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The Source for All Applications in the Mid-IR

Twenty Years On: Current State of the Art in Commercialization and Applications of Quantum Cascade Lasers and Instruments

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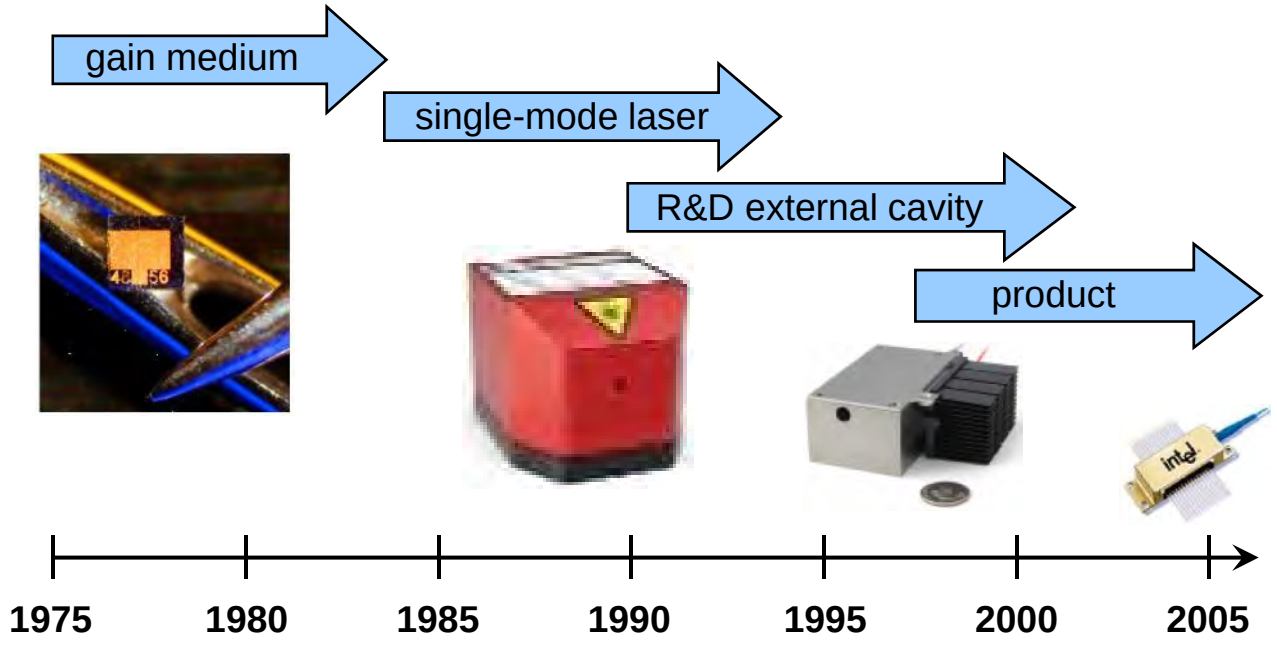
Outline

- Evolution of QCL Products
- Applications of QCL-Based Systems
- What's Next
- Summary

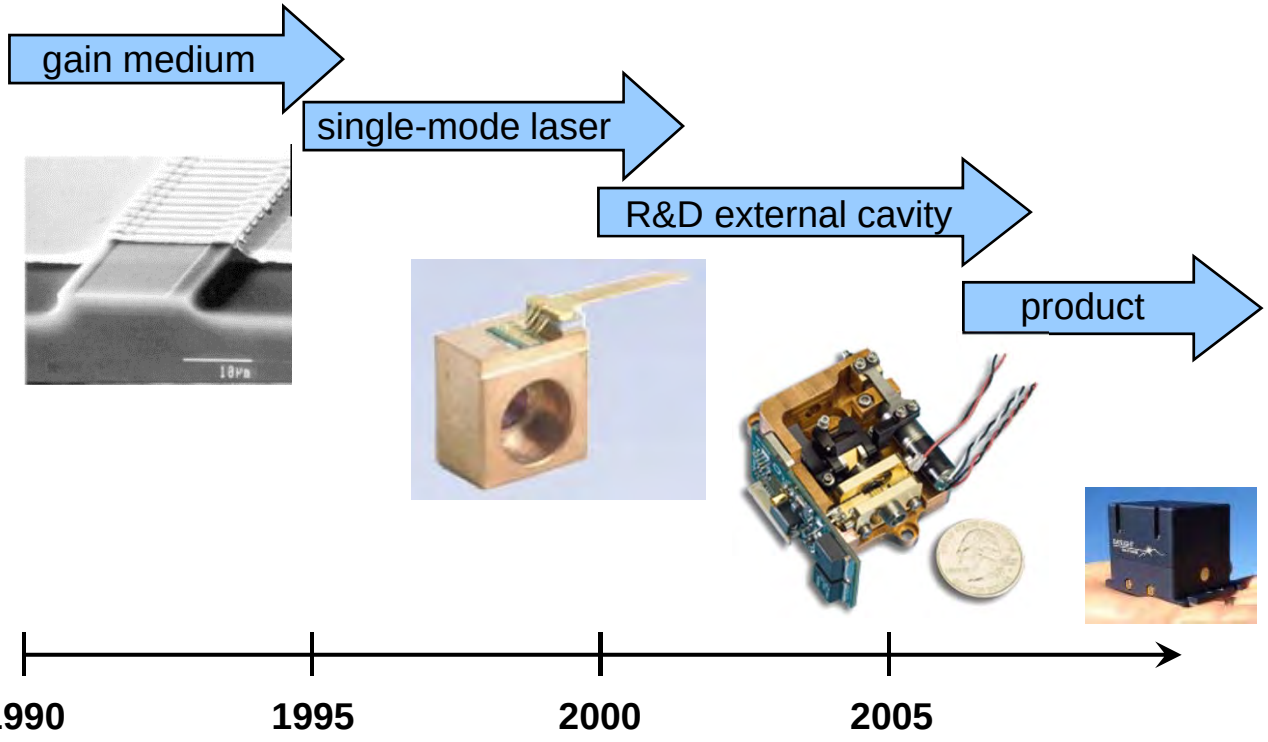
Semiconductor Diode Lasers - Timeline for Commercialization



Example: InGaAs/InP Near-IR Lasers

- Product evolution from invention to commercialization ~20 years
- Tunable (i.e., +/- 2-6%) products now available from 600 nm to 2.0 um
- Example markets served: telecommunications, near-IR spectroscopy

