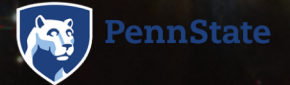


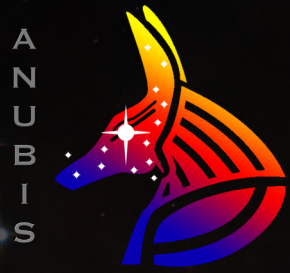
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ANUBIS – A Probe-Class UVO Space Observatory (AstroNomical Uv proBe Imager & Spectrograph)

Paul A. Scowen (Arizona State University), Jon Morse (Boldly Go), David Ardila (JPL), Bala Balasubramanian (JPL), John Bally (U. Colorado - Boulder), Matt Beasley (SwRI), Nick Devereux (Embry Riddle U. - Prescott), John Dyster (Northrop Grumman), Don Figer (Rochester Institute of Technology), Steven Finkelstein (UT Austin), Kevin France (U. Colorado - Boulder), Lisbeth Gavilan (NASA Ames), Varoujan Gorjian (JPL), James Green (U. Colorado – Boulder), Carl Grillmair (Caltech - IPAC), Patrick Hartigan (Rice U.), Amanda Hendrix (PSI), Chris Howk (Notre Dame), Renyu Hu (JPL), John Hutchings (NRC of Canada), Rolf Jansen (Arizona State U.), Stella Kafka (AAVSO), Jim Kasting (Penn State), Juan Larruquert (CSIC, Spain), Gary Matthews (Telescope Technologies), Stephan McCandliss (JHU), Melissa McGrath (SETI), Shouleh Nikzad (JPL), John Raymond (Harvard U.), Raghvendra Sahai (JPL), Oswald Siegmund (UCB - SSL), Phil Stahl (NASA Marshall), Todd Tripp (U. Massachusetts - Amherst), Neal Turner (JPL), Karen Willacy (JPL), Ben Williams (U. Washington), Rogier Windhorst (Arizona State U.), Bob Woodruff (Optical Consultant), Dave Yanatsis (Harris)



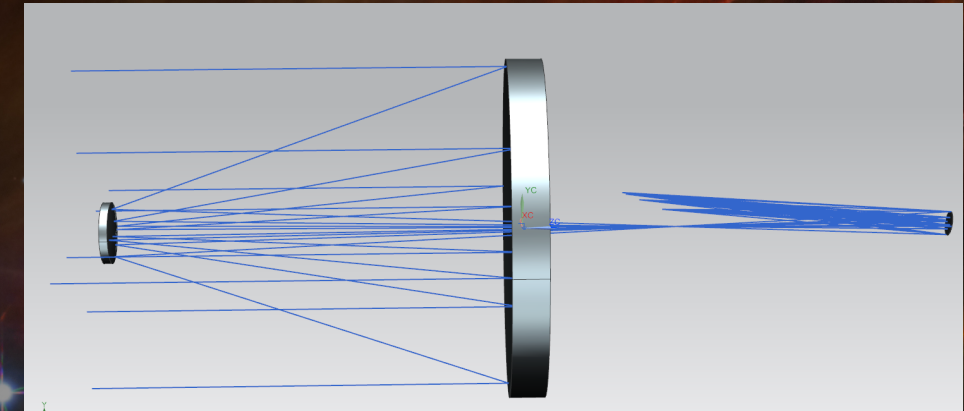
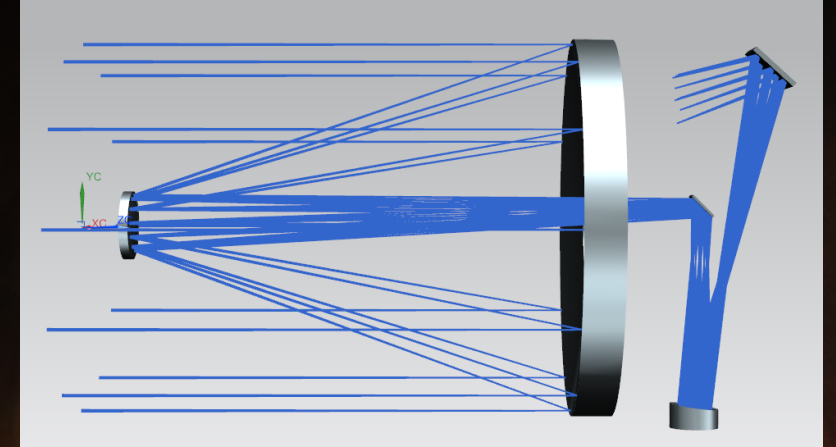


Outline

- An overview of the planned science and science goals
- Mission implementation
- Possible technical risks
- Project schedule
- ANUBIS' place in the overall NASA Astrophysics program

What is ANUBIS?

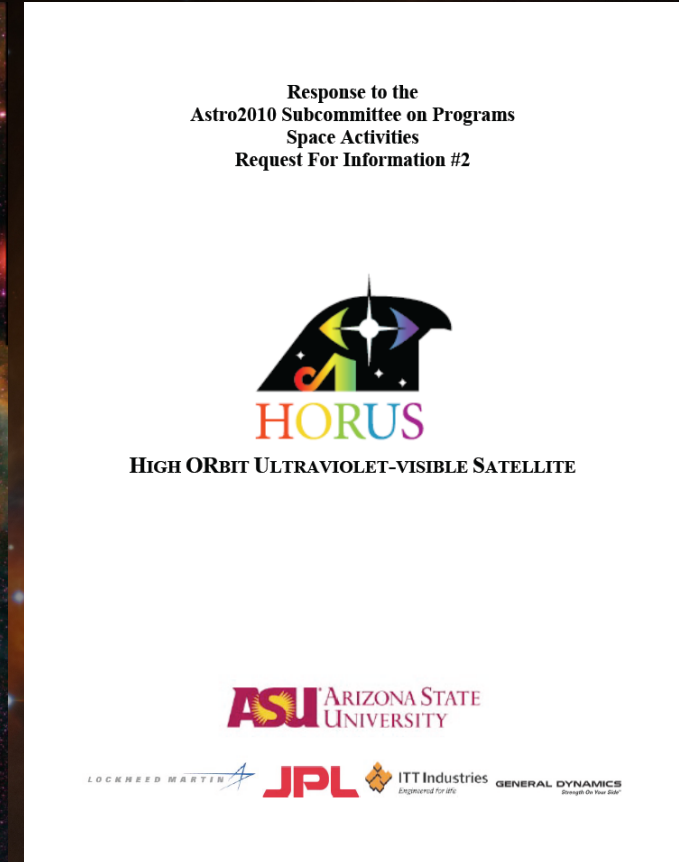
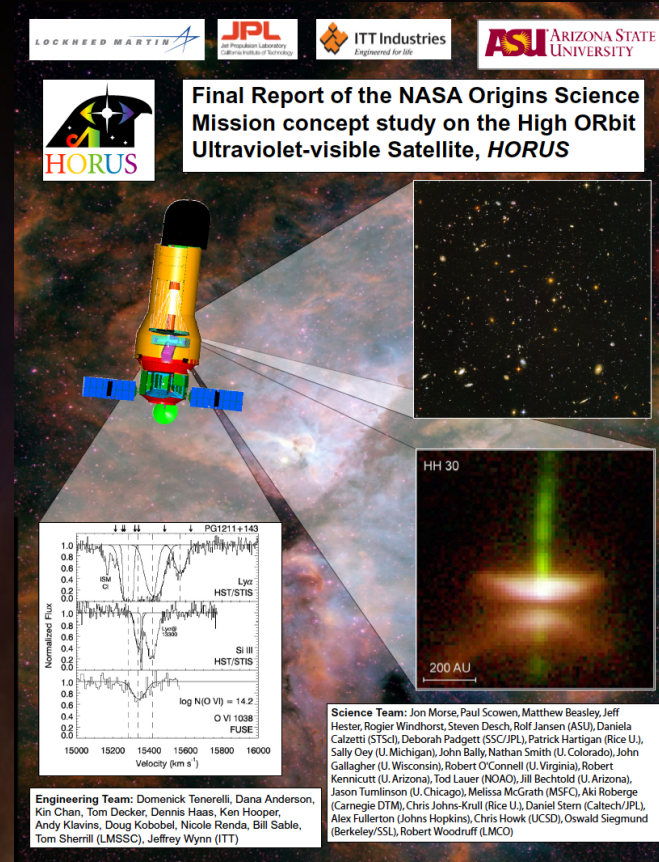
- ANUBIS is a 1.5m UVO space-based observatory using a TMA design w/ UV-enabling coatings
- **ANUBIS UV-Optical Camera:**
 - NUV-optical (200-1100nm) camera
 - Large field of view ~12 arcminutes square
 - Possible use of UV-enhanced CCDs, CMOS or QIS detectors
 - 40 mas pixels
- **ANUBIS FUV Spectrograph:**
 - Resolutions of $R \sim 500$, 3000 and 23,000
 - FUV-NUV bandpass: 100-320nm
 - MCP large-format detectors using new bi-alkali photocathodes deposited using ALD
 - Effective area of more than 2000 cm²
 - Use of MSA over a 2 arcminute square field of view to enable MOS

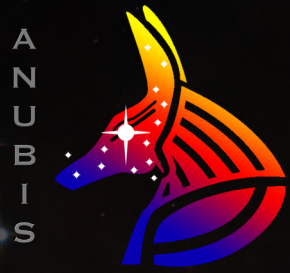


Legacy and Origins



- ANUBIS is a direct derivative of the 2.4m HORUS mission concept study we did in 2005 and redid in 2009 in response to a direct request from the 2010 Decadal Survey.
- Project Management would reside, as a result, with JPL as they helped us conduct the original study and design work
- Much of the costing validation and design work presented today is based on the findings and lessons learned during that study.





Science Drivers and Goals



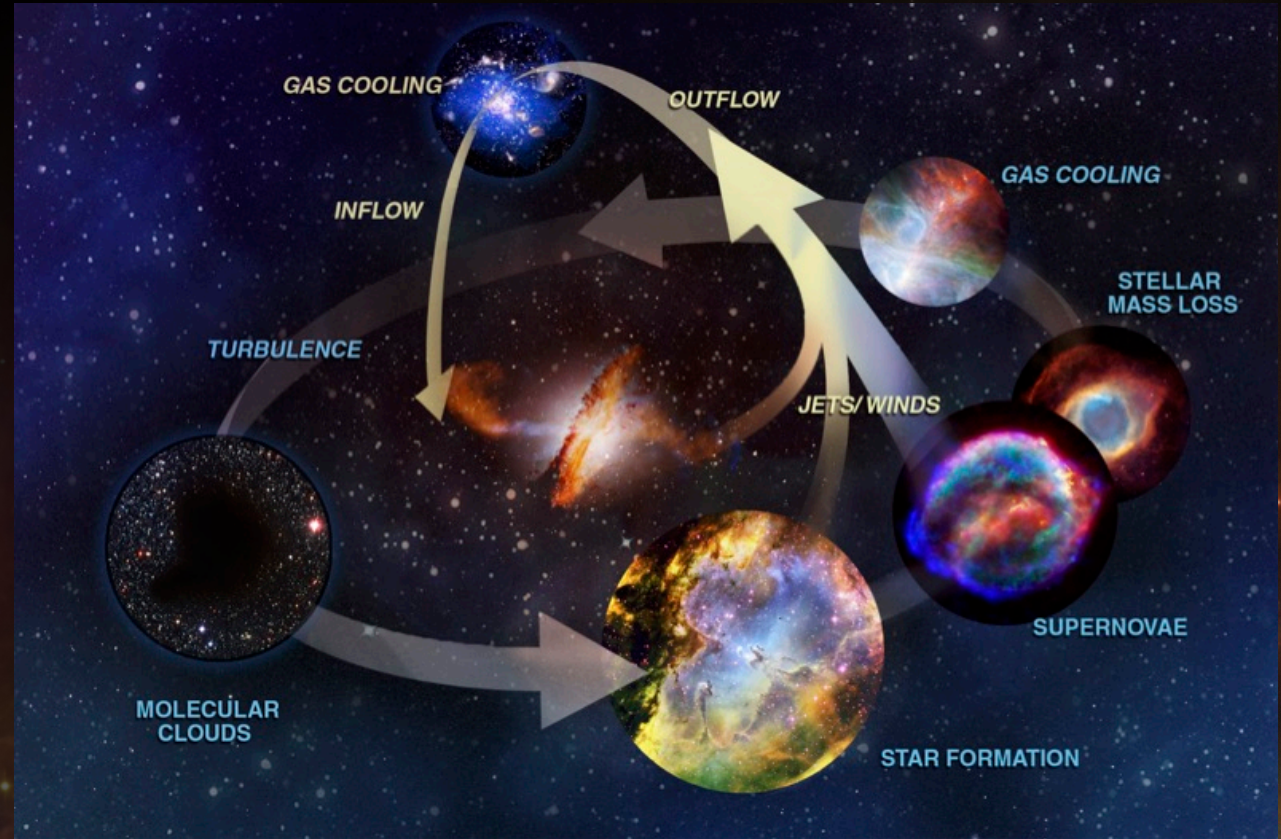
ANUBIS Science Drivers and Goals

- ANUBIS Cosmic Origins science goals align with the 2014 NASA Strategic Plan, Objective 1.6, to “Discover how the universe works, explore how it began and evolved, and search for life on planets around other stars.” Its capabilities will address all three of the 2014 NASA Science Plan Astrophysics science goals to
 - (1) “Probe the origin and destiny of our universe, including the nature of black holes, dark energy, dark matter and gravity”;
 - (2) “Explore the origin and evolution of the galaxies, stars and planets that make up our universe”; and
 - (3) “Discover and study planets around other stars, and explore whether they could harbor life”, with an emphasis on goals (2) and (3).
- There is also alignment with the Planetary Science goals, especially “Advance the understanding of how the chemical and physical processes in our solar system operate, interact and evolve.”
- Many of the UV science goals have been derived from community discussion since the last Decadal at the COPAG-organized FUV workshop held at NASA Goddard in 2015 (summarized in Scowen et al., PASP, 129, 76001, 2017)
- The ANUBIS Science Suite has been designed around leveraging the unique capabilities the mission brings to the table during an anticipated era of large ground-based glass (TMT and GMT) and available on-orbit wide-field NIR imaging (WFIRST):
 - Wide-field diffraction-limited NUV-visible band imaging that provides for both broad and narrow-band filters
 - FUV and NUV high resolution MOS spectroscopy covering 100-320nm

ANUBIS Science Drivers and Goals



- Visible-band Imaging
 - Star formation mapping and diagnostics
 - Galactic Halo mapping of structure and Dark Matter
 - Star Forming Regions and Stellar Halos in Nearby Galaxies
 - Time Domain Astrophysics
- FUV Spectroscopy
 - Circumgalactic Medium studies
 - Solar System science
 - Time domain spectroscopy of Stellar Accretion & AGNs
 - UV spectroscopic diagnostics of gas phase physics across a suite of targets
 - UV spectroscopic monitoring of Exoplanet Host Stars: Exoplanet Atmospheric Loss and Atmospheric Chemistry
 - Ly-Continuum Galaxy Escape Fraction



Star-Formation Science (Bally)

Deep, multi-epoch, $\sim 0.05''$ (NUV) to $0.1''$ (VIS) surveys of entire star-forming complexes:

10s of square degrees X 10s of complexes. (Orion, Perseus, Taurus, Ophiuchus, W3/W4/W5, ...)

- H-alpha, H-beta, [SII], [OI], [OII], [OIII], MgII, and broad-band continuum
- Proper motions of shocks, & stars

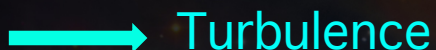
Measure Feedback impacts in the self-regulation of Star Formation

- Outflows, FUV, EUV, winds, ionization, explosions (supernovae, new types of transients)

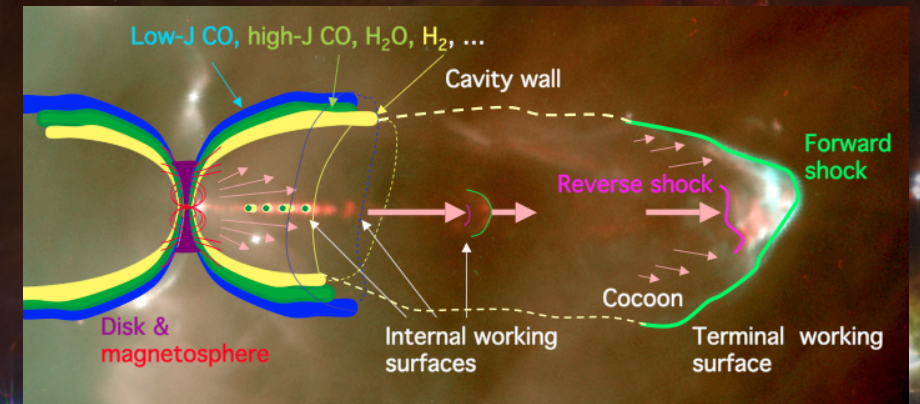
Accretion + Spin + Magnetic Fields (or radiation)



- Fossil record of accretion history, N-body dynamics
- Feedback Impact in Self-Regulation
Couple P, E, directly into parent cloud
- Most (all ?) YSOs have them
All accreting, spinning, magnetized systems?
Total impact on GMCs can exceed UV, winds, SNe...



- What determines stellar masses and the IMF?
Initial Conditions ? Feedback? N-body dynamics?
- Why is the Star Formation Efficiency (SFE) so low?
Turbulence? B ? Feedback ?
- What determines the Star Formation Rate (SFR) ?
External or internal Feedback, B ?

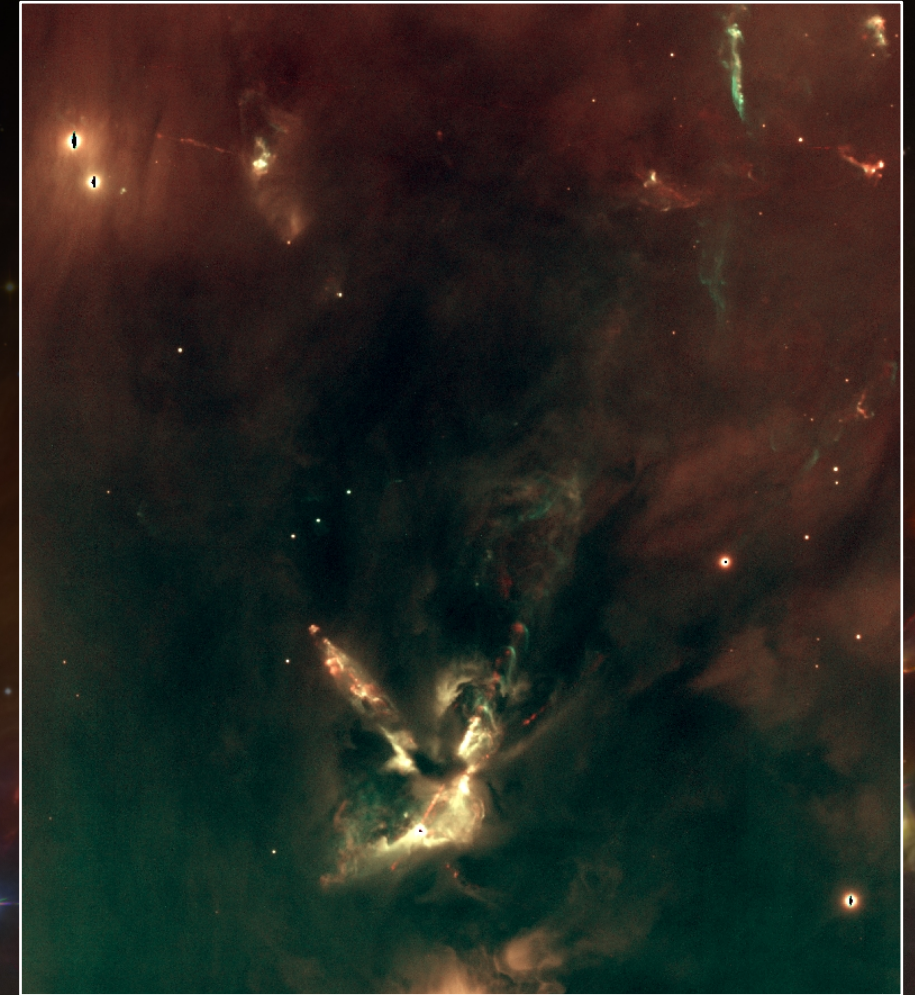


(Nakamura & Li 2009; Carroll+ 2009; Arce+2010; Nakamura+2011; Bally 2015; Federrath+ 2015; Plunkett+2013; 2015; Li+2015; Feddersen+2018; 2019)

Star-Formation Science (Bally)



HH 34 / 201 / 222
Ha [S II] ~0.5" seeing limited
(Subaru)

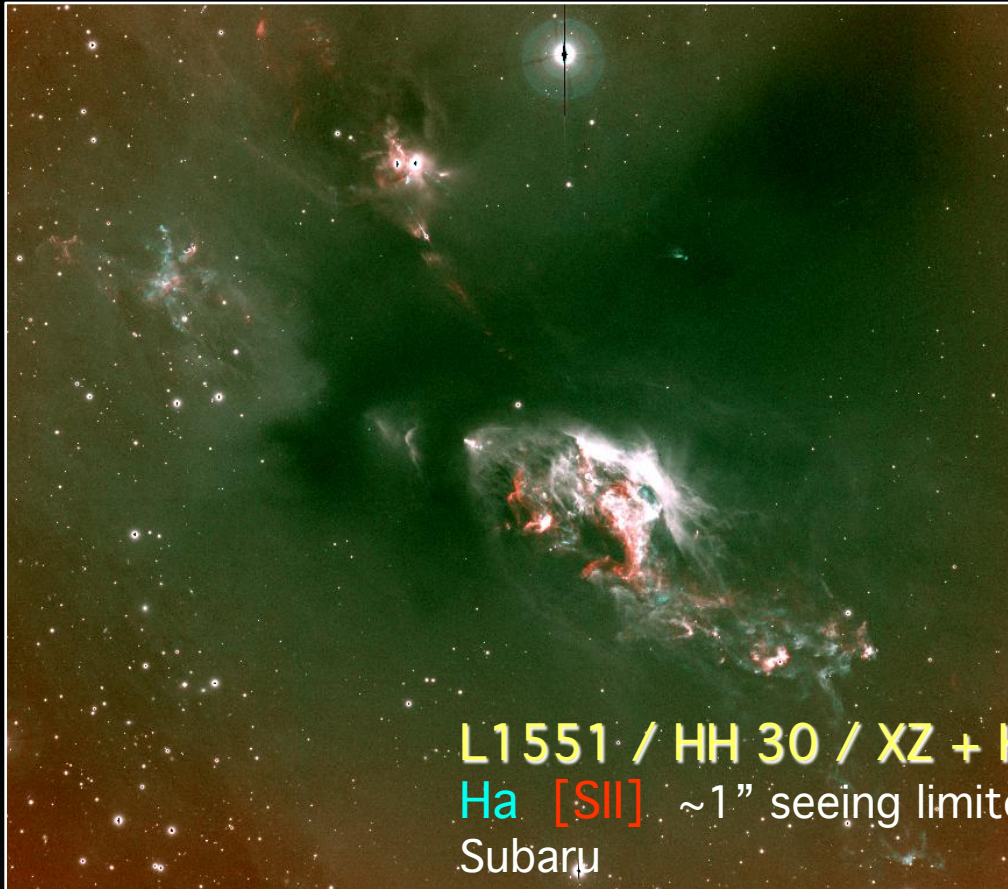


HH 24 Complex: Orion
Ha [S II] ~0.5" seeing limited
(Subaru)

