The Circuit Frontier

Innovating and Expanding ASIC Solutions for Enhanced Biosensing & Seamless Wireless Communications

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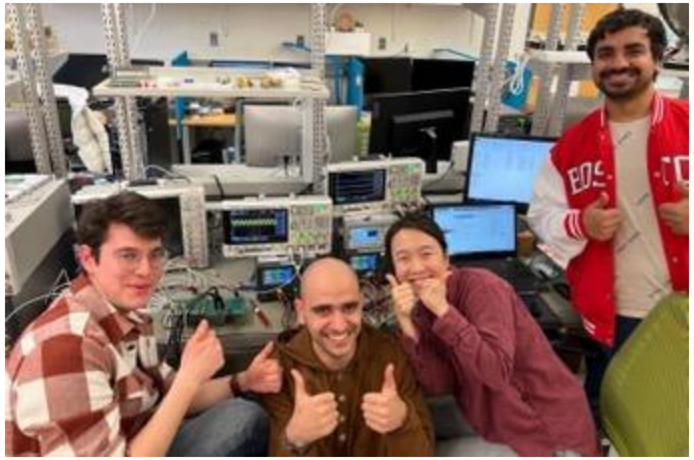
Wireless **I**ntegrated **S**ystems and **E**xtreme **Circuits** Laboratory

Electrical and Computer Engineering Department, Boston University

Wireless Integrated Systems and Extreme Circuits
WISE-Circuits Group

<u>Energy-efficient ASICs</u>

- Human Health
- Environment
- Sustainability
- Communications

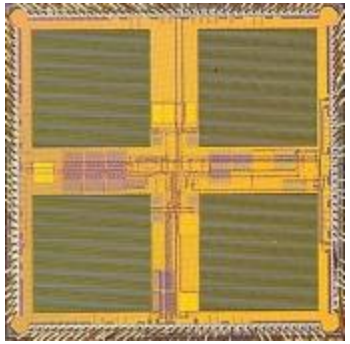


Embrace

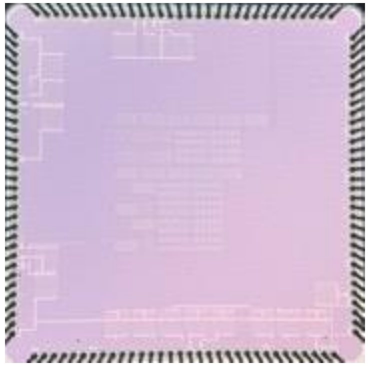
Interdisciplinary Collaborations

WISE-Circuits Custom-Designed Semiconductor Chips

Cyber-Secure Biological Systems

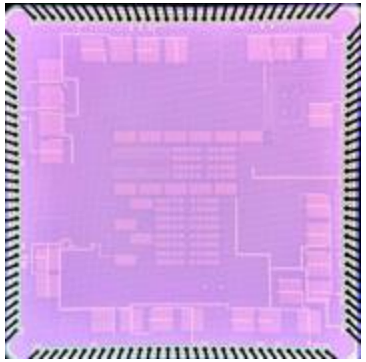


ISSCC SRP’21, CICC’21, BioCAS’22 JSSC’23, Nature’23

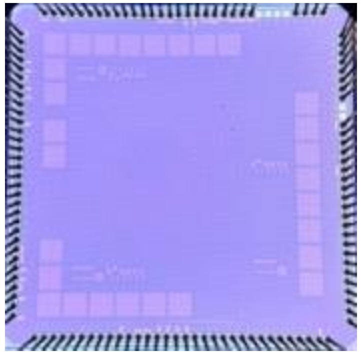


ISSCC SRP’23
Best Poster & Demo Award

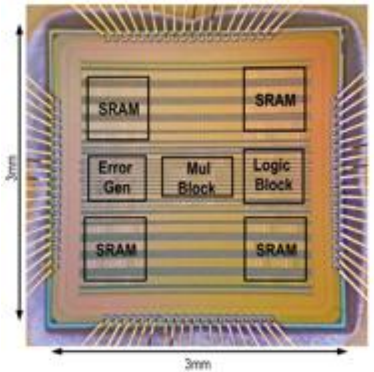
ISSCC’24
TBioCAS’24



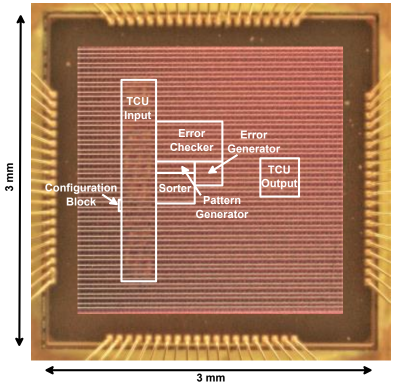
ISSCC’24
TBioCAS’24



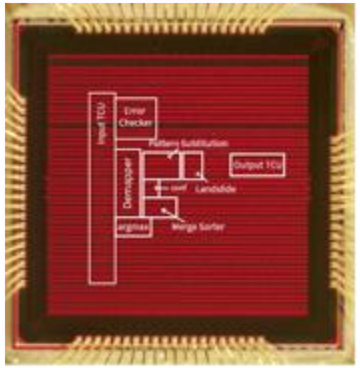
All-in-One Data Decoders



ISSCC SRP’21, ESSCIRC’21
2x Best Demo Award

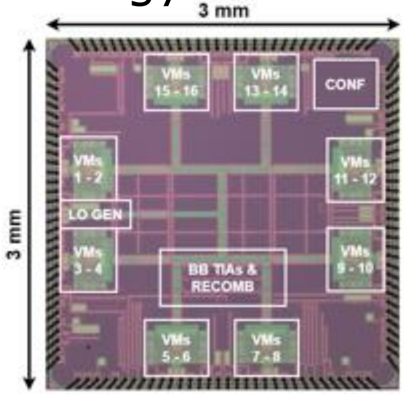


ISSCC’23, JSSC’24

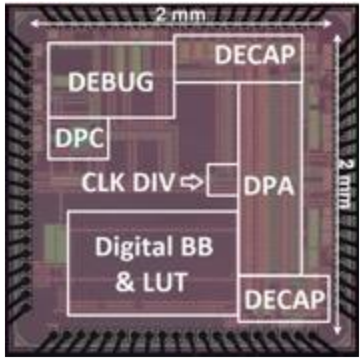


VLSI’25 - Under review

Energy-Efficient Wireless Systems



A-SSCC’23

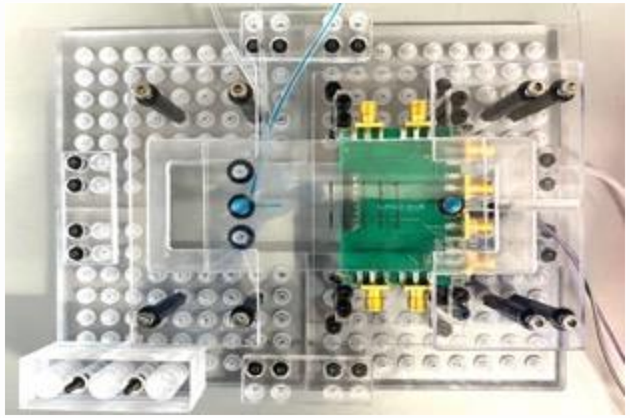


RFIC’25

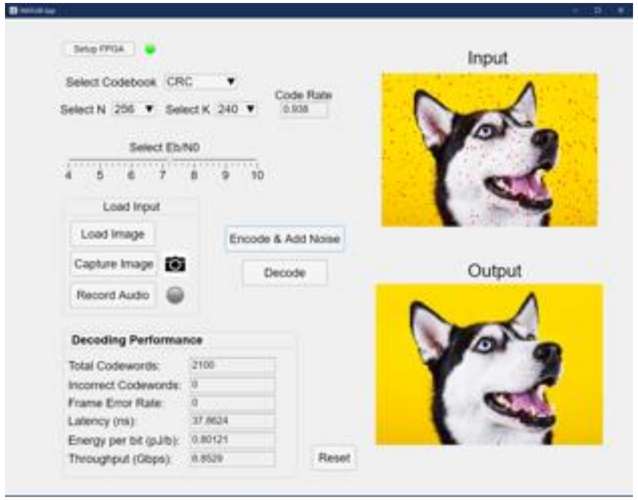
WISE CIRCUITS
WIRELESS INTEGRATED SYSTEMS AND EXTREME CIRCUITS

WISE-Circuits Integrated Hardware Demo Systems

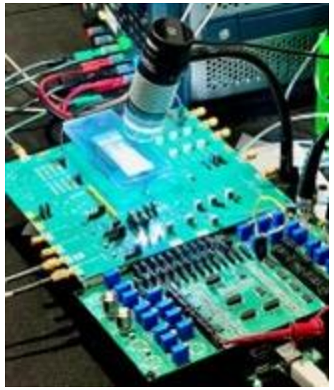
ISSCC SRP'21, CICC'21, BioCAS'22
JSSC'23, Nature'23



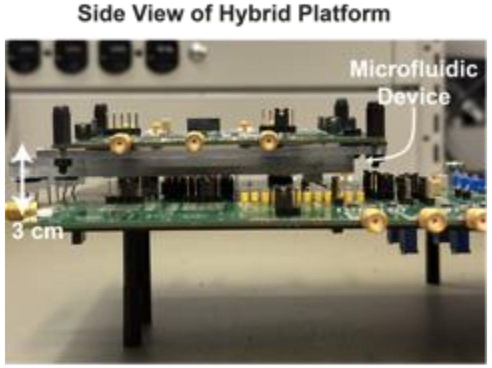
ISSCC SRP'23
Best Poster and Demo Award



ISSCC'23, JSSC'24
2x Best Demo Award



ISSCC'24, TBioCAS'24

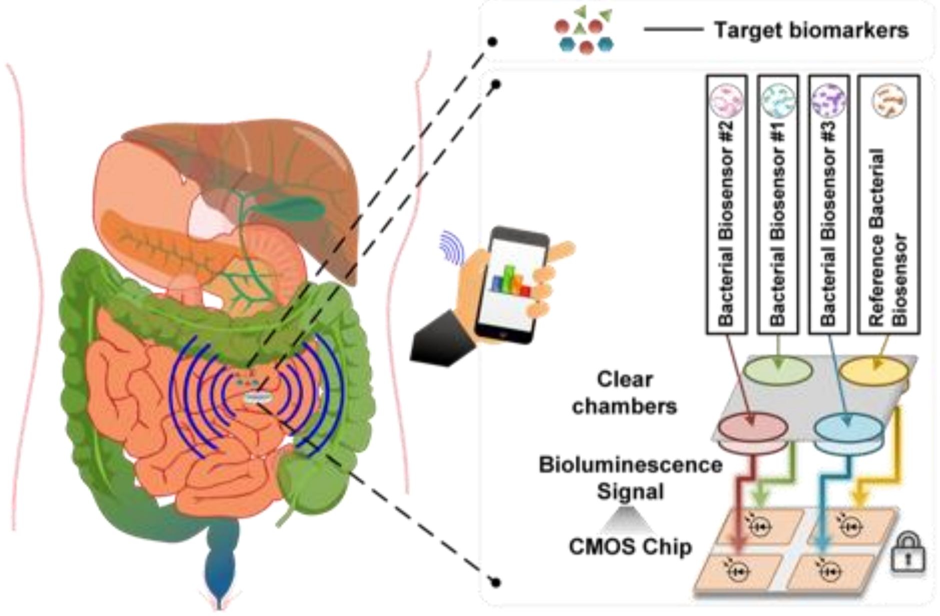


ISSCC'24, TBioCAS'24

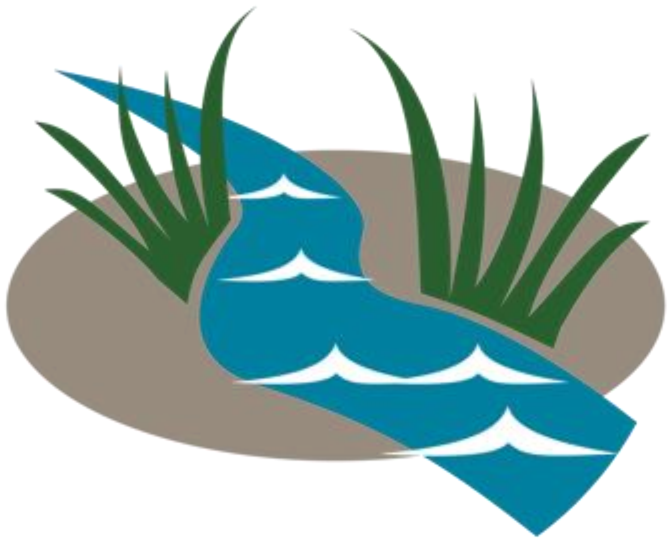
ISSCC'24, TBioCAS'24

Cyber-Secure Biological Systems / All-in-One Data Decoders

Ingestible Bioengineered Capsule



Co-Design of Microfluidics & Custom Electronics for CSBS



Universal Decoder - GRAND

CYBER-SECURE BIOLOGICAL SYSTEMS

BOSTON UNIVERSITY

Massachusetts Institute of Technology

THE LEONA M. AND HARRY B. HELMSLEY CHARITABLE TRUST

CATALYST FOUNDATION
Bridging science and electrical engineering through cross-disciplinary university-level research

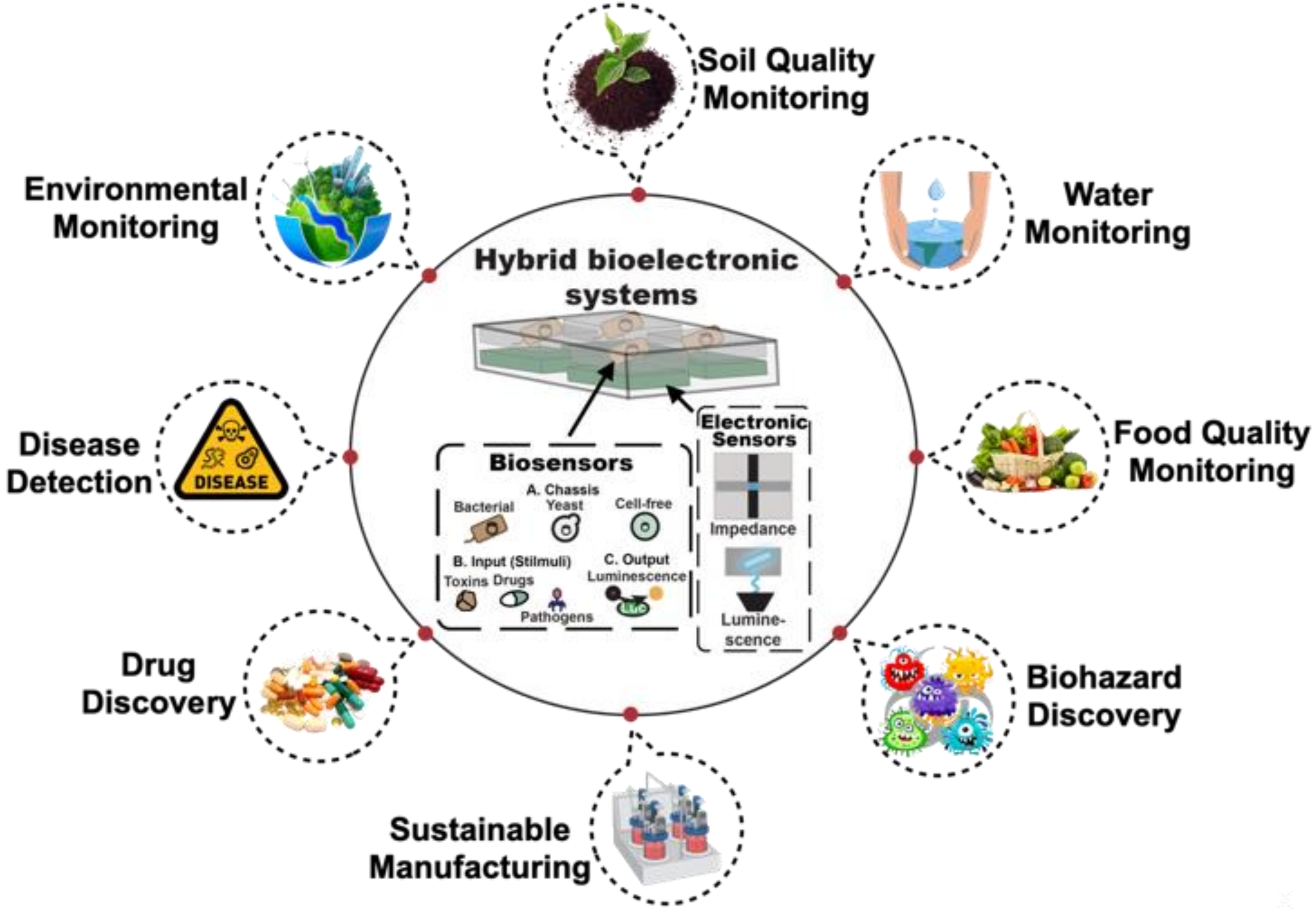
NSF

BioMADE

SCHMIDT FUTURES

SRC Semiconductor Research Corporation

Cyber-Secure Biological Systems (CSBS)



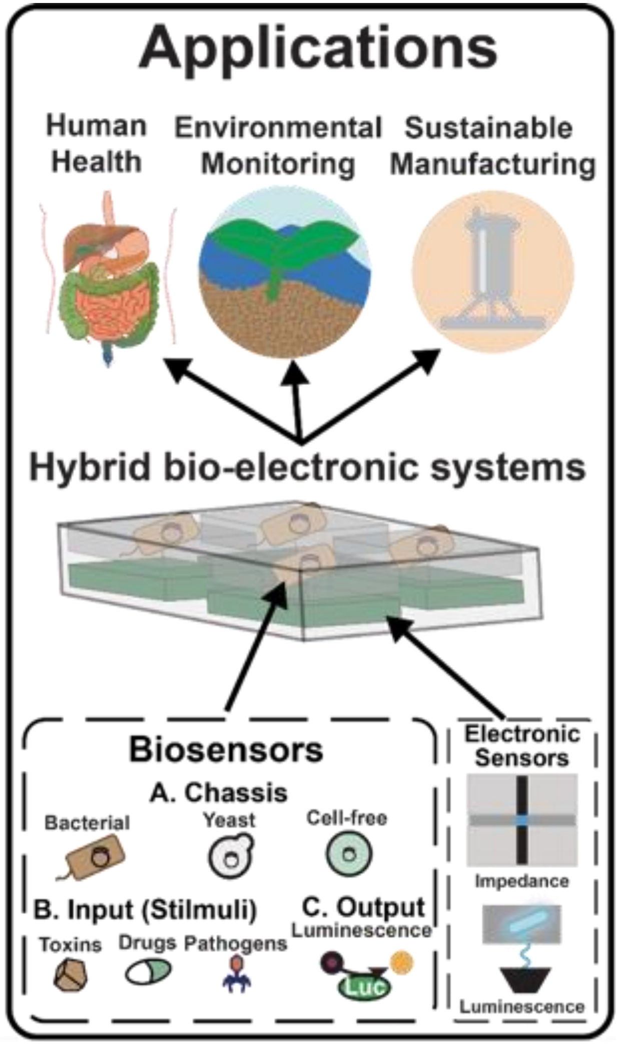
Miniaturization

Power Efficiency

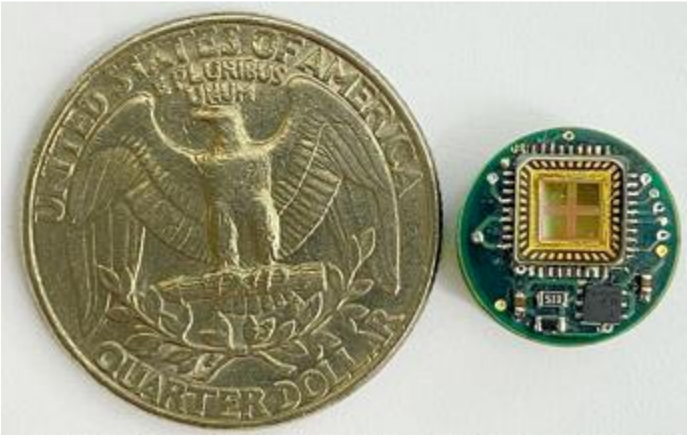
Real-Time Analysis

Multiplexed Sensing

Cyber-Secure Biological Systems (CSBS)



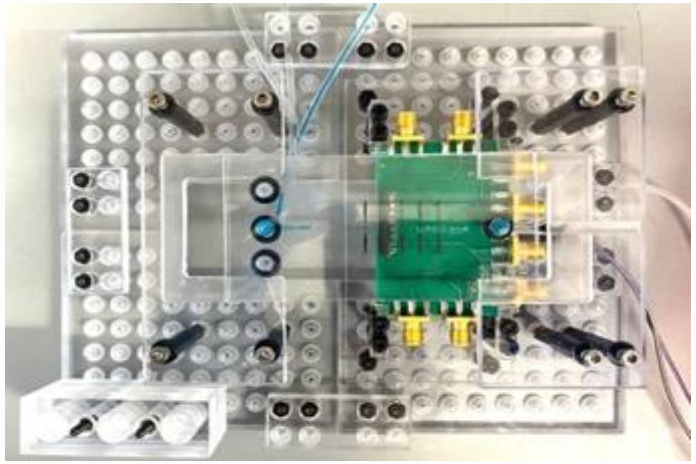
Ingestible Bioengineered Capsule



[ISSCC SRP'21, CICC' 21, BioCAS'22]
[JSSC'23, Nature'23]

Collaborators: Tim Lu (MIT BE/Senti Bio), Gio Traverso (MIT MechE)
Funded by Helmsley Charitable Trust, Catalyst Foundation, **NSF CAREER**

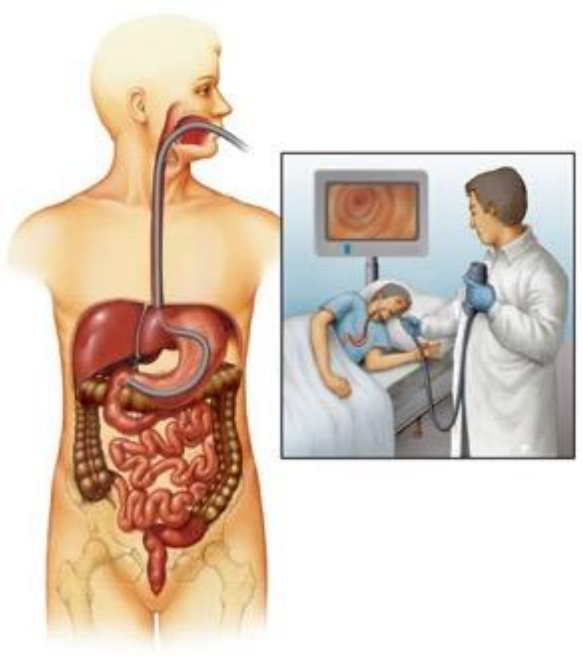
Co-Design of Microfluidics & Custom Electronics for CSBS



[ISSCC SRP'23, ISSCC'24, TBioCAS'24]

Collaborators: Douglas Densmore (BU ECE), Mo Khalil (BU BME), Wilson Wong (BU BME)
Funded by NSF SemiSynBio-II, Catalyst Foundation, SRC

Current Diagnostic Methods

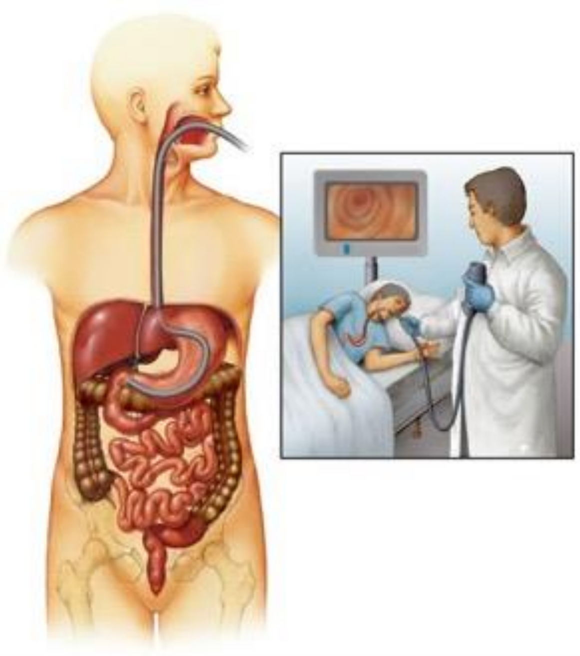


- ☹ No biomarker measurement
- ☹ Invasive
- ☹ Non-real-time monitoring

- ☺ Biomarker measurement
- ☺ Non-invasive
- ☹ Non-real-time monitoring

- ☹ No biomarker measurement
- ☺ Non-invasive
- ☺ Real-time monitoring

Current Diagnostic Methods

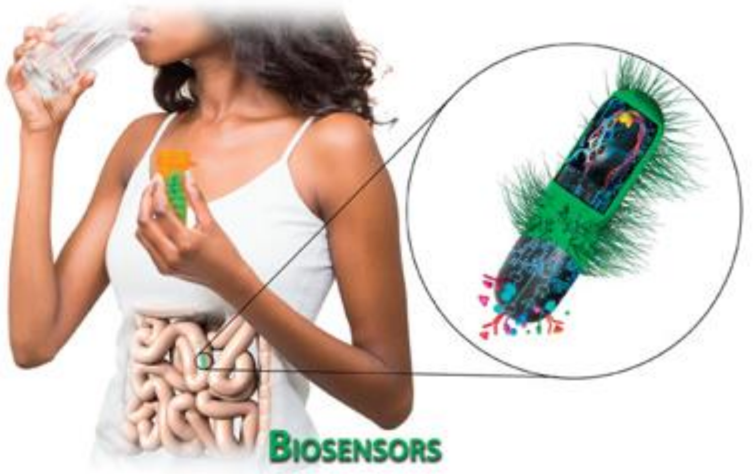


- ☹ No biomarker measurement
- ☹ Invasive
- ☹ Non-real-time monitoring

- ☺ Biomarker measurement
- ☺ Non-invasive
- ☹ Non-real-time monitoring

- ☹ No biomarker measurement
- ☺ Non-invasive
- ☺ Real-time monitoring

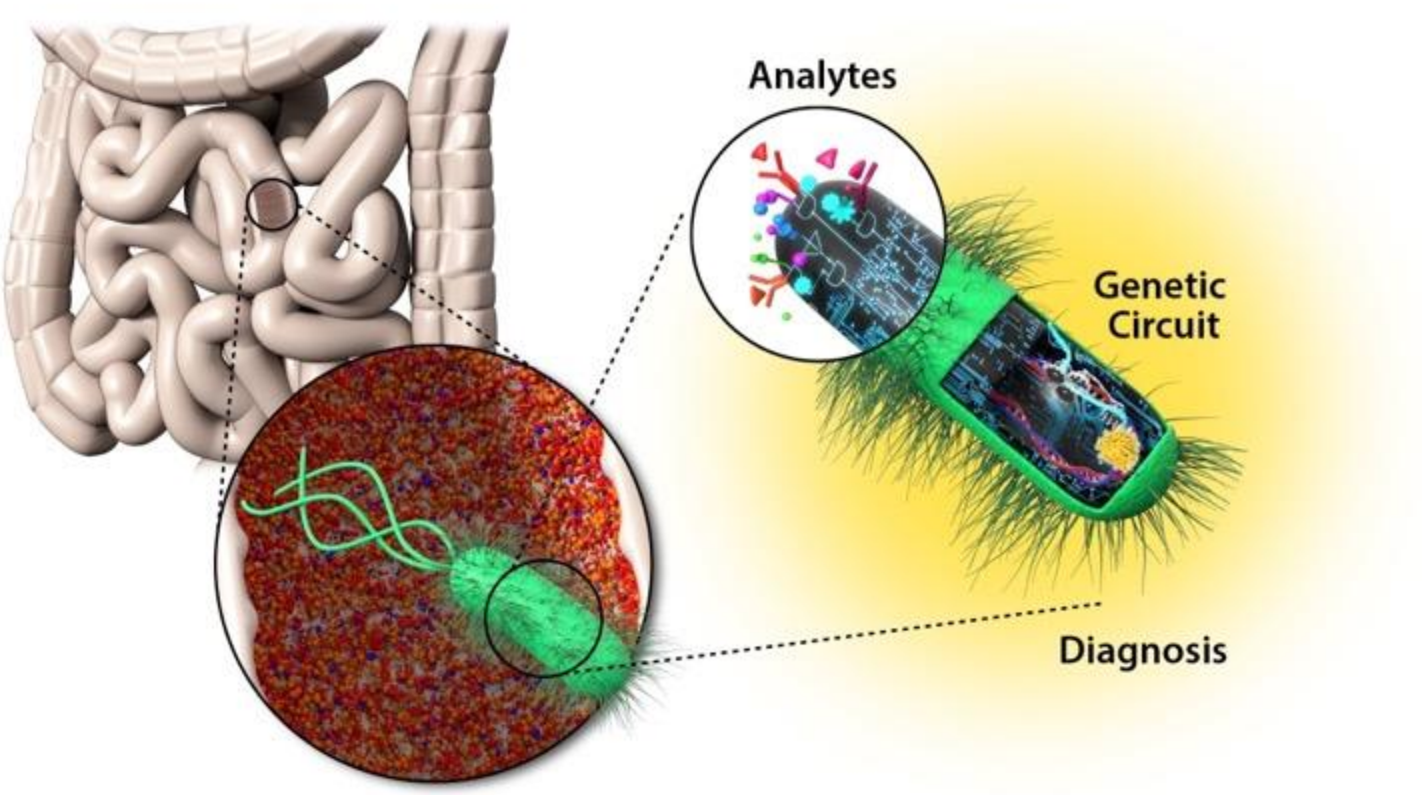
Future



Inda, et al. JACI 2019

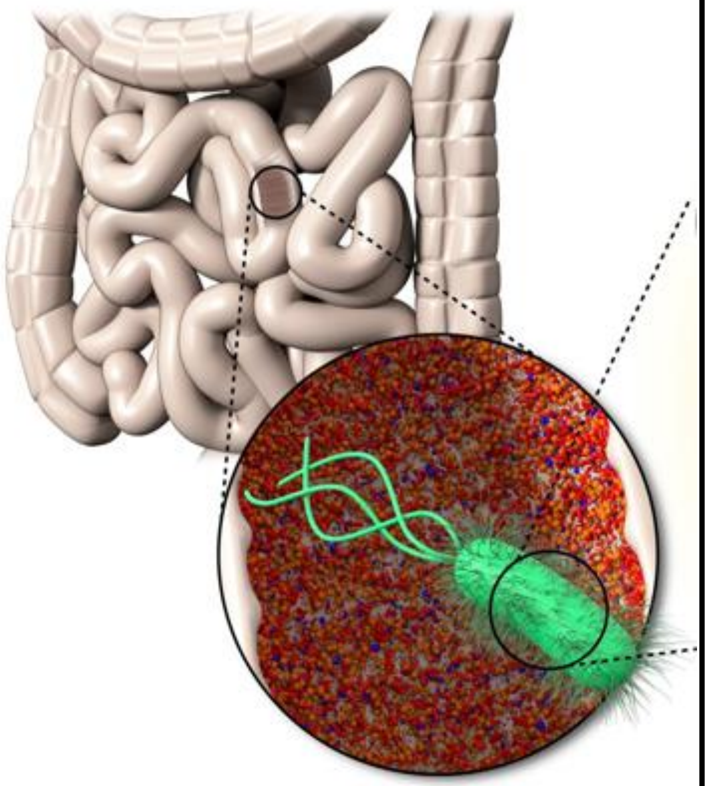
- ☺ Labile disease-mediating molecular measurement
- ☺ Non-invasive
- ☺ Real-time monitoring