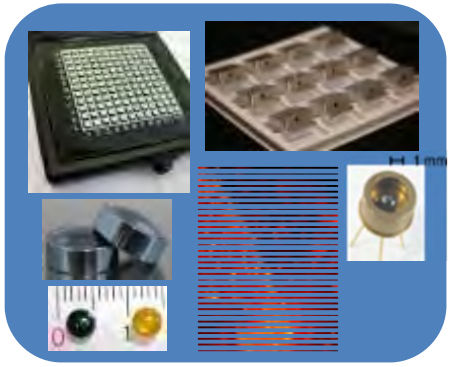
Quantum Cascade Lasers – Timeline for Commercialization

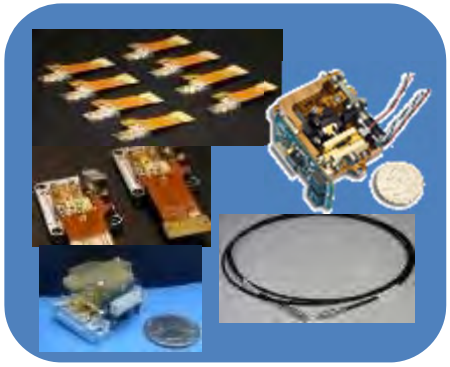


- Product evolution from invention to commercialization ~15 years
- Broadly tunable products now available from <4um to >11um
- *Accelerated time-to-market for QCL-based commercial products*

Technology Transition to Commercial Production

Components → Sub-Assemblies → Systems





Rapid Transition to Commercial Production is Essential for Widespread Adoption of Mid-IR Capabilities

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Commercial Product History

2006 — Broadly-Tunable, Pulsed Turn-Key Lasers

2007 — High Sensitivity, Low-Noise Detectors

2008 — Fixed Wavelength, Turn-Key Lasers

2009 — Ultra-Wide Tuning (>300cm-1) Lasers

2010 — QCL-Based Microscope Imaging System

2011 — MIRcat™ Ultra-Wide Tuning Laser System

2006 — Broadly-Tunable, CW Mode-Hop Free Lasers

2008 — Rapid Scanning Spectrometer

2011 — Aries™ High Power Fixed Wavelength Lasers

2012 — Miniaturized Broadly Tunable Lasers

2013 — Broadly-Tunable, CW MHF (w/ dither) Lasers

QCL-Based Products Have Been Transitioned Into Production to Serve Scientific and Commercial Applications

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High Power and Portable Laser Product History

Military Production System Prototypes

High-Power, Fiber-Coupled Laser System Prototypes

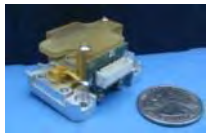
Flight-Qualified Laser Systems

High-Power Spectral Beam Combined Lasers

Military Production System Prototypes

2008 2009 2010 2011 2012 2013

Compact, Battery-Operated Lasers



Lightweight, Rifle Mounted Lasers

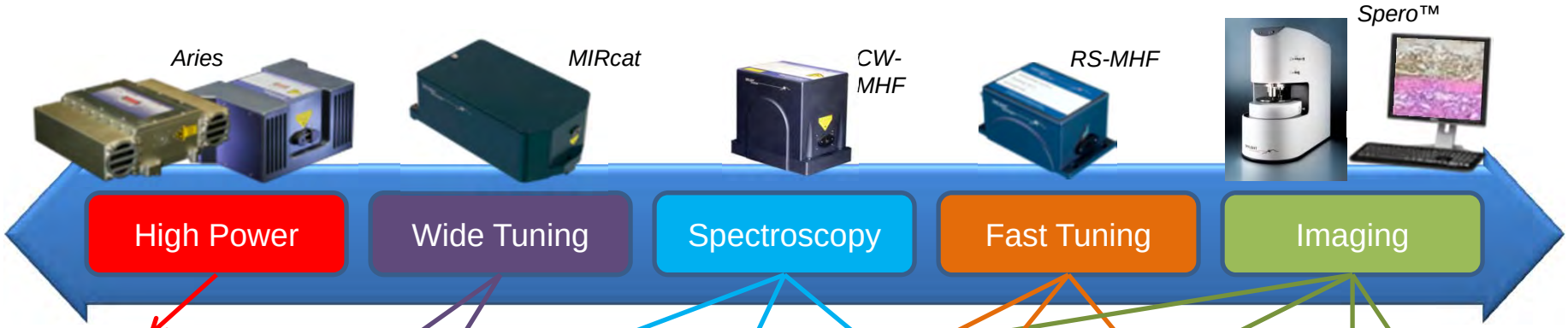
Tripod Mounted, High-Power Lasers

Handheld Targeting Lasers

Handheld and Wearable Beacons

QCL-Based Laser Systems Have Transitioned Into Military Production Programs

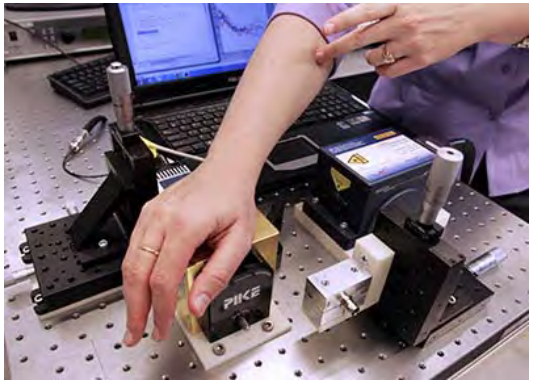
QCL Instrument Performance Capabilities to Address Multiple Applications



- Defense & Security
- Cancer Detection
- SOx Monitor
- H2S Detection
- CH4 Leak Detection
- Nanoscale Imaging
- Breath Analysis
- Pharma Cleaning
- Waste Anesthesia Gas
- Cell Sorting

Diverse Applications Continue to Drive Performance Improvements for QCL Products

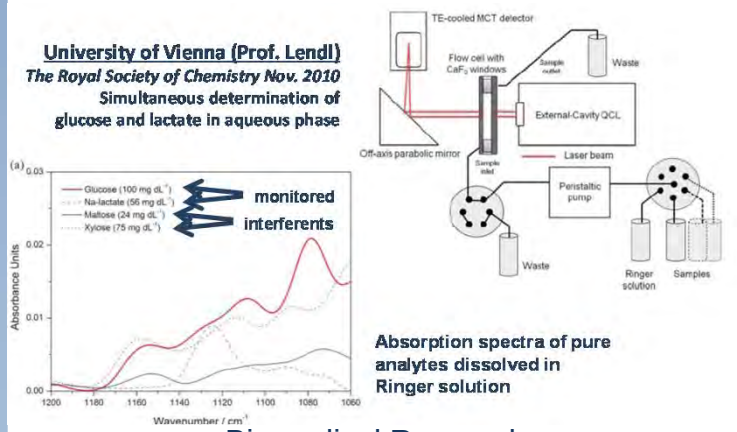
Selected Applications of QCL-Based Products



