# *Raman spectroscopy utilizing a time resolving CMOS SPAD line sensor with a pulsed laser excitation*


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Doctoral student Jere Kekkonen

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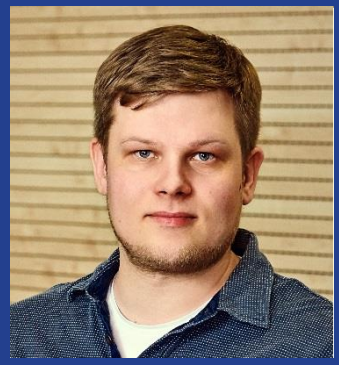

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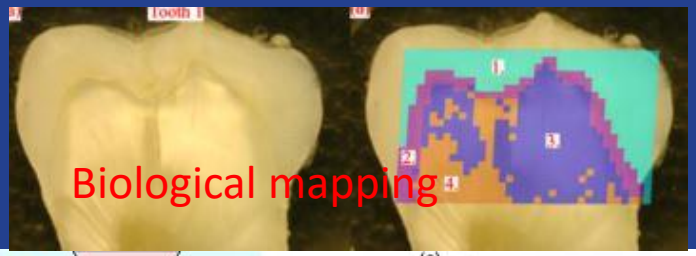
# Outline

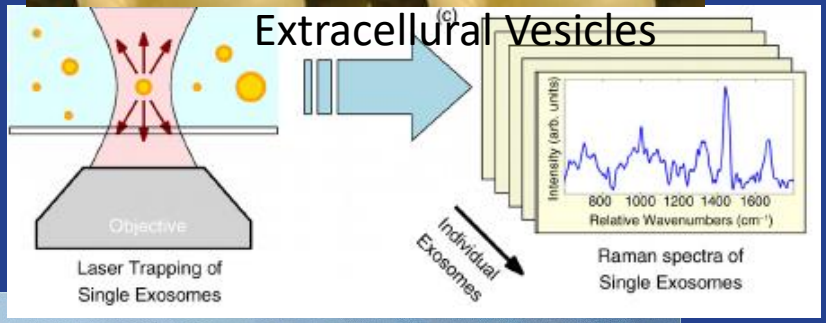
- Motivation
  - Applications
  - Challenges in CW-based Raman spectroscopy
- Time gated Raman spectroscopy
- Advantages using CMOS-based Sensors
- Operation of SPAD with a TDC
- Depth resolving Raman spectroscopy
- Timing skew and distortion
- Timing skew compensation
- Measurement result
  - High fluorescent sample, Depth resolving Raman, Chemical imaging of human teeth
- Conclusions

