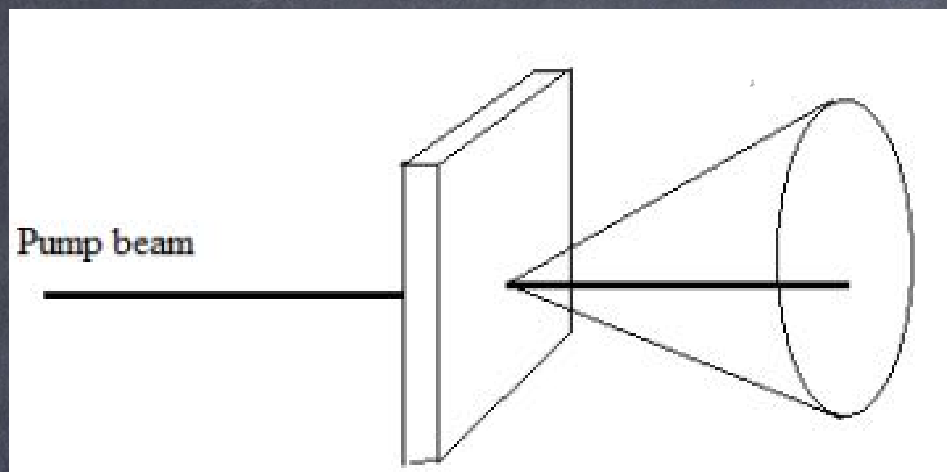


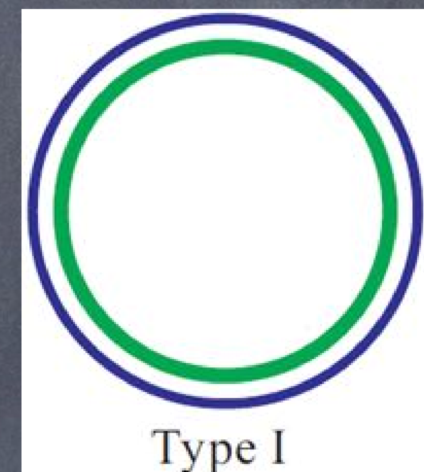

Realization of phase matching
↓
birefrigence crystal



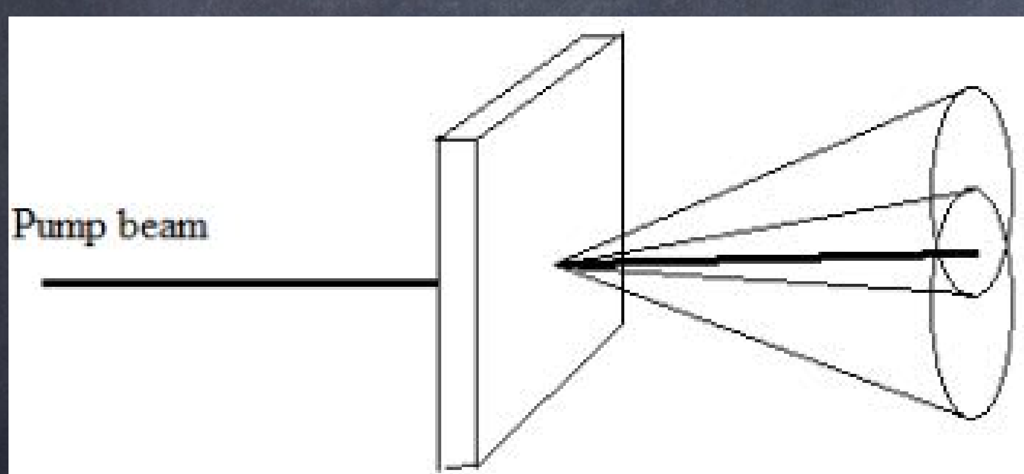
# SPDC Types:

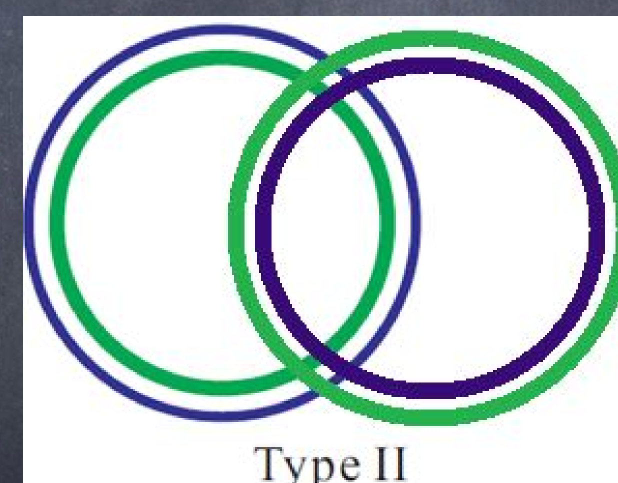
$$\text{Type I}: \; o \longrightarrow e + e, \quad e \longrightarrow o + o,$$



