FPGA-Based MKID Image Cuber for Real-Time Speckle Removal

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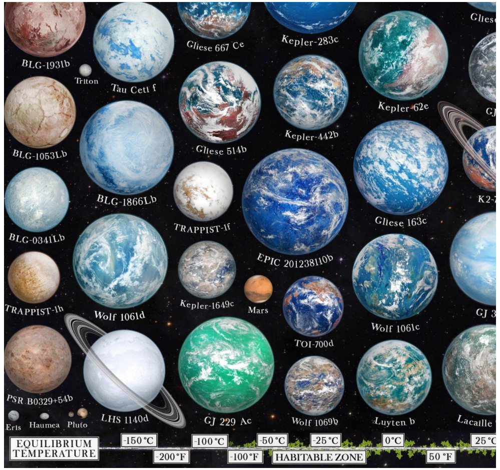
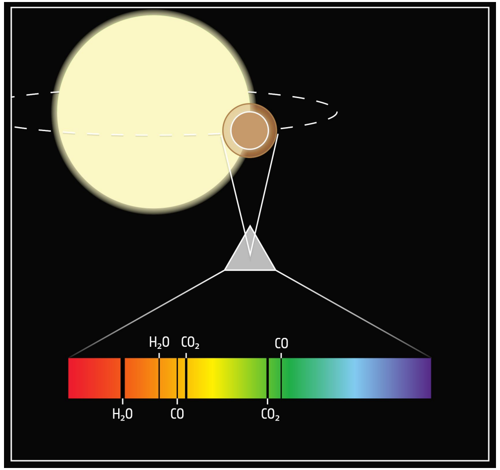
Background/Motivation

- **Exoplanet**: Planet orbiting a star beyond our solar system



- **Observation**: Detect photons coming from the exoplanet

- Collect enough photons and form a spectrum



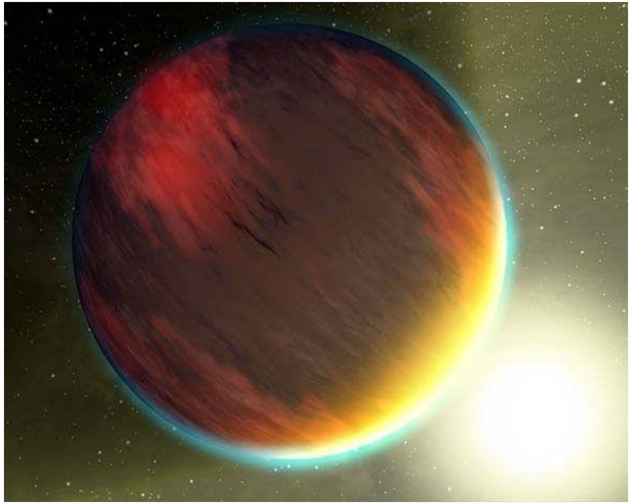
But why do we care about exoplanet spectra?