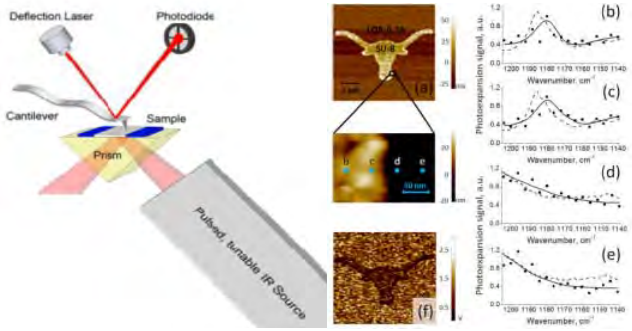
Noninvasive Glucose
(e.g., Gmachl, MIRTHE)

Standoff Detection
(e.g., ORNL)

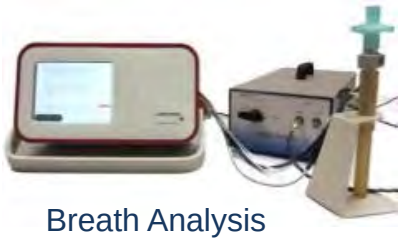
Environmental Monitoring
(e.g., MIRTHE)



Biomedical Research
(e.g., Lendl)



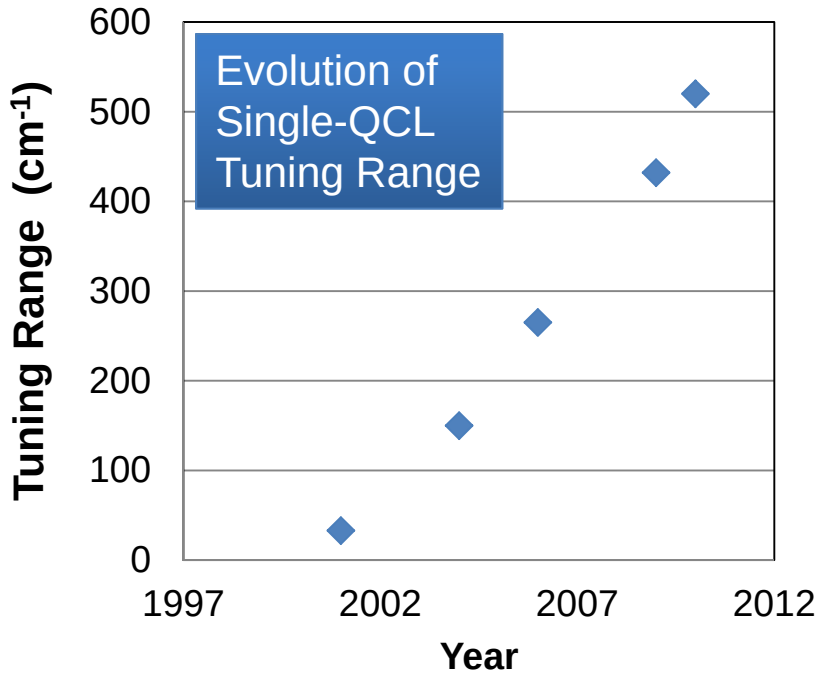
Nanoscale Imaging
(e.g., Belkin, Basov)



Breath Analysis
(e.g., Risby)

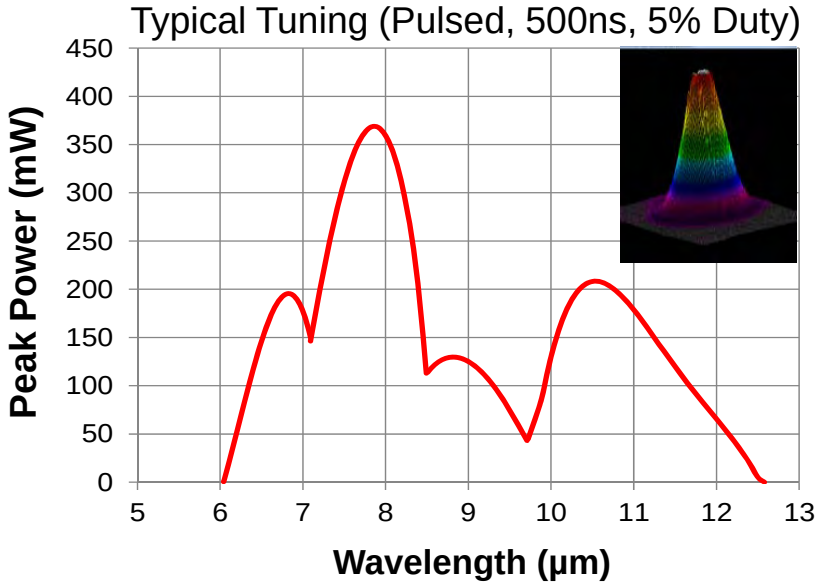
QCL Products Address Demand for Broad Tuning

- "Fingerprint" spectroscopy applications are driving demand for 750 - 1000 cm^{-1} coverage
  - ➢ QCL gain bandwidth continues to increase
  - ➢ Multi-QCL architectures have been commercialized

