

ULTRASAT: A Wide-Field UV Space Telescope

Revolutionize our understanding of the hot transient Universe



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Funding partners	Industry partners
ISA	IAI
WIS	Elop
DESY	Tower
NASA	

Eli Waxman | Weizmann Institute of Science



Outline

- Science goals
 - Implementation
 - Project status
-

Transient astronomy study drivers: I. Open Questions

Sources	Open questions
Gravitational Wave sources Binary Neutron Star (or Black Hole-Neutron Star) mergers	<ul style="list-style-type: none">- Where did the heavy r-process elements form?- What is the current value of H_0?- What are the progenitor systems of merging binaries?
Supernovae	<ul style="list-style-type: none">- How do massive stars explode and affect their environment?
Tidal disruption of stars (TDE) by super-massive black holes (SMBH)	<ul style="list-style-type: none">- What is the distribution of SMBH masses, particularly in small galaxies?- How do they affect their environment?- How is mass accreted onto BH?
...	...

Transient astronomy study drivers: II. Technology

Technology enables telescopes with very large fields of view,
Allowing a systematic “multi-messenger” study of transient events.

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

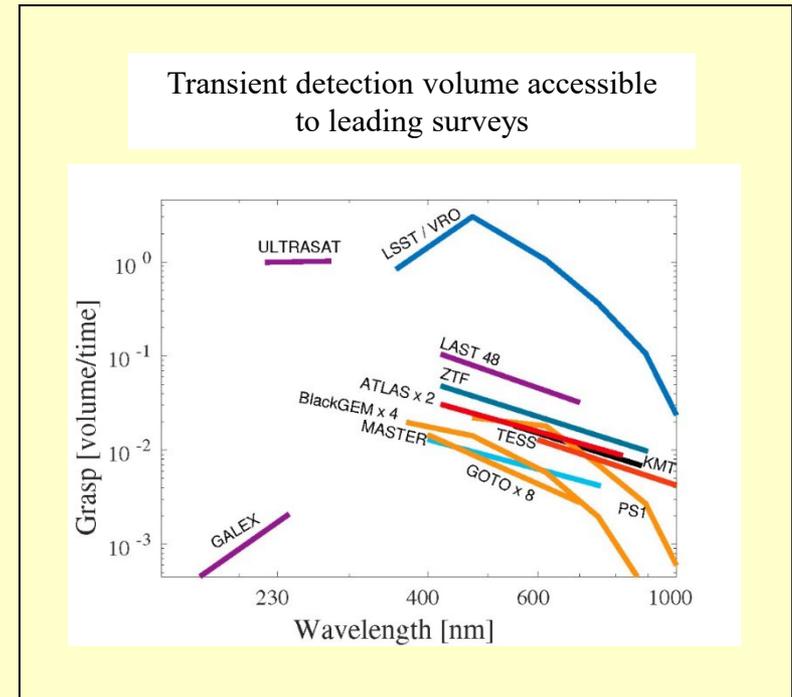
ULTRASAT's uniqueness

Key Properties

- Very large, 200 deg², field of view.
- High UV (230-290nm) sensitivity:
 1.5×10^{-3} ph/cm² s (900s, 5 σ)
[m = 22.5].
- Mean PSF FWHM 8.5".

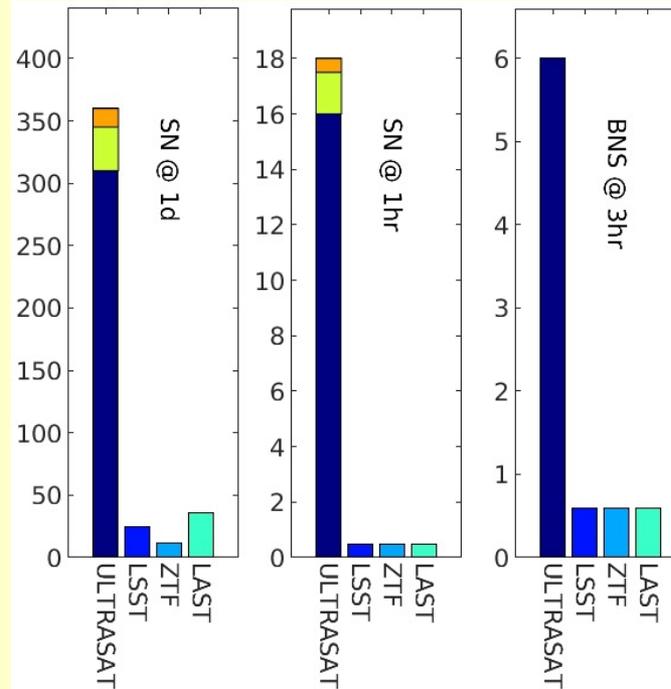
Key Capabilities

- Monitor an unprecedentedly large volume of the Universe.
- New window in wavelength (NUV) and in cadence (minutes - months).
- Real-time alerts to ground/space-based telescopes (GEO orbit), initiating world-wide follow-ups.
- ToO: Instantaneous access to >50% of the sky in <15 min for >3 hr.



ULTRASAT: Systematic, early detection of stellar mergers and explosions

Yearly detection rates of Super-Novae and Binary Neutron Star mergers

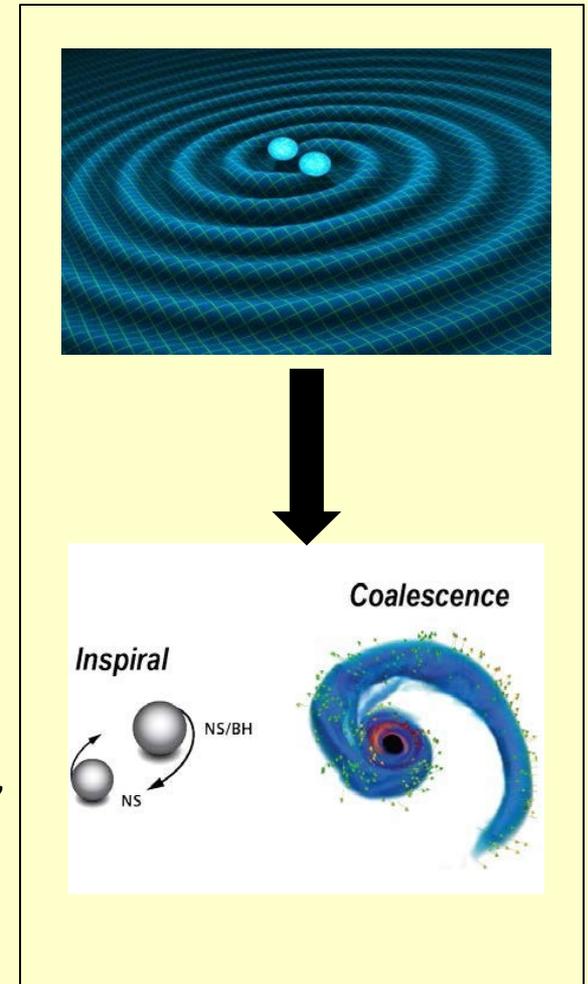


ULTRASAT: A broad science impact

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	> 1000	Discriminate between SD and DD progenitors, dust reddening
Compact Object Transients		
Emission from Gravitational Wave events: NS-NS and NS-BH	~ 25	Constrain the physics of the sources of gravitational waves
Tidal disruption events	> 300 (high-cadence) > 4500 (low-cadence)	Accretion physics, black hole demographics
Quasars and Active Galactic Nuclei		
Continuous UV lightcurves	> 7500	Accretion physics, BLR reverberation mapping, lensed quasars
AGN-related flares & transients	> 100	Accretion physics
Stars & Exoplanets		
Active & Flaring stars	> 4×10^5	Planet habitability, high-energy flare frequency, stellar magnetic structure, gyrochronology, magnetospheres
White dwarfs	> 3×10^4	Planetary systems, debris accretion, rotation-related variability
RR Lyrae	> 1000	Pulsation physics
Nonradial hot pulsators, e.g., α Cyg, δ Scuti, SX Phe, β Cep types	> 250	Asteroseismology
Eclipsing binaries	> 400	Chromosphere and eclipse mapping
Galaxies and Clusters		
All Sky Survey – galaxies	> 10^8	Galaxy Evolution, star formation rate
Gamma Ray Bursts		
GRBs occurring in-field	~ 30	Prompt emission & afterglow physics, dust reddening
Orphan Afterglows	> 30	Fireball Γ and opening angle distributions
Solar System		
Asteroids and other small bodies	> 10^4	Asteroid classification, origin

Key Science Goal 1: Mergers of Neutron Stars

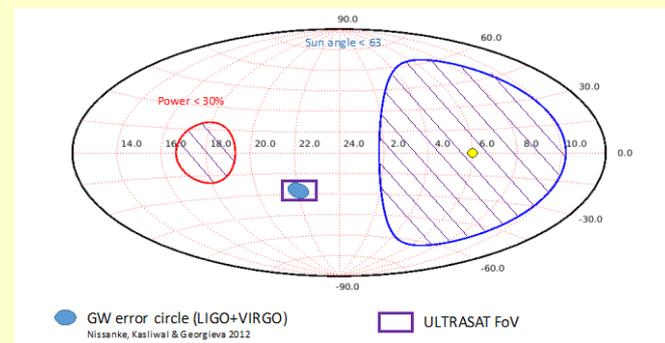
- Nuclear density radioactive material torn and ejected at close to light speed.
May be the source of heavy r-process, rapid neutron capture, elements beyond Fe.
- Detecting light from radioactive material following GW is (one of) the major goals of transient astronomy in the coming decade:
 - Identify 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.