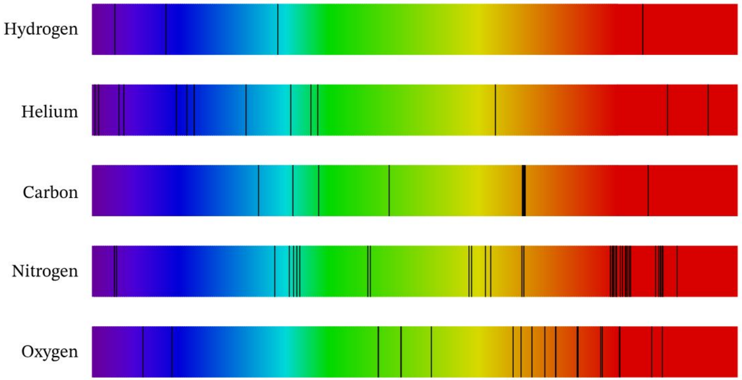
Exoplanet Observation

- The observed photons have passed through the exoplanet's atmosphere

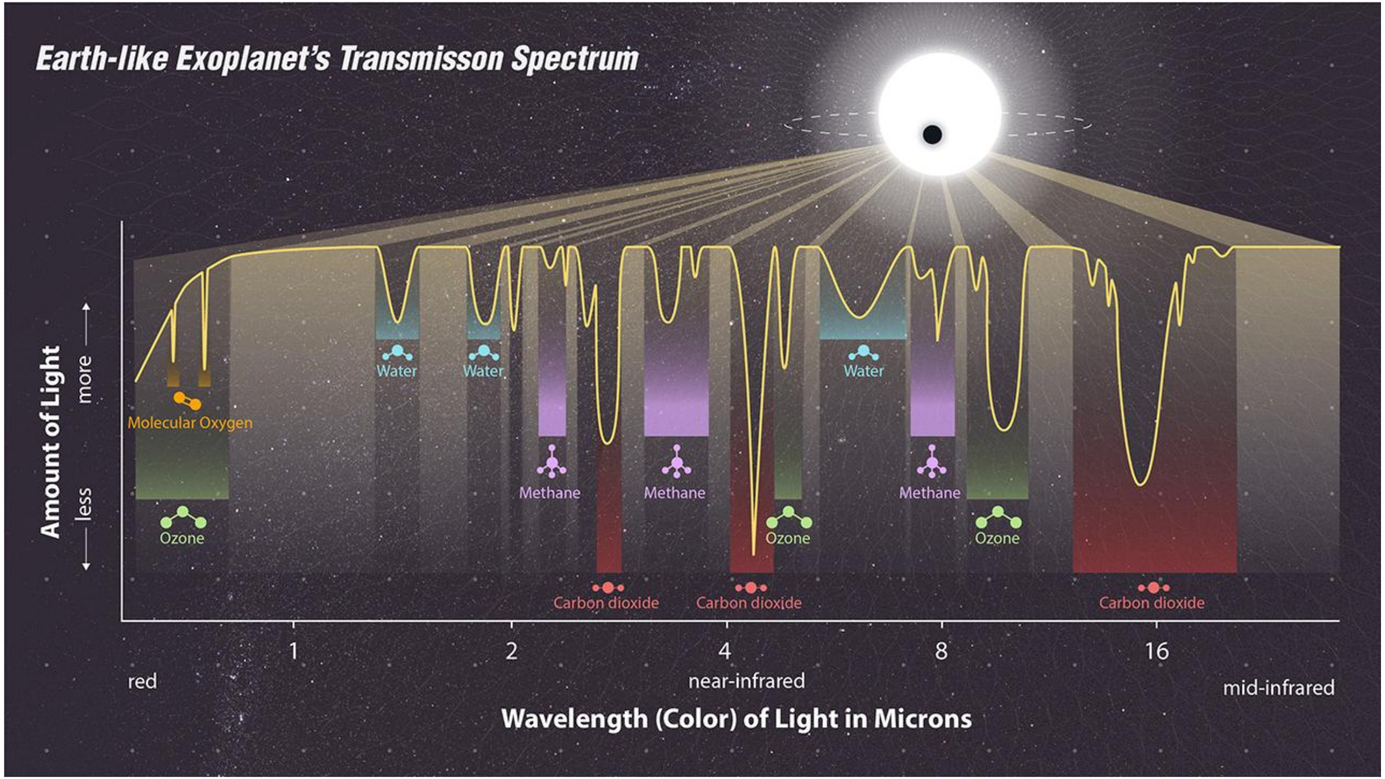
- Atmospheric compounds will create absorption lines

- Finding the absorption spectrum of an organic compound **could imply the existence of life!**





Exoplanet Observation



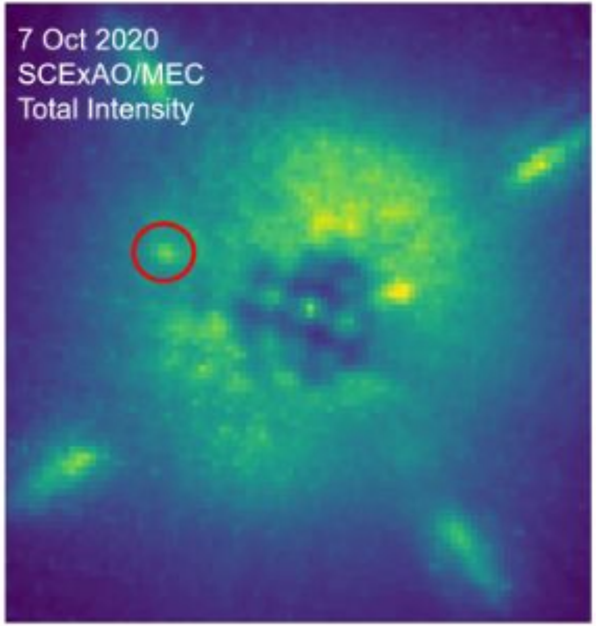
But there’s a problem when observing exoplanets...

Speckles

- When observing an exoplanet, host star photons will also be picked up by the detector

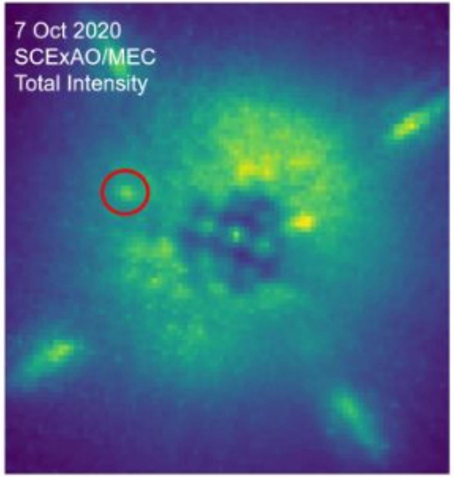
- These photons will be scattered due to turbulence in Earth's atmosphere

- **Result**: Bits of starlight scattered all throughout the image (**speckles**)

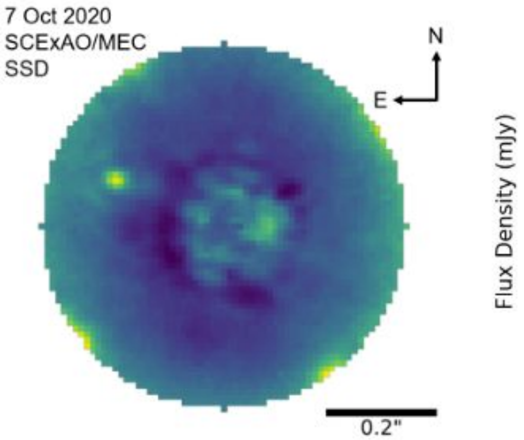


Speckles

- Speckles can overlap with the exoplanet, making it impossible to isolate the planet’s photons



