# Pulsar: Towards Ubiquitous Visible Light Localization

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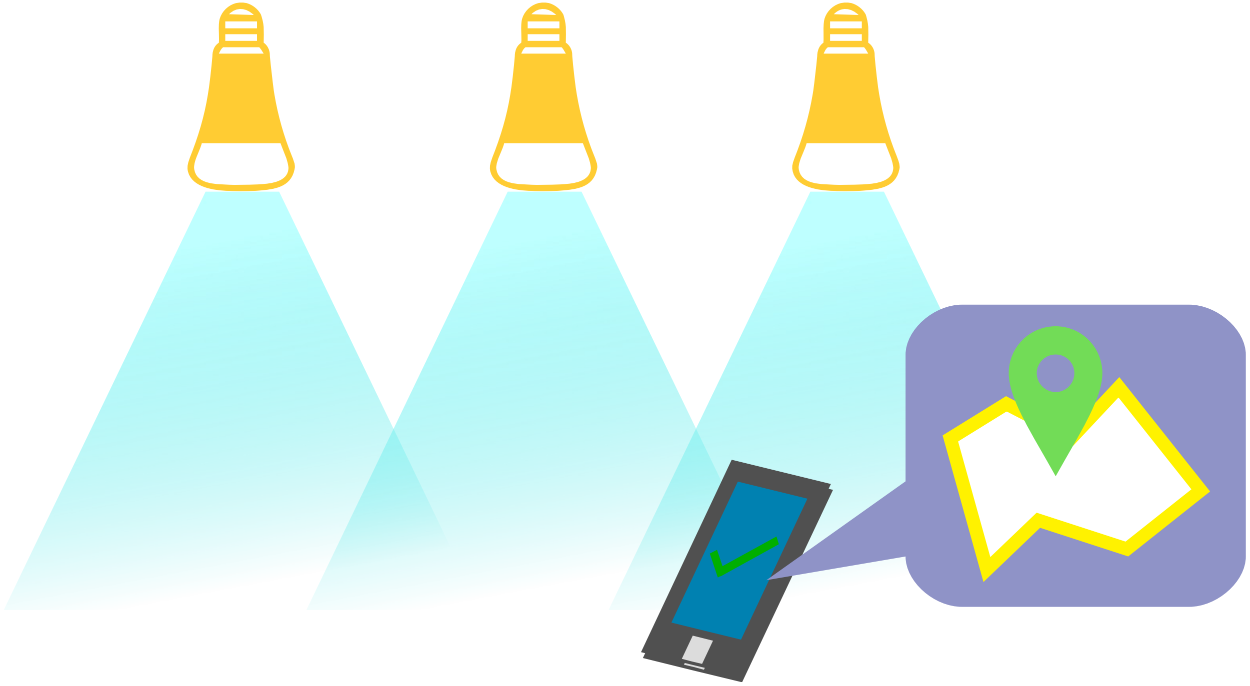
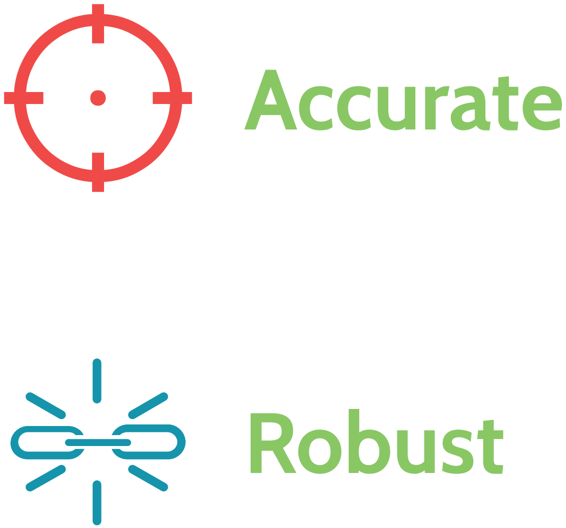
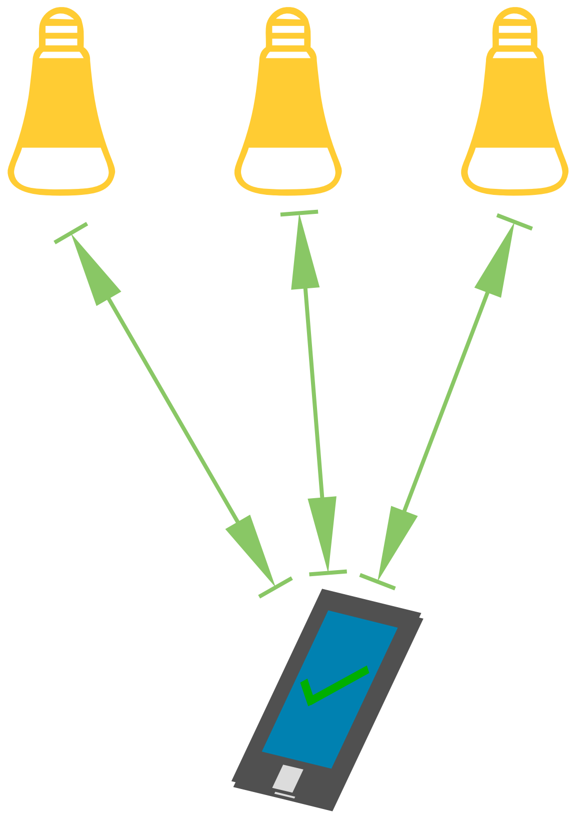
# Visible Light Localization





# Existing Solutions

- Photodiodes
  - Compact
  - Low-power
  - RSS Propagation Modeling

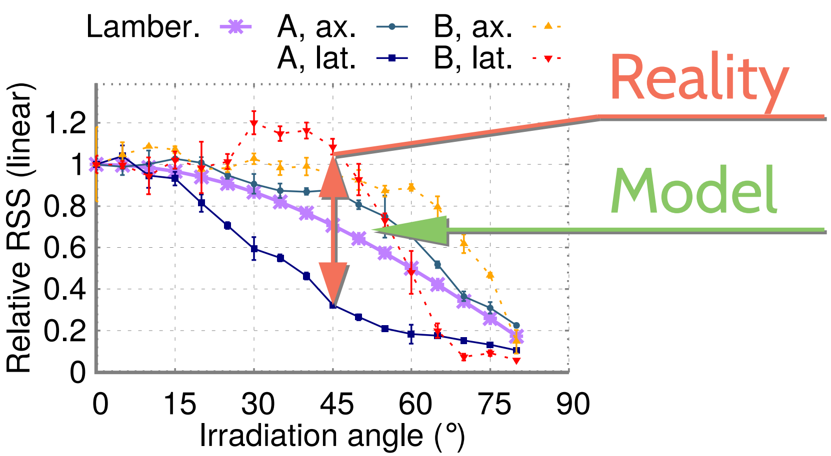


# Existing Solutions

## Photodiodes

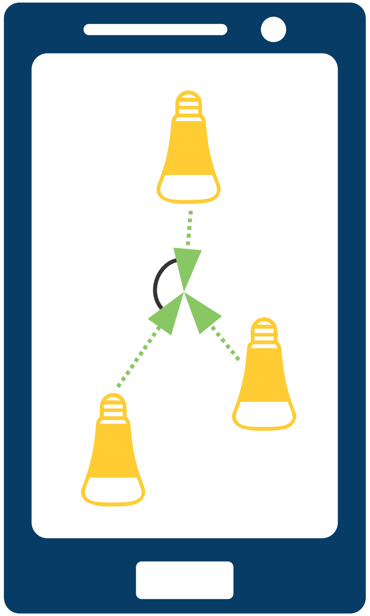
### Channel Model is Unrealistic for Fixtures

