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MIRTHE

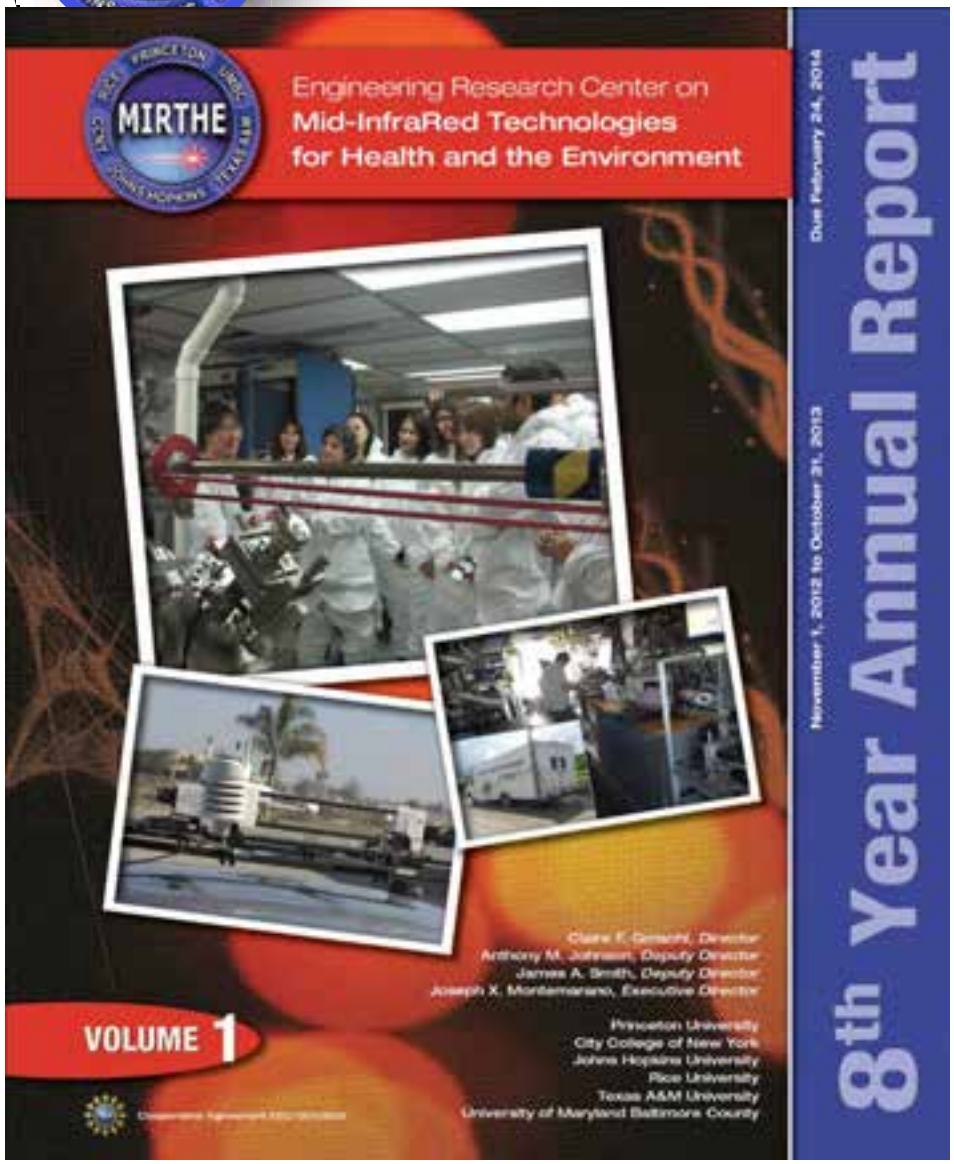
MIRTHE

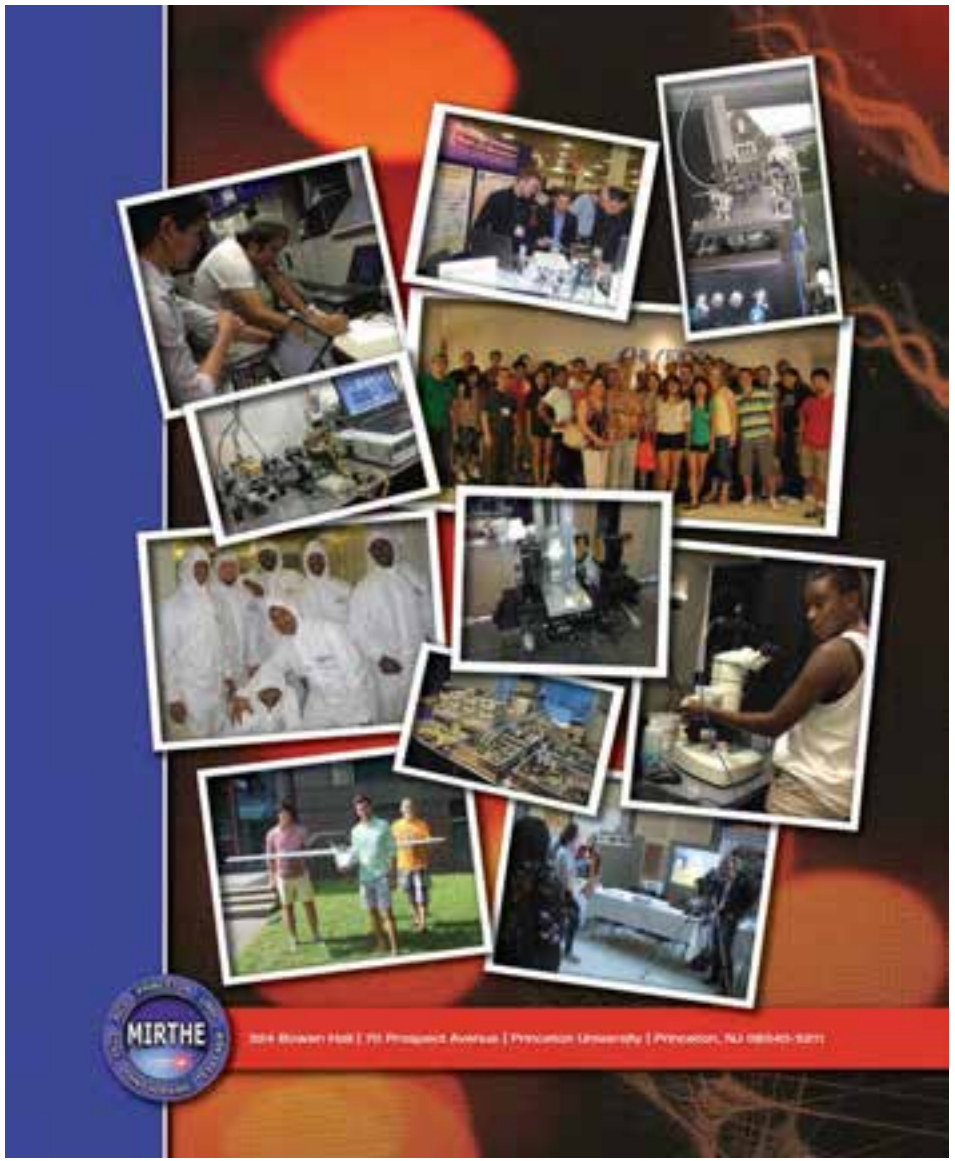
NSF-ERC – Mid-InfraRed Technologies for Health and the Environment

Director
Claire Gmachl
Princeton University

NSF-ERC Cooperative Agreement EEC-0540832

Recent report cover …

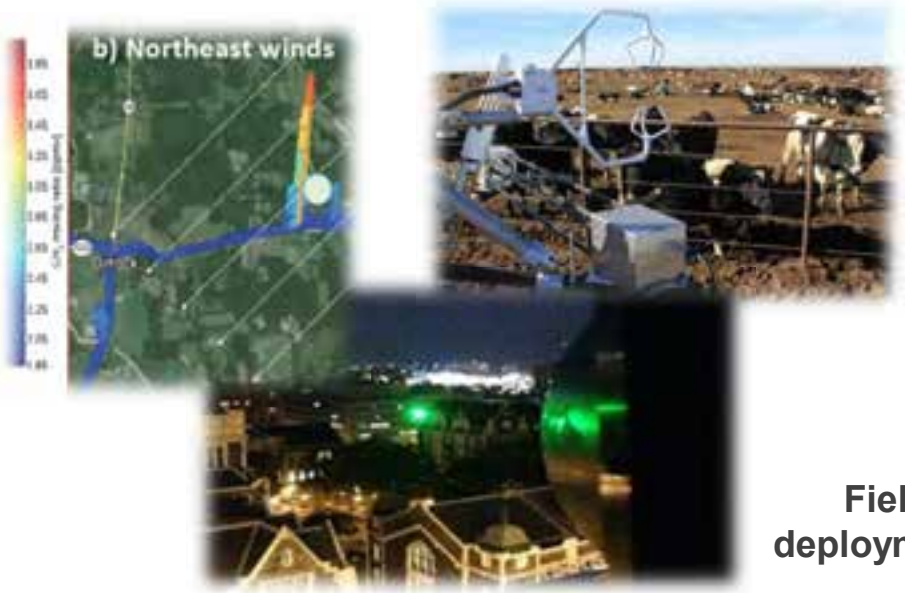




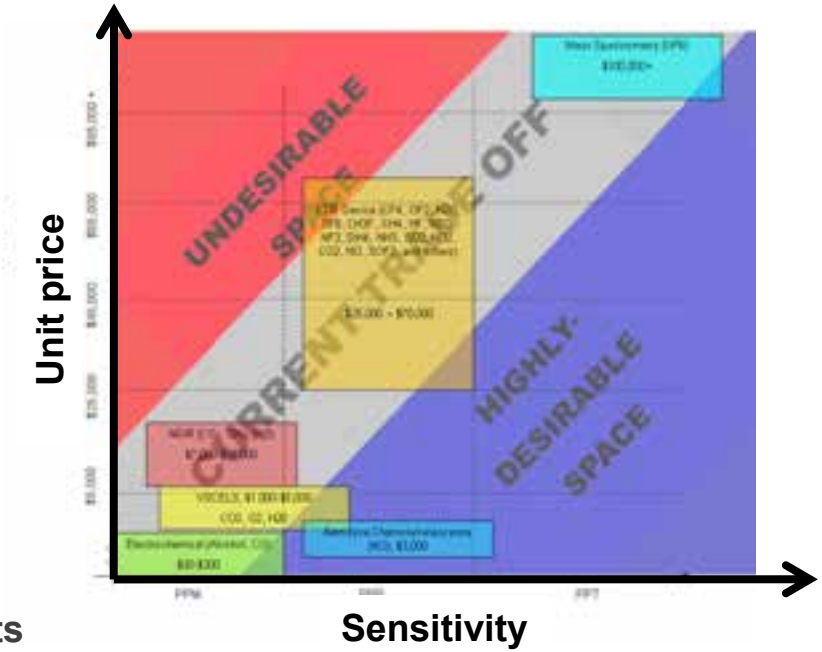
Technology vision

~~Development of a QC-laser-based platform of mid-IR trace gas sensor systems~~

- *Continued growth and expansion* of the QC/mid-IR-laser-based platform of mid-IR trace gas sensor systems
  - Unprecedented high-performance and cost-effective
  - Compactness, autonomy, networking capability, fast response
  - Individual, urban sensor network, global scale
- MIRTHE addresses the important societal challenges
  - Securing a clean, safe, sustainable, and healthy environment
  - Accessible healthcare