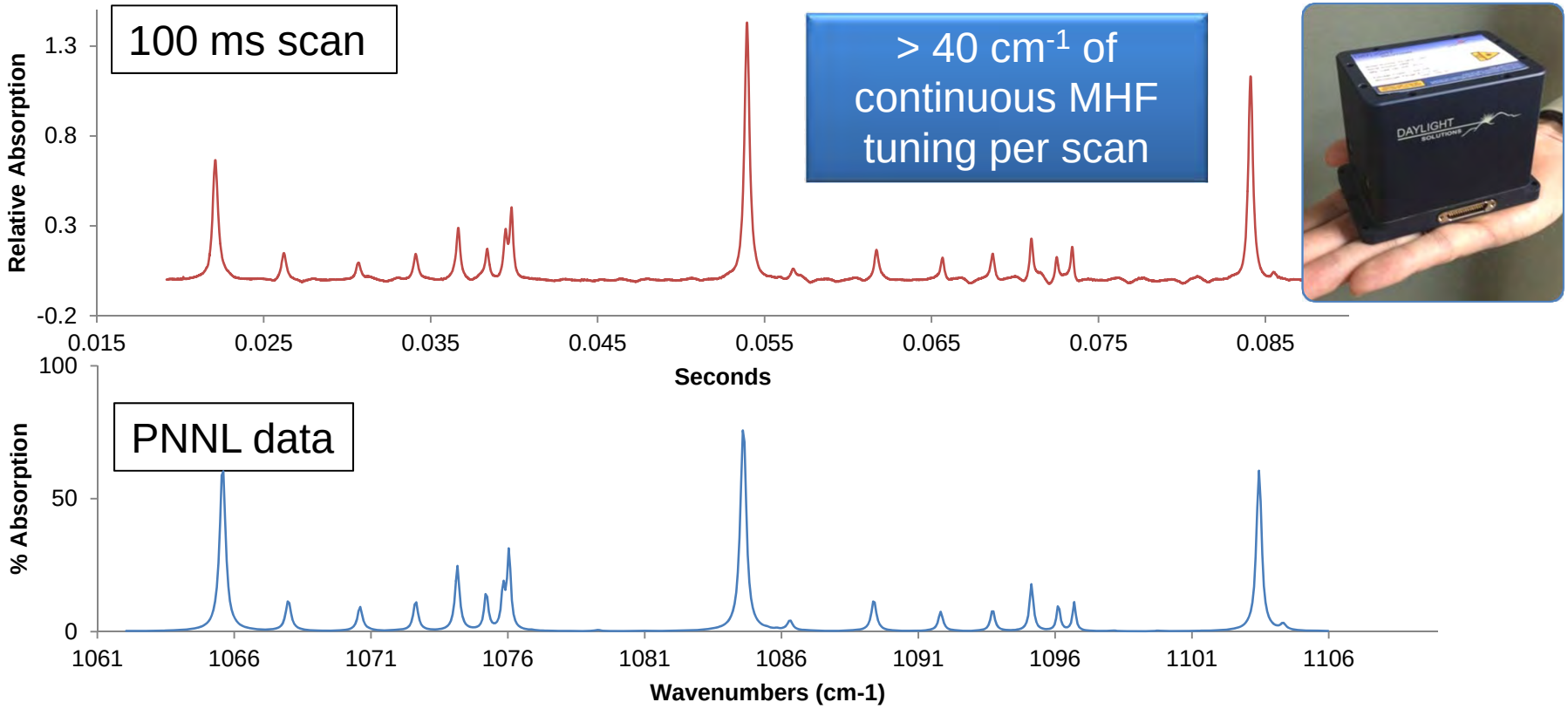


Multi-QCL "MIRcat™"

- *CW or pulsed*
- *< 5 to > 12 µm*
- *Co-axial beams*



Addressing Demand for High Volume: Compact Rapid-Scan CW-MHF OEM Modules



QCL Products Can Meet Future Demand for High Quality of Light

Emerging Application: *QCL-based Microspectroscopy*

(Prof. Wolfgang Petrich's Lab, U. Heidelberg)

Journal of Biomedical Optics 19(11), 111607 (November 2014)

Quantum cascade laser–based hyperspectral imaging of biological tissue

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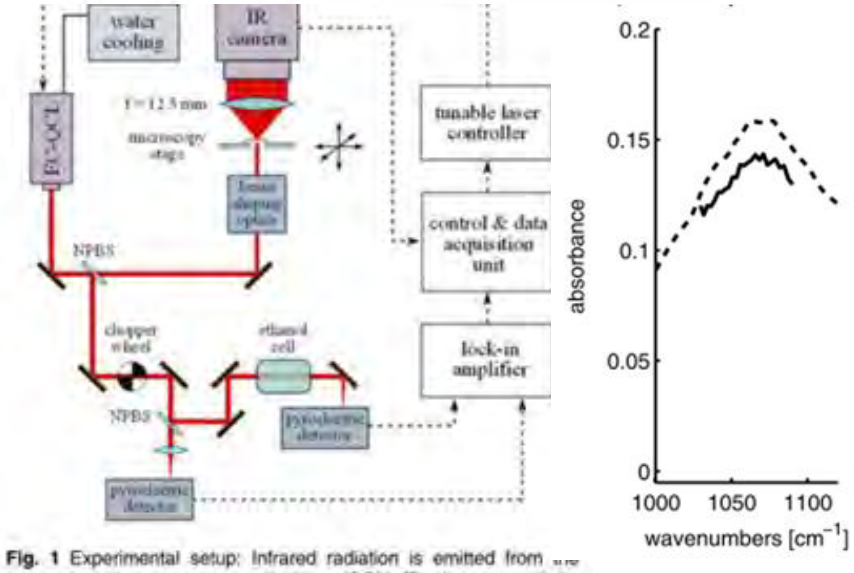
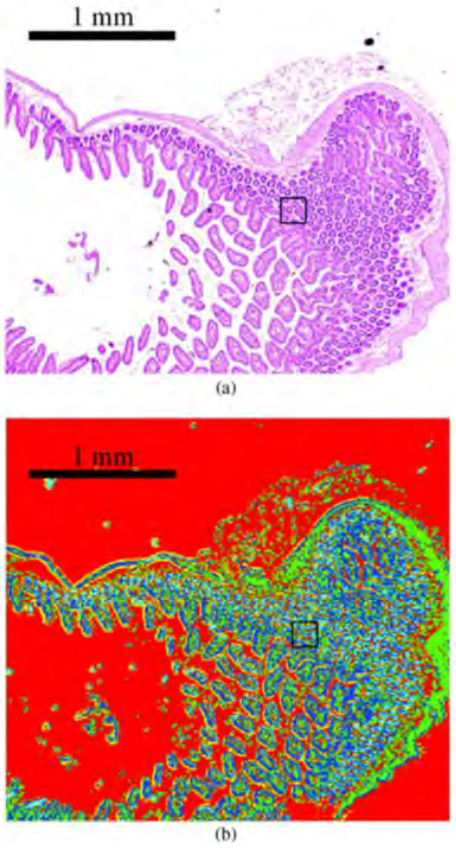


Fig. 1 Experimental setup: Infrared radiation is emitted from ... external cavity quantum cascade laser (QCL). The beam is split by a nonpolarizing beam-splitter for simultaneous power- and wavelength-monitoring as well as sample illumination. NPBS, nonpolarizing beam-splitter.



Vis H&E stained image

QCL image (1030-1090 cm-1)

Mid-Infrared Imaging: Past and Future

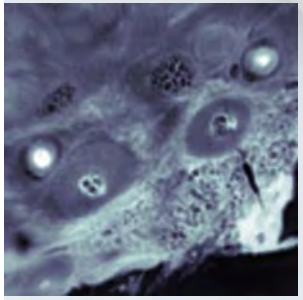
- A "Synchrotron" is a 100+ million dollar facility used to generate mid-IR light which is often used to feed into an FTIR for tissue analysis
- Customers rent time on the system to conduct research

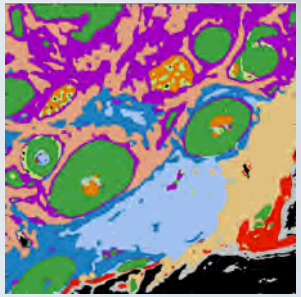
- Daylight's Spero™ Microscope provides "Synchrotron performance on your desktop!"

