

Predicting Atmospheric Turbulence: The Key to Imaging Habitable Planets with Large Telescopes

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GTC Europe 2018

“Innumerable suns exist; innumerable earths revolve around these suns in a manner similar to the way the seven planets revolve around our sun. Living beings inhabit these worlds #

– *Giordano Bruno (1584)*

“Two possibilities exist. Either we are alone in the universe or we are not. Both are equally terrifying #

– *Arthur C. Clarke*

“It is just us* seems like an awful waste of space #

– *Contact, screenplay by Carl Sagan*

The planet must be in the habitable zone of its star\$ not be too ,lose or too (ar



5enera 16 lander* survived 127mn at 897 C* 8: atm

Venus: too close, too hot



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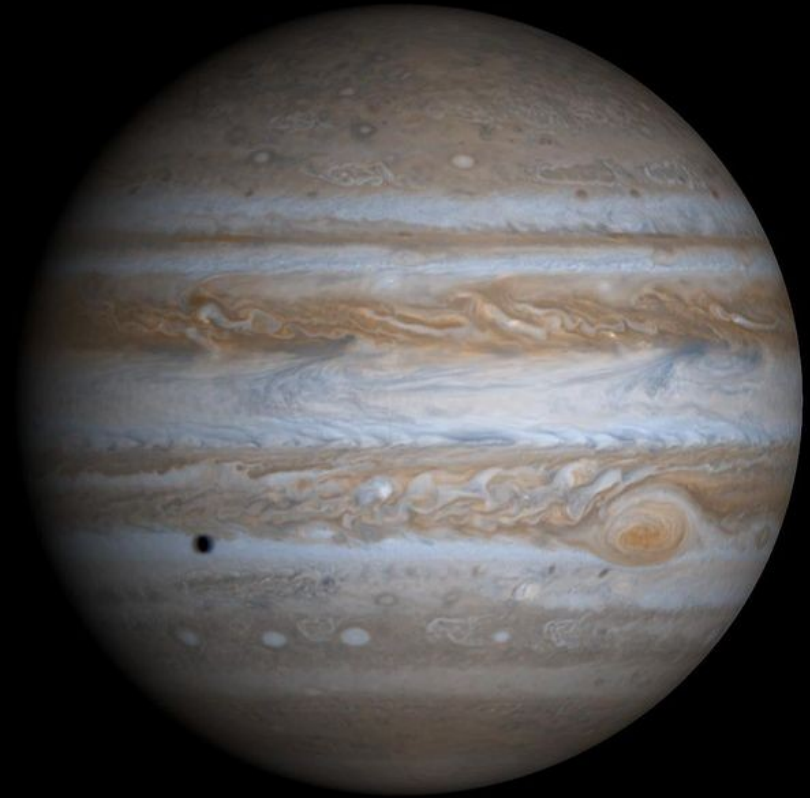
Mars: too far, too cold

/i;e matters\$
not too bi"* not too small



Earth

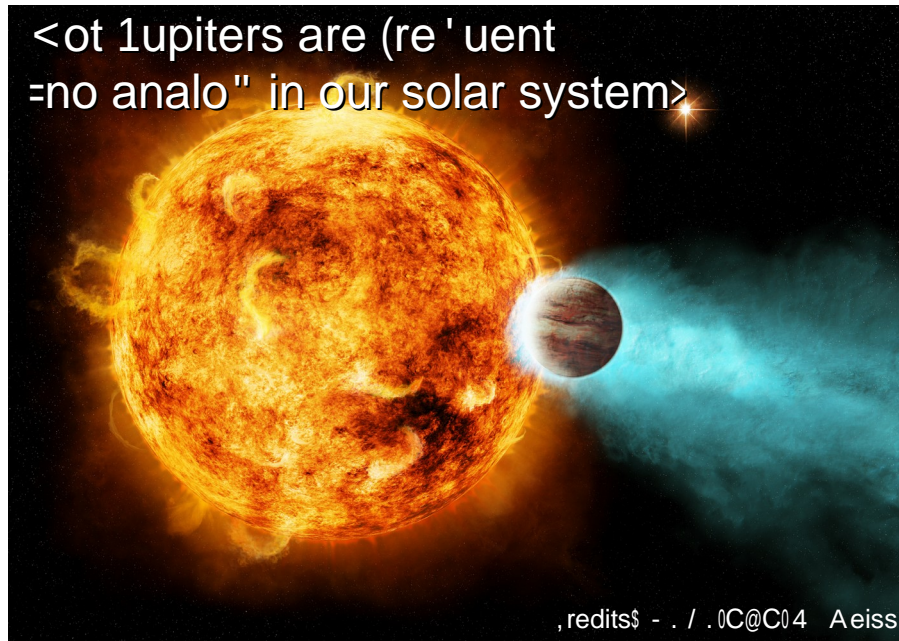
Moon: too small
Weak gravity can't hold atmosphere
No atmosphere



Jupiter: too massive
Gravity holds thick atmosphere
Mostly gas

Key recent findings

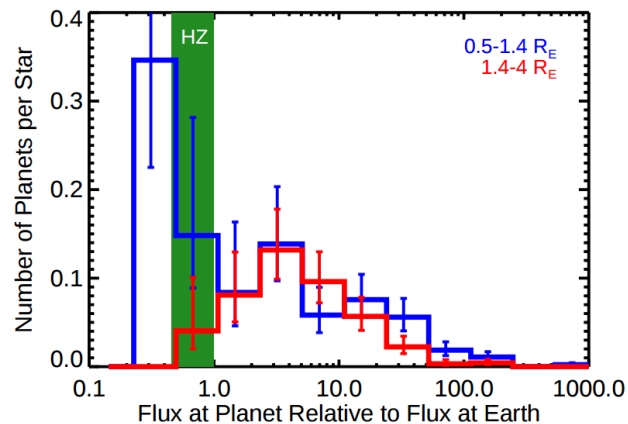
Hot Jupiters are (representative of) "no analog" in our solar system



Planetary systems are common
26 systems with 9 planets

73 planet Trappist-1 system, [https://www.nasa.gov/mission/telescope/kepler11b/kepler11b.html](#)

Earth-size rocky planets are abundant



Dressing & Charbonneau 2013

~10% of Sun-like stars and ~50% of M-type stars have potentially habitable planets



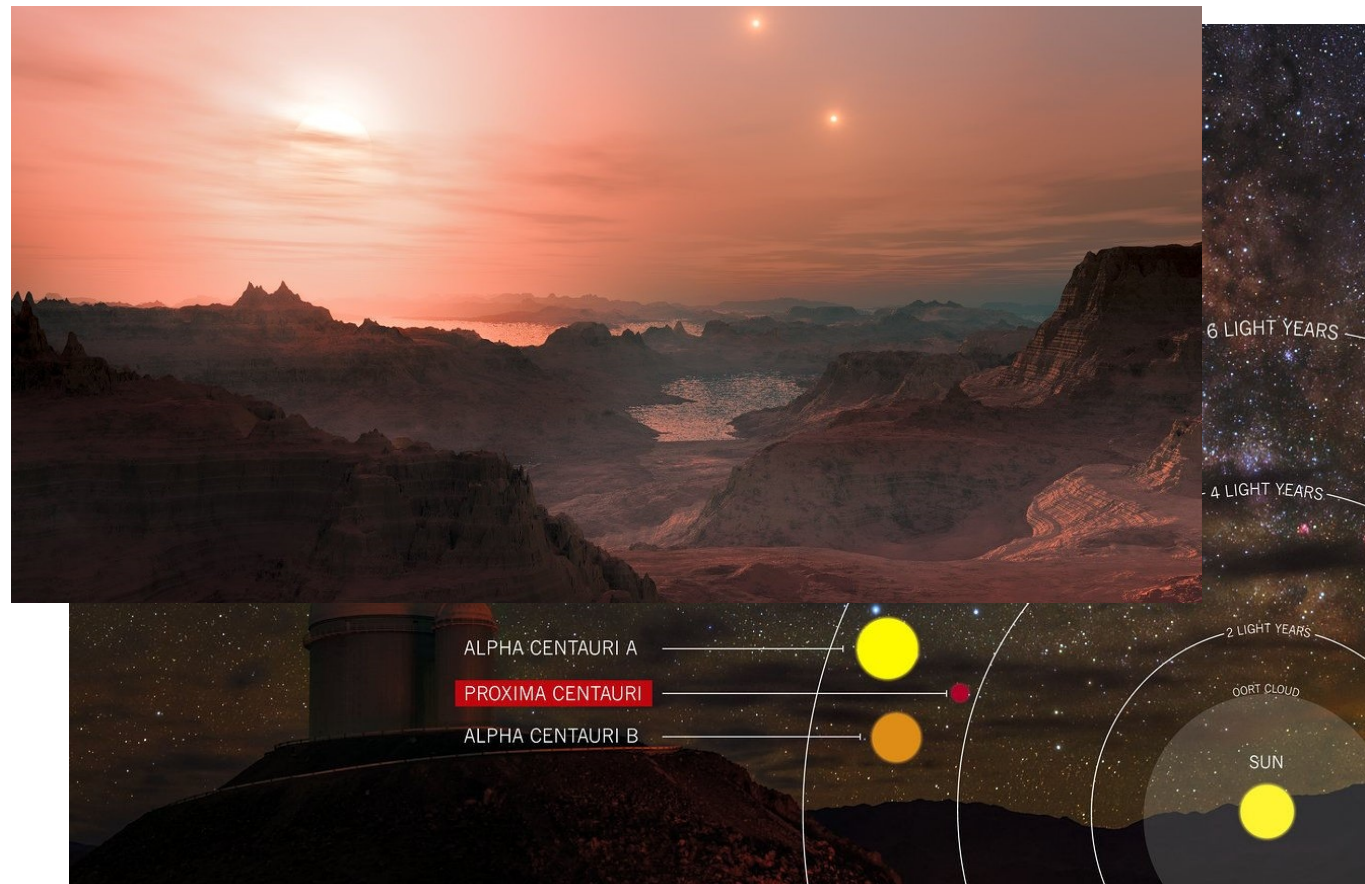
Spectacular recent discoveries around nearby stars

Trappist-1 system
7 planets
C6 in hab ; one
likely rocky, +y
80 ly away



Proxima Centauri b
planet
Possibly habitable

Closest star to our
solar system - only
4.2 light years
away



~300 billion stars in our galaxy



~300 billion stars in our galaxy

~30 billion habitable planets ?

~300 billion stars in our galaxy

~30 billion habitable planets ?

If 100 explorers were sent to visit each habitable for 10 seconds (only 300 million planets/explorer)...

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If 100 explorers were sent to visit each habitable for 10 seconds (only 300 million planets/explorer)...

... it would take 95 yrs to complete the habitable exoplanets tour

~300 billion stars in our galaxy

~30 billion habitable planets ?

If 100 explorers were sent to visit each habitable for 10 seconds (only 300 million planets/explorer)...

... it would take 95 yrs to complete the habitable exoplanets tour ... in our galaxy alone

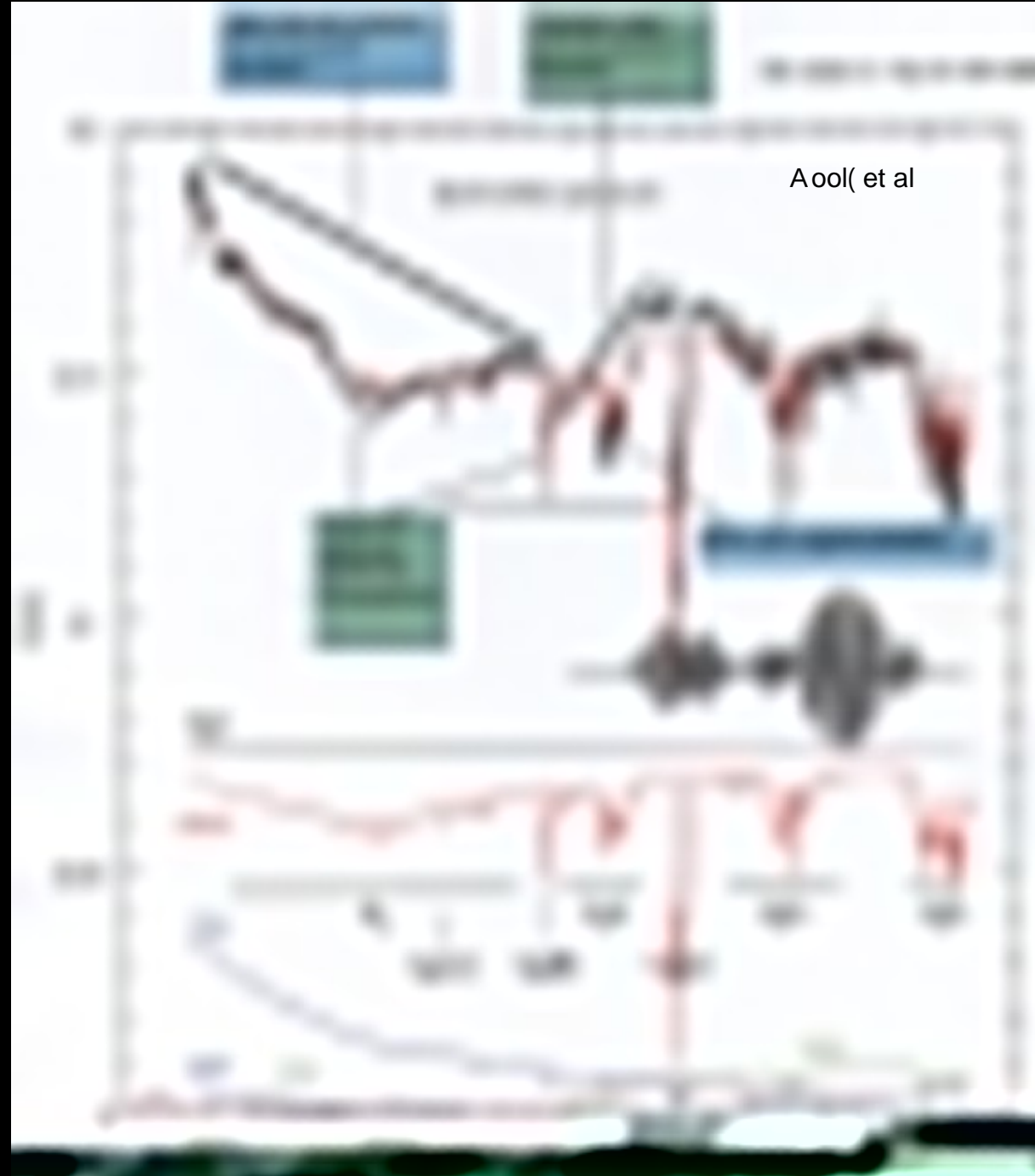
A deep-field astronomical image showing a vast field of galaxies and stars against a black background. The image is filled with numerous galaxies of various shapes and sizes, including spiral, elliptical, and irregular forms. Some galaxies are bright and clear, while others are faint and distant. The stars appear as small, bright points of light, some with diffraction spikes. The overall scene conveys the immense scale and diversity of the universe.