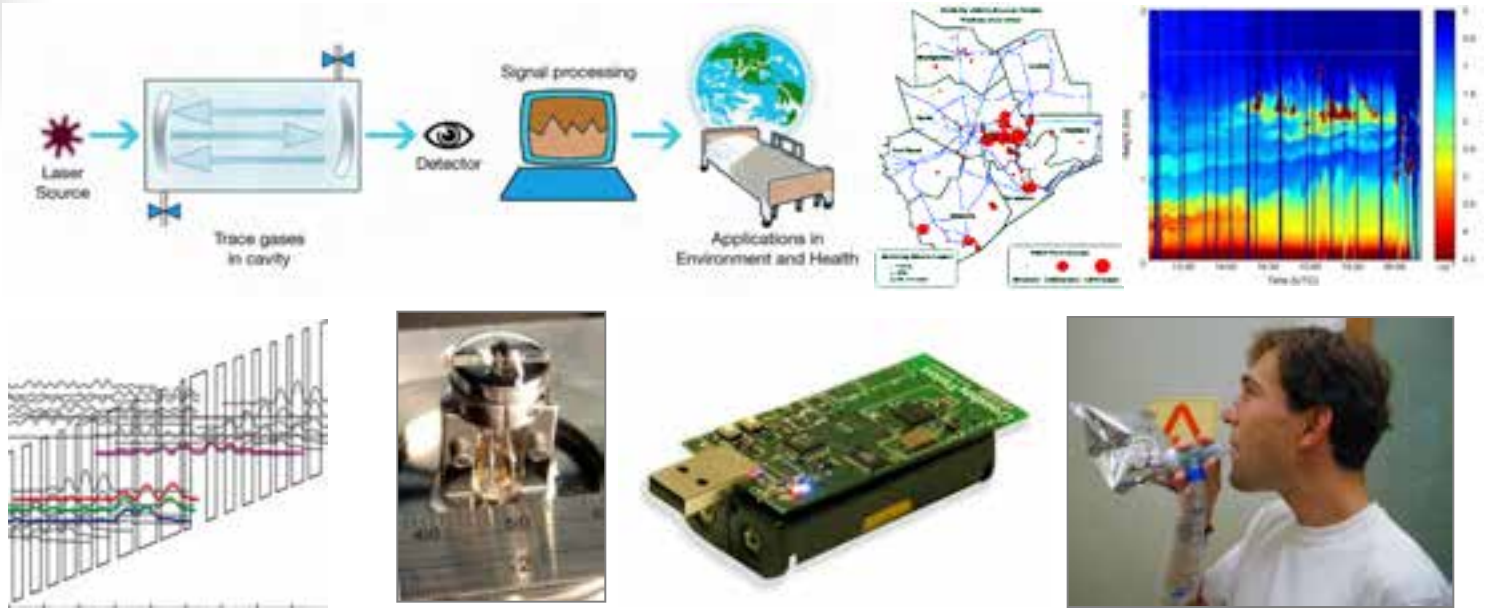
Field deployments

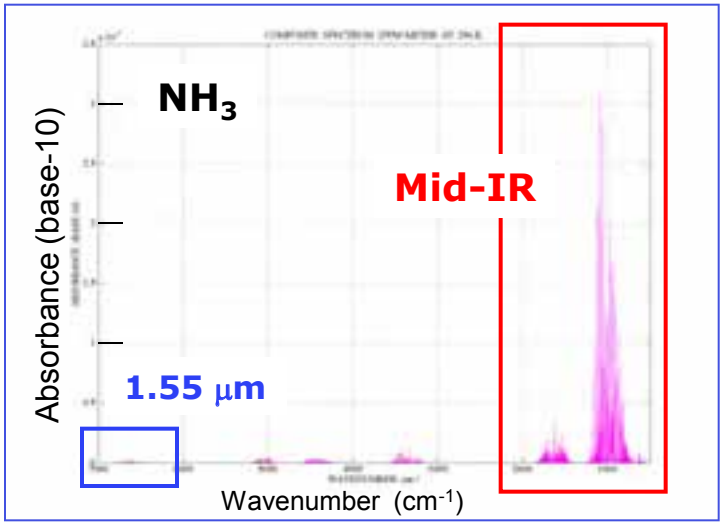


System level goals & barriers addressed

- Individual point sensors
  - Indoor and local outdoor air quality
  - Industrial or automotive monitoring
  - Sensitive (ppb – ppm), compact, easy to use, and low-cost
- Individual point sensors with fast time response
  - Real-time breath monitoring
  - Mobile sensors (automobile, UAVs)
  - Threshold sensing of highly toxic gases
  - Fast, ~ 100ms, time response
- Sensor networks
  - Urban scale pollution sensing & forecasting
  - Network of autonomous sensor nodes with spatial and temporal resolution
  - Include wireless communication module, very low-cost and reliable
- Remote, open path and LIDAR sensors
  - Sensing beyond the metropolitan and towards the global scale
  - National air quality networks and pollution forecasting models
  - Power, beam quality, sensitivity, and low-cost

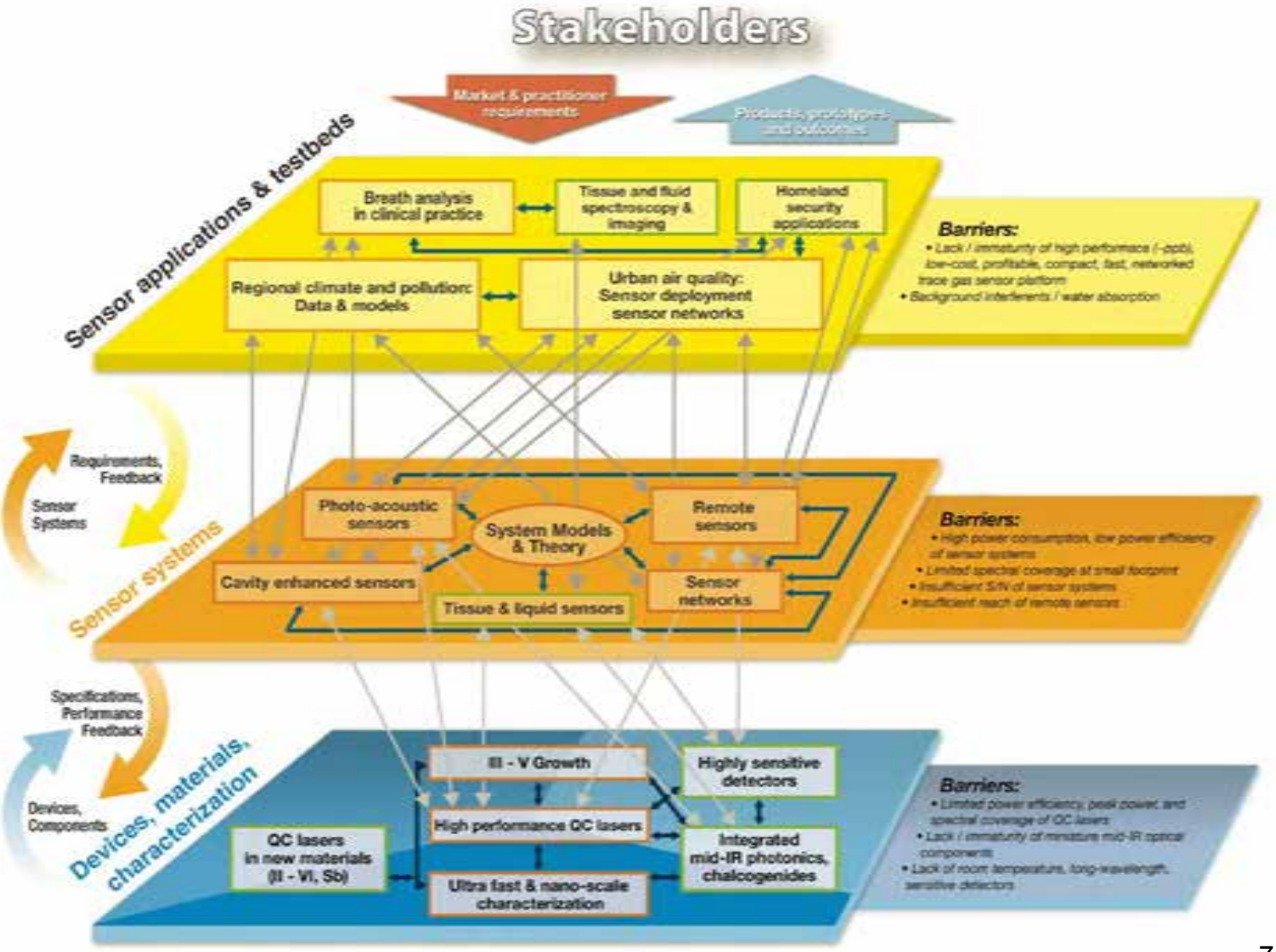
Scientific underpinning of MIRTHE research



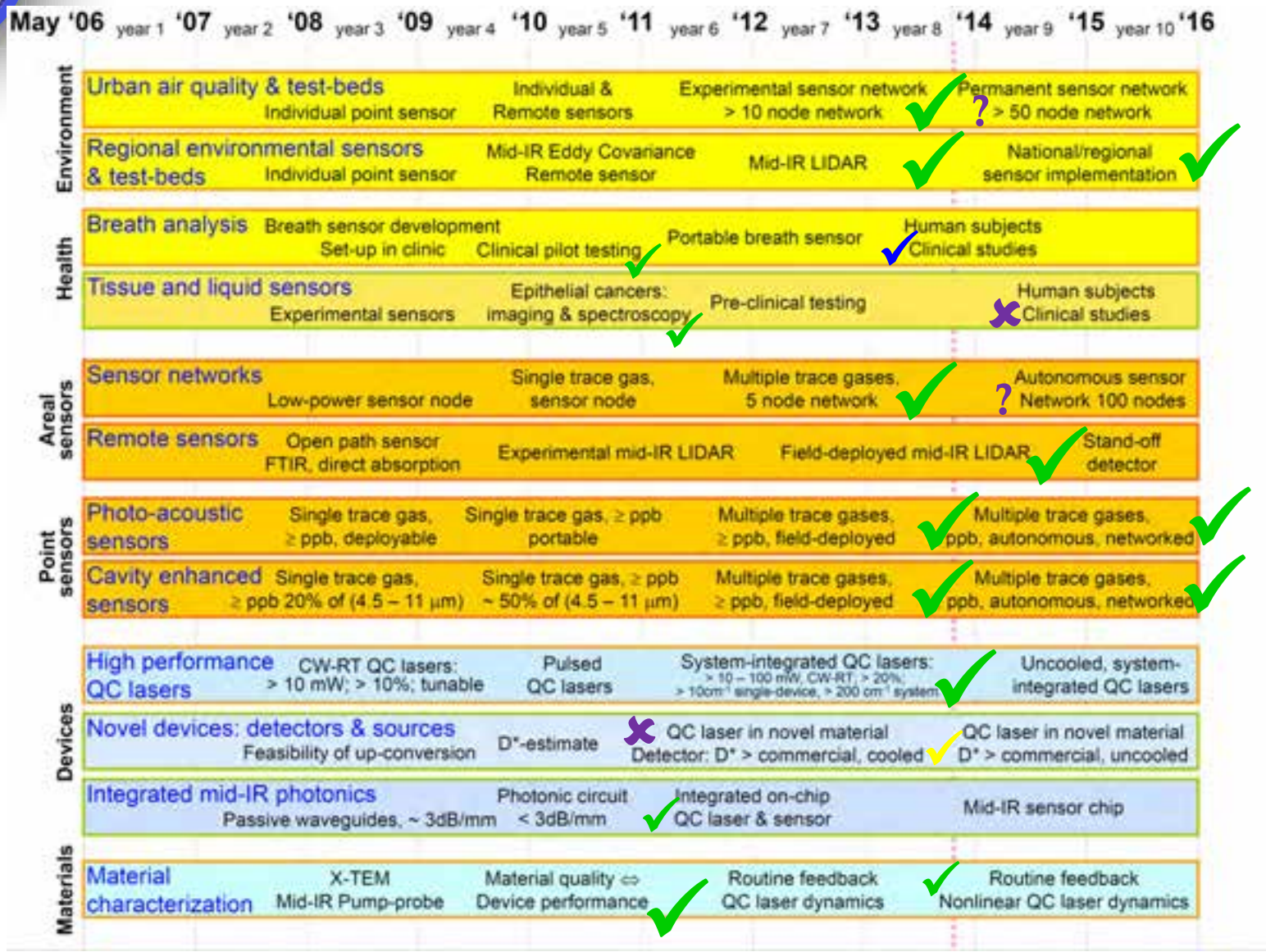


- Molecules uniquely identified
- Sub-ppb sensitivity
- Non-destructive, non-invasive, fast dynamic response.
- Telecom infrastructure / Moore-curve development

Strategic plan: 3-level framework



Timeline chart



Industry & Practitioner Program

NSF-ERC Cooperative Agreement EEC-0540832

Industrial collaboration & tech transfer: Goals & Strategy

- Forge close collaborative connections with industry:
  - Chemical, medical equipment, regulatory …
  - Sensors industry, test & measurement, …
  - Semiconductor industry, devices and subsystems
- Provide center-wide university-industry formal program:
  - Promote partnerships between industrial partners
  - Create technology roadmap for mid-IR sensor systems
  - Create valuable R&D and intellectual property
  - Facilitate effective technology transfer
- Promote ties between industry and students & post-docs:
  - Promote technology transfer & job placement
  - Internships, researcher exchange, interactions at meetings

MIRTHE industry members & practitioners

Total: 49

Partners:

CORNING

DAYLIGHT SOLUTIONS

General Members:

AdTech optics

Agilent Technologies

AIR LIQUIDE

ALPES LASERS

BLOCK engineering

ELI
Epitaxial Laboratory

HAMAMATSU

InfraSign

InfraTec

LASERTEL

LI-COR

MAXION TECHNOLOGIES, INC.