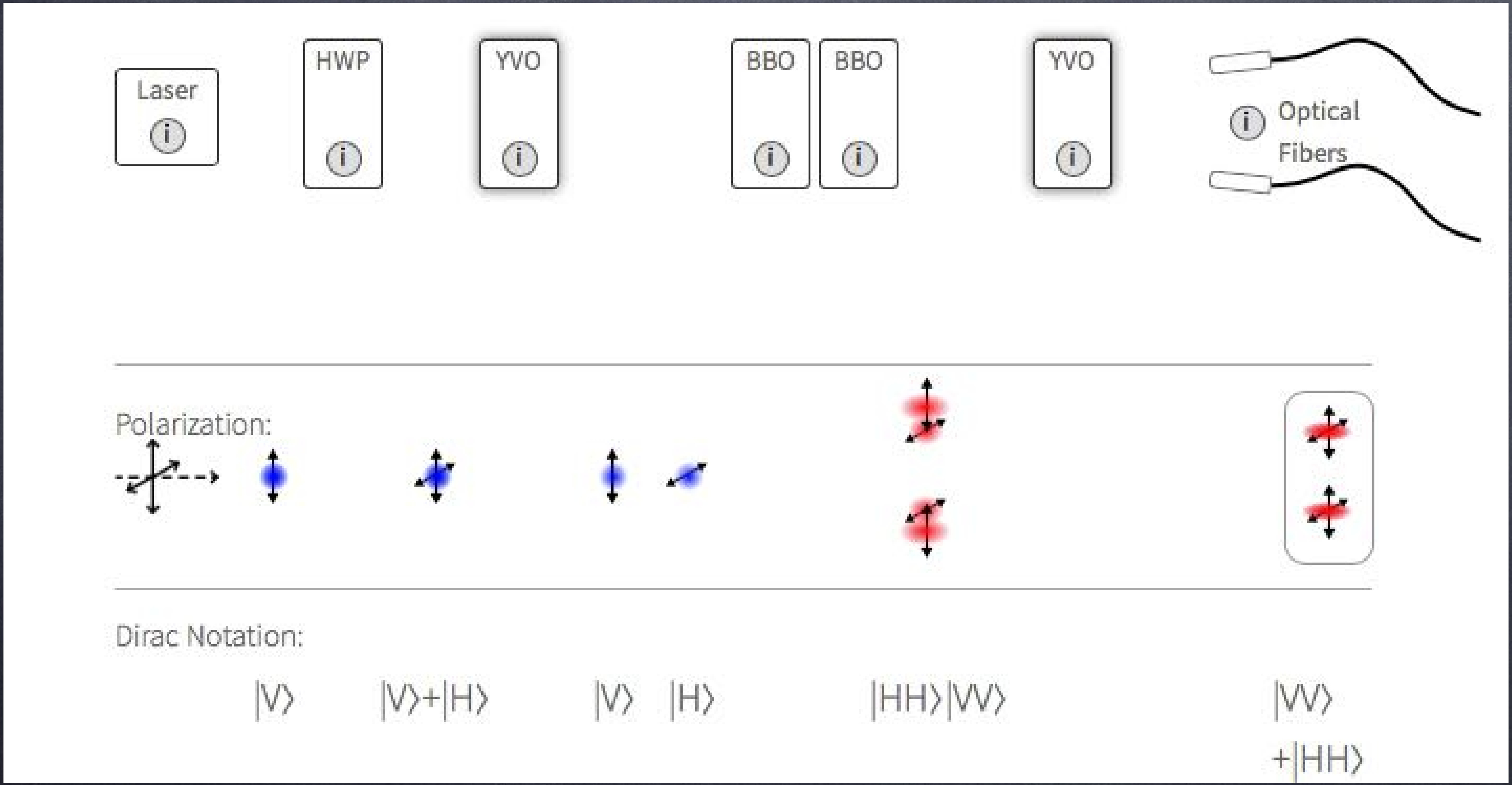

$$\text{Type II}: \; o \longrightarrow o + e, \quad e \longrightarrow o + e.$$



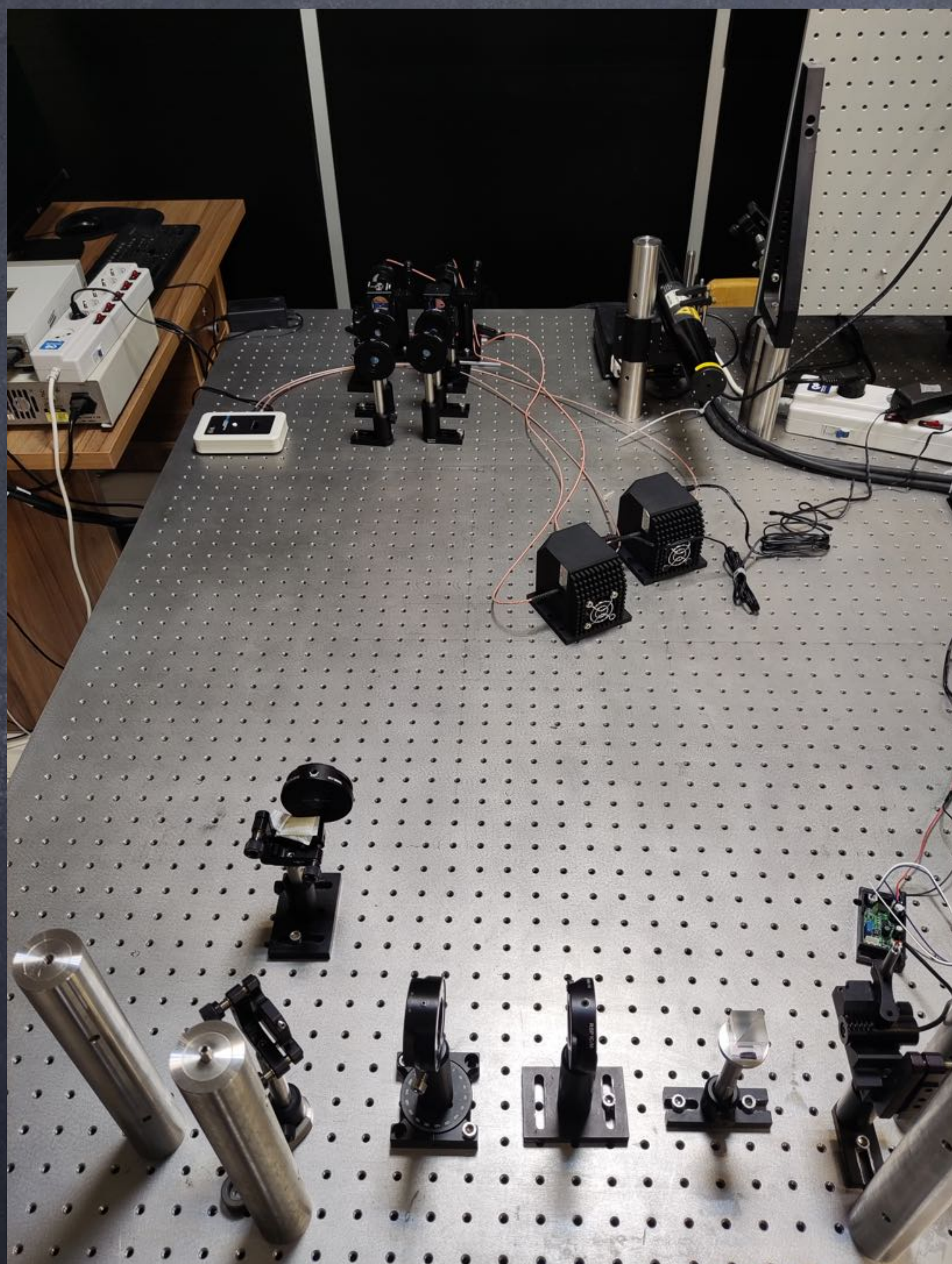