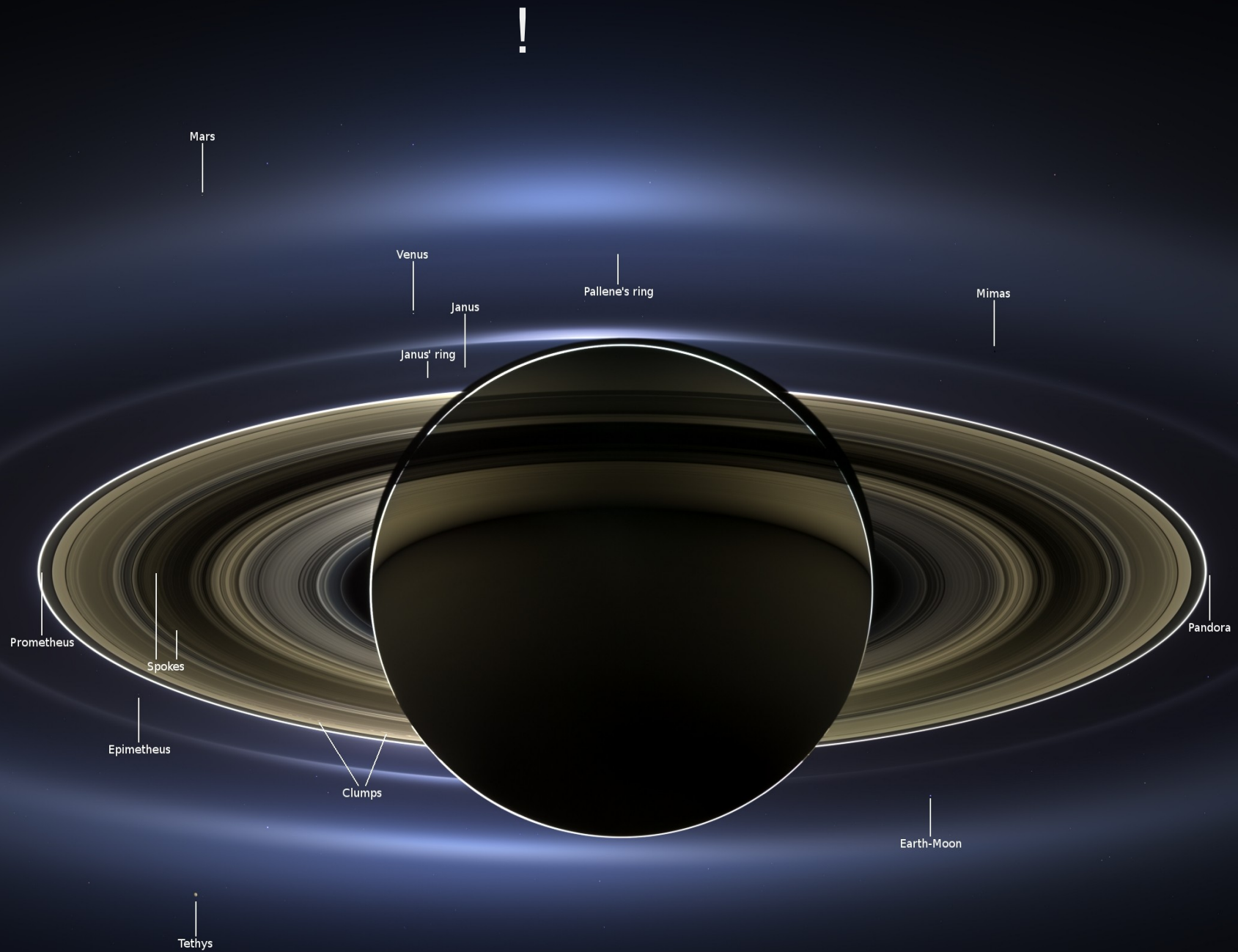
**200 billion galaxies
in the observable
universe**

Why imaging Exoplanets ?

Imaging allows spectroscopy to measure atmospheric composition

Spectrum of Earth taken by looking at Earthshine shows evidence for life and plants





This image was taken by the Cassini spacecraft when it was in Saturn's shadow. Looking back at the inner solar system. Can you spot Earth?

A photograph taken from space showing the planet Saturn in the upper left corner, with its characteristic yellowish-brown bands and a bright ring system. Below Saturn, a thin, curved line of Earth's atmosphere is visible against the black background of space. In the lower right, a small, bright blue-white point of light represents Earth, with a small white arrow pointing directly at it. The word "Saturn" is printed in white text to the left of the planet, and the word "Earth" is printed in white text below the arrow.

Saturn

↑
Earth

Towards Habitable Planets Imaging

Upcoming large
telescopes will (or the
first time) have the
sensitivity to image and
study habitable planets
around nearby stars

Genesis Initiative, Hallen
remains Earth's
atmosphere

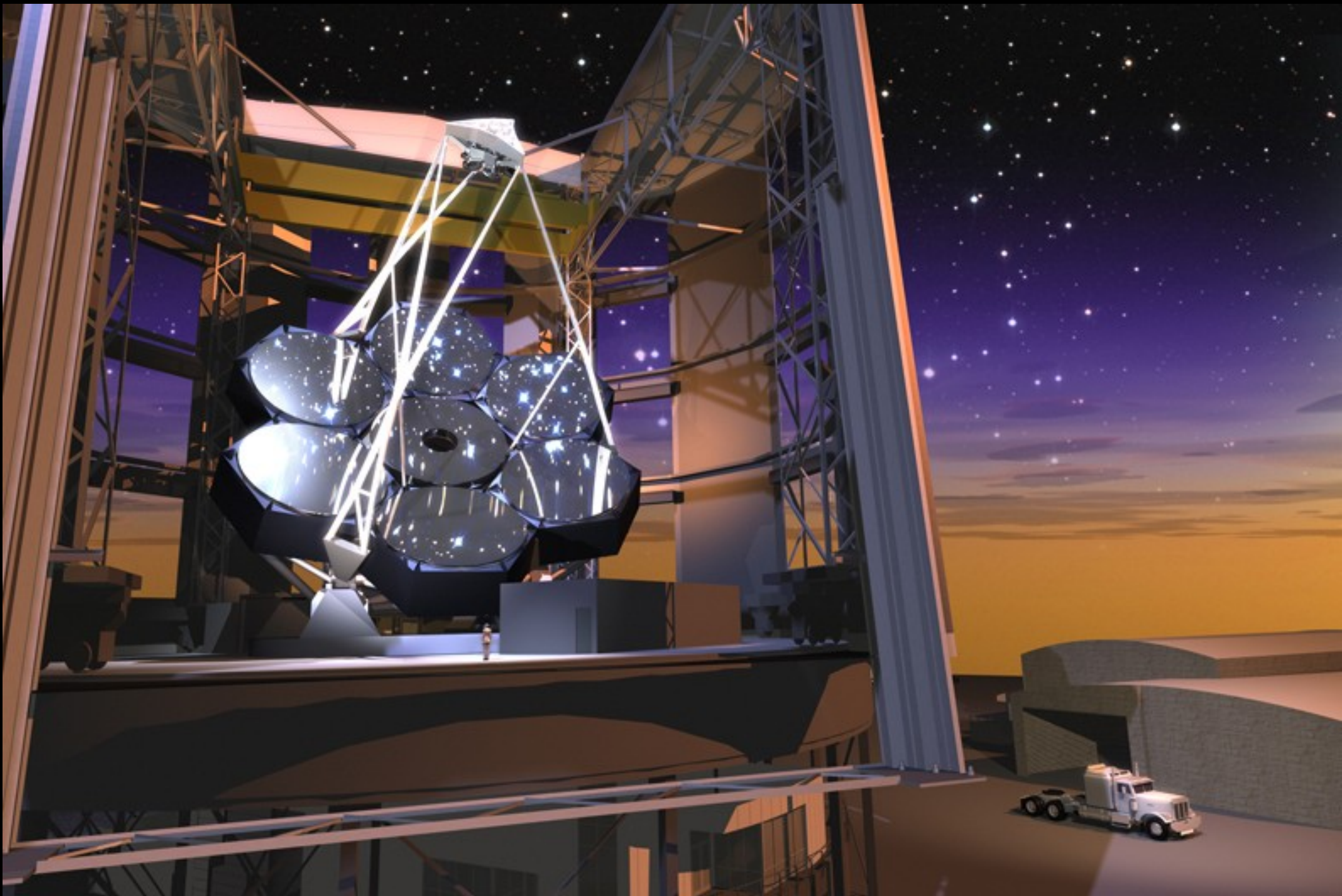


View from Proxima Centauri b planet, the closest
exoplanet from Earth, 4.2 light years away
=artist's guess

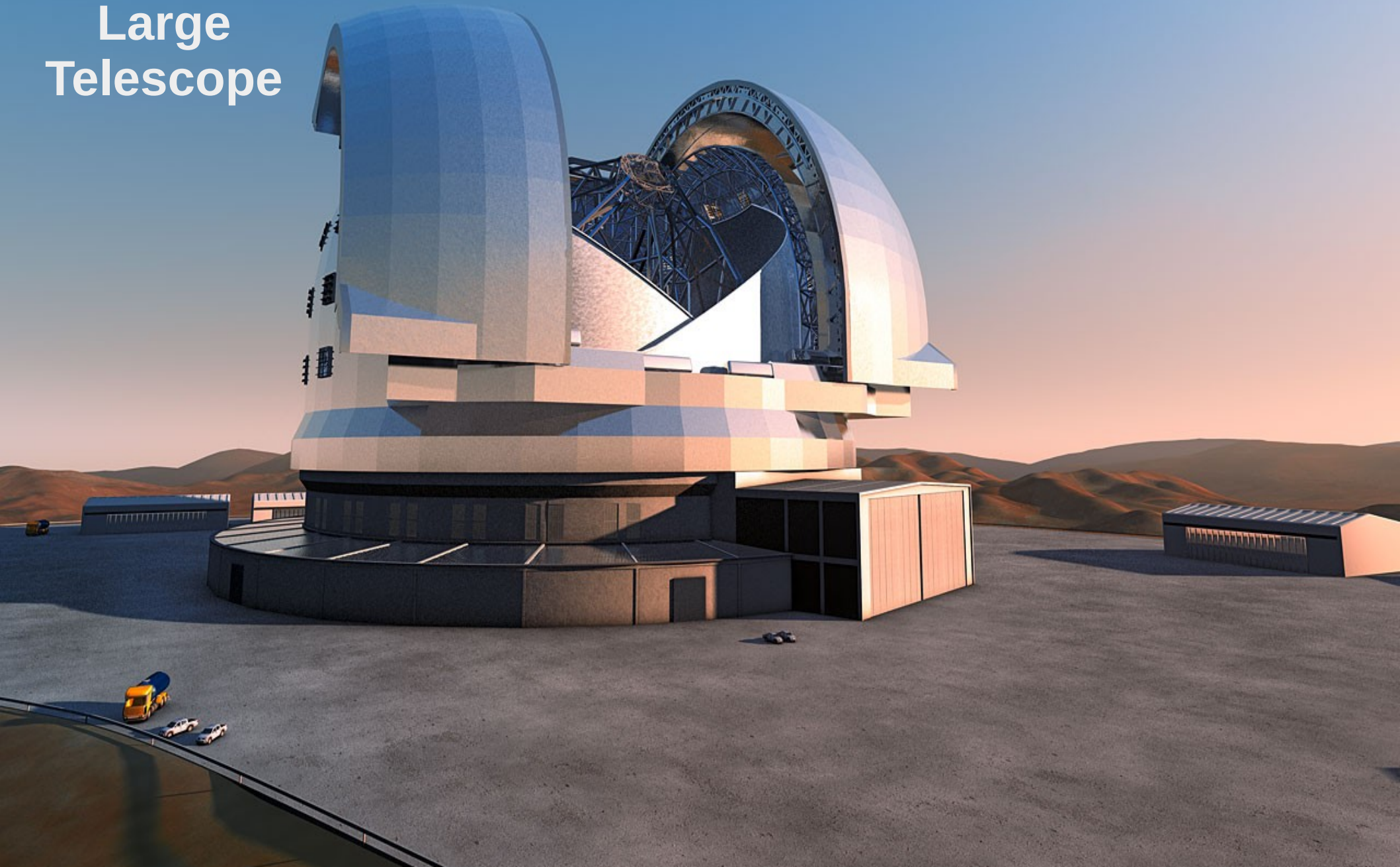
Thirty Meter Telescope



Giant Magellan Telescope



European Extremely Large Telescope



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للعلوم والتقنية
King Abdullah University of
Science and Technology



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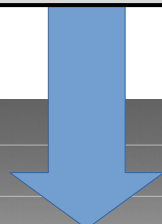
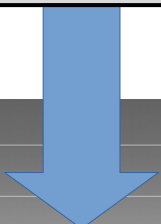
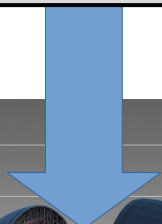


SCEAO Subaru Coronagraphic
Extreme Adaptive Optics

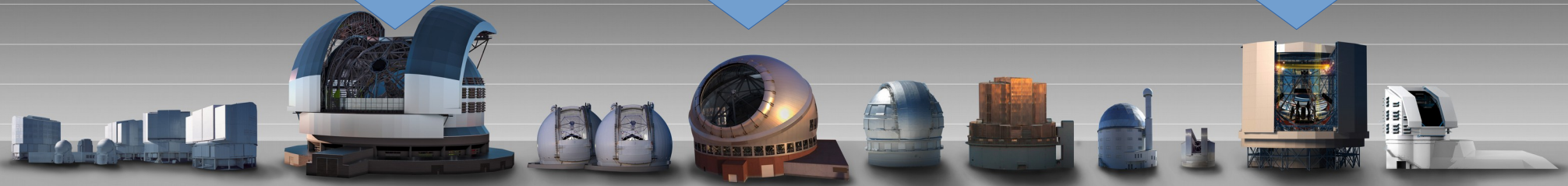
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" #



100 m
80 m
60 m
40 m
20 m



Very Large Telescope Extremely Large Telescope Keck Telescope Thirty Meter Telescope Gran Telescopio Canarias Subaru Telescope South African Large Telescope New Technology Telescope Giant Magellan Telescope Large Synoptic Survey Telescope

Adaptive Optics (AO)

Atmosphere Turbulence Earth's atmosphere introduces strong and (astrophysical) aberrations

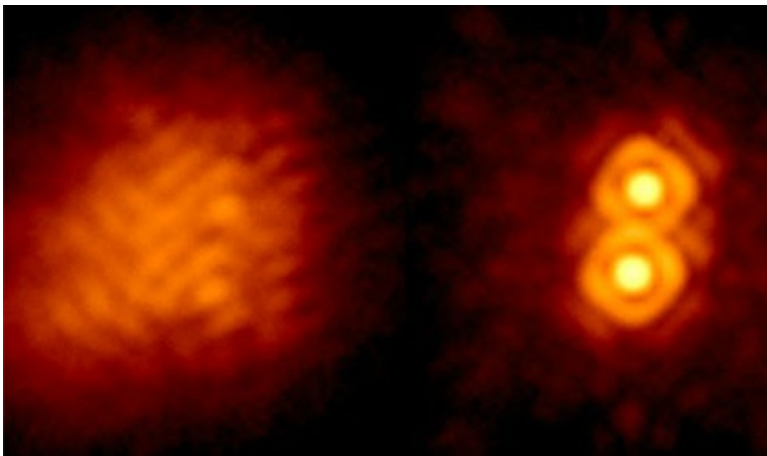
Aberrations must be continuously **measured** and **corrected** to provide sharp images

