A Future of Abundant Space Telescopes

Exploring Cooperative Economies of Scale

Aaron Tohuvavohu (U Toronto)

Why build space telescopes?

- To access all the other wavelengths… (gamma, x-ray, UV, IR, LWR)
- To remove contaminating foregrounds (New Horizons)
- To achieve stable observations (BRITE, Kepler, TESS, Euclid)
- To resolve beyond the seeing limit (HST, Roman)
- To build a high-efficiency observatory (Swift)
- To increase field-of-regard and sky coverage (All of them)
- **To Discover…and Inspire!**

The "Space Spiral"

High to-orbit cost

Higher-cost Missions

Complex Missions with no tolerance for failure

Low number of missions

Challenging Science Requirements

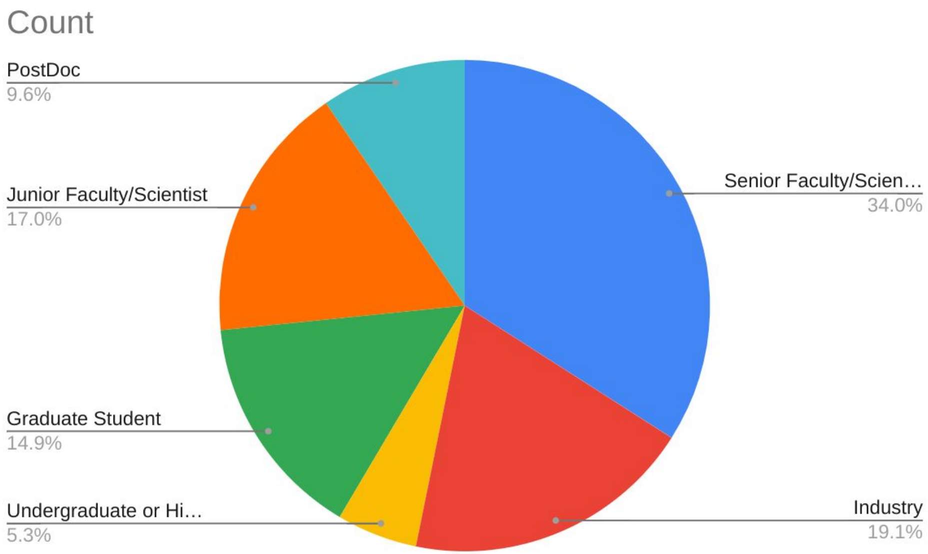
Unique Telescopes

Daniel Apai

How do we break the Space Spiral for astronomy?

- Build non-unique telescopes.
  - But who wants them?
- Need science capabilities sufficient to interest a large user community
  - Demand from community must be large enough to justify building large numbers of telescopes
- So…telescope has to be pretty good (likely not a CubeSat)
- Design a mission explicitly for mass production
- Accept sub-optimal science on first try
  - **At sufficiently low cost, failing faster is better**
  - Integrated mission cost over multiple tries can still be cheaper than one-off with irreducible risk
- Either need a telescope thats sufficiently attractive that every astronomer will want one, at a cost that is accessible…
- Or a science case for an array that requires large number of units

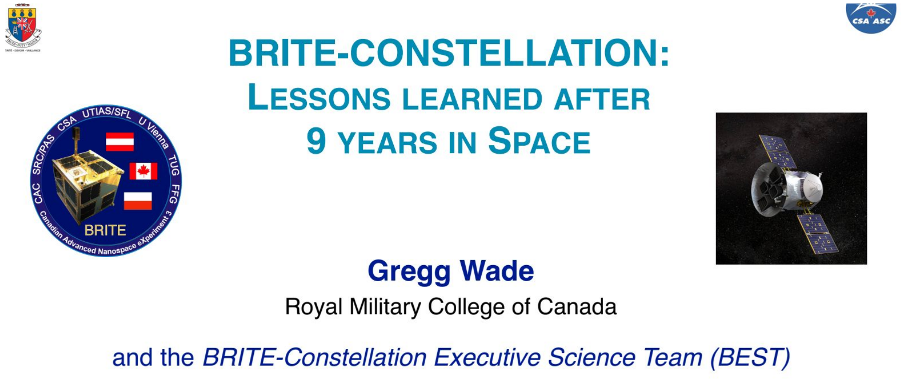
150 people, From Hawaii→ Japan
3 workshops




National Aeronautics and Space Administration
EXPLORE
Opportunities for Astrophysics SmallSat Missions in the Era of New Space
Florence Tan
Deputy Chief Technologist
Science Mission Directorate (SMD)
Chair, Small Spacecraft Coordination Group
NASA Headquarters
June 2022


National Aeronautics and Space Administration
Astrophysics
NASA Astrophysics Small Space Telescopes (SmallSats)
AAS Workshop, Pasadena, June 11, 2022
Michael R. Garcia
SmallSats Lead, Astrophysics Division
Terri Brandt
Deputy Program Scientist, Pioneers/CubeSat


Small Satellite Industrialisation and opportunities for astronomy
Phil Allen BEng MSc
Space Vehicle Architect
Airbus Defence and Space UK


BRITE-CONSTELLATION:
LESSONS LEARNED AFTER 9 YEARS IN SPACE
CSA UTIAS/SFL U Vienna TUG FFG CAC SRC/PAS
BRITE
Canadian Advanced Nanospace eXperiment 3
Gregg Wade
Royal Military College of Canada
and the BRITE-Constellation Executive Science Team (BEST)

Dark and Quiet Skies for Science and Society (It's for astronomers, too)

The Outer Space Institute

Aaron Boley
STCW: 11.06.2022

With thanks to the many researchers working on the sustainability of space

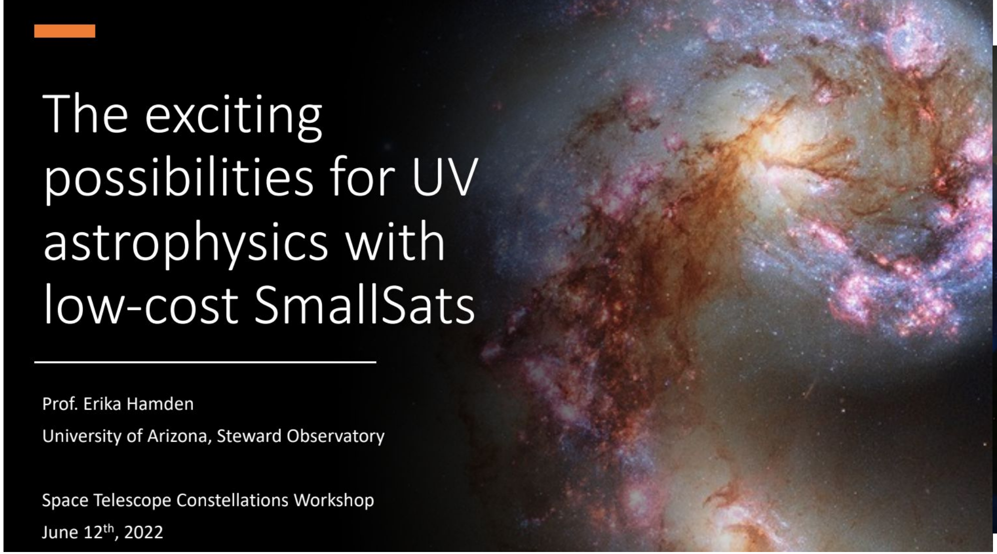
We need to take extra consideration of emerging norms of behaviour and recognize that our actions will be heavily scrutinized

Missteps by a space-based astronomy group could be very damaging for astronomy in general

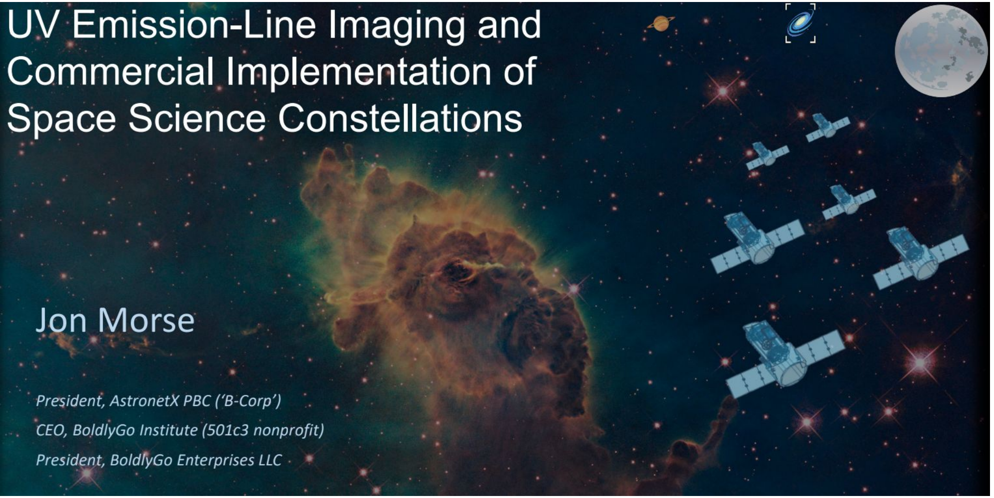
Your satellite might be small, but your actions could be very significant

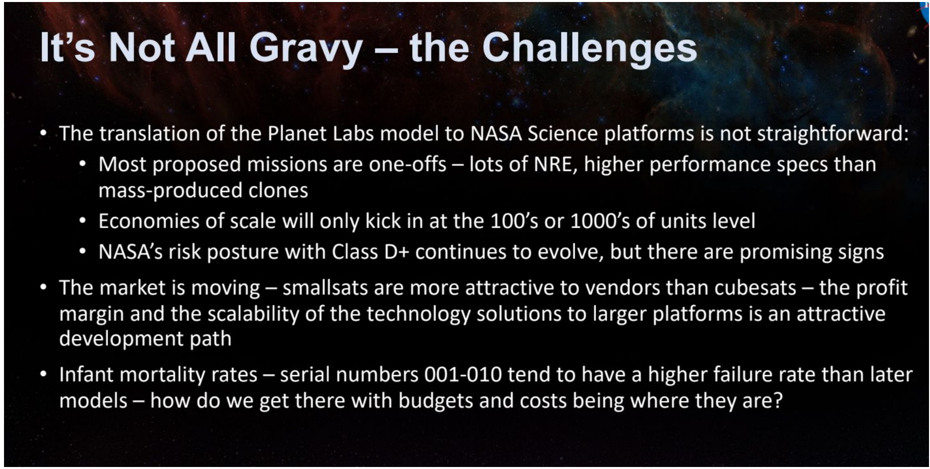
Things to ask yourself

- Are there opportunities to coordinate and cooperate with other projects or activities?
- Do you know the total brightness impact of your constellation at all phases, as well as any equipment abandoned in orbit (e.g., rocket bodies)?
- How will your satellites de-orbit and will they cause interference of some kind?
- Will your operations provide supplemental ephemerides to the community, as we've asked industry to do?
- What is the casualty risk of your mission and are you willing to accept it and export the risk to others?
- How long will your satellite be out-of-shadow for different locations on Earth at different times of year?
- If your satellite is an emitter (LED, laser comms, other areas of the spectrum), how can you minimize the impact of the emission?
- Are your transmissions interfering with radio astronomy?


The exciting possibilities for UV astrophysics with low-cost SmallSats
Prof. Erika Hamden
University of Arizona, Steward Observatory
Space Telescope Constellations Workshop
June 12th, 2022


Goddard
SPACE FLIGHT CENTER
UV Cubesat / Smallsat Constellation Possibilities
Paul Scowen, Code 667
paul.a.scowen@nasa.gov
June 11, 2022
Autonomous Space Telescope Constellations
1


UV Emission-Line Imaging and Commercial Implementation of Space Science Constellations
Jon Morse
President, AstronetX PBC ('B-Corp')
CEO, BoldlyGo Institute (501c3 nonprofit)
President, BoldlyGo Enterprises LLC


It's Not All Gravy – the Challenges
• The translation of the Planet Labs model to NASA Science platforms is not straightforward:
• Most proposed missions are one-offs – lots of NRE, higher performance specs than mass-produced clones
• Economies of scale will only kick in at the 100's or 1000's of units level
• NASA's risk posture with Class D+ continues to evolve, but there are promising signs
• The market is moving – smallsats are more attractive to vendors than cubesats – the profit margin and the scalability of the technology solutions to larger platforms is an attractive development path
• Infant mortality rates – serial numbers 001-010 tend to have a higher failure rate than later models – how do we get there with budgets and costs being where they are?