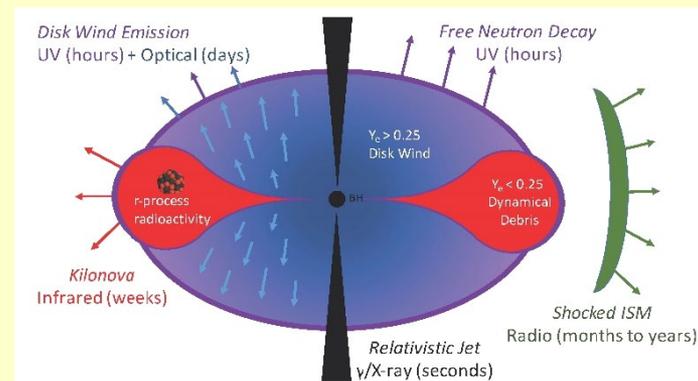
ULTRASAT: GW follow up capabilities

- Starting 2028, GW detectors will increase the detection horizon to ~ 300 Mpc, providing ~ 1 NS-NS merger events per month with ~ 100 squared degree error box.
- ULTRASAT will be sensitive beyond the GW horizon, providing
 - Fast localization of NS-NS/BH mergers: Rapid, < 15 min, access to $> 50\%$ of sky, Covering GW error box in a single image;
 - UV light curves constraining ejecta properties.
- EM detection at other bands- challenging:
 - X-rays: likely 1:100 (beamed).
 - Radio: ~ 1 yr delay.
 - IR: faint, slow.

ULTRASAT's ToO access

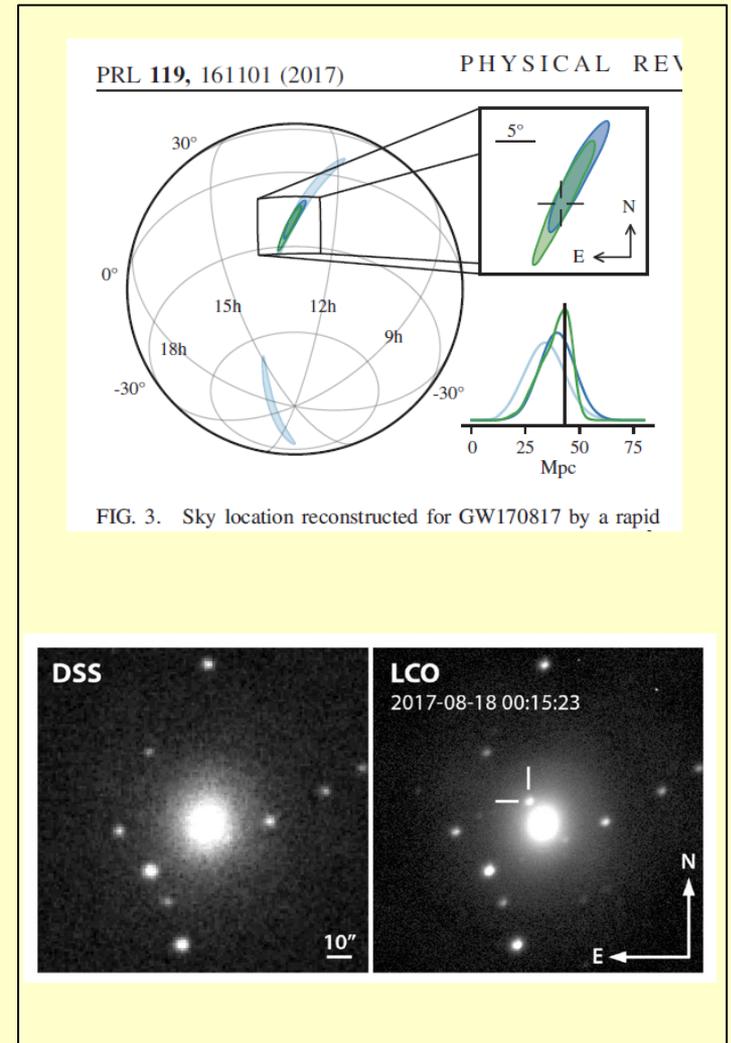


Bright, Early (hr) UV emission expected



Lessons from GW170817, The only NS merger detected so far

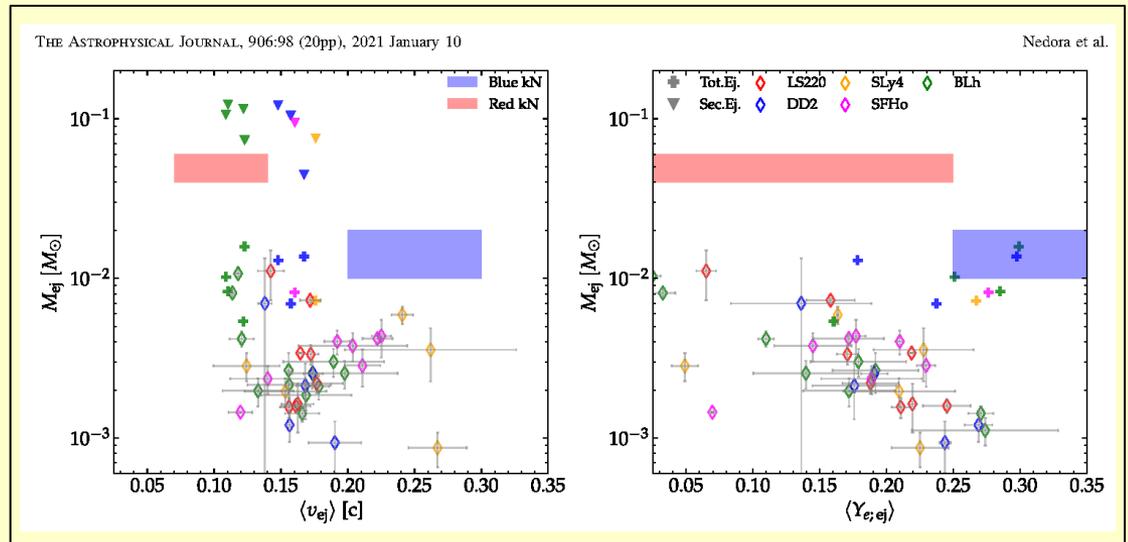
- Very nearby, ~ 40 Mpc.
Light detected after 0.5 day, targeting all galaxies in the GW error box.
UV bright, implying ULTRASAT sensitivity beyond 300 Mpc.
- ULTRASAT is far superior to other searches.
 - A wide field of view is crucial- Identifying light emission by targeting all galaxies will be prohibitive at 300 Mpc, 1000's of galaxies.
 - Detection in other bands (infrared, radio) will be highly challenging.
 - X-ray/ γ -ray detection would not have been possible beyond 40 Mpc.



