ETH zürich


# Measurement and Validation of Energy Harvesting IoT Devices

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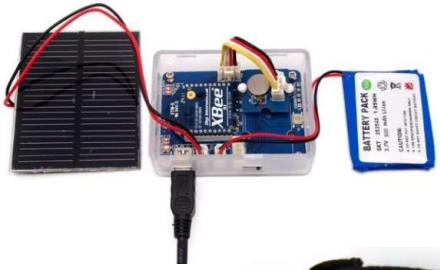
# From Battery- to Harvesting-Based Systems

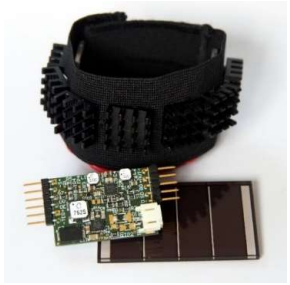
## Battery-Powered

- Constant supply


## Harvesting-Based

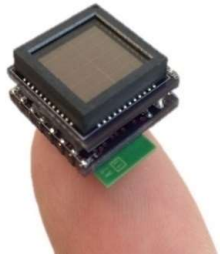
- Variable power
- Storage to mitigate variability

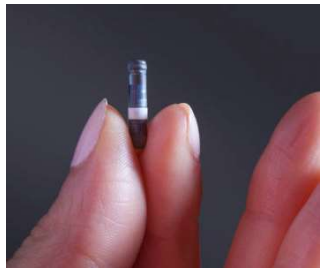


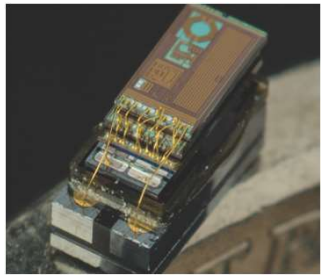



## Transient Computing

- Extremely volatile
- Design for volatility

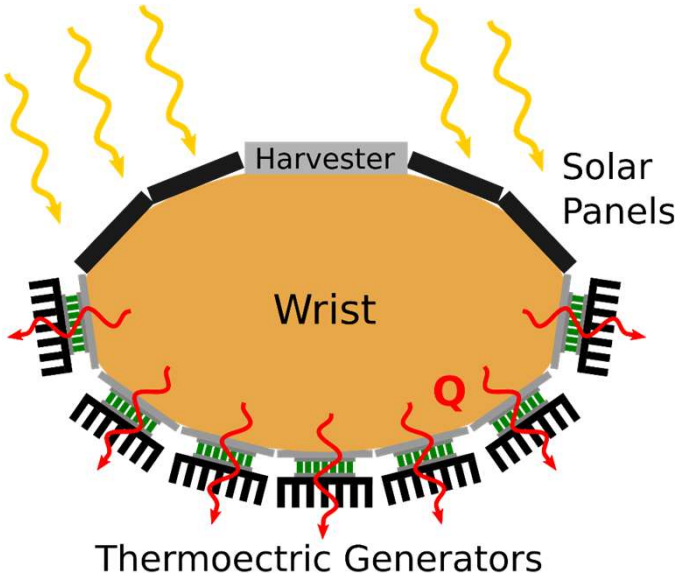






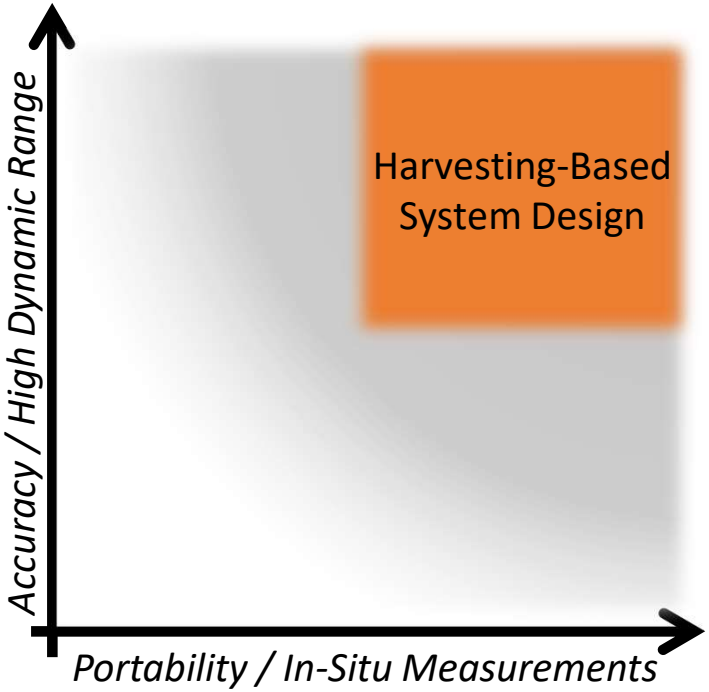
# Example: Multi-Source Wearable Harvesting

- Combining two harvesting sources
  - Solar panels harvest from sun/artificial light
  - TEG modules harvest from body heat
- Variable conditions and energy harvesting
  - Indoor and outdoor scenarios
  - Solar: 0.5 V – 4 V, 0.1 µA – 1 mA
  - Thermal: 1 mV – 100 mV,  1 µA – 1 mA



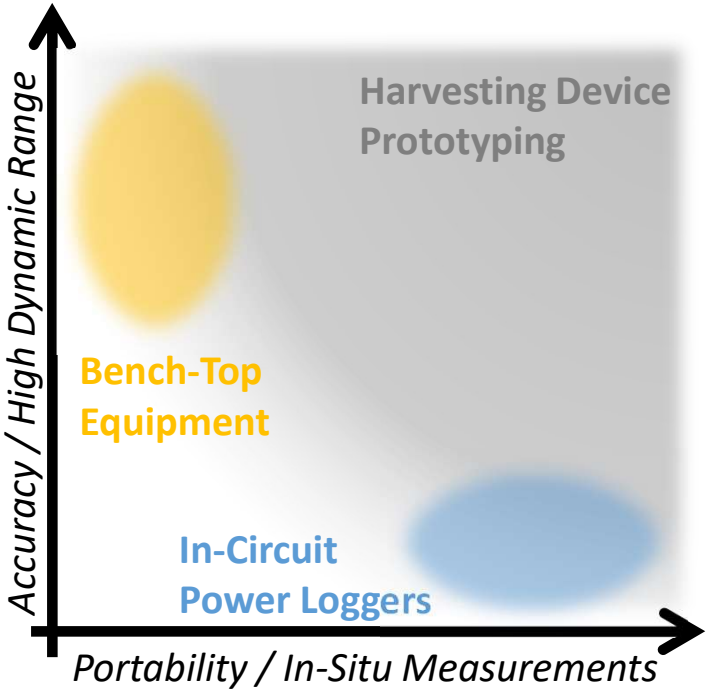
# Energy Harvesting

- New Design Challenges
  - Time variant environmental conditions
    - Impacts harvester design
    - Difficult to reproduce in the lab
  - Wide source ranges (voltage/current)
- Demands for New Development Tools
  - Record environmental conditions
  - Measure/validate in-situ
  - Ultra-low power/current scenarios



