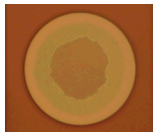
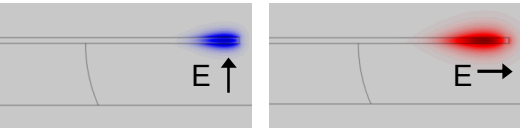
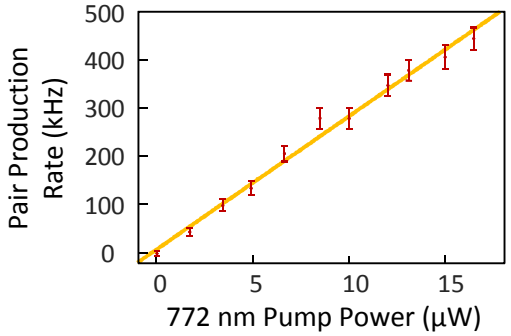
SAND2016-5556C






# Entangled Photon Generation in Lithium Niobate Microdisk Resonators Through Spontaneous Parametric Down Conversion

Ian W. Frank, Jeremy Moore, J.K. Douglas, Ryan Camacho, and Matt Eichenfield

Sandia National Laboratories, Albuquerque, NM

Sandia National Laboratories

*Exceptional service in the national interest*

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

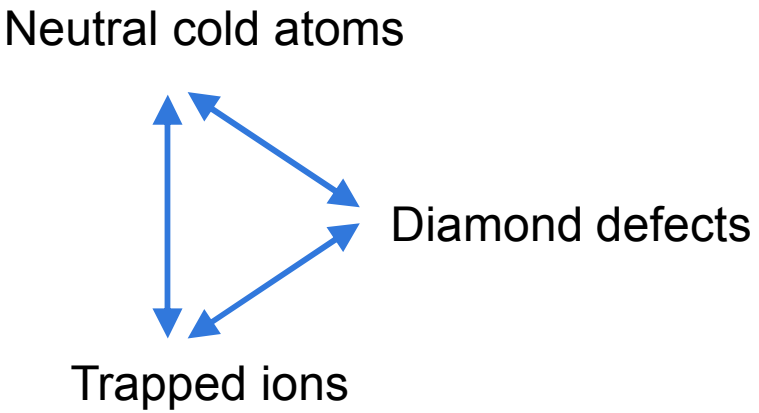
# Outline

Sandia National Laboratories

- Motivation
- Lithium niobate
  - $LiNbO_3$ on Insulator (LNOI)
- Geometric phase matching in LNOI microdisks
- Fabrication/microdisk characterization
- Second harmonic generation (SHG) in LNOI microdisks
- Spontaneous parametric down conversion (SPDC)
  - Conversion efficiency/pair production rate
  - Coincidence spectra
- Conclusion

# Motivation

- Low power, chip-scale frequency conversion
  - Similar system for second harmonic generation, etc.
  - Linking different quantum systems

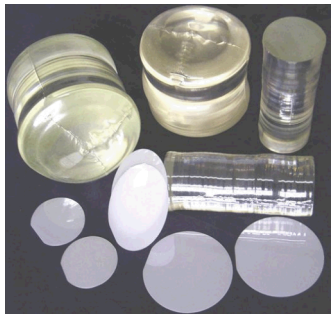



- Entangled photon generation

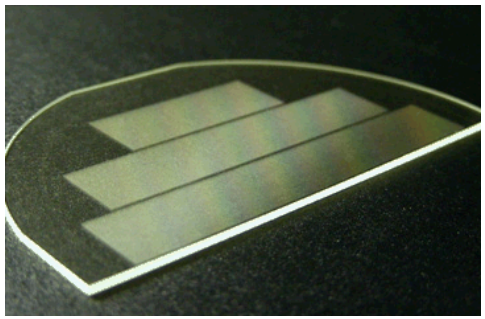
# Lithium Niobate ($LiNbO_3$)

- Many available nonlinear materials
  - BBO
  - KTP
  - $LiTaO_3$
  - AlN
  - GaAs
- $LiNbO_3$
  - Large nonlinear optical coefficient
    - $d_{33} = 31.5pm/V$
    - $d_{31} = 4.5pm/V$
  - Wide transparency window
    - $350nm - 5\mu m$

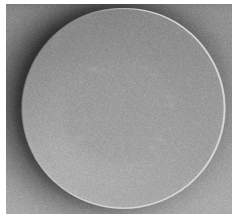
Bulk $LiNbO_3$*

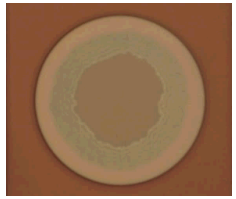


PPLN wafer**



$LiNbO_3$ on Insulator (LNOI) Microdisks



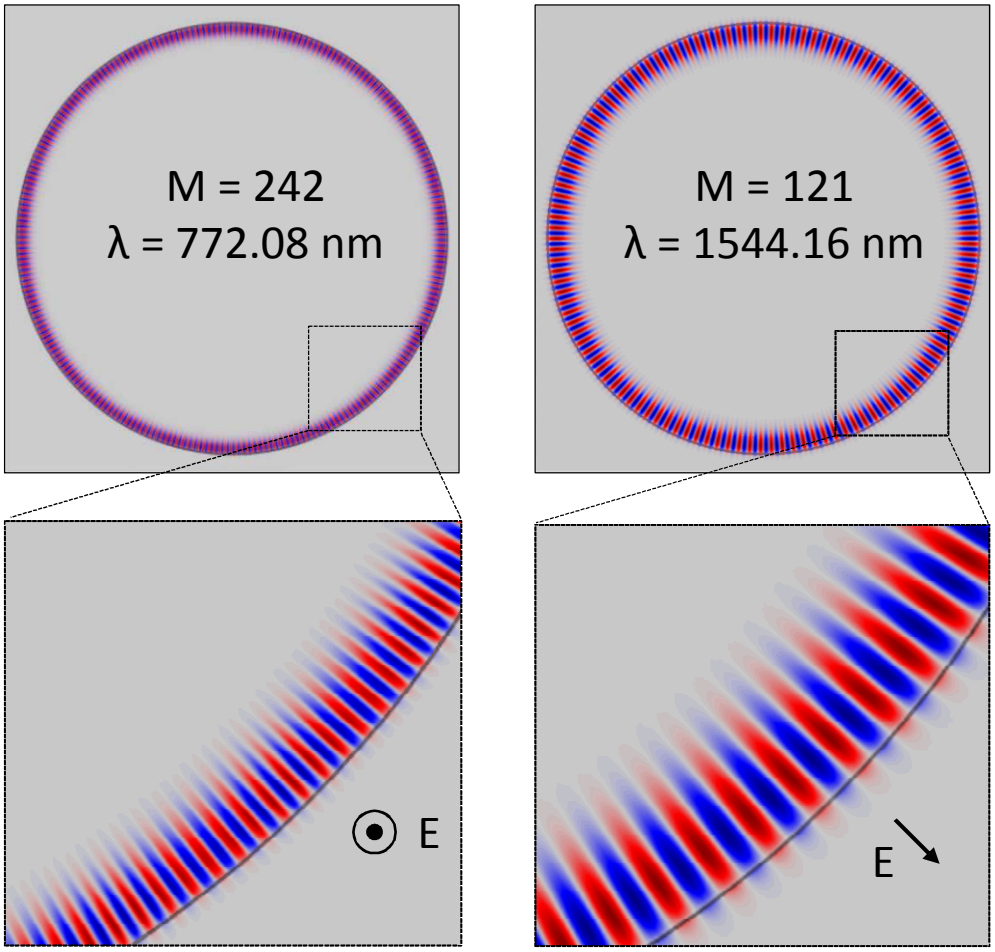


*DFNano

**Deltronic Crystal Industries

# Geometric Phase Matching

## Phase matching condition




Pump

Signal (idler)

Momentum conservation:

$$M_{pump} = 2 \times M_{signal}$$

$$\Delta M = M_{pump} - (2 \times M_{signal}) = 0$$

Energy conservation:

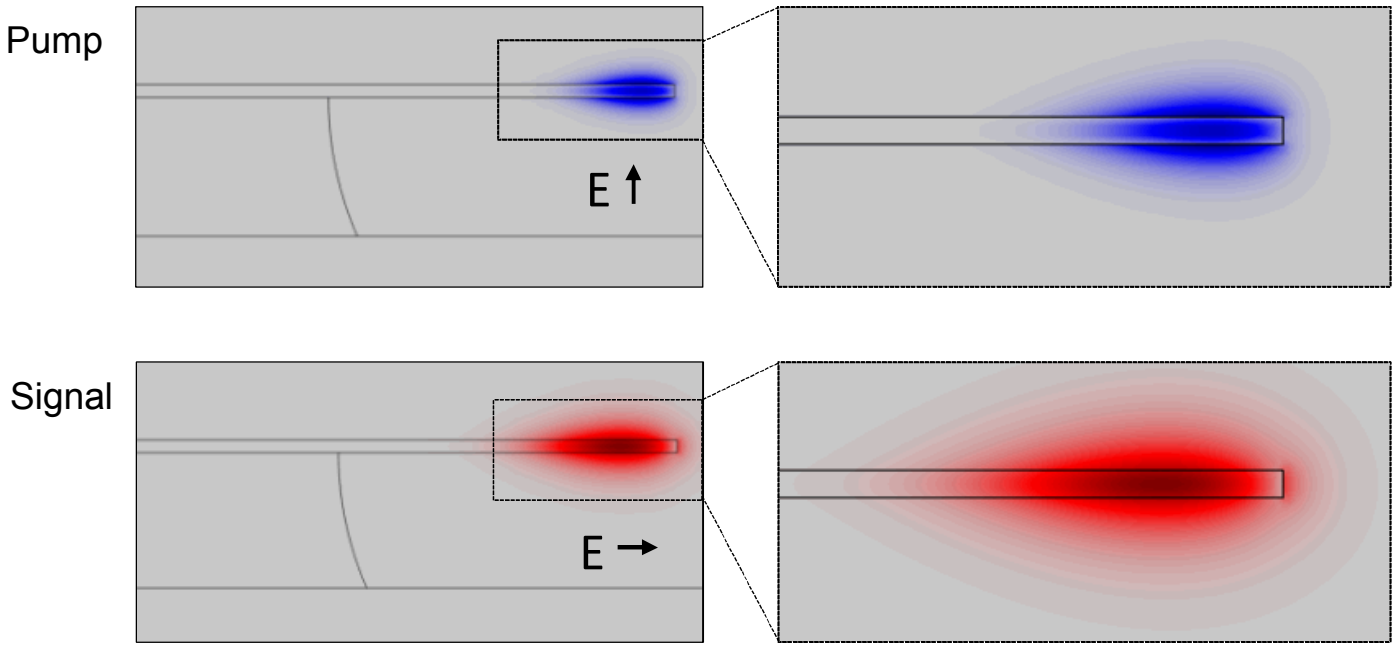
$$\lambda_{pump} = \frac{1}{2} \lambda_{signal}$$

$$f_{pump} = 2 \times f_{signal}$$

$$\Delta f = f_{pump} - (2 \times f_{signal}) = 0$$

# Geometric Phase Matching

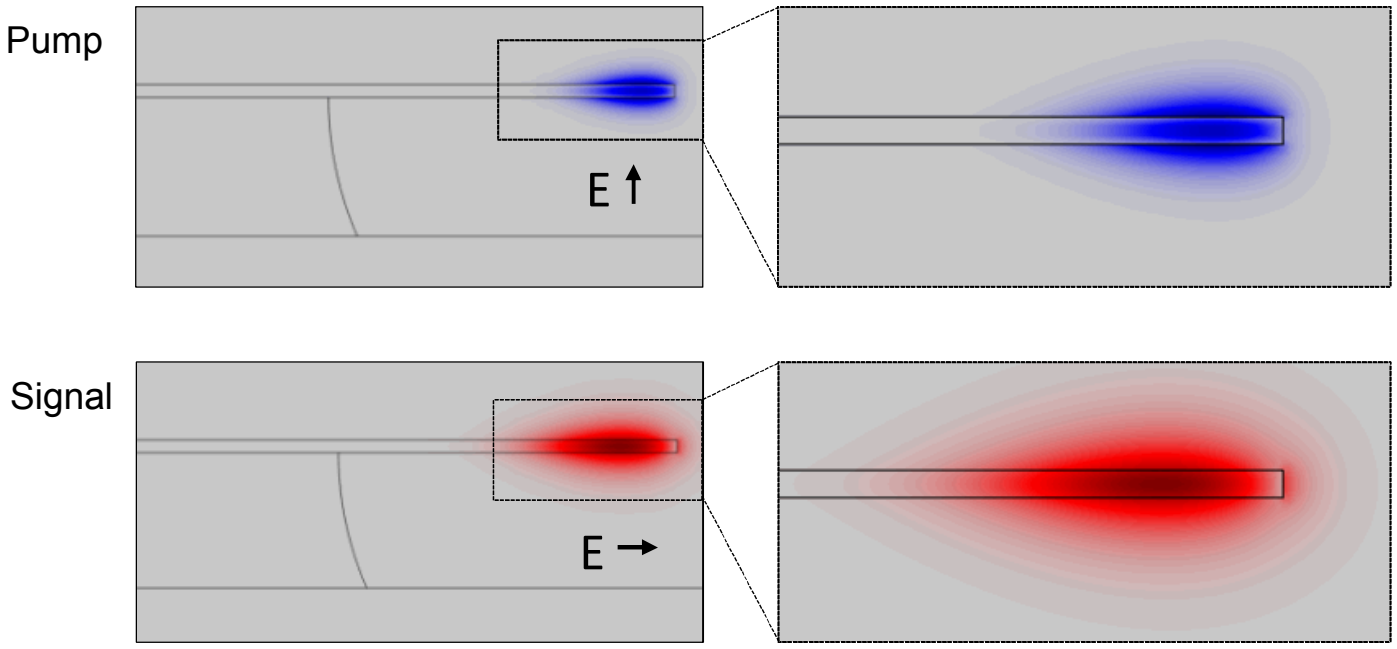
## Mechanism




- Dispersion is a stronger function of aspect ratio for vertically polarized (TM) modes.

# Geometric Phase Matching

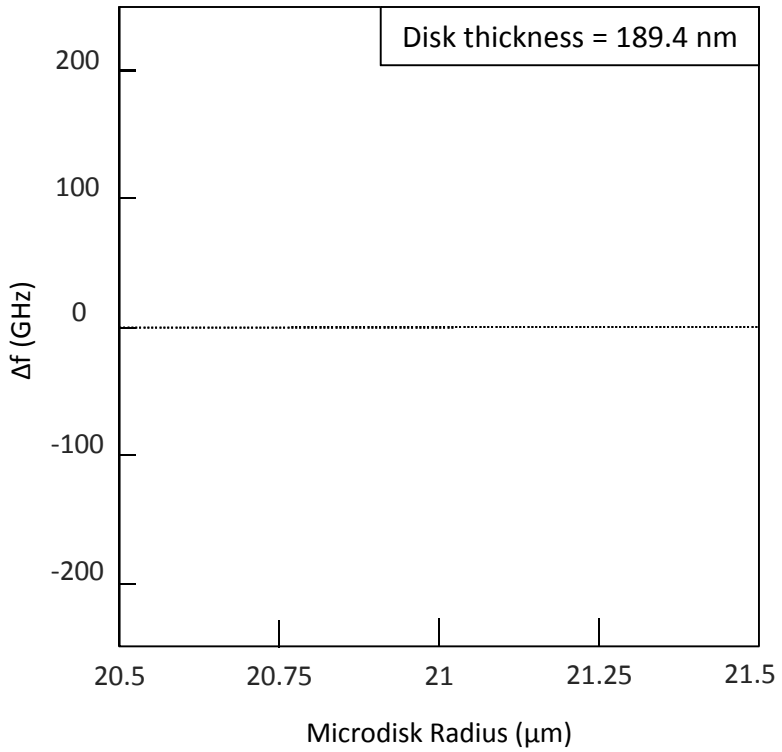
## Mechanism




- Dispersion is a stronger function of aspect ratio for vertically polarized (TM) modes.
- For a given disk thickness and $M_{pump}/M_{signal}$ pair, change the disk radius to achieve phase matching