Lessons from GW170817:

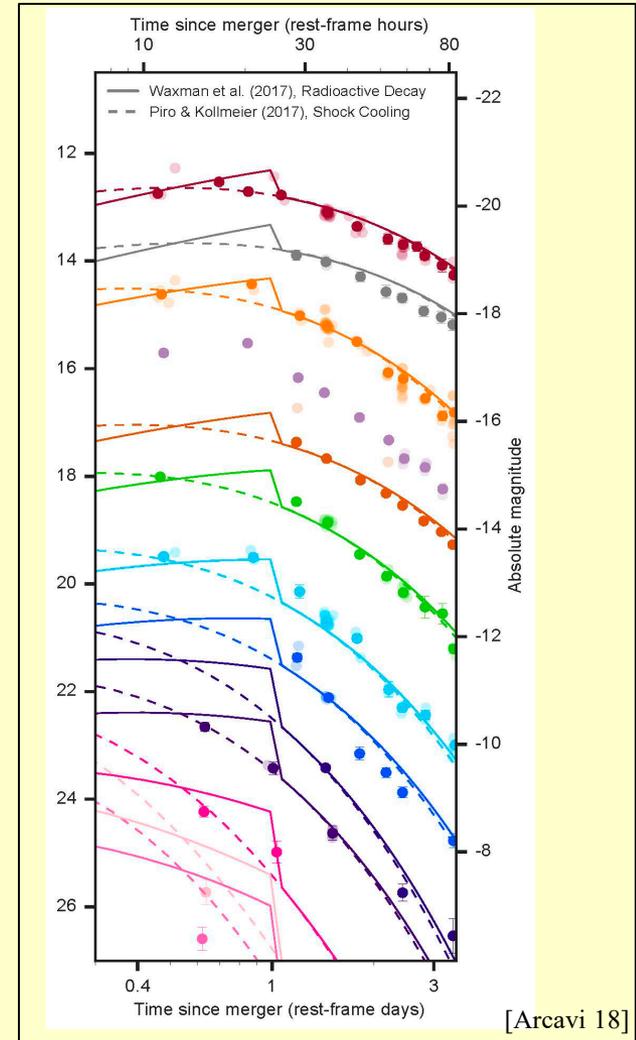
Early UV emission provides unique information

- The early blue-UV emission implies a low opacity component with a larger mass and a higher velocity than was expected in earlier merger calculations.
- Different types of explanations are suggested:
 - Unaccounted for processes enhancing the production of high Y_e plasma (e.g., viscous MHD turbulence), possibly accompanied by strong anisotropy;
 - Non-radioactive radiation sources, e.g., shock breakout.



ULTRASAT's unique contribution to The study of binary NS mergers

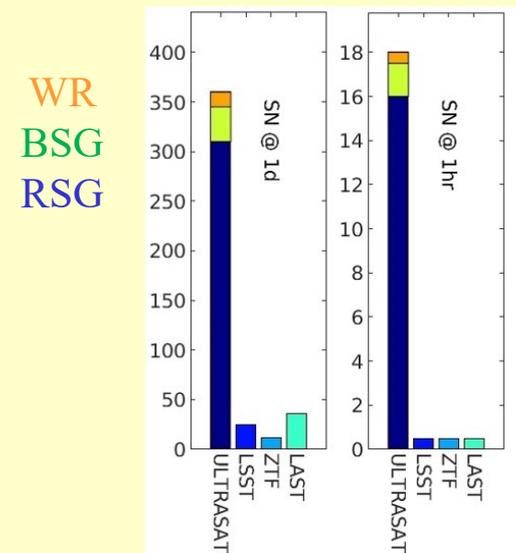
- Providing a systematic detection of events, essential for
 - Determining host and environment diversity,
 - Determining the progenitor system's diversity,
 - Determining angular ejecta structure (viewing angle dependence),
 - Measuring the current H_0 value.
- Enabling early measurements- essential for constraining ejecta structure and composition through the photometric and spectral evolution of the source.
- Providing early UV light curves, essential for discriminating between ejecta structure models, particularly those driven by the early blue-UV emission.



Key science goal 2: Core Collapse Supernovae

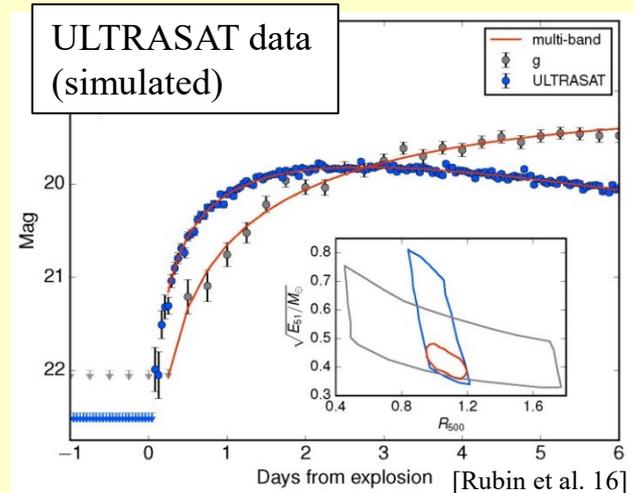
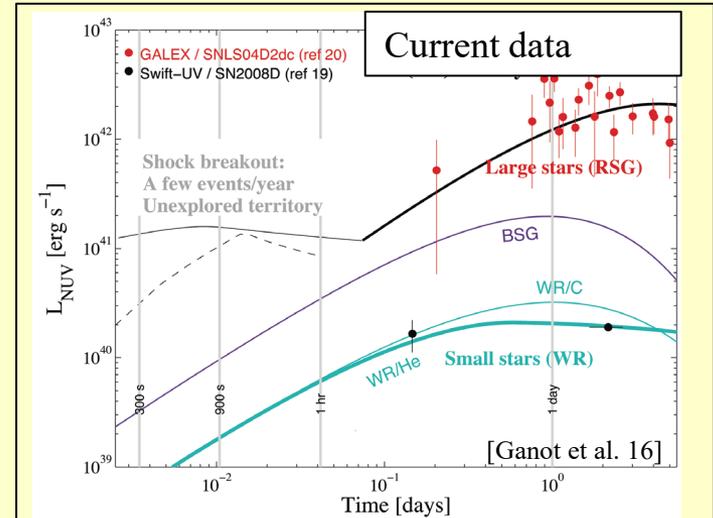
- The supernova (SN) mechanism is not fully understood.
- ULTRASAT will provide
 - High-quality early (<1d) high cadence UV data,
 - Rapid alerts for follow-ups,
 - for **100s of SNe, including rarer types.**
- Enabling a **systematic**
 - Measurement of progenitor radii and surface composition,
 - Mapping progenitors to supernova types;
 - Measurement of explosions' E/M;
 - Determination of extinction;
 - Measurement of pre-explosion mass loss, constraining pre-explosion evolution(and determining the contribution to the ~ 10 TeV neutrino background).

Yearly detection rates



Early UV measurements are key to constraining progenitor and explosion parameters

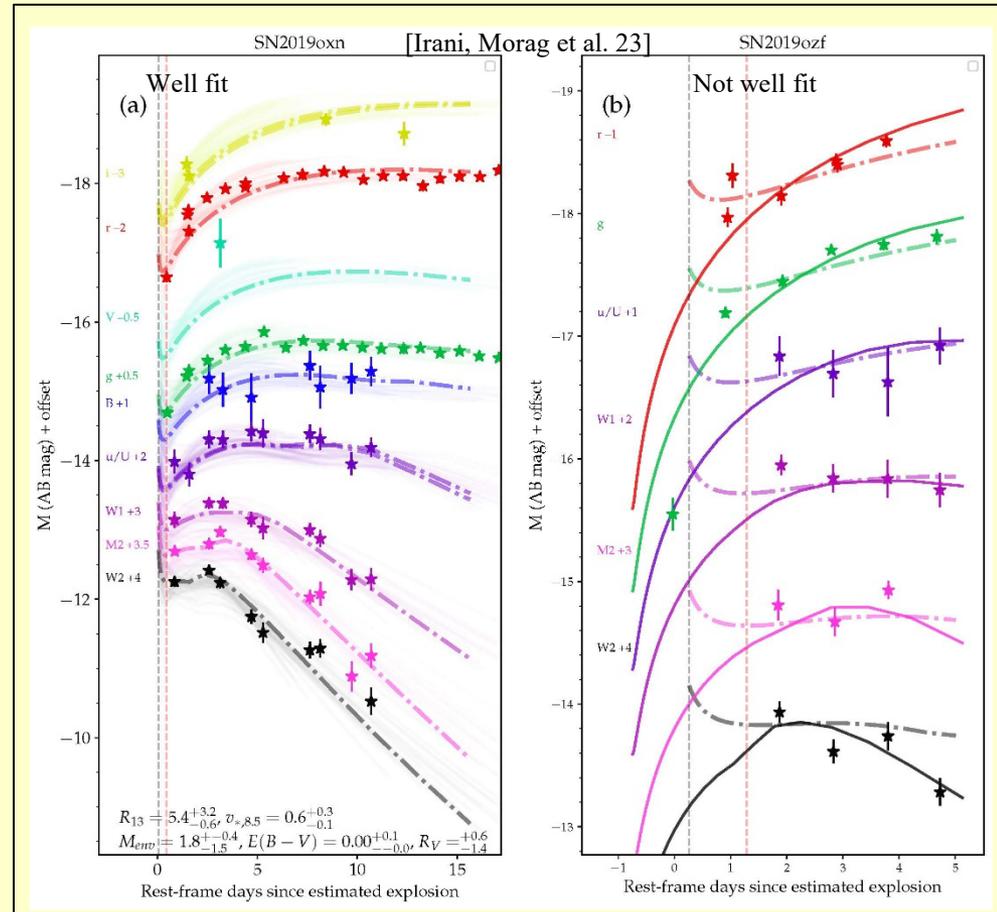
- Existing serendipitous early UV detections demonstrate the validity of the theoretical understanding and the potential for progenitor properties' measurements.
- Stellar radii are determined (mainly) by the (early) timing of the peak UV emission. Optical measurements alone do not constrain the radii (no early peak, model parameter degeneracy).
- The determination of extinction depends on early UV measurements.