Spero™

Shining a New Light on Infrared Imaging™

Visualizing chemistry, without labels or stains

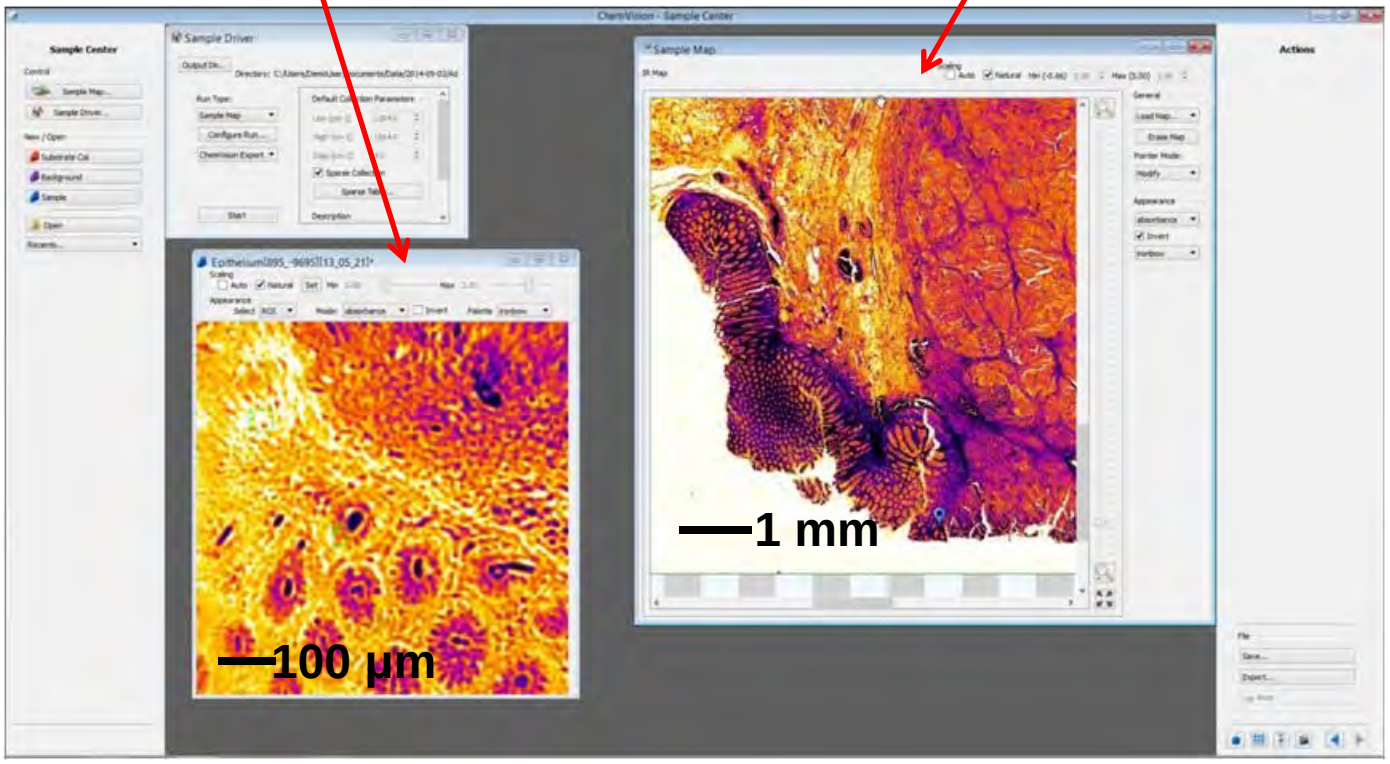




Spero™

- Live IR absorbance image at 30 fps
- 900-1800 cm^{-1} coverage

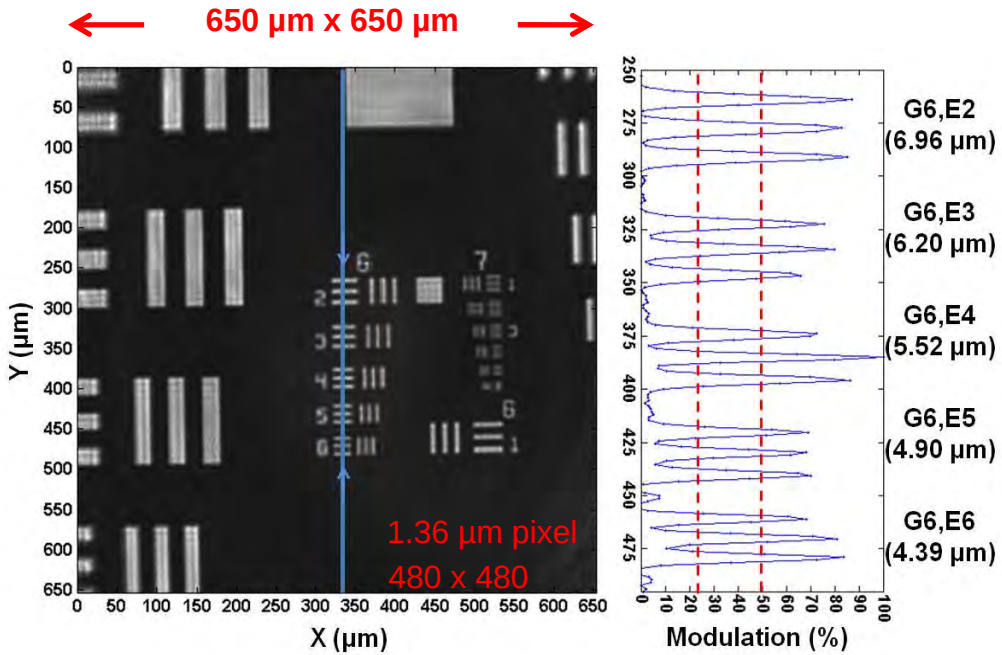
- Wide-area imaging for sample navigation
- Reflection and transmission modes
- Automated stage
- Batch data collection