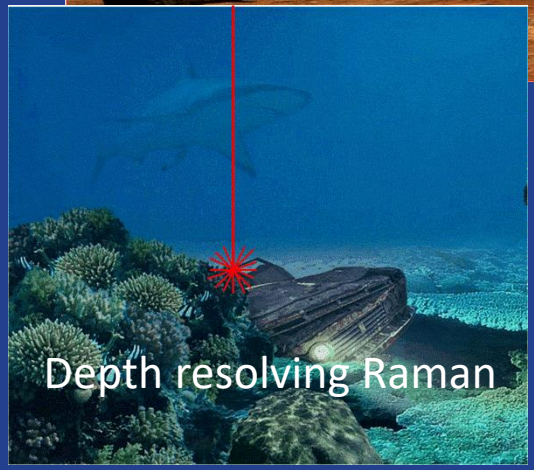
# Motivation

Stand-off mineral detection




Extracellular Vesicles

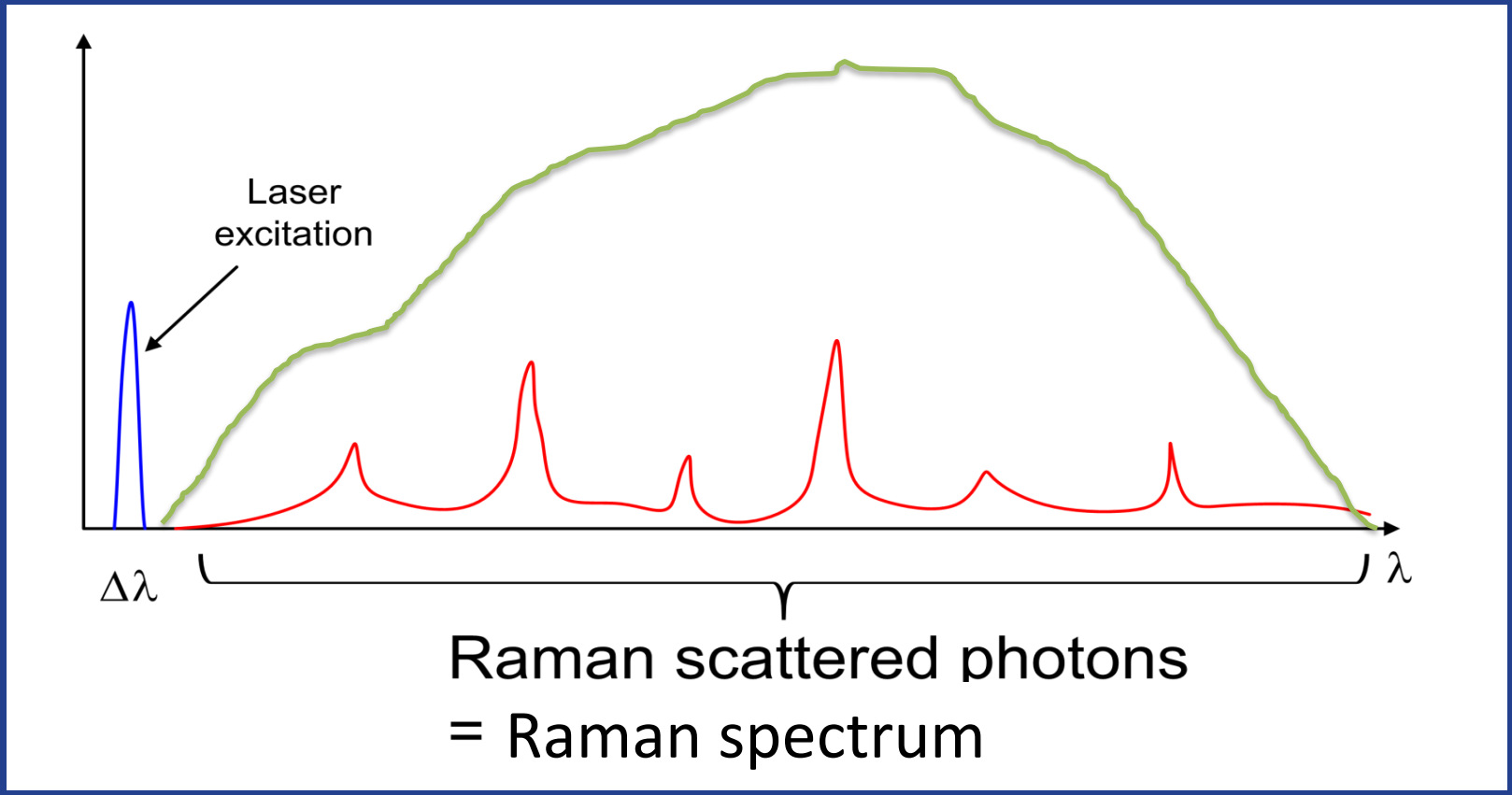



Stand-off explosive detection

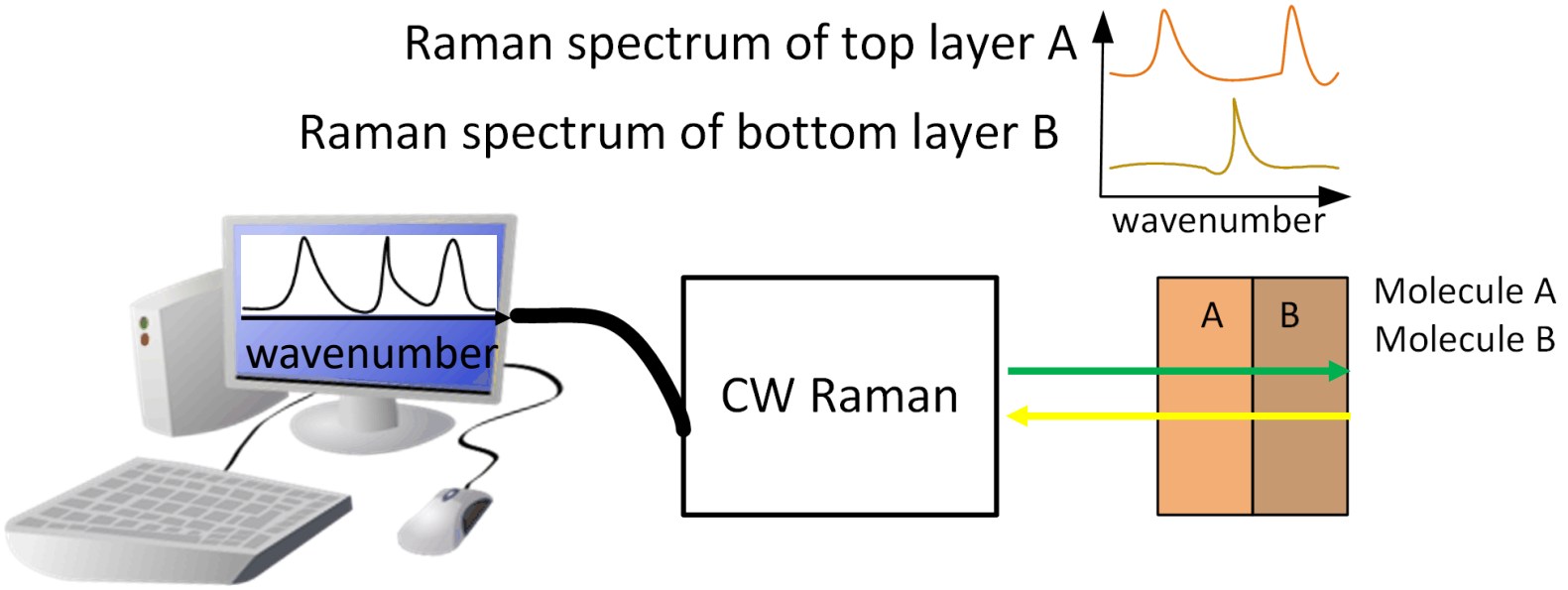
# Challenges

High fluorescence background!



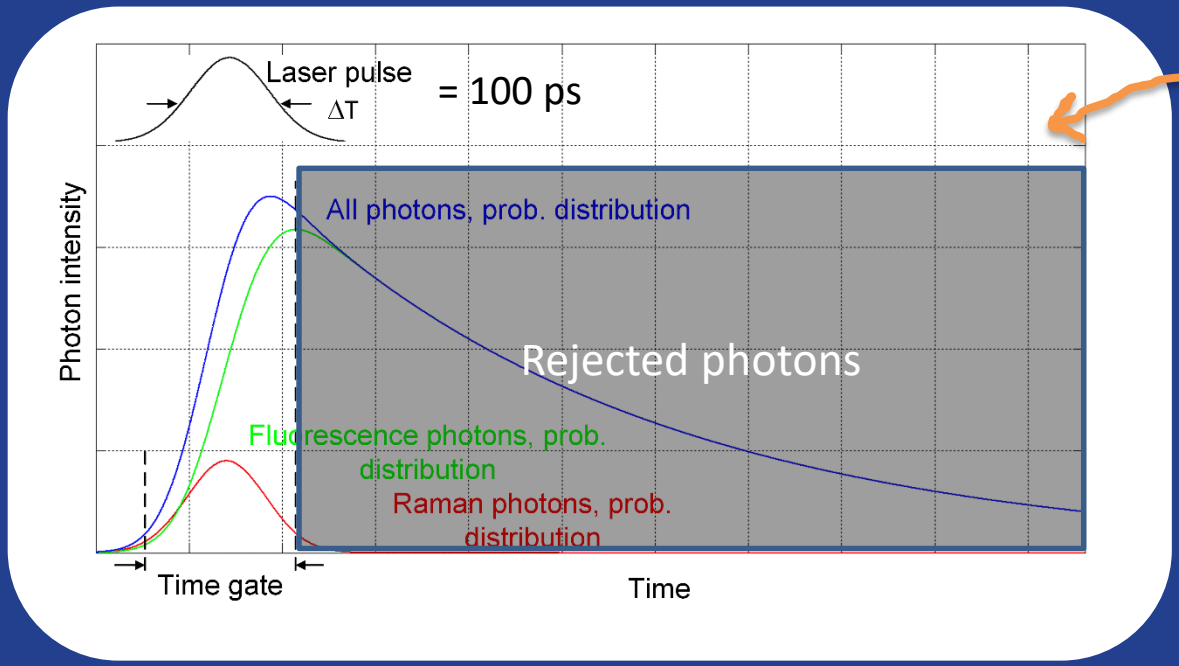
# Challenges

Depth derivation and depth profiling in Raman spectrocopy!



- How to solve Fluorescence background problem in Raman spectroscopy?
- How to achieve depth derivation and profiling with fluorescence suppression?

# Time-gated Raman spectroscopy




**Time domain distribution of single wavenumber**



[1] R. P. Van Duyne, D. L. Jeanmaire, and D. F. Shriver, “Mode-lockedlaser Raman spectroscopy. New technique for the rejection of inter-fering background luminescence signals,”Anal. Chem., vol. 46, no. 2,pp. 213–222, Feb. 1974.

[2] P. Matousek et al., “Fluorescence suppression in resonance Raman spectroscopy using a high-performance picosecond Kerr gate,” J. Raman Spectrosc., vol. 32, no. 12, pp. 983–988, Dec. 2001.