Constraining progenitor and explosion parameters: Proof of concept

- 34 ZTF SN II with at least 1 UV point at $t < 4d$.
- 2/3 (1/2 observed) well fit by emission from expanding stellar ejecta.
Parameters - moderately well constrained.
- The rest (1/3)- emission probably dominated by interaction with dense circumstellar matter (CSM).
- A model for CSM dominated emission spectra was recently constructed (see T. Wasserman's poster).
- Early UV is essential for determining CSM properties (Optical alone – large model parameter degeneracy

[Wasserman & EW 25]).



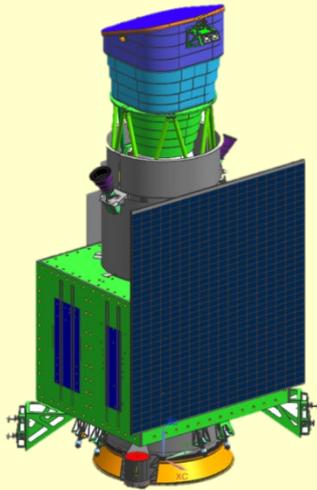
Science goal: Planet habitability

- 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 (O₃ from photo-dissociation of H₂O & CO₂).
 - Flares dominate UV output. Flare rates unknown.
 - ULTRASAT will monitor $\sim 10^6$ 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 (extended).
-

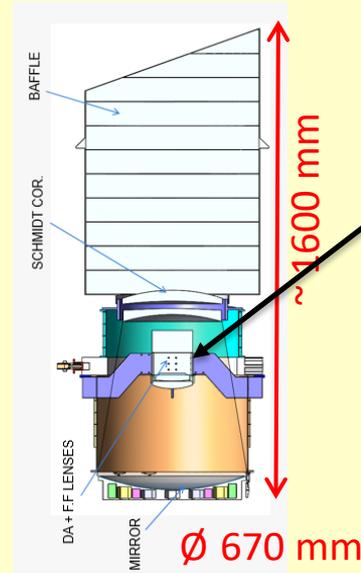
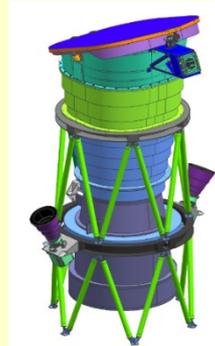
ULTRASAT: Implementation & Collaboration

Management: Program Office @ WIS

Spacecraft: IAI



Telescope: Elop/Elbit



Focal Plane Array
DESY/Helmholtz
(Germany)

Sensor: Tower
(Israel)

Hosted launch to GTO: NASA

Launch 2028

>3.5 year science mission (6 year fuel)

Dimensions: 1.5 x 1.7 x 3.4 (m³)

Power: 500 W

Mass: 500 + 630 (Prop) kg

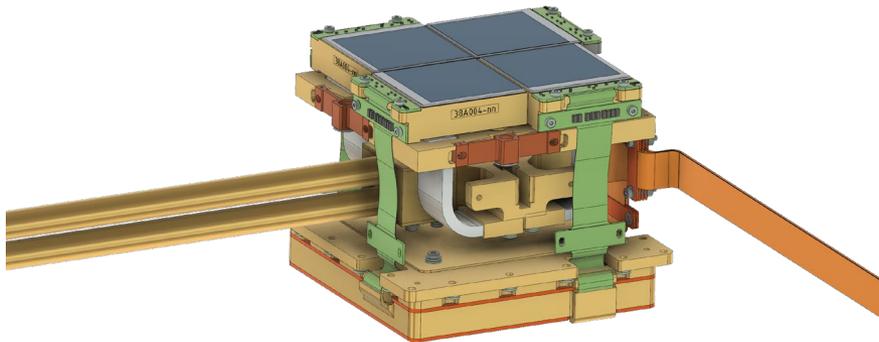
- 230-290nm Sensitivity 1.5×10^{-3} ph/cm²s (900s, 5σ)
Over a field of view >170 deg²
- Translates to requirements* on
 - Optics
 - FOV 170 deg²
 - PSF (Point Spread Function) < 15"
 - Out-of-band suppression < 4×10^{-3} (< 10^{-4} for stray light)
 - Detector
 - QE 60%
 - Dark current < 0.03 e⁻/s (cool to 200 °K)
 - Read noise < 3.5 e⁻
 - Baffle
 - Stray light suppression < 2×10^{-11}
 - Cosmic-ray e⁻ suppression (Cerenkov) < 0.15

*Partial list

- BSI CMOS from Tower Semiconductors
(4 tiles aligned to $< 50 \mu\text{m}$)
- High UV QE using
high-K dielectric coating,
optimized anti-reflection coating
- AnalogValue electronics design, Ramon Space support for space qualified design (e.g., radiation hardness)

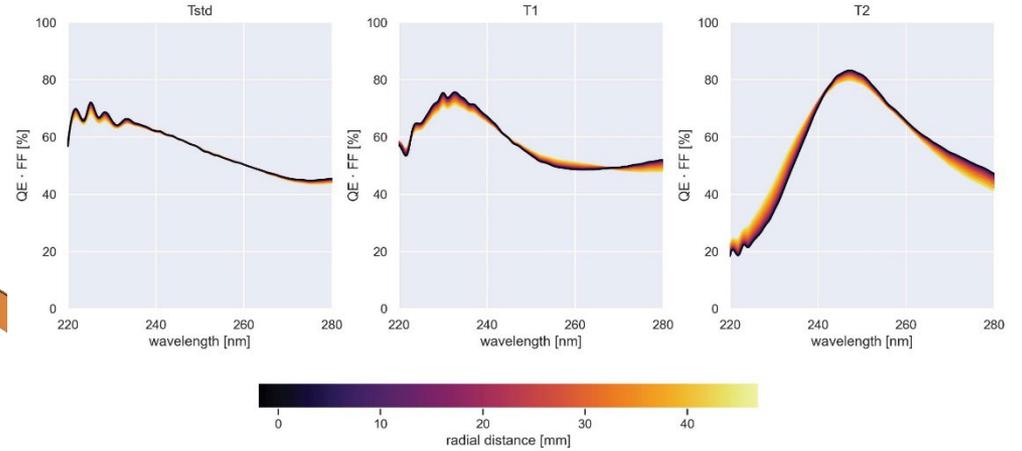
Sensor main Specs.