Before Speckle Elimination



After Speckle Elimination

Speckle Elimination

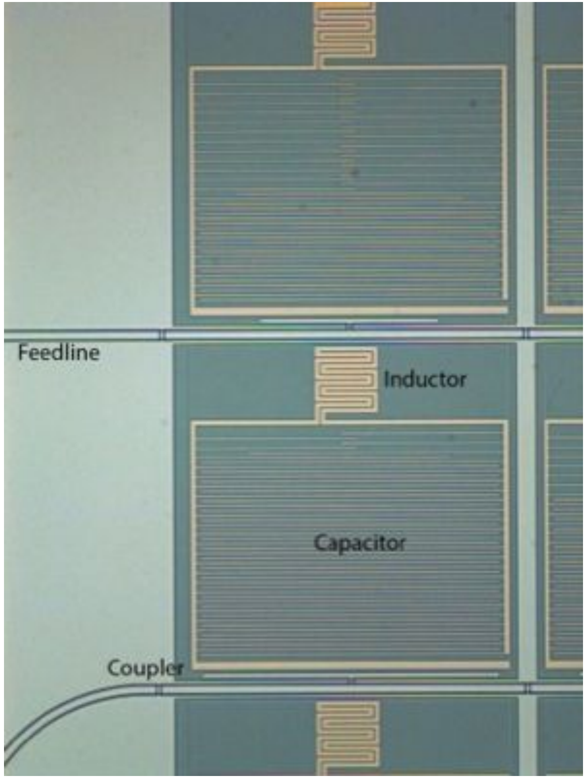
- **Coherent Differential Imaging (CDI)**
    - Method of real-time speckle elimination
- **SCExAO**: Extreme adaptive optics system at Subaru Telescope
    - Mauna Kea, Hawaii
- **SCExAO needs real-time detector data to perform CDI**

SCExAO

All fairly standard so far, but our detectors are unique...

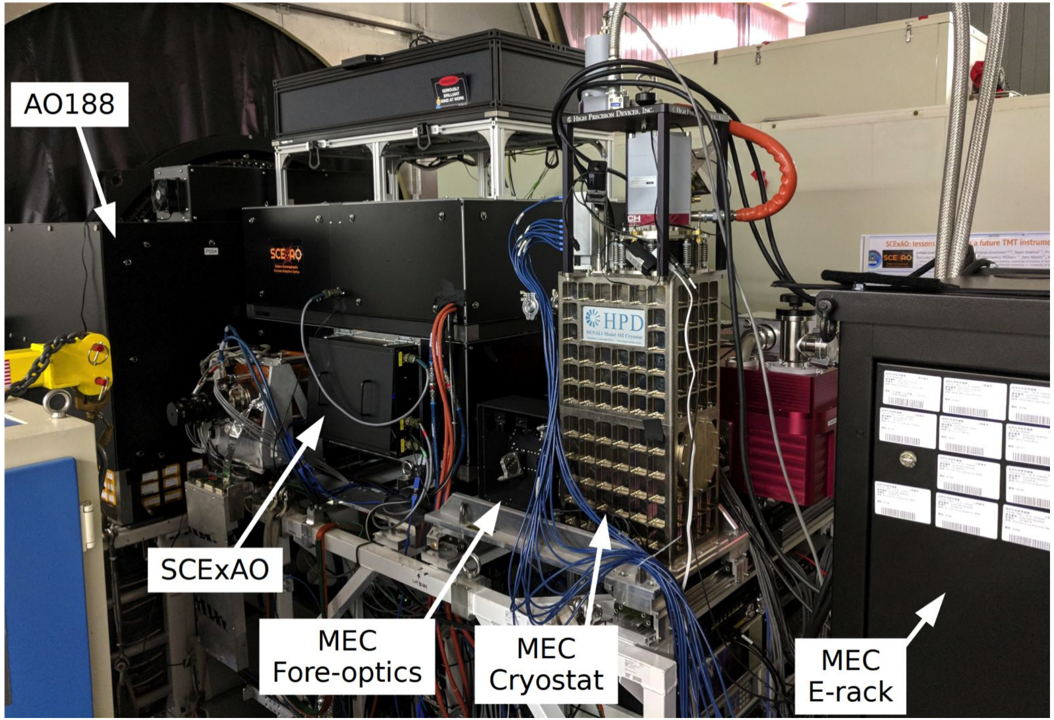
MKIDs

- **MKID:** Microwave Kinetic Inductance Detector
    - Cryogenic superconductors; can detect individual photons
- **Advantages** (over standard detectors)
    - Can detect single photons with no false counts
    - Can determine photon energy (to several percent)
    - Can determine photon arrival time (to a microsecond)
    - Much broader wavelength coverage
- **MEC**: Mazin Lab's **M**KID **E**xoplanet **C**amera



MKID module

Experimental Setup



Atmosphere → Subaru Telescope → AO188 → SCExAO → Science Instrument (MEC)

Speckle Elimination

Recall:

- SCExAO needs real-time detector data

But:

- MKIDs are <u>not</u> standard detectors
- MKID data = photon event stream

SCExAO

Cannot simply send the MKID data to SCExAO!

What's the solution?