### Partial Shadowing and Blockage Breaks Model




# Existing Solutions

- Cameras
  - Accurate
  - Robust
  - Triangulation with Photogrammetry



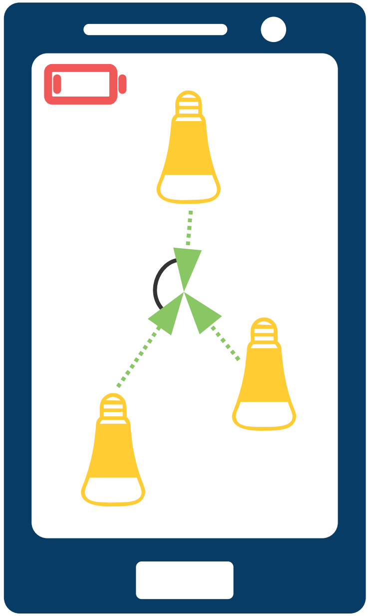
# Existing Solutions

Cameras

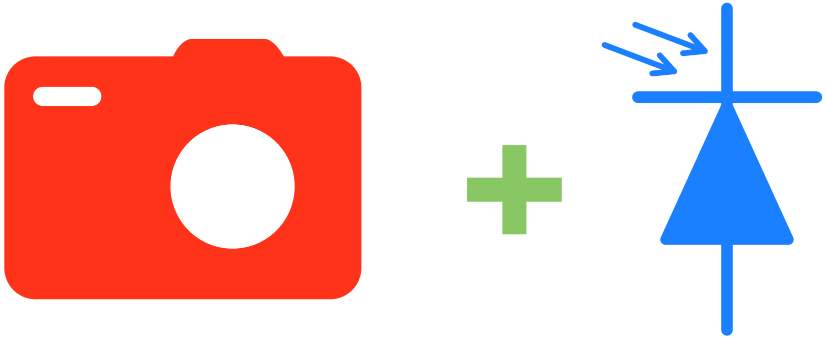
Narrow Field of View

High Energy Consumption

Long Latency

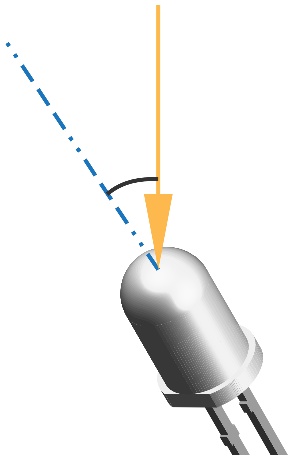


# Achieve Accurate and Low-power Localization

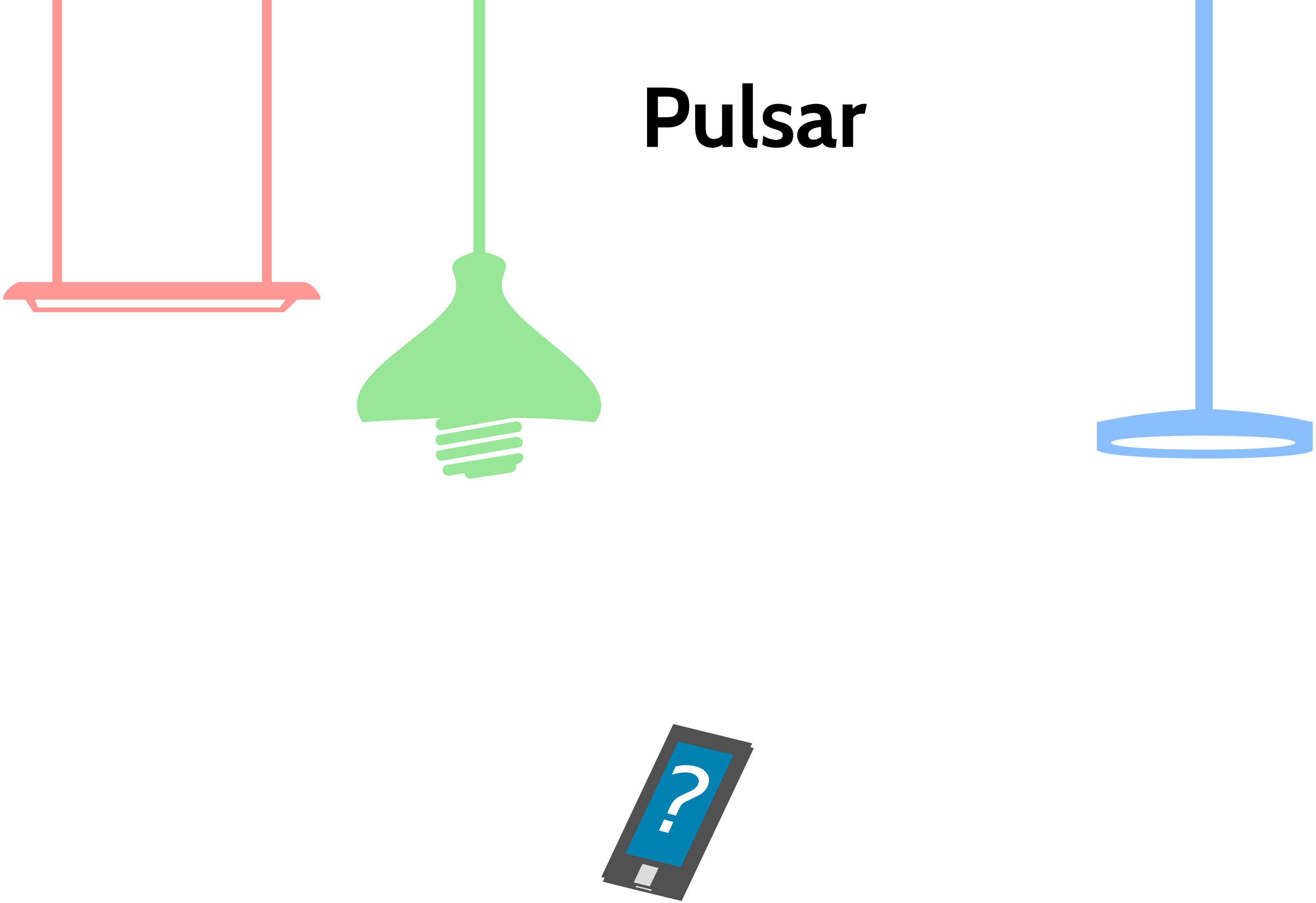


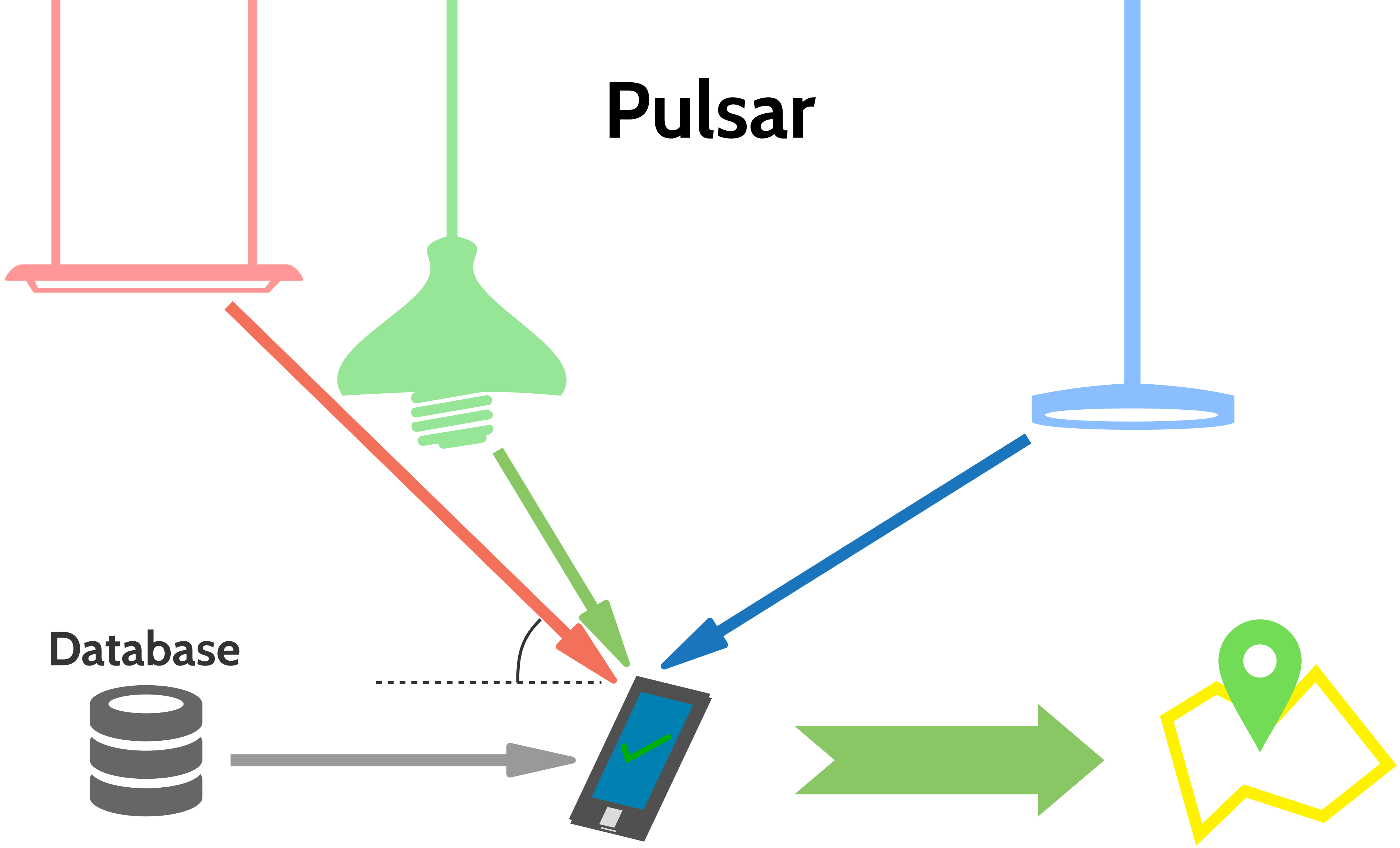
Achieve Accurate and Low-power Localization