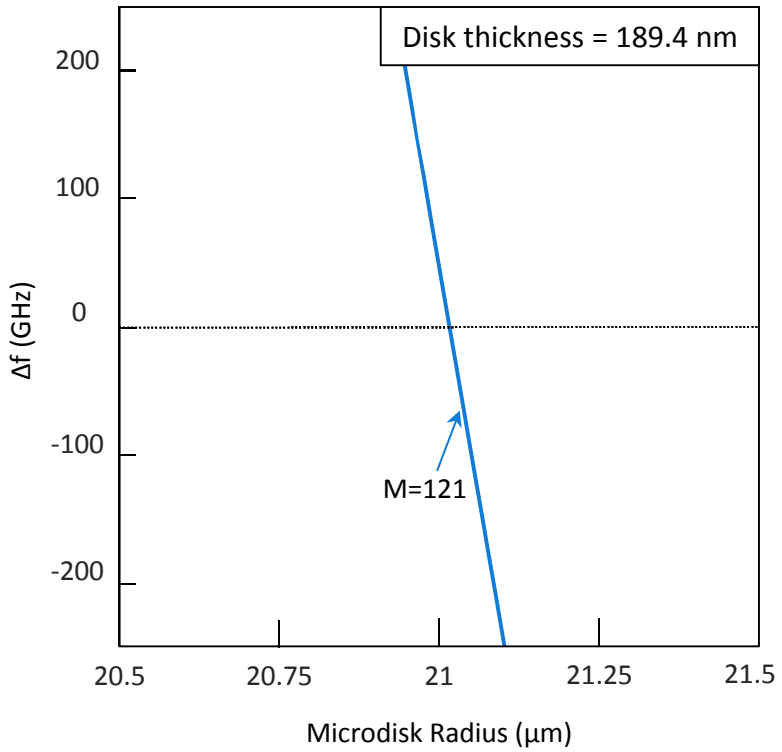
# Geometric Phase Matching

## Phase matching algorithm



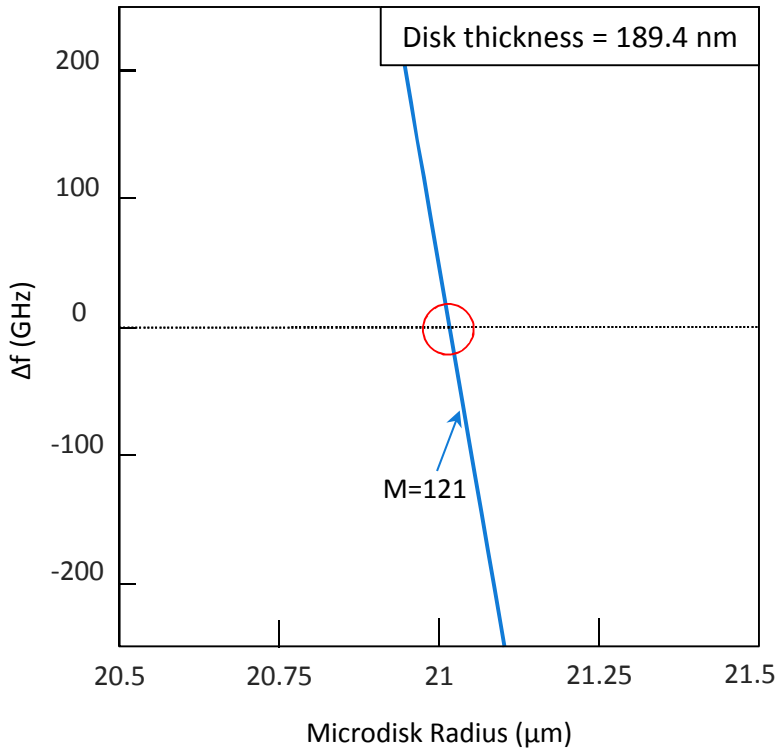
# Geometric Phase Matching

## Phase matching algorithm



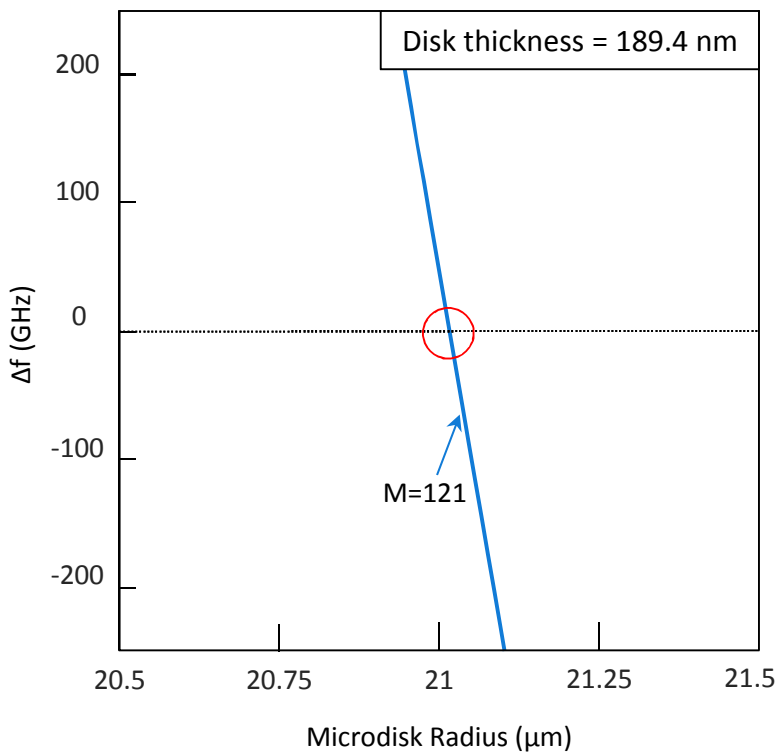
# Geometric Phase Matching

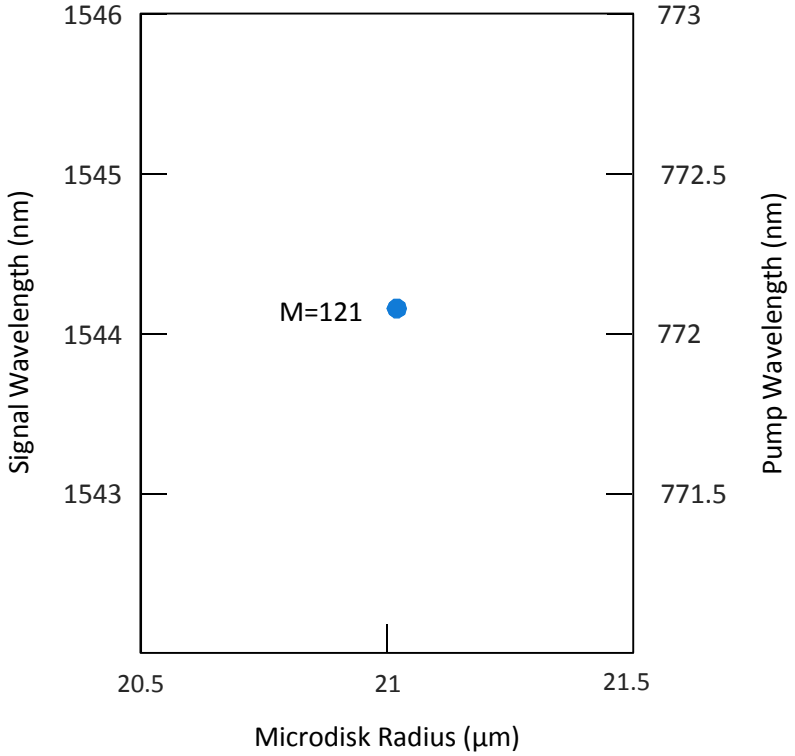
## Phase matching algorithm



# Geometric Phase Matching

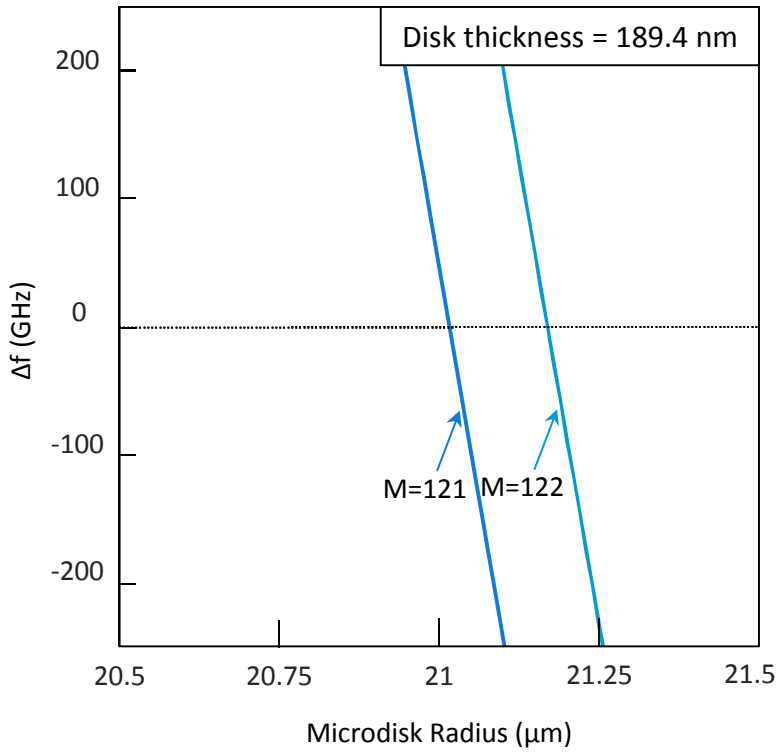
## Phase matching algorithm

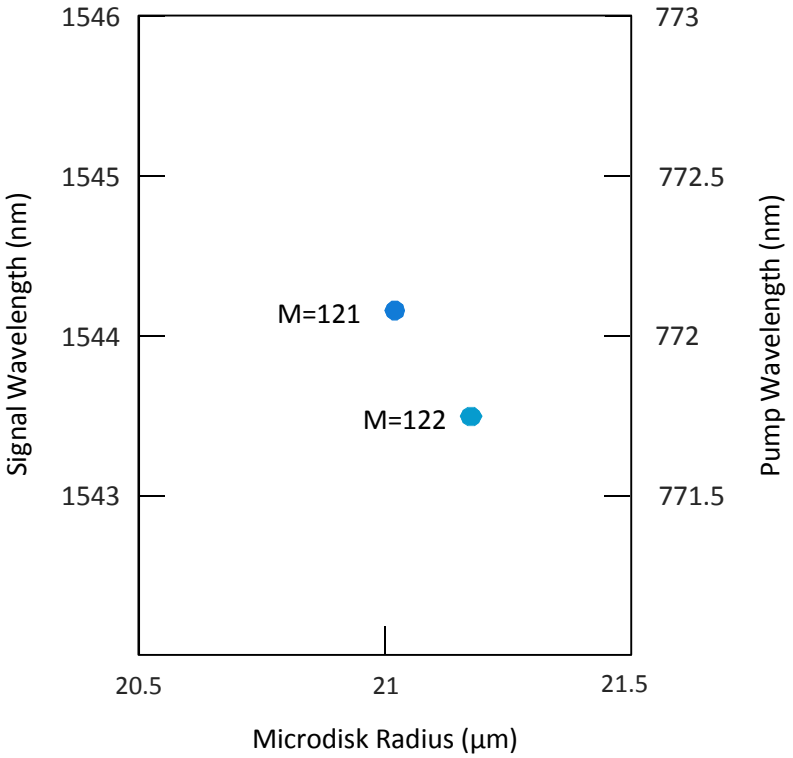


# Geometric Phase Matching

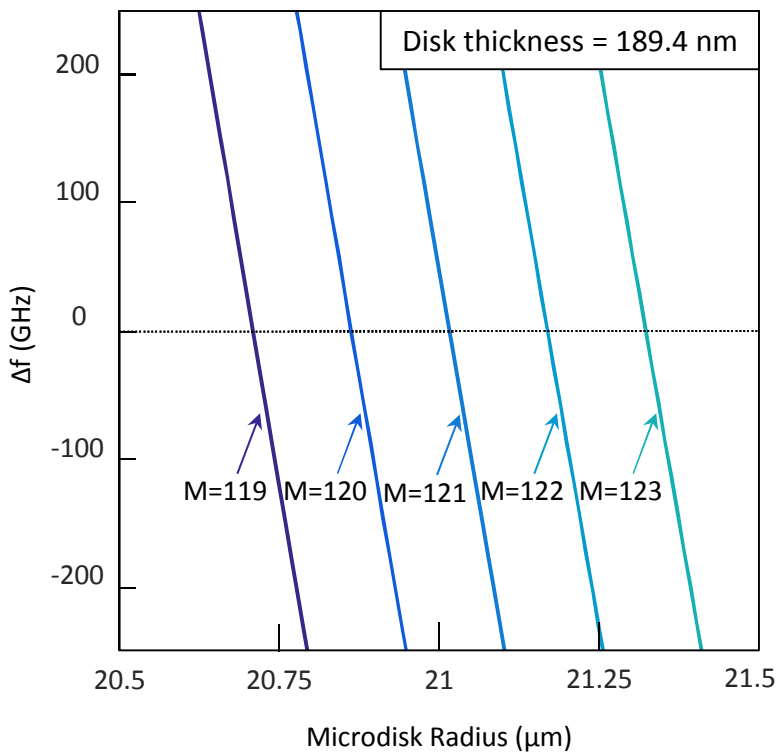
## Phase matching algorithm

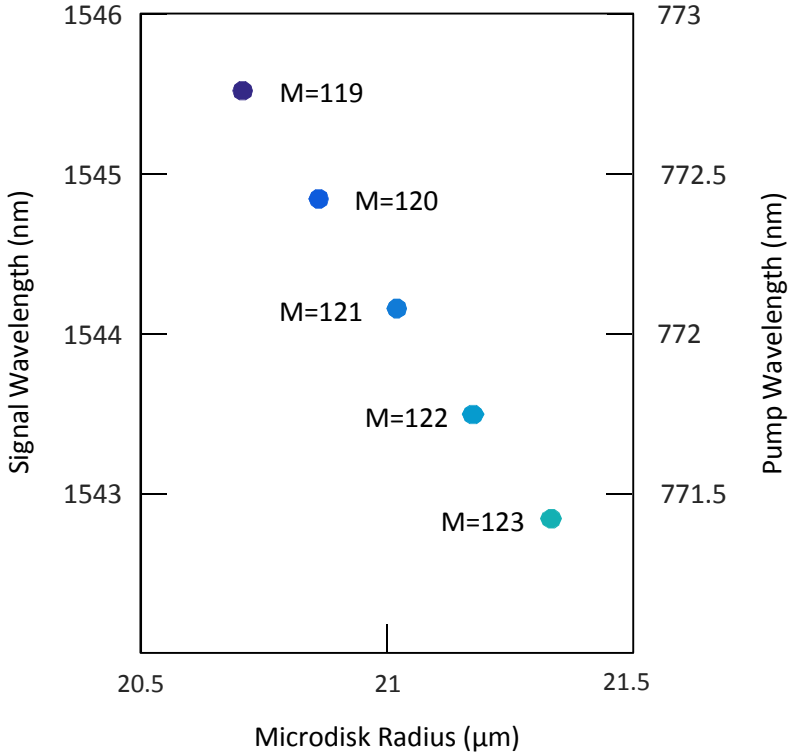


