

# **DESIGN, IMPLEMENTATION, AND EVALUATION OF NAPALI: A NOVEL DISTRIBUTED SENSOR NETWORK FOR IMPROVED POWER QUALITY MONITORING.**

Dr

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March 10, 2020,

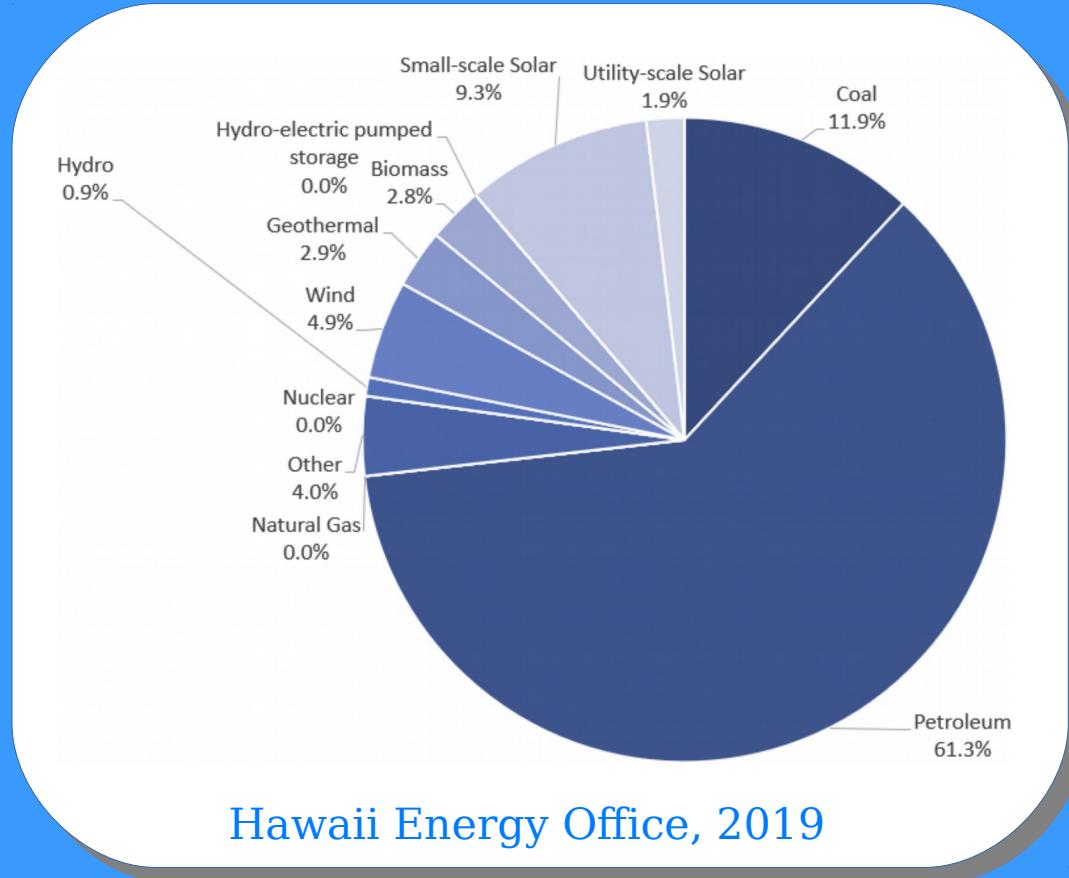


# Outline

- Power Quality
- Napali
- OPQ Network
- Evaluation
- Applications
- Future Work



# Climate Change

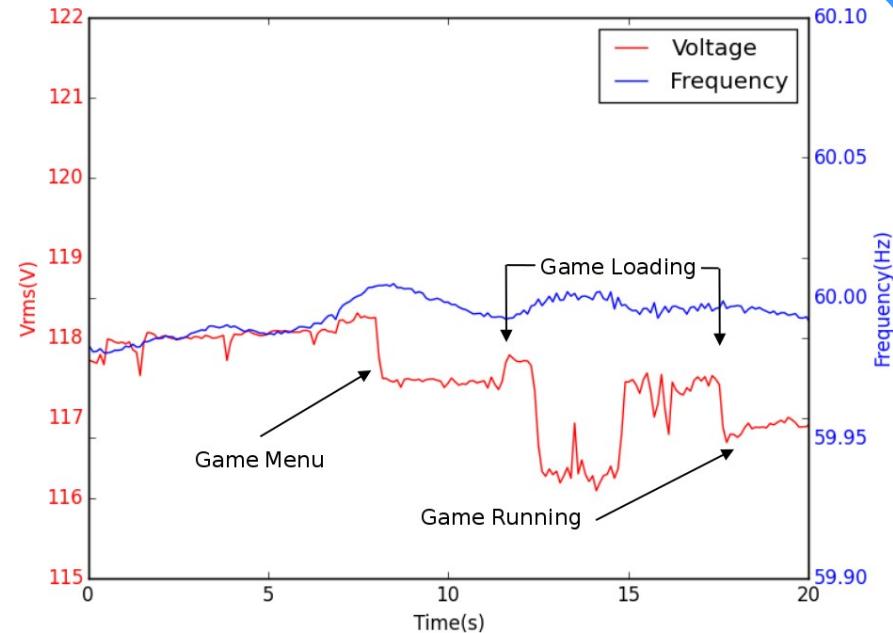
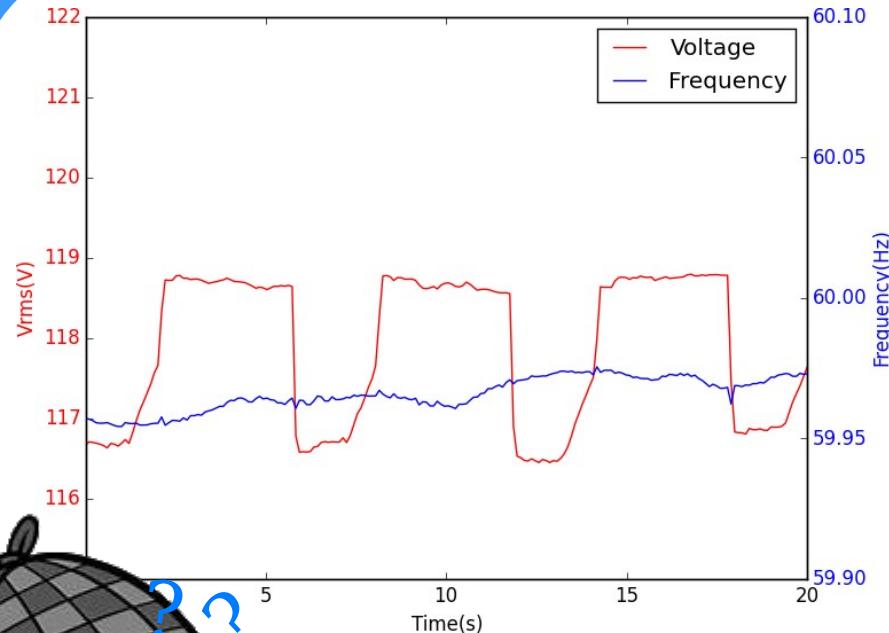


# **Problem of Power Quality**

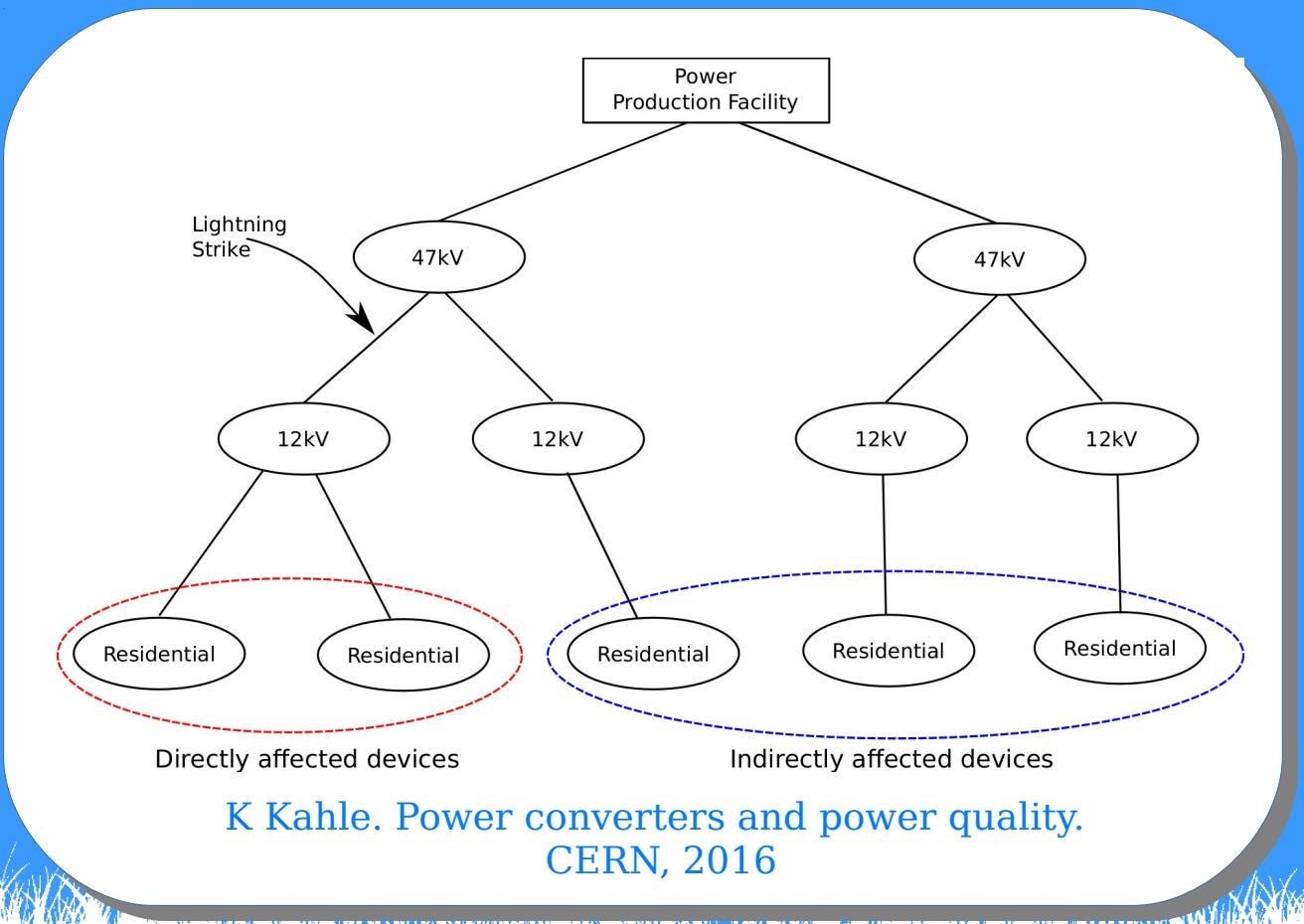
- 1. Amplitude**
- 2. Fundamental Frequency**
- 3. Harmonic Distortion**
- 4. Transient**
- 5. Phase Angle**
- 6. Reactive Power**



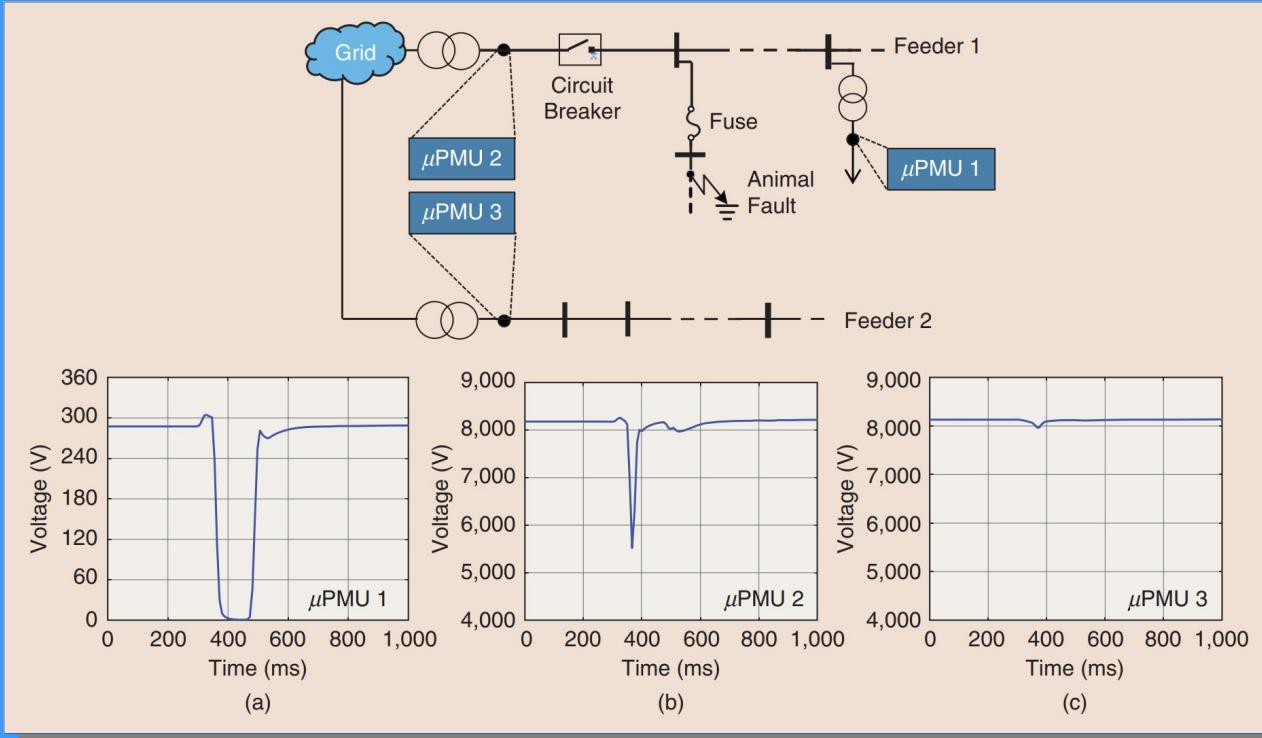
# Where does the disturbance originate?



# Event Propagation



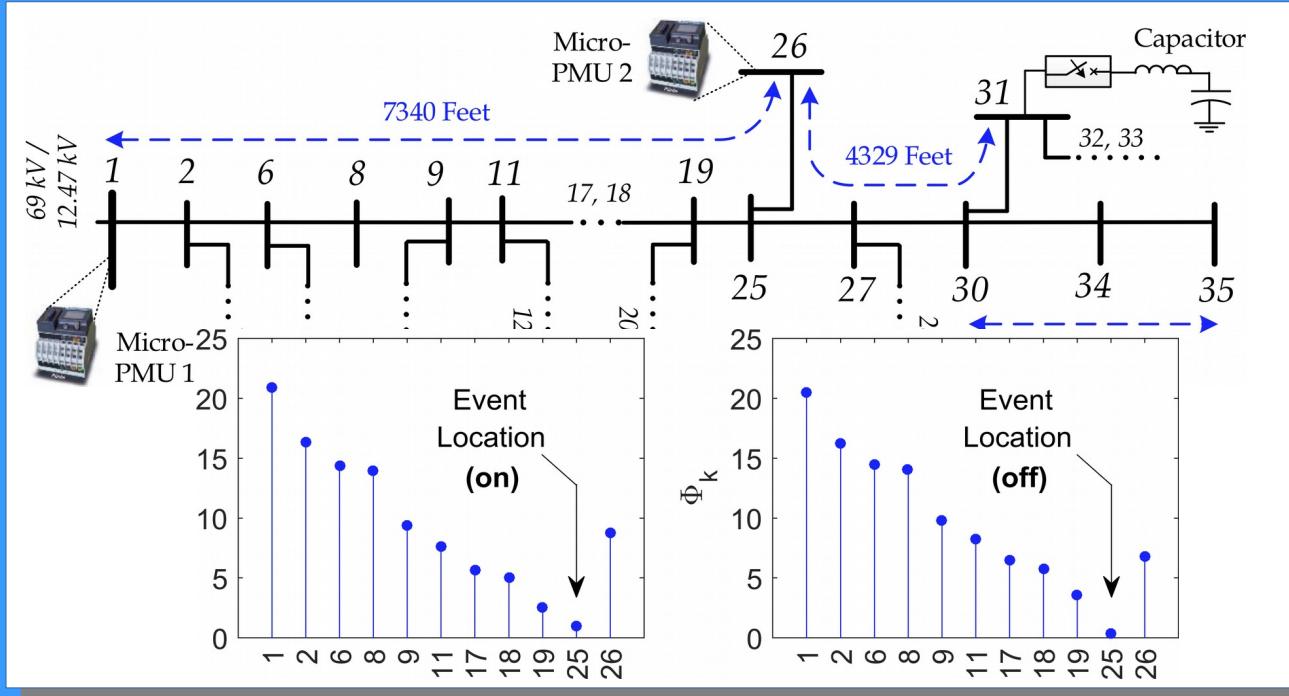
# Manual Detection Methods



"Distribution synchrophasors: Pairing big data with analytics to create actionable information."  
IEEE Power and Energy Magazine (2018)



