MAS.S61

Wireless & Mobile Sensing

Lecture 7:
Ocean IoT

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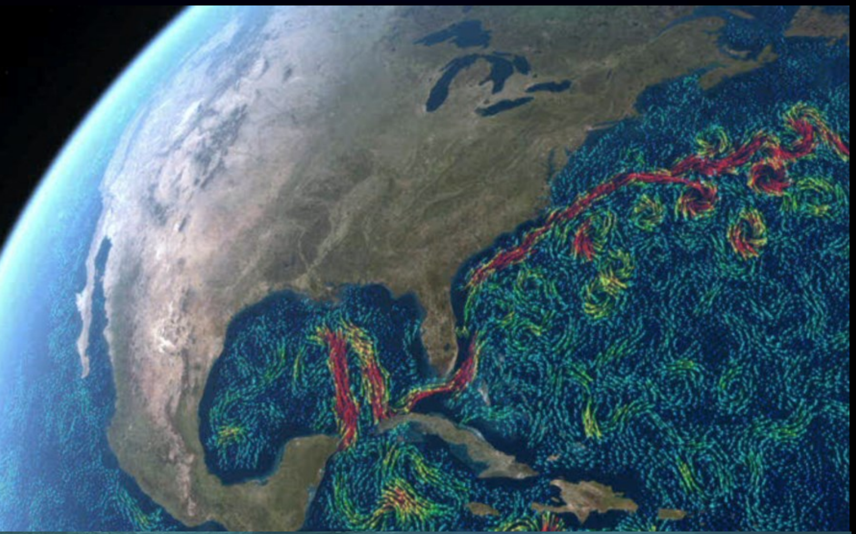
Let’s start with some trivia



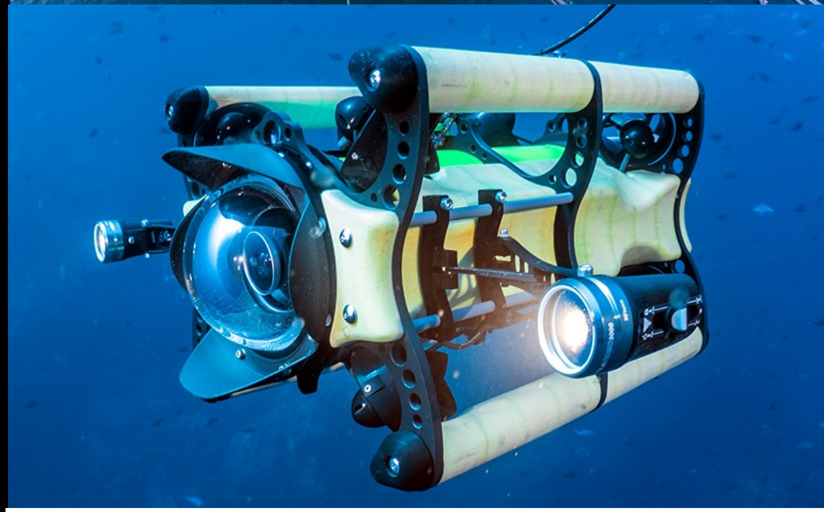
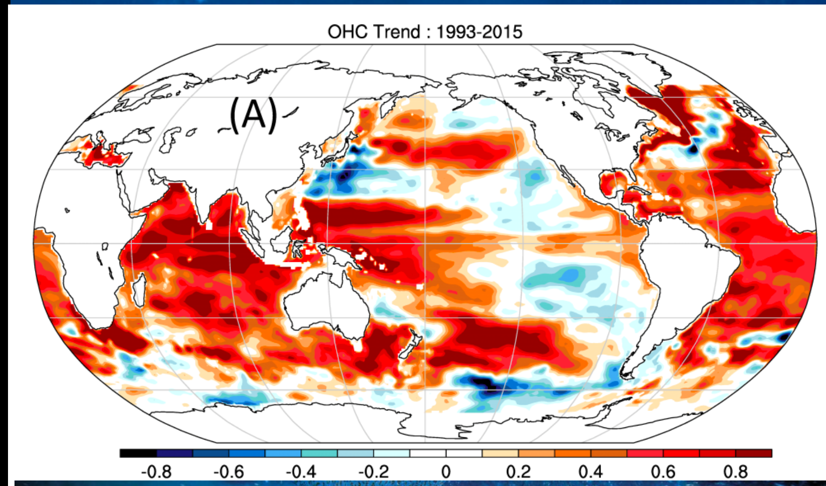


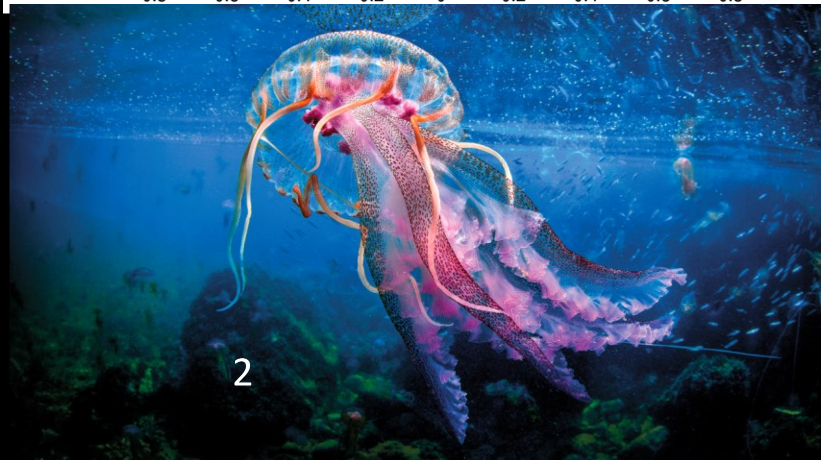

1. How percentage of the ocean floor has never been observed?

2. Out of every 10 marine organisms, how many have never been discovered?

3. What is the world’s fastest-growing food sector?

4. What has more heat content: the ocean or the atmosphere?



Taking the Internet of Things to the Ocean World

30 bn

IoT Devices

Less than 1 in a million of IoT is in the ocean, even it they covers >70% of the planet and has significant needs for food, climate, etc.

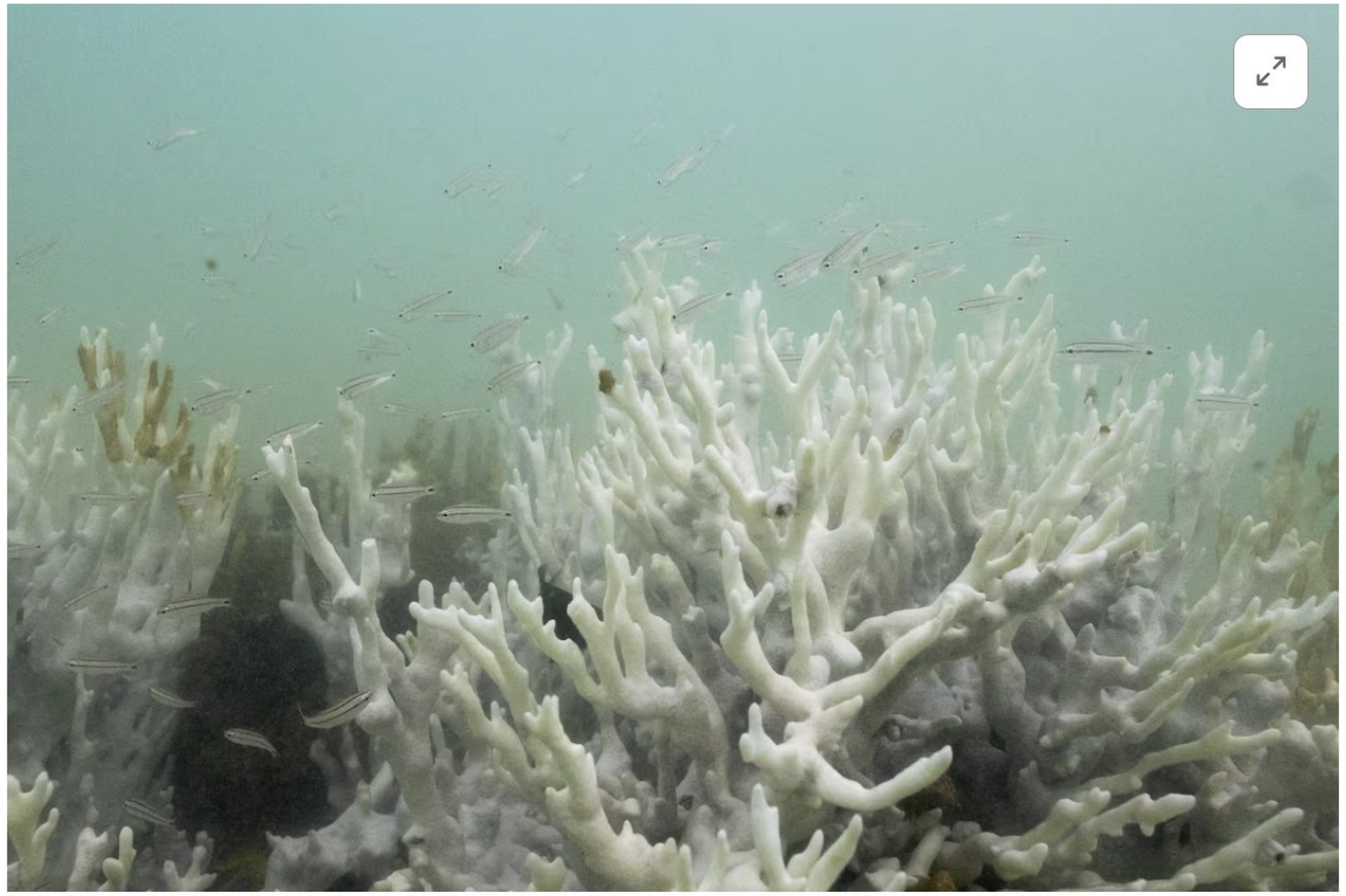
IoT Sensors → **Data** → **Decision Making & Prediction**

This year in Underwater Sensing

Climate tipping points are being crossed, scientists warn ahead of COP30

By **Alison Withers**

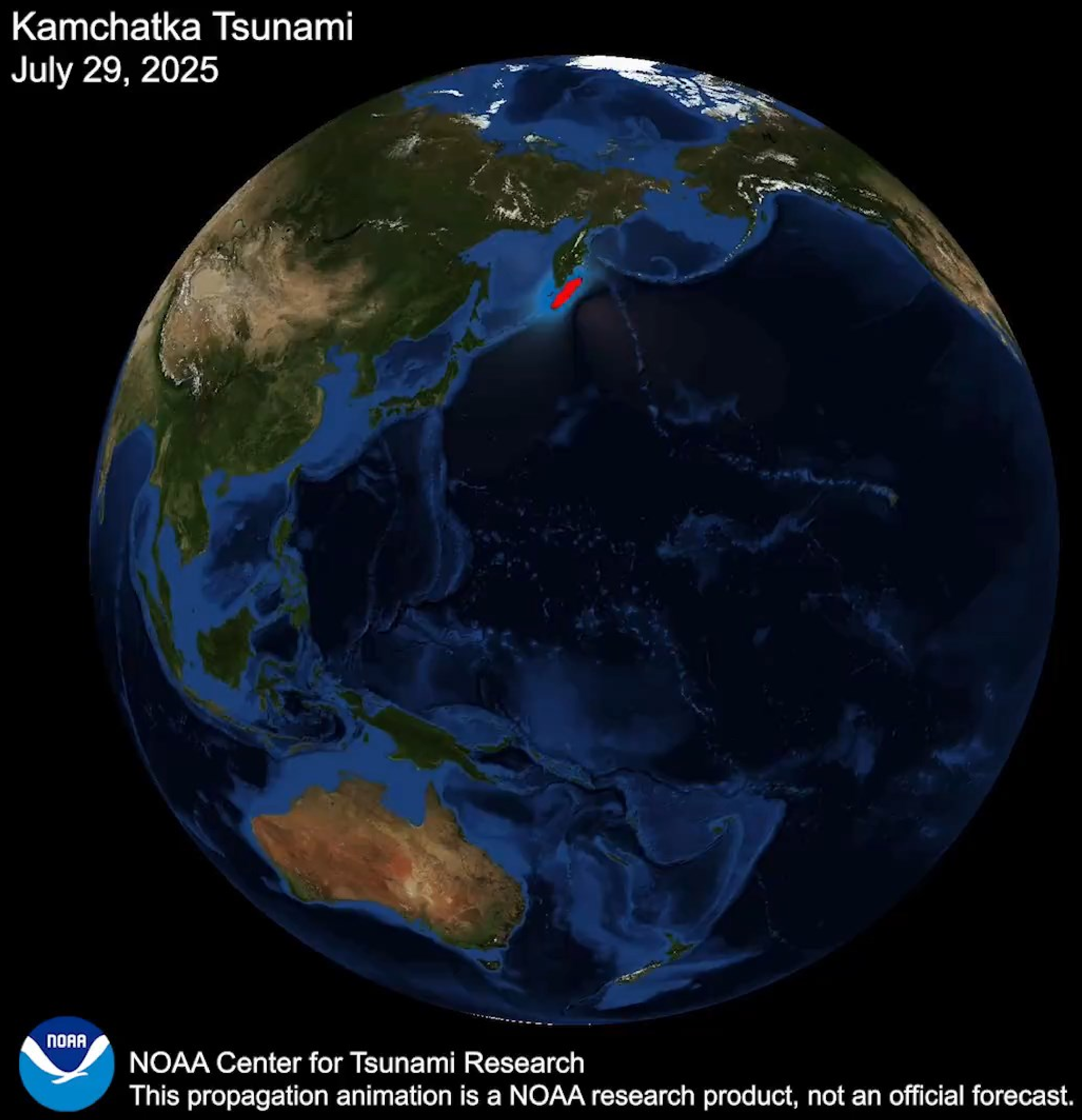
October 13, 2025 6:46 PM GMT · Updated October 13, 2025



[1/4] Bleached coral is seen in a reef at the Costa dos Corais in Japaratinga in the state of Alagoas, Brazil April 16, 2024. REUTERS/Jorge Silva/File Photo Purchase Licensing Rights

Summary

- Climate change is accelerating risks to Amazon, AMOC
- Warm water coral reefs in unstoppable dieback, report finds
- Renewable energy surpasses coal globally, marking a positive climate shift



Wireless & Mobile Sensing

sensing the physical world & transmitting data wirelessly

sensing via the wireless signals or mobile devices

sensing *for* communication

Objectives of Today's Lecture

Learn the **fundamentals, emerging technologies, and applications** of ocean IoT

1. What makes underwater IoT different from in-air IoT?

2. What are the applications of underwater IoT?

Low-power underwater IoT case studies:

3. What are the core principles of underwater backscatter?

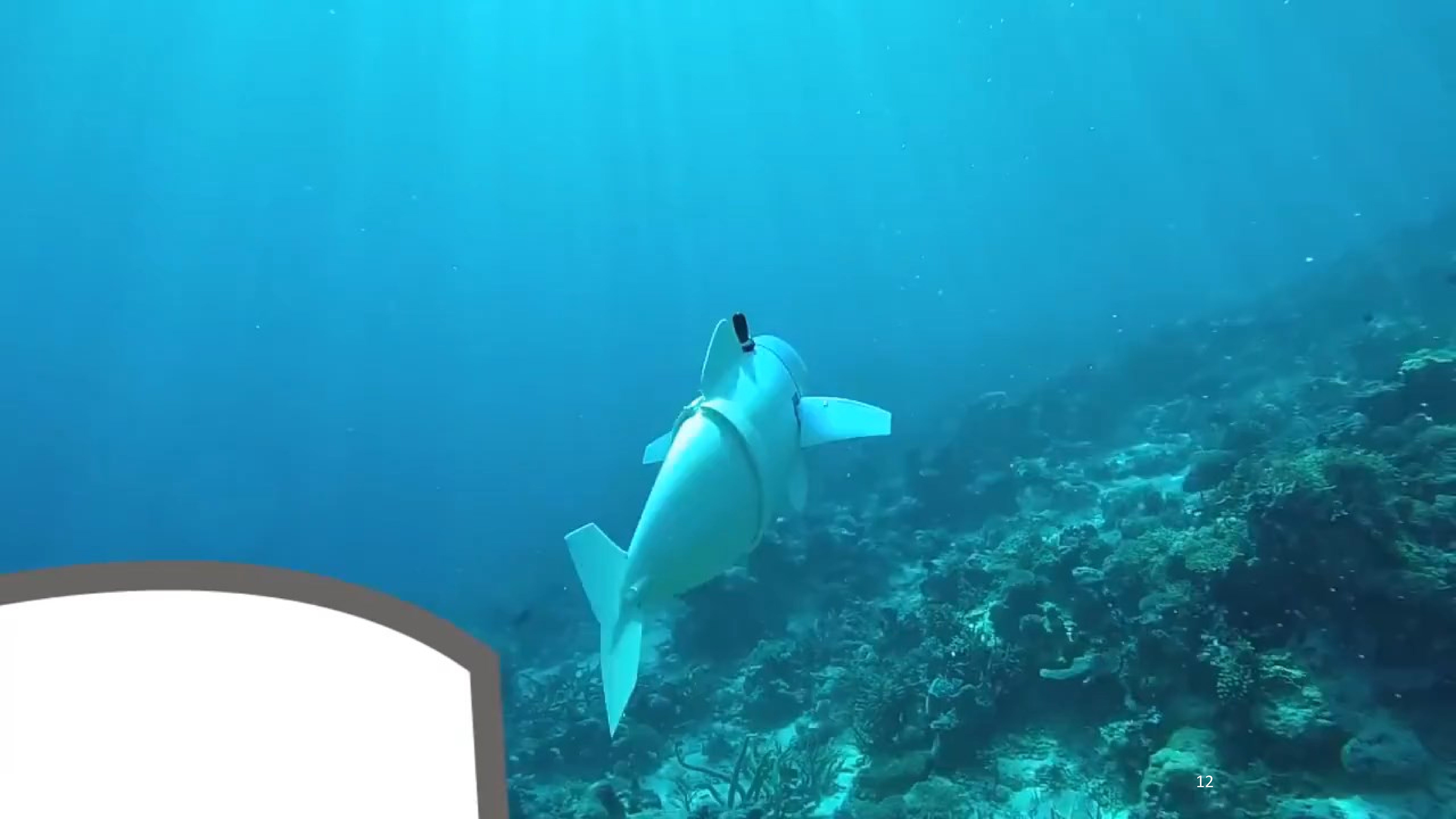
4. How to sense whale location with low-power transmit-only radio?

Why is bringing IoT to the ocean (esp. underwater) hard?

- **Communication:**
  - Can’t use radio (WiFi, bluetooth)
  - Direct underwater-to-air comms remains challenging
- **Power:**
  - No power outlet (access); hard to replace batteries
- **Sensing:**
  - Can’t use GPS (radio signals) for localization
  - Imaging is challenging (light interferes, refracts, etc.)

Example Ocean Connectivity, Sensing, & Power Technologies


ARGO
PROGRAM
BUREAU OF METEOROLOGY



Problem: Battery life of underwater sensors is extremely limited

Low-power underwater transmitters consume 100s of Watts

(e.g., WHOI low-power micro-modem 2019)

↓

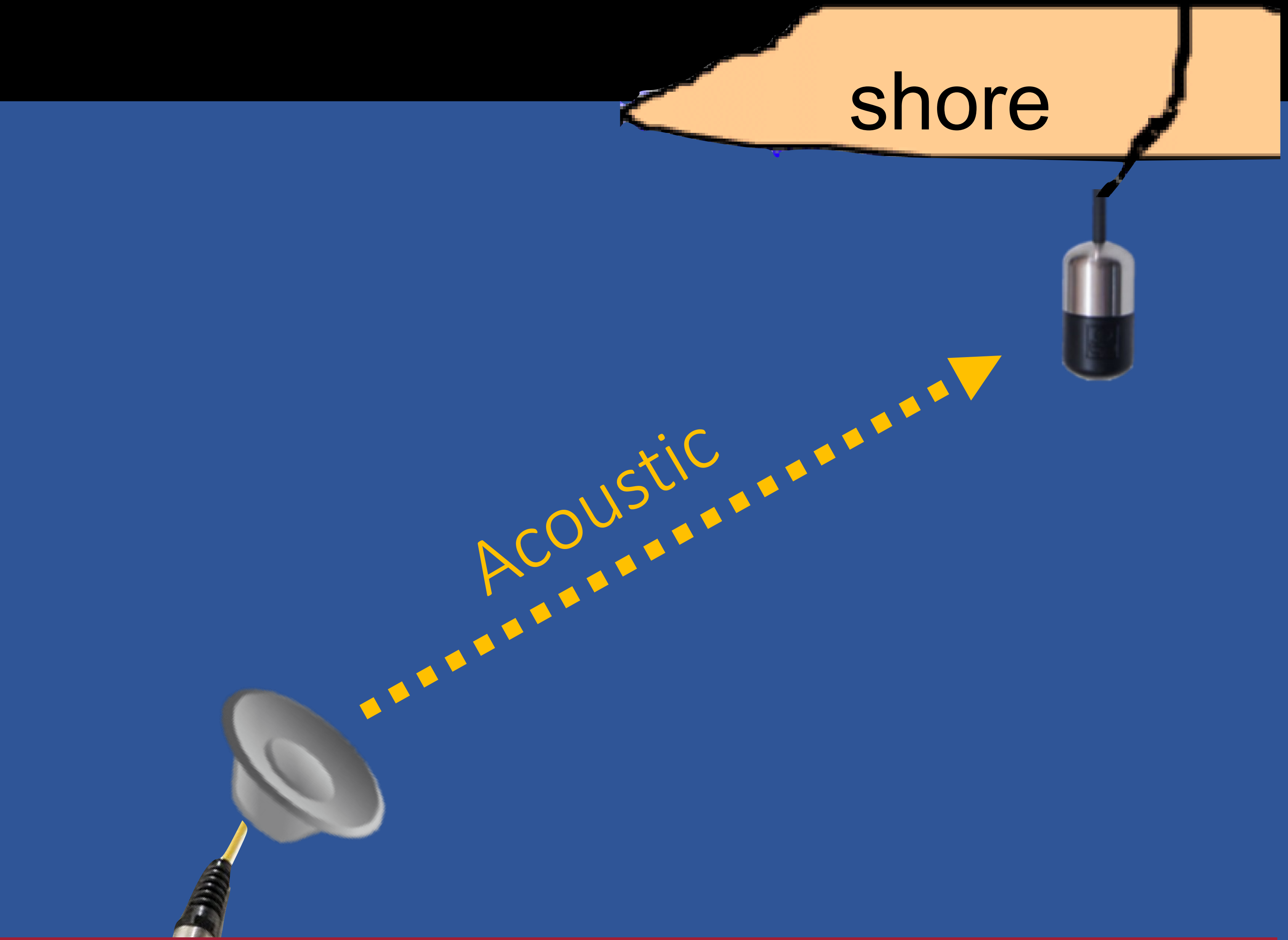
State-of-the-art sensors for tracking marine animals only last for few hours or days