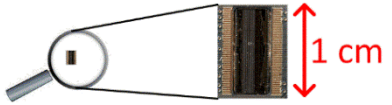
# Advantages of using CMOS technology

**Traditional time-gated Raman setup**

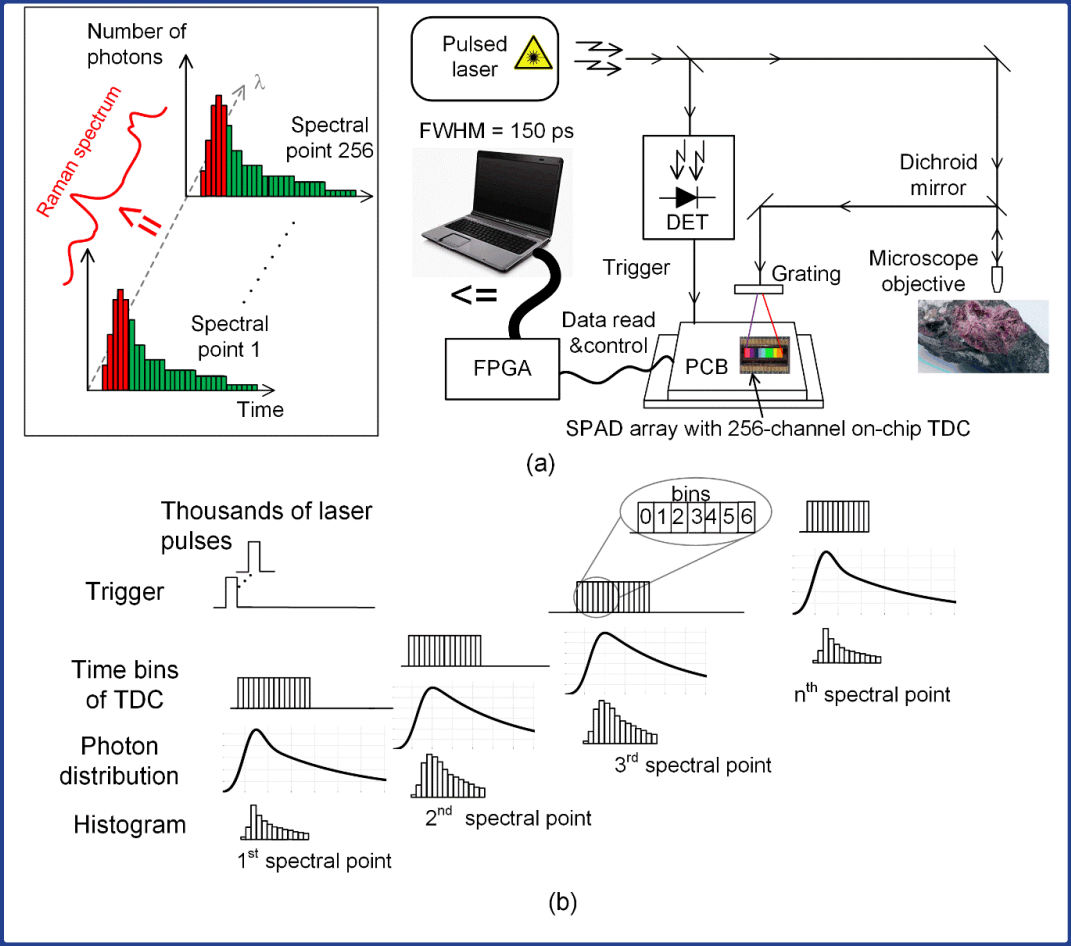

**vs.**

**This work**

**Gating generator and TDC integrated in the same CMOS die with SPAD line sensor**



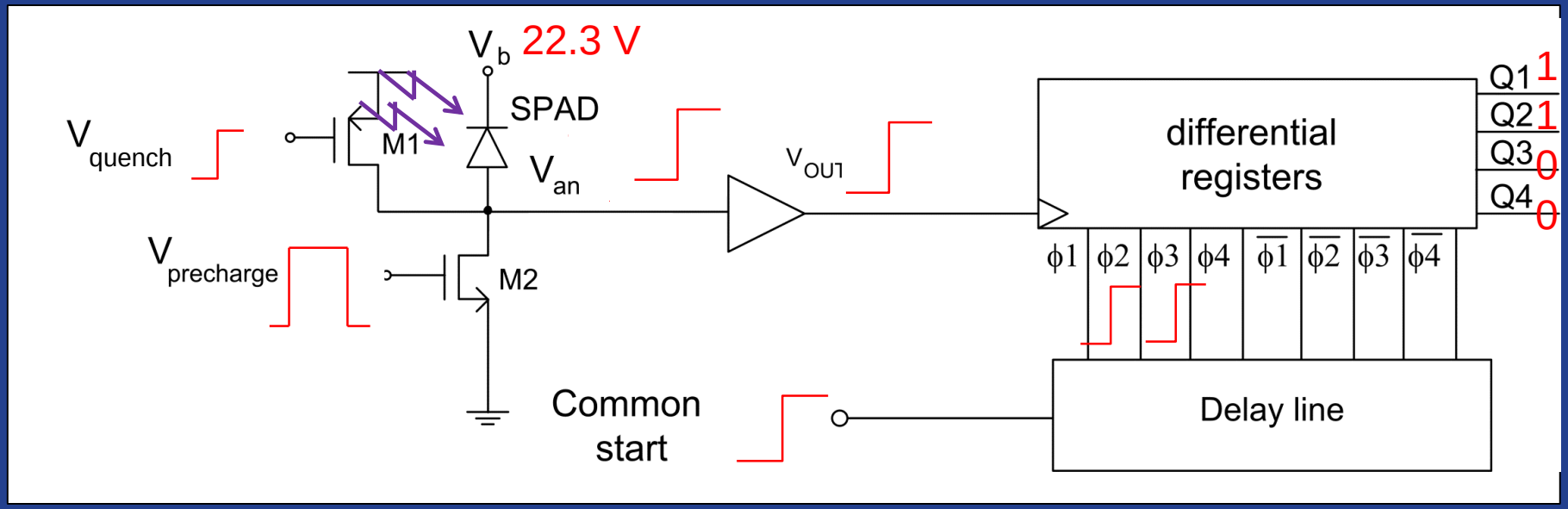

- Raman scattering probability low => Single-photon counting with SPAD
- Line sensor can be integrated into the same die with a time gating and TDC electronics => faster measurements
- Additionally enabling fluorescence life time measurement over full spectral range




λ = 532 nm
Pulse width =150 ps
Pulse rate = 350 kHz
Pulse energy = 1µJ

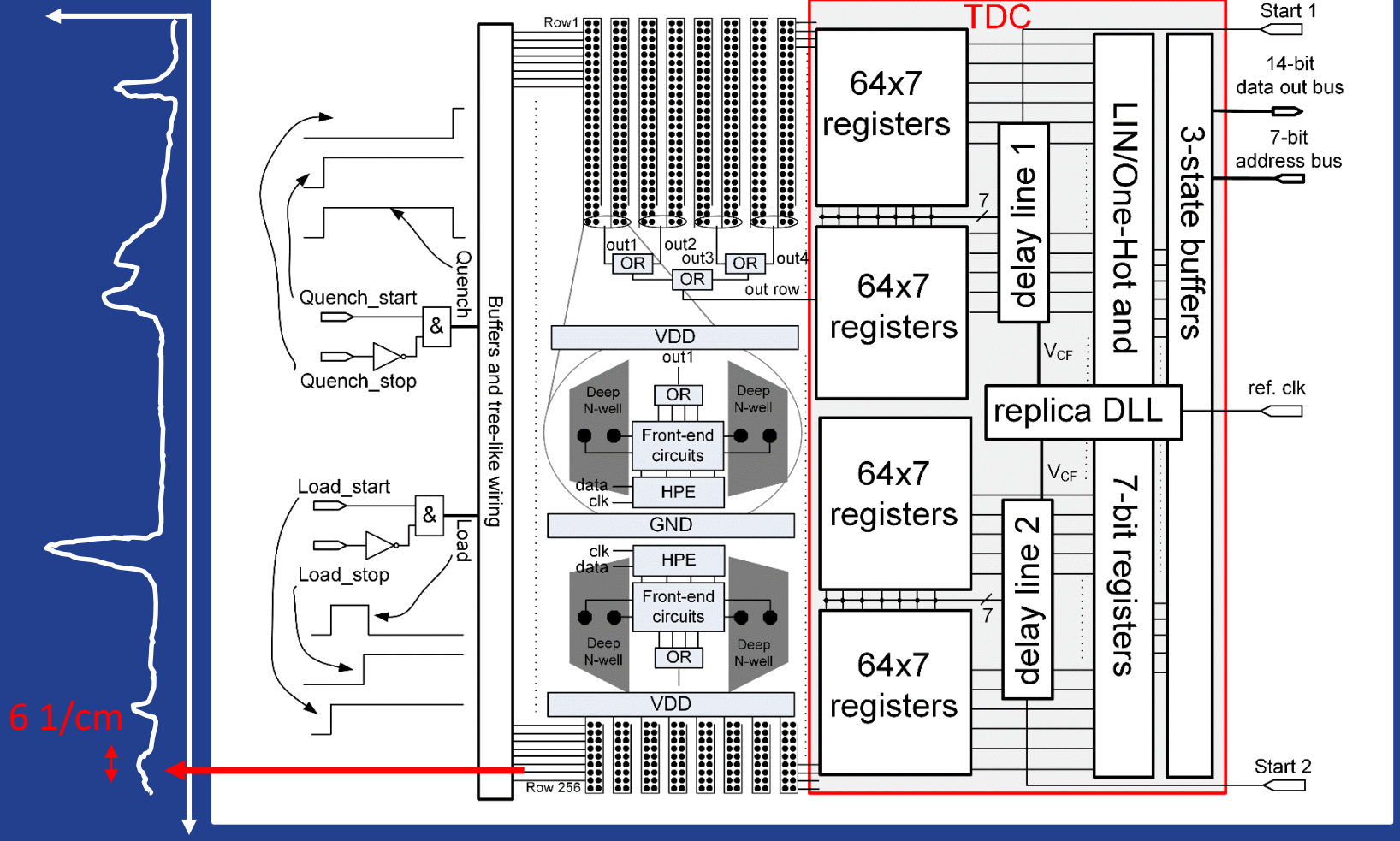
[3] I. Nissinen et. Al.," A Sub-ns Time-gated CMOS Single Photon Avalanche Diode Detector for Raman Spectroscopy," Proc. of ESSDERC'11, 12-16 Sept. 2011, Helsinki, Finland, pp. 375 - 378.
[4] I. Nissinen, J. Nissinen, P. Keränen, D. Stoppa and J. Kostamovaara, " A 16x256 SPAD Line Detector with a 50-ps, 3-bit, 256-channel Time-to-Digital Converter for Raman Spectroscopy," *IEEE Sensors Journal*, vol. 18, no. 9, pp. 3789-3798, 2018.

