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 !ivin" bein"s inhabit these worlds #

– Giordano Bruno (1584)

“Two possibilities exist$ Either we are alone in the %niverse or we are not &oth are e'ually terri(yin" #

– Arthur C. Clarke

“I(it is)ust us* seems li+e an aw(ul waste o(spa,e#

– Contact, screenplay by Carl Sagan

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

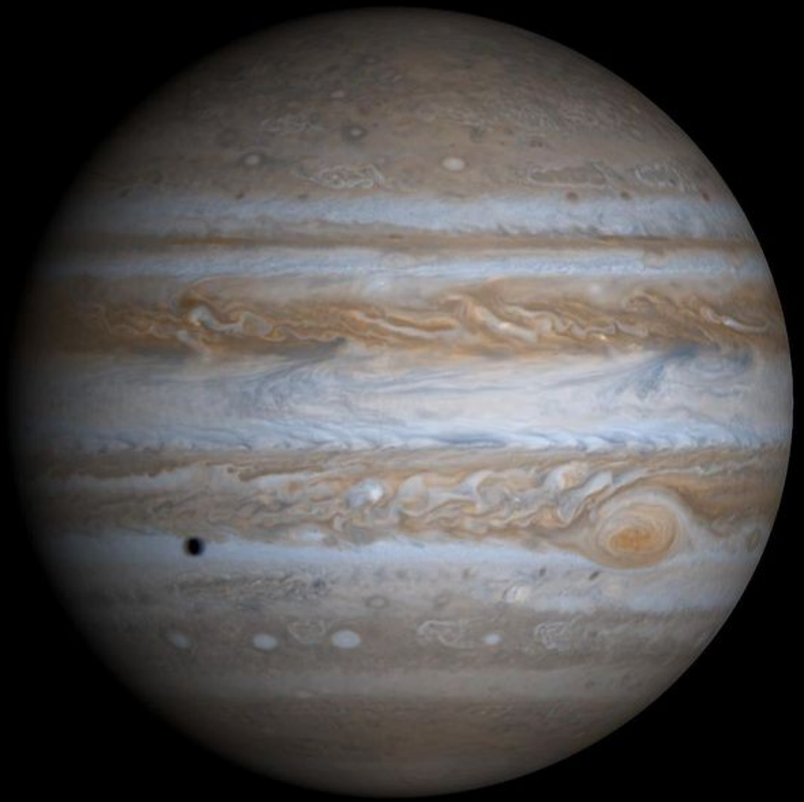
5enera 16 lander* survived 127mn at 897 C* 8: atm

Venus: too close, too hot

Mars: too far, too cold

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

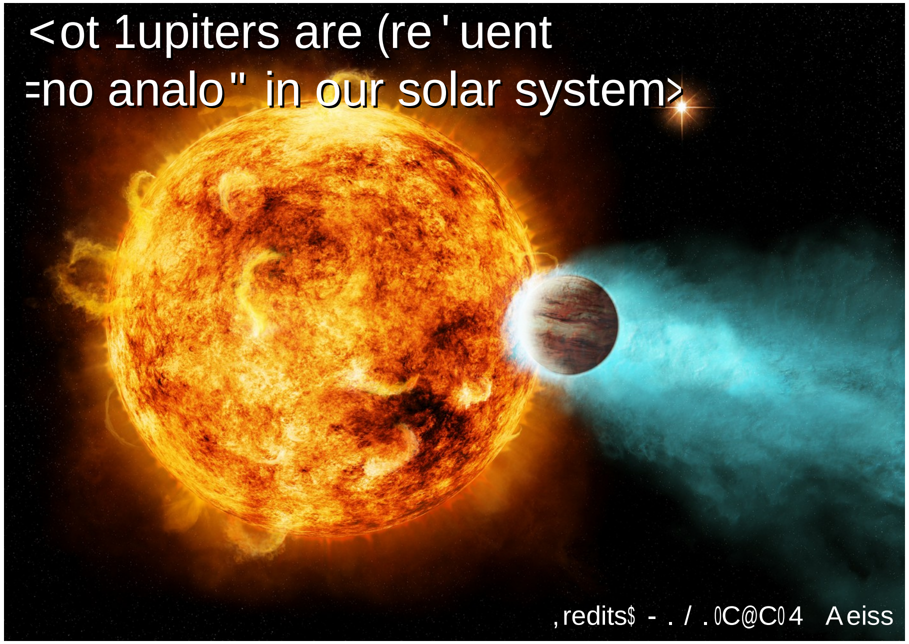
Earth



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

Jupiter: too massive
Gravity holds thick atmosphere
Mostly gas

Key recent findings

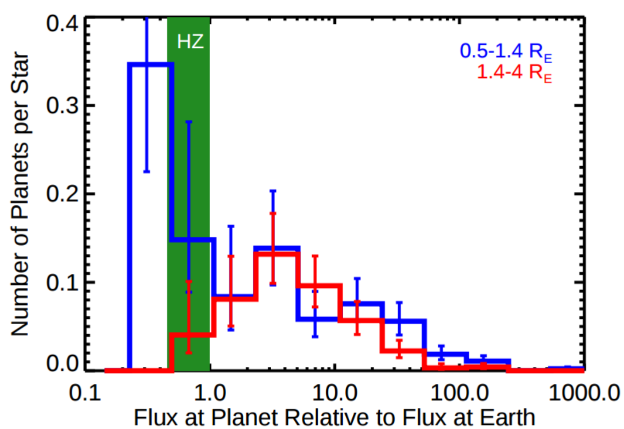


Planetary systems are common

26 systems with ? 9 planets

73planet Trappist31 system* , redit$ - . / . 312 !

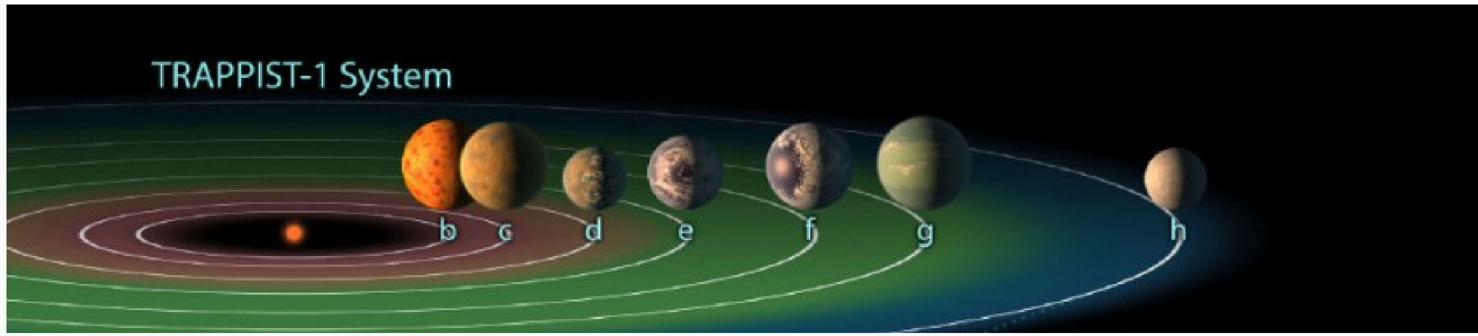
Earth-size rocky planets are abundant



Dressing & Charbonneau 2013

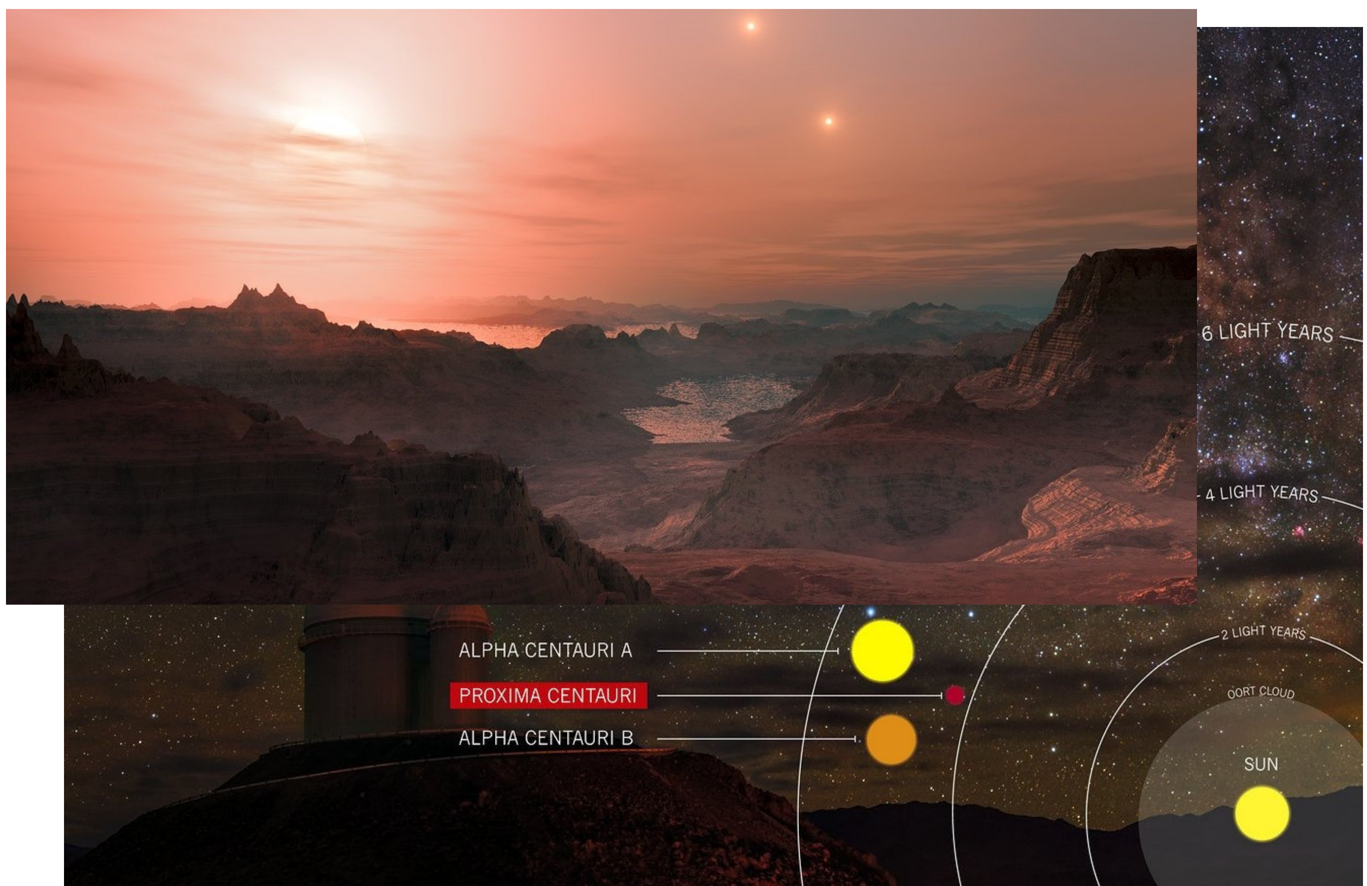
Spectacular recent discoveries around nearby stars

Trappist31 system
7 planets
C6 in hab ;one
li+ely ro , +y
80 ly away



2roxima Cen b
planet
2ossibly habitable

Closest star to our
solar system =only
8 2 li"ht 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)...

~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

~300 billion stars in our galaxy

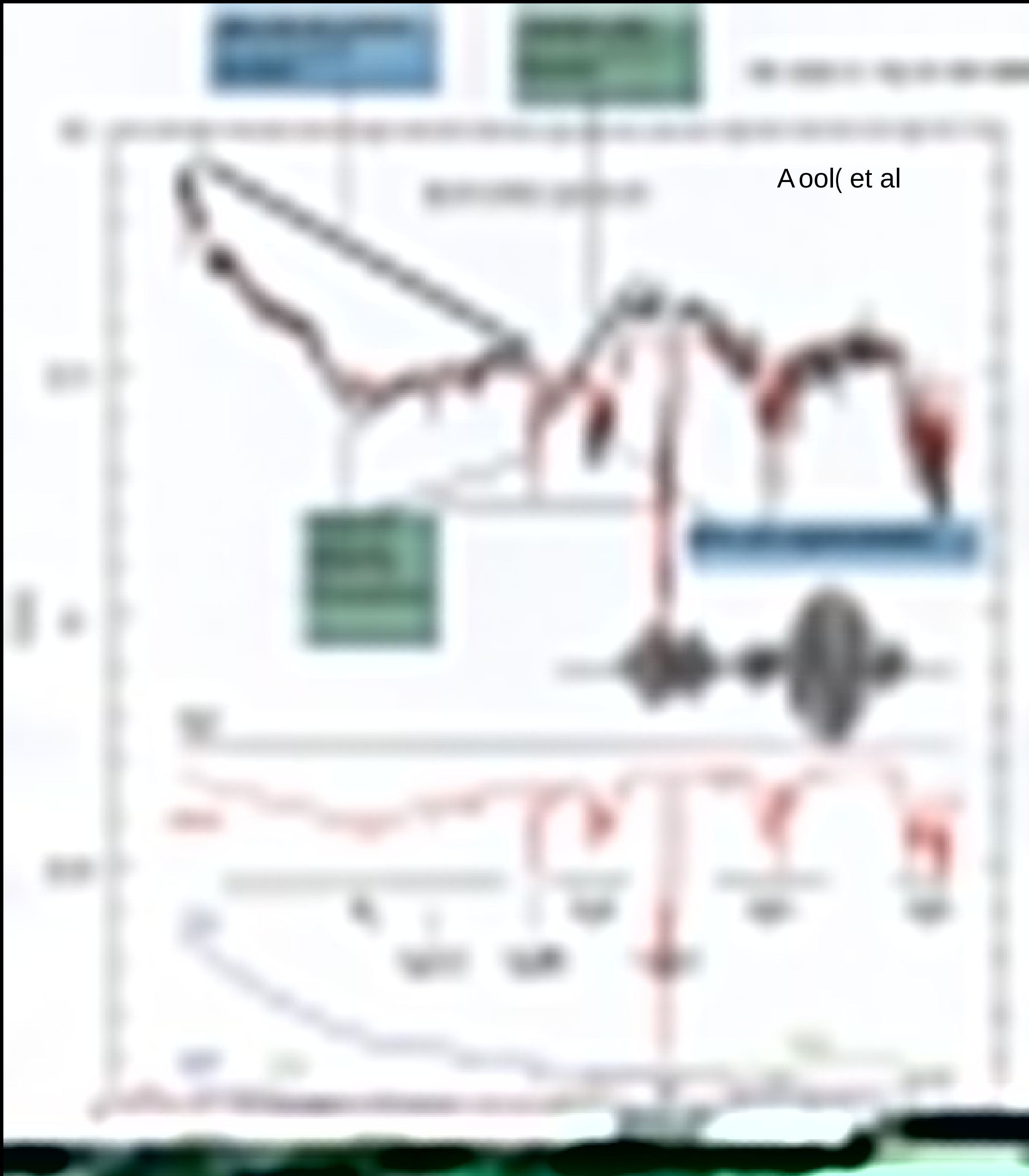
~30 billion habitable planets ?