# PQ Event Localization



"Locating the source of events in power distribution systems using micro-PMU data."  
IEEE Transactions on Power Systems (2018)

# Event Detection



Animal



Detection



Bunny



Classification



Fancy  
Bunny



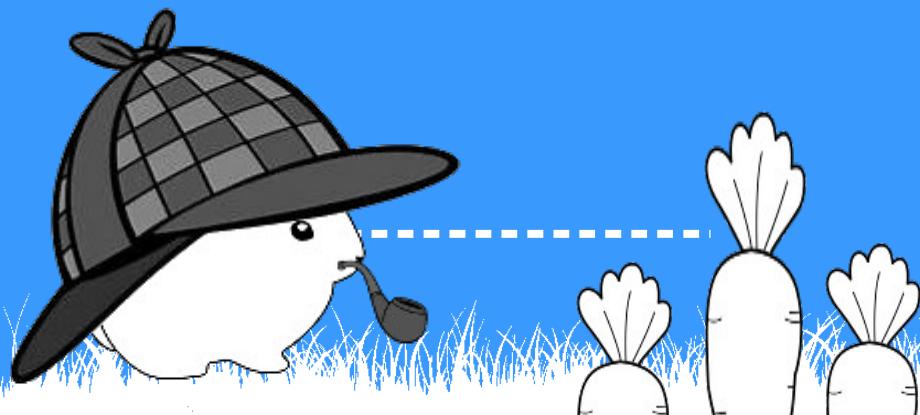
# Event Detection Pipeline

## Threshold Based Detection

Metric Extraction

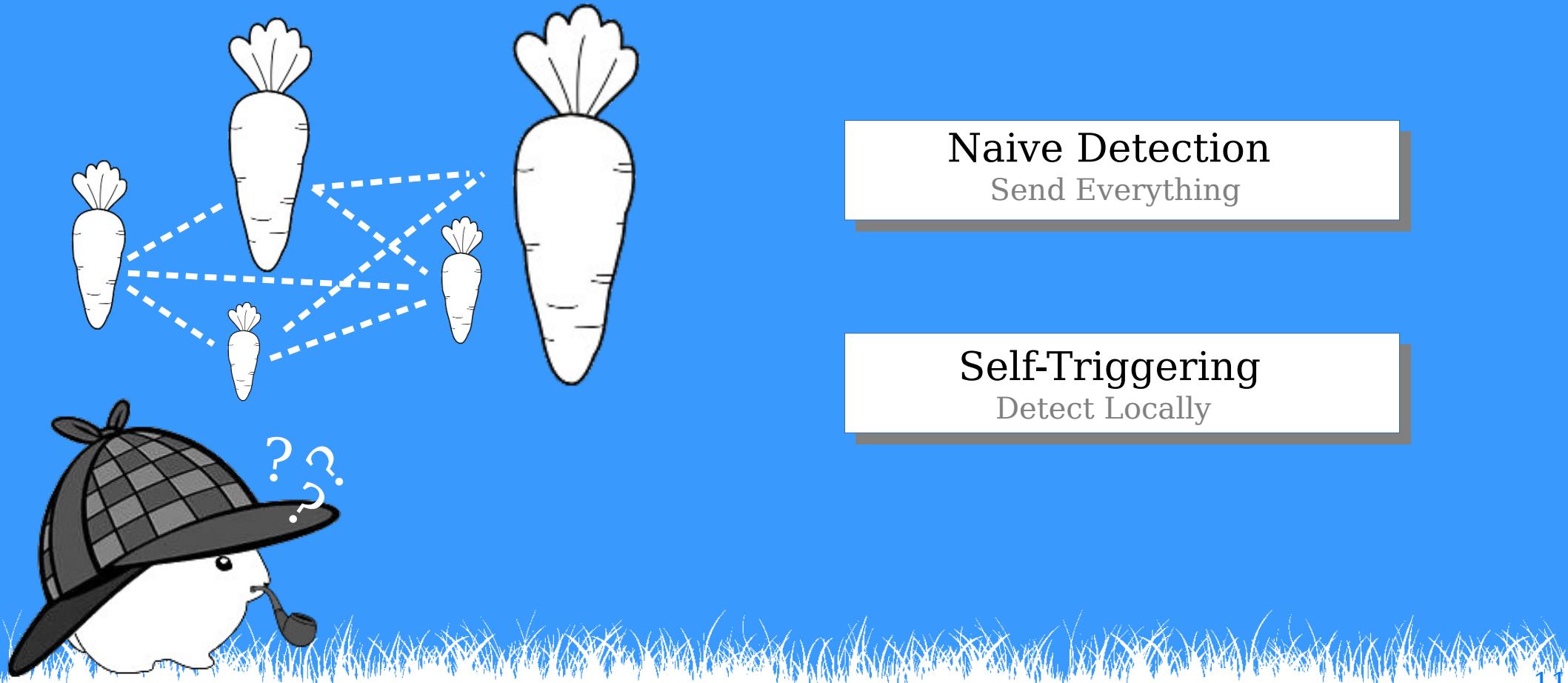
Threshold

Event Storage



# Distributed Event Detection

## Traditional Methods



Naive Detection  
Send Everything

Self-Triggering  
Detect Locally

# Distributed Event Detection

## Industry bleeding edge

Naive Detection  
Send Everything



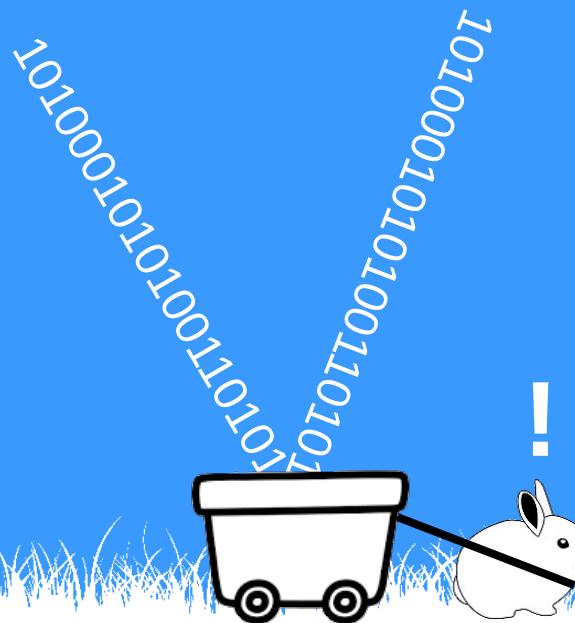
Self-Triggering  
Detect Locally



# Issues with Current Methods

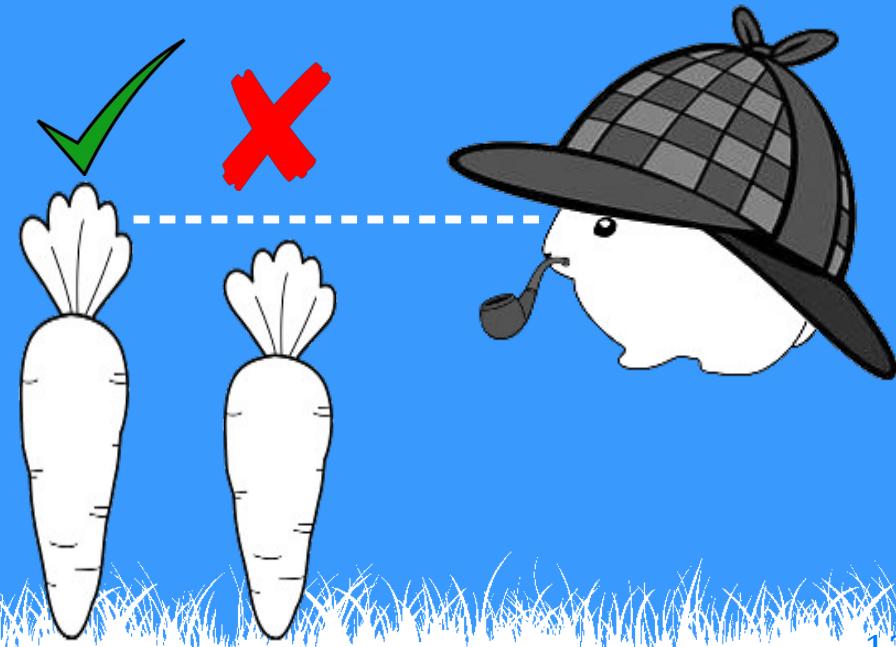
## Naive Detection

- Bandwidth
- Memory



## Self-Triggered

- Detection Efficiency



# Future of PQ Monitoring

The main challenge is to go beyond manual methods based on the intuition and heuristics of human experts...

... it is crucial to develop the machine intelligence needed to automate and scale up the analytics on billions of  $\mu$ PMU measurements and terabytes of data on a daily basis and in real time.

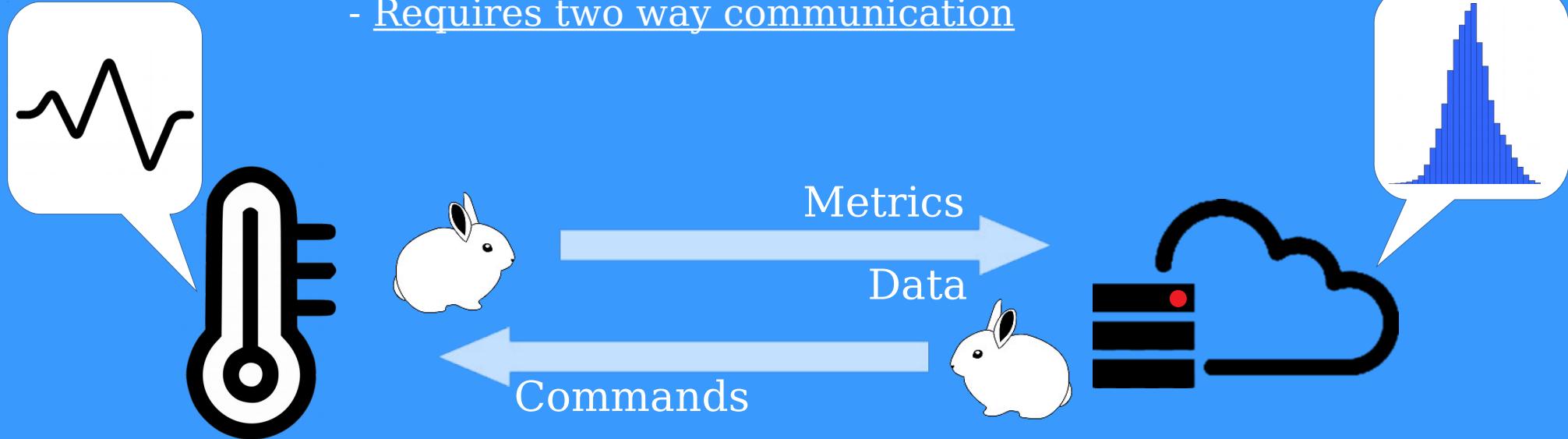
"Distribution synchrophasors: Pairing big data with analytics to create actionable information."  
IEEE Power and Energy Magazine (2018)

I wonder where this is going?



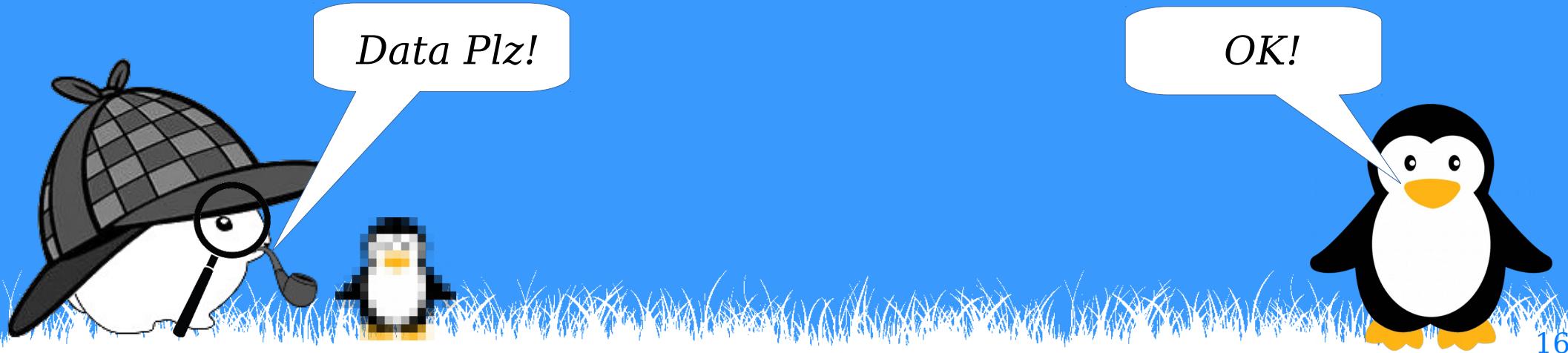
# Napali

- Sensor forward metrics to the sink
- Sensor stores raw data locally
- Sink builds a statistical model of the sensor
- Sink requests data from the sensor
- Requires two way communication



# Napali

- Sink maintains a coarse view of the entire system.
- Sink filters out local events.
- Sink determines which devices participate in event detection



# Claim #1



**Napali provides a novel architecture that is both a feasible solution to the problem of distributed power quality monitoring and provides significant benefits over the two standard alternative architectures.**



## Claim #2



**Napali architecture can, in principle,  
provide benefits for other domains beyond  
power quality.**



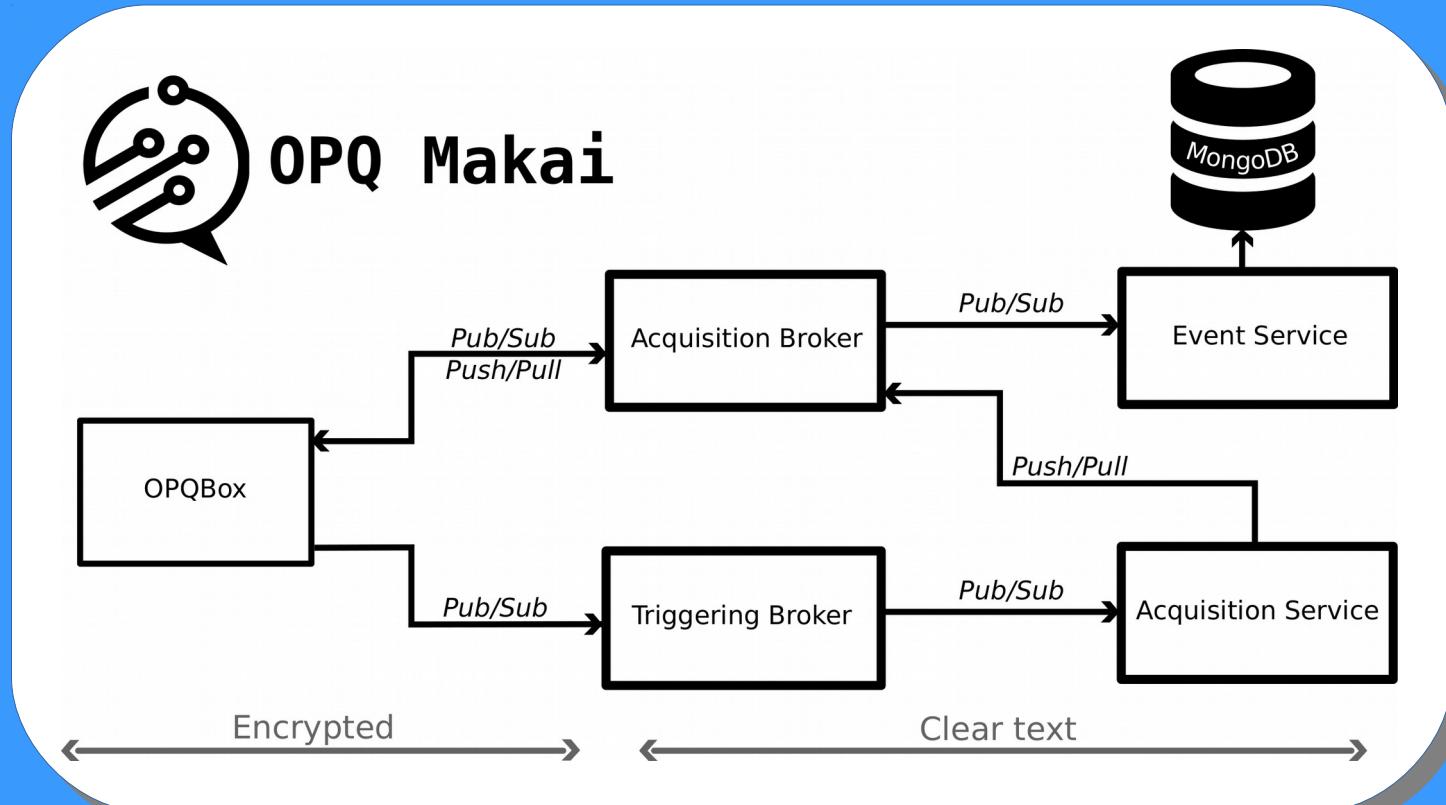
# **Subclaims of the Thesis**

- 1. Napali minimizes bandwidth**
- 2. Napali mitigates device latency effects**
- 3. Napali minimizes sink processing requirements**
- 4. Sub-threshold data acquisition is a viable event detection strategy**
- 5. Temporal locality triggering results in a low false negative detection**