Sense Angle of Arrival with Photodiodes



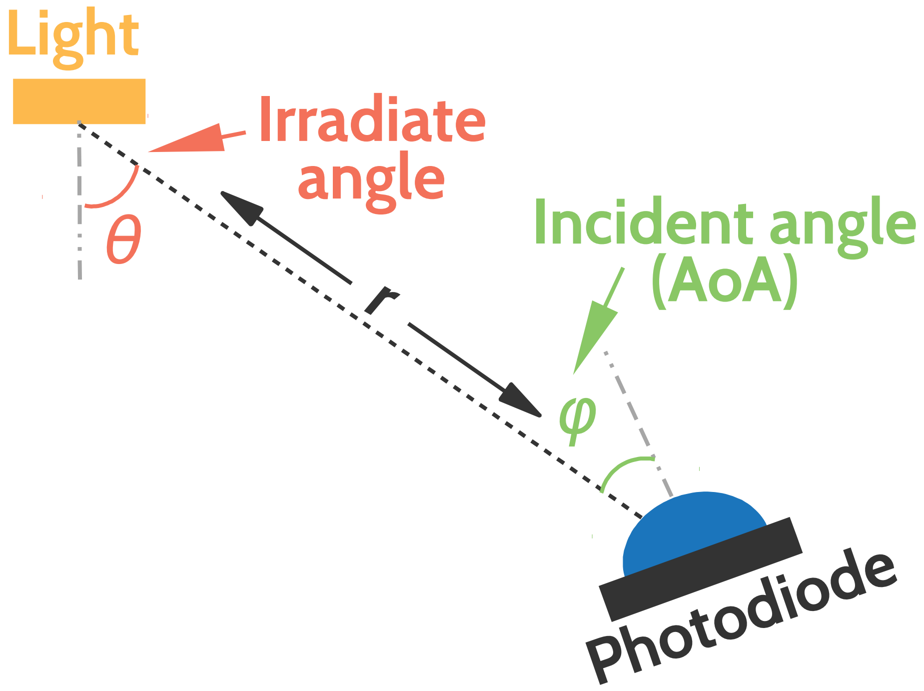
# Pulsar




Pulsar
Database

# Sensing AoA with Photodiodes

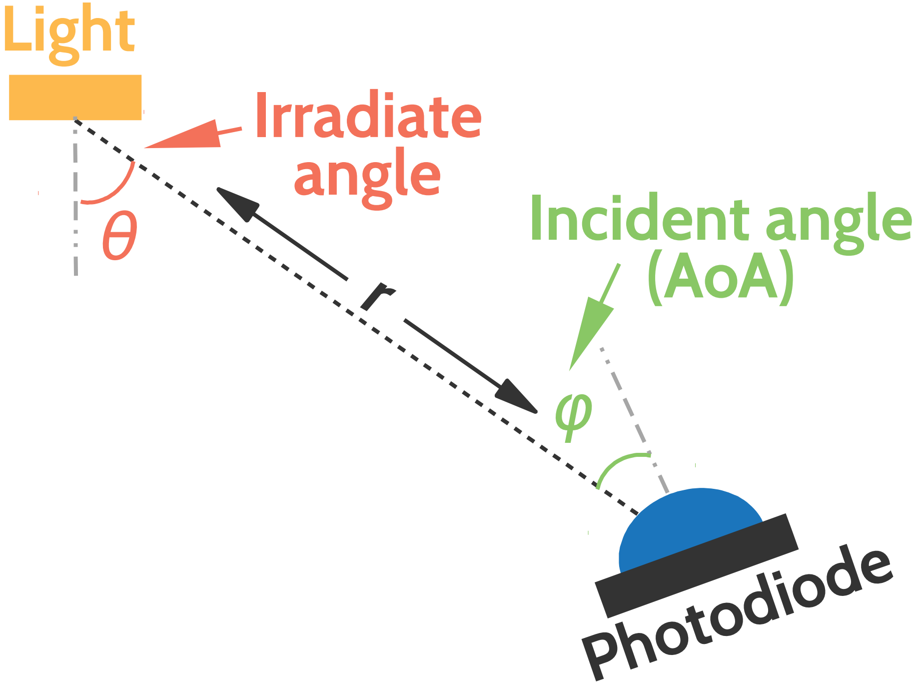
- Review **Channel Model**



# Sensing AoA with Photodiodes

- Review **Channel Model**

$$RSS = P_t\, A_t(\theta)\, \alpha(r)\, A_r(\varphi)$$



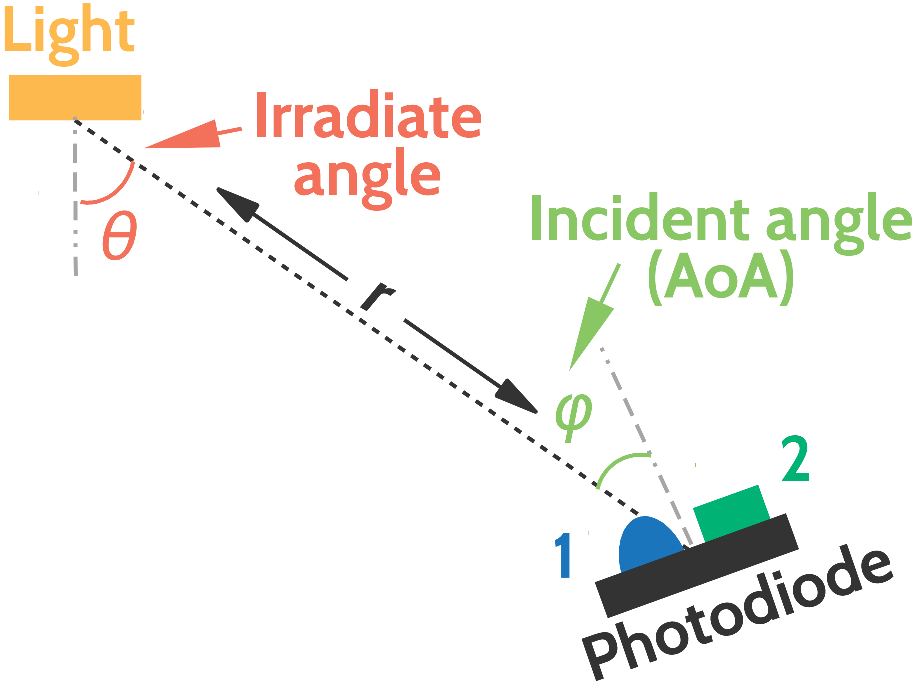
# Sensing AoA with Photodiodes

## Review Channel Model

$$\text{RSS} = P_t A_t(\theta)\, \alpha(r)\, A_r(\varphi)$$

$$\text{RSS}_1 = P_t A_{t1}(\theta_1)\, \alpha(r_1)\, A_{r1}(\varphi_1)$$

$$\text{RSS}_2 = P_t A_{t2}(\theta_2)\, \alpha(r_2)\, A_{r2}(\varphi_2)$$



# Sensing AoA with Photodiodes

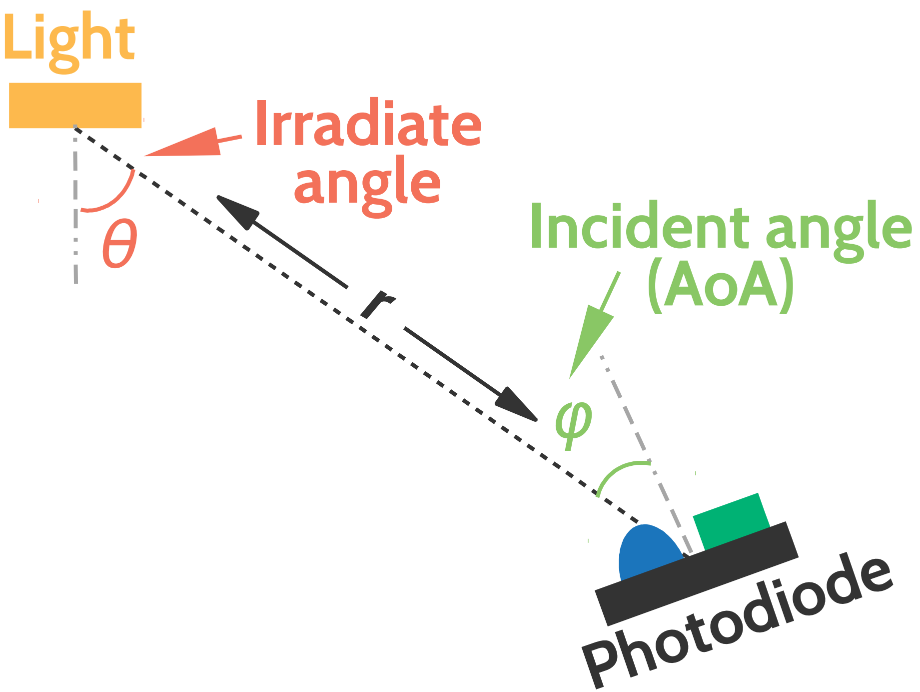
Review **Channel Model**

$$RSS_1 = \boxed{P_t A_{t1}(\theta_1)\, \alpha(r_1)}\ \boxed{A_{r1}(\varphi_1)}$$

$$RSS_2 = \boxed{P_t A_{t2}(\theta_2)\, \alpha(r_2)}\ \boxed{A_{r2}(\varphi_2)}$$

Co-located → Same

Different

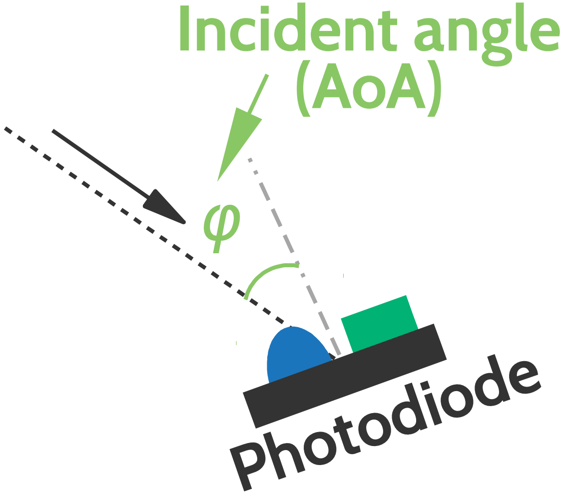


# Sensing AoA with Photodiodes

Assumptions on light are gone!

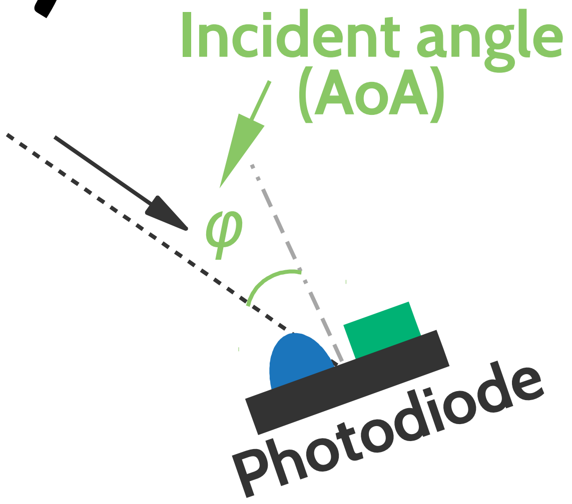
$$\frac{RSS_1}{RSS_2} = \frac{A_{r1}(\varphi_1)}{A_{r2}(\varphi_2)} = A_c(\varphi)$$