Using meteorological satellites as "space telescopes"

A case study with the Great Dimming of Betelgeuse

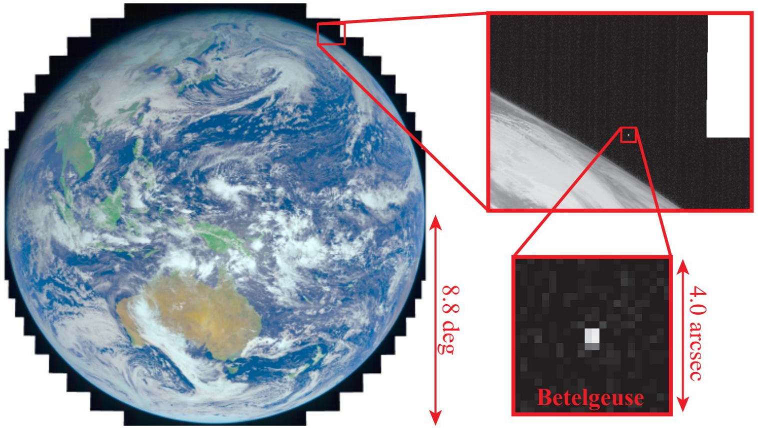
(Taniguchi et al. 2022, Nature Astronomy, DOI: 10.1038/s41550-022-01680-5)
Data available at
https://d-taniguchi-astro.github.io/homepage/Data_Himawari_en.html

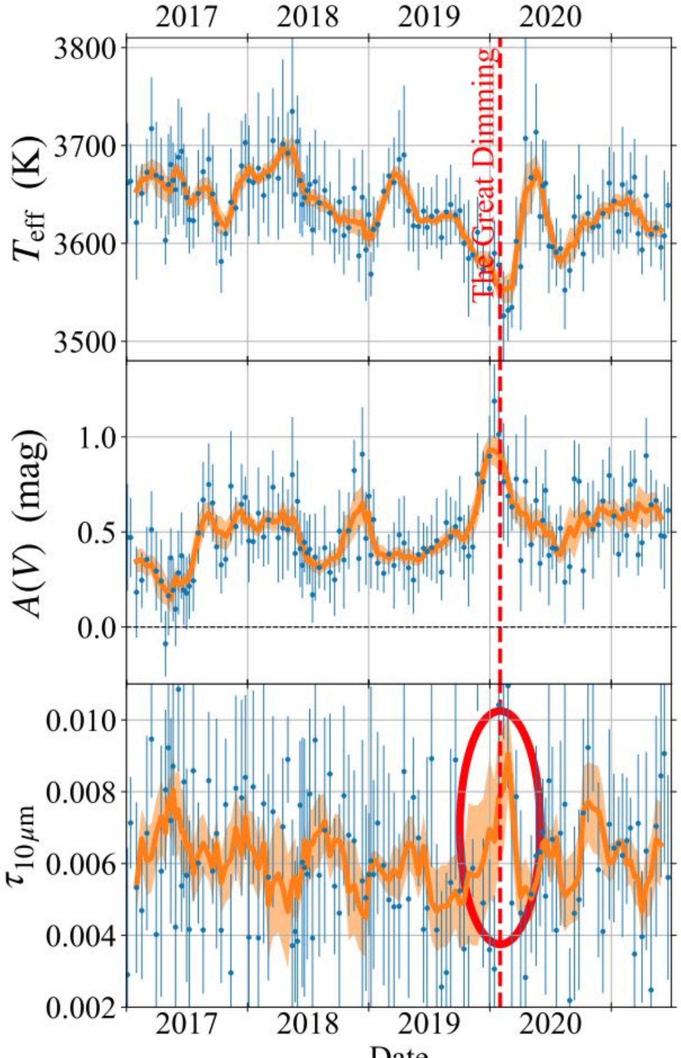
Daisuke Taniguchi

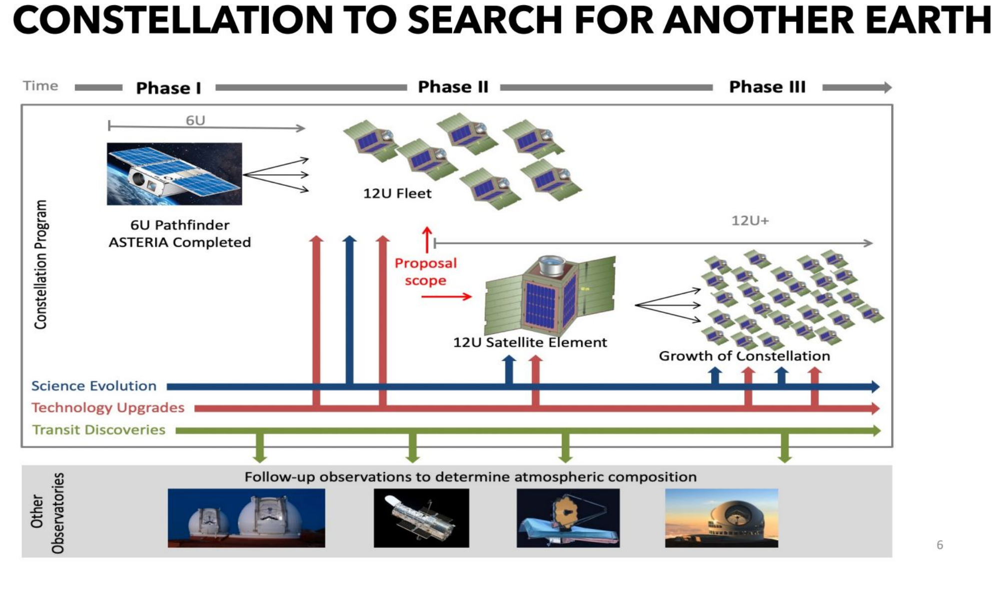
The University of Tokyo

June 11th, 2022
Autonomous Space Telescope Constellations, Day 1

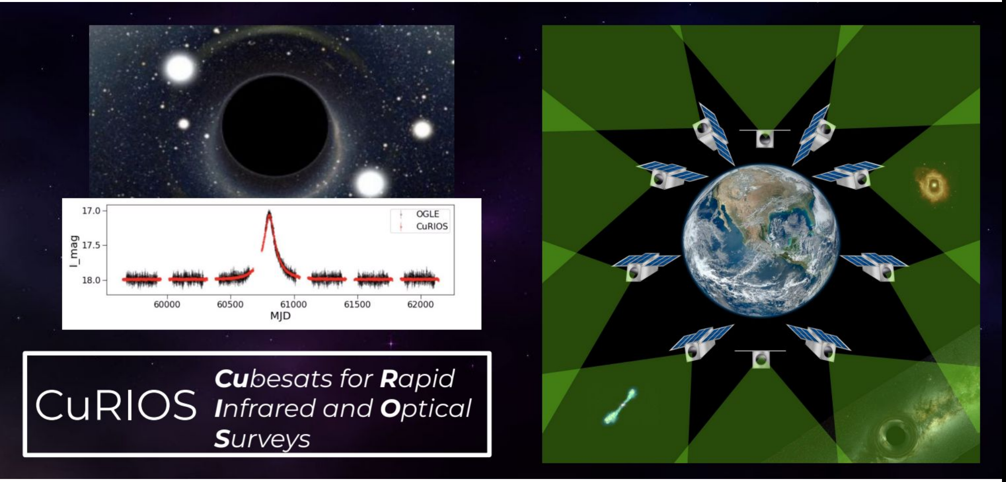
Himawari-8: Japanese geostationary meteorological satellite

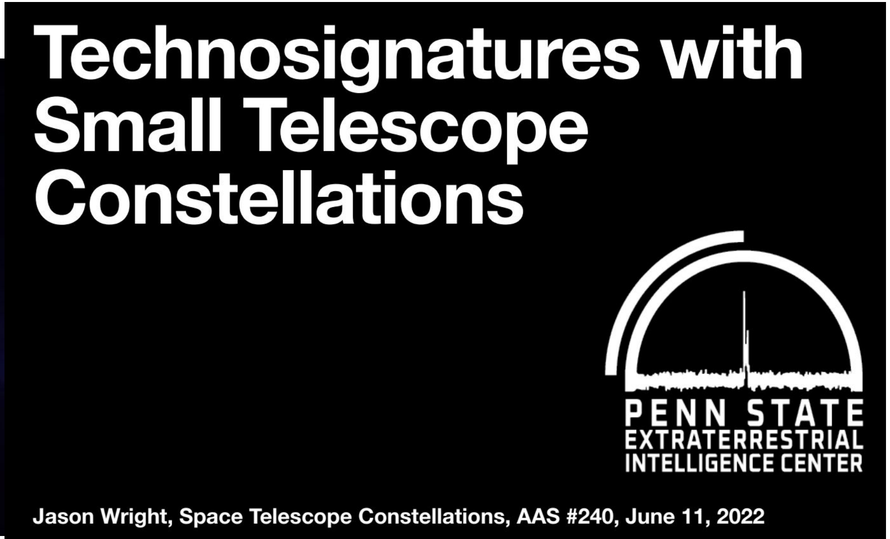





CONSTELLATION TO SEARCH FOR ANOTHER EARTH
Time
Phase I
Phase II
Phase III
6U
6U Pathfinder
ASTERIA Completed
12U Fleet
Constellation Program
12U+
Proposal scope
12U Satellite Element
Growth of Constellation
Science Evolution
Technology Upgrades
Transit Discoveries
Follow-up observations to determine atmospheric composition
Other Observatories
6


Dragonfly in space?
Creating an ultra-low surface brightness UV imager
Deborah Lokhorst
NRC Herzberg Astronomy & Astrophysics Research Centre | Instrument Science Research Associate
AAS 240 Space Telescope Constellations Workshop
1


17.0
17.5
18.0
I_mag
OGLE
CuRIOS
60000
60500
61000
61500
62000
MJD
CuRIOS
Cubesats for Rapid Infrared and Optical Surveys

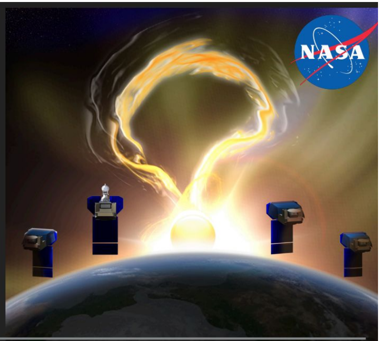

Technosignatures with Small Telescope Constellations
PENN STATE
EXTRATERRESTRIAL
INTELLIGENCE CENTER
Jason Wright, Space Telescope Constellations, AAS #240, June 11, 2022

CODA 40-50cm Aluminum Cassegrain

- Program Goal: Produce an inexpensive telescope that could be produced in large quantities for ESPA Grande class missions with minimal NRE
- Features
  - Fabricated from readily available 6061 Aluminum
  - Bulk materials allow for multiple sets of mirror to be produced quickly
  - Flexible relay design allows for multiple channels & wide variety of detectors to be hosted
  - Utilizes existing state of the art processes and coatings for optical elements

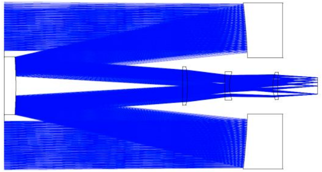
CODA is not a revolutionary telescope design in terms of performance, its purpose is to be revolutionary from a manufacturing and acquisition perspective with a target cost of <$1M per unit

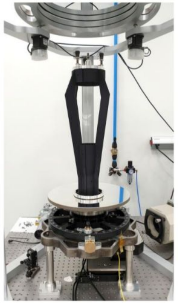
Polarimeter to UNify the Corona and Heliosphere



A CONSTELLATION TO OBSERVE THE INNER HELIOSPHERE

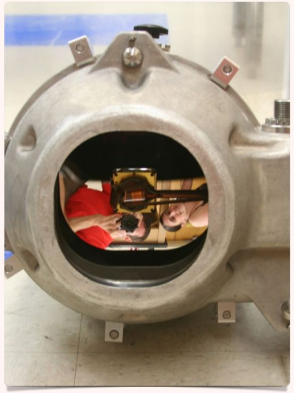
350 mm Space Qualified Payload





Dall–Kirkham Design
F/6, 1° FOV, designed for high production rate

REPLICATION (ON THE GROUND)



AUTONOMOUS SPACECRAFT OPERATIONS: LESSONS LEARNED FROM *SWIFT*

JAMIE A. KENNEA (Penn St[...])

MOCET Cost Estimating Relationships (CERs)

Earth Science, Explorers, and Near Earth Discovery Helio Astro

CER Name	Equation	Inputs	R^2	SEE
Earth Science, Explorers, and Near Earth Discovery Helio Astro Checkout CER	$Y = P*1.95$	P = Prime mission operations average monthly cost	0.90	29.7%
Earth Science Prime Operations CER	$Y = 0.5338 * MC^{0.8868} * 0.7546^{IO} * NI^{0.1814}$	MC = Mission Class (0.25 Micro, 1 Small, 2 Medium, 6 Flagship) IO = Instrument Only (0 No, 1 Yes) NI = Number of Instruments (1 to N)	0.98	24.2%
Explorer Prime Operations CER	$Y = 0.4219 * MC^{0.6599} * ST^{0.4775} * NI^{0.1917}$	MC = Mission Class (0.25 Micro (MO), 1 Small (SMEX), 2 Medium (MIDEX)) ST = Science Therme (1 Heliophysics, 2 Astrophysics) NI = Number of Instruments (1 to N)	0.80	24.6%
Near Earth Discovery Helio Astro Prime Operations	$Y = 0.3071 * MC^{0.8717} * ST^{0.9699} * NI^{0.5718}$	MC = Mission Class (2 Medium , 3 Large, 6 Flagship) ST = Science Therme (1 Heliophysics, 2 Astrophysics) NI = Number of Instruments (1 to N)	0.94	20.6%

*Y = Average Monthly cost for phase (FY13)

- **So we're in a cost modeling wild west here. Good luck guys!**

AIKO AUTOMATING SPACECRAFT OPERATIONS WITH orbital_OLIVER June 12th 2[...]