# Geometric Phase Matching

## Phase matching algorithm

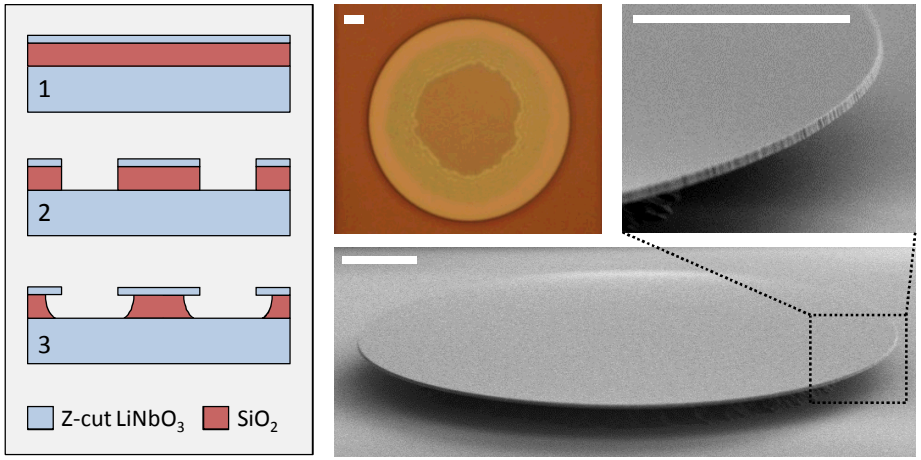


# $LiNbO_3$ on Insulator (LNOI) Microdisks

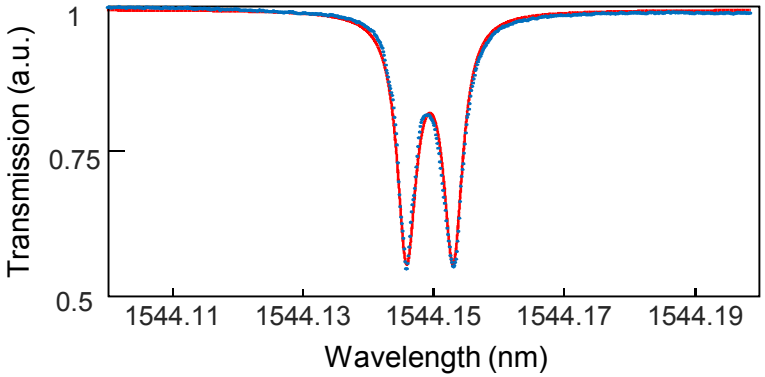
## Fabrication Process

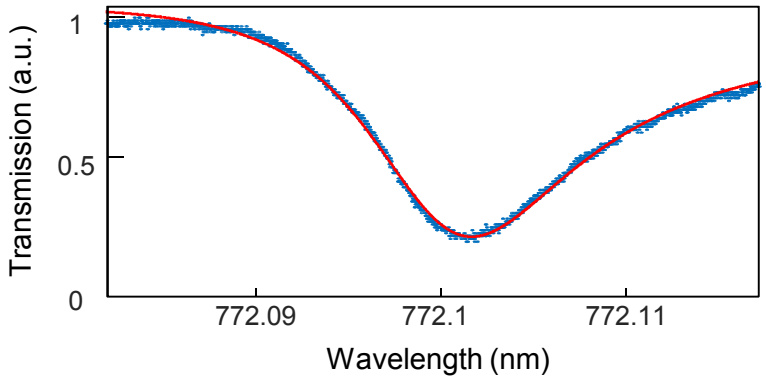
1) LNOI wafer
   - 200nm/2µm/0.5mm
   - $LiNbO_3/SiO_2/LiNbO_3$
2) Pattern, etch
   - Optical lithography
   - Argon plasma etch to define disks
3) Undercut etch
   - Vapor HF undercut to release disks



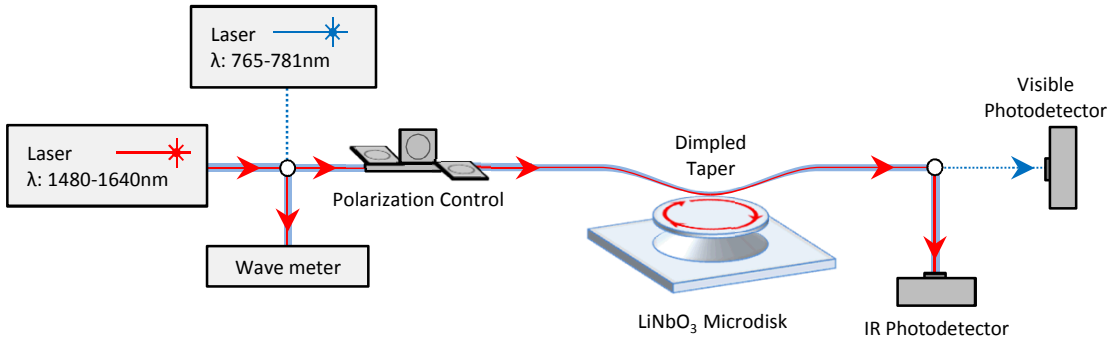

## Optical Quality Factor

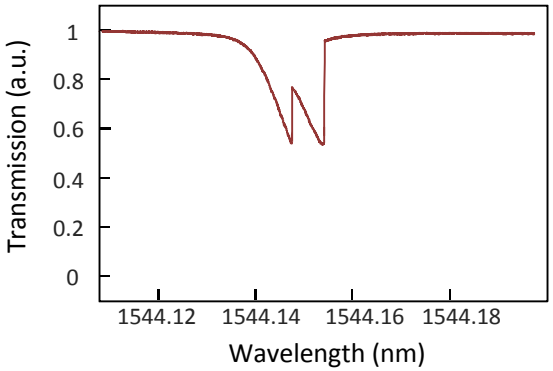
- $Q_{1550} = 570{,}000$
- $Q_{775} = 75{,}500$