Fixed once manufactured



# Sensing AoA with Photodiodes

$$\varphi = A_c^{-1}\left(\frac{RSS_1}{RSS_2}\right)$$



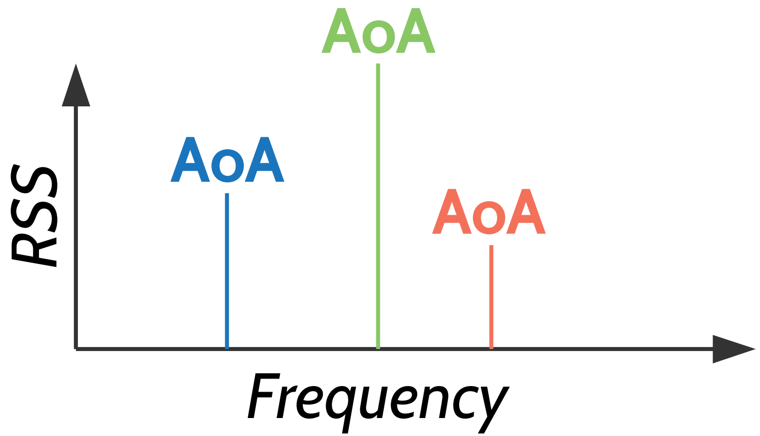
# Sensing AoA with Photodiodes

$$\varphi(f) = A_c^{-1}\left[\frac{RSS_1(f)}{RSS_2(f)}\right]$$

RSS at each frequency

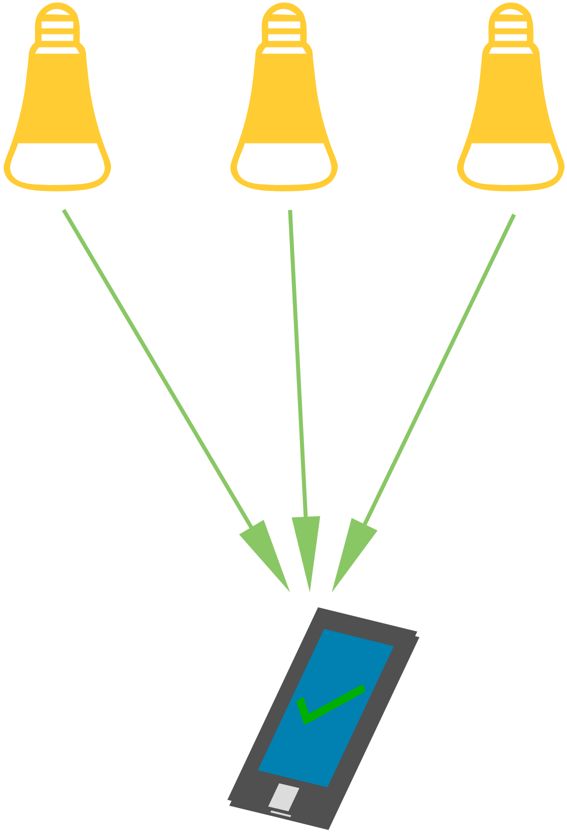
↓

AoA at each frequency



# Light Extraction

**Triangulation:** >= 3 lights required

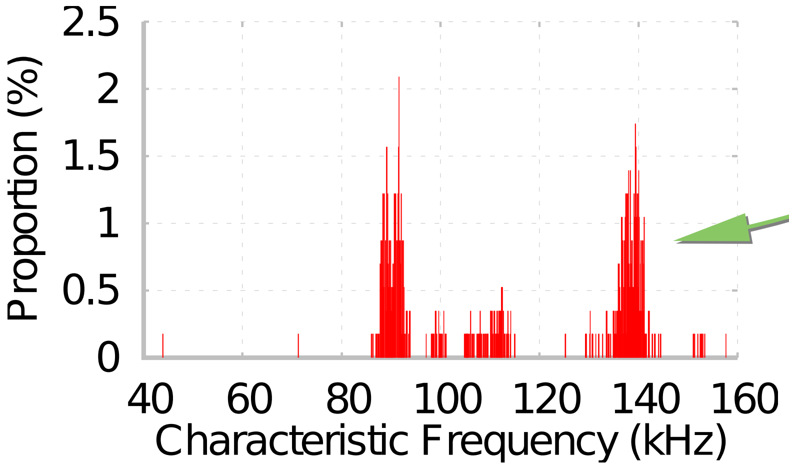


# Light Extraction

**Triangulation:** >= 3 lights required

Separate from spectrum:

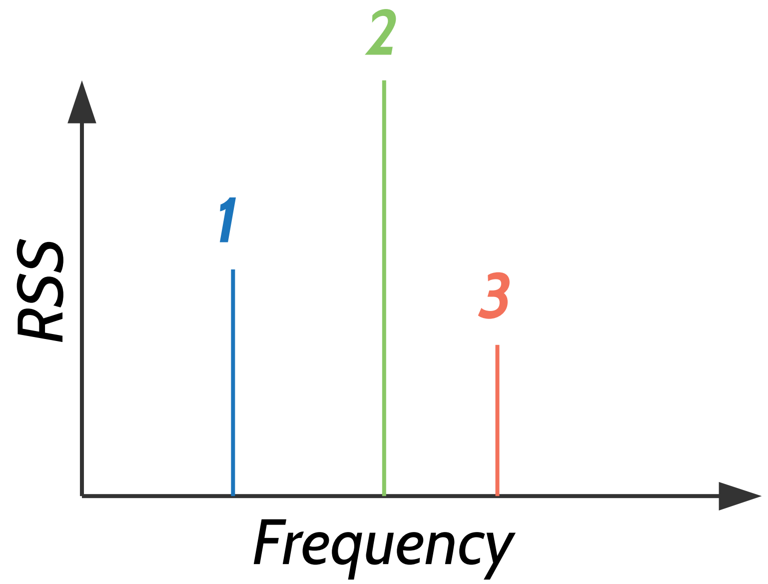
Leverage diversity in **Characteristic Frequency**




(LiTell, MobiCom'16)

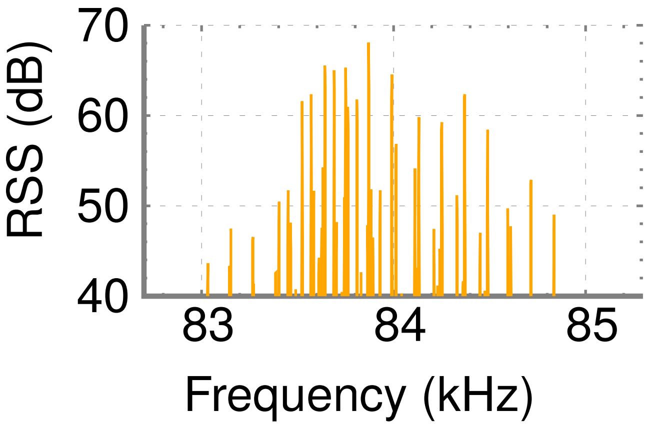
# Light Extraction

**This should be easy**, right?



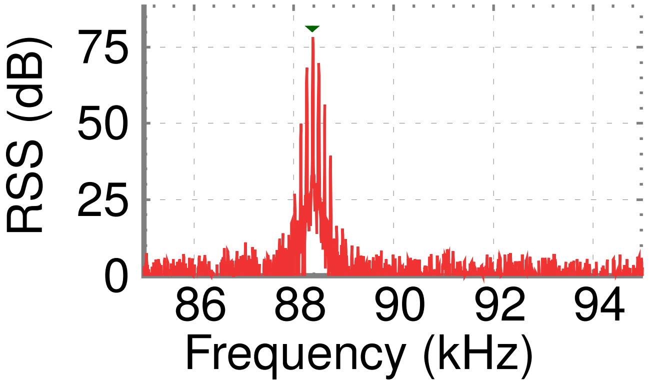
# Light Extraction

Wrong!



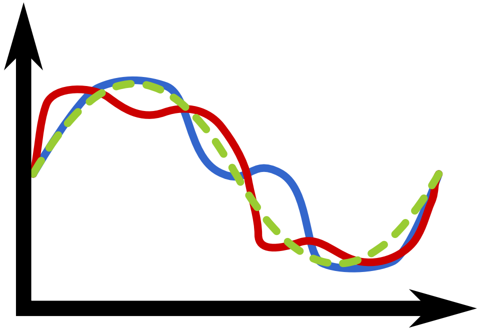
# Light Extraction

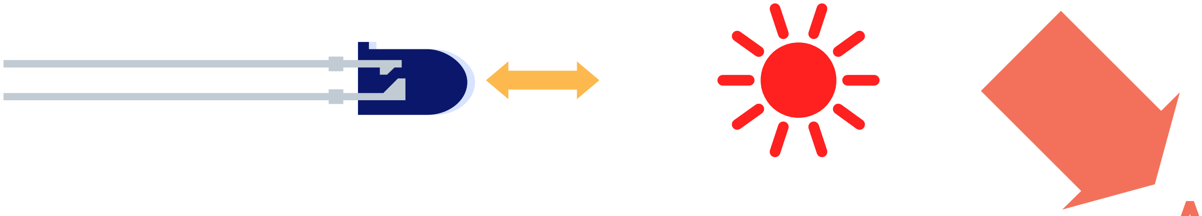
## 🔍 Spurious peaks!