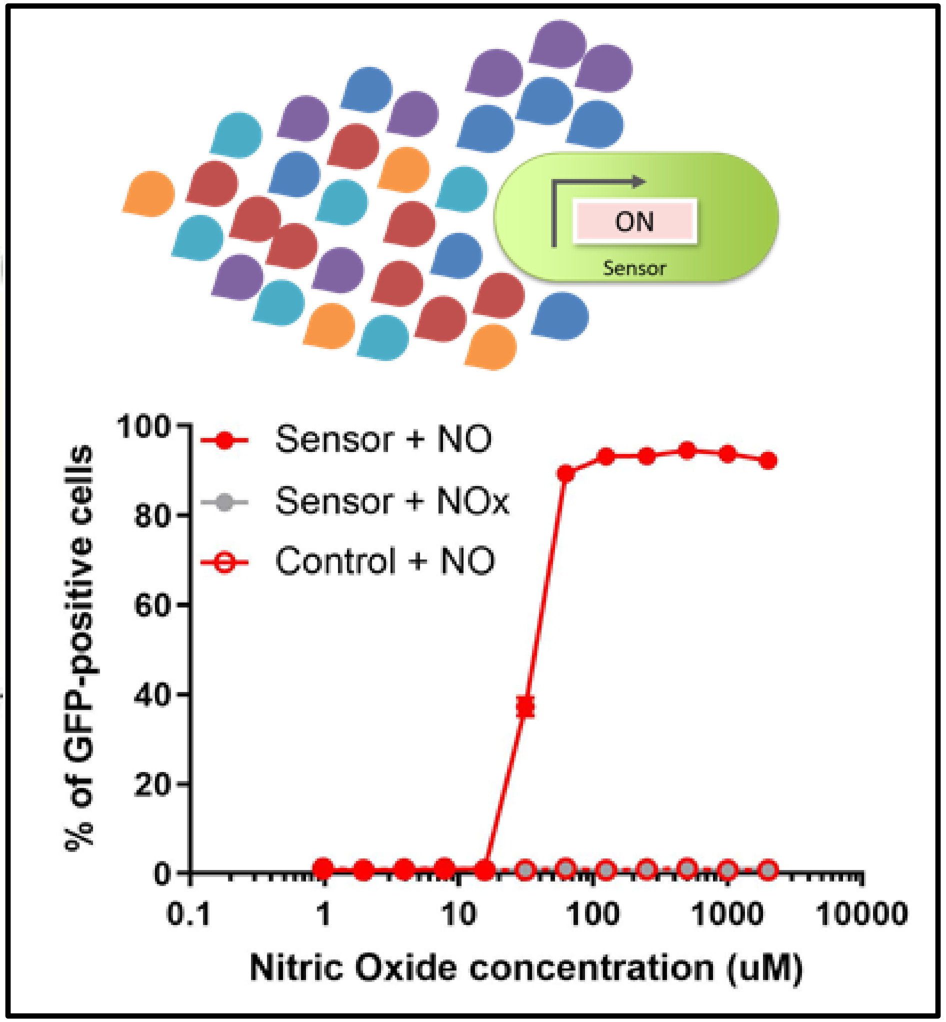
Genetically-Engineered Bacterial Sensors



M.E. Inda, et al., “Cell-based biosensors for immunology, inflammation, and allergy,” The Journal of Allergy and Clinical Immunology, 2019.

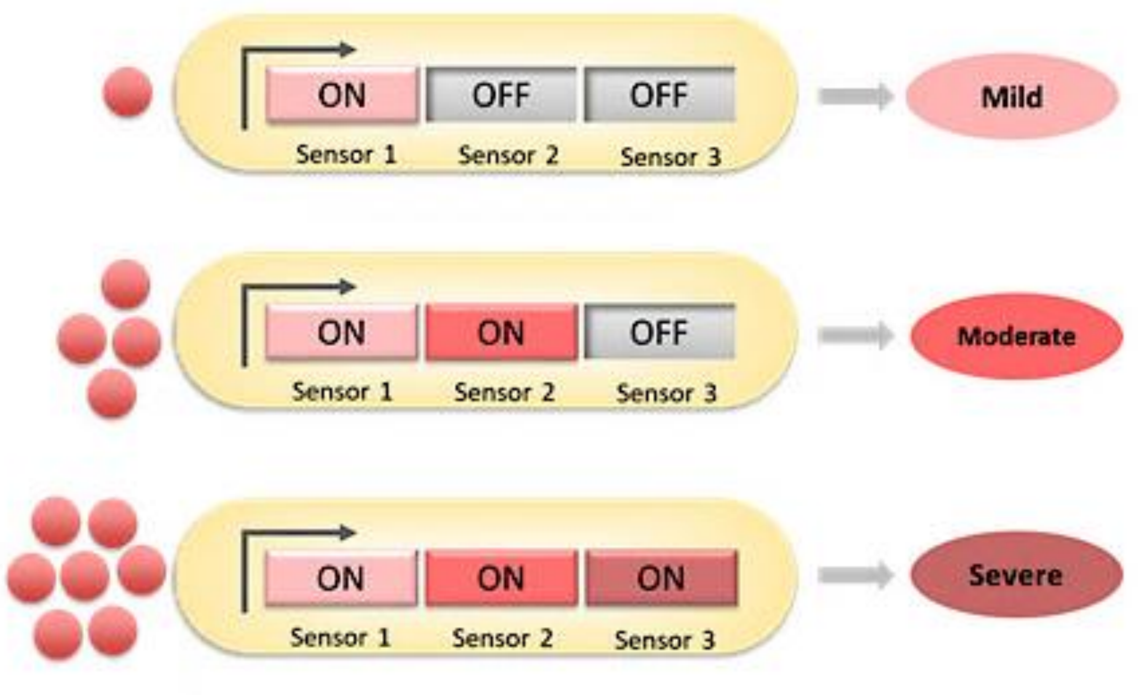
Digital Biosensor for Nitric Oxide

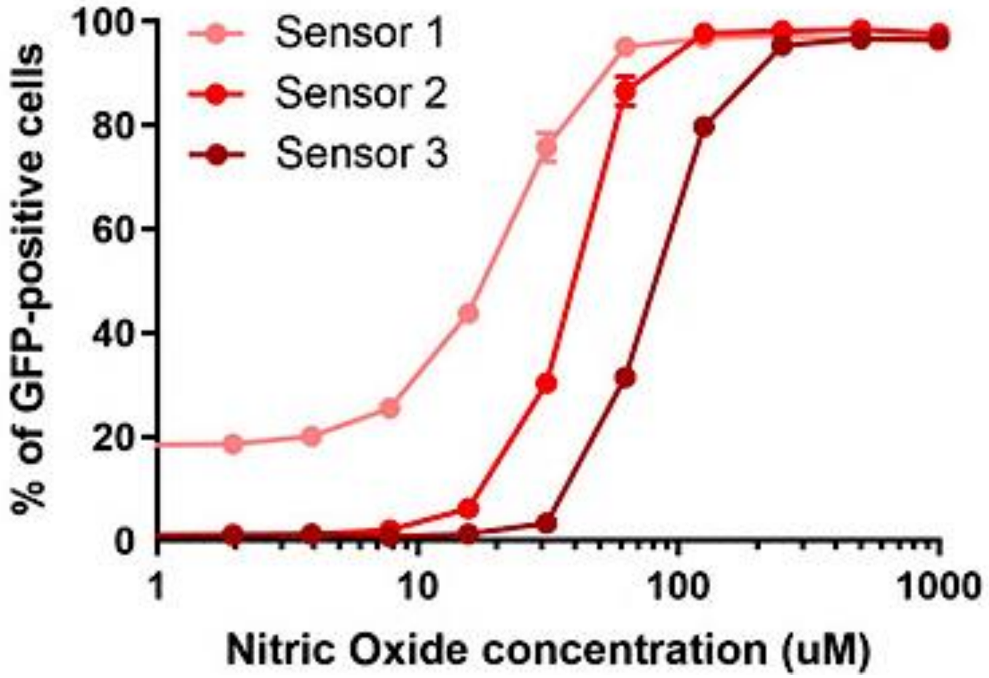




M.E. Inda, et al., "Cell-based biosensors for immunology, inflammation, and allergy," The Journal of Allergy and Clinical Immunology, 2019.
M.E. Inda-Webb, M. Jimenez, Q. Liu, et al., "Sub-1.4 cm^3 capsule for detecting labile inflammatory biomarkers in situ," **Nature,** 2023.

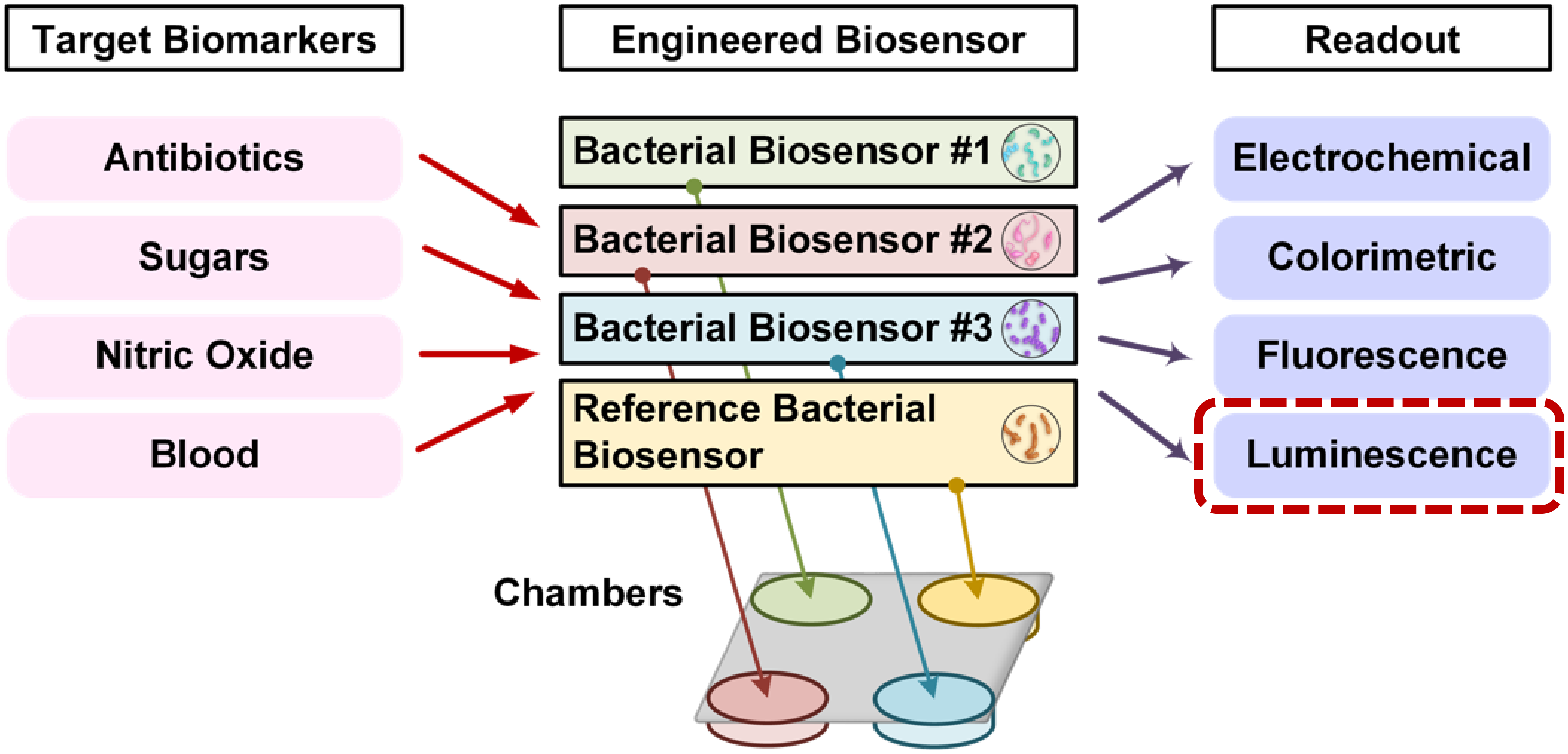
Disease-Stage Detector: Mild, Moderate, Severe





M.E. Inda-Webb, M. Jimenez, Q. Liu, et al., “Sub-1.4 cm^3 capsule for detecting labile inflammatory biomarkers in situ,” **Nature,** 2023.

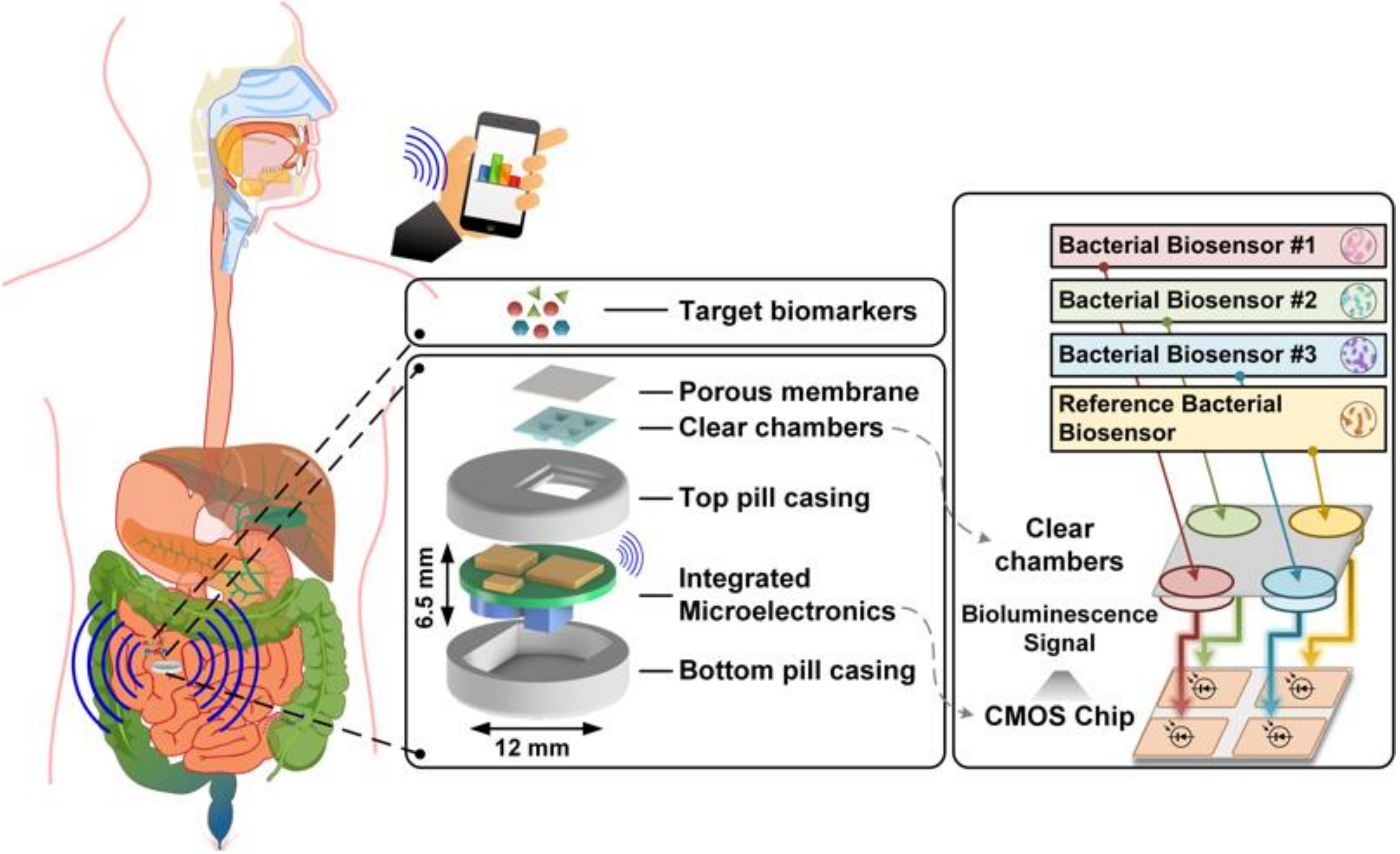
Biological Sensors and Readout



C. Zhu, et al., "A Packaged Ingestible Bio-Pill with 15-Pixel Multiplexed Fluorescence Nucleic-Acid Sensor and Bi-Directional Wireless Interface for In-Vivo Bio-Molecular Sensing," IEEE VLSI Circuits, 2020.

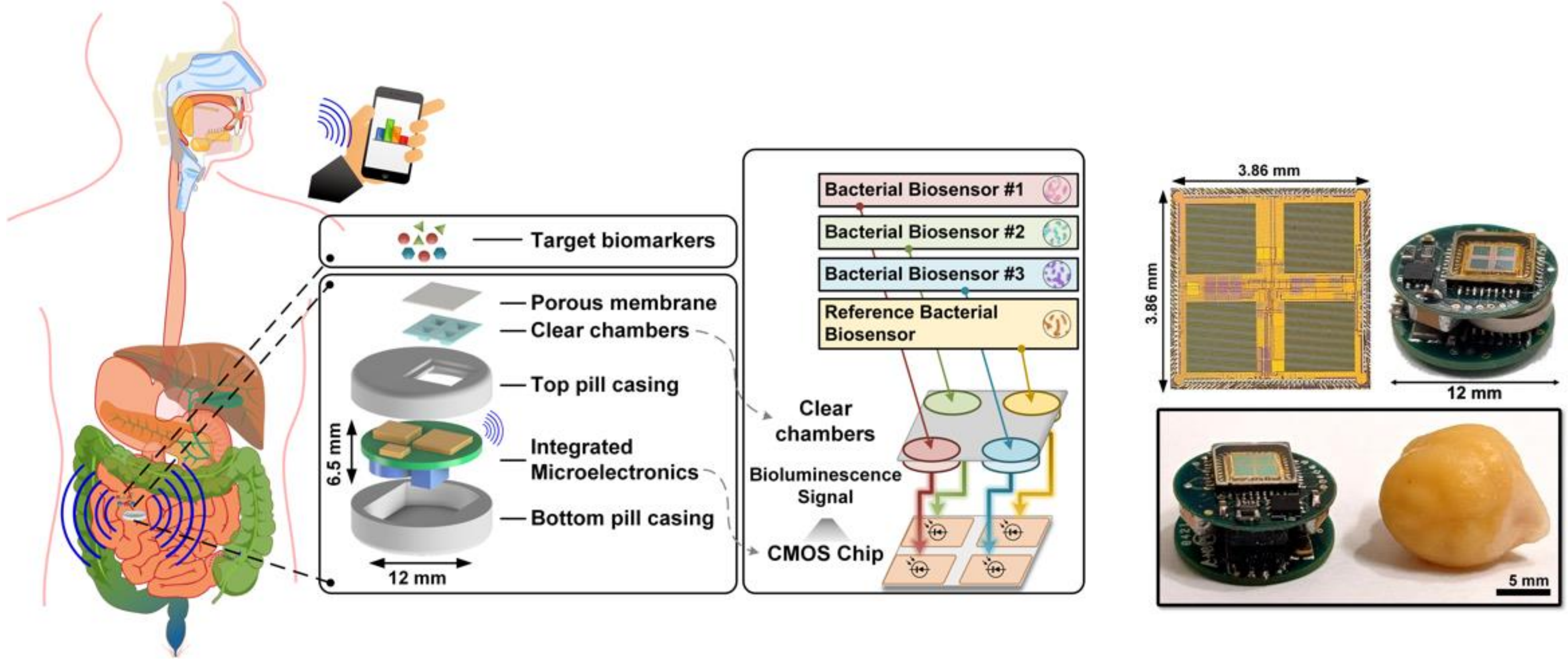
F. Aghlmand, et al., "A 65-nm CMOS Fluorescence Sensor for Dynamic Monitoring of Living Cells," IEEE JSSC, 2023.

Disease Diagnosis and Monitoring
Synthetic Biology & Hardware Coupling



Q. Liu, et al., "Zero-Crossing-Based Bio-Engineered Sensors," IEEE CICC, 2021.
Q. Liu, et al., "A Threshold-based Bioluminescence Detector with a CMOS-Integrated Photodiode Array in 65 nm for a Multi-Diagnostic Ingestible Capsule," **IEEE JSSC**, 2023.
M.E. Inda-Webb, M. Jimenez, Q. Liu, et al., "Sub-1.4 cm^3 capsule for detecting labile inflammatory biomarkers in situ," **Nature,** 2023.

Disease Diagnosis and Monitoring Synthetic Biology & Hardware Coupling



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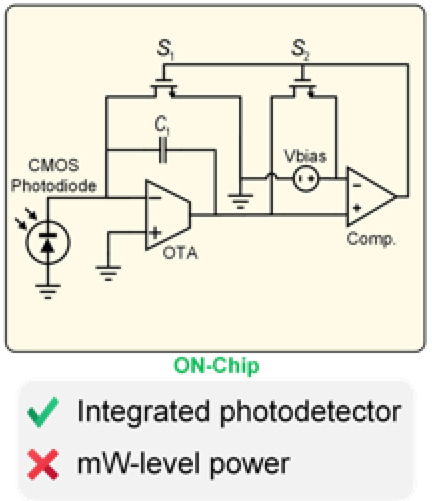
Q. Liu, et al., "A Threshold-based Bioluminescence Detector with a CMOS-Integrated Photodiode Array in 65 nm for a Multi-Diagnostic Ingestible Capsule," **IEEE JSSC**, 2023.
M.E. Inda-Webb, M. Jimenez, Q. Liu, et al., "Sub-1.4 cm^3 capsule for detecting labile inflammatory biomarkers in situ," **Nature,** 2023.

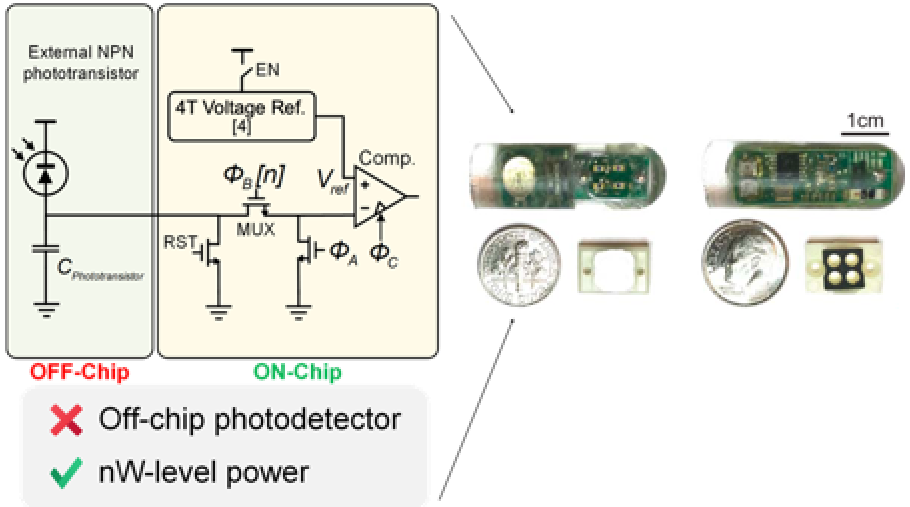
Luminescence Readout Systems

	Power level	Source	Size
Commercial 	Watt	Wall-plug	m scale
Research 	Milliwatt Nanowatt	Battery	cm scale

TCAS-I '07

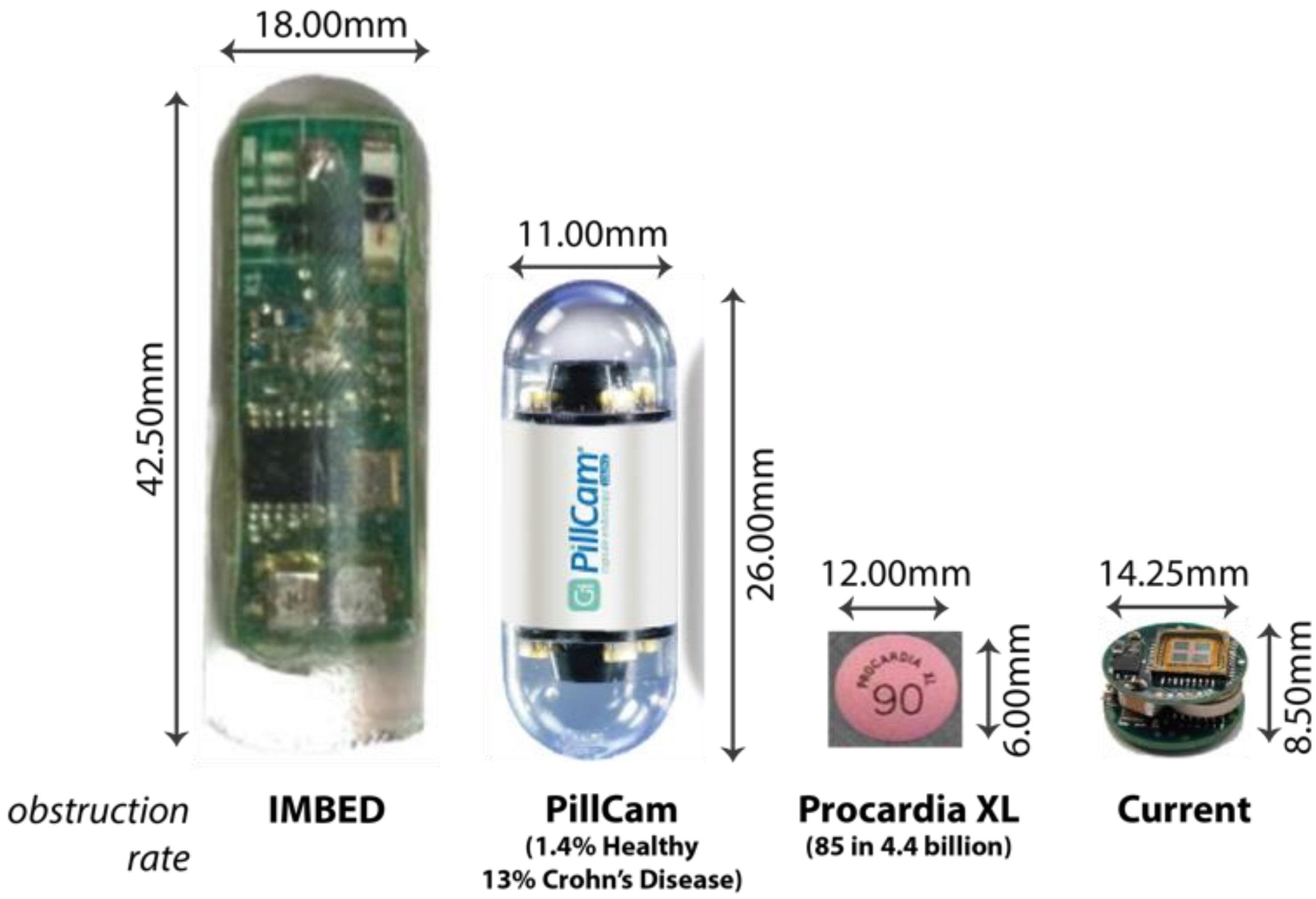


ISSCC '17 and Science '18



S. Islam, et al., IEEE TCAS-I, 2007.
M. Mimee, et al., Science, 2018.
P. Nadeau, et al., IEEE ISSCC, 2017.

Ingestible Capsule Miniaturization



C. Steiger, et al., "Ingestible electronics for diagnostics and therapy," Nature Reviews Materials, 2019.
M.E. Inda-Webb, M. Jimenez, Q. Liu, et al., "Sub-1.4 cm^3 capsule for detecting labile inflammatory biomarkers in situ," **Nature,** 2023.

