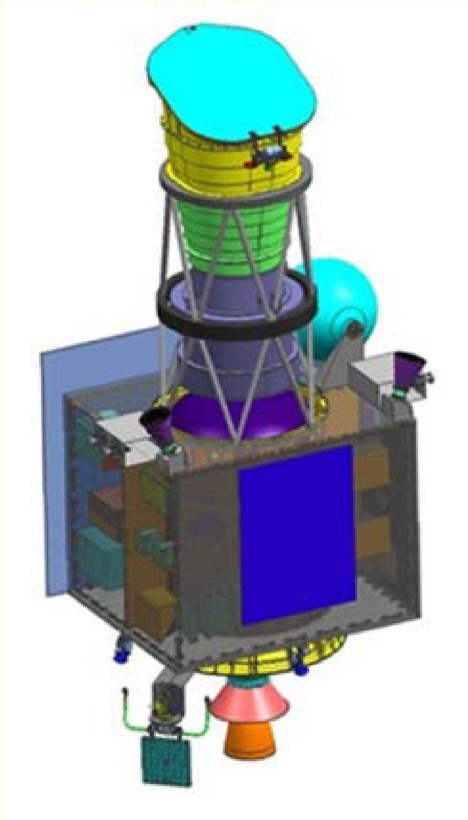
ULTRASAT: A Wide-Field UV Space Telescope

Revolutionizing our view of the transient Universe



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Admin	R. Baram (WIS)
Fin/Admin oversight	H. Atsits (WIS)

Funding partners
ISA
WIS
DESY
NASA

Industry partners
IAI
Elop
Tower

The study of Transient Cosmic Phenomena is taking Center Stage

An exciting frontier, many fundamental open questions

Sources	**Open questions**
Collisions and mergers of stars	- Where did the heavy elements, from Iron to Gold and Uranium, form? - How do black holes form? - What is the current expansion rate of the Universe?
Explosive deaths of massive stars	- How do massive stars explode and affect their environment?
Tidal disruption of stars by super-massive black holes (SMBH)	- What is the SMBH "demographics"? - How do they affect their environment? - How is mass accreted onto BH?
…	…

Why now?

Technology enables telescopes with very large fields of view,

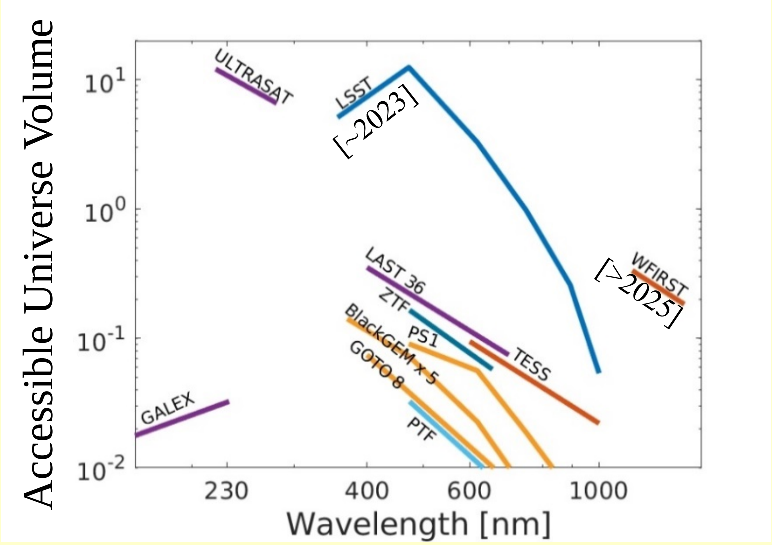
Allowing a systematic study of transient events.

ULTRASAT will be unique and superior to all other missions

- ULTRASAT's Unique capabilities
- Very large (200 deg^2) field of view
- High UV (220-280nm) sensitivity:
  $f = 1.5 \times 10^{-3}$ ph/cm^2 s (900s, 5σ)
  [$m = -2.5 \log_{10}(f/f_0) = 22.4$]
- Geo-stationary orbit

- UV advantages
- Low sky background
- Strong signals from hot sources
- Unique information

Transient detection rates of leading surveys



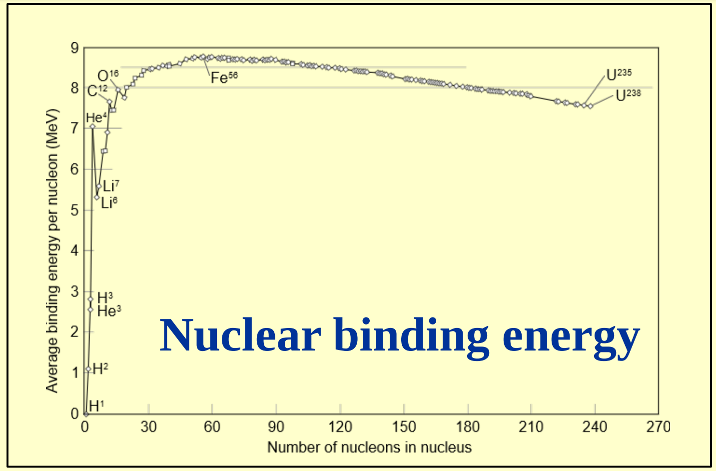
- Monitor an unprecedentedly large volume of the Universe
- New window in wavelength (NUV) and in cadence (min - mon).
- Real-time alerts to ground/space-based telescopes, initiate world-wide follow-ups.

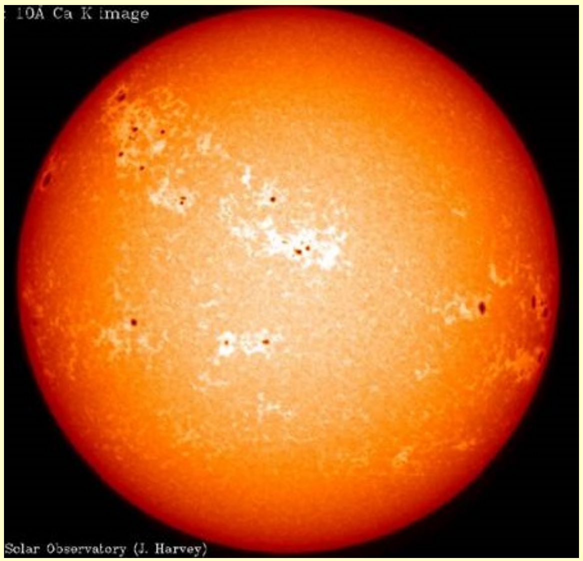
ULTRASAT: Science highlights

Source Type		# Events per 3 yr mission	Science Impact
Supernovae			
	Shock break-out and Early (shock cooling) of core collapse SNe	>40 >500	Understand the explosive death of massive stars
	Superluminous SNe	>250	Early evolution, shock cooling emission
	Type Ia SNe	>40	Discriminate between SD and DD progenitors
Compact Object Transients			
	Emission from Gravitational Wave events: NS-NS and NS-BH	~25	Constrain the physics of the sources of gravitational waves
	Cataclysmic variables	>25	Accretion and outburst physics
	Tidal disruption of stars by black holes	>250	Accretion physics, black hole demographics
Quasars and Active Galactic Nuclei			
	Continuous UV lightcurves	>7500	Accretion physics, BLR Reverberation mapping
Stars			
	M star flares	$>4\times10^5$	Planet habitability, magnetospheres
	RR Lyrae	>1000	Pulsation physics
	Nonradial hot pulsators, e.g., α Cyg, δ Scuti, SX Phe, β Cep etc. types	>250	Asteroseismology
	Eclipsing binaries	>400	Chromosphere and eclipse mapping
Galaxies and Clusters			
	All Sky Survey – galaxies	$>10^8$	Galaxy Evolution, star formation rate

Key Science Goal 1: Mergers of Neutron Stars

The evolution of Massive stars: Some open questions





"Dead" remnants of massive stars

?

Massive Stars
$M \sim 10 \times M_{sun}$

Neutron Star
$1\ M_{sun}$
10 km
10^{14}g/cc

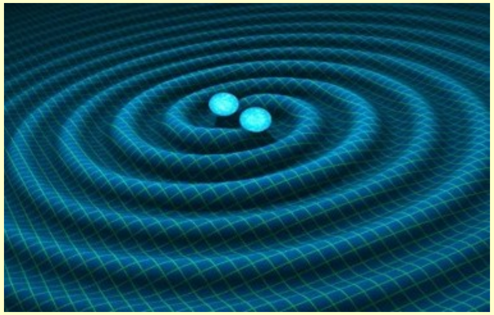
Black Hole
$1\ M_{sun}$
3 km

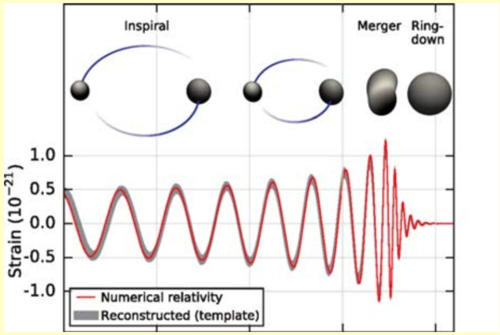
Burn H → He → C/O → Si → Fe

- Once nuclear energy source exhausted, collapse and explode as Supernova- How?
- Where were the elements beyond Fe produced?

Merging Binary Neutron Stars / Black Holes

- Most stars "live" in binaries
- Massive star binaries may lead to the formation of binary Neutron Star / Black Hole systems
- "Tight" NS/BH binaries, separation < 1 Million km, can merge by emitting Gravitational Waves (GW).
- GW Detection- A fundamental test of GR (1916)
- 2016:
  LIGO detects a 2x 30 solar mass BH binary merger.
  Distance ~ 1 Billion light years
  2017: Physics Nobel Prize (Weiss, Barish, Thorne).



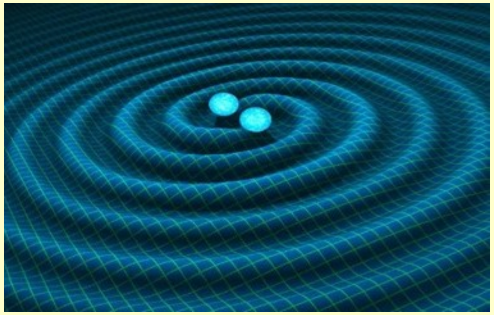


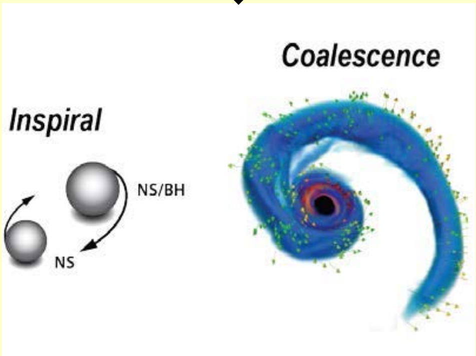
Detecting GW and light from NS-NS/BH mergers

- Nuclear density radioactive material torn and ejected at close to light speed. May be the source of heavy, “rapid neutron capture”, elements beyond Iron.

- Detecting light from radioactive material following GW is (one of) the major goals of astronomy in the coming decade:

- Identify the origin of heavy elements
- Study the properties of material at nuclear density
- Accurately localize the merger, identify host galaxy → Measure the current expansion rate H_0 of the Universe
- Identify environment → Constrain progenitor system





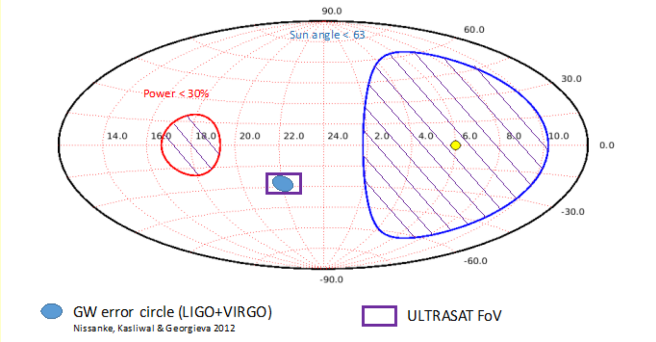
ULTRASAT Key Science Goal 1: GW sources

- Starting early 2025, GW detectors will improve detection horizon to ~ 1 Billion light years, provide ~ 10 NS-NS merger events per year, with ~100 squared degree error box.
  (Until then - a few in total.)

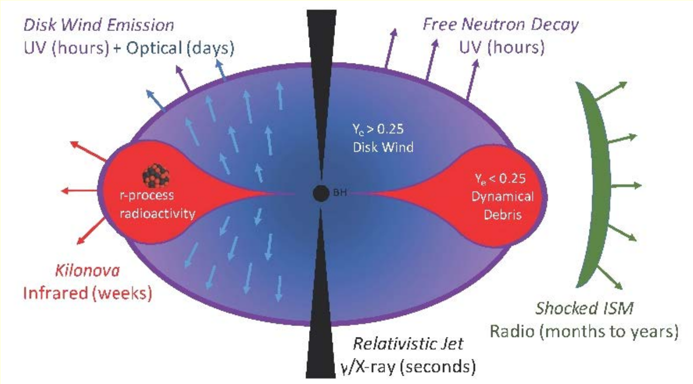
- EM detection- ULTRASAT:
  - Instantaneous >50% of sky in <15 min. (8 times better than ground based).
  - GW error box in a single image.
  - Sensitive out to ~ 1 Billion light years.