# Light Extraction

- **Causes:**
  - Powerline harmonics
  - User motion





Artifacts

# Light Extraction

- **Causes:**
  - Powerline harmonics
  - User motion
- **Observe:**
  - AoA unaffected
  - Same AoA = from the Same Light

# Light Extraction

- Causes:
  - Powerline harmonics
  - User motion
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  - AoA unaffected
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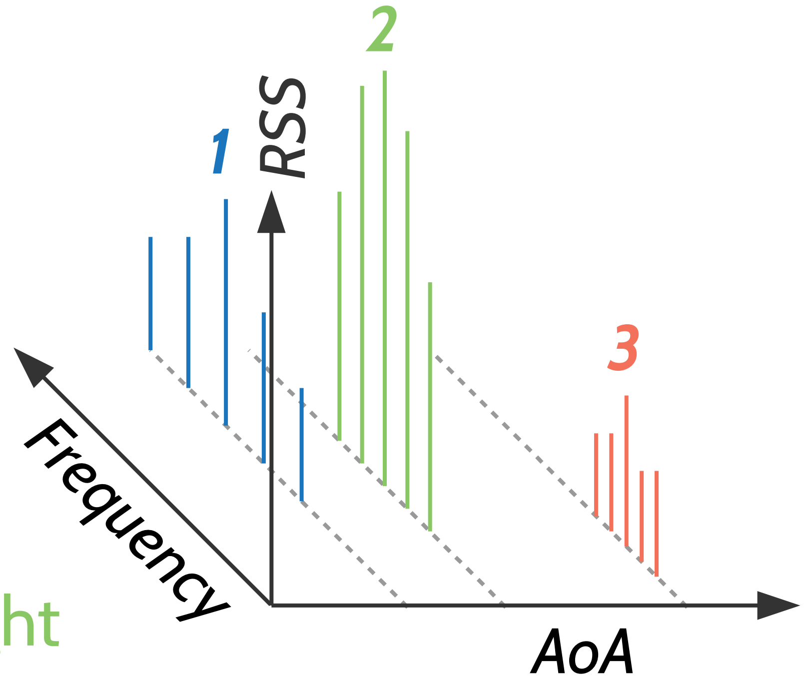
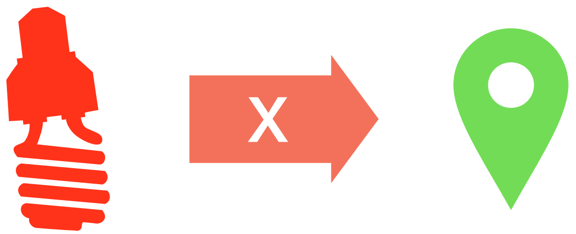



Separate by AoA Clusters

# Light Identification

- **Frequency to ID:**
  - Match individual lights = poor accuracy



# Light Identification

- **Frequency to ID:**
  - Match individual lights = poor accuracy
- **Observe:**
  - Correct match likely in ones with lowest freq error
  - Lights in Field-of-View are close to each other

# Light Identification

- **Solution:**
  - Identify by whole group of lights
  - Each frequency = 2~3 candidate ID
- ✓ Tightly-packed group with low freq error

# Localization

## Triangulation:

- 3D coordinates from 3 vector equations
- >= 4 lights: solves orientation

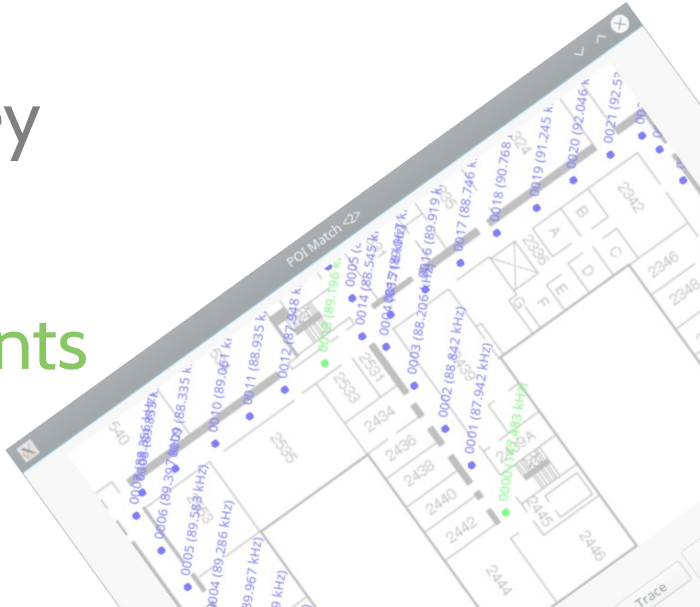
# Light Registration

- Registration is hard work
  - Even smart bulbs do not know their own locations!

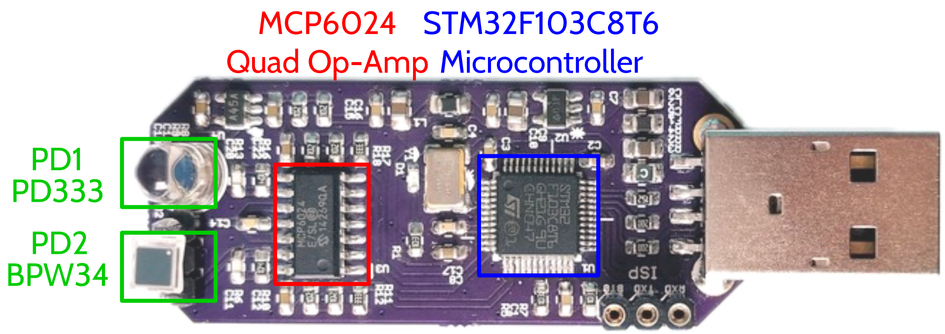
# Light Registration

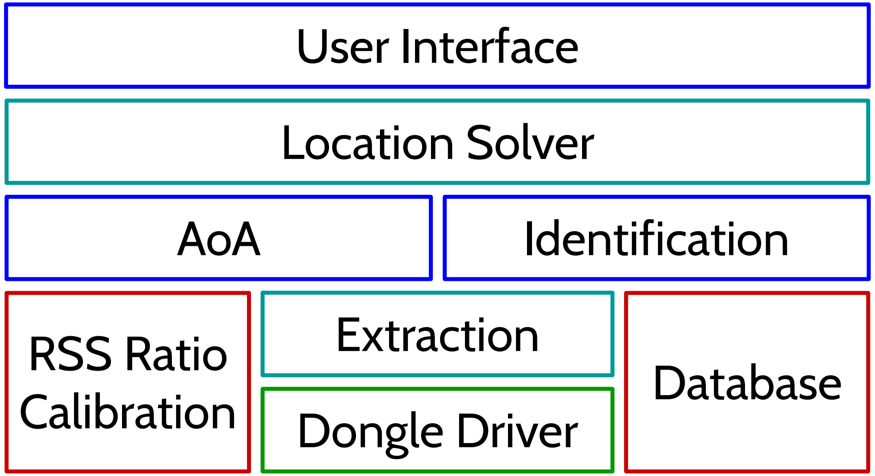
- Registration is hard work
  - Even **smart bulb** does not know its **own location**!
- **Motion tracking with Tango**
  - Record relative location during survey
  - Map to absolute location on map