Image Cuber

- Convert MKID photon event stream into 3D **image cubes**

- **Image Cube**: 3D array of photon counts
  - x-coordinate
  - y-coordinate
  - wavelength

- **These image cubes can be processed & sent to SCExAO**

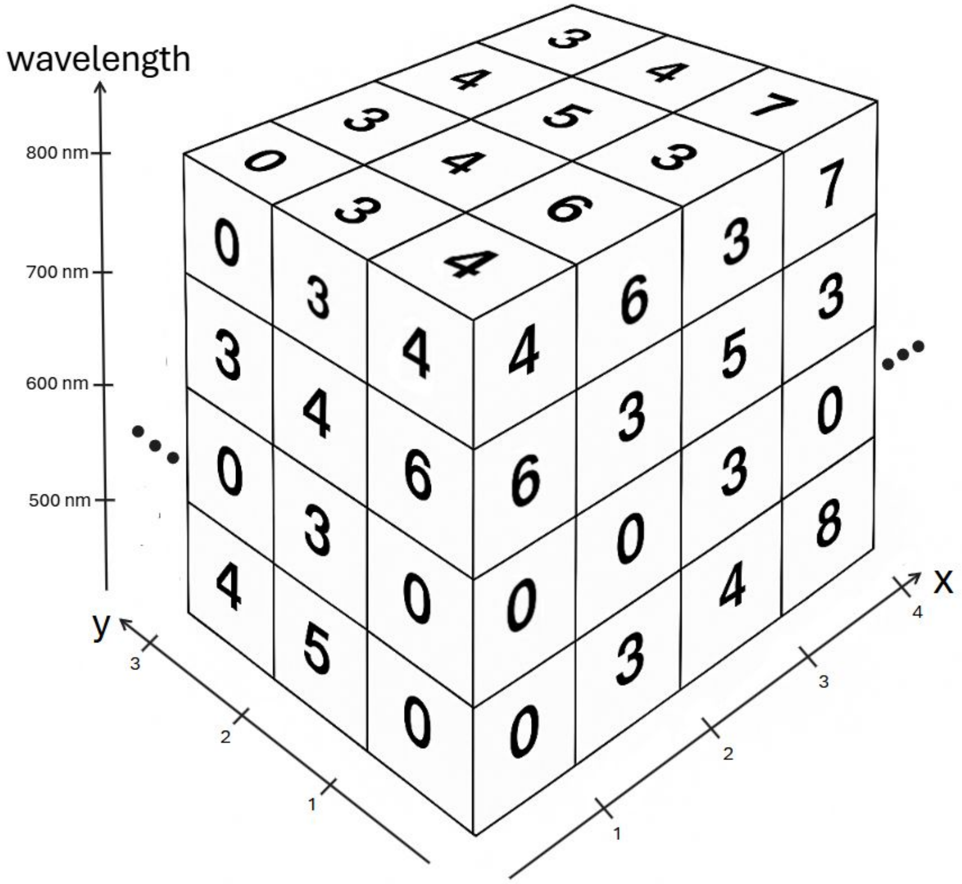


Image Cuber