Photosensitive surface	90x90 mm
Pixel size	9.5 μm
Pixel scale	5.4"
Operation waveband	230-290nm
Mean QE in Operation band	>60%
Operation temperature	200 \pm 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)



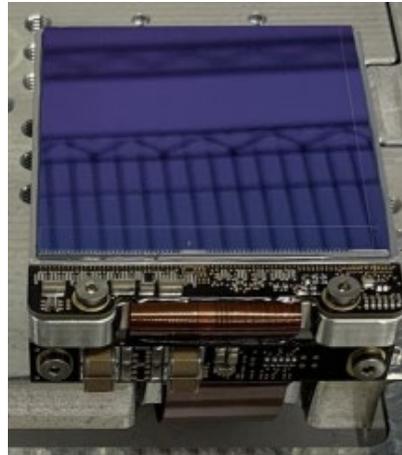
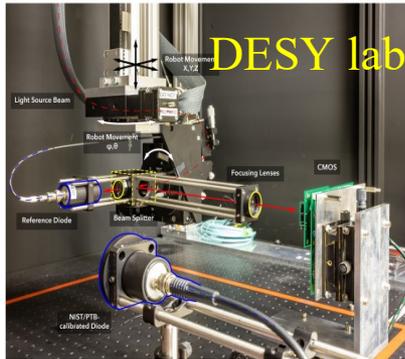
Tstd: T.J. SC_207; Wafer 13
T1: T.J. SC_205; Wafer 3
T2: T.J. SC_204; Wafer 18

Aoi-Weighted SCOUT Quantum Efficiency - Interpolation: Cubic



UC-3400-PT015-01_Scout_characterizat or_status_2021-02-05

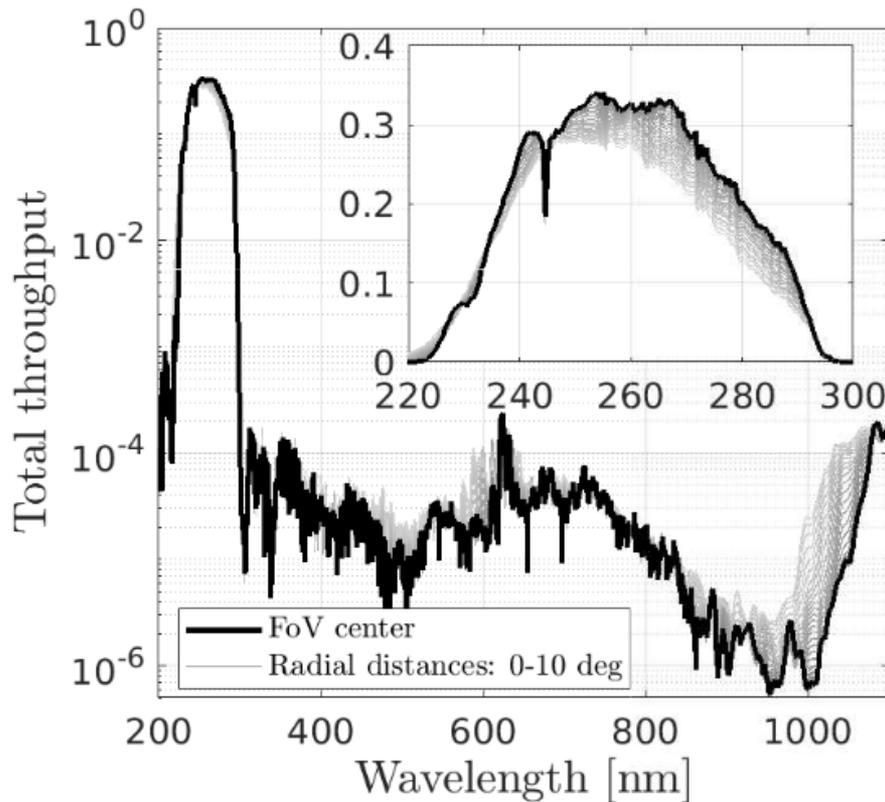
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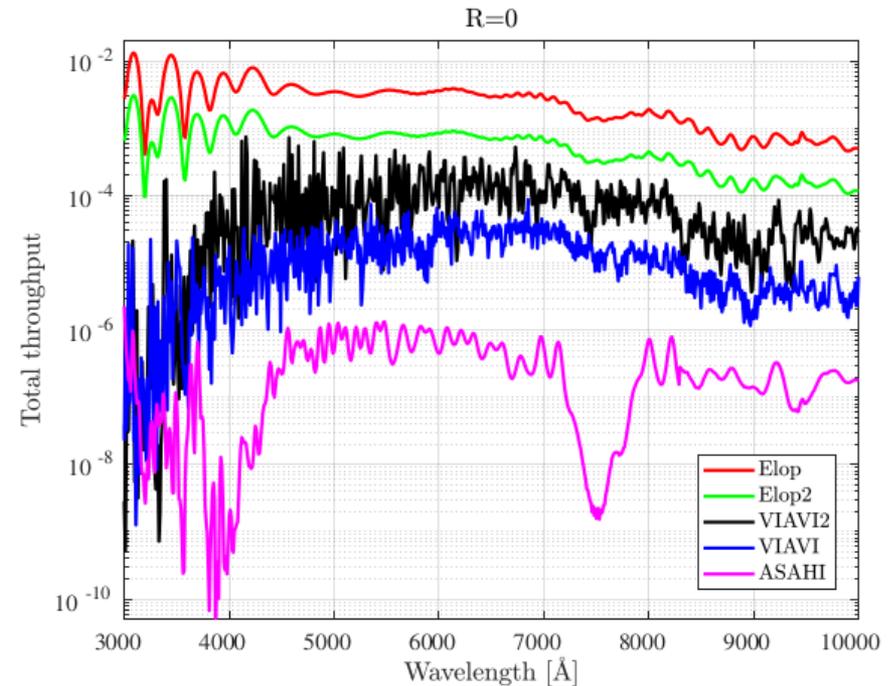
For more details: Asif et al. 2021
Bastian-Querner et al. 2021
Liran et al . 2022

Meets out-of-band attenuation requirements

Total throughput

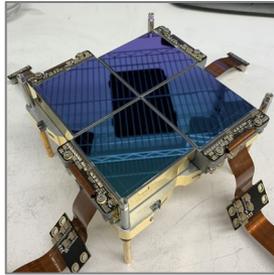
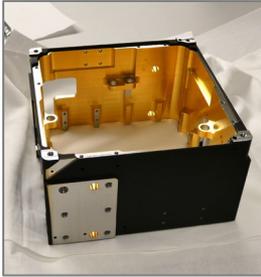


Out of band

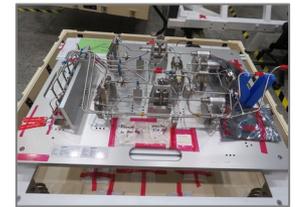
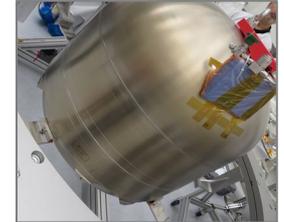
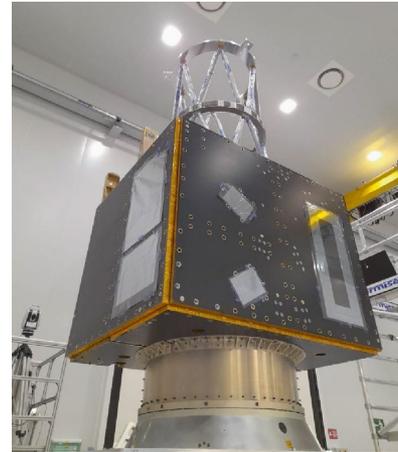


- The significant technology risks have been retired (sensors QE; Coatings performance; Stray light rejection...).
 - Focal plane array/Telescope/Bus CDRs completed and approved.
 - All LLIs have been purchased; all major components have arrived in Israel (solar panels delayed).
 - We are in the construction phase: Focal plane array DM & EM integrated, Bus and Telescope integration started.
-

Camera structure and sensors (development models)



Spacecraft bus & propulsion system



Telescope structure and optics



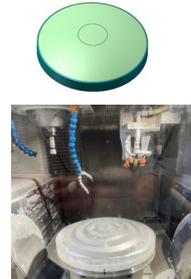
MIRROR



BEZEL



FF2
VANE



FS SC1



MIRROR
TUBE



CaF2 SC2

- The significant technology risks have been retired (sensors QE; Coatings performance; Stray light rejection...).
 - Focal plane array/Telescope/Bus CDRs completed and approved.
 - All LLIs have been purchased; all major components have arrived in Israel (solar panels delayed).
 - We are in the construction phase: Focal plane array DM & EM integrated, Bus and Telescope integration started.
 - Remaining risks identified and managed:
 - Complex Interfaces,
 - Contamination prevention and control.
 - Affordable Mission cost, approx. \$120M (excluding launch).
-

ULTRASAT: Mission profile

- ALL SKY SURVEY
 - 3hr/day during the first 6 months
 - 7x deeper than current (GALEX) (23 AB limiting mag @ $|b| > 30^\circ$)
 - LONG STARES
 - 2 directions near the Ecliptic poles, minimize Galactic extinction and zodiac bgnd
 - 21 hr/d – 5 min cadence, 200 deg²
 - 3 hr/d – 4[1] d cadence, 8000 [2000] deg²
 - 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 (~33%)
 - Continuous transmission to the ground
-

Science Operation Center (SOC)



5Mbps Downlink
(5-10 MHz)
Ku Band

Ground station (IAI)

Tasking

Raw
Image

The SOC supports all the scientific aspects of the mission:

- Observation planning and schedule, ToOs;
- Identifying transients and alerting the community (< 15 min);
- Science archive.