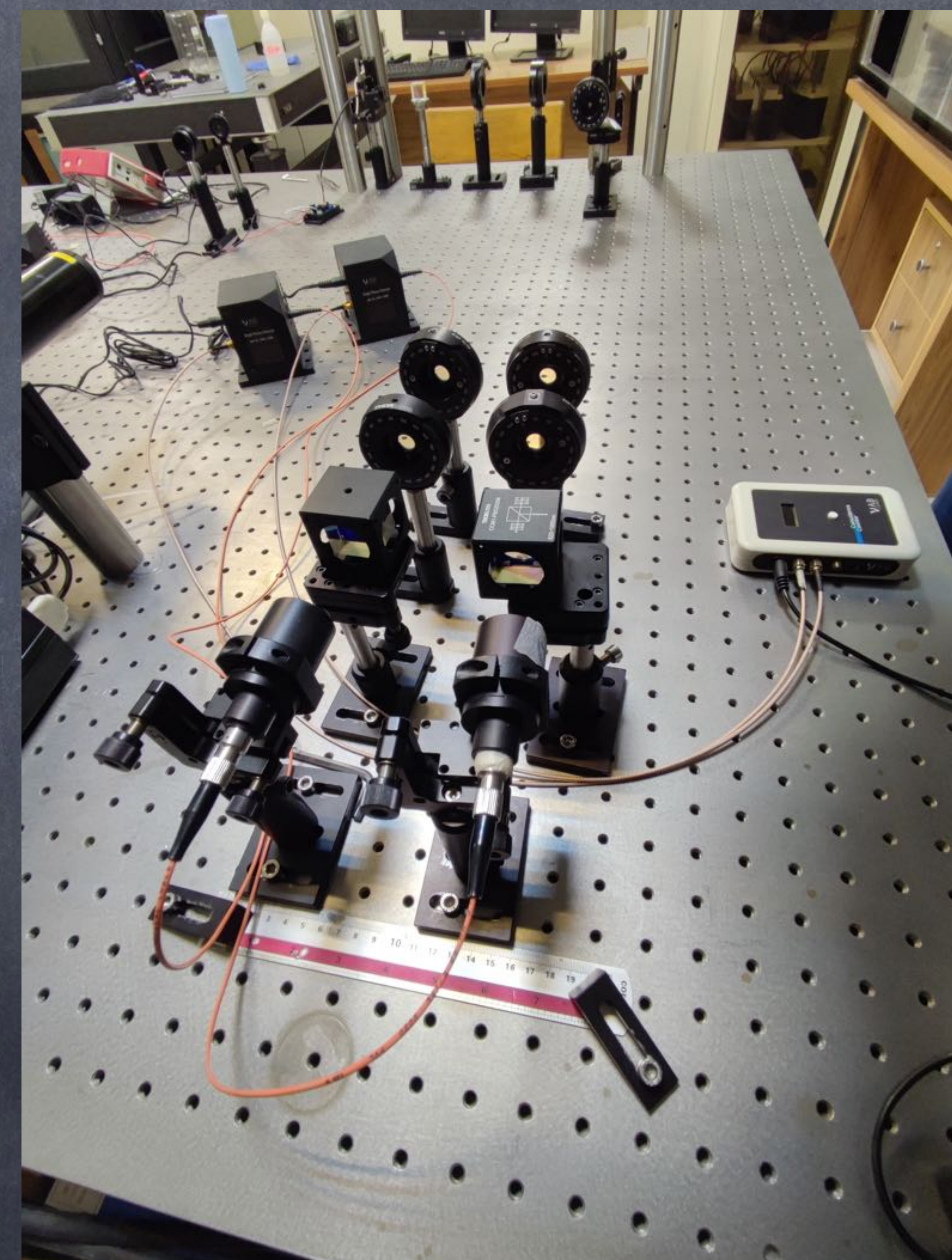

phase matching process Can controlled by
1- crystal 2- proper crystal cutting 3- $\Delta\lambda_p(\Delta\lambda_d)$