1. Each photon event contains several pieces of data
2. Cuber uses this data to determine each photon's pixel and wavelength
3. Cuber places each photon in the corresponding pixel/wavelength bin
4. Outputs image cube with all of this info!

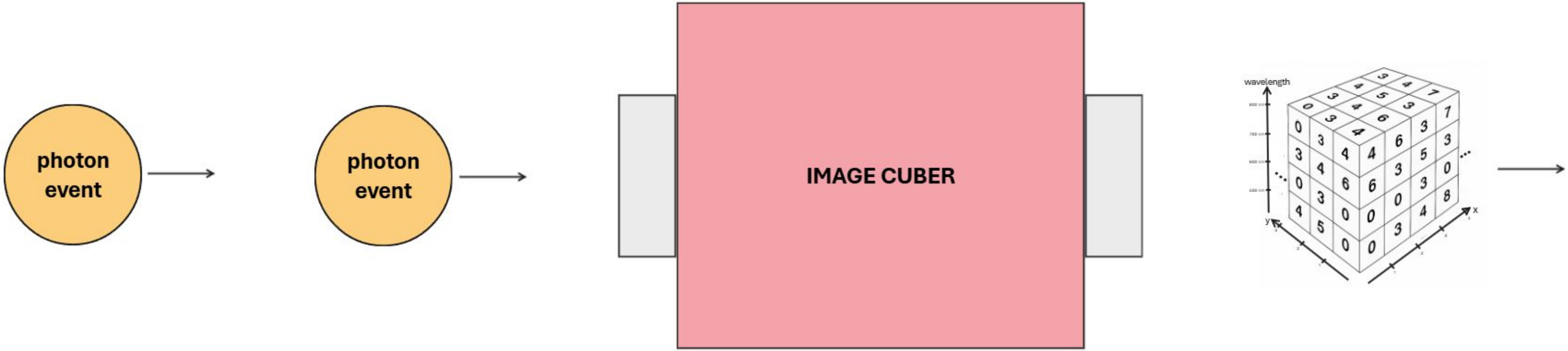
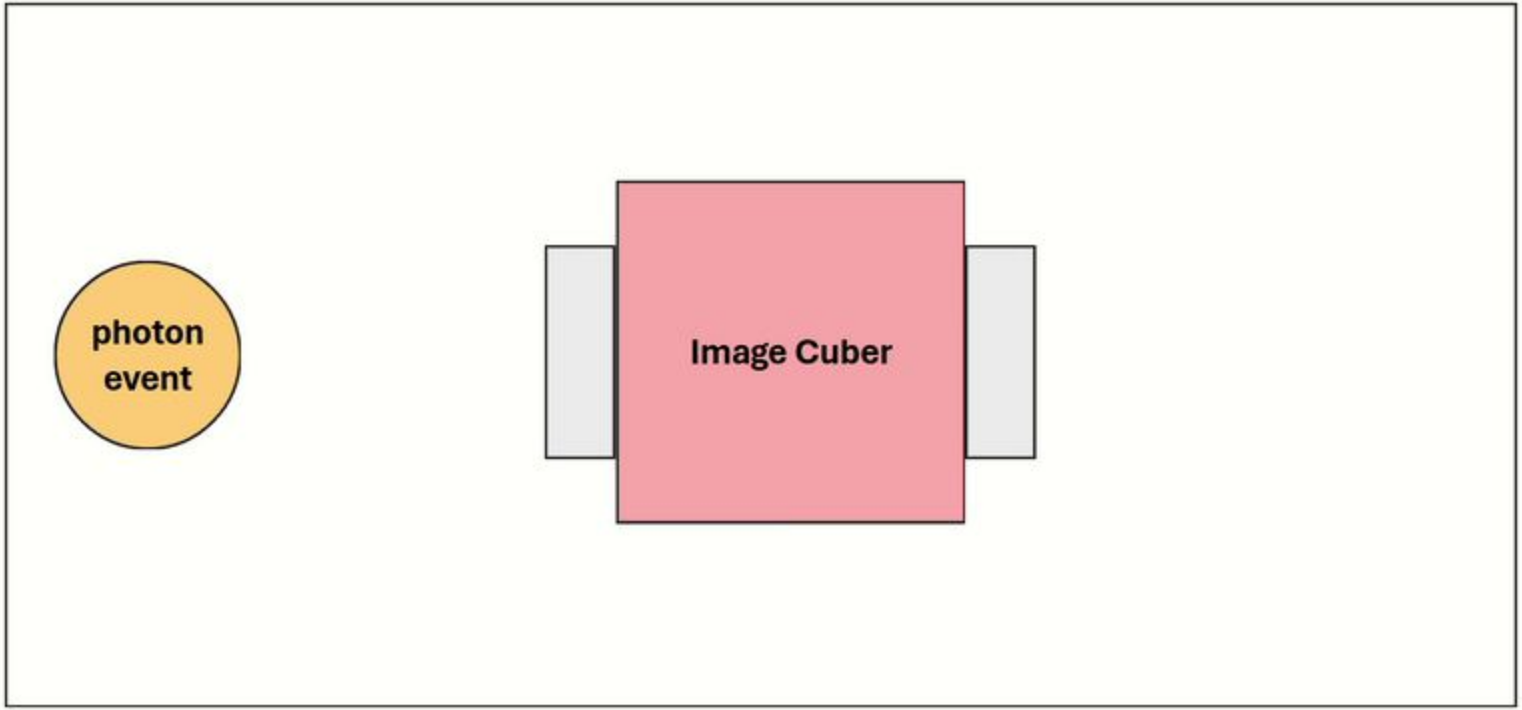