Star-Formation Science (Bally)

Stars Form in Transient clusters:

Surface area covering factor of shocks responsible for feedback is large on deep images



L1551 / HH 30 / XZ + HL Tau (Taurus)

Ha [SII] ~1" seeing limited

Subaru

NGC 1333 (Perseus)

Ha H₂ ~1" seeing limited

KPNO 4m Mosaic CCD + Spitzer





Substructure and Dark Matter in the Galactic Halo (Grillmair)

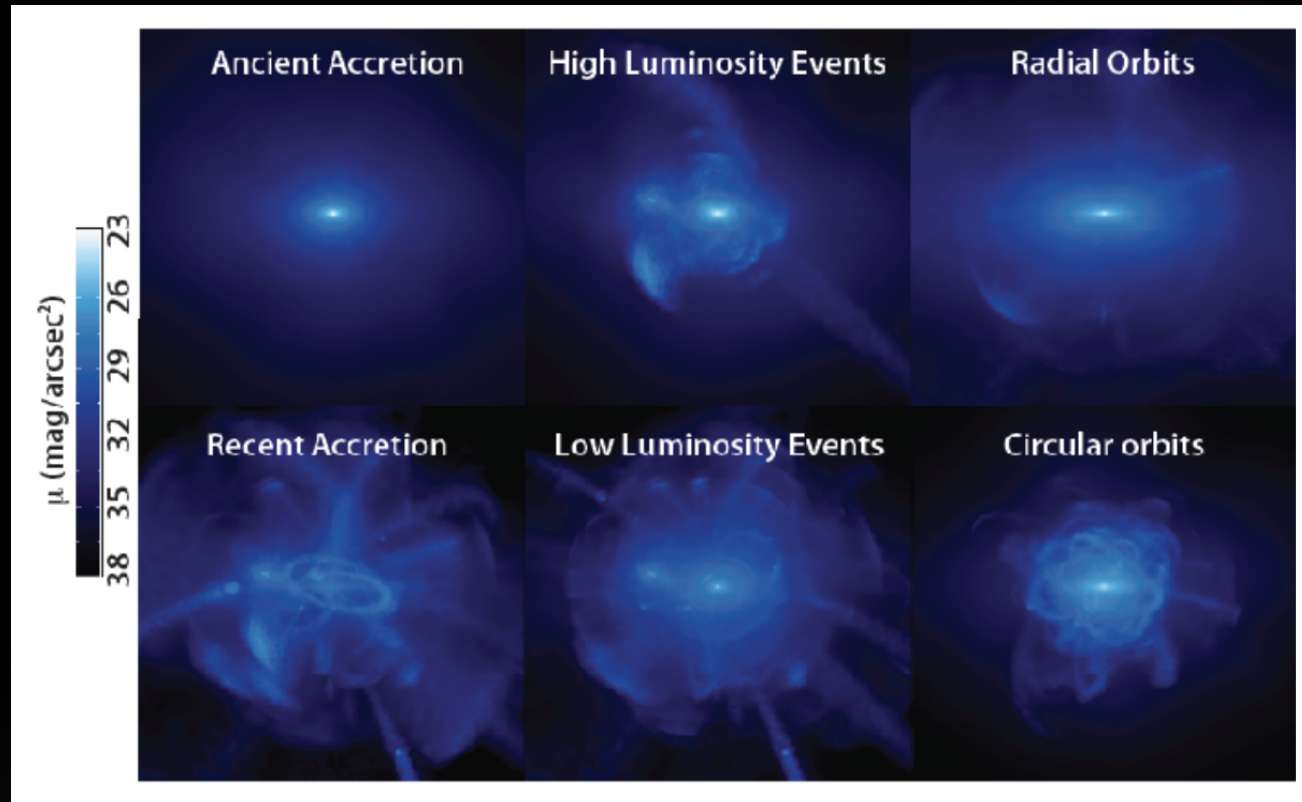
- More than 60 stellar debris streams have now been found in the Milky Way halo.
- These streams record the early accretion history of our Galaxy, and constrain the global shape of the Galactic potential.
- The coldest, globular cluster streams are exquisitely sensitive to any disturbances or irregularities in the Galactic potential. They are consequently superb dark matter subhalo detectors.
- Significant gaps and spurs have already been found in the GD-1 and ATLAS/Aliqa Uma streams. Recent modeling of these gaps suggest that there may be problems with the predictions of the current cold dark matter paradigm. To make more substantive statements, we need a larger sample of streams, at greater distances, with improved membership probabilities.
- Gaia has enabled the detection and physical characterization of many streams in the nearby halo. However, a magnitude limit of ~ 20 severely limits the distances to which we can detect streams (typically < 15 kpc).

Substructure and Dark Matter in the Galactic Halo (Grillmair)



- By surveying large areas of sky, at multiple epochs, to intermediate depths ($g \sim 25$, 3σ , about 2 hrs), ANUBIS will enable the detection of halo streams out to ~ 200 kpc, or nearly the virial radius of the Milky Way Galaxy.
- Optimal color-magnitude/proper motion filtering techniques applied to ANUBIS multi-epoch photometry and astrometry will enable detection of substructures down to the equivalent of less than 36 mag/arcsec^2 . Sensitivity to stream gaps will be several times better than with Gaia or any existing or planned ground-based survey.
- Such a survey will naturally also detect many more ultrafaint dwarf galaxies, stellar debris clouds, and other accretion relics.

Nearby Galaxies Science: Stellar Halos (Williams)



ANUBIS will detect and characterize young components in stellar halo structures

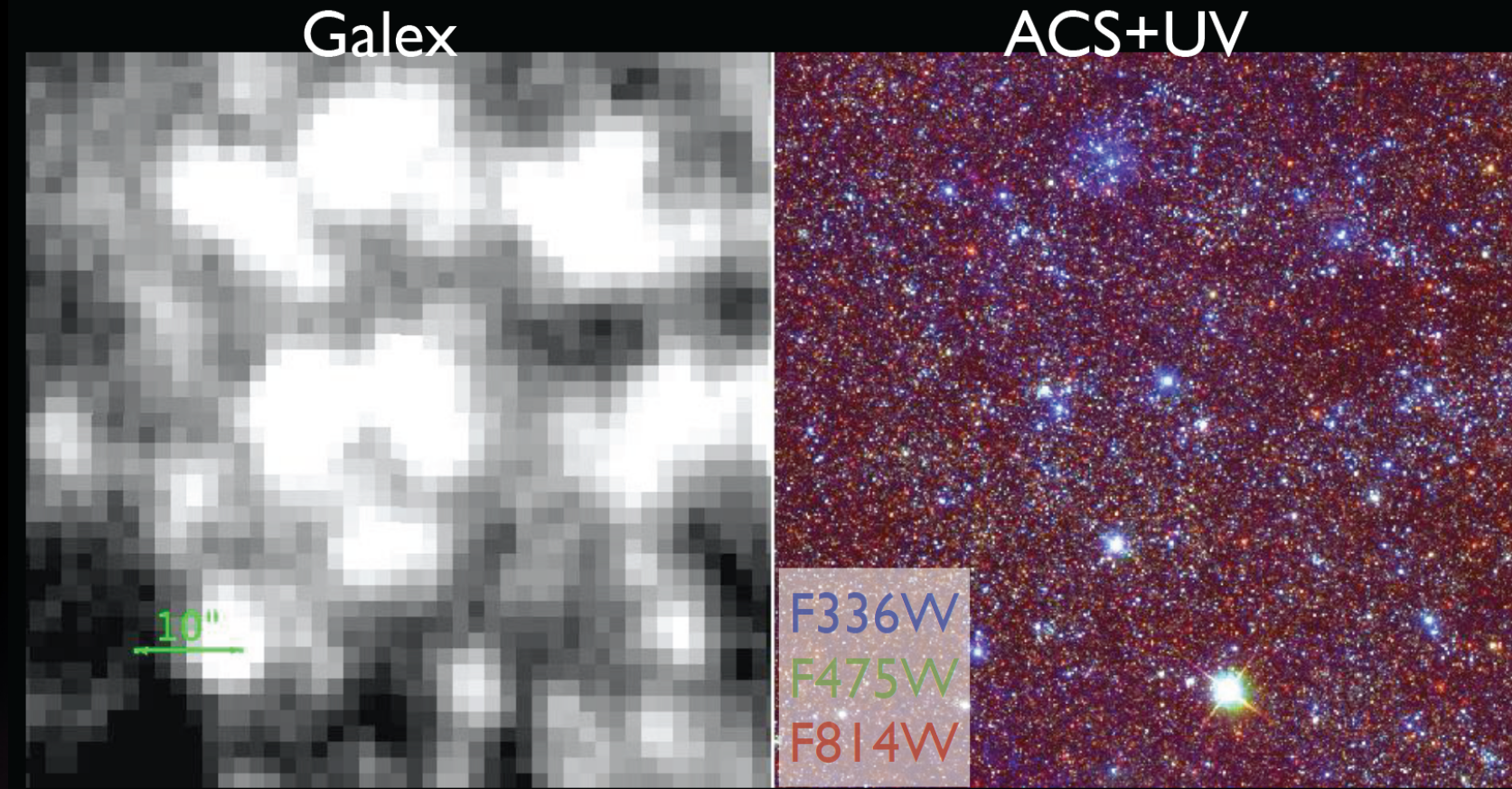
Bullock and Johnston (2005) Example Halos of Varying Accretion Histories

Nearby Galaxies Science: Star Forming Regions (Williams)

- Sensitive to massive stars
 - Traces star formation, winds, mass loss, metal enrichment, SN feedback
- Directly detects *individual* stars analogous to those responsible for UV flux from distant galaxies

High resolution necessary to resolve stars responsible for UV emission
ANUBIS will detect and obtain spectroscopy for these stars in all star forming regions of nearby galaxies, probing star formation in a wide variety of environments

Nearby Galaxies Science: Star Forming Regions (Williams)



High resolution necessary to resolve stars responsible for UV emission
ANUBIS will detect and obtain spectroscopy for these stars in all star forming regions of nearby galaxies, probing star formation in a wide variety of environments

Time Domain Astrophysics (Jansen)

- Time-domain monitoring of the JWST NEP Time-Domain Field (which has accumulated a wealth of ancillary data from X-rays through long-wave radio these past three years -- <http://lambda.la.asu.edu/jwst/neptdf>) to monitor transients at cosmological distances associated with star formation (SNe, GRBs) and growth of super massive black holes (flares and TDEs).
 - multi-wavelength monitoring provides characterization of transient sources
 - HST and JWST fields of view are not conducive to blind surveys of rare transients; X-rays (Chandra,XMM,NuSTAR,Lynx?) + ANUBIS + WFIRST + radio are a natural complement with comparably wide FoVs.
- Accumulating medium-deep to deep wide-field imaging at $\sim 0.1''$ resolution by end-of-mission (or each successive year) stacking of monitoring data in the UV--Visible, complementing WFIRST near-IR and surpassing TESS depth and resolution

Time Domain Astrophysics (Jansen)

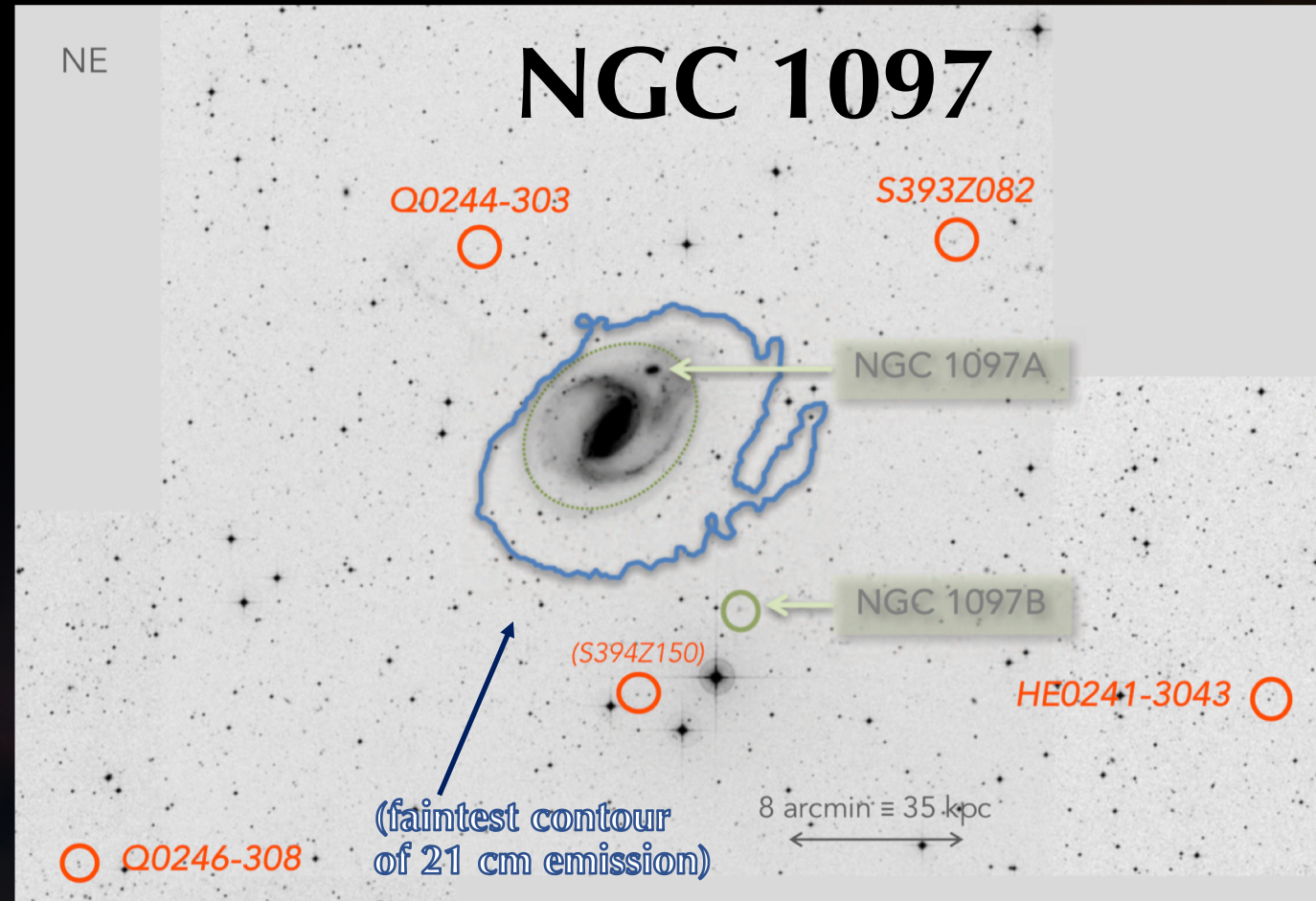
- Monitoring of one or more SEP fields in the outskirts of the LMC (or, depending on the instantaneous FoV, a large contiguous portion of the LMC), to monitor variability of winds and outflows of massive stars in late stages of their evolution, and monitoring of young stellar objects and their outflows (HH-objects, T Tauri and similar stars) to monitor accretion rates and feedback to their surrounding ISM through winds, outflows, jets
 - this could be narrow-band monitoring (proper motion, shocks, bullets)
 - this could be FUV spectroscopic monitoring (variable line emission)

NB: the locations of obscured star formation are assumed to be known from prior WFIRST near-IR imaging (and perhaps grism spectroscopy), and extant Spitzer/IRAC and MIPS surveys (low resolution, but sensitive to heavily obscured SF), which would retire the risk of not having the full overview of star formation at various stages.



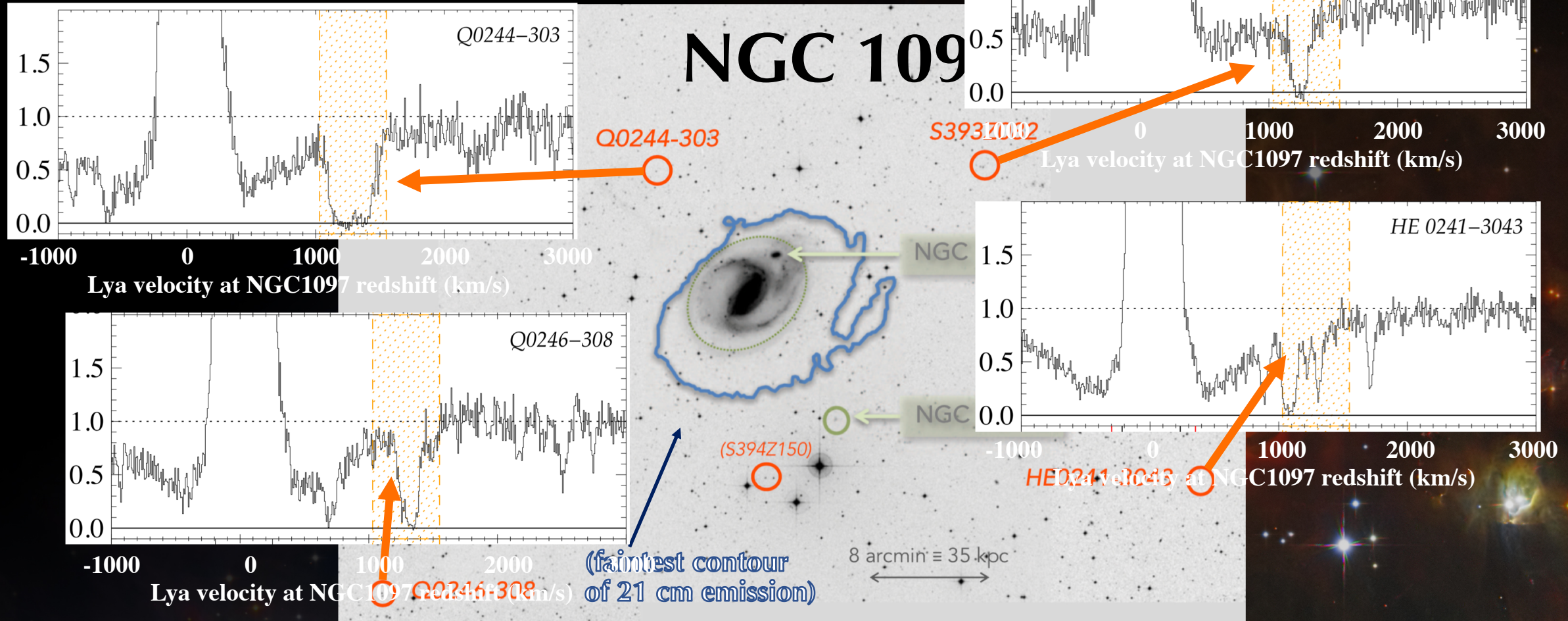
The Circumgalactic Medium: A New Frontier of Galaxy Evolution (Tripp)

ANUBIS discovery space: many QSOs can be found behind galaxies (e.g., Bowen et al. 2016, see below), but very few multiprobe studies have been done with HST



The Circumgalactic Medium: A New Frontier of Galaxy Evolution (Tripp)

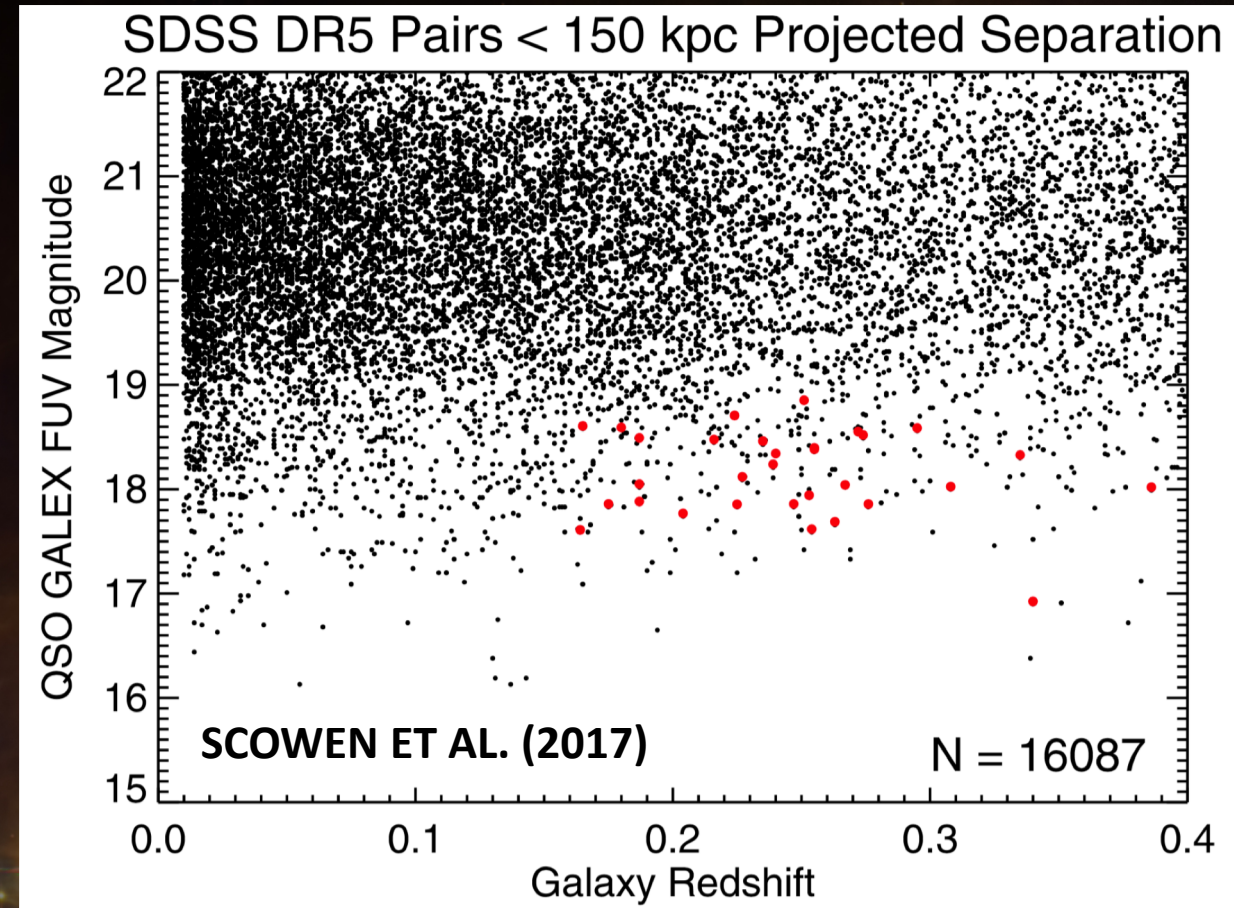
$\text{Ly}\alpha$ absorption clearly shows that NGC1097 has a huge, rotating H I disk (much larger than the 21cm disk), with either a Keplerian dropoff in rotation velocity or an inflow component