# Spontaneouse Parametric Down-Conversion (SPDC)



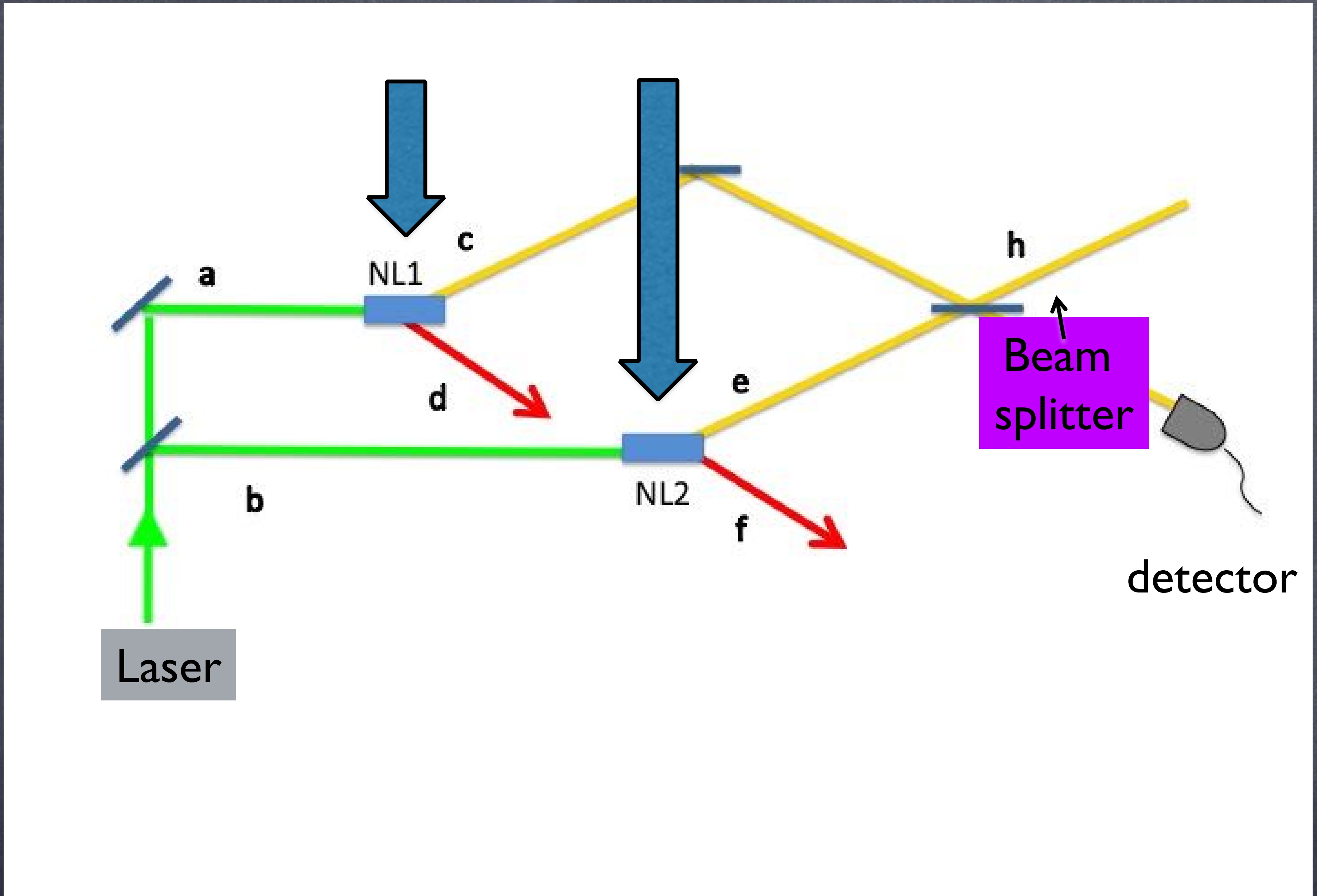
# Bell inequality Test & Quantum Tomography