# Operation of SPAD with TDC

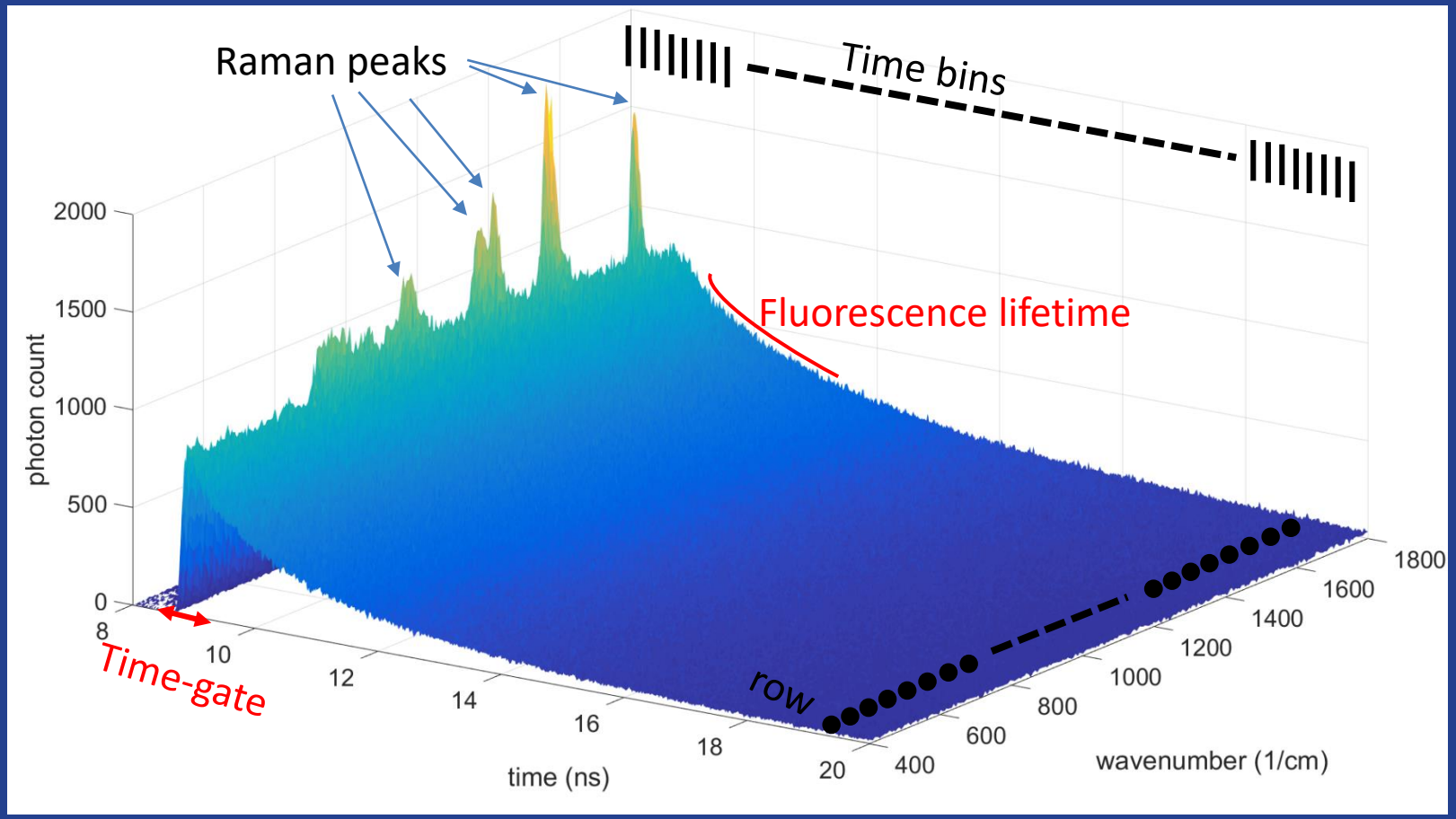


# Block diagram 16x256 SPAD array with TDCs

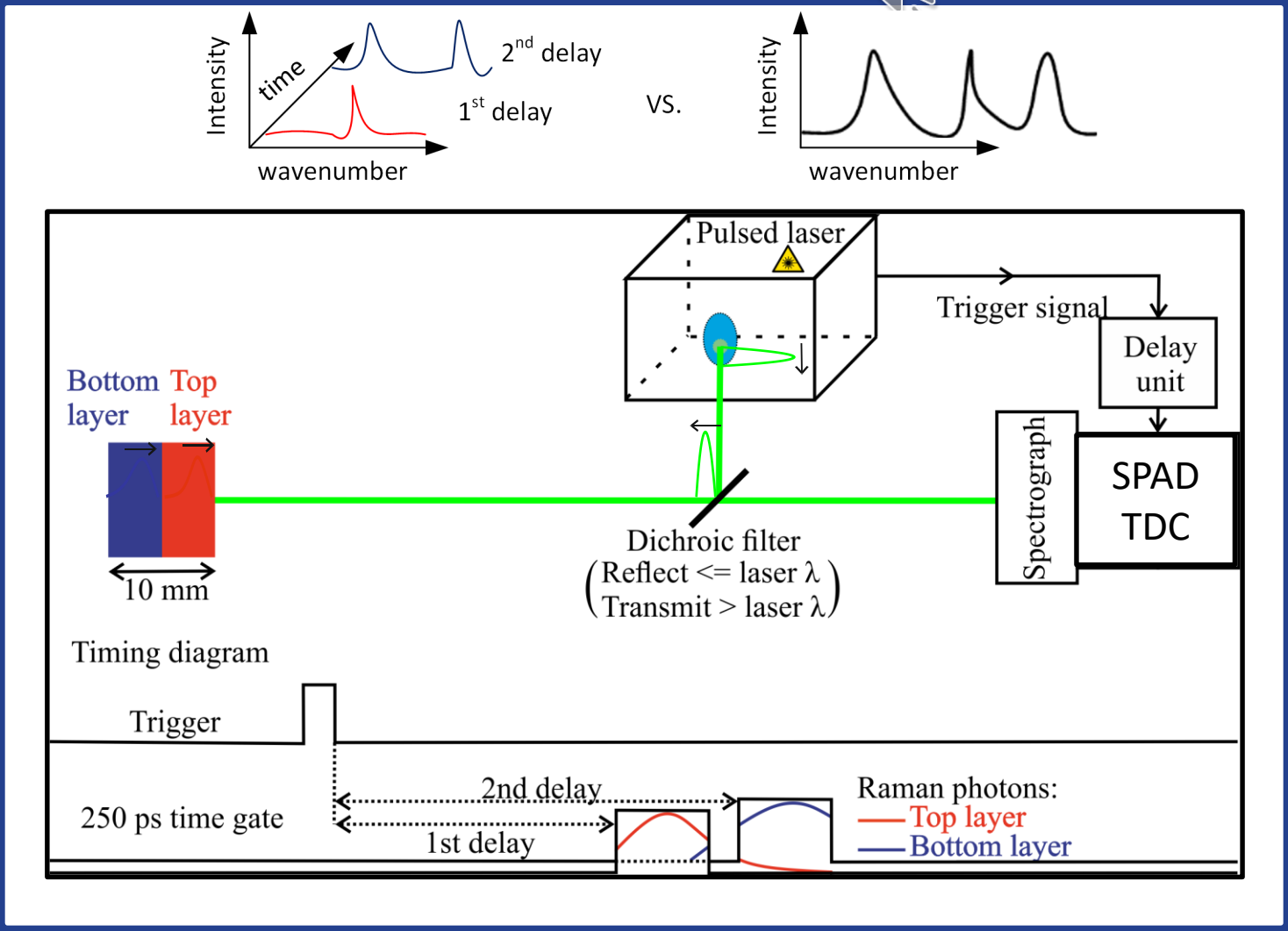
- Nominal LSB = 100ps (can be adjusted within 50ps -200 ps)