PICARRO

Tektronix

TigerOptics

TRUMPF

Affiliates:

Boston Electronics

GHO VENTURES

ILX Lightwave

innpho.com

INTELLIGENT MATERIAL

IRflex

LaserMax

Laseram Inc.

OKSI OPTO-KNOWLEDGE SYSTEMS INC.

PHYSICAL SCIENCES INC.

REDSHIFT

RF TELEMATICS

SCINOVATION

sentinel photonics

SOBERLINK

WAVELENGTH ELECTRONICS

Media Affiliates:

LaserFocusWorld

PHOTONICS MEDIA

Spectroscopy

Non-profit/Gov:

NIST

Pacific Northwest NATIONAL LABORATORY

Science & Technology Facilities Council
Rutherford Appleton Laboratory

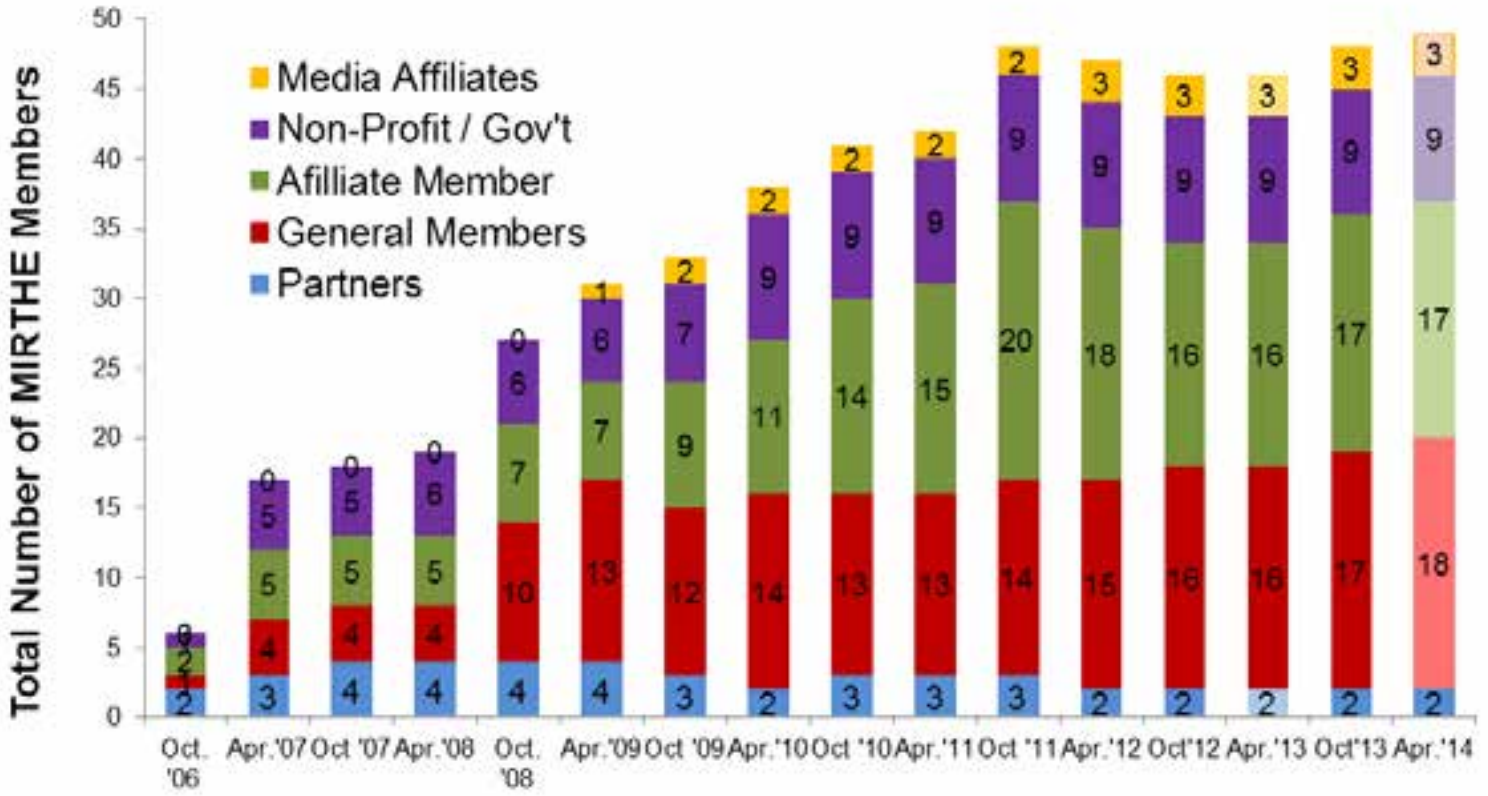
Sandia National Laboratories

Space Dynamics LABORATORY

Membership trends and financial support

Members Growth across all categories

Total # 49



MIRTHE start-ups

Name of Firm	Date Established	Name of Principle & Relationship to ERC	Technology
PRIMIS Technologies	Fall 2007 Dormant 2010	Kale Franz , Anthony Hoffman, Scott Howard (former graduate students)	Development of QCLs
Sentinel Photonics	April 2010	Stephen So (former post doctoral fellow, currently industry member, CEO)	Development of High-efficiency laser based gas sensors
Scinovation	March 2011	Yan Zhang (former graduate student, currently industry member, CEO)	Development of QCLs based sensor systems
Not known yet	mid - 2014	Yin Wang (a former graduate student; currently a CEO)	Development of QCLs based biomedical sensor systems

Sentinel Photonics showcases their new product at CLEO 2013

Yan Zhan, CEO of Scinovation with Rafal Lewicki , MIRTHE former post-doc showcase jointly developed sensor at MIRTHE booth at CLEO 2012

- 2012 recognized as the NJ Business Growth Success Awardee of the year
- 2013 lunched new product that made sales to major instrumentation companies
- 2013 NSF ERC-SECO award with MIRTHE
- 2010-2013 grew from 2 to 5 employees (hired a former MIRTHE postdoc, and hosted one MIRTHE REU student)

- 2012-2013 collaboration with MIRTHE on development of QCLs based sensor system
- 2012 showcased of a prototype at international show CLEO
- 2012-2013 test-bed with MIRTHE: measurements of air quality in Beijing
- 2013 project with MIRTHE funded by the National Geography and the Alibaba Group.

Engagement of Investment Community

MIRTHE Investment Focus Group

is

a group of venture capitalists and angel investors seeking opportunities emerging from MIRTHE technologies

Mission:

Introduction of venture capital to mid-IR technologies and applications opportunities
Exposure to MIRTHE small and large company members
Opportunities to nurture MIRTHE related start-ups

- *Formed in early 2010; Co-chaired by Dr. Mort Collins and Dr. Ralph Taylor-Smith of Battelle Venture*
- *21 board members have been recruited*
- *4 workshops has been held: Oct. 2010 on all MIRTHE applications; Oct. 2011 on medical applications, April 2012 and May 2013 on defense and security; next workshop May 7, 2014 at DSS*

IFG workshop @ Princeton University

IFG workshop @ the Defense, Security & Sensing conference, Baltimore, MD

Education & Education Outreach Program

NSF-ERC Cooperative Agreement EEC-0540832

Vision & Goals

- MIRTHE's graduates recognize, understand, and address societal challenges
- MIRTHE's graduates are knowledgeable and trained in problem solving
- MIRTHE's graduates join a globally competitive and diverse U.S. workforce

- Engineering excellence
- Interdisciplinarity and cross-institutionality
- Diversity
- Leadership

Strategic plan: University-level programs

- Research
  - Graduate research and training
  - REU & year-round undergraduate research
  - MIRTHE post-doctoral fellowships
- Mobility and mentoring
  - Exchange: MIRTHE, industry, international
  - MIRTHE All Hands Summer Workshop
  - Mentoring and recruiting of women and minorities
  - Student leadership activities
- Formal teaching
  - Cross-disciplinary team-taught MIRTHE course
  - MIRTHE's effect on course offerings and formal teaching
  - Hiring of MIRTHE junior faculty
  - MIRTHE library
- Public relations (exposure) and leadership
  - MIRTHE @ CLEO/QELS
  - MIRTHE @ IQCLSW/ITQW, other conferences
  - Leadership and mentoring in K- 12 outreach
  - Entrepreneurial training and interactions with industry

Grad student operating a sensor in field deployment in Beijing, China.

REU students in the lab

MIRTHE at Photonics West

Strategic plan: Pre-college level

- **Focus on individual students and programs**
  - High School student summer research internship
  - YSAP (Young Science Achievers Program)
  - Research work with non-science & non-engineering students
- **Maximum breadth outreach**
  - Science Fairs
  - Science Festivals & Expos
  - Open Houses & lab demos
- **Support of individual faculty activities**
  - Visits to schools
  - Open Houses & lab demos
  - General public relations
- **Teacher programs for K-12 schools**
  - RET program and translation of engineering research results into the classroom

YSAP Outreach

Faculty visits to schools

Student-industry interactions & PR

- Internships and researcher exchange and hiring
- SLC retreat
- Presentations at MIRTHE related conferences
- Interactions at meetings and conferences
  - CLEO, IQCLSW / ITQW, Photonics West, …
- Joint publications
- Research productivity

Students and post docs meet at Photonics West

	Total Number	+ Graduate students & Post-docs	* Under-graduate students	# Industry or government collaborator	(MM) Authors from multiple MIRTHE partners	(MED) Authors from multiple engineering disciplines	(EF) Authors from engineering & non-engineering fields
Journal Publications	**120**	82	13	22	16	44	14
Conference Proceedings	**43**	35	2	3	1	16	8
Conference Presentations	**118**	72	17	21	15	29	7
In Trade Journals	**6**	1	1	0	0	0	0
Other	**10**	1	0	1	0	0	0
Total	**297**	**191**	**33**	**47**	**32**	**89**	**29**

Grad students at the CLEO network dinner.

Innovation and business plan competitions

4th Annual Innovation Forum, Keller Center (2009)

Stephen So (post-doc) won 2nd place, and next year launched Sentinel Photonics

NSF-ERC Elevator Pitch Contest (2011)

Tracy Tsai (grad. student) won 2nd prize

7th Annual Innovation Forum, Keller Center (2012)

Michal Nikodem (post-doc) won 2nd place

Optoelectronics Start-up Challenge at Photonics West 2012

Yin Wang (grad. student) won 2nd prize

8th Annual Innovation Forum, Keller Center (2013)

Lei Tao (post-doc.) won a 1st prize

Arvind Ravikumar (grad. student) won a 3rd prize

Research Highlights

NSF-ERC Cooperative Agreement EEC-0540832

A Multi-Sensor Field Deployment for Assessing Anthropogenic Influences on Carbon, Nitrogen and Water Cycling