The Future is Now: Luminescence Readout Systems

	Power level	Source	Size
Commercial 	Watt	Wall-plug	m scale
Research 	Milliwatt Nanowatt	Battery	cm scale
Future 	**Nanowatt**	**Energy Harvesting**	**mm scale**

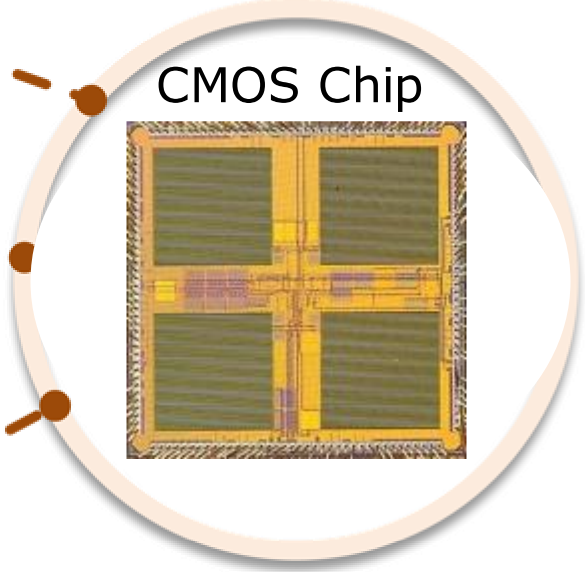
Y. Lee, et al., "A Modular 1 mm^3 Die-Stacked Sensing Platform With Low Power I^2C Inter-Die Communication and Multi-Modal Energy Harvesting," IEEE JSSC, 2013.
C. Steiger, et al., “Ingestible electronics for diagnostics and therapy,” Nature Reviews Materials, 2019.

Custom Integrated Bioluminescence Detector

Scalable Biomarker Detection
Integrated CMOS photodiodes

High Resolution
Threshold-based bioluminescence detection

nW-level Power Consumption
Threshold-based bioluminescence detection
Dual-duty-cycling front end



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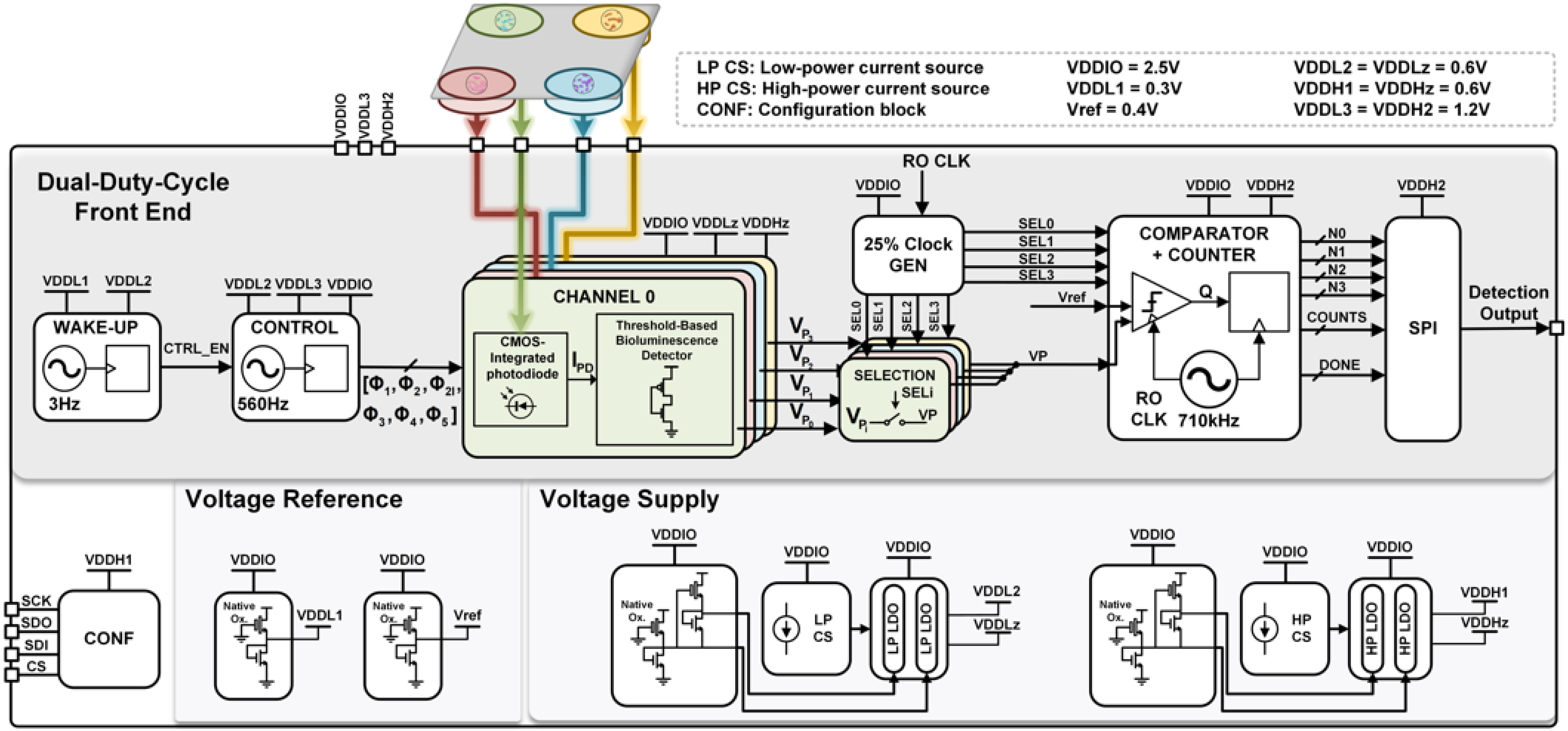
Q. Liu, et al., "A Threshold-based Bioluminescence Detector with a CMOS-Integrated Photodiode Array in 65 nm for a Multi-Diagnostic Ingestible Capsule," **IEEE JSSC**, 2023.
M.E. Inda-Webb, M. Jimenez, Q. Liu, et al., "Sub-1.4 cm^3 capsule for detecting labile inflammatory biomarkers in situ," **Nature,** 2023.

Threshold-Based Bioluminescence Detector



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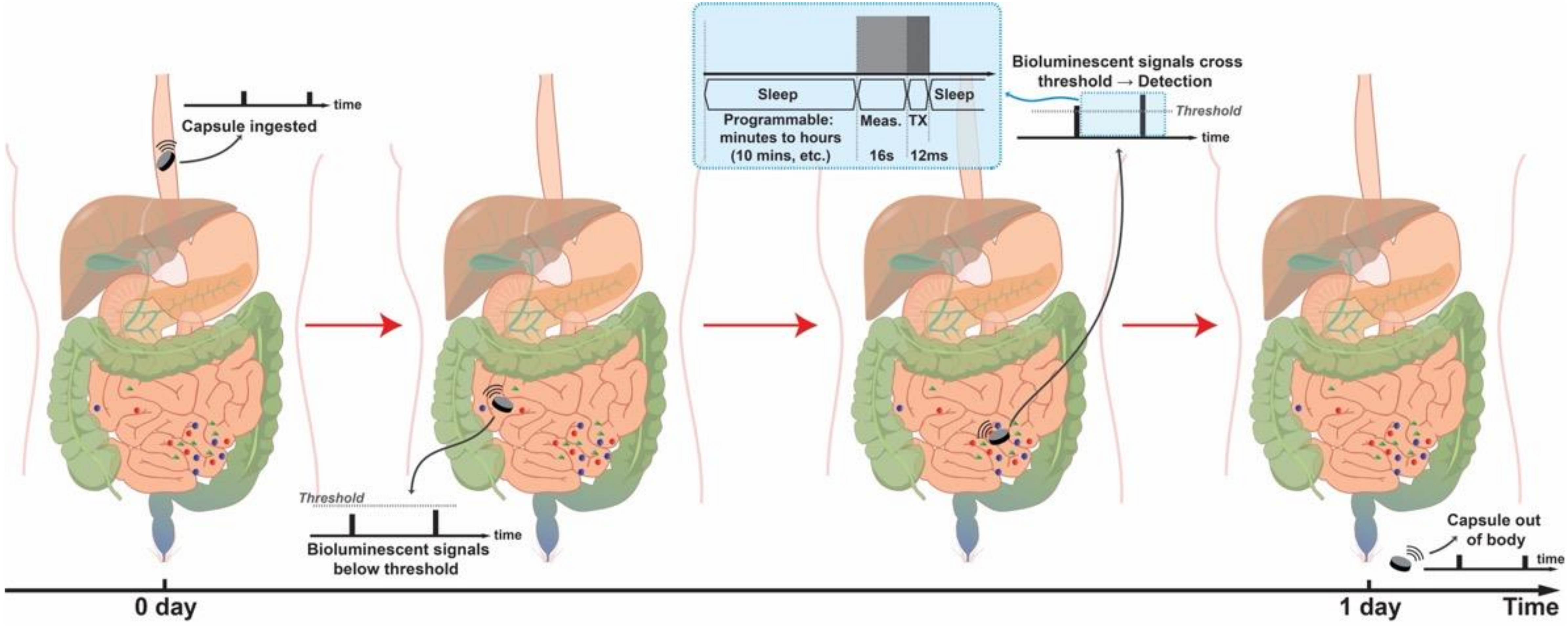
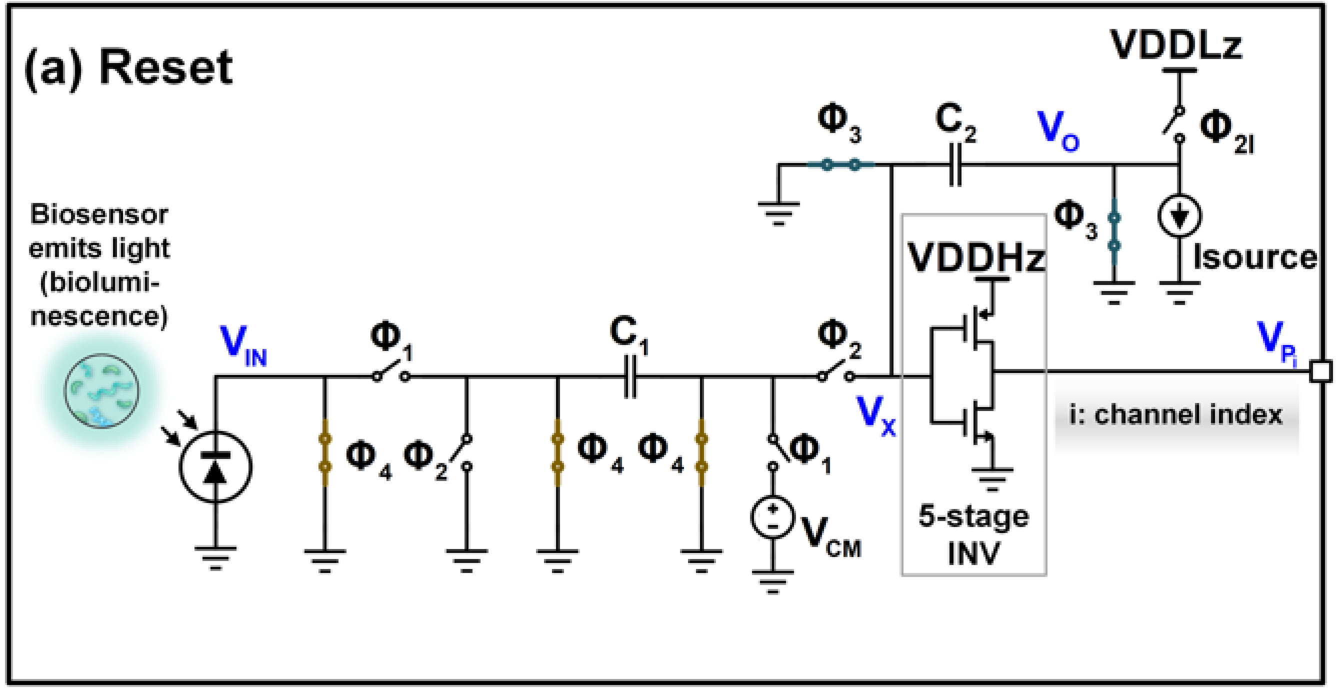
M.E. Inda-Webb, M. Jimenez, Q. Liu, et al., "Sub-1.4 cm^3 capsule for detecting labile inflammatory biomarkers in situ," **Nature,** 2023.

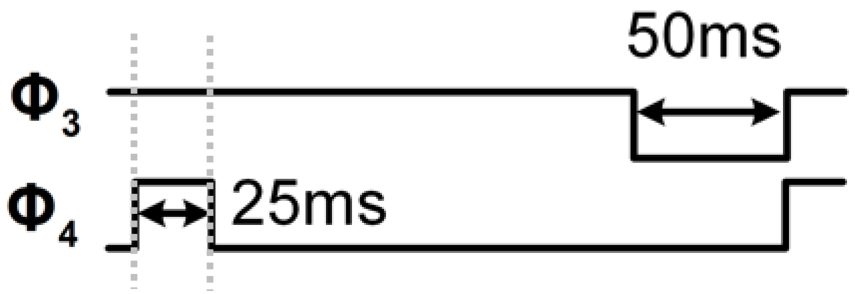
Dual-Duty-Cycling Front End



Q. Liu, et al., "Zero-Crossing-Based Bio-Engineered Sensors," IEEE CICC, 2021.
Q. Liu, et al., "A Threshold-based Bioluminescence Detector with a CMOS-Integrated Photodiode Array in 65 nm for a Multi-Diagnostic Ingestible Capsule," **IEEE JSSC**, 2023.
M.E. Inda-Webb, M. Jimenez, Q. Liu, et al., "Sub-1.4 cm^3 capsule for detecting labile inflammatory biomarkers in situ," **Nature,** 2023.

Operational Phases: Reset





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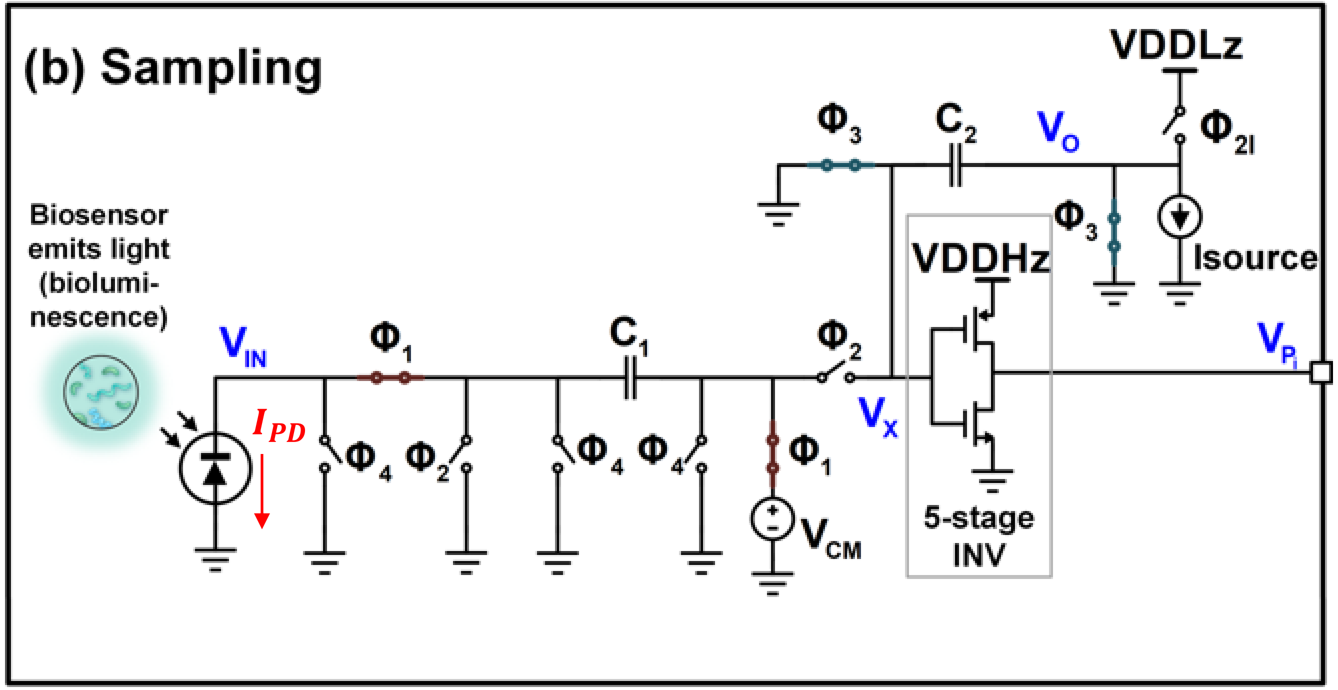
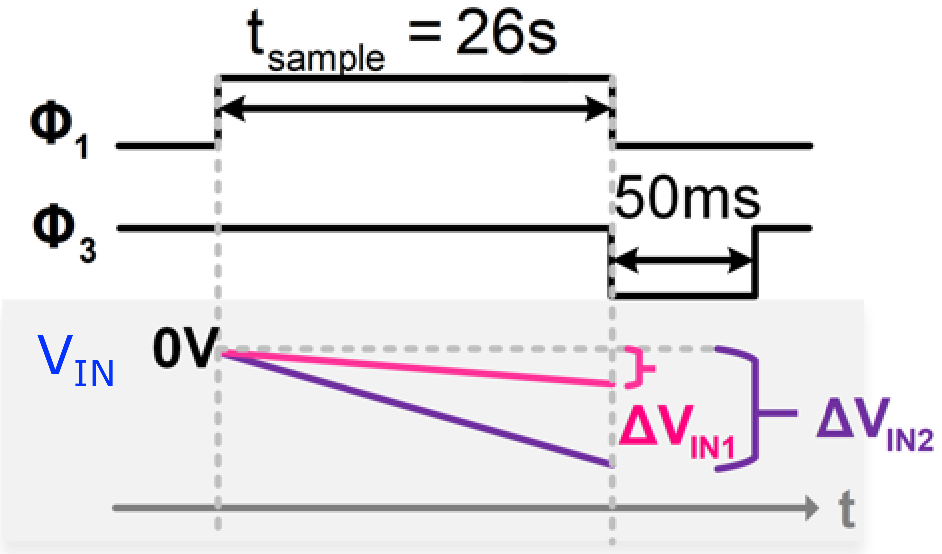
M.E. Inda-Webb, M. Jimenez, Q. Liu, et al., "Sub-1.4 cm^3 capsule for detecting labile inflammatory biomarkers in situ," **Nature,** 2023.

Operational Phases: Sampling





$$I_{PD1} < I_{PD2} \Rightarrow \Delta V_{IN1} < \Delta V_{IN2}$$

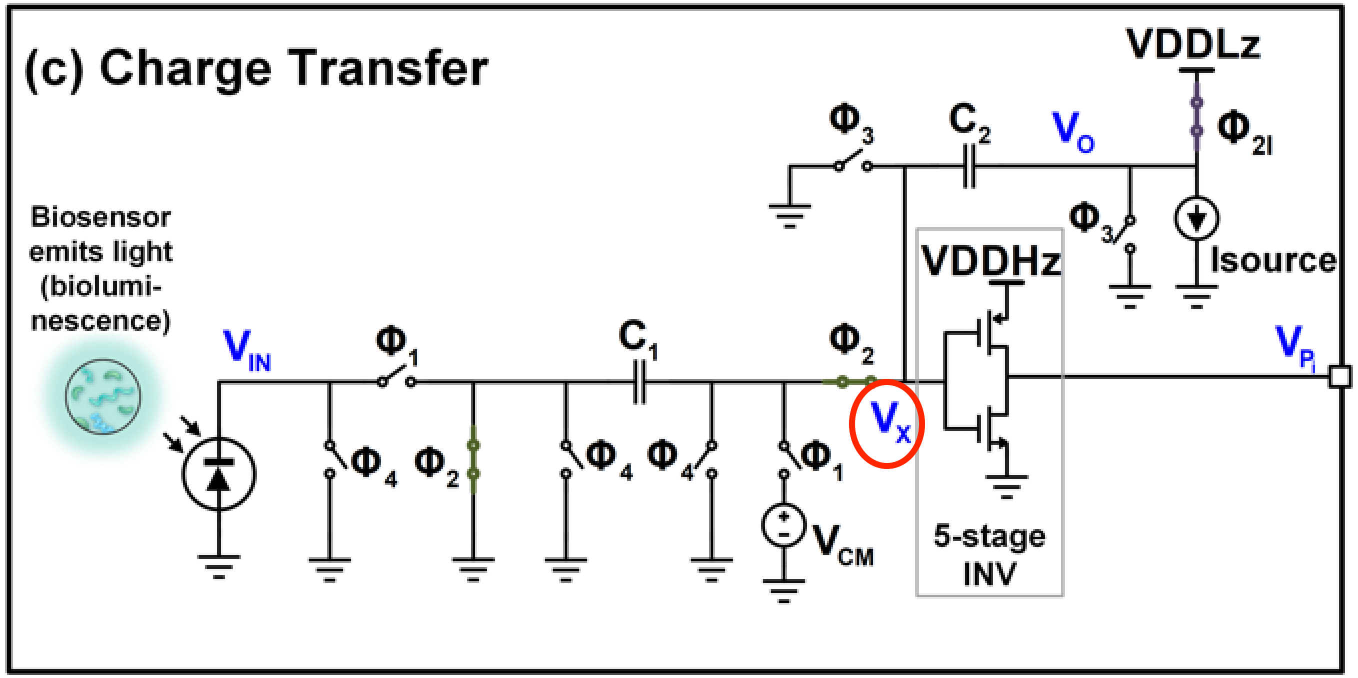
$$\Delta V_{IN} = \frac{I_{PD} \cdot \mathrm{t_{Sample}}}{C_{PD}}$$

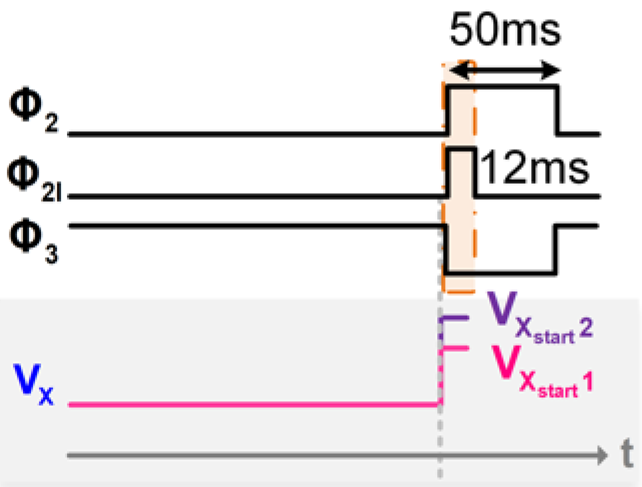
$$Q_{Sample} = \mathrm{C_1} \cdot (V_{CM} + \Delta V_{IN})$$

$$C_1 = 20pF \quad C_2 = 5pF$$

Q. Liu, et al., "Zero-Crossing-Based Bio-Engineered Sensors," IEEE CICC, 2021.
Q. Liu, et al., "A Threshold-based Bioluminescence Detector with a CMOS-Integrated Photodiode Array in 65 nm for a Multi-Diagnostic Ingestible Capsule," **IEEE JSSC**, 2023.
M.E. Inda-Webb, M. Jimenez, Q. Liu, et al., "Sub-1.4 cm³ capsule for detecting labile inflammatory biomarkers in situ," **Nature,** 2023.

Operational Phases: Charge Transfer





$$I_{PD1} < I_{PD2} \Rightarrow V_{X_{start}1} < V_{X_{start}2}$$

$$Q_{Transfer} = C_1 \cdot V_X + C_2(V_X - V_{DD})$$

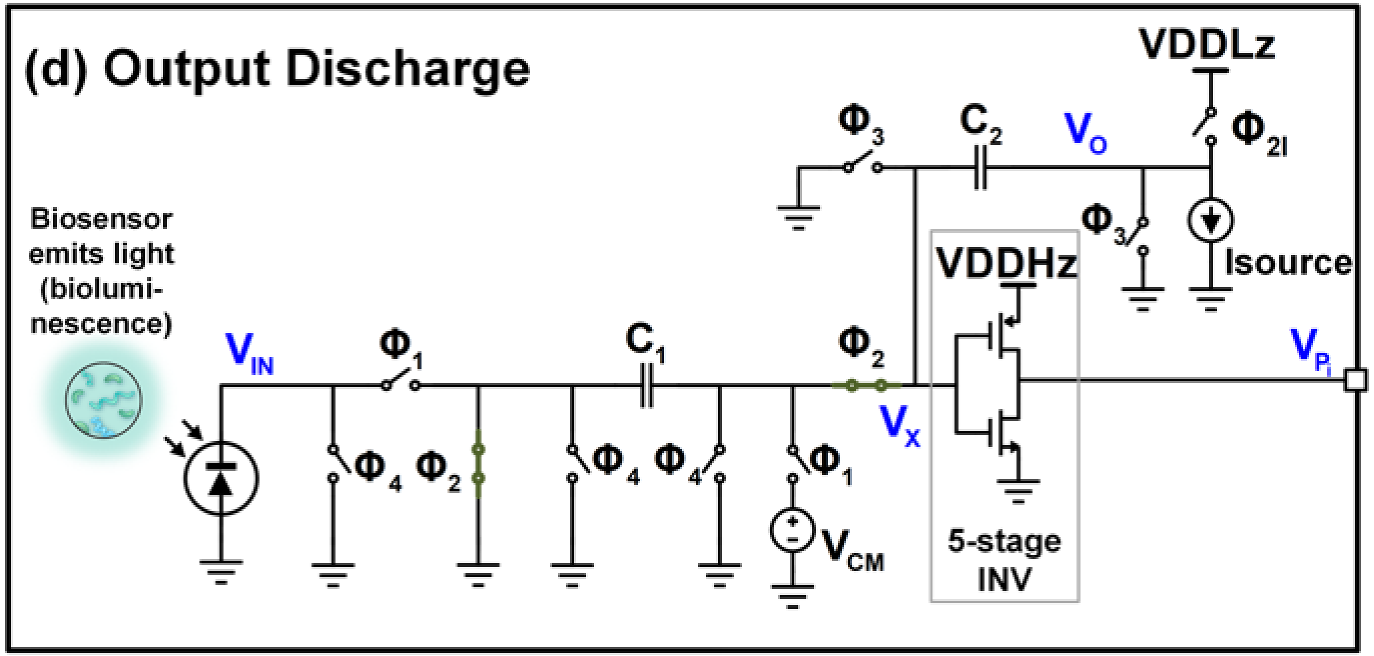
$$Q_{Sample} = Q_{Transfer}$$

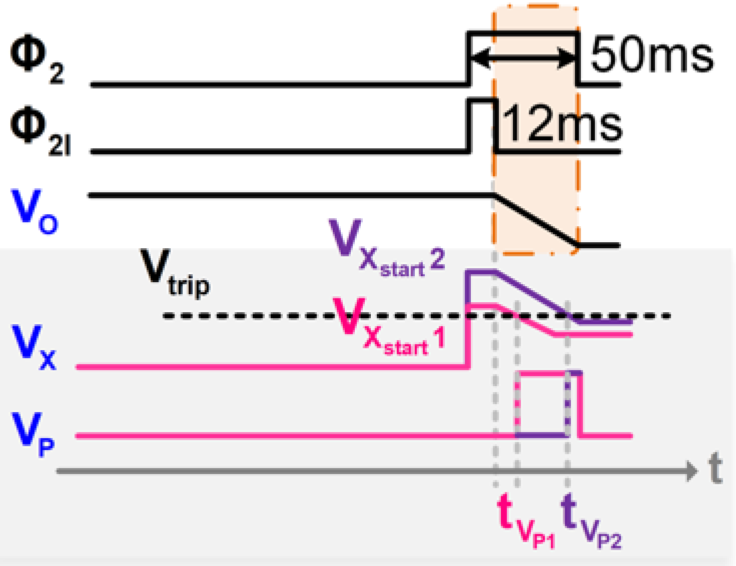
$$V_{X_{start}} = \frac{(V_{CM} + \Delta V_{IN}) \cdot C_1 + V_{DD} \cdot C_2}{C_1 + C_2}$$

$$V_O = V_{DD} = 600\ mV \quad V_{CM} = 300mV$$

Q. Liu, et al., "Zero-Crossing-Based Bio-Engineered Sensors," IEEE CICC, 2021.
Q. Liu, et al., "A Threshold-based Bioluminescence Detector with a CMOS-Integrated Photodiode Array in 65 nm for a Multi-Diagnostic Ingestible Capsule," **IEEE JSSC**, 2023.
M.E. Inda-Webb, M. Jimenez, Q. Liu, et al., "Sub-1.4 cm^3 capsule for detecting labile inflammatory biomarkers in situ," **Nature,** 2023.

Operational Phases: Output Discharge





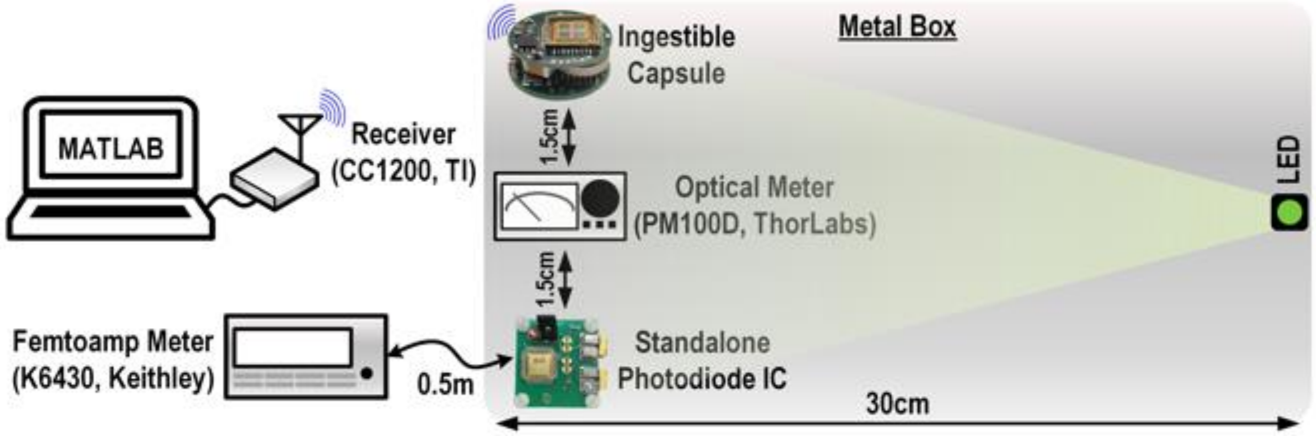
$$I_{PD1} < I_{PD2} \Rightarrow t_{V_{P1}} < t_{V_{P2}}$$

$$\frac{dV_O}{dt} = \frac{I_{source}}{C_1 || C_2} = \frac{I_{source}}{C_1 \cdot C_2}(C_1 + C_2)$$

$$\frac{dV_X}{dt} = \frac{I_{source}}{C_1} \qquad I_{source} = 320pA$$

Q. Liu, et al., "Zero-Crossing-Based Bio-Engineered Sensors," IEEE CICC, 2021.
Q. Liu, et al., "A Threshold-based Bioluminescence Detector with a CMOS-Integrated Photodiode Array in 65 nm for a Multi-Diagnostic Ingestible Capsule," **IEEE JSSC**, 2023.
M.E. Inda-Webb, M. Jimenez, Q. Liu, et al., "Sub-1.4 cm^3 capsule for detecting labile inflammatory biomarkers in situ," **Nature,** 2023.