# Existing Measurement Solutions

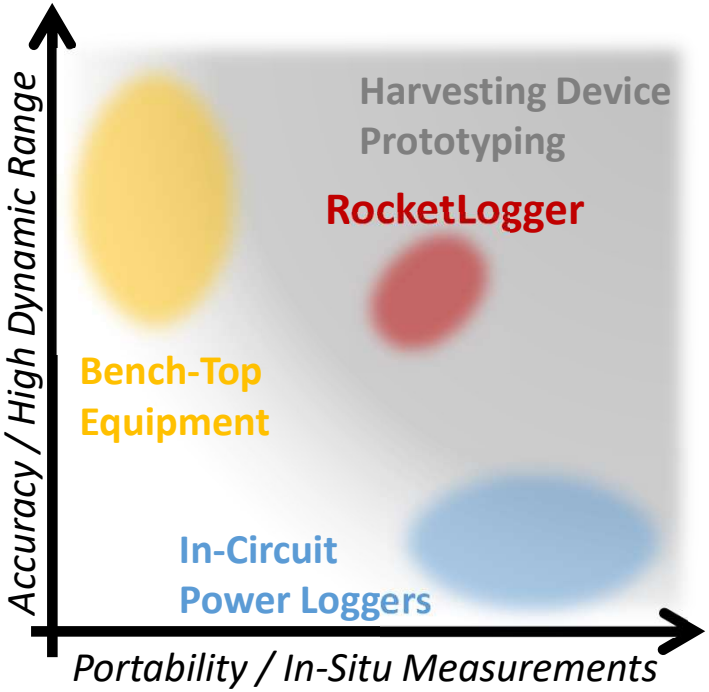
- Lab bench-top equipment
  - Keithley 2000/Keysight 34400 DMM
  - High voltage AC supply, bulky
- In-circuit power measurement
  - NEAT [1] embedded power logger
  - µMonitor [2], SPOT [3] energy monitors
  - Designed for battery powered systems
- Device do not include environmental logging



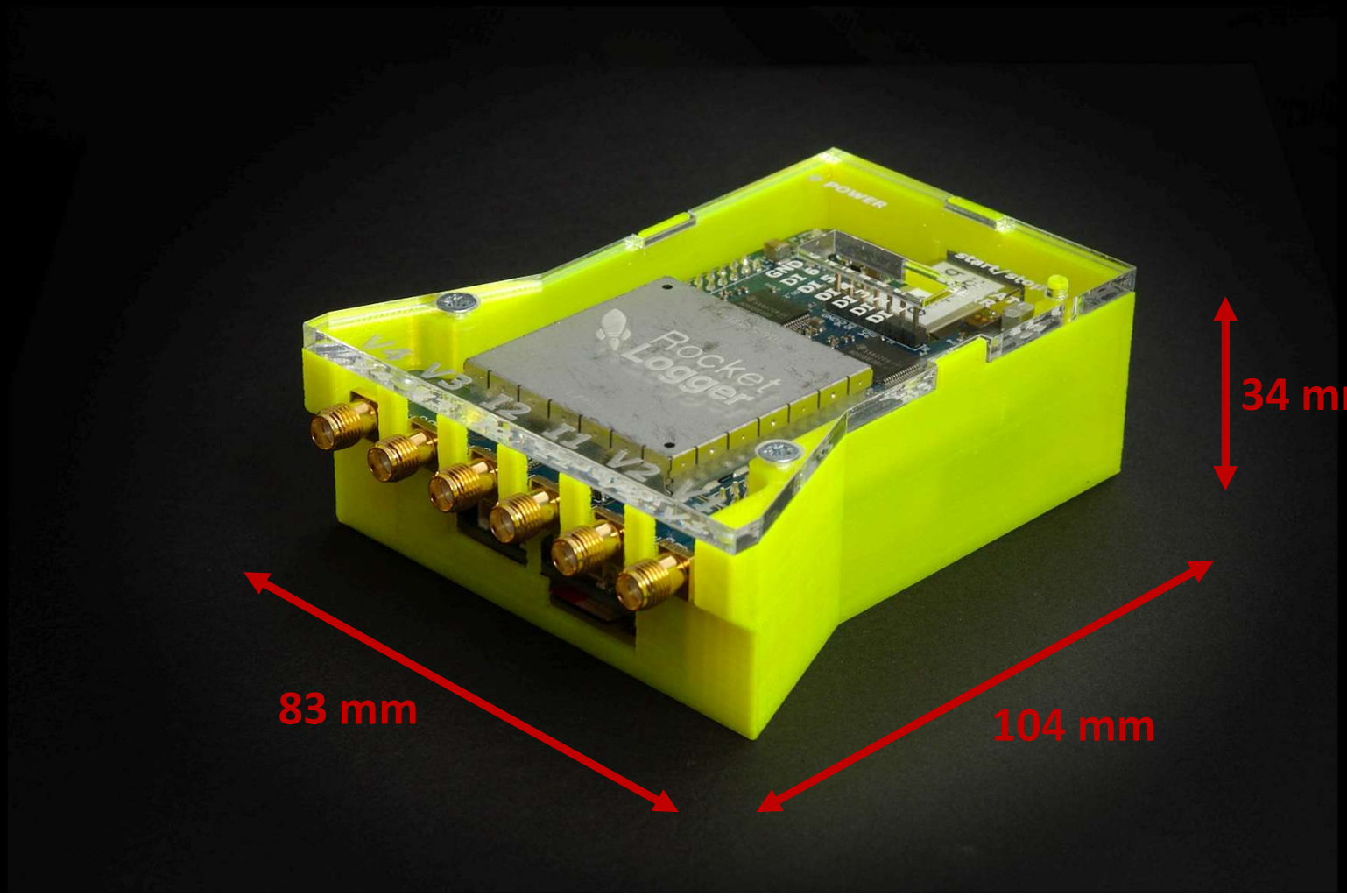

[1] N. Brouwers et al., *"NEAT: A Novel Energy Analysis Toolkit for Freeroaming Smartphones,"* SenSys, 2014.
[2] S. Naderiparizi et al., *"µMonitor: In-situ Energy Monitoring with Microwatt Power Consumption,"* RFID, 2016.
[3] R. Zhou et al., *"Nemo: A high-fidelity noninvasive power meter system for wireless sensor networks,"* IPSN, 2013.