SPACE OPERATIONS:
CAN WE DO BETTER?

1. **Planning**
2. **Execution**
3. **Analysis**
4. **Re-planning**
5. **Downlink**
6. **Distribution**

1 2 3 4 5 6

time

M^{4}OPT

Multi-**M**ission **M**ulti-**M**essenger **O**bservation **P**lanning **T**oolkit

Workshop on Autonomnous Constellations
American Astronomical Society Meeting
June 12, 2022 • Pasadena, CA

ARACHNE

ARACHNE

ARACHNE

Continuous UV/Vis/IR Access to the Whole Night Sky from Space in the Era of Multi-messenger Astrophysics

ARACHNE

ARACHNE

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GLOBAL SECURITY

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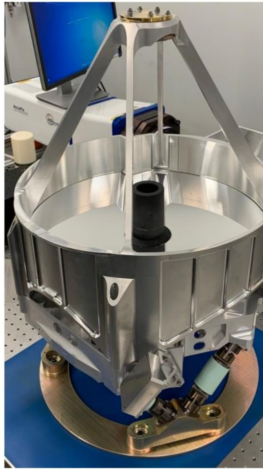


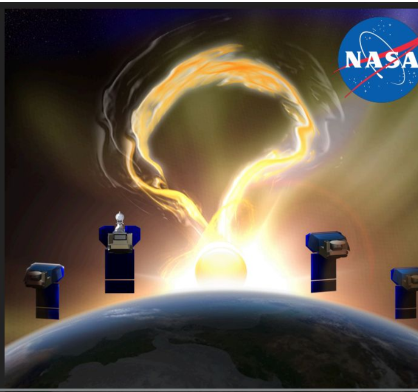
Solution: CuRIOS

CuRIOS will employ a swarm of optical/near-IR CubeSats to provide all-sky all-the-time monitoring of star death and afterlife by observing transient phenomena originating from black holes and neutron stars.

PUNCH

Polarimeter to UNify the Corona and Heliosphere

A CONSTELLATION TO OBSERVE THE INNER HELIOSPHERE



No High-Performance Low-Cost UV/Optical Camera System

ARACHNE

ARACHNE

ARACHNE

Continuous UV/Vis/IR Access to the Whole Night Sky from Space in the Era of Multi-messenger Astrophysics

ARACHNE

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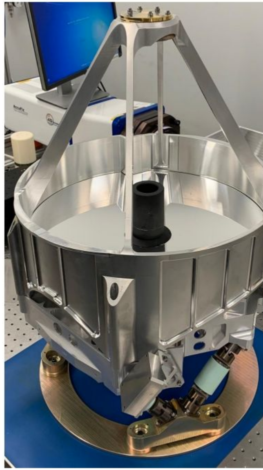
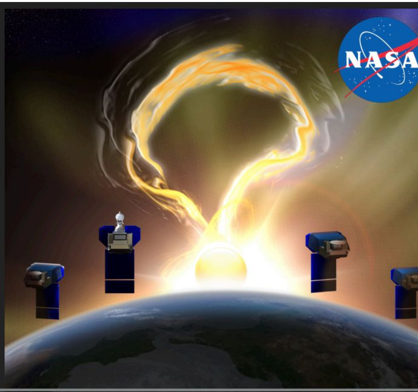


NNSA

…g transient
…a originating from
…k holes and neutron stars.

POLARIMETER TO UNIFY THE CORONA AND HELIOSPHERE

A CONSTELLATION TO OBSERVE THE INNER HELIOSPHERE



Astronomy-grade space cameras

Are ****** expensive! This means less astrophysics.

Why so expensive?

Dominated by recurrent engineering, qual, cert costs, and then incumbent market advantage charging for ‘heritage’

We need to get this cost lower if we want a future of abundant space telescopes!

Other parts of the (small) system (spacecraft, optics) have begun to drop in cost, but the camera systems haven’t met cost scaling requirements yet.







(we) LUVS Telescope(s)



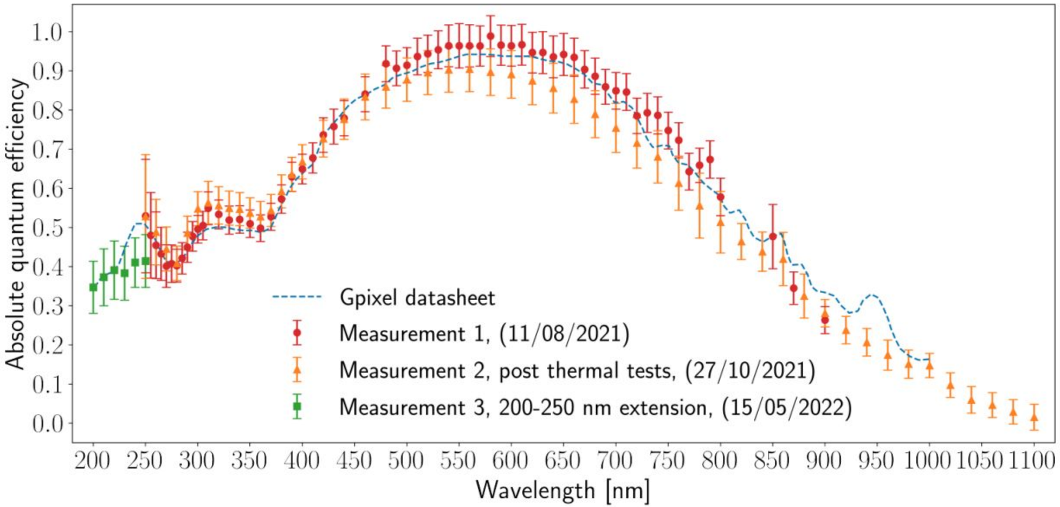


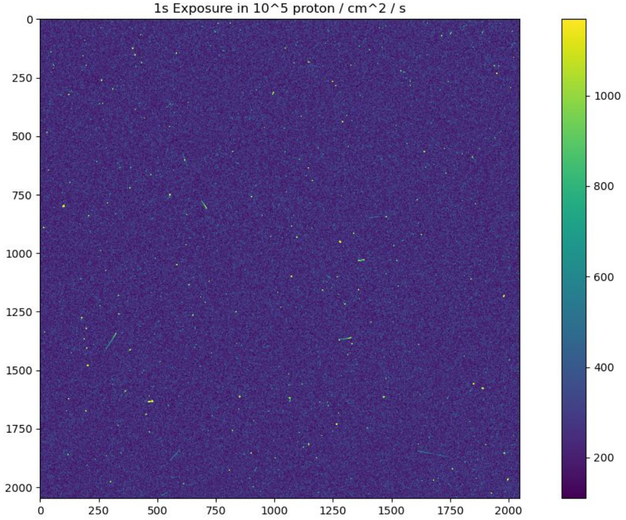


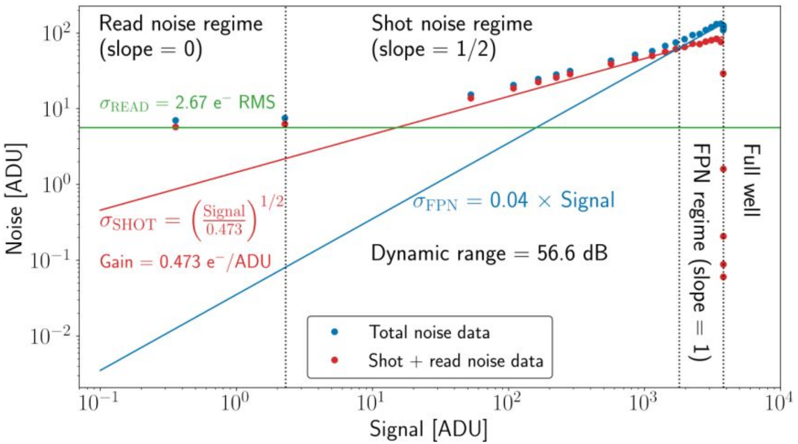
LUVCam

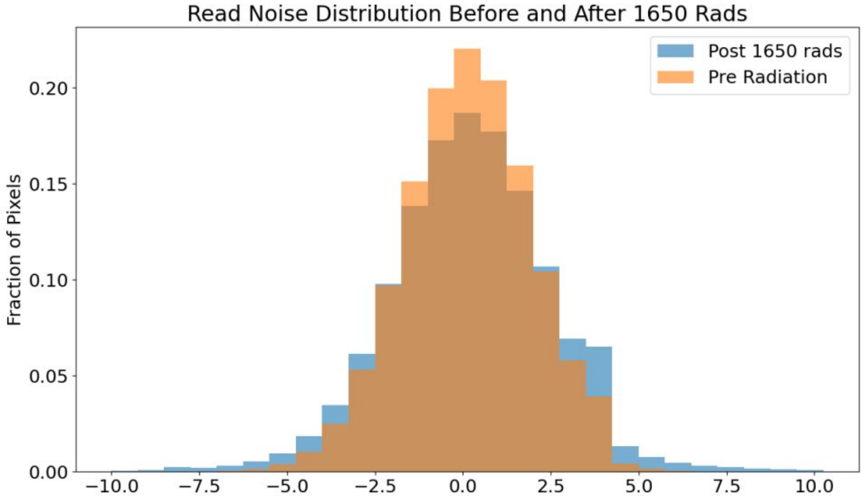
Kindling the romance for space telescopes

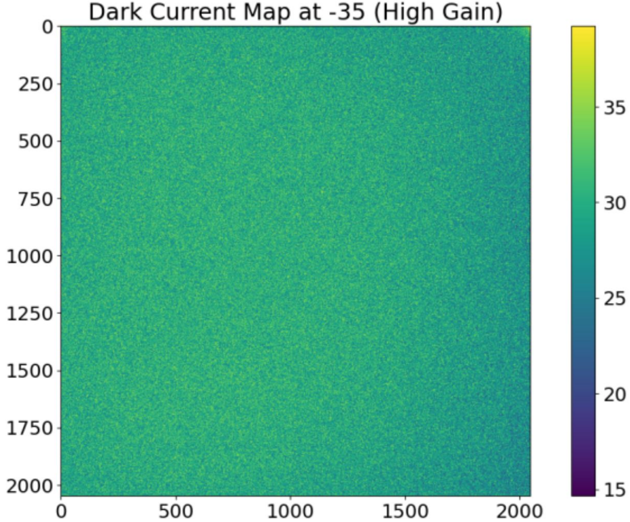
Resolution	16 MP (4096x4096)
Pixel size	9x9 microns
Optical format	36.8 x 36.8 mm
Shutter type	Rolling
Read noise	<3.5 e^-
Dark current	0.05 e^-/pixel/s @ -30C
Power	<1.4 W
Full well capacity	39k/74k e^-




1s Exposure in 10^5 proton / cm^2 / s

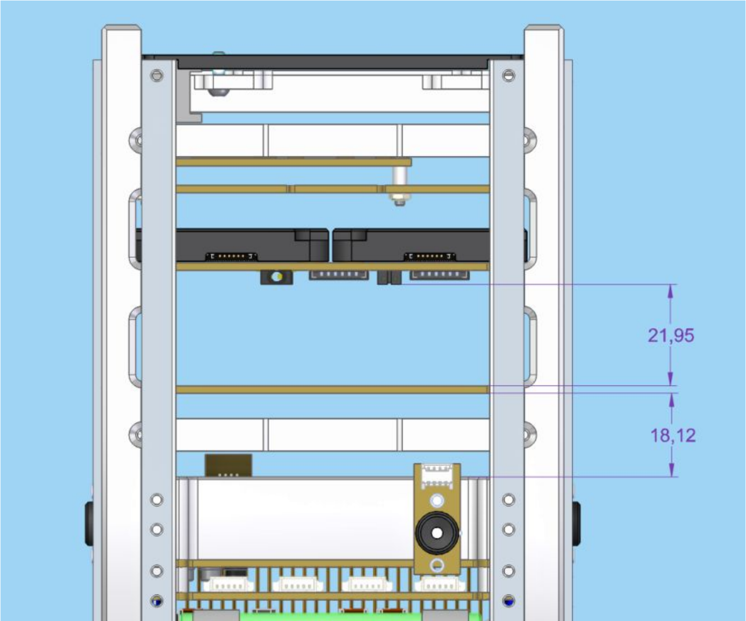

Read noise regime
(slope = 0)
Shot noise regime
(slope = 1/2)
σ_{READ} = 2.67 e⁻ RMS
$\sigma_{\mathrm{SHOT}} = \left(\frac{\mathrm{Signal}}{0.473}\right)^{1/2}$
Gain = 0.473 e⁻/ADU
σ_{FPN} = 0.04 × Signal
Dynamic range = 56.6 dB
FPN regime (slope = 1)
Full well
Total noise data
Shot + read noise data
Noise [ADU]
Signal [ADU]