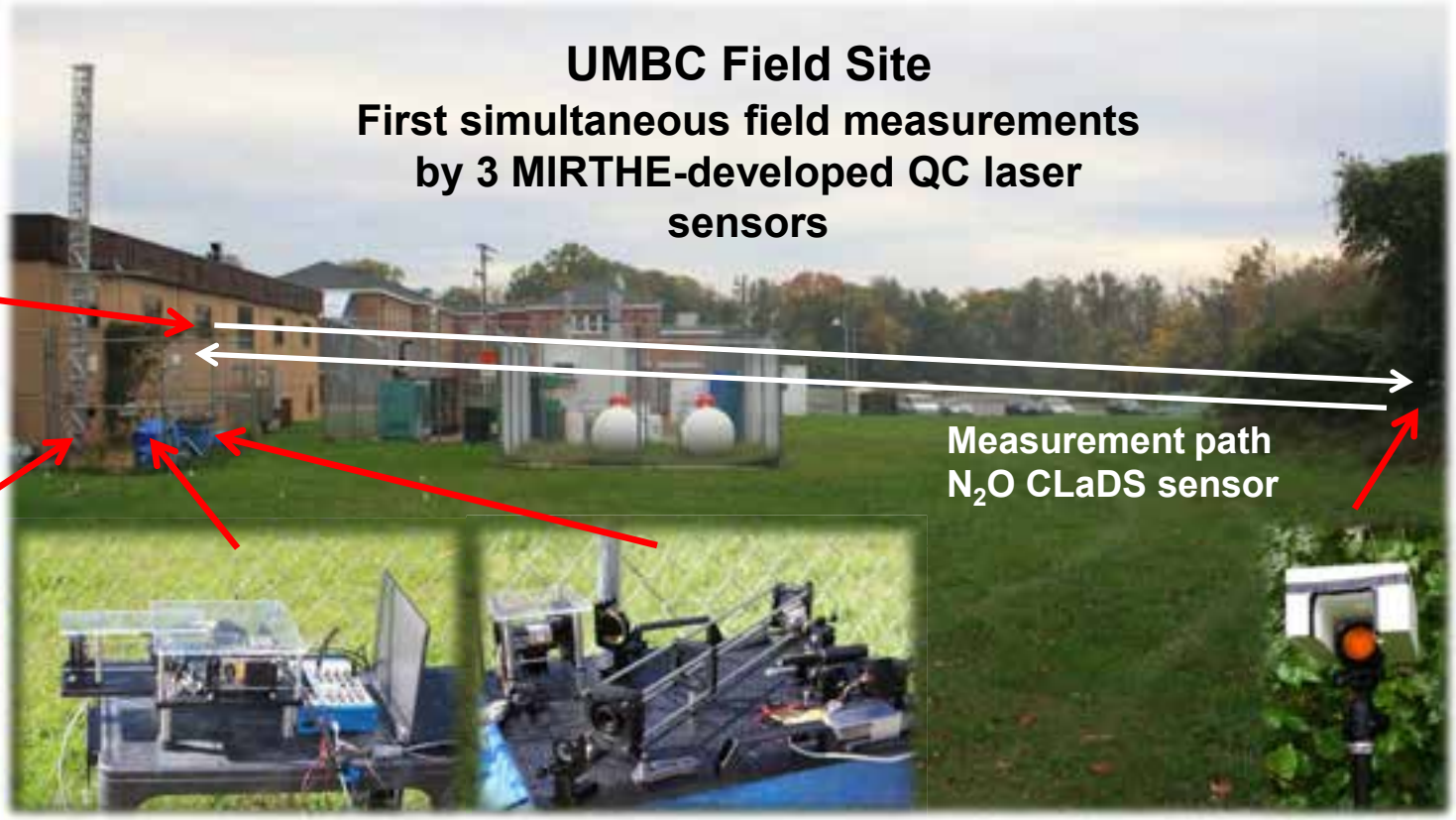
Two field deployments:

Part I: October 24-November 2, 2011; part II: April 13-25, 2012

SLIP – project: David Miller et al.

N_2O

CO_2/CH_4



N_2O/CO

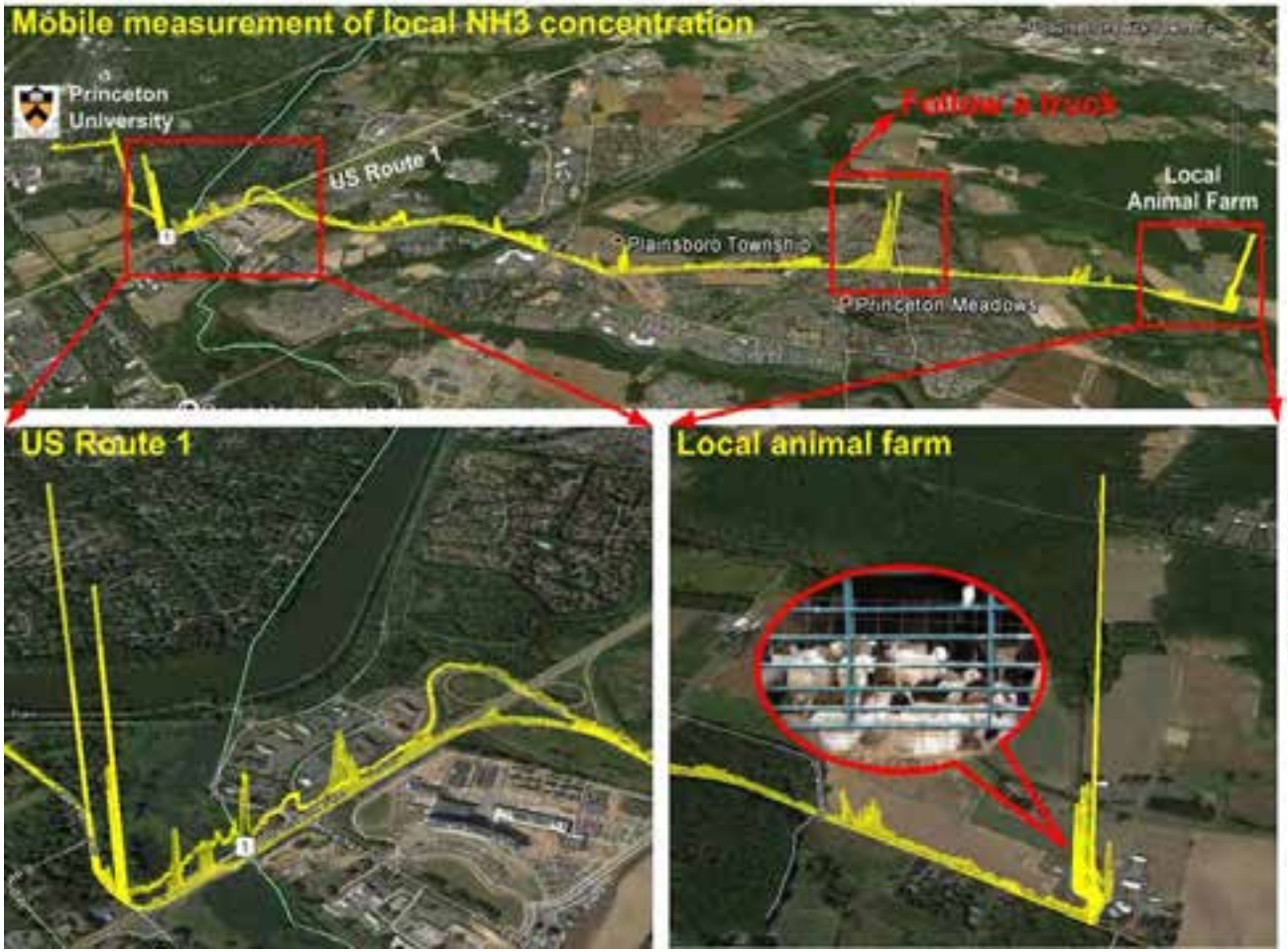
NH_3

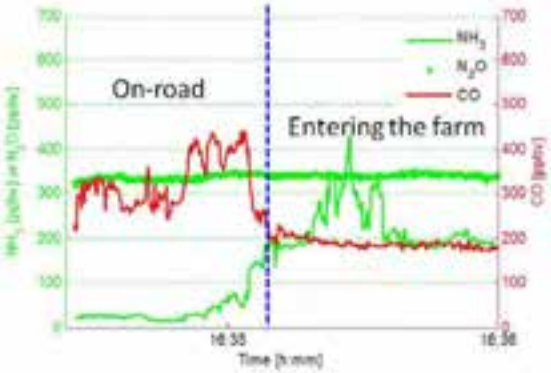
Retro-reflector

Collaborations:

Prof. Claire Welty, Chemical, Biochemical, and Environmental Engineering, UMBC and Baltimore Ecosystem Study

Portability: 2012 Field Campaigns



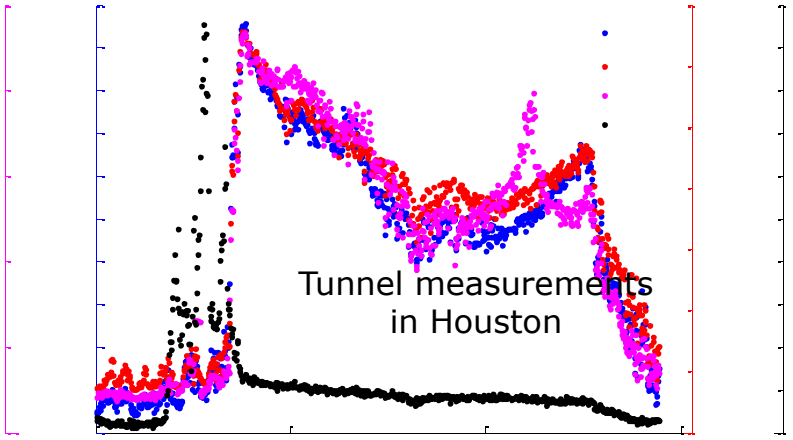


Simultaneous NH_3/N_2O/CO measurements near Princeton area. CO is a tracer for combustion.

Mark Zondlo & group, Princeton University

SLIP – Multi-sensor Field Deployments

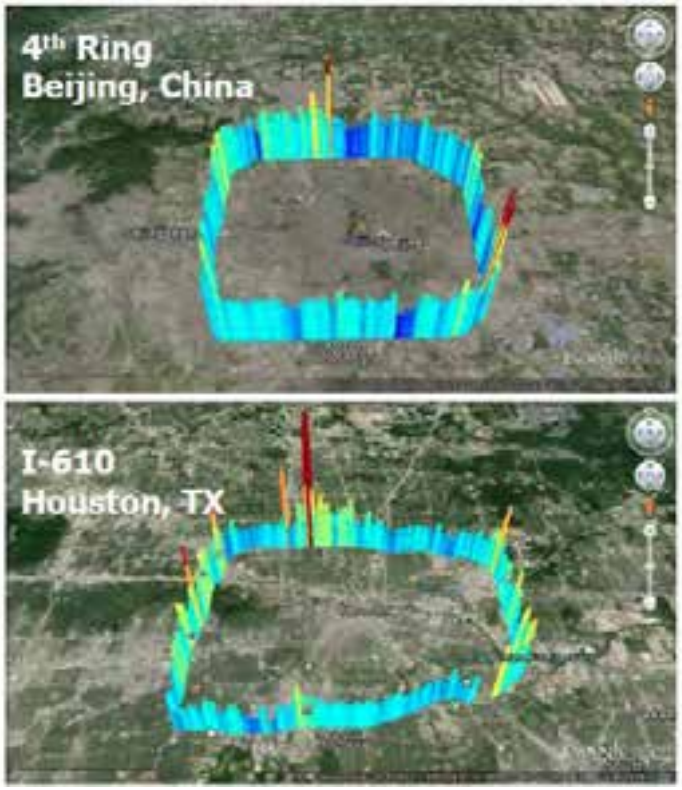
Mark Zondlo & group, Princeton University
Industry collaborators



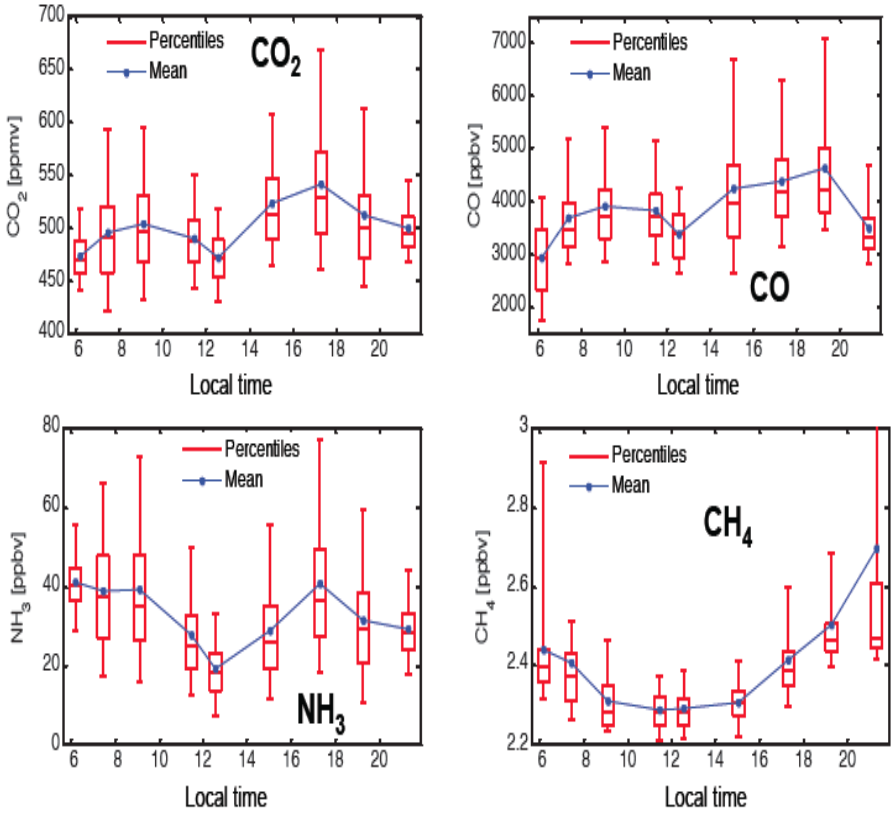
Mobile platform measurements in Houston testbed