- EM detection in other bands-challenging:
  - X-rays: likely 1:100 (beamed).
  - Radio: ~1yr delay

ULTRSAT's ToO access



Bright, Early (hr) UV emission expected



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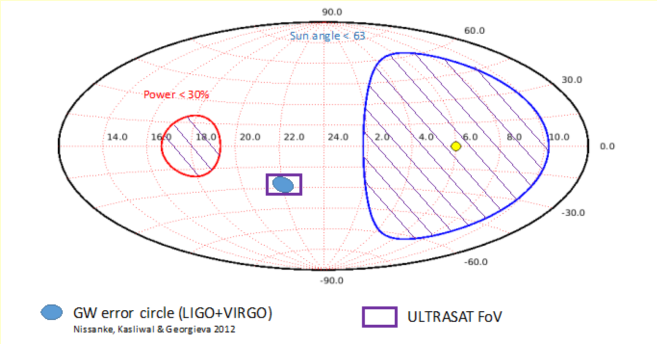

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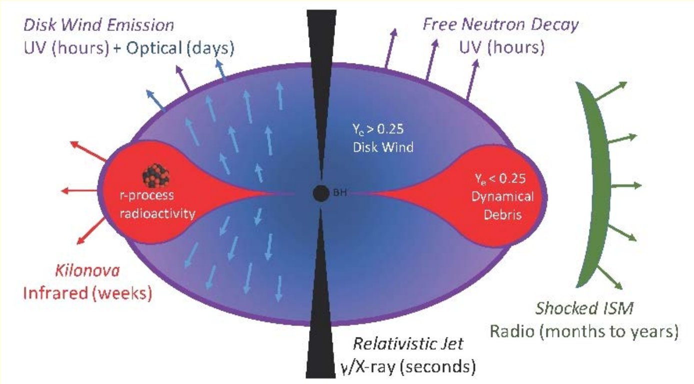


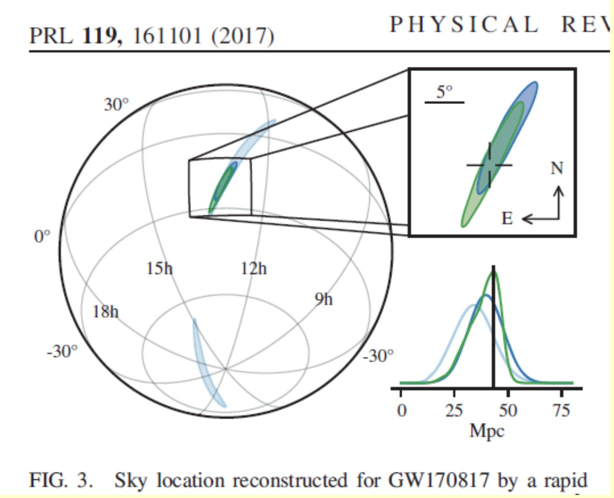
Must be in space by 2025

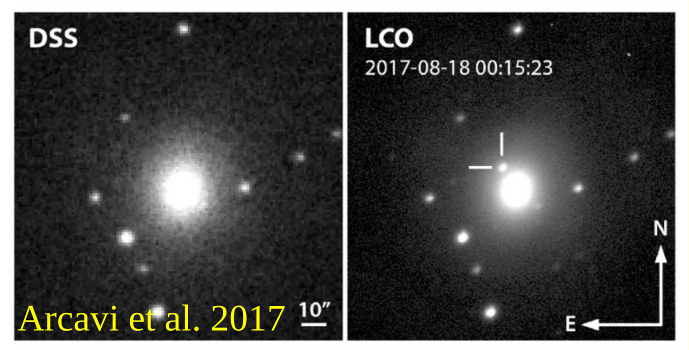
First detection of GW from a NS merger [2017]

- Very nearby, 120 M light-yrs.
  Light detected after 0.5 day, Very UV bright

- ULTRASAT is far superior to other searches:
  - GW error box covered in single image,
    vs search over ~10^3 galaxies at 1B light-yrs.
  - EM detection in other bands-challenging.
    X, γ: GW170817 NOT detectable 200M l-yrs.
    IR, Radio: Challenging and late detection.

- Heavy elements beyond Iron – produced.
  - How heavy (Germanium or Gold) – uncertain.
  - More detections, with earlier light detection,
    are required.
  - Early UV has unique discriminating power.





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PRL **119**, 161101 (2017) PHYSICAL REV

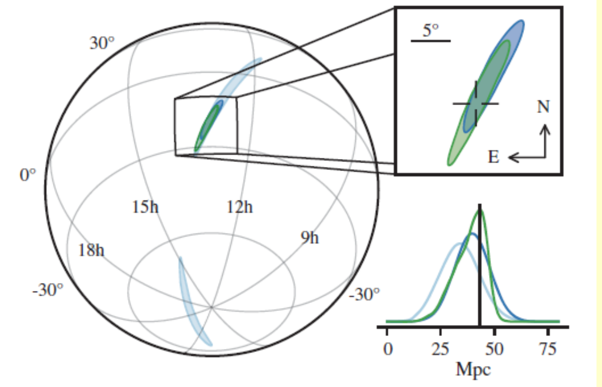
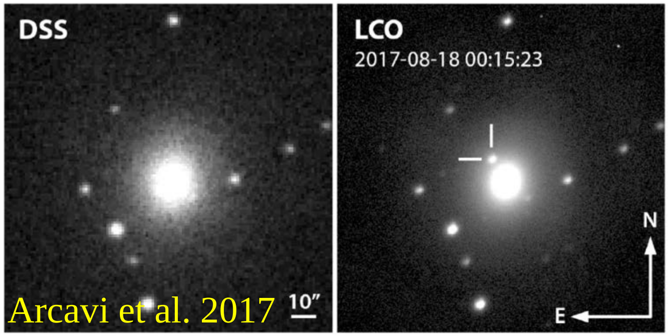


FIG. 3. Sky location reconstructed for GW170817 by a rapid



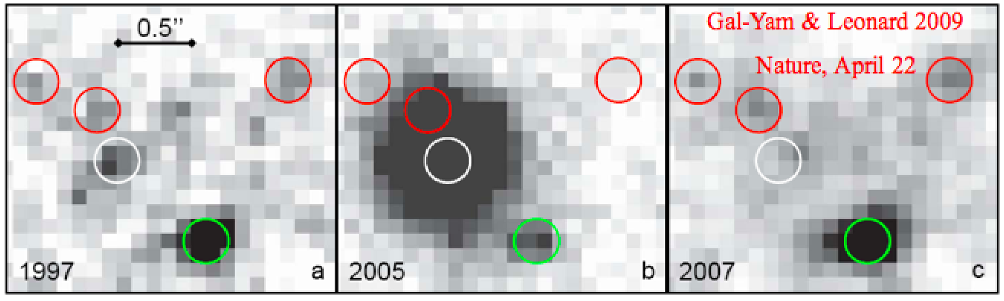
Strong support to ULTRASAT

Key science goal 2: Deaths of Massive stars

- Supernova mechanism not understood.
- Key to progress:

- Identify the "initial conditions", which stars explode as which SNe?

- So far- a handful of associations: pre- vs post- explosion high-res. galaxy images



- An alternative- Early, <1d, UV emission

carries unique signatures of the progenitor ("erased" at later time):

- Progenitor type (size, envelope composition),

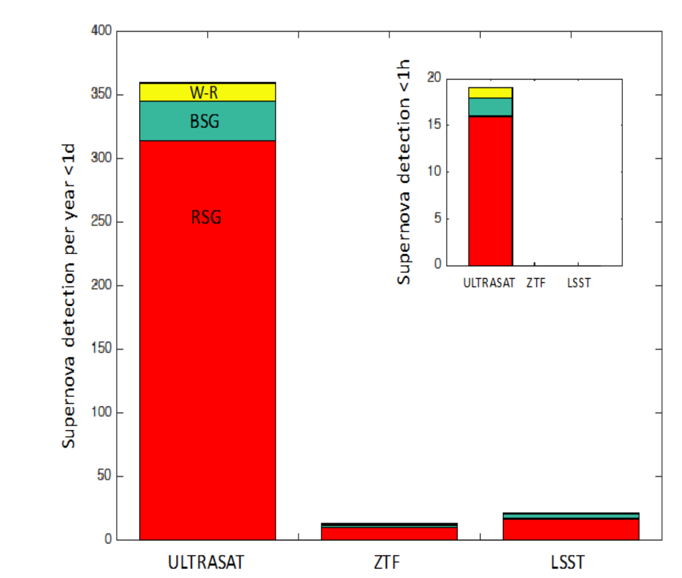
- Explosion properties,

- Pre-explosion evolution.

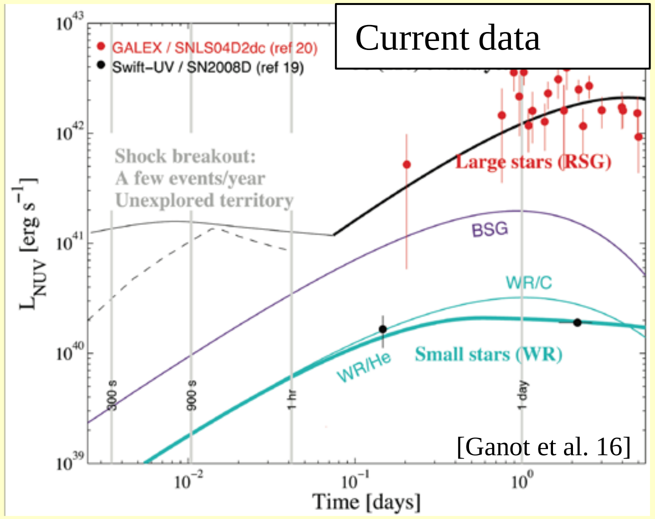
SN explosions: ULTRASAT's uniqueness

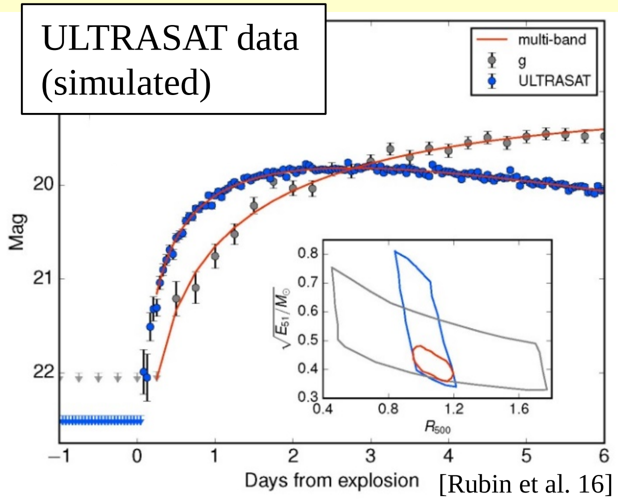
ULTRASAT

- High quality early UV data,
  Rapid alerts for follow-ups.
- Determine progenitor and environment
  properties for all, including rare, SN types.



Ganot et al. 2016; ApJ, 820, 57





Science goal: Planet habitability

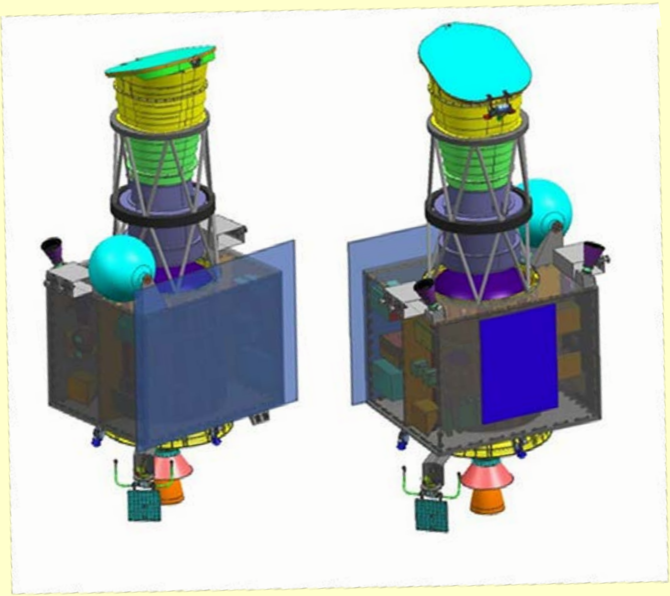
- UV flares and Coronal Mass ejections around prime candidate stars for terrestrial planet searches (M-dwarfs/young Solar analogues)
  - Severely limit habitability,
  - May allow prebiotic chemistry,
  - May produce false positive biomarker signatures (O_3 from photo-dissociation of H_2O & CO_2).

- Flares dominate UV output. Flare rates unknown.

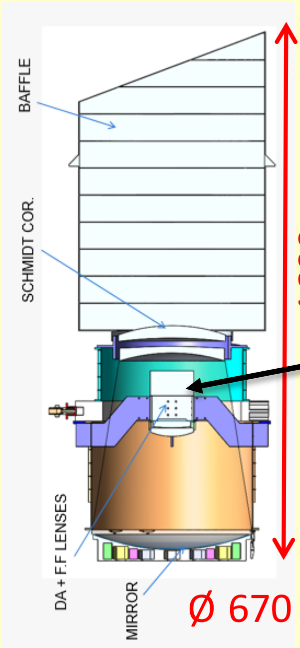
- ULTRASAT will monitor ~10^6 stars
  - Determine NUV flare frequency and luminosity distribution as functions of both spectral subclass and stellar rotation period,
  - Determine best habitable planet candidates (e.g., from TESS) for expensive spectroscopic bio-marker searches, e.g. by JWST.