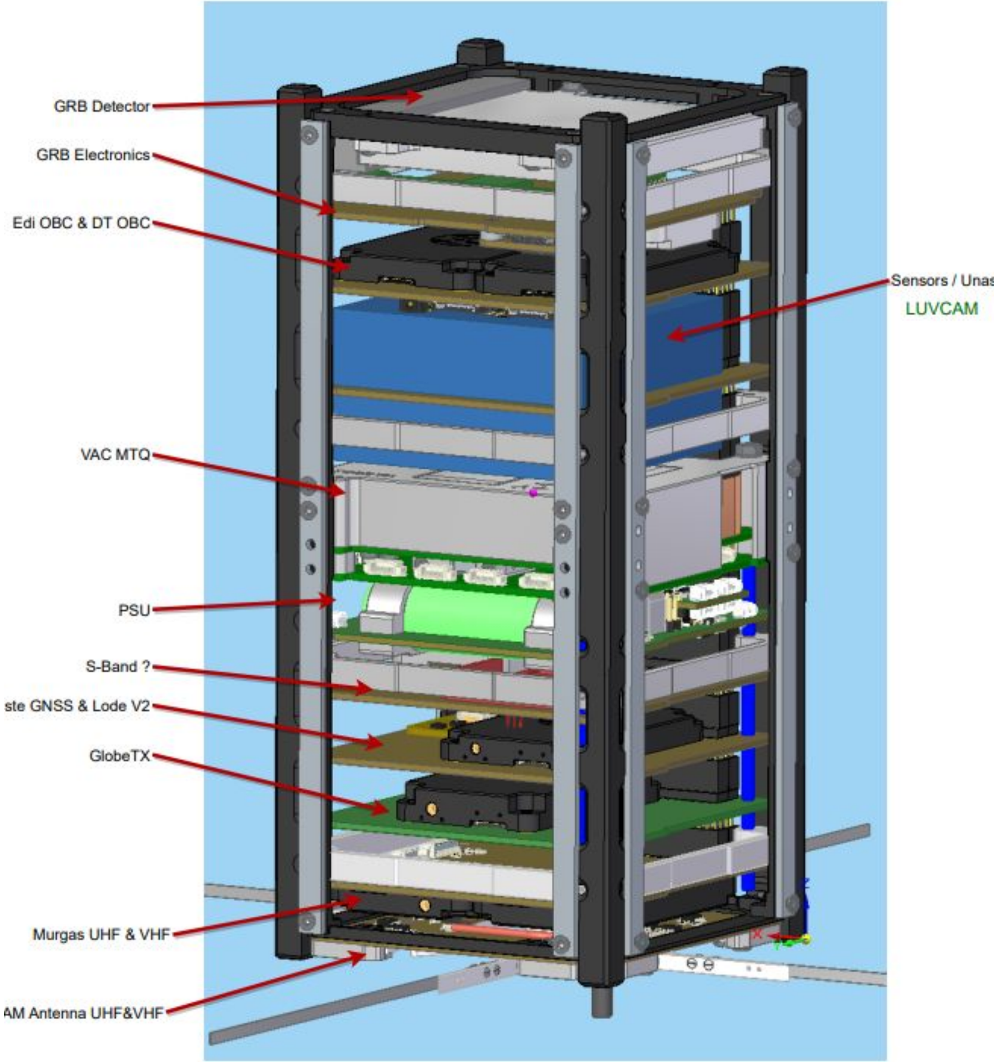

Read Noise Distribution Before and After 1650 Rads
Post 1650 rads
Pre Radiation
Fraction of Pixels


Dark Current Map at -35 (High Gain)

Real friends give you space on their spacecraft…(with 6 months to deliver)

- Space for the CMOS sensor, readout electronics, and associated temp+hk sensors. **Tech Demo**

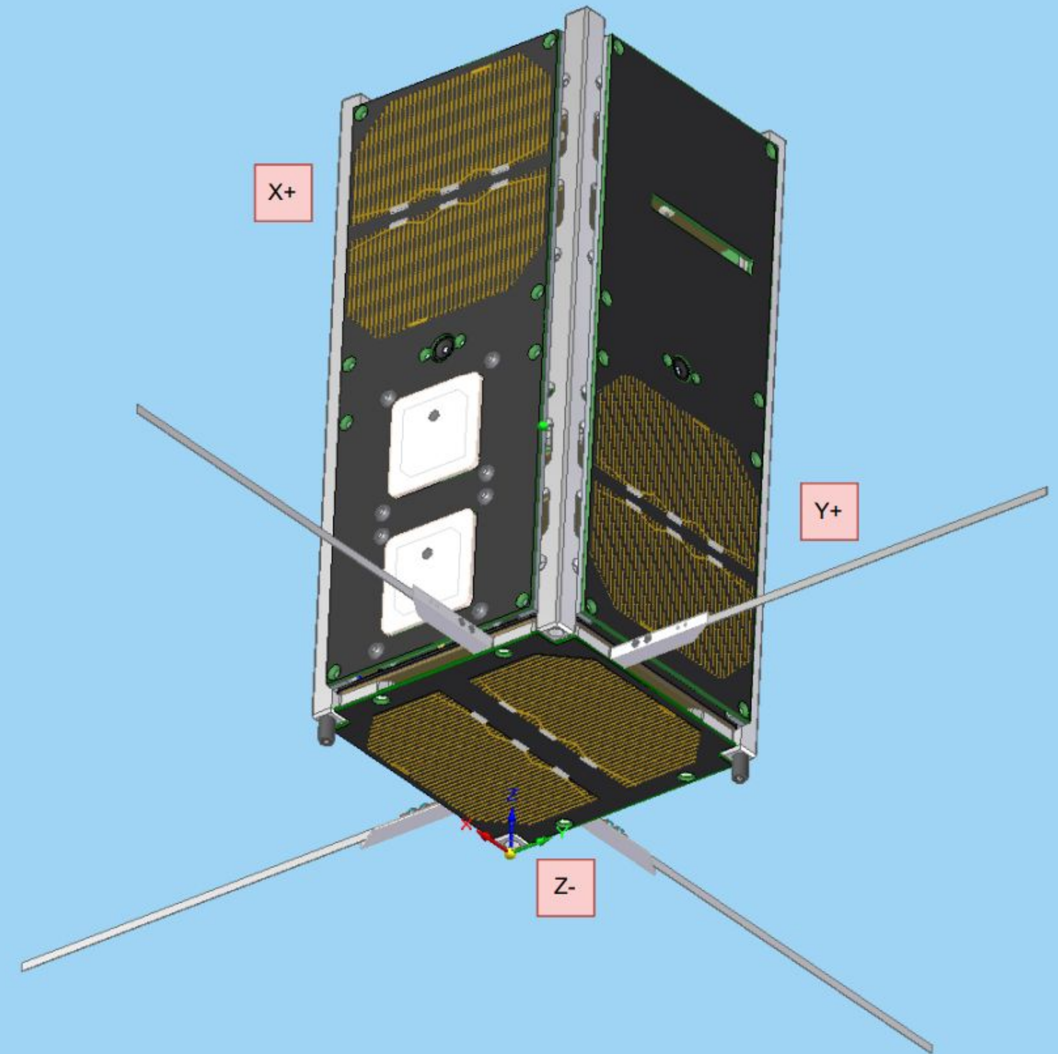




But Side Access Panel unused in +Y

Baselined for radiator plate, but tempting to add an optical path for the CMOS to see space

What could a little (~2cm aperture) UV optic do?

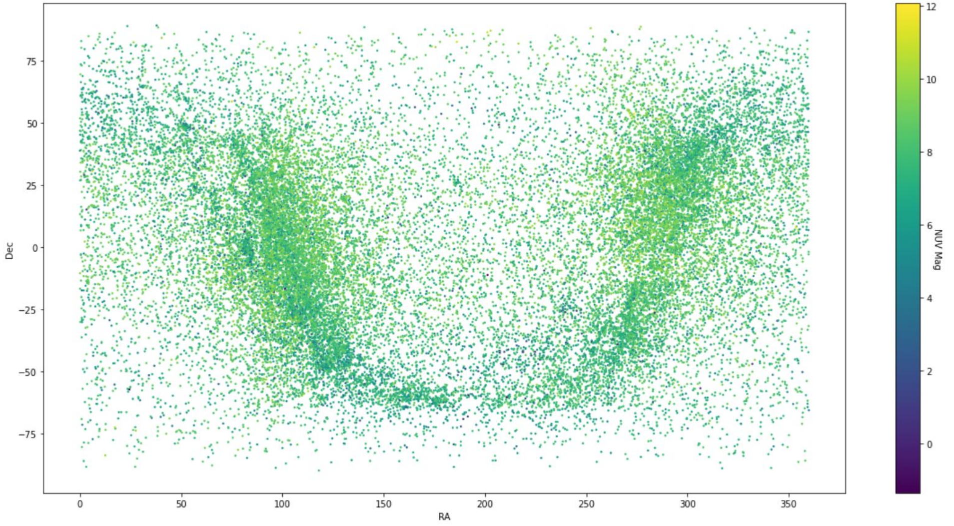


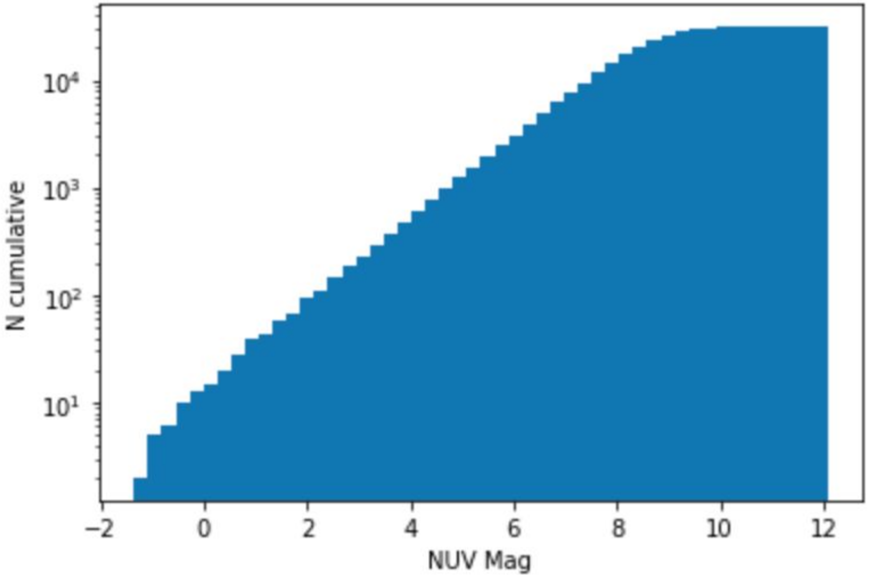
Last UV survey of bright stars was in 1973 (TD-1)

GALEX had bright limit of 9th mag in NUV

31,215 sources down to NUV mag 12 in TD-1

Even in Galactic center source density < $2/\mathrm{deg}^2$





Optical design (240-300 nm)

20mm aperture

Front aperture bandpass filter

Folded optical path

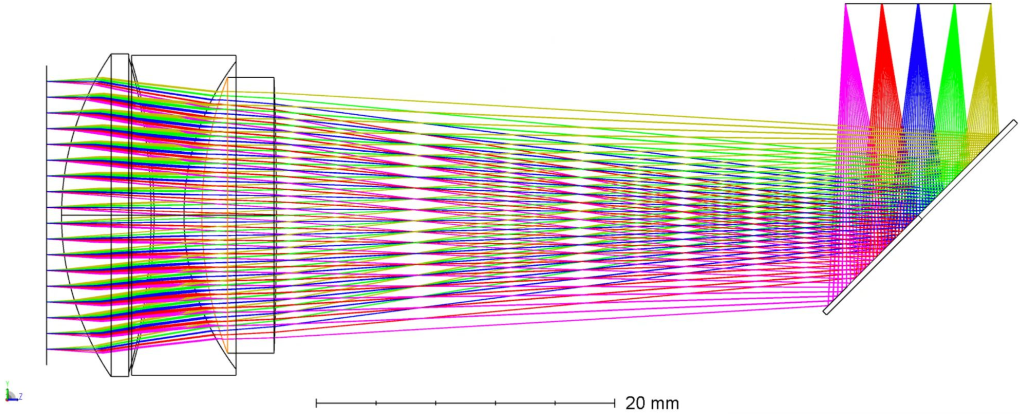
70mm EFL

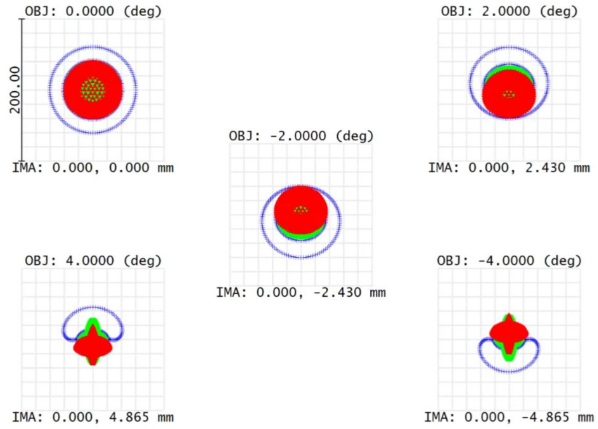
26.5” pixel scale

7.5 x 7.5 deg (1024 x 1024 pix)