Urban Emissions of Greenhouse Gases and Air Pollutants

Mark Zondlo & group, Princeton University
CARE Beijing collaborators



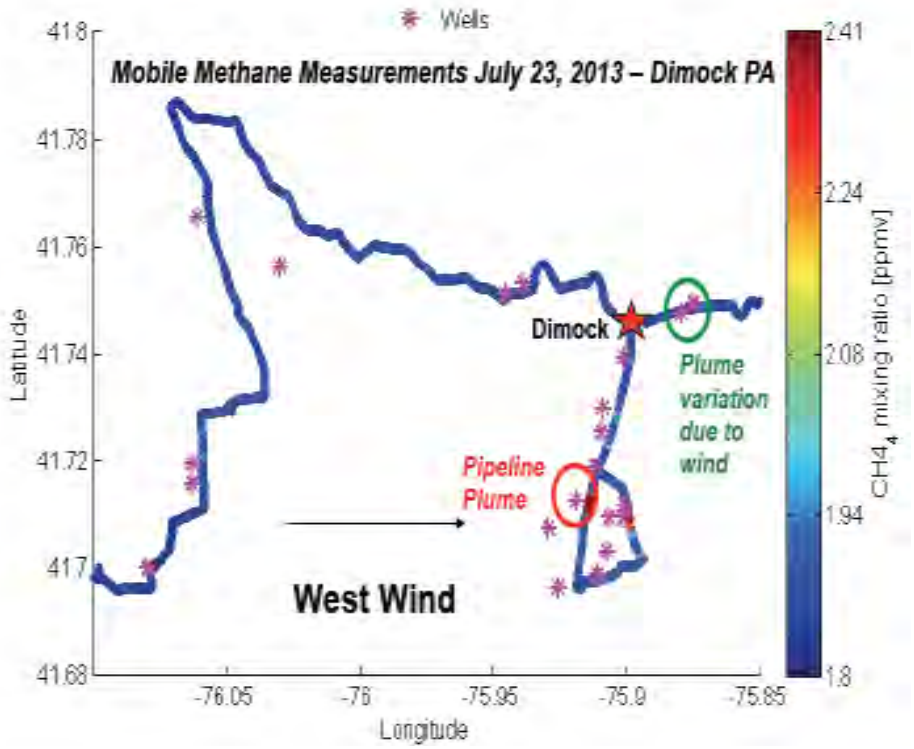
Ammonia distributions along freeways in Beijing (top) and Houston (bottom).

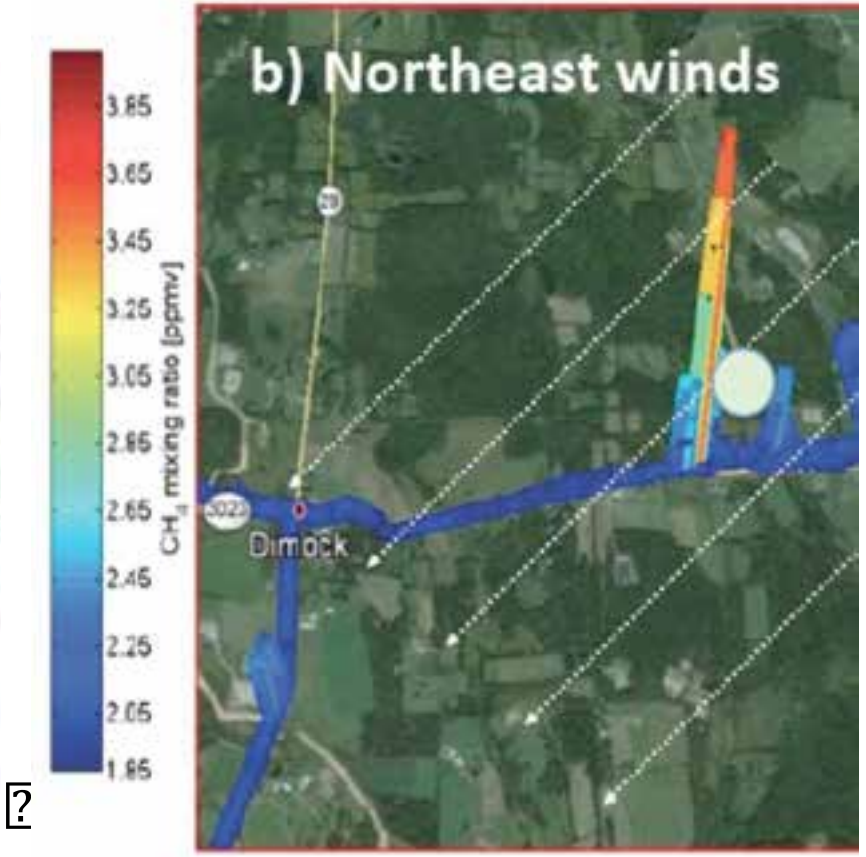


Diurnal variations of trace gases in Beijing.

Fugitive Methane Sensing

Mark Zondlo & group, Princeton University





Sampling of fracking pads in the Marcellus Shale by drive-by surveys.

Measurements of CH_4 near two fracking pads.

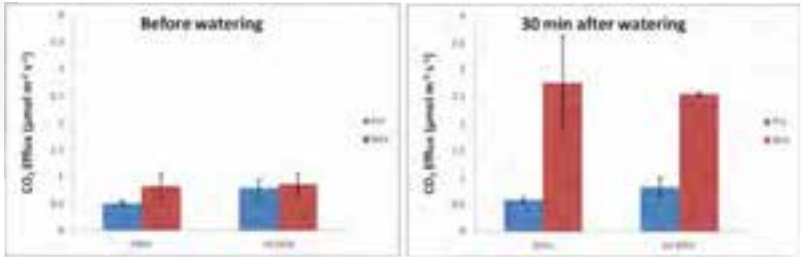
Understanding the Carbon Cycle

Kathy Szlavecz & group, Johns Hopkins University

Climate models predict prolonged dry periods and high-intensity rain events throughout the US in the 21st century

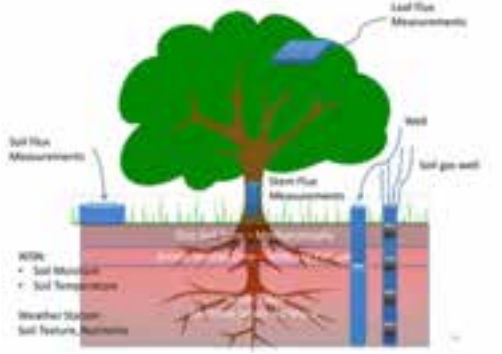
Soil C response is studied in rainfall manipulation experiments

CO_2 Efflux following drought and intense wetting



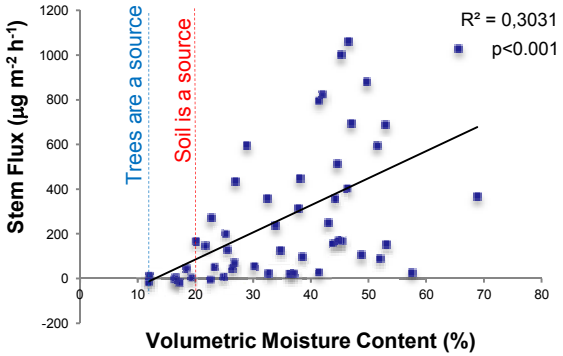
The 3rd generation WSN is monitoring abotic conditions

When will a forest ecosystem switch from sink to source?



CH_4 flux is measured from soil and tree trunks

Trees emit CH_4 even at low soil moisture and soil acts as sink

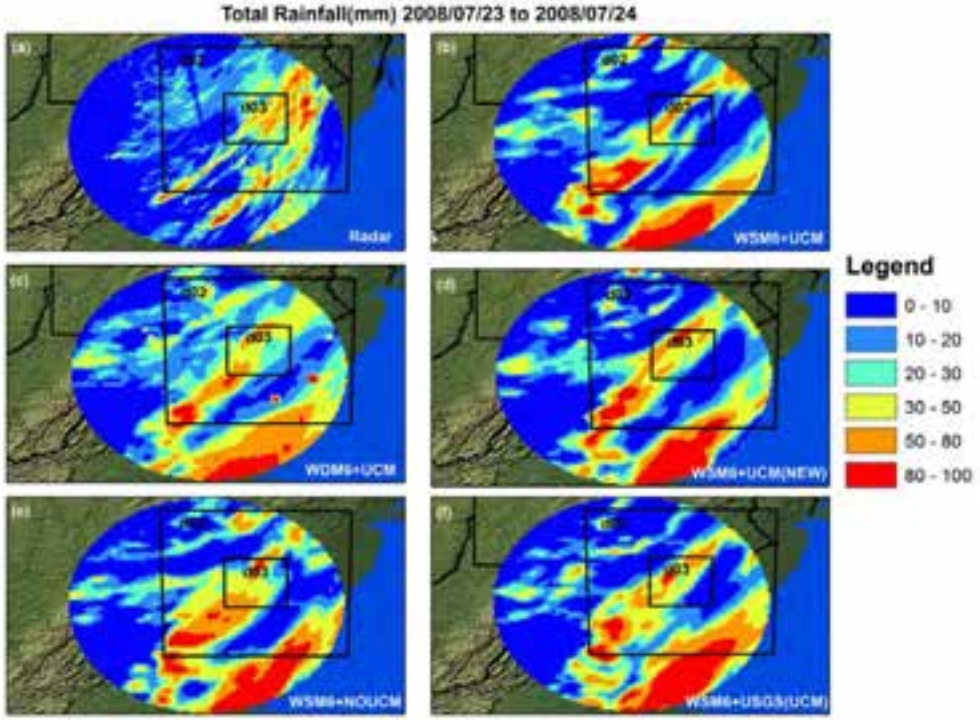


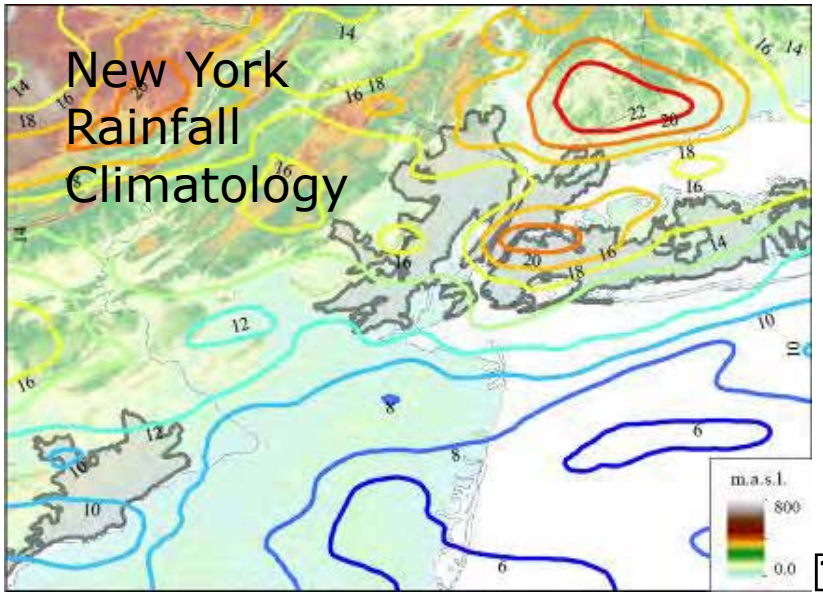
Urban Climate Modeling

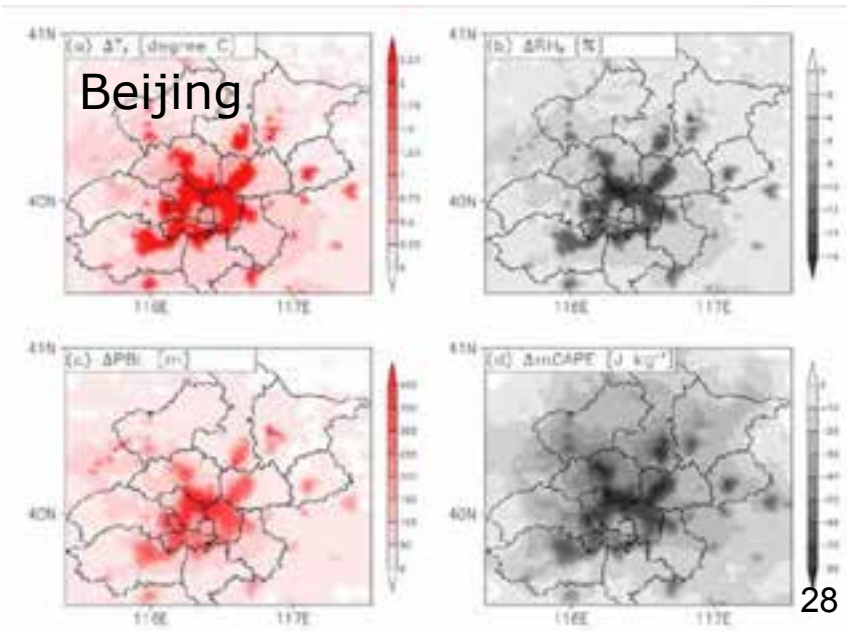
Jim Smith & group,
Princeton University

Urban Modeling of regional climate: New York, Baltimore and Beijing testbeds.