The Circumgalactic Medium (Tripp)

There are many known QSOs that are bright enough for this, but little has been done due to HST oversubscription. AS A DEDICATED MISSION, ANUBIS CAN DO THIS WITH STATISTICALLY USEFUL SAMPLES

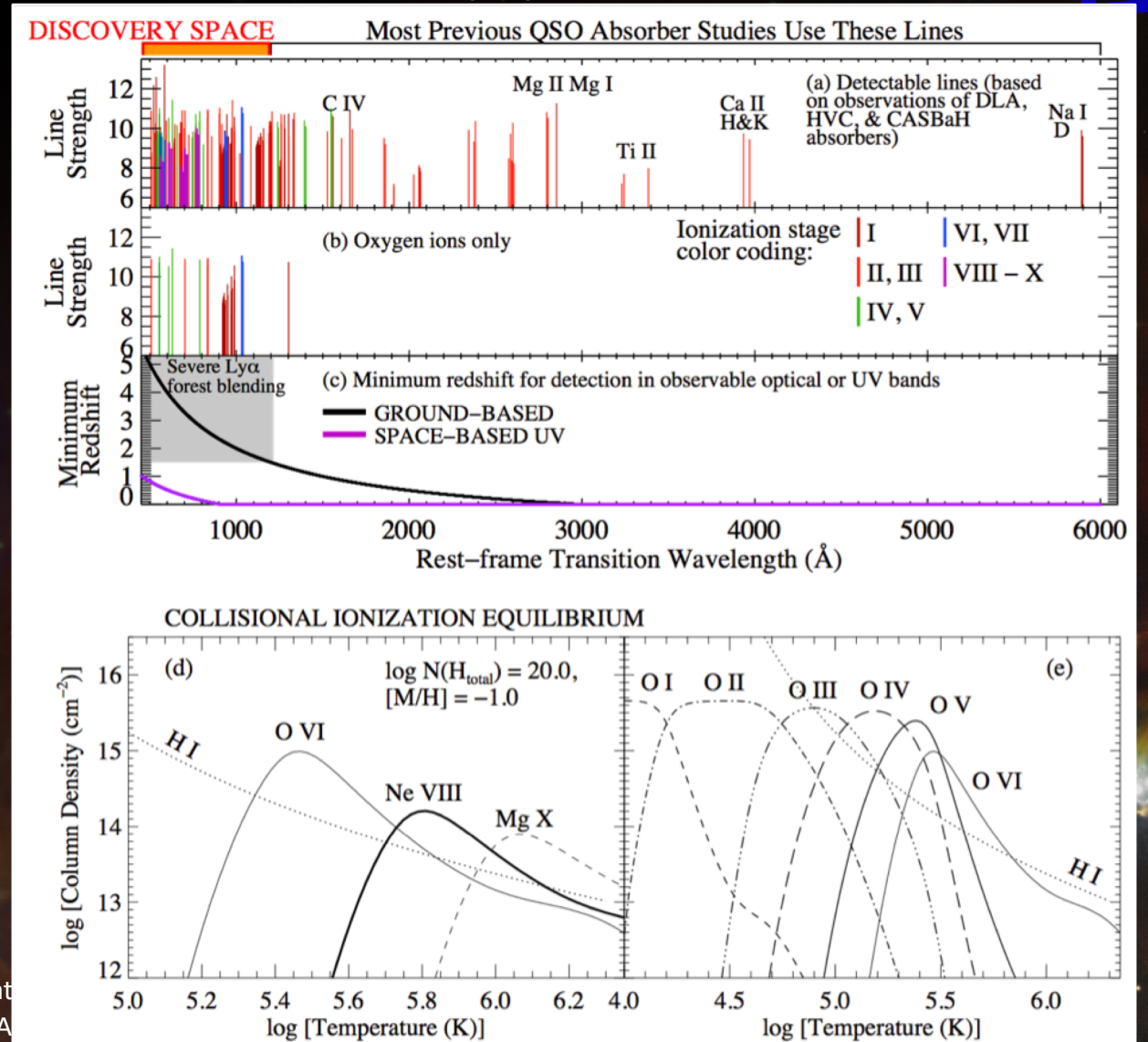
- RIGHT: QSO-galaxy pairs with < 150 kpc projected separation (from SDSS DR5)
- RED DOTS: QSOs that have been observed with HST as of 2017





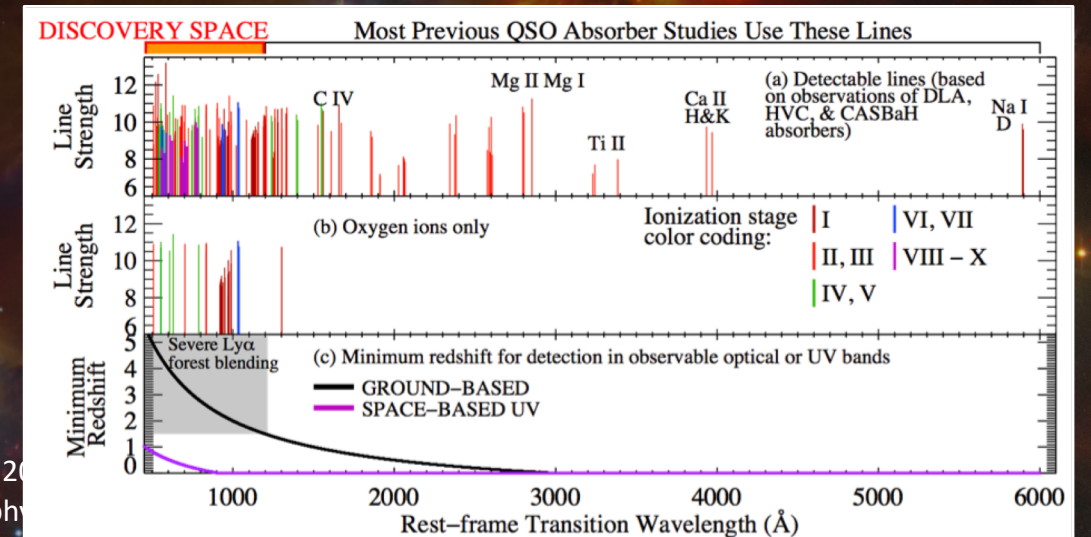
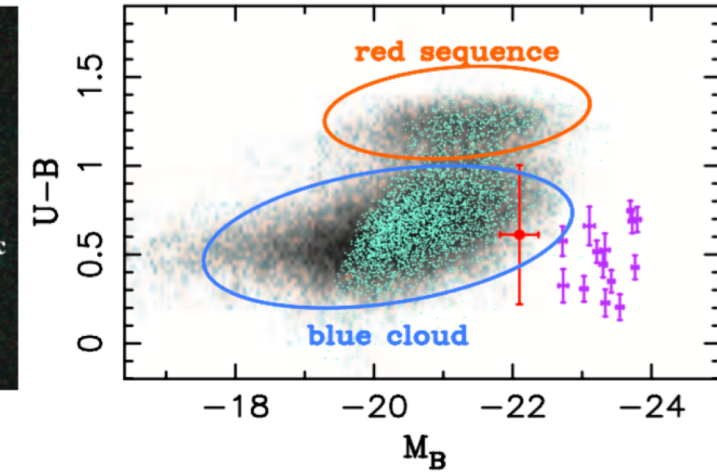
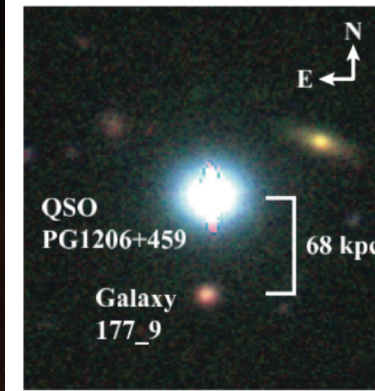
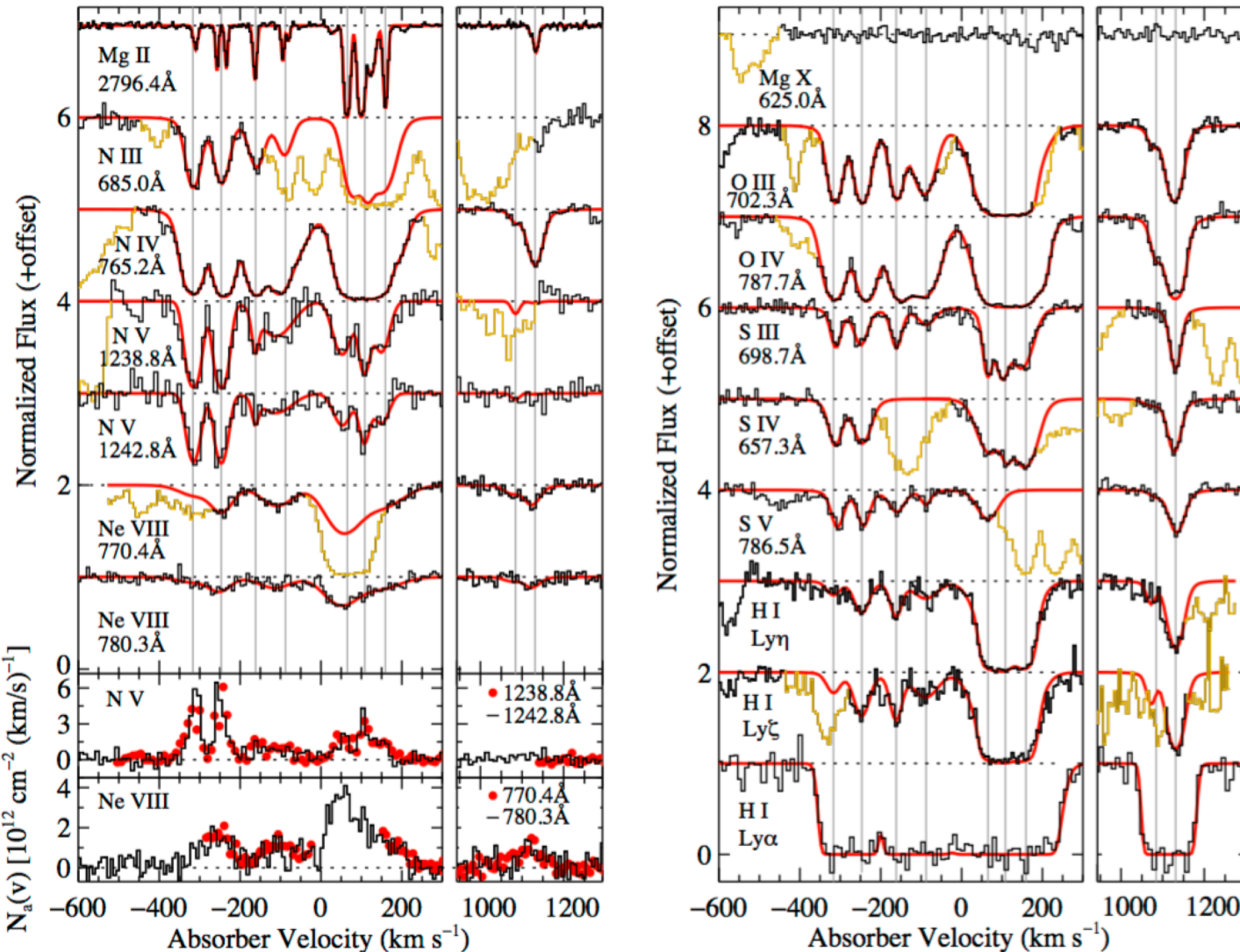
The Circumgalactic Medium (Tripp)

ANUBIS discovery space:
THE DEEP ULTRAVIOLET
(see science white paper by
Tripp)



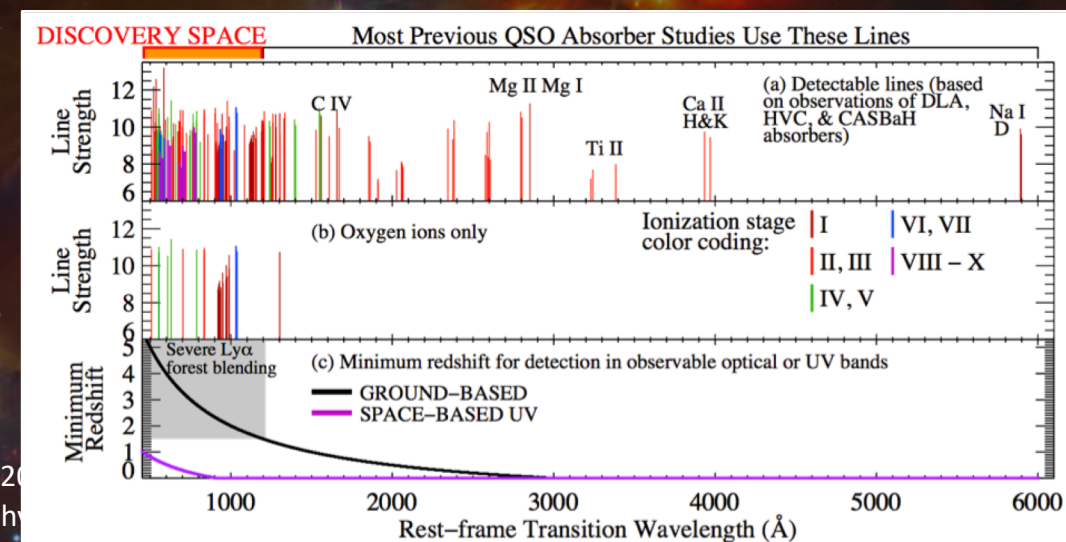
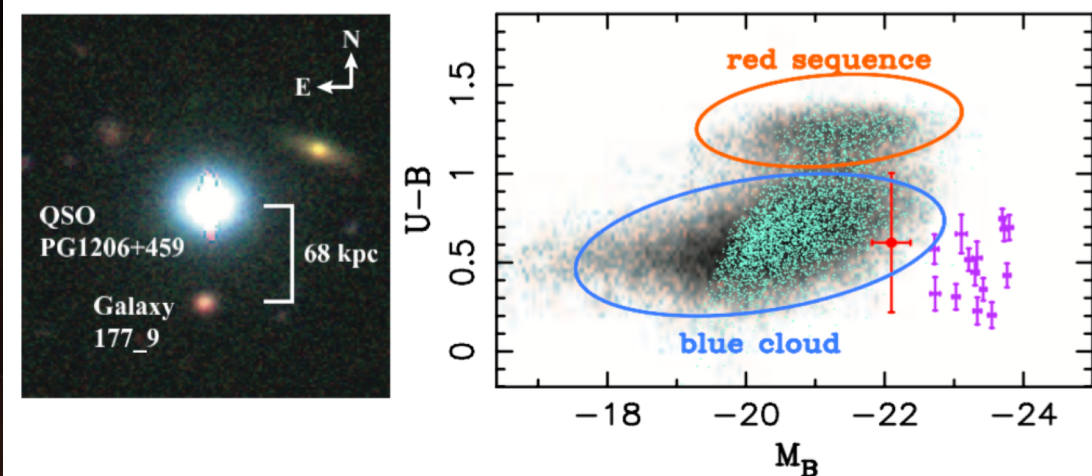
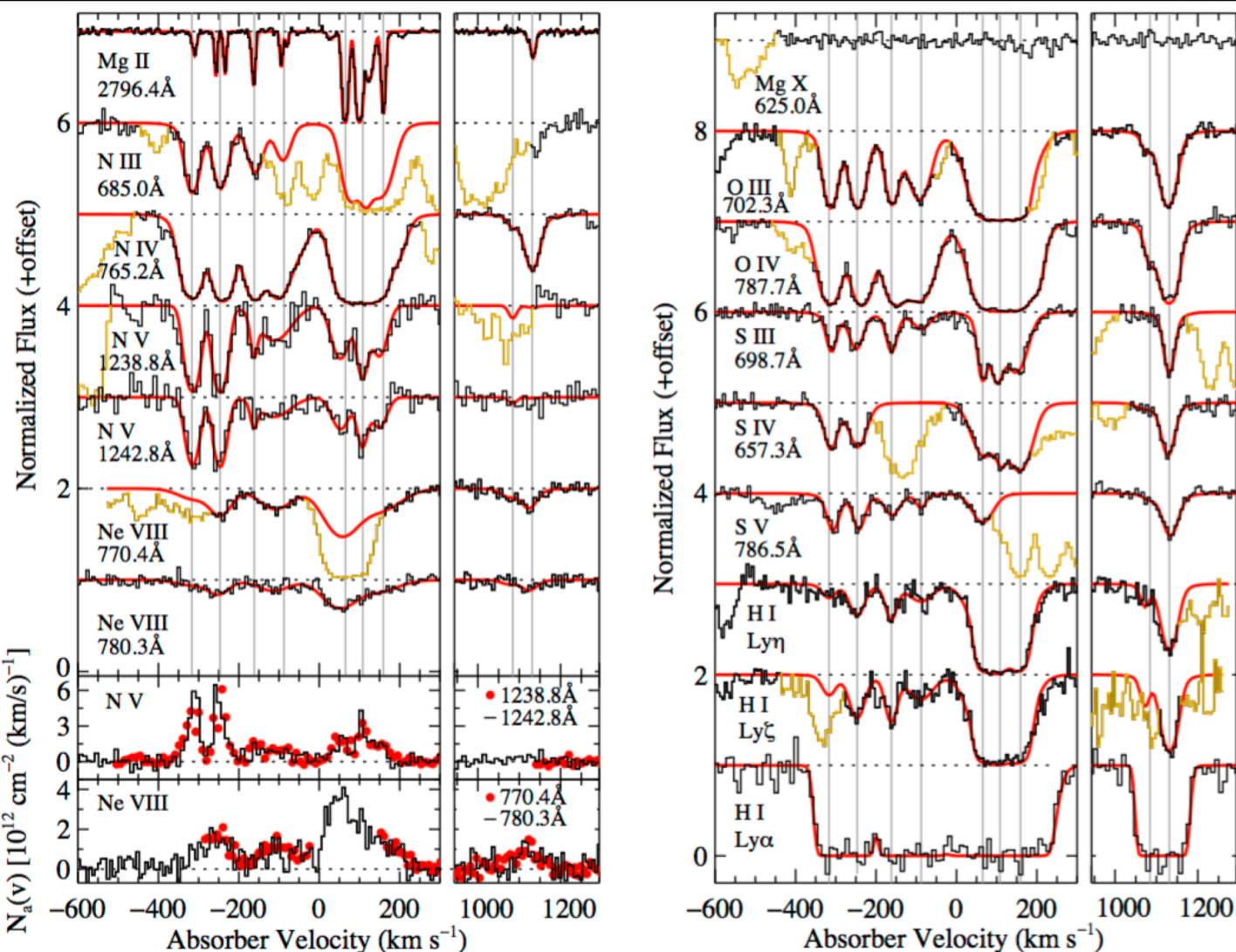
Example: The Hidden Mass and Large Spatial Extent of a Poststarburst Galaxy Outflow (Tripp et al. 2011)

- Warm-hot plasma at $10^{5.5}$ K contains 10-150 times more mass than the cold gas
- The wind extends to >68 kpc, and some portion of it will escape
- Feedback, caught in the act



WITH A DEDICATED SURVEY OF QSOS AT $Z = 1$ TO 2, ANUBIS CAN GREATLY EXPAND THE SAMPLES THAT PROBE THE DEEP ULTRAVIOLET

- Warm-hot plasma at $10^{5.5}$ K contains 10-150 times more mass than the cold gas
- The wind extends to >68 kpc, and some portion of it will escape
- Feedback, caught in the act



Solar System Science with ANUBIS (Hendrix)



- Jupiter system.
 - Mission-related investigations (e.g., post-Juno support, pre-JUICE observations of the Jupiter system) are enhanced and complemented using ANUBIS coverage.
 - Studies of numerous aspects of the system are enabled using the UV capabilities and long-duration coverage on varying timescales, including aurorae and airglow of Galilean satellites, Io and its plasma torus, Europa and its atmosphere, and the Jovian aurorae.
- Comets.
 - Cometary-related questions can be addressed largely using UV spectroscopic observations of numerous cometary targets over large spatial and temporal scales.
 - which volatiles drive cometary activity as a function of heliocentric distance?
 - what is the parentage of the species that are typically observed from ground-based observatories?
 - Furthermore, understanding the inventory of cometary nuclei and studying their internal compositional heterogeneities are important in assessing their role in several solar system processes, including the delivery of volatiles to the early terrestrial planets and the impact hazard at Earth.
- Asteroids.
 - Asteroids, particularly near-Earth objects (NEOs), have been poorly studied thus far in the UV. As potential future targets for human visitation and for characterization for planetary protection purposes, NEOs should be characterized thoroughly by observing many targets over a wide wavelength range. The UV region is particularly sensitive in studying space weathering effects and carbon species; UV spectra can be merged with existing visible spectra. All of this relates to composition and physical structure, which in turn are related to mitigation strategies for the impact hazard at Earth.

Solar System Science with ANUBIS (Hendrix)



- Giant planets.
 - For many aurorae and atmosphere investigations, UV imaging and spectroscopic capabilities are required.
 - A facility with significant time allocated to solar system targets is ideal for studying atmospheric dynamics, including photometric studies of changing planetary conditions of cloud cover related to vertical motions and studies of horizontal motions.
- Saturn system.
 - Wide-field abilities allow the investigation of Enceladus activity monitoring, system OH observations, and ring-magnetosphere-moon interactions in the post-Cassini era. Titan seasonal variations can be studied via cloud monitoring, haze layer imaging and UV stellar occultations.
- Uranus, Neptune.
 - Synoptic observations of ice giant atmospheres, particularly in the blue, are enabled with ANUBIS.
- Mars, Venus.
 - UV imaging and spectroscopic capabilities on ANUBIS can be used to study airglow (e.g. faint neutral atomic oxygen, hydrogen in upper atmospheres) and aurora for paleoclimate studies and mission support.
- Serendipitous opportunities (e.g., Shoemaker-Levy 9; outbursts on main belt comets) can be accommodated.

UV Time-domain Spectroscopy (Sahai)

Understanding Accretion Flows -- a central problem in astrophysics.