Imaging exoplanets is particularly demanding* as the planet is much fainter than the star it orbits\$ very little room for error

Modern AO for exoplanet imaging is referred to as **Extreme-AO**

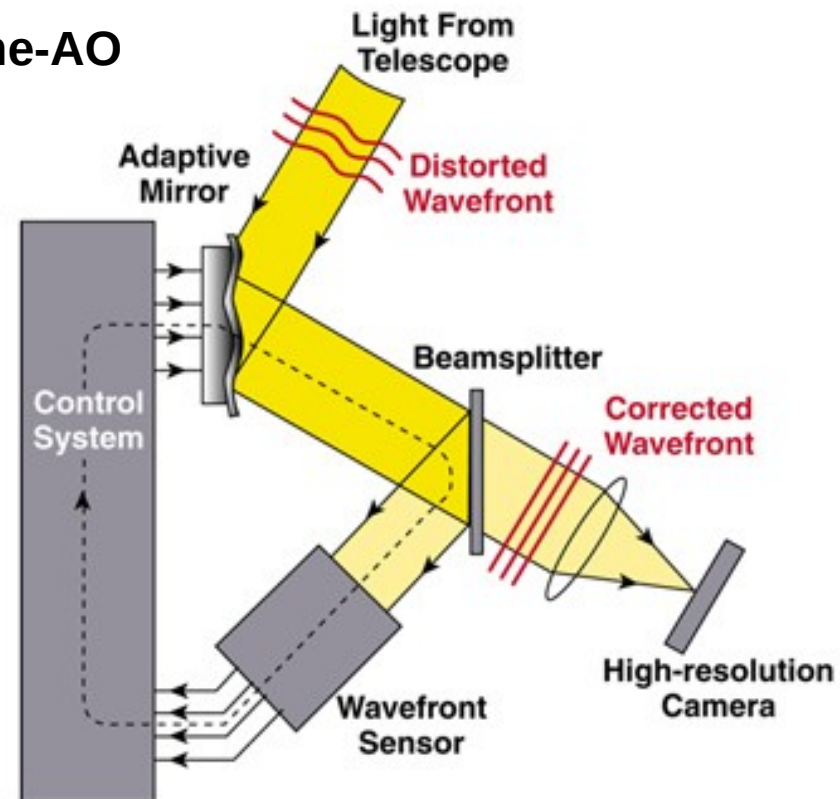
NGST

NGST



Palomar obs / NASA JPL

Feedback loop:
next cycle
corrects the
(small) errors of
the last cycle



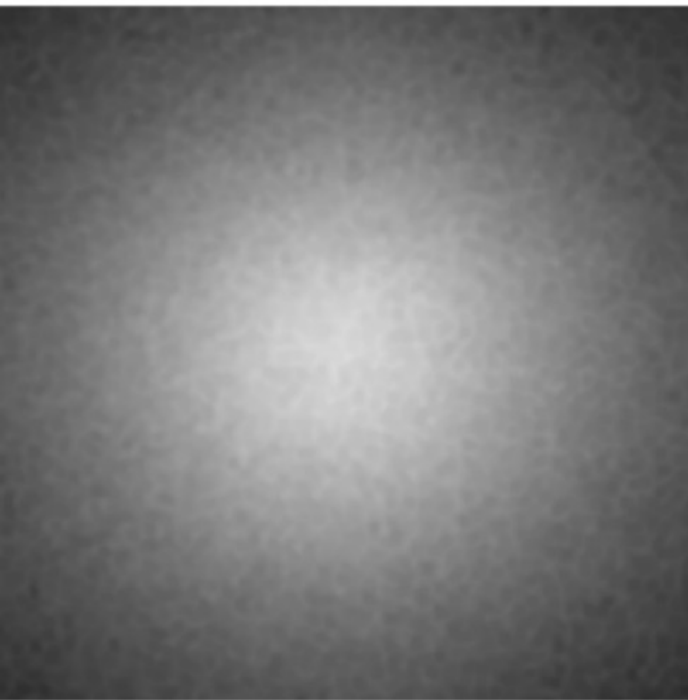
Imaging exoplanets requires “Extreme-AO”

- 1: ExAO control radius
- 2: Telescope spider diffraction
- 3: Diffraction rings
- 4: Ghost spider diffraction
- 5: “butterfly” wind effect
- 6: Coronagraphic leak (low order aberrations)

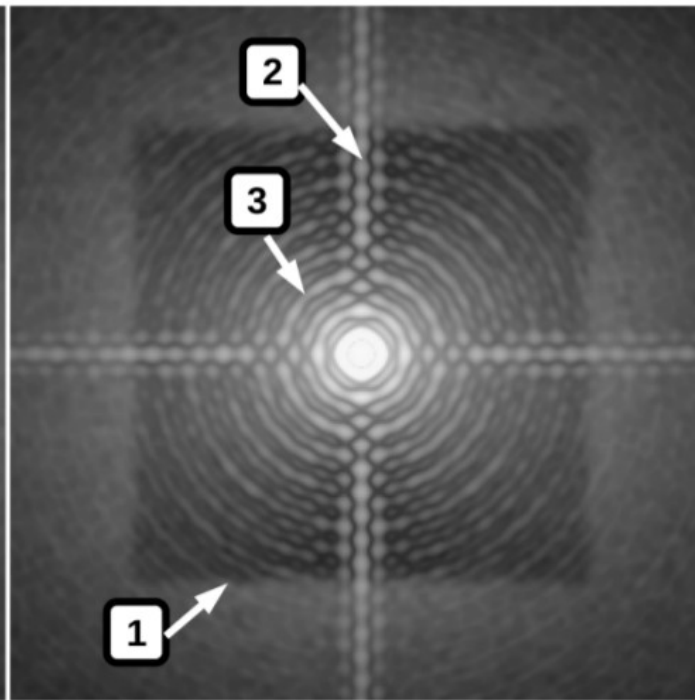
Simulated images below show how Extreme-AO and Coronagraphy deliver high contrast image of a star

Monochromatic PSFs, 1.65 μ m
No photon noise
10m/s wind speed, single layer
4ms wavefront control lag

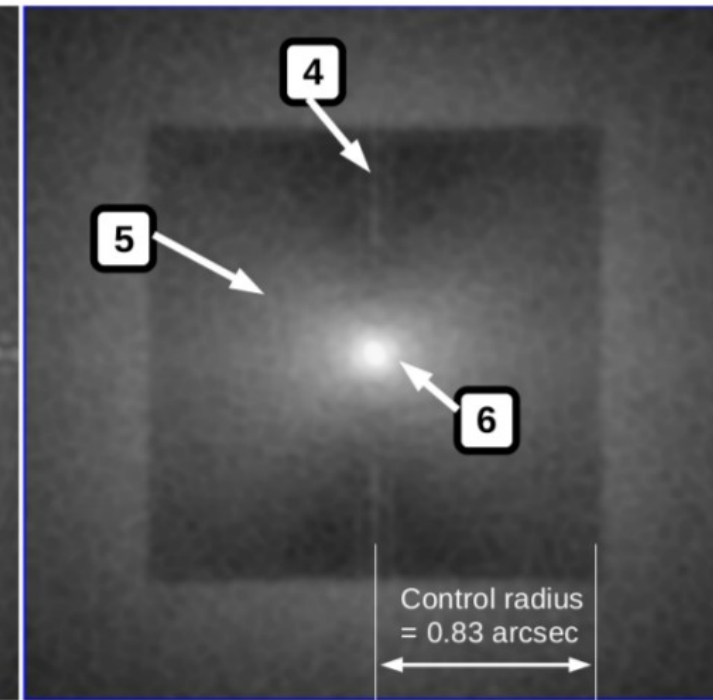
No AO correction



Extreme-AO correction



Extreme-AO + coronagraph



-4.7

-4.4

-4.1

-3.8

-3.5

-3.2

Contrast (10-base log)

-2.9

-2.6

-2.3

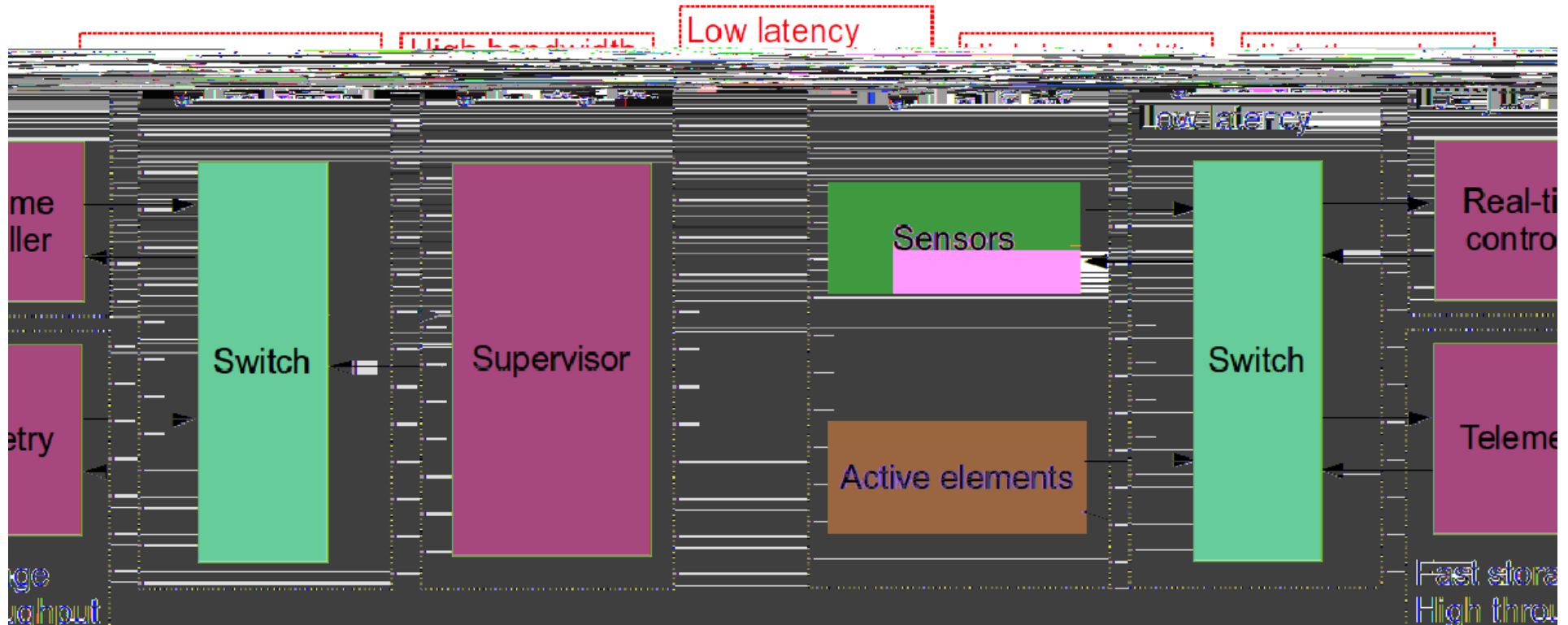
ExAO is a formidable HPC challenge

Cameras with 100*000N pixels each take images of starlight every 600 us = 6 * 10⁻⁶ s to drive deformable mirrors with 10*000s actuators

Within 600 us* we must

- Read the images* move them (from cameras to computer hardware memory)
- Process the images to reconstruct the optical aberrations experienced by light through Earth's atmosphere
- Compute the deformable mirror's shape=s> that will cancel the aberrations =10*000s of degrees of freedom>
- Apply the shapes and give enough time (for the mirror to move)

AO real-time controller



<2C (a, ility with 6 main subsystems

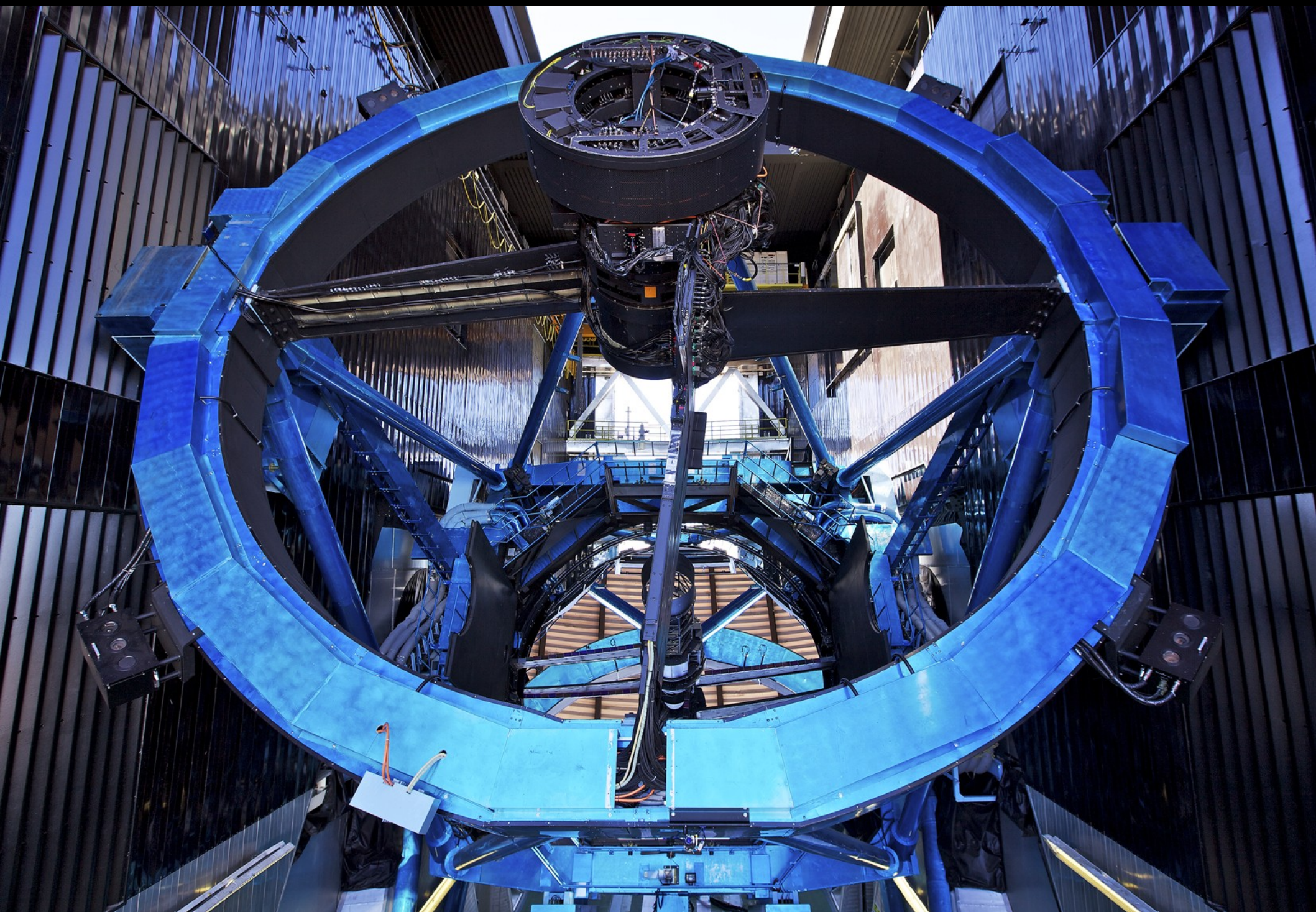
- <ard Beal3Time , ontroller\$ per(orms the main . G , ontrol loop
- Telemetry\$ store system data at hi" h (ramerate
- / upervisor\$ update the hard real3time loop parameters

Keck II Telescope, 8.2m diameter, has an exoplanet-imaging instrument = Lick & G
The instrument team is developing advanced Extreme-UV techniques

Our test facility...