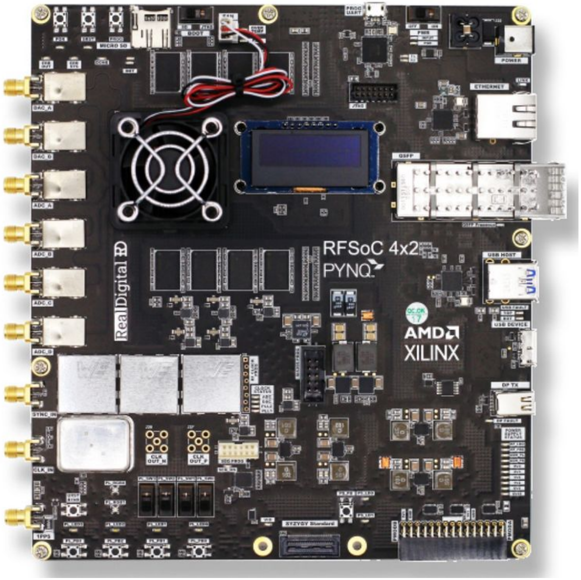
Image Cuber



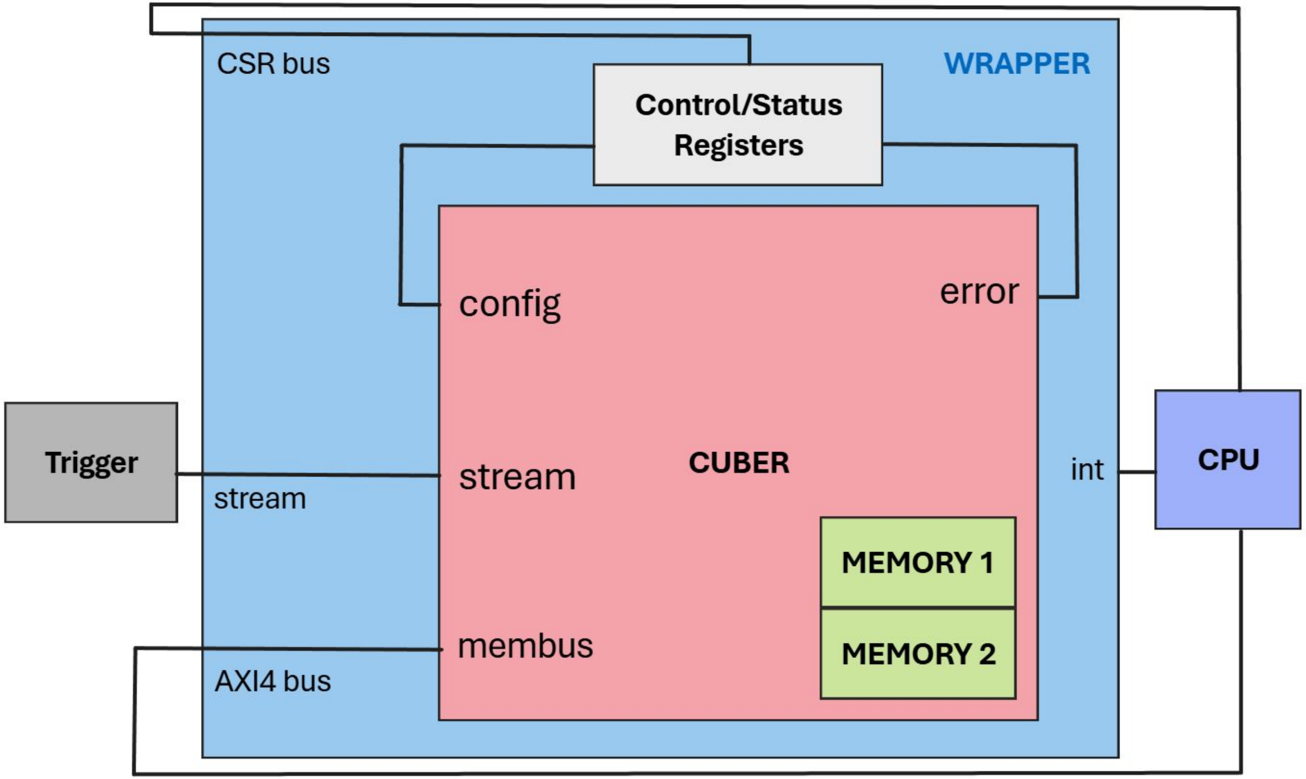
But there’s a catch

FPGA

- CDI requires about 100k image cubes per second
  - Computer is too slow for this
  - Need to use **FPGA** (Field Programmable Gate Array)



General System Summary



Project Outline

Project Timeline

- Build Image Cuber
- Build Wrapper
- Integrate into existing readout system
- Optimize to meet timing requirements
- Build driver

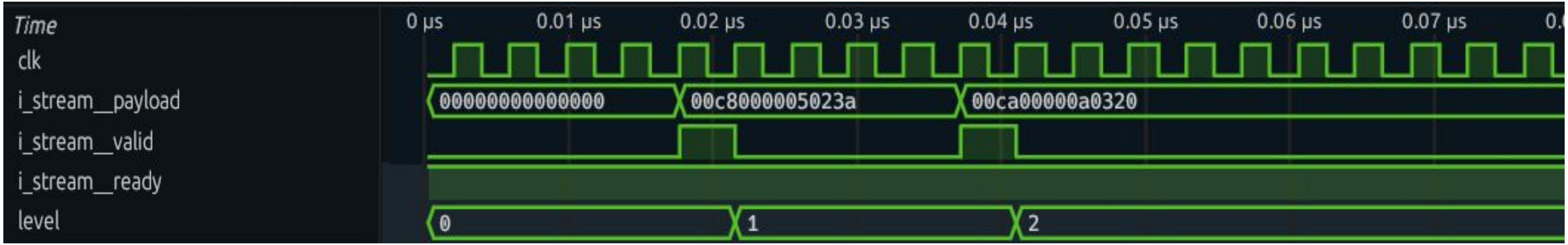
Results

Results

- Throughout most of the project process, tests were run with simulated photon events

- When the project was completed, tests were performed with lasers
    - Controllable brightness (i.e. photon rate)
    - See if image cubes contain expected photon counts

Results



- Test Case: 2 photon events
    - Queue level increments as expected

How are these photon events detailed in memory?

Results

- Memory address indicates the pixel

- Memory data indicates photon counts for that pixel
  - Each byte (2 hex digits) represents a wavelength bin

Bin 4 Bin 2

Example data: 0F00012B (hex)

Bin 3 Bin 1

Results

Bin 4 Bin 2

Example data: 0F00012B (hex)

Bin 3 Bin 1

- 43 photons in bin 1 (0x2B = 43)
- 1 photon in bin 2 (0x01 = 1)
- 0 photons in bin 3 (0x00 = 0)
- 15 photons in bin 4 (0x0F = 15)

Results

Bin 4 Bin 2

Example data: 0F00012B (hex)

Bin 3 Bin 1

Simulation: Photon 1: Pixel = 310, wavelength = 540 nm (bin 1)
Photon 2: Pixel = 312, wavelength = 670 nm (bin 2)

- Photon counts placed into correct bins!