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


200 billion galaxies
in the observable
universe

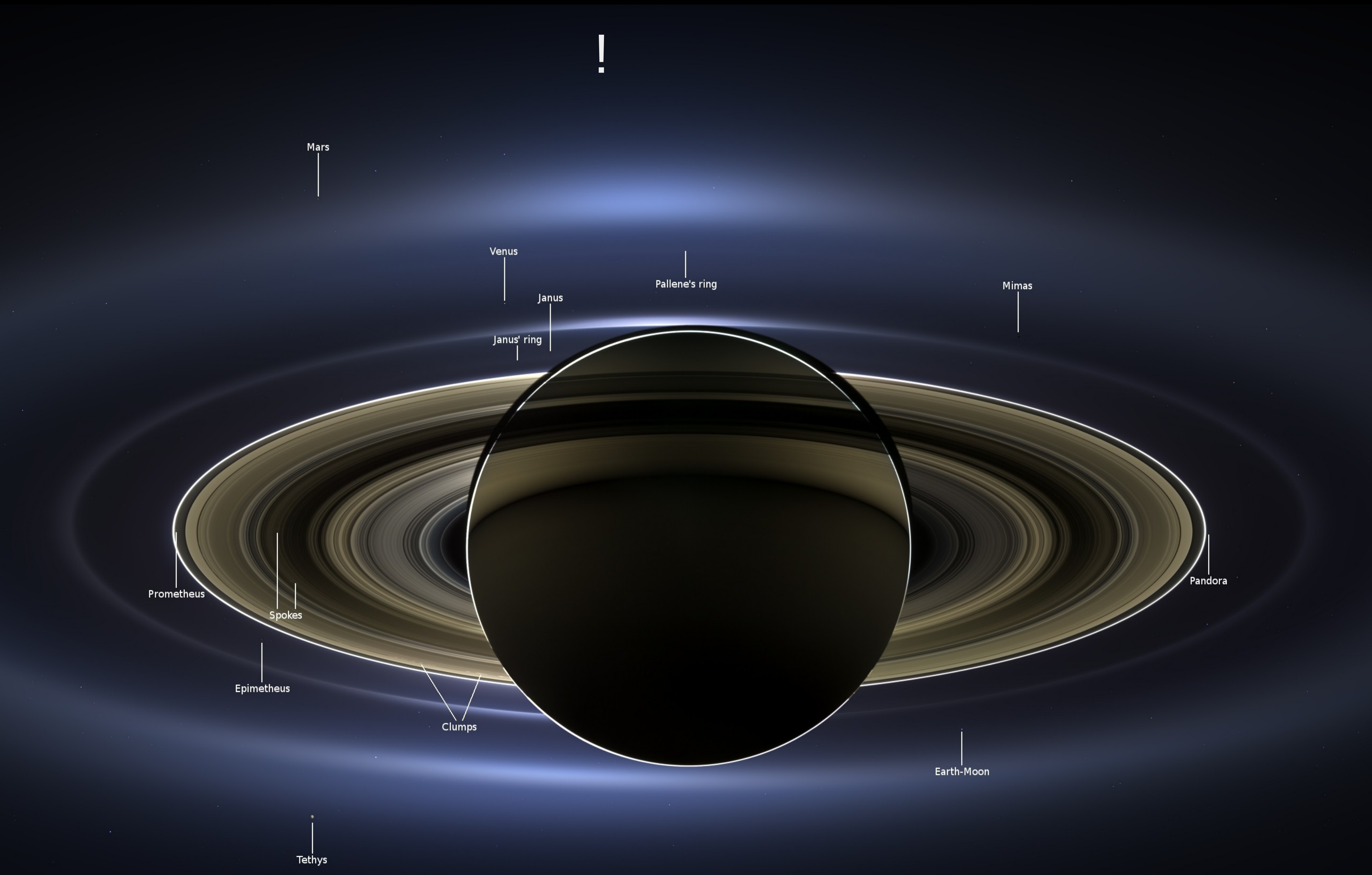
Why imaging Exoplanets ?



Ima"in" allows spe,tros,opy to measure atmosphere ,omposition

/pe,trum o(Earth =ta+en by loo+in" at Earthshine> shows eviden,e (or li(e and plants

!



This ima"e was ta+en by the Cassini spa,e,ra(t when it was in /aturn s shadow E loo+in" ba,+ at the inner solar system Can you spot Earth F


Saturn
Earth

Towards Habitable Planets Imaging

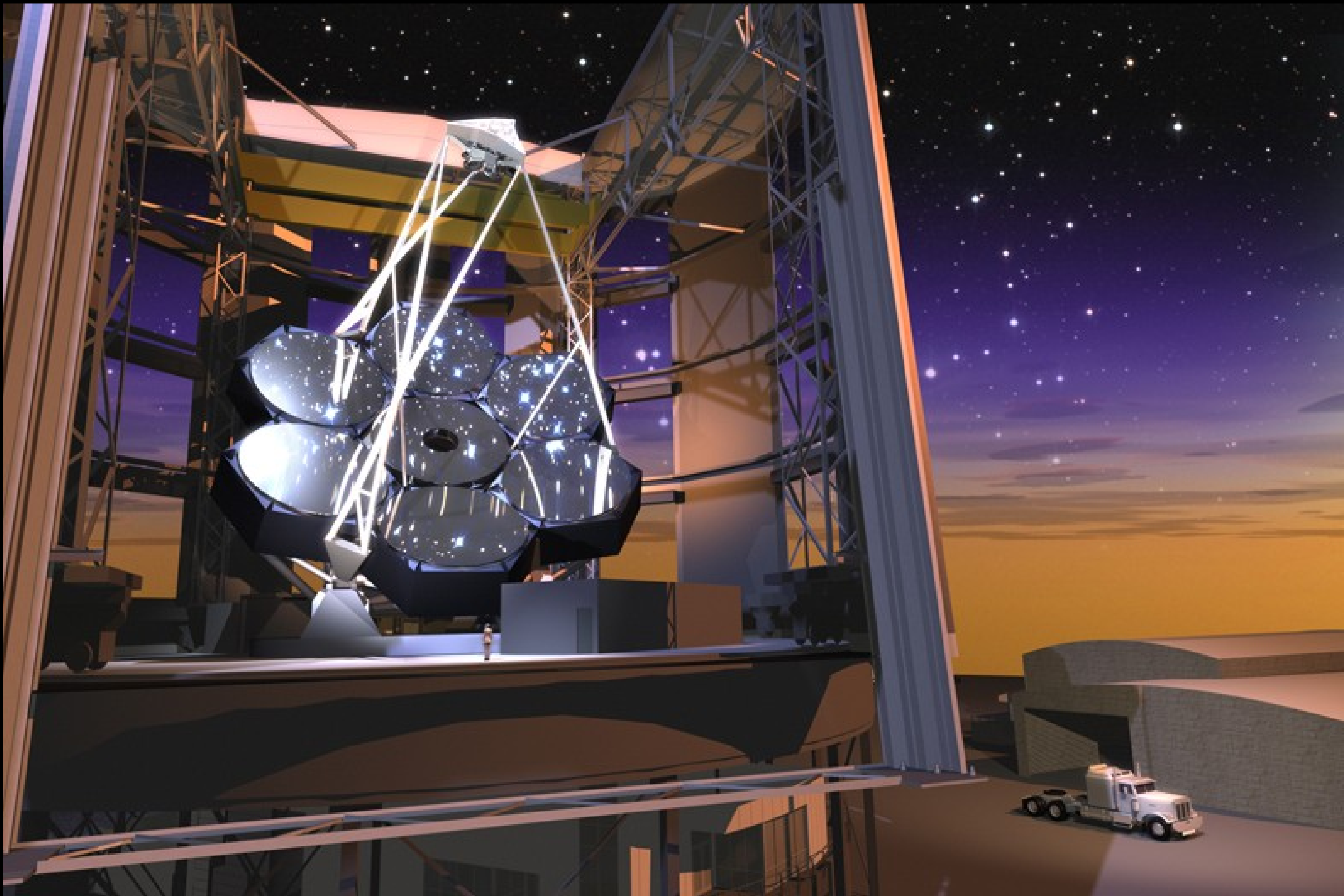
%p,omin" lar"e teles,opes will* (or the (irst time* have the sensitivity to ima"e and study habitable planets around nearby stars

Gne si"ni(i,ant ,hallen"e remains$ Earth's atmosphere

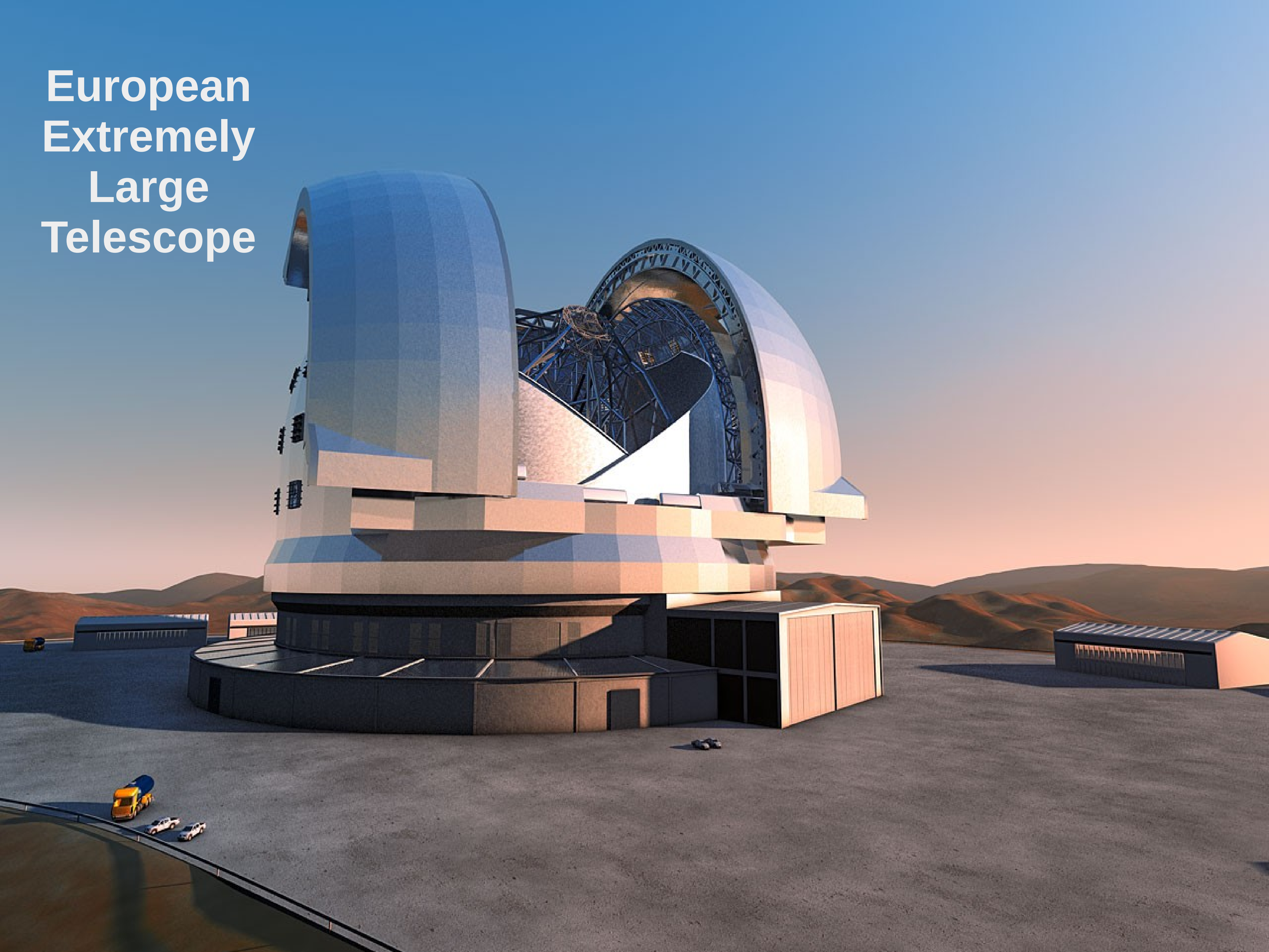
5iew (rom 2roxima Centauri b planet* the ,losest exoplanet (rom Earth* 8 2 li"ht year away =artist's "uess>

Thirty Meter Telescope

Giant Magellan Telescope



European Extremely Large Telescope



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<u>Hatem Ltaief | Jalal /u++ari</u>

K.%/T =/audi .rabia>

%',

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<u>. rnaud /evin*</u>

<u>1ulien &ernard*</u>

<u>**Damien Gradatour**</u>

Gbservatoire de 2aris (Green Flash

=Hran,e>

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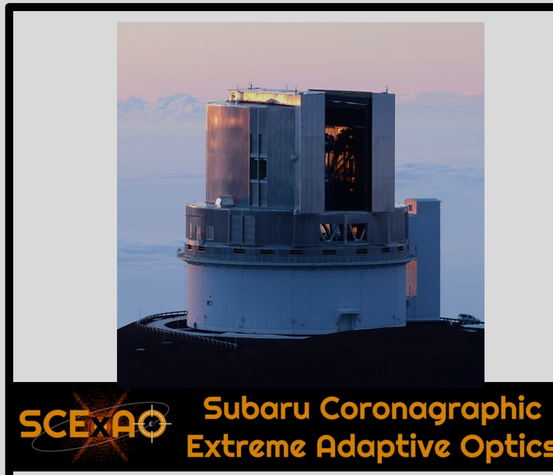

<u>**Olivier Guyon*** 1ulien !o;i* -our /+a(</u>

/ubaru Teles,ope (

/CEx.G

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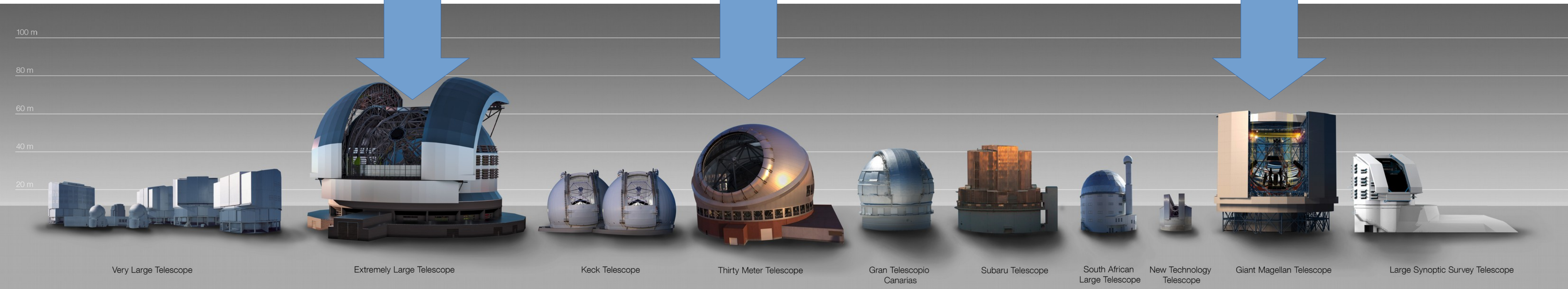


Adaptive Optics (AO)

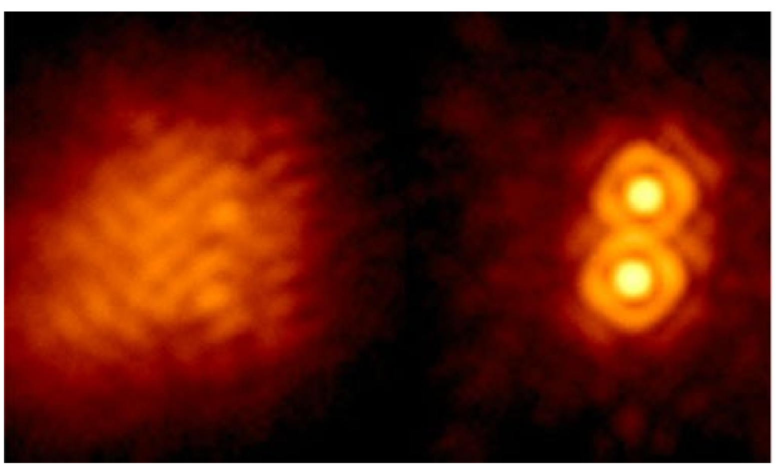
Atmosphere Turbulence$ Earth s atmosphere introdu,es stron" and (ast opti,al aberrations