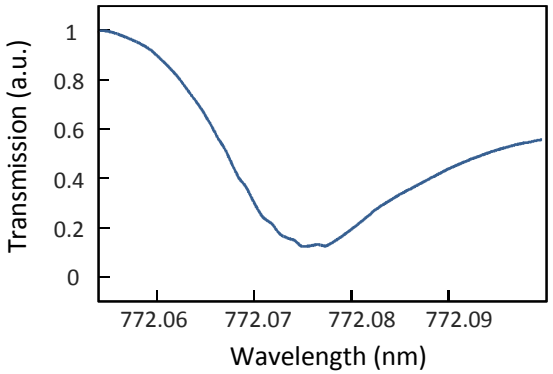


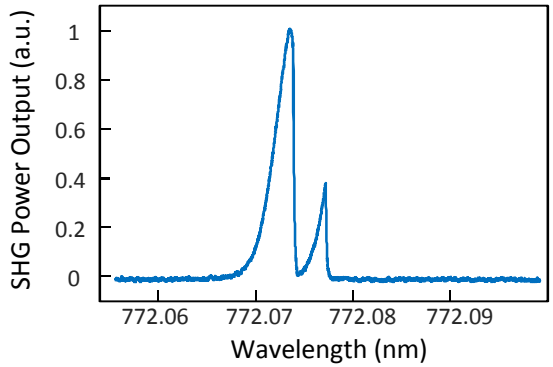



# Experimental Confirmation of Phase Matching



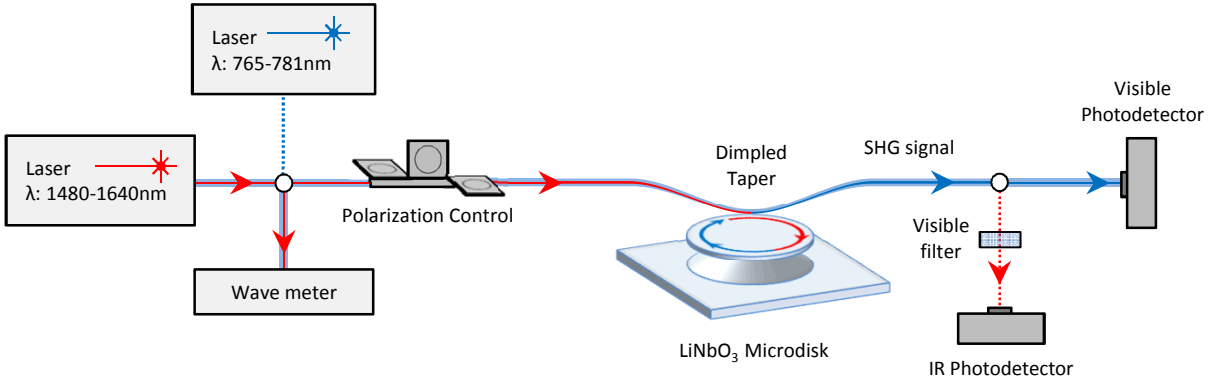



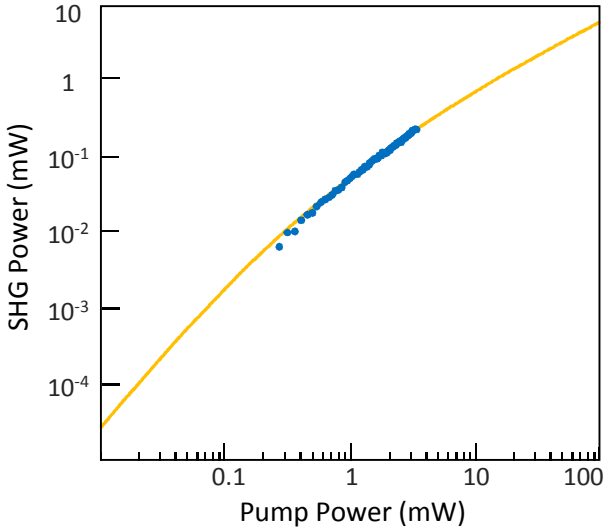



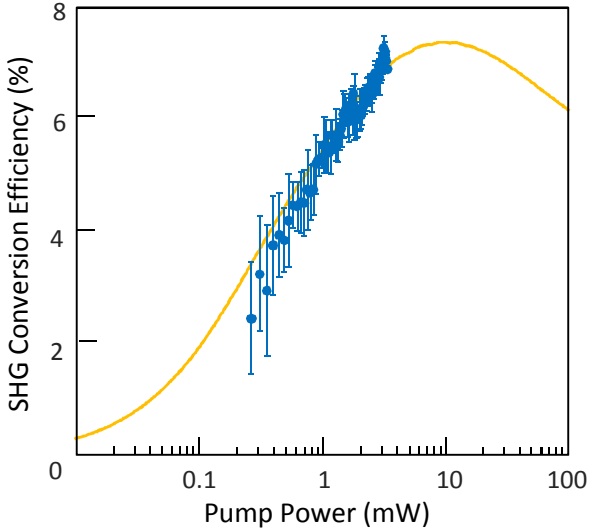




- Energy conservation
  - Spectral overlap of pump and signal resonator modes
- Momentum conservation
  - $M_{pump}, M_{signal}$ verified from transmission spectra, FEM modeling
    - $M_{pump} = 242$
    - $M_{signal} = 121$

# Second Harmonic Generation

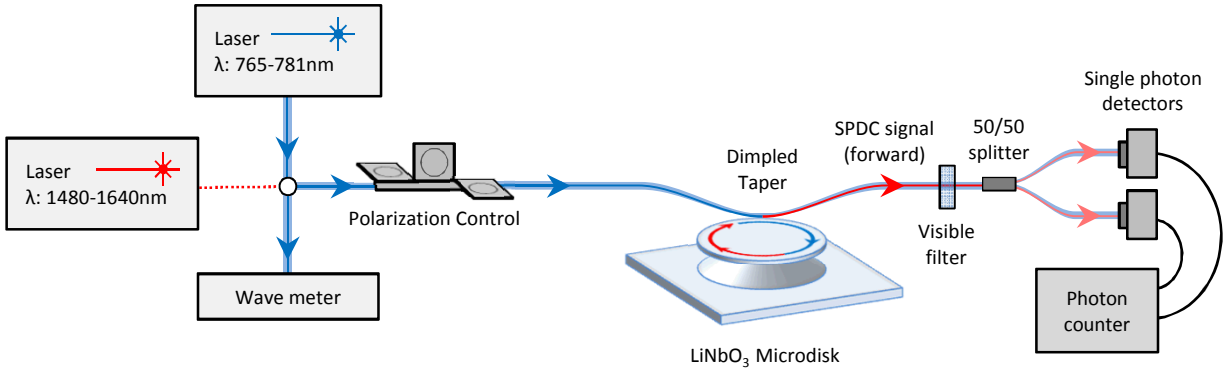


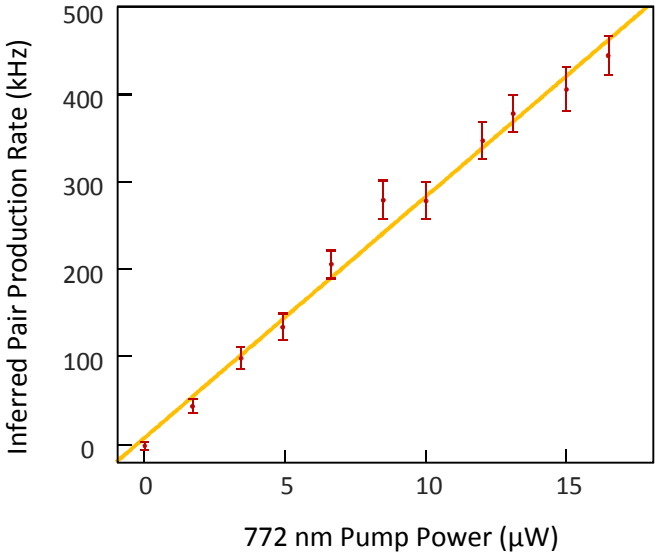




- Identical phase matching for SHG/SPDC
- 1550nm → 775nm
  - Efficiency = 7.8%
  - $P_{pump}$ = 3.14mW