ULTRASAT: Implementation & Collaboration

Spacecraft: IAI



Telescope: Elop/Elbit



Focal Plane Array ("Camera"): DESY/Helmholtz

Sensor: Tower

Hosted launch to GEO (GTO): NASA

Launch Q4 2024, >3 year science mission

Dimentions: 1.5 x 1.1 x 3.0 (m^3)
Power: 300 W
Mass: 400 + 500 (Prop) kg

ULTRASAT: Mission profile

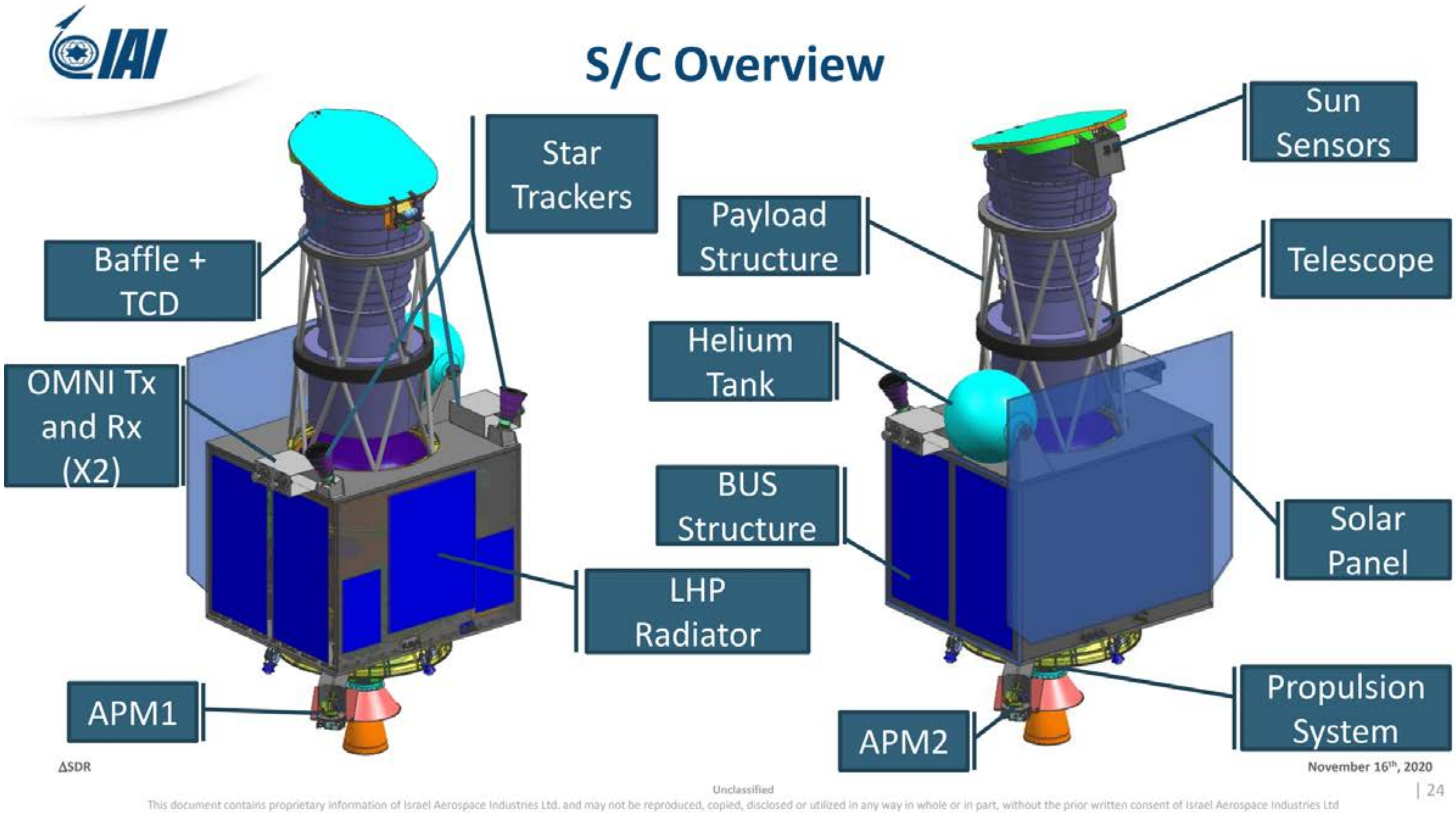
- ALL SKY SURVEY
  - 3hr/day during the first 6 months
  - 7x deeper than state-of-the art (GALEX) (23 AB limiting mag @ |b|>30°)

- LONG STARES
  - 2 directions near the Ecliptic poles, minimize Galactic extinction and zodiac bgnd
  - Real-time data download and analysis
  - Alerts within 15min of observations

- Targets of Opportunity (ToO's)
  - Instantaneous >50% of the sky in <15 min for >3 h
  - No limit on ToO number, except for max 75 with negative power balance (~15%)
  - Continuous transmission to the ground

Spacecraft & Telescope

S/C Configuration



Telescope & Camera Requirements

- 220-280nm Sensitivity 1.5×10^{-3} ph/cm^{2}s (900s, 5σ)
  Over a field of view of 170 deg^2

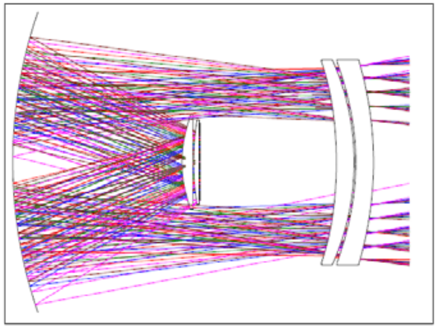
- Translates to requirements* on

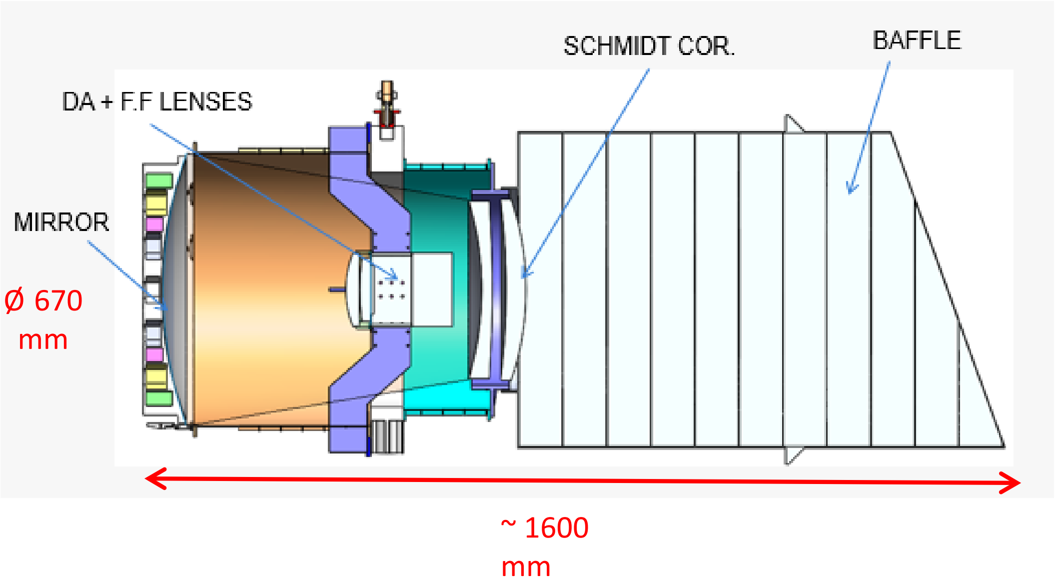
Optics	- FOV 170 deg^2
	- PSF (Point Spread Function) < 15”
	- Out-of-band suppression $<4\times10^{-3}$
Detector	- QE 70%
	- Dark current < 0.03 e^-/s (cool to 200 °K)
	- Read noise < 3.5 e^-
Baffle	- Stray light suppression < 2×10^{-11}
	- Cosmic-ray e^- suppression (Cerenkov) < 0.15

*Partial list

Telescope: Main Components

- Baffle
- Schmidt Corrector
  - Reduce Spherical aberration
  - 33 cm clear aperture
  - Fused Silica & CaF_2 (tandem)
- Mirror
  - 50 cm
- Field Flattener lens
  - Reduces Field Curvature
- Detector Assembly
- Added after PDR
  - Out-of-band filter at FF
  - Focus mechanism at FF





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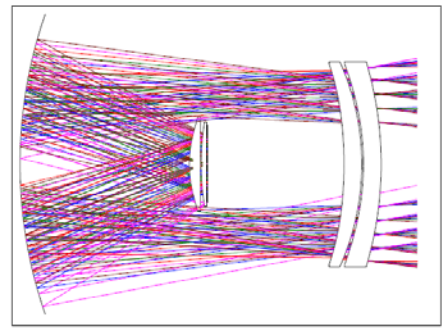
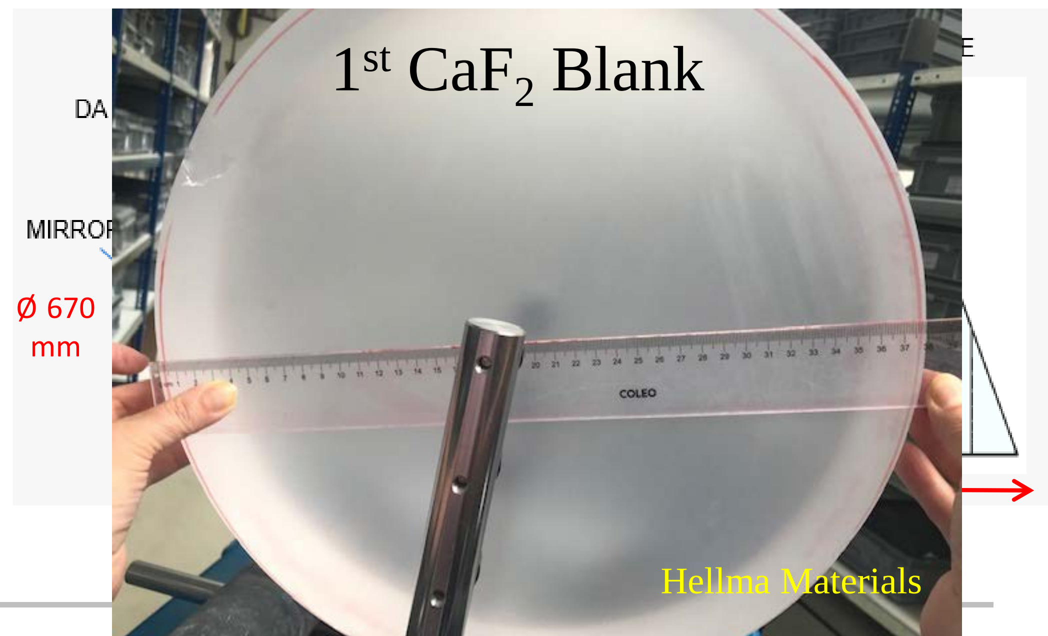
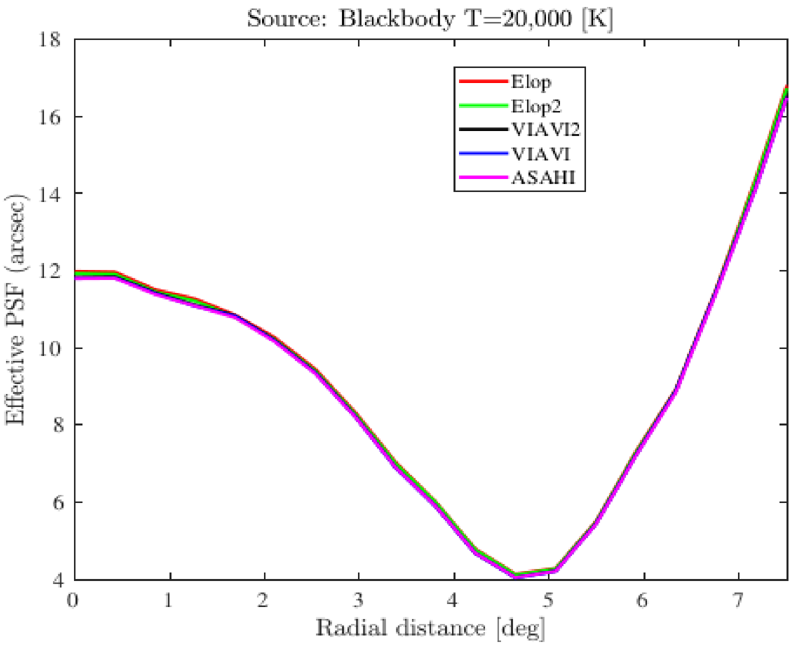