Keck II Telescope, 4,000 ft Mauna Kea, Hawaii
8200m altitude

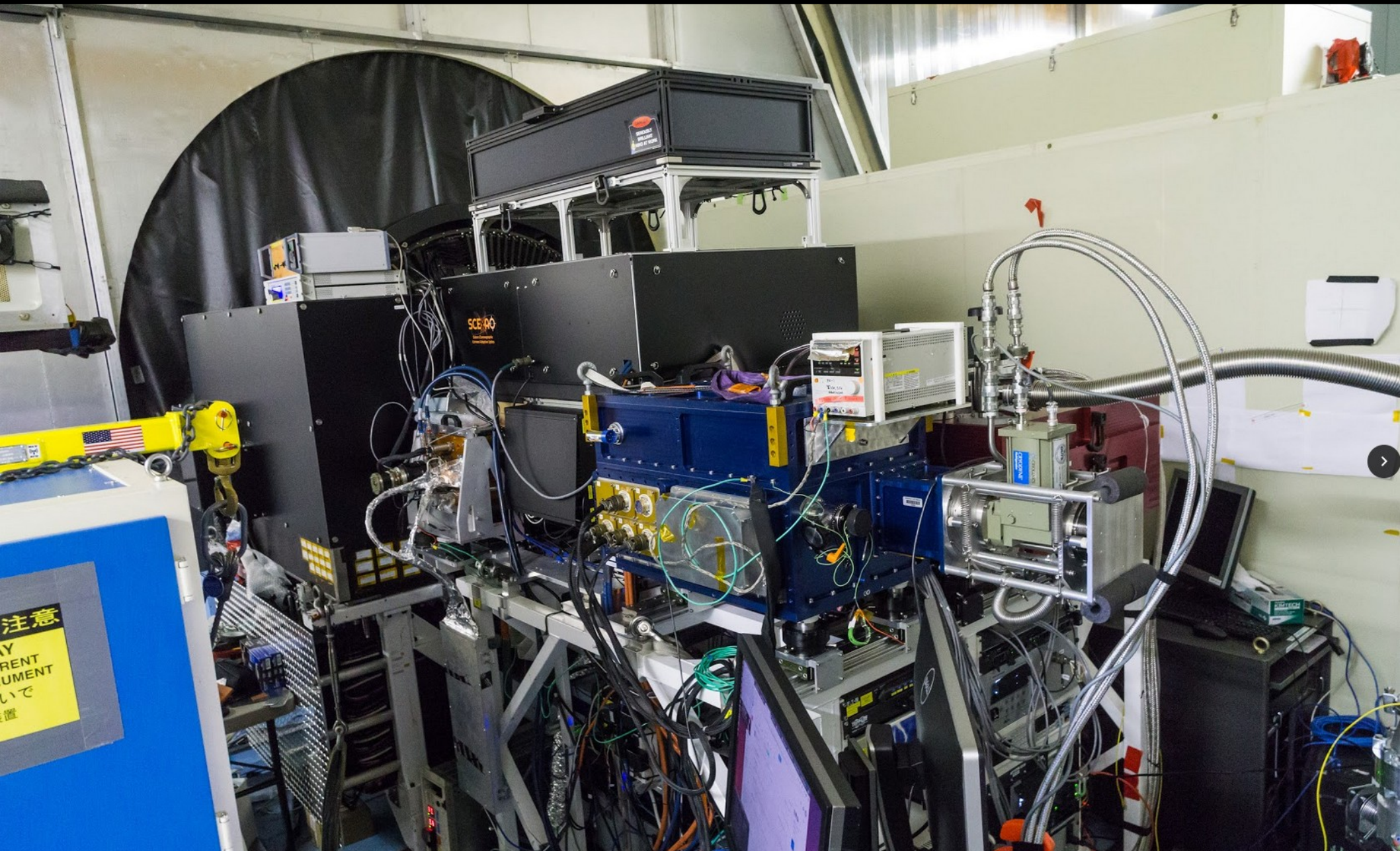




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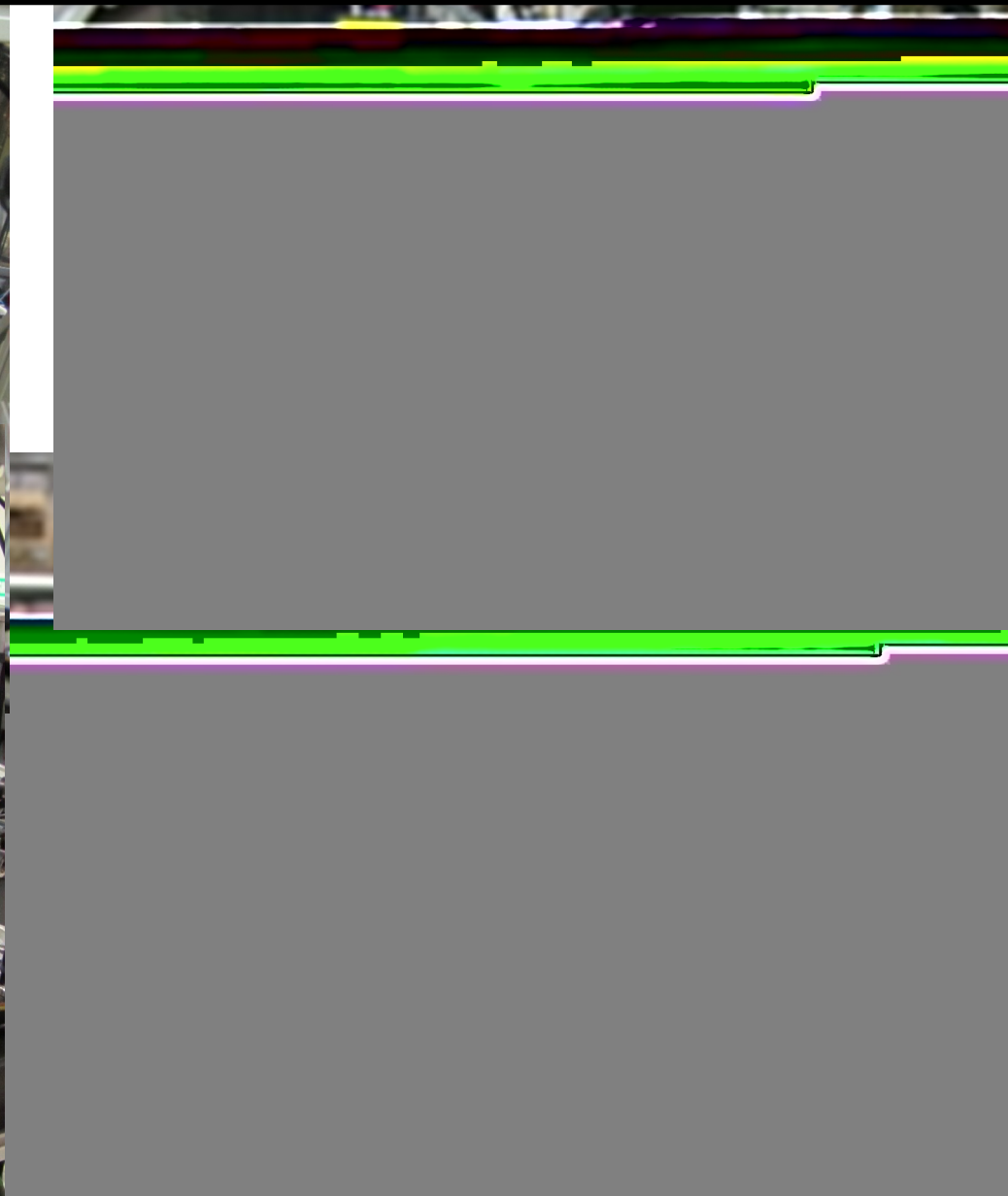
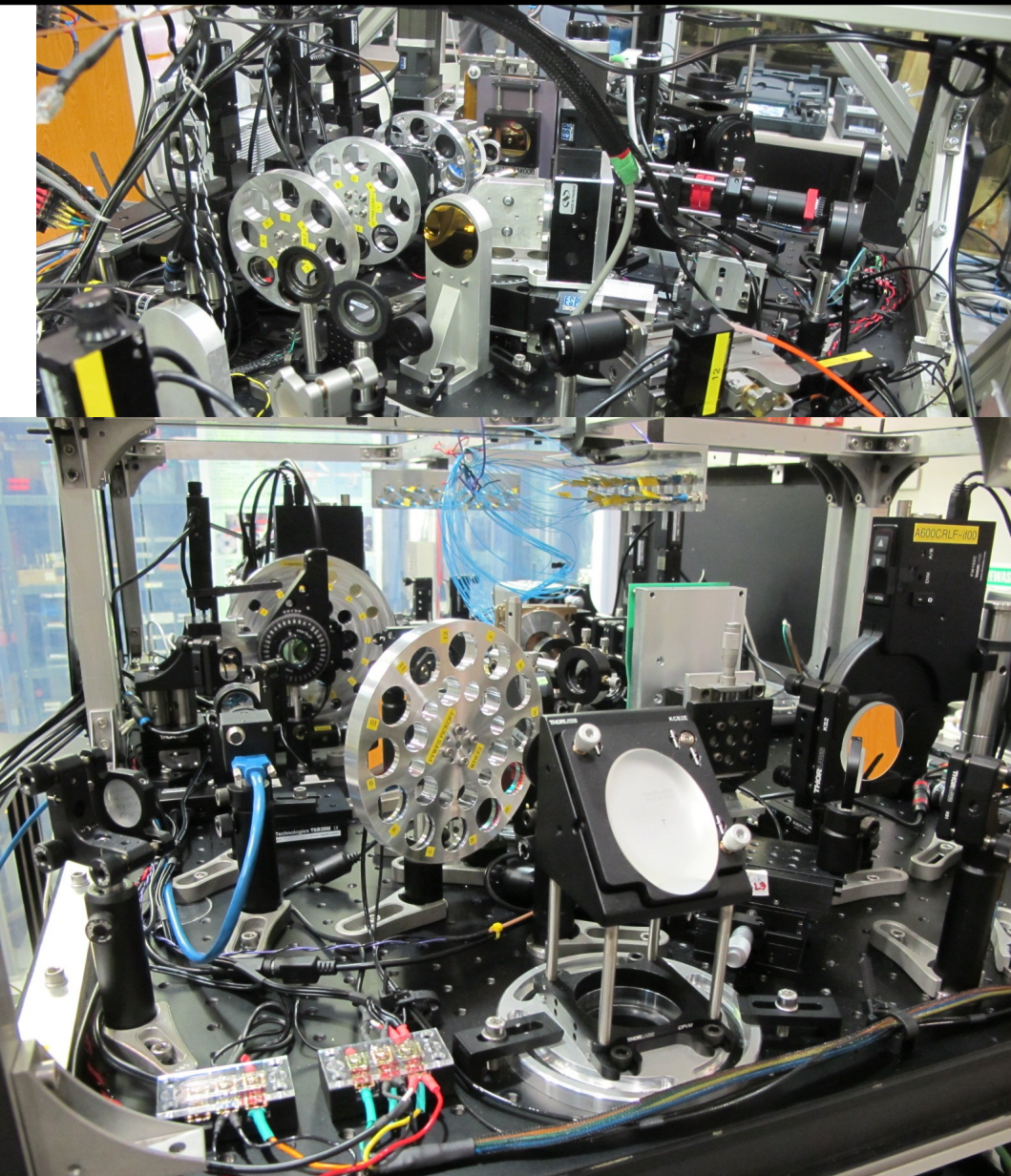
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SCEXAO Subaru Coronagraphic Extreme Adaptive Optics



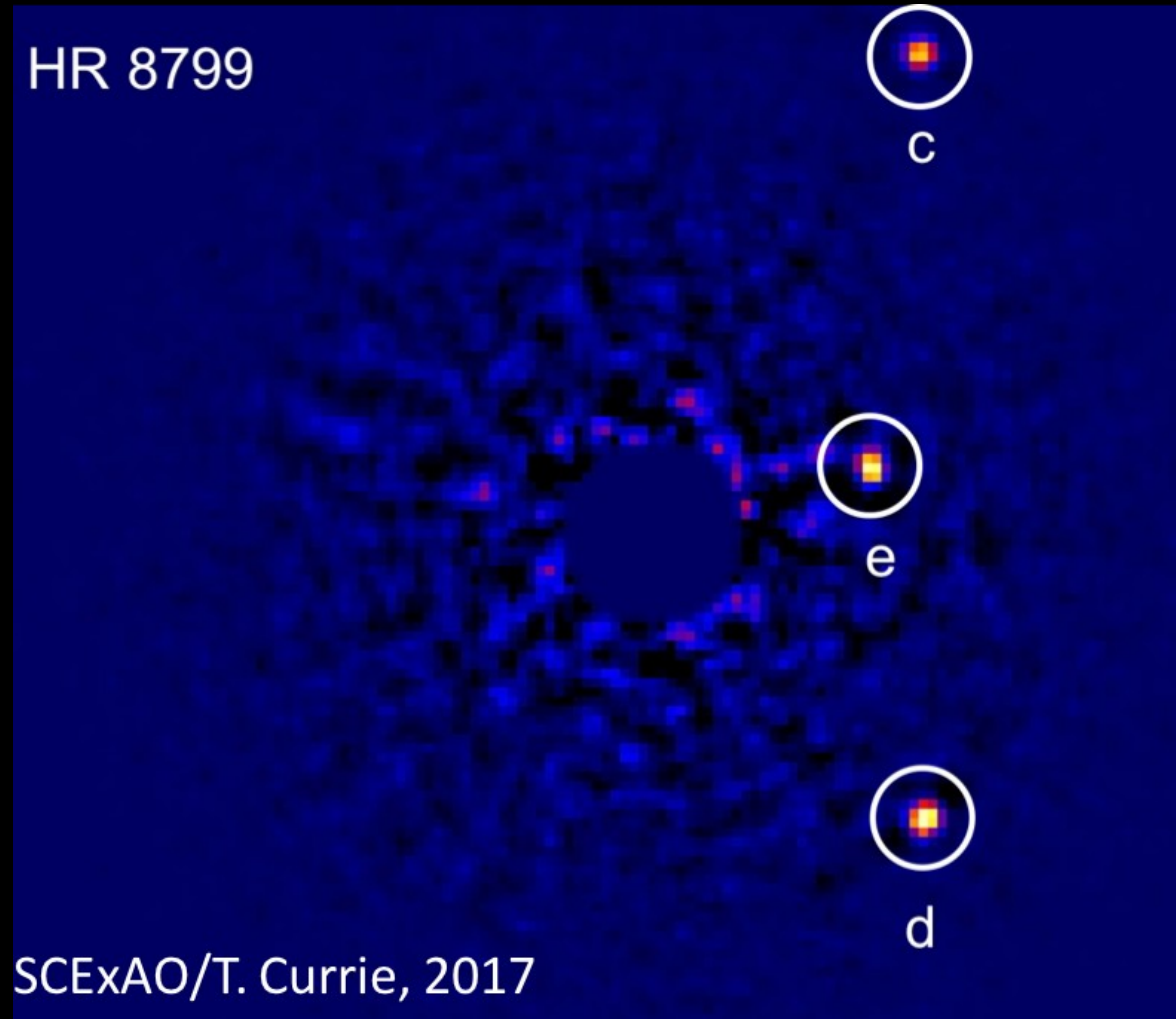


Subaru Coronagraphic Extreme Adaptive Optics



HR8799

Hour planets* orbital periods on the order o(100yr
Ea, h planet 9 to 7 1upiter 4 ass