3 objectives (2 IR, 1 Vis)
(IR) 0.7 NA, 12.5x
(IR) 0.15 NA, 4x
(Vis) 0.15 NA, 4x

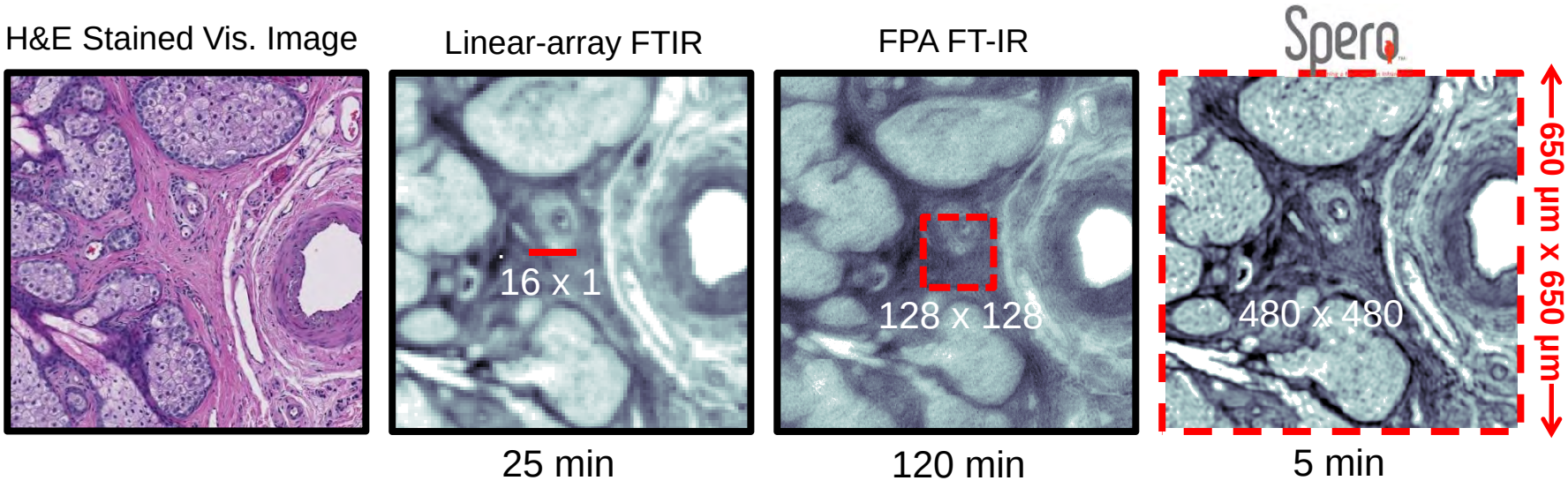
(cancerous colon tissue on BaF2 substrate)

High Spatial Resolution Spectrochemical Imaging



Spero™ Provides Near-Diffraction-Limited Performance

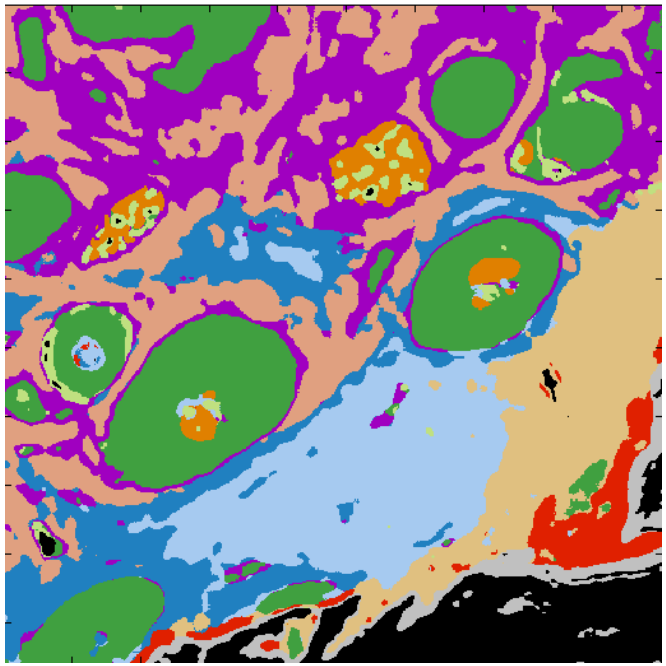
High-Definition Spectrochemical Imaging



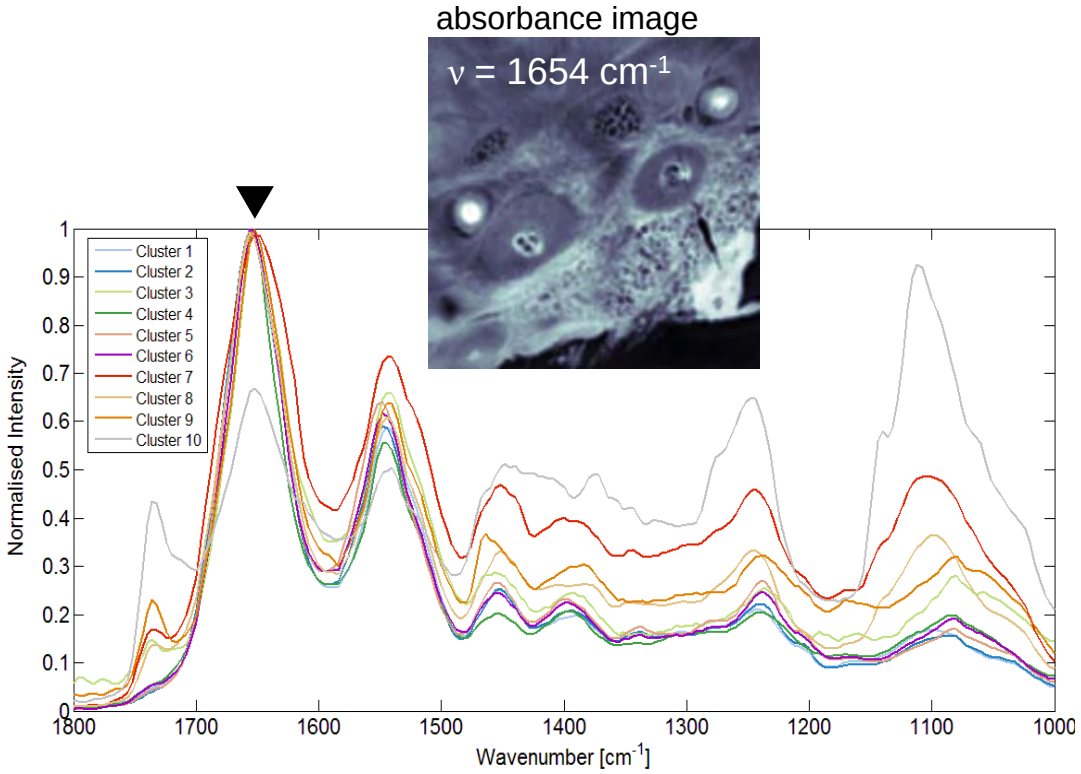
Spero™ Combines Best-In-Class Performance of Imaging Techniques