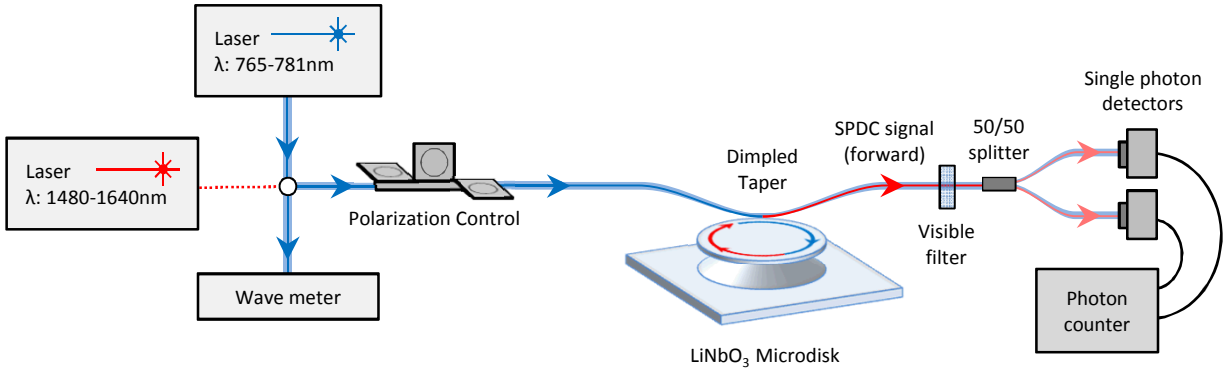
# SPDC Pair Production

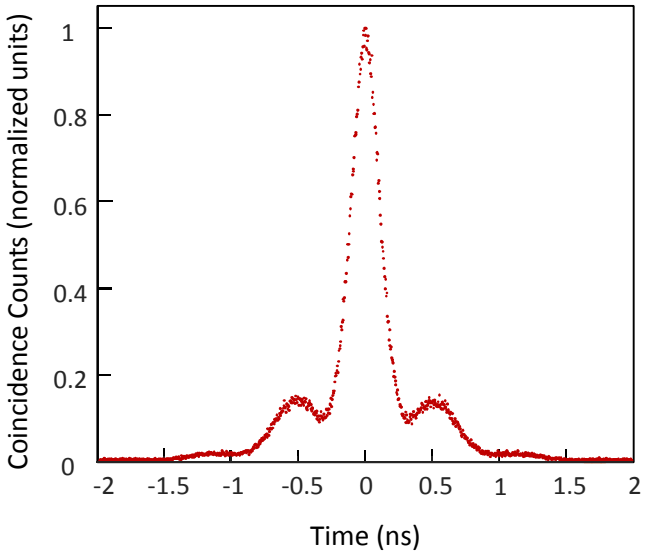


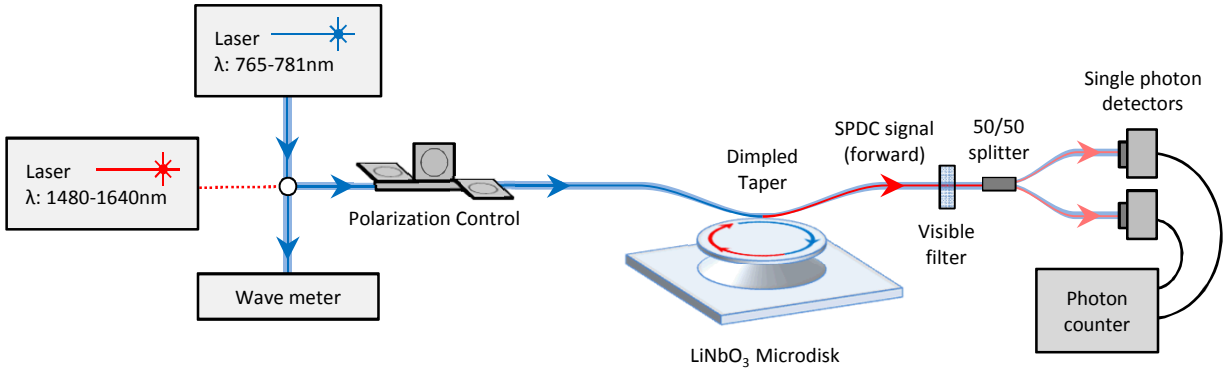

Conversion efficiency $= 6 \times 10^{-9}$
Pair production rate $= 27 kHz/\mu W$

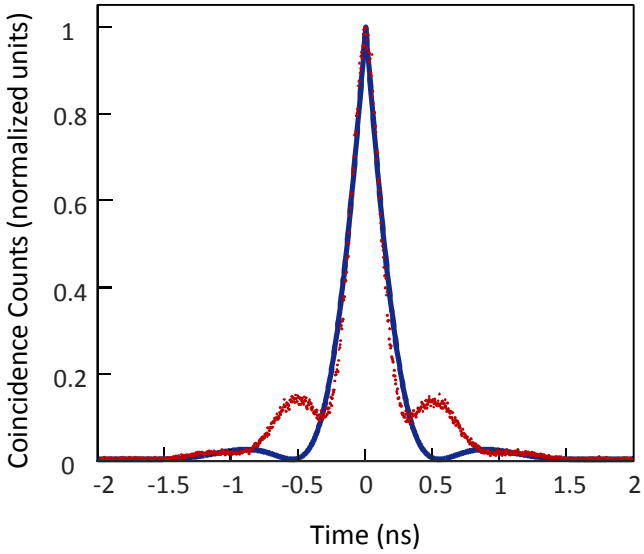
# SPDC Coincidence (Forward Direction)



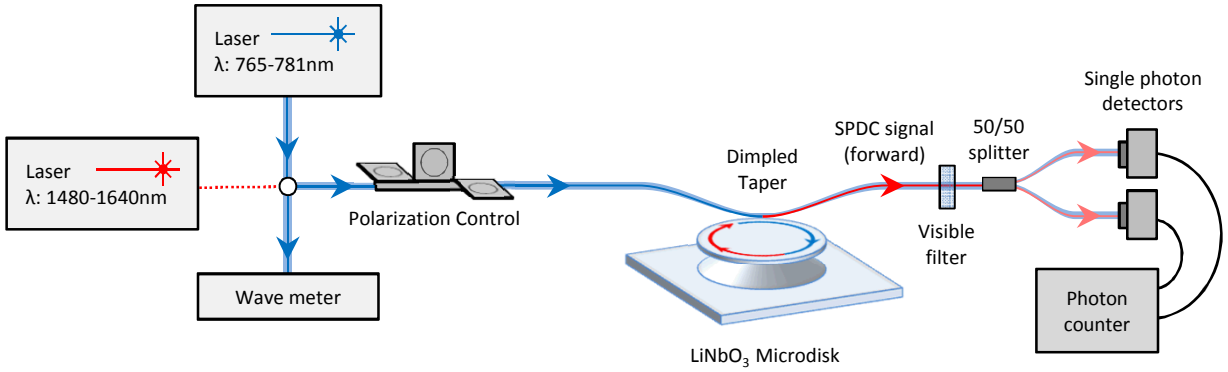
# SPDC Coincidence (Forward Direction)