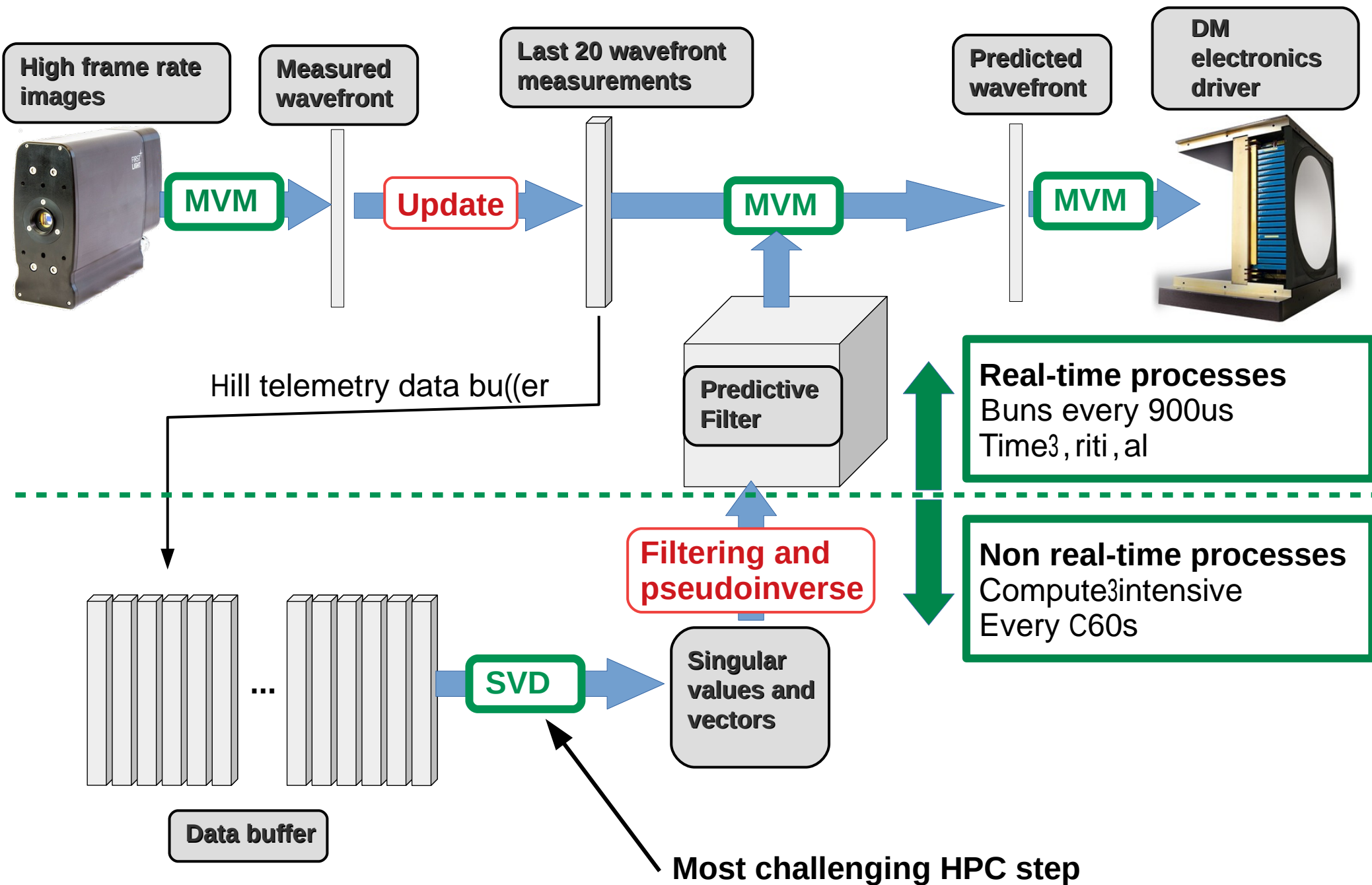


Predictive Control

#E as if it wasn't hard enough already !" – Hatem Ltaief, 2018

-
-
- **Predictive control** optimally uses the last (few measurements to predict the aberrations at the exact time of correction
-
-
- **CHALLENGE:** The temporal relationships between past and future aberrations are not known in advance and change continuously =depends on wind speeds and many other things>
- Models must continuously learn/update them* and apply them in real time at 236 Hz ;

Algorithm: mixed CPU / GPU implementation



Computing Hardware

One of two GPU chassis

\$," # /0)111
2345 %.



Re-thinking adaptive optics

The machine learning approach to predictive control is part of a wider new approach to adaptive optics

Conventional adaptive optics (pre-2018):

Calibrate = usually in lab* and T < E - apply pre-computed control law

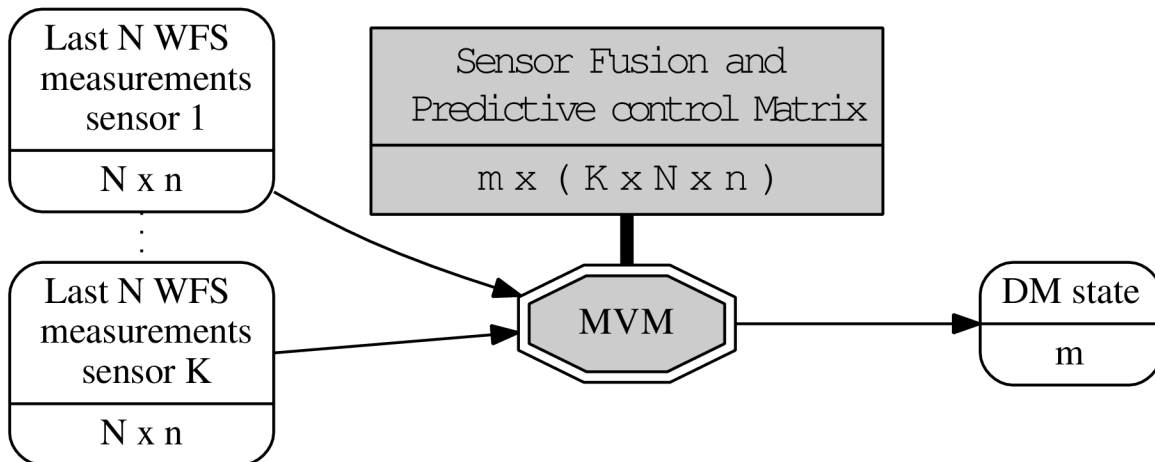
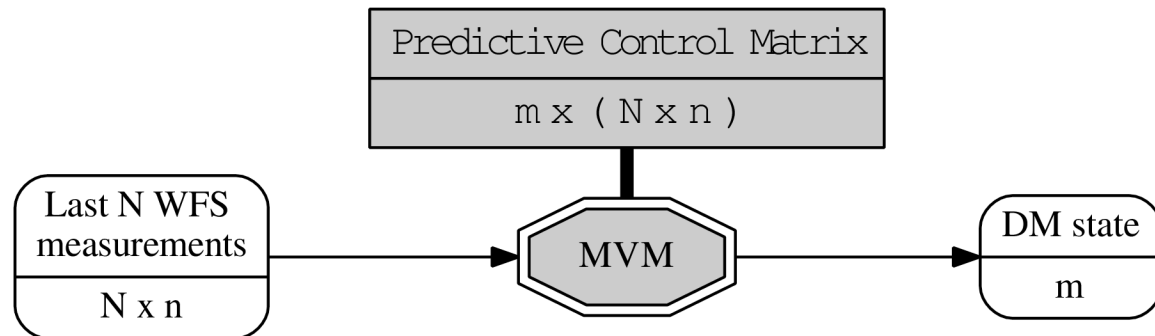
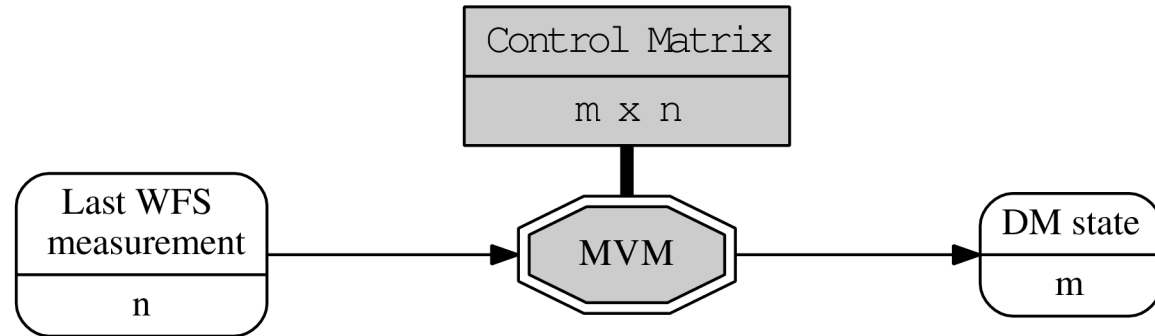
Machine learning based AO:

Control law is continuously optimised based on analysis of real-time measurements

Includes predictive control and sensor fusion

Predictive Control and Sensor Fusion

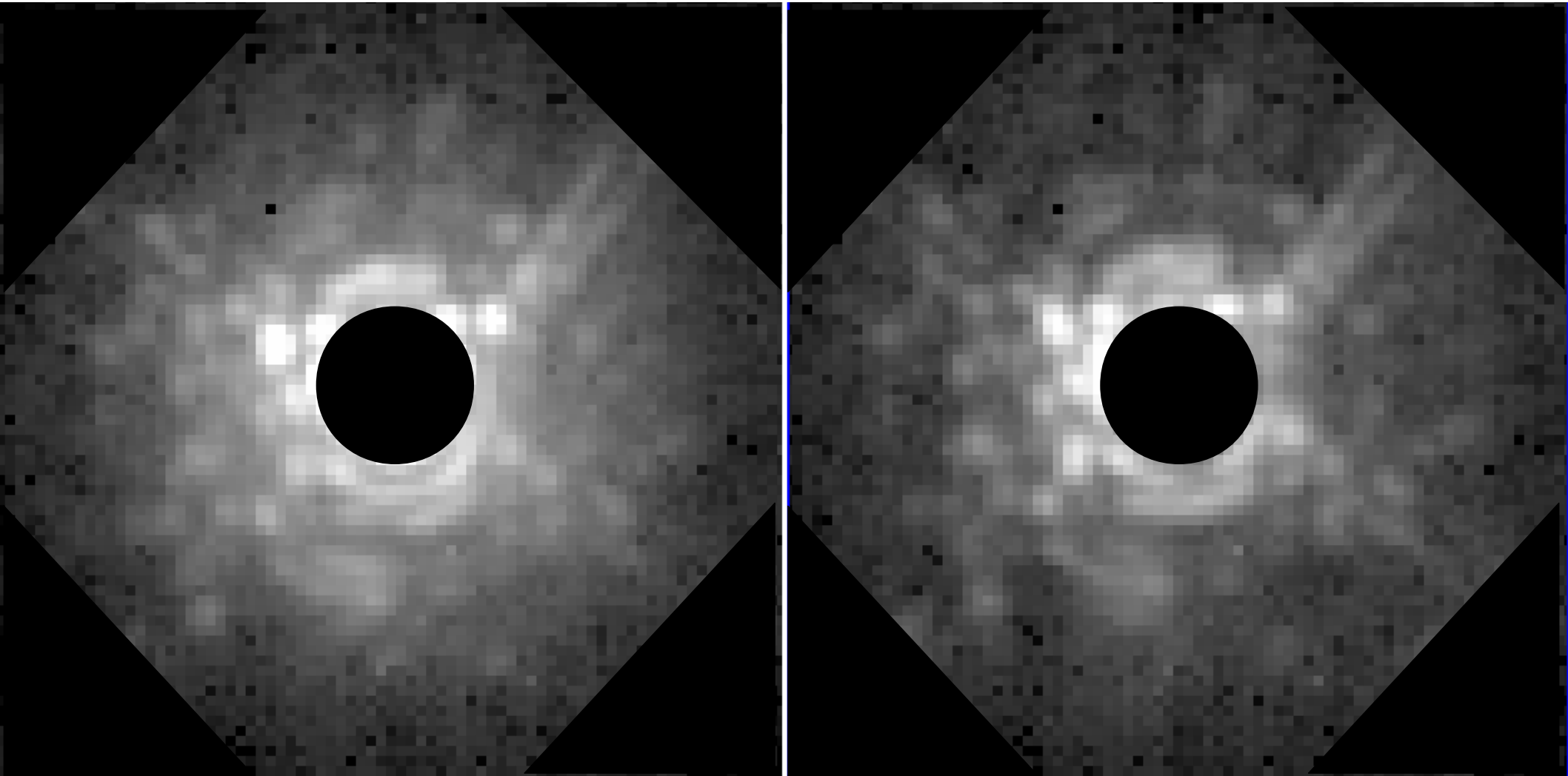
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 Ae measure response



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 • Ae must ,ontinuously
 derive ,ontrol al"orithm
 (rom realtime telemetry

First on-sky results (2 kHz, 50 sec update)