- *Speed (5X faster than current state-of-the-art)*
- *Spatial Resolution (comparable to visible; H&E)*
- *Field of View (meets industry standard for clinical samples)*
- *Fingerprint Spectra (comparable to state-of-the-art lab instruments)*

High-Fidelity Spectra Covering Fingerprint Band

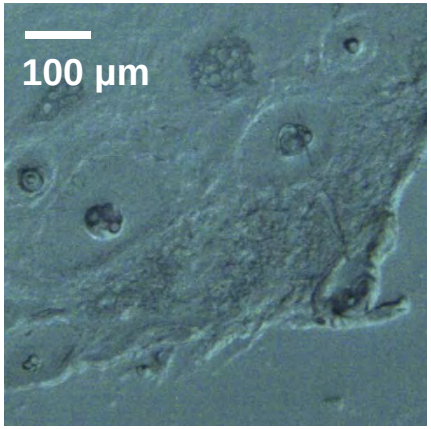


10 level HCA

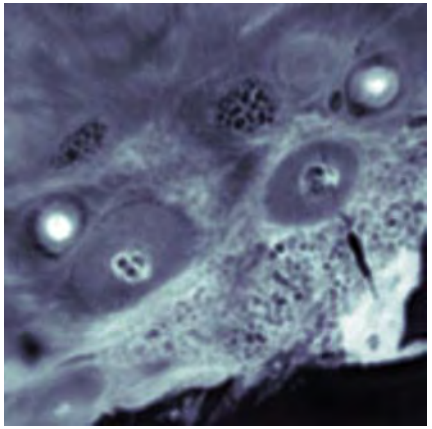


Mean cluster spectra

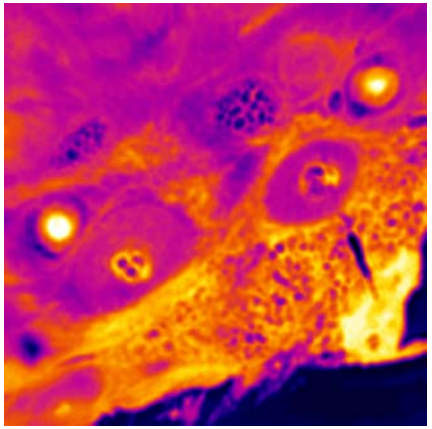
Digital Staining



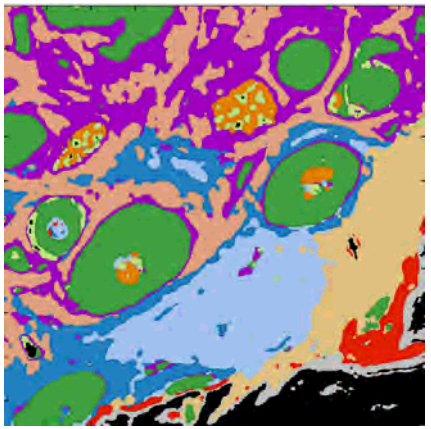
Visible image (Unstained)



Monochrome absorbance image at 1654 cm^{-1}



False color absorbance image at 1654 cm^{-1}



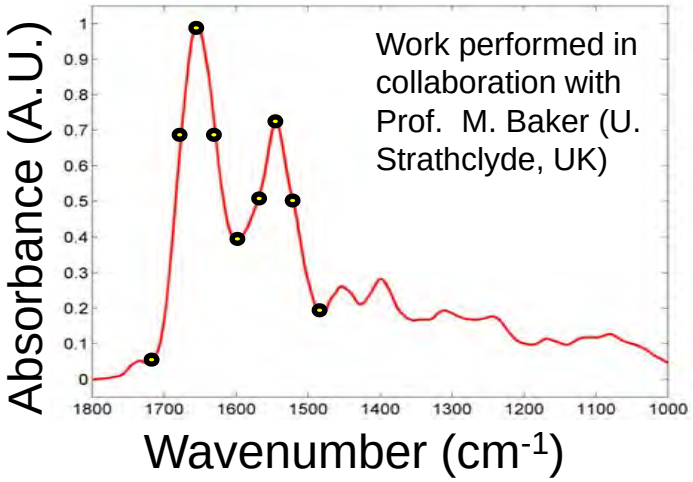
Digital Stained Image

Spero™ provides a rapid, label-free method for segmentation based on the unique spectral fingerprint at each pixel

Tissue sample courtesy of Dr. Jin Kang, Johns Hopkins University

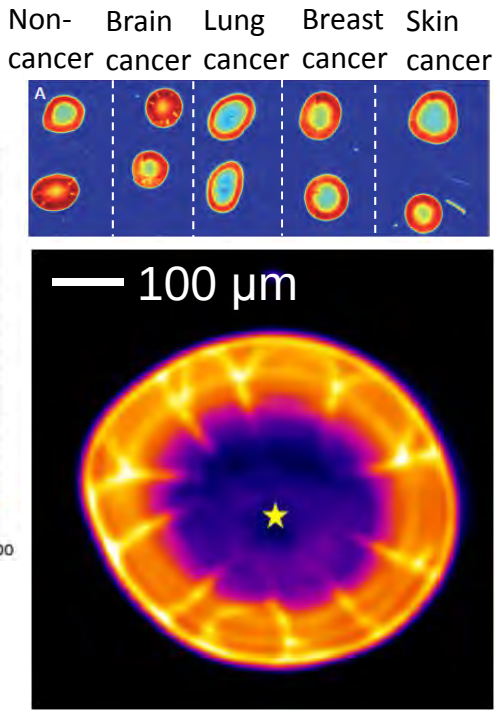
QCLs Enable High-throughput Protocols

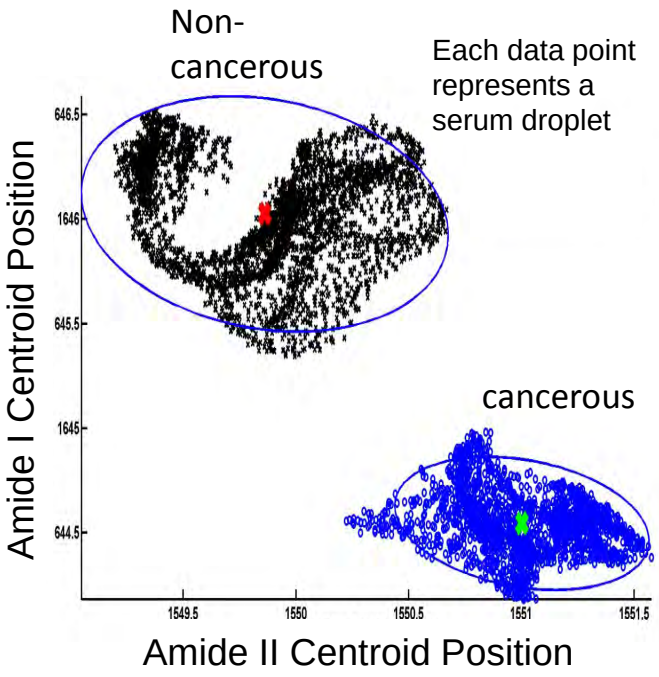
- Sparse data collection using only 9 frequencies clustered around Amide I and II bands enables robust segmentation between diseased and non-diseased blood serum droplets
- Enables large-scale multiplexing applications with precision micro-droplet techniques



