Cosmic Evolution Through UV Spectroscopy (CETUS) Probe Mission Concept Study

William Danchi

+

CETUS Study Team

ASTRO2020 EOS-1 Panel Meeting

1/27/2020

Outline

- Science Objectives
- Implementation
- Technology
- Schedule

Key references:

- Final Report
- Decadal 2020 Whitepaper
- Optical Design paper published in JATIS – Reference:

  Woodruff, R., et al. 2019, JATIS 18084

The CETUS Study Team

William Danchi (PI, GSFC), Sara Heap (Science PI, GSFC Emerita)

Co-Investigators: **Steve Kendrick** (Kendrick Aerospace Consulting), **Tony Hull** (Kendrick Aerospace Consulting, Univ. NM), **Robert Woodruff** (Woodruff Consulting), Jim Burge & Martin Valente (Arizona Optical Sciences), Kelly Dodson & Greg Miehle (Orbital ATK, now Northrup Grumman Innovative Solutions - San Diego***),*** *Steve McCandliss (Johns Hopkins Univ.)*

Science Team *(Collaborators)*: L. Bianchi, T. Heckman, A. Szalay, R. Wyse*, (Johns Hopkins Univ.)*; E. Dwek, J. Rigby (GSFC); J. Greene, D. Spergel (Princeton); I. Roederer (U. Michigan); D. Stark (U. Arizona); J. Trump, K. Whitaker (U. Conn.) + many more

Technical Collaborators: S. Nikzad (JPL); O. Siegmund, J. Vallerga (U.C. Berkeley SSL); Q. Gong, S.H. Moseley, **L. Purves**, B. Rauscher (GSFC)

GSFC Engineering Support Team: **Mike Rhee**, Mike Choi, Walt Smith, Eric Stoneking, and many others (about 14 total) …

Also contributions from Brian Fleming and Kevin France at University of Colorado, and William "Chip" Eckles from Northrup Grumman Innovative Solutions – Gilbert, AZ (formerly Orbital ATK – Gilbert) …

See the report and white paper for a full list … a total of about 60 people contributed to CETUS over the last two+ years.

Why UV Science? Why Now?

- UV science affects all areas of modern astronomy and astrophysics. UV spectral lines provide key diagnostics for physical conditions from stars to galaxies.
- In the time between the retirement of HST and the start of observations with LUVOIR or HabEx, a broadly capable UV space observatory is vital to continued progress and new discoveries.
- Technological advances allow for improved sensitivity and capabilities, with Multi-Object Spectrographs using Microshutter Arrays, improved detectors with higher QEs, higher reflectivity mirror coatings, and polishing techniques for improved mid-spatial frequency performance and low surface roughness.

CETUS is a response to the 2010 Decadal

Cosmology and Fundamental Physics (CFP) ✓CFP 3 What is dark matter? **Galactic Neighborhood (GAN)** ✓GAN 1 What are the flows of matter and energy in the circumgalactic medium? ✓GAN 2 What controls the mass-energy-chemical cycles within galaxies? ✓GAN 3 What is the fossil record of galaxy assembly from the first stars to present?	**Galaxies Across Cosmic Time (GCT)** ✓PGCT 1 How do cosmic structures form and evolve? ✓GCT 2 How do baryons cycle in and out of galaxies, what do they do while they are there? ✓GCT 3 How do black holes grow, radiate, and influence their surroundings? **Stars and Stellar Evolution (SSE)** ✓SSE 3 How do the lives of massive stars end? **Planetary Systems and Star Formation (PSF)** ✓PSF 4 Do habitable worlds exist around other stars?

Key Scientific Objectives

Galaxy evolution:

- Why did rate of conversion of gas into stars and the growth of black holes peak 10 billion years ago (at redshift, z ~ 2) and then decline?
- What explains the co-evolution of galaxy bulges and nuclear black holes (AGN's)?
- How did the Hubble Sequence emerge?
- How did galaxies come to look like the ones we see today?