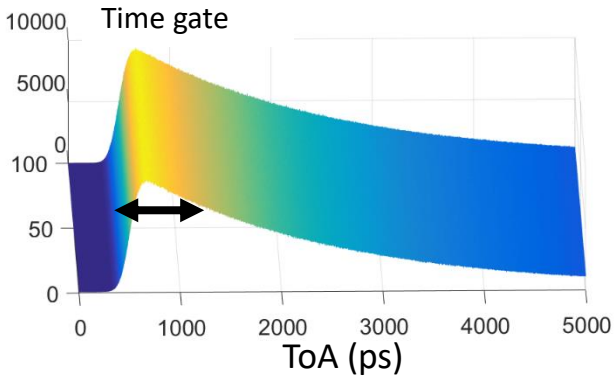
# Raman spectra and fluorescence lifetime by post processing data



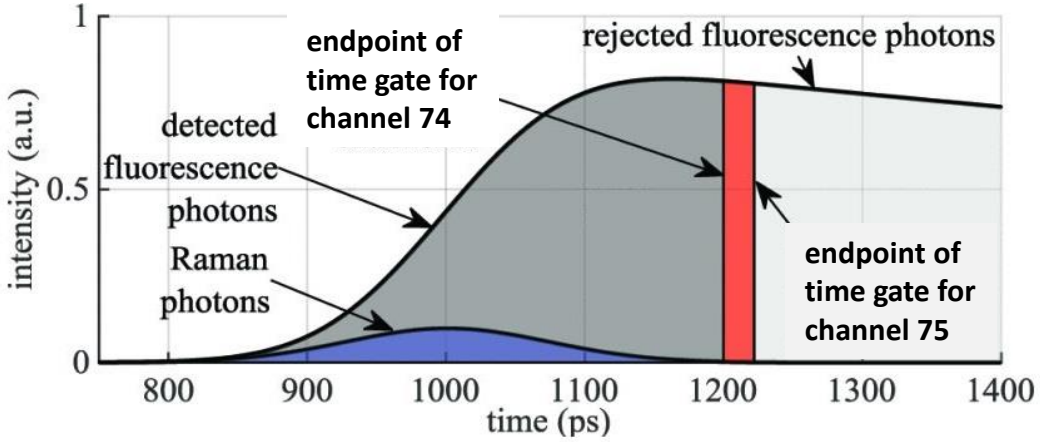
# Depth resolving Raman spectrometer

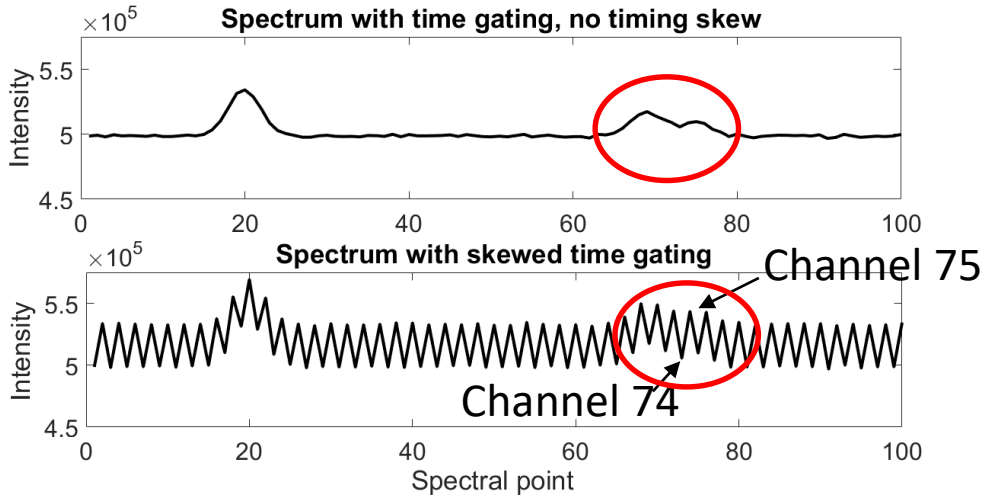


# Timing skew and distortion




- Mismatch =>Time gate width variation => distortion
- Distortion directly proportinal to Fluorescence intensity
- SDR cannot be improved by increasing integration time => Compensation required

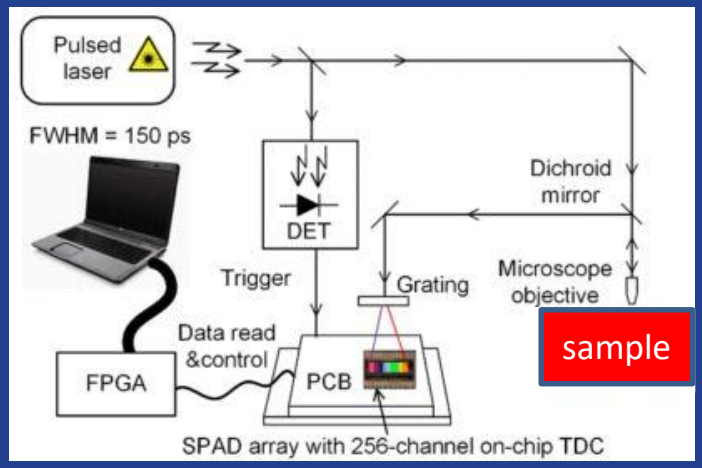


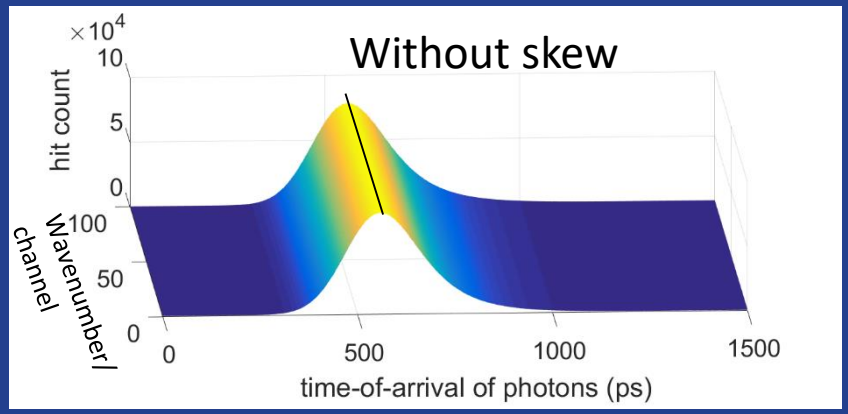




[9] T. Talala and I. Nissinen, "Timing Skew Compensation Methods for CMOS SPAD Line Sensors Used for Raman Spectroscopy," *2019 IEEE SENSORS*, Montreal, QC, Canada, 2019, pp. 1-4.