Only 2 refractive elements reqd to get PSF << ADCS jitter

Triplet design gets spots ~2.5x smaller (EE 60% < 2 pix radius across field)

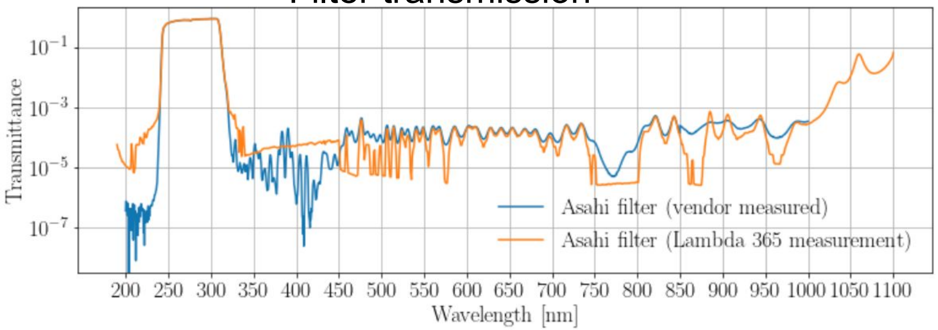




2cm aperture

×

Filter transmission

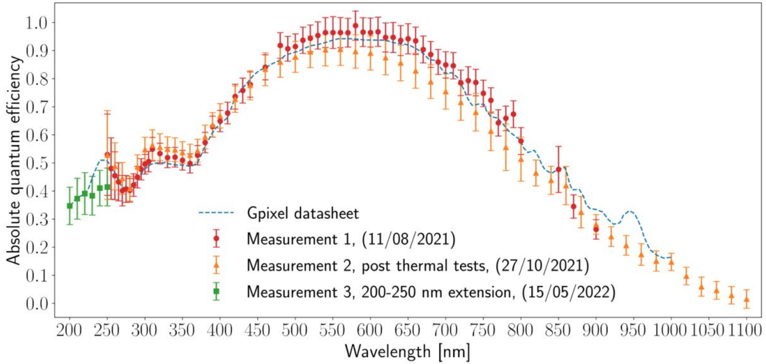


×

Transmission/reflectance of 4 elements

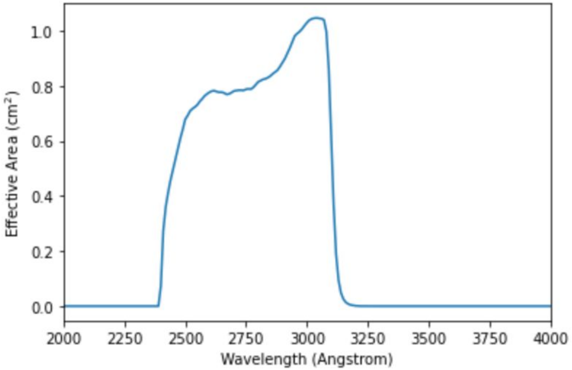
$(0.85)^4$

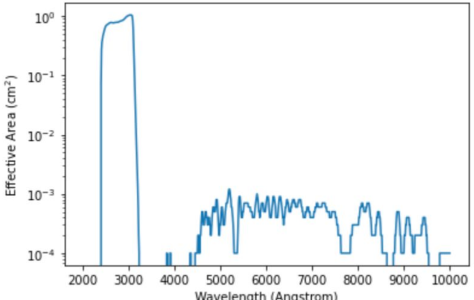
×



Camera QE

=

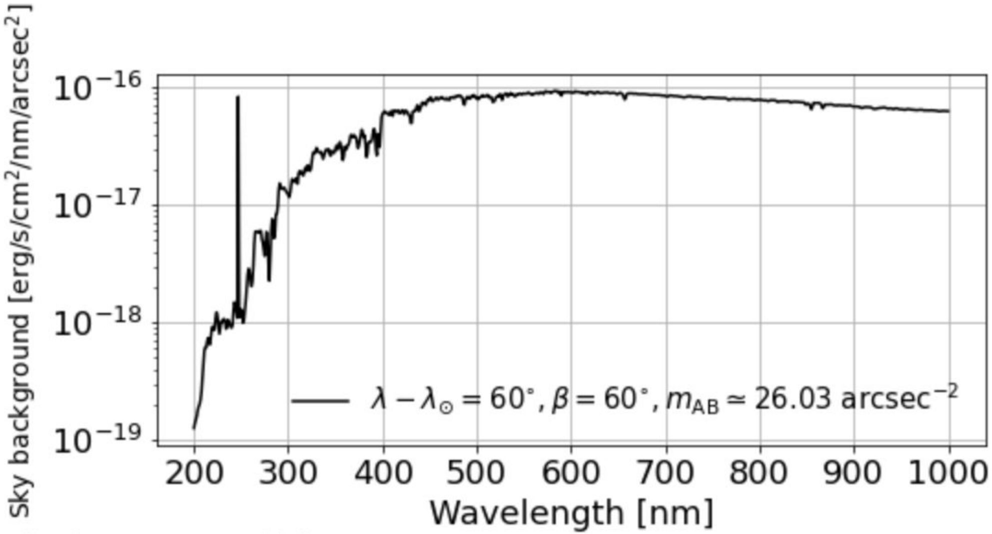


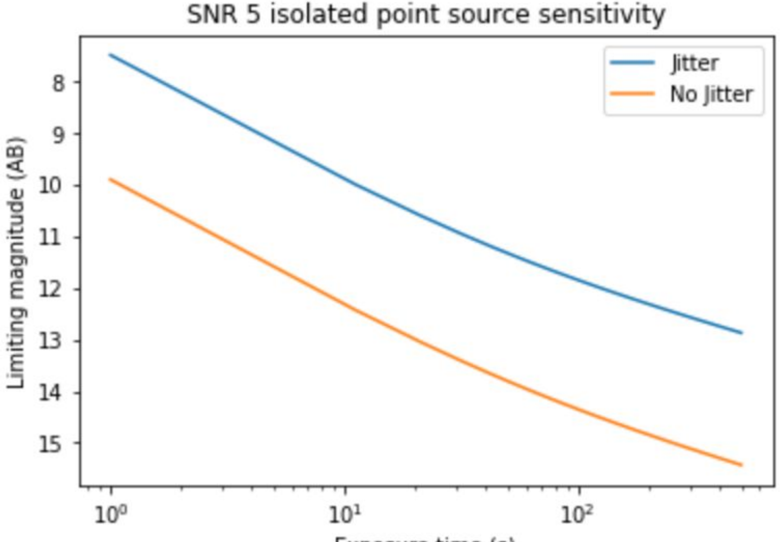


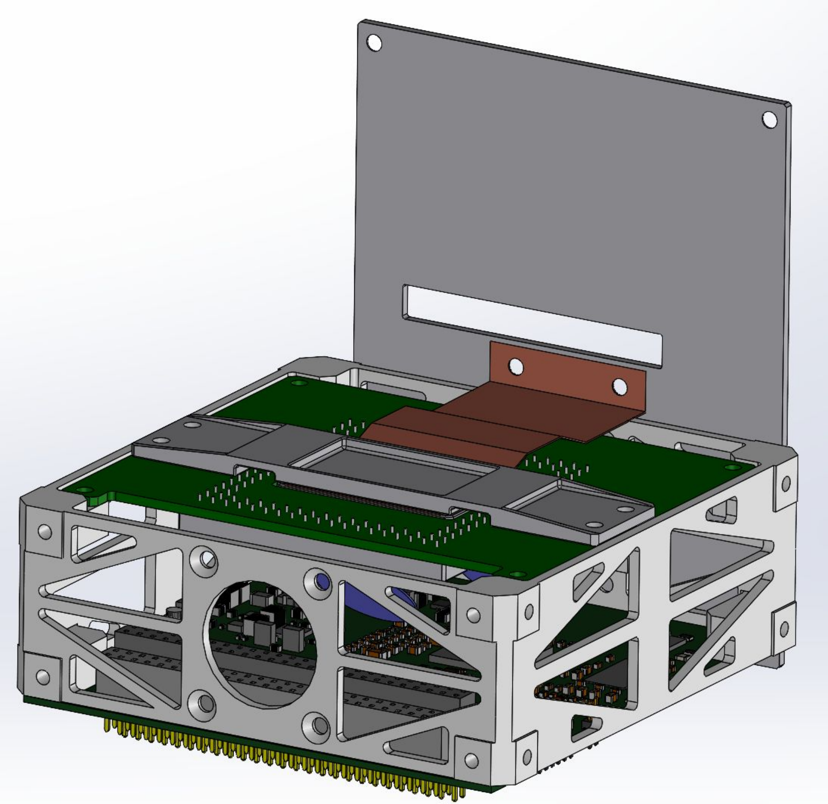
Projected performance

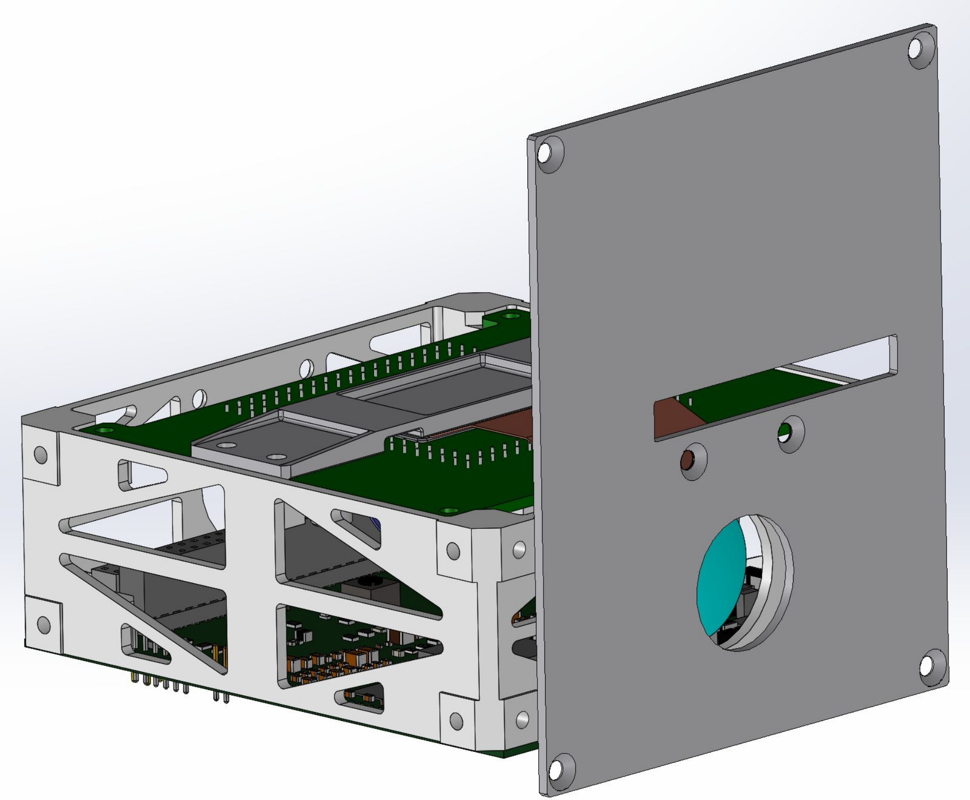
Assumptions:

- Optical characteristics as previous slide
- Jitter 0.15 deg 1-sigma
- Read noise 3.7 e^-/pix
- DC: 0.1 e^-/pix/s at 0 C
- Circular aperture at 60% EE
- Imaging in eclipse only
- Bkg as →