# Can the yellow paths interfere?

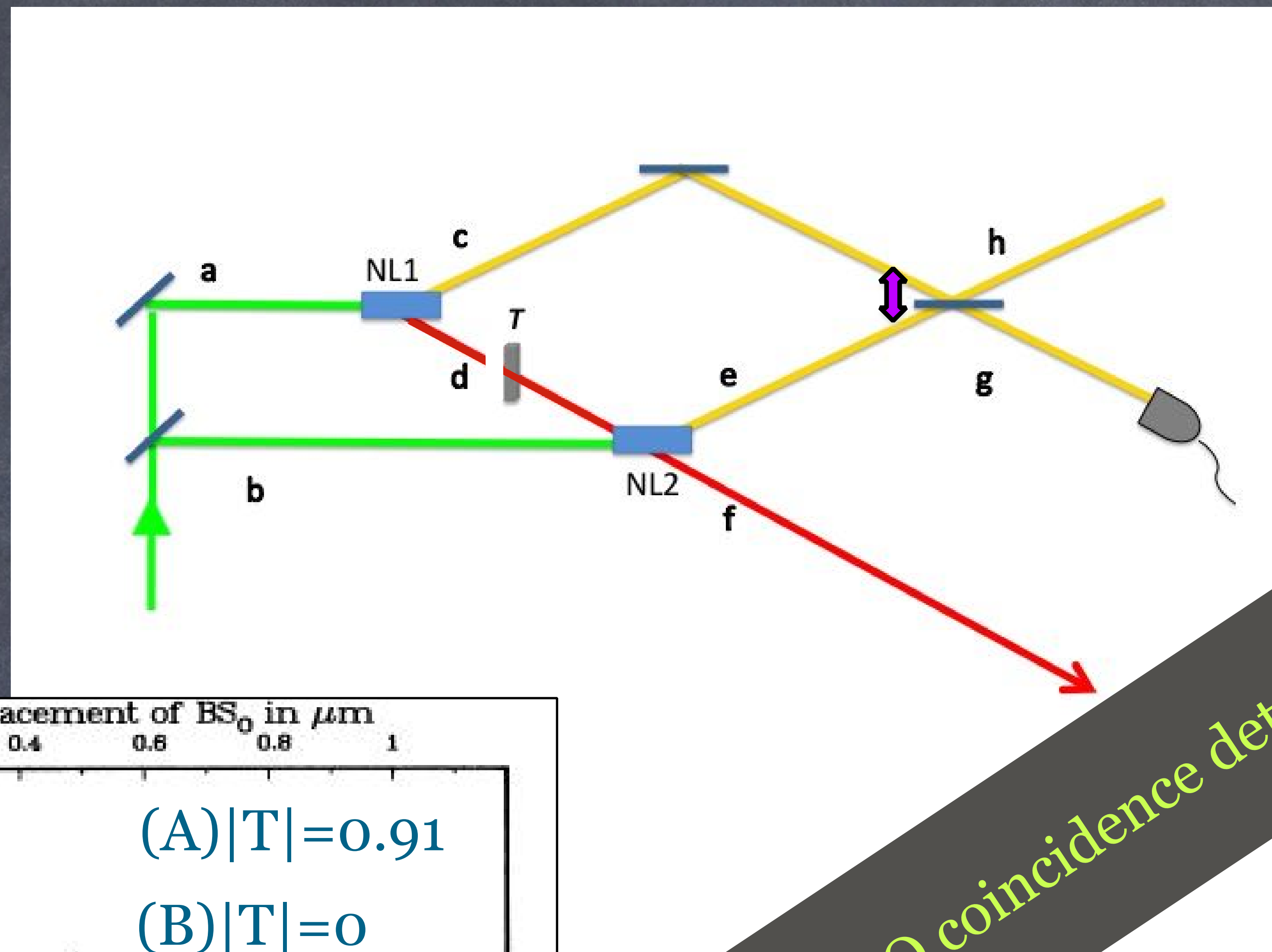
Two SPDC sources

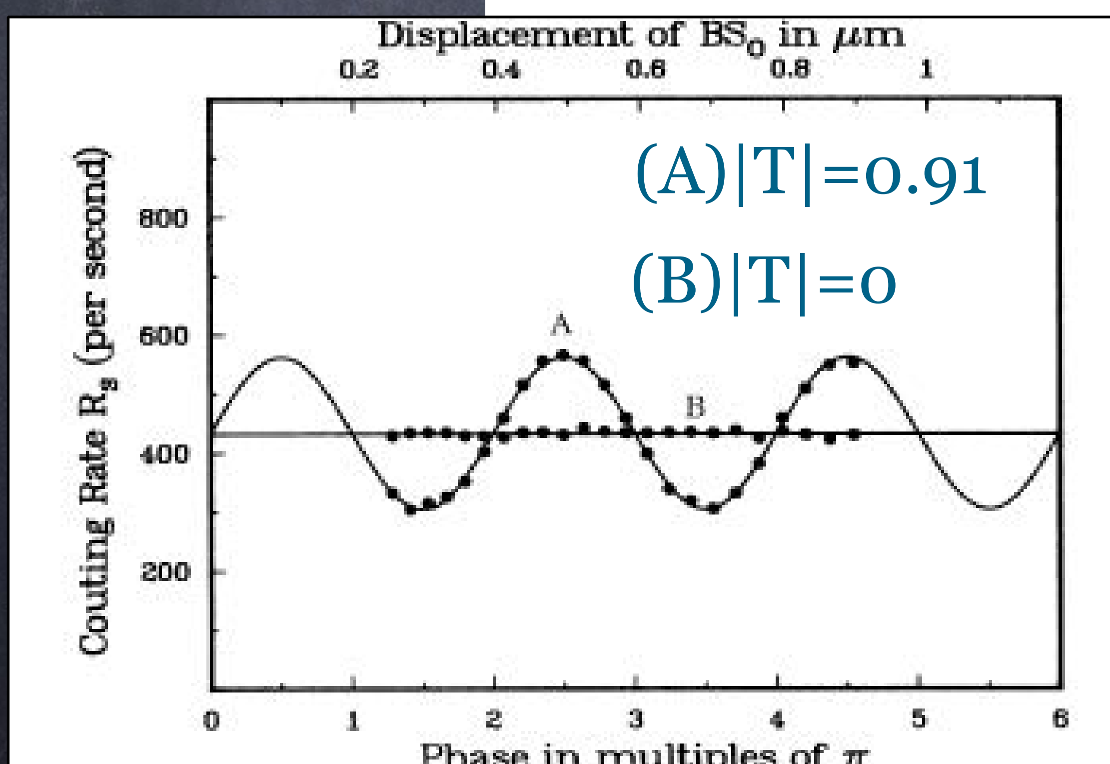



NO!