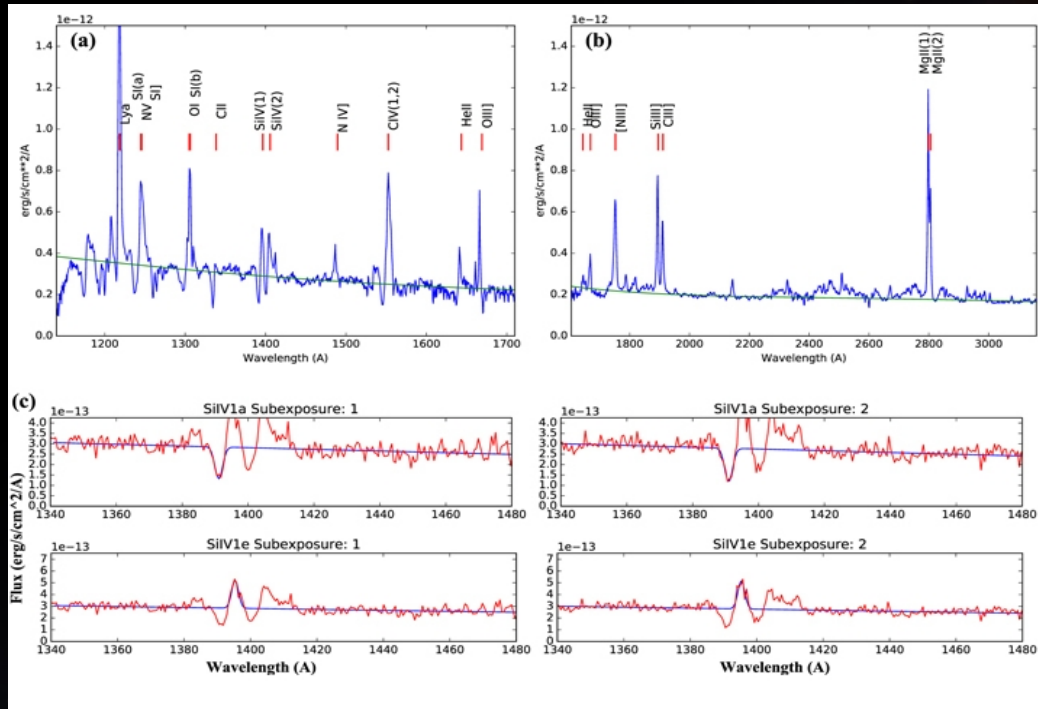
Accretion flows play major roles in stars and galaxies, and are important for understanding fundamental problems such as

- How young stars grow?
- How old stars die as a result of close binary interactions?
- How are massive black holes in the centers of galaxies, fed?

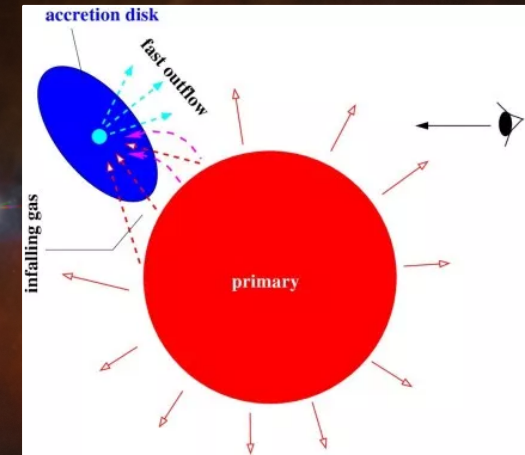
The plasma in accretion streams and flares is typically very hot (10,000 K to 100,000 K) -- emits UV radiation that can only be observed from space-based platforms.

Accretion Phenomena in Stars (Sahai)

Accretion flows are inherently time-variable, undergoing regular or erratic outbursts, interspersed by quiet periods. *Time-resolved UV spectroscopy* can mapping the accretion source, by tying temporal changes to the central source via radial variations in infall/outflow speed, and addressing details of the accretion process such as how quickly gas spirals inwards, as well as the locations where the plasma stream pauses, allowing material pile-up and release, producing outbursts, flickering, and/or high-velocity jets.



(top) UV spectra of the dying star Y Gem, due to accretion onto a companion; (bottom) fitted absorption and emission components probing infall and outflow kinematics (Sahai+2018)



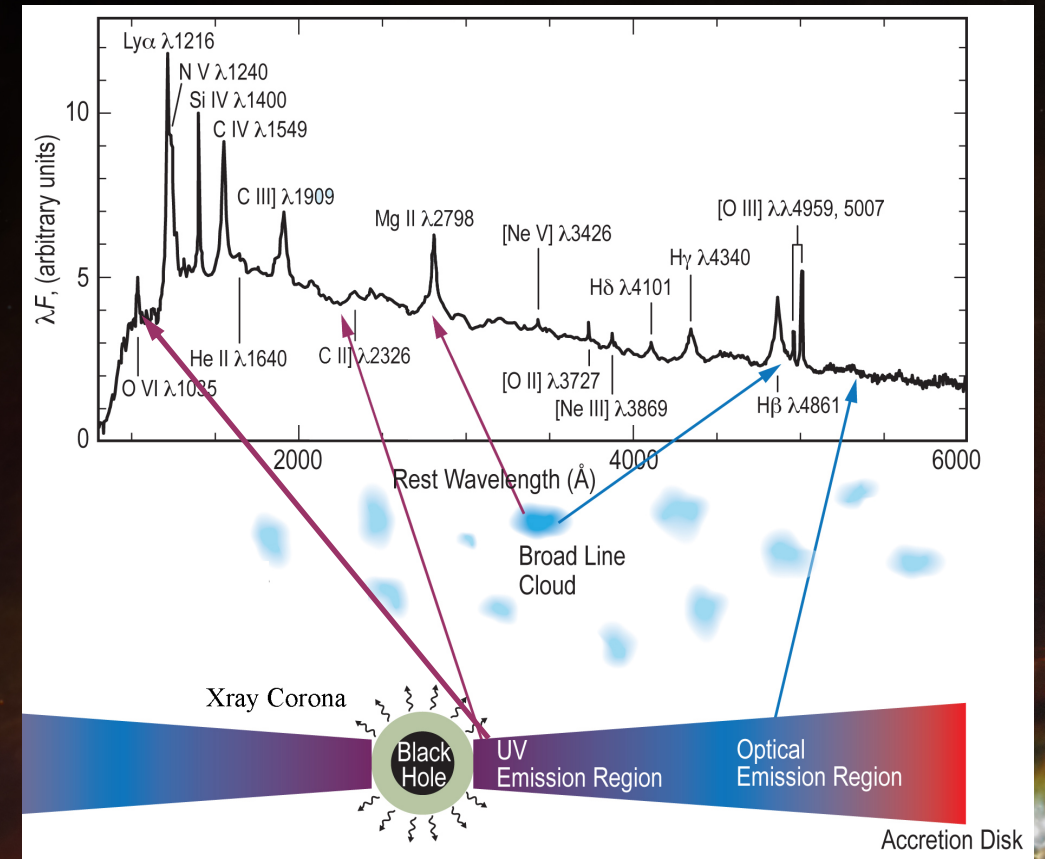
Schematics model of Y Gem, its companion, accretion and outflow (Sahai+2018)

Accretion Phenomena in Active Galactic Nuclei (Sahai)

UV variability is a sensitive probe of the surroundings of supermassive black holes (SMBH) at the centers of AGN.

Reverberation Mapping: Monitoring the relative variability between the continuum and emission lines, we can

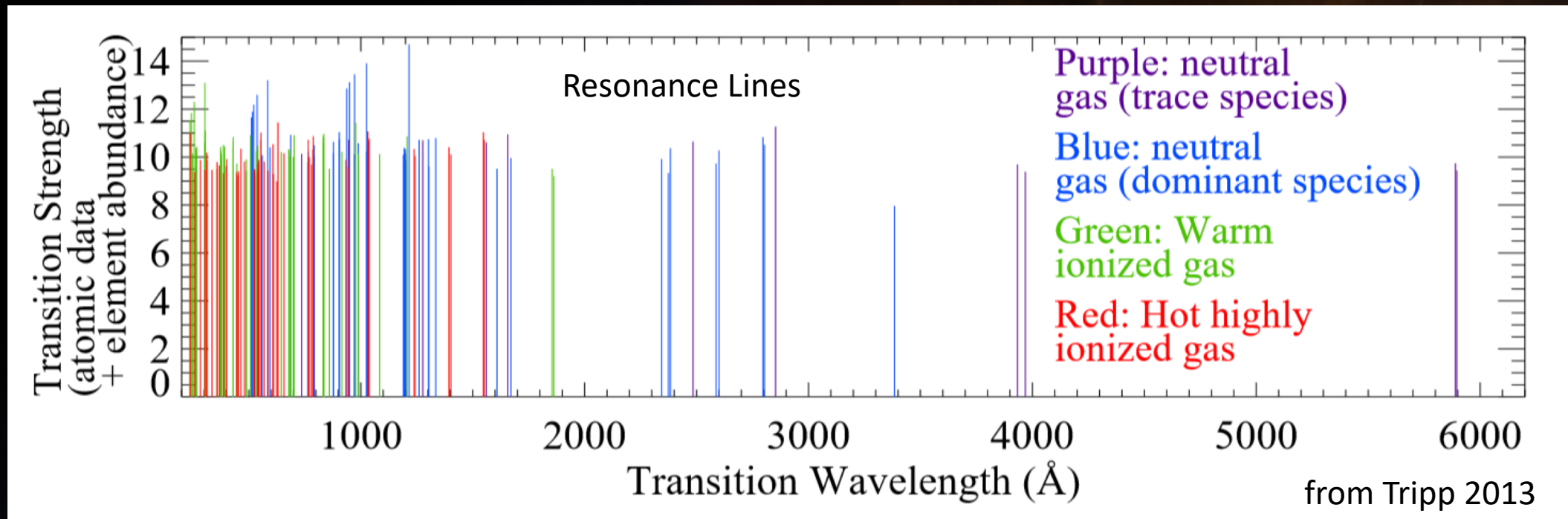
- extract the mass of the supermassive black hole -- UV continuum emerges closest to the SMBH and the highest ionization BLR clouds are also closest to the SMBH, hence least contamination from other sources, thus giving the best black hole mass values.
- The far-UV is the best probe of the structure of the accretion disk closest to the SMBH.



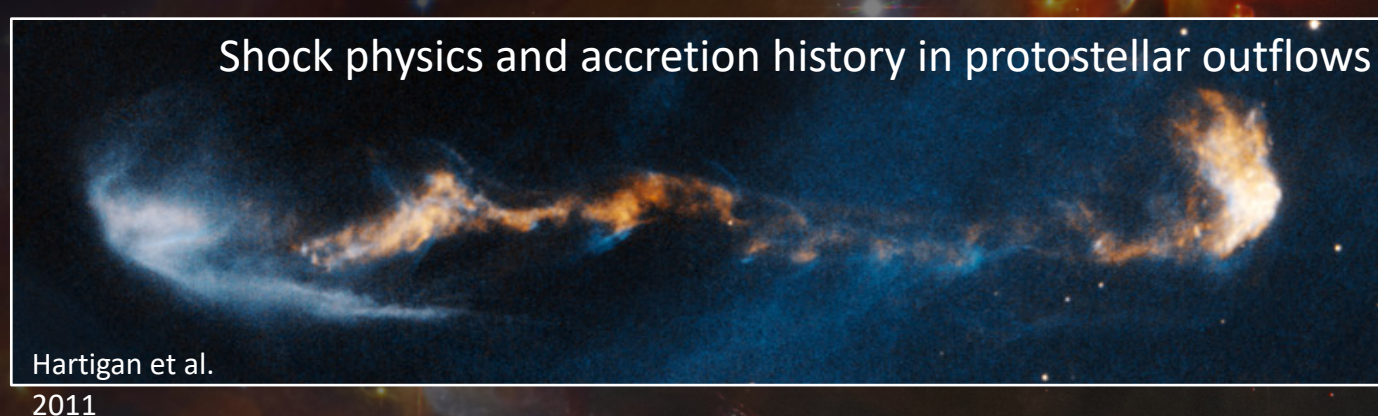
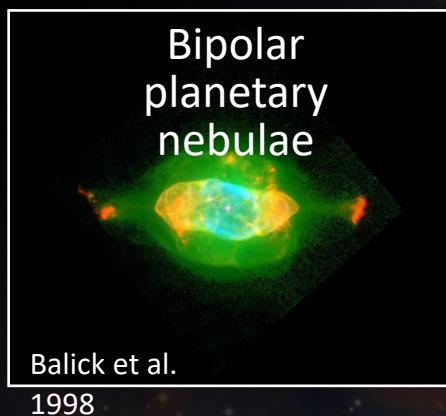
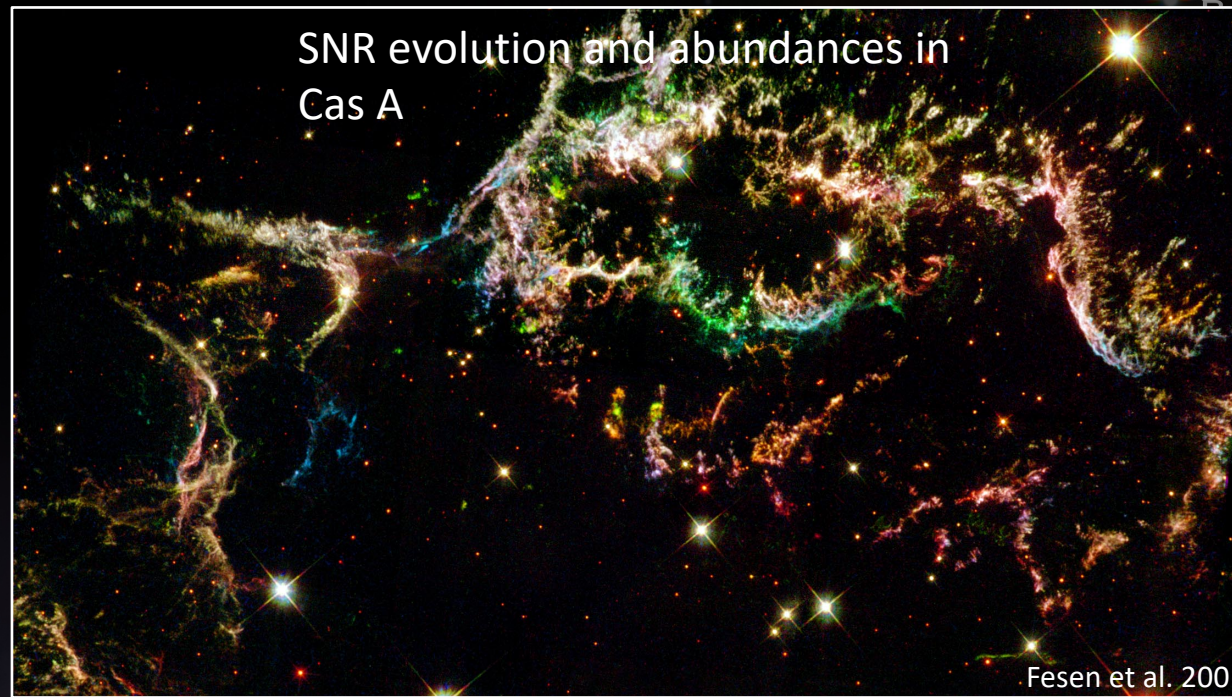
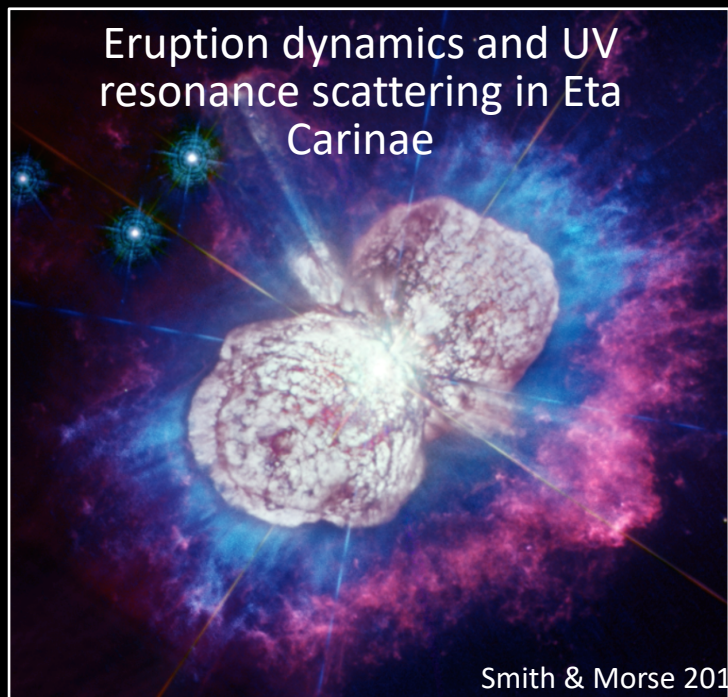
Not to scale

Satellite access to Ultraviolet wavelengths

- Wide range of diagnostics for probing physical conditions:
 - Near-UV (NUV) from 2000 - 3200Å, Far-UV (FUV) from ~900 - 2000Å
 - Detector and coating technologies usually differ in NUV vs FUV
 - Extreme-UV (EUV) features from 100-900Å accessible in high-redshift galaxies



Continuing the HST Legacy of Time Domain observations of hydrodynamic flows in the coming decades

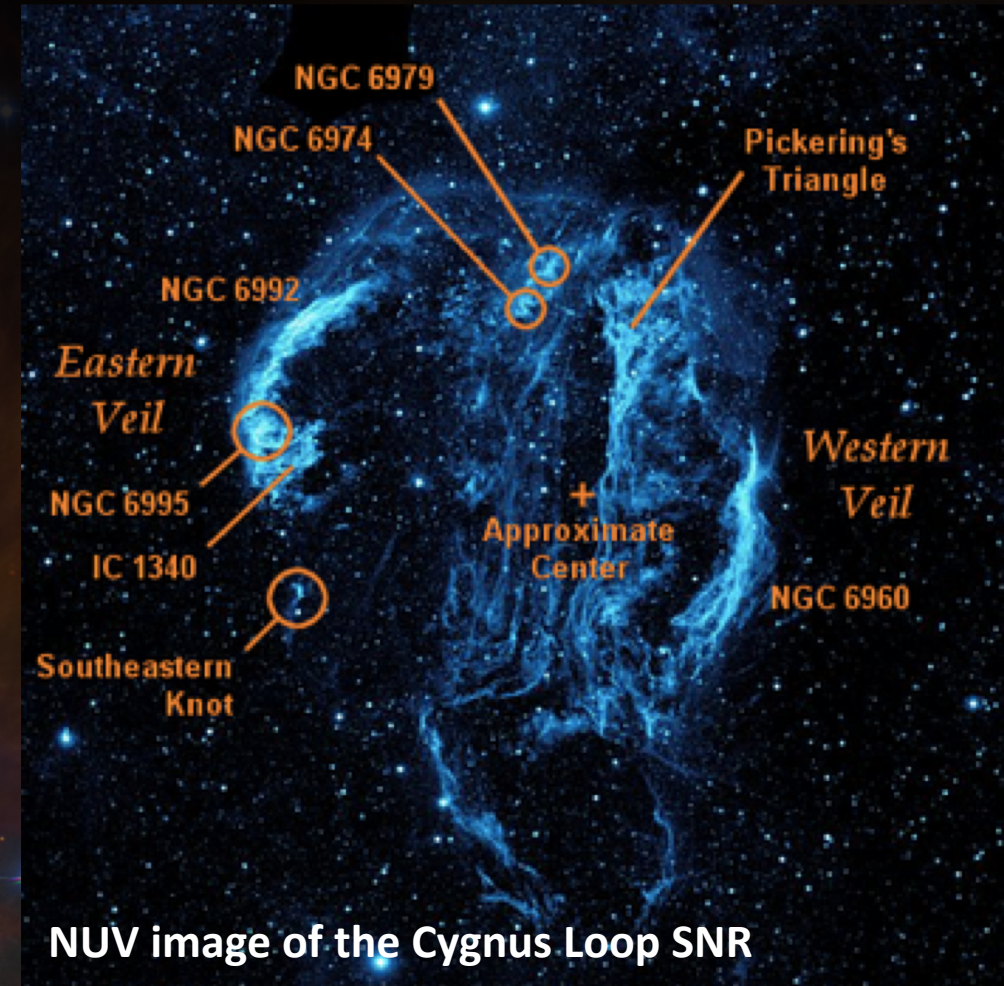


UV Spectroscopy (Raymond)

When the HST mission ends, astronomers will be blind in the UV

UV spectroscopy has the unique abilities to

- Observe plasma in the 10^5 to 10^6 K range
- Observe the resonance lines of H_2
- Low density gas through absorption lines
- Lines of many ions of individual elements
- Abundances of elements such as C and Si
- Size distribution and composition of Dust
- Provide density diagnostics for 10^6 to 10^{12} cm^{-3}

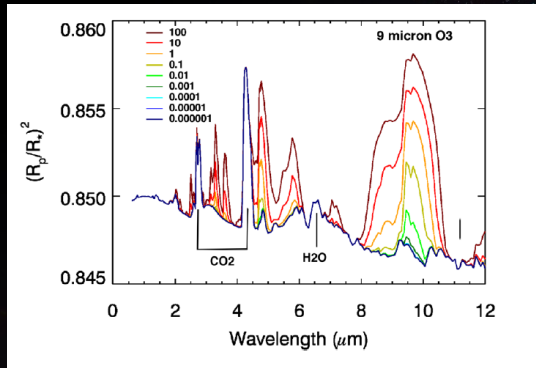


NUV image of the Cygnus Loop SNR

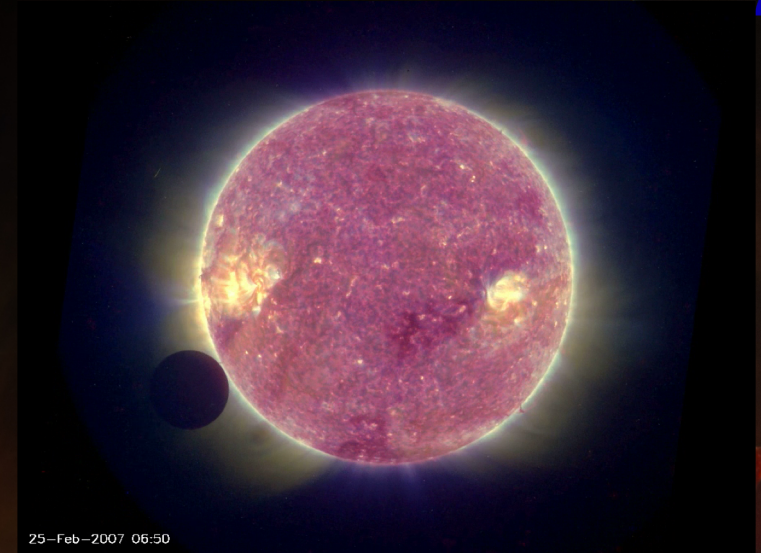
Targets for UV Spectroscopy (Raymond)