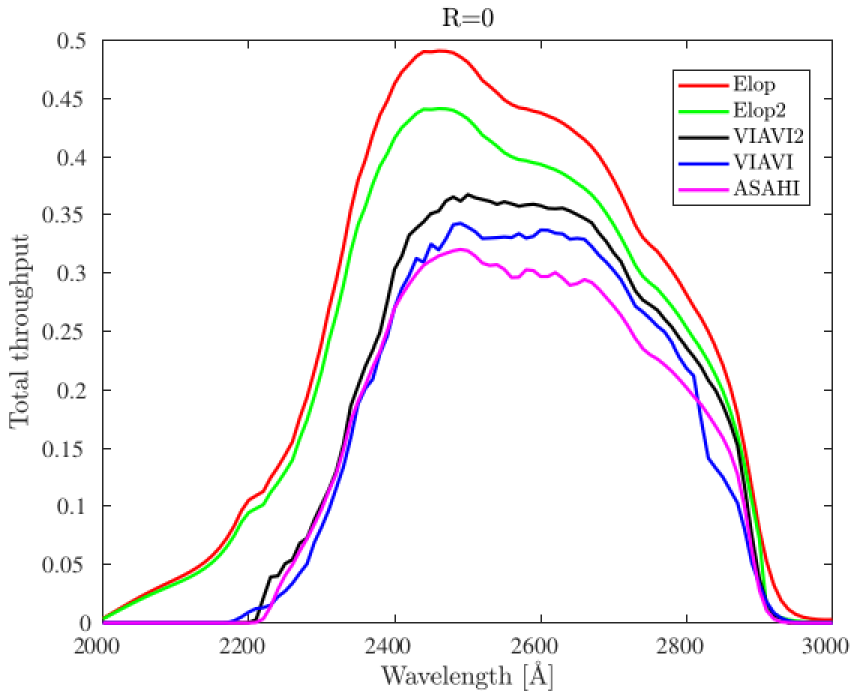


Effective PSF (model): Meets requirements

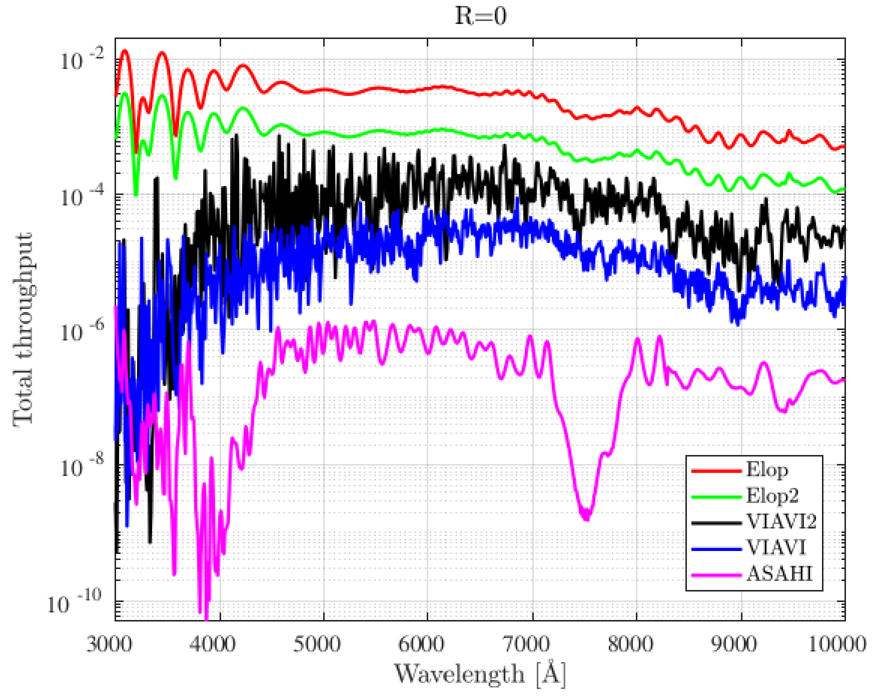


Optics coatings & Filters (Measured): Meets out-of-band attenuation requirements

Inband

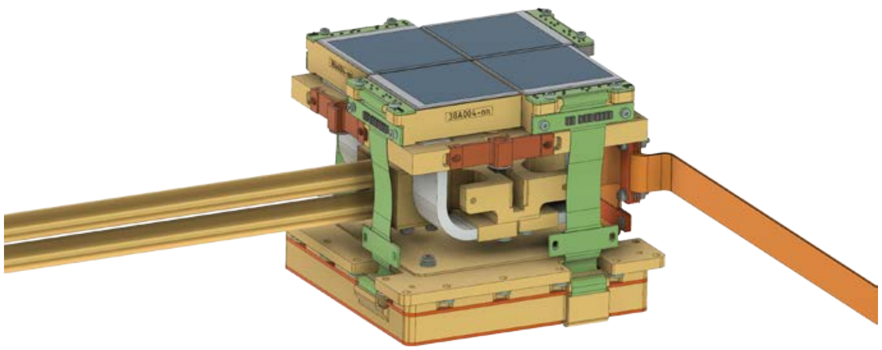


Out of band



Focal Plane array: Main characteristics

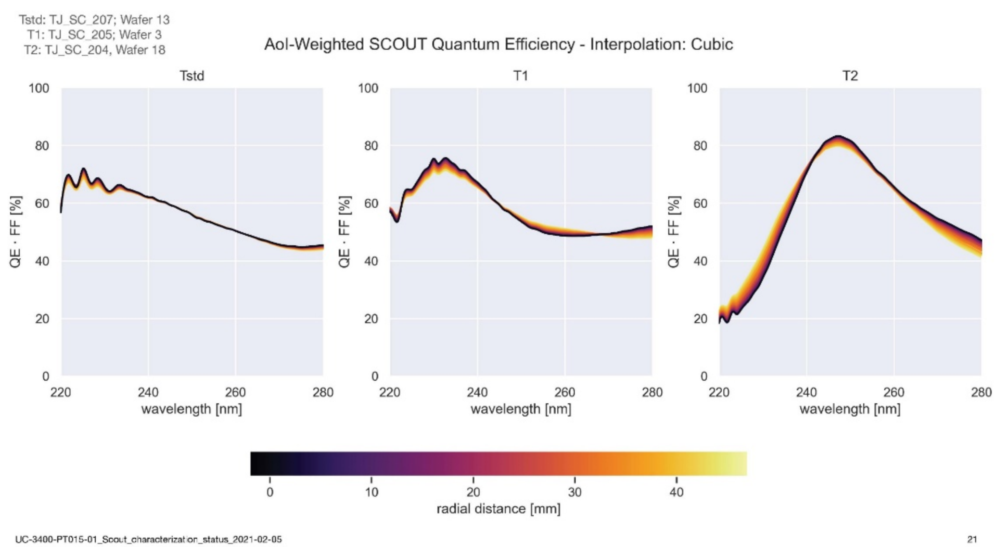
- BSI CMOS from TowerJazz
  (4 tiles aligned to < 50 μm)
- High UV QE using
  high-K dielectric coating,
  optimized anti-reflection coating
- Ramon Space support for space qualified design (e.g., radiation hardness)

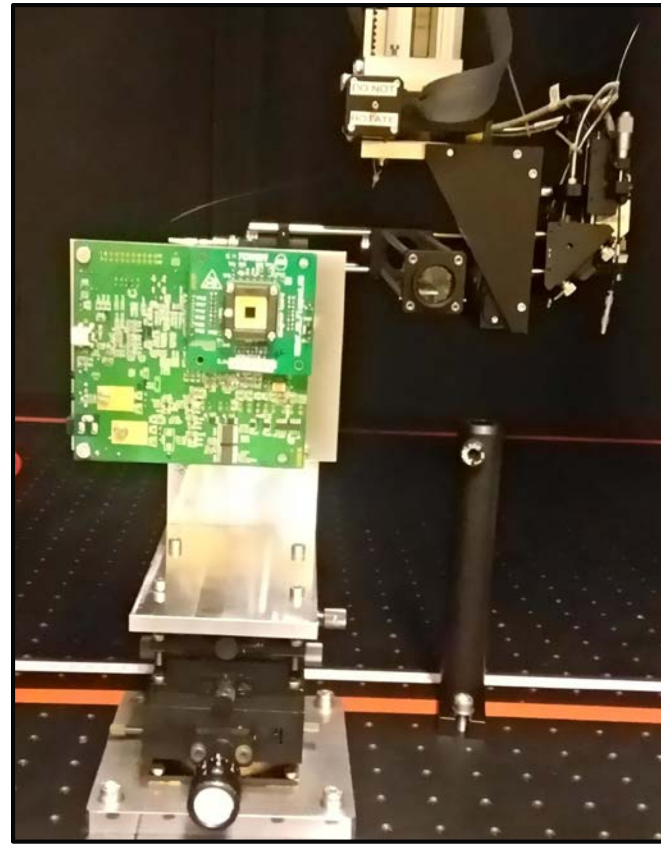


<u>Sensor main Specs.</u>

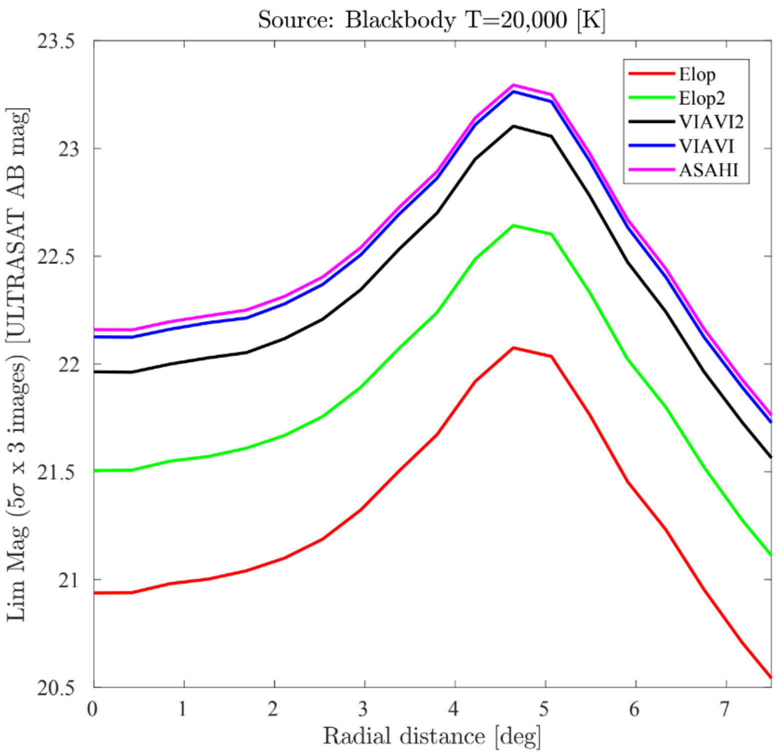
Photosensitive surface	90x90 mm
Pixel size	9.5 μm
Operation waveband	220-280nm
Mean QE in Operation band	>70%
Operation temperature	200±5 °K
Dark current @ 200 °K	<0.03 e^-/sec
Readout mode	Rolling shutter
Readout time	<25 sec
Readout noise @ High-gain	<3.5 e^-/pixel
Electronic cross-Talk	<0.01%
Pixel sampling scheme	HDR capability
Low-gain Well capacity	140-155 Ke^-
High-gain Well capacity	16-21 Ke^-
Bits per Pixel – total (data only)	14 (13)

“Scouts” QE (Measured): Meets requirements





Sensitivity: Meets requirements



- Optics: Model
  Will be measured on ground
- Coatings, filters, QE: Measured
  (samples & scouts)

$f = 1.5 \times 10^{-3}$ ph/cm^2 s (900s, 5σ)

$m = -2.5 \log_{10}(f/f_0) = 22.4$

Ground station
and
Science Operation Center (SOC)

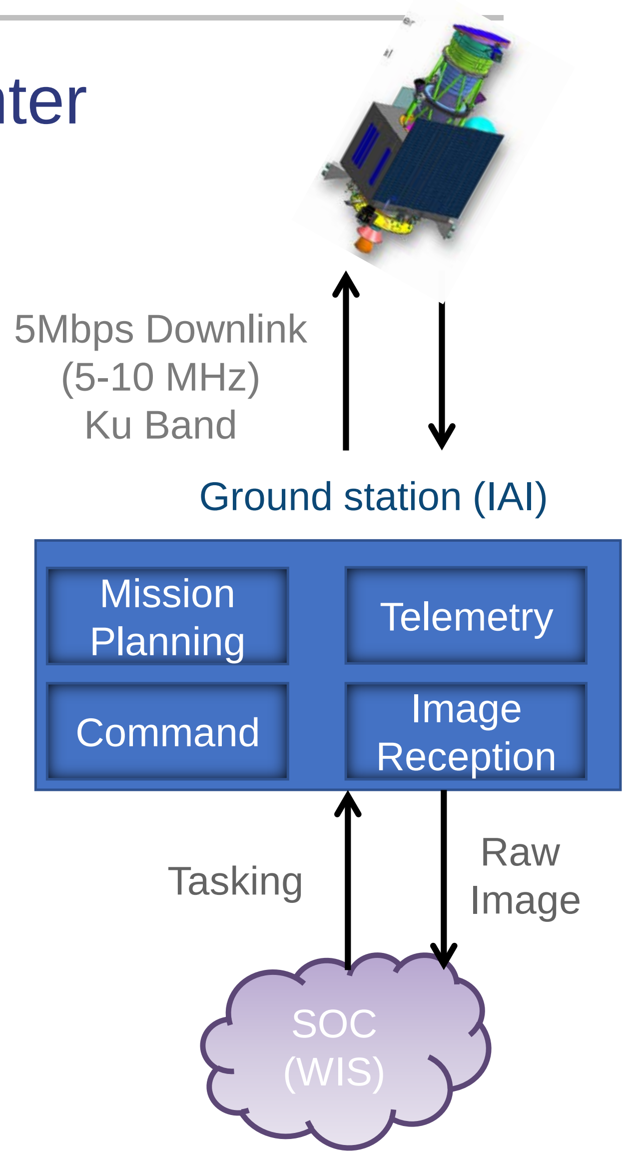
Science Operation Center

Purpose:

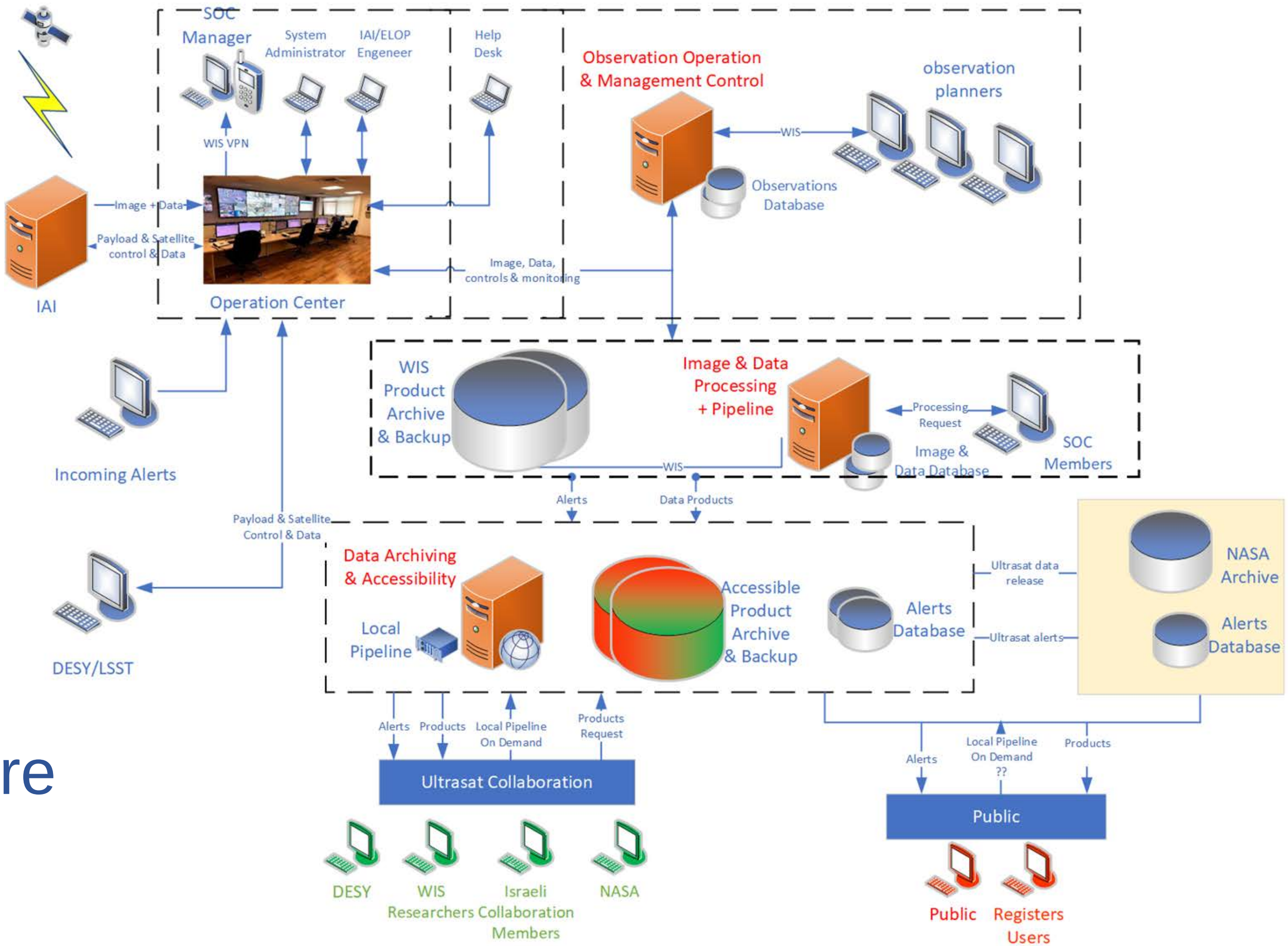
- The ULTRASAT Science Operation Center (SOC) will support all scientific aspects of the ULTRASAT mission

Objectives:

- Observation operations (Plan and schedule, ToOs, Decontamination)
- Interface to IAI Ground Control Segment
- Image and Data processing
- Scientific Data Products archiving
- Ultrasat Alerts generation
- Data Accessibility (multiple products, access methods and permissions, WEB)
- External Interface to DESY/LSST/NASA etc.