→ 2.5x raw contrast improvement



** &) 6147+

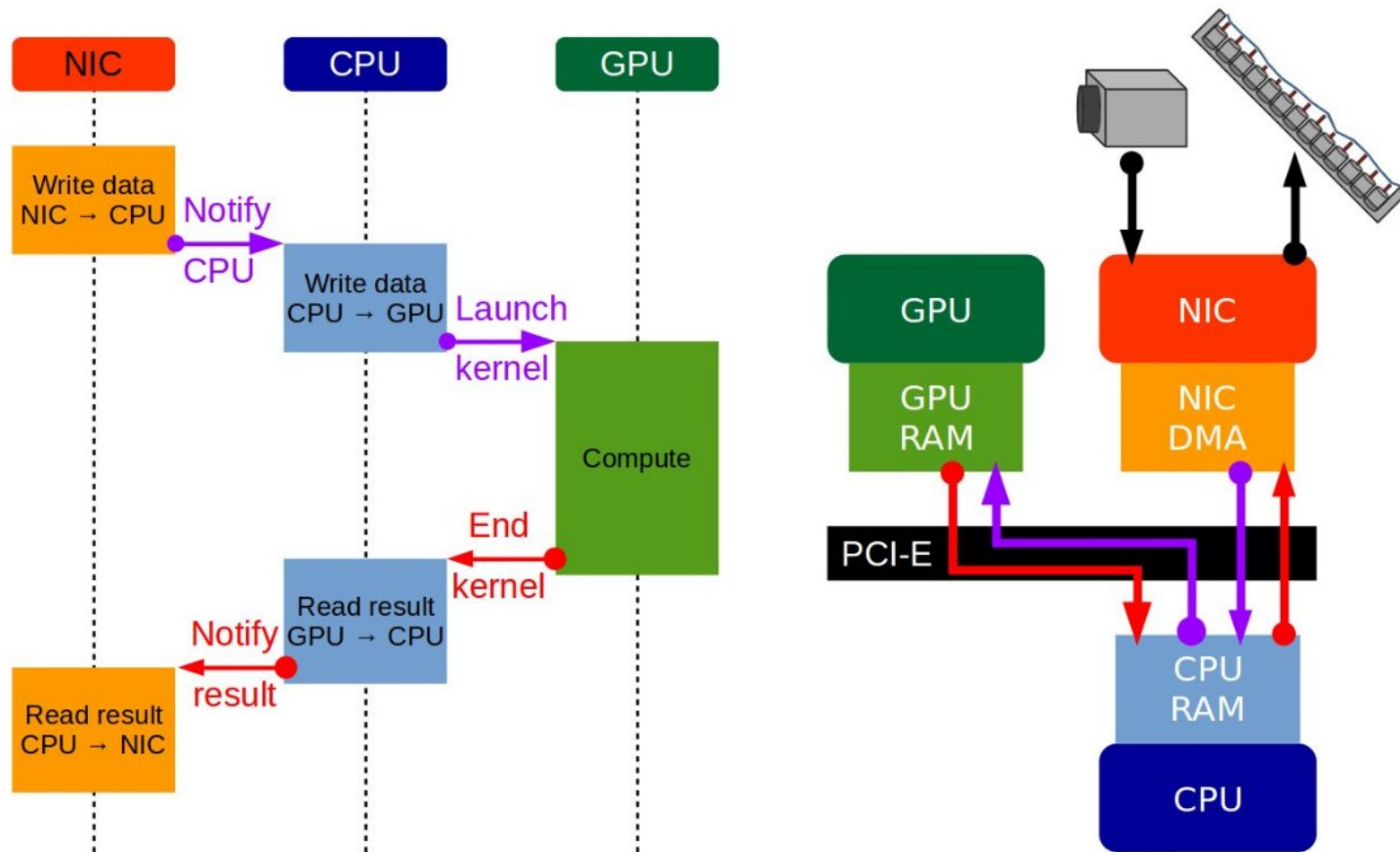
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/ ame star* same exposure time* same intensity s , ale

Ongoing research

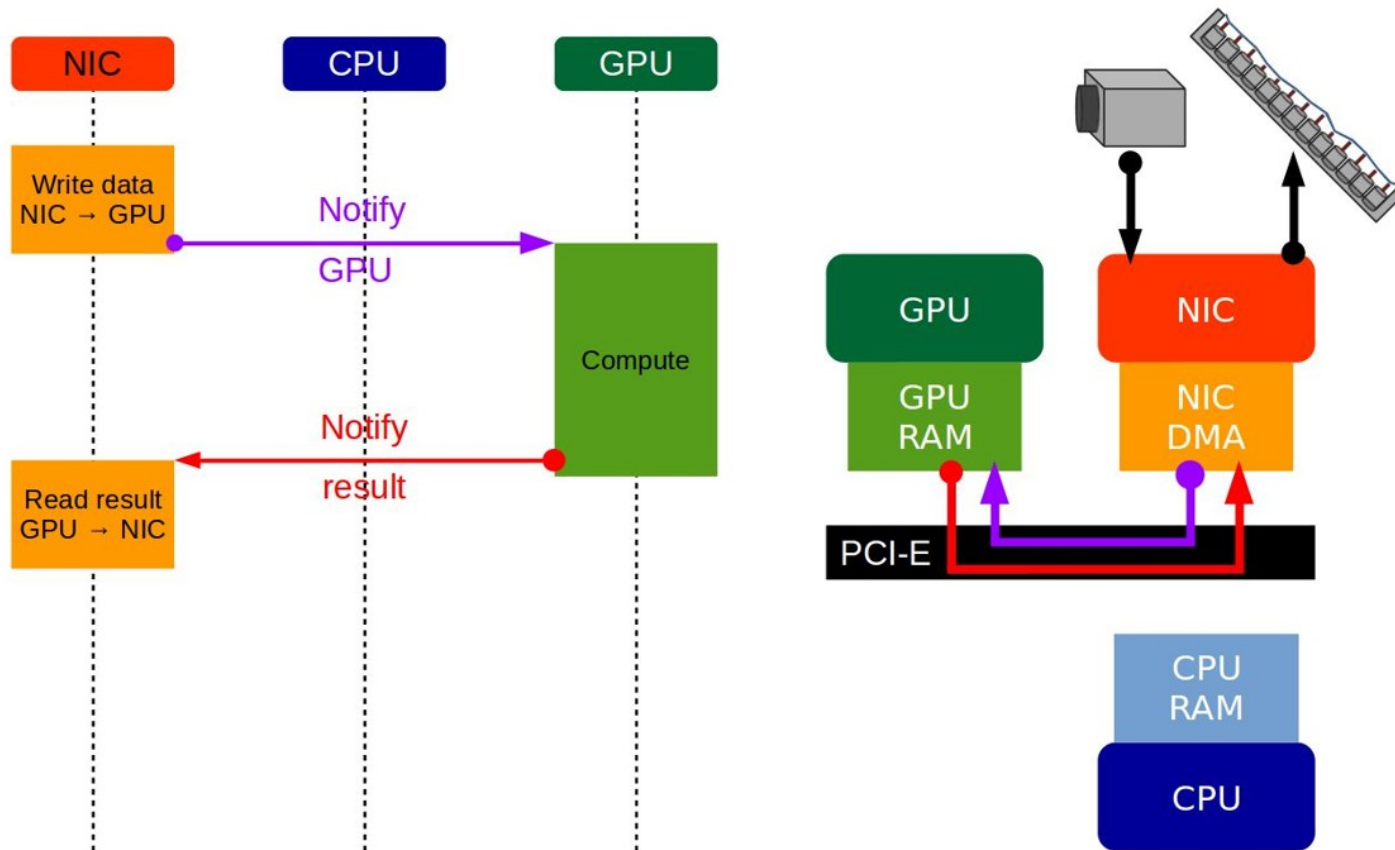
Low latency data acquisition and processing

/ standard acquisition pipeline

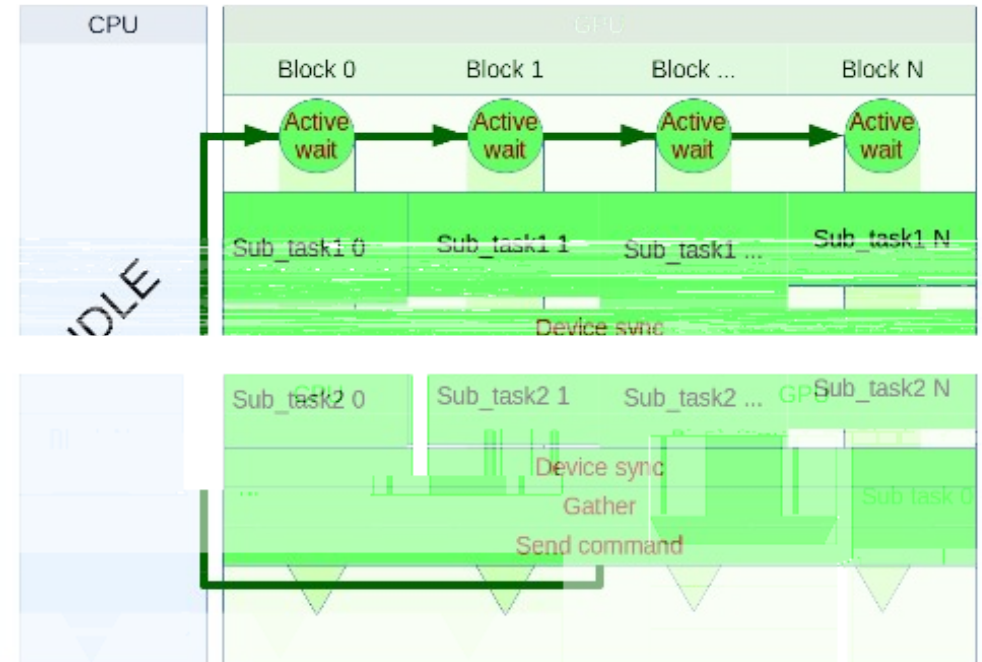
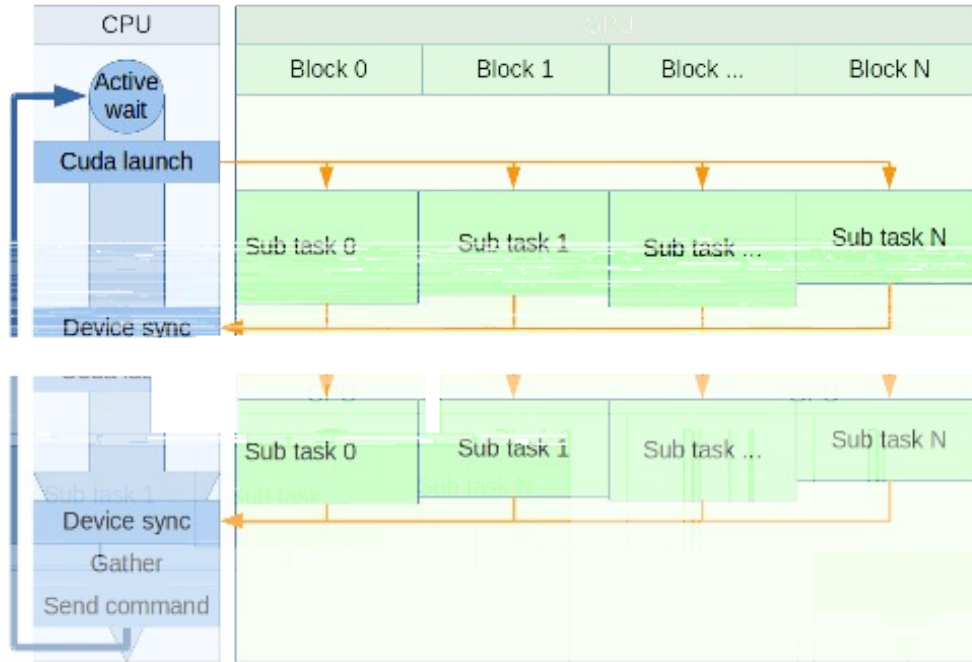