[Animal Biotelemetry’15, Scientific Reports’17]

Technology that Enables Underwater Backscatter (Batteryless) Networking

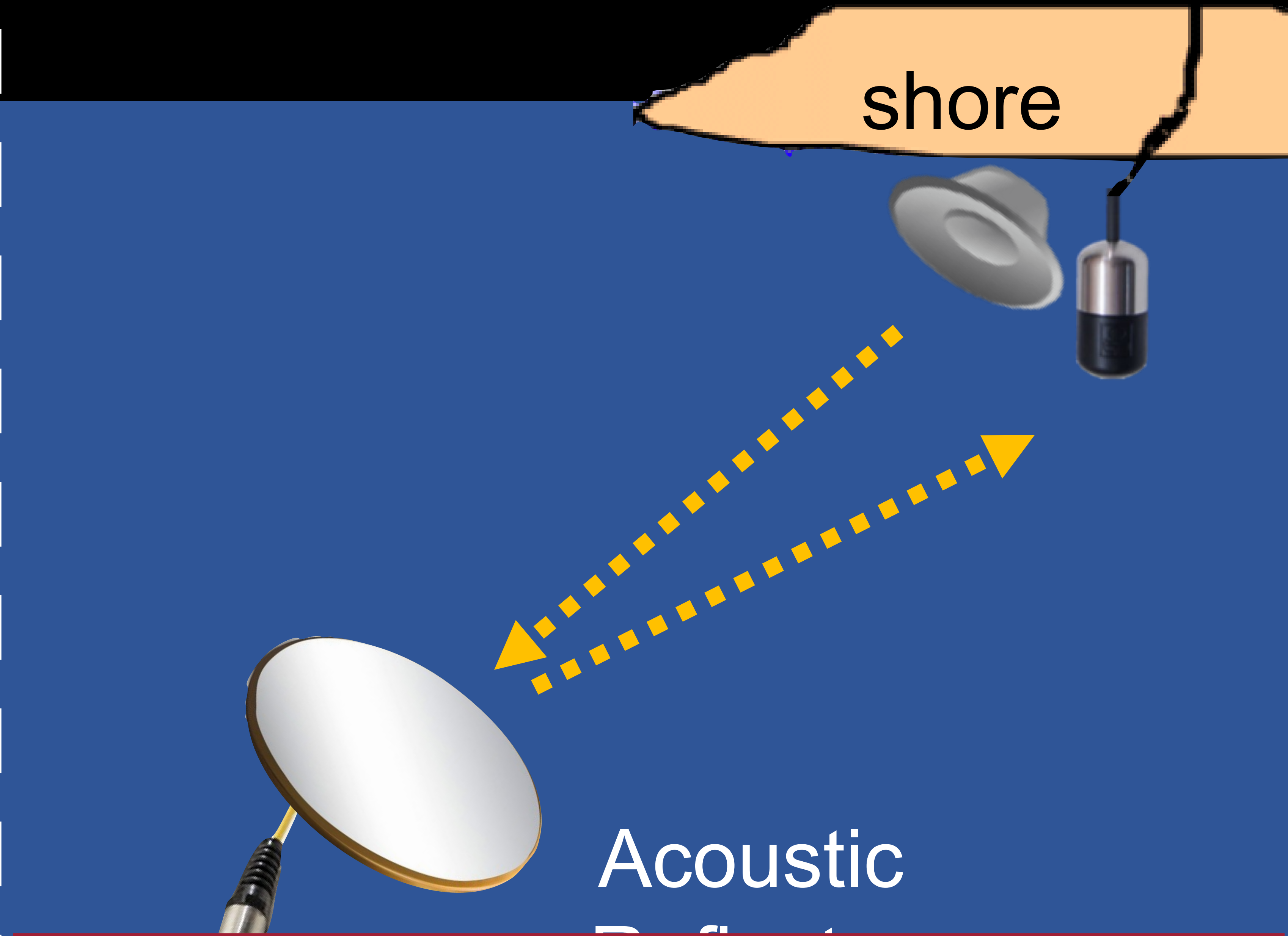
PAB (ACM SIGCOMM'19)

Traditional Approach



Sensor generates its own acoustic signal

Underwater Backscatter

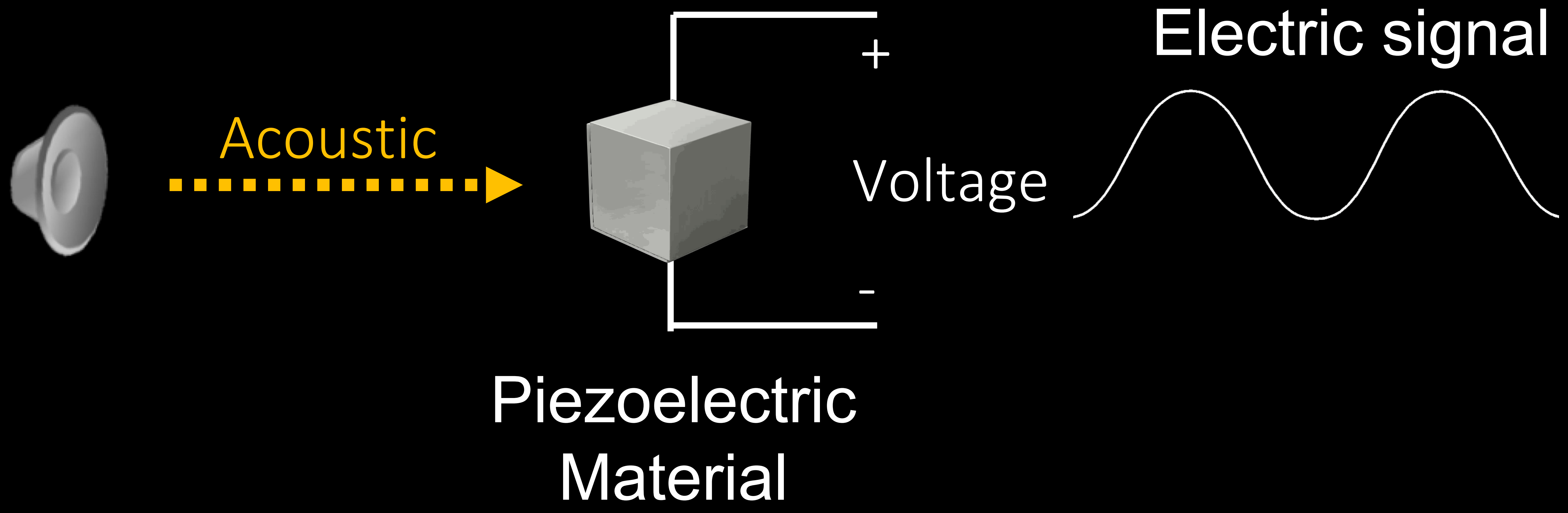


Sensor reflects an existing acoustic signal

How can we control the reflections of acoustic signals?

Key Idea: Use piezoelectricity to design programmable acoustic reflectors

Piezoelectric materials transform mechanical to electrical energy



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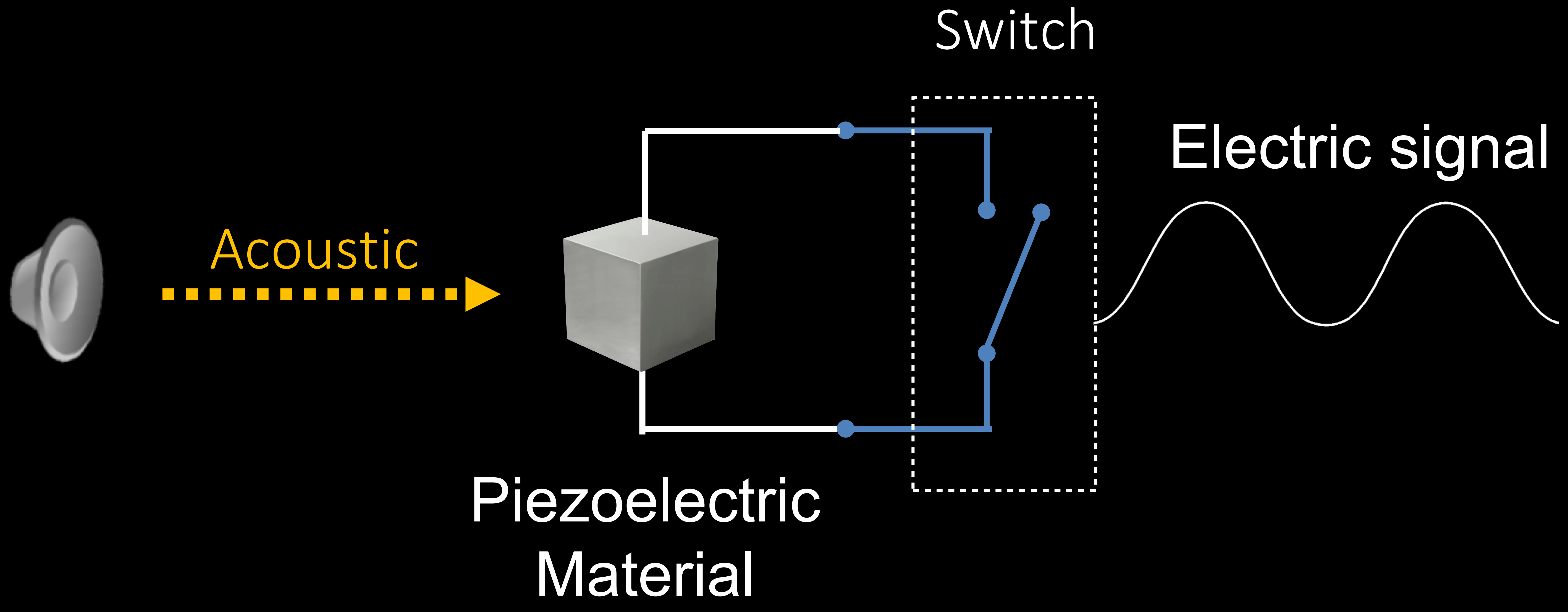

Key Idea: Use piezoelectricity to design programmable acoustic reflectors

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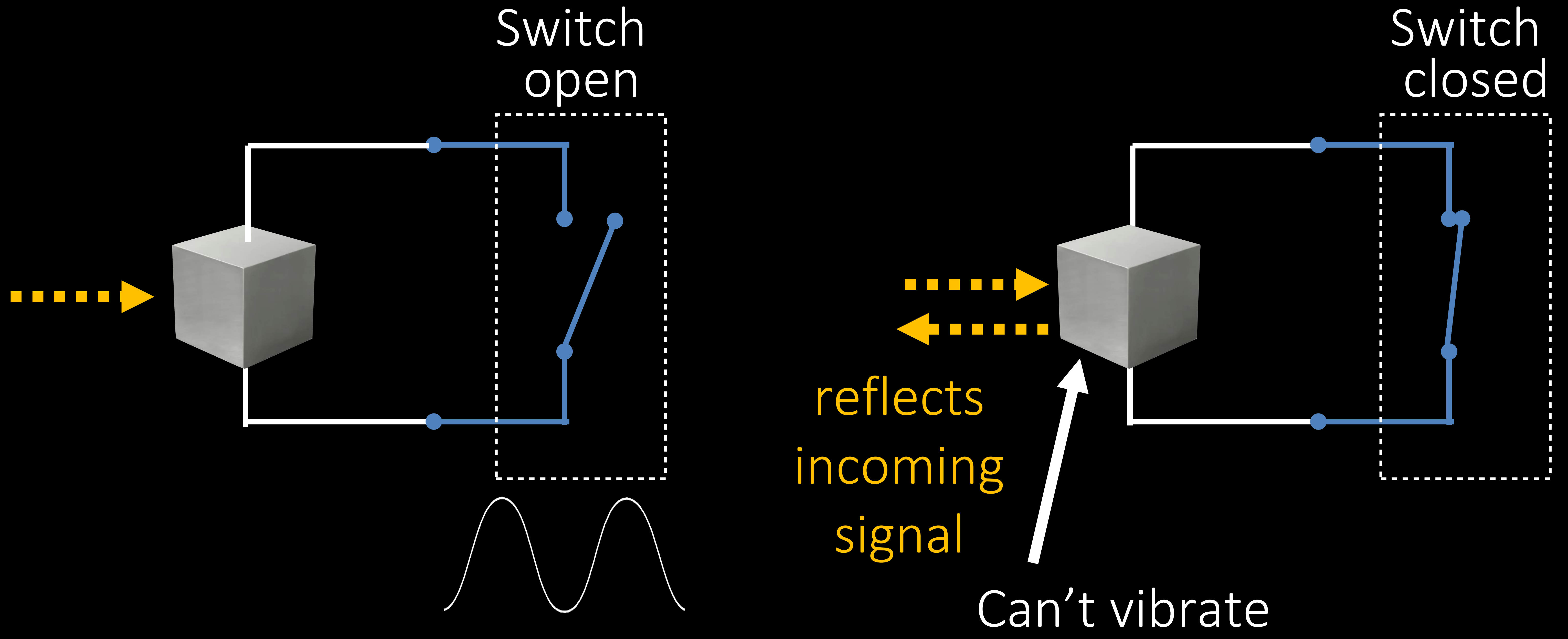
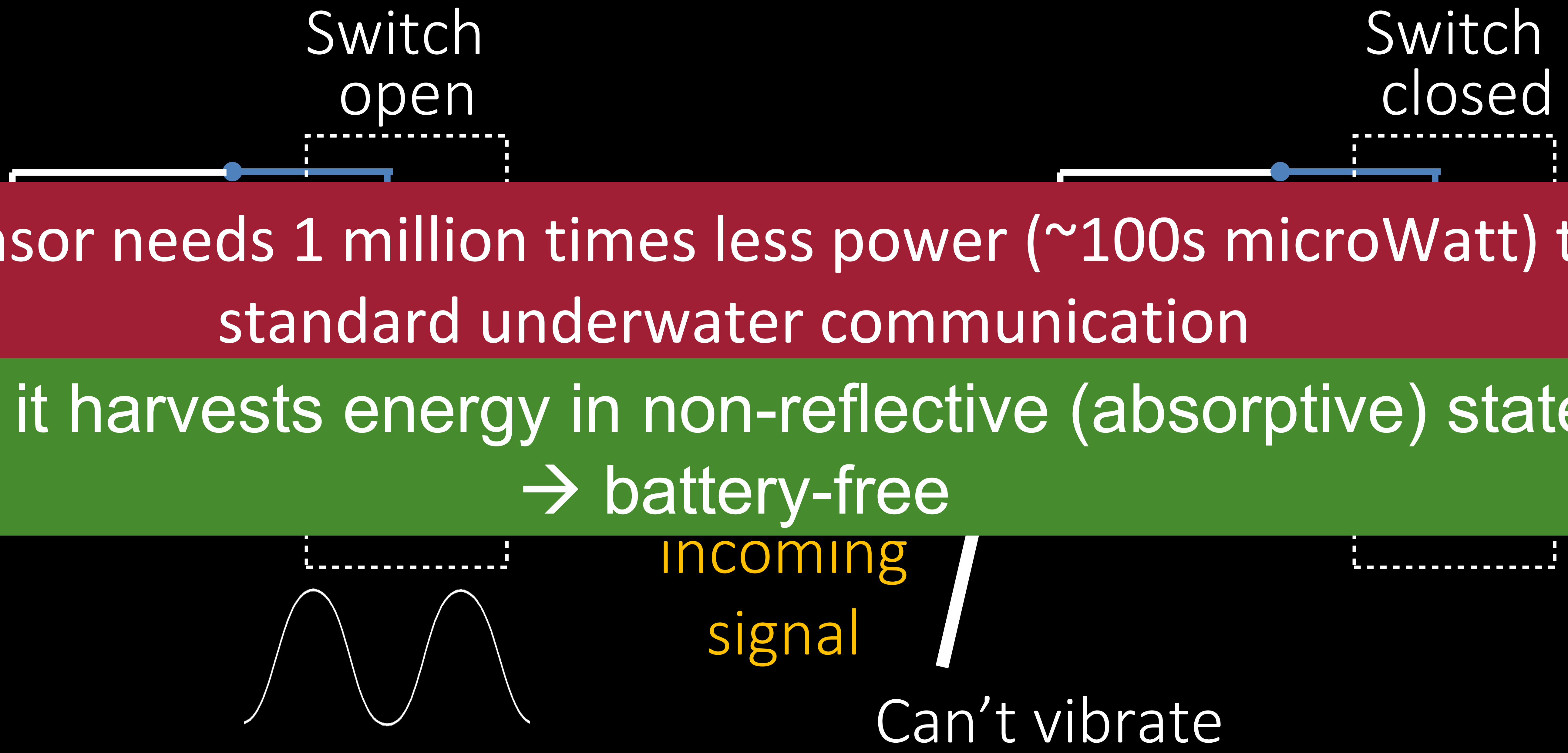
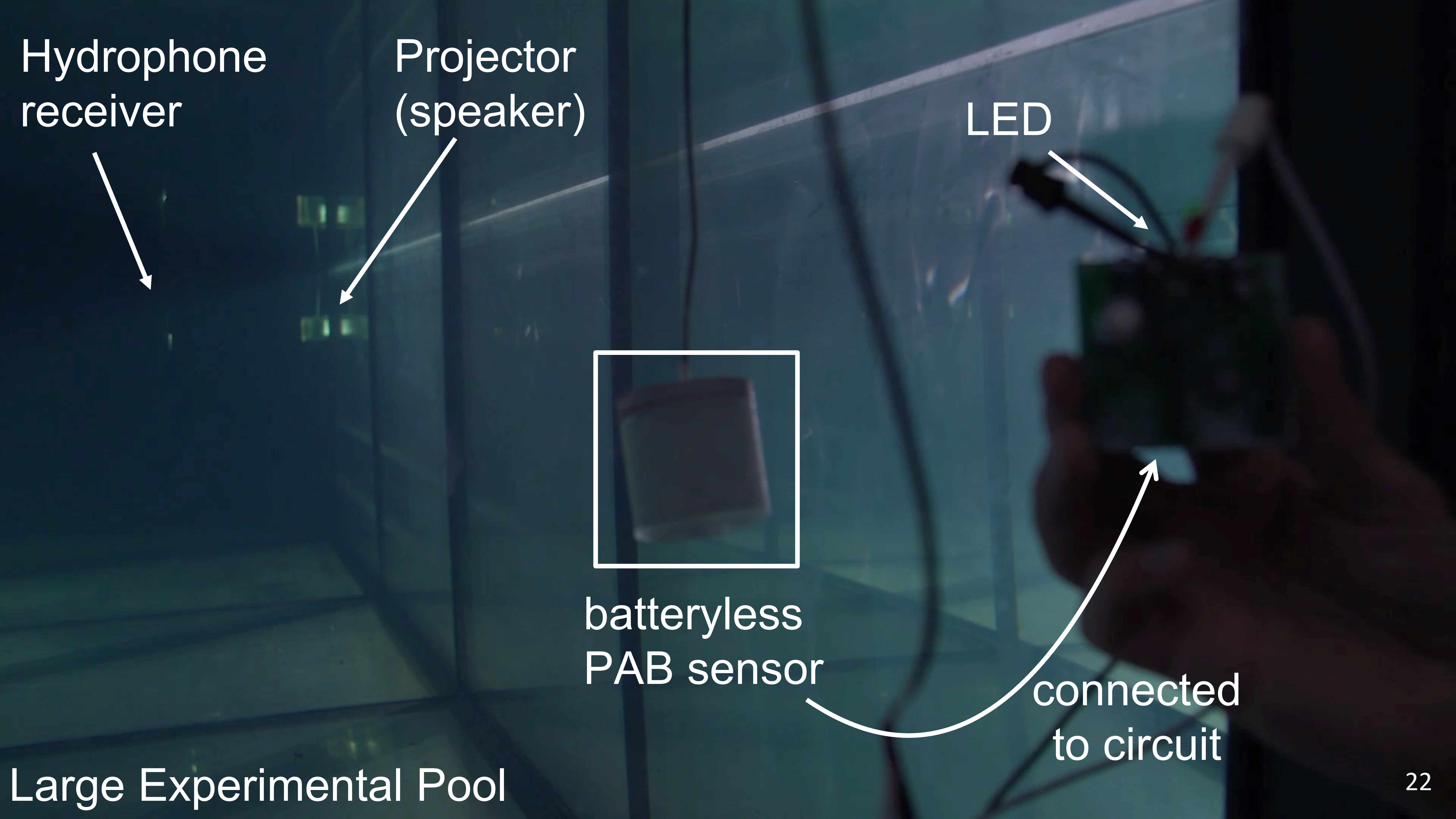