Optical Characterization



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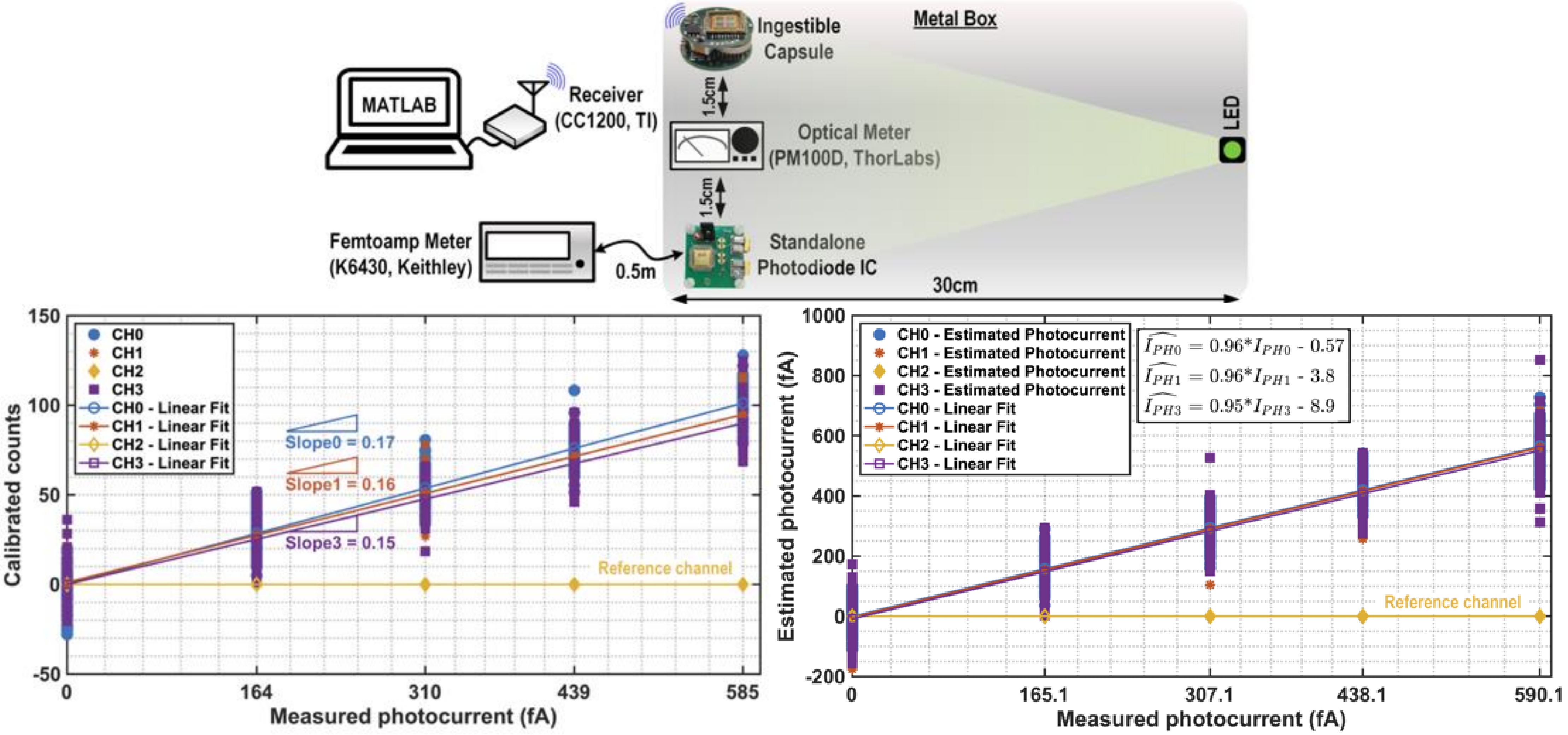

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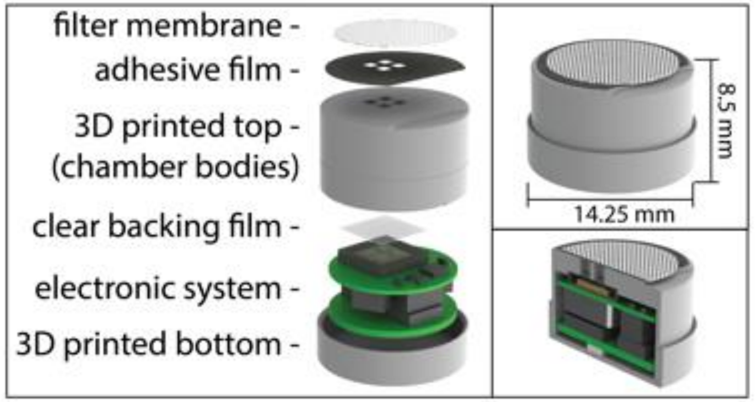

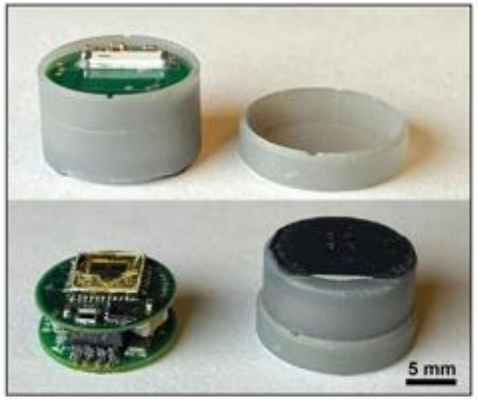

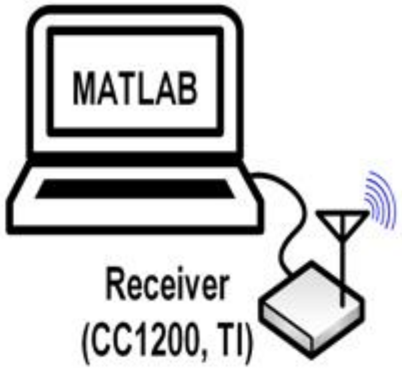

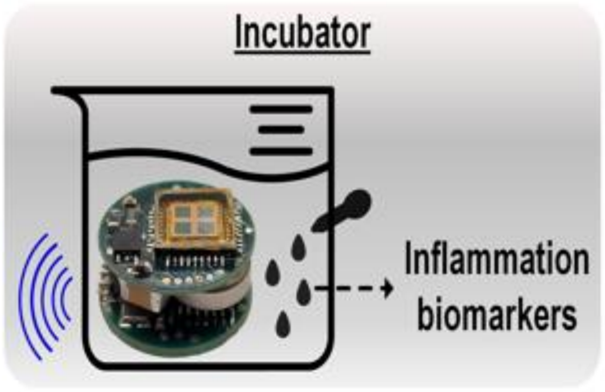

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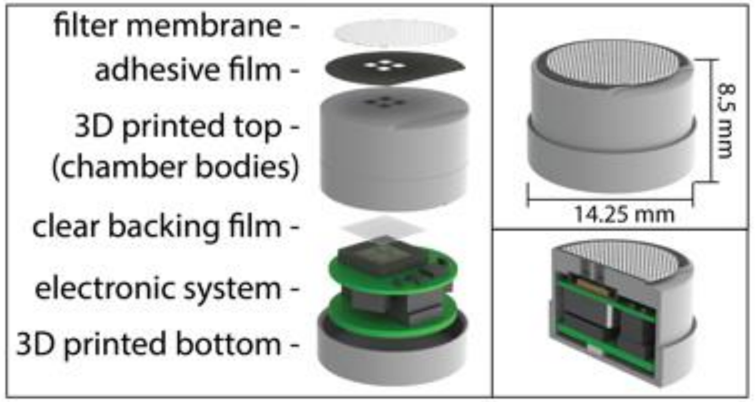

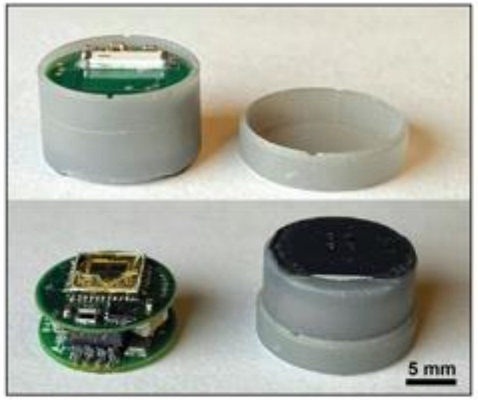

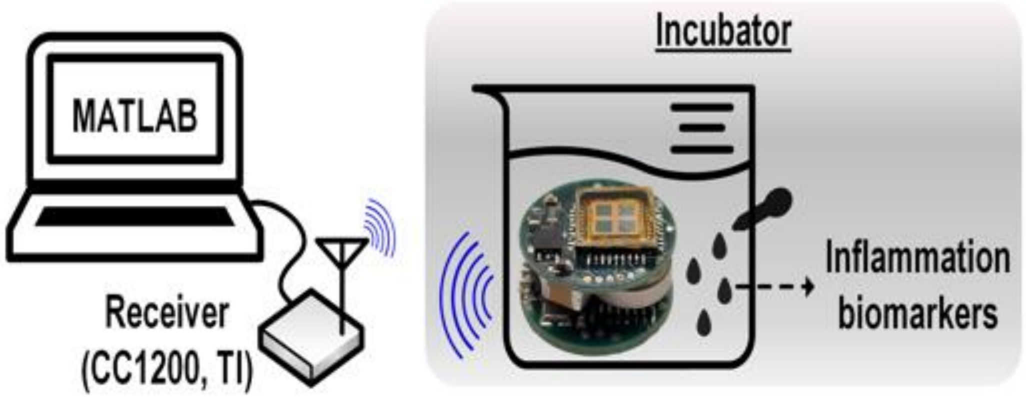

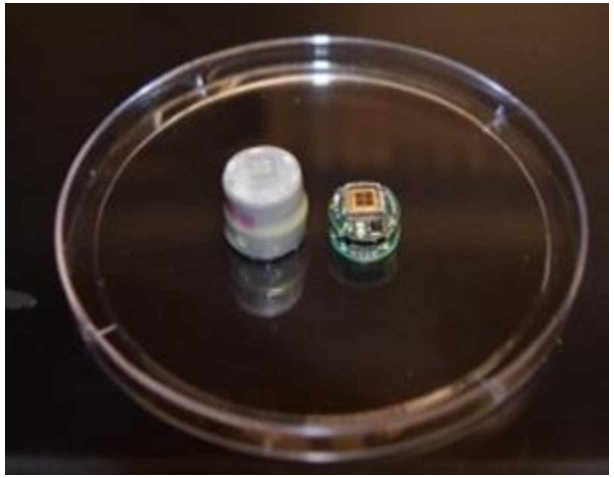

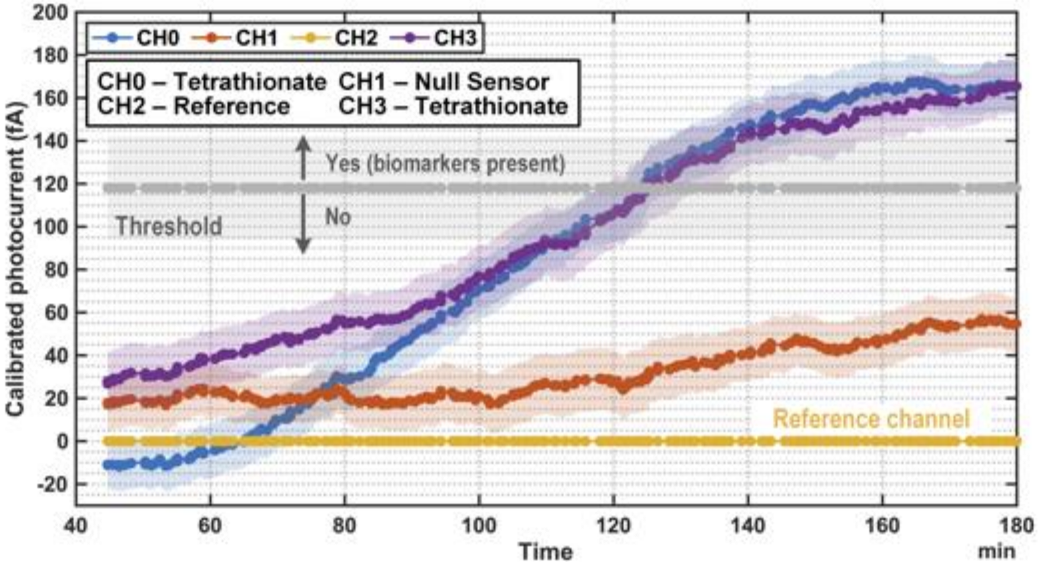

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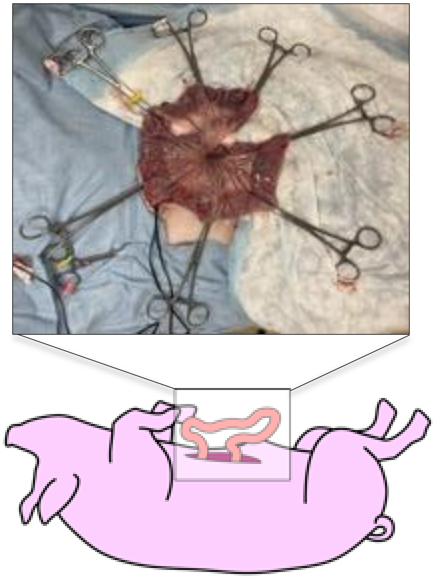
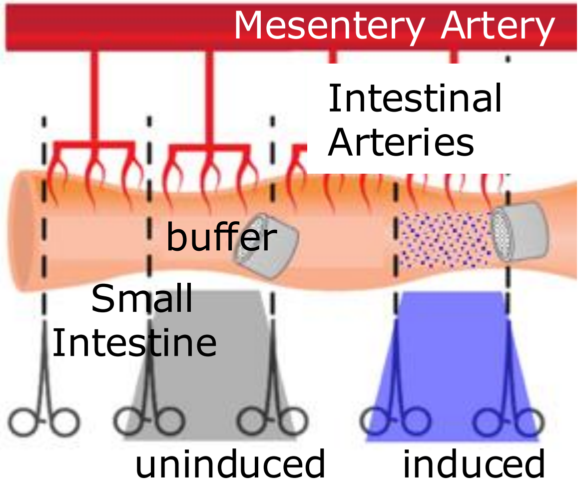
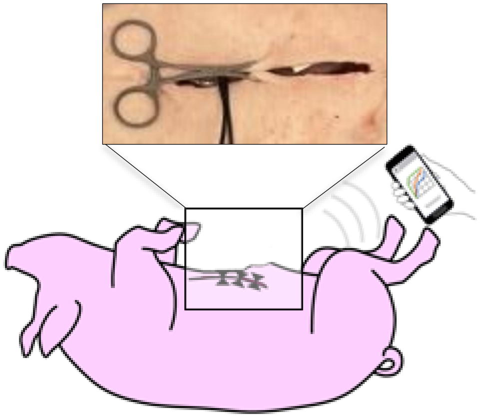




Compartmentalized intestine with the devices inside the abdomen
37°C



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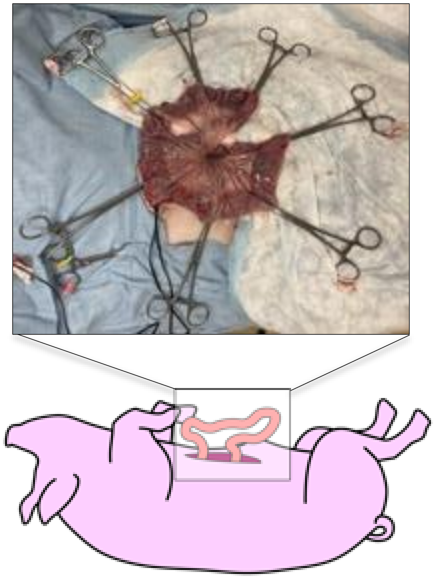

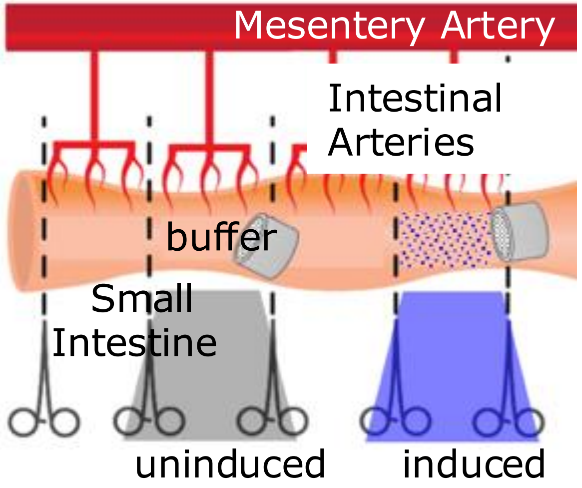

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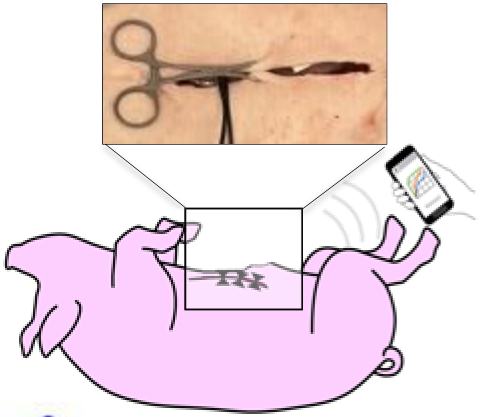

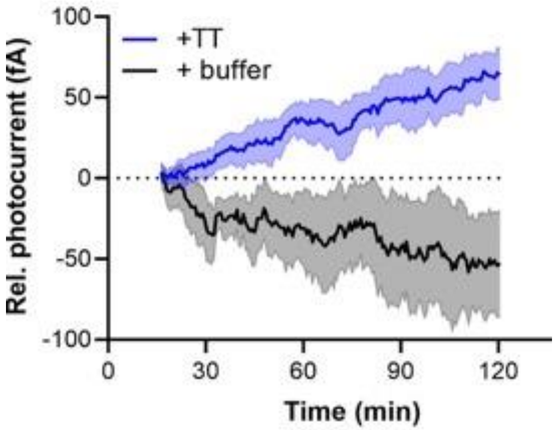

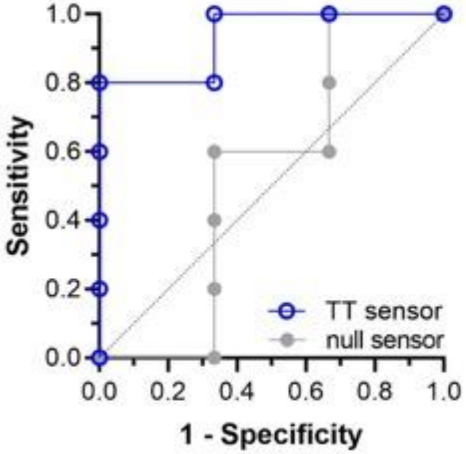

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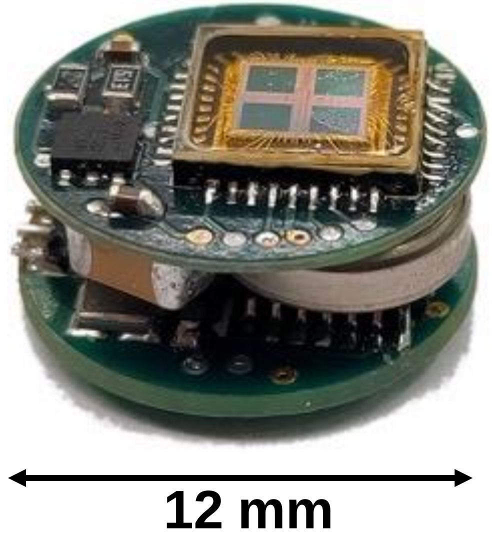
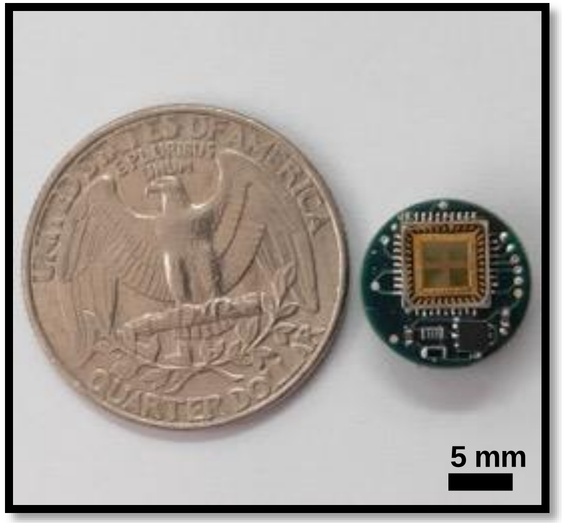
Conclusions

- Threshold-based bioluminescence detection with a dual-duty-cycling front end
- fA-level photocurrent detection with **5.4x lower minimum detectable signal** and **2.1x higher resolution** in a mm-scale capsule (**6.4x smaller volume**)
- **59nW** active power consumption for the custom integrated photodetector readout
- **Multiplexed labile** biomarker detection via a **mm-scale capsule** for continuous and minimally-invasive disease monitoring in the gastrointestinal tract





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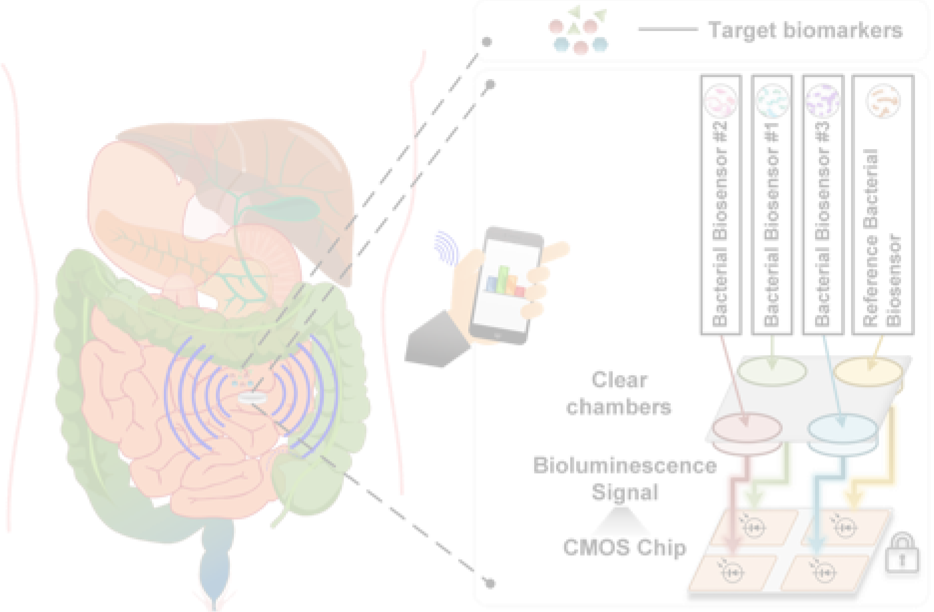
What’s Next?

- Ultra-low-power custom wireless transmitter:
  - 138nW for 232 bits per 26 seconds*
  - Using a crystal-less MICS TX consuming 15.5nJ/bit at 200kb/s*
- Multi-modal sensing and calibration
- Security assessment of the ingestible devices
- Embedding security via low-power hardware solutions

A. Yasar, et al., “Live Demonstration: Cyber Attack Against an Ingestible Medical Device,” IEEE BioCAS, 2022.
* M. Song, et al., “A 3.5mm×3.8mm Crystal-Less MICS Transceiver Featuring Coverages of ±160ppm Carrier Frequency Offset and 4.8-VSWR Antenna Impedance for Insertable Smart Pills”, IEEE ISSCC, 2020.

Cyber-Secure Biological Systems / All-in-One Data Decoders

Ingestible Bioengineered Capsule

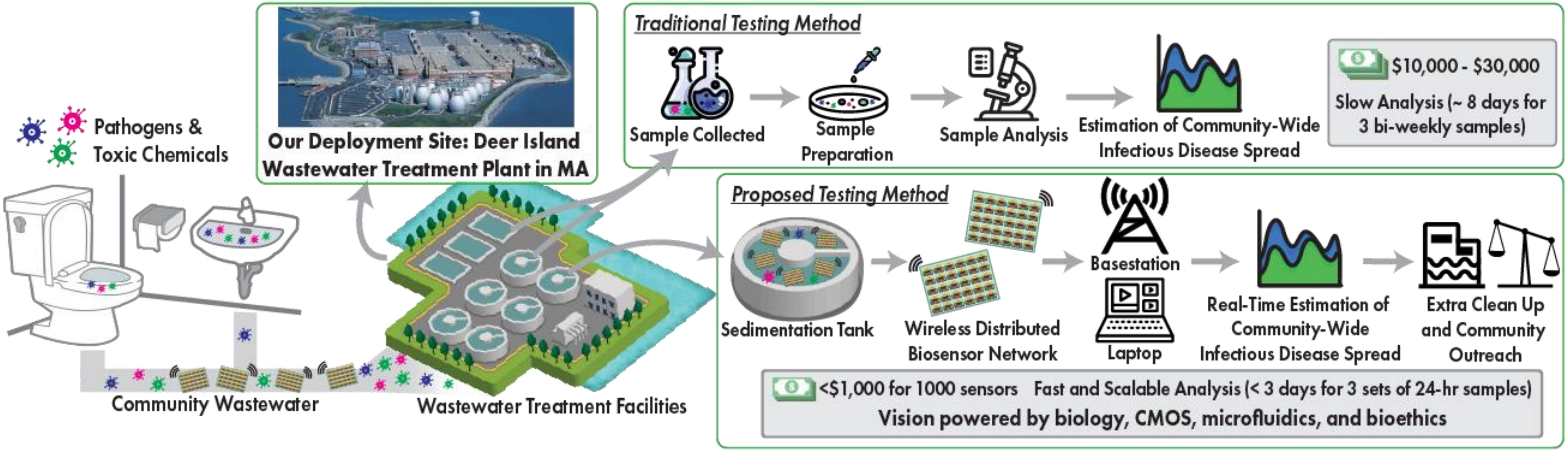


Co-Design of Microfluidics & Custom Electronics for CSBS

Universal Decoder - GRAND

Wastewater Surveillance in MA

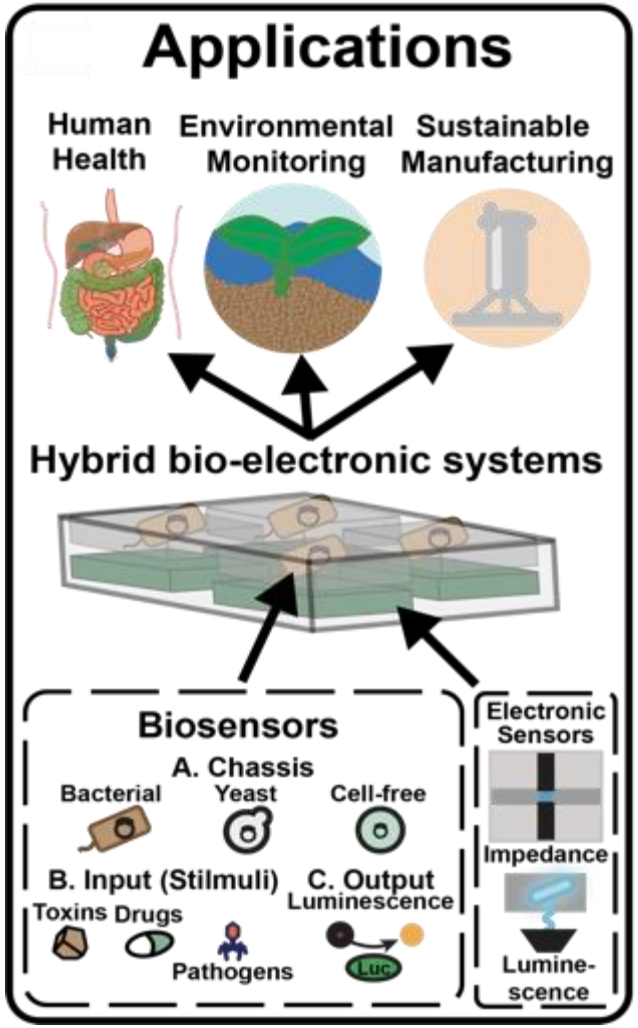
Semiconductor Research Corporation

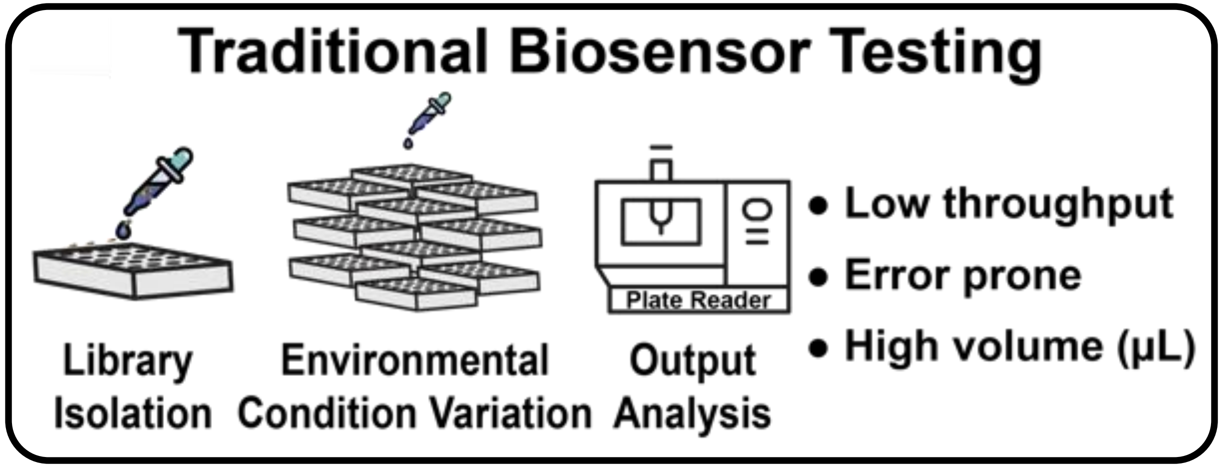


- **Real-time monitoring** of toxic chemicals & pathogens
- Wireless biosensor network for **distributed** wastewater surveillance
- **Low-cost** detection (<$1000 for 1000 sensors)
- **Fast** & **scalable** analysis (<3 days for 3 sets of 24-hr samples)