. berrations must be ,ontinuously **measured** and **corrected** to provide sharp ima"es

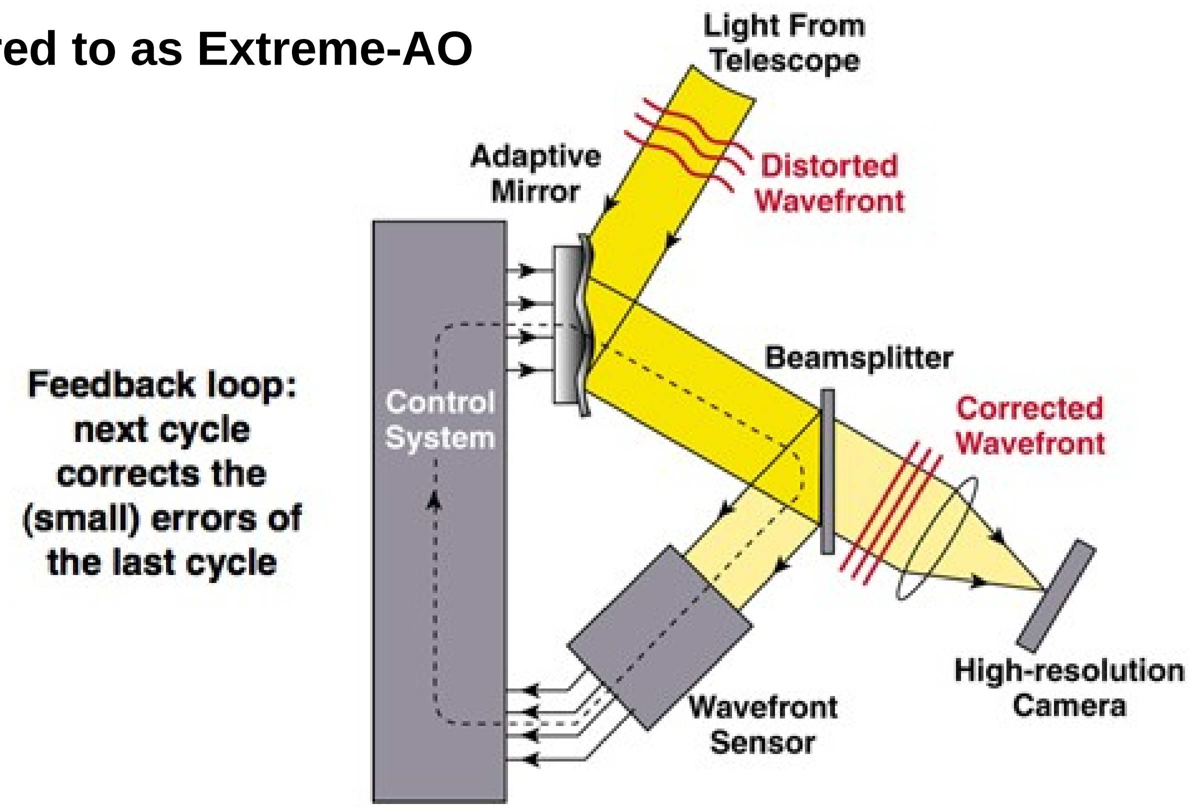
Ima"in" exoplanets is parti,ularly demandin"* as the planet is mu,h (ainter that the star it orbits$ very little room (or error L

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

. G GHH . G G -



Palomar obs / NASA JPL

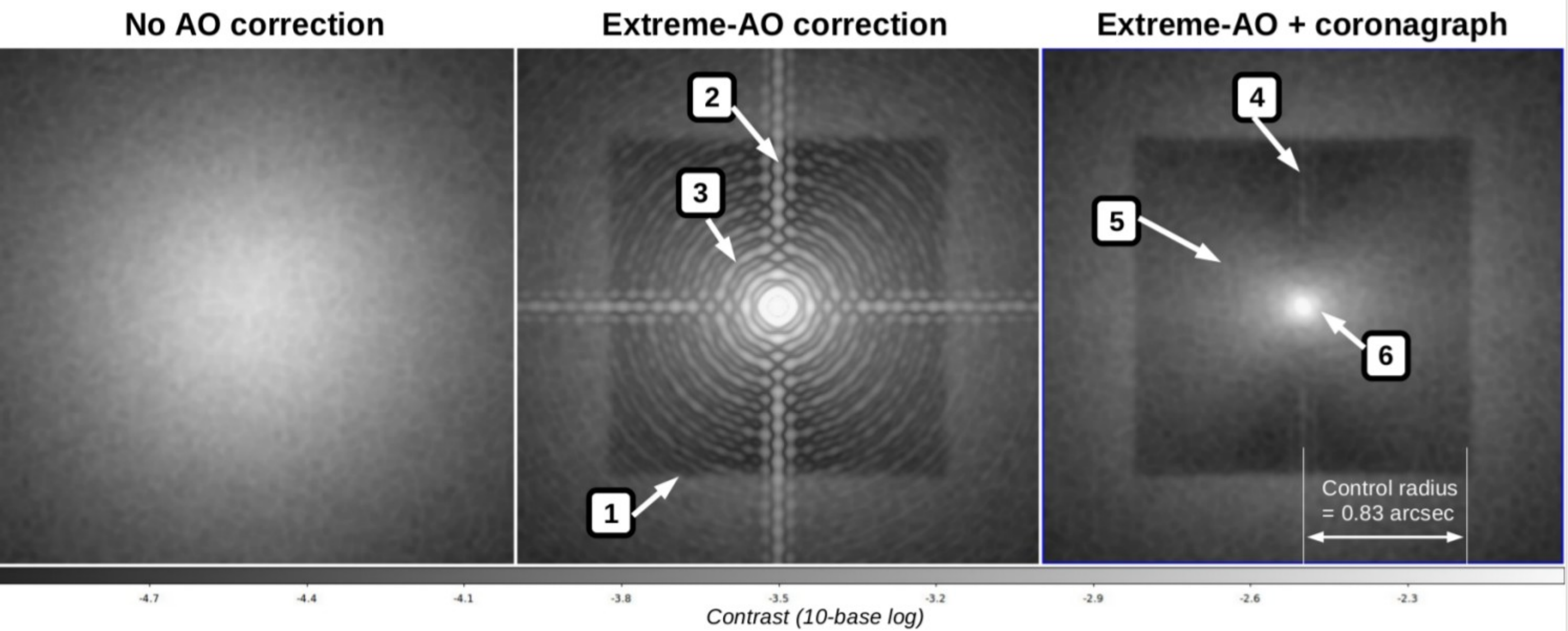


Imaging exoplanets requires “Extreme-AO”

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)

/ imulated ima"es below show how Extreme3 . G and Corona"raphy deliver hi"h ,ontrast ima"e o(a star

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



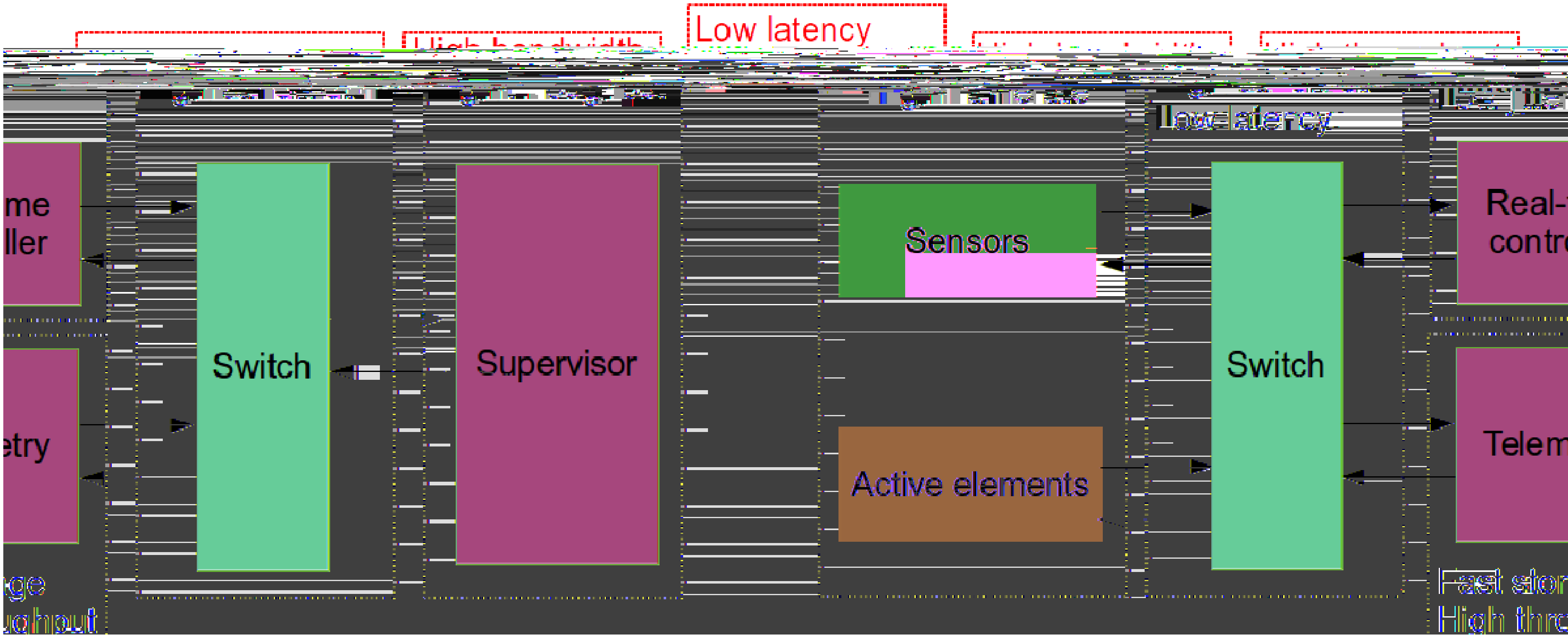
ExAO is a formidable HPC challenge

Cameras with 100*000N pixels ea,h ta+e ima"es o(starli"ht every C600 us =6 +<;> to drive de(ormable mirror=s> with 10*000s a,tuators

Aithin 600 us* we must$

- Bead the ima"es* move them (rom ,ameras to ,omputer hardware memory
- 2ro,ess the ima"es to re,onstru,t the opti,al aberrations experien,ed by li"ht throu"h Earth's atmosphere
- Compute the de(ormable mirror=s> shape=s> that will ,an,el the aberrations =10*000s o(de"rees o((reedom>
- . pply the shapes and "ive enou"h time (or the mirror to move

AO real-time controller



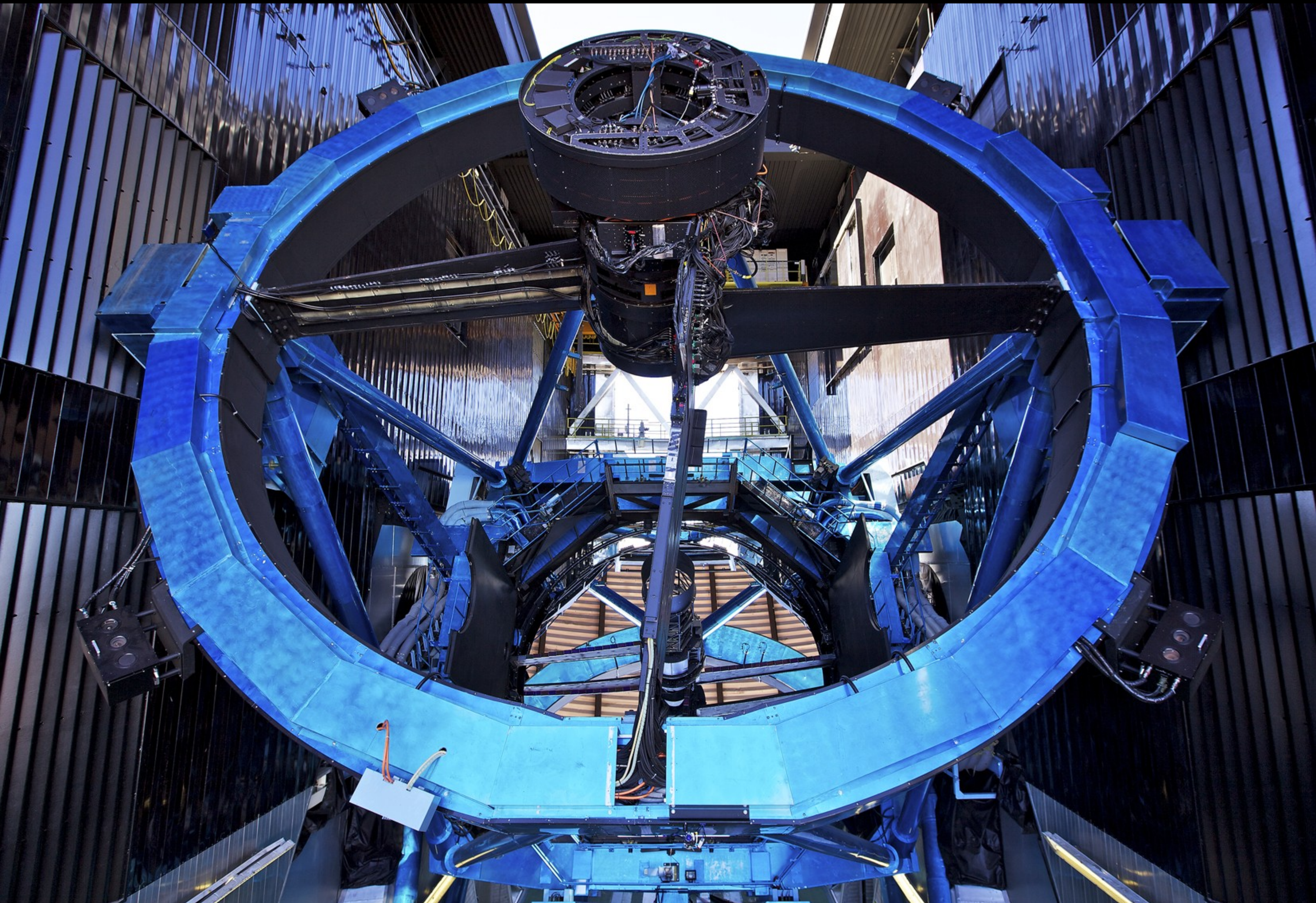
<2C (a,ility with 6 main subsystems

- <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

/ubaru Teles,ope =8 2m diameter> has an exoplanet3ima"in" instrument =/CEx.G>
The instrument team is developin" advan,ed Extreme3.G te,hni'ues