Low latency data acquisition and processing

• , ' uisition pipeline with G2%dire , t



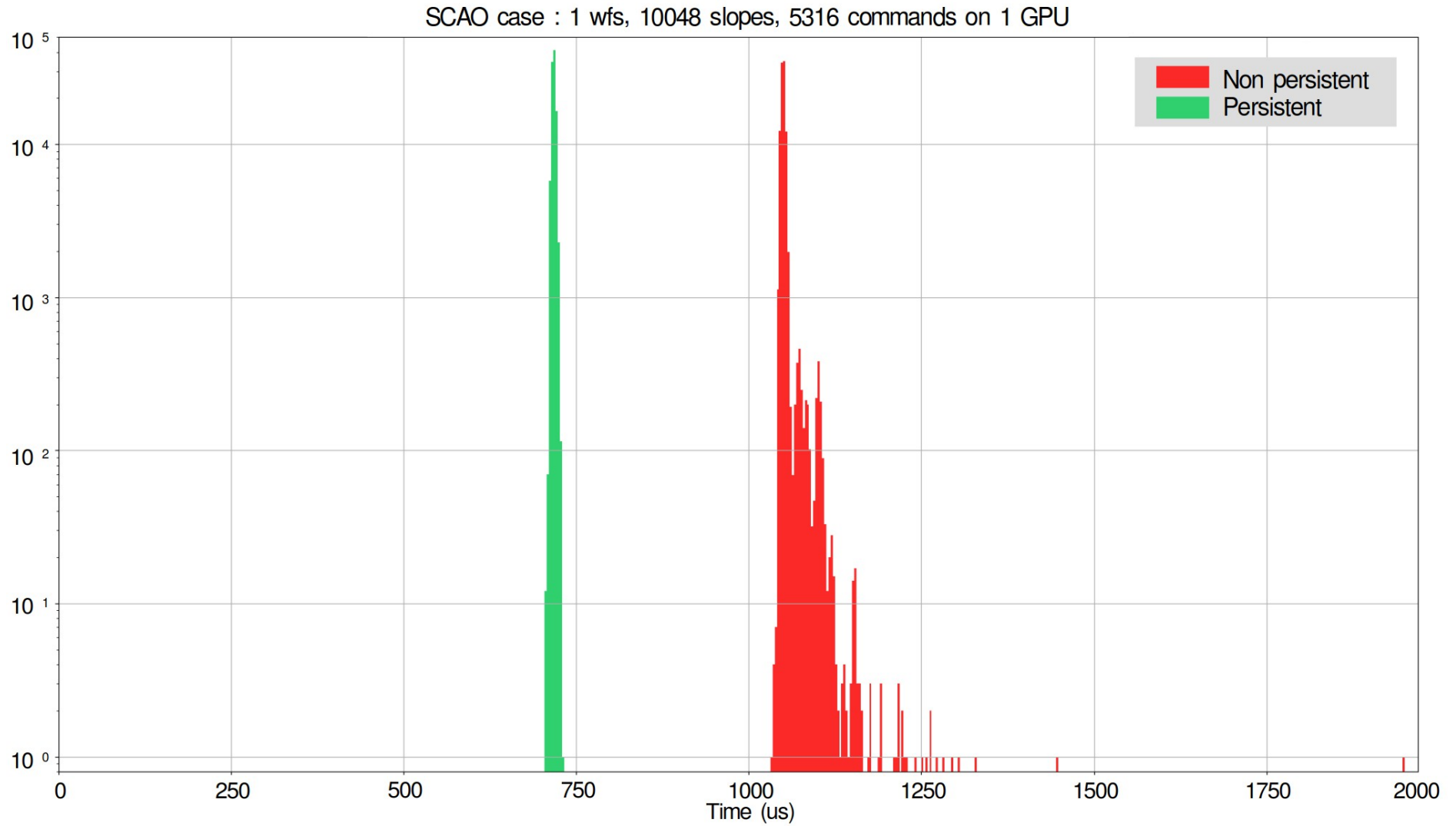
Persistent kernels



Concept of a never ending GPU kernel

- Remove C2G interactions / synchronization is done on device

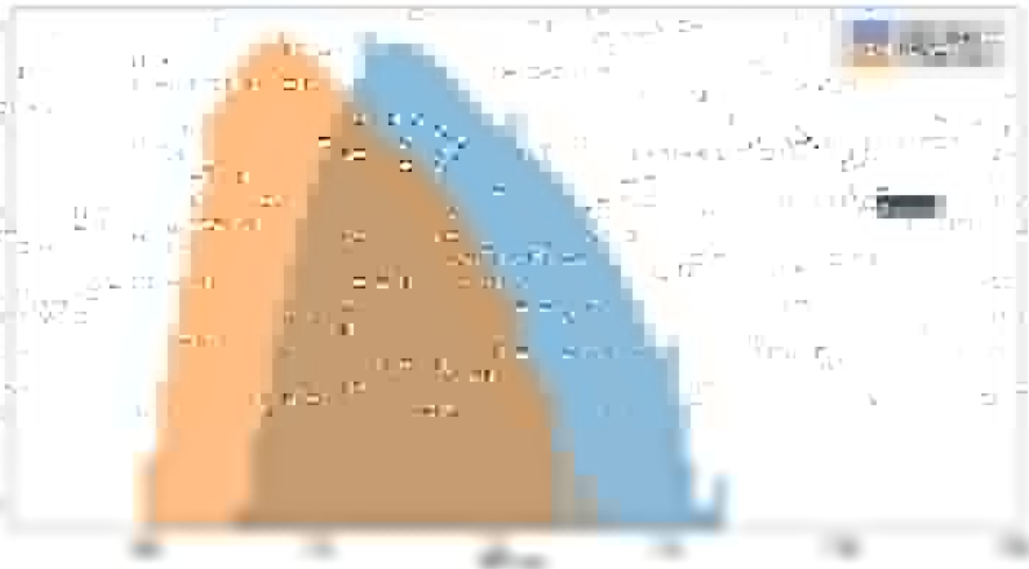
Persistent kernels



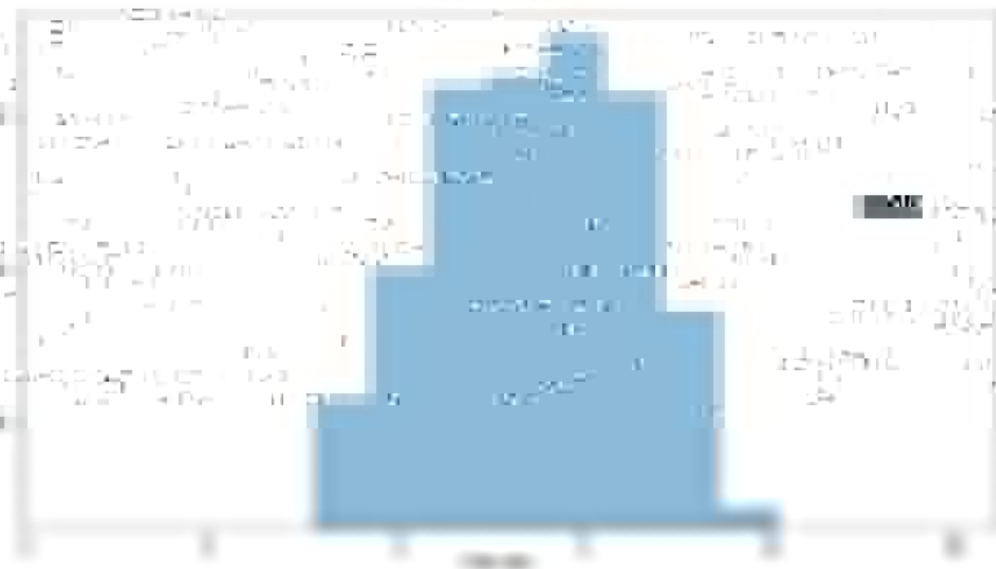
FPGA + GPU pipeline



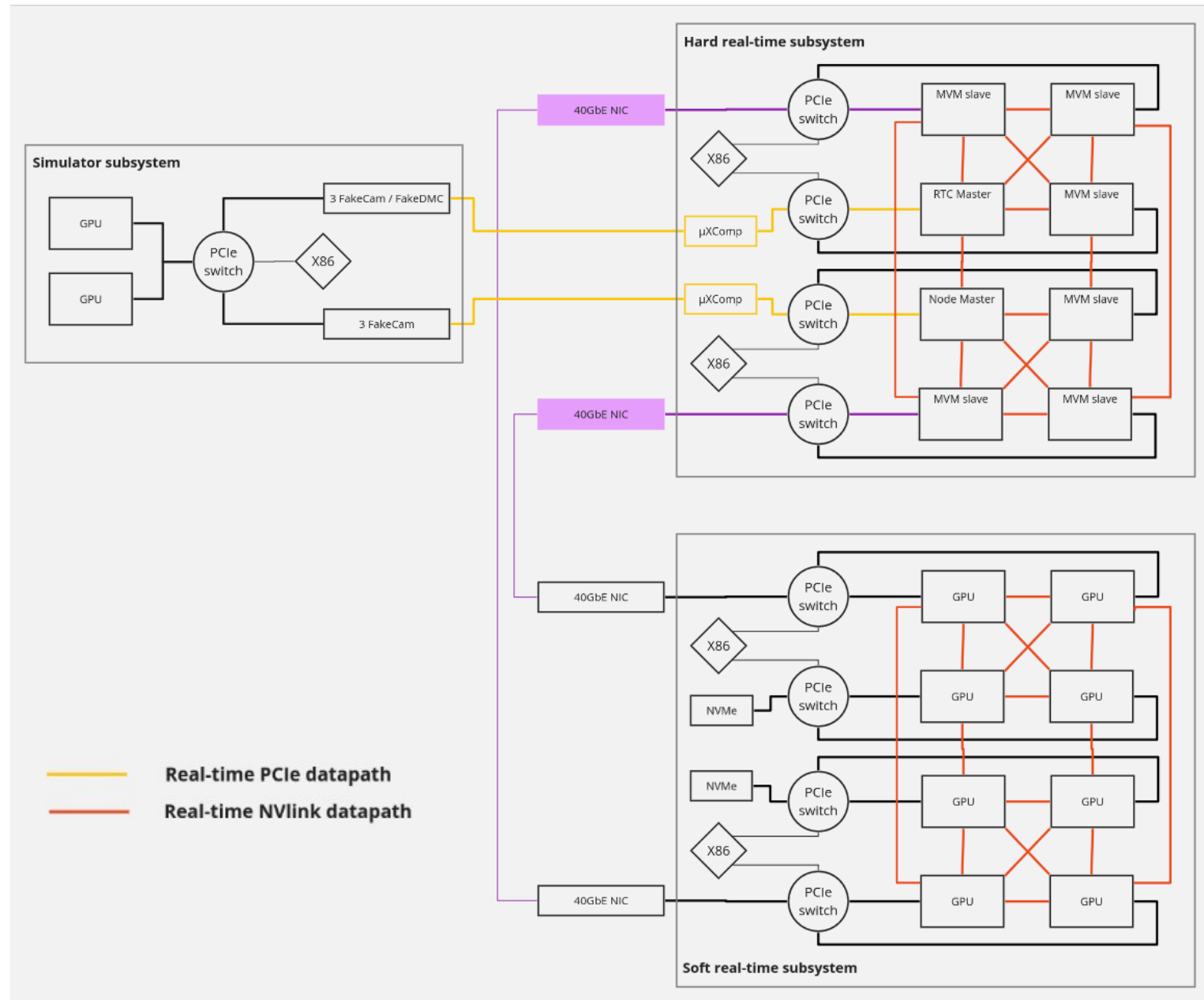
FPGA time vs GPU time based on clock measurement



Difference time



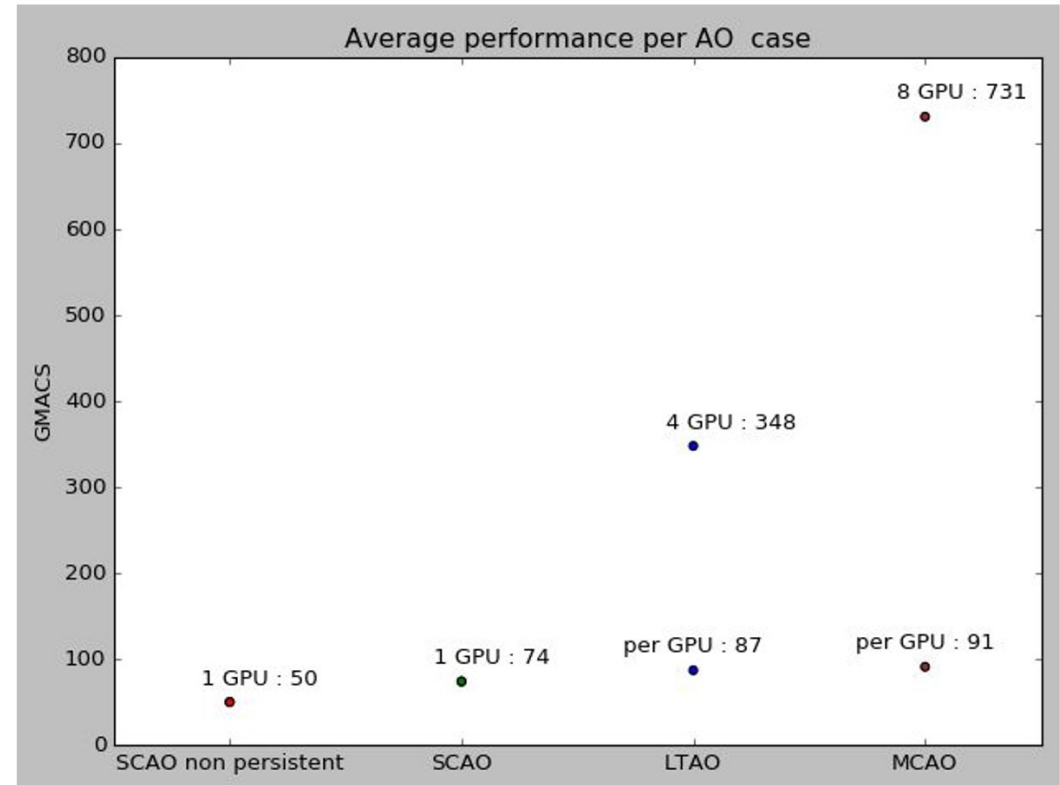
ELT RTC prototype based on DGX-1



ELT RTC prototype based on DGX-1

Table 2. Equivalent Giga Multiply Accumulates / s obtained in the various cases

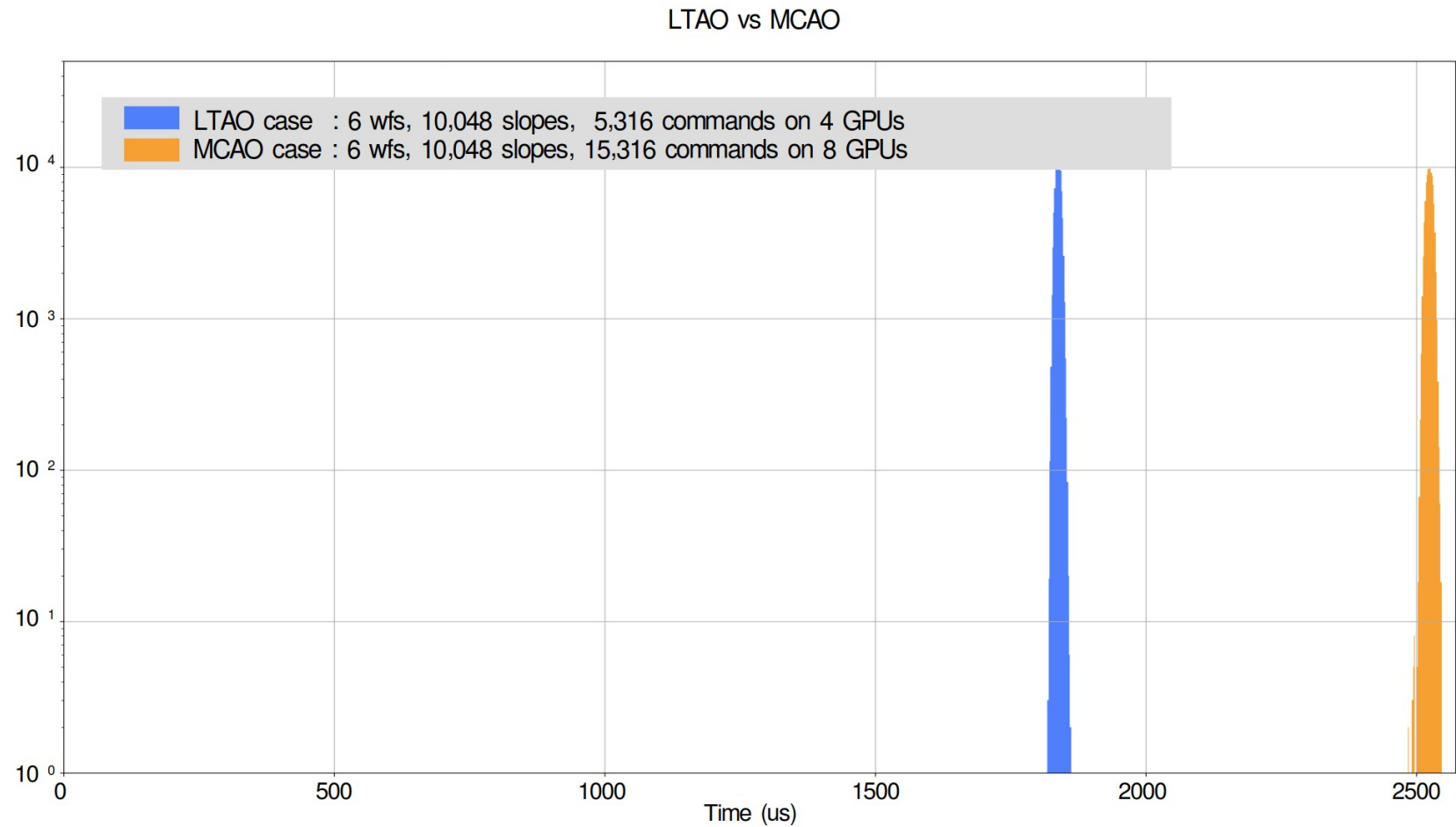
name	N GPU	global GMAC/s	GMAC/s per GPU	scale per GPU
SCAO	1	74	74	1
LTAO	4	348	87	x1.5
MCAO	8	731	91	x2.25