Collaborators: Douglas Densmore, Mo Khalil, Wilson Wong – BU

Droplet Microfluidics Embedded with CMOS ICs





Collaborator: Douglas Densmore – BU

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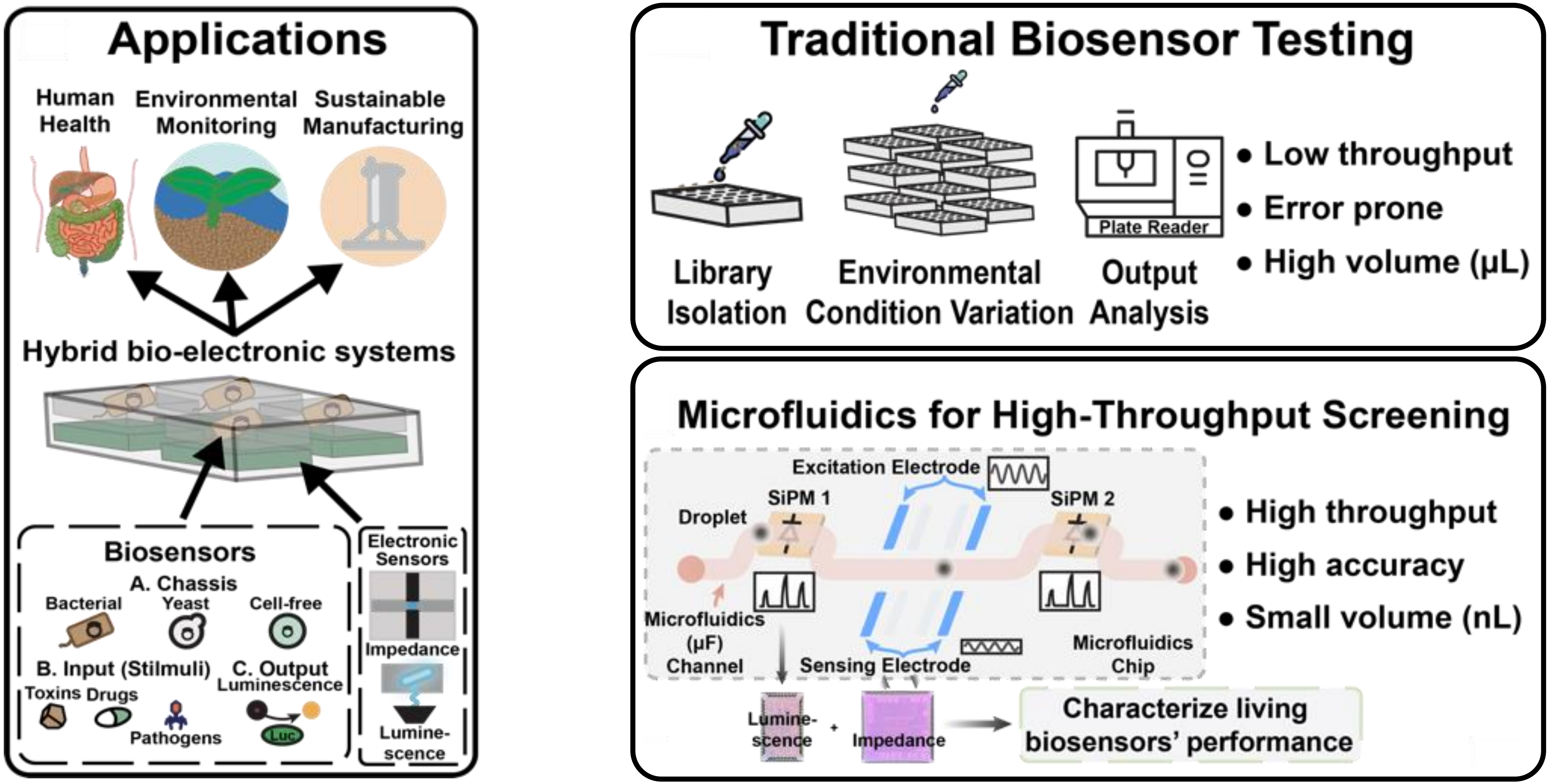

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Q. Liu, et al., "Integrated Real-Time CMOS Luminescence Sensing and Impedance Spectroscopy in Droplet Microfluidics," **IEEE TBioCAS**, ISSCC 2024 Special Issue.

Single Droplet Sensing is Essential for HTS

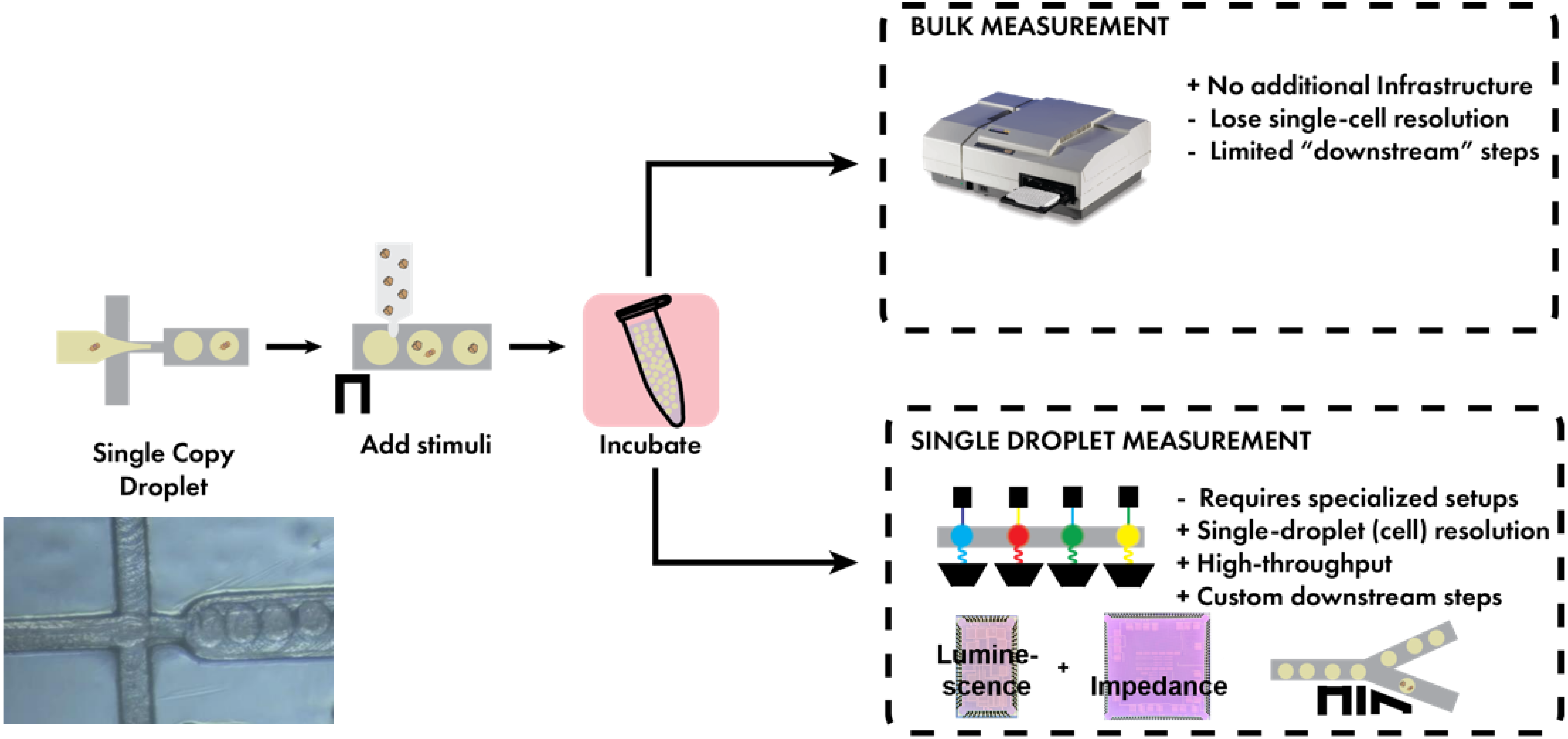
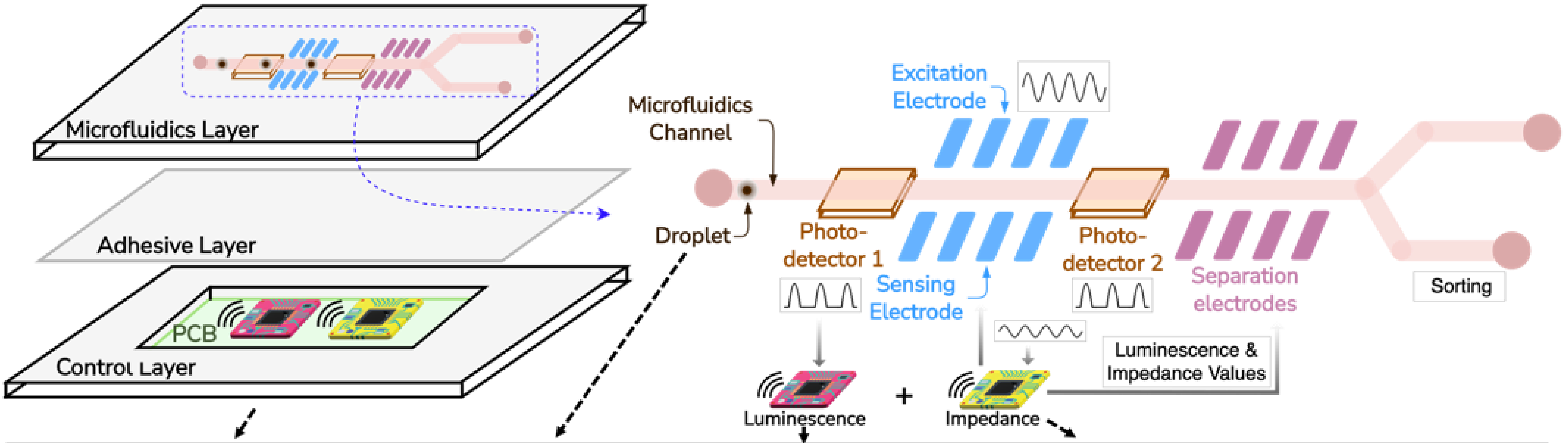


Figure courtesy of David McIntyre

Collaborator: Douglas Densmore – BU

Co-Design Approach
Droplet Microfluidics & Electronics for Biosensing



Microfluidic Device	Droplet Microfluidics	Luminescence Detection	Impedance Spectroscopy
✓ rapid-prototyped ✓ low-cost & modular ✓ conductive ink & polycarbonate	✓ real-time droplet detection in nL ✓ short residence time in ms-level	✓ high resolution (6.7 nA/count) ✓ weak light level detection from nL droplets (38.2 nL)	✓ low noise (2.4 pA_{rms} input-referred noise @ BW=1kHz) ✓ nL-volume droplet detection (4 nL)

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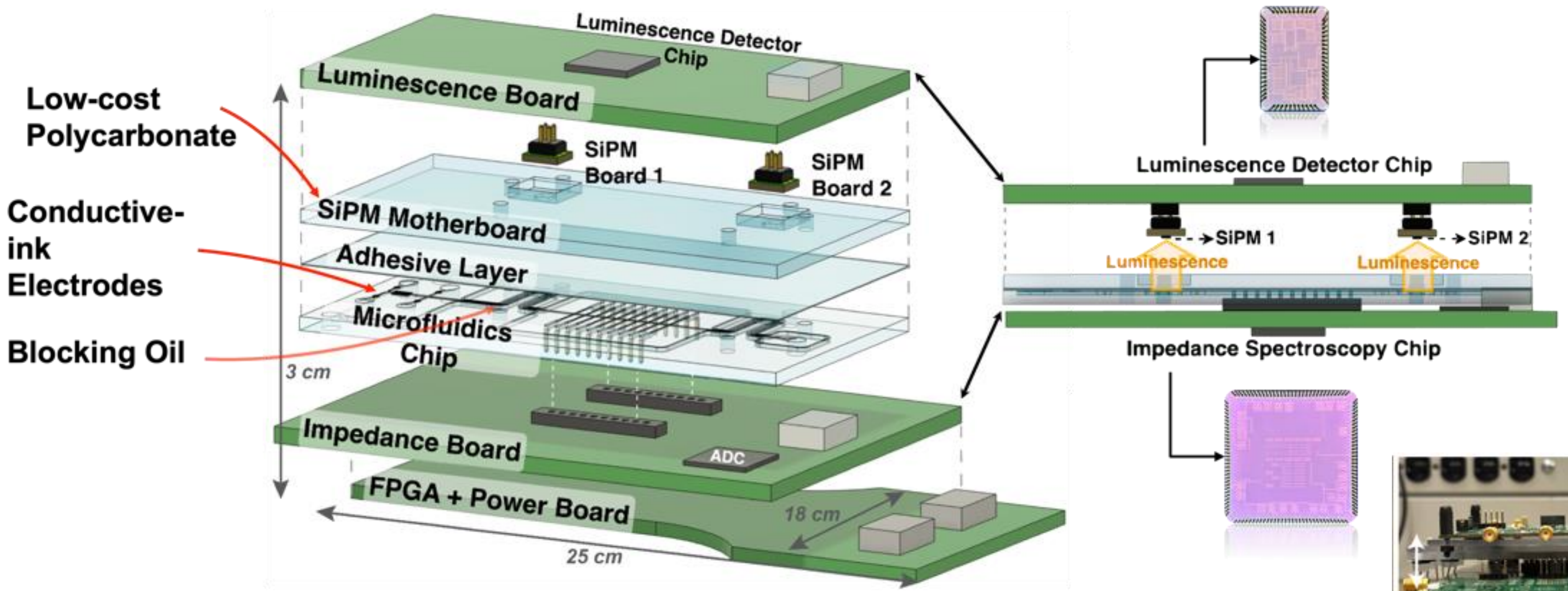

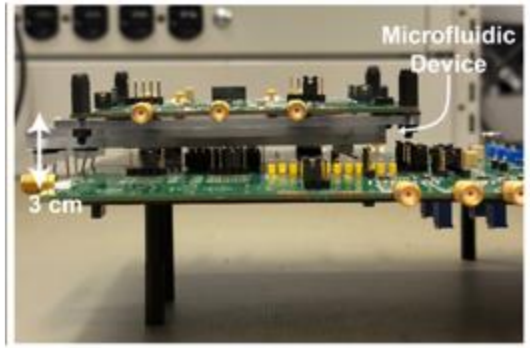

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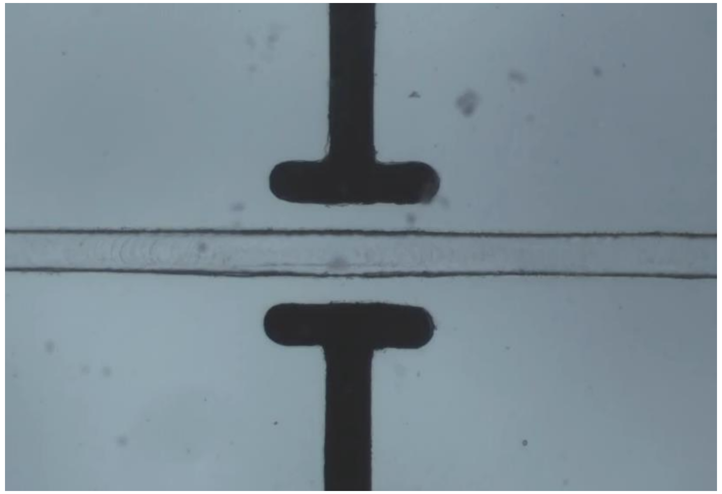
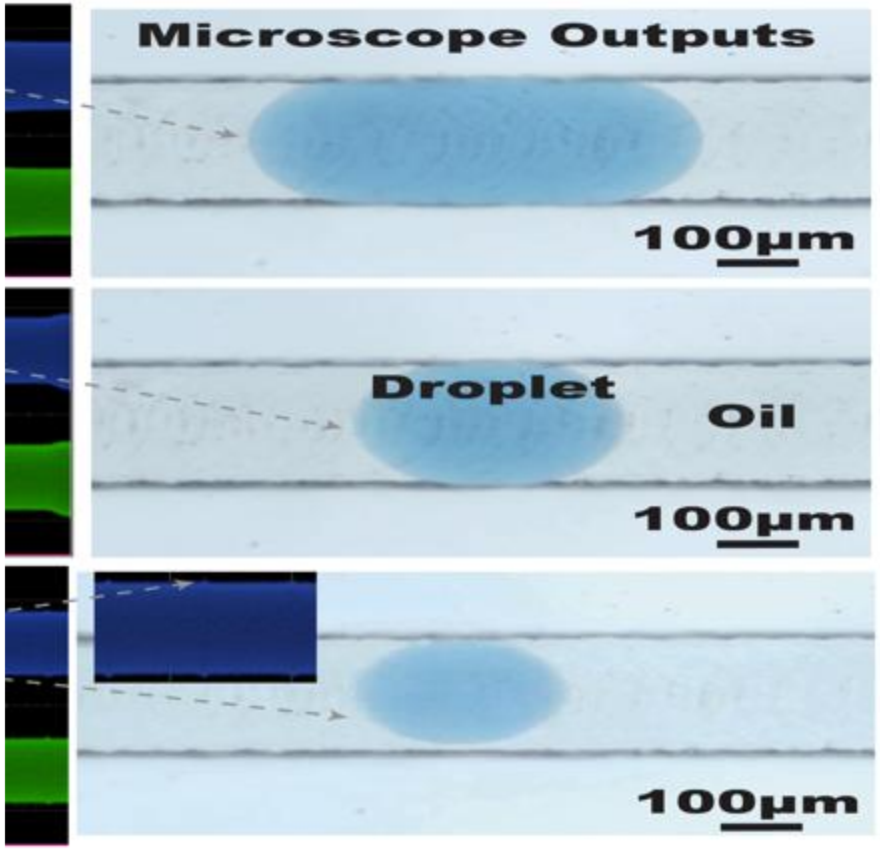
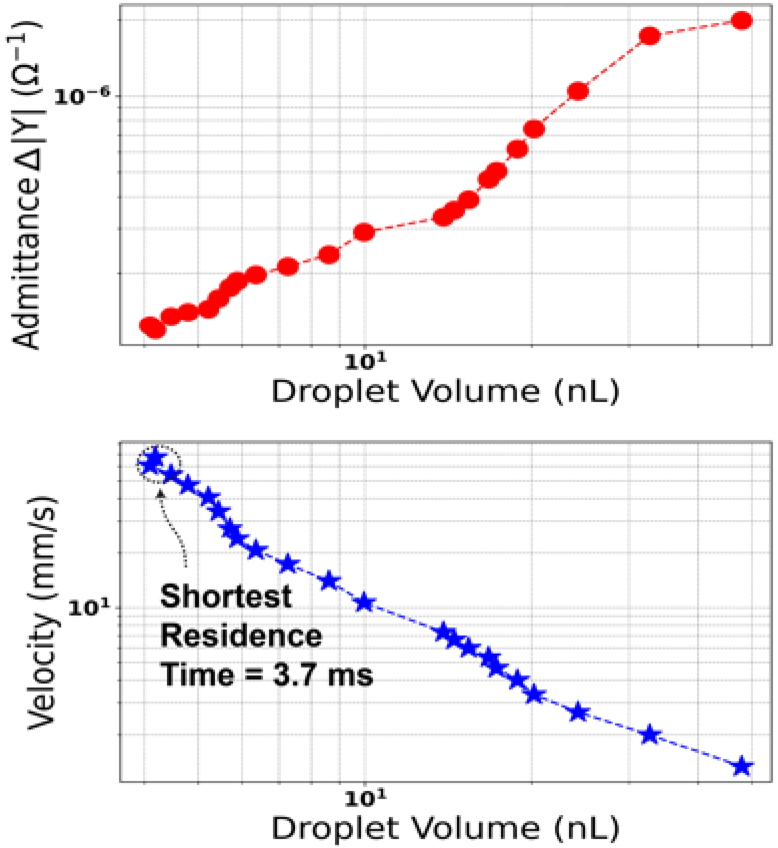
Real-time Droplet Detection via Impedance Spectroscopy







4 nL droplet with residence time of **3.7 ms**

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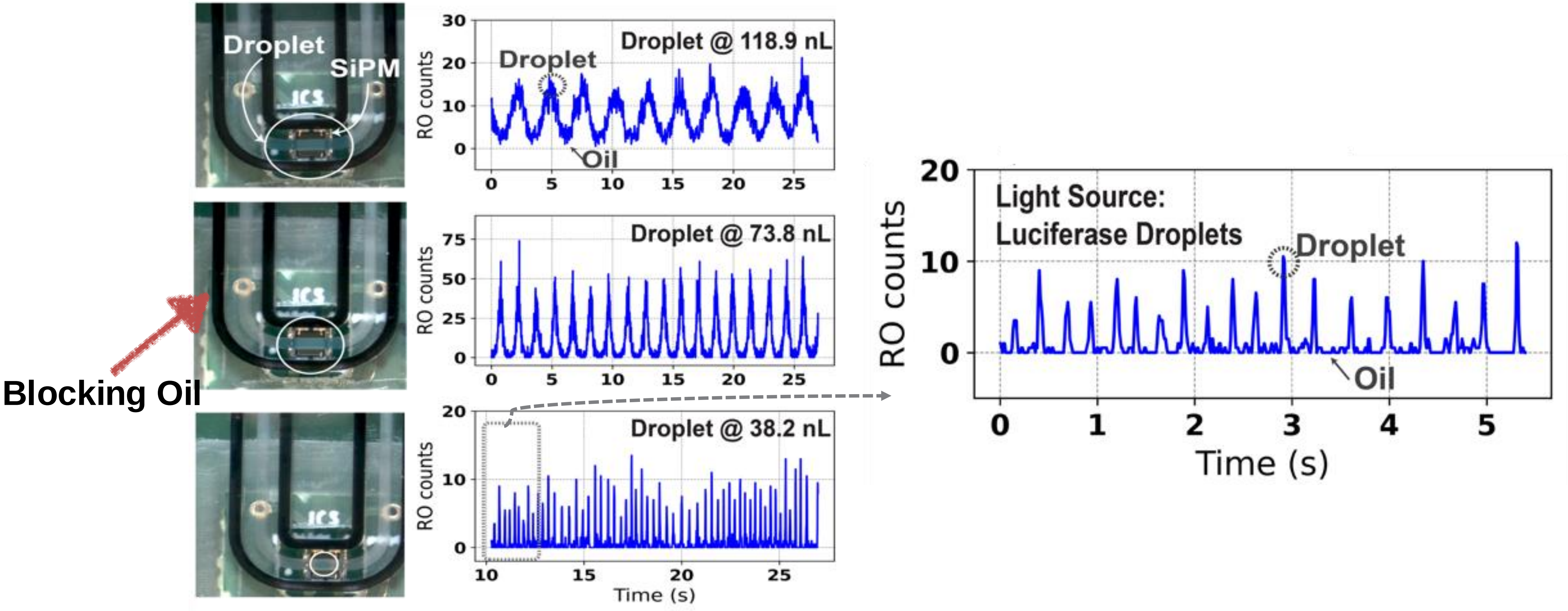
Real-time Luminescence Droplet Detection



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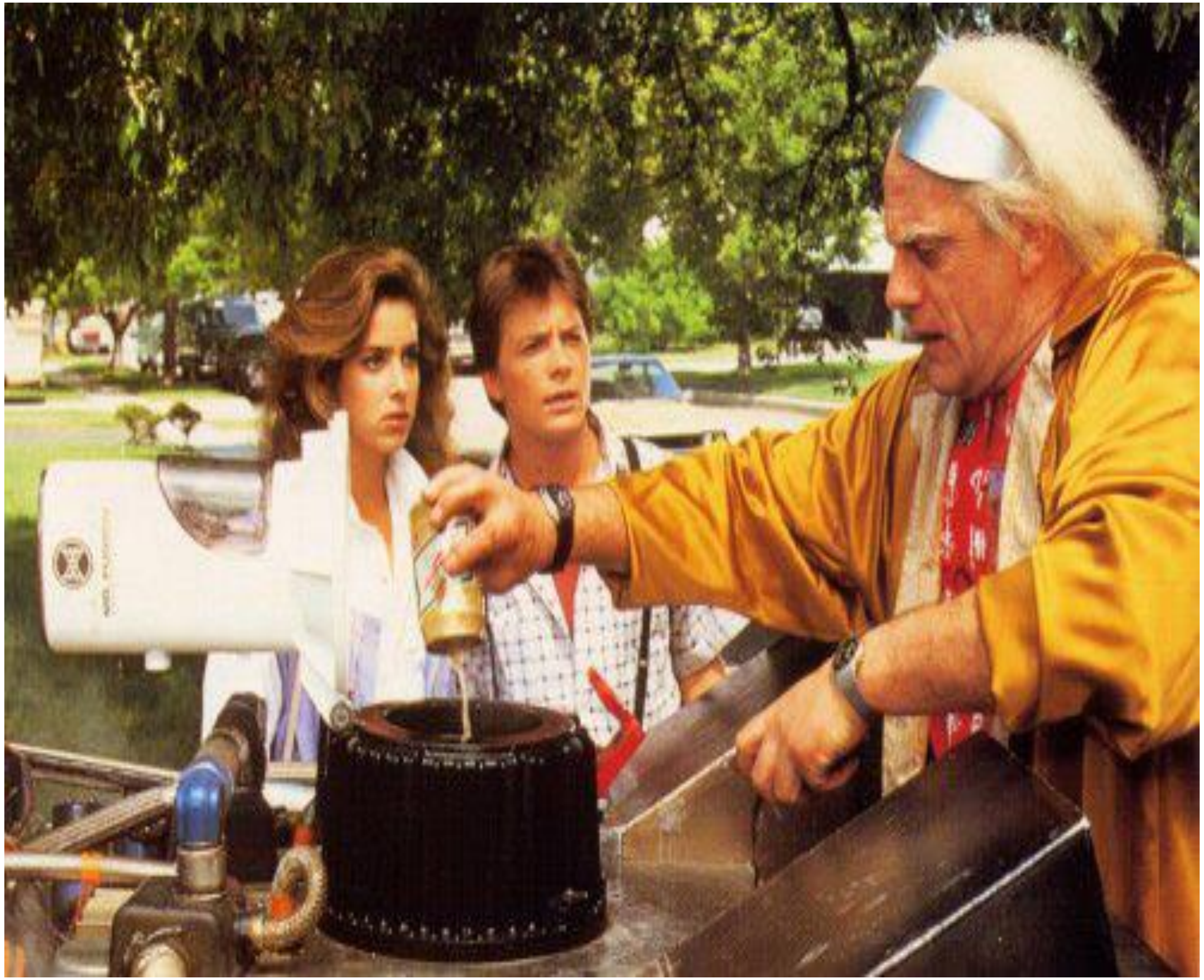
Taking in the Waste: Bioreactor Innovation



PI & Co-PIs: Andrew Magyar - Capra BioSciences, Rabia Yazicigil - Boston University (BU), Douglas Densmore - BU DAMP Lab, Ahmad (Mo) Khalil – BU, Next Rung