SOC Architecture



Science Operation Center

<u>Location:</u>

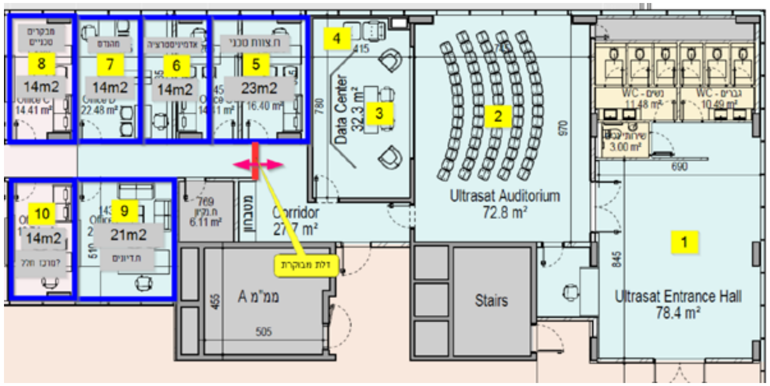
- ➢ The SOC will be located at WIS
  - Start operations in the current building
  - New building: Dedicated area, including visiting auditorium
- ➢ Planning and development phase initiated

<u>SOC development project:</u>

- ➢ Top-level requirements and development plan were defined
- ➢ Image processing development on-going

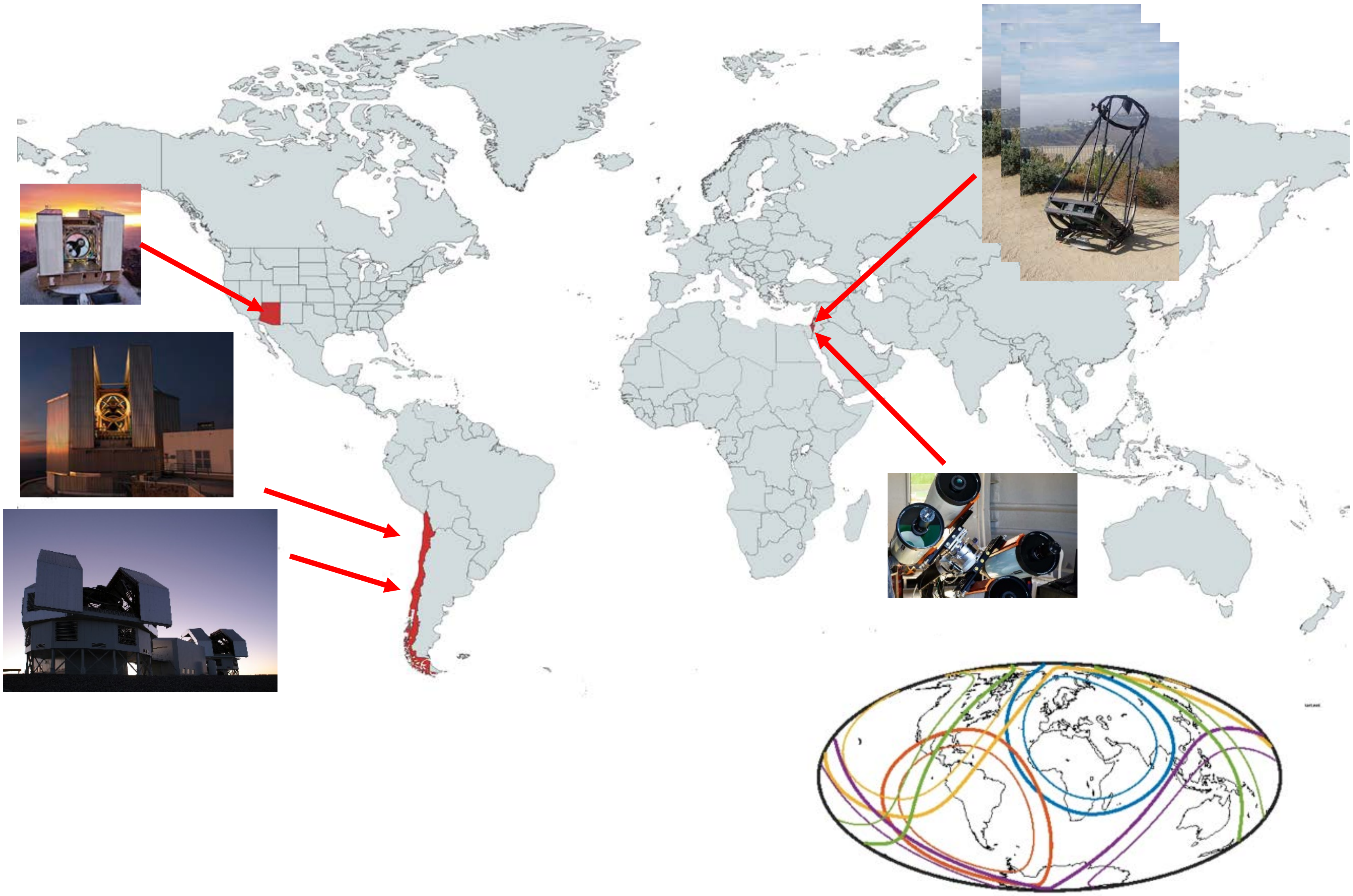
<u>Current building</u>

<u>New building</u>



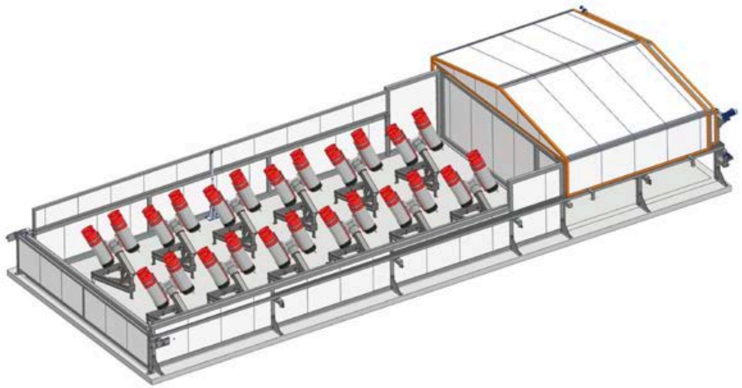
Supporting the ULTRASAT Mission

WIS ground-based optical follow up programs



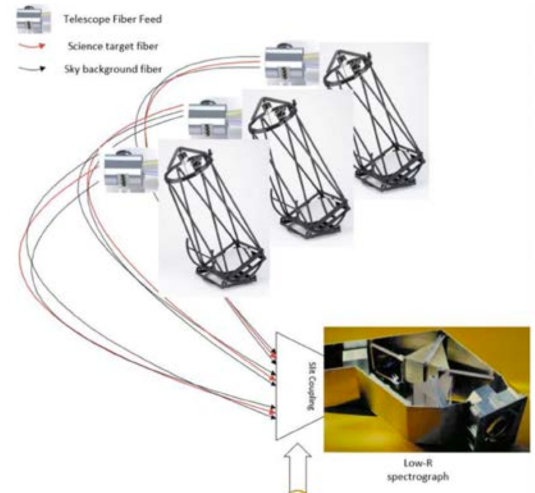
Supporting the ULTRASAT Mission
WIS Observatory in Neot Semadar

LAST - The Large Array Survey Telescopes: Photometry



# of Telescopes x Aperture	48 x 11”
Oprtation Band	Visible: $400-850nm$
FoV – Aperture: Narrow Field of View	$7.4\ sq.degrees$ / 1.5m
FoV – Aperture: Max Field of View	$\sim355\ sq.degrees$ / 28cm
Exposure Time	$15sec$

LAST Spec: Spectroscopy



# of Telescopes x Aperture	18 x 24”
Oprtation Band	Visible: $400-850nm$
Effective Aperture	2.5 m
Low Spectral Resolution	$\Delta\lambda = 20\text{Å}\ (1000\ km\ s^{-1})$
High Spectral Resolution	$\Delta\lambda = 0.25\text{Å}\ (15\ km\ s^{-1})$

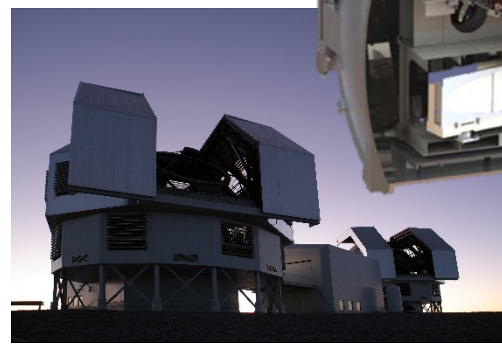
Supporting the ULTRASAT Mission

Spectroscopy @ Chile

SOXs

Telescope	**ESO 3.8m New Technology Telescope**
Oprtation Band	VIS-NIR: 360nm – 2.1μm
Spectral Resolution	$\Delta\lambda = 20Å\ (1000\ km\ s^{-1})$

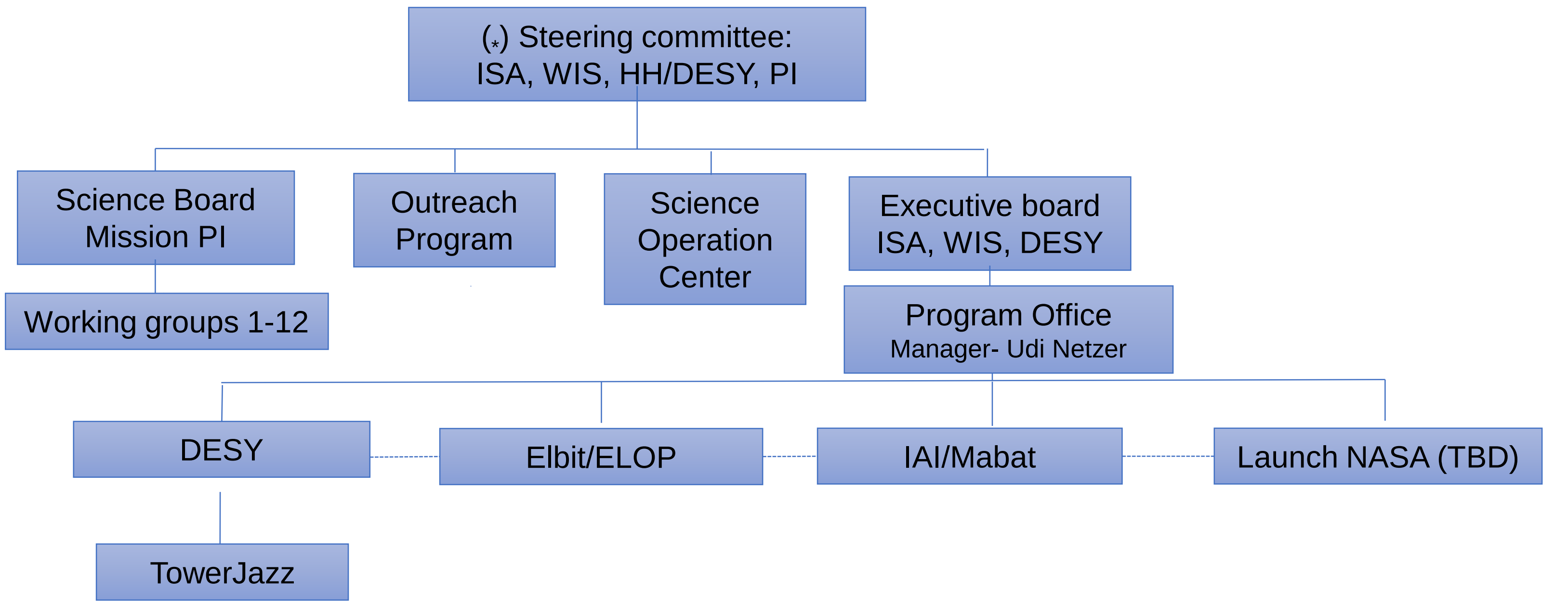
Spectroscopy at Magellan: G-CLEF



Telescope	**6.5 m Magellan Clay**
Oprtation Band	VIS-NIR: 350nm – 950nm
Spectral Resolution	$\Delta\lambda = 0.04Å\ (2.2\ km\ s^{-1})$

Program management

Implementation Organization



(*) All future Agencies providing substantial support will be part of the Steering Committee.