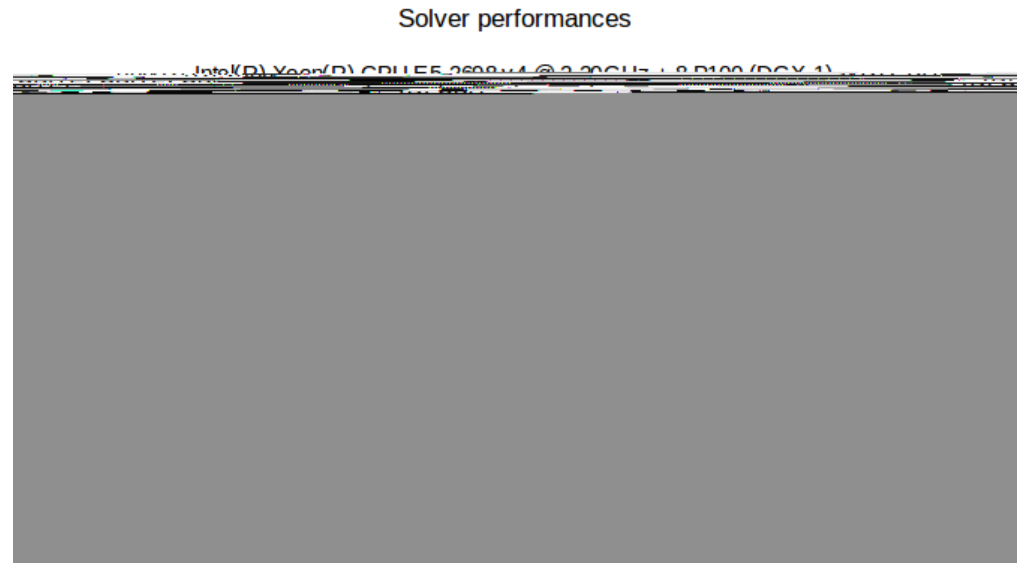
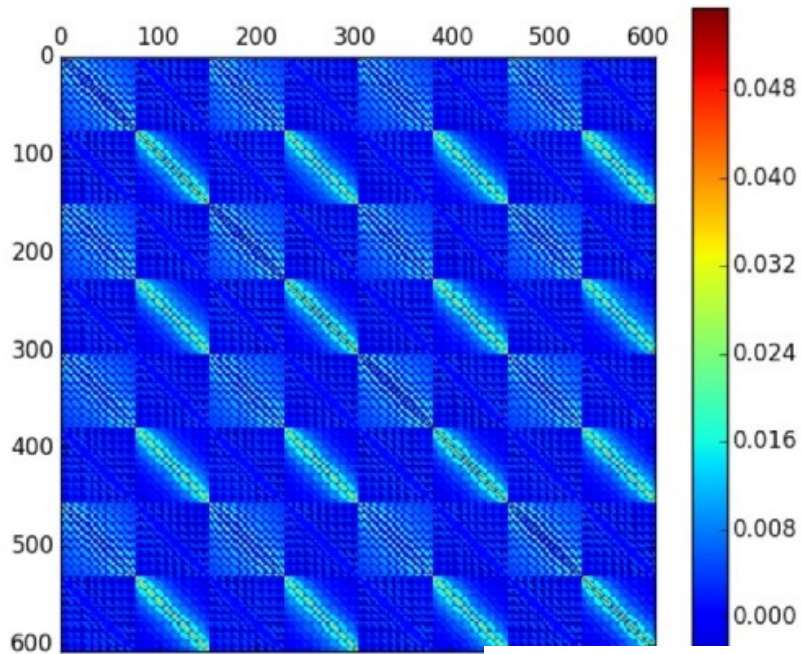
!evera" in" the (ull bandwidth o(<& 42

- BT pipeline dominated by 4 5 4
- Bea , hin" over 790 G&0s on a sin"le G2% =i e :8P o(measured mem &A>
- / , al ed well on multiple G2%s\$ the more data you (eed the G2% with* the better

Time to solution determinism on multiple GPUs

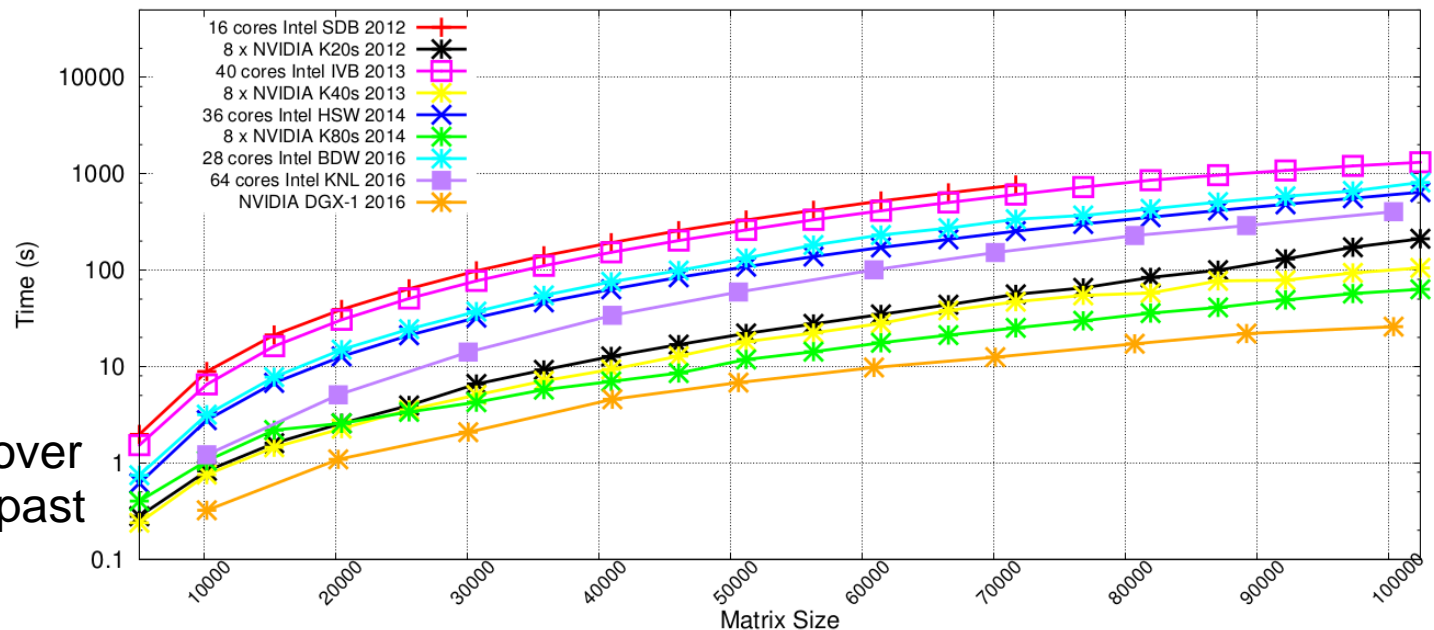


GPUs are good for supervision as well



XL matrix inversion

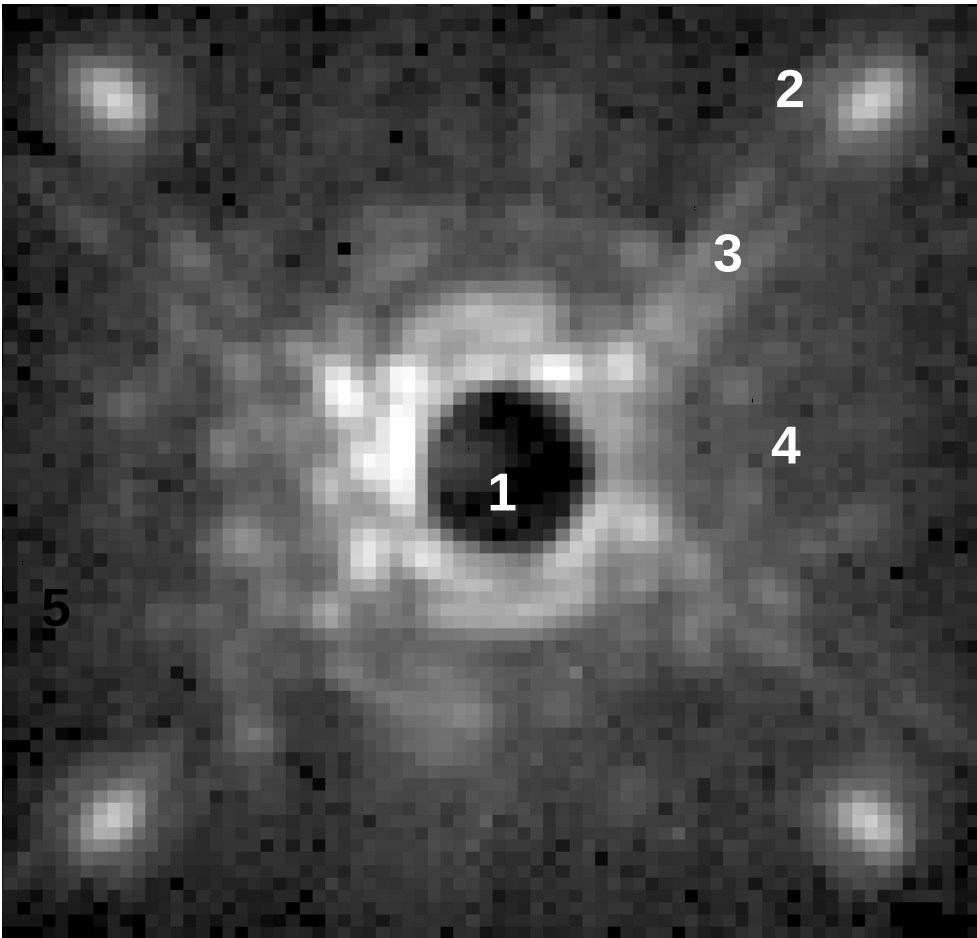
- Solver maps well on G2% architecture
- Consistent speedup over C2% clusters (or the past 10 years)



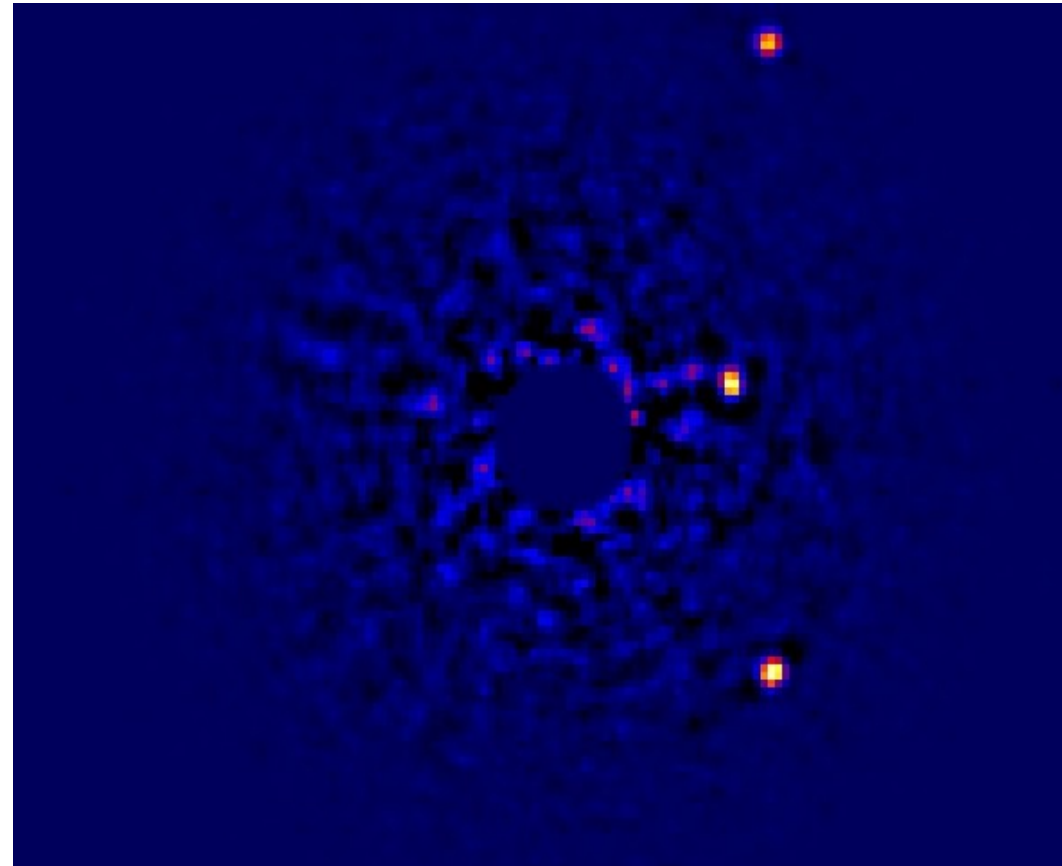
Future opportunities

AI for image processing

RAW image



PROCESSED image

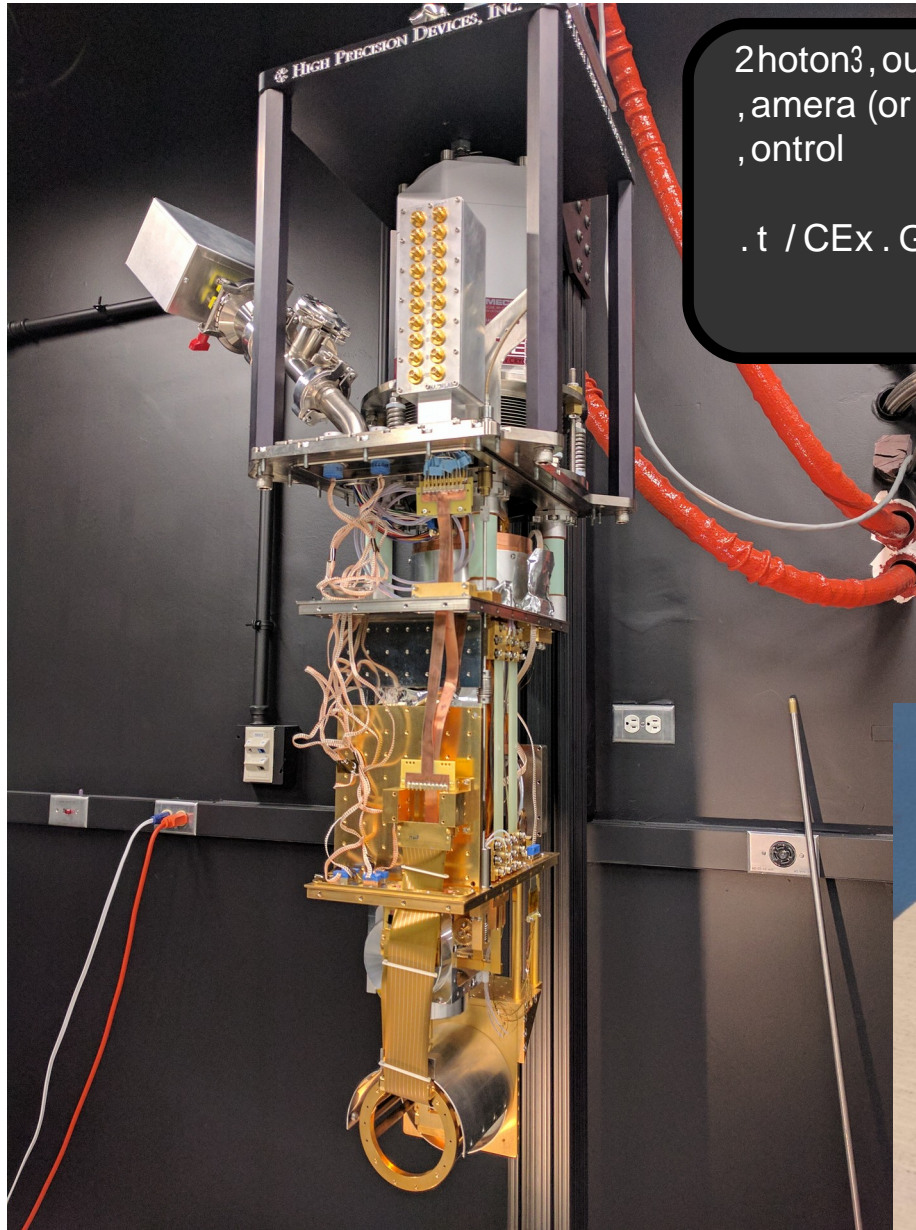


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Cameras are getting faster and better

Photon-counting, wavelength resolving 140x140 pixel camera



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,amera (or +< ; speed spe, +le
,ontrol

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