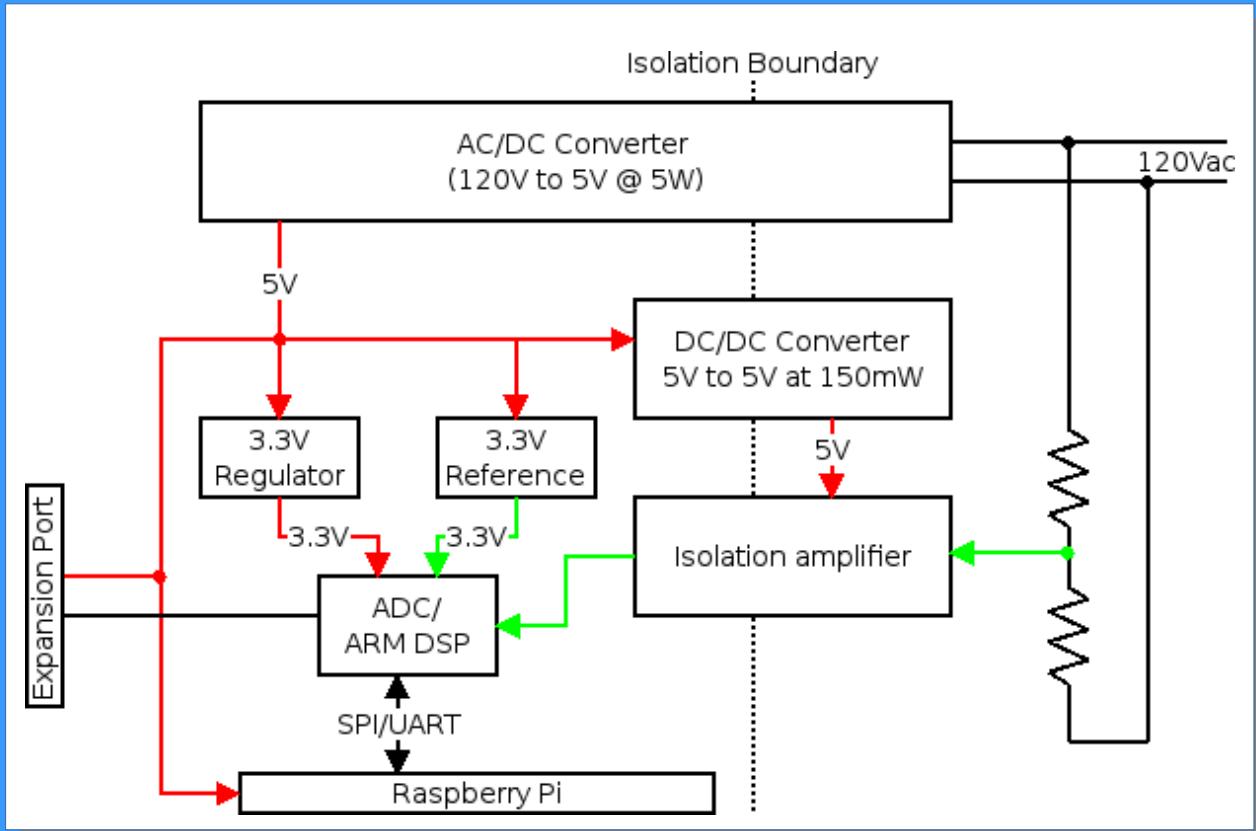
# Open Power Quality

## Gridwide event detection



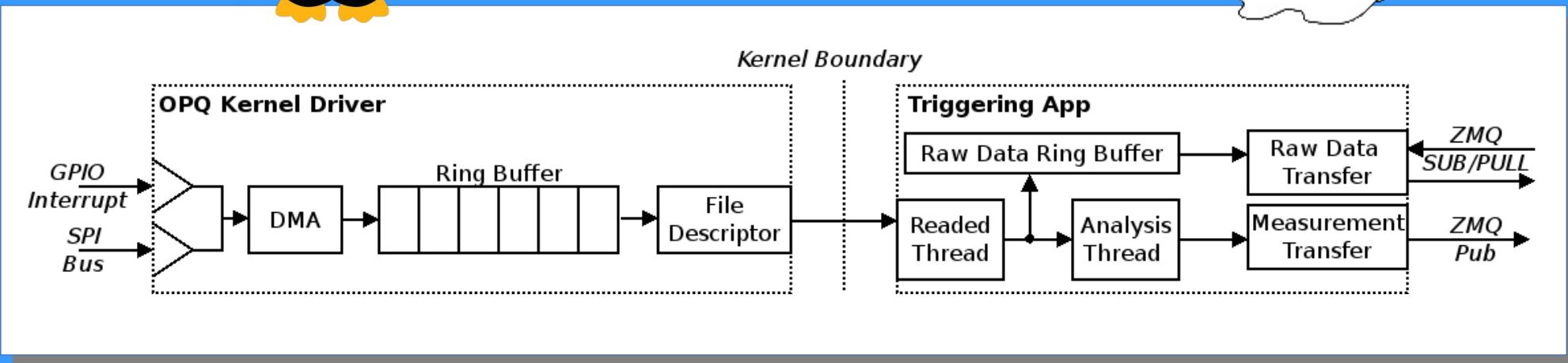
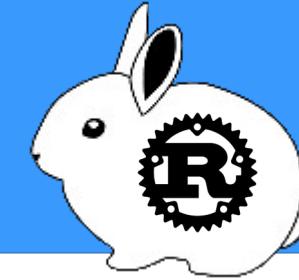
# OPQ Box

## Hardware



# OPQ Box

## Software



# OPQ Box

## Metrics

### Metrics:

- $V_{rms}$
- Fundamental Frequency
- THD
- Transient

### Transmission Rate:

- 1s (Mean/Min/Max)

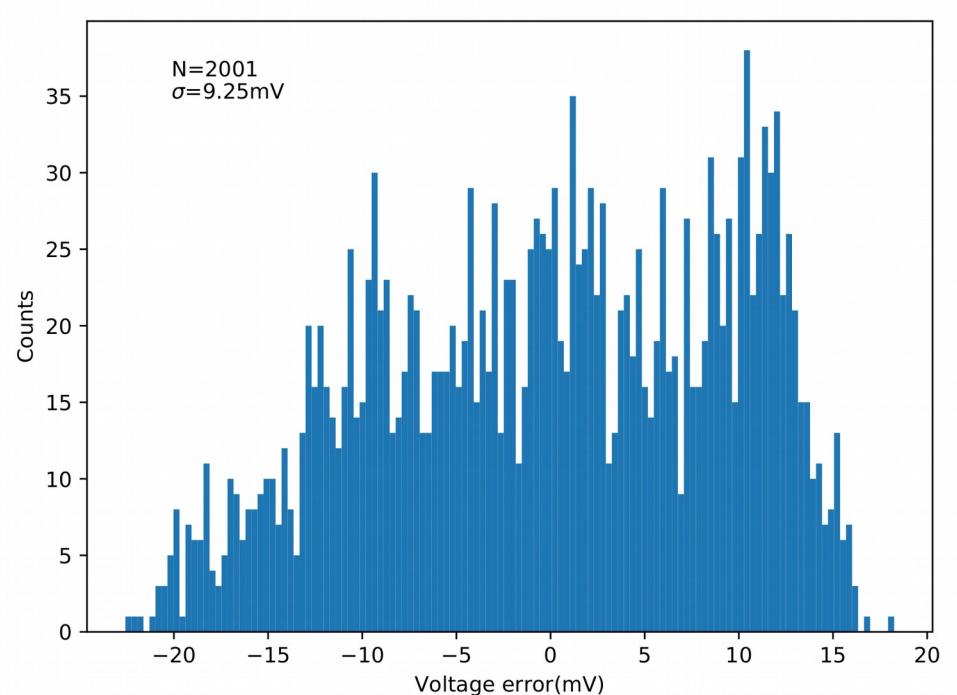
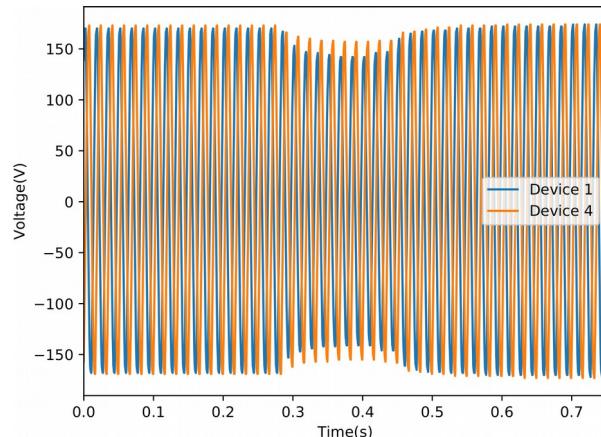
### RDRB:

- 1 Hour



# In-vitro Validation

## Amplitude( $V_{rms}$ )

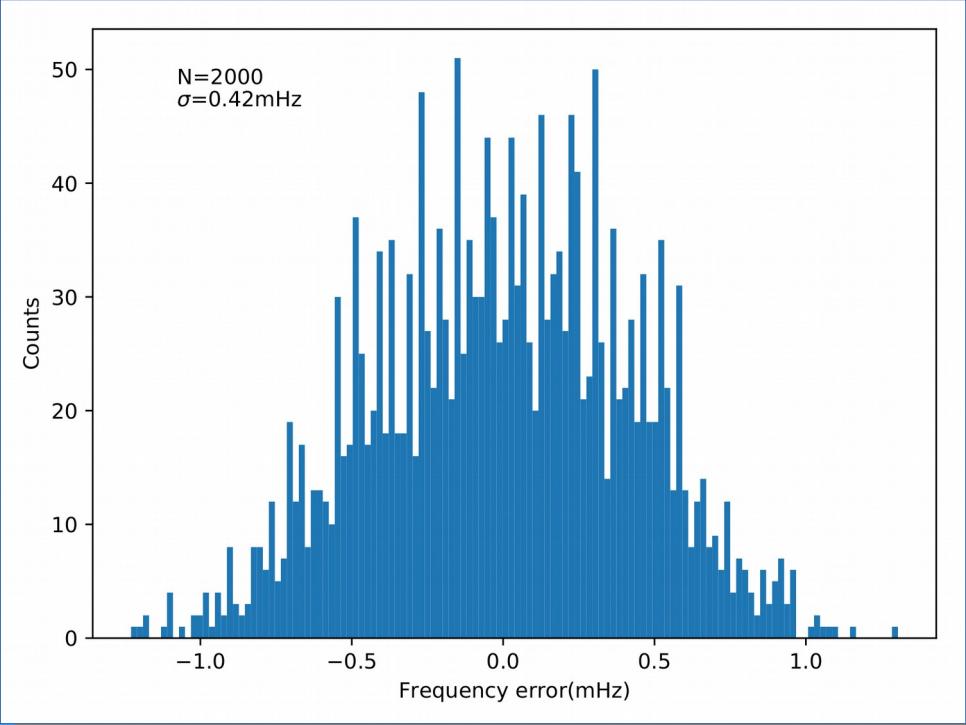
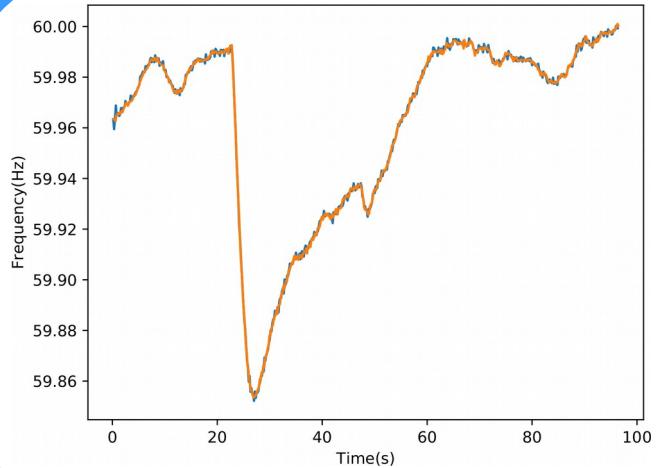


Validation against sdg1025



# In-vitro Validation

## Frequency $f_{\text{fundamental}}$

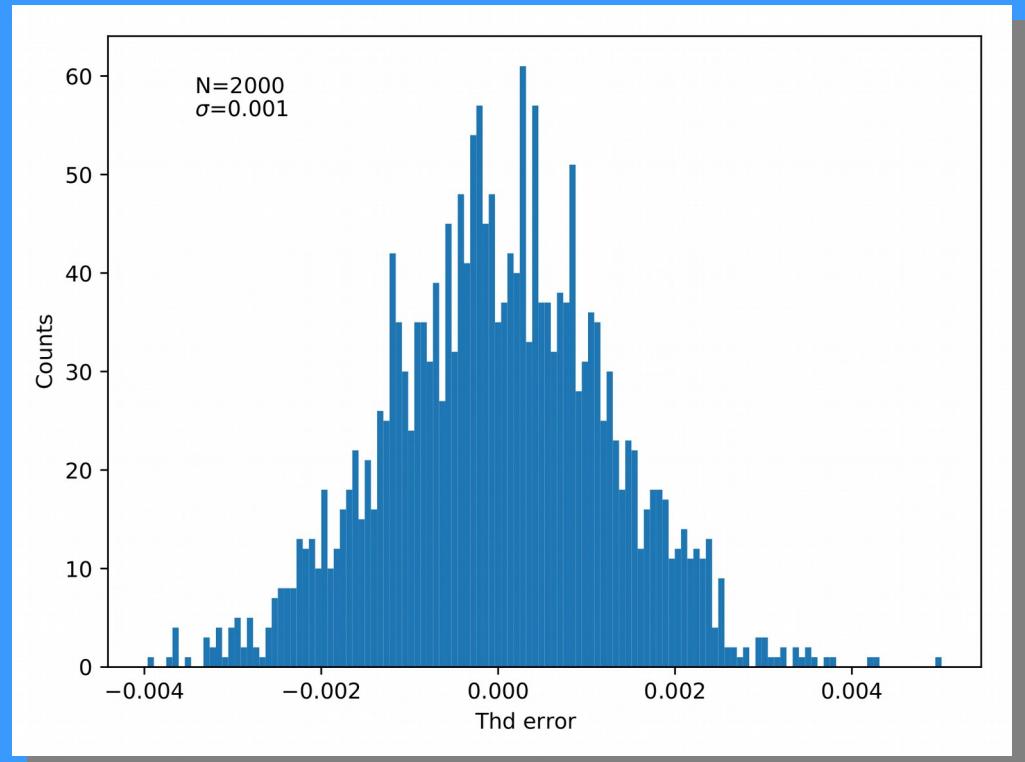
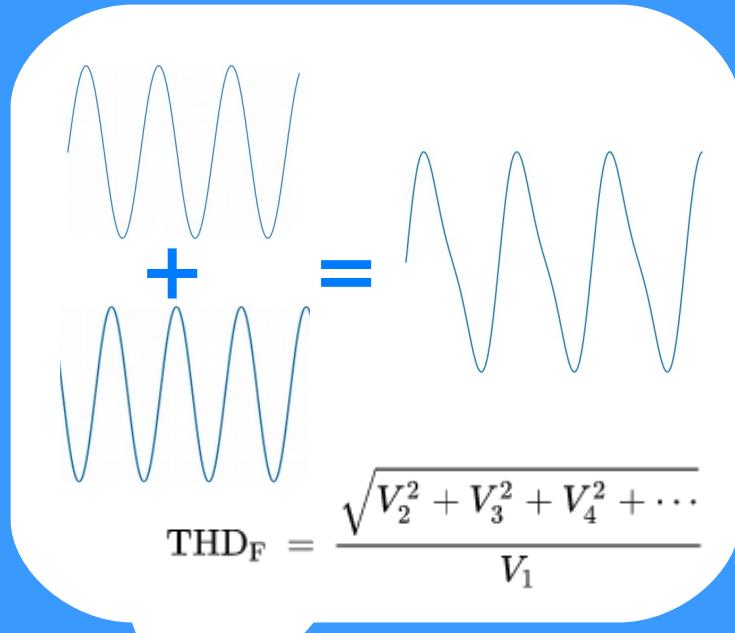