Because d and f carry information as to where the detected yellow photon came from

# Can the yellow paths interfere? Yes



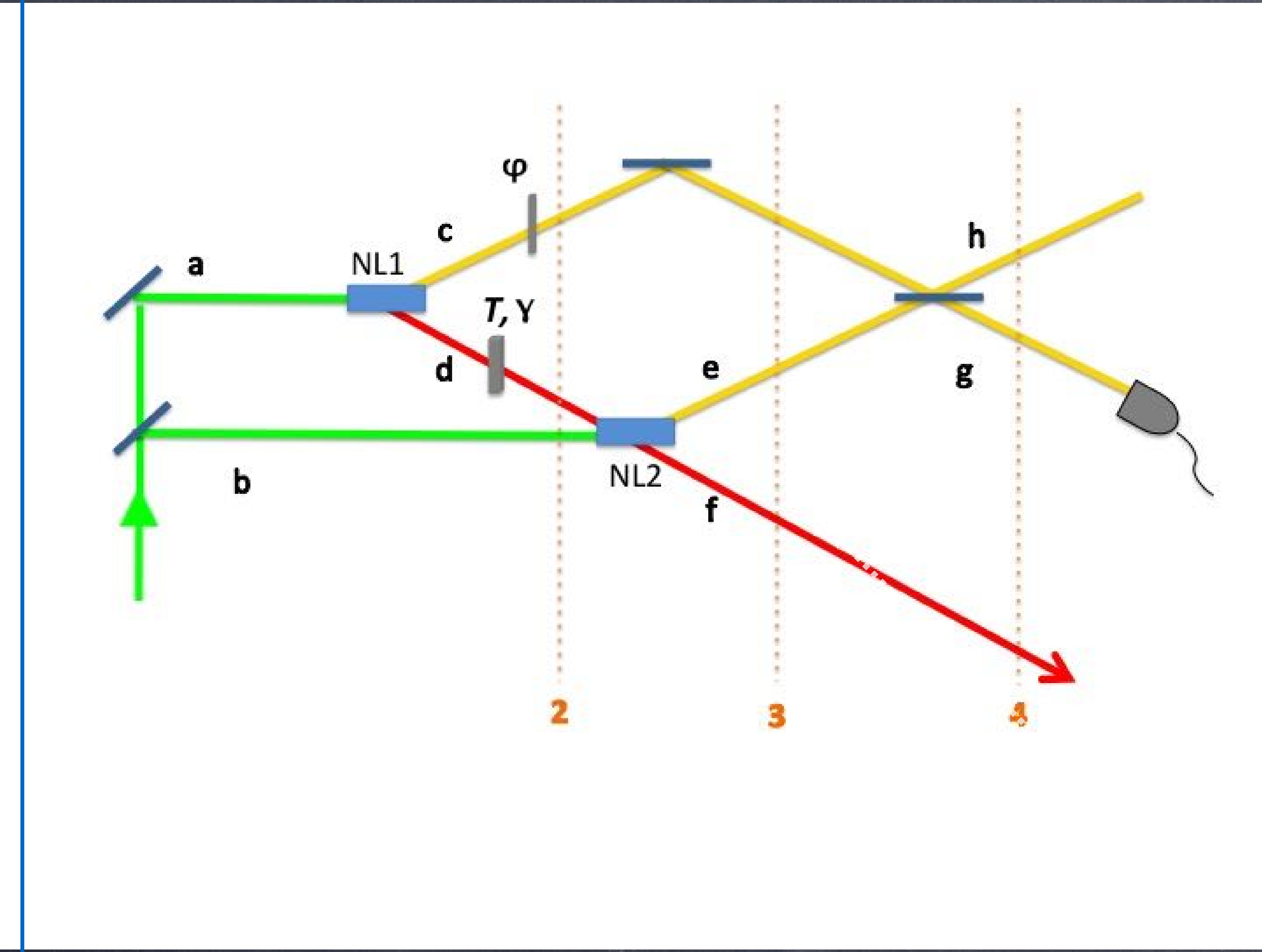

NO coincidence detections!

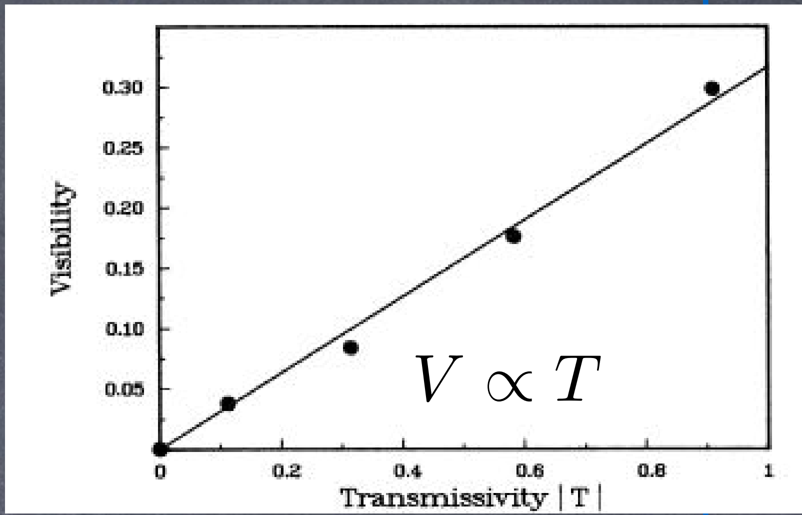
Only one pair of photons is generated!

This is NOT two photon interference!

Zou, Wang, Mandel, Phys Rev. Lett. 67, 318 (1991)