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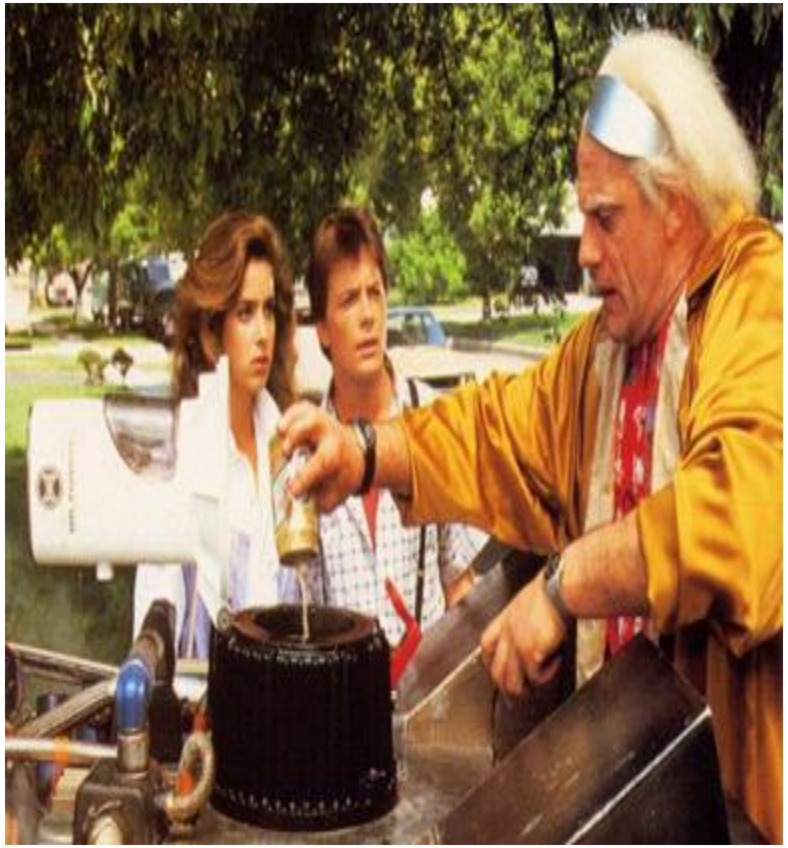


Traditional Bioreactor Monitoring

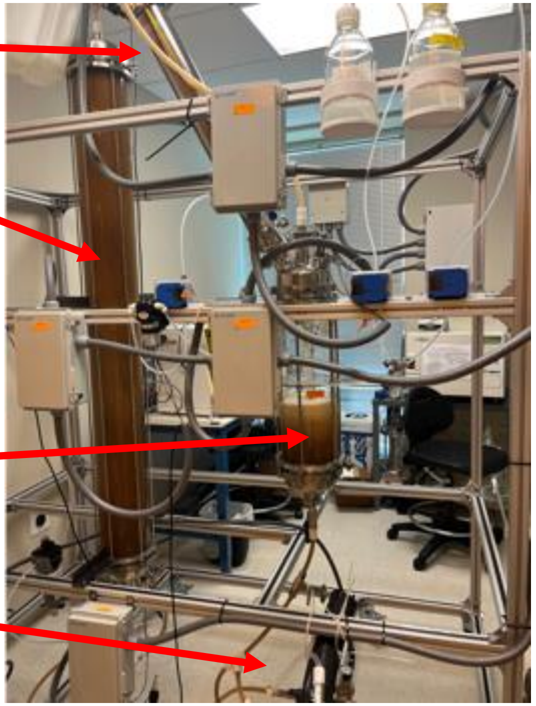
Oxygen, **$359**

Feedstock, **$20,000 - $200,000**

Optical cell density, **$1000**

Product, **$20,000 - $200,000**

pH, Temp, **$457**

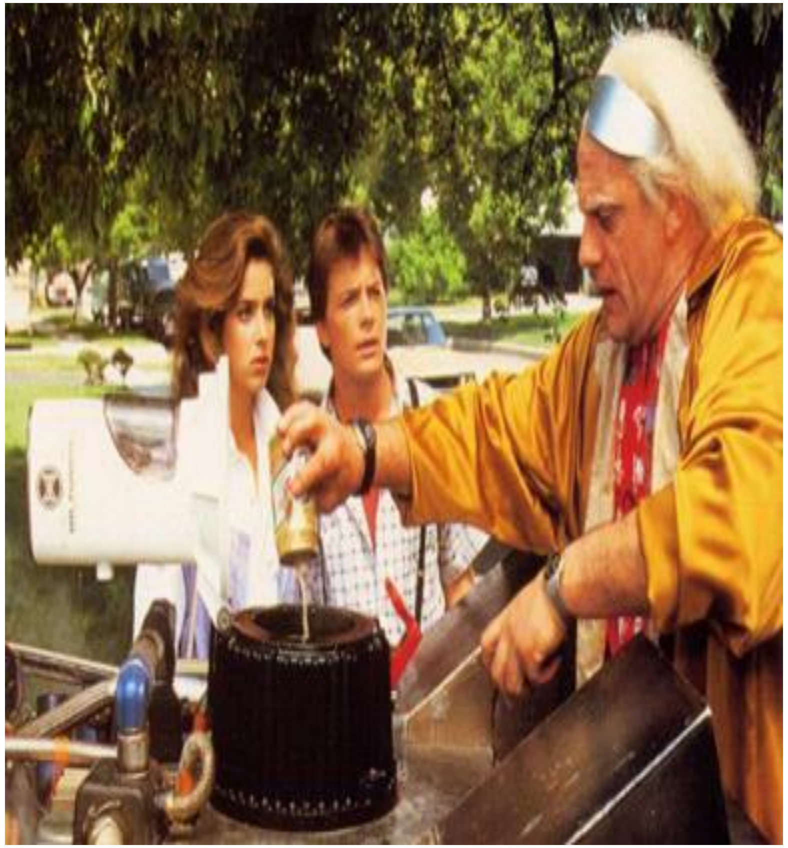


- Large form factor, wired connection
- Offline data processing
- Contamination risk
- Limited spatial coverage
- Unsecured

Collaborators: Tao Yu, Lei Poo, and Benoit Dufort – ADI, Andrew Magyar - Capra BioSciences, Douglas Densmore - BU DAMP Lab, Ahmad (Mo) Khalil – BU, Next Rung

Taking in the Waste:

Bioreactor Innovation



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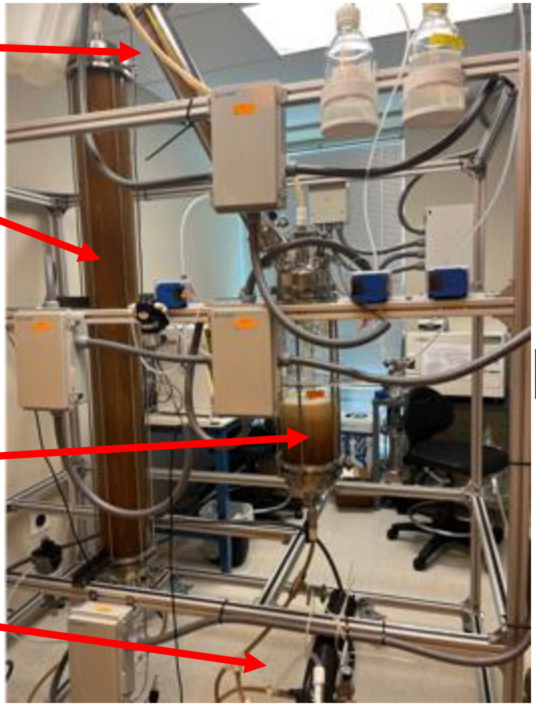

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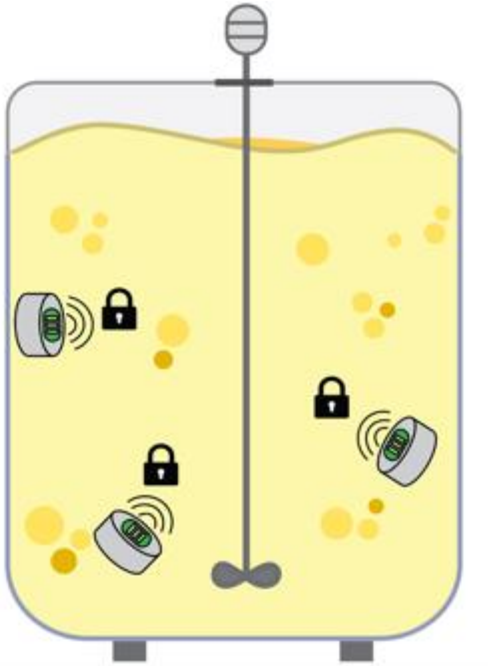
Proposed Secure, Wireless Floating Sensors for Bioreactor

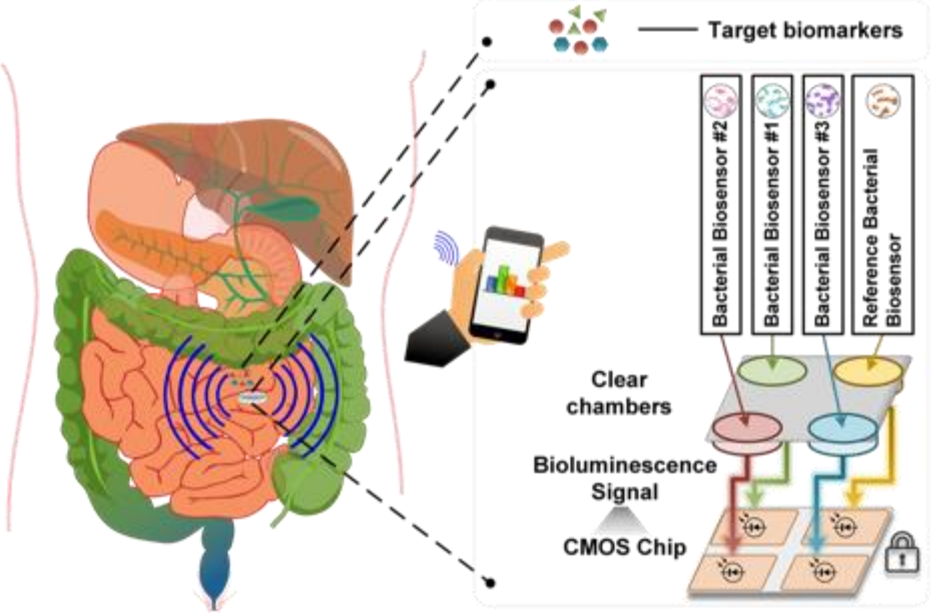


- Low cost (<$10)
- Real-time monitoring
- Miniaturized form factor
- Wide spatial coverage
- Embedded security

Collaborators: Tao Yu, Lei Poo, and Benoit Dufort – ADI, Andrew Magyar - Capra BioSciences, Douglas Densmore - BU DAMP Lab, Ahmad (Mo) Khalil – BU, Next Rung

Cyber-Secure Biological Systems / All-in-One Data Decoders

Ingestible Bioengineered Capsule



Co-Design of Microfluidics & Custom Electronics for CSBS

Universal Decoder - GRAND

Cyber-Secure Biological Systems / All-in-One Data Decoders

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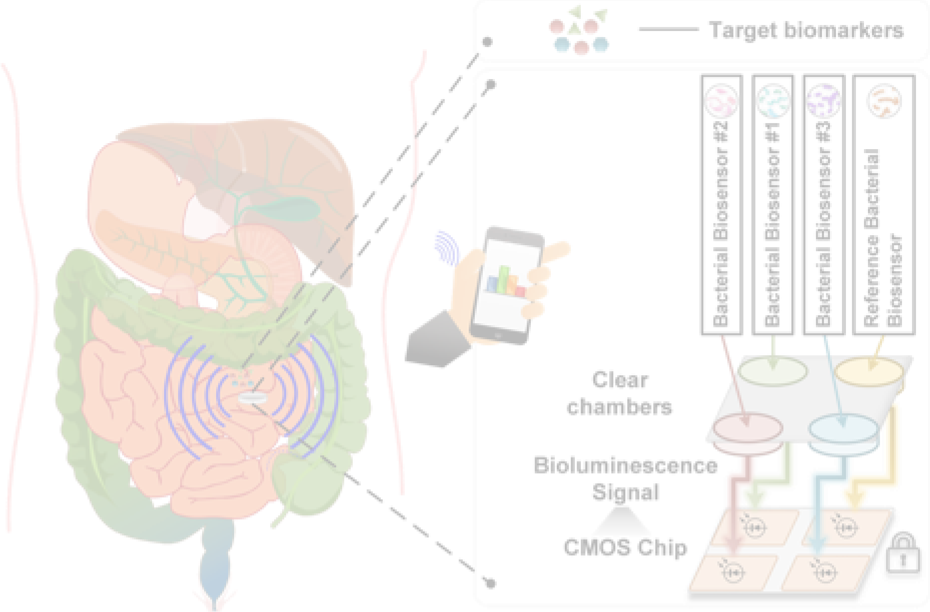


Co-Design of Microfluidics & Custom Electronics for CSBS

Universal Decoder - GRAND

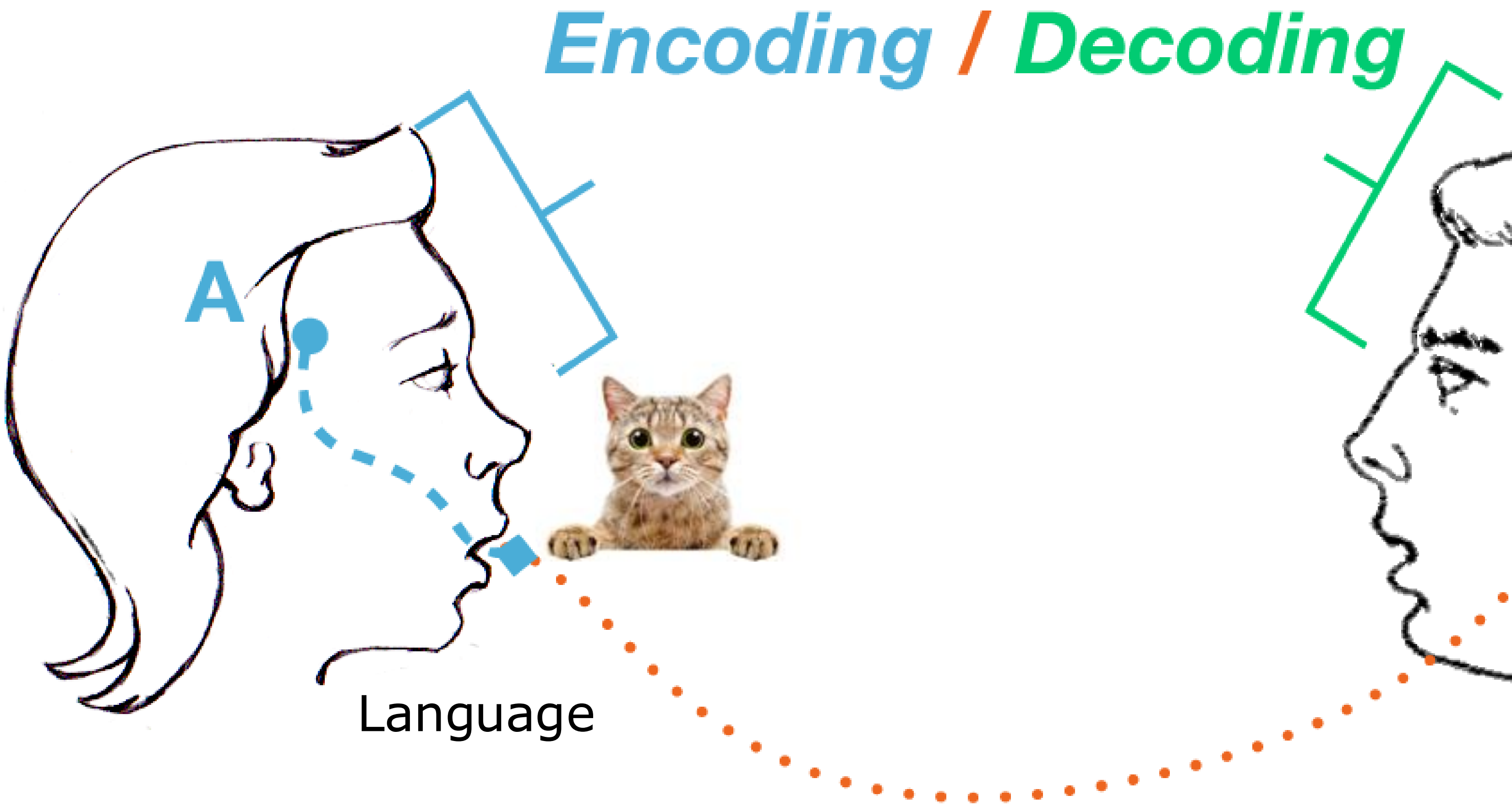
Decode **ANY** code with

GRAND

granddecoder.mit.edu

Partially supported by Battelle grant and Science Foundation Ireland.

Encoding / Decoding



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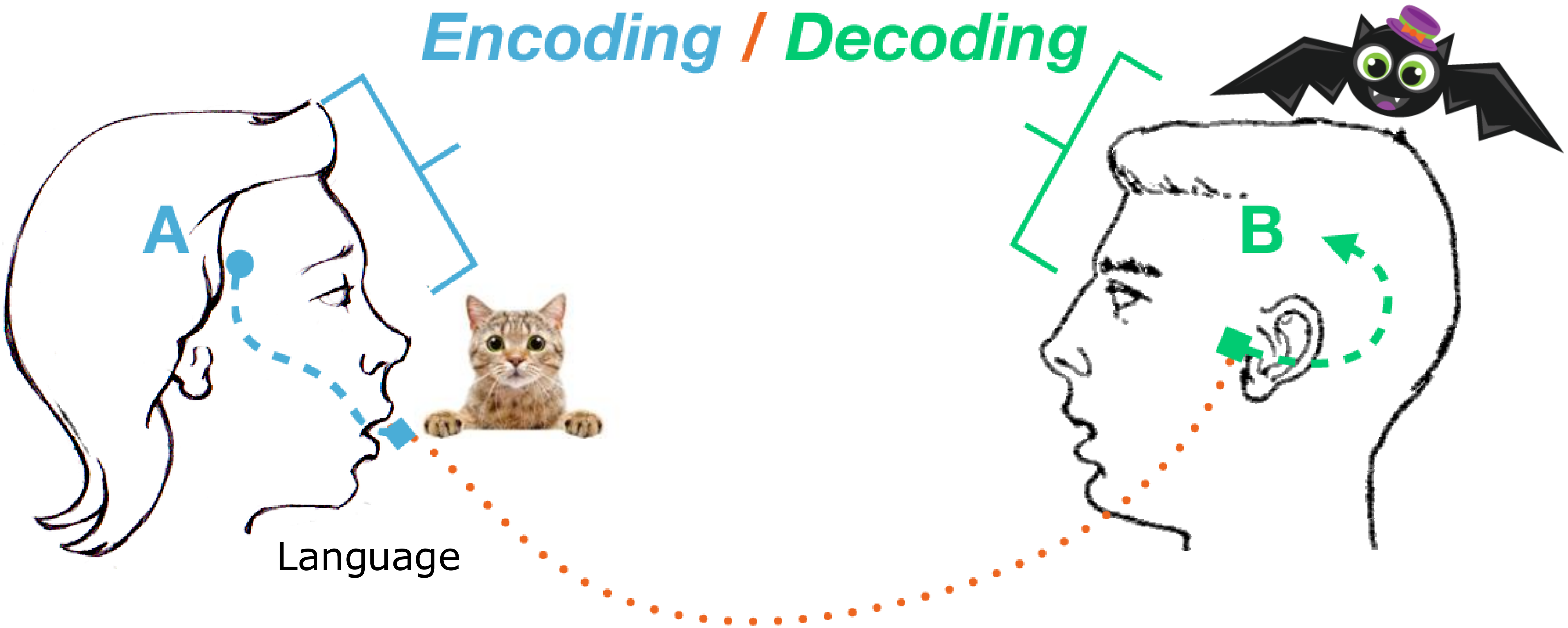

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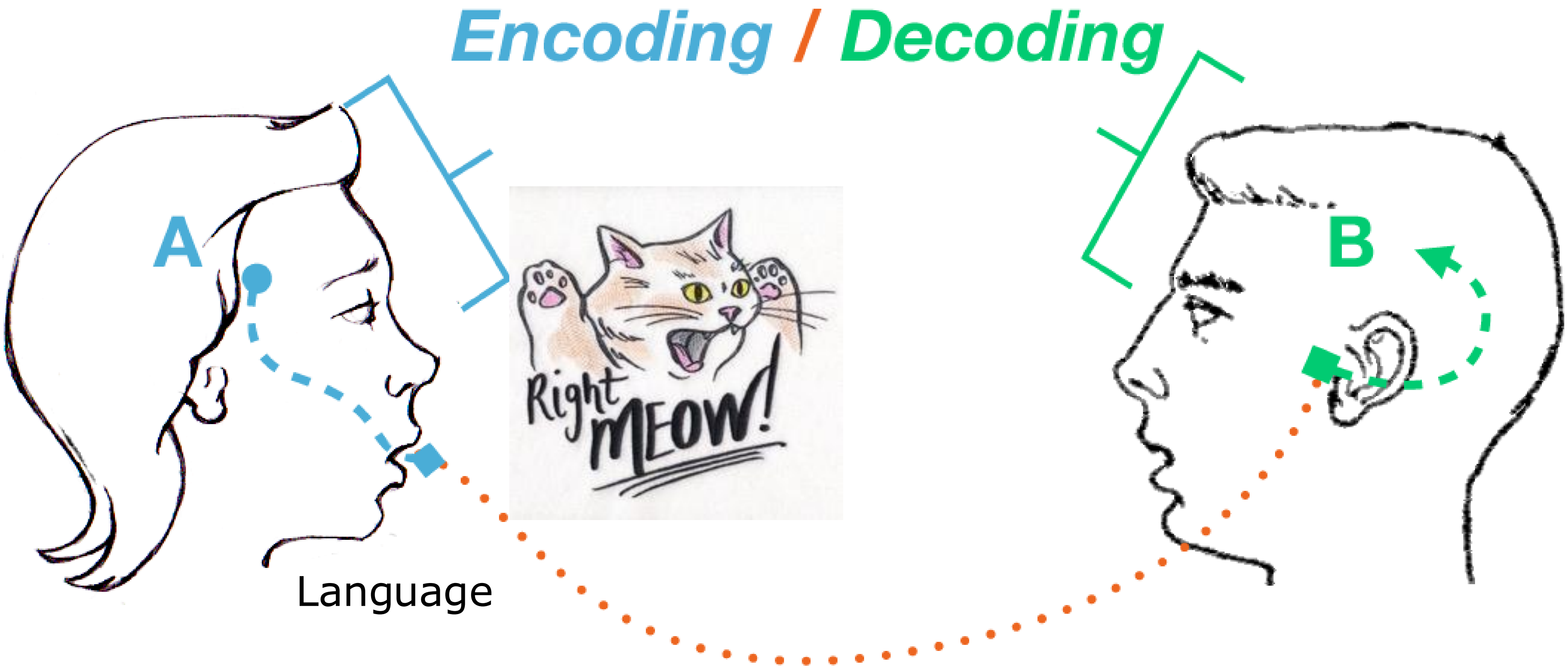

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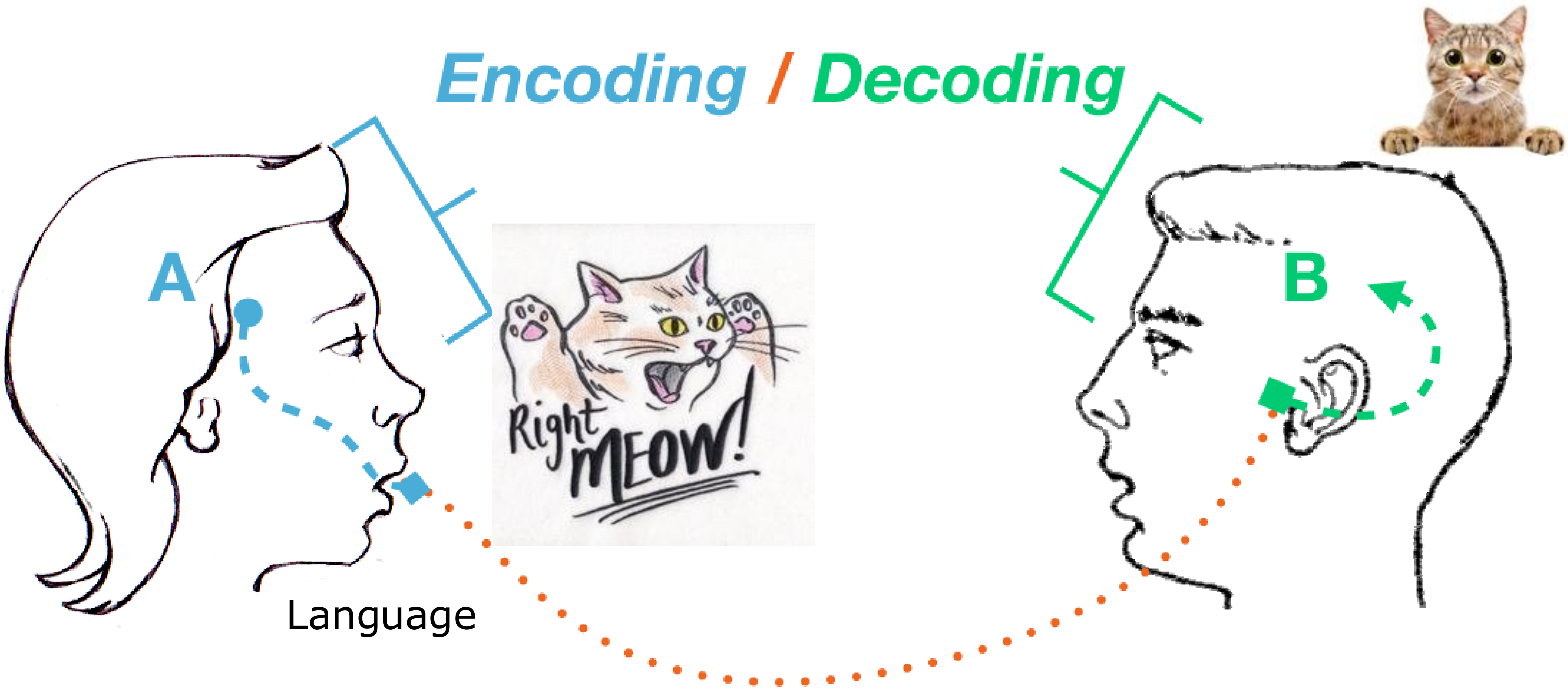
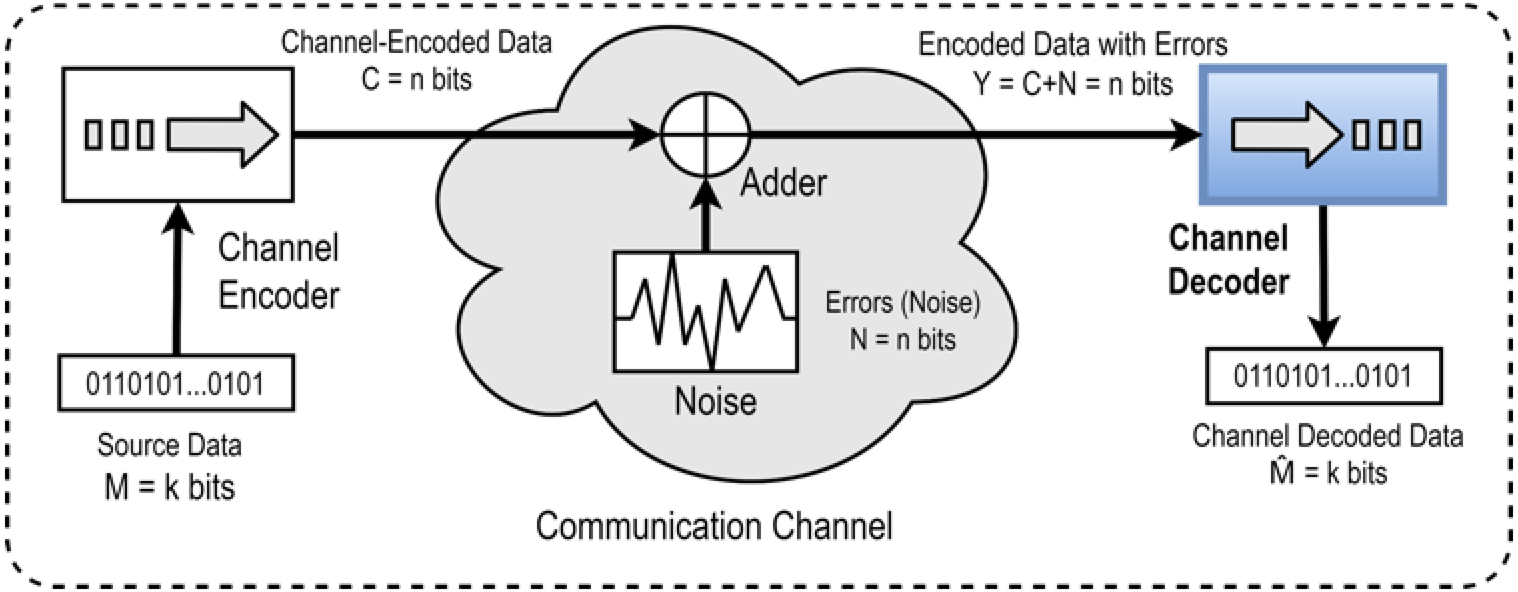


Channel Encoding / Decoding



Standard Paradigm:
Co-Design of Restricted Code / Decoder Pairs

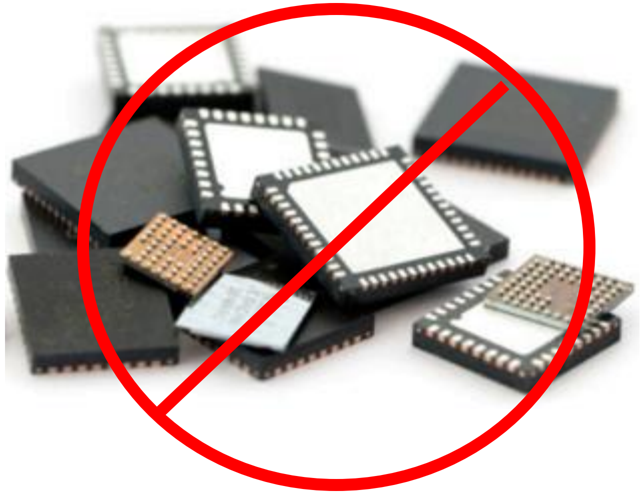
- Distinct chip required to decode each code (code-specific decoders)
- Requires standardization

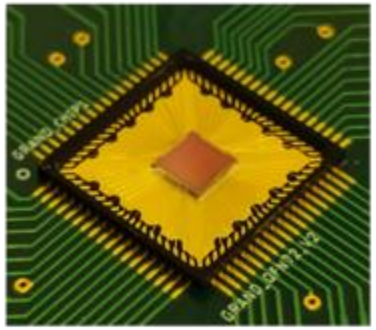
Error Detection Only ←	CRC
Majority Logic ←	RM
Berlekamp-Massey ←	BCH
CA-SCL ←	CA-Polar
No decoder ←	RLC

5G

LDPC – 1960s
CA-Polar – 2010s

Universal Decoding of Any Code: GRAND





Error Detection Only ←	CRC	→ GRAND
Majority Logic ←	RM	→ GRAND
Berlekamp-Massey ←	BCH	→ GRAND
CA-SCL ←	CA-Polar	→ GRAND
No decoder ←	RLC	→ GRAND

A. Riaz, et al., "A Sub-0.8pJ/b 16.3Gbps/mm^2 Universal Soft-Detection Decoder Using ORBGRAND in 40nm CMOS," **IEEE ISSCC**, 2023.
A. Riaz, et al., "Multi-Code Multi-Rate Universal Maximum Likelihood Decoder using GRAND," **IEEE ESSCIRC**, 2021.
K. R. Duffy, et al., "Capacity-Achieving Guessing Random Additive Noise Decoding," IEEE Trans. on Information Theory, 2019.