Major Project Decisions Since Kickoff (Sep 19)

Topic	Subsystem	When
TowerJazz - Detector supplier	Camera	March 2020
Focus mechanism	Telescope	March 2020
Direct to GEO → GTO	**Spacecraft / Launcher**	**July 2020**
CaF2 lenses	Telescope	October 2020
G5 optical model	Telescope	October 2020
Propulsion system	Spacecraft	November 2020
UV ARC selection	Camera	February 2021
Model plan (EM, EQM, PFM)	Camera/Telescope/Spacecraft	February 2021
Wafer post processing and die packaging	Camera	February 2021
Filter addition	Telescope	June 2021

Major Project Decisions Since Kickoff (Sep 19)

Budget & Timeline impact

- Direct to GEO → GTO
  - Cost increase (propulsion system & re-design). Risk identified, partners committed to extra-cost at kickoff.
  - 6 Month launch delay- does not affect arrival time at GEO slot.
- Filter addition
  - Approx. 2 mon delay.

Topic	Subsystem	When
TowerJazz - Detector supplier	Camera	March 2020
Focus mechanism	Telescope	March 2020
Direct to GEO → GTO	**Spacecraft / Launcher**	**July 2020**
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Program Timeline

Mile Stone	ARO + Month	Time
Kick off	0 (23 September 2019)	"Q4" 2019
SRR	3	Q1 2020
SDR	6	Q2 2020
PDR	16	Q1 2021
CDR	27	Q4 2021
Supply of Camera	39	Q4 2022
Supply of Payload	49	Q4 2023
DRB	59	Q3 2024
Launch	63	Q4 2024

Financing Principles

- ISA: 2/3 of S/C and Payload, Operational costs, outreach program
- WIS: 1/3 of S/C and Payload, Scientific mission, Data Center, Program Management, outreach, education program
- DESY: Camera, Scientific participation
- NASA: Launcher, Scientific participation

- Program overall cost approx. $105M

Risks

- Challenging time line
- Complex Interfaces
- Contamination prevention and control

Outreach & Education

Outreach & Education

High-school physics students:

- In collaboration with Schwartz/Reisman Science Education Center
- A dedicated "30% program" for matriculation exams in physics:
  - ➢ "hands-on" work with data - understanding and explaining the observed universe
  - ➢ Science questions studied by ULTRASAT (e.g., the Universe expansion rate)
- Two pilot programs - fall semester of 2021

Public outreach - young students and general public (jointly with ISA):

- In collaboration with Davidson Institute of Science Education as a "flagship project"
- Preliminary program includes, e.g.:
  - ➢ Visits at the Science Operation Center
  - ➢ Scientists on-line, teaching the teachers, "theater" productions-podcasts, Youtube short videos
  - ➢ Small scale traveling exhibition to be presented in malls/schools/community centers

A Science Driven Collaboration

- 12 Science Working Groups - WG members receive real time data access
  Open to all (and already including most) Israeli astronomers

- NASA Launch contribution-
  Science return: 8 US PIs (NASA funded) in WG’s

- DESY Camera contribution-
  Science return: 3 DESY PIs in WG’s

- LSST collaboration – advanced negotiations
  - Joint LSST/ULTRASAT alerts
  - Real time access to LSST data for Israeli astronomers
    Science return: US PIs in WG’s

ULTRASAT: Impact

- Provide groundbreaking high profile science
  with a small, affordable satellite.

- Put Israel at the forefront of Observational Astrophysics.

- Put Israeli industry at the forefront of a global movement to explore the Universe with small, affordable satellites.

- Enhance international collaborations with leading Agencies and Industries.
  NASA are joining an Israeli led Science project.

- Draw Israeli students to science and technology studies.
  Education & Outreach program in construction.

Backup

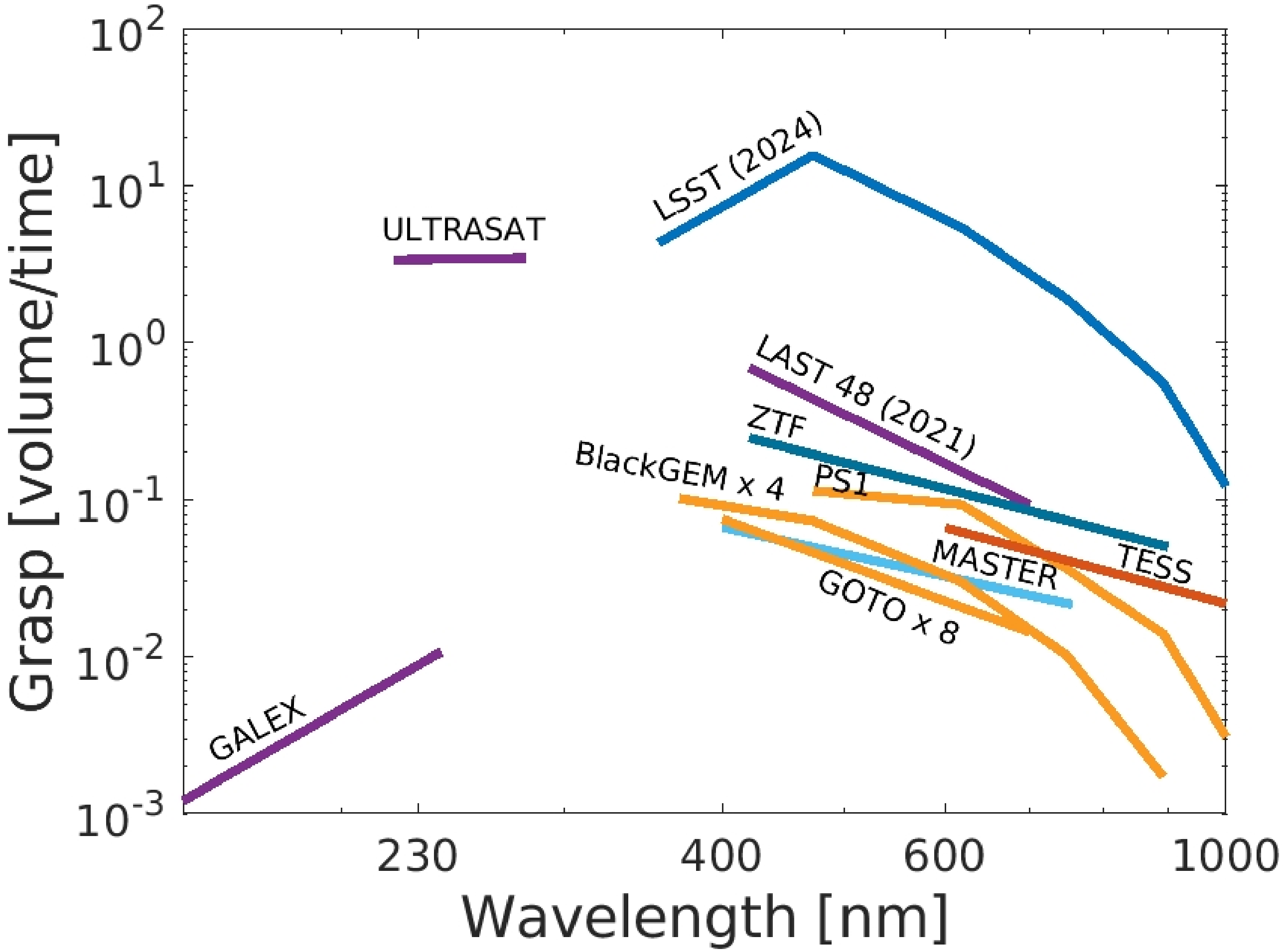
Why now?

Technology enables telescopes with very large fields of view,

Allowing a systematic study of transient events.

- Optical (LSST), Radio (LOFAR, SKA)
- X/γ-ray (Fermi, AstroSat, SVOM; HAWC, CTA, LHAASO)
- Gravitational Waves (LIGO, Virgo)
- ν (IceCube, KM3NeT)

- Missing: UV

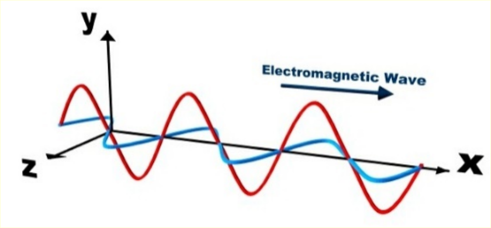

Grasp [volume/time]
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
ULTRASAT
LSST (2024)
LAST 48 (2021)
ZTF
BlackGEM x 4
PS1
MASTER
TESS
GOTO x 8
GALEX
230
400
600
1000
Wavelength [nm]

Gravitational Waves

Electro-Magnetic Transmitter

Accelerating electric charge (dipole) → **EM Wave** →

e^-



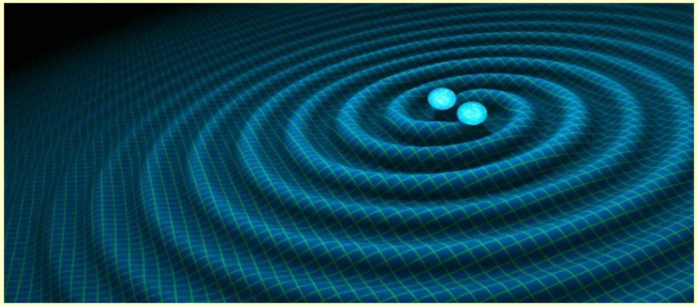
Receiver

Accelerating electric charge

e^-

Gravitational "Transmitter"

Accelerating mass (Quadrupole) → **GW** →



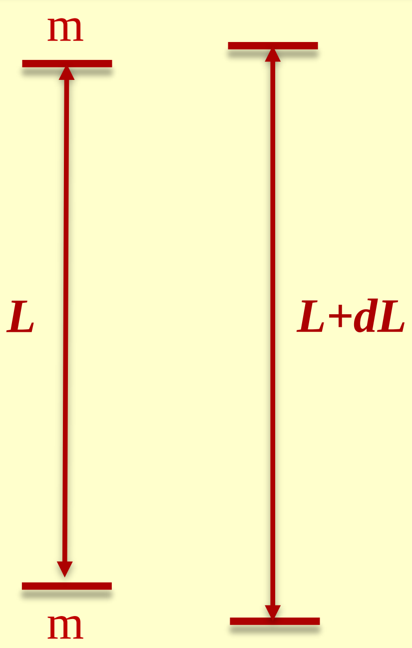
Gravitational Antenna

Accelerating mass

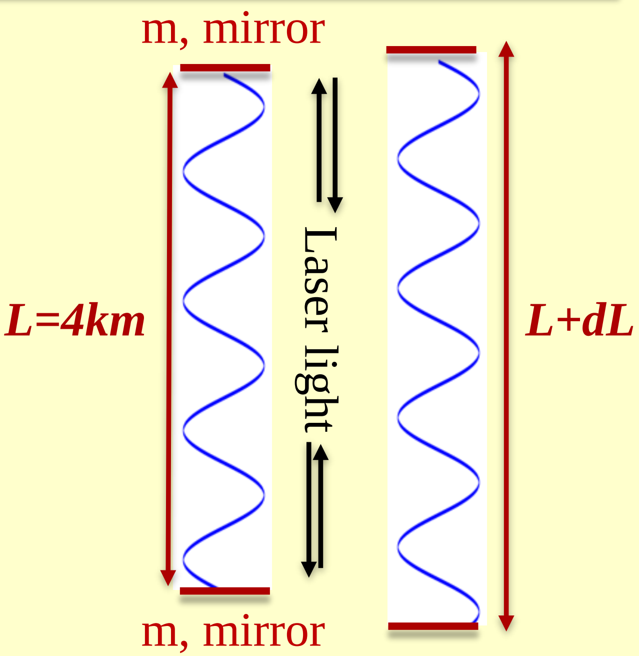
m

Detecting Gravitational Waves: The Challenge

- Predicted by Einstein's theory of gravity in 1916
- Challenge: $\frac{dL}{L} = 10^{-21}$



First direct detection of Gravitational Waves [2016]

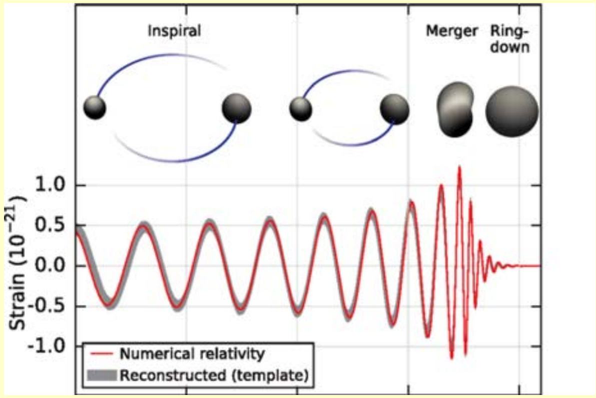


- 2016:
  LIGO detects a 2x 30 solar mass BH binary merger.
  Distance ~ 1 Billion light years