# Induced Coherence without Induced



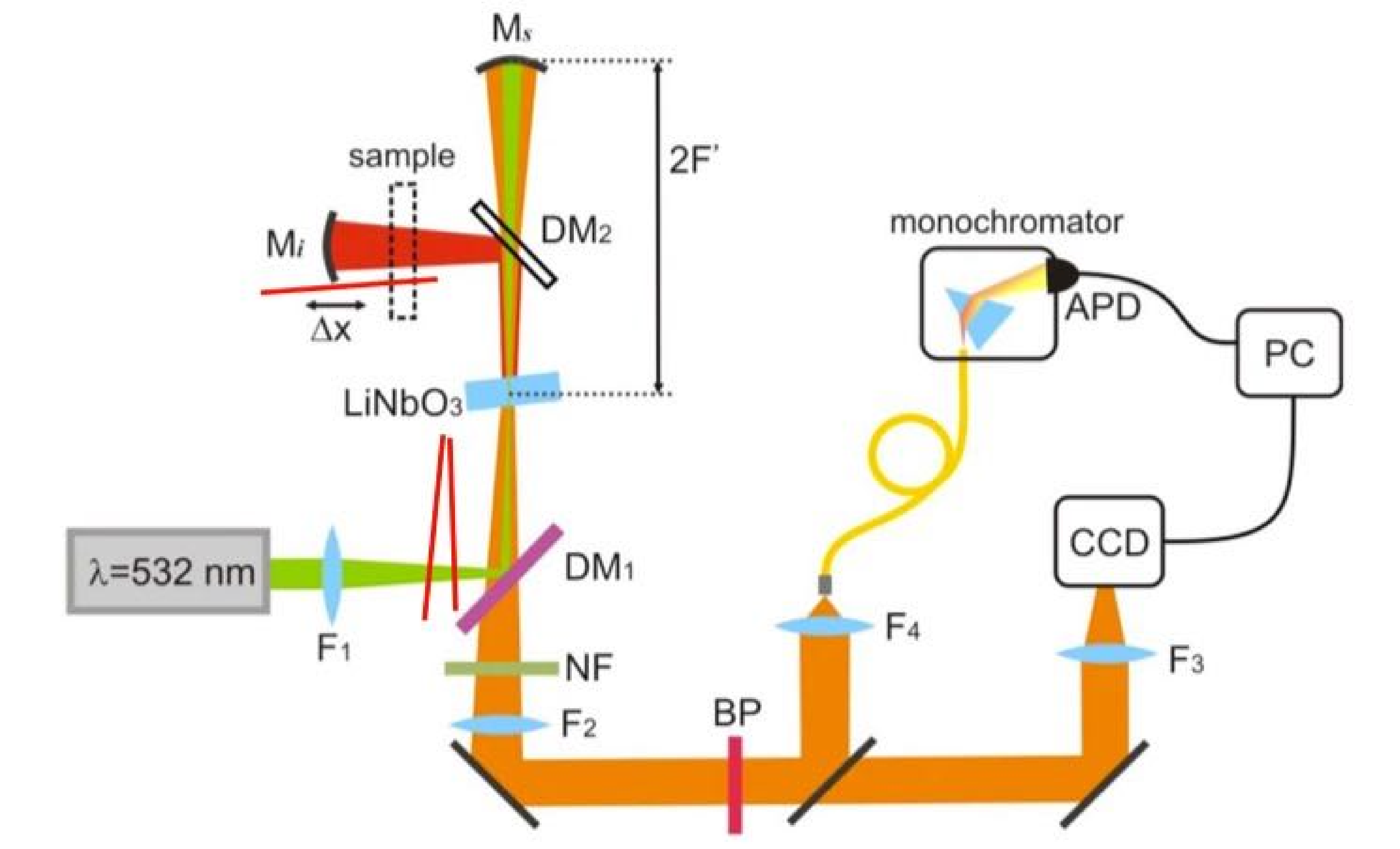

**1** $$\frac{1}{\sqrt{2}}(|a\rangle + |b\rangle)$$

**2** $$\frac{1}{\sqrt{2}}(Te^{i\phi}e^{i\gamma}|c\rangle|d\rangle + |b\rangle)$$

**3** $$\frac{1}{\sqrt{2}}(Te^{i\phi}e^{i\gamma}|c\rangle|f\rangle + |e\rangle|f\rangle)$$

**4** $$P_g = \frac{1}{2}[1 + T\cos(\phi + \gamma)]$$

# Experimental setup




$$|\Psi\rangle = |\psi\rangle_1 + |\psi\rangle_2 = |\mathrm{vac}\rangle + \tilde{\eta}\iint \mathrm{d}\omega_s \mathrm{d}\omega_i F(\omega_s,\, \omega_i) a_{s1}^{+} a_{i1}^{+} |\mathrm{vac}\rangle$$
$$+ \tilde{\eta} \mathrm{e}^{\mathrm{i}\varphi_p} \iint \mathrm{d}\omega_s \mathrm{d}\omega_i F(\omega_s,\, \omega_i) a_{s2}^{+} a_{i2}^{+} |\mathrm{vac}\rangle,$$