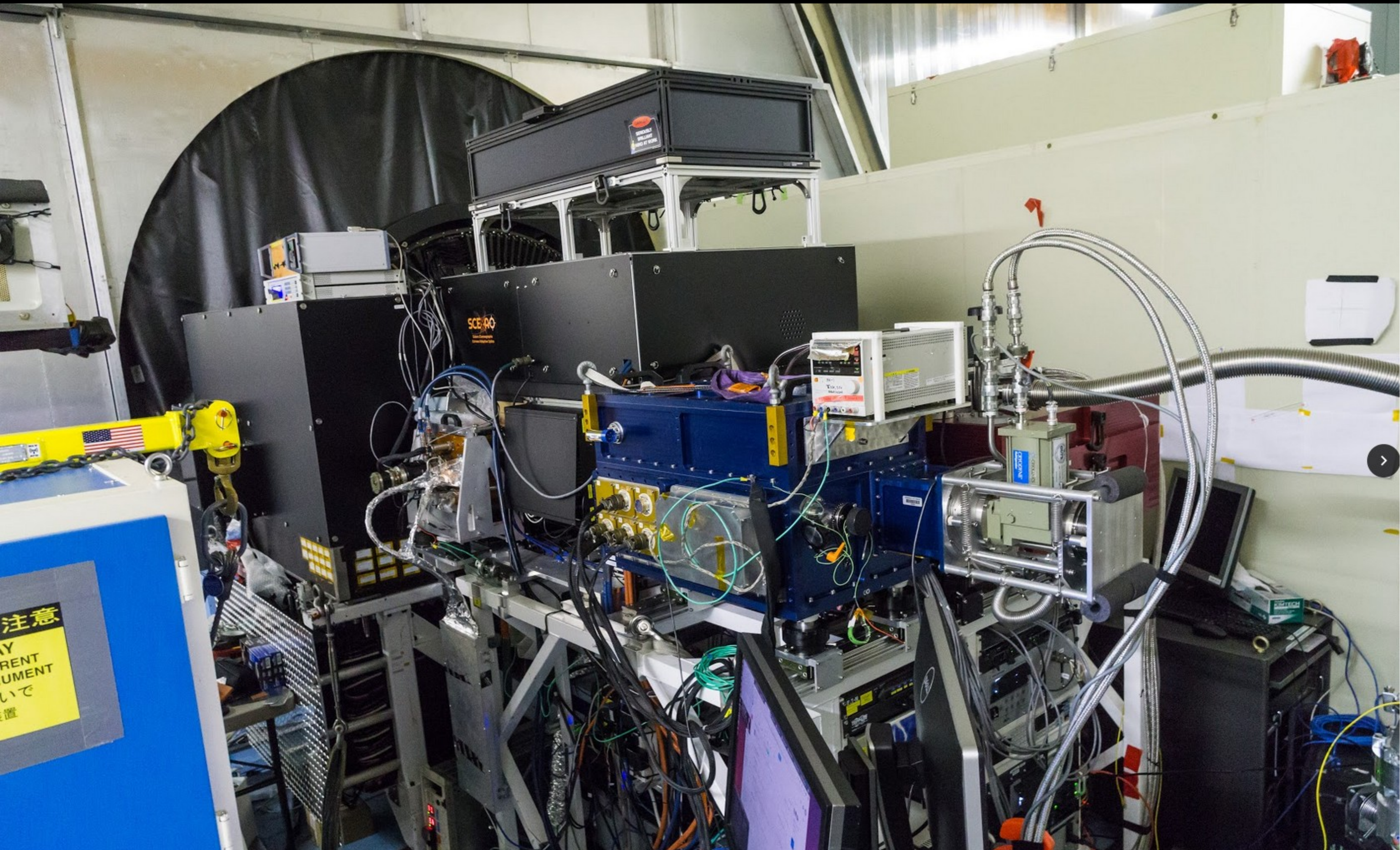
Our test facility...

/ubaru Teles,ope* 4auna Kea* <awaii
8200m altitude



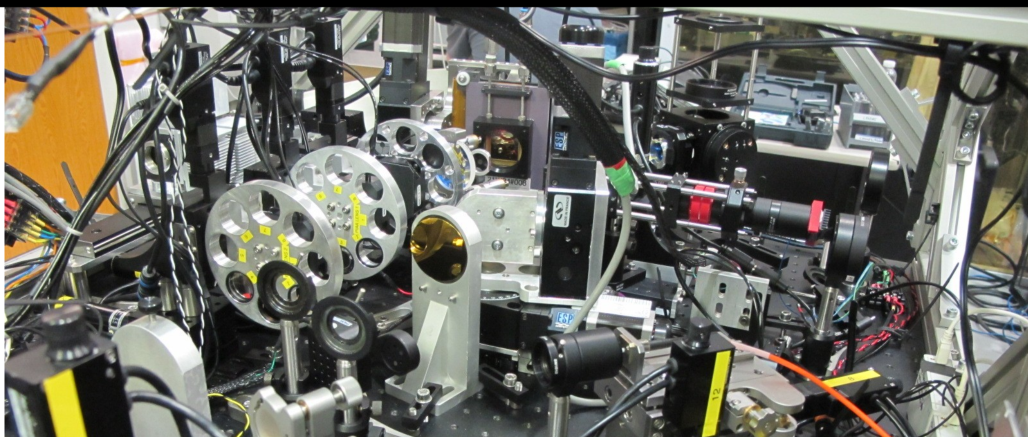
/ubaru Teles,ope =view (rom inside dome> 2hoto"raph by Enri,o /a,hetti

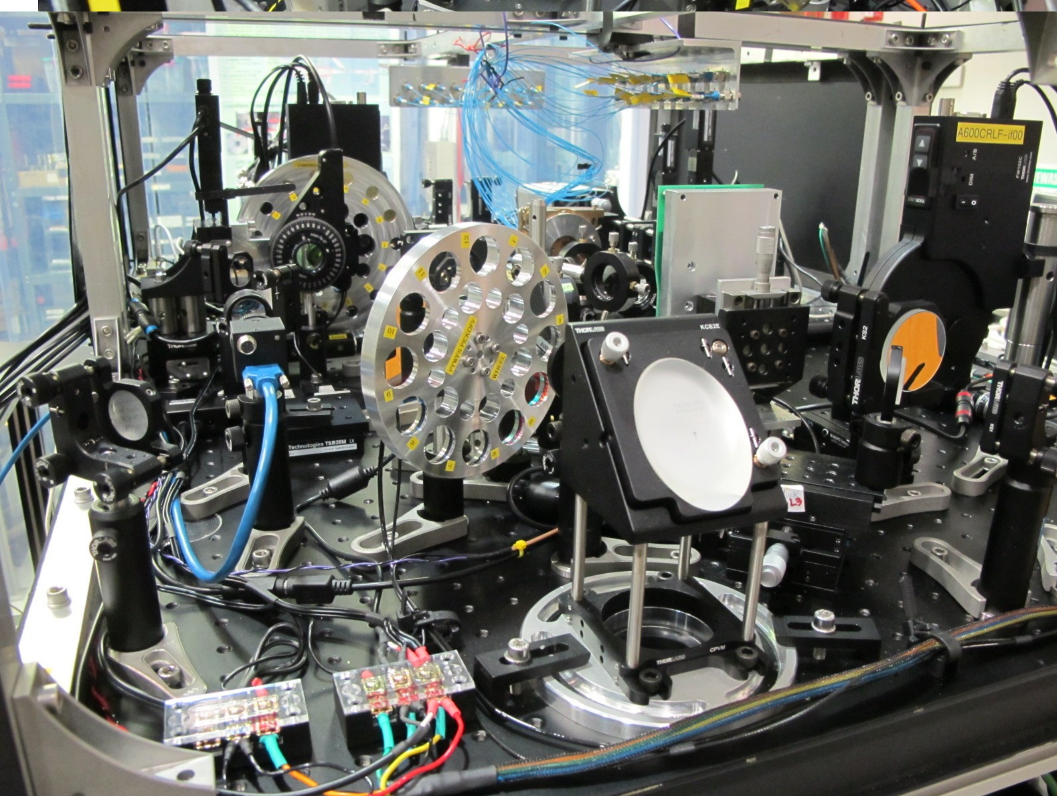
Subaru Coronagraphic Extreme Adaptive Optics