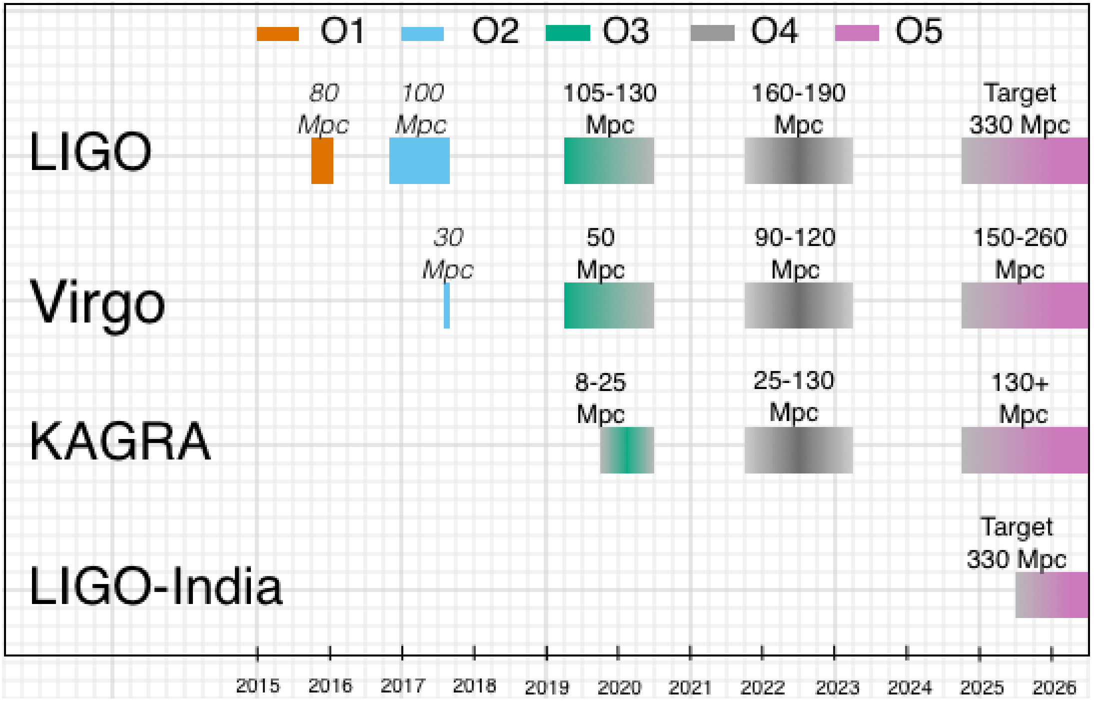
$$h = \frac{dL}{L} \approx \frac{R_S}{d} = 10^{-21} \frac{M/\ 10M_{Sun}}{d/1G\ light{-}yr}$$

$$f \approx \frac{c}{2\pi R_S} = 1 \frac{1}{M/10M_{Sun}} \text{kHz}$$

- 2017 Physics Nobel Prize (Weiss, Barish, Thorne).



GW detector network timeline

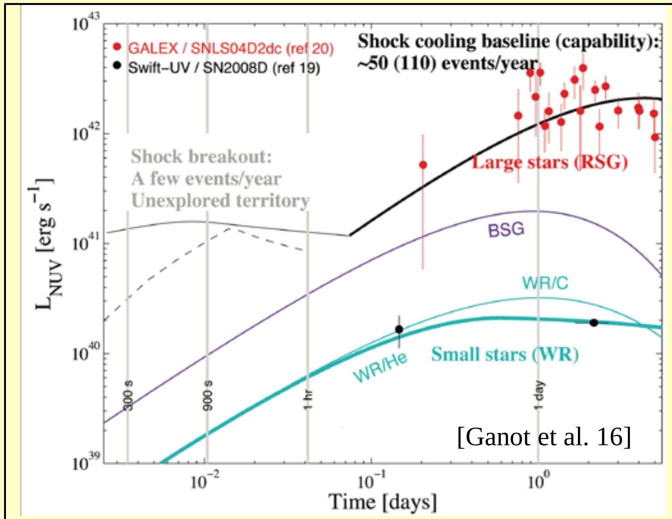


Key science goal 2: Deaths of Massive stars

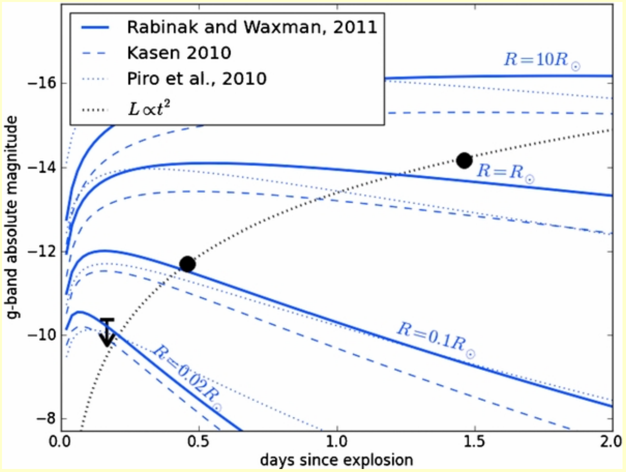
- Early UV/opt.: status.
- A handful of (late, low-quality) RSG explosions.
- Space UV (lucky) detection of 1 SN Ib:
  $R=10^{11}$cm; He + C/O envelope; E/M
- A handful of type Ia non detections:
  $R_* < 4\times10^9$cm → White Dwarfs.

- Current data
- Validate models,
- Direct constraints on compact progenitors,
- Demonstrate potential.

- ULTRASAT:
- >100/yr, <1d, high quality UV,
  Map all (including rare) SN types.
- Rapid alerts for follow-ups.



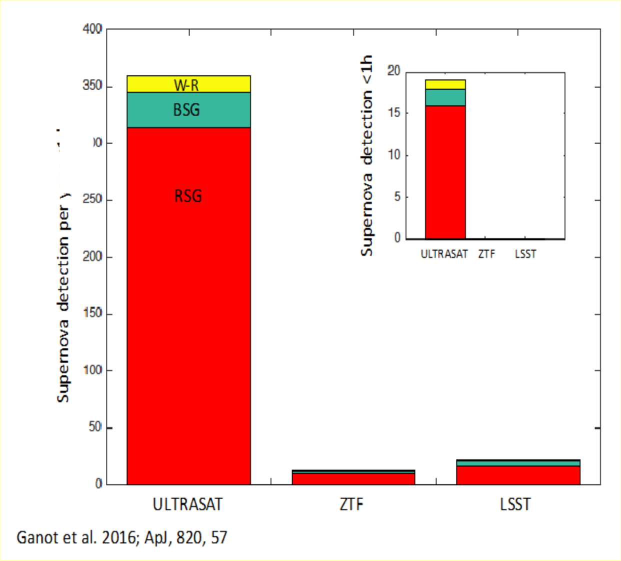
[Ganot et al. 16]



[Bloom et al. 11, Maoz et al. 14]

SN explosions: ULTRASAT's uniqueness

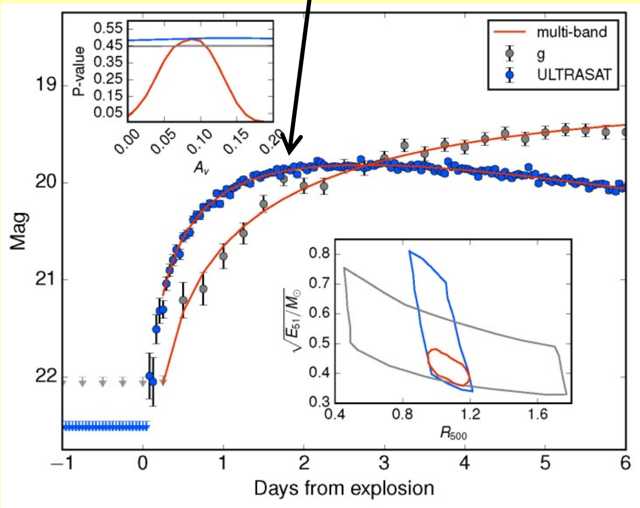
ULTRASAT is
an order of magnitude more powerful discovery machine than any other survey



ULTRASAT will map all (including rare) SN types

Why UV?

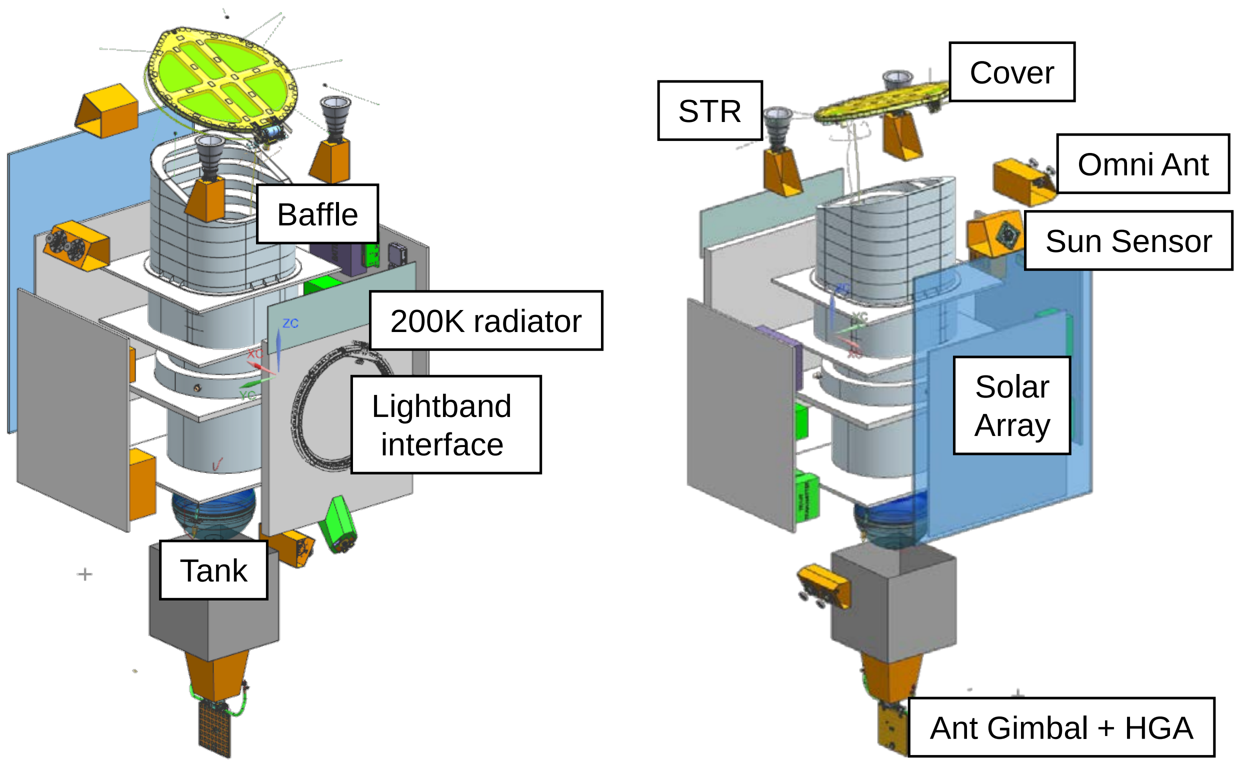
t (T=1 eV) → R_*



[Rubin et al. 16]

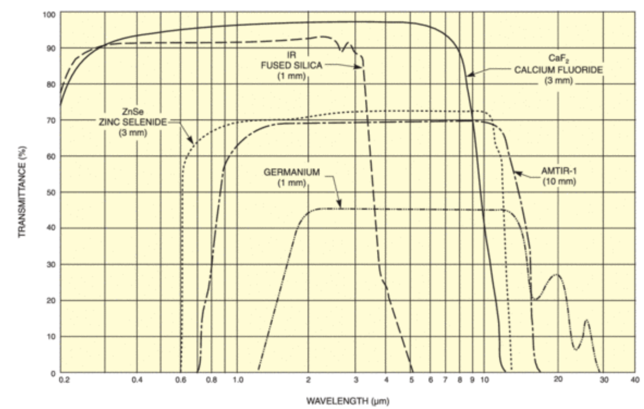
Recombination at T < 1 eV
→ no optical peak, structure degeneracy

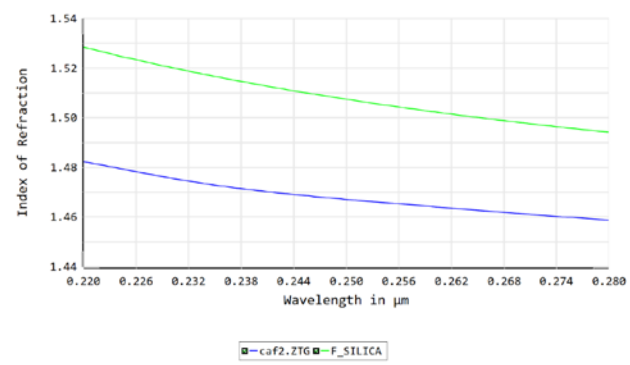
S/C Configuration



ULTRASAT Optical Design Guidelines

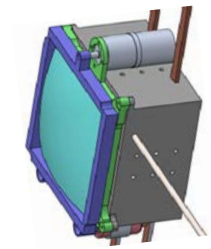
- Challenges:
  - Limited materials with high transmission in the UV, namely CaF_2, Fused Silica and Sapphire.
  - High slope of dispersion curve at shorter wavelengths.
- A modified Schmidt telescope:
  - CaF_2 and Fused silica work in tandem to minimize chromatic aberrations.
  - Meniscus corrector plates before telescope pupil to balance aberrations across the FoV.
  - A Field Flattener pair to correct primary mirror focal plane curvature.
- Sapphire Filter
  - High rejection of out-of-band wavelength requires >1000 layers.
  - Requires a stiff substrate to avoid stresses (i.e., localized changes in the wavefront).
  - Use of high index of refraction sub-micron layers of HfO_2 annealed at high temperatures.
  - Unique cut along the crystal to minimize Birefringence takes into account the telescope fast beam.