- ISM: composition, velocity structure, ionization state
- Supernova remnants, HH Objects, H II regions, Planetary Nebulae
- Galaxies: star forming regions, Haloes, Winds
- AGN: activity, reverberation, TDEs
- Exoplanets: Ly α from exospheres
- Hot Stars: Winds, compositions
- Cool Stars: Flares, CMEs, Coronae
- Active Binaries: Accreting Black Holes, Neutron Stars, WDs
- Young Stars: Jets, Fluorescence, Winds

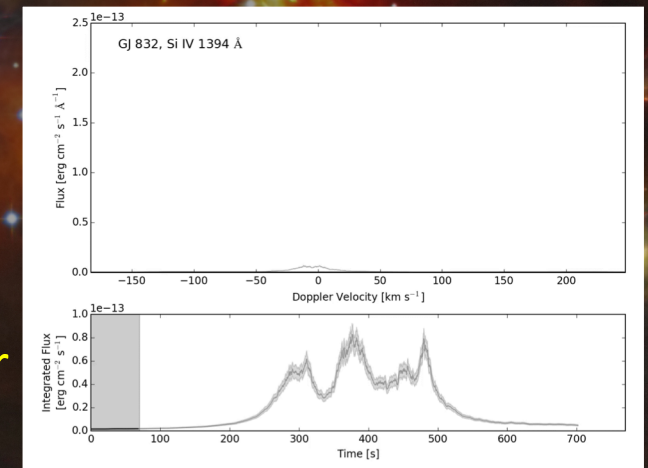
FUV Spectroscopy of Planet Hosting Stars: Stellar Monitoring (France)



JWST Planetary Observations



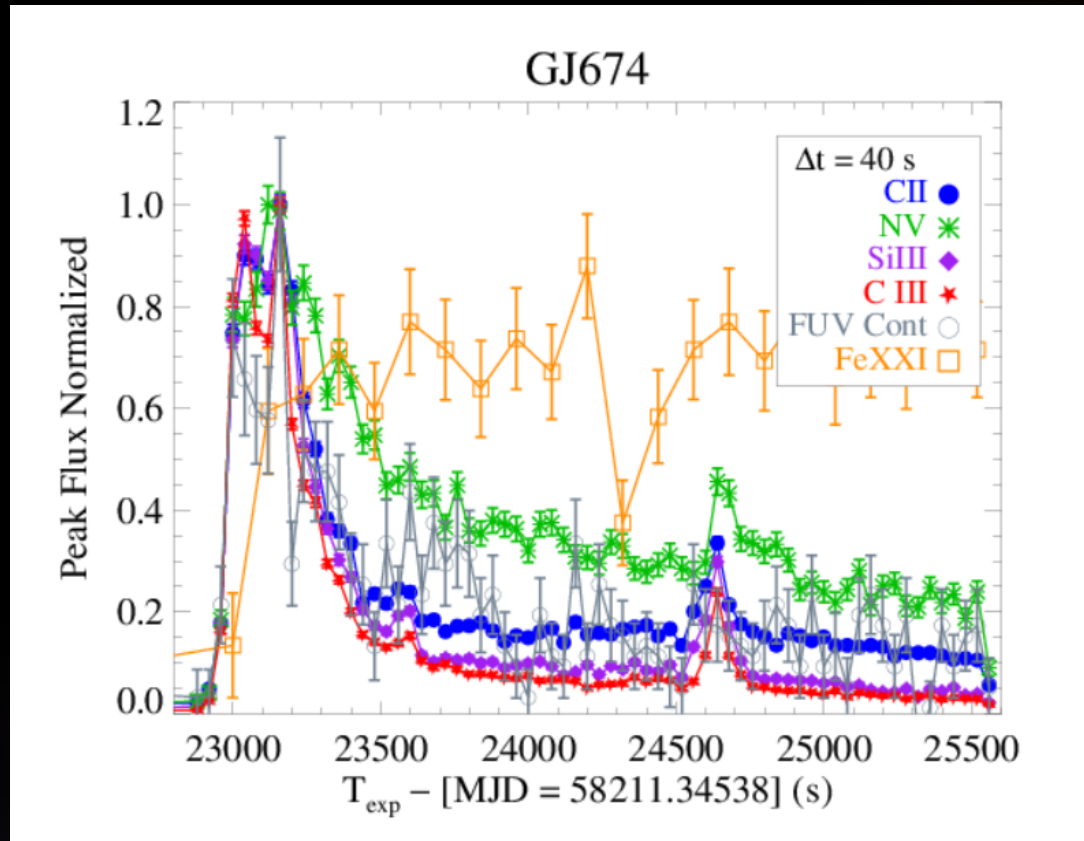
ANUBIS Stellar Observations



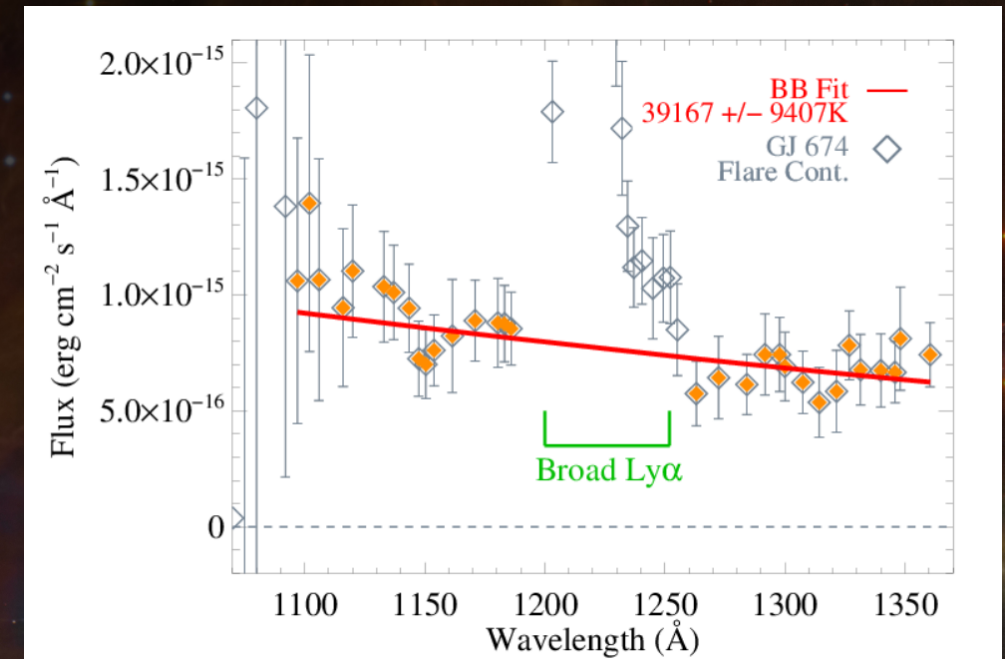
FUV observations of exoplanet host stars: Mass loss and Atmospheric Chemistry (France)

- Quiescent and Flare Radiation Environments

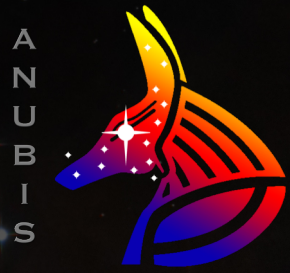
- High-temperature FUV continuum during flares ($T_{\text{BB}} > 30,000$ K)



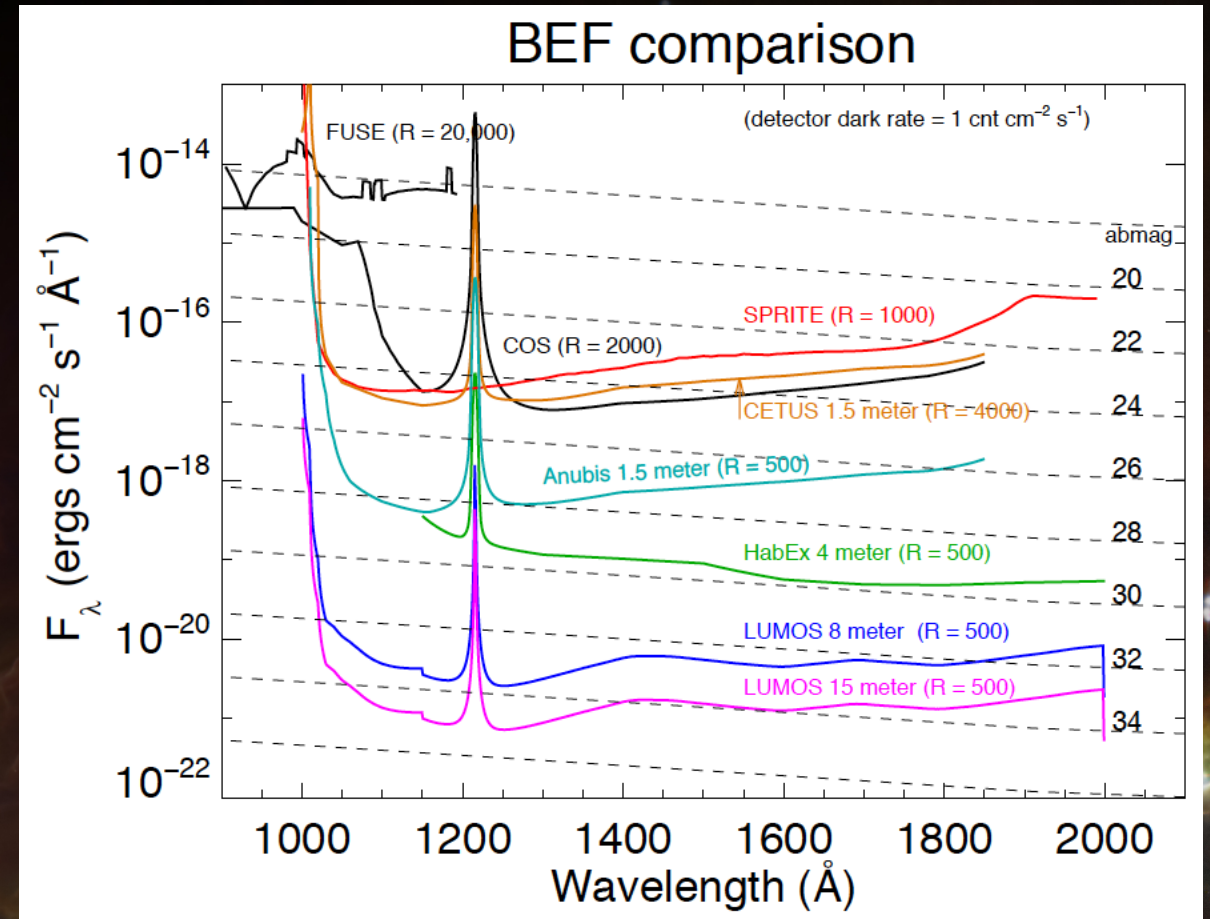
Froning, Kowalski, France, et al. (2019-ApJL)



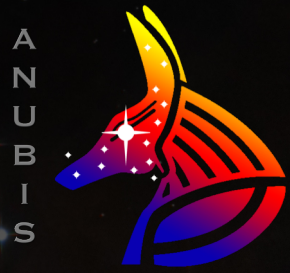
Ly-Continuum Galaxy Escape Fraction (McCandliss)



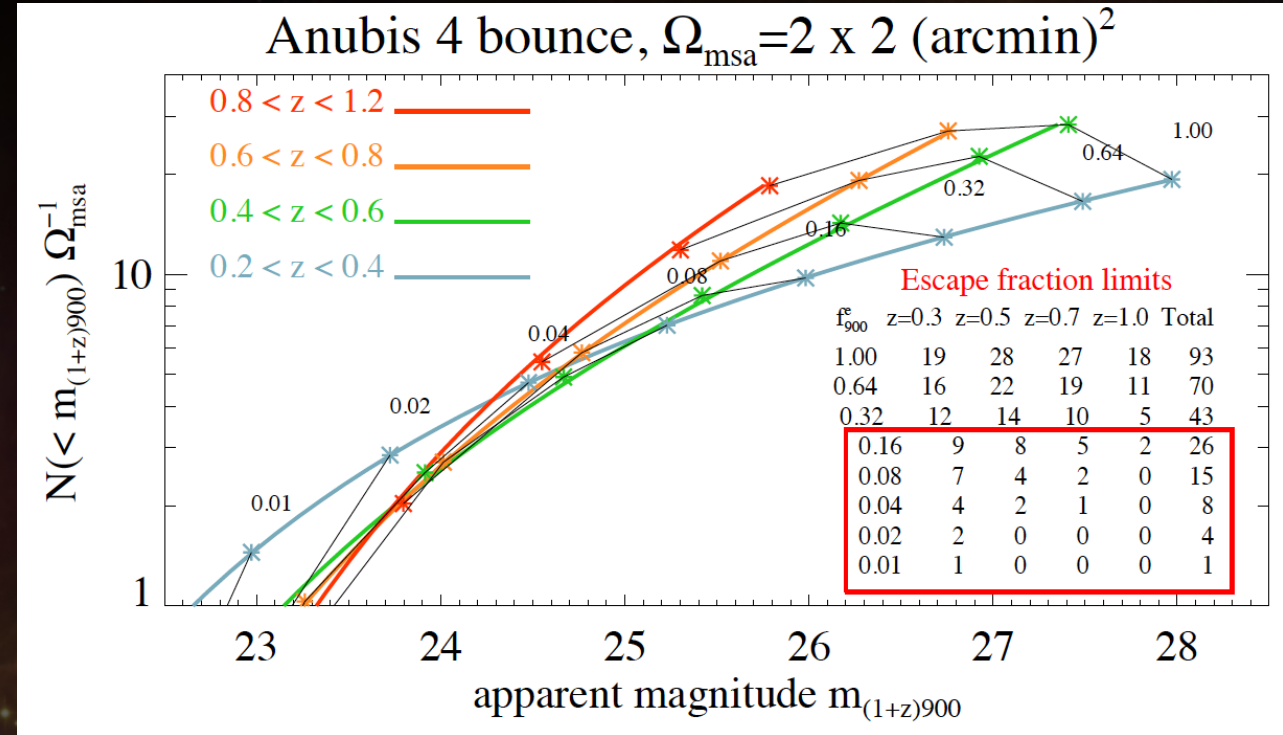
- Measurement of the degree of H-ionizing photons that escape from galaxies has to be done locally due to Ly- α forest absorption from high- z
- Across a 2'x2' field (MOS) in a single 10 hour pointing you can establish limits on the escape fraction to 16% for 26 objects, 9 of which are at a redshift of around 0.3, 8 of which are at a redshift of 0.5, 5 of which are at a redshift of 0.7 and 2 of which are out to $z=1$.
- At a limiting escape fraction of 4% you get 4, 2 and 1 at redshifts of 0.3, 0.5 and 0.7 respectively in a single pointing of 10 hours.
- We can compare this to Anne Jaskot's HST-COS LyC program which uses 136 orbits to find limits of 5% at a $S/N > 5$ on 67 objects at $z \sim 0.3$.
- ANUBIS can survey to around the same sort of depth as with HST-COS, but we do so much more efficiently.



Ly-Continuum Galaxy Escape Fraction (McCandliss)

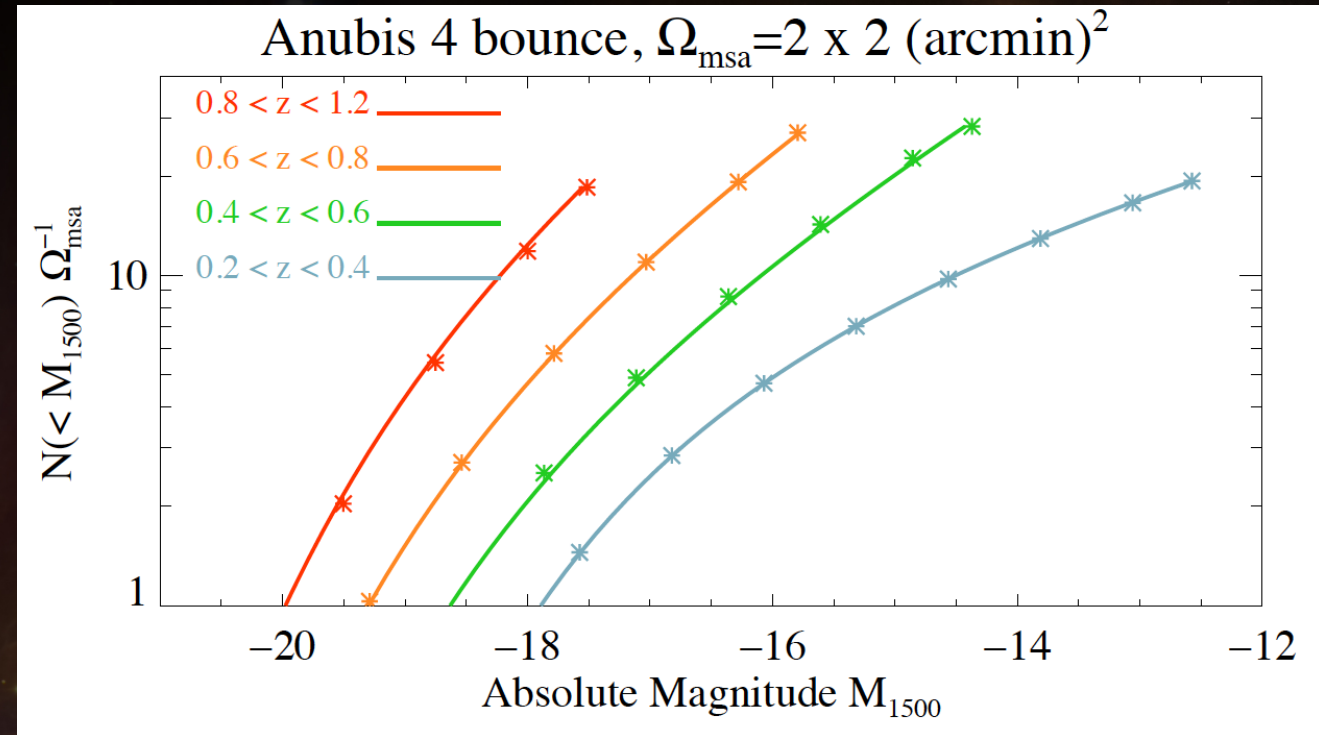


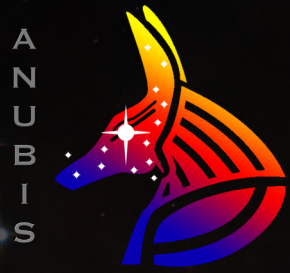
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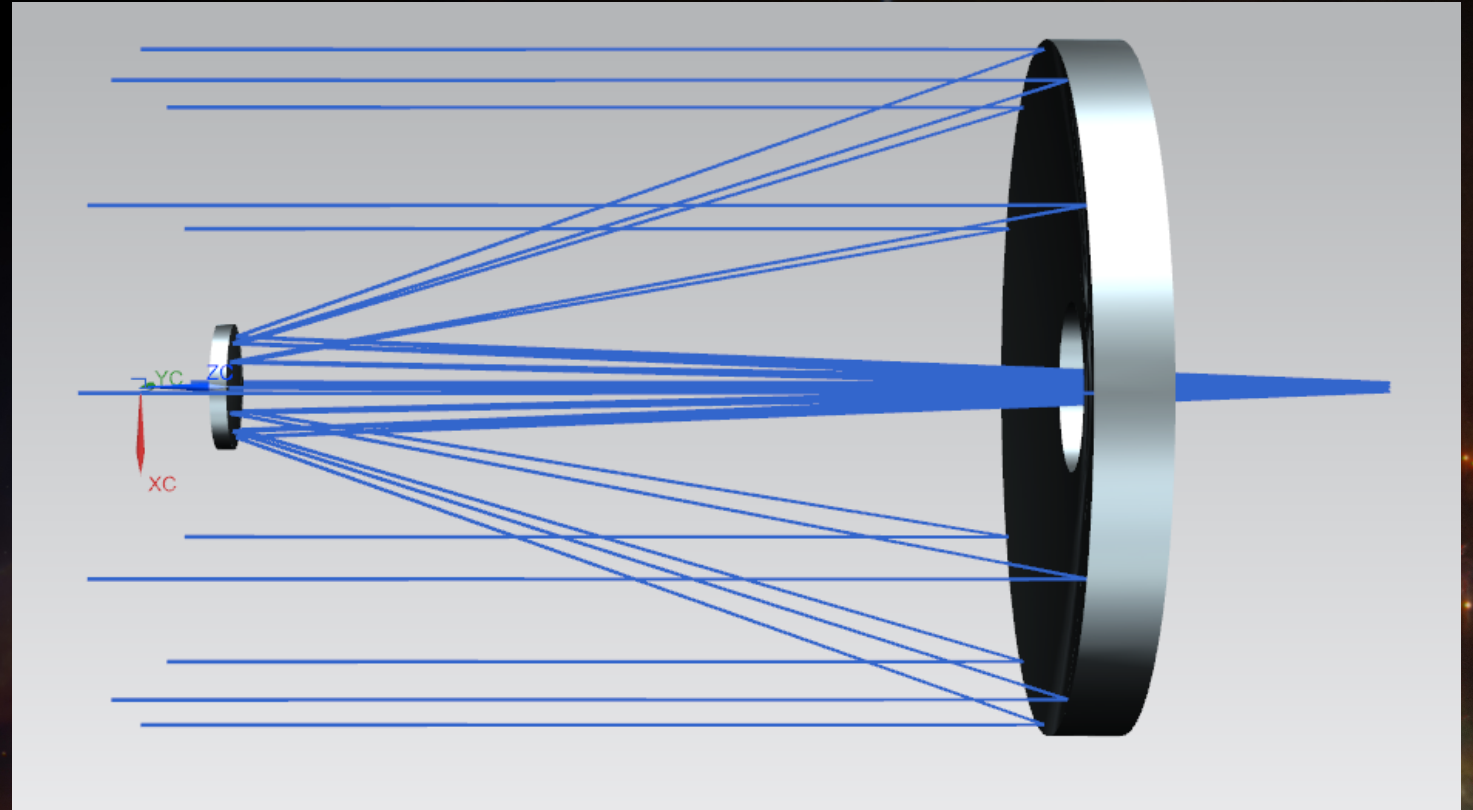