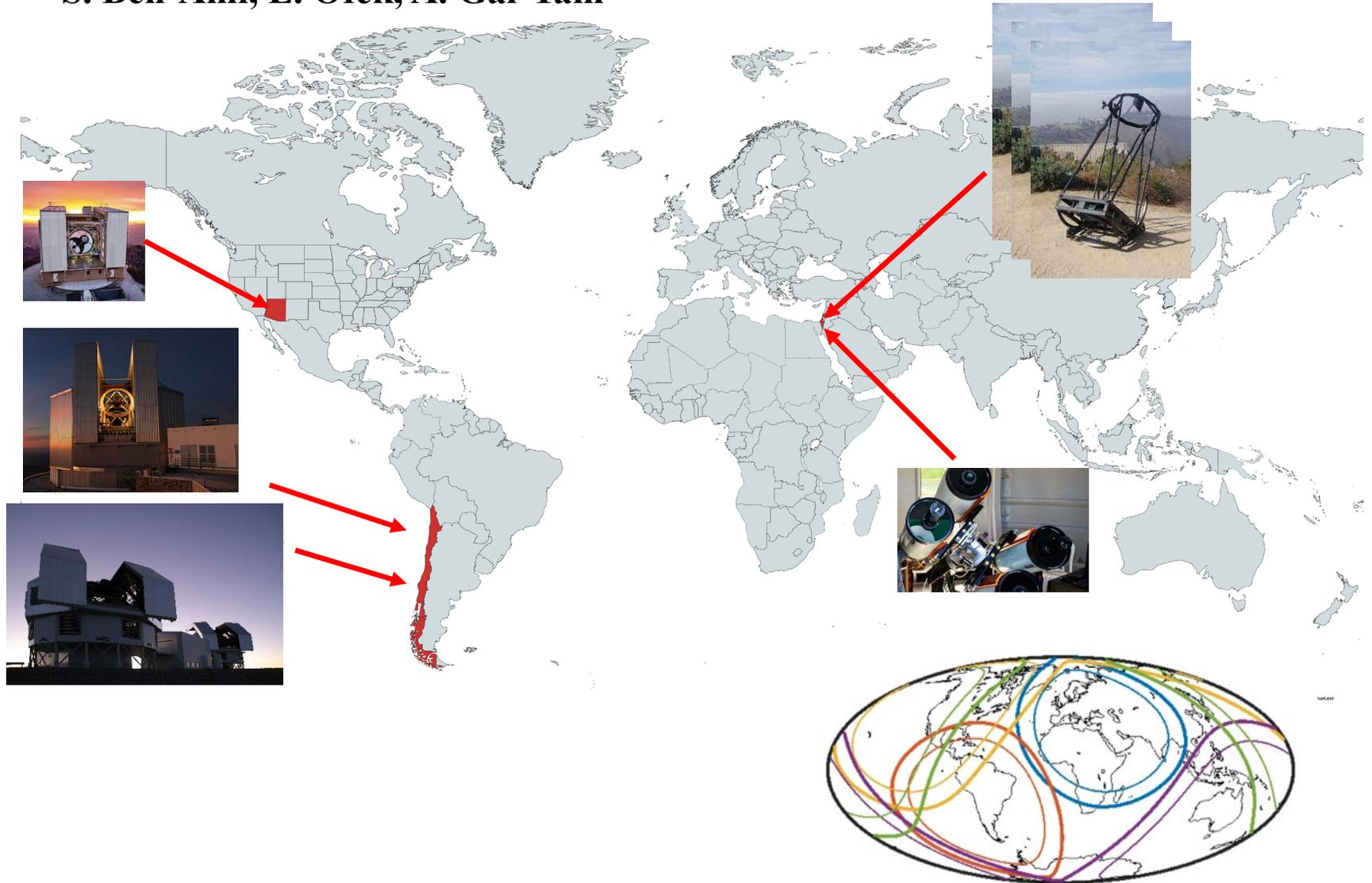
- A major component of the education and outreach program (with Davidson Inst.)



Supporting the ULTRASAT Mission

WIS ground-based optical follow up programs

S. Ben-Ami, E. Ofek, A. Gal-Yam



ULTRASAT: Science collaboration

- Data policy: Alerts are public in real time;
12 mon. proprietary period for all other data products;
13 Science working groups-
Science Working Group members receive real-time data access.
 - Open to all (and already including most) Israeli astronomers.
 - NASA Launch contribution - 8 US PIs (NASA funded) in WG's.
 - VRO (LSST) collaboration- 7 US PIs joined WG's.
 - DESY Camera contribution - 6 DESY PIs in WG's.
 - Czech NUV+FUV QUVIK satellite (~2 sq. deg FoV) - Follow-up ULTRASAT targets.
 - LJMU (robotic 2m telescope @ La Palma) - Follow-up ULTRASAT targets.
-

ULTRASAT: Science impact

- Revolutionize our view of the hot transient Universe:
 - Discovery volume 300 X GALEX,
 - Continuous min-mon cadence at 22.5 mag in a new window (NUV),
 - Real-time alerts to ground/space-based telescopes.
- A broad impact:
GW sources, SNe, variable and flare stars, AGN, TDEs, compact objects, galaxies.
- Groundbreaking science with an affordable satellite mission.

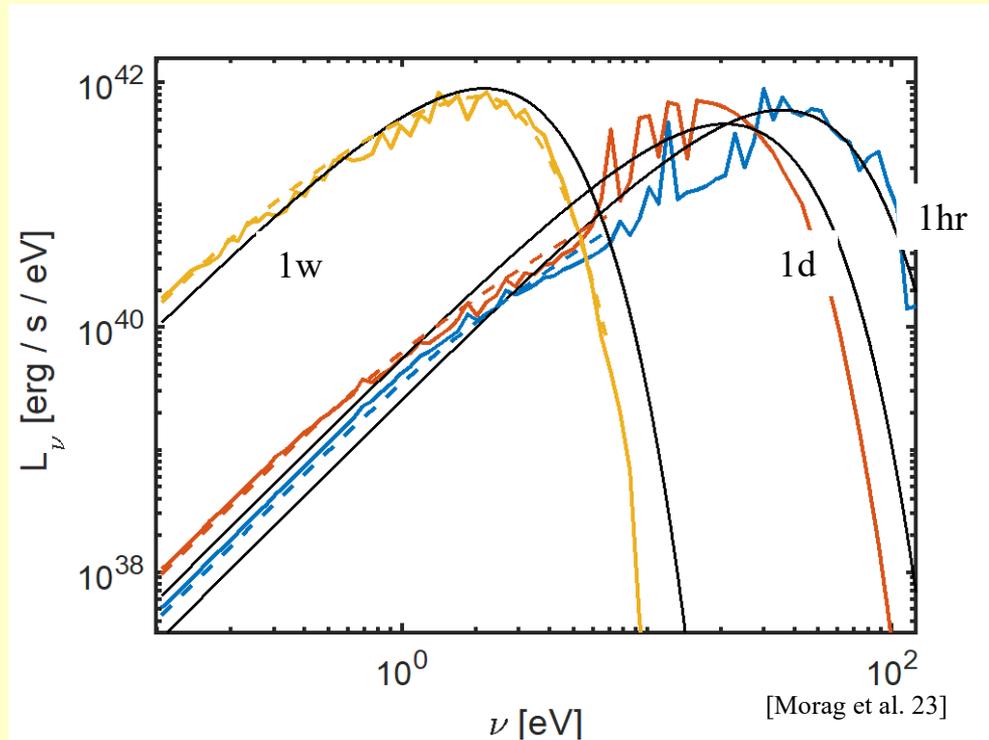
arXiv:2304.14482 – “ULTRASAT: A wide-field time-domain UV space telescope”
provides a detailed description of the mission and its science goals.

Backup slides

Shock cooling – Accurate robust analytic model

Multi-group rad-hydro calculations with bb & bf opacity demonstrate, for RSG:

- Spectra close to BB
- Small deviations at IR and FUV suppression- well described by analytic expressions.
- Systematic model prediction uncertainties: 10-20%.