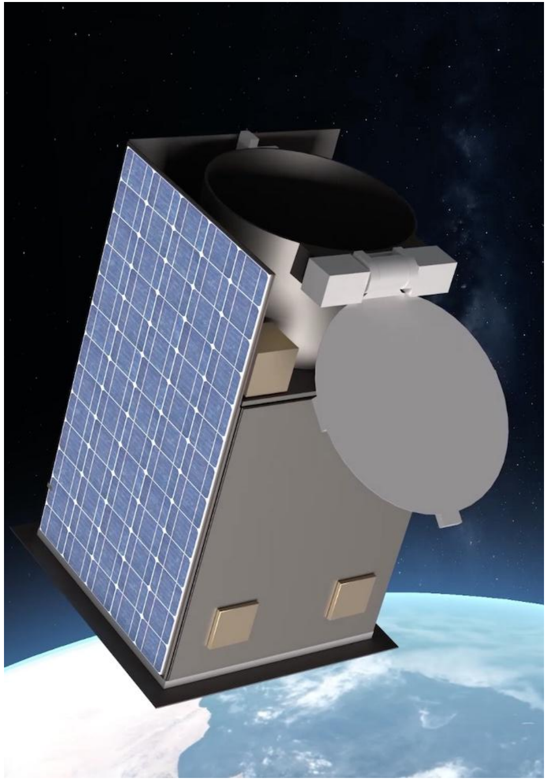


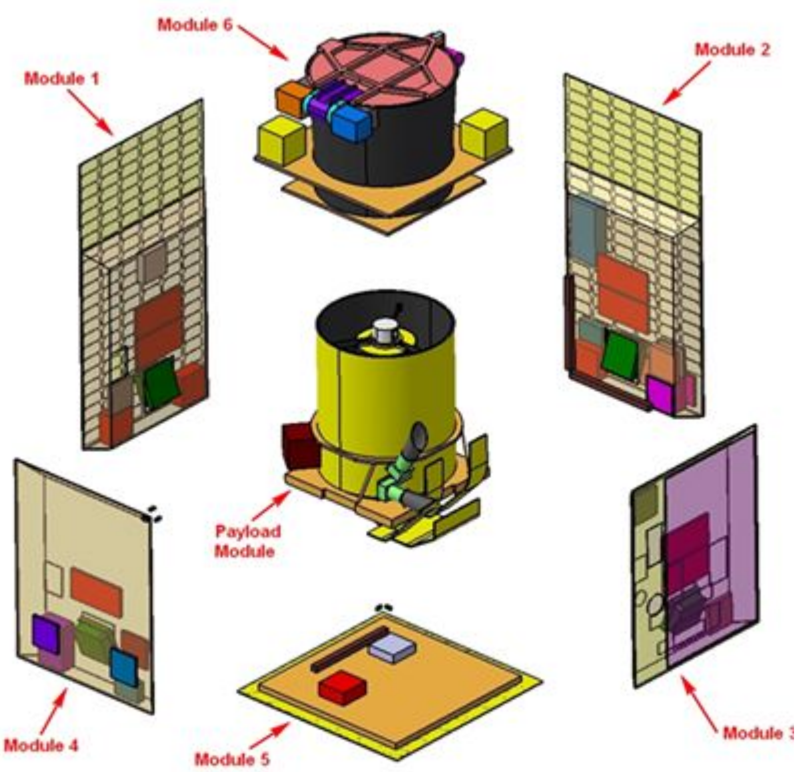


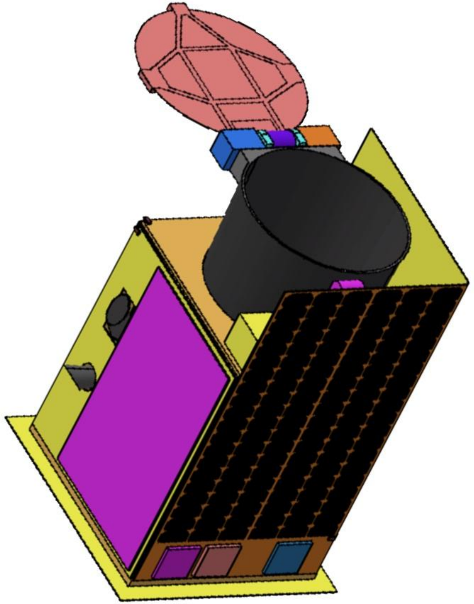


Quick UltraViolet Imager for Kilonovae (QUVIK)

35 cm, 5 deg^2, 2” pixels in (at least) 2 simultaneous UV channels







The Future is Bright (and full of telescopes)

… if we will it

Starlink Example

- SpaceX needs revenue stream to fund Highway to Mars
- Conventional satellite industry (EO, etc) insufficiently large to keep up with increasing capacity and falling launch costs
- SpaceX (temporarily) saturated the market for launch demand, but only worth ~$2B/yr …
  - not nearly enough for Mars
  - Not much more money to be made in excessively undercutting competition
- Need more cash for huge rocket with no customers…

So:

- Needs product with such overwhelming large consumer base to buy many many launches and subsidize new rocket
- Product should require launches, provide sufficient revenue stream
- Become their own customer, saturate launch capacity

Starlink Example

Communications/Internet provides the massive customer base

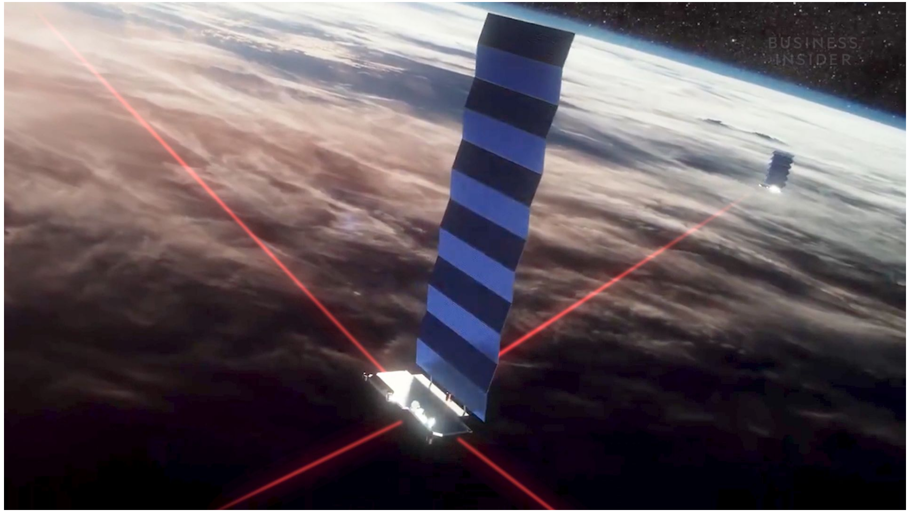
But this customer base only exists if cost is low enough (to compete with terrestrial ISP at the margins)

Leverage cheap launch, unique access

Low-orbit simultaneously provides lower latency, lower sat cost, <u>but also launch demand for continuous replenishment</u>

Shorter orbital lifetime decreases survivability/engineering requirements typical of GEO sats

Break paradigm of low #, high cost GEO sats by building thousands, iterating quickly on design flaws, get to mass production to control costs

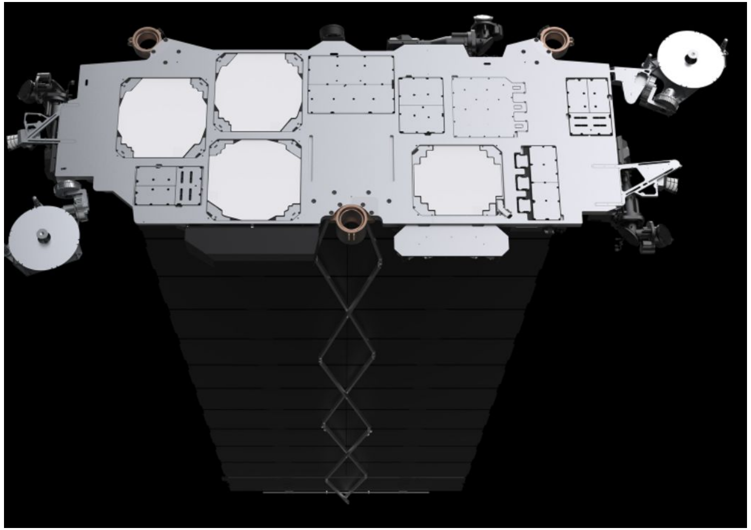


Starlink contd.

- ~300 kg (v1.5)
- ~3.2 x 1.6 x 0.2 m (stowed)
- 6 kW power generation
- Ion thruster
- Onboard autonomy
- Optical (laser) comms x 2
- 4 phased array, 2 parabolic antennas
- >20 Gbps throughput
- Development cycle ~3 months

Cost per unit?

Starlink contd…



<$300,000

After first 50

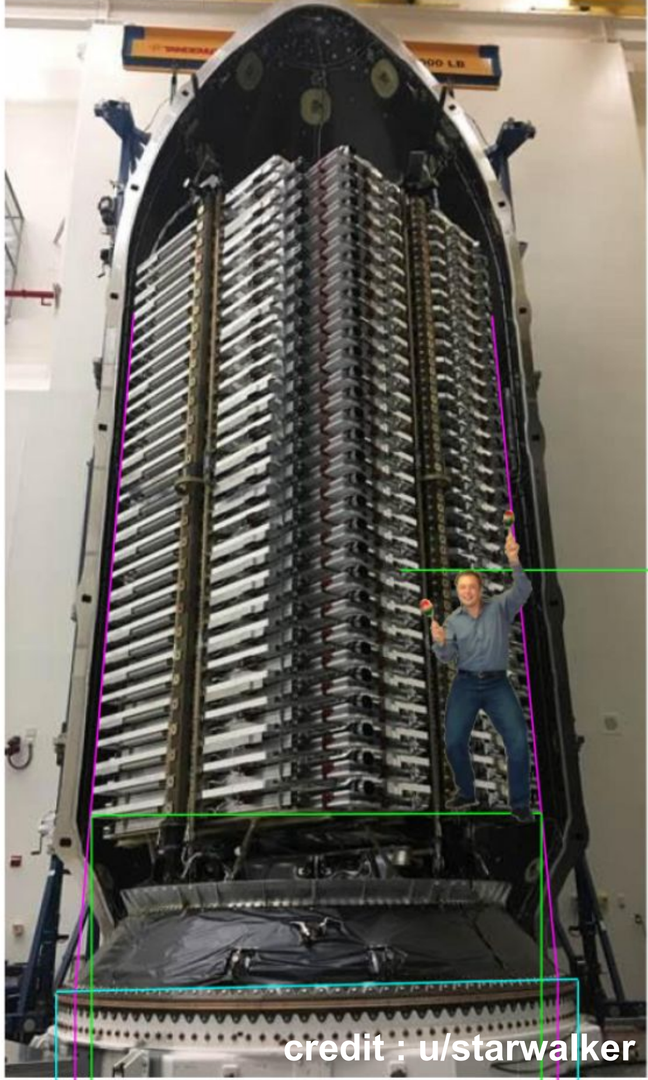
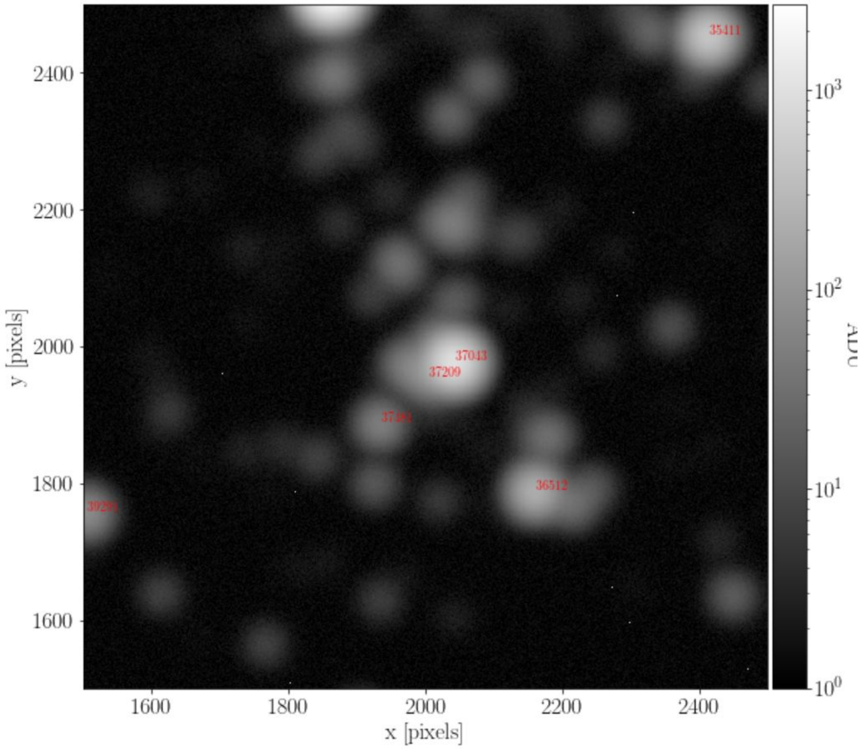
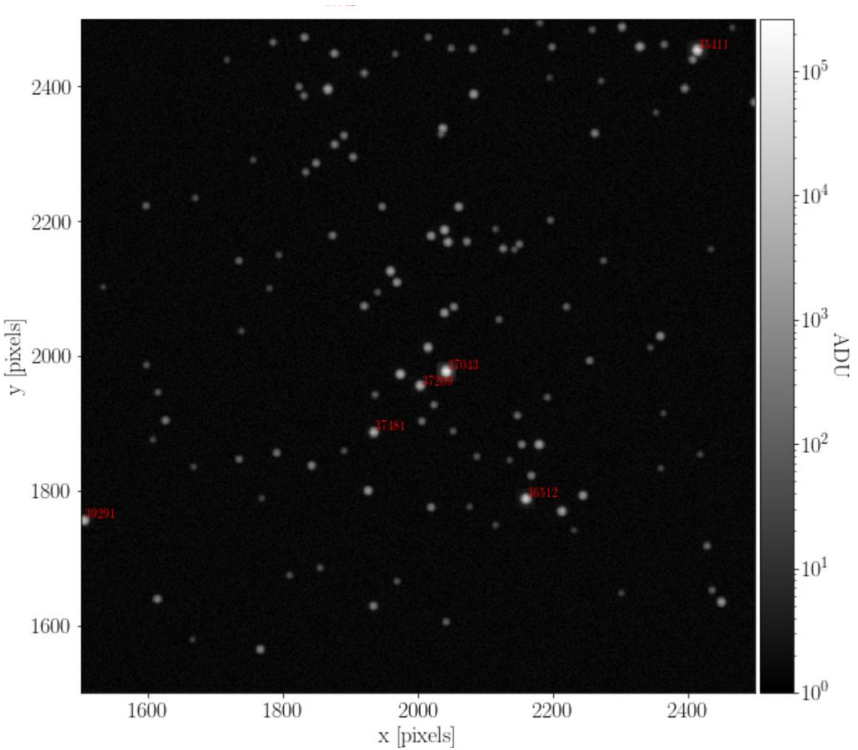