Validation against sdg1025



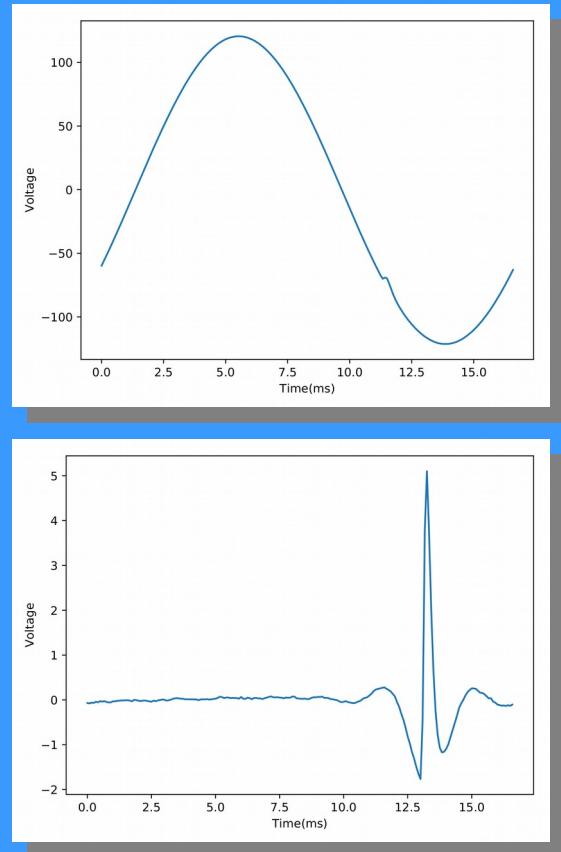
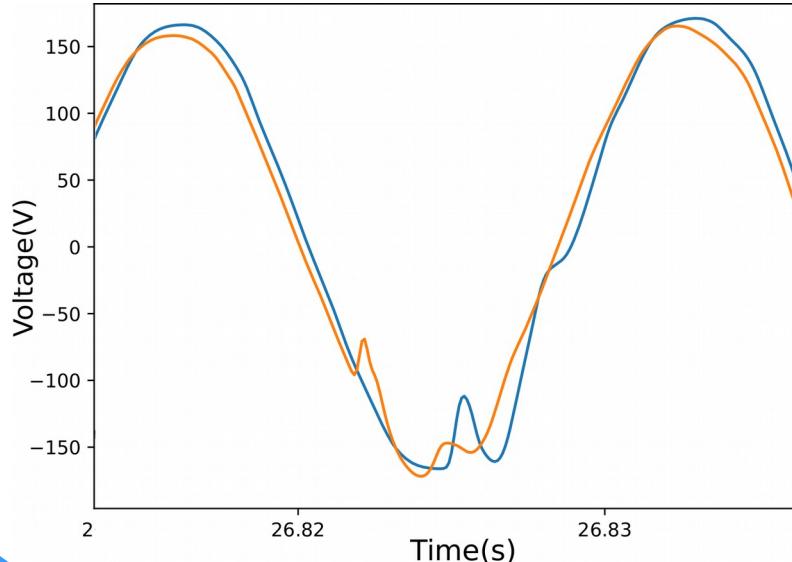
# In-vitro Validation

## Total Harmonic Distortion

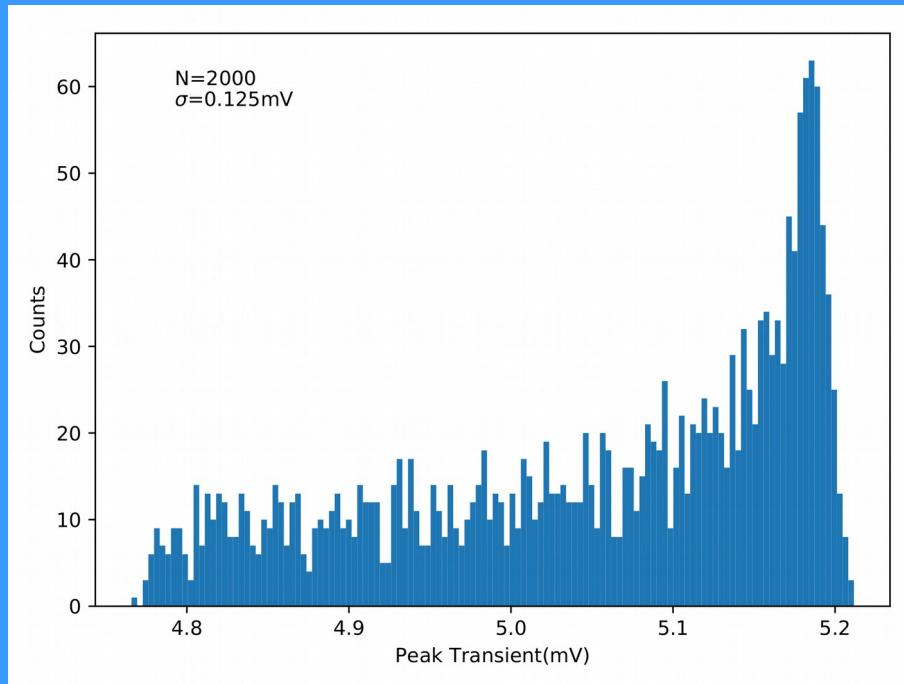


Validation against sdg1025

# In-vitro Validation Transients



# In-vitro Validation Transients



Validation against sdg1025

# Napali Device Model

**For each device:**

- mean
- std

**Leaky mean:**

$$\mu_{n+1} = (1 - \alpha) * \mu_n + \alpha * m$$

$$\mu_{n+1}^2 = (1 - \alpha) * \mu_n^2 + \alpha * m^2$$

$$\sigma_n^2 = \mu_n^2 - (\mu_n)^2$$

$$\sigma_n = \sqrt{\sigma_n^2}$$



**Event chronology:**

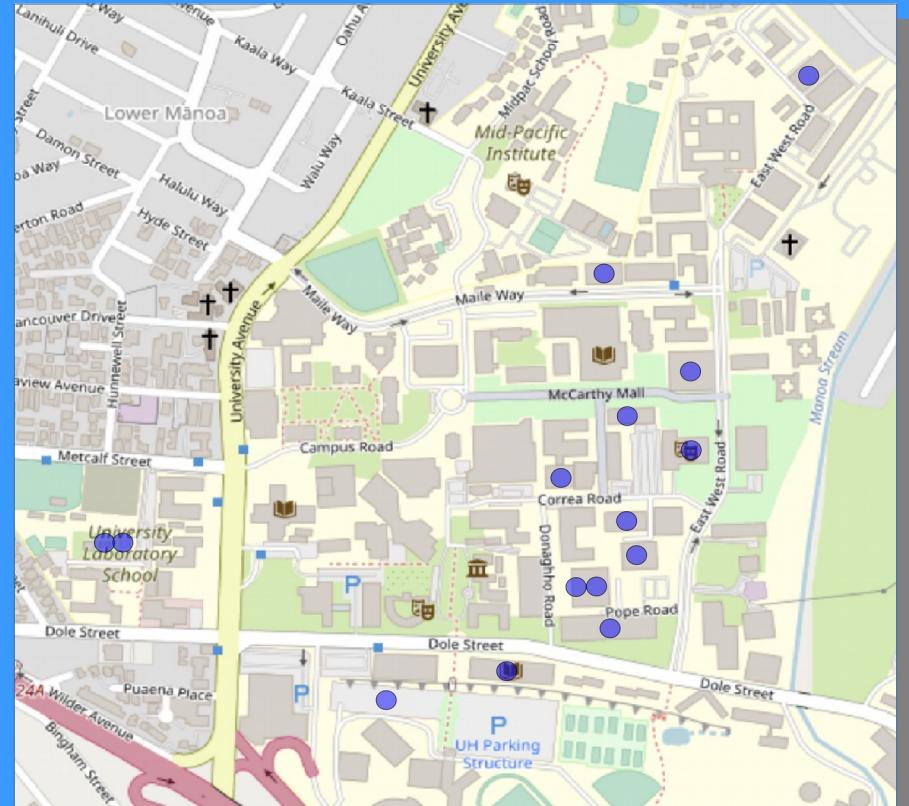
1. Any device passes threshold.
2. Record any device  $> 3*\text{std}$ .
3. Wait until all devices are below threshold.
4. If device count is  $> 1$  request data from
  - Devices which passed threshold.
  - Devices with a metric  $> 3*\text{std}$ .
5. If device count == 1:
  - No request is made.
6. Return to monitoring.

# UH Deployment

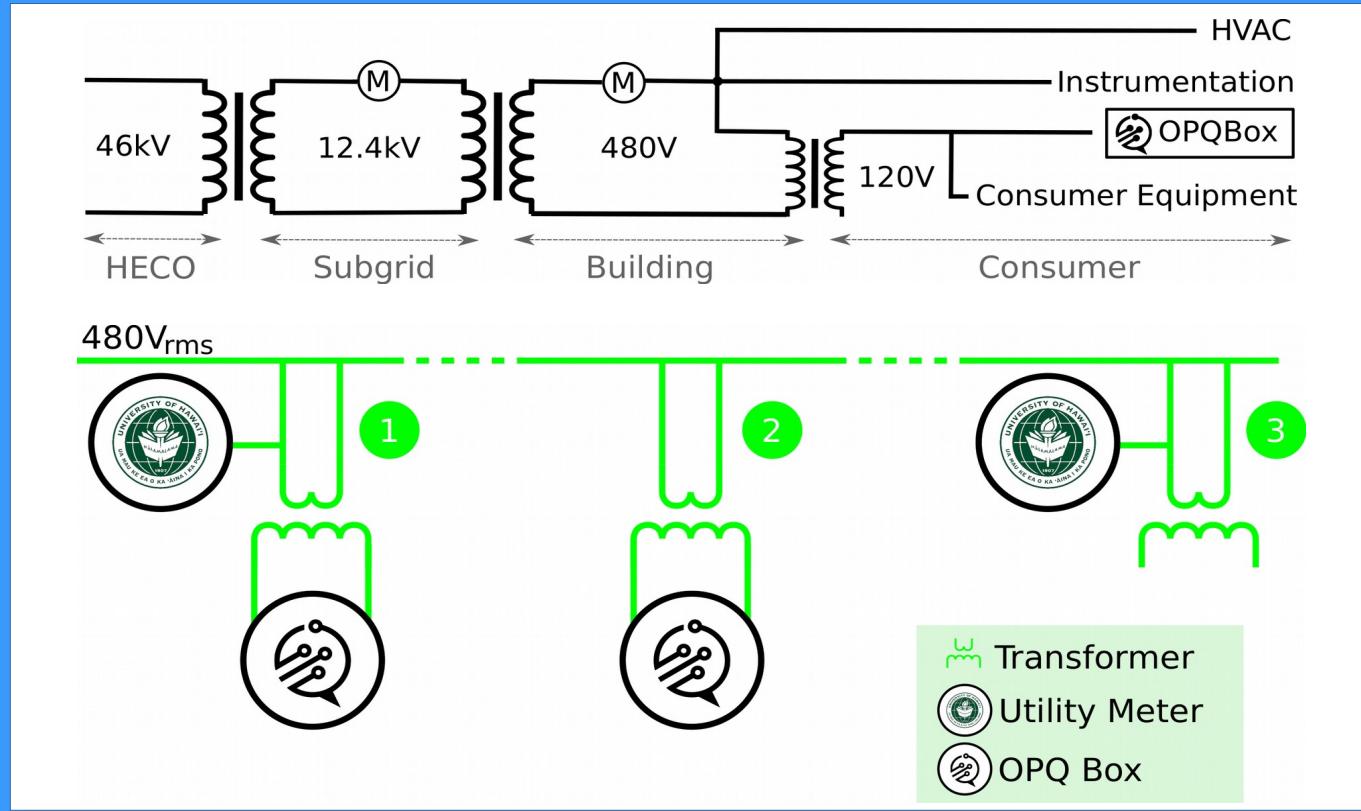
## in-situ validation

- 15 Devices.
- 3 months of data.
- Still running.

Anyone want a PQ network?

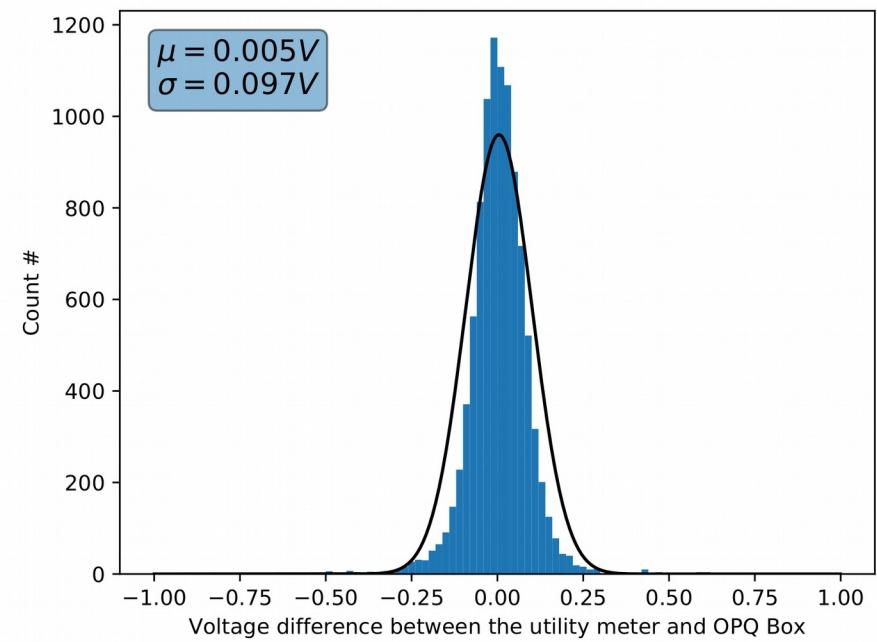
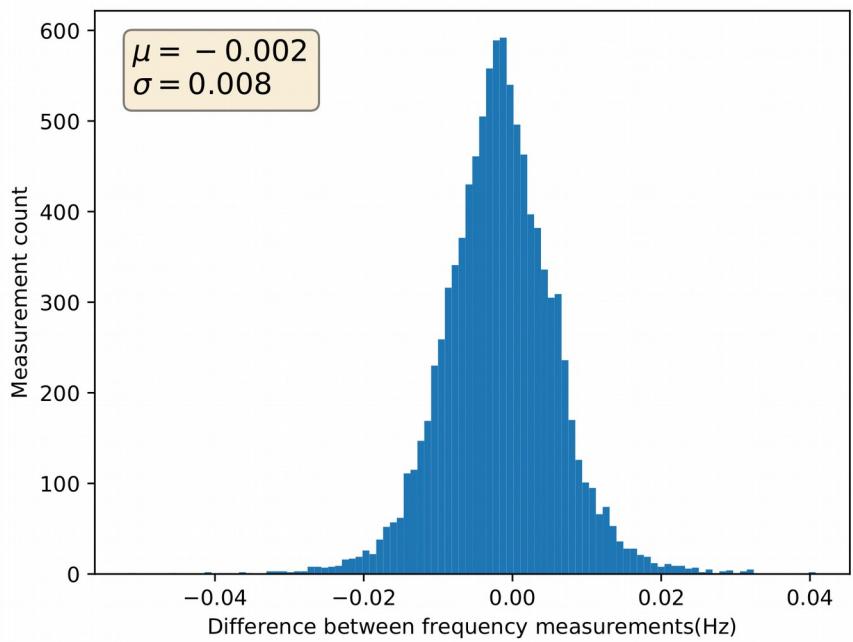