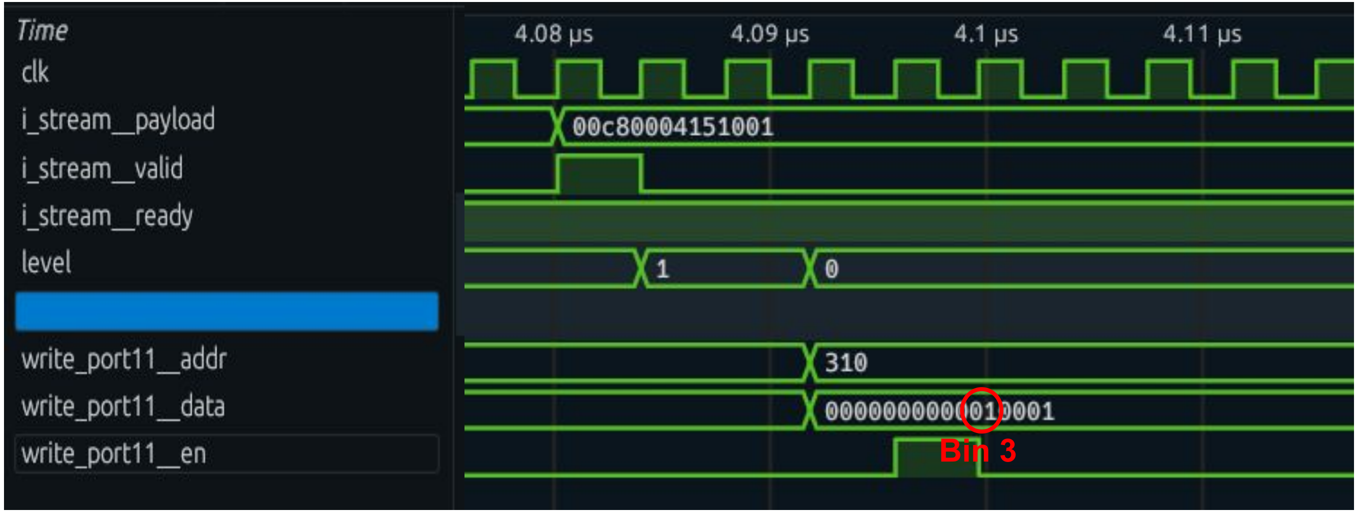
Results

Bin 4 Bin 2

Example data: 0F00012B (hex)

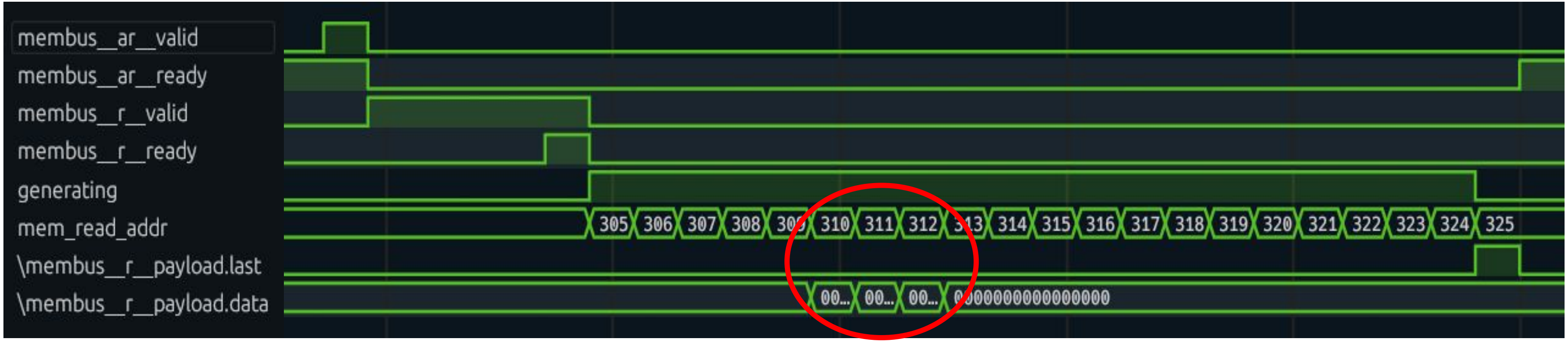
Bin 3 Bin 1

- Third photon test event
  - Same pixel as photon 1 → same memory address (310)
  - Wavelength = 740 nm - wavelength bin 3



Results

- Testing the CPU reading system (high-performance AXI4 protocol)
    - Burst read starting from address 305, length = 20



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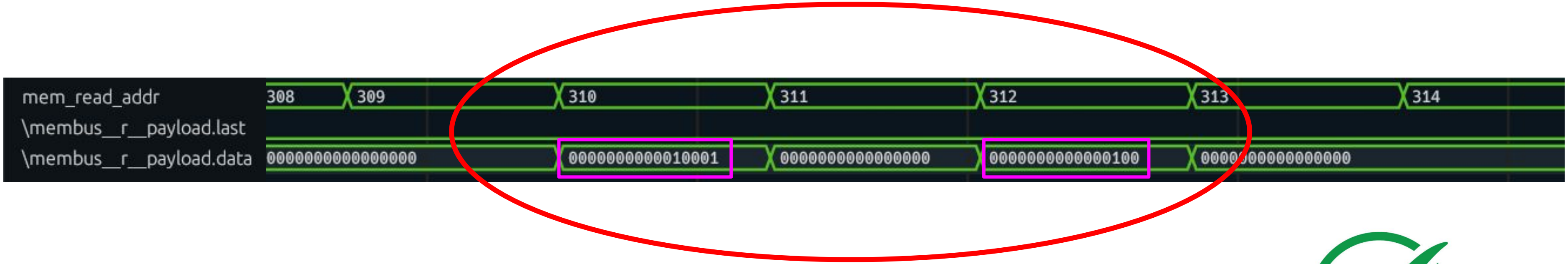