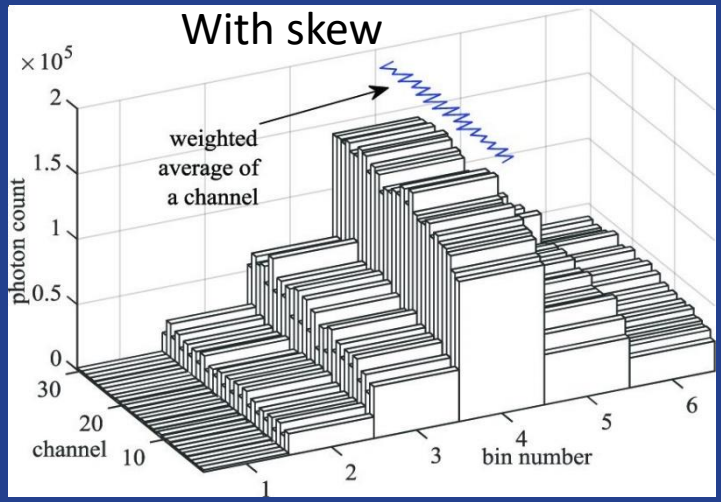
# Timing Skew compensation method

- Raman spectometer is used similarly as in normal Raman measurement but with fluorescence sample (Erythrosin B) with lifetime of 90 ps (IRFs at every spectral point)




- With skew the peak position of IRF is variating as a function of the time skew of channel
- Weighted averages of channels (wavenumber) are calculated
- Used to compensate for the distortion at every wavenumber



# Application areas SPAD-based Raman spectroscopy


[5] Y. Maruyama, J. Blacksberg and E. Charbon, " A 1024 x 8, 700-ps time-gated SPAD line sensor for planetary surface exploration with laser Raman spectroscopy and LIBS ", *IEEE J. Solid-State Circuits*, vol. 49, no. 1, pp. 179-189, Jan. 2014.

[6] K. Ehrlich et al., "PH sensing through a single optical fibre using SERS and CMOS SPAD line arrays", *Opt. Express*, vol. 25, no. 25, pp. 30976-30986, Dec. 2017.

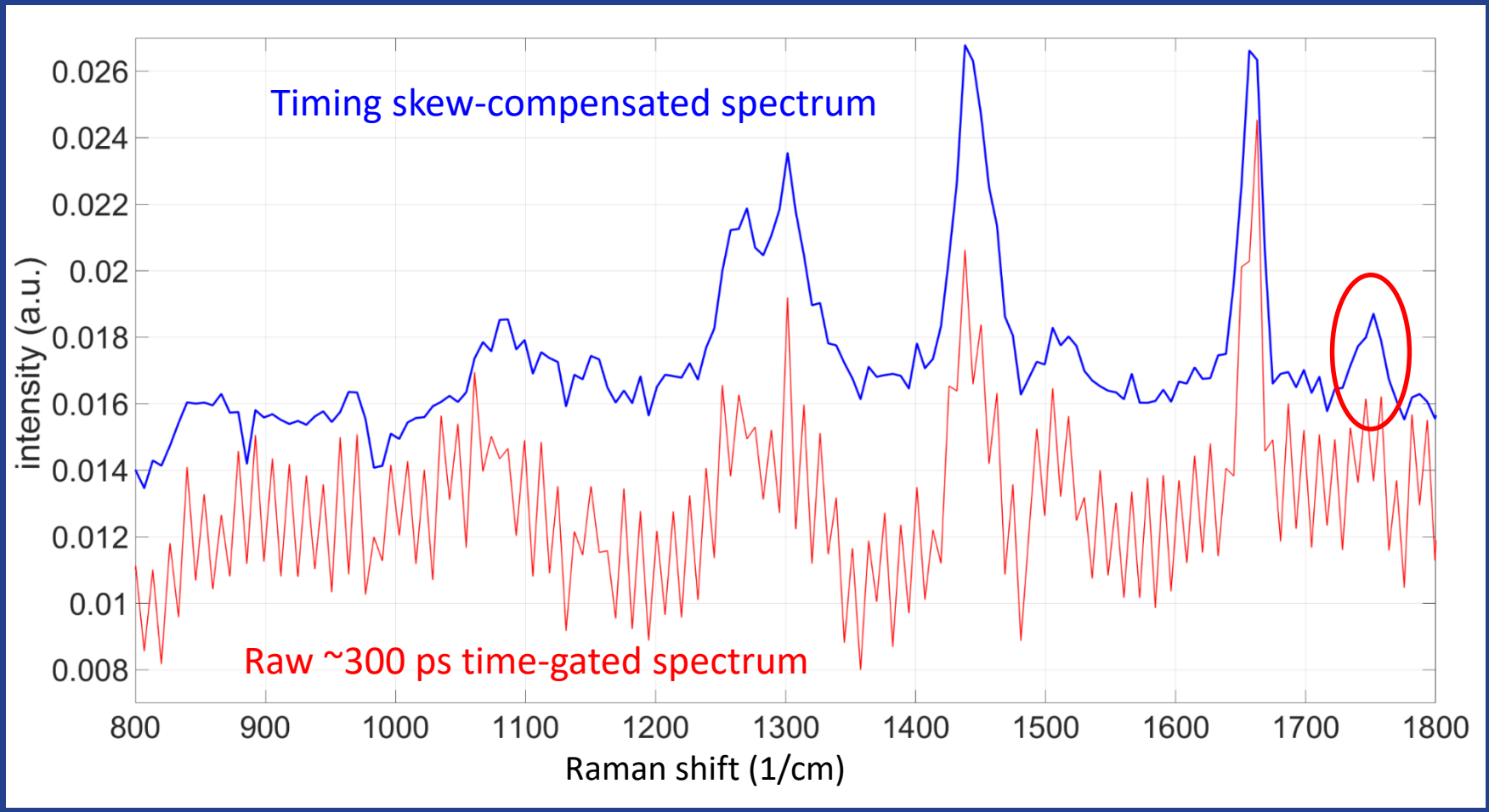
[7] T. Lipiäinen et al., "Time-gated Raman spectroscopy for quantitative determination of solid-state forms of fluorescent pharmaceuticals", *Anal. Chem.*, vol. 90, no. 7, pp. 4832-4839, Apr. 2018.

[8] A. Usai, N. Finlayson, C. D. Gregory, C. J. Campbell and R. K. Henderson, "Separating fluorescence from Raman spectra using a CMOS SPAD TCSPC line sensor for biomedical applications", *Proc. SPIE 10873 Optical Biopsy XVII: Toward Real-Time Spectroscopic Imaging and Diagnosis*, 2019.