✅ Eliminates complicated measurements

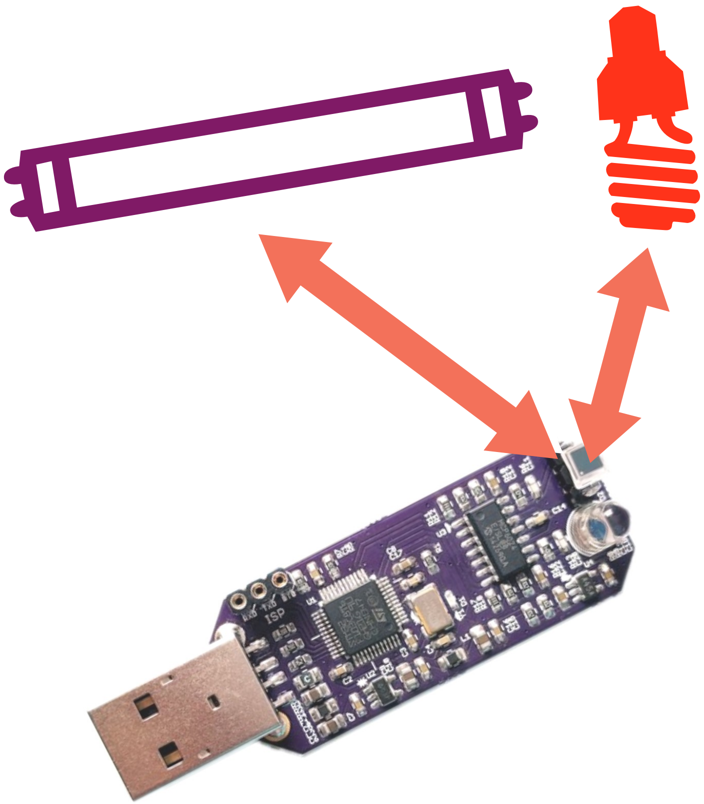


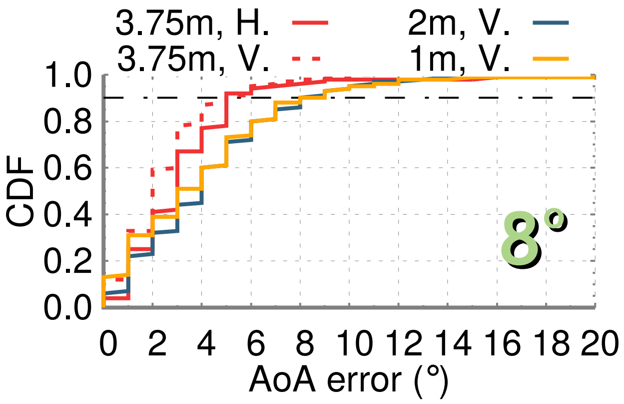
# Implementation

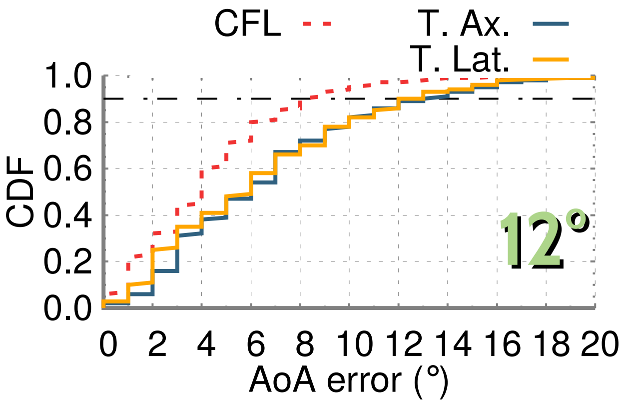


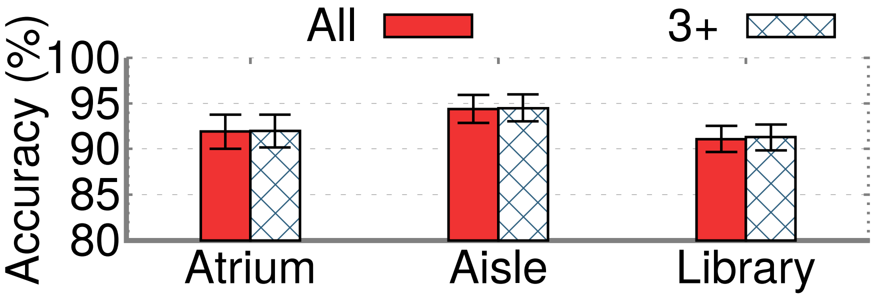
# Accuracy of AoA Sensing





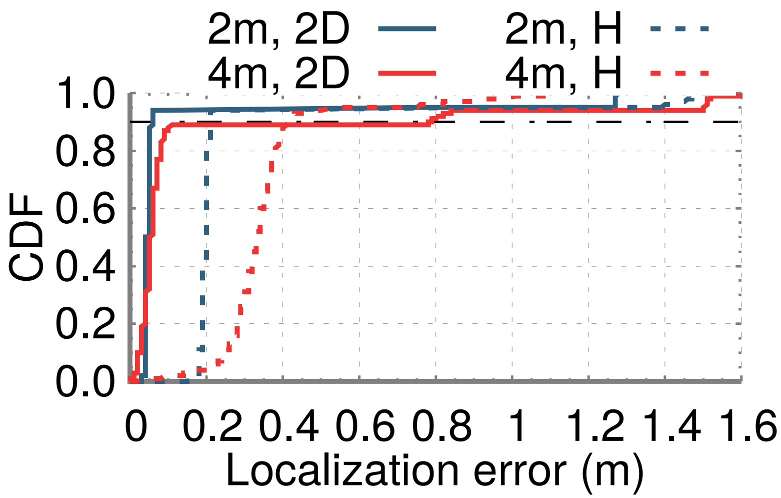



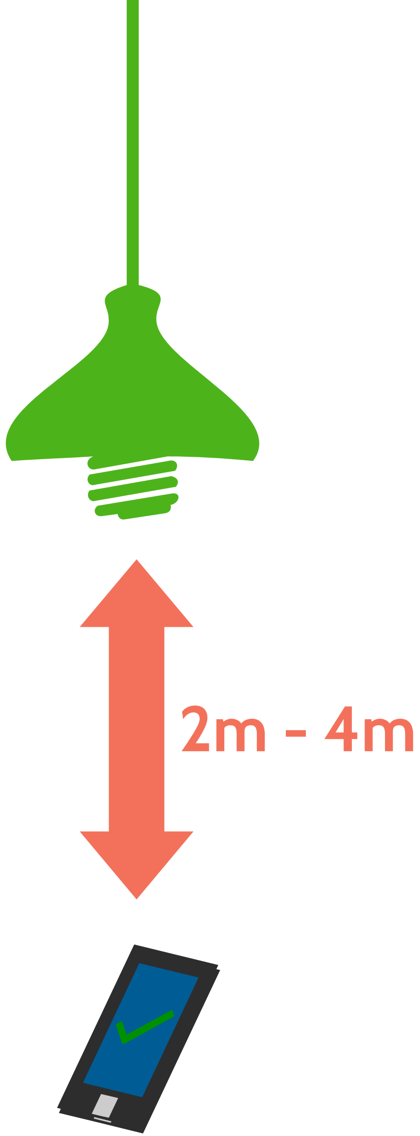
# Identification



# Localization

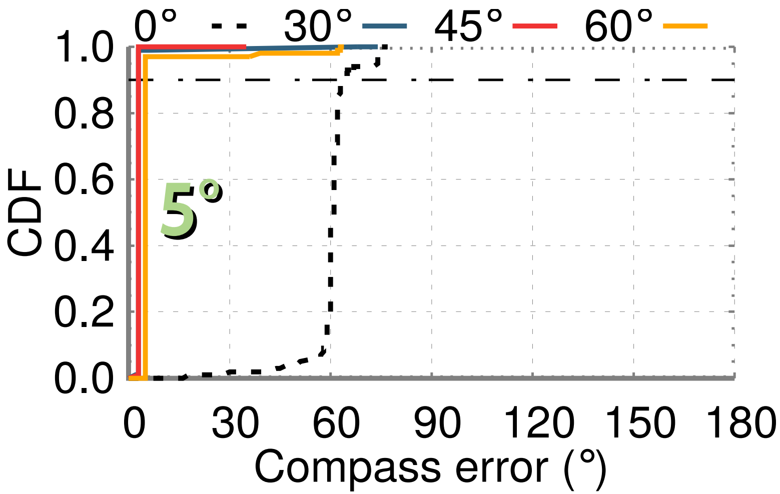


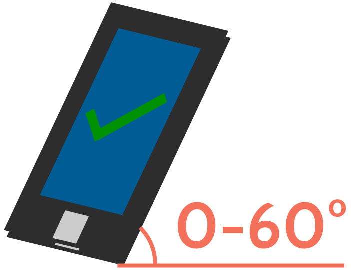


# Orientation

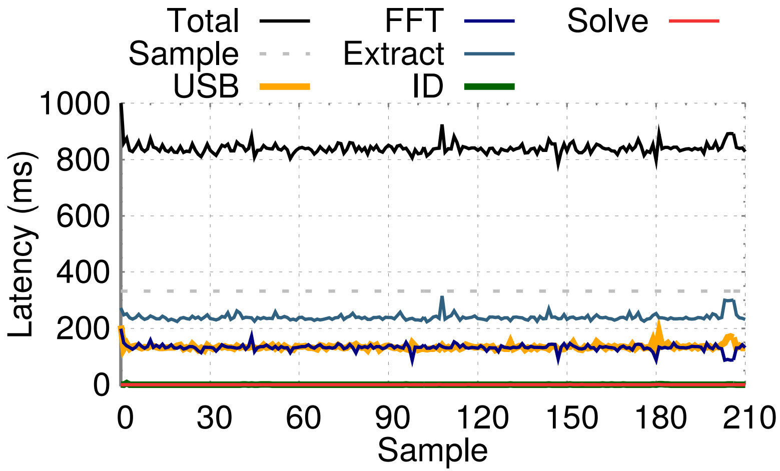




# Latency



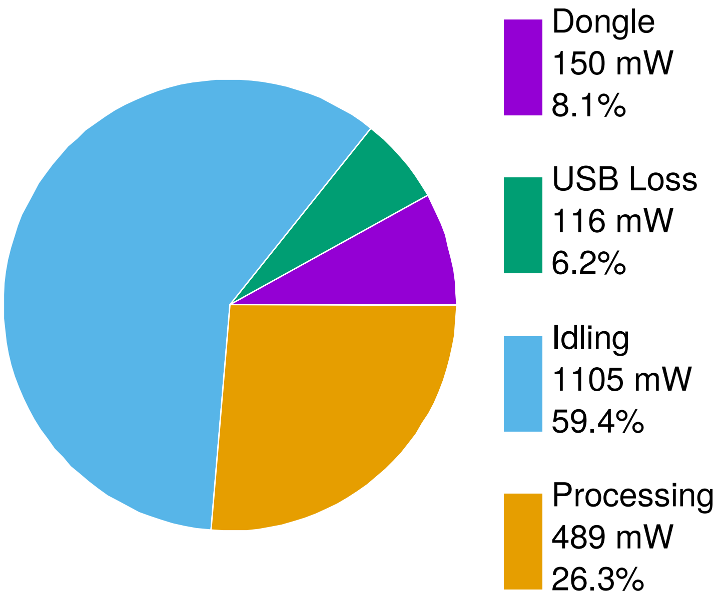


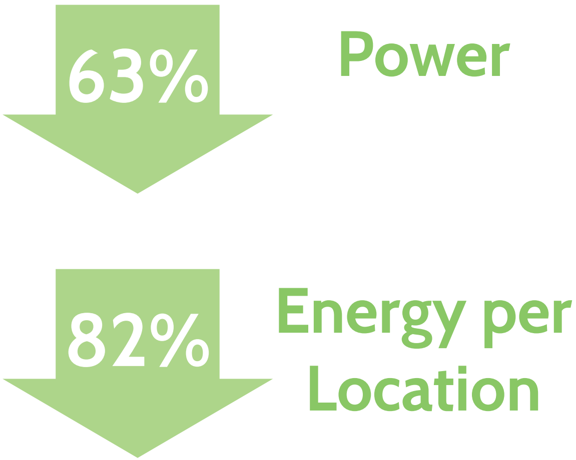
Total
FFT
Solve
Sample
Extract
USB
ID
Latency (ms)
1000
800
600
400
200
0
0
30
60
90
120
150
180
210
Sample


50%

# Energy




Dongle
150 mW
8.1%
USB Loss
116 mW
6.2%
Idling
1105 mW
59.4%
Processing
489 mW
26.3%