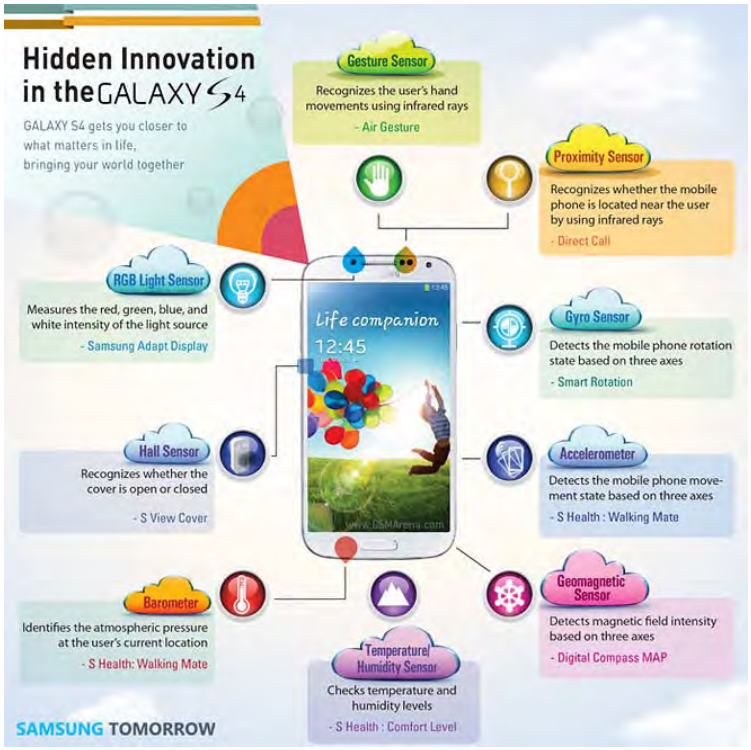
Work performed in collaboration with Prof. M. Baker (U. Strathclyde, UK)

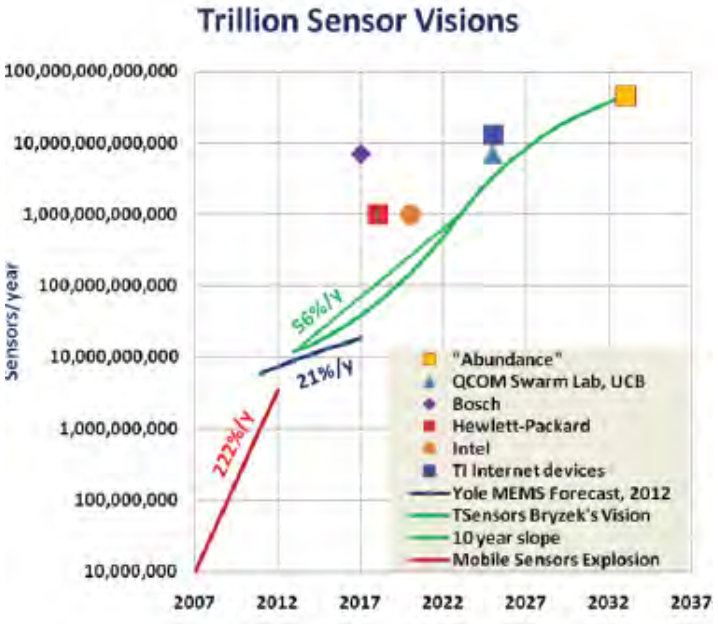
Raw pixel spectrum extracted from x, y position marked (yellow star) in b)





Sensors Are Becoming Ubiquitous





- Four sensor types shipped over 1B units each in 2012
  - microphone, acceleration, gyro, compass
- Demand driven by sensor-based smart systems
  - Addressing global problems (e.g., energy, healthcare)
- Industry/Research creating roadmaps to Trillion Sensors

Sensing the World Around Us

How is my workout going?

Do I have the right prescription?

Is my fruit ripe yet?

Should I have this checked?

What is today's air quality?

Is my food still good?

What is the quality?

Do I need to replace my groceries?

Molecular Sensors Provide Valuable Information About The Chemical Composition of Materials

The Future of Mid-IR Sensing

- Mid-IR spectroscopy has been proven in many sensing applications
- Significant overlap with applications for Health and Home
- Movements such as the “Quantified Self”, Personal Fitness Monitoring, Personalized Medicine, Environmental Monitoring and Smart Appliances are driving demand for consumer-volume sensors

Early Stage Commercialization - Lessons Learned

- Pioneering new technology involves risk, but provides strong:
  - Foundation of critical technology elements for new markets
  - Competitive & IP position
- Leveraging proven technology accelerates development
- Scientific market provides visibility on new application trends
  - And creates strong product culture with “Quality of Light”
- Core technology is critical; QCLs provide:
  - Disruptive technology that accelerates market adoption
    - Scientific: new, often unique performance opening up new applications
    - Defense: rugged, high-reliability systems with robust quality foundation
    - Commercial: scalable platform for high volume opportunities
  - Performance flexibility suited to a wide range of applications

Summary

- Timeline for QCL commercialization has been faster than near-IR
  - Much near-IR has been leveraged!
- QCL capabilities (e.g., power, gain bandwidth) have advanced significantly during the past 10 years of commercial products
- QCLs have found their way in to many niche applications in spectroscopy, Scientific instrumentation and sensing
- QCL-based products have been proven and adopted in Military applications, requiring/demonstrating extremely high levels of ruggedization and reliability
- QCL-based products have been integrated into many meaningful applications; currently undergoing field testing and evaluation
- QCL-based systems are poised to see breakout opportunities and wide commercial adoption within the next 10 years!

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PEO IEWS (US Army)

NAVAIR

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