Baltimore: Urban Canopy Model

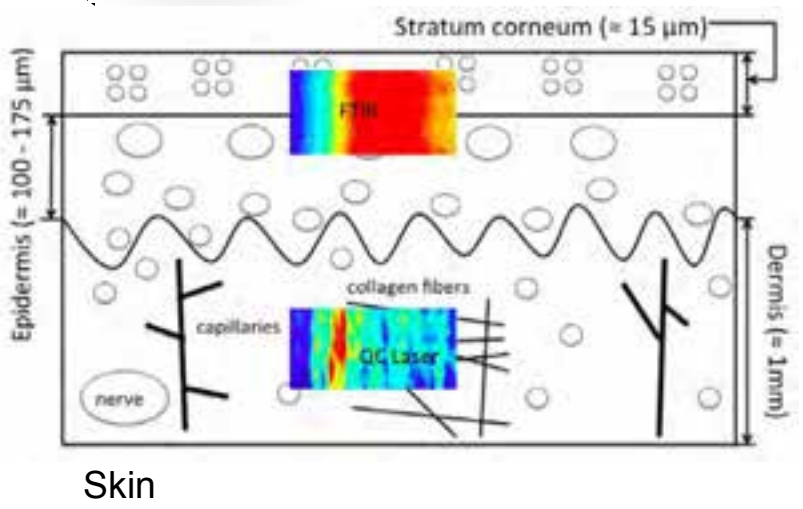






Noninvasive, in-vivo Glucose Detection

Sabbir Liakat et al, Princeton University



Skin

Lock-in Amplifier

Data Acquisition

TE-Cooled MCT Detector

Integrating Sphere

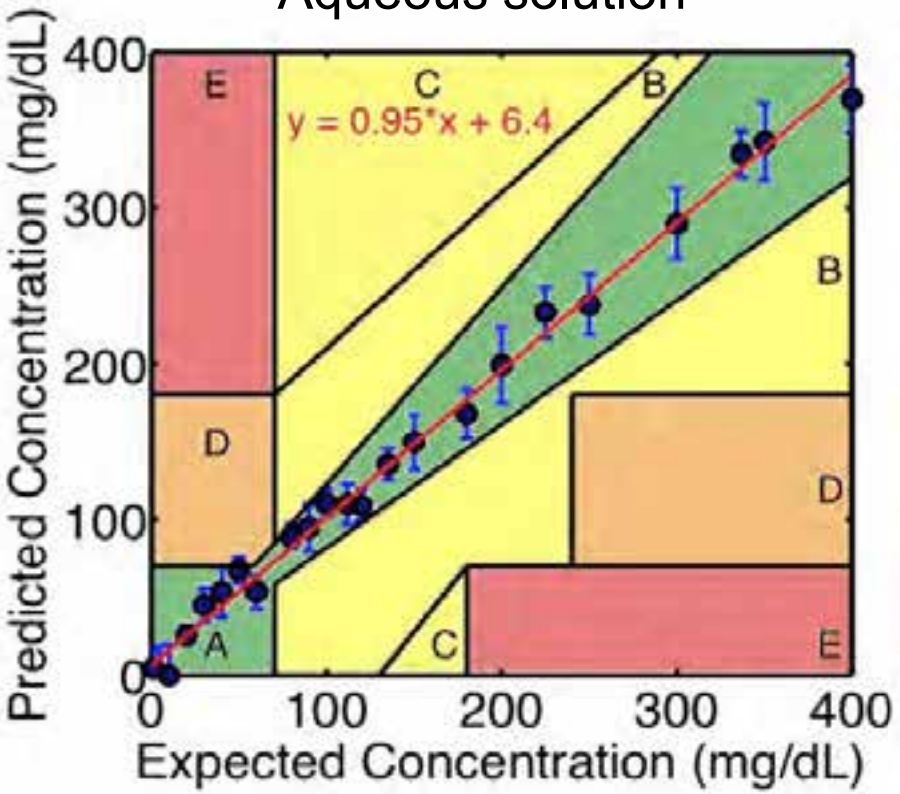
Lens

Daylight Solutions EC-QC laser

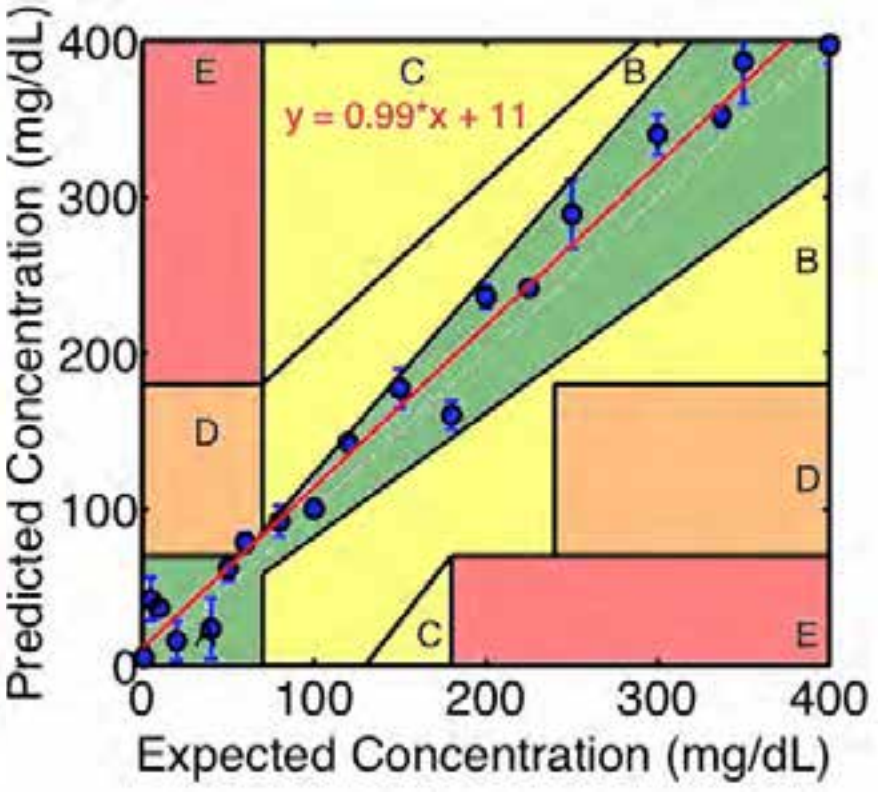
55 kHz pulse, 1% duty cycle, 100 mW peak power

In Vitro Glucose Detection

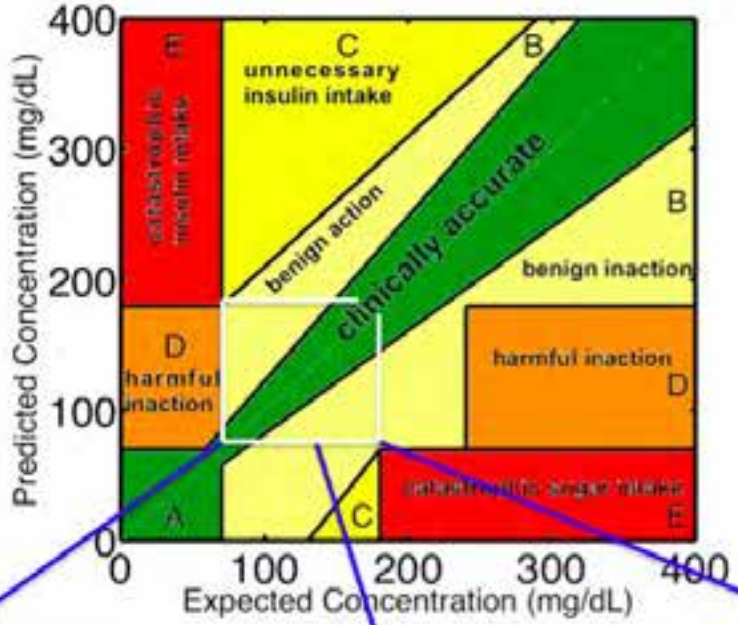
Aqueous solution



Serum solution

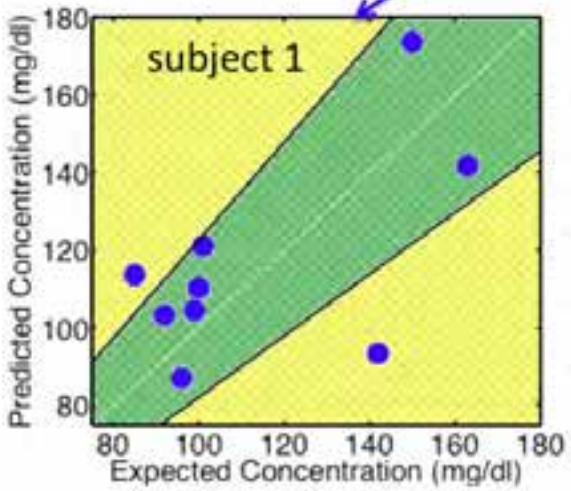


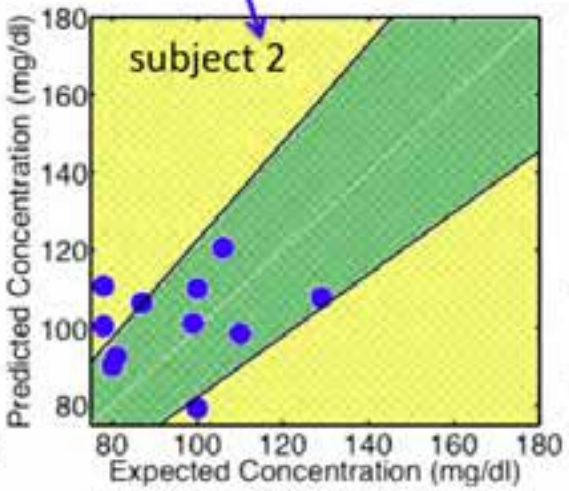
Quantification of Glucose Prediction Accuracy: Clarke Grid