GRAND Algorithm

$$Y = X + E$$

Received Codeword

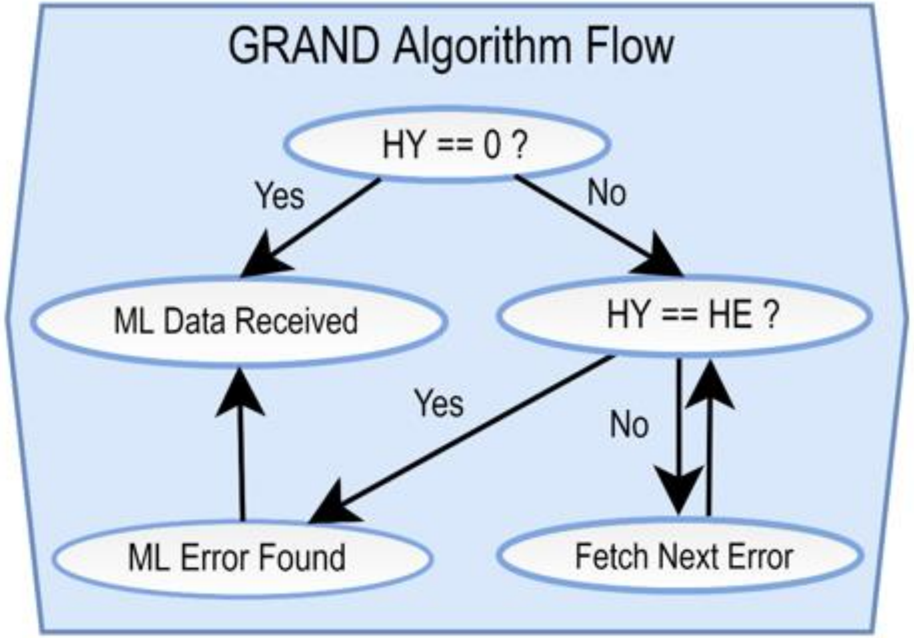
Transmitted Codeword

Effect of Noise

$$H.Y = \underset{0}{\cancel{H.X}} + H.E$$

Parity Matrix

$$H.Y = H.E$$



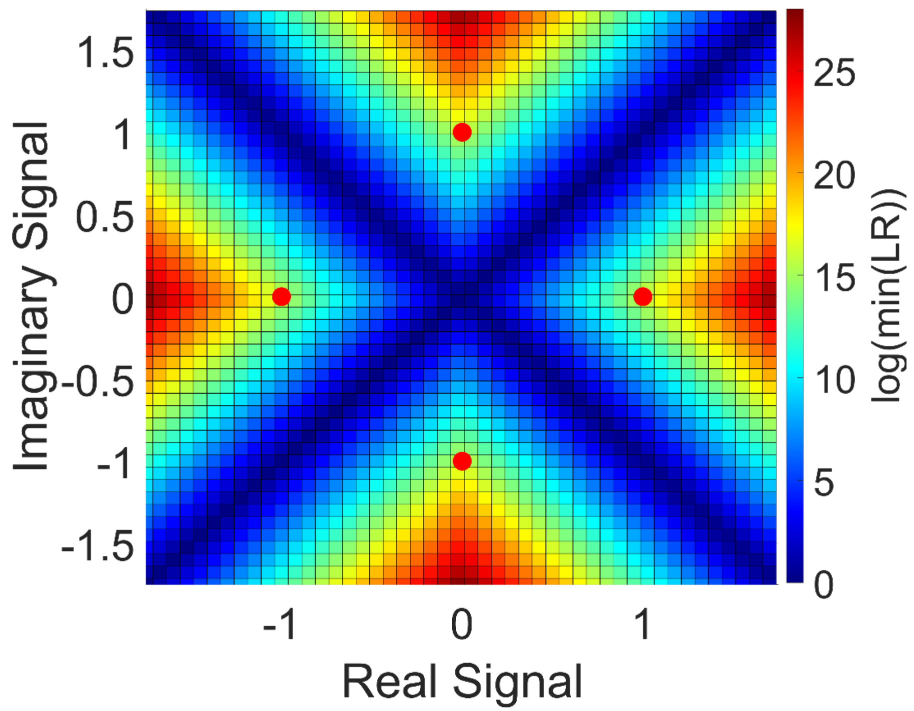
*ML: Maximum Likelihood
*H: Parity-Check Matrix

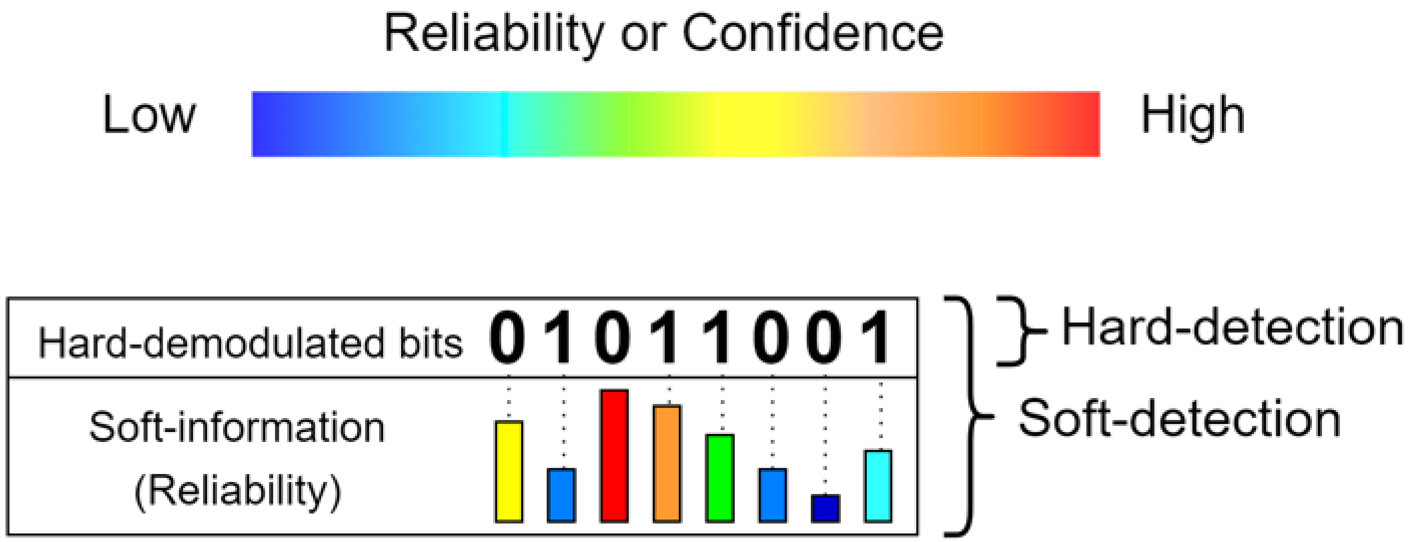
- Conventional decoders identify X from codebook structure
- GRAND directly determines effect of noise E

K. R. Duffy, et al., "Capacity-Achieving Guessing Random Additive Noise Decoding," IEEE Trans. on Information Theory, 2019.

Universal Soft-Detection Decoder Architecture Using ORBGRAND

Soft-Detection Channel

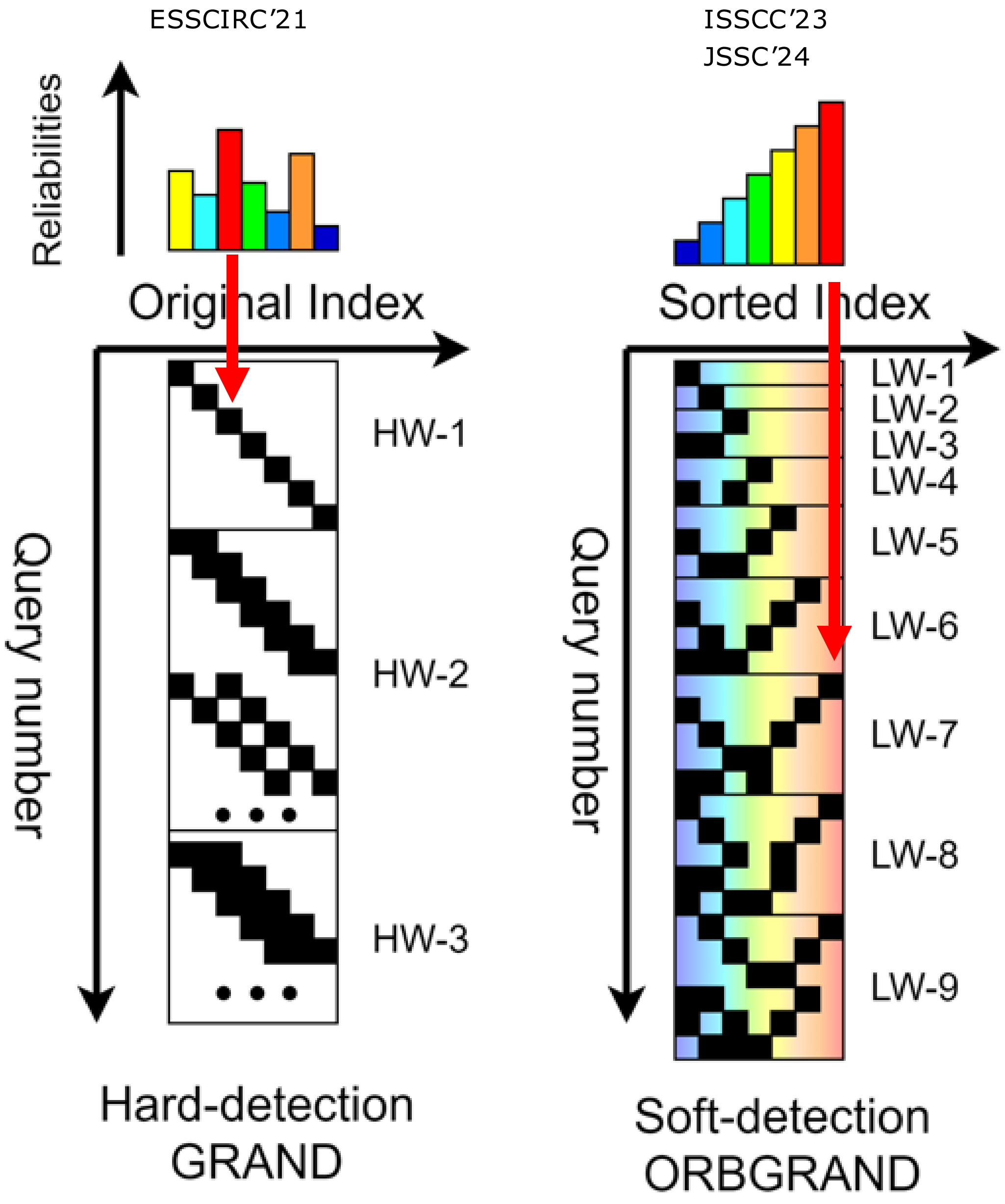




- Soft-detection:
  - Additional soft information for each received bit
  - Indicates reliability in demodulation
  - ~2-3 dB gain in decoding

Logistic Weight

- Hard-detection
  - No sorting required
  - Increasing HW order
  - Same HW equally likely
- Soft-detection
  - Sort reliability
  - Increasing LW order
  - Same LW equally likely



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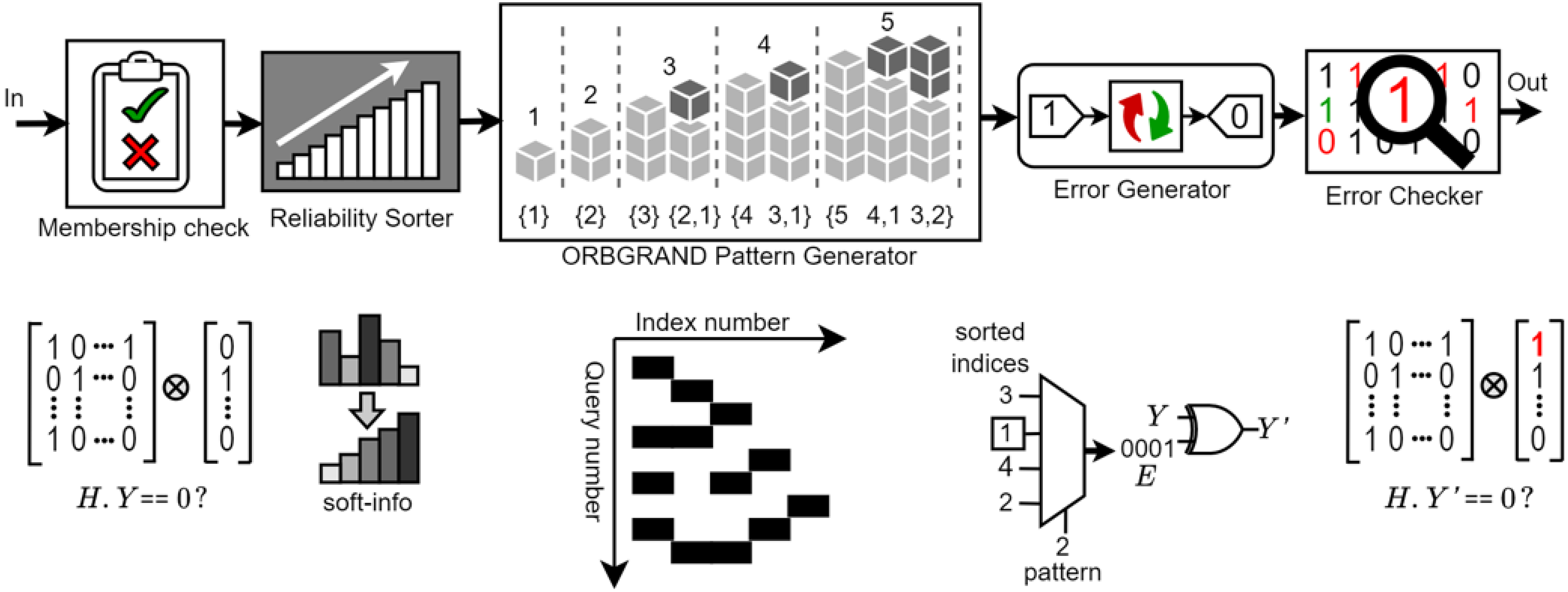
A. Riaz, et al., "A Sub-0.8-pJ/bit Universal Soft-Detection Decoder Using ORBGRAND," IEEE JSSC, 2024.

Universal Soft-Detection Decoder ORBGRAND



K. R. Duffy, et al., "Ordered Reliability Bits Guessing Random Additive Noise Decoding," IEEE TSP, 2022.
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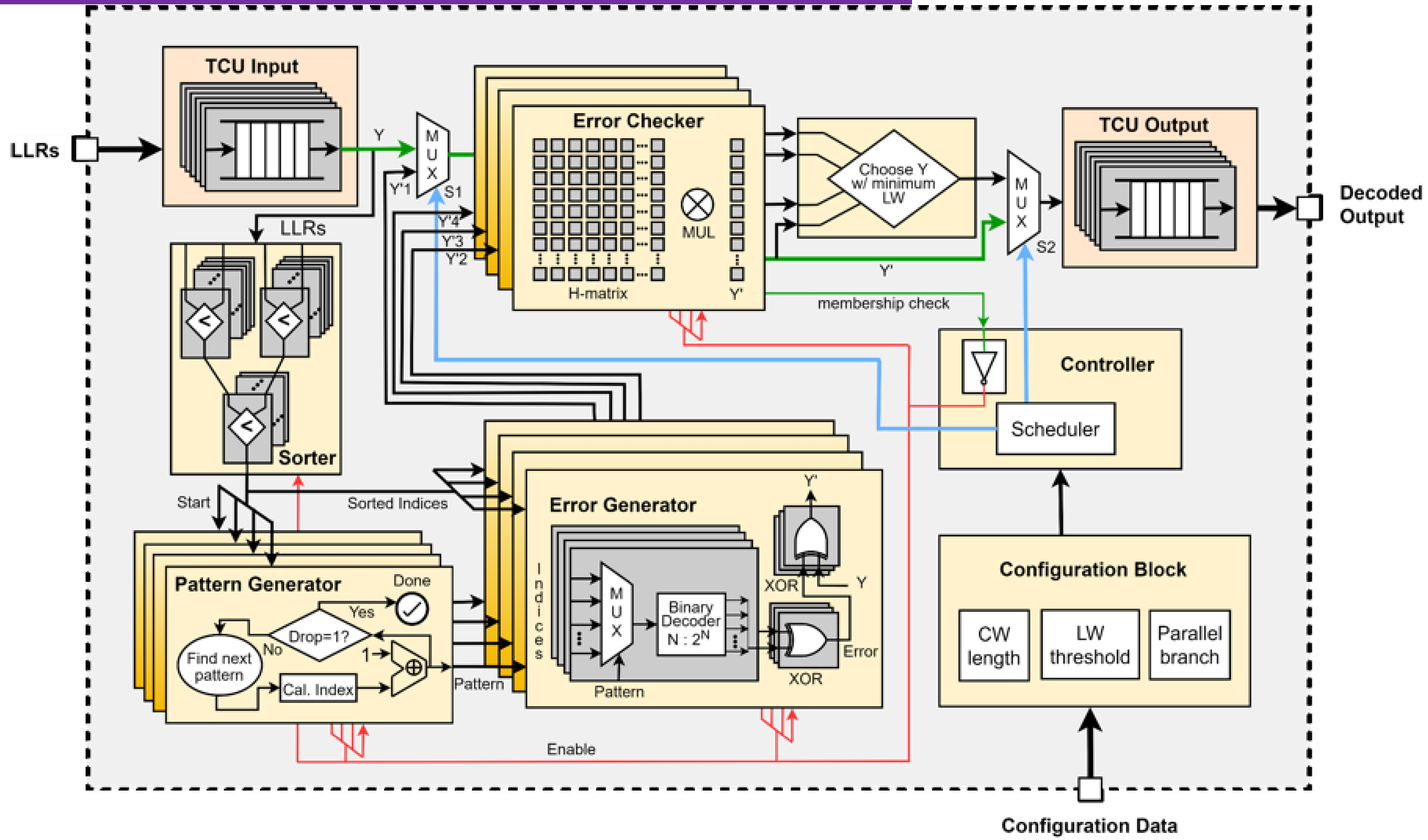
A. Riaz, et al., "A Sub-0.8-pJ/bit Universal Soft-Detection Decoder Using ORBGRAND," IEEE JSSC, 2024.

ORBGRAND Architecture



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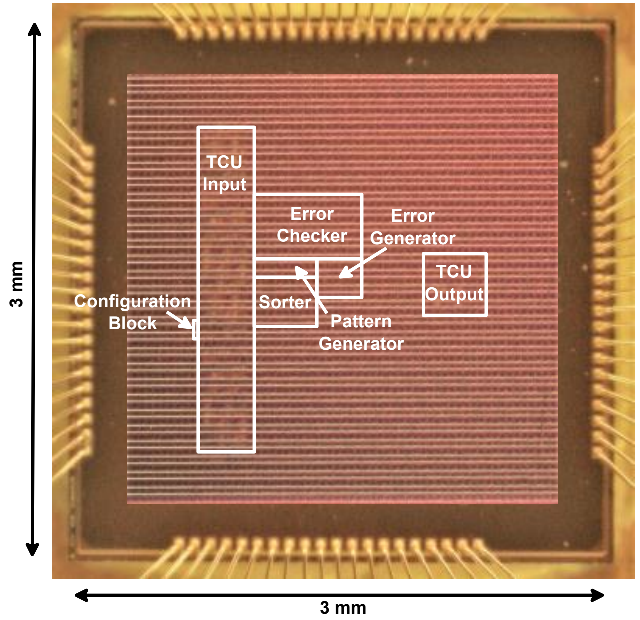
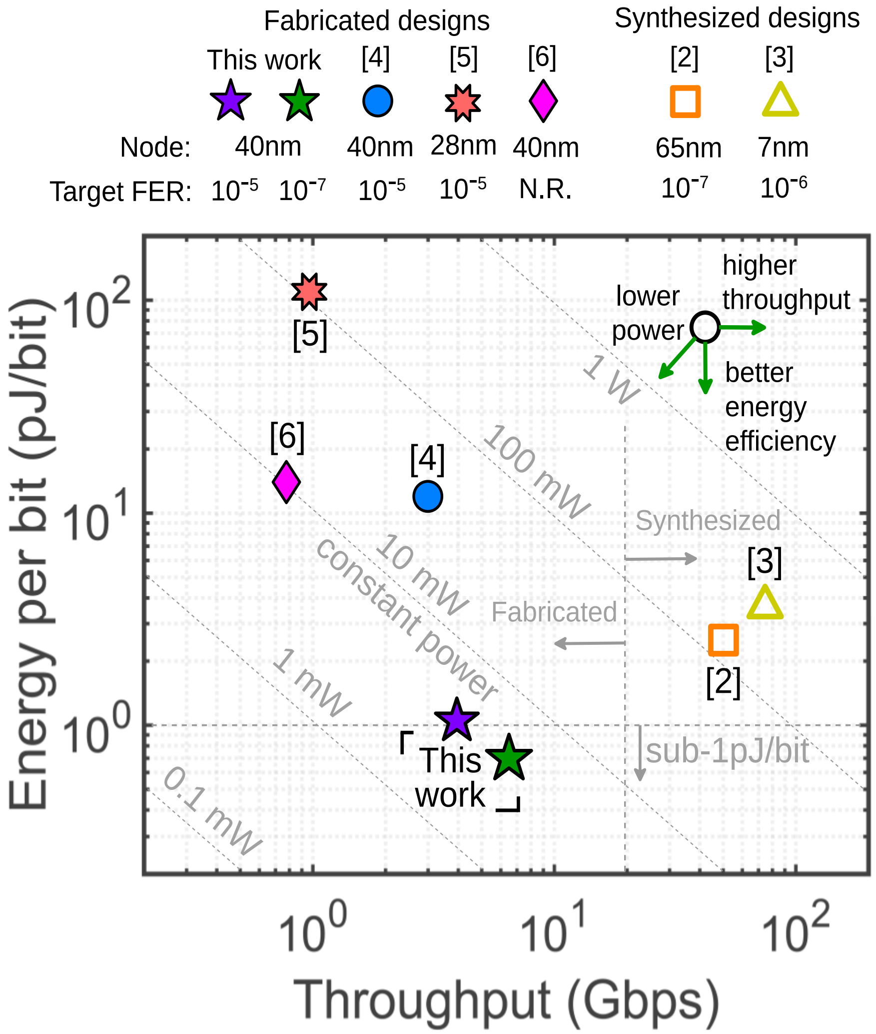
A. Riaz, et al., "A Sub-0.8-pJ/bit Universal Soft-Detection Decoder Using ORBGRAND," IEEE JSSC, 2024.

A Sub-0.8 pJ/bit Universal Soft-detection Decoder

- **Lowest** energy per bit: Sub-0.8 pJ/bit
- **Universal** soft-detection decoder: CA-Polar, CRC
- Area efficiency: 16.3 Gb/s/mm²
- **Ultra-low** power: 4.9mW
- **Configurable** code length/rate support





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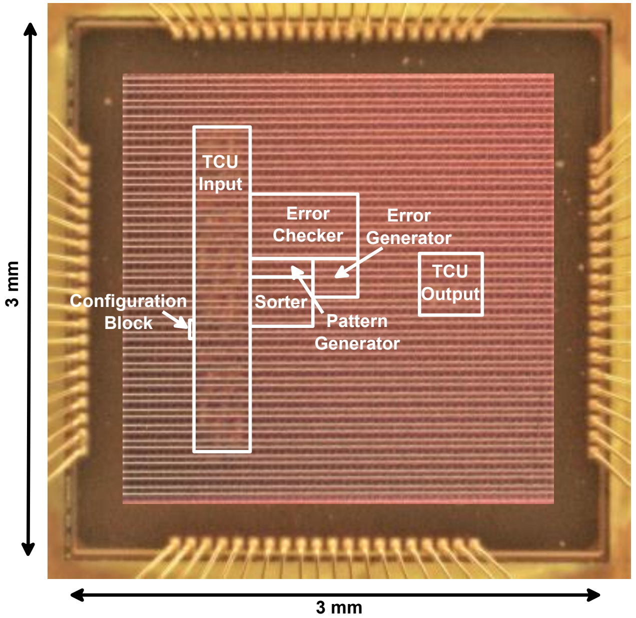

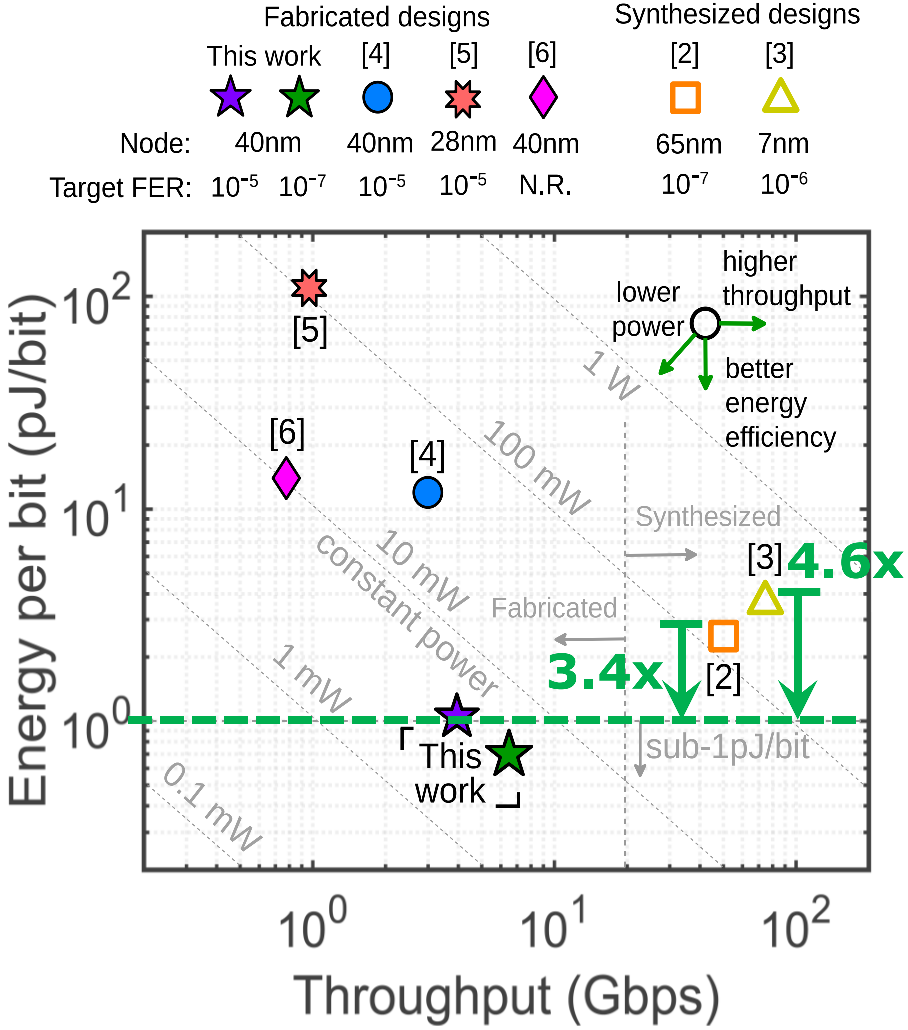

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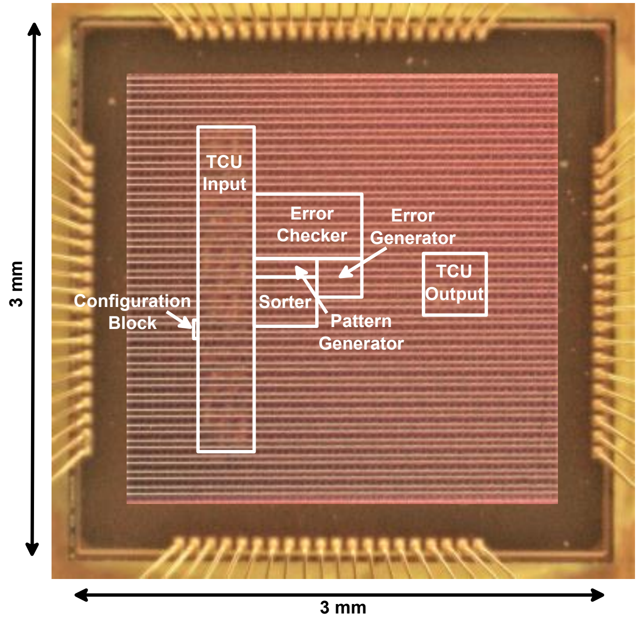