# Portable High Precision Measurements

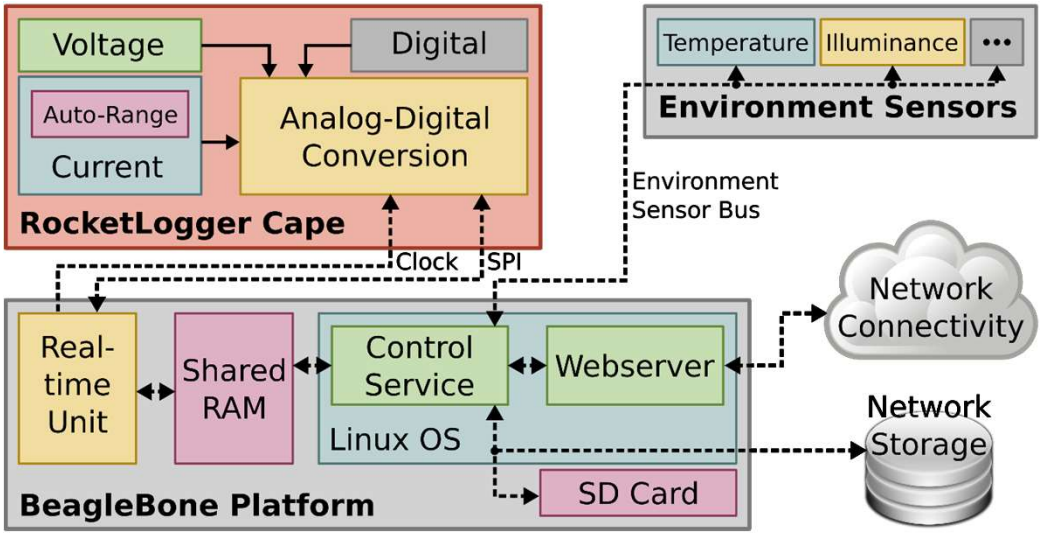
- ✓ High-dynamic range power measurements
- ✓ Portable design for in-situ measurements
- ✓ Environment monitoring



# The RocketLogger



# RocketLogger Architecture

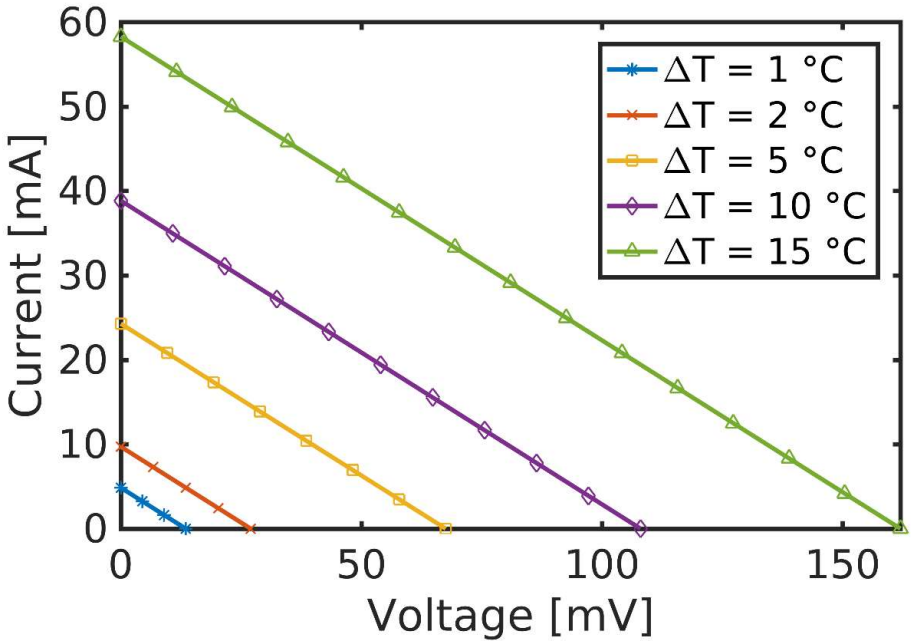



2x Current, 4x Voltage, 6x Digital Inputs

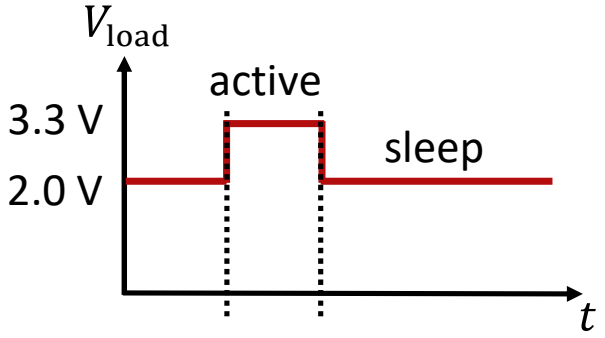
- External bus for environment sensors
  - Flexible sensor selection and placement
- Analog measurement frontend
  - Precision current and voltage measurement
  - Seamless auto-ranging from 4 nA to 500 mA
  - Simultaneous logging of digital inputs
- Data management on top of Linux OS
  - Network for remote control & observation
  - Real-time unit for low latency data processing