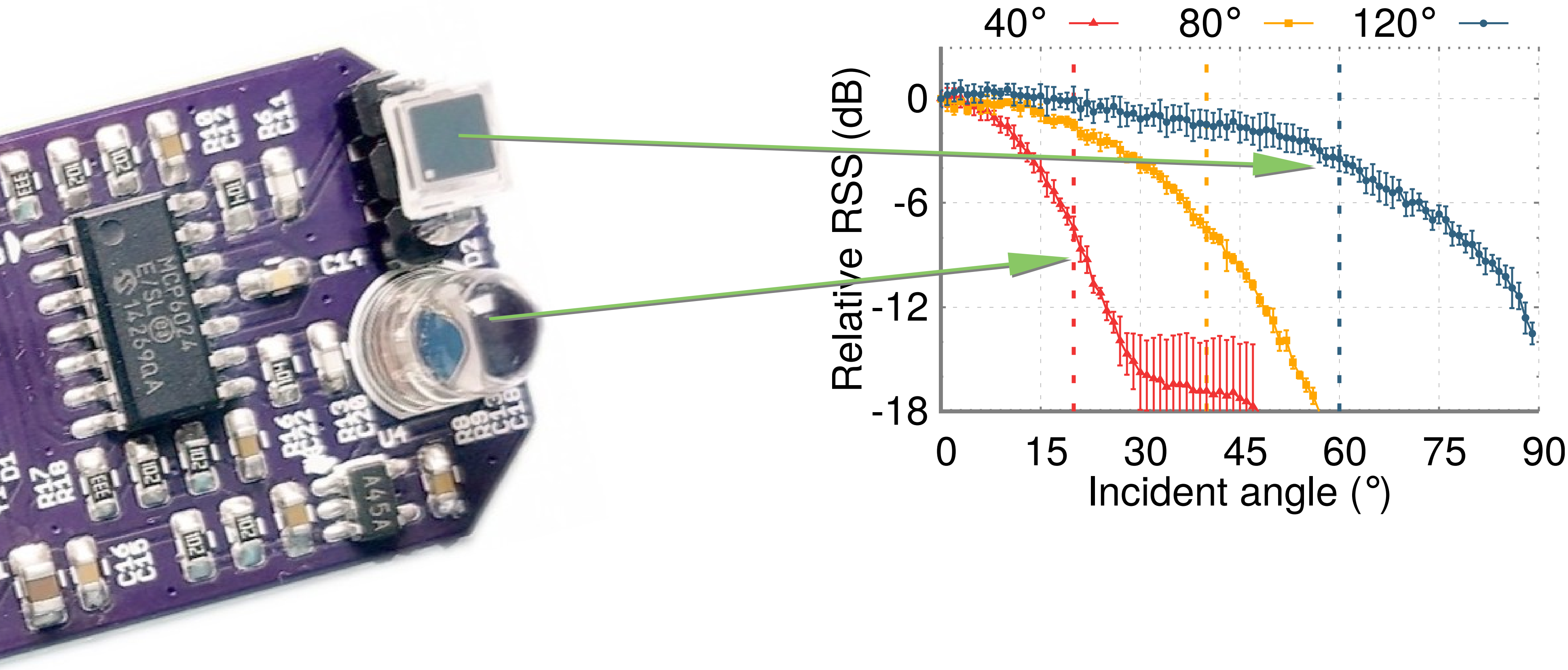

63%
Power
82%
Energy per Location

# Thanks!

Visit http://dword1511.info/me for papers and slides!

# Backups

# Photodiodes with Different FoV



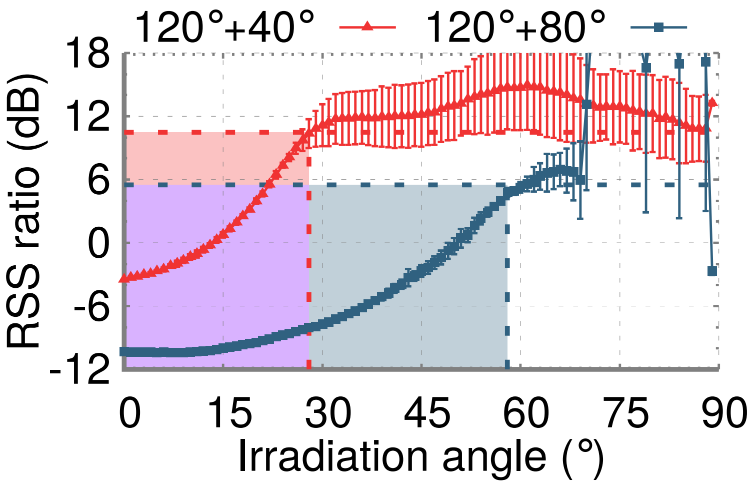
# Angle-of-Arrival Range

- Does $A_c^{-1}$ exist ? ($A_c$ has to be monotonic)
- There is always a monotonic range
- RSS ratio < threshold

  = AoA usable

  RSS ratio > threshold

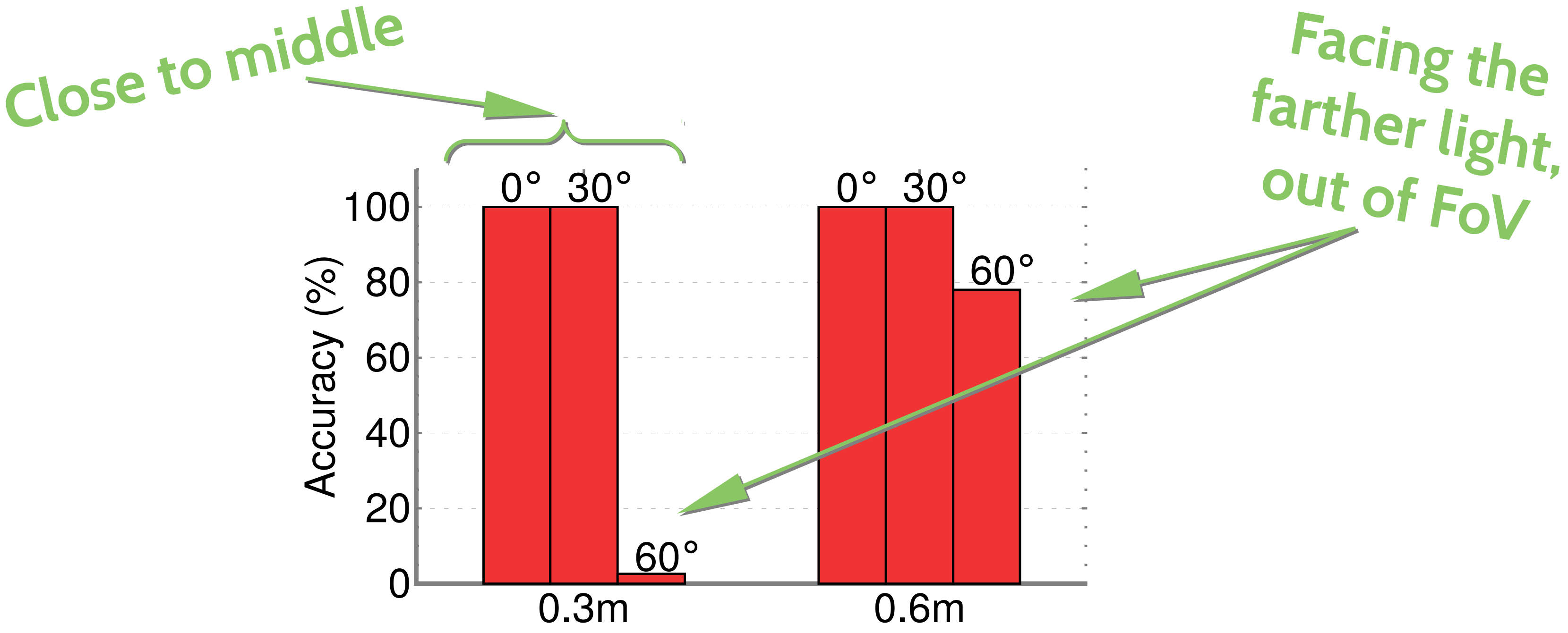
  = AoA ambiguous



# Sparse Light Deployment

- **Insufficient # of lights:**
  - 1 light    assume proximity
  - 2 lights    AoA allows "guessing" nearest light
    - Assume similar lights ("guess")
    - Compensate for PD angular response ("true RSS")
    - Higher "true RSS" likely closer