# UH Deployment



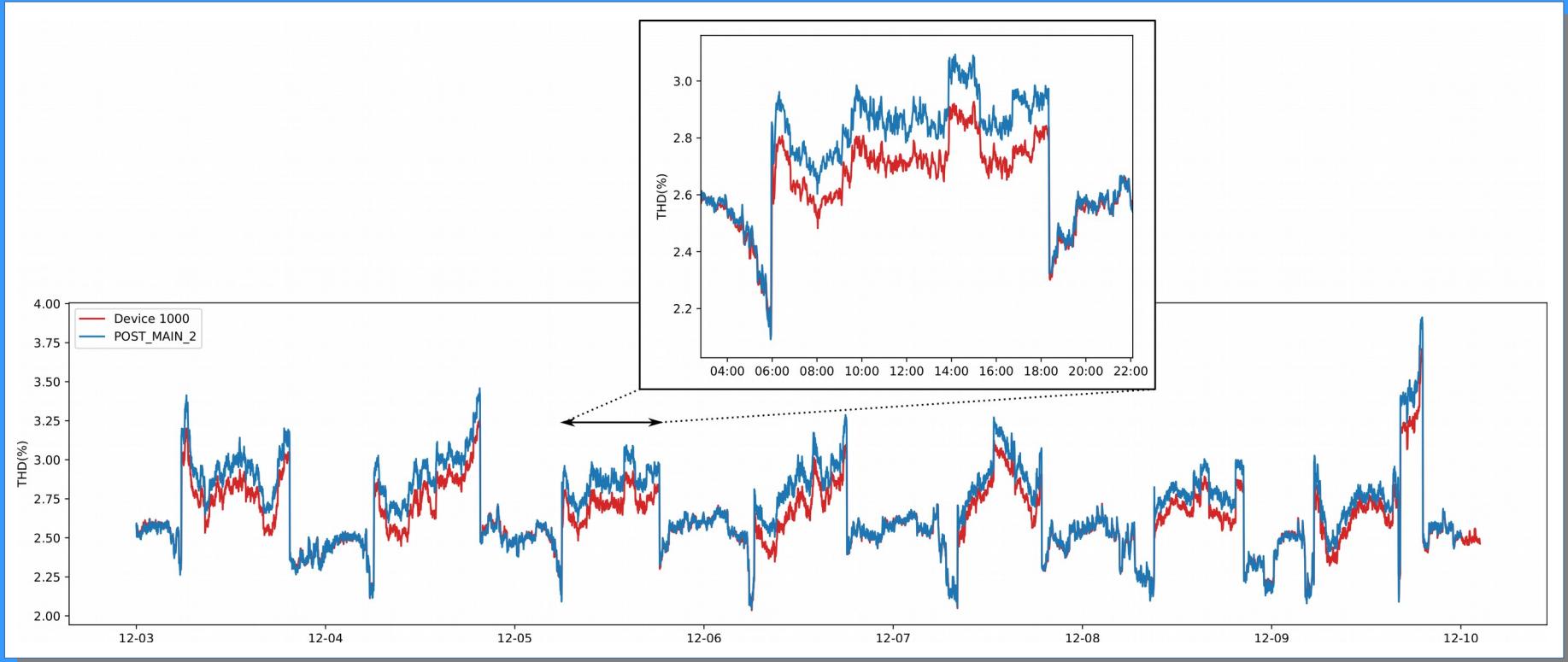
# In-vivo validation of OPQ Box

## Comparison with UH meters(frequency and V<sub>rms</sub>)



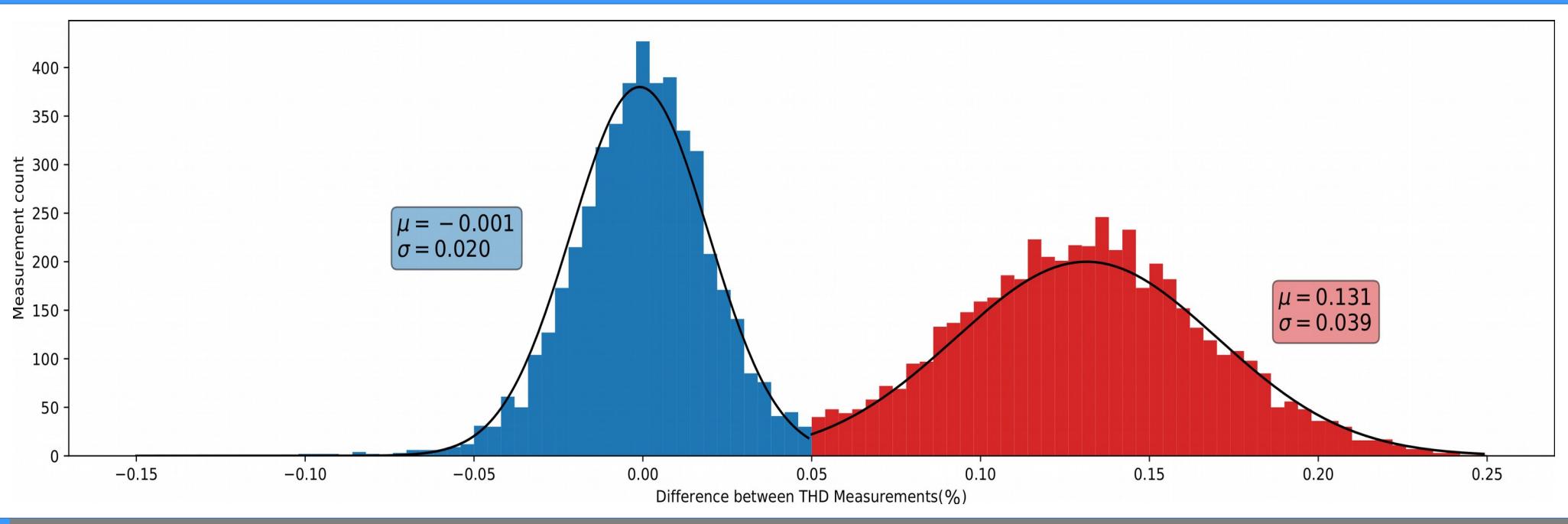
# In-vivo validation of OPQ Box

## Comparison with UH meters(THD)



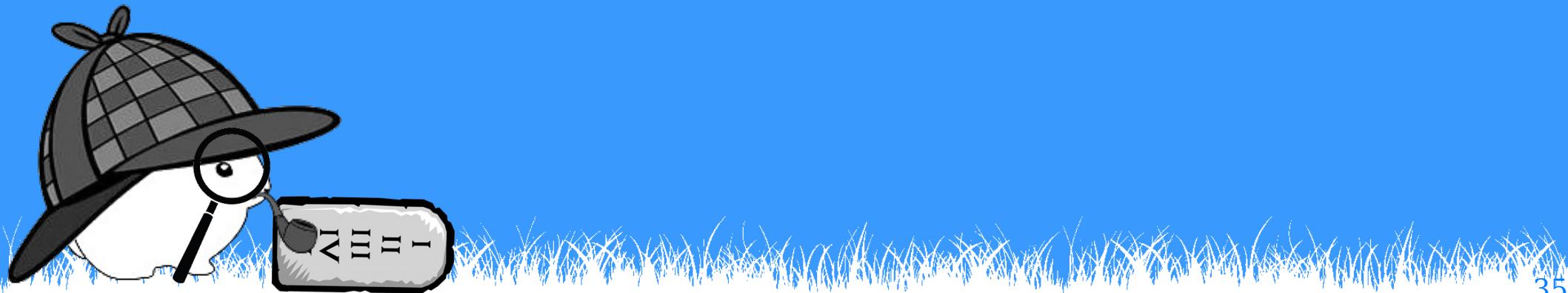
# In-vivo validation of OPQ Box

## Comparison with UH meters(THD)

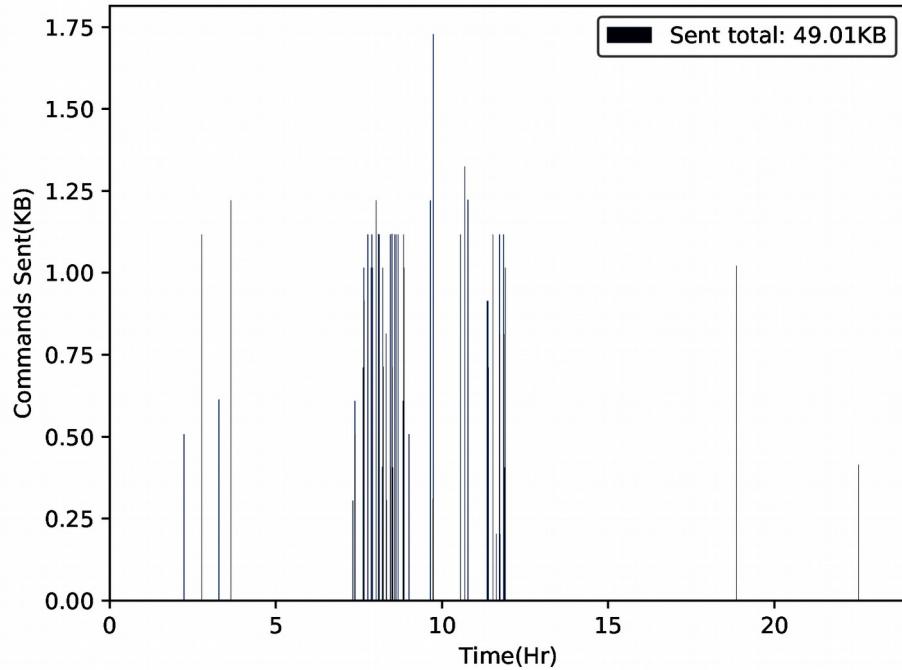
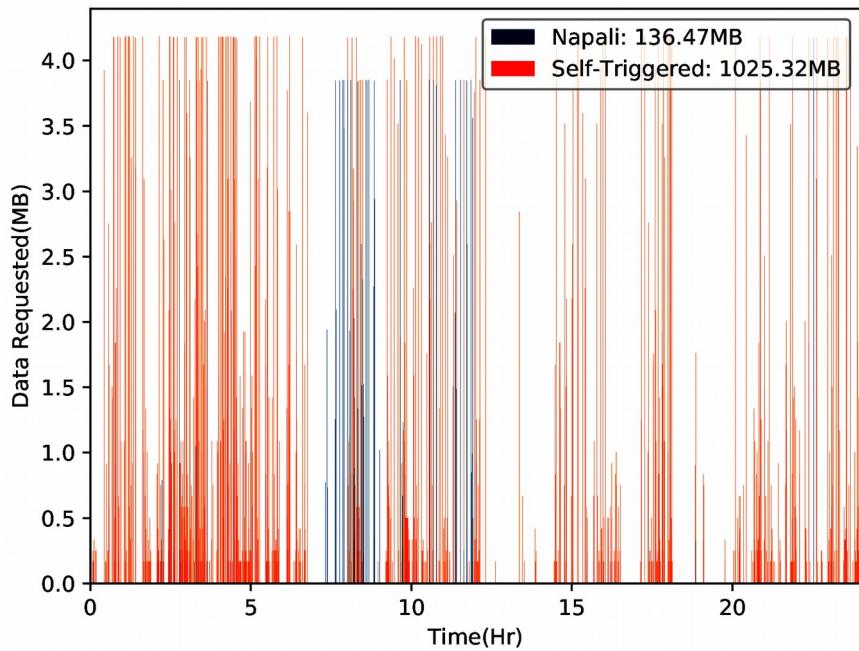


# Testing Claims

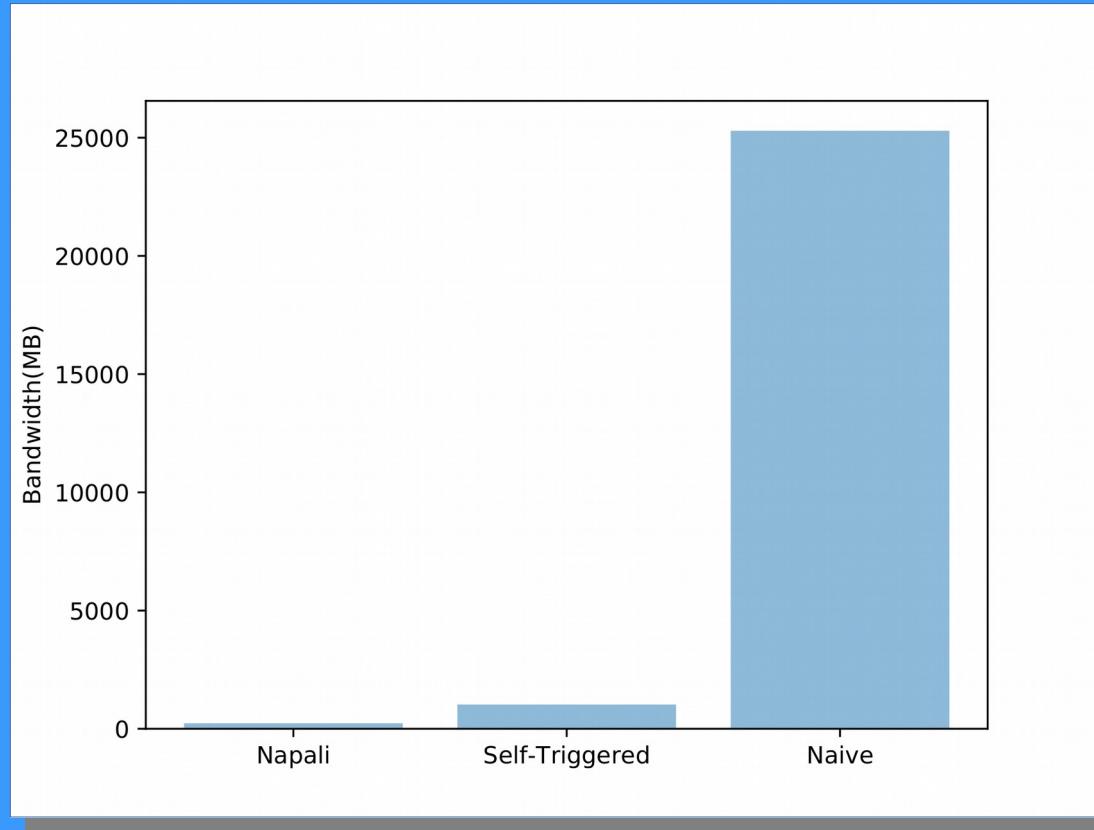
1. Napali minimizes bandwidth usage
2. Napali mitigates device latency effects
3. Napali minimizes sink processing requirements
4. Sub-threshold data acquisition is a viable event detection strategy
5. Temporal locality triggering results in a low false negative detection



# Claim: Napali Bandwidth Advantage



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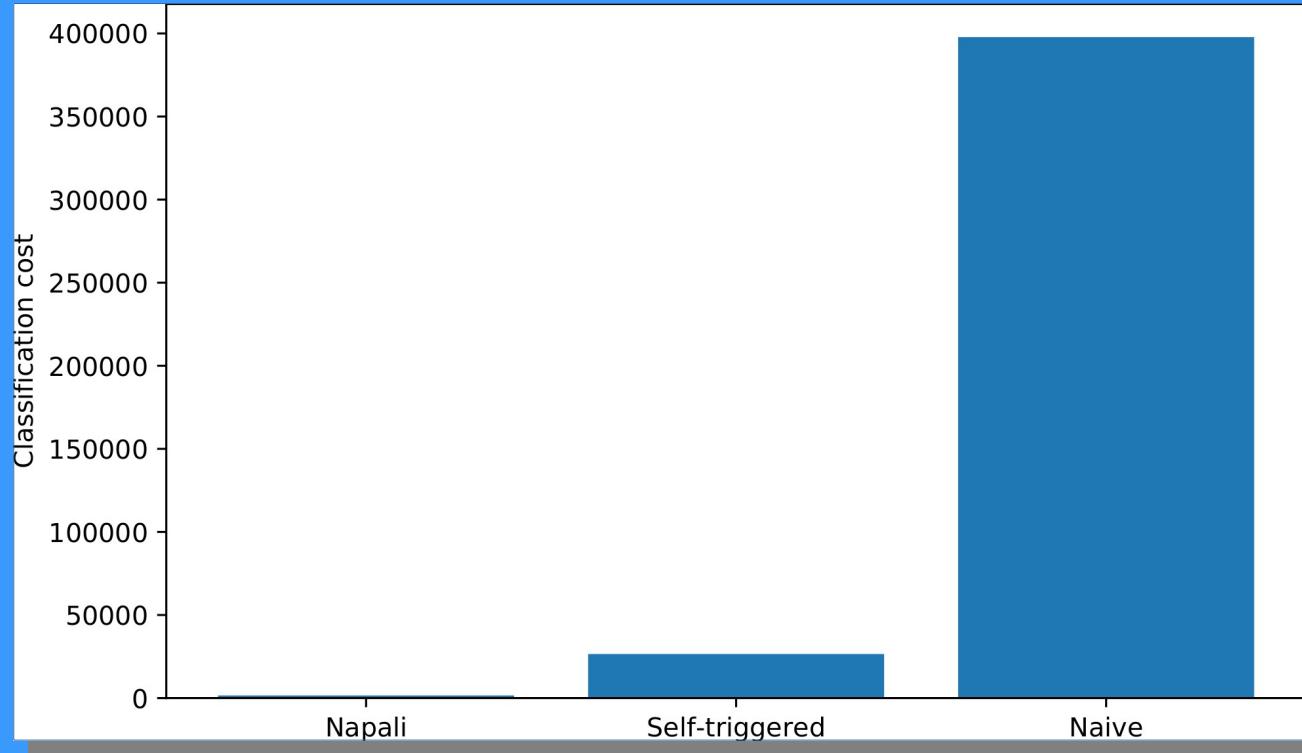