# Measuring Voltages in Energy Harvesting Devices

- TEG I-V characteristics

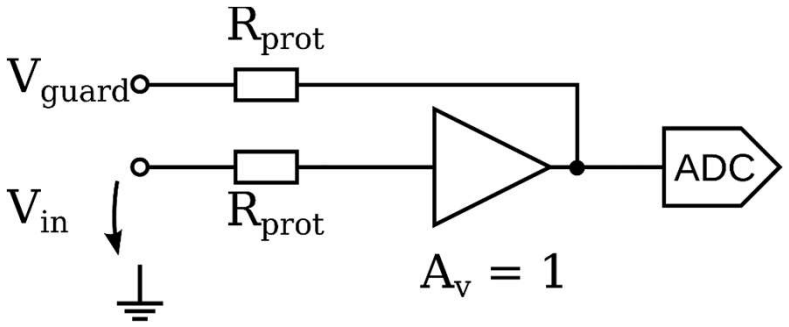



- Low-power microcontroller architectures



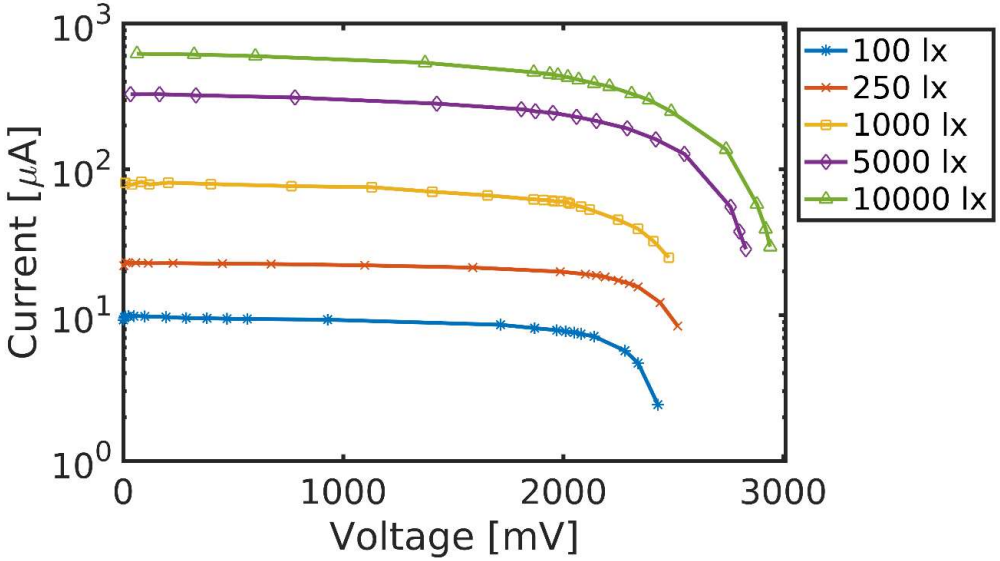
# Voltage Measurement and Digital Inputs

- Limited voltage range requirement
  - Energy sources in mV – V range
  - Precision ADC sufficient for µV accuracy
- Minimize input leakage
  - Disturbs parallel low current measurements
  - Shielding of measurement probes

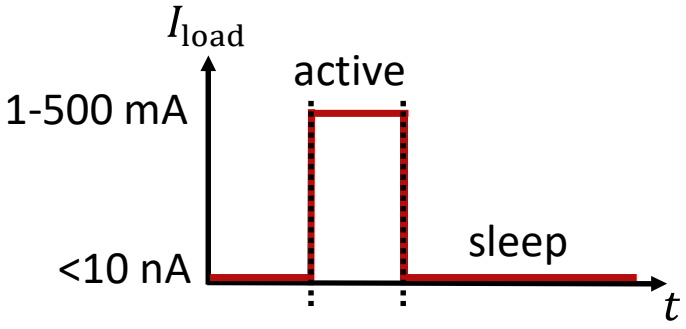


# Measuring Currents in Energy Harvesting Devices

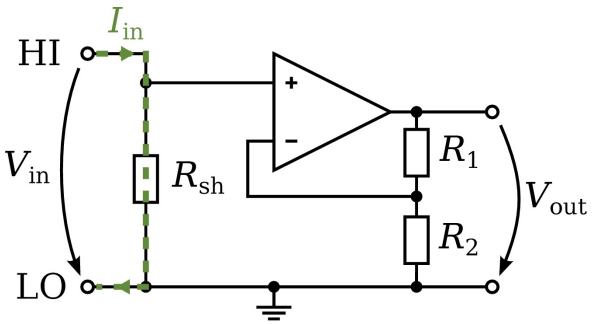
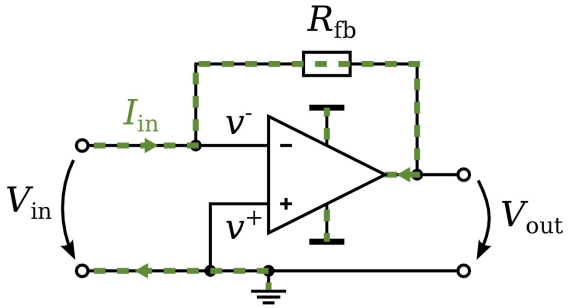
- Solar I-V characteristics




- Low-power microcontroller architectures

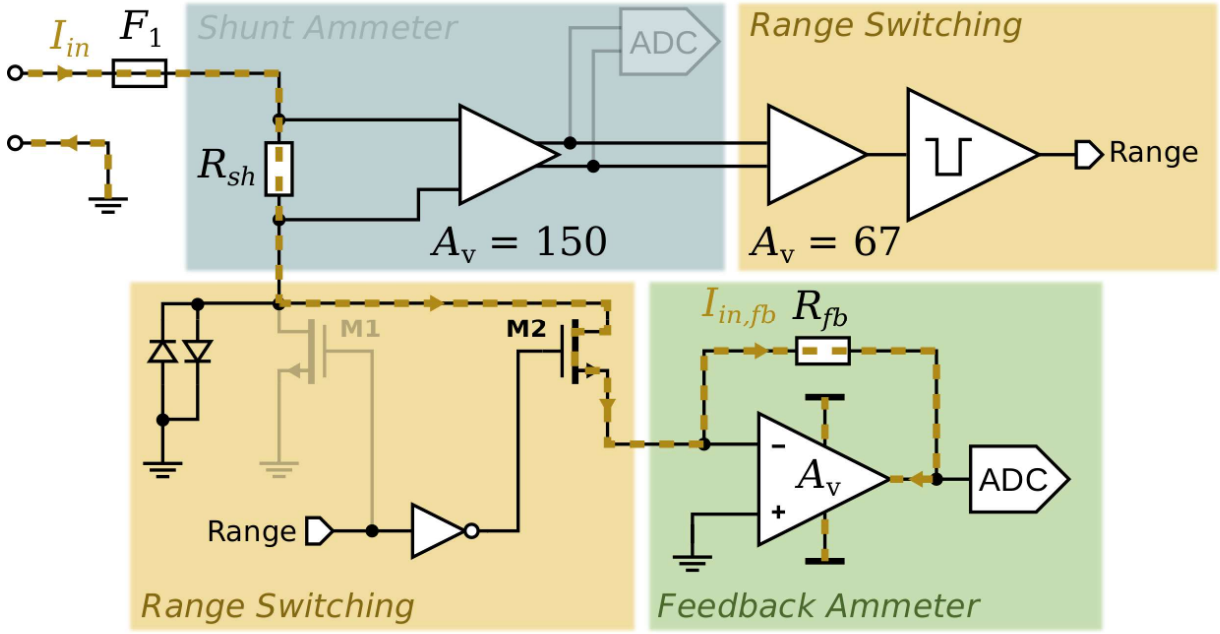


# Precision Current Measurement

| | | |
|---|---|---|
| *Measurement Circuit* |  |  |
| | **Shunt Ammeter** | **Feedback Ammeter** |
| *High Currents* | Supports high currents $I_{in}$ | Saturation at high currents $I_{in}$ |
| *Burden Voltage* $V_{in}$ | Increases with $I_{in}$ | Virtually zero |
| *Low Currents* | Amplification limited by noise | Large current to voltage amplification |