Laser Test Results

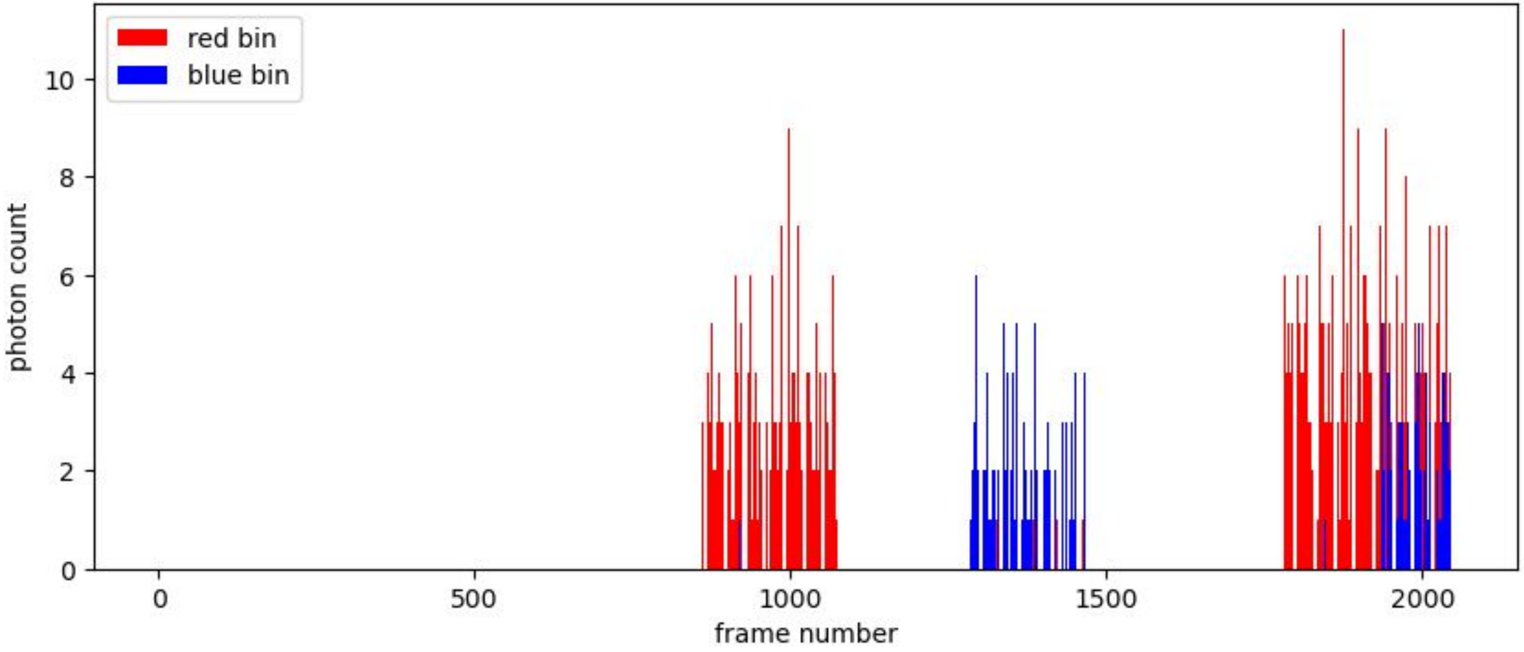
Disclaimer: Very rough test setup!

- No microlens array to focus the photons → poor wavelength discrimination

- Therefore, this test was only performed with red and blue lasers

Results

- **Test Run**: Red pulse (on/off), blue pulse (on/off), red on, blue on



Conclusion

- The next time MEC is brought out to the Subaru Telescope, the new readout system can be used to feed real-time data to SCExAO for CDI

- This will improve our ability to discriminate speckles, and therefore improve our ability to accurately observe exoplanet spectra

- One small step forward in the world of experimental astrophysics!

Subaru Telescope

Thank you

Supplemental Slides

MKID Theory

- Incident photons change the surface impedance of a superconductor through the **kinetic inductance effect**.
  - The kinetic inductance effect occurs because energy can be stored in the **supercurrent** of a superconductor.
  - Reversing the direction of the supercurrent requires extracting the kinetic energy stored in the supercurrent, which yields an **extra inductance**.
- This change can be accurately measured by placing this superconducting inductor in a lithographed **resonator**.
- A **microwave probe signal** is tuned to the resonant frequency of the resonator, and <u>any photons which are absorbed in the inductor will imprint their signature as changes in phase and amplitude of the probe signal</u>.

MKID Advantages

- Individual photon counting
- Energy resolution (essentially built-in spectroscopy)
- Time resolution (microsecond photon arrival times)
- Zero read noise / false counts
- Real-time speckle discrimination capabilities (due to the real-time wavelength and timestamps)

Summary: MKIDs can detect individual photons with zero noise or false counts, and can estimate their energy and arrival time in real-time (essentially equivalent to built-in real-time spectroscopy). This not only allows for precise imaging of the planet, but also allows for real-time speckle discrimination, which is a big issue in general exoplanet imaging.

CDI Theory

- Star is very far away → acts like a point source → starlight hitting detector is coherent (electric field has a well-defined phase)
- Planet light is incoherent with the starlight
- CDI involves modulating deformable mirrors
  - See how light intensity changes
  - Find which pixels contain speckles
- Based on this, you can construct a map of starlight (speckles) in your image
- Mathematically subtract these speckles

FPGA vs Microcontroller

Aspect	FPGA	Microcontroller
Definition	Adaptable hardware device	Small integrated computer
Programming	Complex, uses specialized languages	Easier, uses high-level languages
Flexibility	Highly flexible	Less flexible
Processing Power	High power	Lower power
Parallel Processing	Great for parallel tasks	Limited parallel processing
Cost	More expensive	More budget-friendly
Power Consumption	High power usage	Low power usage
Ease of Use	Complex programming	Easier programming
Versatility	Specialized applications	General-purpose tasks
Real-Time Processing	Excellent for real-time	Capable but not specialized