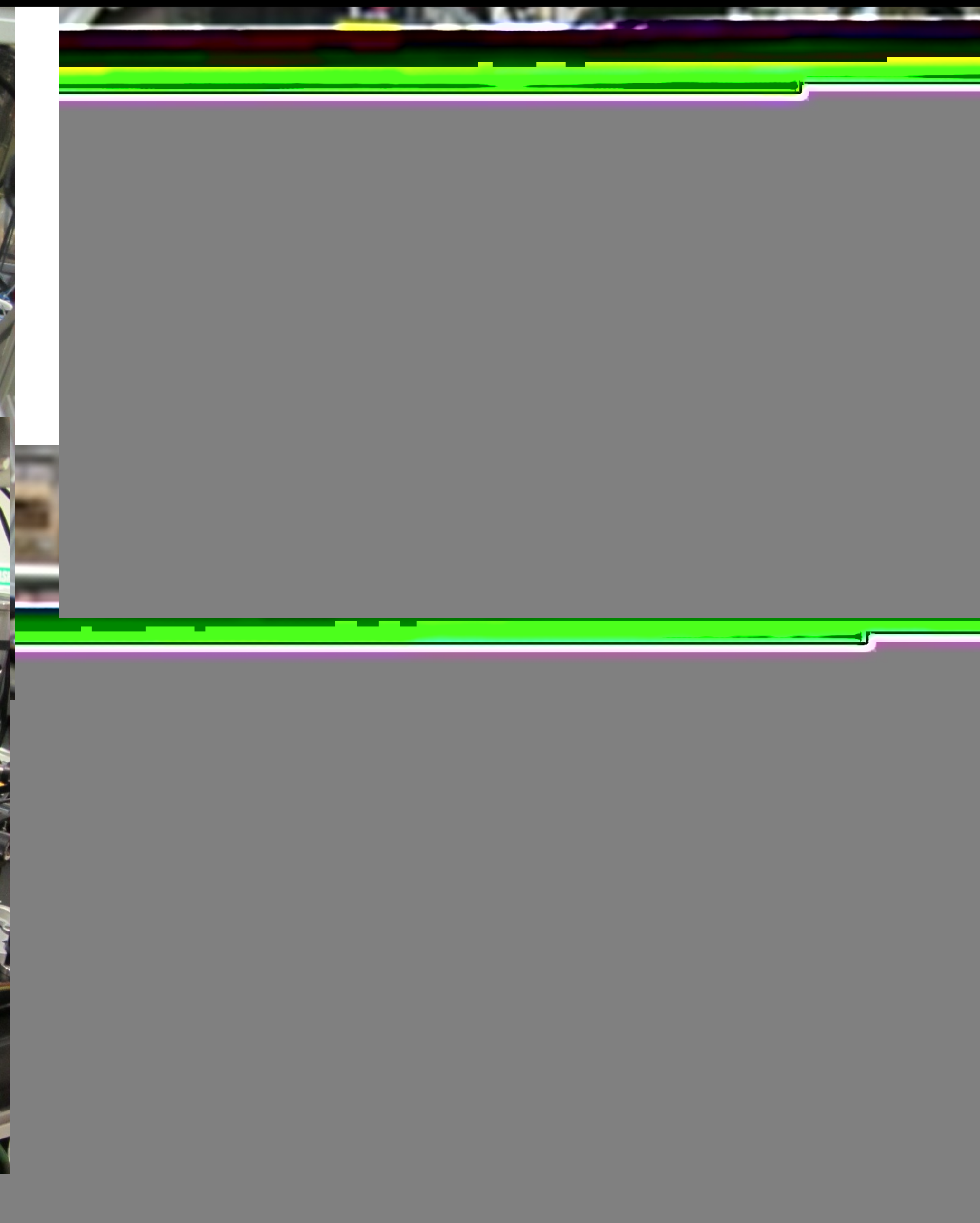


SCExAO

Subaru Coronagraphic Extreme Adaptive Optics

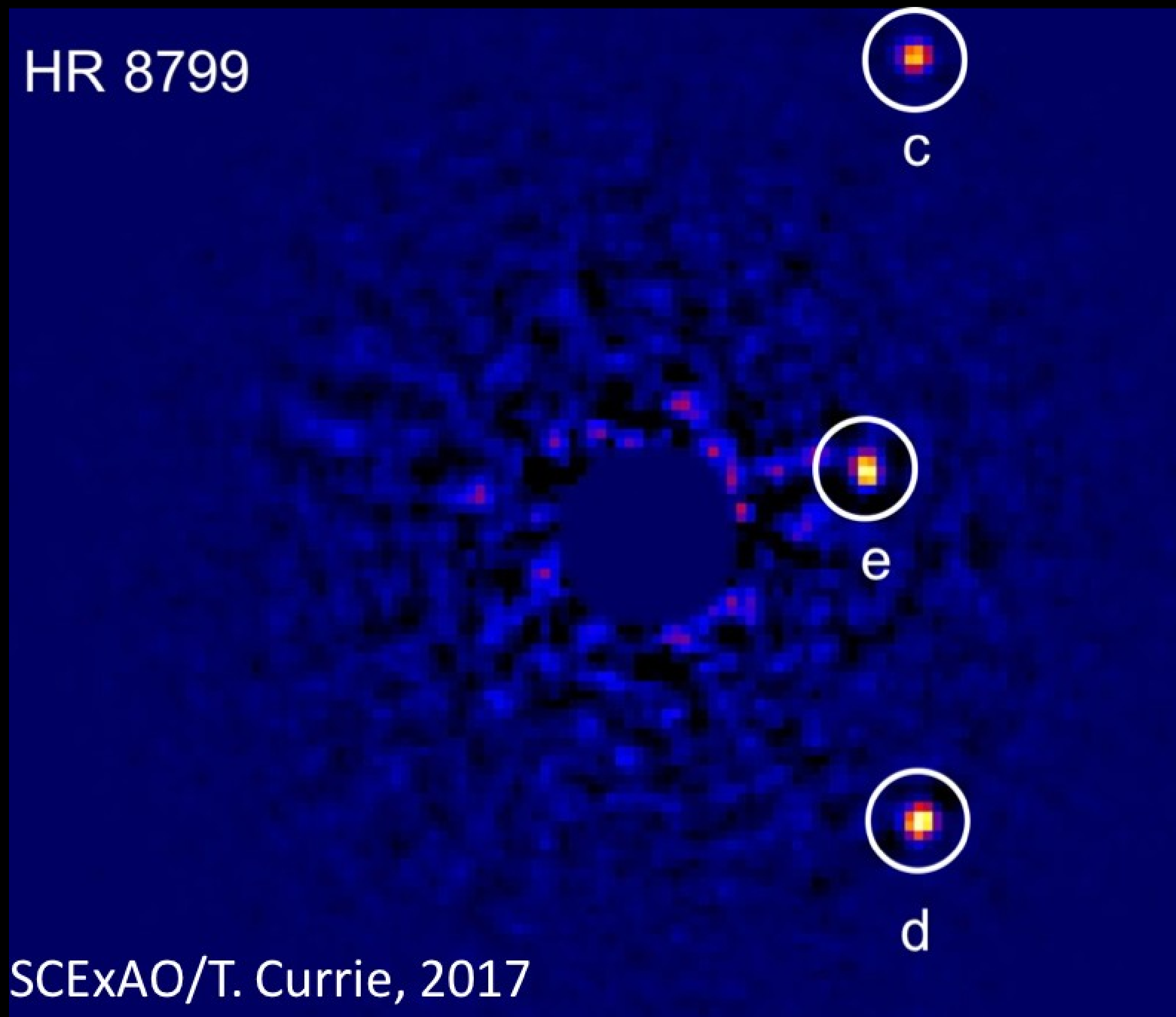






HR8799

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

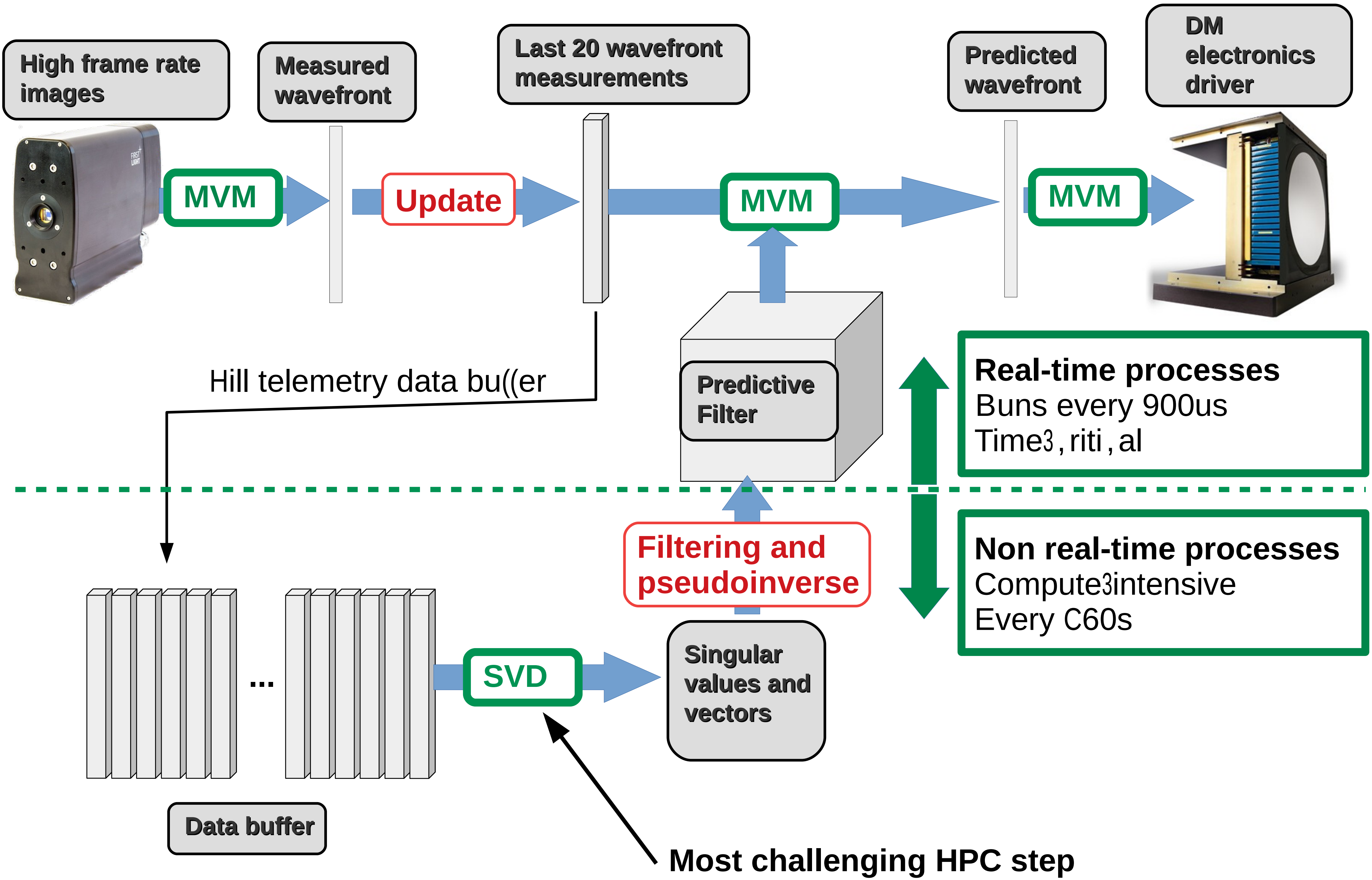


Predictive Control

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

-
-
- **<u>Predictive control</u>** optimally uses the last (ew measurements to predi,t the aberrations at the exa,t time o(,orre,tion
-
-
- **CHALLENGE:** The temporal relationships between past and (uture aberrations are not +nown in advan,e and ,han"e ,ontinuously =depends on wind speeds and many other thin"s>
- M Ae must ,ontinuously learn0update them* and apply them in real3 time at 236 +< ;

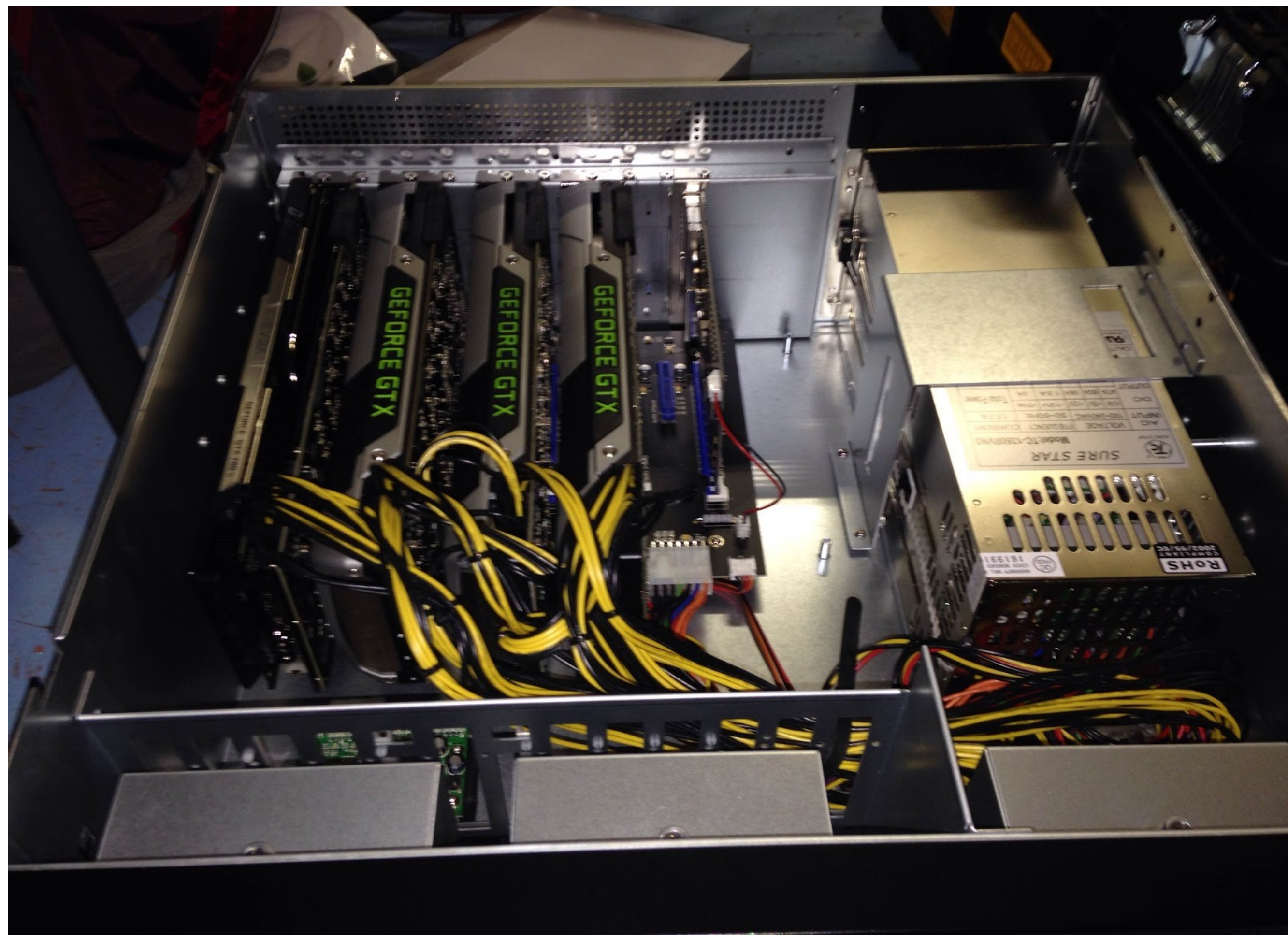
Algorithm: mixed CPU / GPU implementation



Computing Hardware

$," #   /0)111
2345 %.

One of two GPU chassis



Re-thinking adaptive optics

The ma,hine learnin" approa,h to predi,tive ,ontrol is part o(a wider new approa,h to adaptive opti,s

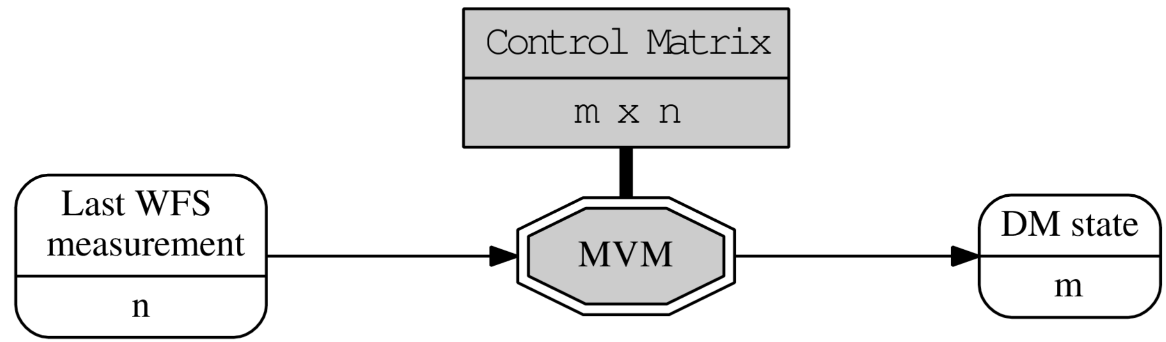
Conventional adaptive optics (pre-2018):
Calibrate =usually in lab>* and T<E- apply pre3,omputed ,ontrol law

Machine learning based AO:
Control law is ,ontinuously optimi;ed based on analysis o(real3time measurements
In,ludes predi,tive ,ontrol and sensor (usion

Predictive Control and Sensor Fusion

, # !

A e **measure** response



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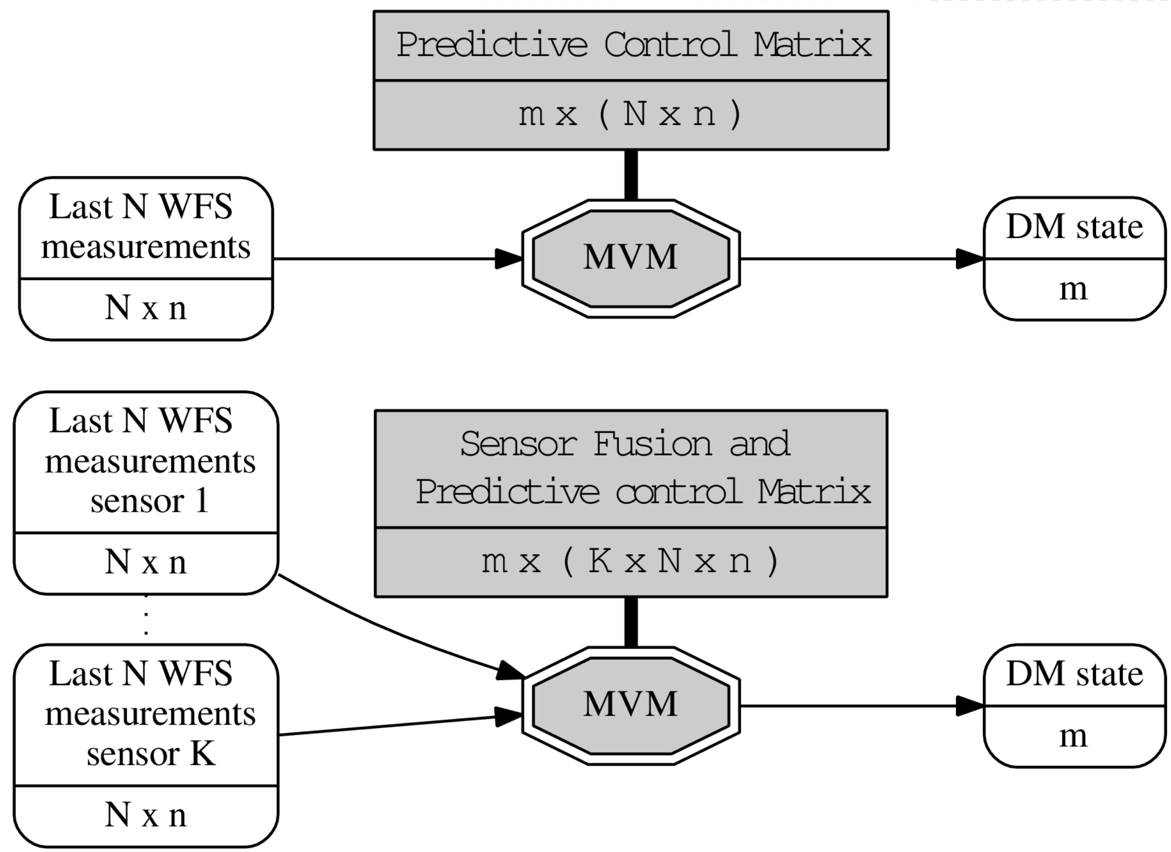
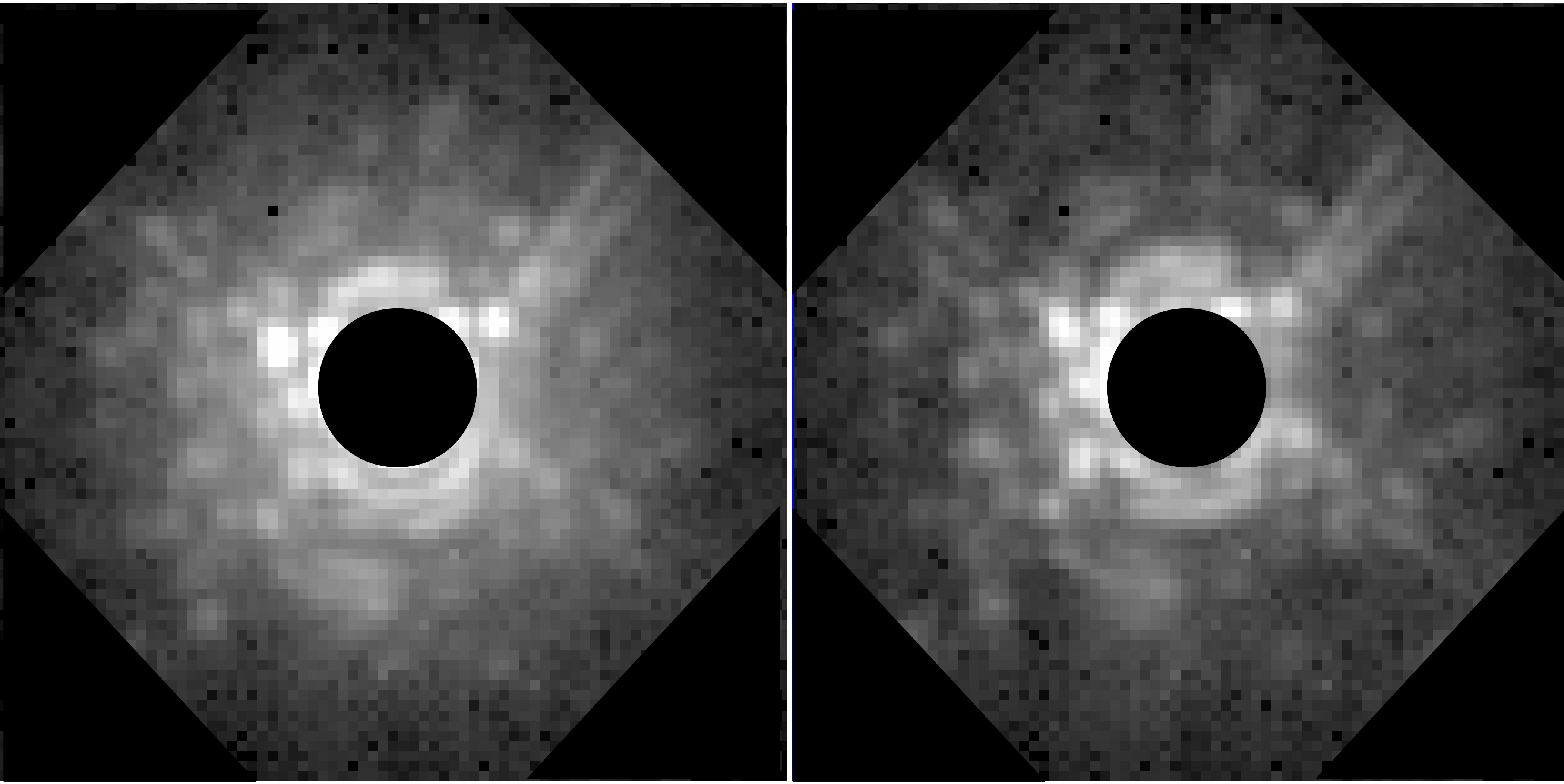
A e **must** ,ontinuously derive ,ontrol al"orithm (rom realtime telemetry