Image simulations

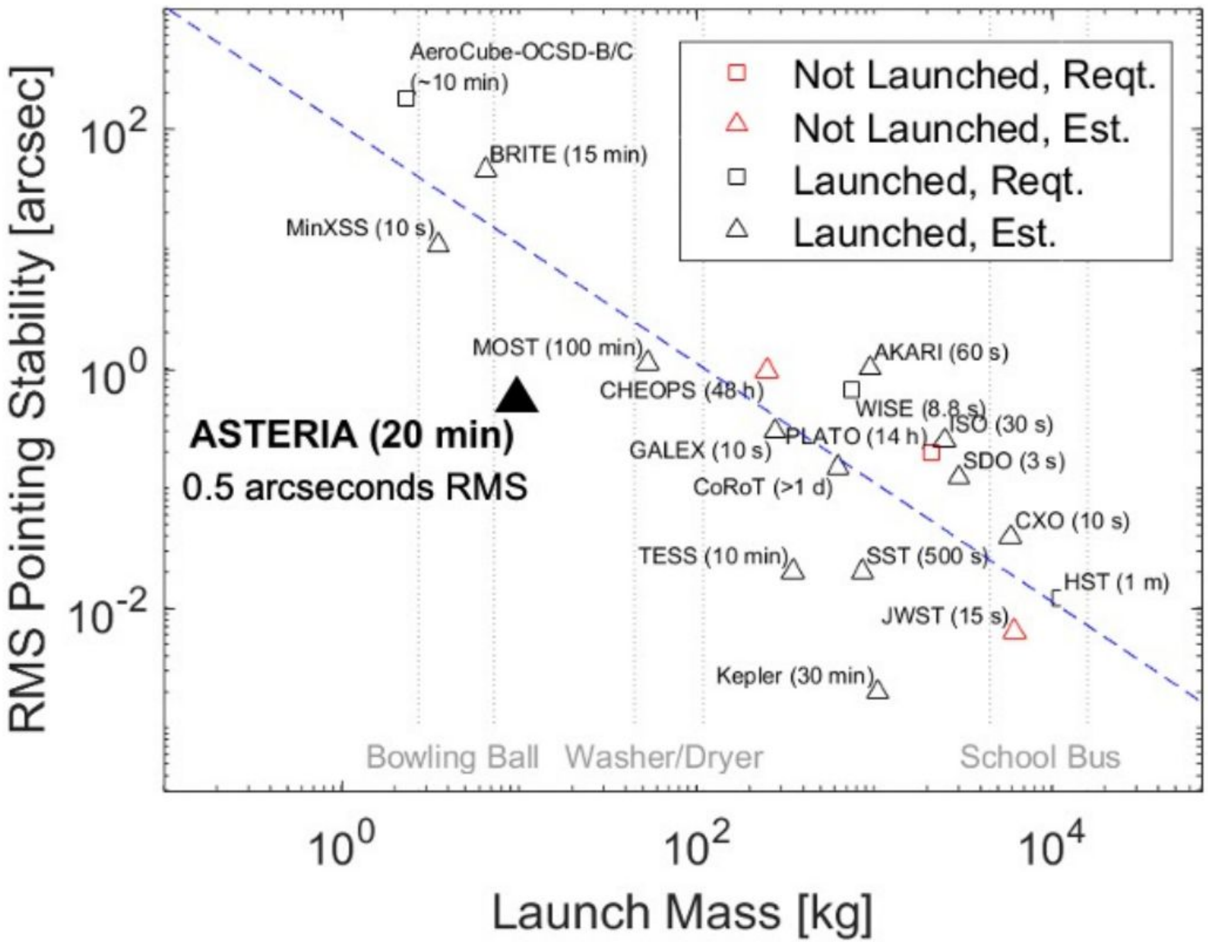
80s on Orion Nebula

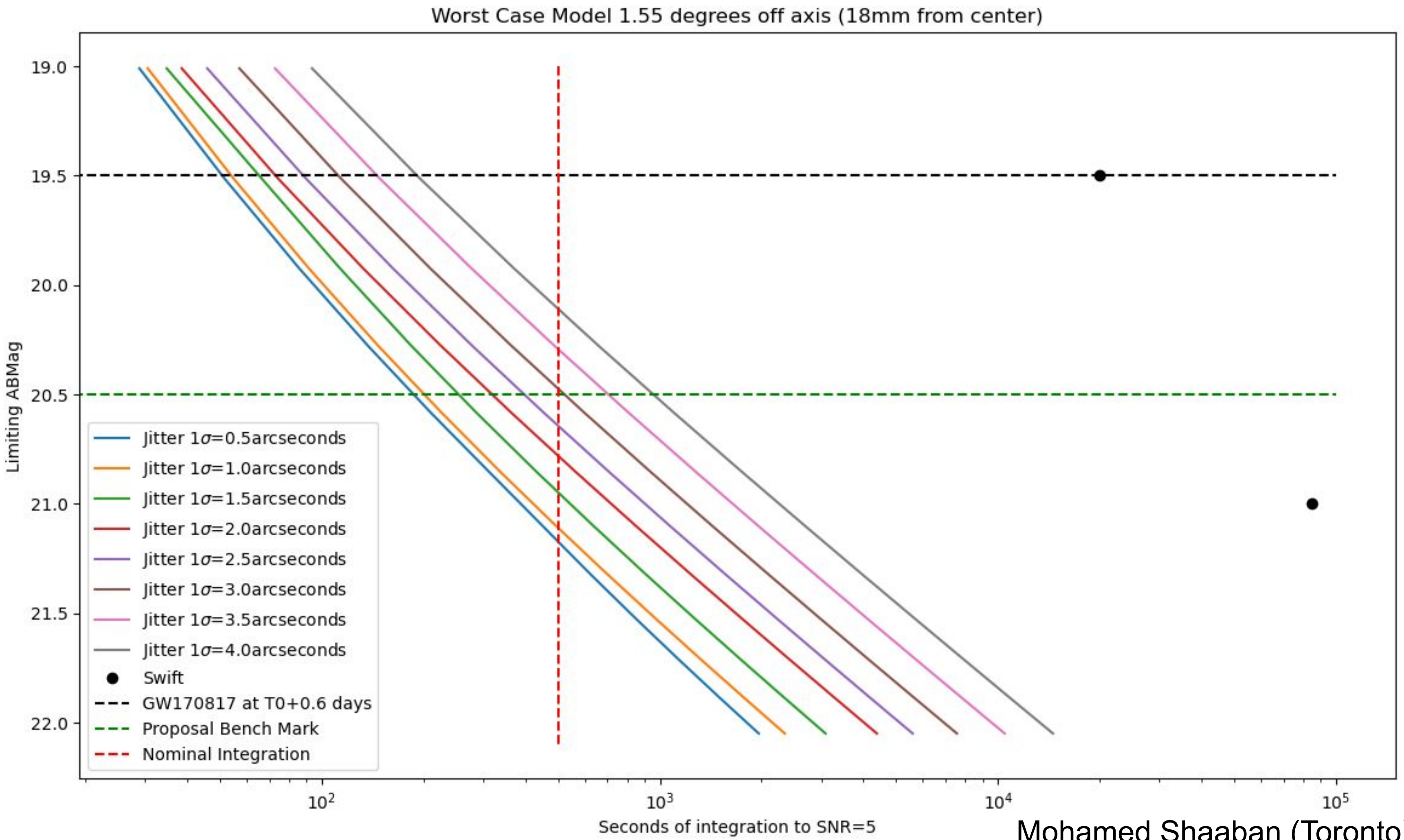


Jitter dominates

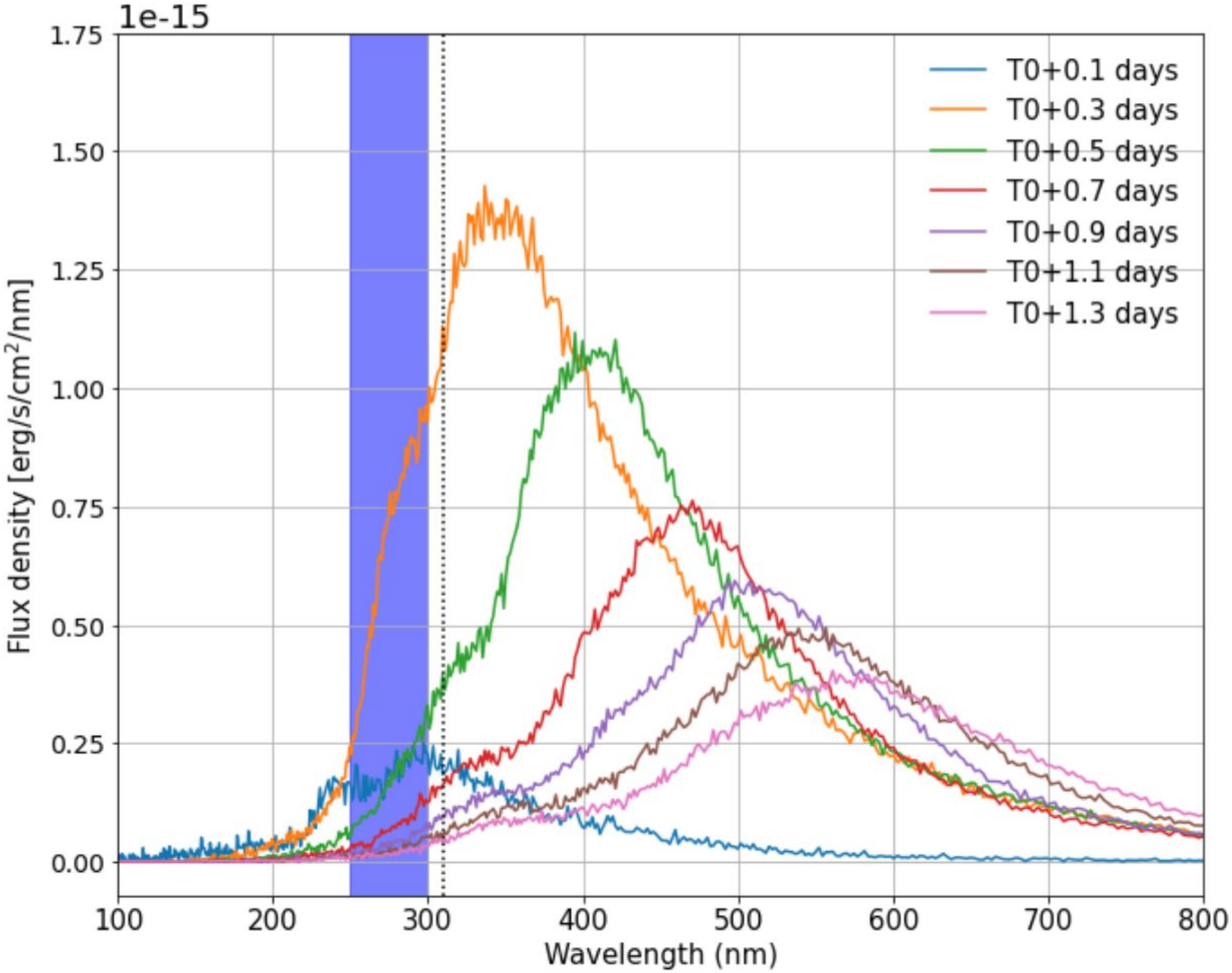


Jitter/Pointing Stability is a sensitivity and resolution limiter up SmallSat Class