Combine advantages by switching both circuits

# Seamless Range Switching




$I_{in} \geq 2$ mA: High Range

- Stunt ammeter only
- Small shunt resistor, low burden voltage

$I_{in} < 2$ mA: Low Range

- Feedback ammeter
- High output voltage, precise measurement

# Performance Evaluation

## Extensive Characterization

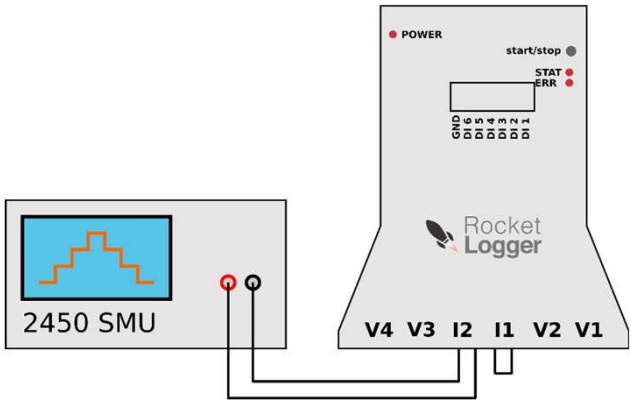
- **DC Accuracy**
- **Noise Floor**
- **DC Input Leakage Current**
- **DC Burden Voltage**
- Power Consumption
- Analog Bandwidth
- Input Capacitance
- Temperature Drift
- Threshold Voltage
- Input Offset Voltage
- Propagation Delay
- Input Capacitance
- Range Switching Time
- Transient Burden Voltage
- Crosstalk

## Today's Focus

- Accuracy
- Noise characterization
- Impact on device under test
  - Input leakage
  - Burden voltage (voltage drop at input)
- Sample Rate: 1 kSPS (64 kSPS in paper)

# Characterization Setup

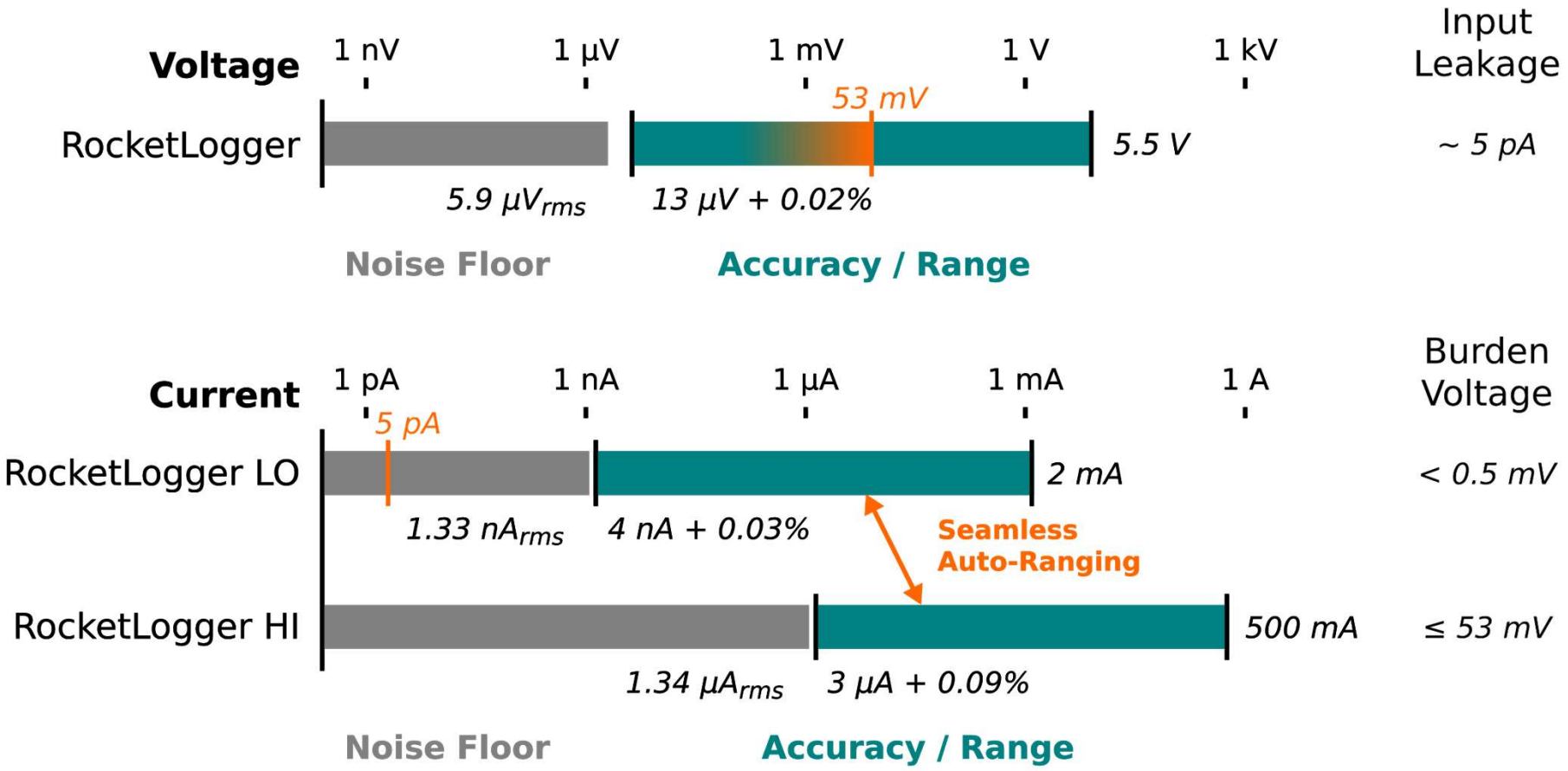
- Device Calibration
  - Full range voltage/current sweeps using Keithley 2450 source meter
  - Linear fitting of ADC output to ground truth