Mission Implementation

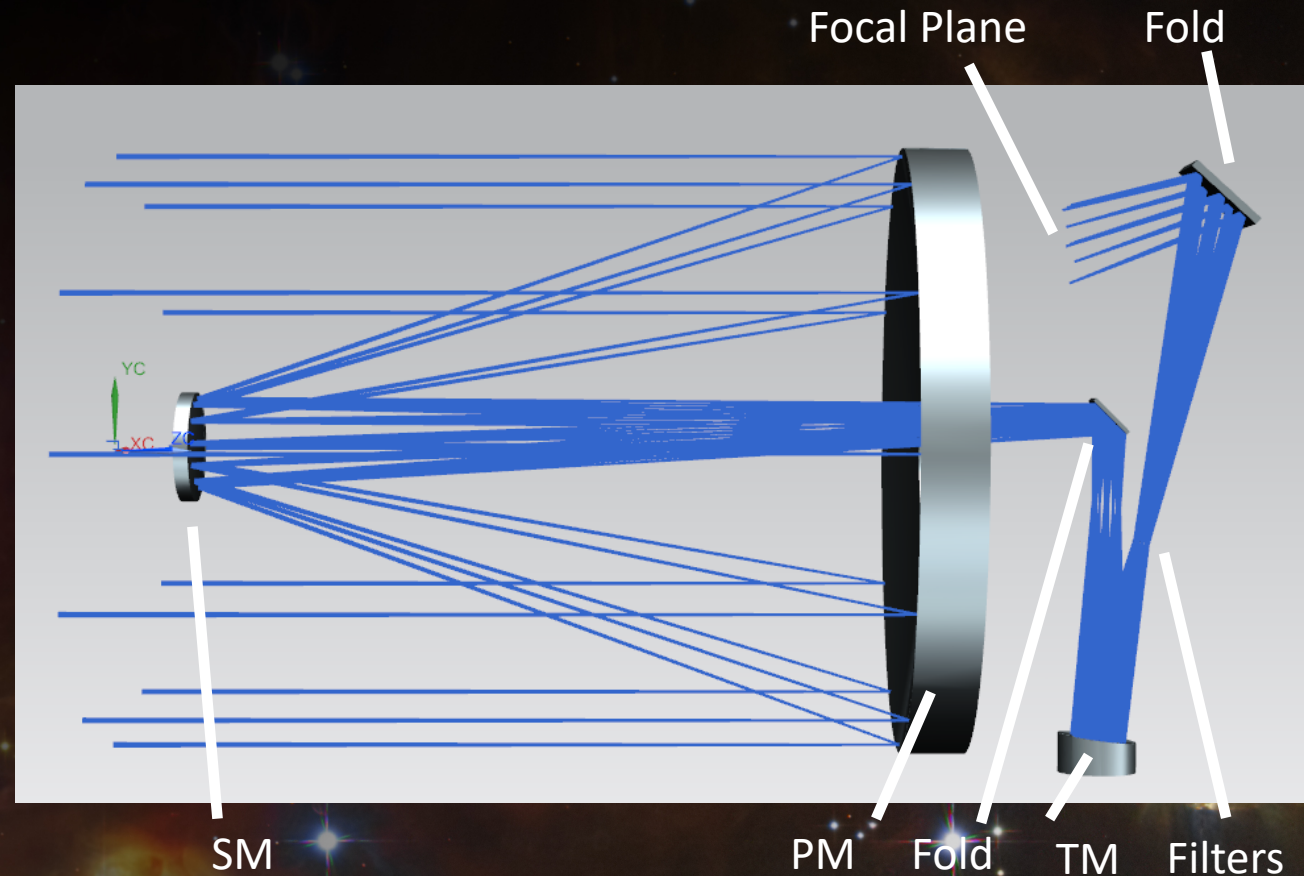
ANUBIS Telescope

- TMA Design
- 1.5m primary, 28cm secondary
- 1.7m² clear aperture
- Zerodur material
- Diffraction limited at 500nm
- PSF ~ 80 mas
- 40 mas 10 micron pixels
- 12' field of view
- eLiF coatings to provide reflectivity 100-1100nm



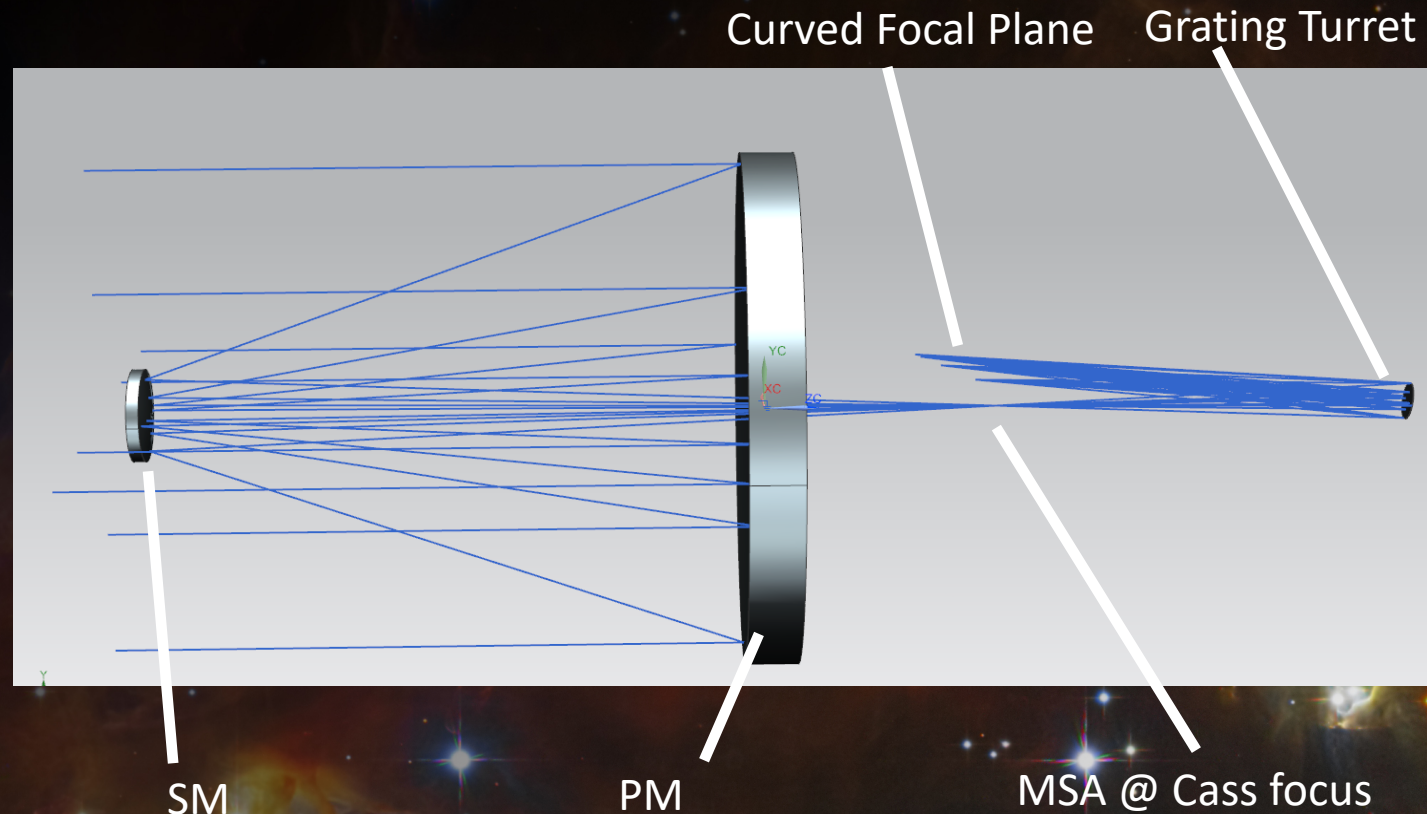
ANUBIS UV-Optical Camera

- Baseline use of e2v 290-99 CCD, 9216x9232 pixels @ 10 microns
- Delta-doped to enhance blue response while retaining red
- Focal plane uses 2x2 butted CCDs
- 12.2'x12.3' field of view
- Baseline suite of 20 filters – 10 narrowband, 20 broadband
- Covers 200-1100nm
- Provides nearly an order of magnitude increase in $A\Omega$ compared to HST-ACS



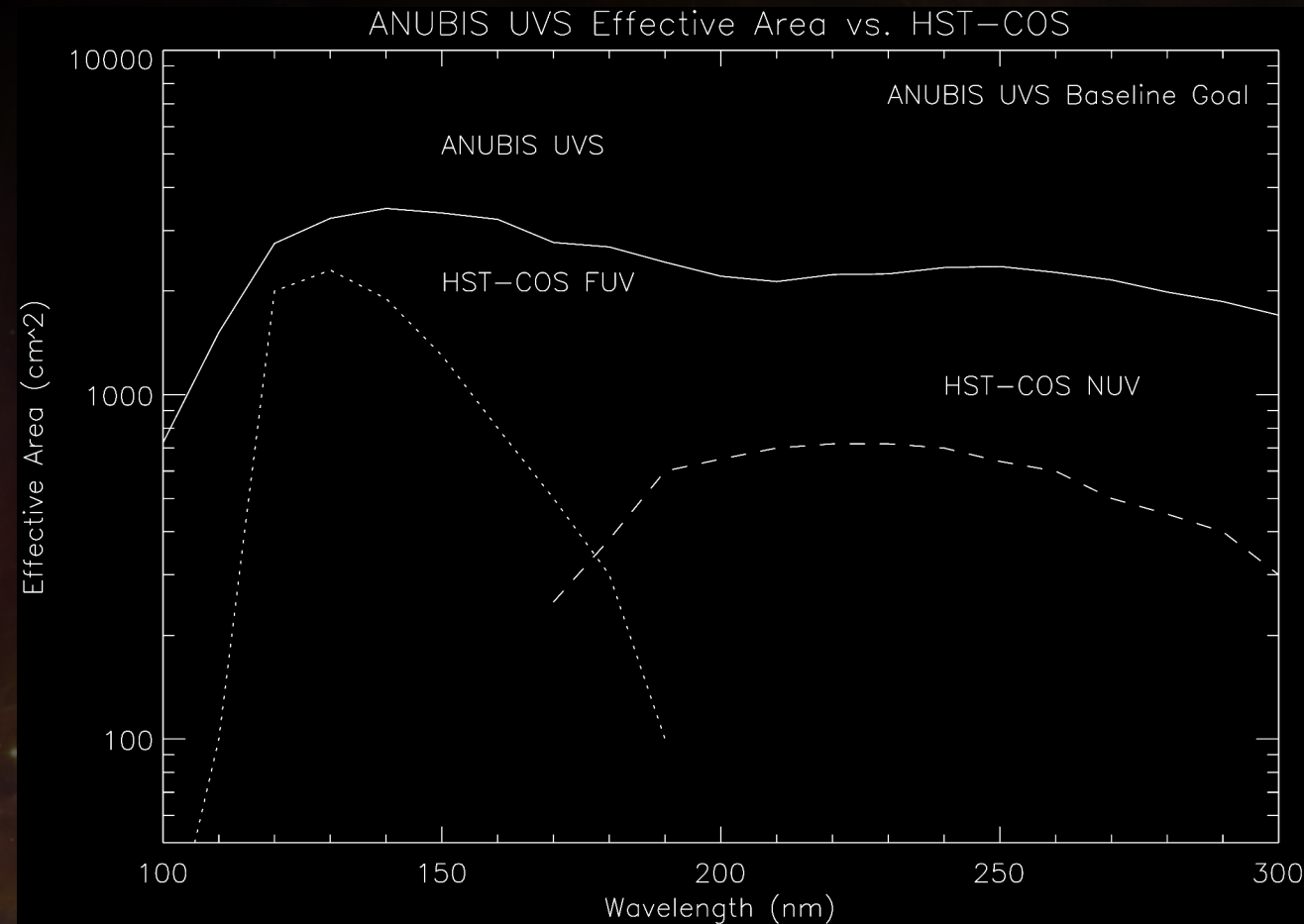
ANUBIS UV Spectrograph

- Rowland FUV design delivering $R=23,000$ resolution across 100-320nm
- Baseline use of curved bi-alkali MCPs across a 200mm focal plane assuming 20 micron pores
- 3-bounce design delivers excellent throughput
- Supports $R=500$, 3000 and 23k resolutions using a grating turret (5x23k gratings to cover 100-320nm)
- Provides a 2'x2' field at the Cass focus allowing MOS using an MSA – providing 8"x4" independent slits across the field

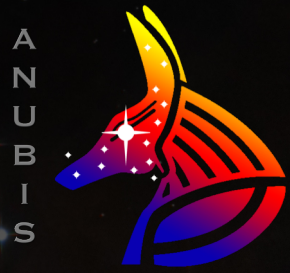


ANUBIS UV Spectrograph

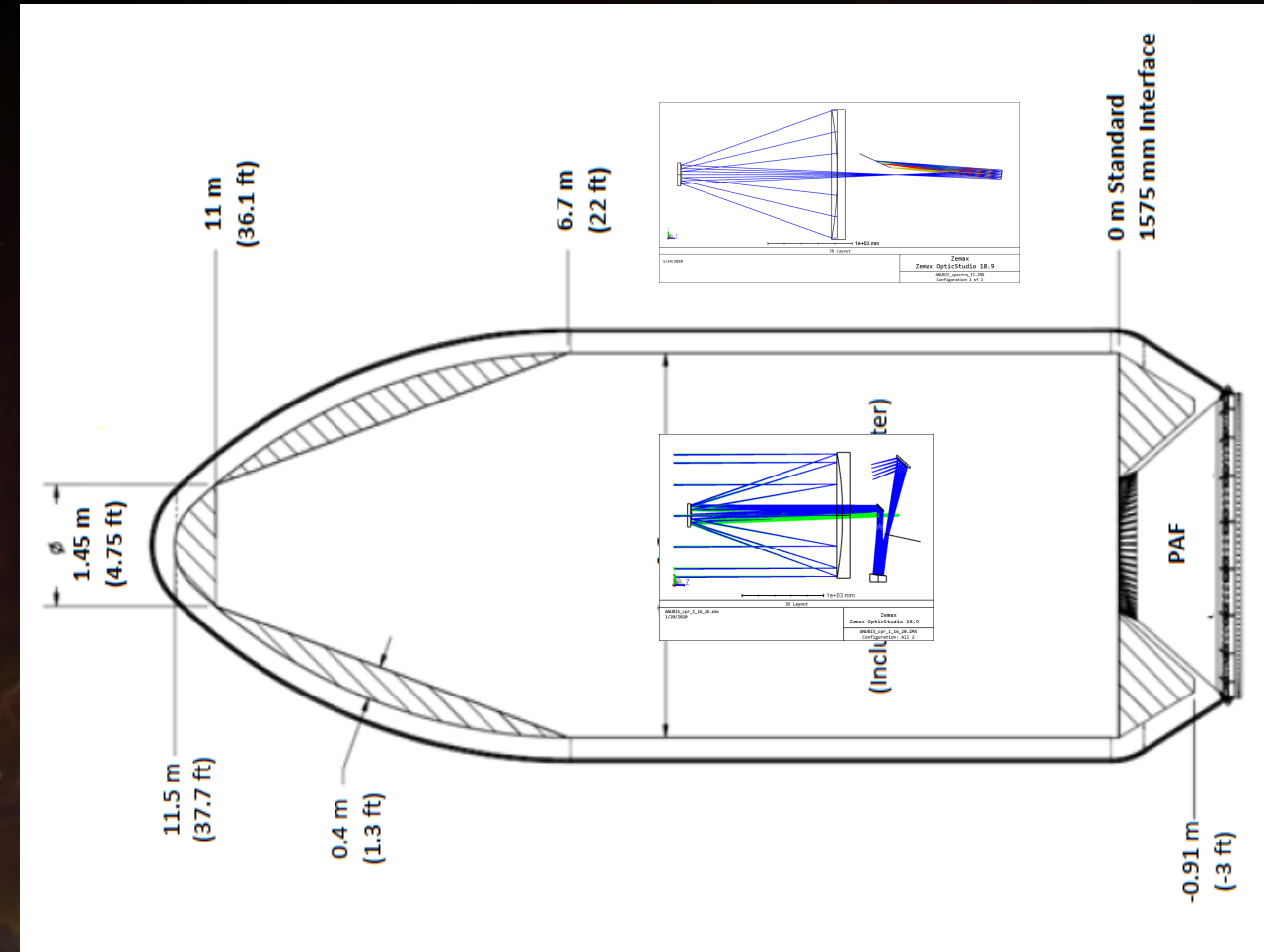
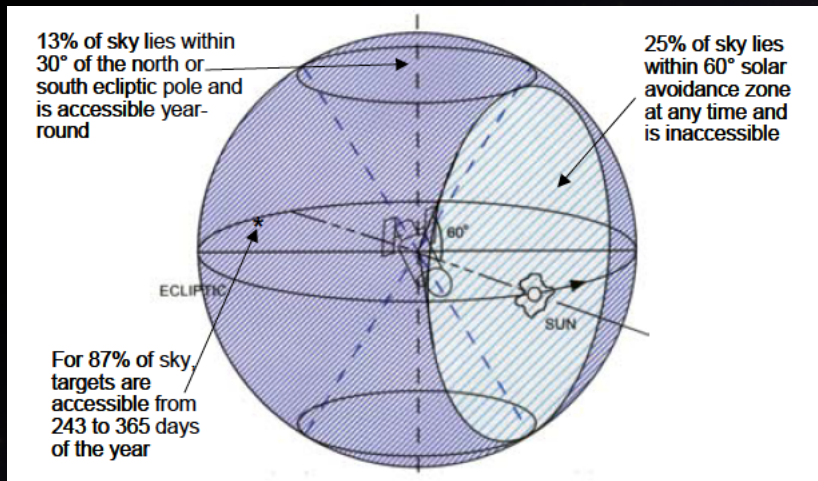
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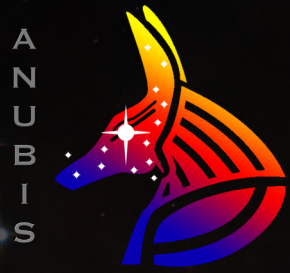


ANUBIS Mission Parameters



- 4 year mission baseline
- To maximize survey and observing efficiency, orbit at either Earth-Sun L2 or Earth-Sun trailaway
- Observatory will likely be less than 3000 Kg in mass allowing the use of Falcon heavy to achieve L2 orbit – the observatory comfortably fits into the fairing



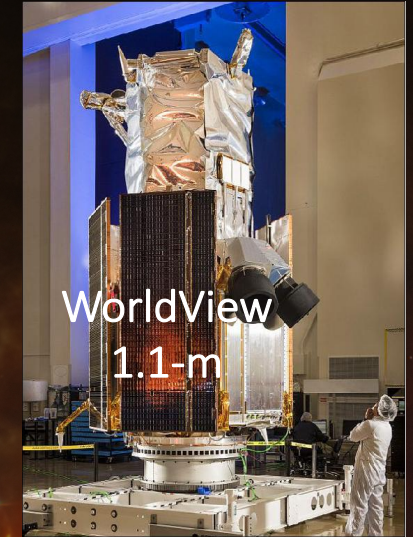
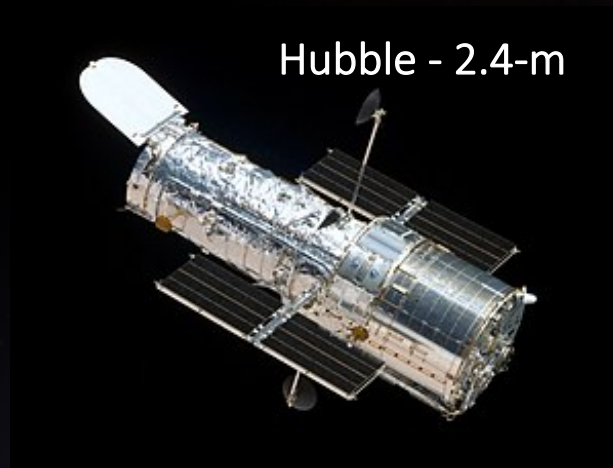


Technical Risk

1.5-meter UVOIR Space Telescopes are TRL9 (Stahl)



- 1.5-m UVOIR space telescopes for general astrophysics are TRL9.
- No technology development needed. They are just engineering



1.5-meter UVOIR Space Telescope: Cost Estimate (Stahl)

Cost can be estimated for the ANUBIS telescope ($D = 1.5\text{m}$, $\lambda = 0.5\ \mu\text{m}$, $T = 280\text{K}$, $\text{YOD} = 2022$) using Stahl, “Multivariable Parametric Cost Model for Ground and Space Telescope Assemblies”, Decadal White Paper, 2019.

$$\text{OTAS (FY17)} = \$20\text{M} \times 30^{(S/G)} \times D^{(1.7)} \times \lambda^{(-0.5)} \times T^{(-0.25)} \times e^{(-0.028)(Y-1960)}$$

where:

- (S/G) = 1 for Space OTAs
= 0 for Ground OTAs
- D = Effective Telescope Aperture Diameter
- λ = Wavelength of Diffraction Limited Performance
- T = Operating Temperature
- YOD = Year of Development, i.e. start of Phase C/D or Issue of Contracts.

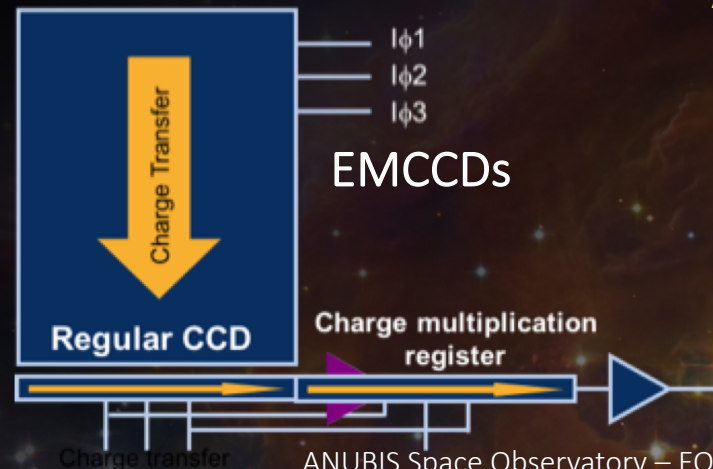
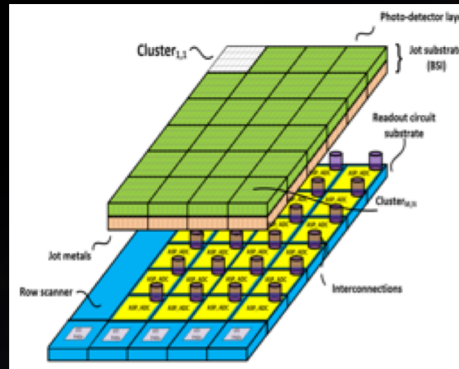
Cost is 50% likely to be less than $\sim \$ 73\text{M}$

Cost is 85% likely to be less than $\sim \$ 110\text{M}$

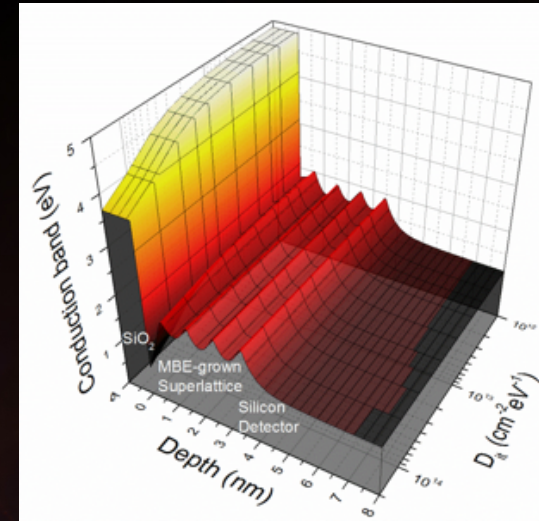
2D-doped Silicon Arrays for High QE, Low Noise, and Stable Response (Nikzad)

Agnostic to architecture and applicable to virtually *all* silicon arrays

EMCCDs, CCDs,
Quanta Image Sensor
CMOS
SPADs
sCMOS
Skipper CCD
APDs
Hybrid Arrays
P-channel and n-channel
.....