First on-sky results (2 kHz, 50 sec update) → 2.5x raw contrast improvement



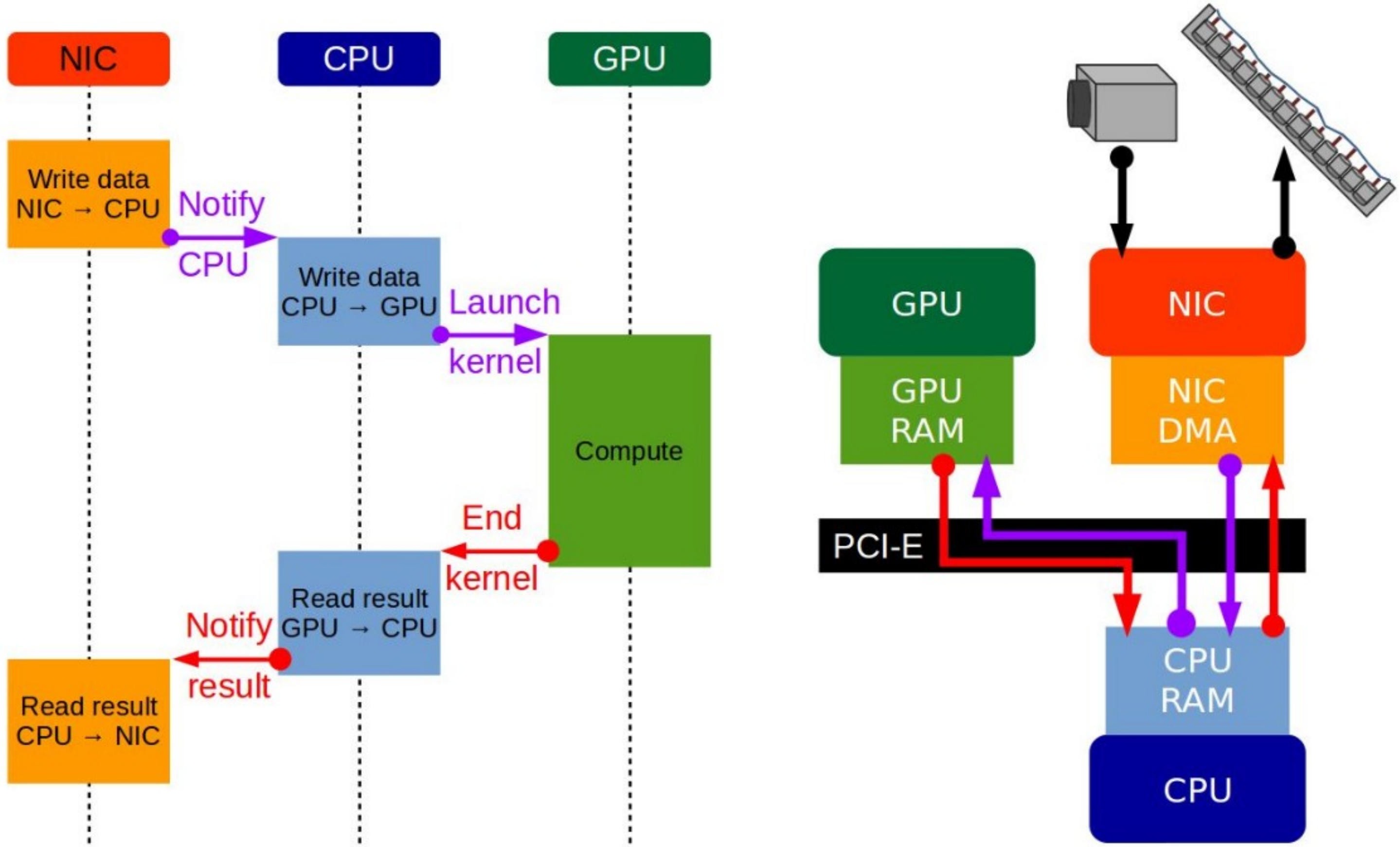
** &) 6147+ 8

. vera"e o(98 ,onse,utives 0 9s ima"es =20 se, exposure>* 6 mn apart
/ ame star* same exposure time* same intensity s,ale

Ongoing research

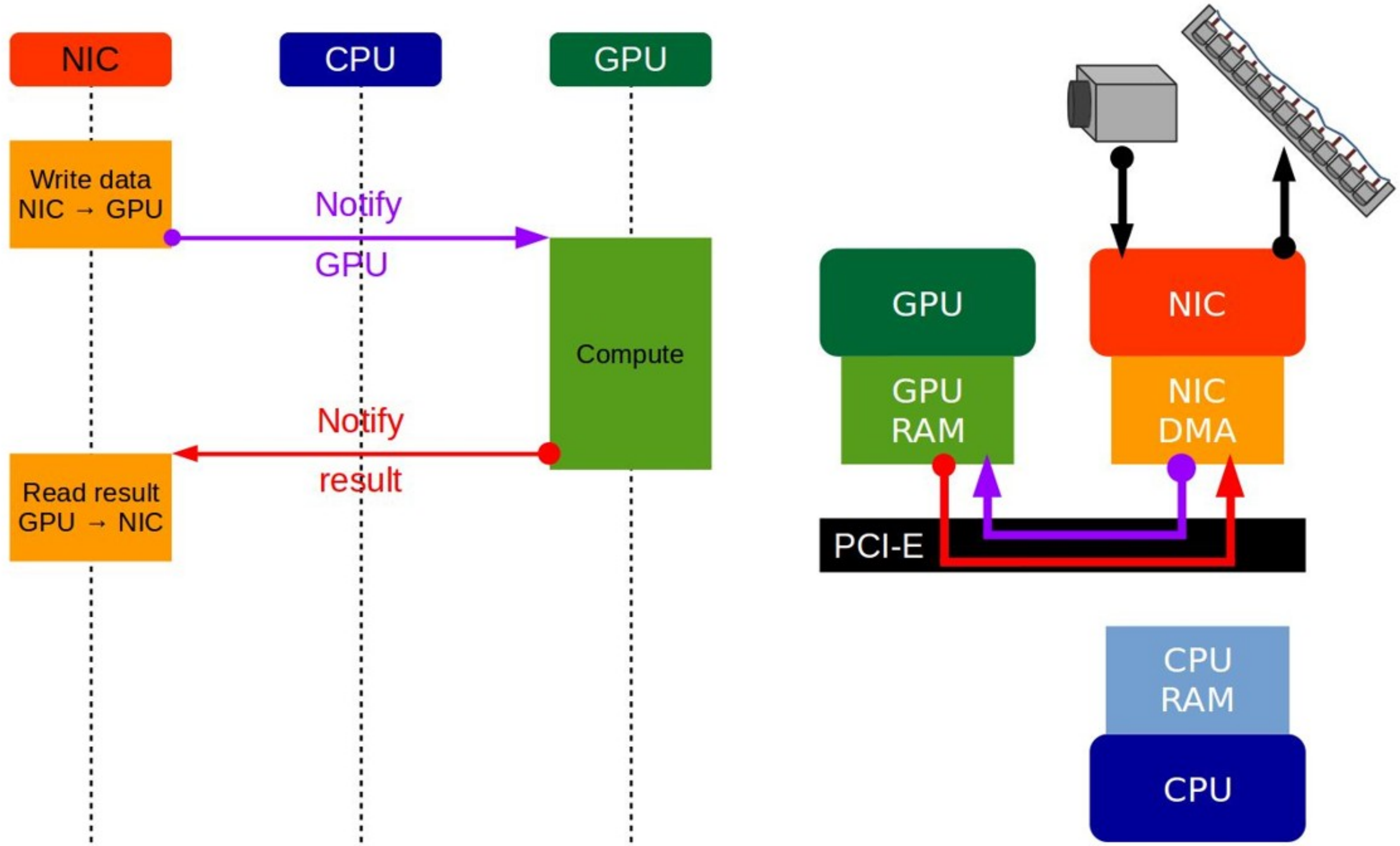
Low latency data acquisition and processing