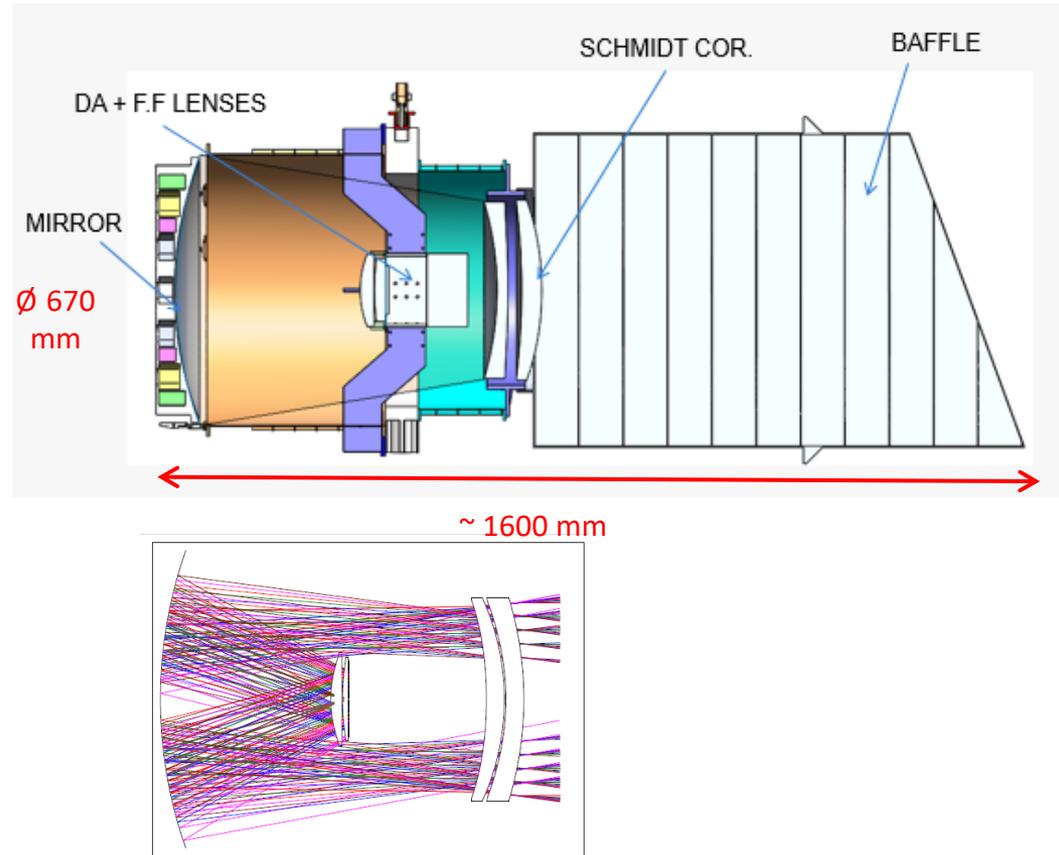


Analytic models essential for

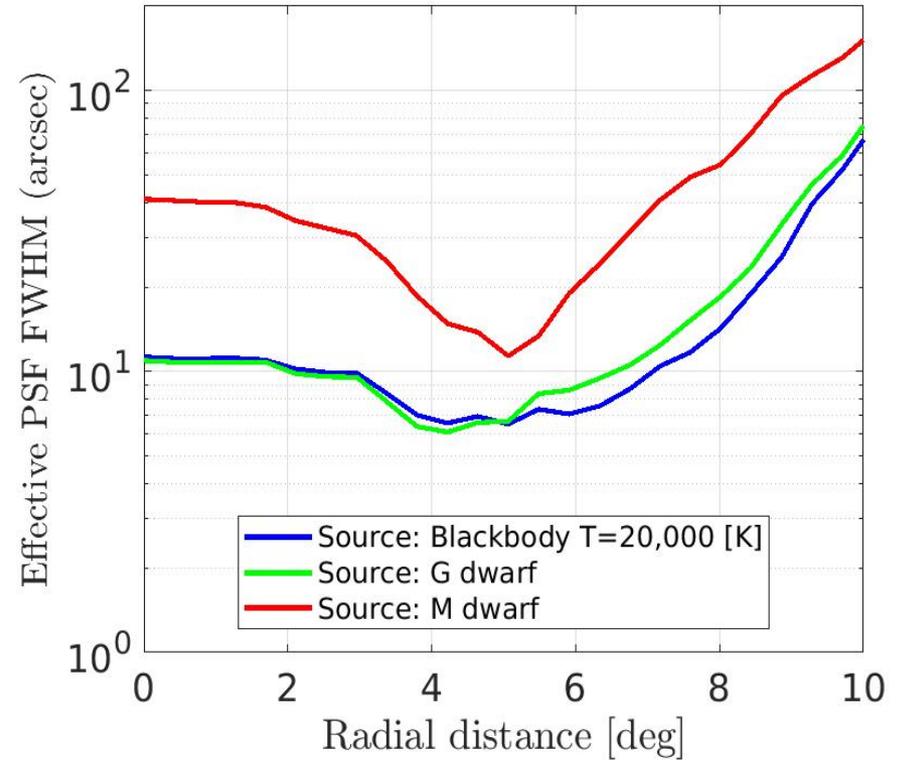
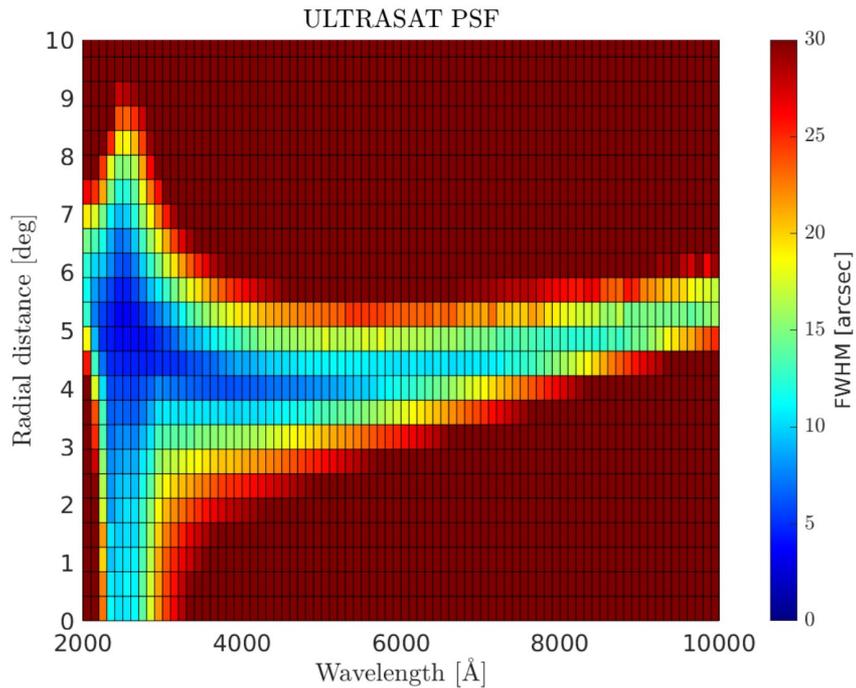
- Understanding,
- Parameter inference from data.

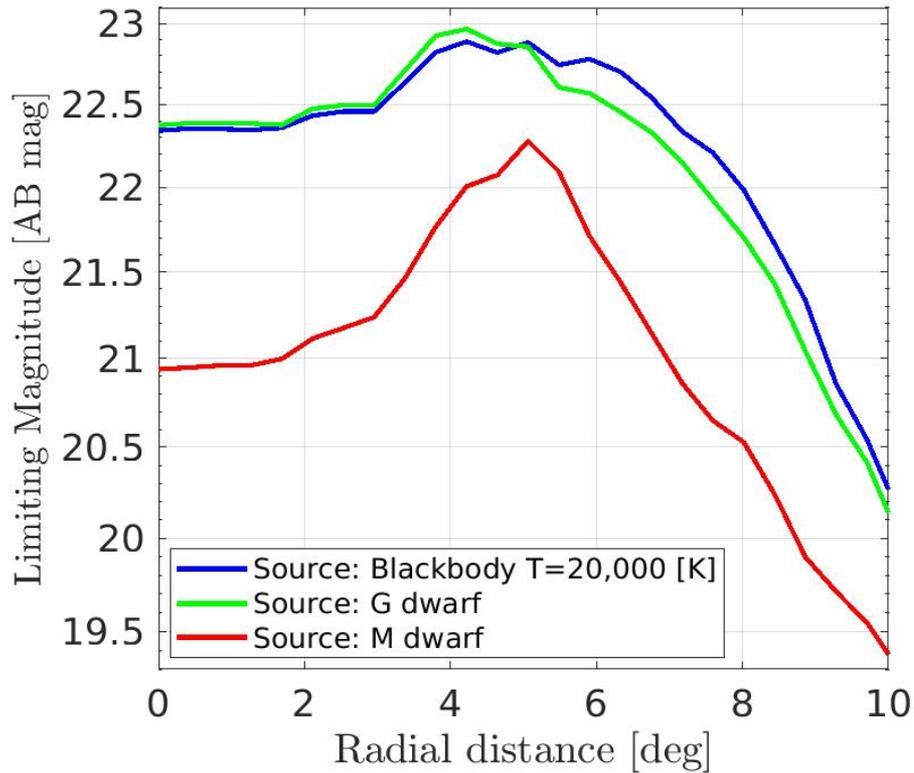
Solid color: numeric MG calculations
Black: $BB(T_c)$ [Rabinak & EW 11, Sapir & EW 17]
Dashed color: analytic corrections to BB