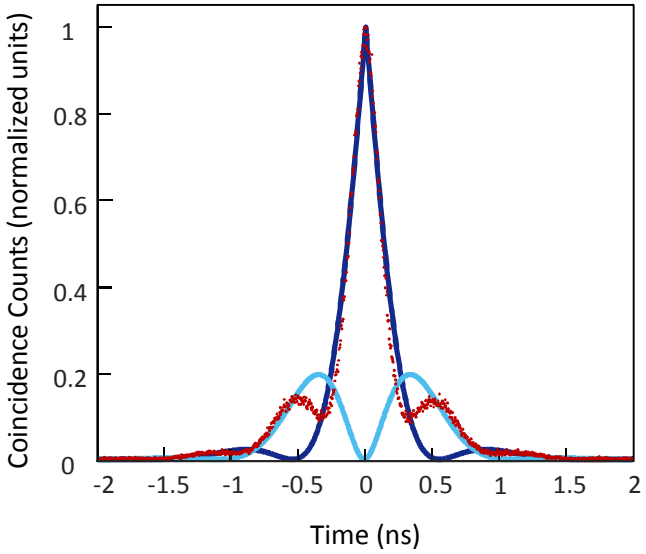



$$y = \left|\cos(\kappa_{BS}\, t)e^{-k_{tot}t}\right|^2$$

# SPDC Coincidence (Forward Direction)

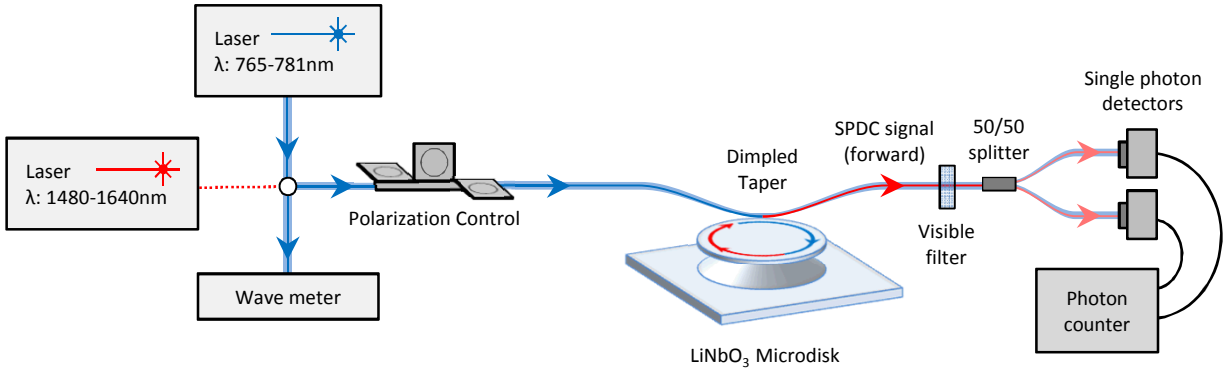


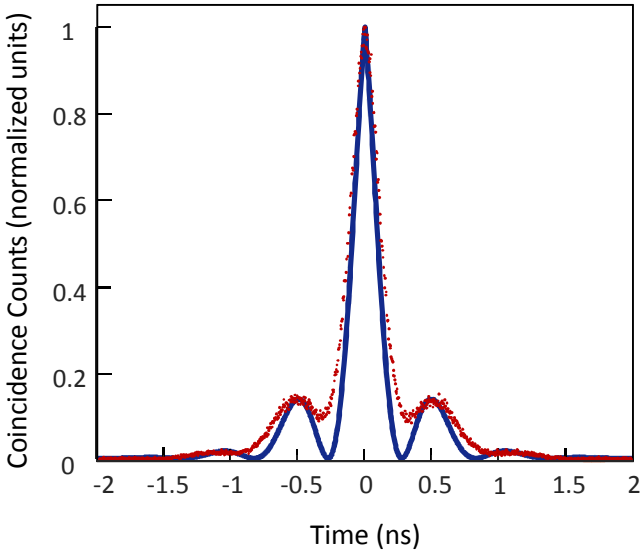




$$y = \left|\cos(\kappa_{BS}\, t)e^{-k_{tot}t}\right|^2$$

$$y = \left|\sin(\kappa_{BS}\, t)e^{-k_{tot}t}\right|^2$$

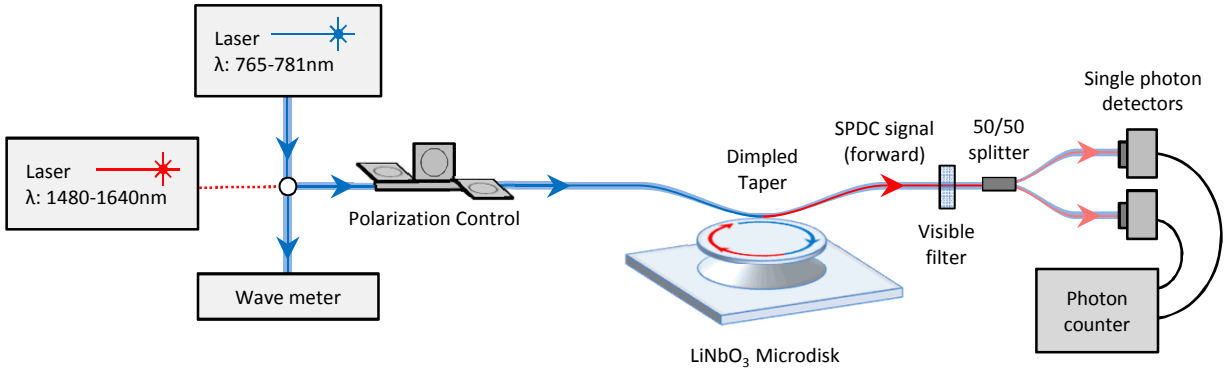
# SPDC Coincidence (Forward Direction)

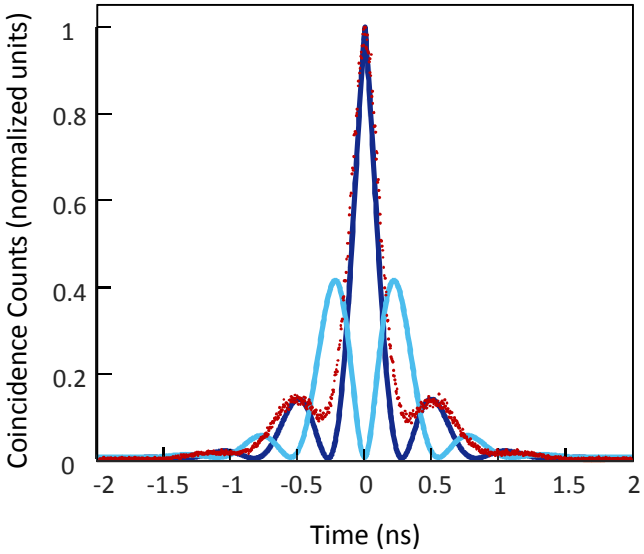



$$y = \left|\cos(2\,\kappa_{BS}\,t)e^{-k_{tot}t}\right|^2$$

# SPDC Coincidence (Forward Direction)

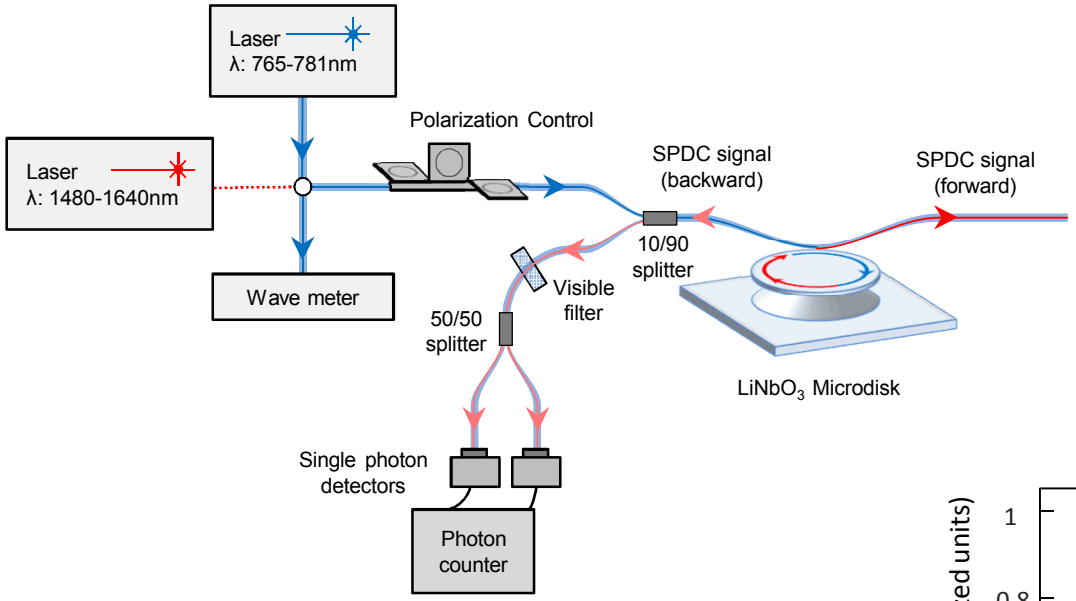


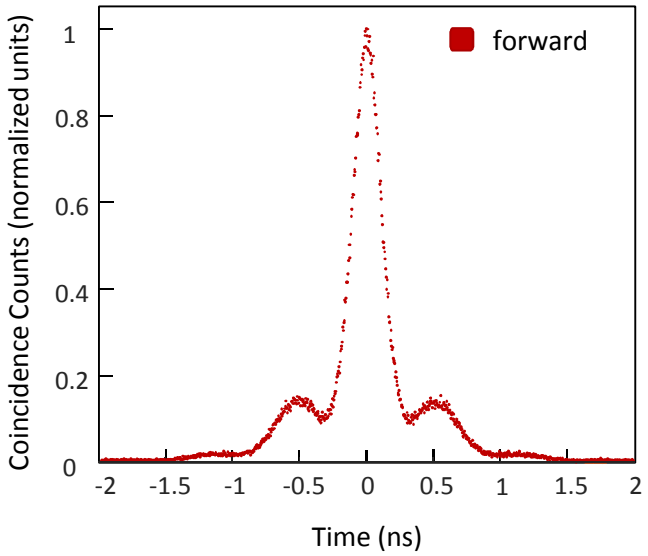




$$y = \left|\cos(2\,\kappa_{BS}\,t)e^{-k_{tot}t}\right|^2$$

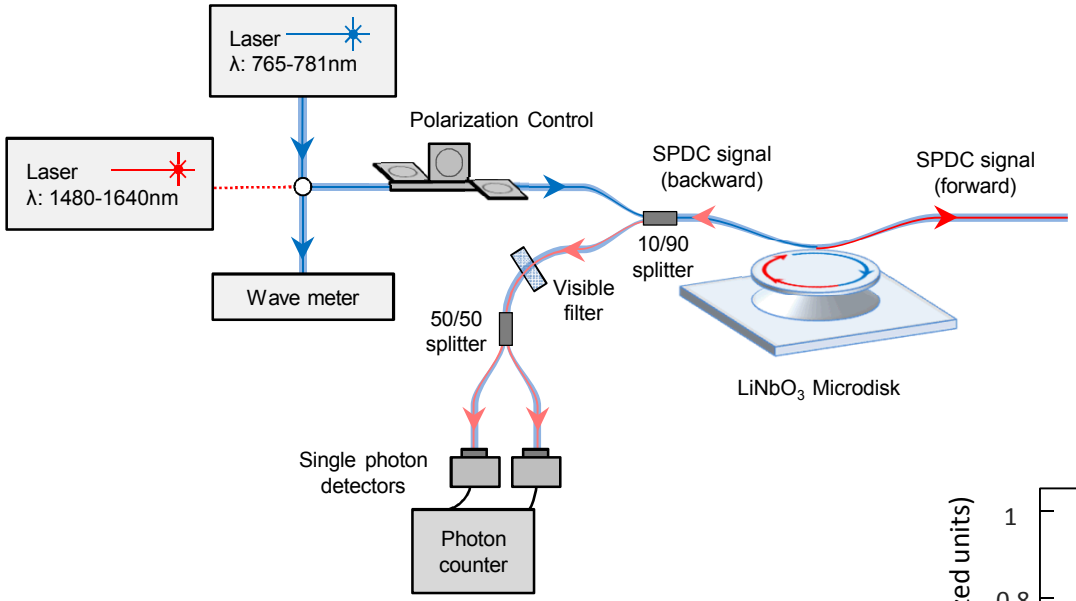
$$y = \left|\sin(2\,\kappa_{BS}\,t)e^{-k_{tot}t}\right|^2$$