# Measurement results

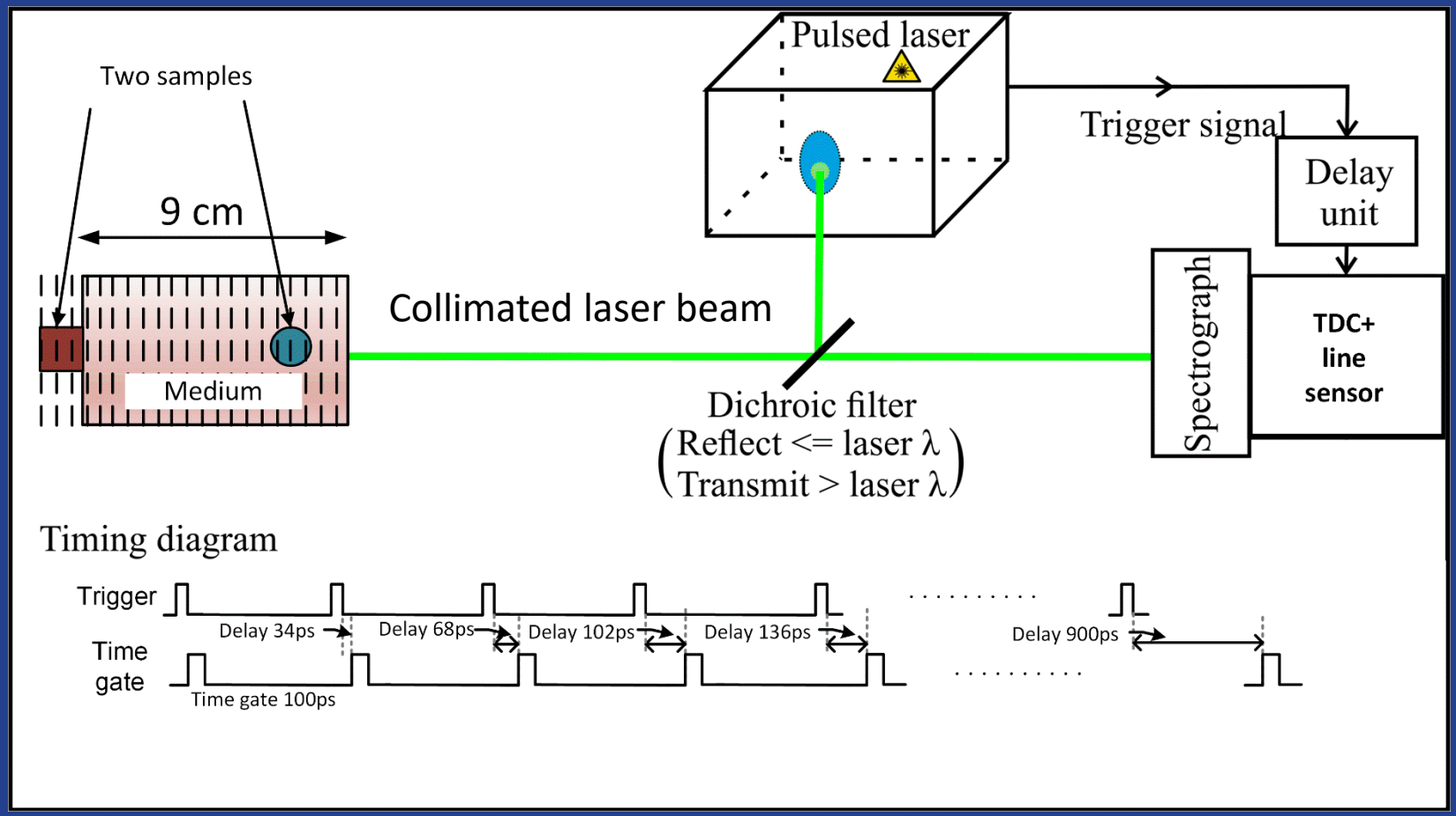
# High fluorescence sample

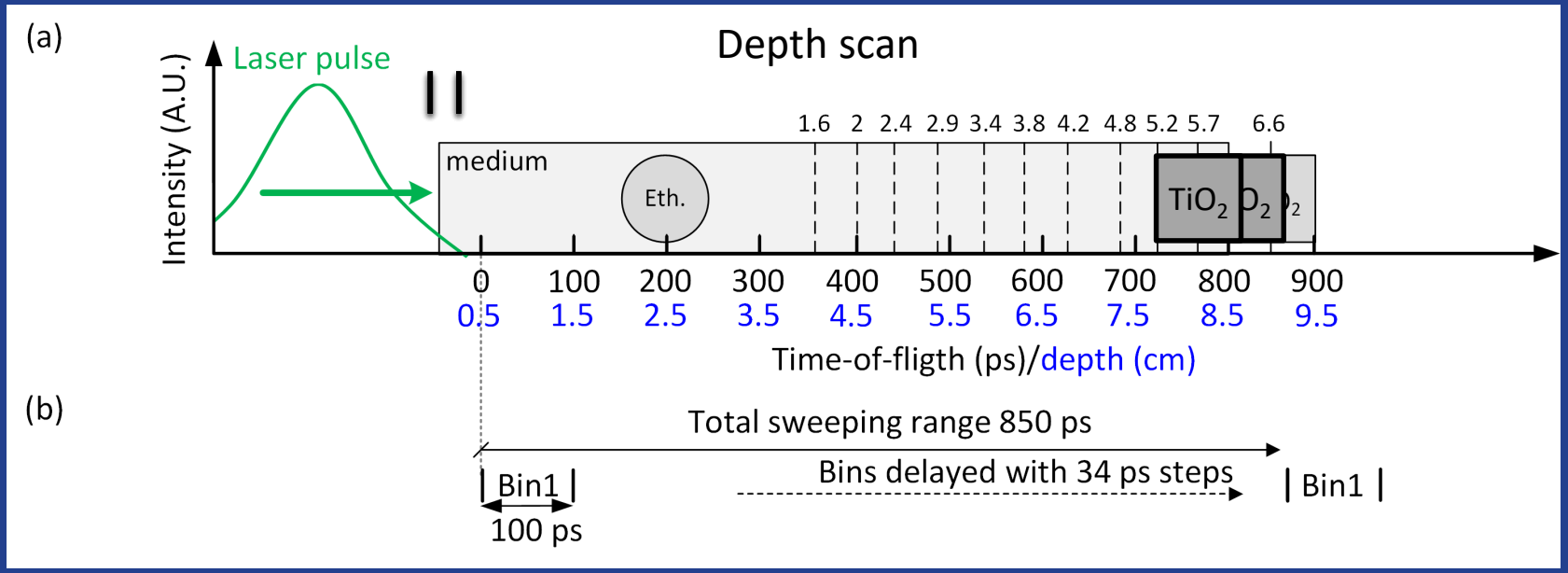
- Sesame seed oil => high fluorescence level and short life time ~2ns



# Results of depth resolving Raman spectrometer

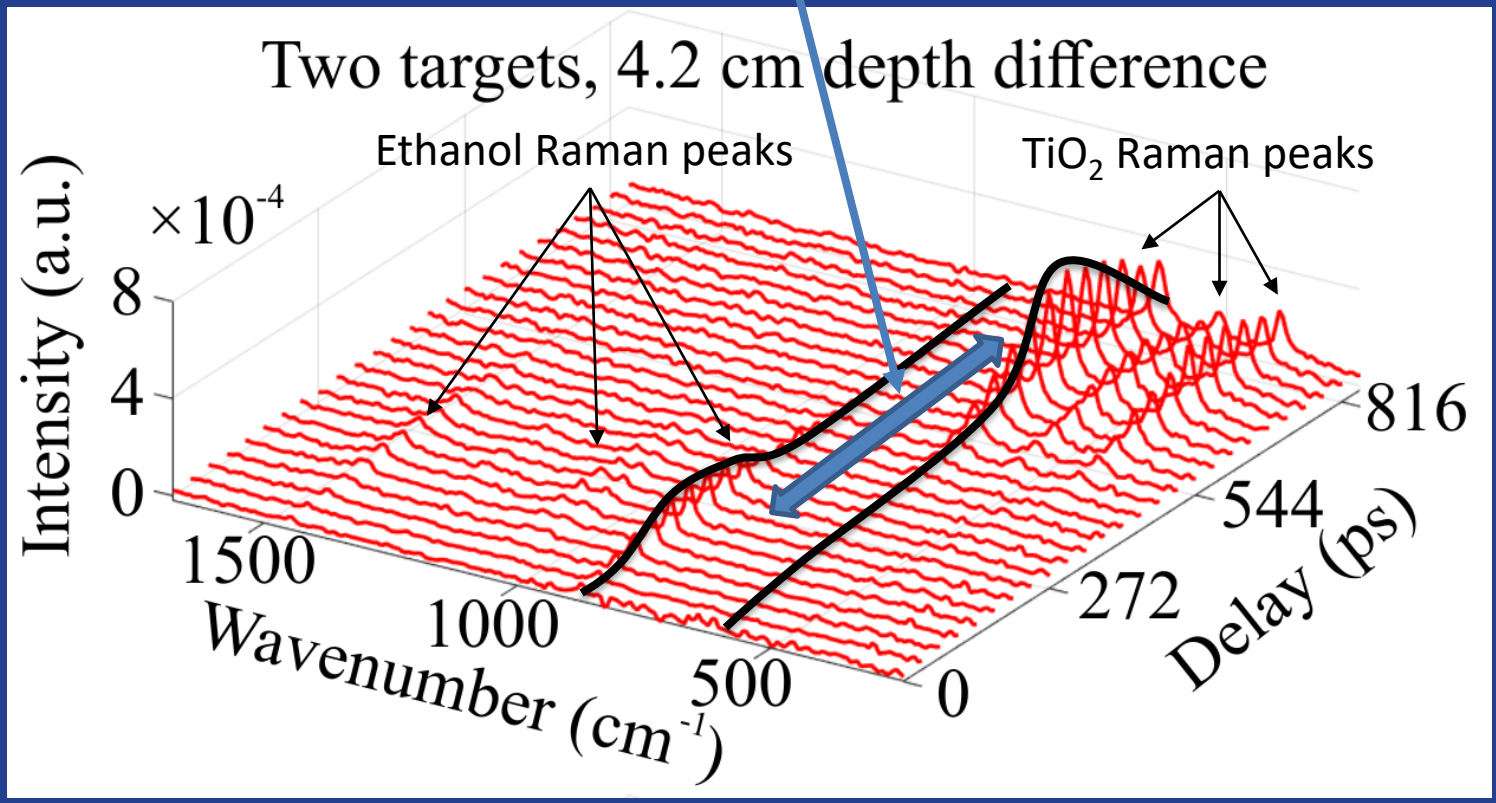
- Photon collection was not optimized by using proper optics