/ tandard a , ' uisition pipeline

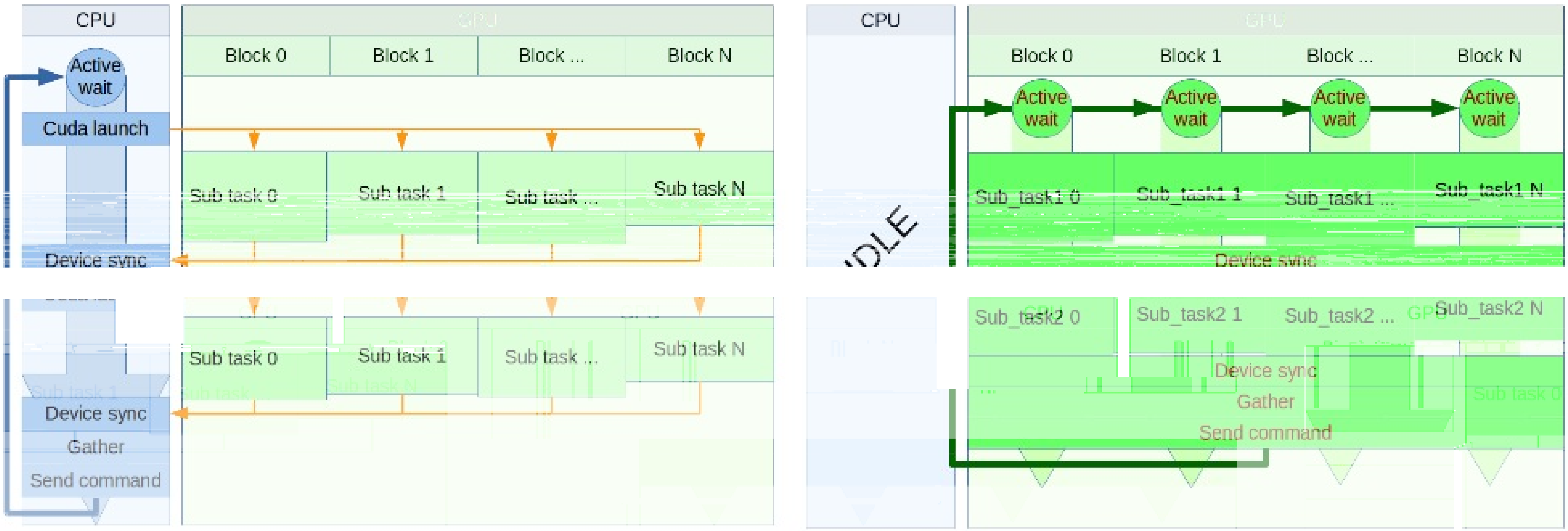


Low latency data acquisition and processing

. , ' uisition pipeline with G2%dire , t



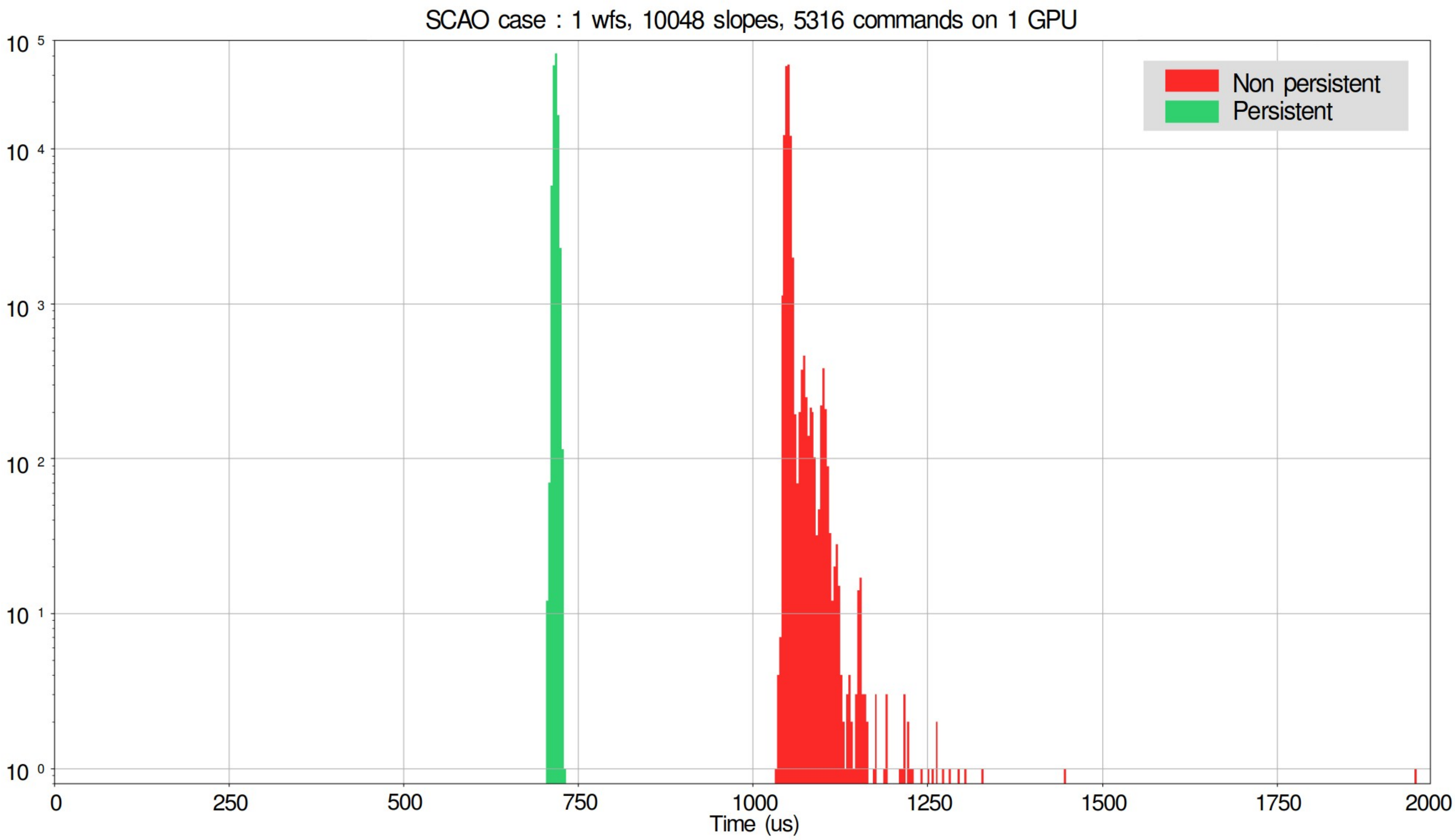
Persistent kernels



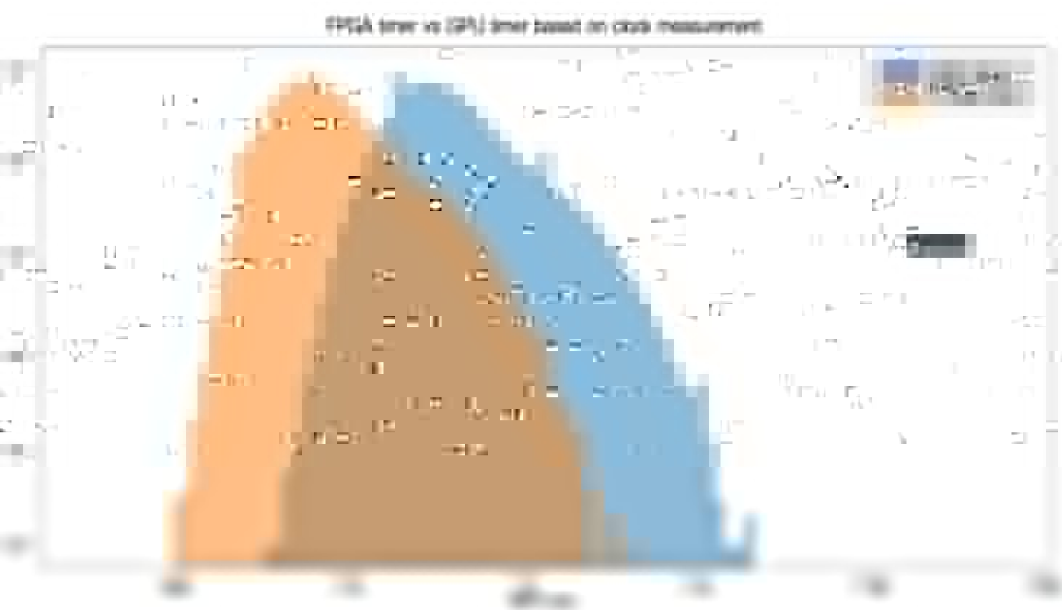
Con,ept o(a never endin" G2% +ernel

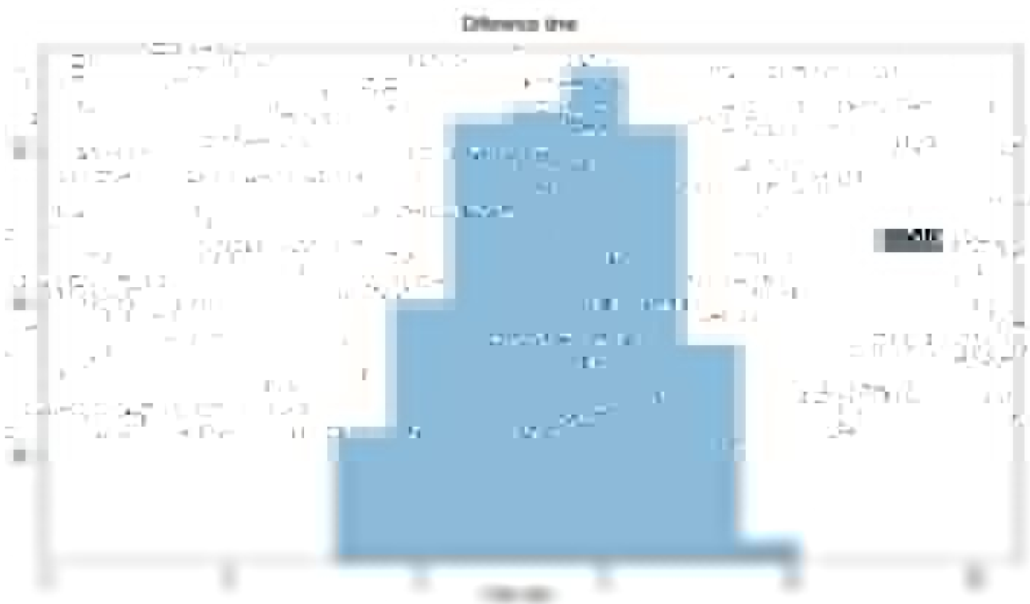
- Bemove C2%3G2% intera,tions
/yn,hroni;ation is done on devi,e

Persistent kernels

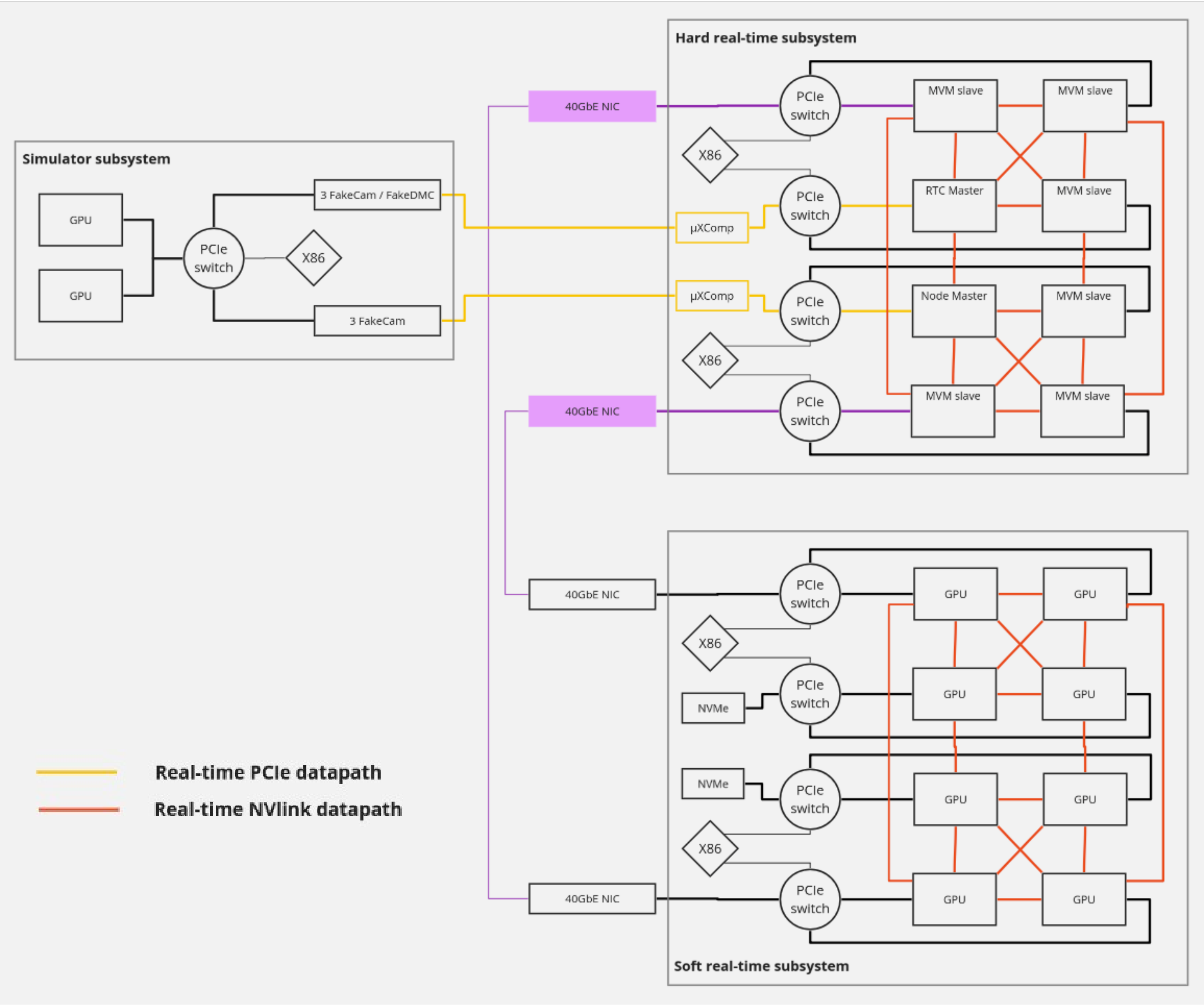


FPGA + GPU pipeline





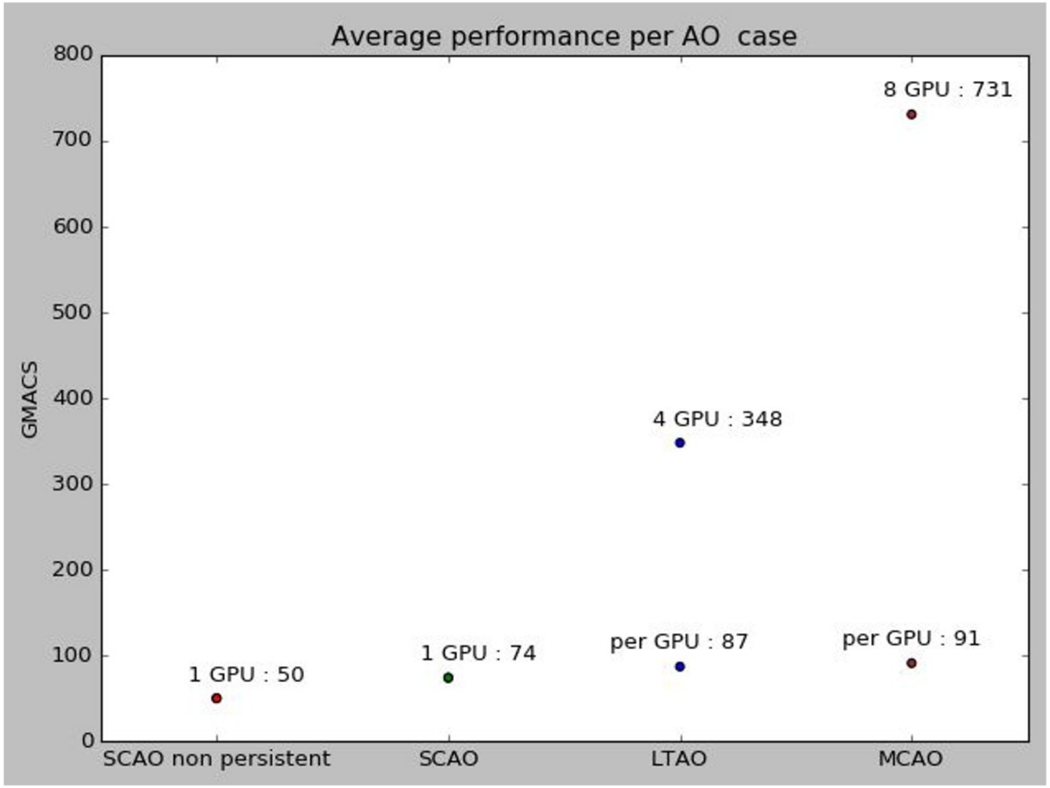
ELT RTC prototype based on DGX-1



ELT RTC prototype based on DGX-1

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

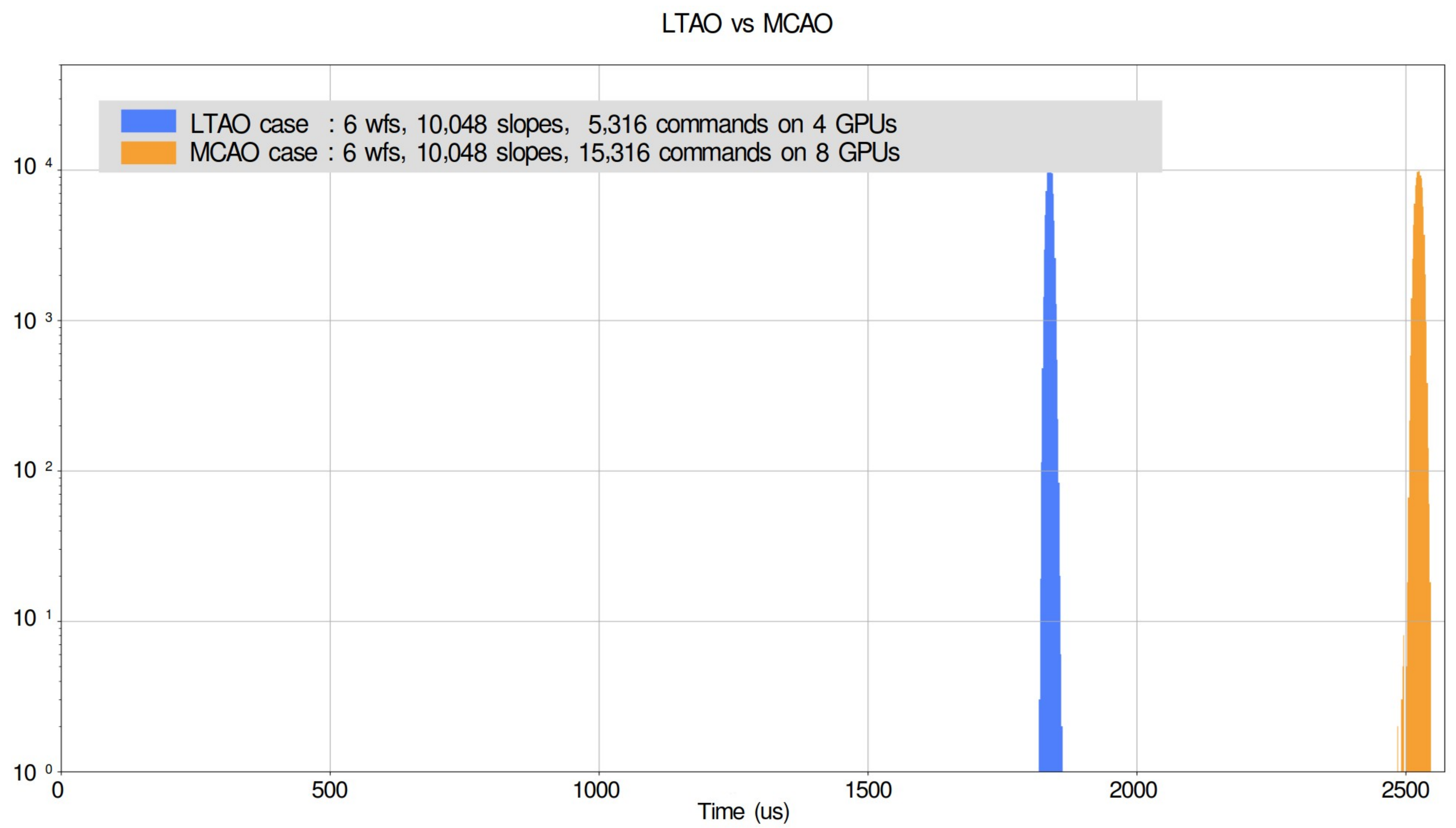
name	N GPU	global GMAC/s	GMAC/s per GPU	scale per GPU
SCAO	1	74	74	1
LTAO	4	348	87	x1.5
MCAO	8	731	91	x2.25