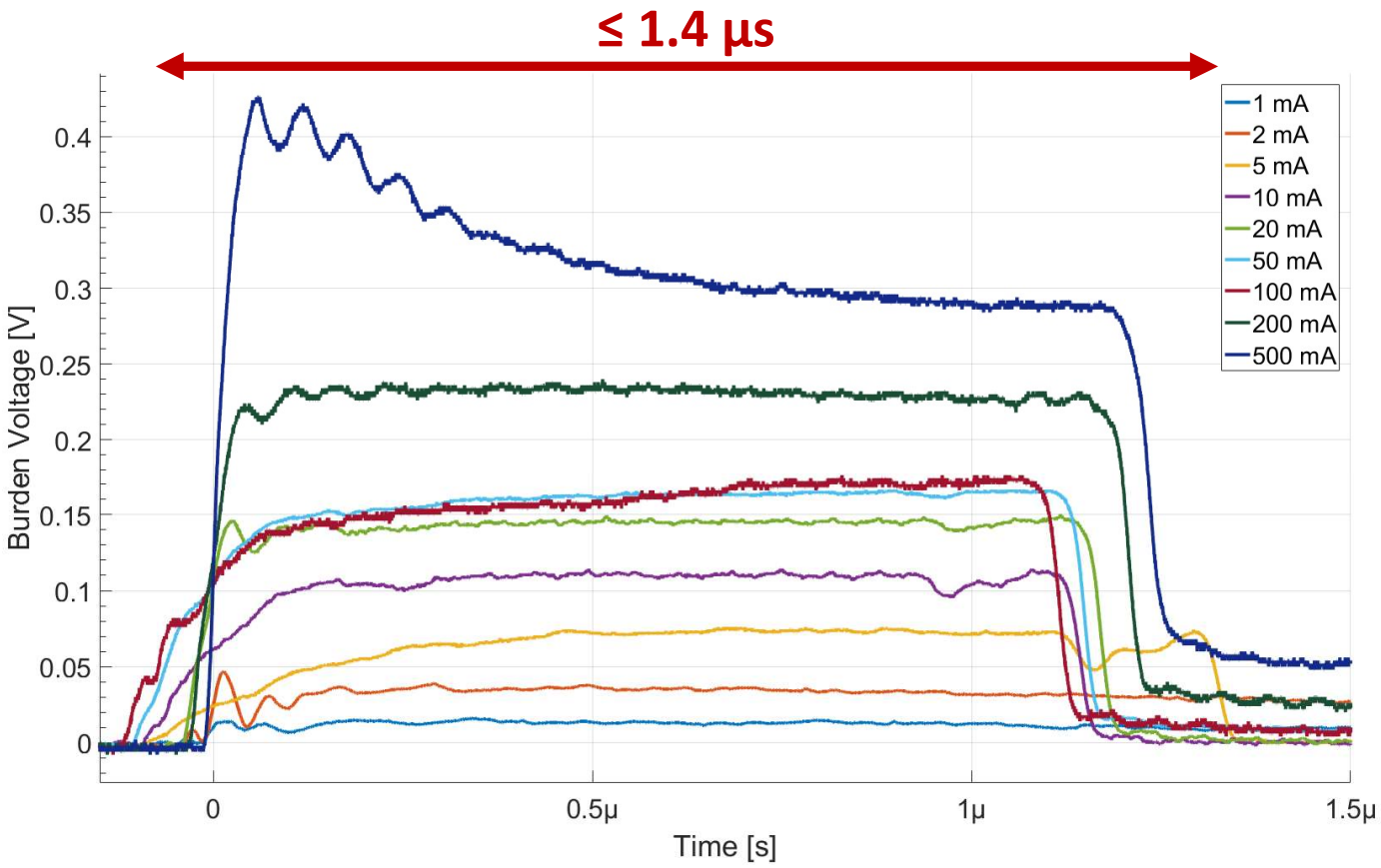

- DC Accuracy
  - Repeat full range sweeps after 24h
  - Calculate relative and constant offset errors

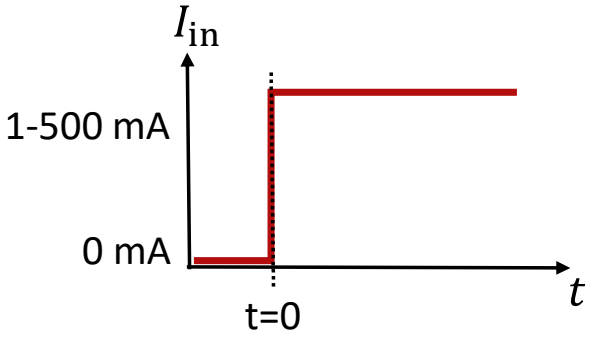
- Zero Input RMS Noise Characterization
  - Current channel inputs shorted
  - Voltage inputs connected to GND