Piezo-Acoustic Backscatter

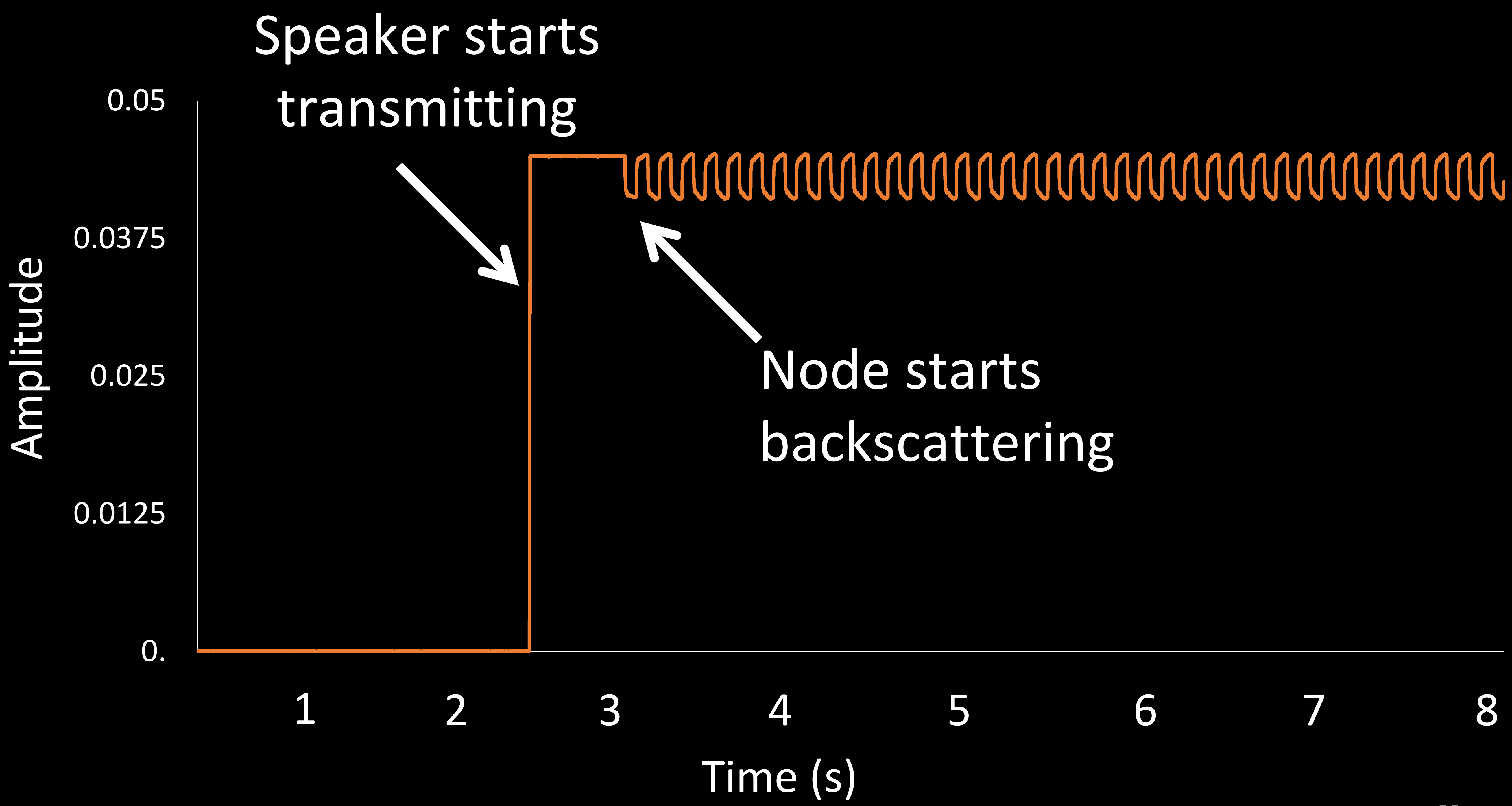


PAB sensor needs 1 million times less power (~100s microWatt) than standard underwater communication

And it harvests energy in non-reflective (absorptive) state
→ battery-free


Hydrophone
receiver
Projector
(speaker)
LED
batteryless
PAB sensor
connected
to circuit
Large Experimental Pool

Measuring the Backscatter Signal (by Hydrophone)

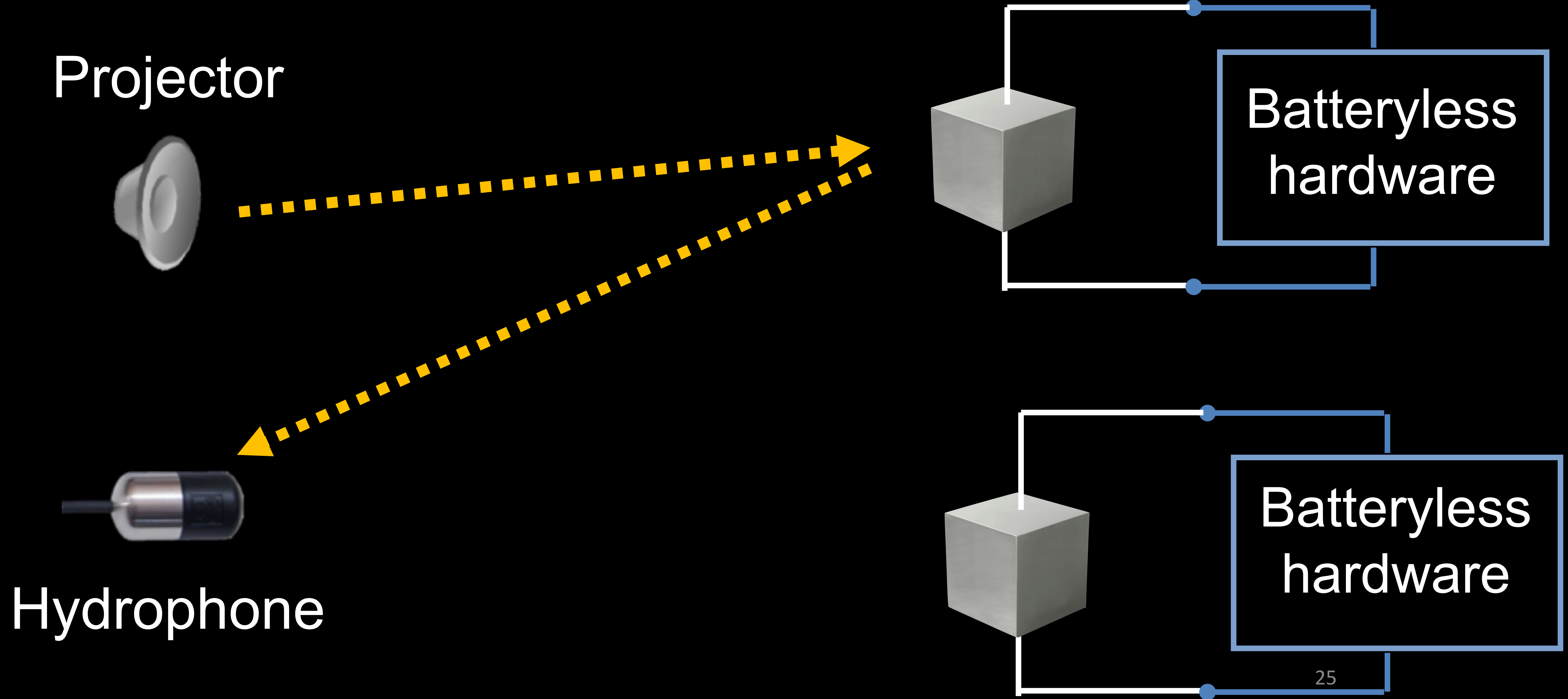


How can we extend underwater backscatter to multiple nodes?

Extending to Multiple Nodes

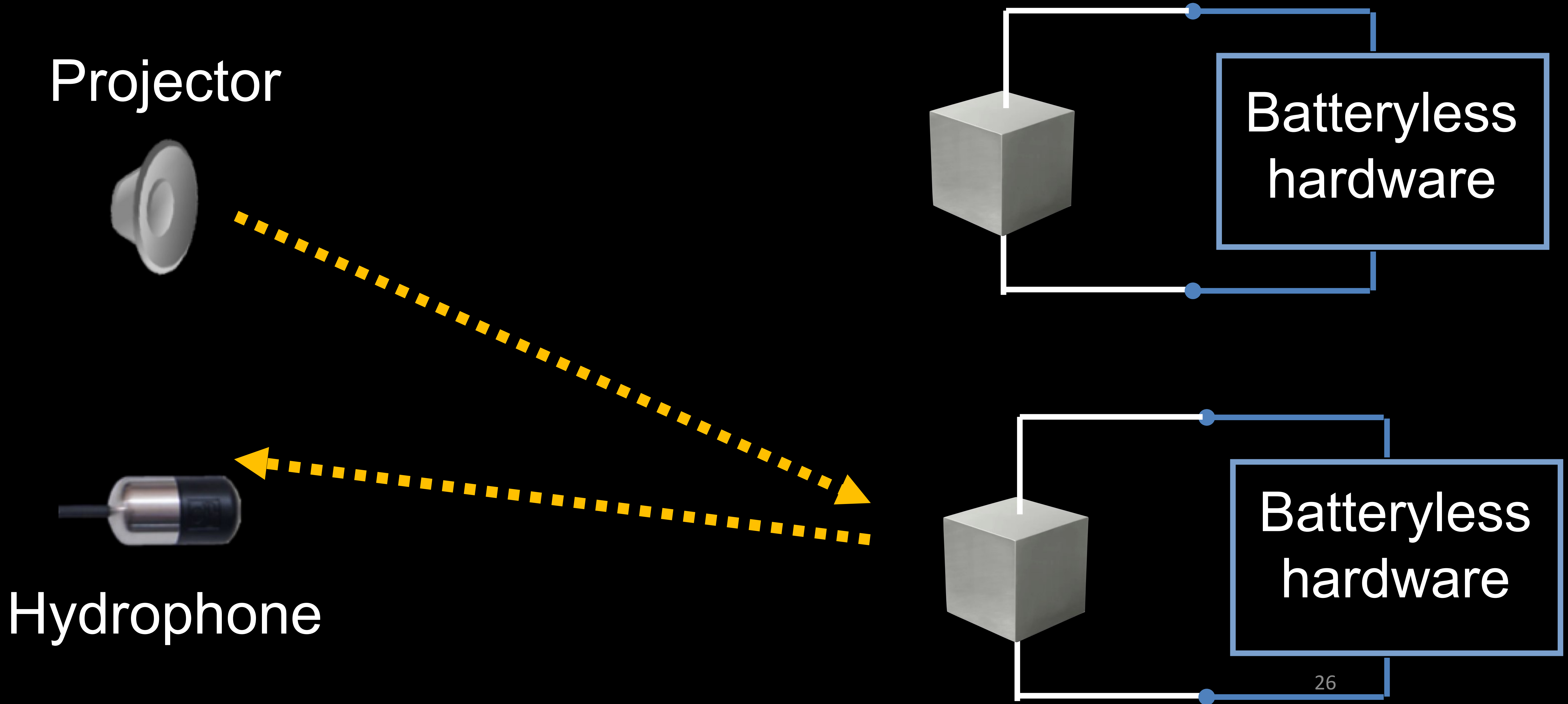
Option 1: Time Division Multiplexing

[SIGCOMM’25 Echorider]



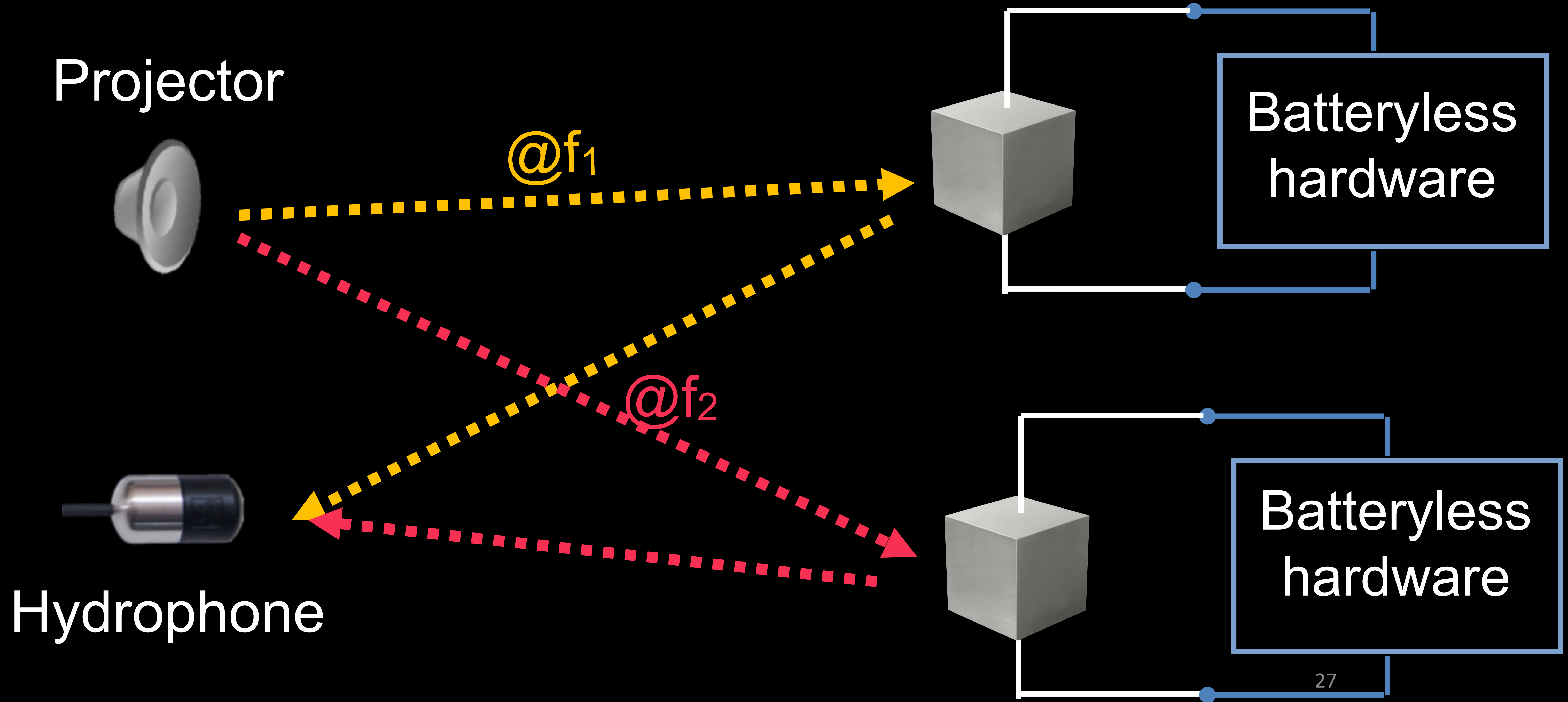
Extending to Multiple Nodes

Option 1: Time Division Multiplexing



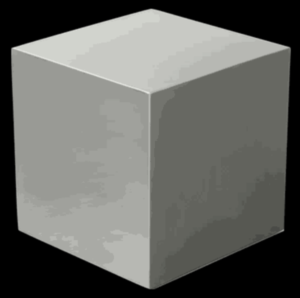
Extending to Multiple Nodes

Option 2: Frequency Division Multiplexing



Extending to Multiple Nodes

Problem: Resonance of piezoelectrics limits their bandwidth



Extending to Multiple Nodes

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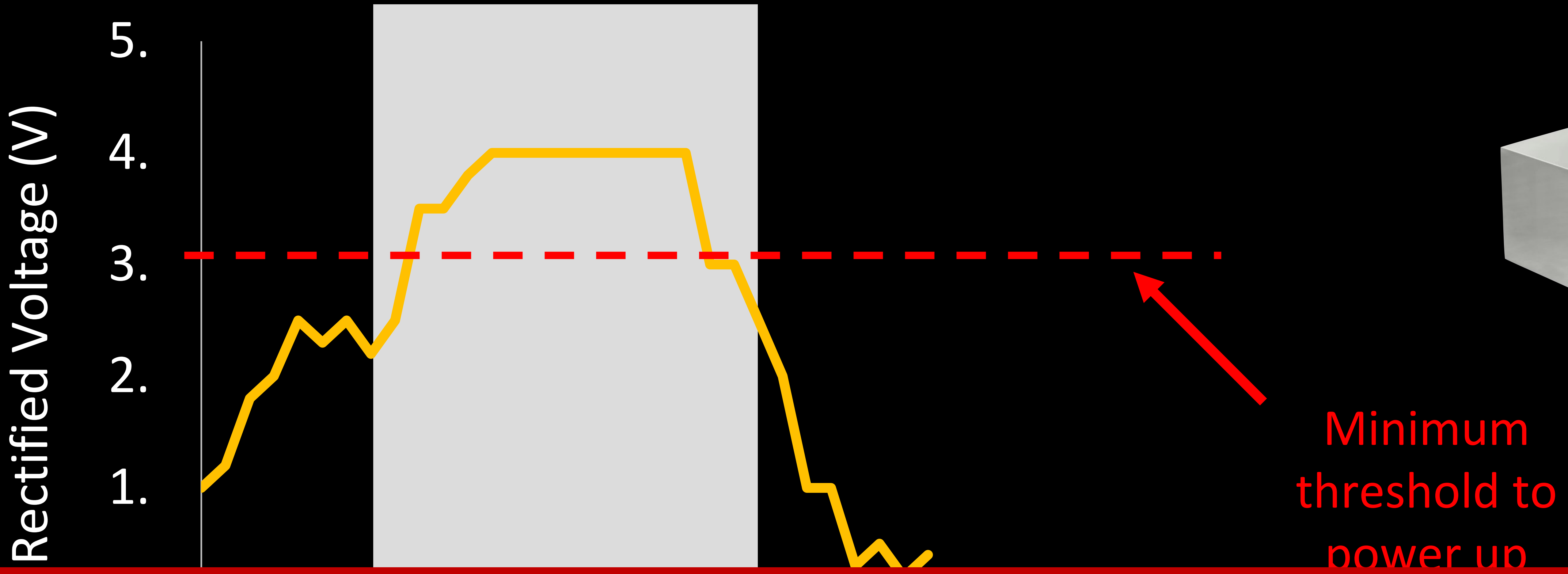


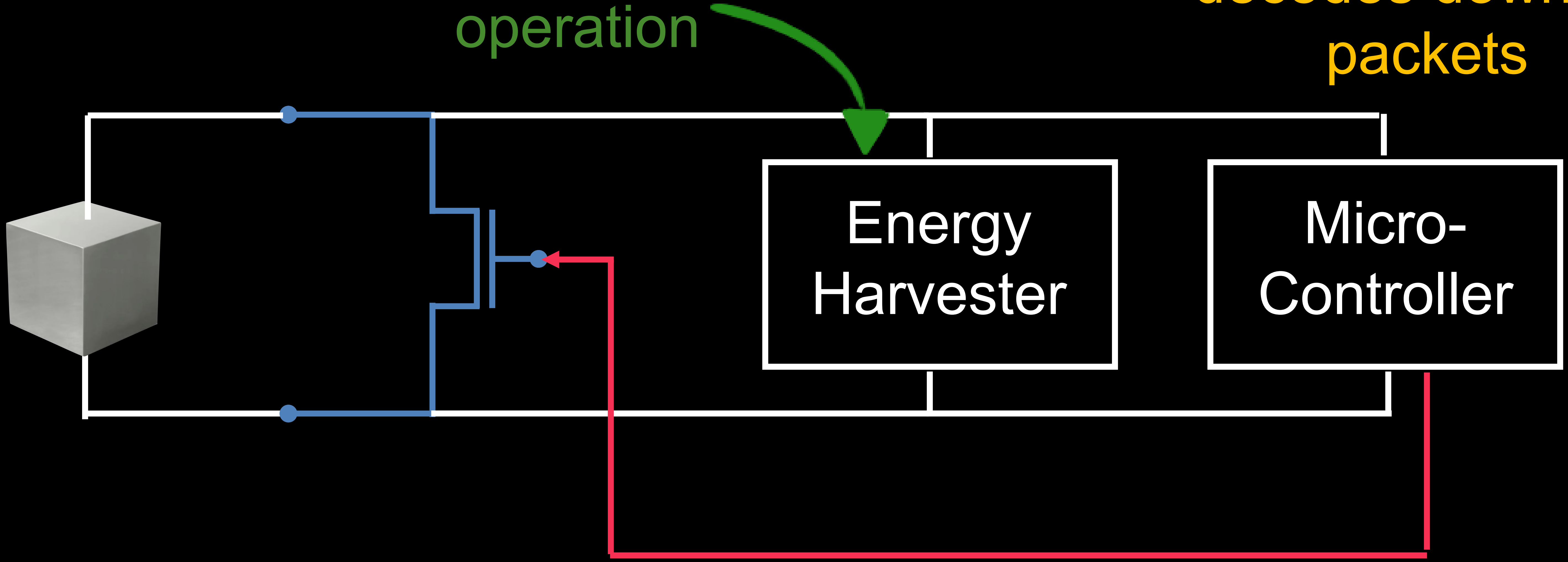
Operating at resonance maximizes energy harvesting but limits concurrent transmissions (and FDMA)

<u>Solution Idea:</u> Shift the resonance frequency *itself* to a different channel

Solution Idea: Shift the resonance frequency itself to a different channel

enables battery less operation

decodes downlink packets



encodes uplink packets by switching transistor

Solution Idea: Shift the resonance frequency *itself* to a different channel

resonance frequency determined by interaction between piezo & the batteryless circuit

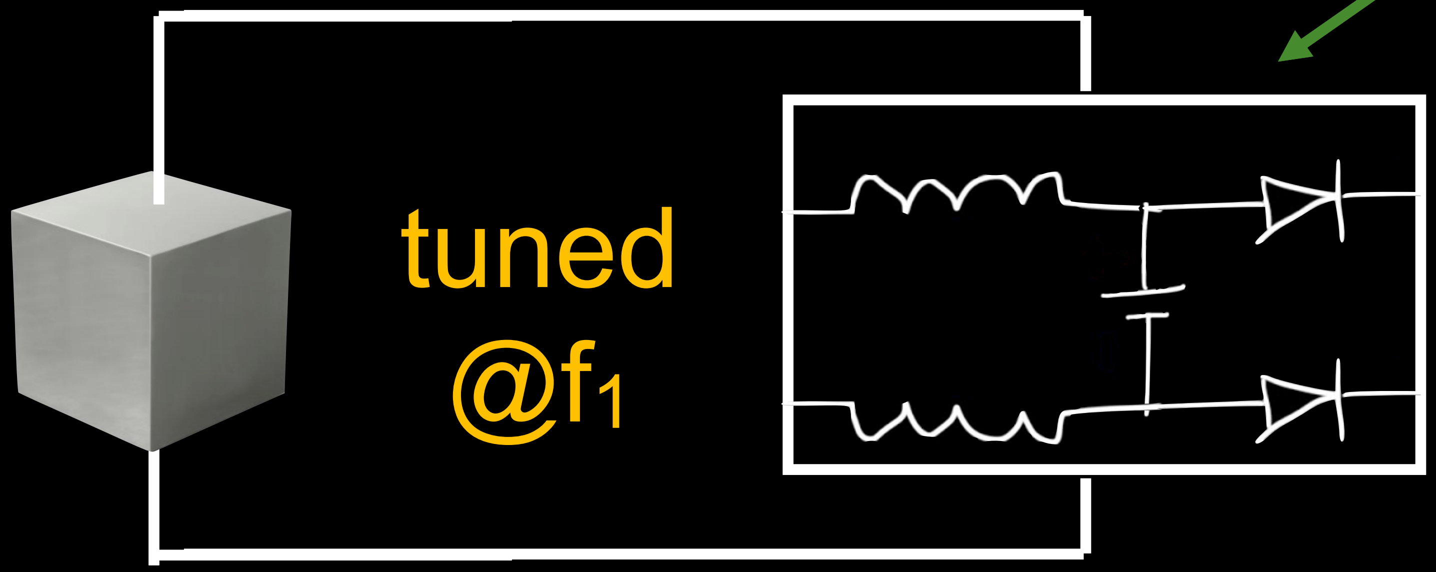
$$Z_{circuit}(f) = Z^*_{piezo}(f)$$

frequency dependent

→Tune the circuit to a different frequency

<u>Solution Idea:</u> Shift the resonance frequency *itself* to a different channel

resonance frequency determined by interaction between piezo & the batteryless circuit