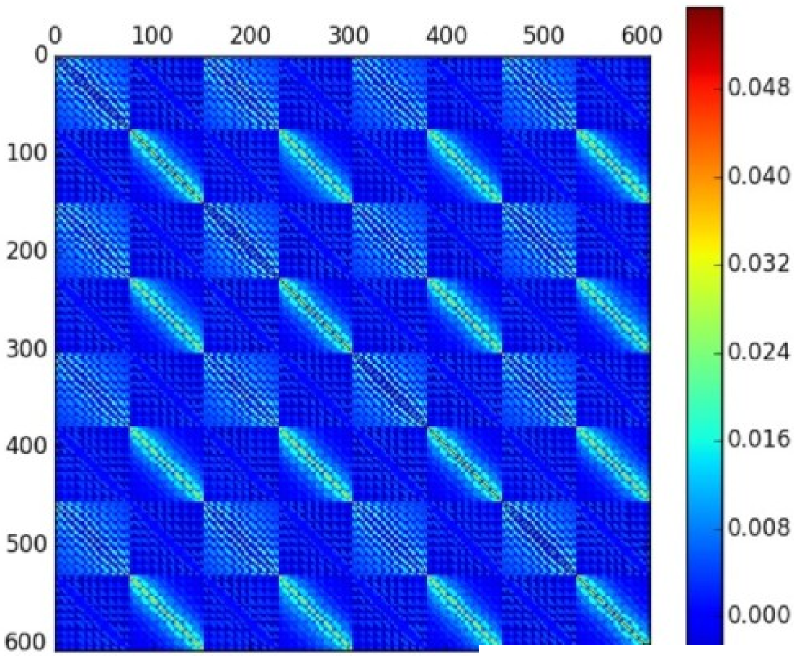
!evera"in" the (ull bandwidth o(<&42

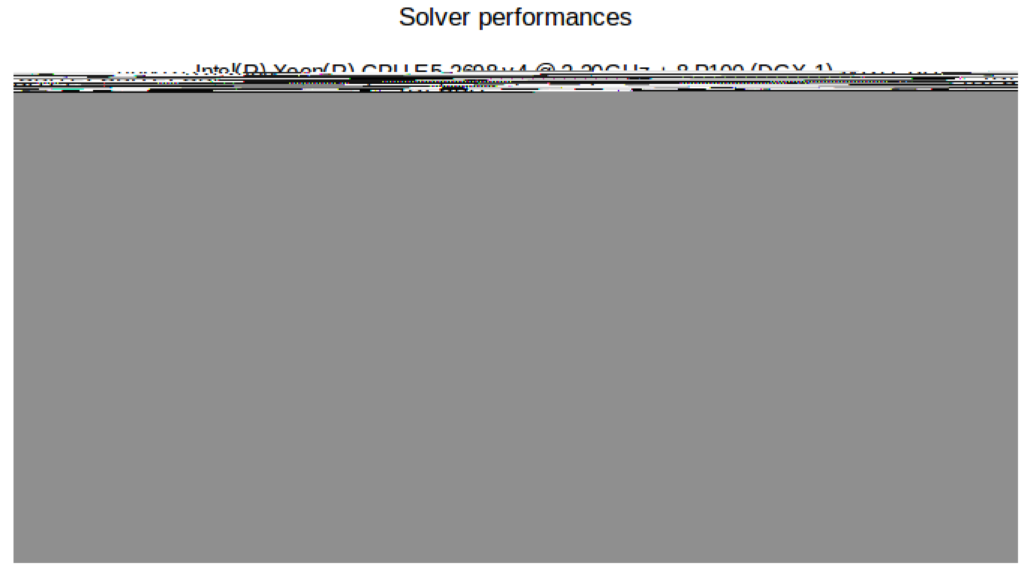
- BT pipeline dominated by 454
- Bea,hin" over 790 G&0s on a sin"le G2% =i e :8P o(measured mem &A>
- /,aled well on multiple G2%s$ the more data you (eed the G2% with* the better

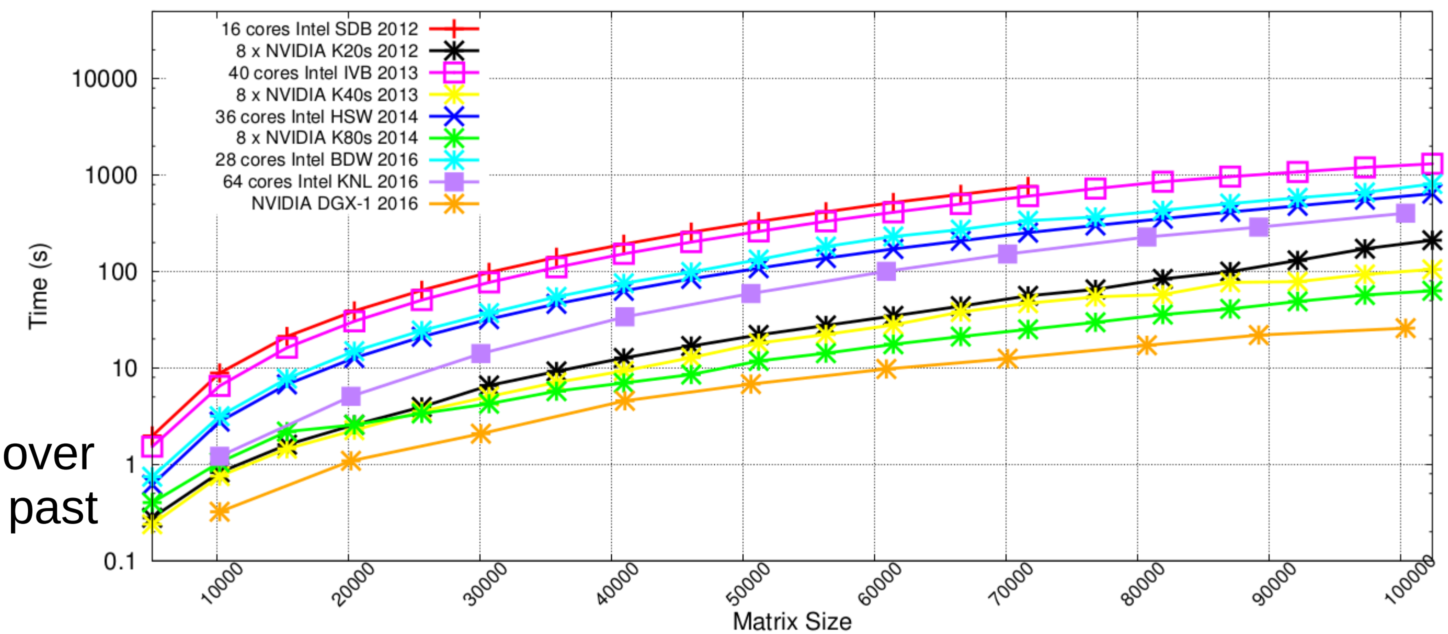
Time to solution determinism on multiple GPUs



GPUs are good for supervision as well







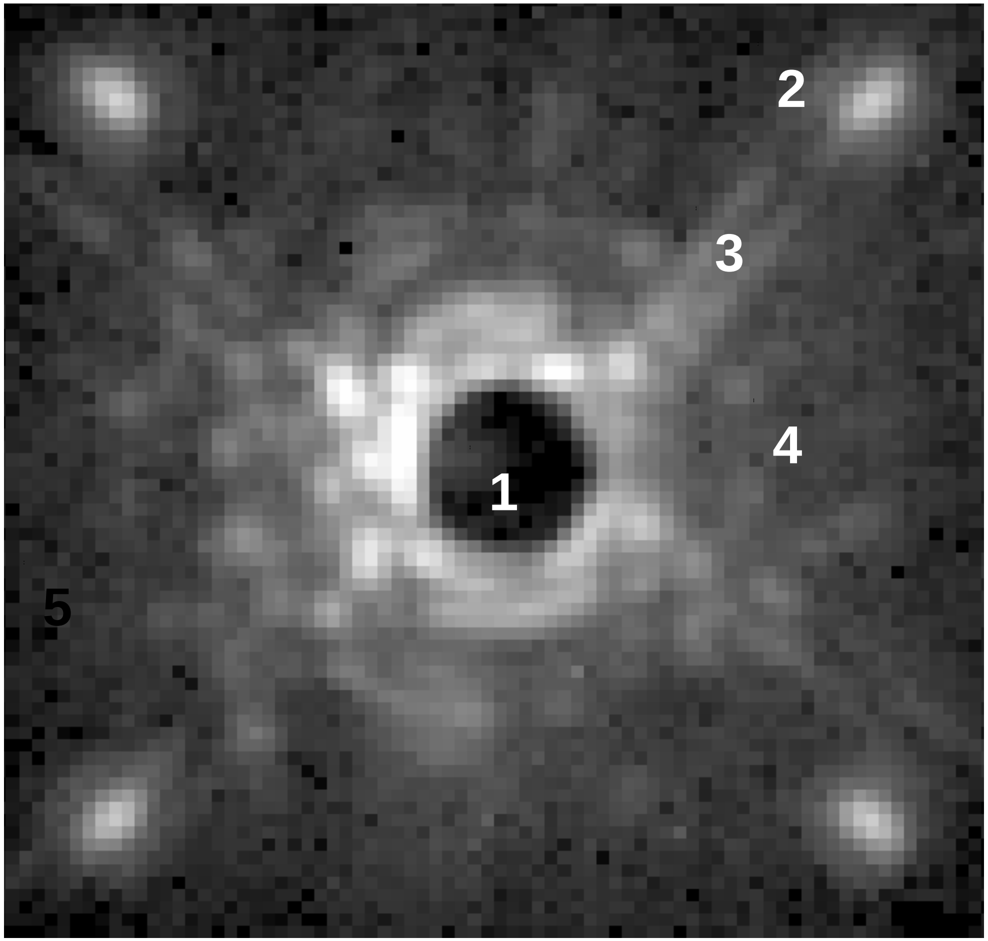
XL matrix inversion

- /olver maps well on G2% ar,hite,ture
- Consistent speedup over C2% ,lusters (or the past 0 years

Future opportunities

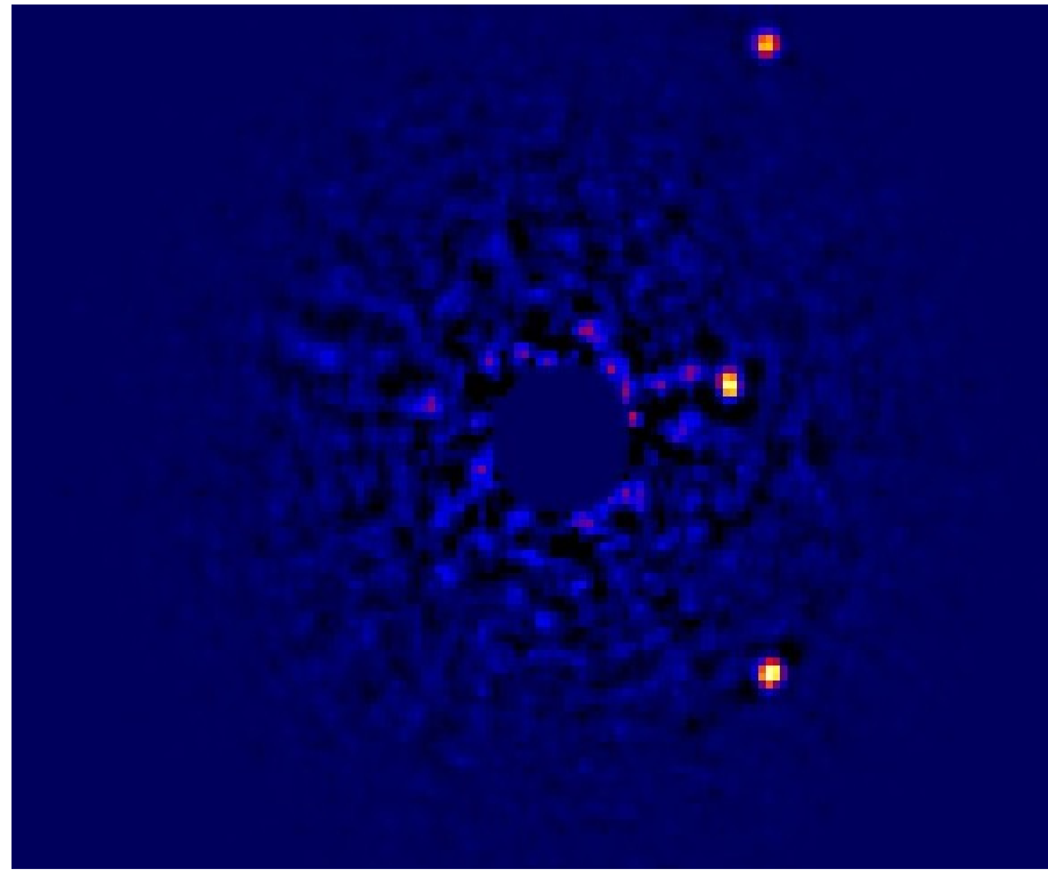
AI for image processing

RAW image



3! , *
7! , $ & +
/! 9
:! $ 8
0! ' 9

PROCESSED image



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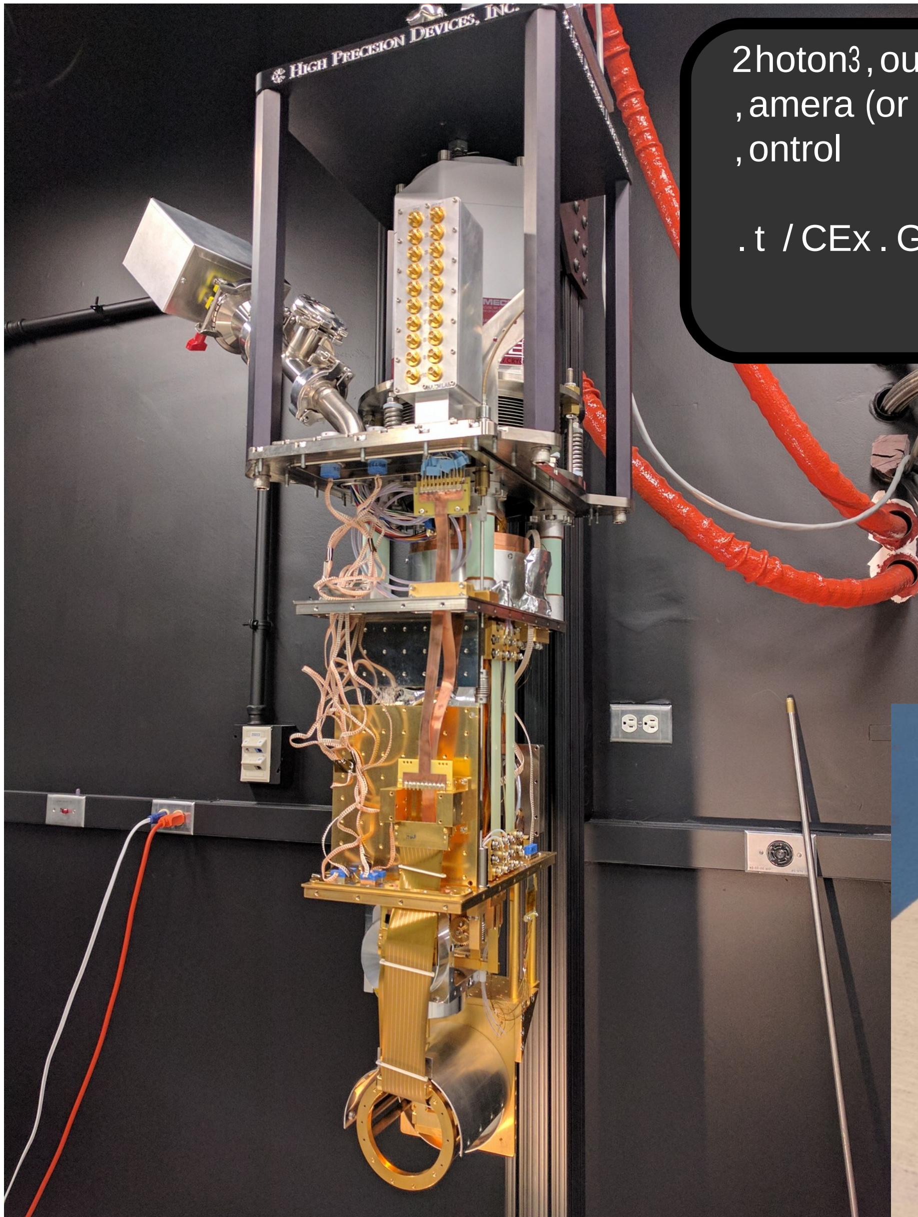
Cameras are getting faster and better

Photon-counting, wavelength resolving 140x140 pixel camera



2hoton3,ountin" near3IB 4KIJs
,amera (or +<; speed spe,+le
,ontrol

.t /CEx.G sin,e 4ar,h 2018