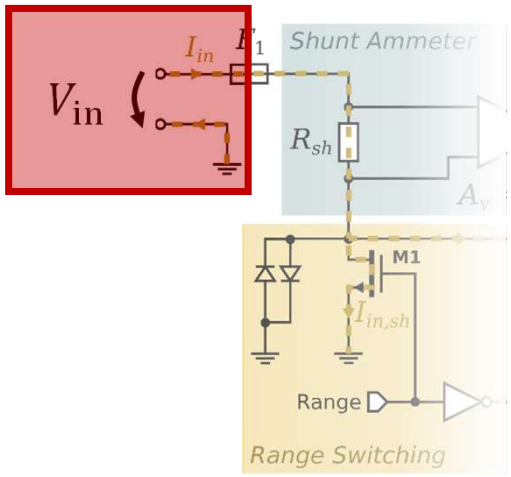
# Measurement Characteristics



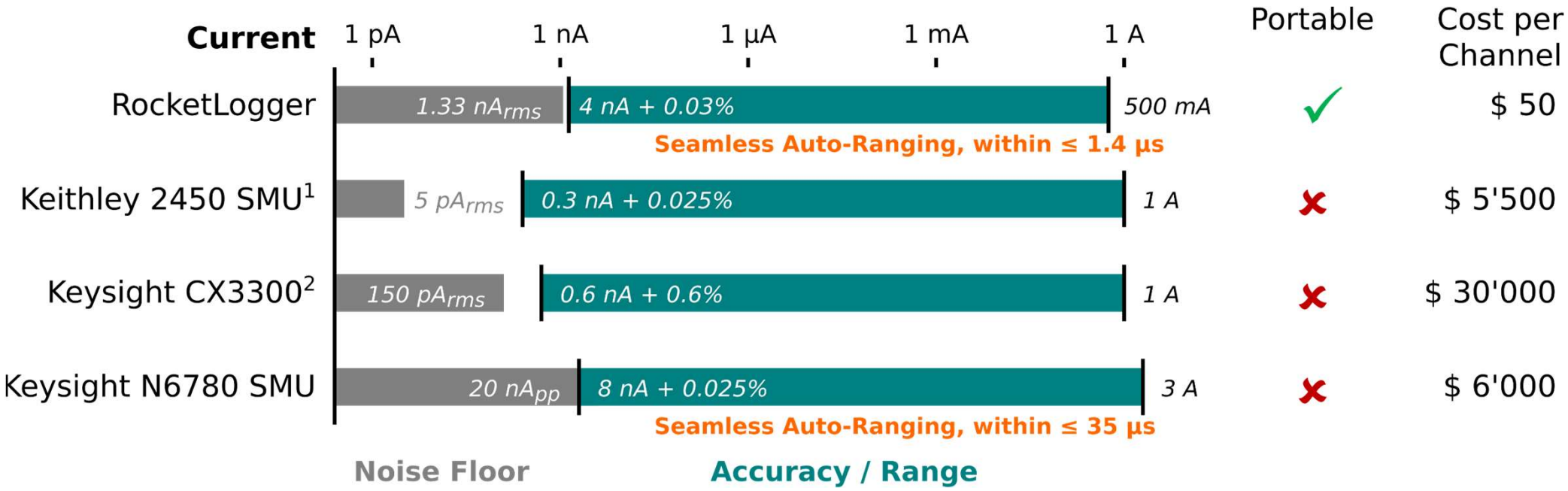
# Range Switching: Step Response



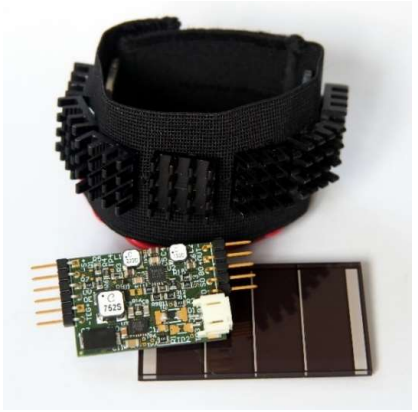
# Performance Comparison to Start of the Art

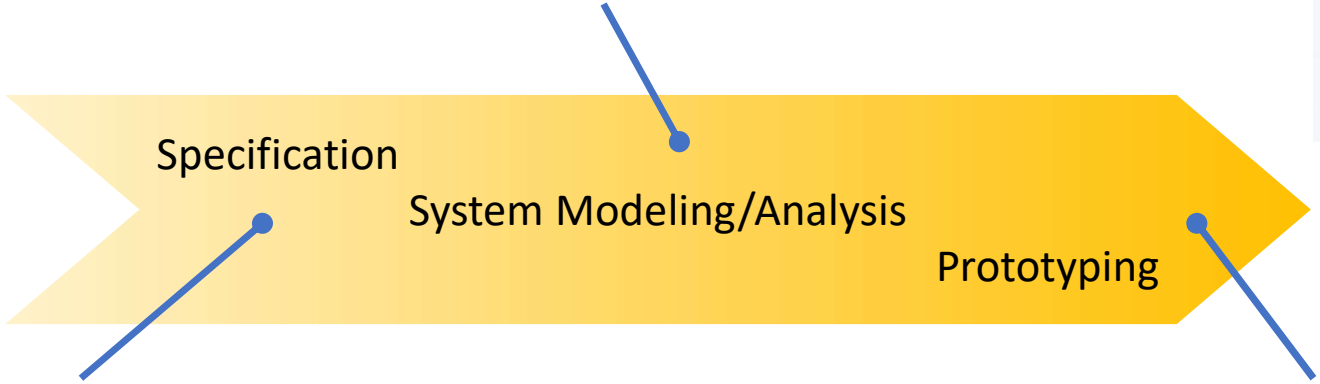


# RocketLogger Case Studies

## Multi-Source Energy Harvesting Wristband

- Evaluate power in indoor/outdoor scenarios
- Correlate available  power with environmental conditions