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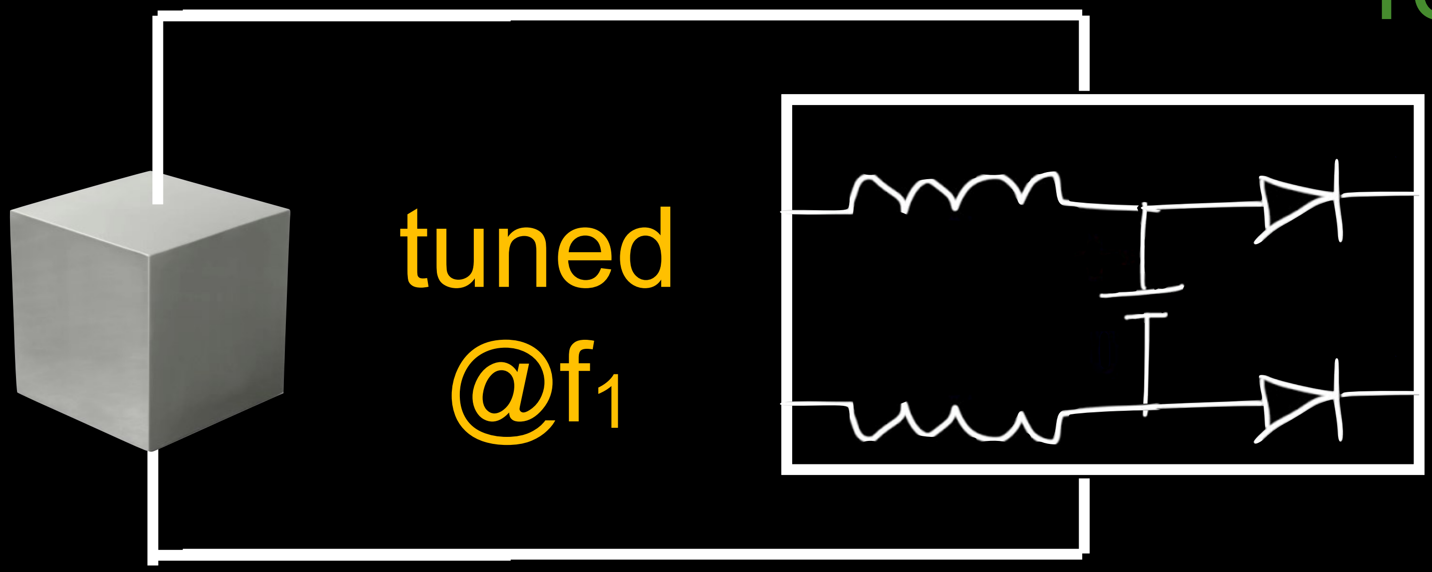

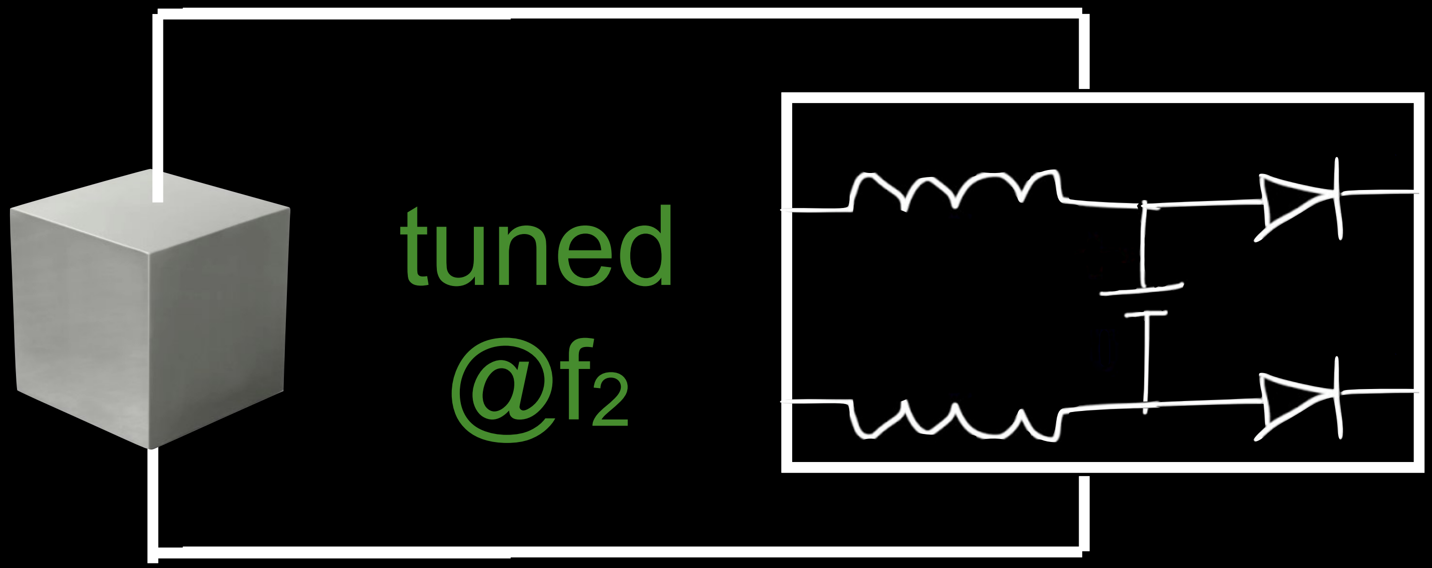

resonance frequency determined by interaction between piezo & the batteryless circuit

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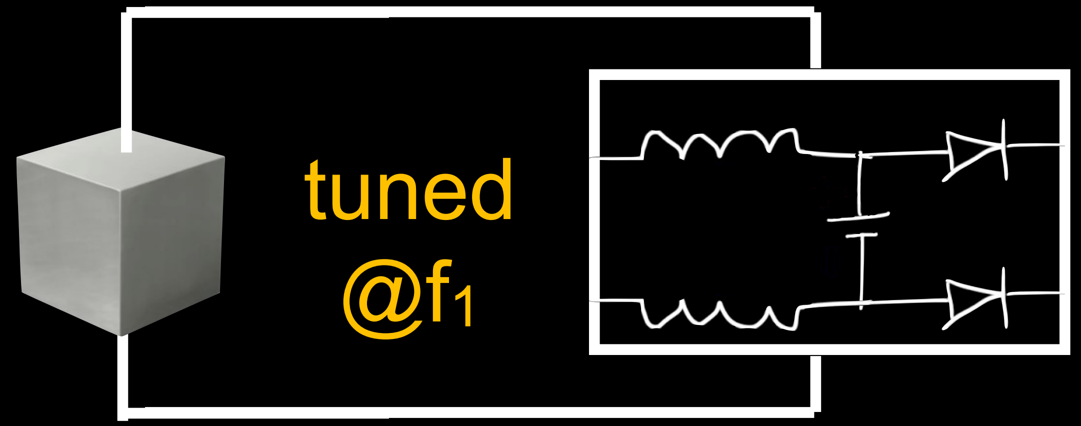
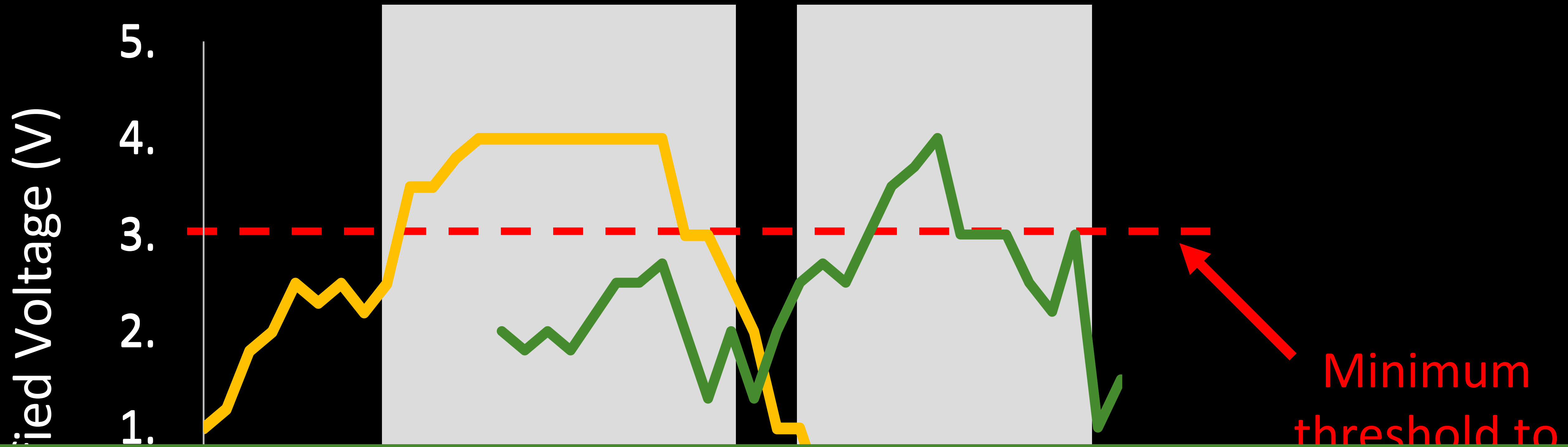
frequency dependent

→Tune the circuit to a different frequency

<u>Solution Idea:</u> Shift the resonance frequency *itself* to a different channel

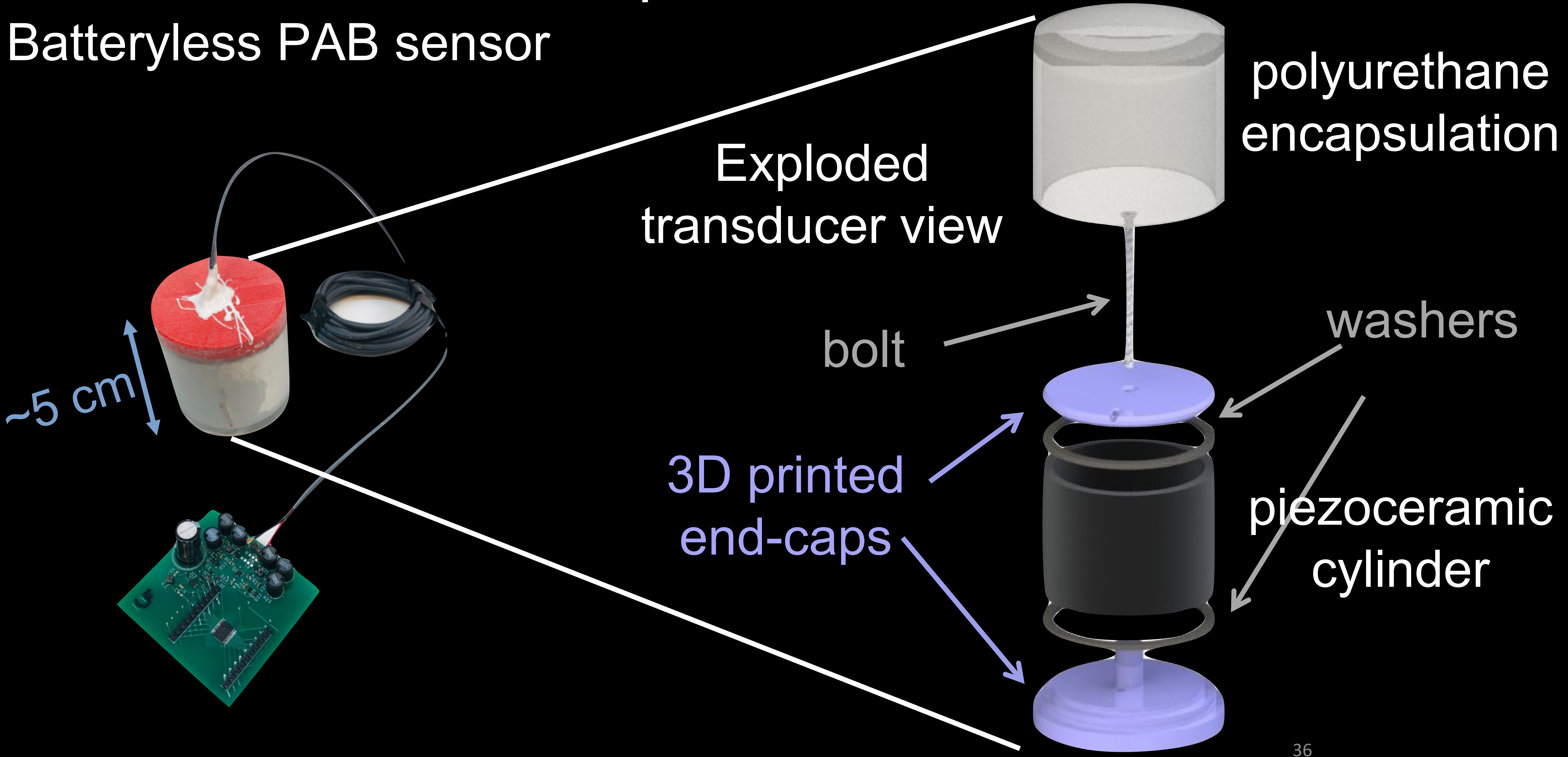




Extend the idea to uplink communication using a MIMO-style decoder adapted to backscatter resonance modes

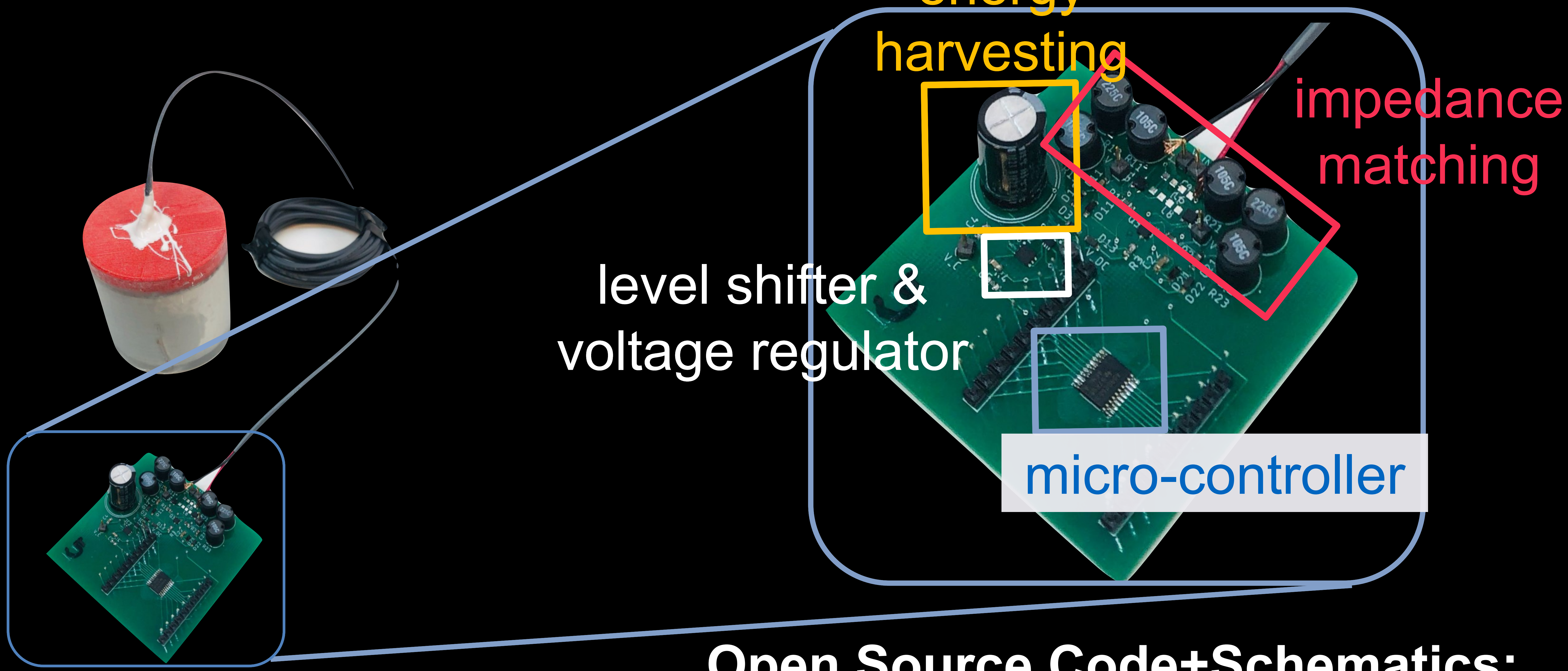
Frequency (KHz)

Implementation



Implementation

Batteryless PAB sensor



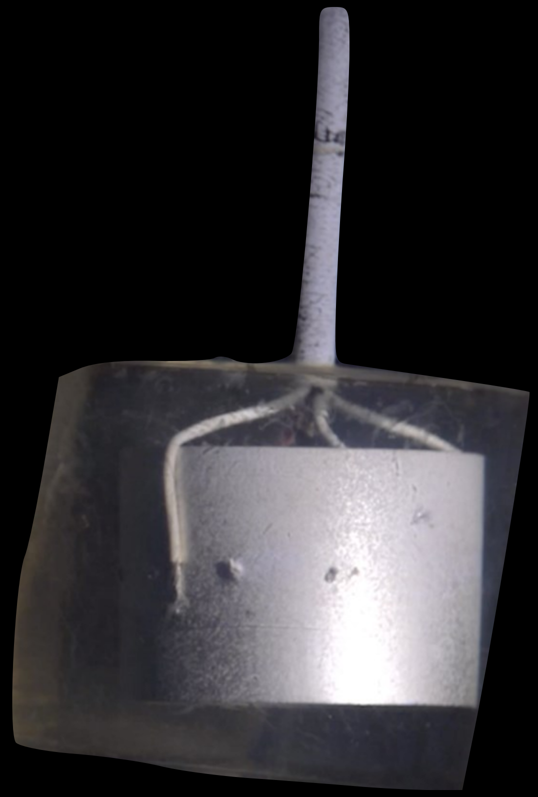
Open Source Code+Schematics:

https://github.com/saadafzal24/Underwater-Backscatter

Implementation

Batteryless PAB sensor

Projector

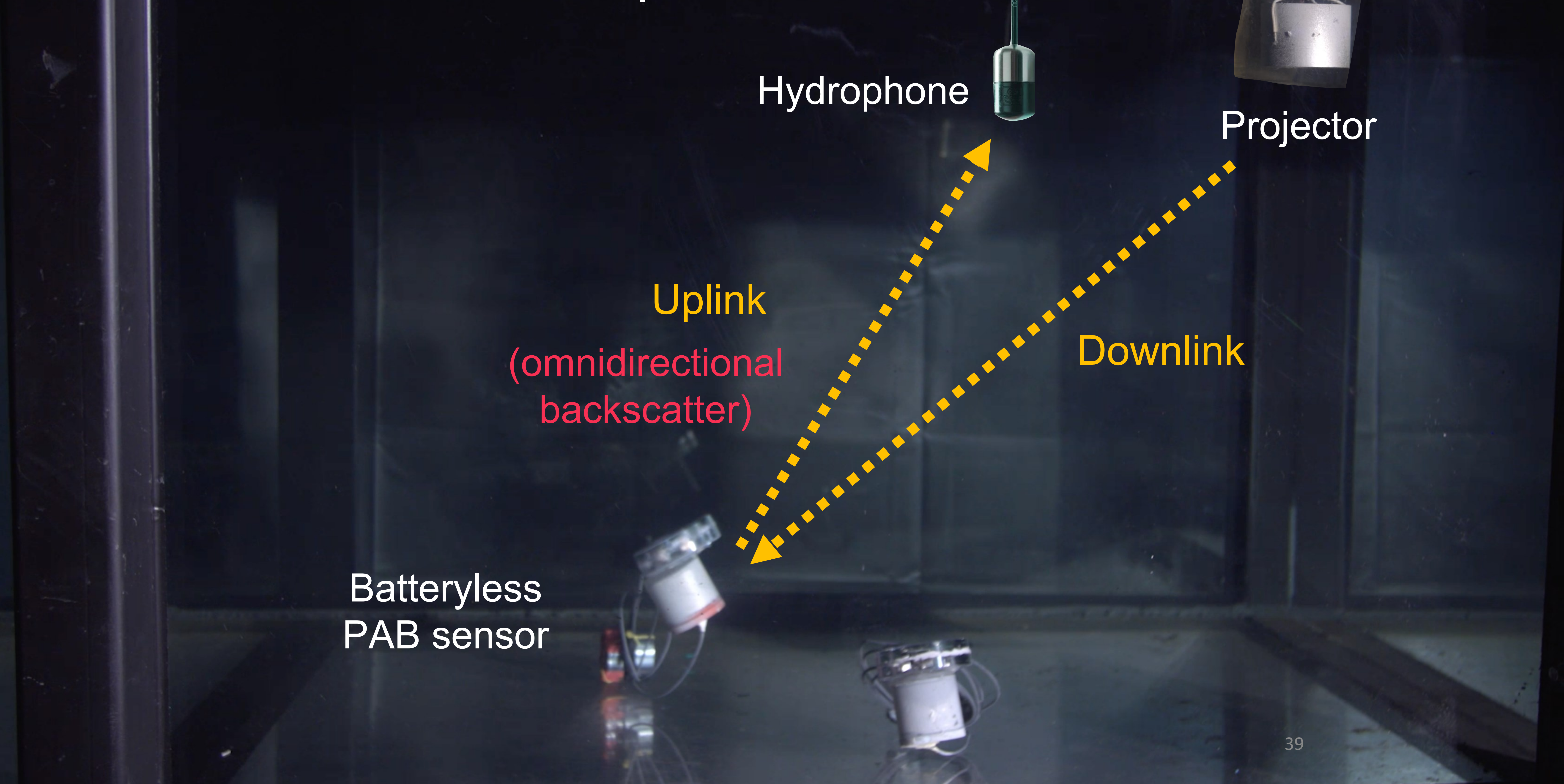


fabricated in-house

Hydrophone

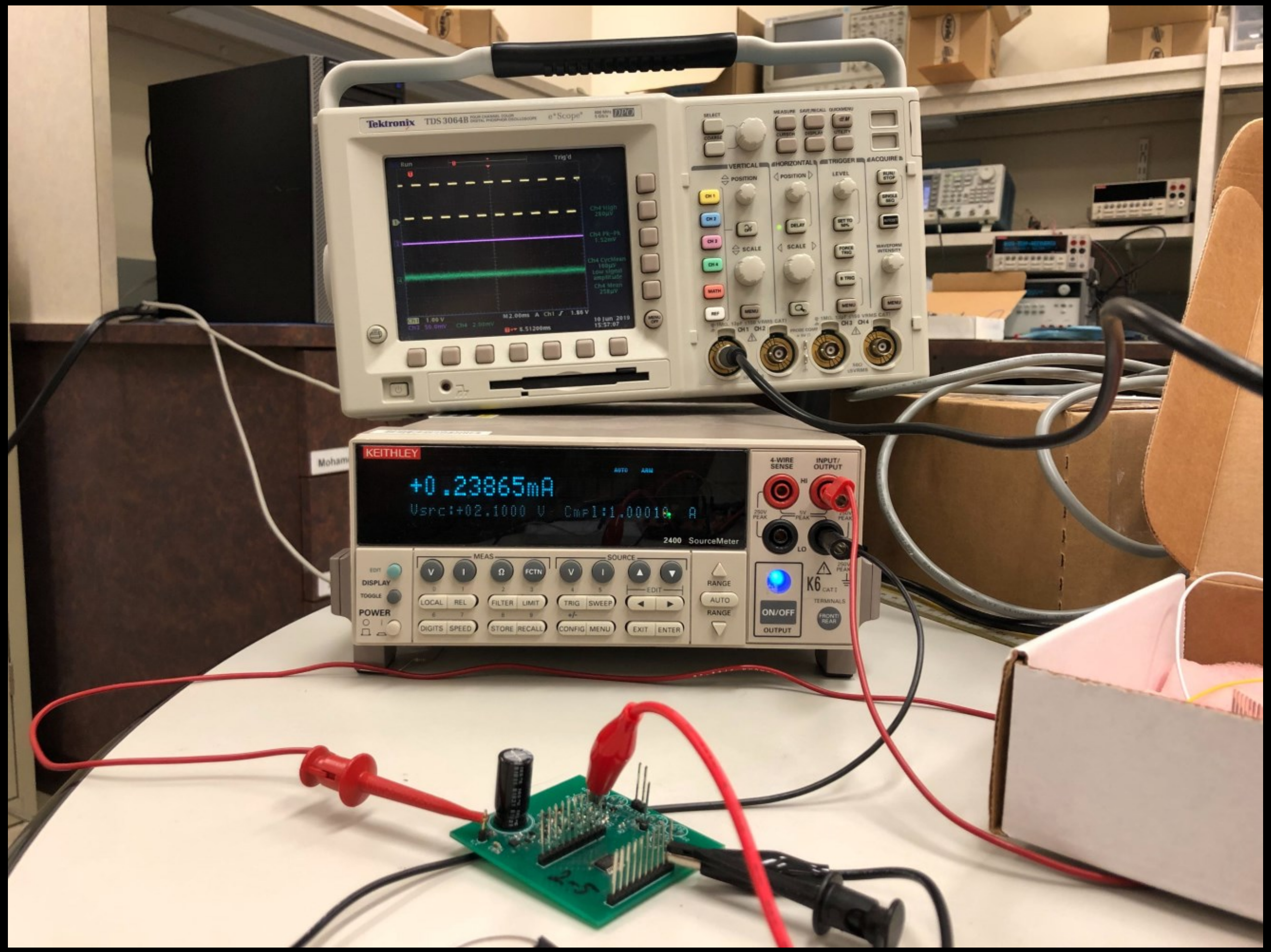
Aquarian H2A

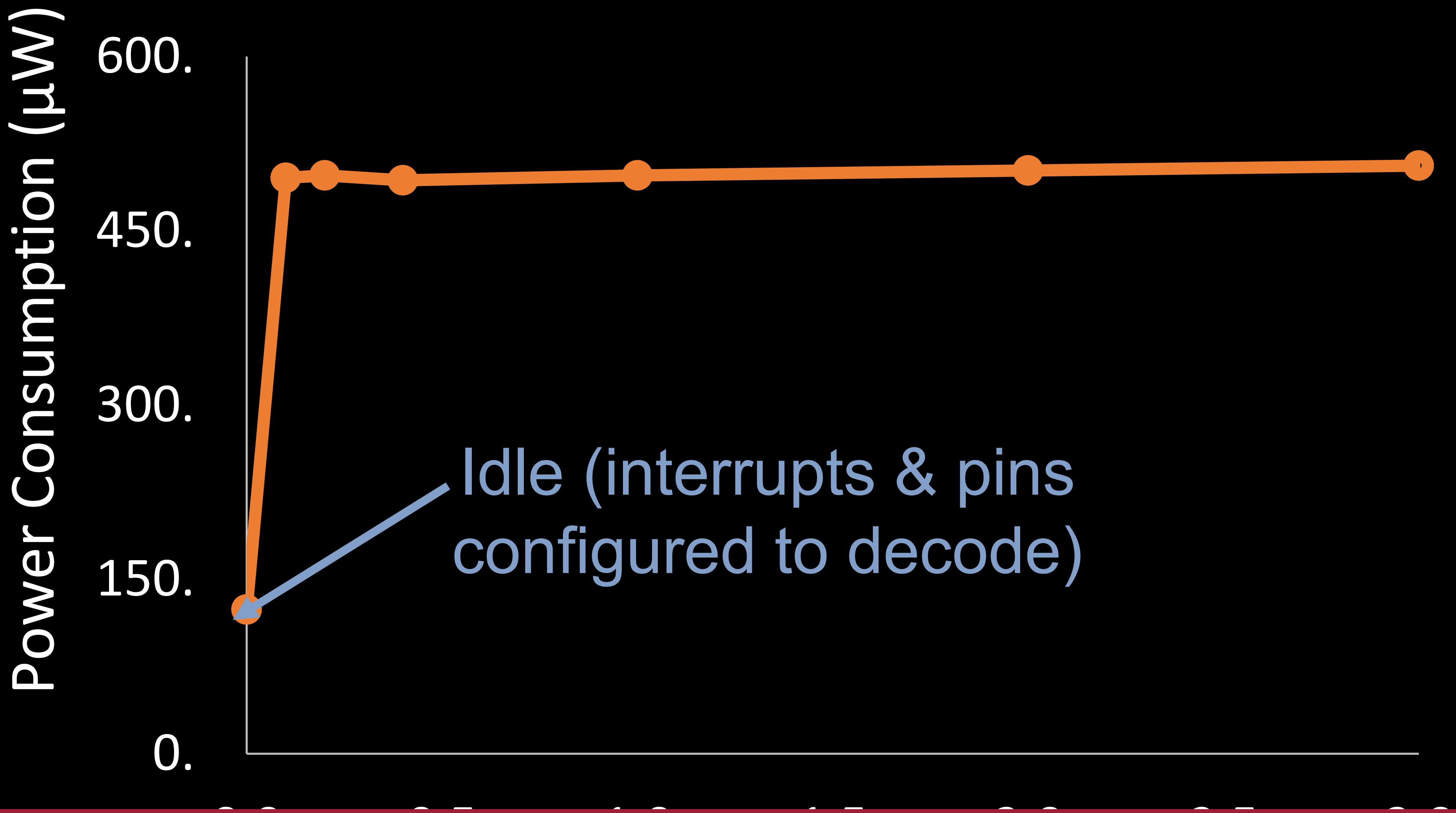
Implementation



Power Consumption

Empirically measured using Keithley 2400 source meter

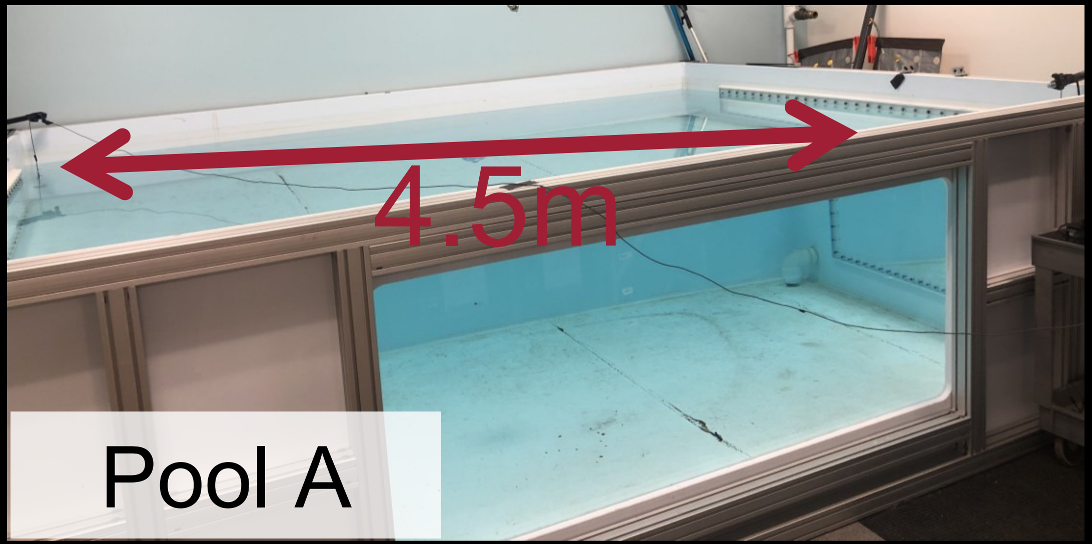


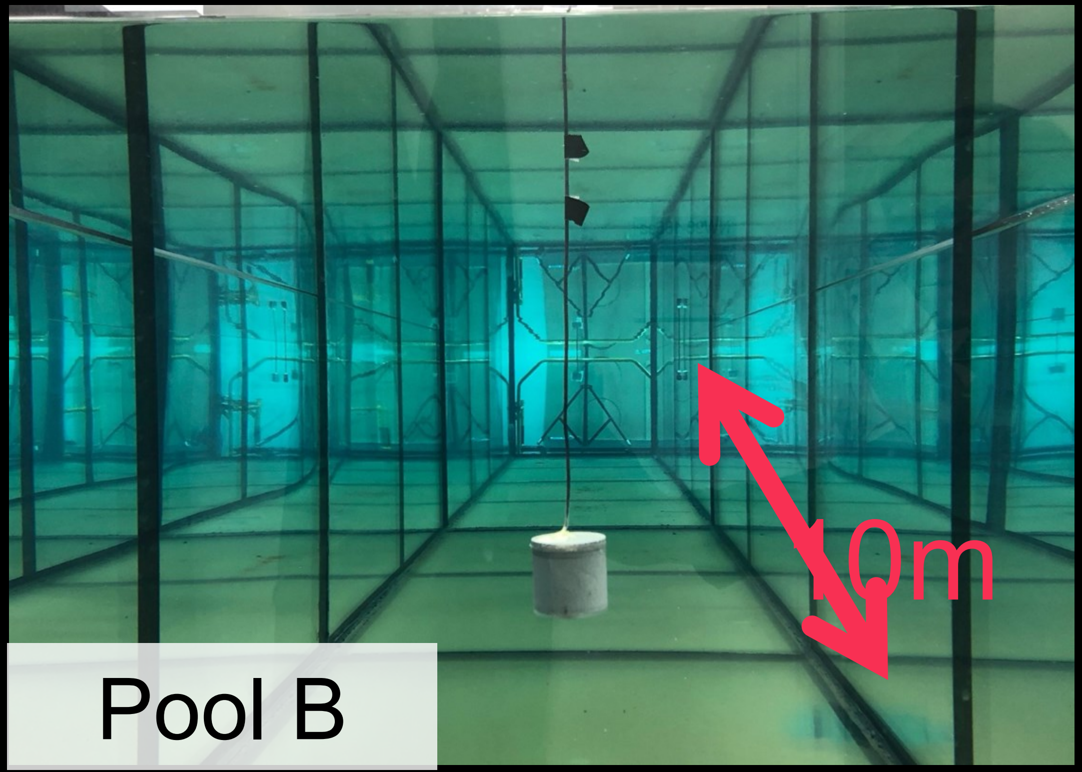


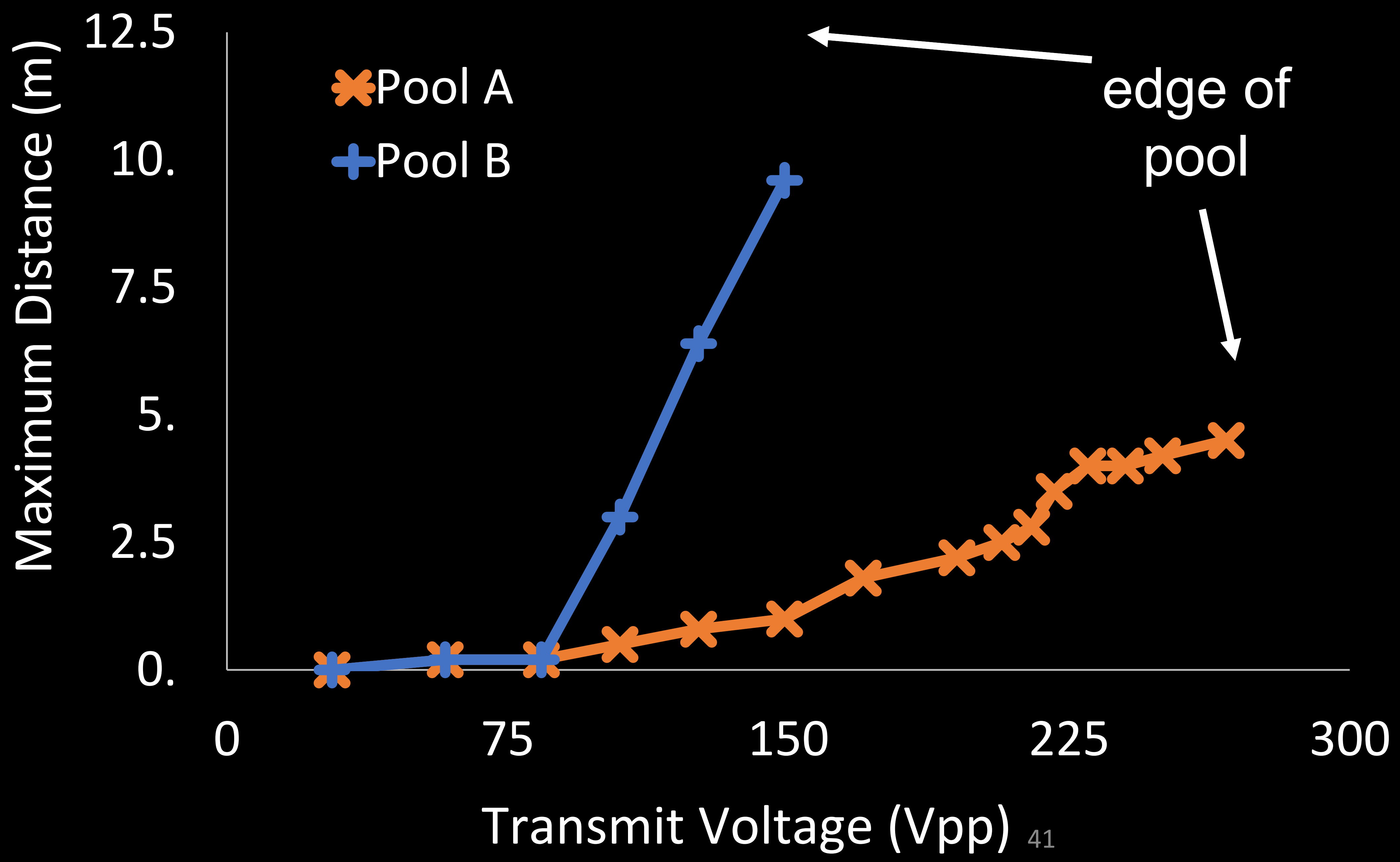
1 million times less power than state-of-the-art low-power underwater sensors [WHOI micro-modem 2019]

Power-up Range

Experiment: Vary power and distance to sensor

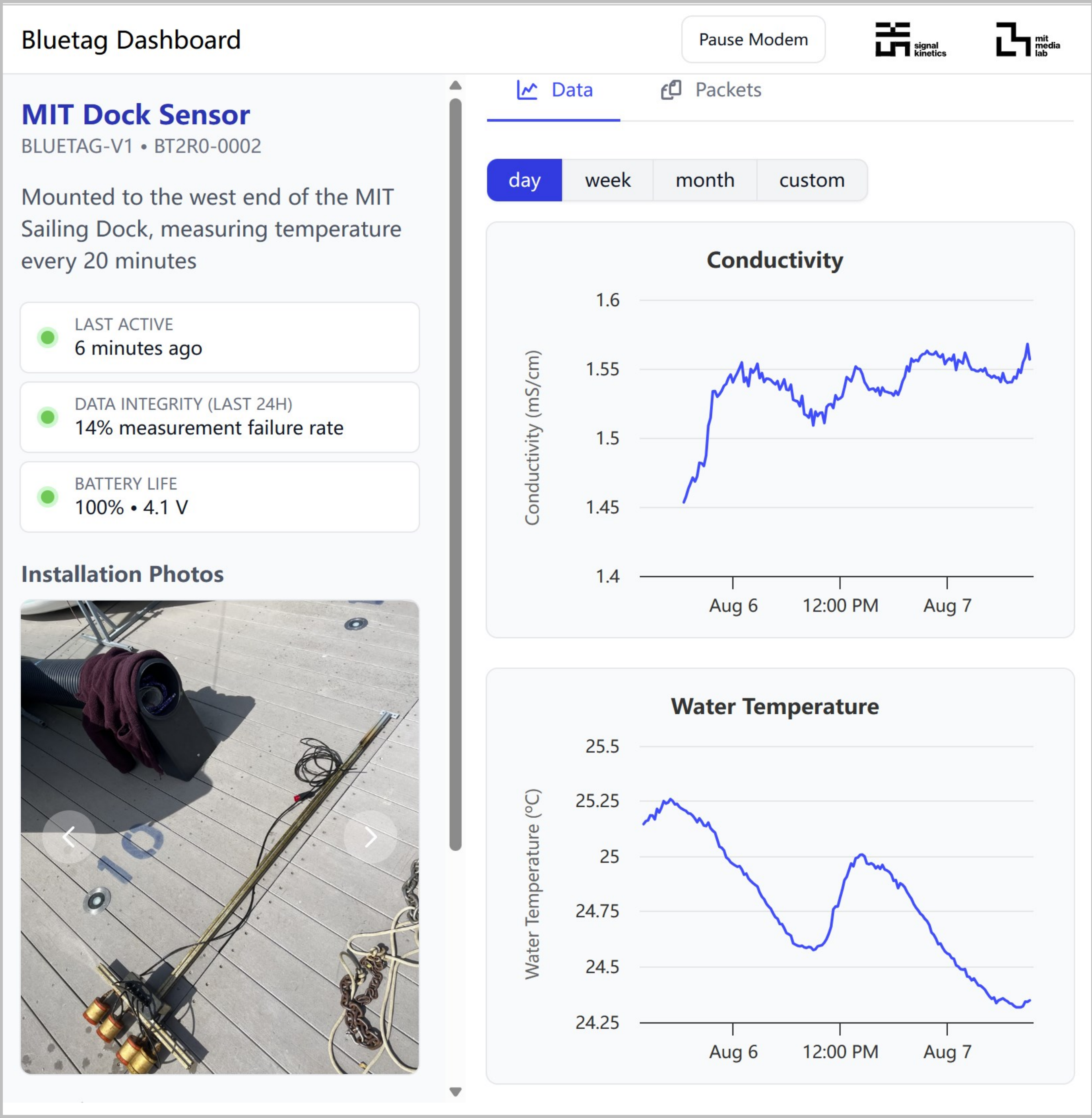






1,000s of experimental trials

battery-free node with
temp & pressure senso

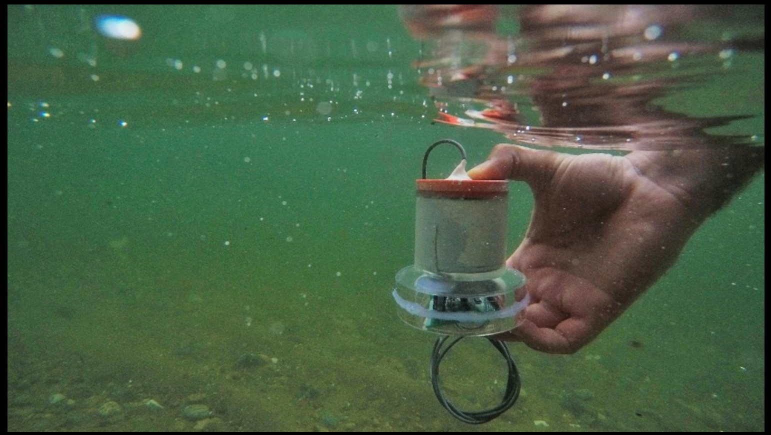


Live long-term deployment in Charles River since June
https://sk-modem.mit.edu/

Underwater Backscatter

[ACM SIGCOMM'19]

Principles of underwater Backscatter (this lecture)



- 1 million times more energy-efficient than conventional underwater sensor networks
  - Nodes communicate by reflecting instead of generating sound
- Applications in ocean sensing, climate change monitoring, scientific discovery, aquaculture...