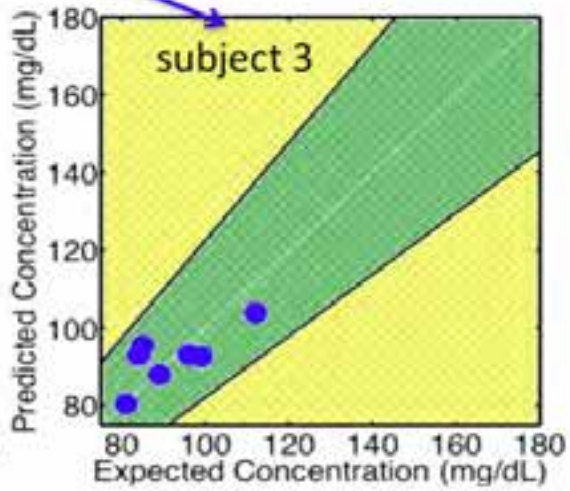


PLSR predictions on three healthy human subjects

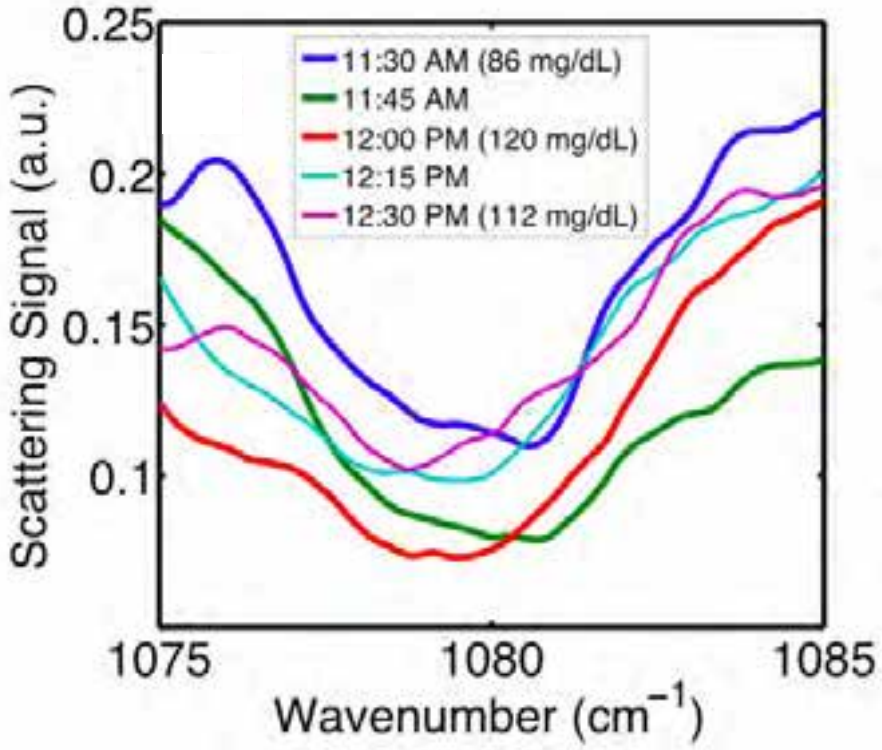
Calibration uses representative spectra of four different concentrations

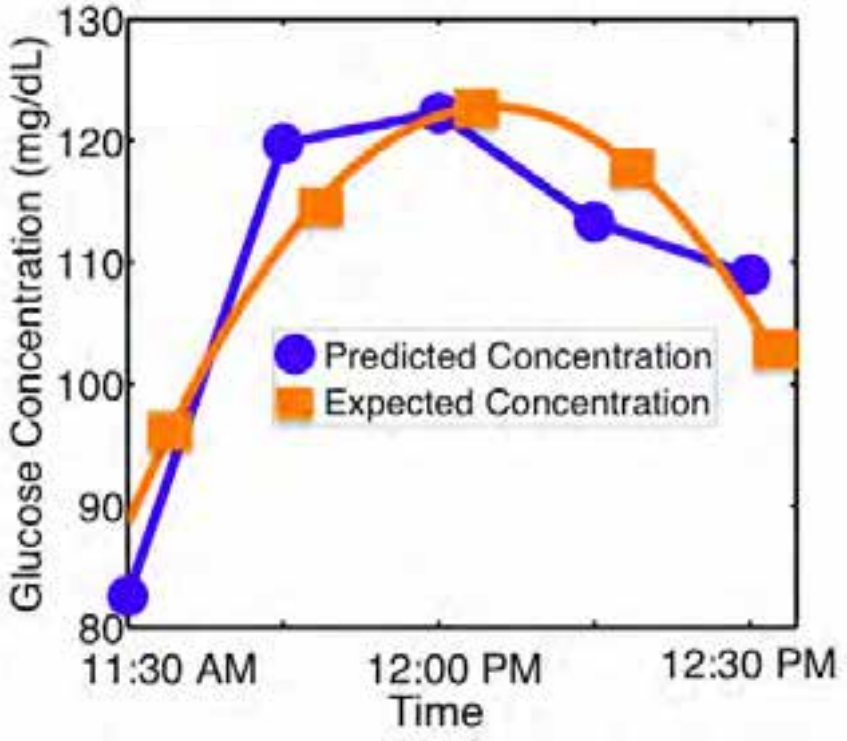






Real-Time Spectral Changes vs. Glucose Concentration





Strong correlation of predicted glucose concentrations to measured concentrations over an hour in 15 minute intervals.

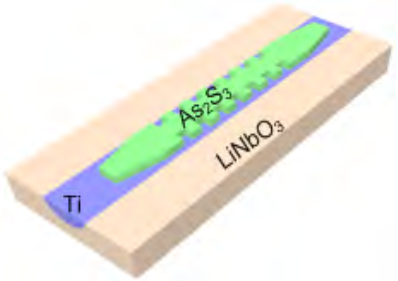
Chalcogenide Waveguide Devices for Mid-IR Sensing

Christi Madsen & group, TAMU

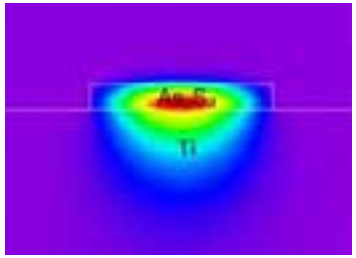
Novel grating- assisted devices for Mid-IR

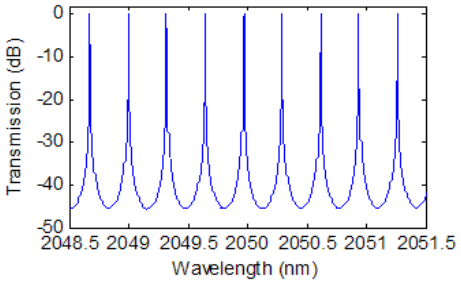
Four Wave Mixing for Improved Detection SNR

Integrated sidewall gratings with linear tapers for low-loss input/output coupling.



Mode intensity profile of TE_0 mode at 2.05 μm, ~35% confinment

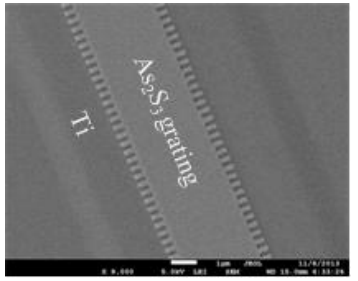




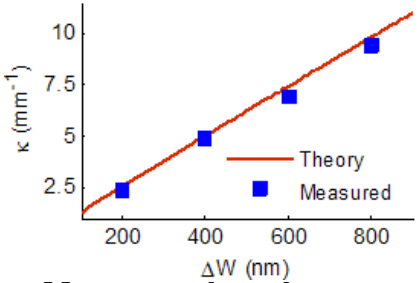
Transmittance of a 3 mm cavity.

$$Q = \frac{\lambda}{\Delta\lambda_{3dB}} = 1.86 \times 10^6$$

$$FSR = \frac{\lambda^2}{2 n_{eff} L_{cavity}} = 323.4\,pm$$

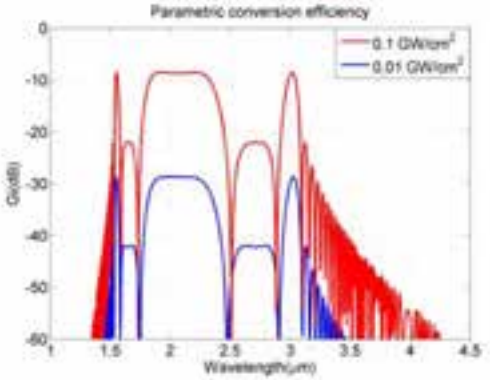


Fabricated sidewall gratings on Ti:$LiNbO_3$.

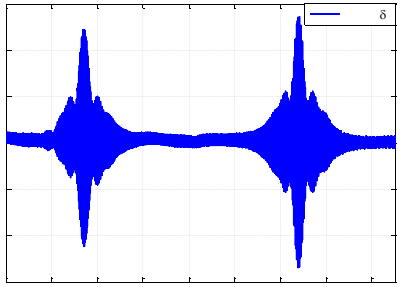


Measured and theoretical coupling coefficients vs. grating depth ΔW.

Simulated Conversion



Waveguide dispersion measurement in mid-IR



Optical low coherence interferometer: amplitude and group delay response.

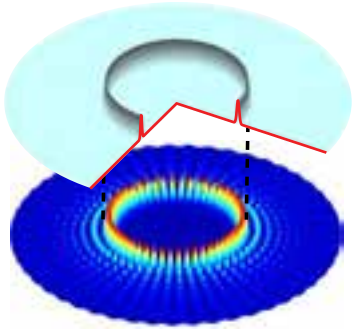
Universal method for power enhancement in QCLs by spatially selective pumping

Hakan Tureci & group, Princeton

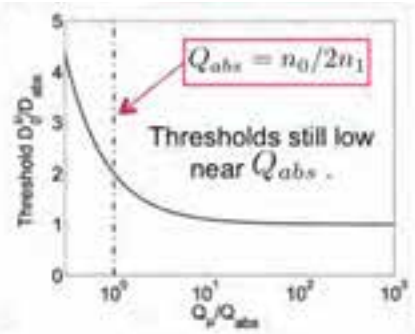
Steady-state Ab Initio Laser Theory (SALT)

↓

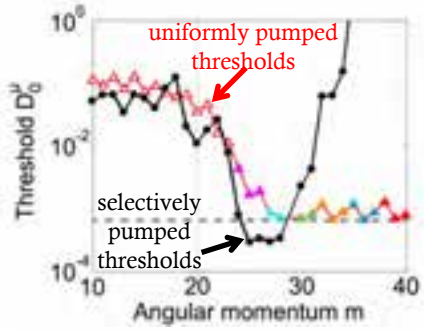
Theory + Simulation

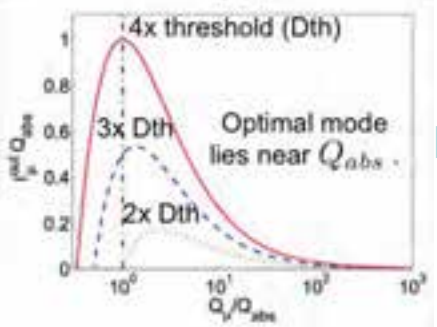


Selectively pump the optimal mode

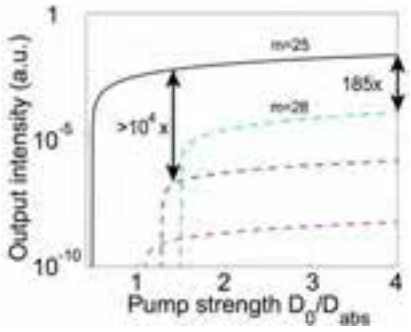


Threshold of selected mode reduced by ~5x

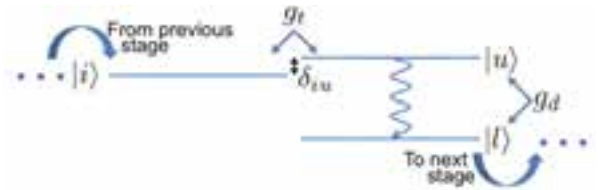




Emission from selected mode 185x higher



QCL gain medium modeling



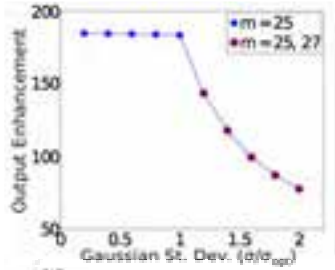
$$H = H_0 + g_d E(t)(|u\rangle\langle l| + h.c.) + g_t(|i\rangle\langle u| + h.c.)$$

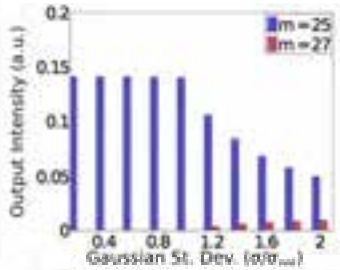
$$\dot{\rho} = -\frac{i}{\hbar}[H, \rho] + \mathcal{D}_r[\rho] + \mathcal{D}_d[\rho]$$

- QCL represented as cascade of 3-level systems
- model accounts for relaxation and dephasing decay
- Solved in steady-state to yield current and light output as functions of detuning between injector and upper levels

Lateral Current Spreading

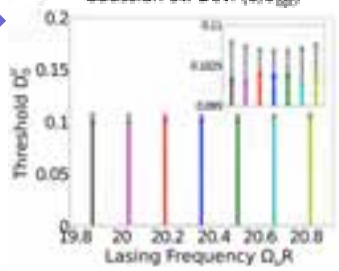
Enhancement of ~80x for current spreading to twice the optimum contact width