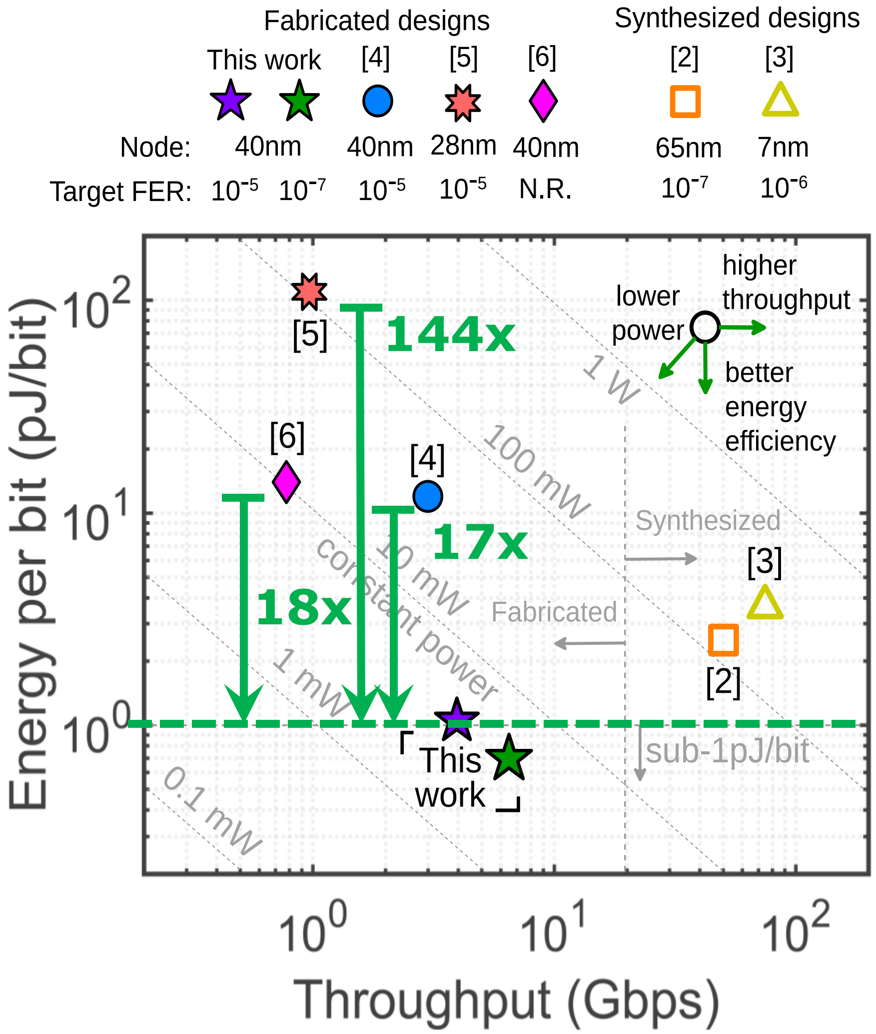

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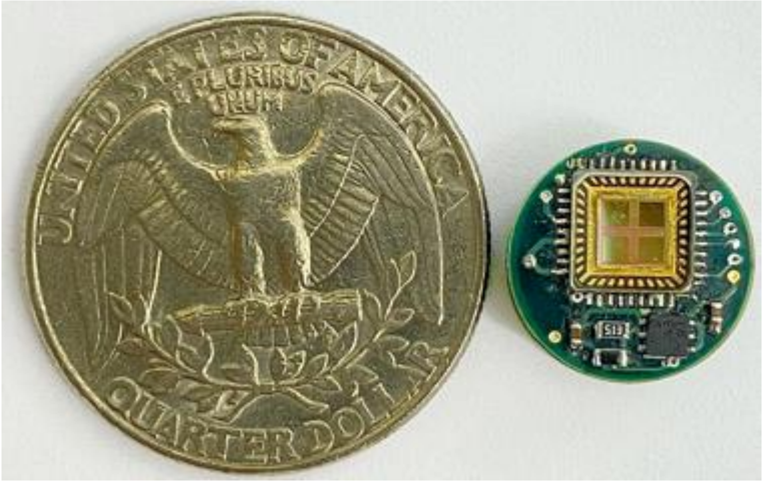
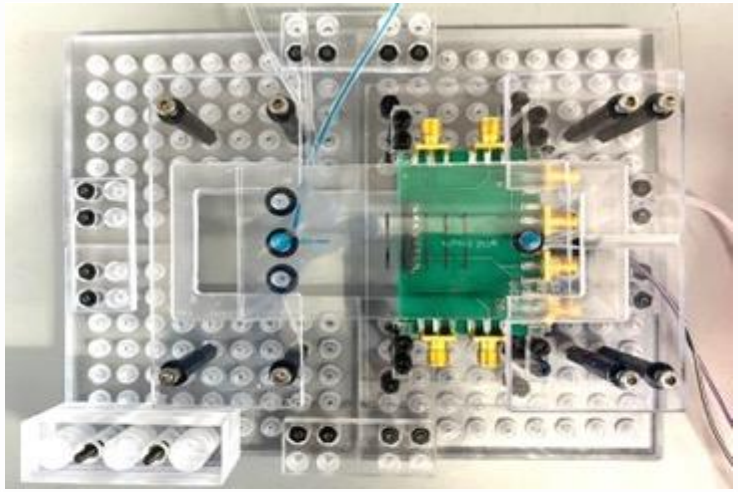
Conclusions
Revisiting WISE-Circuits Research Areas

Cyber-Secure Biological Systems

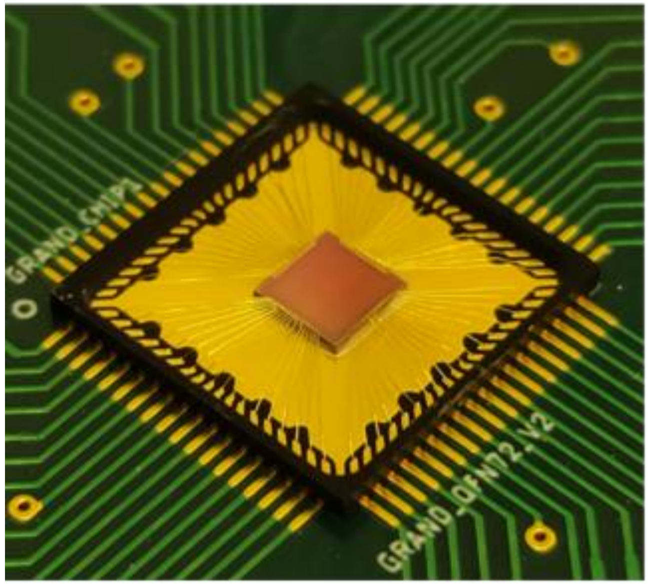


ISSCC SRP’21, CICC’21, BioCAS’22
JSSC’23, **Nature’23**



ISSCC SRP’23 **Best Poster Award**
ISSCC’24, TBioCAS’24

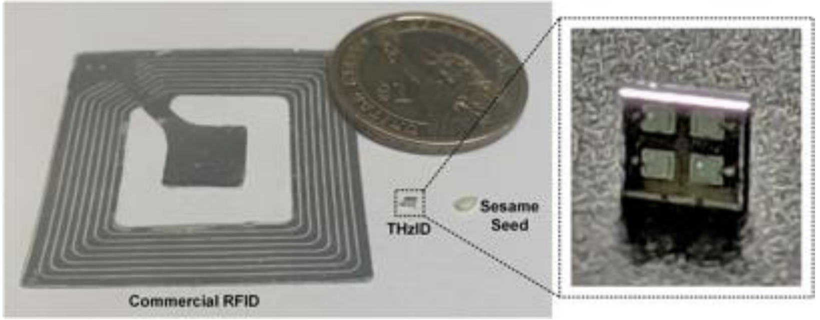
Universal Decoder - GRAND



ISSCC SRP’21, **ESSCIRC’21**, Globecom’21
5G WF’21, **ICC’22**, FNWF’22, **ICC’23**
WoWMOM’23, ISIT’23, **ISSCC’23, JSSC’24**
COMSNETS’23 **Best Demo Award**
COMSNETS’22 **Best Research Demo Award**

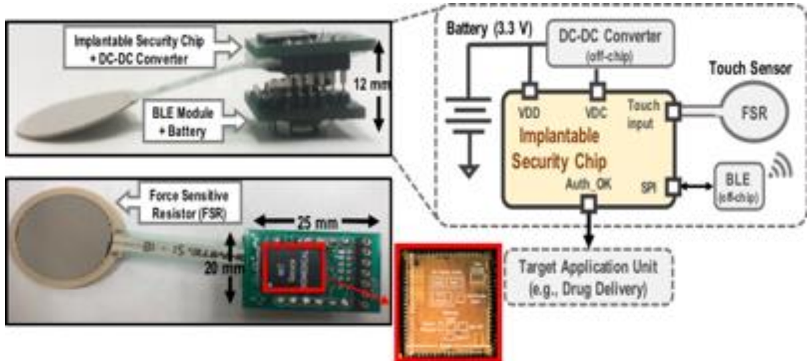
Conclusions
Revisiting WISE-Circuits Research Areas

Secure Package-Less THz ID



ISSCC’20, JSSC’21, SSCM’20, OJ-SSCS’23

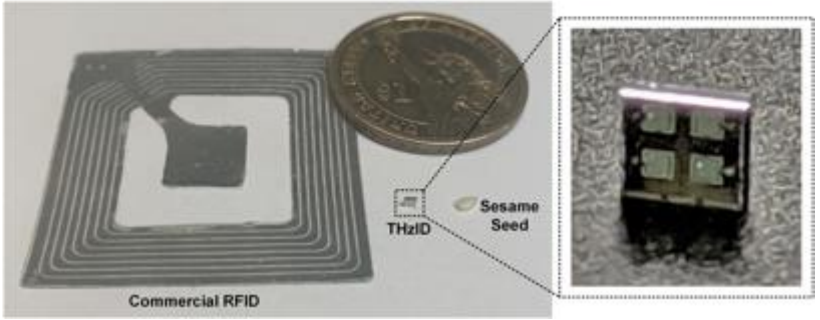
Secure Drug Delivery



CICC’20, SSCM’20, CBMS’21, OJ-SSCS’23

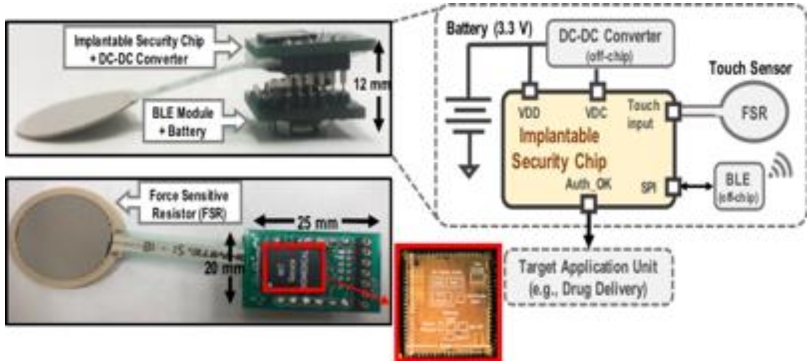
Conclusions
Revisiting WISE-Circuits Research Areas

Secure Package-Less THz ID



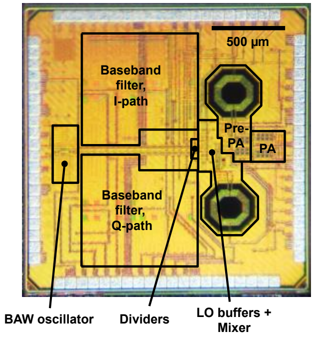
ISSCC'20, JSSC'21, SSCM'20, OJ-SSCS'23

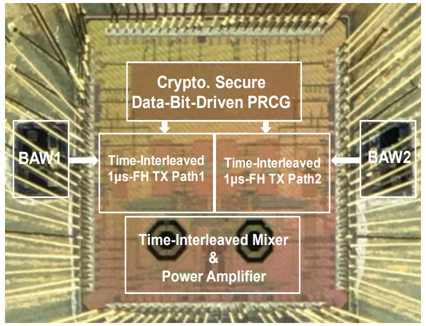
Secure Drug Delivery



CICC'20, SSCM'20, CBMS'21, OJ-SSCS'23

Secure Wireless Communications

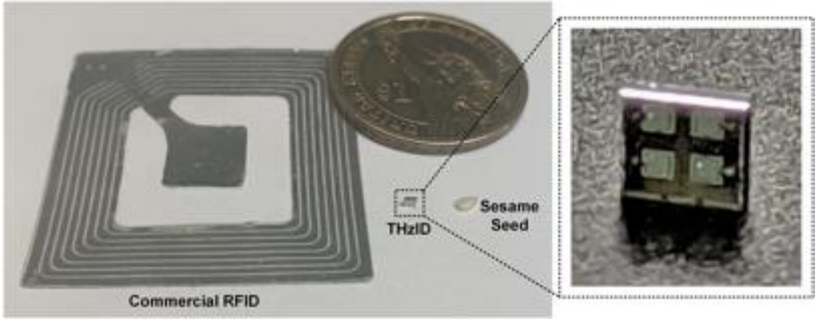




ESSCIRC'17, RFIC'18, SSCM'20, OJ-SSCS'23

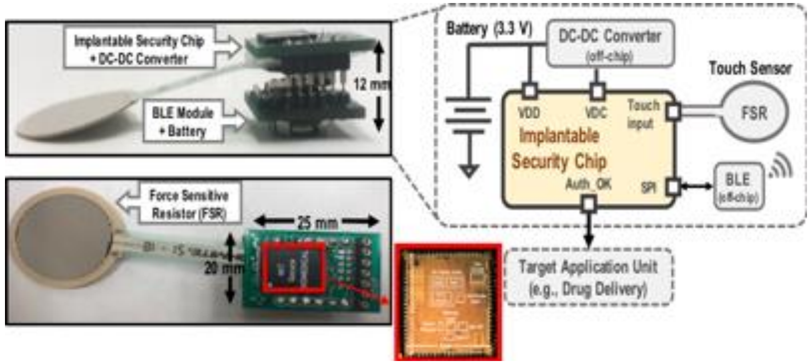
Conclusions
Revisiting WISE-Circuits Research Areas

Secure Package-Less THz ID



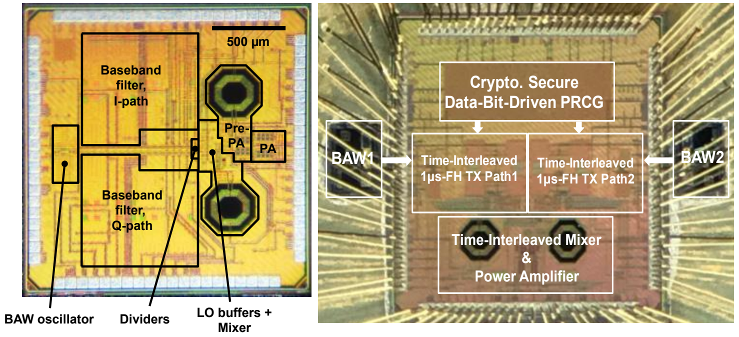
ISSCC’20, JSSC’21, SSCM’20, OJ-SSCS’23

Secure Drug Delivery



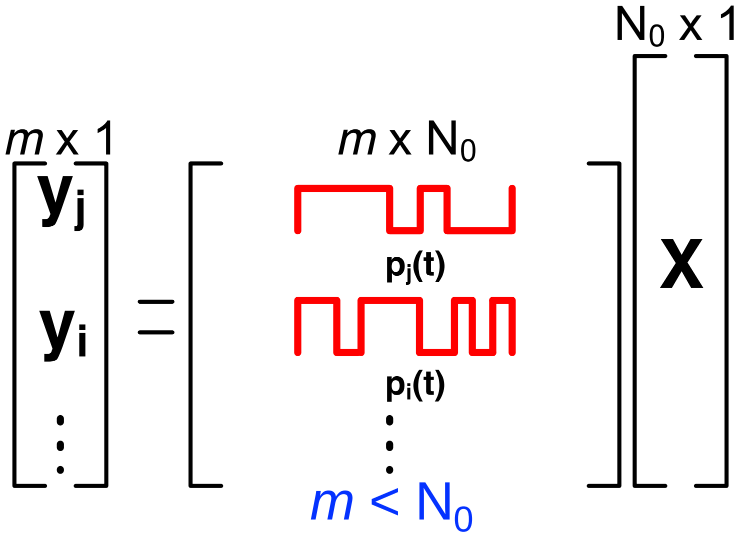
CICC’20, SSCM’20, CBMS’21, OJ-SSCS’23

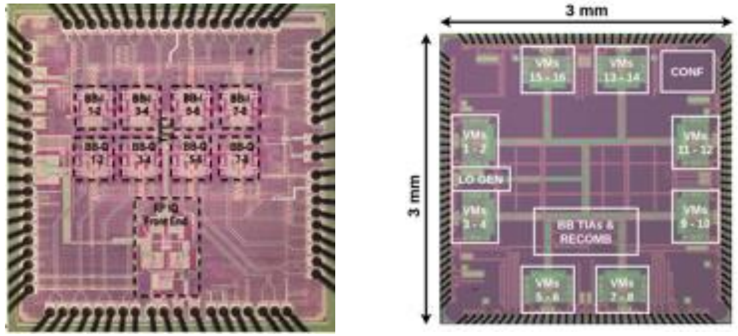
Secure Wireless Communications



ESSCIRC’17, RFIC’18, SSCM’20, OJ-SSCS’23

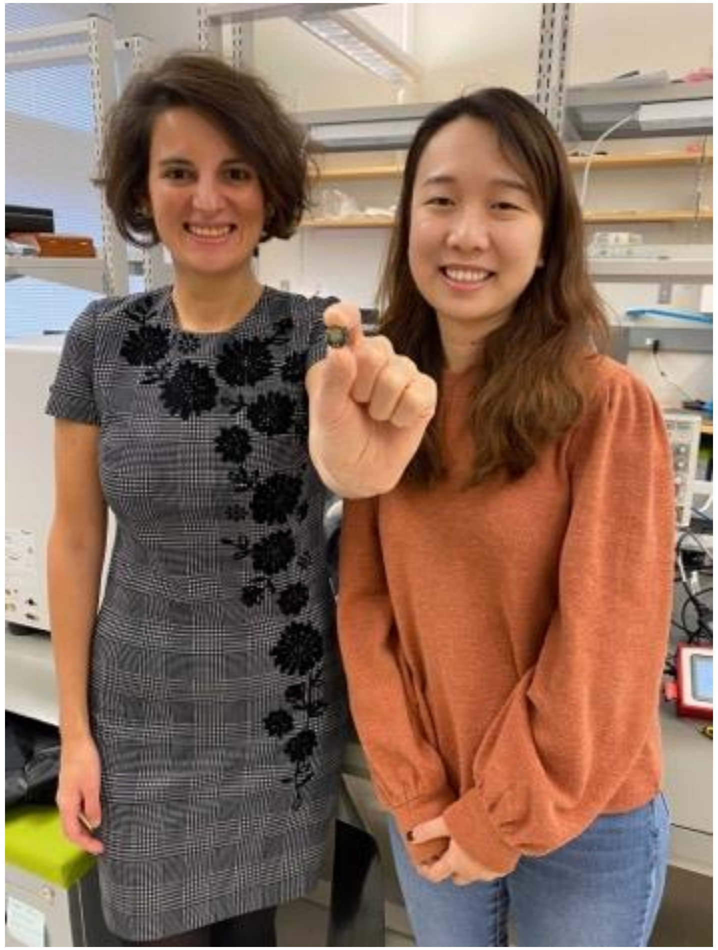
Energy-Efficient Wireless Systems





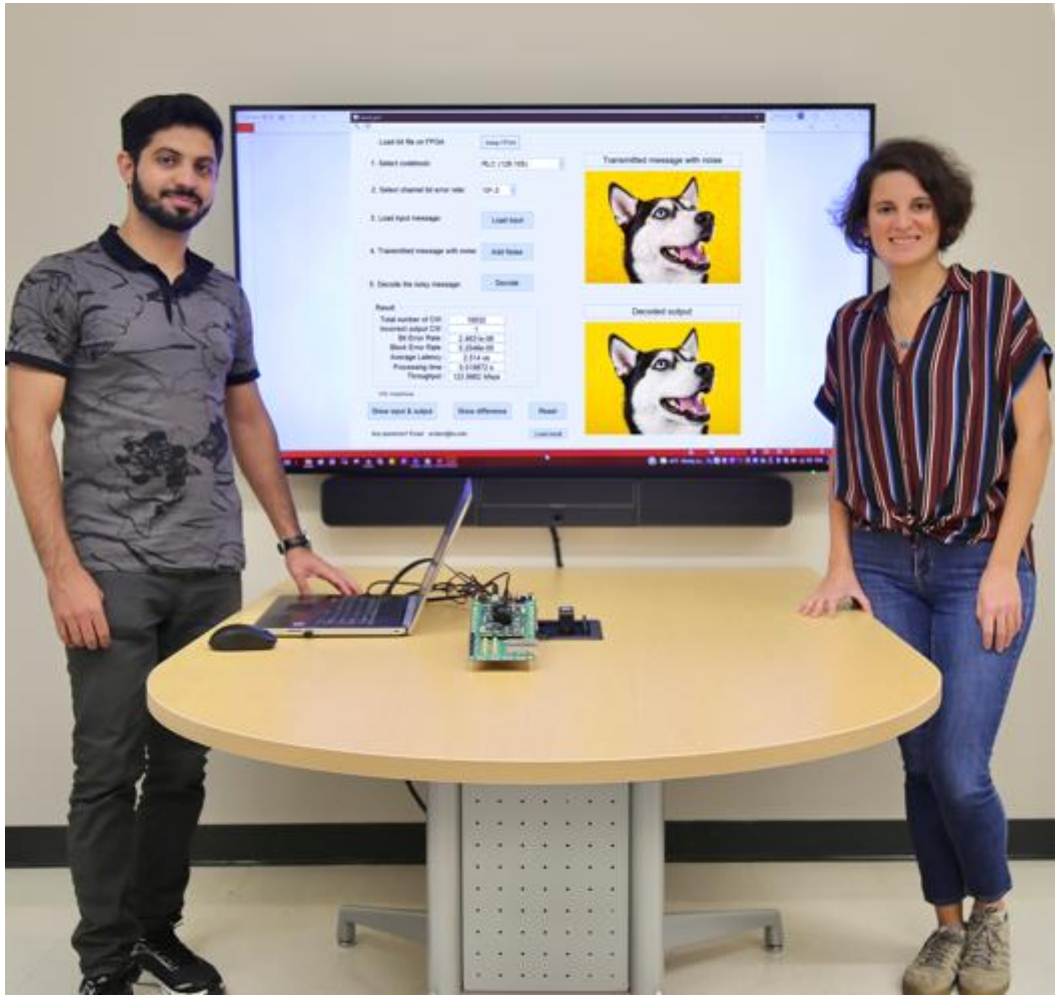
ISSCC’15, JSSC’15, RFIC’16, TCASI’18, SPM’19, ICASSP’22, A-SSCC’23

Acknowledgements: Bioelectronics Collaborators



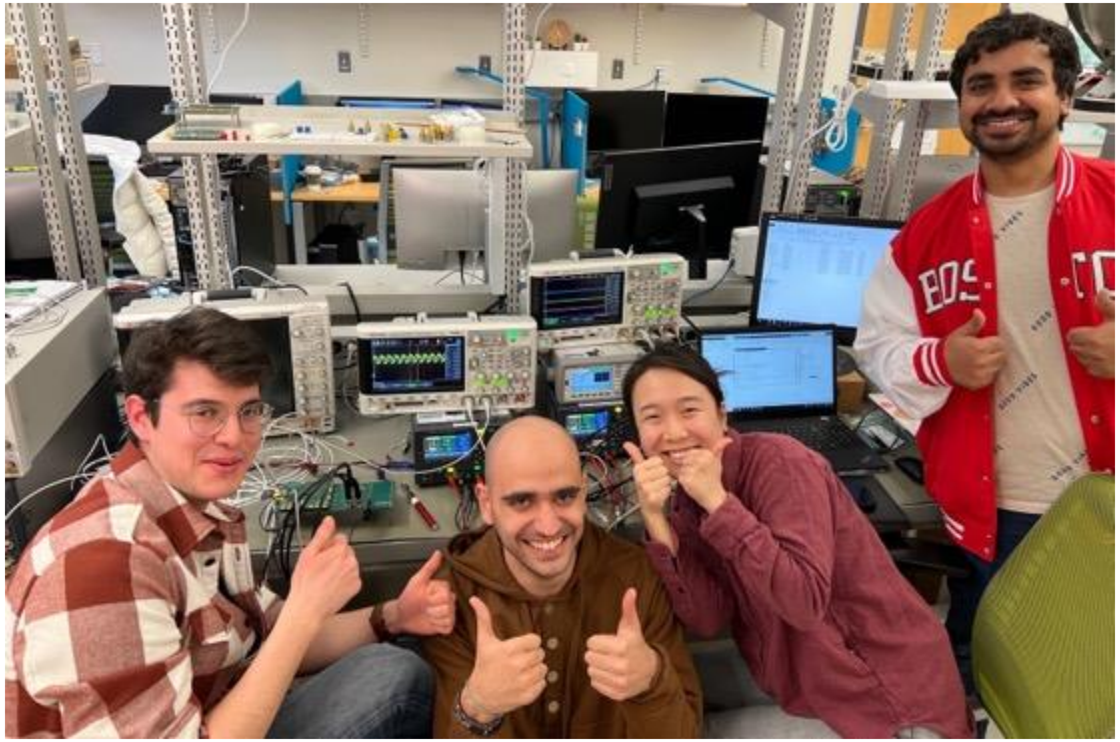
- Douglas Densmore, BU ECE
- Ahmad Khalil, BU BME
- Wilson Wong, BU BME
- James Galagan, BU BME
- Miguel Jimenez, BU BME
- Timothy Lu, MIT BE (Now Senti Bio)
- Giovanni Traverso, MIT MechE
- Phillip Nadeau, Analog Devices (ADI)
- Andrew Magyar, Liz Onderko, Capra Biosciences
- CIDAR Lab: David McIntyre, Diana Arguijo, Aya Kassem
- Khalil Lab: Ezira Yimer Wolle, Colin Kunze
- Wong Lab: Jingyao Chen
- Lu Lab: Maria Eugenia Inda, Yong Lai
- Traverso Lab: Miguel Jimenez, Christoph Steiger
- WISE-Circuits Lab: Qijun (Mandy) Liu, Alperen Yasar, Dilara Caygara

Acknowledgements: GRAND Collaborators



- Muriel Medard, MIT RLE
- Ken Duffy, Northeastern University
- David Starobinski, BU ECE
- Medard Lab: Amit Solomon, Wei An
- Duffy Lab: Kevin Galligan
- Starobinski Lab: Stefan Gvozdenovic
- WISE-Circuits Lab: Arslan Riaz, Vaibhav Bansal, Alperen Yasar, Furkan Ercan, Zeynep Ece Kizilates, Akshaya Bali, Timur Zirtiloglu, Arman Tan

Acknowledgements: Security & Signal Processing Collaborators



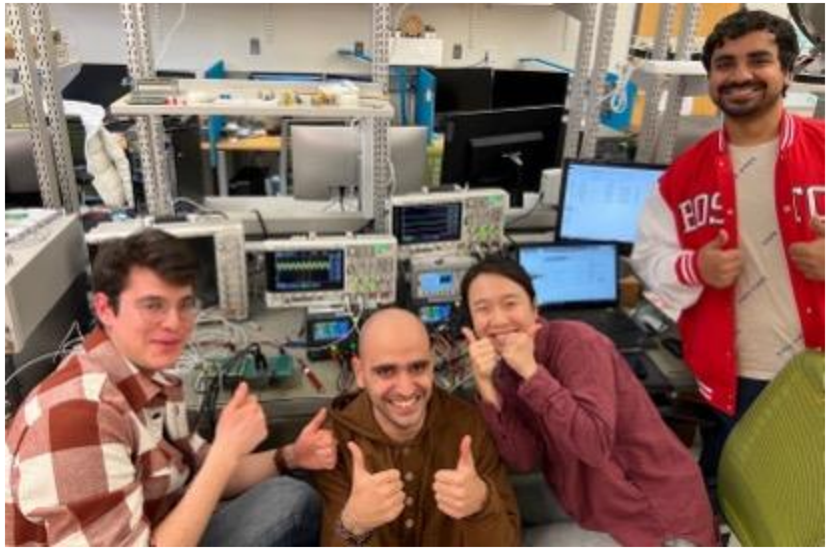
- Ajay Joshi, BU ECE
- David Starobinski, BU ECE
- Yonina Eldar, Weizmann Institute of Science
- Nir Shlezinger, Ben-Gurion University of the Negev
- Tao Yu, Lei Poo, Benoit Dufort, Chiraag Juvekar, Sam Fuller, Analog Devices (ADI)
- Ruonan Han, MIT EECS
- Anantha Chandrakasan, MIT EECS
- Joshi Lab: Rashmi Agrawal
- Han Lab: Mohamed Ibrahim, Muhammad Ibrahim Wasiq Khan
- Chandrakasan Lab (Co-mentored by me): Jongchan Woo, Eunseok Lee, Saurav Maji
- WISE-Circuits Lab: Timur Zirtiloglu, Arman Tan, Alperen Yasar, Eyyup Tasci

Acknowledgements: WISE-Circuits Group









Since Fall 2018

8 Ph.D. Students	2 Postdoctoral Researchers	9 M.S. Researchers	32 Undergraduate Researchers