Led to multiple Advances

- First-of-their kind systems: first battery-free underwater camera, battery-free underwater GPS, etc.

  (Nature Communications'22, IROS'23, MobiCom'25...)

- New comms theory for underwater backscatter

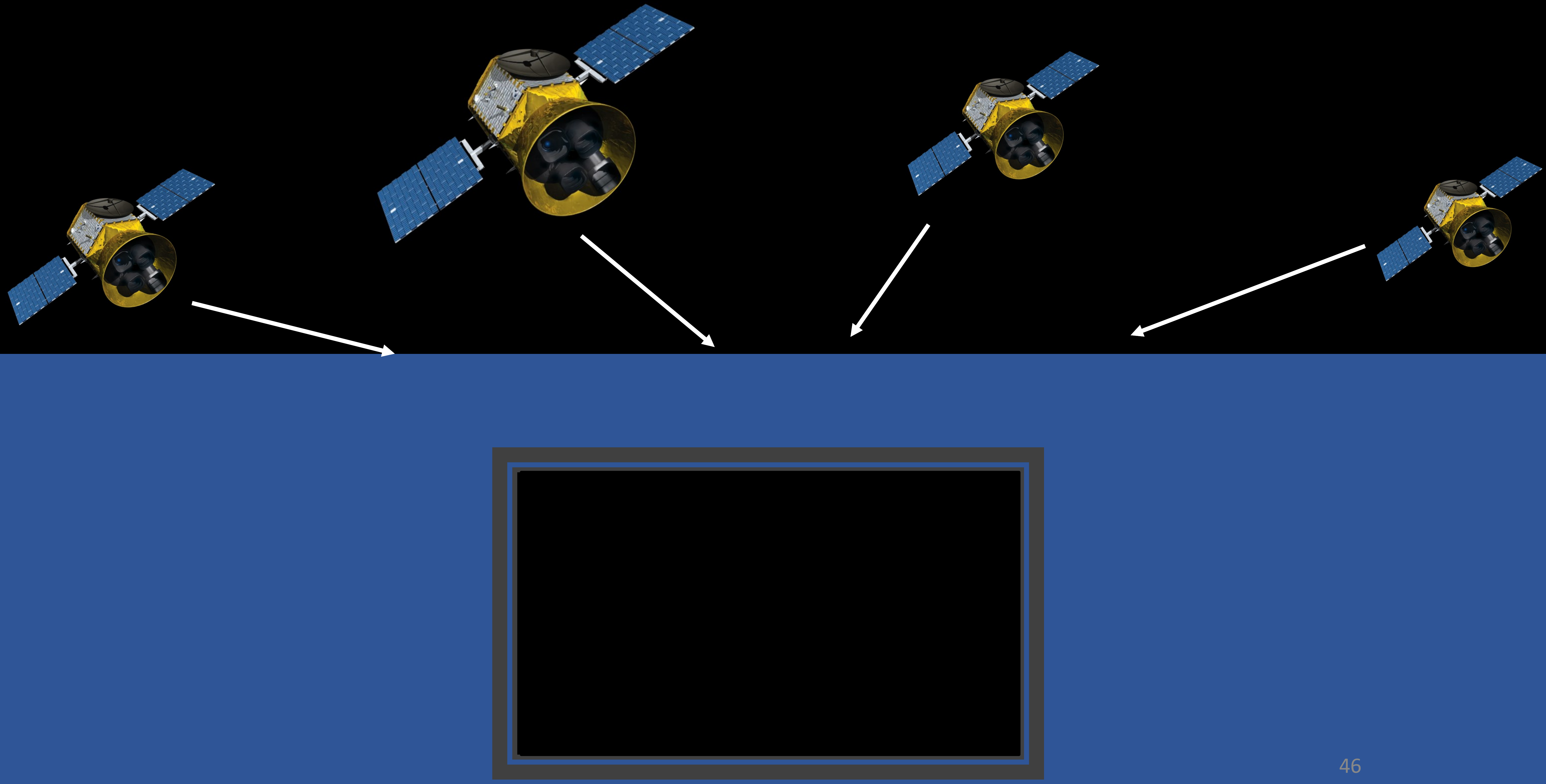
  (MobiCom'23, IEEE J. Ocean Eng'25)

- Coastal deployment & testing in the Atlantic Ocean (Northeast), Pacific Ocean (Hawaii), Red Sea, ...

Can we enable battery-free underwater localization?

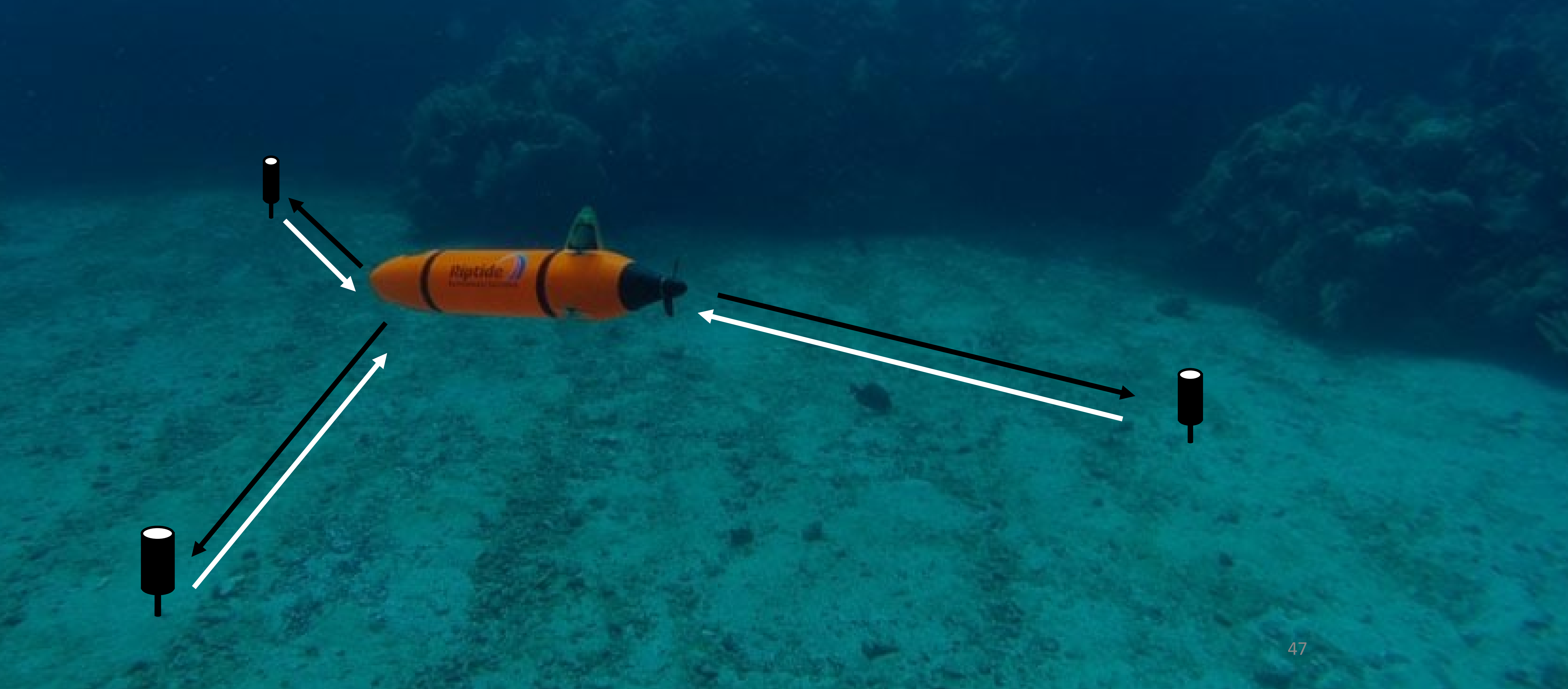
Global Positioning System (GPS)

Global Positioning System (GPS)



Conventional Underwater Positioning

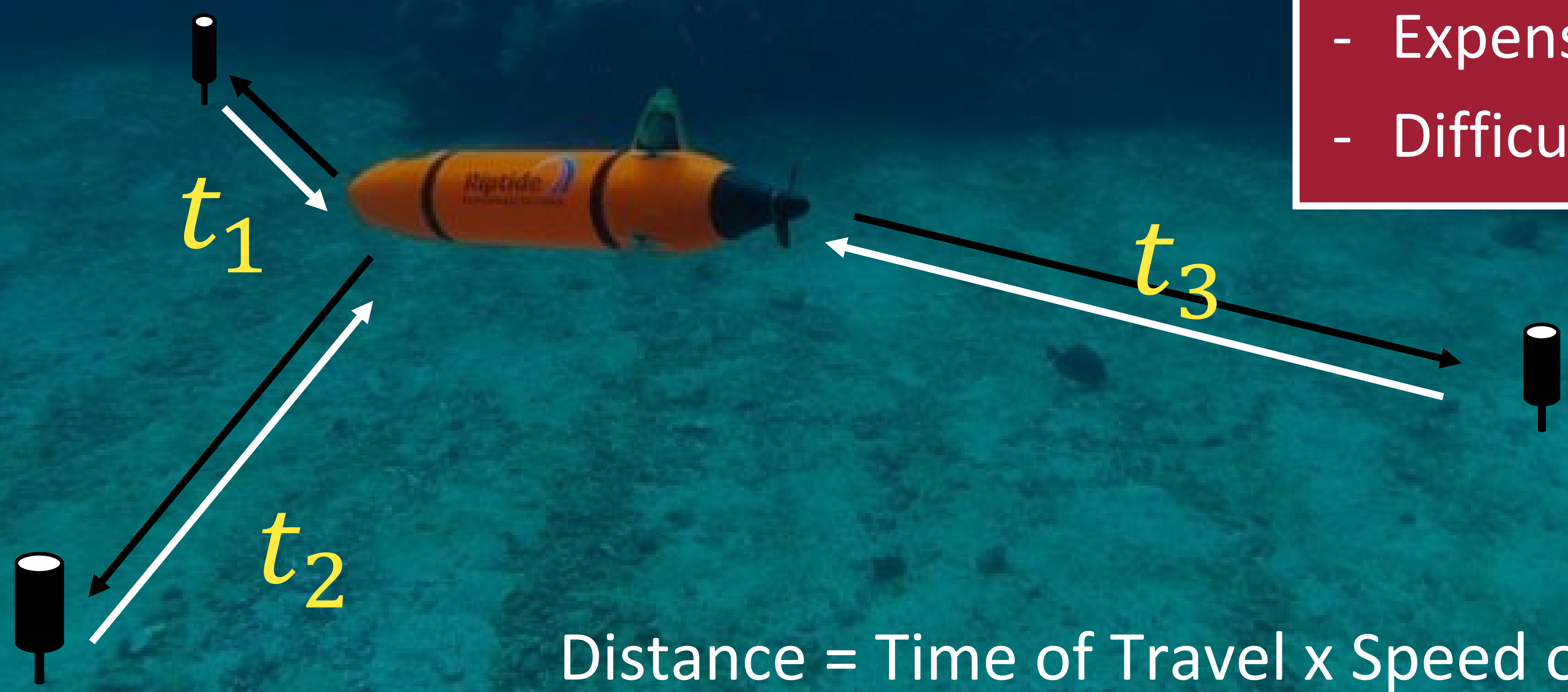
Works by measuring distances to deployed anchors



Conventional Underwater Positioning

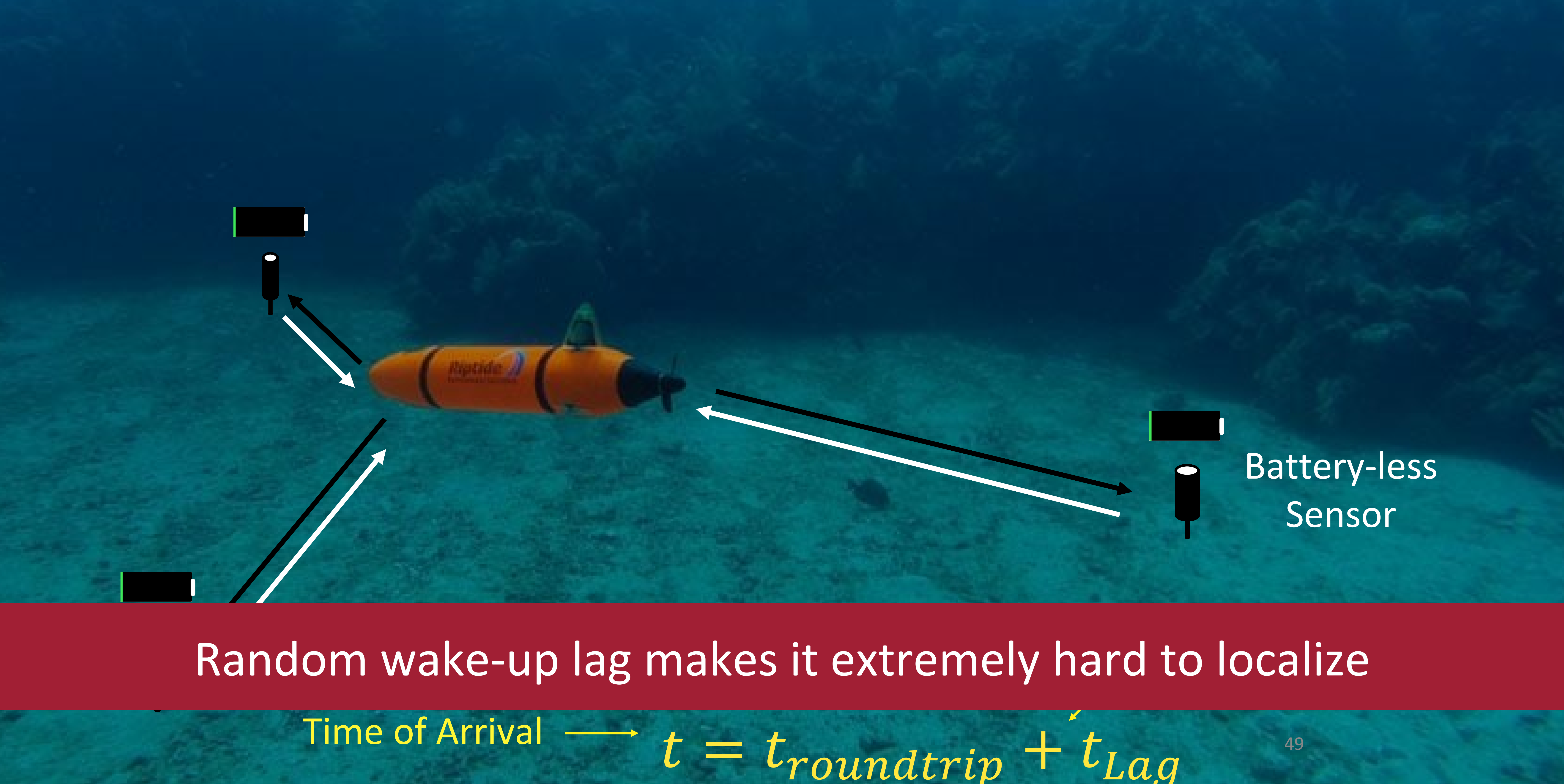
Works by measuring distances to deployed anchors

- Batteries run out of energy
- Expensive packaging
- Difficult to scale



Distance = Time of Travel x Speed of Sound

Batteryless Underwater Positioning



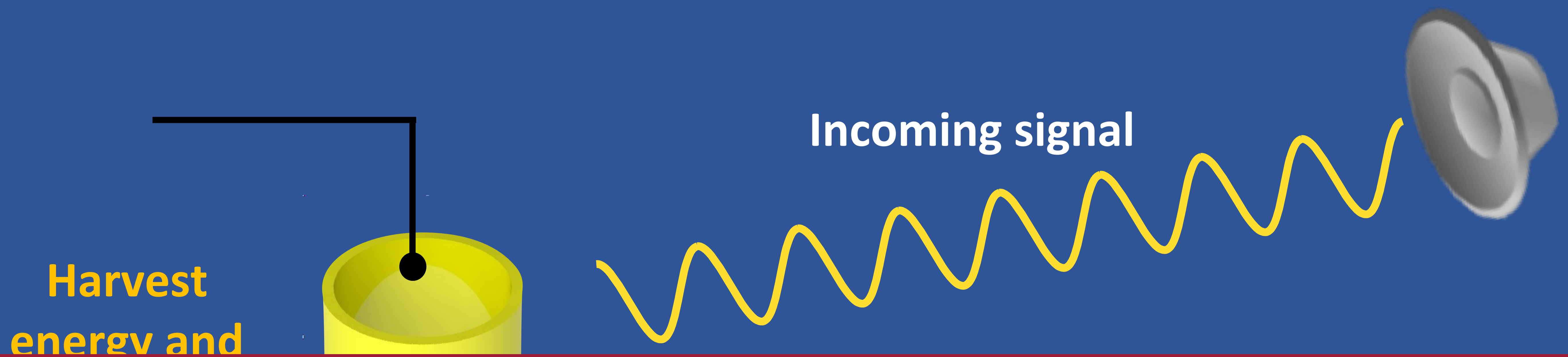
Random wake-up lag makes it extremely hard to localize

Time of Arrival ⟶ $t = t_{roundtrip} + t_{Lag}$

Key Idea: Underwater positioning using backscatter sensor

Key Idea: Underwater positioning using backscatter sensor

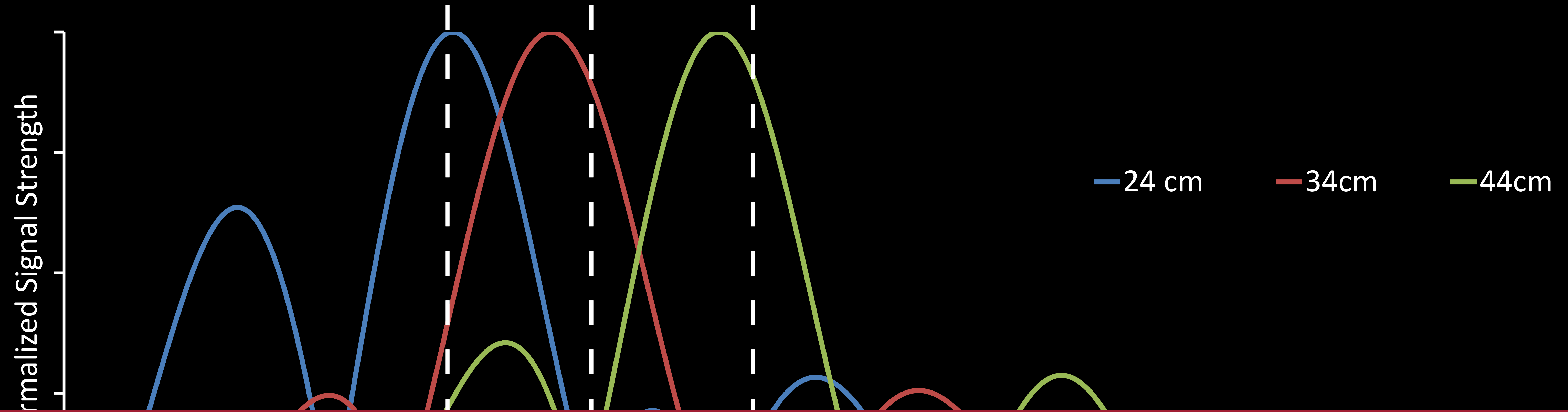
Measure "phase" instead of measuring time



Backscatter acts as a code and the phase of the continuous signal is not impacted by the wake-up lag

Use multi-frequency estimation to compute the time-of-flight from backscatter reflections [ACM HotNets'20]

Preliminary Experimental Evaluation in the River



Early results show localization accuracy of ~10 cm

We expanded this with multi-hydrophone AoA (IROS 2024) and mobility-resilient Chirp waveforms (MobiCom 2025)

Objectives of Today's Lecture

Learn the **fundamentals, emerging technologies, and applications** of ocean IoT

1. What makes underwater IoT different from in-air IoT?
2. What are the applications of underwater IoT?

Low-power underwater IoT case studies:

3. What are the core principles of underwater backscatter?
4. How to sense whale location with low-power transmit-only radio?