- Baffle
- Schmidt Corrector
 - Reduce Spherical aberration
 - 33 cm clear aperture
 - Fused Silica & CaF₂ (tandem)
- Mirror
 - 50 cm
- Field Flattener lens
 - Reduces Field Curvature
 - Fused Silica & CaF₂ (tandem)
 - Focus mechanism
- Out-of-band suppression-
Sapphire filter
- Focal plane array (Detector
Assembly)



For more details: Ban-Ami et al . 2022





Noise source	Variance (e ⁻ /pix)
Zodiac (Survey)	27
Cerenkov (75%)	15
Stray light (max)	12
Dark current @ 200 °K	12
Readout noise ^2	6
Electronic cross-Talk	2
Total	75

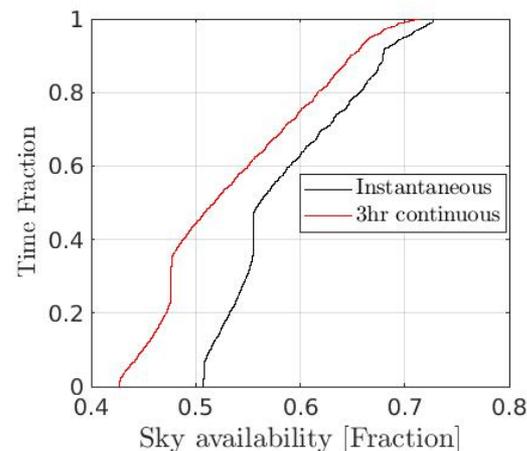
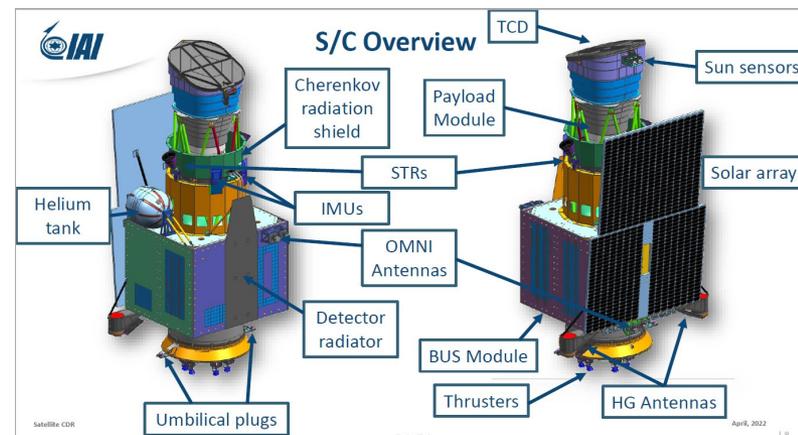
$$f = 1.5 \times 10^{-3} \text{ ph/cm}^2 \text{ s } (900\text{s}, 5\sigma)$$

$$m = 22.5$$

Spacecraft

- Launch (provided by NASA) into GTO orbit
 - Self propulsion to GEO orbit
 - Final orbit – Slot 4-West
 - Full Station Keeping
- **Continuous transmission** to the ground
- **Instantaneous >50% of the sky in <15 min**
- No limit on number of ToO's, except for max 25/yr with negative energy balance ("Hard ToO")
- Duration of Hard ToO: >3 h

Mission lifetime	>3 years
Kinematic lifetime	6 years
Science observations availability	>90%
Pointing stability	<3.0" over 300s (3σ)
Data Downlink rate	>5 Mbps
Pointing slew agility	>30°/min

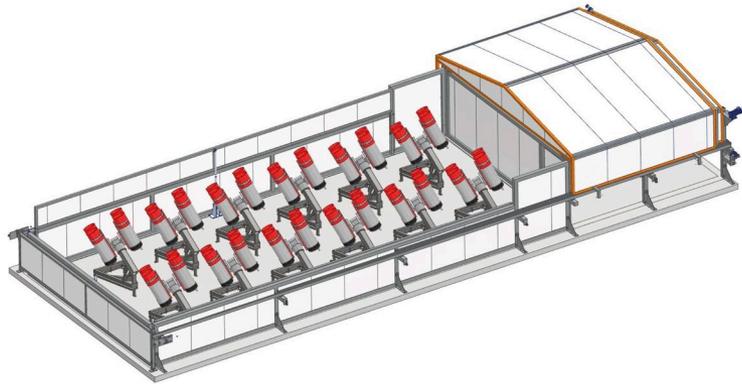


Shvartzvald+ in perp.

Supporting the ULTRASAT Mission

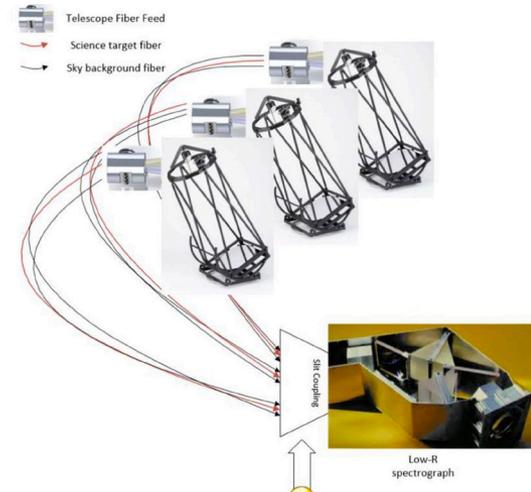
WIS Observatory in Neot Semadar

LAST - The Large Array Survey
Telescopes: Photometry



# of Telescopes x Aperture	48 x 11"
Optation Band	Visible: 400 – 850nm
FoV – Aperture:	7.4 sq. degrees / 1.5m
Narrow Field of View	
FoV – Aperture:	~355 sq. degrees / 28cm
Max Field of View	
Exposure Time	15sec

MAST: Spectroscopy



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

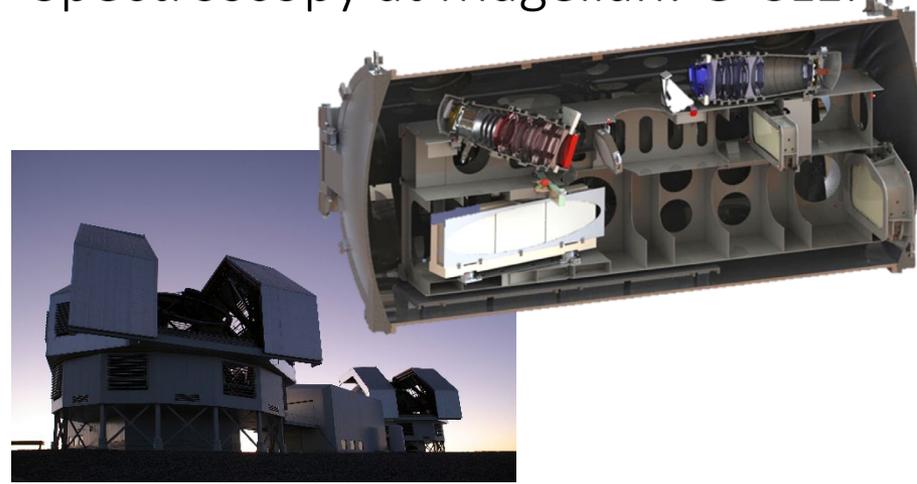
Supporting the ULTRASAT Mission Spectroscopy @ Chile

SOXs



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

Spectroscopy at Magellan: G-CLEF



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

Strong support to ULTRASAT