# Sparse Light Deployment



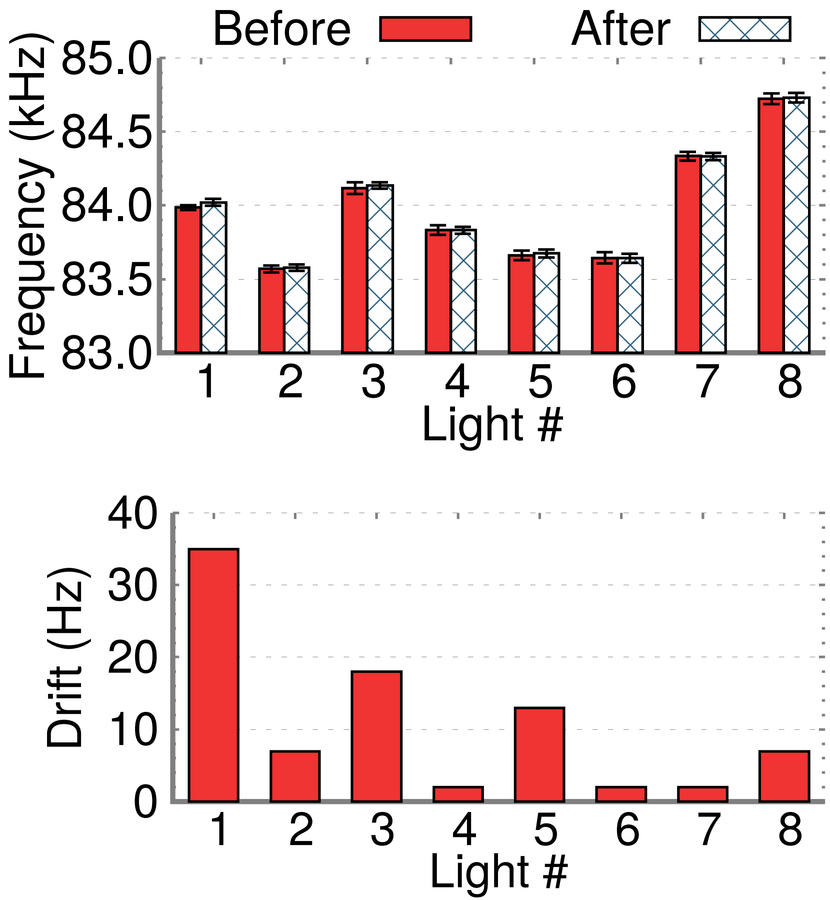

Identify nearest light from 2

# Normal Vector

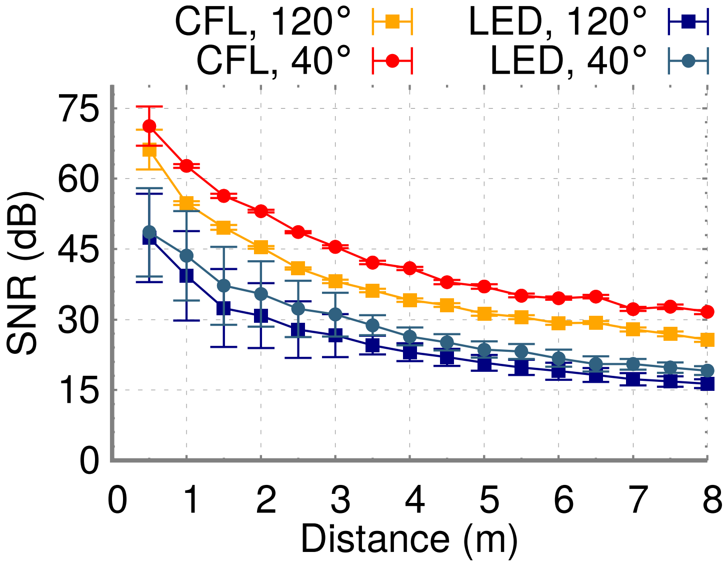

Measured with accelerometer w.r.t gravity (also compass if < 4 lights)

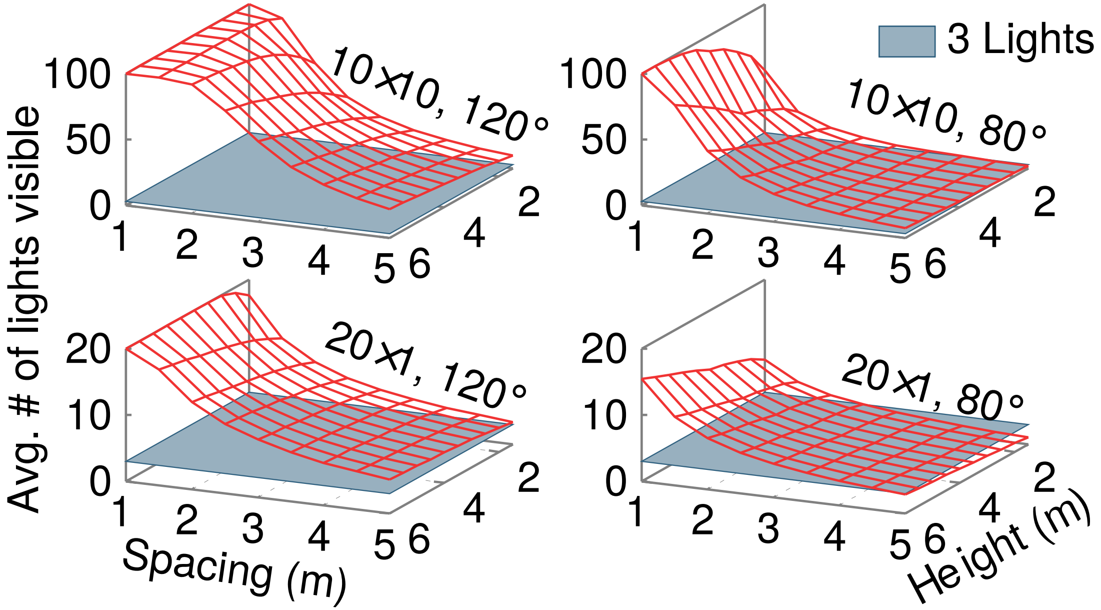
Orientation is w.r.t screen

# Annual Drift

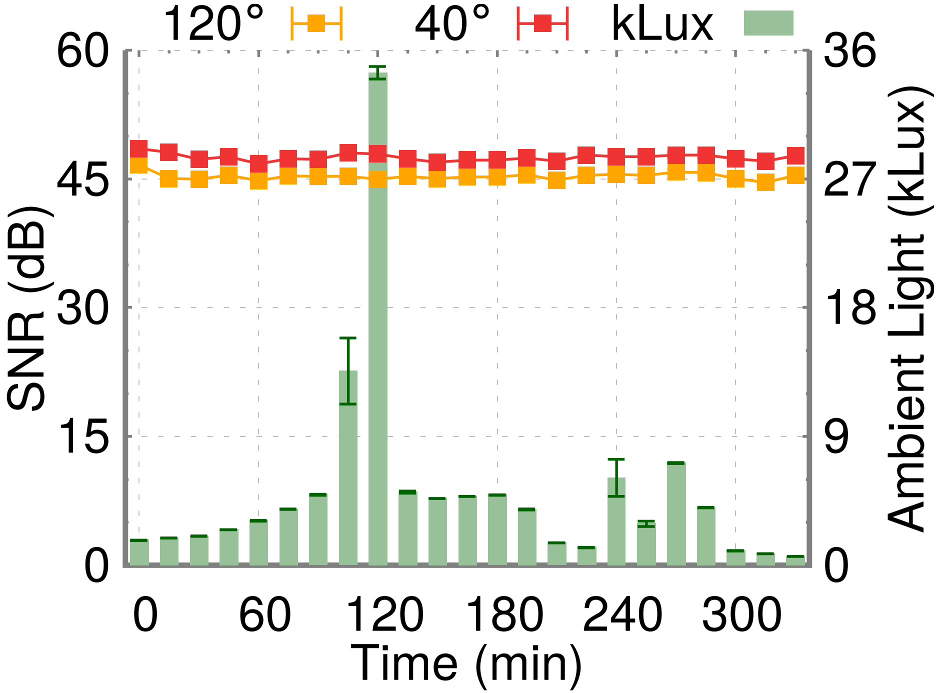


# Sensitivity & Coverage



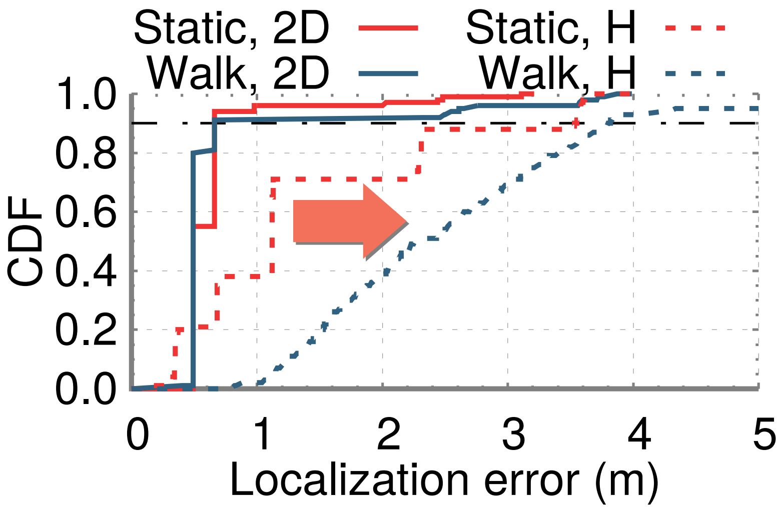
# Ambient Light

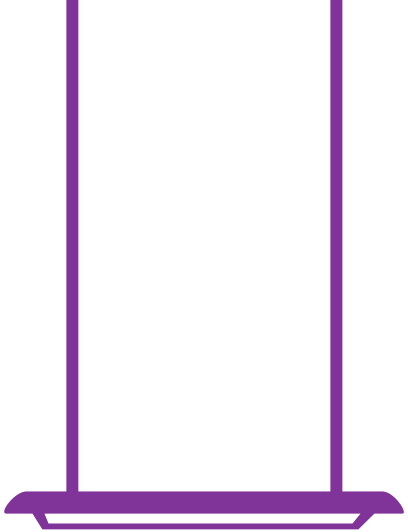


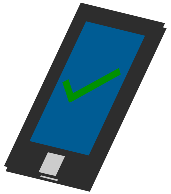

PD FFT
50.0
38.9
27.8
16.7
5.6
-5.6
-16.7
-27.8
-38.9
-50.0
dB
A
B
Frequency (kHz)

# Mobility




Static, 2D
Static, H
Walk, 2D
Walk, H
1.0
0.8
0.6
0.4
0.2
0.0
CDF
0
1
2
3
4
5
Localization error (m)





# Is Sampling Expensive?

- STM32L0/L4 (2015-ish)
  - <300uA, 2.5V @ 12-bit, 1Msps
  - We need 8-bit, 300 Ksps (or less): probably ~ 100uA / 250uW?

| | | | | | | |
|---|---|---|---|---|---|---|
| $I_{DDA}$(ADC) | ADC consumption from the $V_{DDA}$ supply | fs = 5 Msps | - | 730 | 830 | µA |
| | | fs = 1 Msps | - | 160 | 220 | |
| | | fs = 10 ksps | - | 16 | 50 | |
| $I_{DDV\_S}$(ADC) | ADC consumption from the $V_{REF+}$ single ended mode | fs = 5 Msps | | | | |
| | | fs = 1 Msps | | | | |
| | | fs = 10 ksps | | | | |

**Table 53. ADC characteristics**

| Symbol | Parameter | Conditions | Min | Typ | Max | Unit |
|---|---|---|---|---|---|---|
| $V_{DDA}$ | Analog supply voltage for ADC ON | Fast channel | 1.65 | - | 3.6 | V |
| | | Standard channels | 1.75[1] | - | 3.6 | |
| $I_{DDA}$ (ADC) | Current consumption of the ADC on $V_{DDA}$ | 1.14 Msps | - | 200 | - | µA |
| | | 10 ksps | - | 40 | - | |
| | Current consumption of the ADC on $V_{DD}$[2] | 1.14 Msps | - | 70 | - | |
| | | 10 ksps | - | 1 | - | |