What is Whale Rendezvous & Why It Matters

- **Definition**: "Rendezvous" = obtaining visual observations of whales at sea surface
- **Why critical for marine biology:**
  - Validate tag deployments and sensor data
  - Photo-identification of individuals
  - Study social interactions and proximity...
- **Science Goal (Project CETI):** Decode sperm whale communication
  - Requires: acoustic data + visual context + behavioral observations

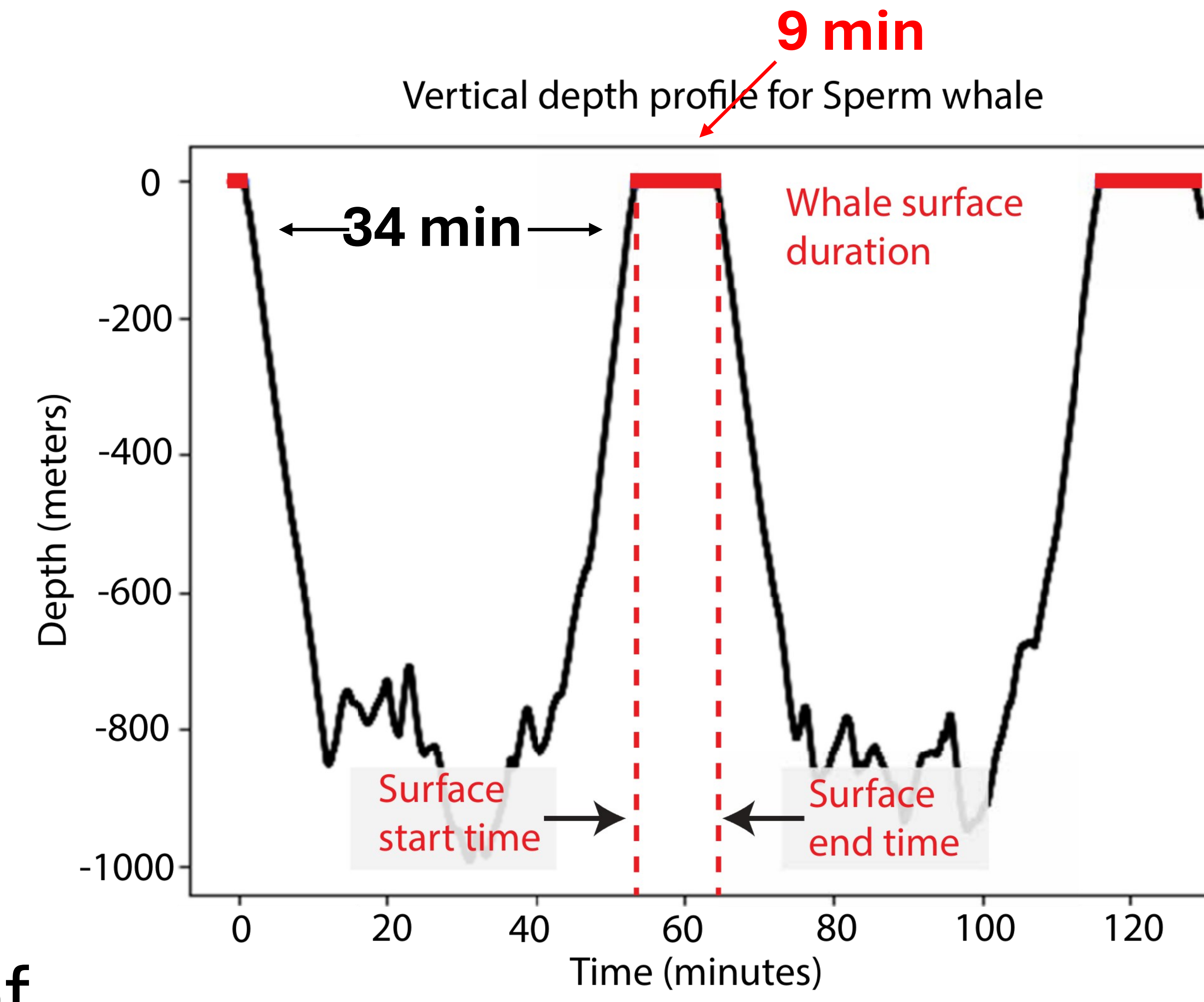
Challenges in Whale Rendezvous

- Sperm Whales Are Underwater 75% of the Time
  - Time-sensitive and stochastic occurrences

Problem: tracking whales is **labor-intensive** and **inefficient**

1. Localization requires **manual** operation of VHF directional antennas
   - Labor-intensive → can't afford large fleets → limited coverage.

2. The tracking is **reactive**, missing chances of short rendezvous windows.
   - Signal detected → Steer the boat → whale gone



How to Build an Autonomous Whale Tracking System

Sensing (whale localization)

Replaces: Manual VHF operation

Function: Autonomously localize whales

Inputs:

VHF signals from tags → VHF Drones

Acoustic clicks from whales → Hydrophones

Outputs:

Angle-of-arrival (AOA) estimates

Fused position beliefs

Results: Field-tested with Drone prototypes

Robot autonomy

Replaces: Reactive boat steering

Function: Plan optimal multi-robot routes

Inputs:

Current whale position estimates

Observed surfacing times

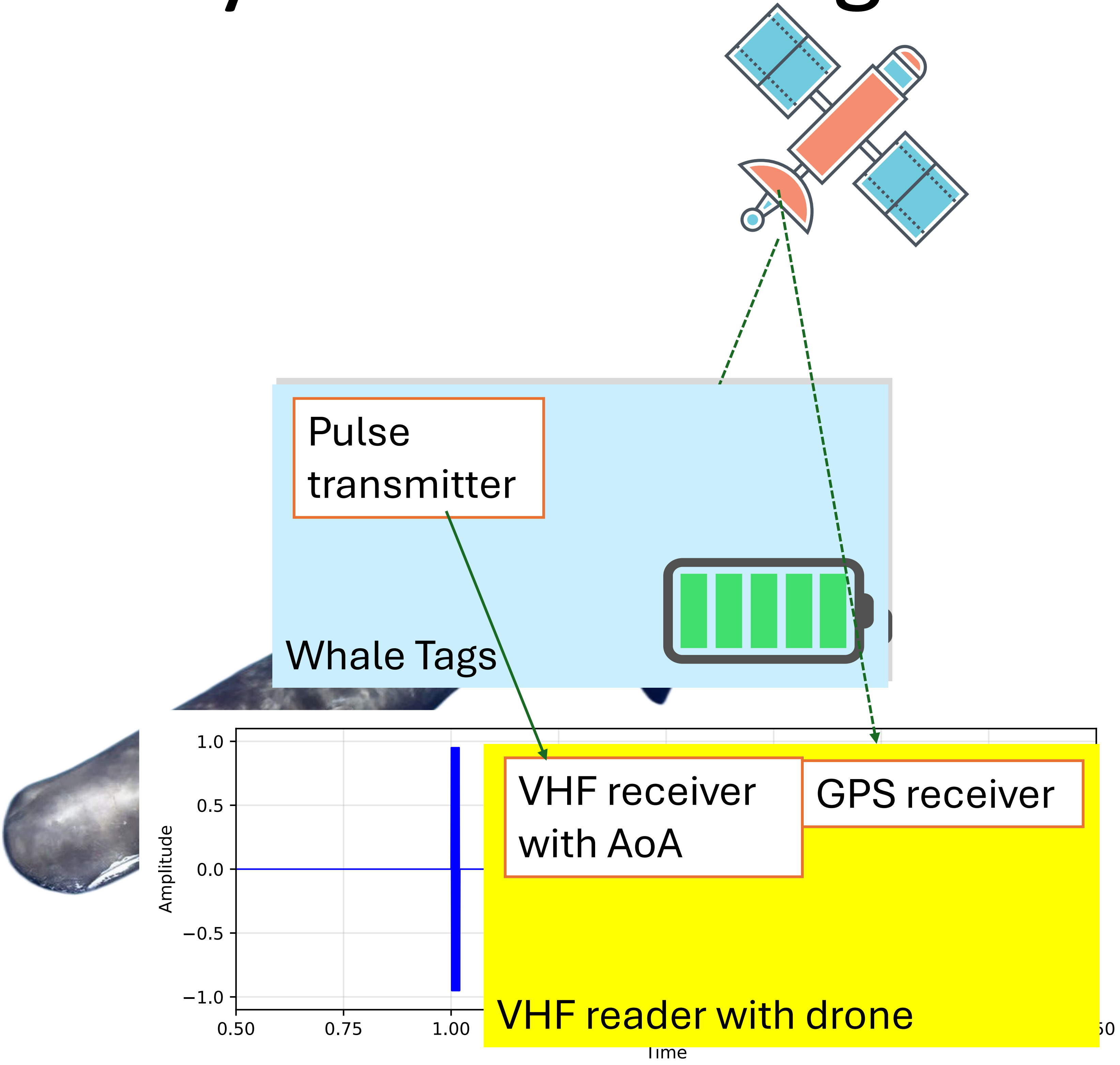
Outputs:

Whale-to-robot assignments

Robot speed & heading commands

Results: Trace driven simulation

Why VHF Pulse Tags? Power-Efficiency Trade-offs



- GPS receiver is power hungry
  - Always-on reception (with LNA)
  - Transmits location data back
  - Shortens deployments time
- Transmit-only VHF tags
  - VHF: ~150 MHz, CW pulse
  - Pulse width (radio ON): 20ms typ
  - Pulse interval: 1 sec typ (1:50)
- Battery life example:
  10dBm, 80%-efficient PA ➔ 0.25mW avg

@ 3.6V * 8Ah ➔ 10^5 hours or **13 years**

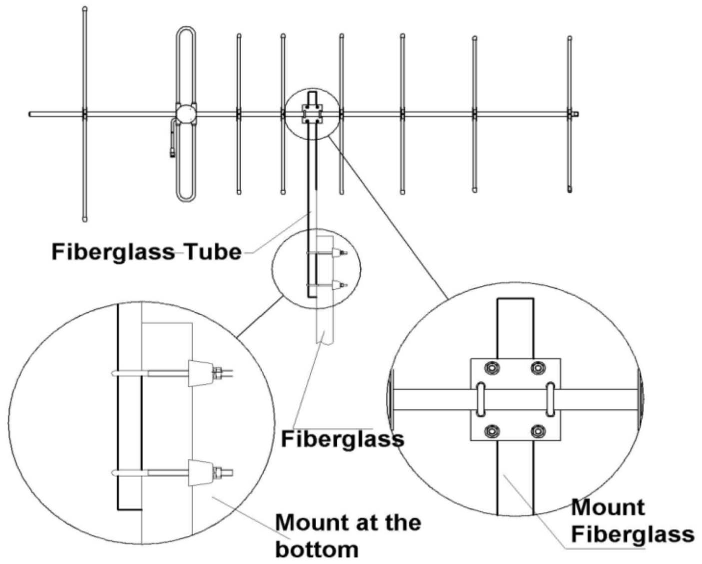
- **GPS offloaded to energy-privileged drones**

Problems with conventional VHF Tracking

Specifications

Model	TDJ-150CG
Freq.Range-MHz	134~173
Gain-dBi	11.2
Hor.Beamwidth-°	44
Ver.Beamwidth-°	40
F/B Ratio-dB	≥16
VSWR	≤1.5
Impedance-Ω	50
Polarization	Liner(Vertical or Horizontal)
Max.Power-W	100
Connector	N female or customized
Length-m	2.2 (may vary with frequency)
Weight-Kg	3.2 (may vary with frequency)
Mast Diameter-mm	40-50

Installation Sketch



1. Mount the fiberglass in the middle with assistant clamp as per, please keep the body in balance;
2. Fasten the fiberglass tube on the support pole, aiming at the direction of communication;
3. Adjust the azimuth angle of antenna to maximum the signal;
4. Fasten all the screws, do waterproof well for the connectors.

- **Manual operation:** Requires operator to sweep antenna
- **Large directional antennas:** Bulky, slow to reorient
- **Bad accuracy:** poor angular resolution given size limit

"Portable" Yagi-Uda Antenna example

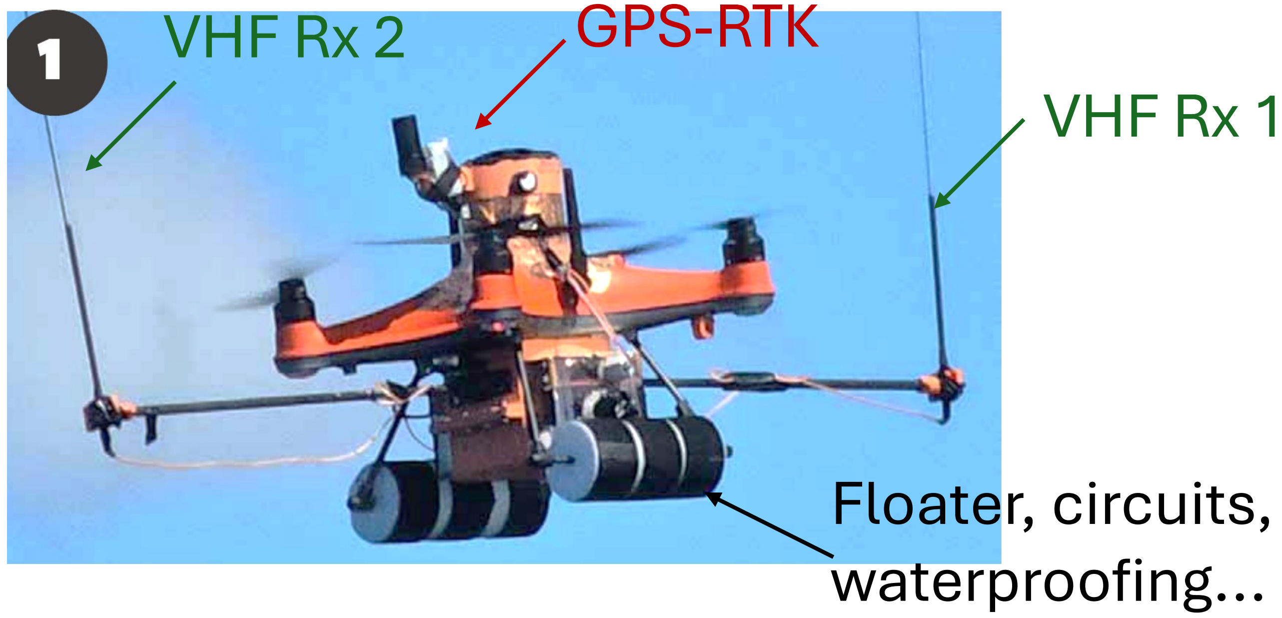
$\lambda = c / f = 3 \times 10^8$ m/s / $(150 \times 10^6$ Hz) = 2 meters

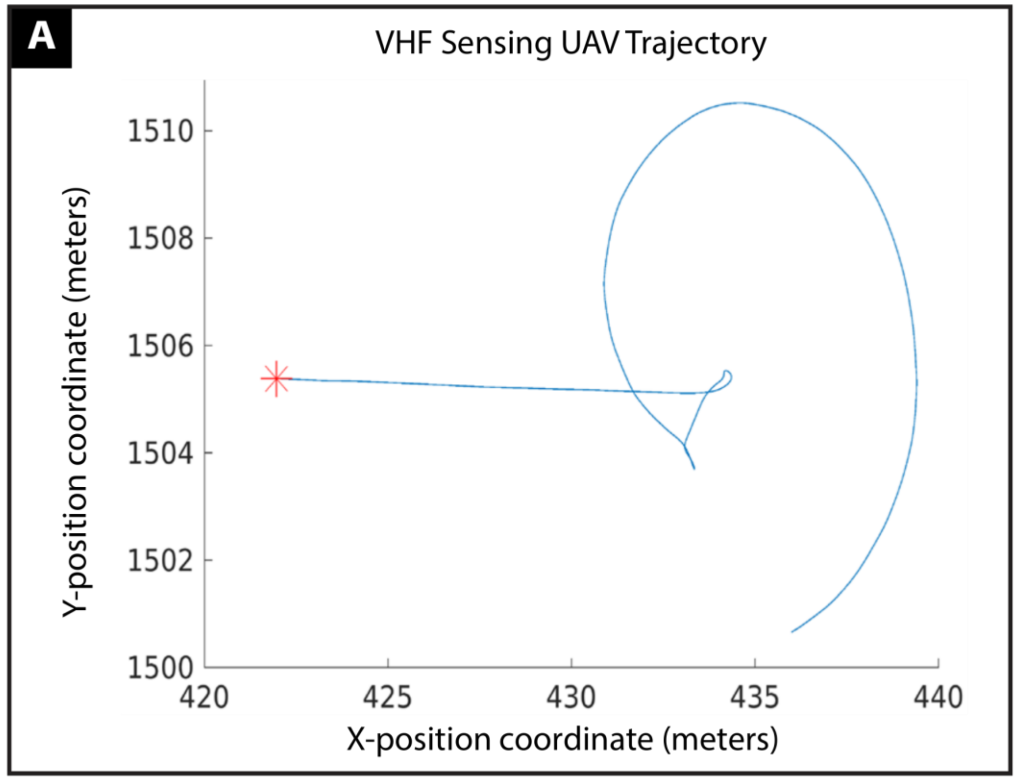
Director Spacing = $0.15\lambda = 0.15 \times 2$ m = 0.3 meters

Total boom length = $7 \times$ spacing = 2.1 meters

more gain (resolution) ⇔ more λs in size

Contribution: Emulating a Large Antenna Array with a Flying Radio





The Problem:

- Small UAV payload → can't fit multi-element antenna array
- Need high angular resolution for accurate bearing

The Solution: Synthetic Aperture Radar (SAR)

- UAV flies arbitrary path collecting VHF pulses (~40 sec)
- Motion creates **virtual circular array** in post-processing – Array shape from GPS (cm accuracy)
- Two omnidirectional antennas (≥λ/2 separation)

Challenge: Carrier-Frequency Offset (CFO)

- Wildlife VHF tags use **low-cost crystal oscillators**
  - Each pulse has **arbitrary initial phase** $\psi(t)$
- Single-Antenna SAR: At UAV position i (Assume orientation $\phi_i = 0$), receiving signal from tag at direction (ϕ_T) from distance d:

$$\widehat{h_i} = \underbrace{A \cdot \exp j\psi(t_i)}_{\text{CFO term}} \cdot \exp\left(j\frac{2\pi d}{\lambda}\cos(\phi_T)\right)$$

- Hologram: $f(\phi) = \left|\frac{1}{n}\sum_{i=1}^{n}\left(\widehat{h_i} \cdot a_i^*(\phi)\right)\right|^2$
  - Steering vector: $a_i(\phi) = \exp\left(j\frac{2\pi d}{\lambda}\cos(\phi)\right)$

$$f(\phi) = \left|\frac{1}{n}\sum_{i=1}^{n} A \cdot \underbrace{\exp\left(j\psi(t_i)\right)}_{\text{random phases}} \cdot \exp\left(j\frac{2\pi d}{\lambda}[\cos(\phi_T) - \cos(\phi)]\right)\right|^2$$

- Expecting constructive interference at $\phi = \phi_T$, but becomes destructive with ψ factors
  - Also translation-dependent on unknown d

Solution: CFO cancellation with two antennas

- **Key Insight**: CFO is Canceling Random Phase with Relative Channel Measurements to both antennas at the same instant!

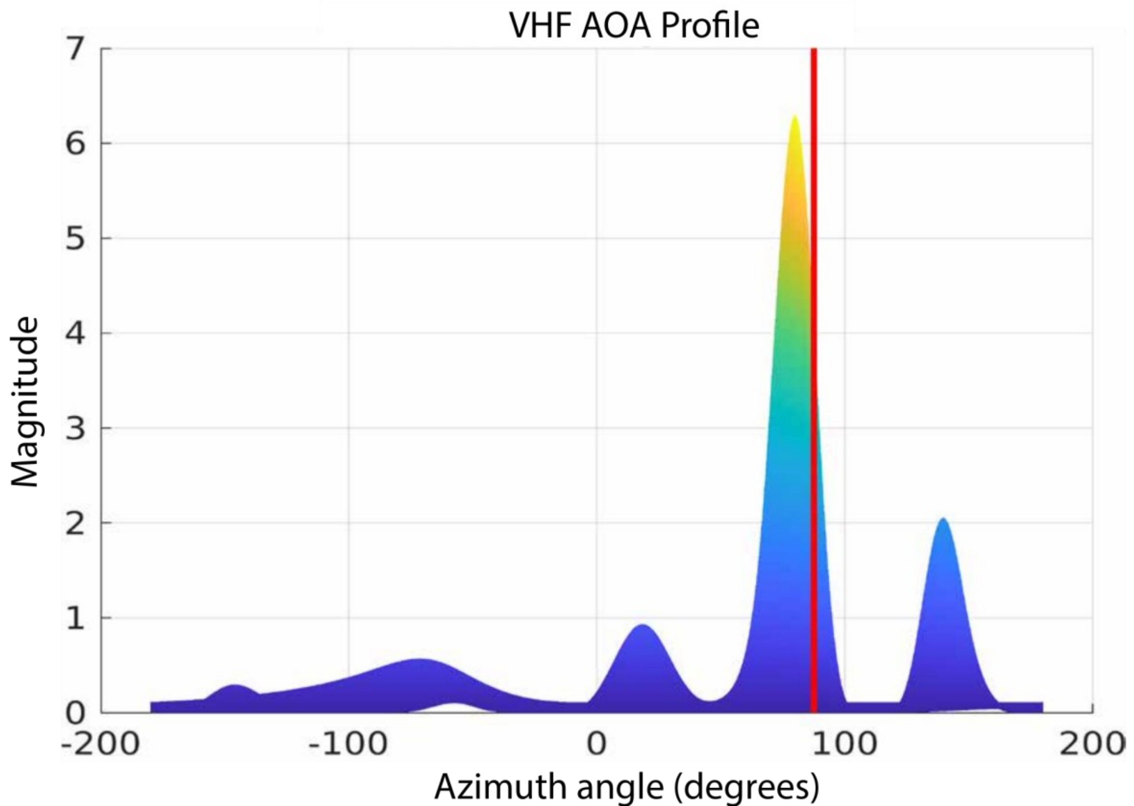
- Two receive Antennas on UAV (spaced $\Delta d = d_2 - d_1$) from tag at direction ϕ_T:

$$\widehat{h_i^{(1)}} = A \cdot \underbrace{\exp(j\psi(t_i))}_{\text{CFO}} \cdot \exp\left(j\frac{2\pi d_1}{\lambda}\cos(\phi_T)\right)$$