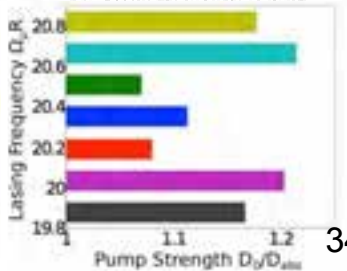




Mode Selection in 1D Cavity

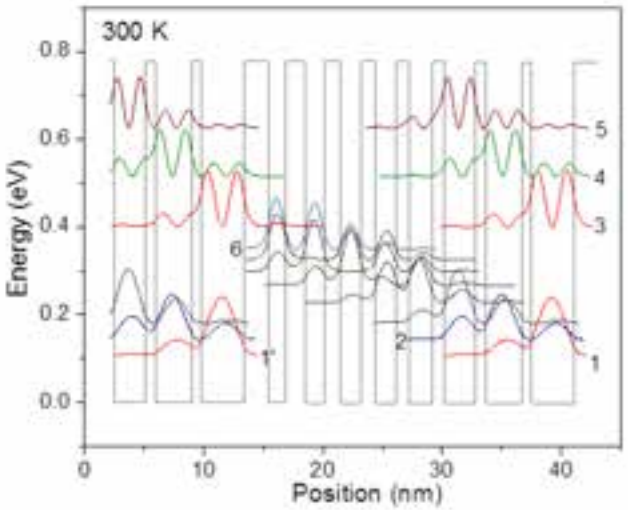
Strongly overlapping modes selected with slightly reduced thresholds and single-mode emission for up to 1.2x pump power at threshold

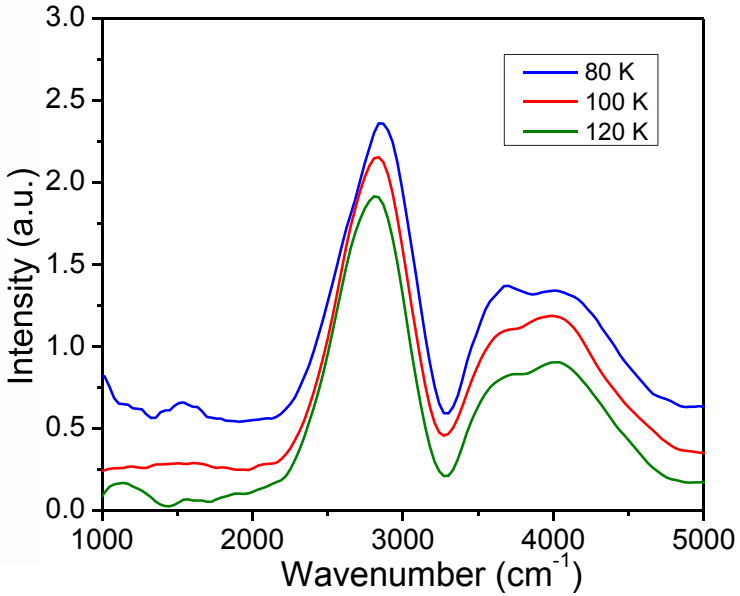


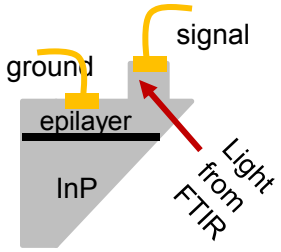


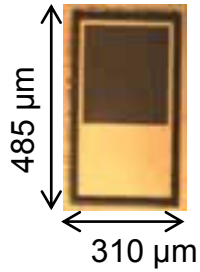
Intersubband devices in II-VI materials

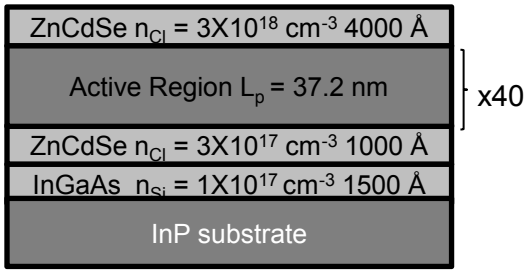
Arvind Ravikumar et al, Princeton University
CCNY Collaboration











II-VI QC Detector

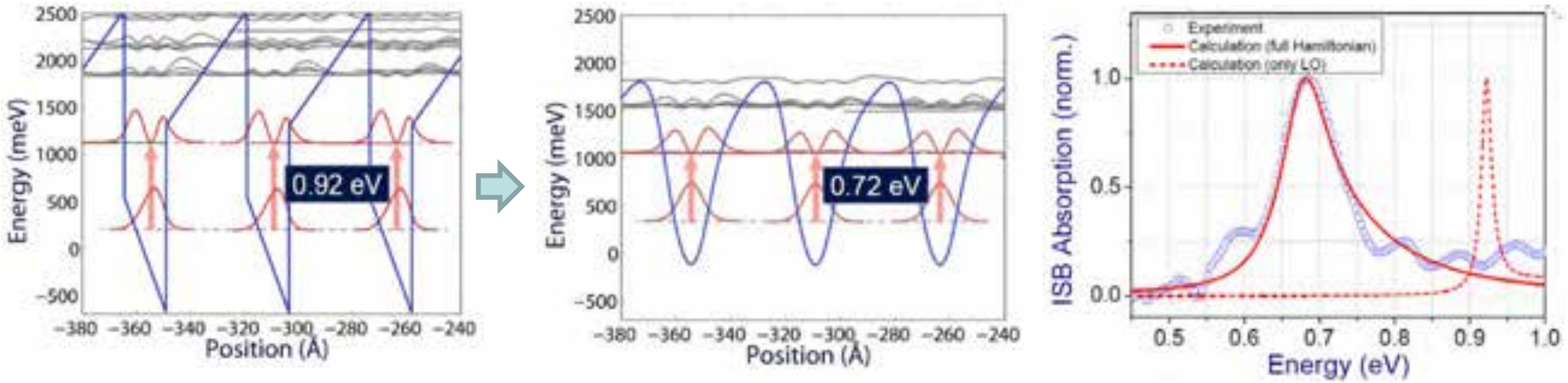
- Demonstrated the first II-VI based QC Detector with high detectivity of ~2.5x10^{10} cm√Hz/W at 80 K.
- Extractor doping to reduce back scattering and increase R_oA product at room temperature.

Intersubband devices in III-Nitrides

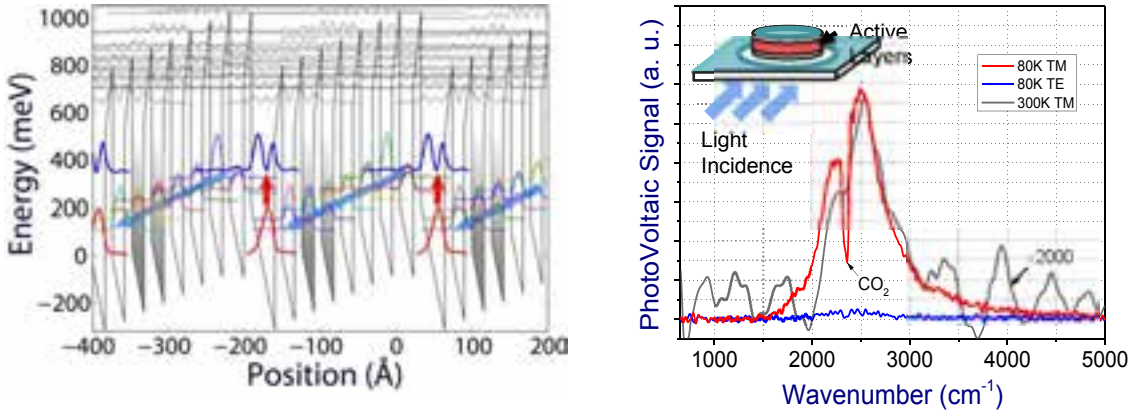
Yu Song et al, Princeton University
Corning Inc. Collaboration

III-Nitride Multiple QWs grown by MOCVD

Raj Bhat, et al. Corning Inc.

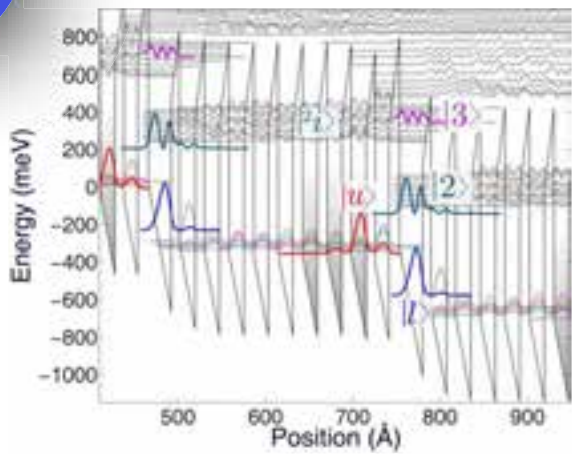


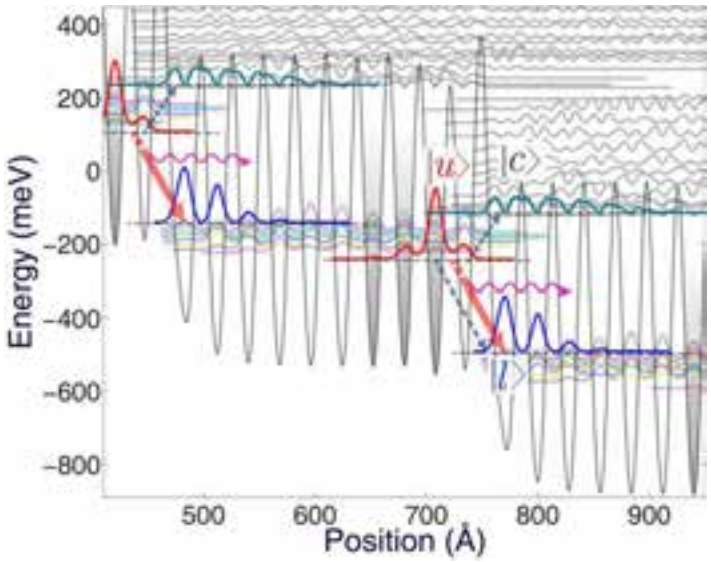
Full quantitative model including interface roughness → excellent agreement btw. design and intersubband absorption



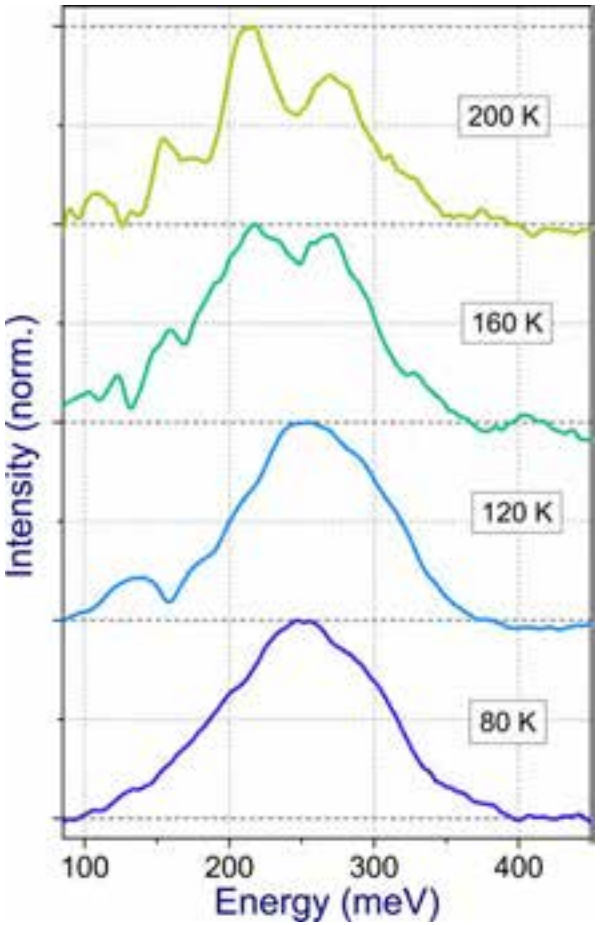
III-Nitrides QC Detector grown by MOCVD; design of emitter structures in III-Nitrides

Intersubband EL emission in III-Nitrides





Intersubband EL



Full quantitative model including interface roughness
→ fundamental wavefunction changes

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