*Exquisite!*



# Claim: Computational Cost

## classification cost



*Flawless!*

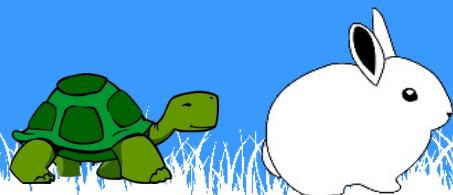


# Claim: Latency

Late metrics over 24 hours

$$Buffer_{naive} = 2 * latency_{max} * (Datarate) * (\#ofdevice)$$

$$Buffer_{napali} = 2 * latency_{max} * (Metric\ rate) * (\#ofdevice)$$



# Claim: Napali Sink Computational Cost Advantage

$$C_{total} = C_{metric\_extraction} + C_{detection}$$

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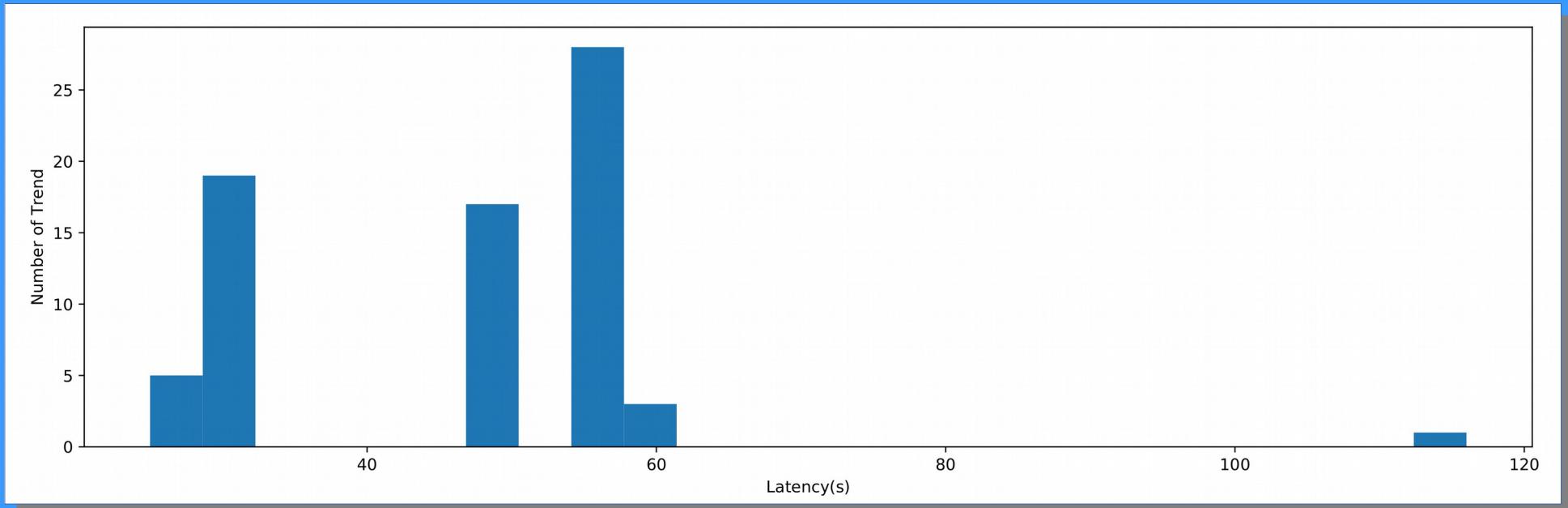
Napali	0	10uS
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Naive	800uS	10uS
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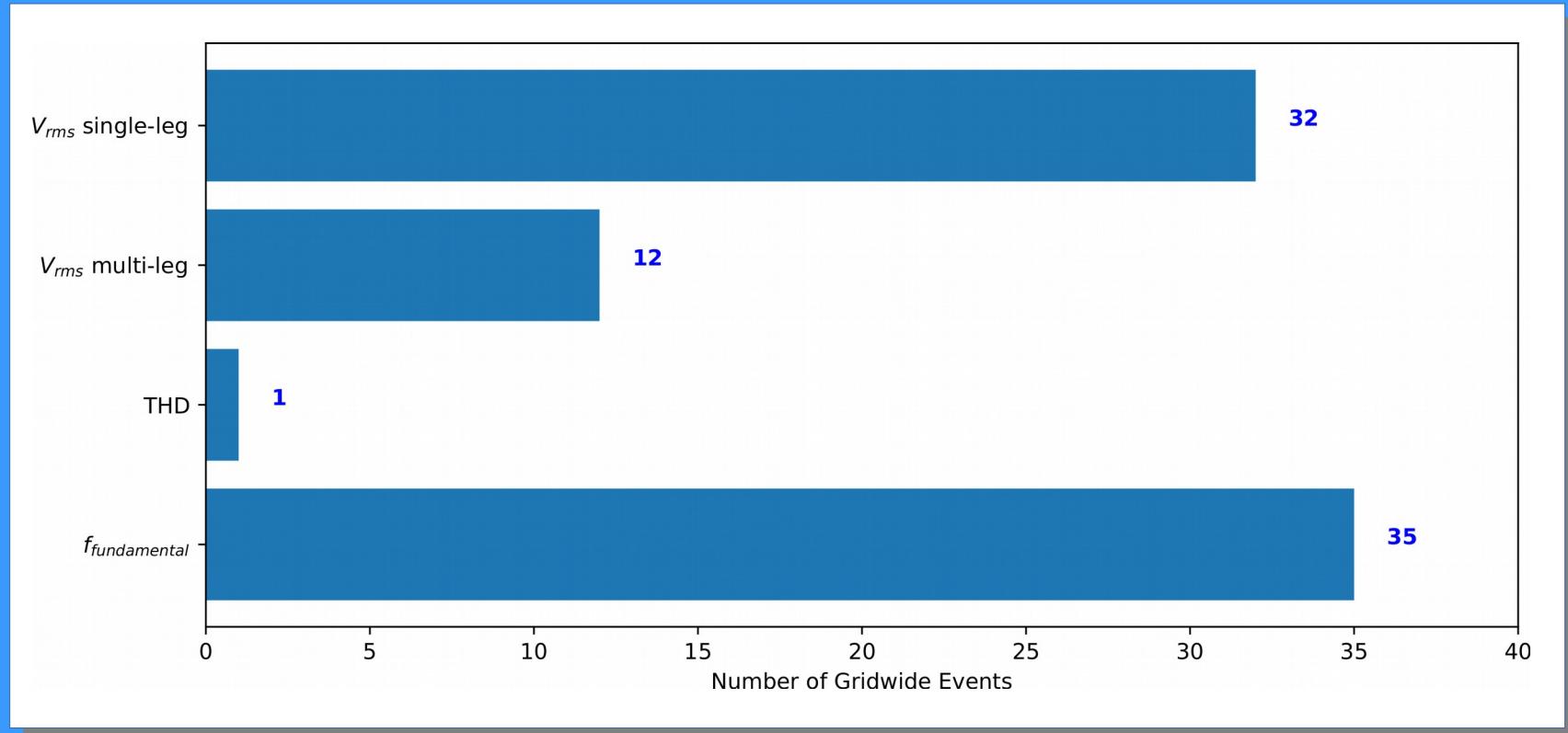
**1 device 1 second**

# Claim: Napali Latency Sensitivity

## Late metrics over 24 hours

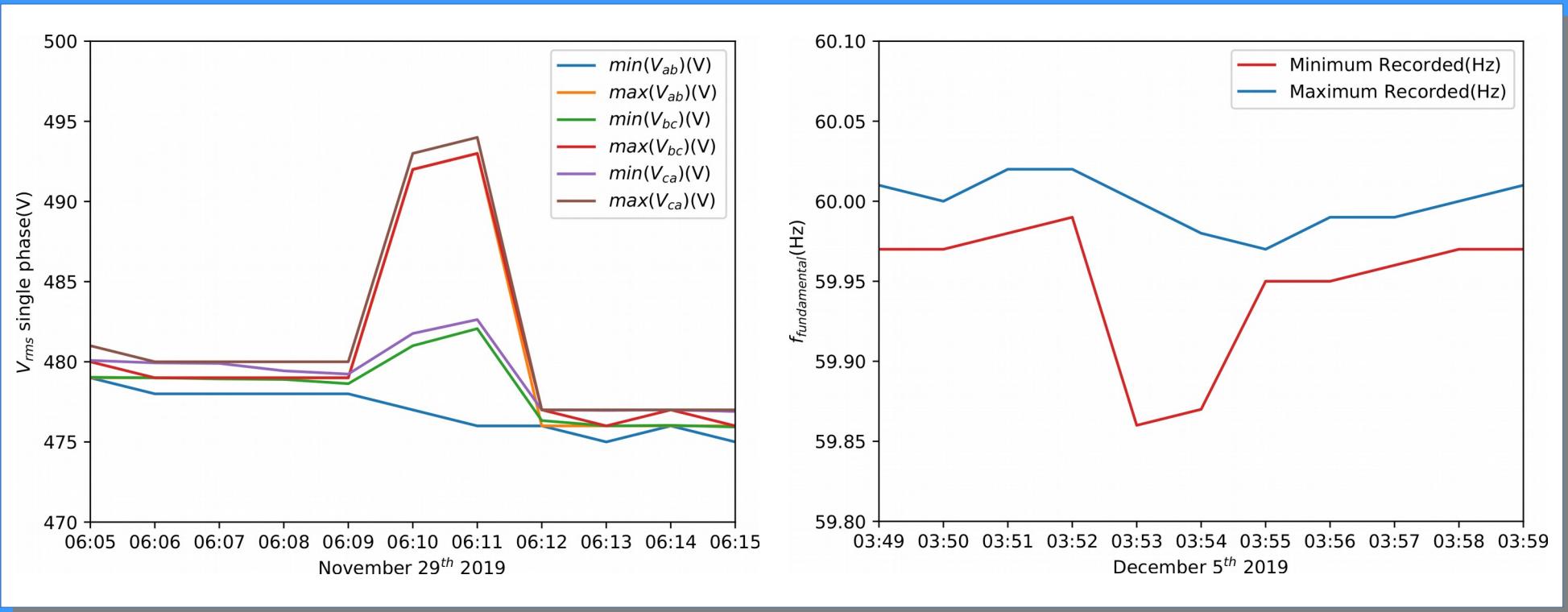


# Claim: Temporal locality for event detection



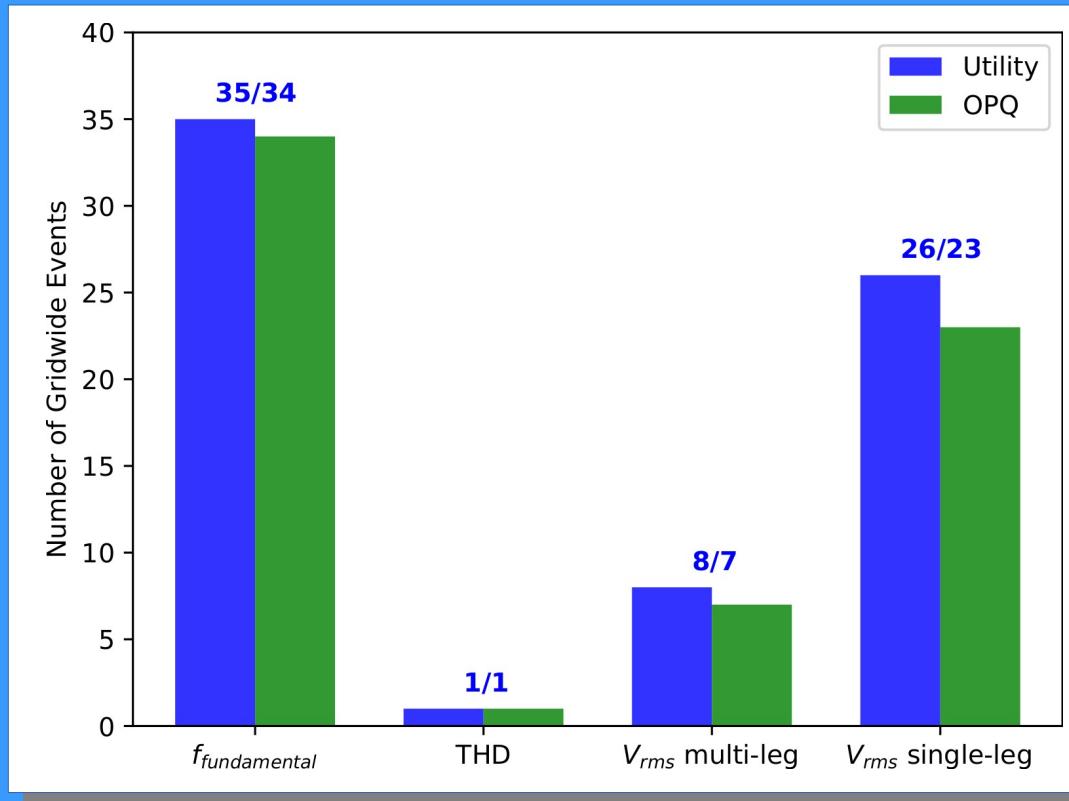
# Claim: Temporal locality for event detection

## Ground truth event examples.



# Claim: Temporal locality for event detection

## Detected events



*Marvelous!*



# Claim: Sub-threshold Events Detection Capability

## 1. Select events where:

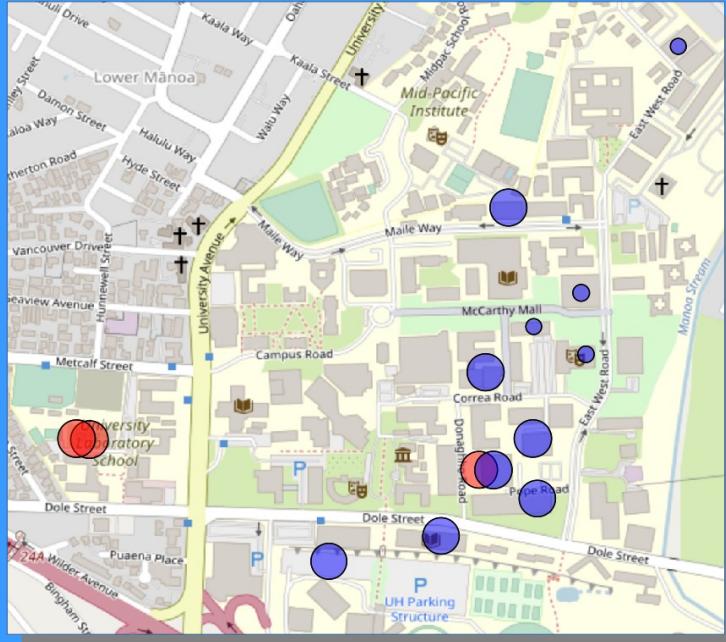
- single collocated utility meter passes threshold.
- one or more non-collocated utility meters passes threshold.