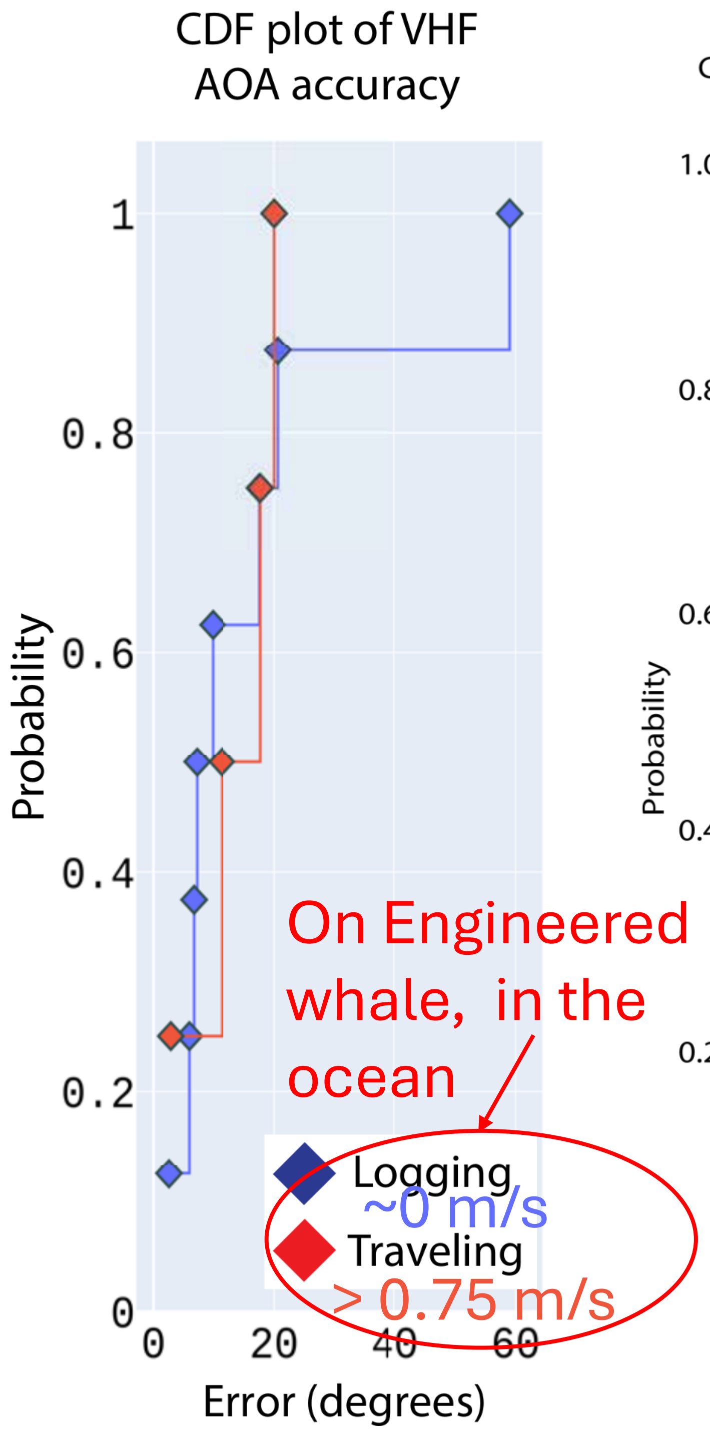
$$\widehat{h_i^{(2)}} = A \cdot \underbrace{\exp(j\psi(t_i))}_{\text{same CFO!}} \cdot \exp\left(j\frac{2\pi d_2}{\lambda}\cos(\phi_T)\right)$$

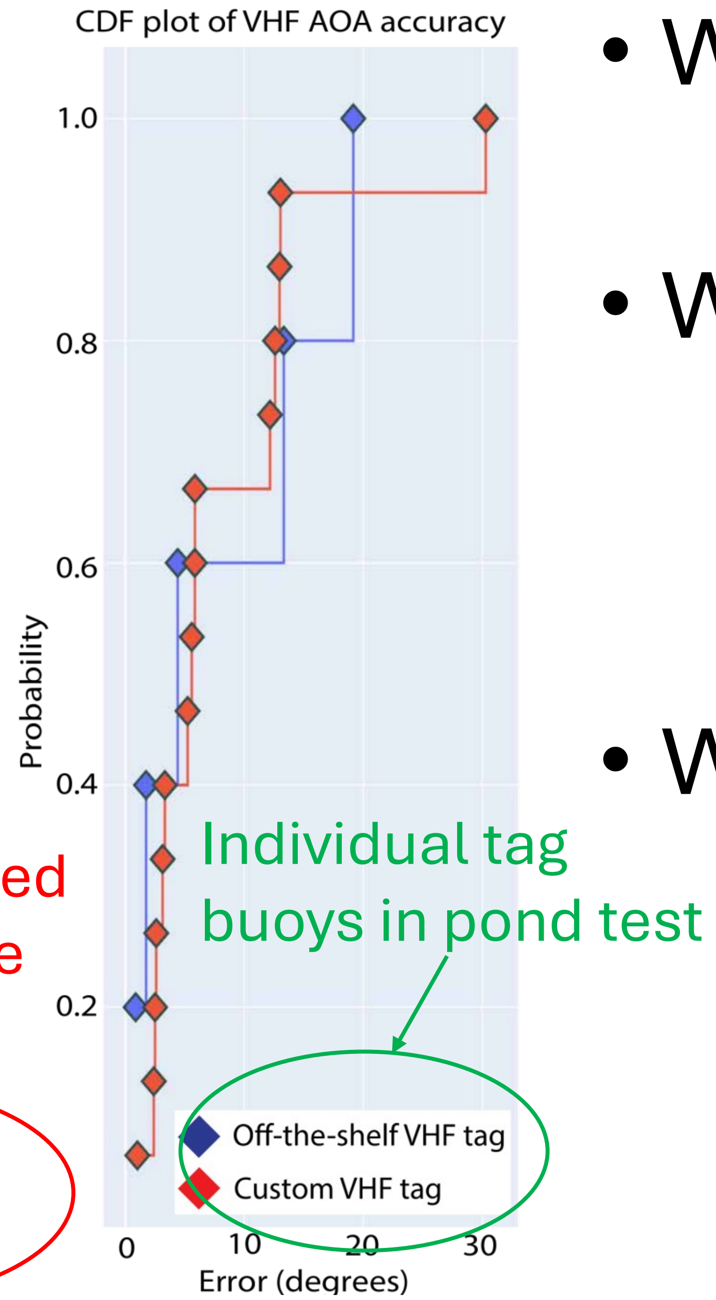
- Relative channel: $\widehat{h_i} = \widehat{h_i^{(2)}} \cdot \left(\widehat{h_i^{(1)}}\right)^* = \frac{A^2}{\text{const}} \cdot \exp\left(j\frac{2\pi\Delta d}{\lambda}\cos(\phi_T)\right)$
  - CFO terms disappears and phase only depends on geometry
  - Hologram produces perfect peak at $\phi = \phi_T$

$$f(\phi) = \left|\frac{1}{n}\sum_{i=1}^{n} \widehat{h_i} \cdot \exp\left(j\frac{2\pi\Delta r}{\lambda}\cos(\phi)\right)\right|^2$$



VHF AoA results





- What's wrong with this plot?
  - 12 samples total, lacking statistical rigor
- Why so few samples?
  - Mobility + Remote mission + uncontrolled environments + many devices to operate
  - Slightly better (17+8) in controlled pond tests
- What can we "honestly" conclude?

✅ Proof of concept – prototype survived

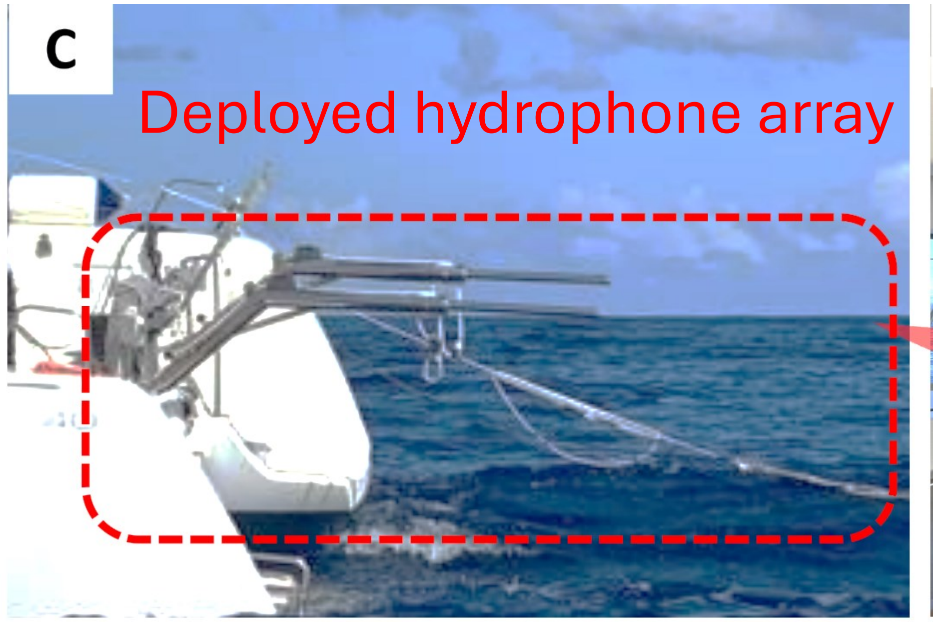
✅ Order of magnitude: ~10° Error, ocean tests varies more than pond/static tests

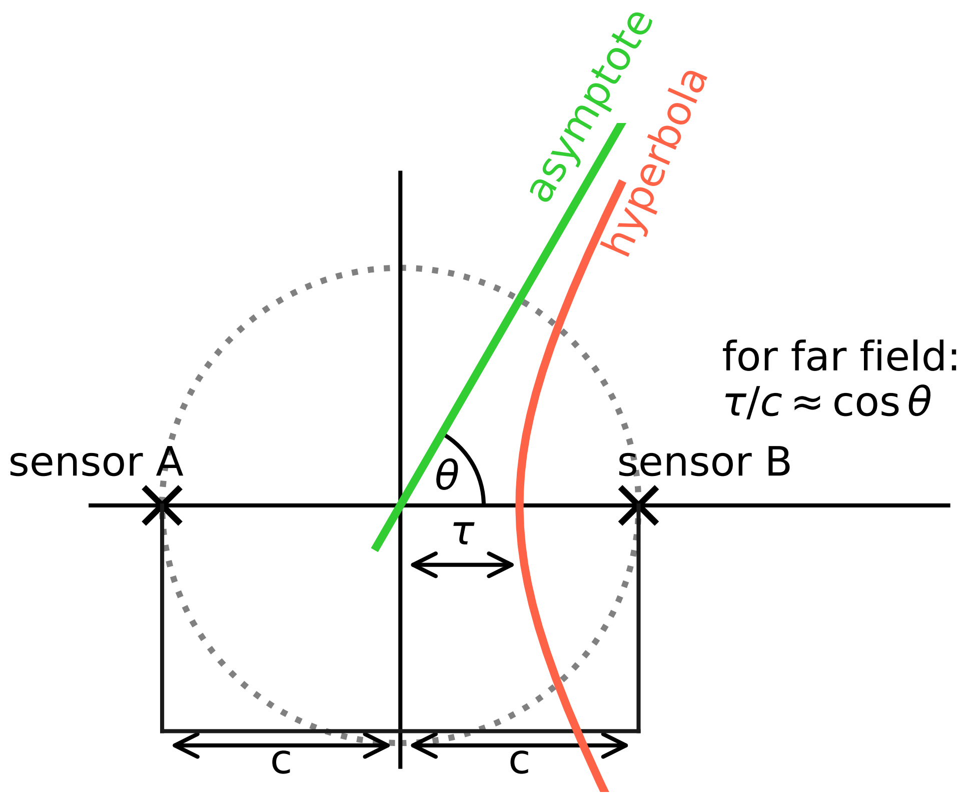
❌ Impact of whale mobility on system performance

Why need both VHF and Acoustic AoA?

	VHF (This Paper's Focus)	**Acoustic (existing tool: PAMGuard)**
Medium	Air ✓ / Water ✗	Air ✗ / Water ✓
Phase coverage	**Surface only (~25%)**	**Underwater only (~75%)**
Source	Artificial tag (requires tagging)	Whale's own clicks (passive)
Signal timing	**Periodic: 1 Hz reliable pulses**	Sporadic: irregular clicks
Interference (SINR)	Relatively cleaner channel	"Constant lookout for neighboring fishing or tourist boats"
Critical for...	Detecting surfacing events	Tracking during long dives

Acoustic AOA - Listening to Whale Clicks





- Data input: hydrophone array
- PAMGuard detects and filters whale "clicks" sound pulses
- Correlation with signal generates time of arrival
- Angle θ from Time **Difference** on hydrophones
- Kalman filter (**UKF**) fuses sensor and past data

New Location estimate = Filter(**Past** location belief, **new** noisy AoA)

Results: "Estimated" 3° error – but picky on environments

Autonomous rendezvous

Goal: Meet the whale (location constraint) when it surfaces next time (time constraint)

Available Inputs are Noisy:

- Whale position estimates, e.g. $\pm 10°$ AoA and ± 400 m location
- Observed surfacing times (noisy future predictions, e.g. surfaced now, will surface again in 40 ± 10 min)

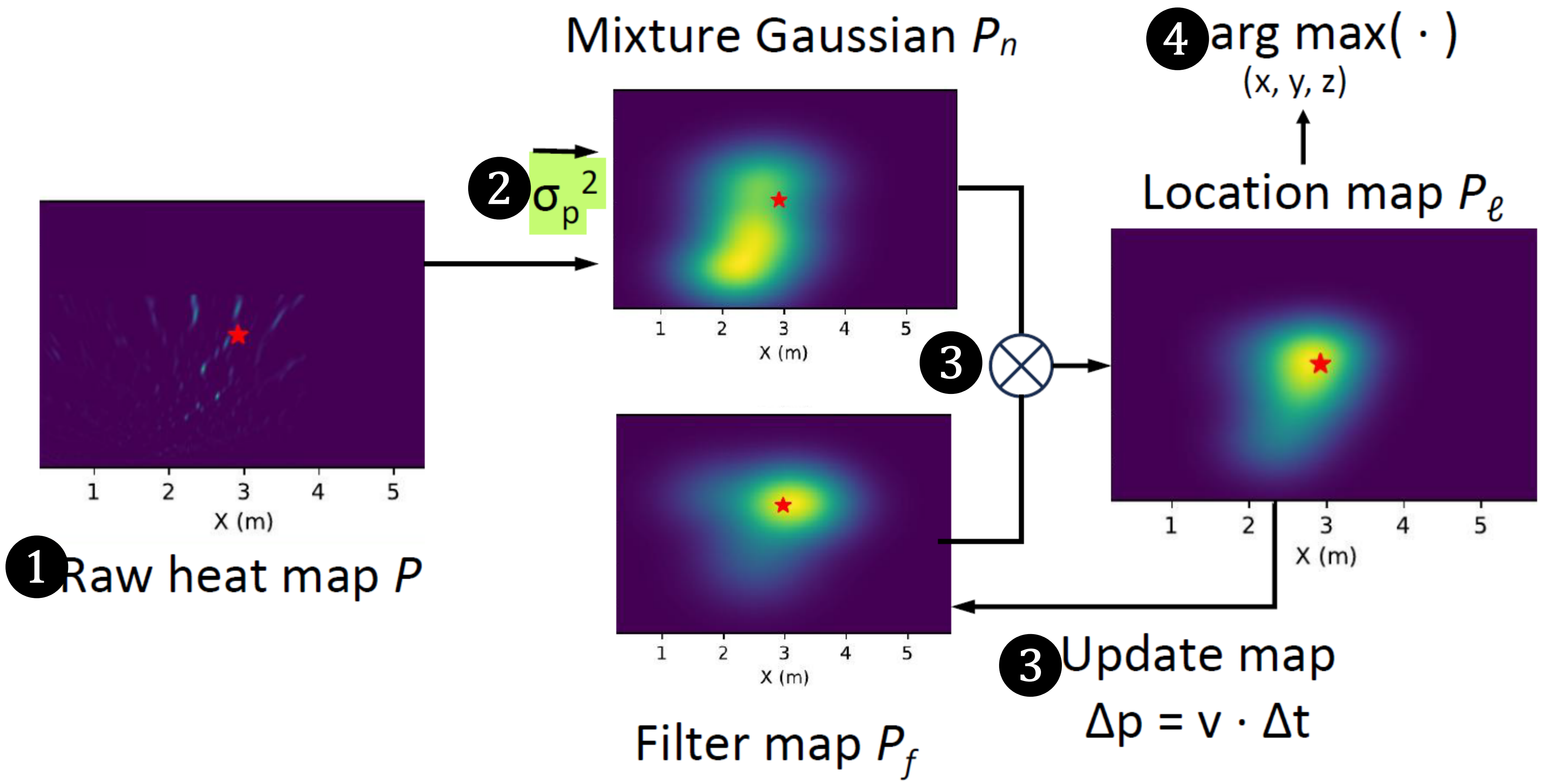
How to tackle the uncertainty?

1. **Model the statistical distribution** of whale states (position + time)

2. **High level policy: assign** which robot head to which whale that maximizes **expected** rendezvous success over planning horizon

3. Low-level execution: Navigate to assigned whale at specific speed to arrive when it surfaces

Particle filter modeling the whale statistics



- Idea: Represent uncertainty with a collection of samples (particles)
- Example: 2D localization that are spatial-temporally dependent
  - ❶ Obtain raw measurement (scattered, spiky heatmap)
  - ❷ Diffuse it with some realistic variance σ_p^2
  - ❸ Combine current and historical particles deterministically; evolve
  - ❹ Output the best decision over the particles
- Additional dimensions for the whale task: whale velocity, surface times, reachability.

Example: Particle filter for estimating **location**

[3D-BLUE: Backscatter Localization for Underwater Robotics (IROS')]

End-to-end robotic rendezvous with whales?

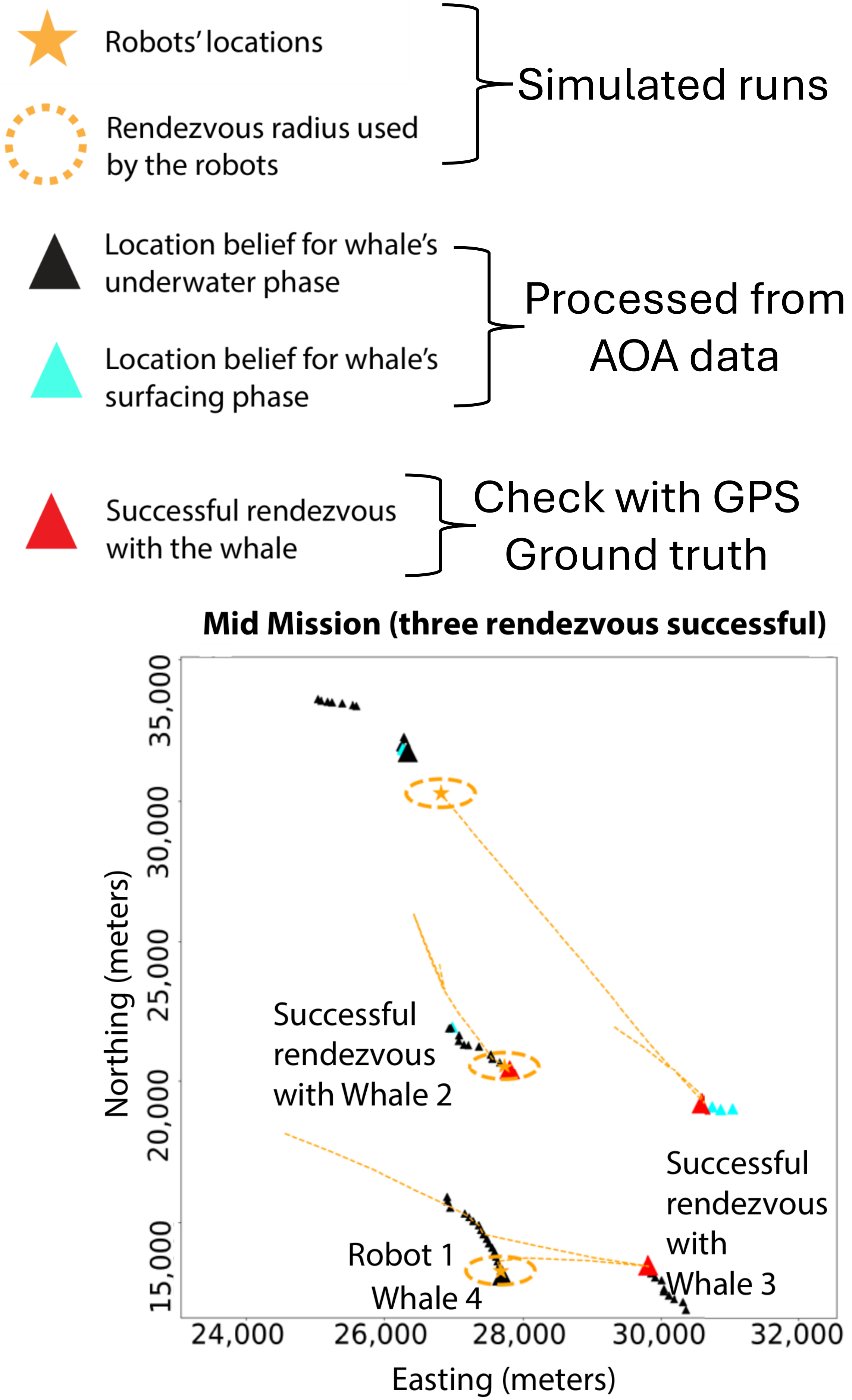
Requirement for end-to-end tests	Current Status
Deploy VHF tags on whales	❌ Only collecting acoustics from whales
Real-time AoA (acoustic and VHF), communicated across robots	❌ recorded and processed offline
Distributed multi-agent policy	❌ Centralized policy that iteratively rollout each robot
Maritime (ruggedized) aerial drones + surface vehicles	❌ Only aerial drones

SYSTEMS LESSON: Staged Validation Under Practical Constraints

- Pond tests → Engineered whale → ~~(Future) Real whales + real robots~~
- Prove algorithms work with real sensors before solving deployment infrastructure

Trace driven simulation

- **Collect real sensor data at sea with timestamps:**
  - VHF AOA from UAV flights
  - Acoustic AOA from towed array
  - Ground truth whale positions – “Engineered whale” with GPS
- **Replay in simulation:**
  - Feed real sensor measurements to autonomy algorithm
  - Apply planning commands to virtual robots
  - Simulate robot movements (v_{max} = 15 m/s)
- **Key assumption:** Robot actions **do NOT affect** whale behavior
  - Allows valid replay of **real** sensor traces with **simulated** robot responses



Rendezvous radius (meters) 200 300 500

Simulation results

Success rate: % of whales with robot within ρ meters at surfacing

-- radius ~500 m vs median location error: 224 m

- VHF AoA improves success to ~50% (more accurate location)
- Greedy baseline fails (~30% success) because ignoring the future trends
  - Signal detected → Steer the robot → whale gone when robot arrives

Objectives of Today's Lecture

Learn the **fundamentals, emerging technologies, and applications** of ocean IoT

1. What makes underwater IoT different from in-air IoT?
2. What are the applications of underwater IoT?

Low-power underwater IoT case studies:

3. What are the core principles of underwater backscatter?
4. How to sense whale location with low-power transmit-only radio?

This Class: Ocean IoT

- Underwater Backscatter
- Autonomous robotic whale rendezvous

Next Class: NetAI

Students' presentation (~25 min + QA)

NeWRF: A Deep Learning Framework for Wireless Radiation Field Reconstruction and Channel Prediction @Fritz Duvigneaud

- Babel: A Scalable Pre-trained Model for Multi-Modal Sensing via Expandable Modality Alignment @Siddharth Somasundaram

Project Progress report 1 (Nov 7)