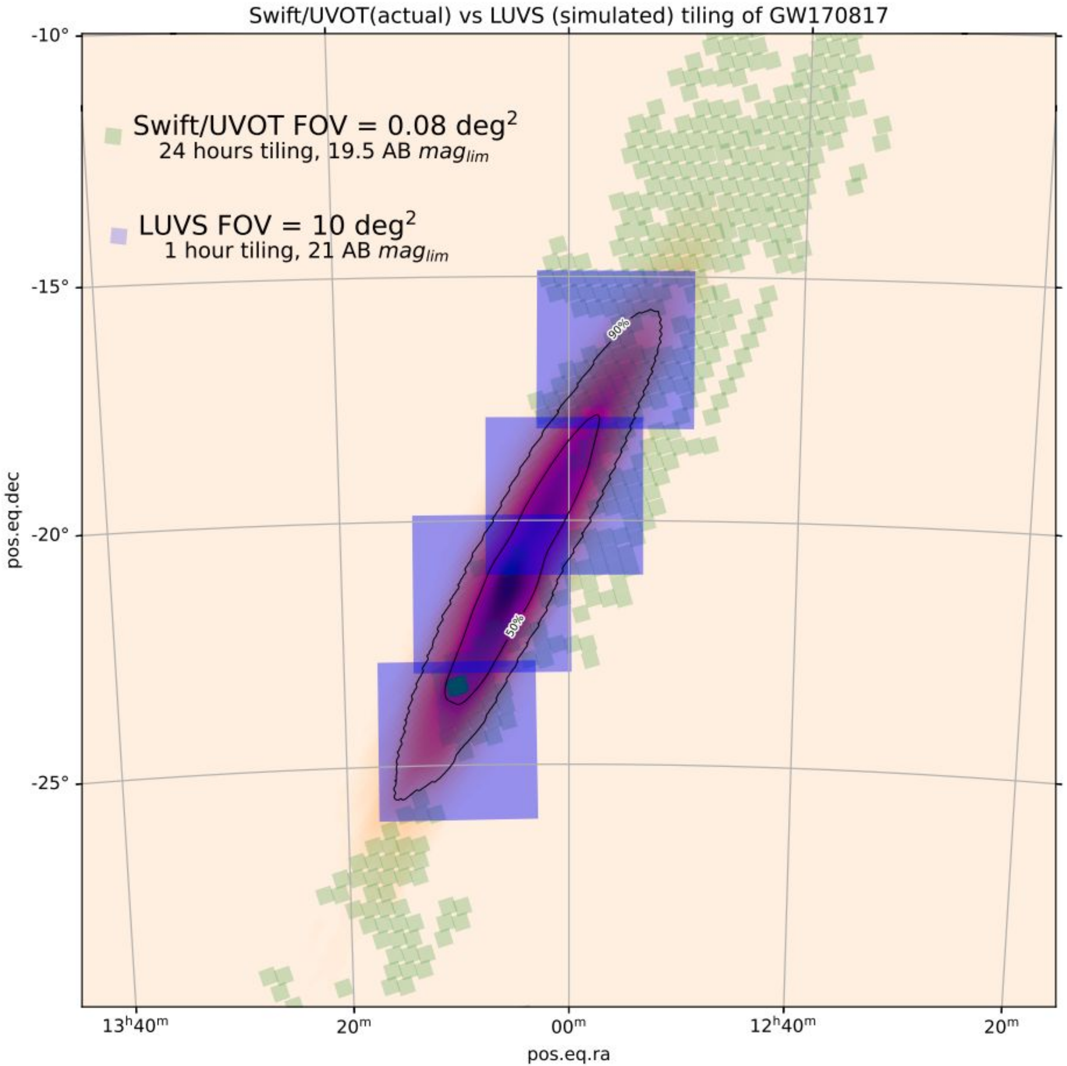


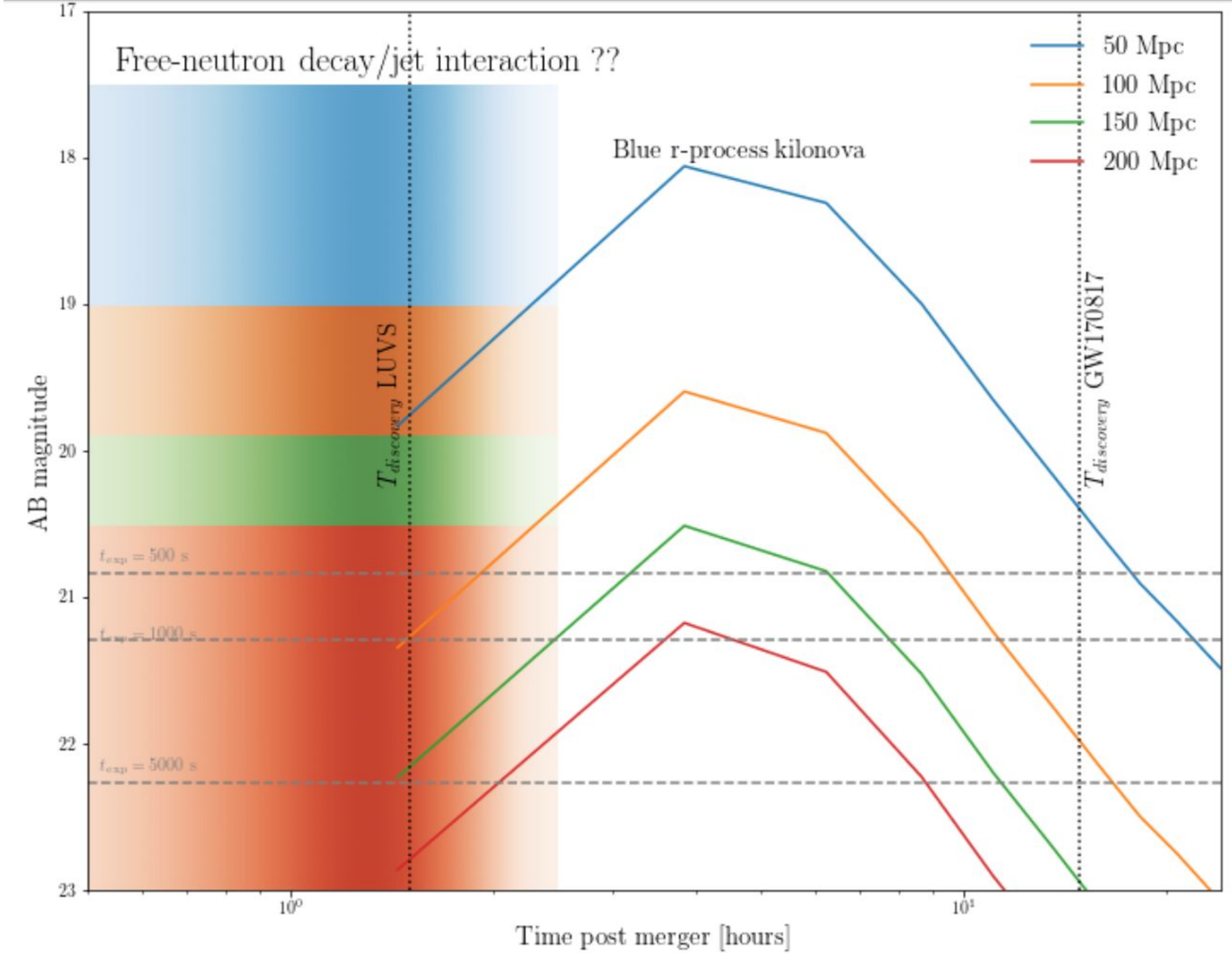


Mohamed Shaaban (Toronto)



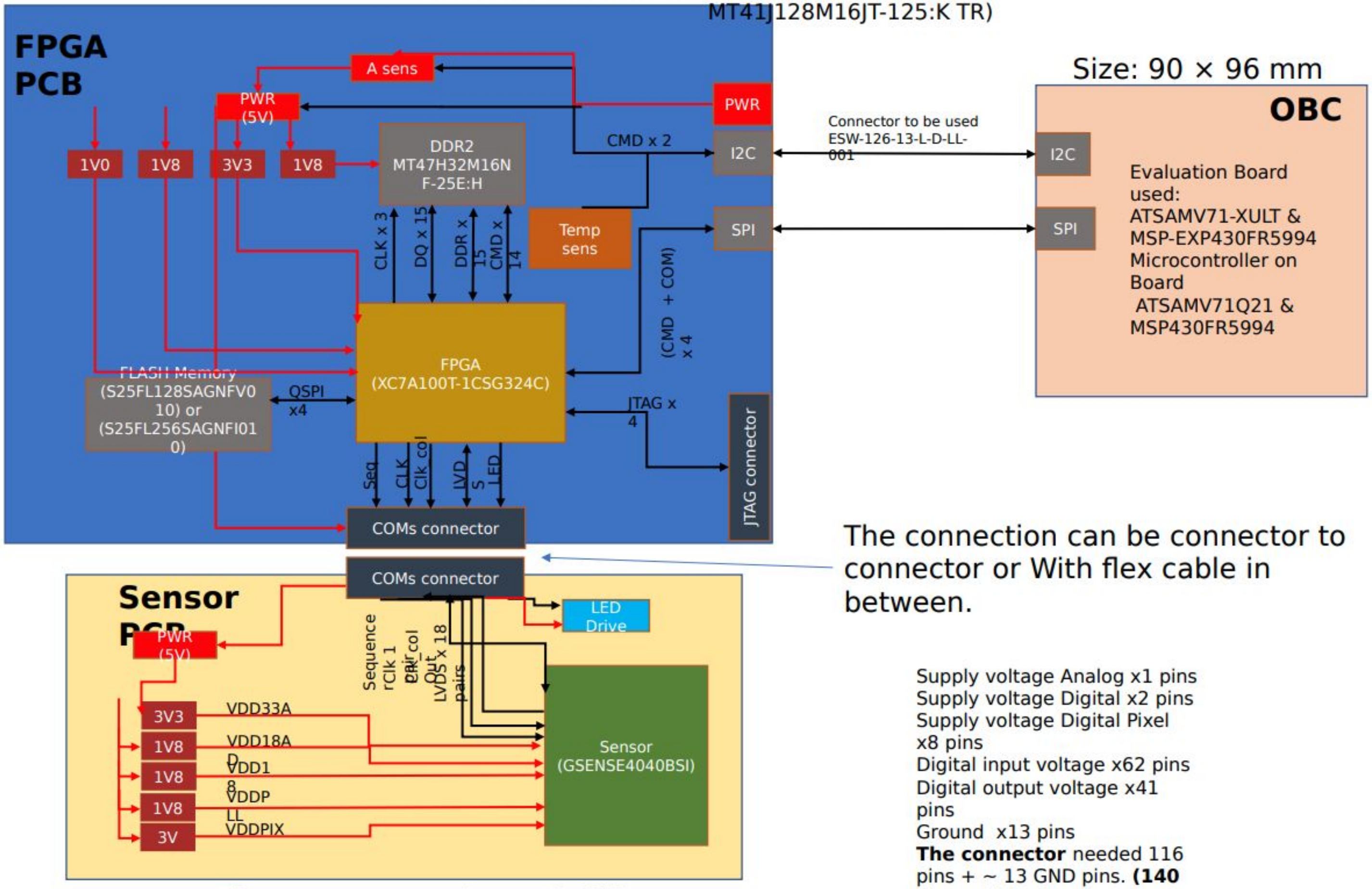
1e-15
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
Flux density [erg/s/cm^2/nm]
100
200
300
400
500
600
700
800
Wavelength (nm)
T0+0.1 days
T0+0.3 days
T0+0.5 days
T0+0.7 days
T0+0.9 days
T0+1.1 days
T0+1.3 days


Swift/UVOT(actual) vs LUVS (simulated) tiling of GW170817
Swift/UVOT FOV = 0.08 deg^2
24 hours tiling, 19.5 AB mag_{lim}
LUVS FOV = 10 deg^2
1 hour tiling, 21 AB mag_{lim}
90%
50%
-10°
-15°
-20°
-25°
pos.eq.dec
13^{h}40^m
20^m
00^m
12^{h}40^m
20^m
pos.eq.ra



Free-neutron decay/jet interaction ??
Blue r-process kilonova
50 Mpc
100 Mpc
150 Mpc
200 Mpc
$T_{discovery}$ LUVS
$T_{discovery}$ GW170817
$t_{exp} = 500$ s
$t_{exp} = 1000$ s
$t_{exp} = 5000$ s
AB magnitude
17
18
19
20
21
22
23
10^0
10^1
Time post merger [hours]

We can use the following DDR3 instead of DDR2 (FPGA board: MT41J128M16JT-125:K TR)



The connection can be connector to connector or With flex cable in between.

Supply voltage Analog x1 pins
Supply voltage Digital x2 pins
Supply voltage Digital Pixel x8 pins
Digital input voltage x62 pins
Digital output voltage x41 pins
Ground x13 pins
The connector needed 116 pins + ~ 13 GND pins. **(140 Pins will be fine)**

Power consumption: <1.4W