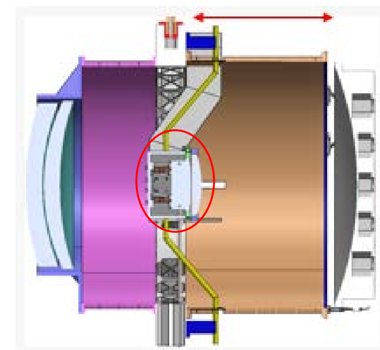


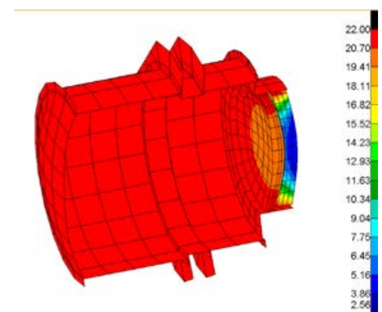


Design Considerations

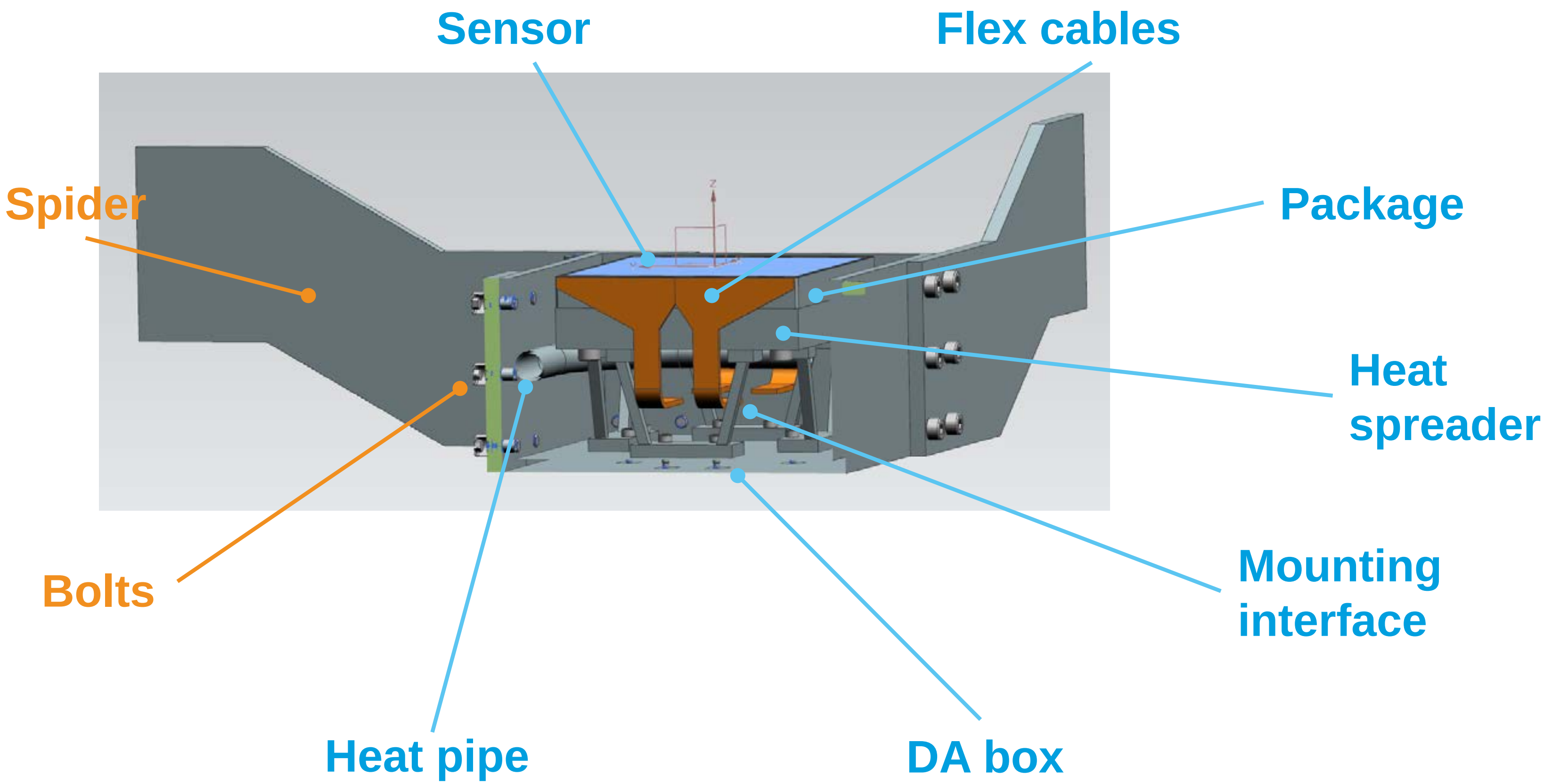
- Short Focal Depth
  - A theoretical 20 um
  - High Stability needed
- Thermal Gradients
  - First lens exposed to outer space
  - Thermal analysis accuracy
- Focus Mechanism
  - FF vs Mirror
- Contamination
  - Particular and molecular
  - High absorption coefficient







Camera components

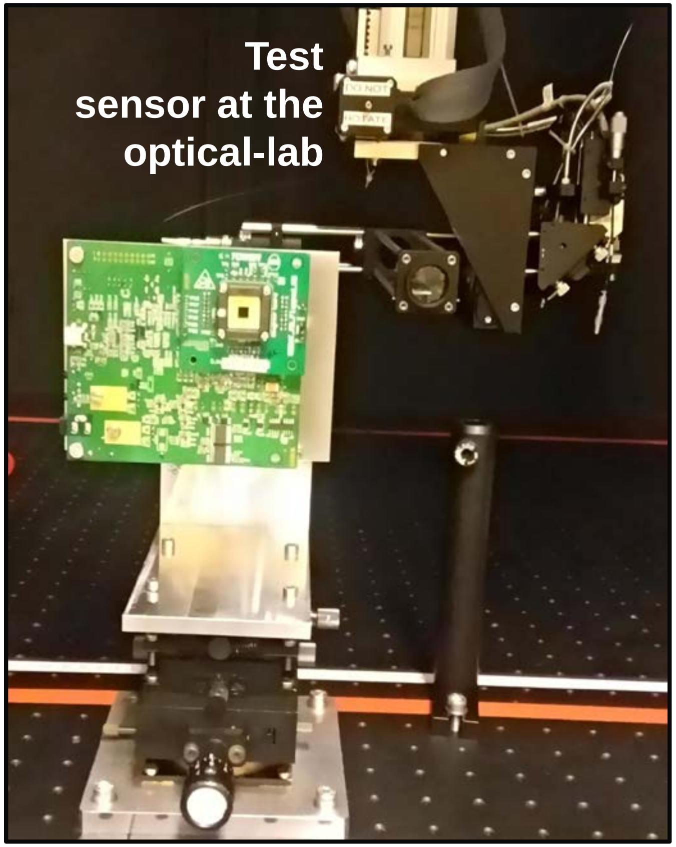


ELOP
DESY

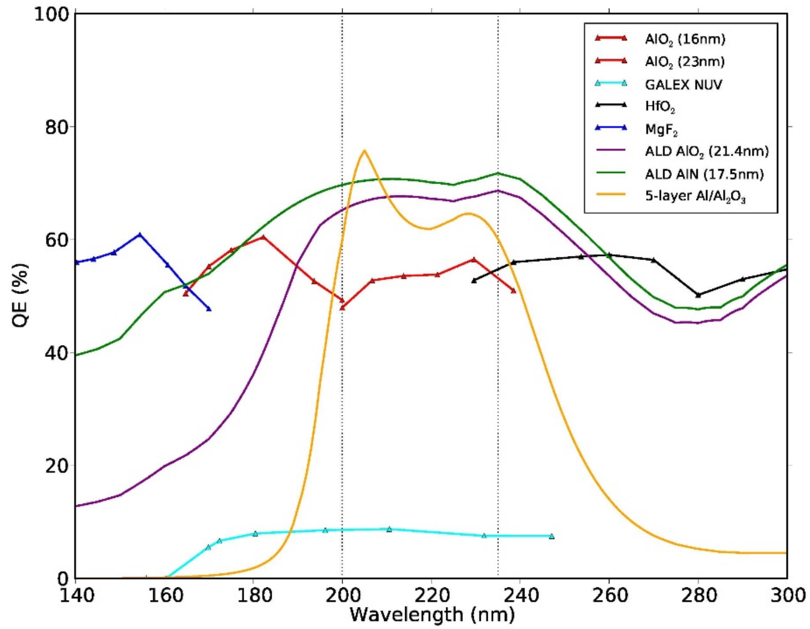
Camera time line

- **11/2018**: ‘Can DESY do a UV space camera?’
- **07/2019**: ‘Yes we can!’ – budget secured
- **09/2019**: Program Kick off
- **01/2020**: System Requirements Review
- **03/2020**: System Design Review
- **12/2020**: Preliminary Design Review
- **01/2021**: Prototypes characterized (ARC selection), sensor designed and in production.

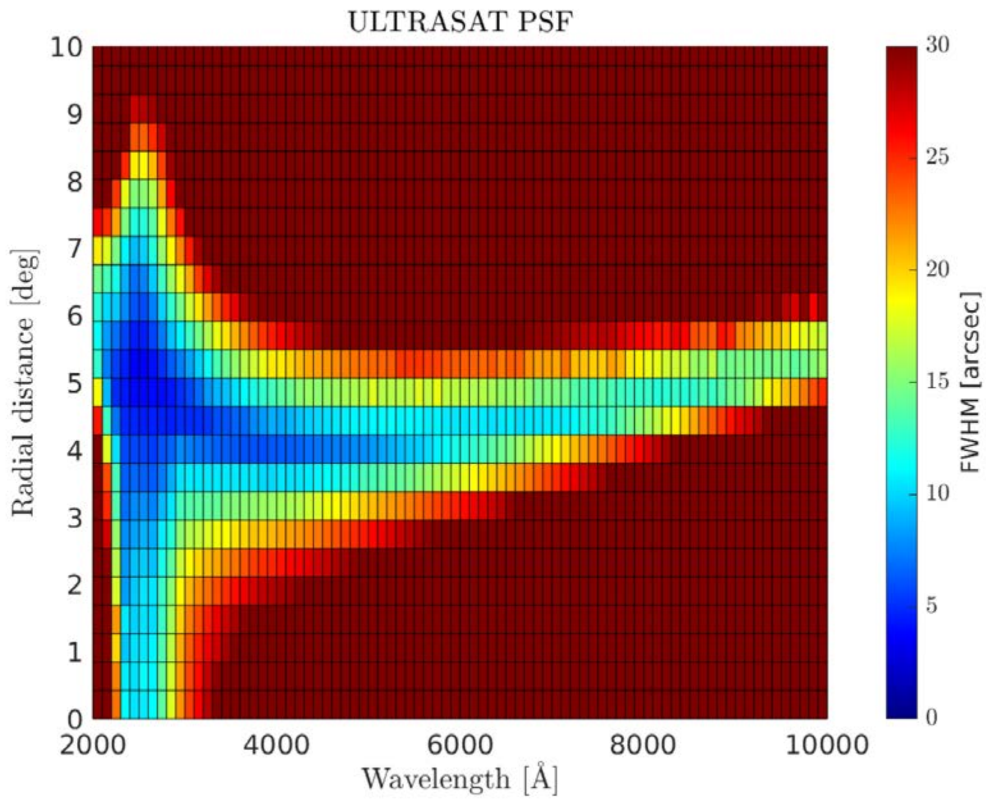
- Team of 11 FTE in full swing
- Space expertise build-up with new hires, DLR cooperation, external international advisory board
- Time line in particular in Corona times the single most challenging aspect!



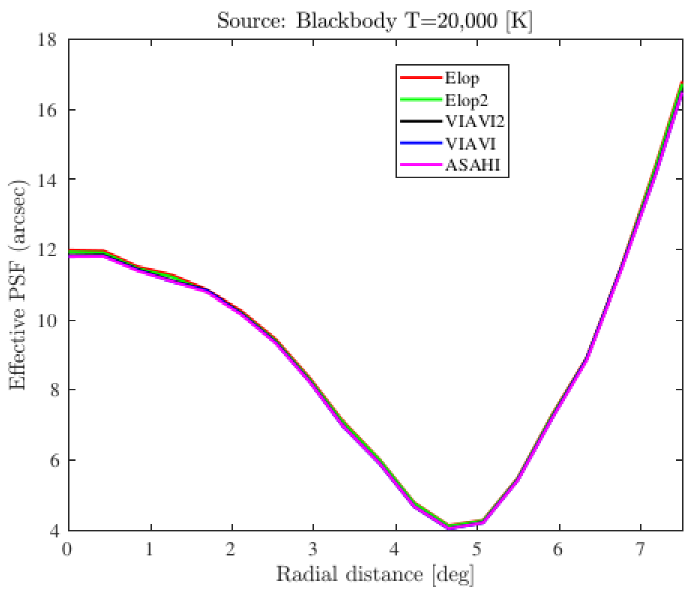
Anti-reflection coatings (ARC) for QE optimization

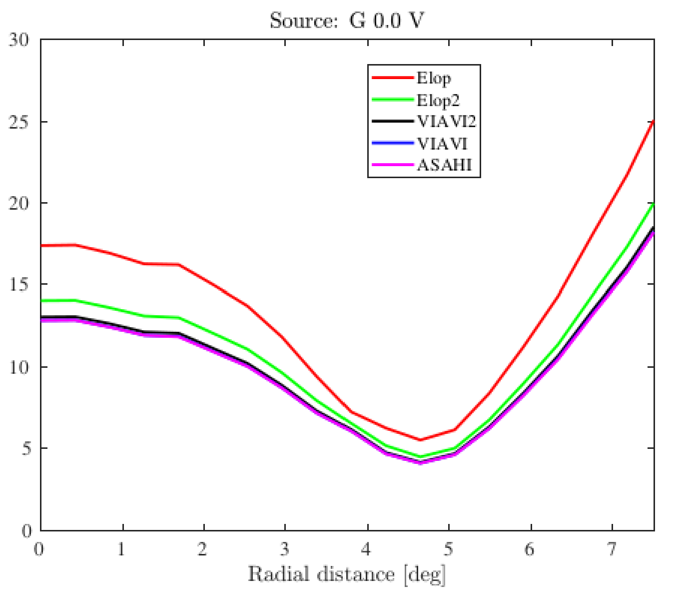


Chromatic PSF



Effective PSF





Ground Station

- Terminal @ IAI/MBT GEO Ground Station
  - Command & Control, Telemetry Processing
  - Immediate ToO tasking
  - Receive imagery data, deliver to WIS (SOC)
- High-rate Ku communication
- Perform ranging for orbit determination