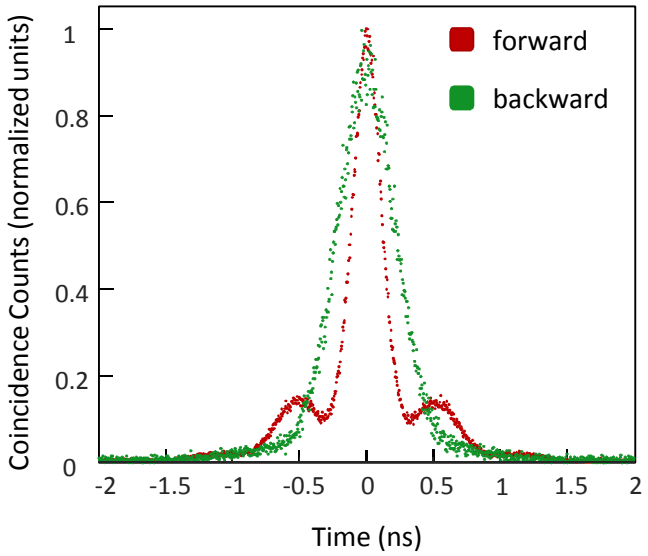
# SPDC Coincidence (Backward Direction)



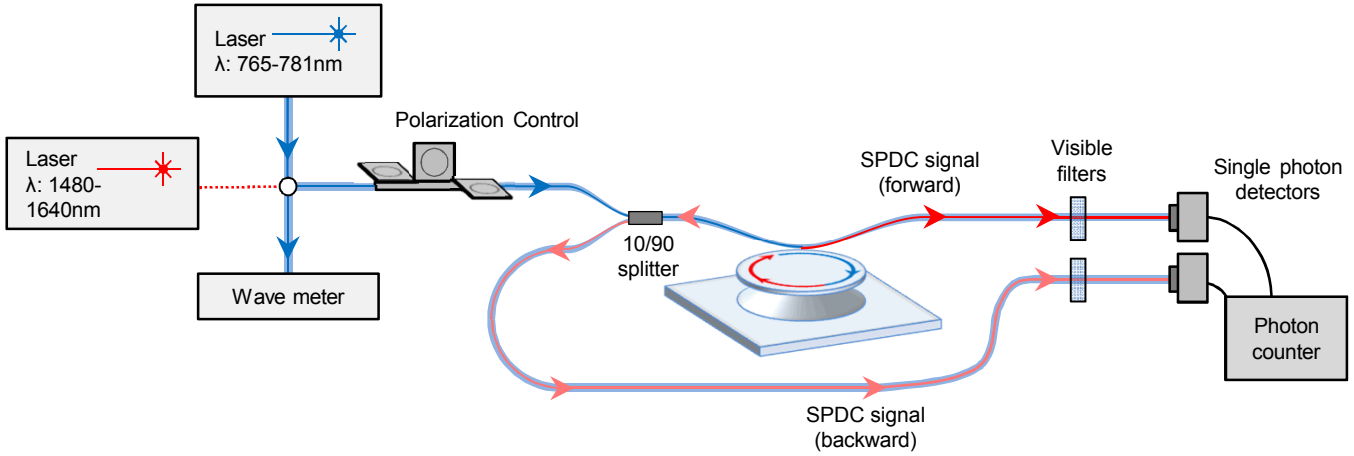



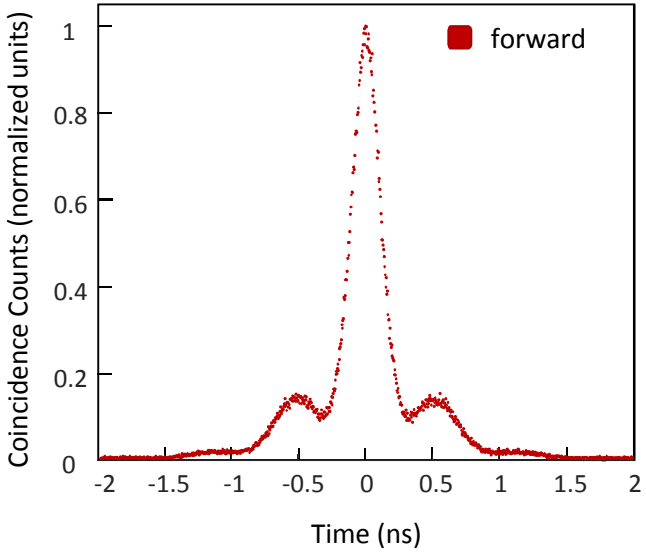
# SPDC Coincidence (Backward Direction)



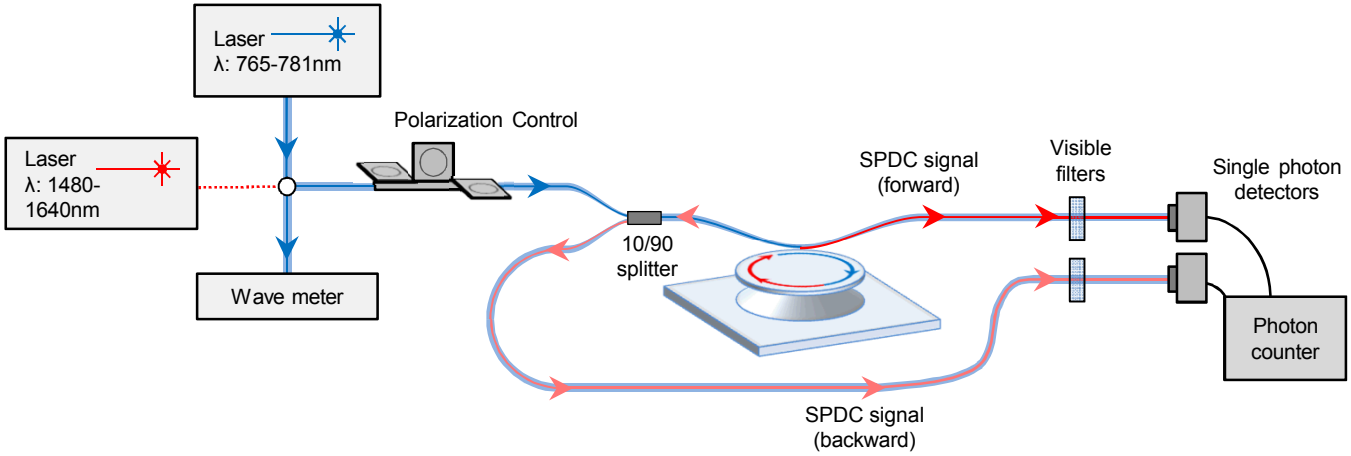



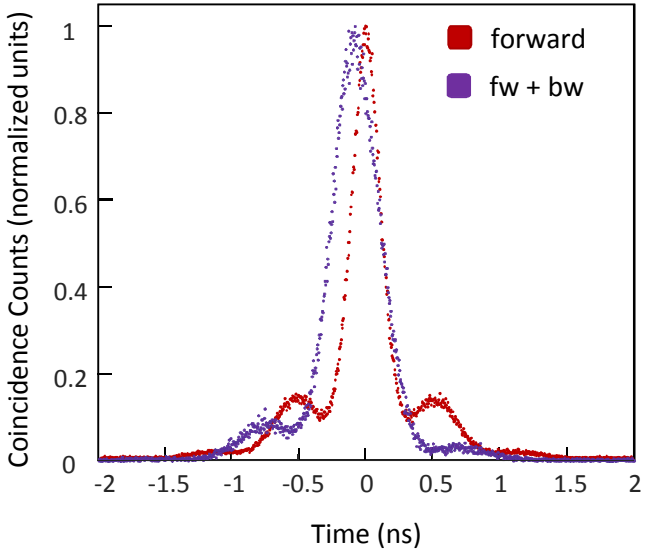
# SPDC Coincidence (Forward + Backward)



# SPDC Coincidence (Forward + Backward)



# Conclusion

Sandia National Laboratories

- LNOI microdisks for nonlinear frequency conversion
  - Geometric phase matching
- SHG
  - 1550nm → 775 nm
  - 7% conversion efficiency at 3.1mW input power
- SPDC
  - 775 nm → 1550nm
  - Conversion efficiency $= 6 \times 10^{-9}$
  - Pair production rate $= 27 kHz/\mu W$
  - Interesting coincidence behavior due to coherent backscattering

Sandia National Laboratories

# Thank You!