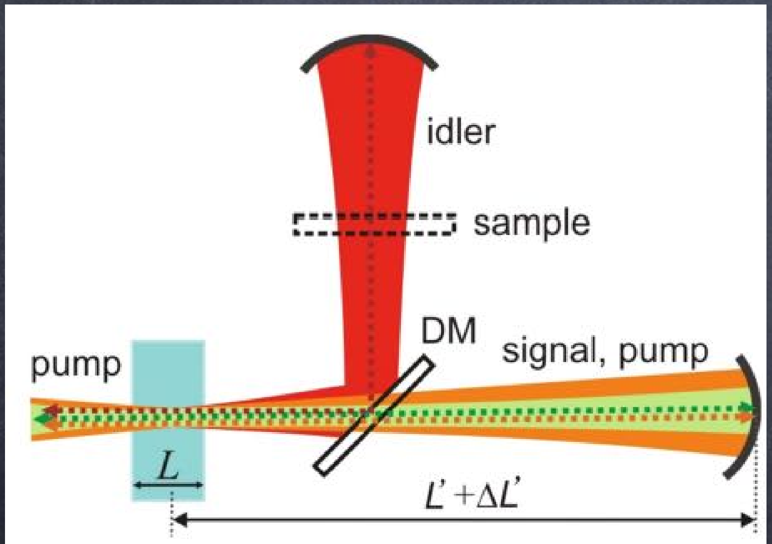


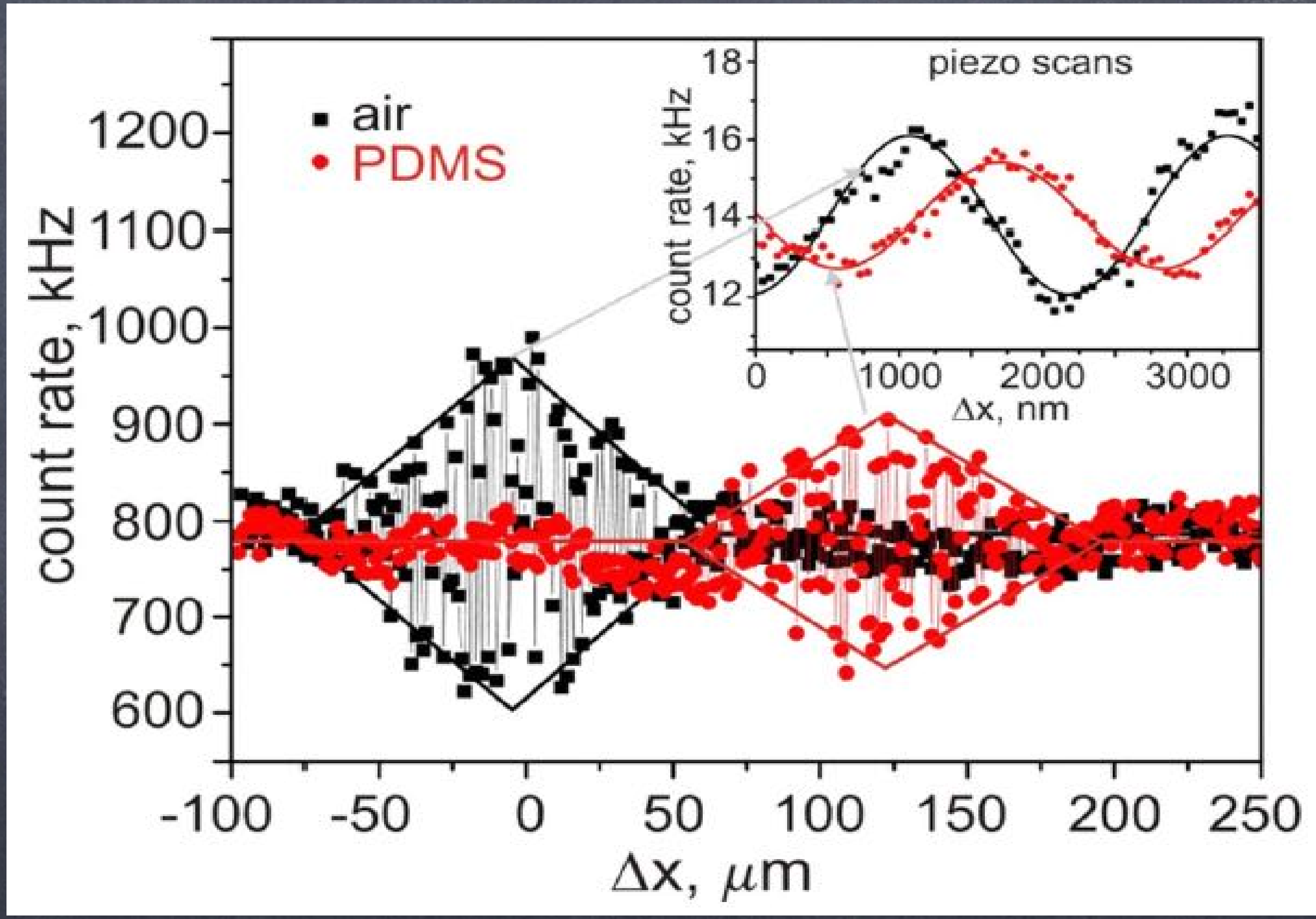
Paterova, A., et al. "Measurement of infrared optical constants with visible photons." New Journal of Physics **20**(4): 043015. (2018).

# Measurement and Optical characterization

$$\Delta L' = 2(n_i' - n_i^{\text{air}}) L_m,$$

$$|r|^2 \equiv R = \left( \frac{n_i' - n_i^{\text{air}}}{n_i' + n_i^{\text{air}}} \right)^2$$



# Measurement and Optical characterization

$$P_s \propto 2[1 + |\tau_i|^2 |\mu(\Delta t)| \cos(\varphi_p - \varphi_s - \varphi_i + \arg\tau^2 + \arg\mu(\Delta t))],$$

$$\mu(\Delta t) = \int |F(\Omega)|^2 \mathrm{e}^{-\mathrm{i}\Omega\Delta t} \mathrm{d}\Omega,$$

$$\Delta t = t_0 + t_2 - t_1$$

$$\Delta\varphi_i = 2\frac{2\pi n_i'}{\lambda_i}\Delta x$$

$$V = \frac{P_s^{\max} - P_s^{\min}}{P_s^{\max} + P_s^{\min}} = |\mu(\Delta t)||\tau|^2$$

$$\frac{V}{V_{\mathrm{ref}}} = \frac{|\tau_{\mathrm{app}}|^2 |\tau|^2}{|\tau_{\mathrm{app}}|^2} = |\tau|^2 \equiv T$$

$$|\tau|^2 = ((1 - |r|^2)\mathrm{e}^{-\frac{\alpha L_m}{2}})^2 = (1 - R)^2 \mathrm{e}^{-\alpha L_m}$$

# همکاران:

دکتر مهدی داودی

دکتر علی مهری تونابی

دکتر حمزه نورالهی

سعید اکبری(دانشجوی دکتری)

Thank you for your attention

Questions??

دومین همایش ملی
فناوری‌های کوانتومی ظهور