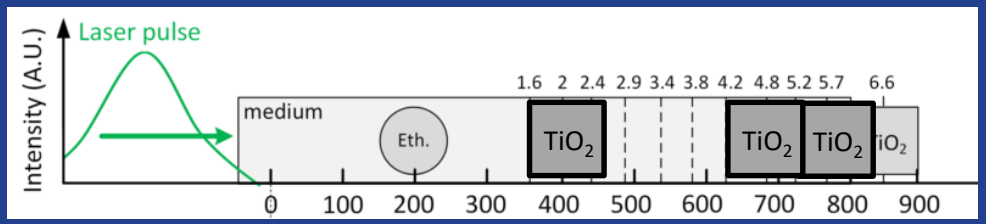



(a)
Depth scan
Laser pulse
Intensity (A.U.)
medium
Eth.
1.6 2 2.4 2.9 3.4 3.8 4.2 4.8 5.2 5.7 6.6
$TiO_2$
0 100 200 300 400 500 600 700 800 900
0.5 1.5 2.5 3.5 4.5 5.5 6.5 7.5 8.5 9.5
Time-of-fligth (ps)/depth (cm)
(b)
Total sweeping range 850 ps
Bins delayed with 34 ps steps
Bin1
100 ps
Bin1

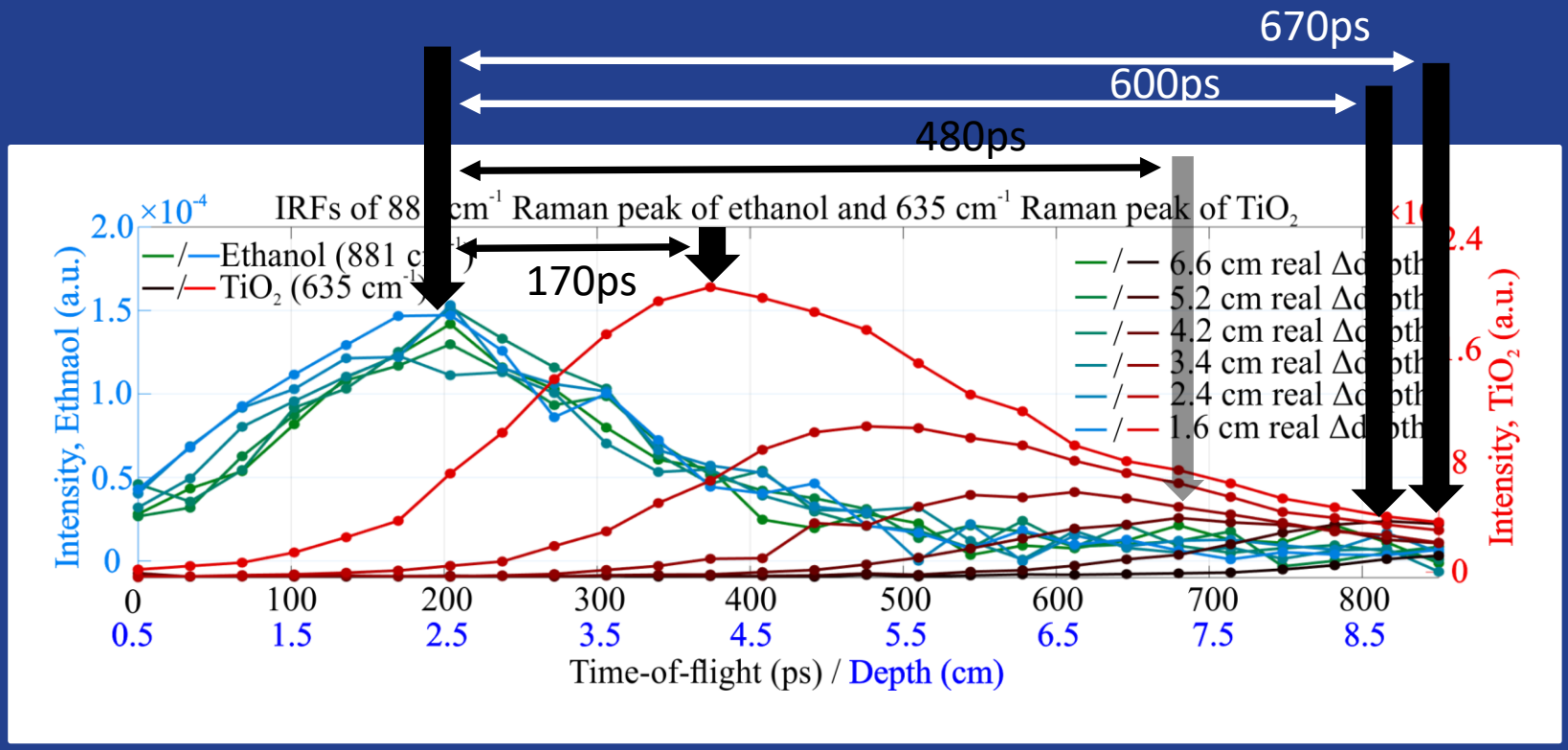
# Raman spectra as a function of a depth

**Delay difference => 4.2 cm separation between samples**






**± 0.43 cm**



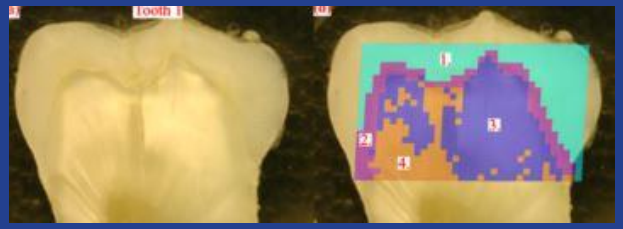

[10] J. Kekkonen, J. Nissinen and I. Nissinen, "Depth Analysis of Semi-Transparent Media by a Time-Correlated CMOS SPAD Line Sensor-Based Depth-Resolving Raman Spectrometer," in IEEE Sensors Journal, vol. 19, no. 16, pp. 6711-6720, 15 Aug.15, 2019.

[11] J. Kekkonen, J. Nissinen, J. Kostamovaara and I. Nissinen, "Distance-Resolving Raman Radar Based on a Time-Correlated CMOS Single-Photon Avalanche Diode Line Sensor," *Journal of Sensors*, vol. 18, no. 10, 3200, 2018.

# Some other application areas for tim-resolving Raman spectroscopy

## Chemical imaging of human teeth

- Collaboration with Prof. Vuokko Anttonen and Dr. Mikko Finnilä



## Time-gated Raman in mapping of eudialyte and catapleiite

- Collaboration with Dr. Saara Kaski and Dr. Häkkänen and M.Sc. Sari Romppanen


[12] J. Kekkonen, M. A. J. Finnilä, J. Heikkinen, V. Anttonen and I. Nissinen, ”Chemical imaging of human teeth by a time-resolved Raman spectrometer based on a CMOS single-photon avalanche diode line sensor,” Analyst 144 (20), pp. 6089-6097, 2019.

[13] S. Romppanen, H. Häkkänen, J. Kekkonen, J. Nissinen, I. Nissinen, J. Kostamovaara and S. Kaski, ”Time-gated Raman and laser-induced breakdown spectroscopy in mapping of eudialyte and catapleiite,” Journal of Raman spectroscopy, early view, May 2019.

# Conclusions

- Time-resolving CMOS-based SPAD array can be used effecively to suppress fluorescence background in a pulsed Raman spectroscopy
- Line sensor with time-gating and time interval measurement units can be fabricated in the same die to decrease the size and complexity of Raman sensor
- Timing skew compensation method is needed to achieve proper SDR  with high fluorescent samples
- A Pulsed laser and time-resolving SPAD sensor enables a depth-resolving Raman spectroscopy with sub-cm accuracy.