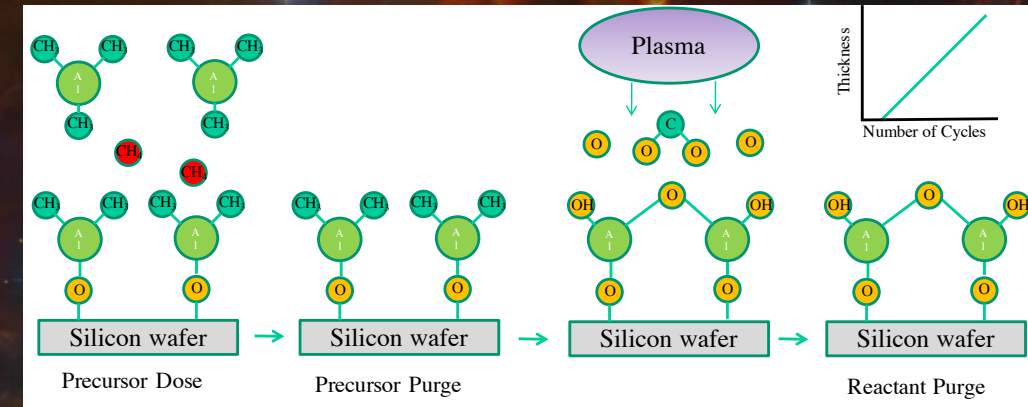
2D-doping and precision coatings



2D doping (delta doping and superlattice doping)

MBE and ALD used for surface and interface engineering to optimize performance

Atomic Layer Deposition: antireflection coating & metal dielectric filters



Broadband Detectors

P-channel and n-channel
Full Depletion CCDs

Demonstrated in 12
megapixel, 10 μm pixel
with high QE
(200-1000 nm).

TRL 6

CMOS Arrays

2-D doping on multiple
CMOS designs and formats

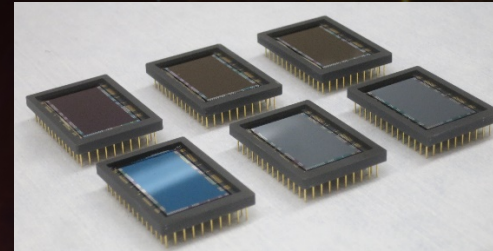
Scientific CMOS arrays with
< 5 e⁻ read noise and high
QE (200 – 1000 nm)

TRL 5+

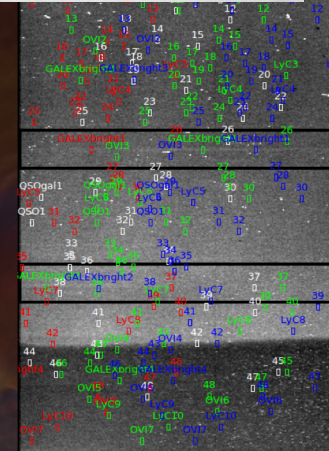
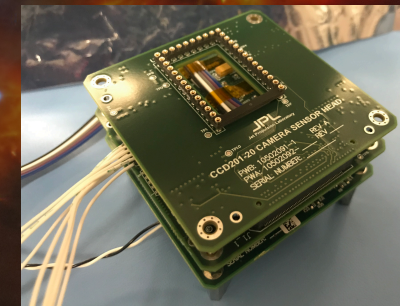
Photon Counting Detectors

Delta doped and Custom
Coated Electron Multiplying
CCDs (EMCCDs)

FIREBall-2, SHIELDS,
Palomar-CWI
TRL 5



Delta doped
and Custom
Coated Quanta
Image
Sensor (CMOS)
Arrays
TRL 2-3



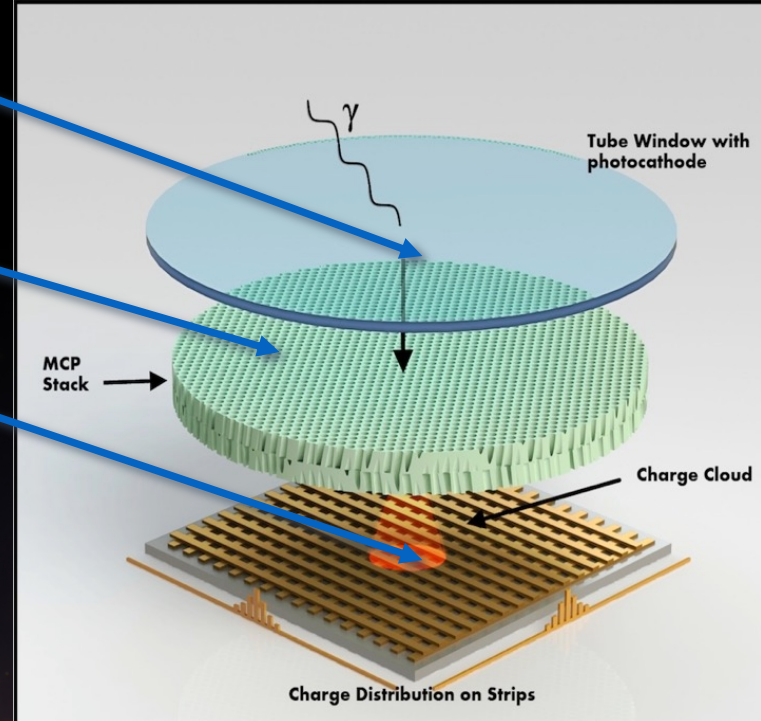
Jet Propulsion Laboratory
California Institute of Technology

FUV Microchannel Plate Detectors with Cross Strip Readout (Siegmond)

Photocathode converts photon to electron

MCP(s) amplify electron by 10^4 to 10^7

Cross strip anode event charge centroid



An XS readout MCP sealed tube imaging sensor scheme. A photocathode is deposited on a window facing a pair of MCPs. Emitted photoelectrons are detected by the MCPs multiplied and collected by several strips in each axis of the anode to enable event centroid positions to be calculated.

Microchannel Plates.

Atomic Layer Deposited (ALD) MCPs
Large area formats up to 20cm. 10 & 20 μ m pores.
Very low background rates (<0.05 events/cm²/sec) and low gamma event sensitivity ($\div 3$).
Extended lifetimes ($>4 \times 10^{13}$ events/cm²).
Economical and robust.

Cross strip anodes.

Open face formats of 50mm, 100mm with $\leq 20\mu$ m FWHM spatial resolution.
Event rates >5 MHz
Low gain ($\sim 10^6$) operation.
Sealed tube anodes for 50mm (100mm soon)

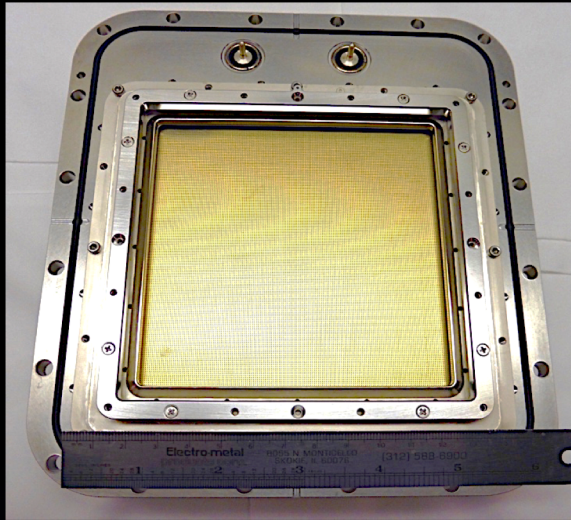
Photocathodes.

60% CsI @115nm, up to 20cm format.
Bialkali $\geq 30\%$ below 200nm. 360nm cutoff demonstrated, 20cm format.
GaN in development, get 60% @120nm, $\sim 50\%$ @200nm, 40% @250nm, cutoff at 370nm.

Cross Strip (XS) Detector Evolution (Siegmund)



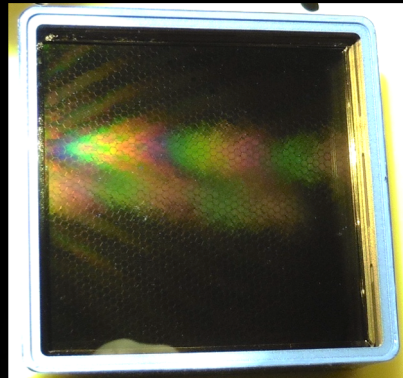
100 mm XS detector demonstrated with ALD MCPs, $<20\mu\text{m}$ spatial resolution, >5 MHz rates, background ~ 0.05 events $\text{cm}^{-2} \text{sec}^{-1}$. Vibration, thermal, radiation, vacuum environmental tests passed.



"Open" 100 mm XS detector selected for sub orbital flight(s) in ~ 2022 .

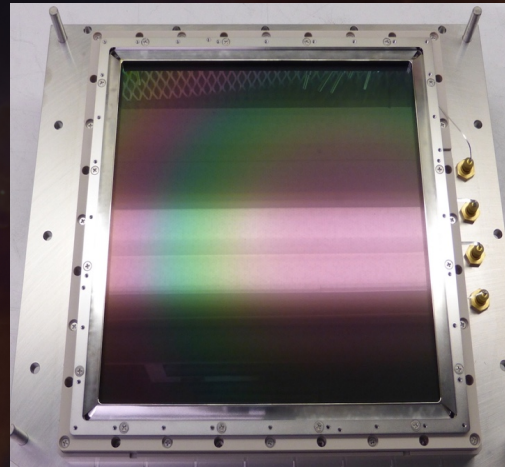
Also selected for 100mm sealed tube XS implementation 2020-2023.

SMT Electronics for XS achieves $<20 \mu\text{m}$ FWHM spatial resolution $16\text{k} \times 16\text{k}$ (digitized) pixel format >5 MHz global count rate at low $\sim 1.5 \times 10^6$ gain



Open face 40 mm XS detector flown successfully 4x on CHES Rocket payload. $\sim 25\mu\text{m}$ resolution @ MHz rates.

200 mm ALD MCP detector with KBr cathode flown successfully 2x (DEUCE).

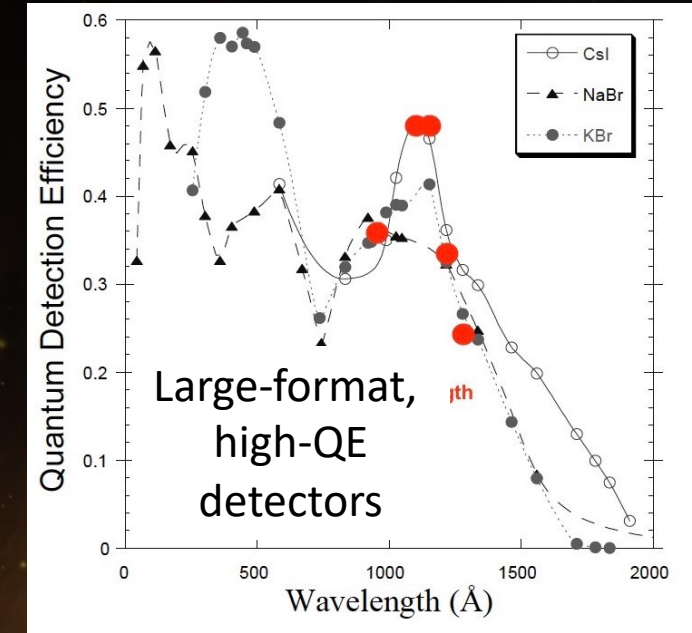
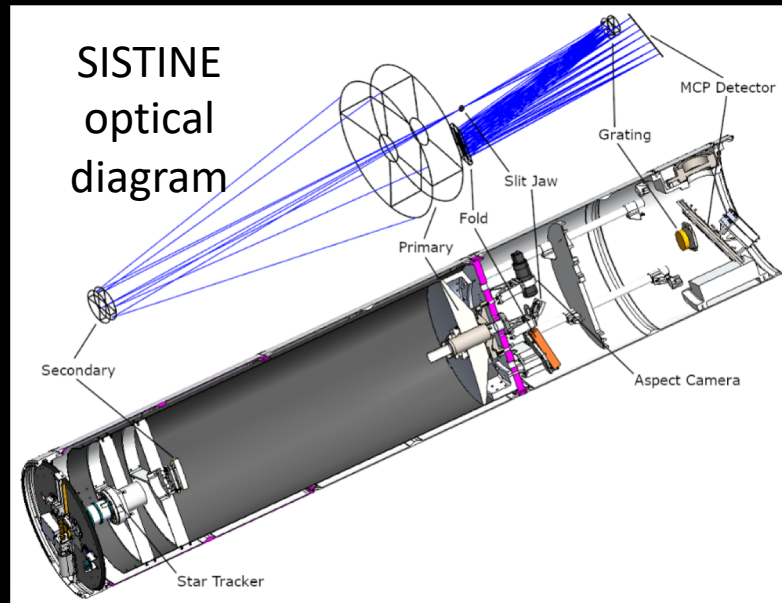


50 mm Photonis Planacon sealed tube with a pair of ALD 60:1 MCPs and bialkali photocathode. Funded SAT program developing MgF_2 windowed Planacons with XS readout, UV cathodes, by 2021.

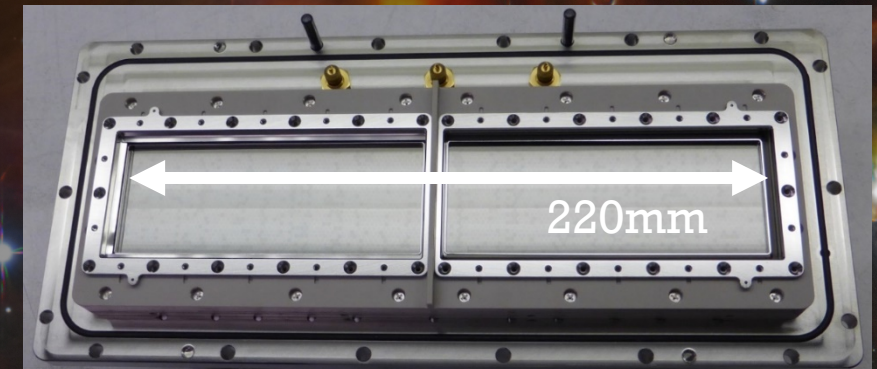


1st generation ASIC electronics for XS anodes is currently under test, providing power and space savings.

UV Coatings and Large-format Detectors for FUTURE UV/optical Missions: SISTINE Rocket Payload (France)

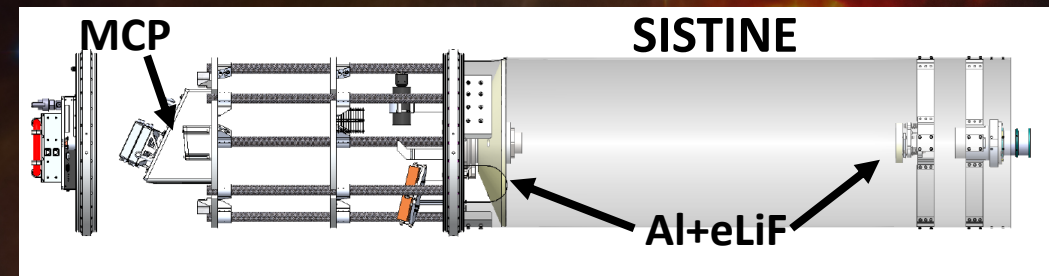
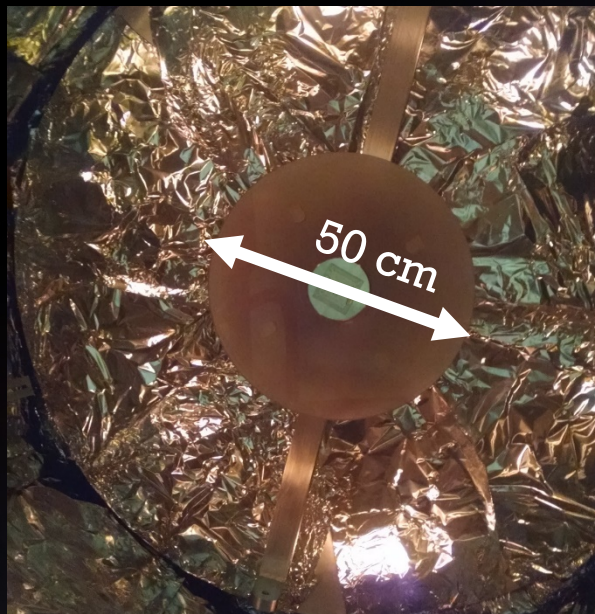


SISTINE Pathfinder Spectrograph:
--large (220mm x 40mm) photon counting detector, 1 MHz global rate limit (~50x HST-COS)



UV Coatings and Large-format Detectors for FUTURE UV/optical Missions: SISTINE Rocket Payload (France)

SISTINE Pathfinder Spectrograph:
 --Al+eLiF coatings on shaped mirrors, up to 0.5m
 --first time these coatings, baselined for LUVOIR, have been deposited on large (> 2") and shaped optics

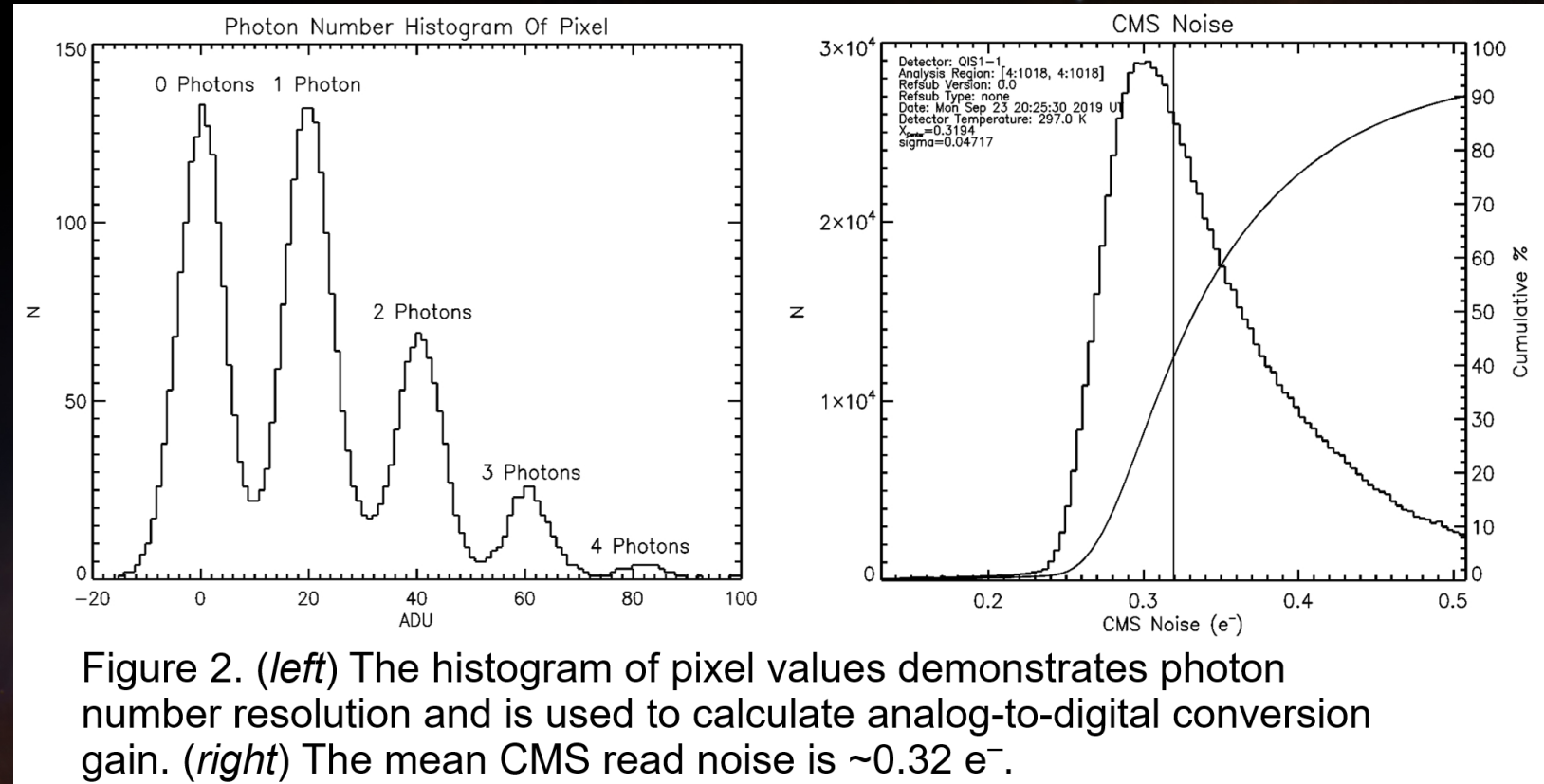


Single Photon Sensing Detectors (Figer)

- A project funded by NASA's Strategic Astrophysics Technology program (COR).
- The goals of the project are to:
 - characterize an existing low-noise CMOS detector in the lab, at a telescope, and after high energy irradiation simulating a space environment
 - propose design modifications to bring the performance of the technology closer to specifications for the intended applications
- The work is significant because it would enable quantum-limited imaging in gigapixel formats for very low cost.
- The primary innovation is the pixel design that demonstrates single-photon-sensing and photon-number-resolving performance.
- With the success of this program, it will be possible to design and deploy gigapixel ultra-low-noise detectors for UV/Vis missions.
- Potential applications include any that require low-light level performance (astro, planetary, Earth, helio, quantum, etc.).