## 2. Compare the OPQ data with utility meters.

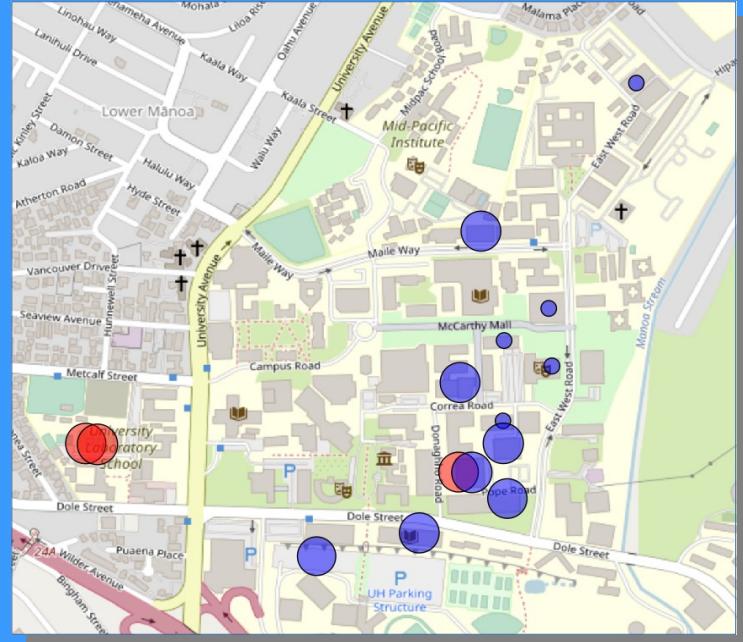
**Only 3 events!**



# Event #1 and #2

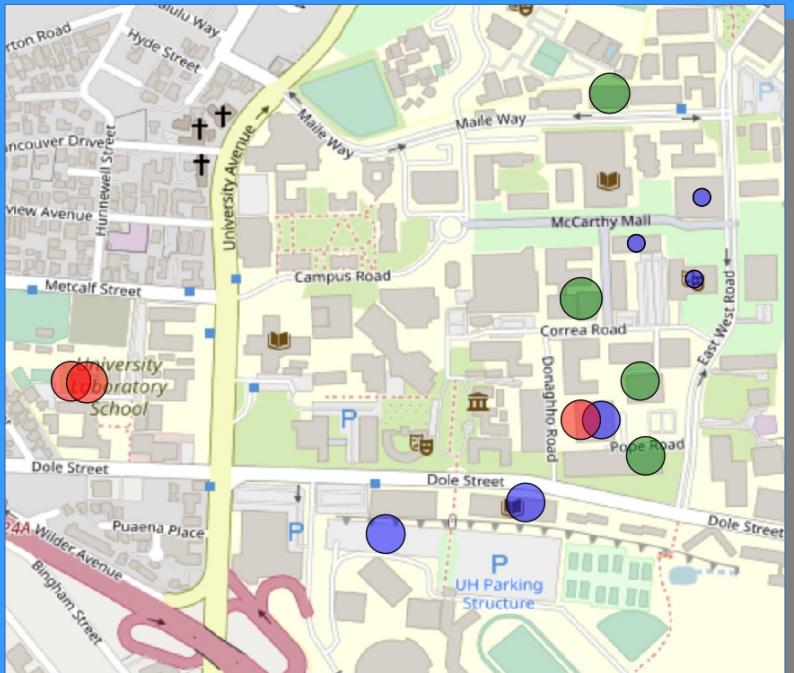


5 Utility Meters  
15 OPQ Boxes

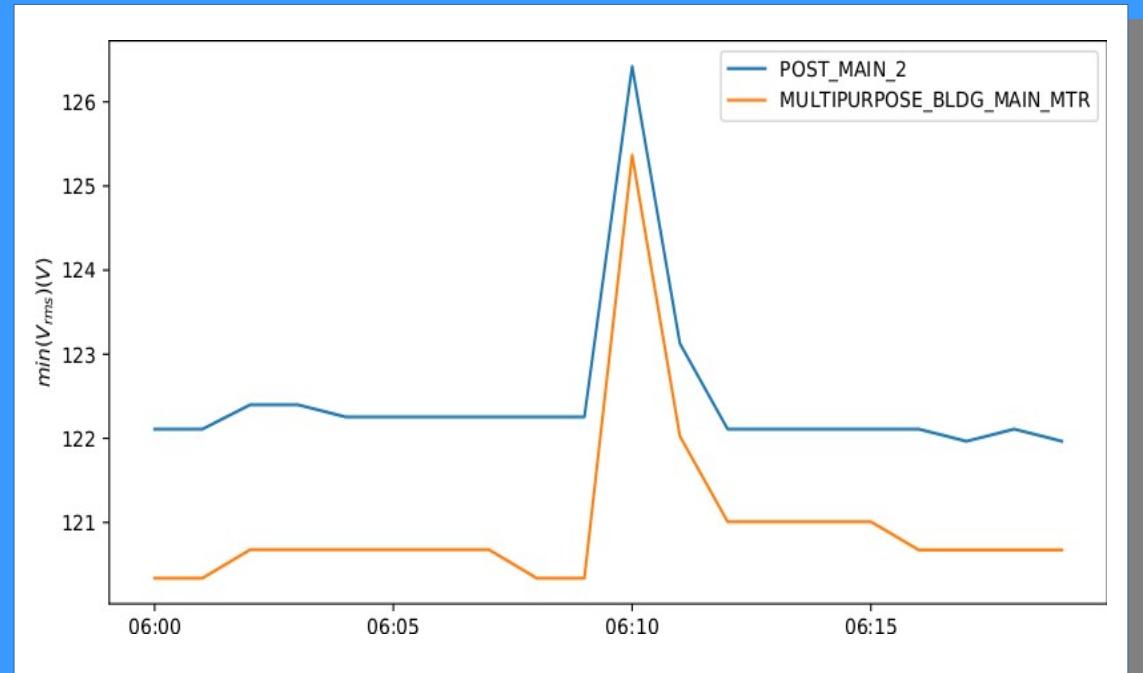


4 Utility Meters  
14 OPQ Boxes

# Event #3

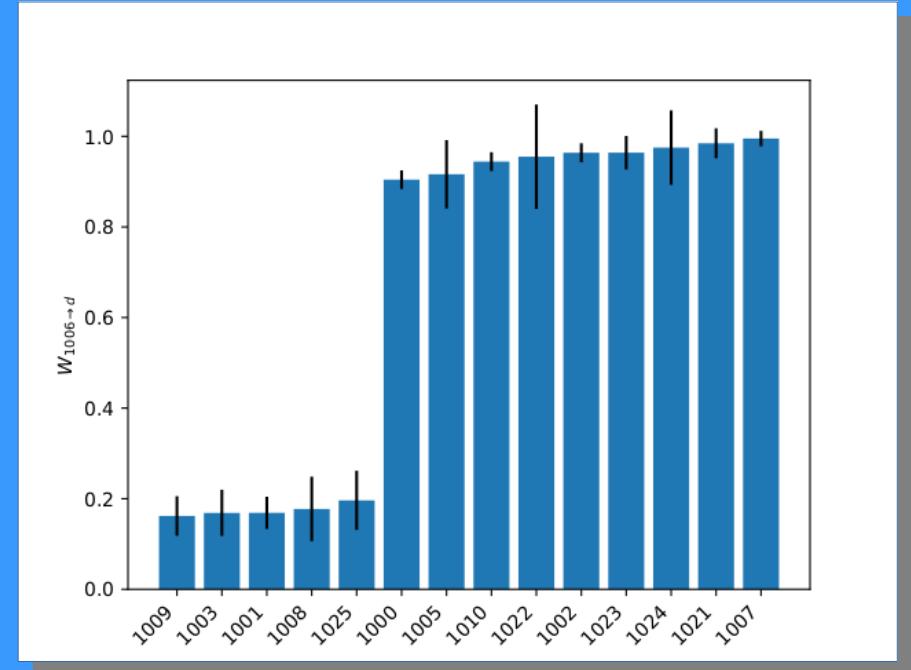


13 OPQ Boxes

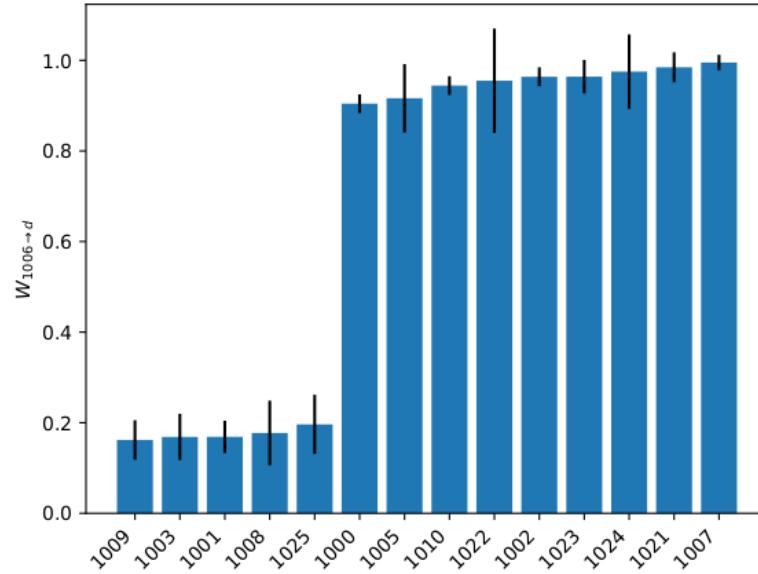
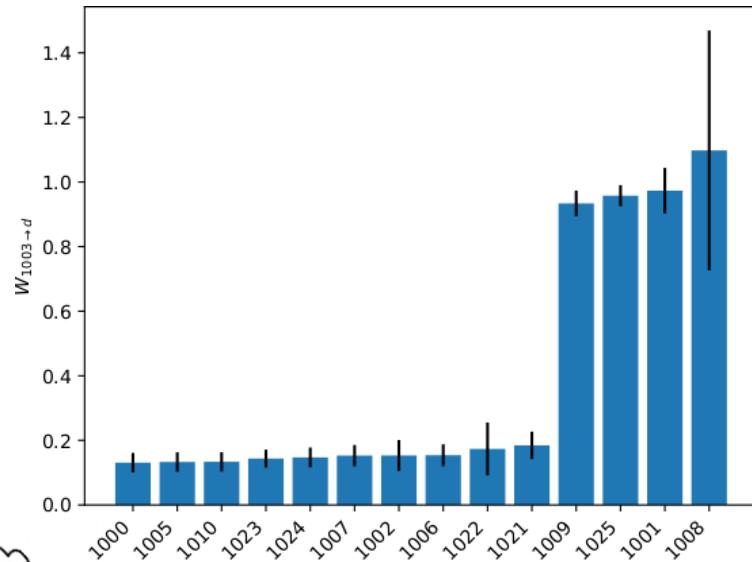


2 Utility Meters

# Is it possible to cluster events?



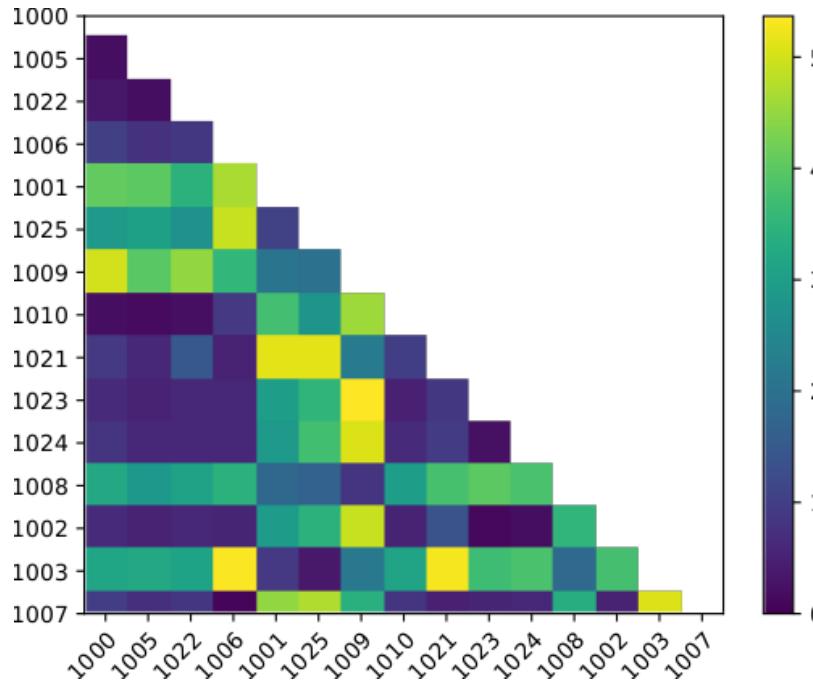
# Bifurcation of the UH power Grid



# Pairwise Dissimilarity

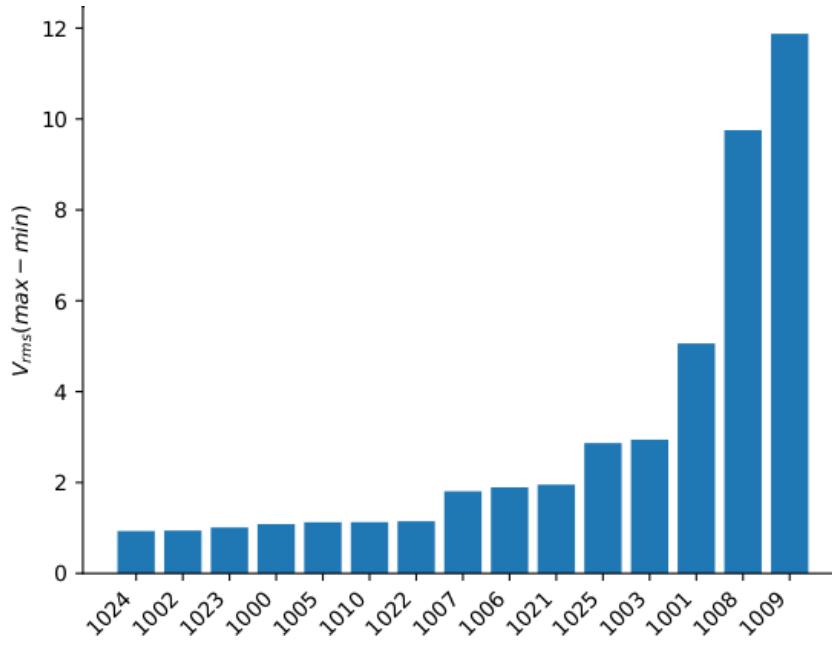
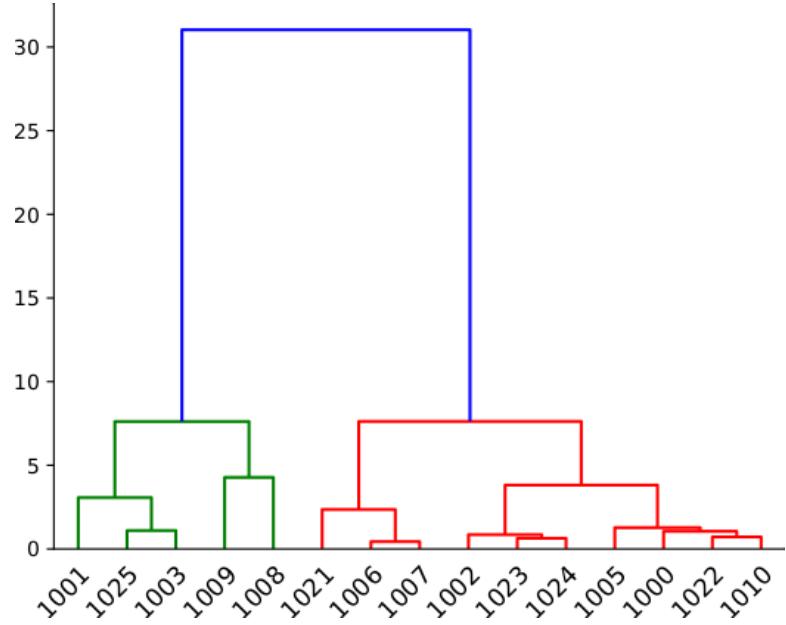
$V_{rms}$

$$D_{p \rightarrow d}^{rms} = \frac{1}{n} \sum_n |(\max(V_{rms}) - \min(V_{rms}))_p - (\max(V_{rms}) - \min(V_{rms}))_d|$$



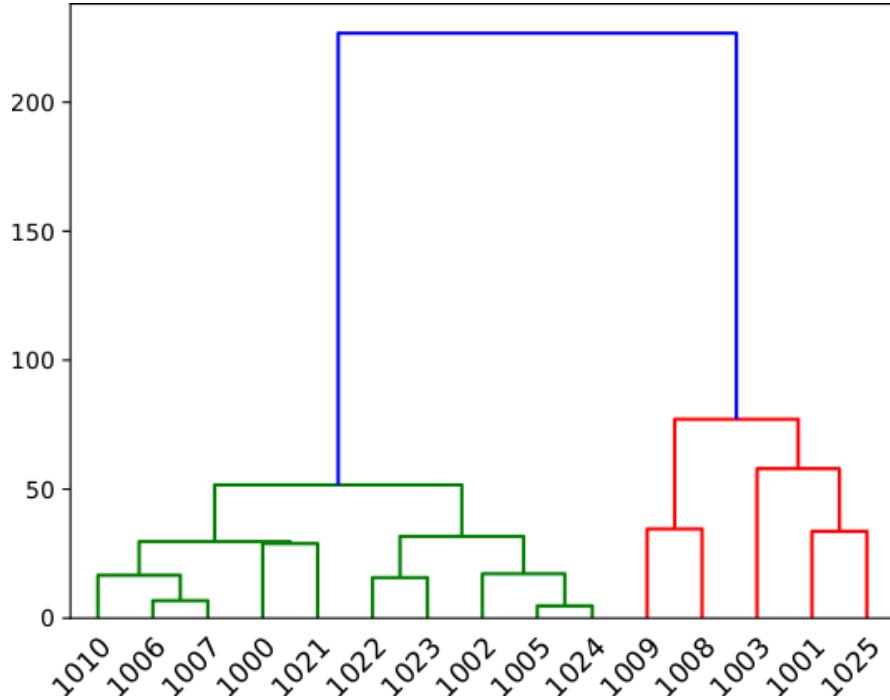
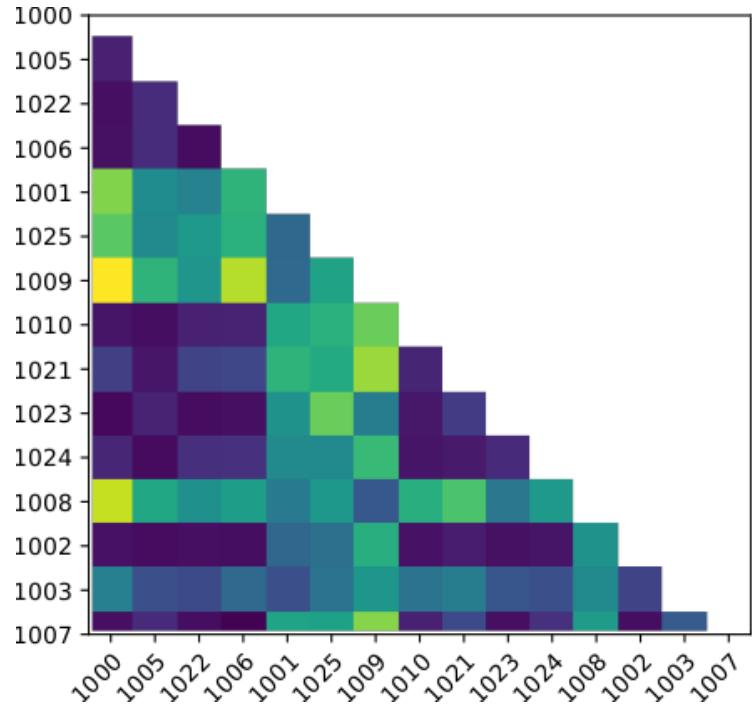
# Clustering