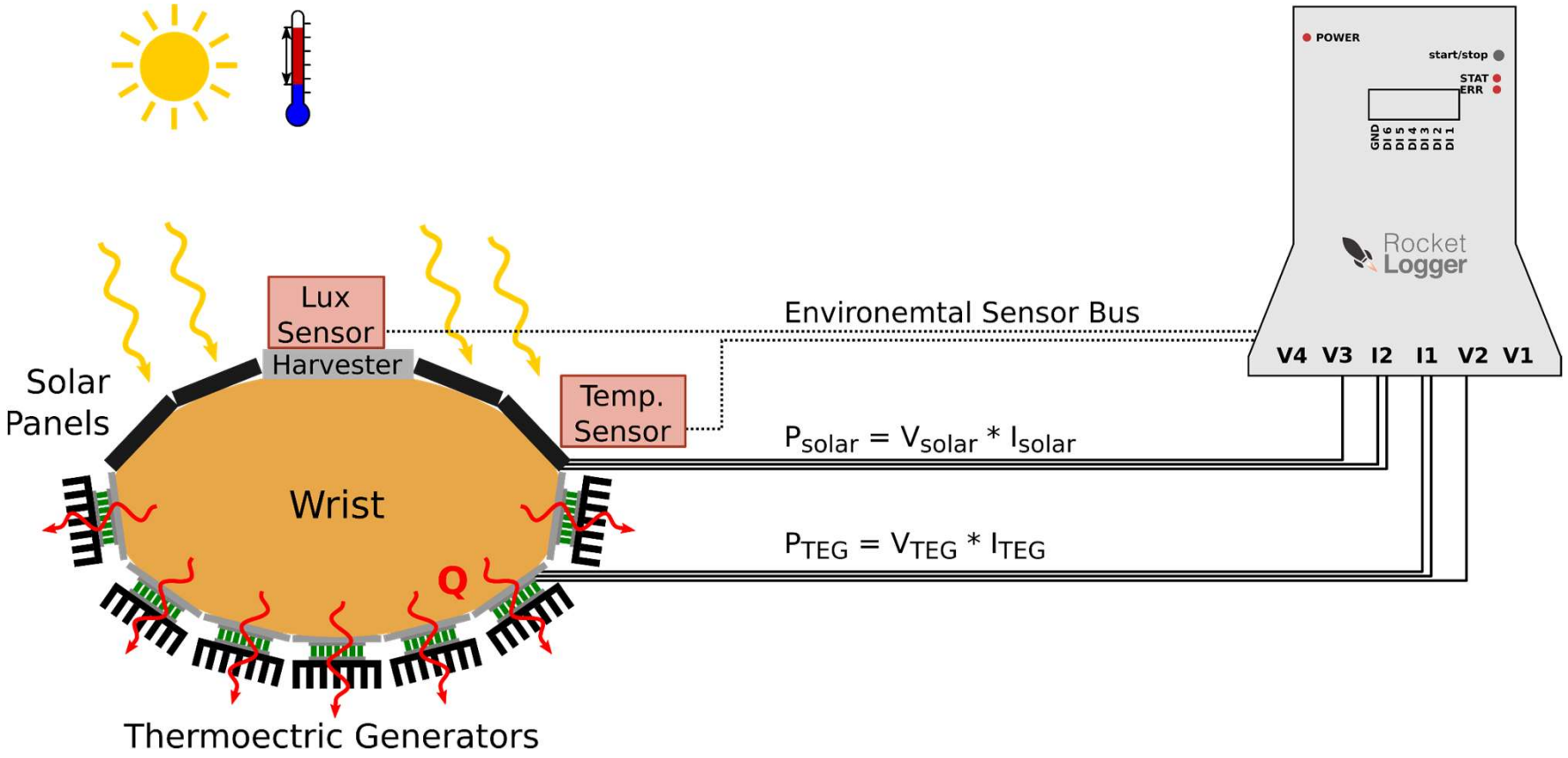

### Low Power Optimization

- Application focused power evaluation

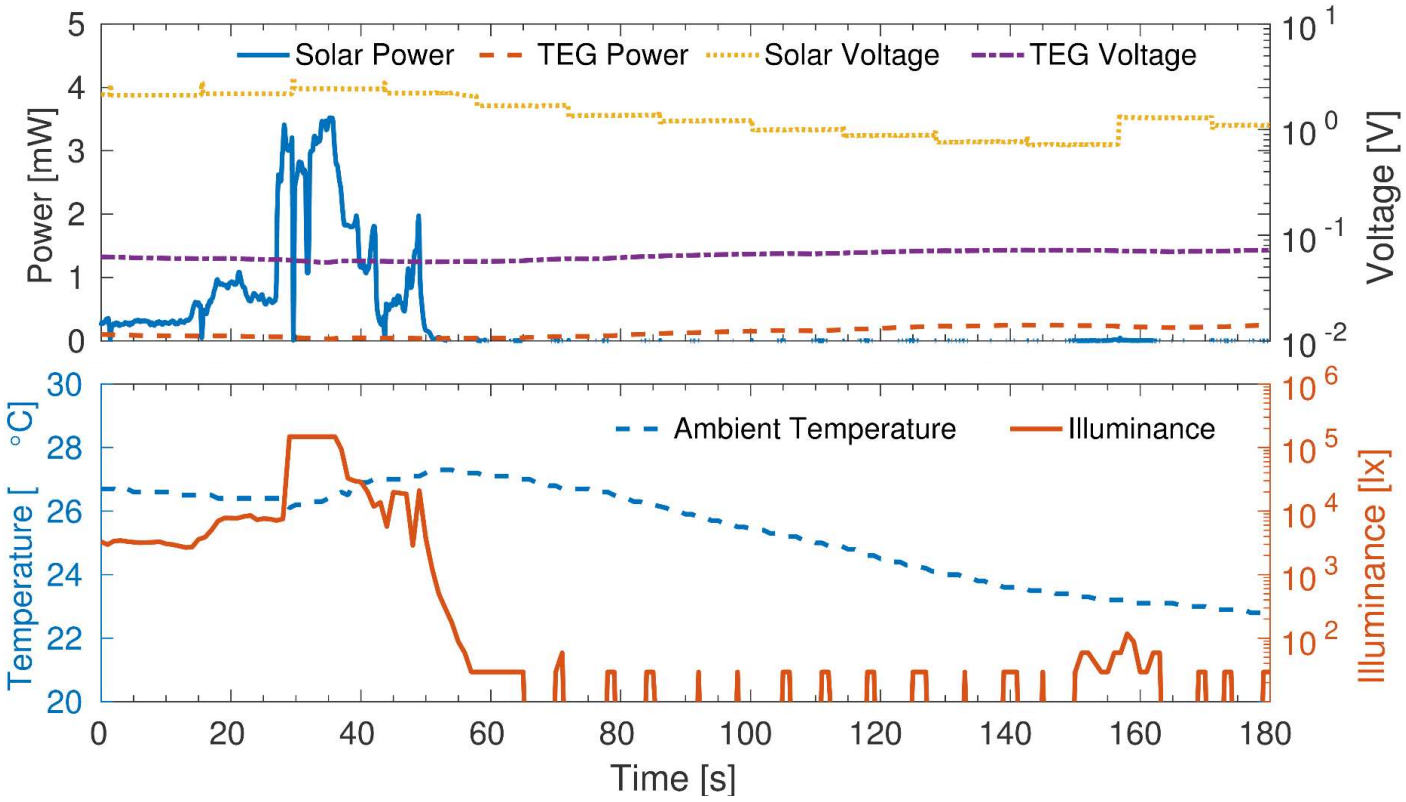
### Long-Term Validation

- In-situ application validation

# Mobile Measurement of Harvesting Wristband



# Measurement Results of Harvesting Wristband




- Evaluation Results
  - Solar dominates outdoor
  - TEG dominates indoor
- Mobile Measurements
  - Precise multi-harvester characterization
  - Monitoring of variable environment conditions

# RocketLogger in Summary

**Remote Web Interface**

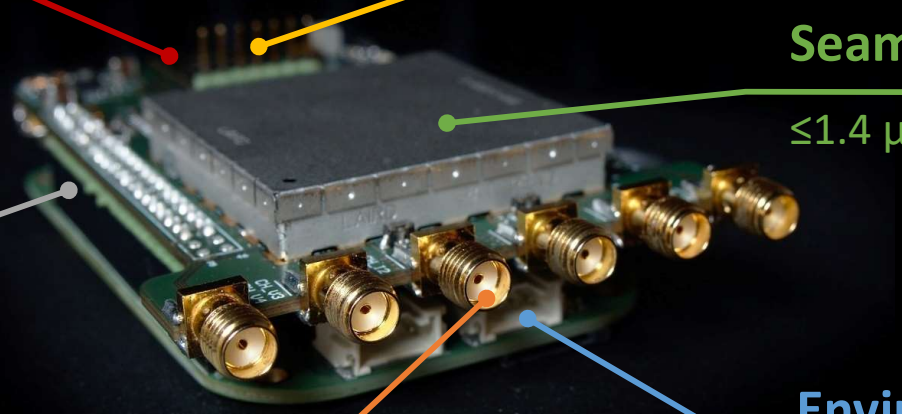
remote control and observation

**Portable Size**

in-situ measurements

**High Dynamic Range Measurement**

4 nA – 500 mA, and 13 µV – 5.5 V range



**Mixed-Signal Capability**

digital inputs for state monitoring

**Seamless Range Switching**

≤1.4 µs, @ ≤430 mV drop

**Environmental Sensor Hub**

extensible measurement platform


**Hardware and Software fully Open Source:**

https://rocketlogger.ethz.ch/

https://gitlab.ethz.ch/tec/public/rocketlogger/

**External Image Sources**

- Btnode [slide 2]
  http://www.btnode.ethz.ch/
- Solar Wireless Sensor Node [slide 2]
  https://www.seeedstudio.com/Wireless-Sensor-Node-Solar-Kit-p-919.html
- Implantable Sensor [slide 2]
  http://ous.eversensediabetes.com/products/eversense-sensor/
- Michigan Micro Mote [slide 2]
  http://www.computerhistory.org/atchm/the-worlds-smallest-computer/
- Cypress Solar Energy Harvesting Node [slide 2]
  http://www.prnewswire.com/news-releases/cypress-introduces-the-worlds-lowest-power-energy-harvesting-power-management-ics-for-battery-free-wireless-sensor-nodes-300130529.html
- Wireless GPS Sensor Node [slide 2]
  https://www.permasense.ch/