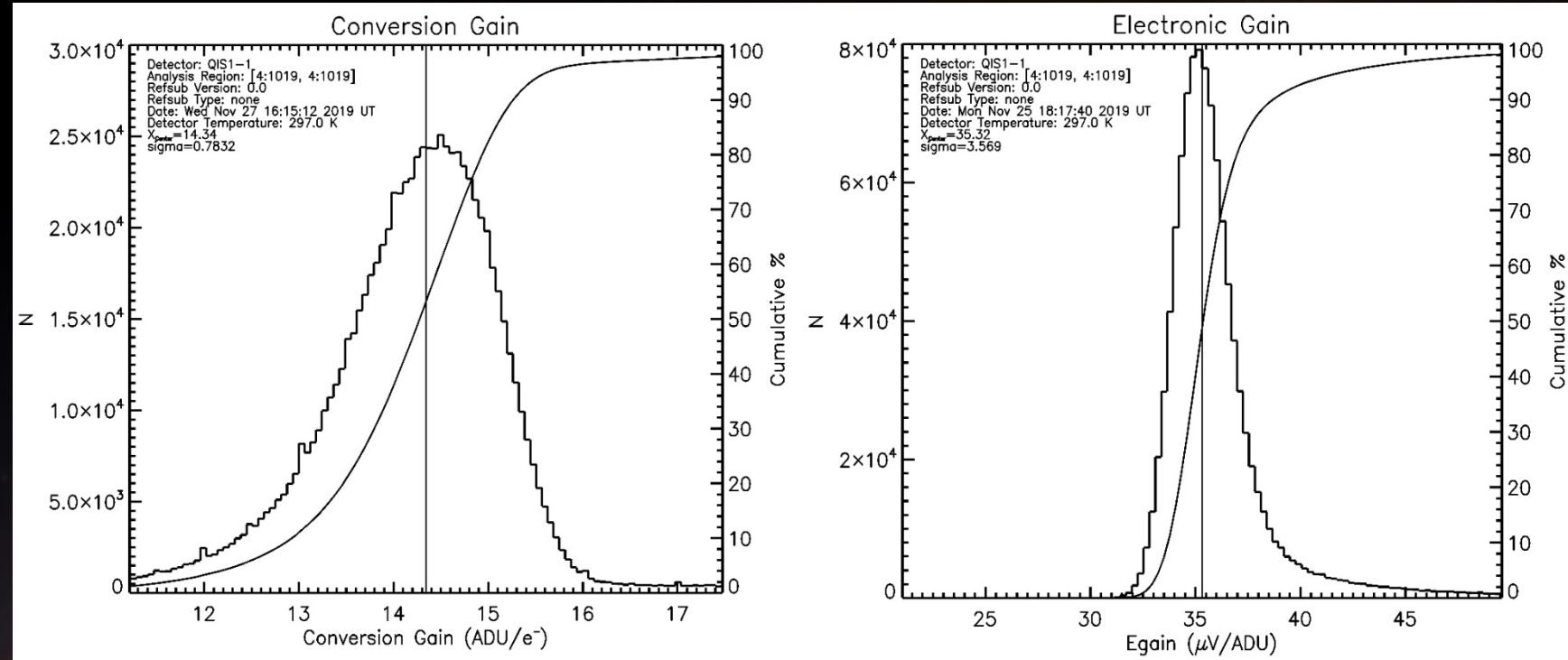
Single Photon Sensing Detectors (Figer)

- Progress to date:
 - RIT CfD received 20 prototype detectors packaged in a camera.
 - We established single-photon-sensing and photon-number-resolving performance.
 - A significant fraction of the acquisition and reduction software is complete.



Single Photon Sensing Detectors (Figer)

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(left) A histogram of (ADU/e^-) gain of the detector array. The mean gain is $\sim 14.3 \text{ ADU}/e^-$. (right) A histogram of electronic gain ($\mu\text{V}/\text{ADU}$) electronic gain. The mean gain is $\sim 35.3 \mu\text{V}/\text{ADU}$. The mean output sensitivity is $500 \mu\text{V}/e^-$.

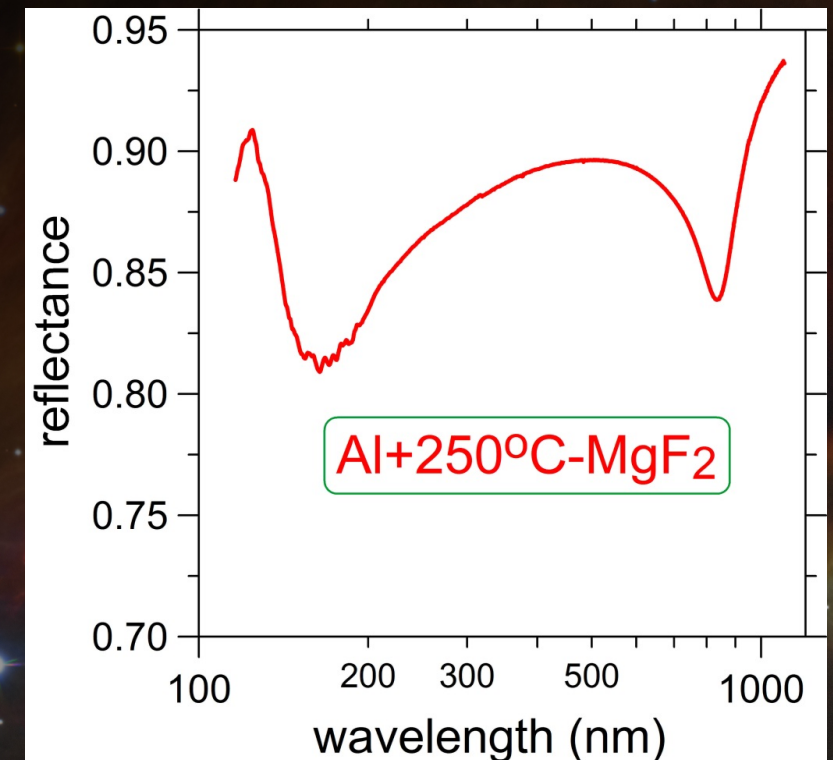
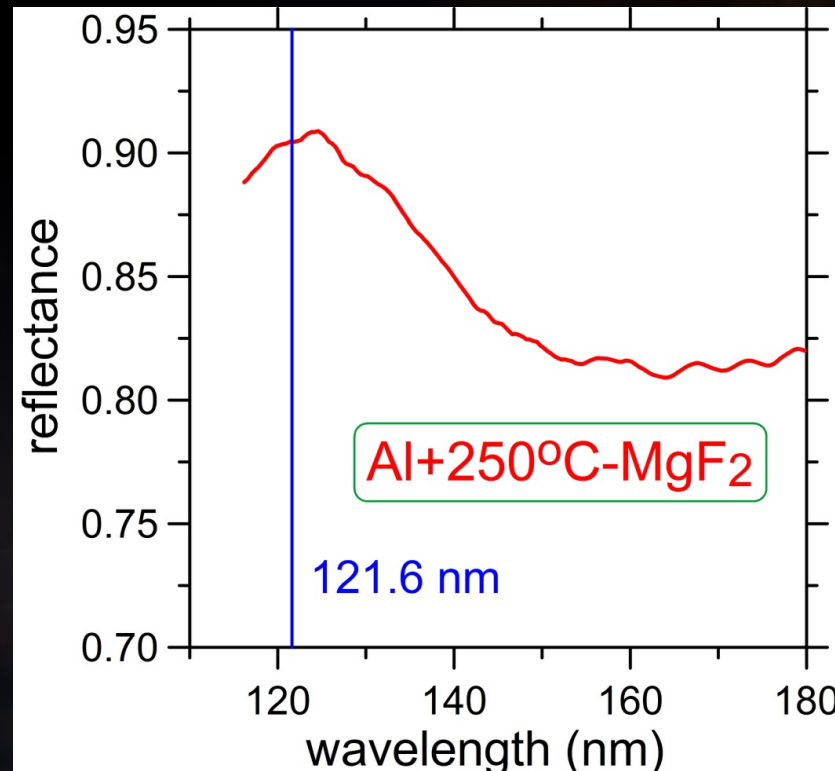
UV Coatings Developed for GOLD (Larruquert)

High performance FUV coatings.

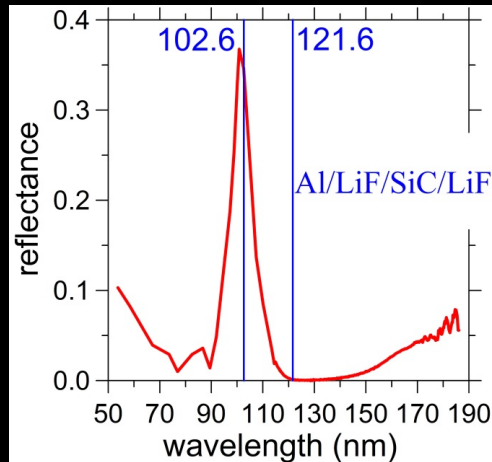
Deposition by evaporation+ion-beam-sputtering

Opt. Express 26, 9363 (2018)

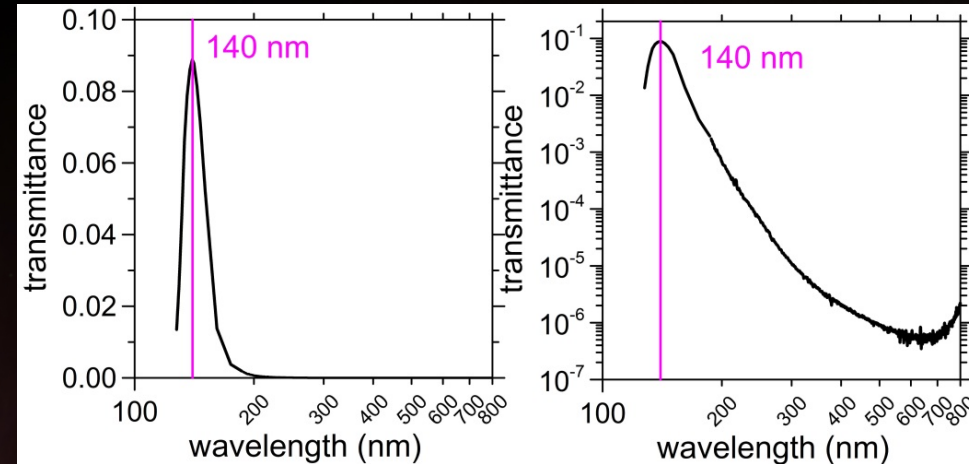
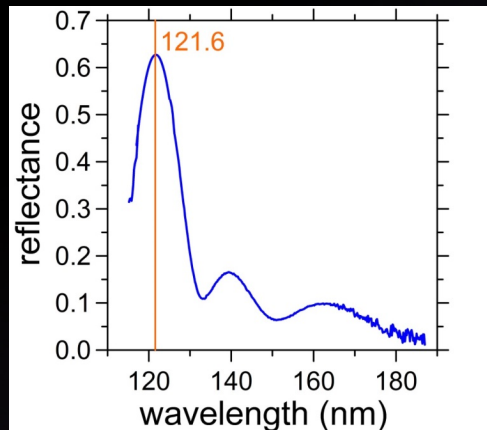
Al+MgF₂ deposited
by evaporation
MgF₂ deposited on
hot Al



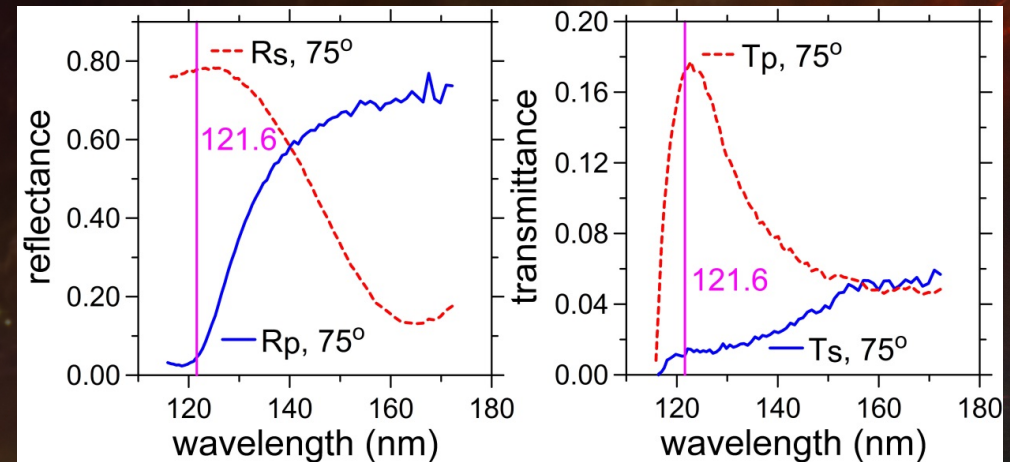
UV Coatings Developed for GOLD (Larruquert)



NARROWBAND MIRRORS



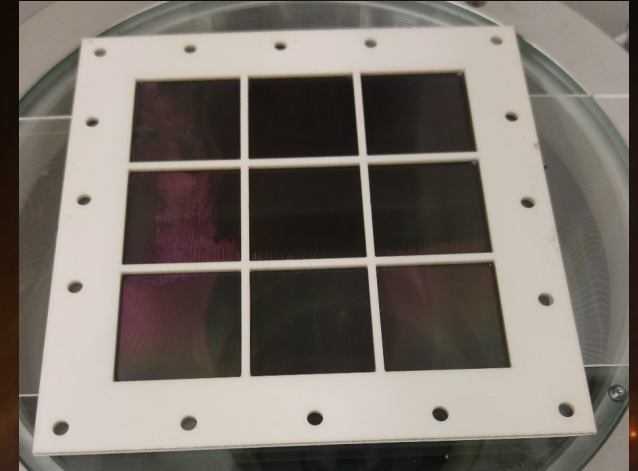
Filters



Polarizers

Scalable Microshutter Systems for UV, Visible, and Infrared Spectroscopy (Greenhouse)

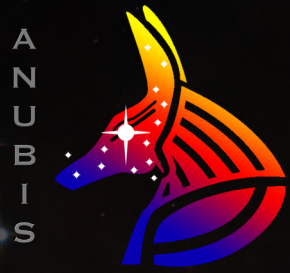
- Next generation Micro-Shutters (NGMSA): <https://asd.gsfc.nasa.gov/ngmsa/>
- Funding: SAT award, 3 year duration. Year 2 started in Sep 2019. We expect that there will have to be subsequent SAT support after year 3 (Sep 2021) to carry the development to a point at which funding can be handed-off to a selected strategic mission.
- We expect the probe-class customers to lag by ~2 years due to the AO process that is being considered for the Probe program. This would enable any probes to benefit from the NRE investment made by the strategic mission (e.g., if the instrument uses the same NGMSA product as HabEx then the cost to a probe project would be a minimum)
- The SAT project goal is to take the large format array (840 x 420) from TRL-3 to -5. The major accomplishment of year 1 was to get this format array design through vibration and acoustic testing for spaceflight. This was successful, and **the current TRL is now 4.**
- Much of our development work has been done on a small format (128 x 64) pilot arrays. This format progressed from TRL-4 to -9 during year 1 with the successful flight of FORTIS.



Mechanical array that passed vibe and acoustic tests

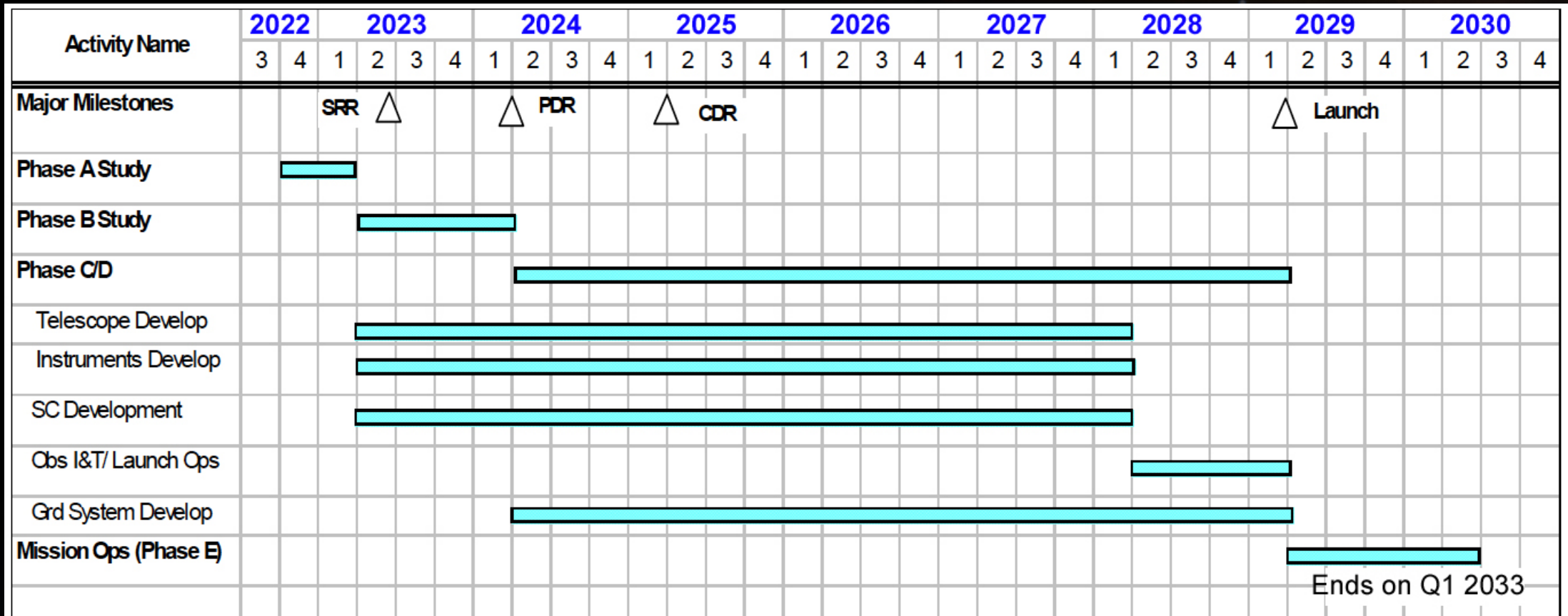
Contamination

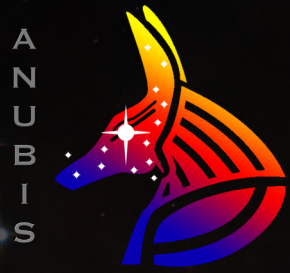
- Any FUV mission must factor in additional care in handling and cleanroom ratings for AIT
- Contamination cannot be prevented, but it can be budgeted over the lifetime of the mission from assembly through EOL
- Use of industry standards for handling combined with witness sample monitoring and periodic bake-out and cleaning rinses, together with choice of UV-friendly materials with ultra-low outgassing can mitigate the rate of contamination
- On-orbit heat biasing of critical surfaces can prevent build-up and combine with occasional bake-outs can provide for many years of operation without penalty (as shown by FUSE)



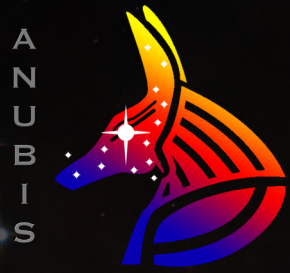
Project Schedule

Tentative Mission Schedule





Strategic Value



ANUBIS Delivers NASA Strategic Goals

- High-resolution, widefield UVO imaging surveys combined with time domain coverage will provide a vital complement to NASA's Wide Field Infrared Survey Telescope (WFIRST).
- ANUBIS Cosmic Origins science goals align with the 2014 NASA Strategic Plan, Objective 1.6, to "Discover how the universe works, explore how it began and evolved, and search for life on planets around other stars." Its capabilities will address all three of the 2014 NASA Science Plan Astrophysics science goals to
 - (1) "Probe the origin and destiny of our universe, including the nature of black holes, dark energy, dark matter and gravity";
 - (2) "Explore the origin and evolution of the galaxies, stars and planets that make up our universe"; and
 - (3) "Discover and study planets around other stars, and explore whether they could harbor life", with an emphasis on goals (2) and (3).
- There is also alignment with the Planetary Science goals, especially "Advance the understanding of how the chemical and physical processes in our solar system operate, interact and evolve."
- ANUBIS combines a true discovery survey camera with nearly an order of magnitude better AO than the Hubble Space Telescope (HST), and larger collecting area and higher resolution (spatial, spectral) than GALEX. The concept leverages modern advances in UVO mirror, coating and detector technologies to maximize its scientific impact within the specified Probe-class price point range, and by providing unique capabilities not offered by any other contemporaneous facility.

Cost Estimation and Validation

- The overall comparison between our initial estimates and the cost validation we did with partners JPL offer reasonable agreement.
- We originally omitted some costs that should have been carried such as Science (!) and Mission Ground Ops.
- However, we believe that if ANUBIS were to be proposed, we could and would work to trim the Payload and the Flight System.
- At this level of fidelity, we believe we can demonstrate that the science and capabilities we need can be delivered within a Probe-class budget.

The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

WBS Element	ANUBIS Cost Estimate	Kepler-like Bus (FY20 \$M)
Phase A	Included below	7
01 Project Management	90	42
02 Project System Engineering / 12 Mission Design	Included above	31
03 Safety & Mission Assurance	Included above	25
04 Science	-	47
05 Payload System	390	398
06 Flight System / 10 Project SIT	120	193
07 Mission Operations System	-	47
09 Ground Data System	-	Included above
Subtotal Phase A-D Cost	600	791
Reserves (Phase A-D)	180	237
Total Phase A-D Cost	780	1,028
Phase E/F Cost (w/o Reserves)	120	146
Reserves (Phase E/F)	-	22
Total Phase E/F (including Reserves)	120	168
Ground Tracking	-	-
Launch Vehicle	75	75
Total Phase A-F Cost	975	1,271

Defraying costs on a UVO Probe-class mission

- Meaningful contributions to Probe-class missions – such as funding for instrumentation, operations, and data analysis – could be made through public-private partnerships at demonstrated levels of philanthropic support for astronomical facilities
 - Recommend that Astro2020 and NASA express the desire for contributions to space missions by private foundations (e.g., Moore, Keck, Simons, Breakthrough, etc.) and even commercial entities, and then facilitate contributions rather than leaving it up to which PI's have the “right” connections
- International partnerships
 - Many foreign space agencies would like to participate in a “Hubble 2” mission

Unconventional Partnerships

- Cost-Sharing on a 1.5-m class UVO observatory mission may be possible with the Planetary Sciences Division (PSD) since there are currently 2 or 3 solar system observatory concepts being planned for the planetary decadal survey.
- However there is no track record of doing space telescopes through Discovery or New Frontiers in the past decade.
- Such a collaboration would likely involve allowing planetary scientists to contribute to setting the instrument requirements. It might also require dedicating 30-50% of the observing time to solar system object monitoring & surveys.
- Together with potential international partnerships, this would be a way to keep APD costs down.

Probe Mission Calls

- If the Decadal Survey opts to recommend a Probe Mission AO as a competition, and that it be held in the next year or so, the likelihood of success in such a competition would likely be heavily skewed towards those concepts that have received significant funding (way more than \$100K) either from APD (e.g., EXO-C, EXO-S) or through Congressional programmatic earmarks (especially Starshade).
- If the Decadal thinks that competition is the preferred method to pursue, we believe that they need to recommend that NASA level the playing field.
- For example, as a possible model, PSD has included New Frontiers tech development competitions (called [Homesteader](#)) prior to the formal AO, where PSD has awarded several >\$1-2M grants for a small set of teams to develop technologies needed by the missions on the Decadal's New Frontiers mission list.