$V_{rms}$



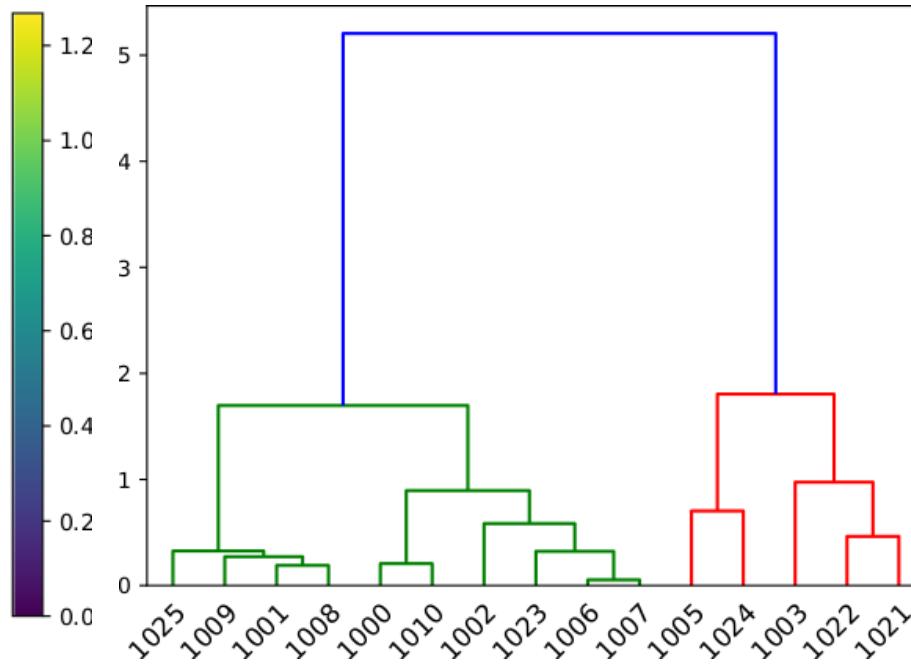
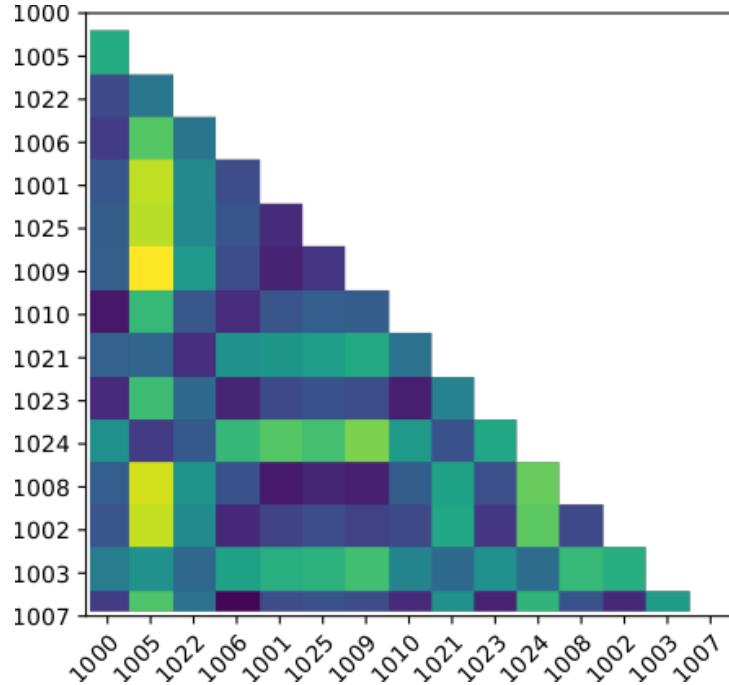
# Clustering

## Transients



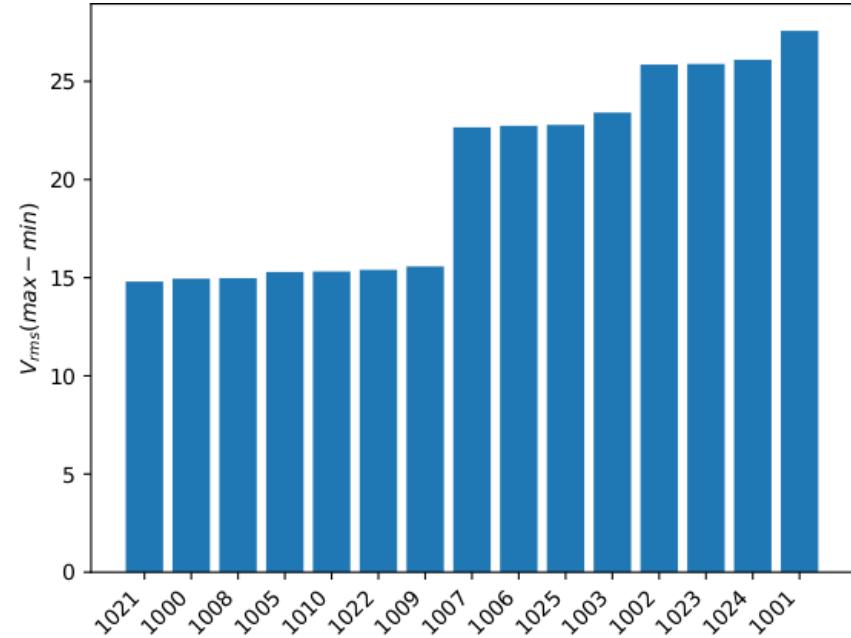
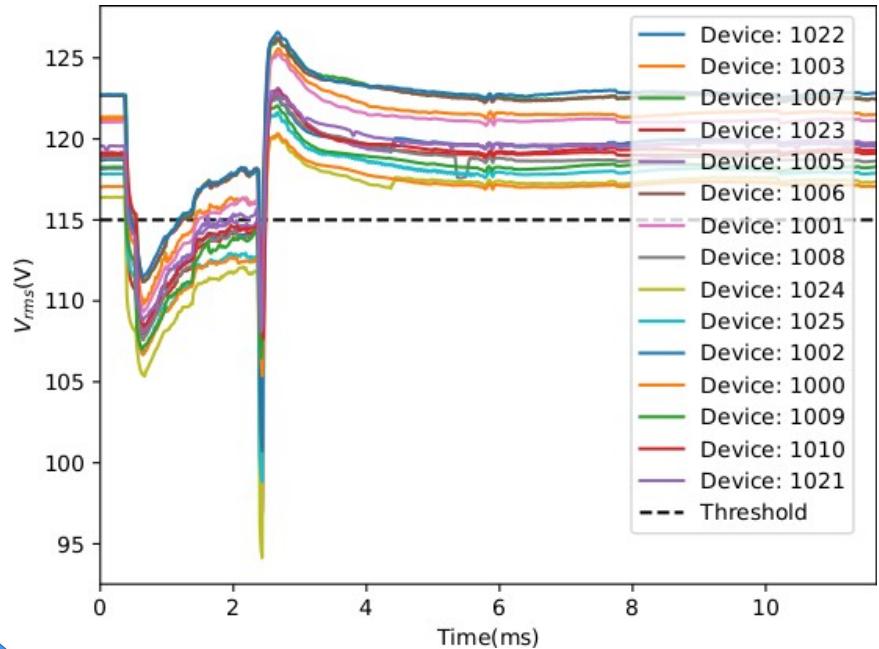
# Clustering

## THD



# True Gridwide Events

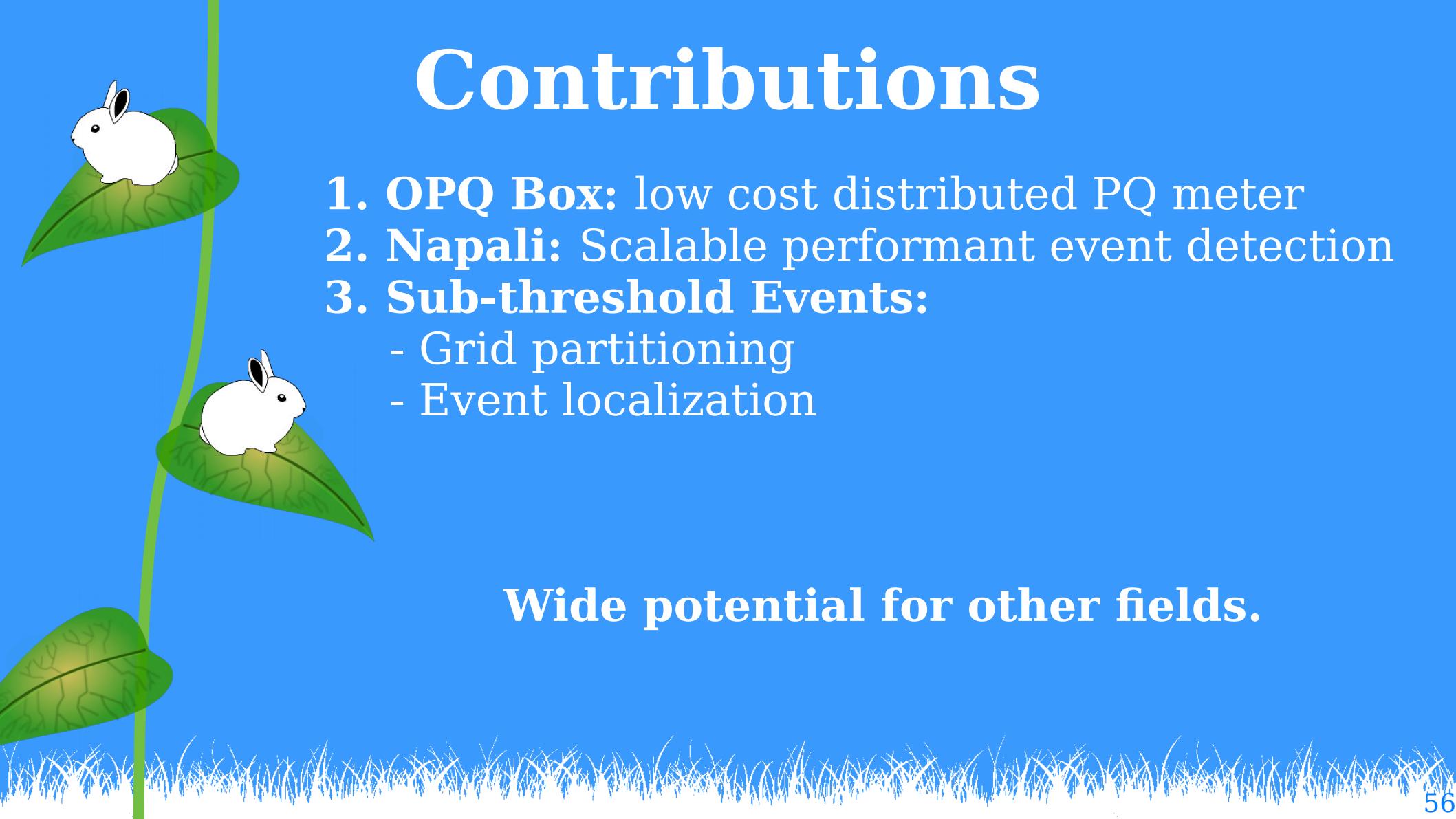
## THD



# Sub-threshold Triggering

1. Partitioning of the power grid.
2. Localization of anomalies.
3. Napali scalability improvements.





# Contributions

1. **OPQ Box:** low cost distributed PQ meter
2. **Napali:** Scalable performant event detection
3. **Sub-threshold Events:**
  - Grid partitioning
  - Event localization

**Wide potential for other fields.**

# Napali in other domains

## Lightning detection

### Current System:

- Remote area deployment
- Satellite communication

### With Napali:

- Metropolitan Area
- Abundant communication



# Napali in other domains

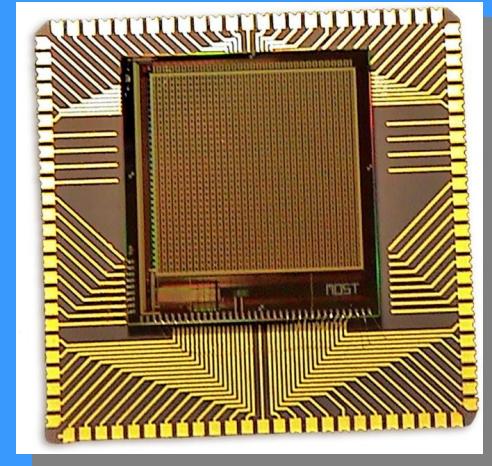
## Gunshot Detection

### Current System:

- No geographically distributed system in literature.

### With Napali:

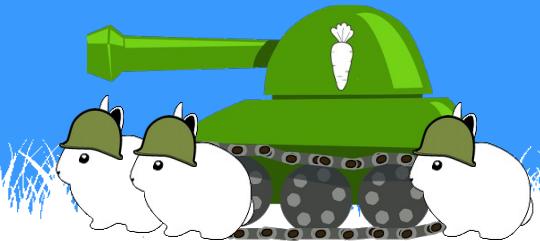
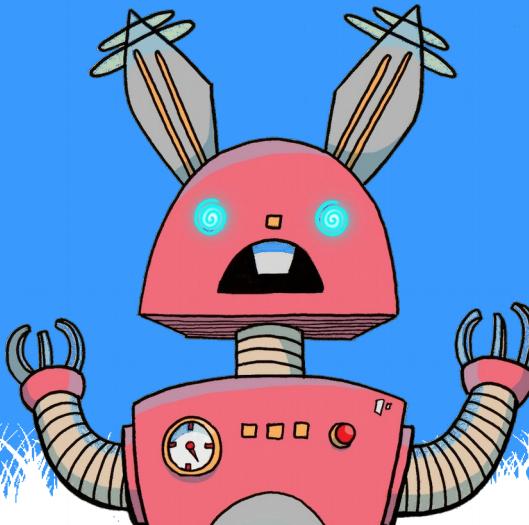
- Metropolitan area coverage.



MOST Sensor  
Oceanit 2017

# Future Work

- 1. AI instead of statistical model**
- 2. Scalability study**
- 3. Privacy study**
- 4. Power outage resiliency**
- 5. Integration with Utility**





Fishy



Tiger and Turtle  
2012-2019



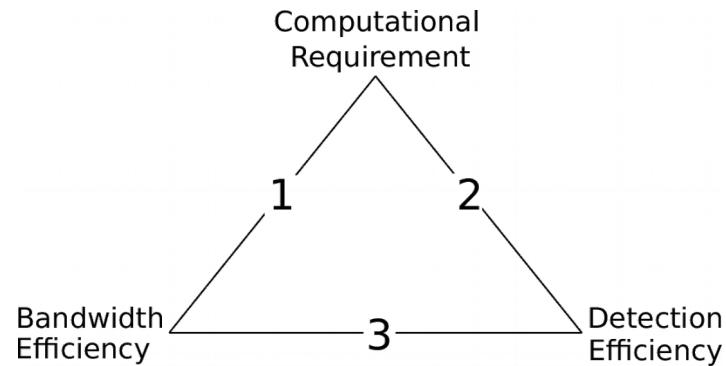


Thanks!



# Comparison From Sensors Perspective

*Pick Two!*

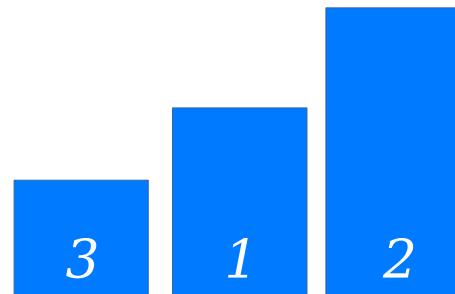


1. Self-Triggered
2. Naive
3. Napali



# Comparison From Sink Perspective

*Computational Cost:*



1. Self-Triggered
2. Naive
3. Napali



# **Additional Benefits of Napali**

## **Outside the scope of this thesis**

- 1. Increased flexibility with respect to privacy protection.**
- 2. Increased resiliency with respect to power failure**