Sources of gravitational waves and other transient events:

- Localize and determine key heavy elements created in neutron star merger events and other transient sources
- Determine if neutron star mergers account for half of all elements heavier than iron in the universe

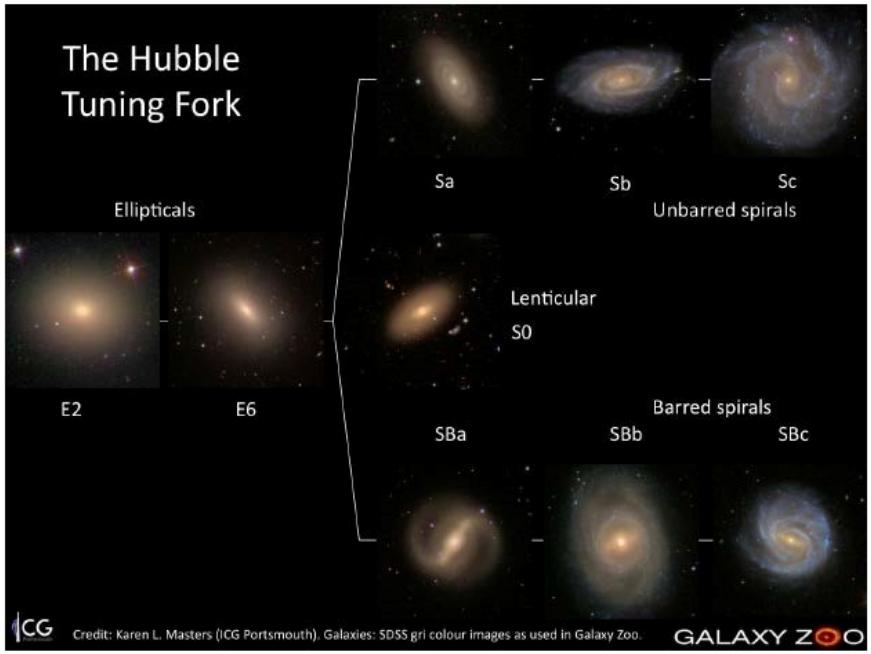
Cosmic Origins, Stellar Astrophysics, and Exoplanet Science:

- Perform stellar paleontology. Search for and characterize very metal poor stars to determine nature of first stars and supernovae.
- Discover analogues to high-redshift, star-forming galaxies by providing a large sample of nearby galaxies with gas-phase metallicities below 20% solar.
- Stellar astrophysics -- stellar activity, flares, coronae – particularly for M, K, G stars
- Characterize the (X) UV spectrum of stars with potentially habitable planets, including M stars

What is CETUS?
A 1.5-m UV telescope with three instruments

Instrument	Capability
1.5-m telescope	Wide field of view accommodating two wide-field science instruments and the echelle spectrograph
	FUV sensitivity down to 1,000 Å
NUV multi-object slit spectrograph (MOS) with microshutter array	Wide field of view: 17.4′ x 17.4′
	Simultaneous slit spectra of ~100 sources
	Shutter size: 2.75″ x 5.50″
	Long-slit option: 2.75″ x 17.4′
	Wavelength range: 1,800-3,500 Å
	Spectral resolving power: R~1,000
	Limiting sensitivity: $F\lambda = 4 \times 10^{-18}$ erg/s/cm^2/Å
FUV & NUV camera (CAM)	Field of view: 17.4′ x 17.4′
	Wavelength range: 1150-1800 Å; 1,800-3,500 Å
	Angular resolution: 0.55″; 0.33″
	Sensitivity (1 hour): m_{AB}=27; m_{AB}=26
FUV & NUV point slit spectrograph (PSS)	Field of viw set by slit: 0.2″-2″x360″; 0.2″-2″ x 3″
	Wavelength range: 1,000-1800 Å; 1,800-3,500 Å
	Spectral Resolving Power (RP): 20,000; 40,000
	Effective area (cm^2): 2000 (max); ~1000

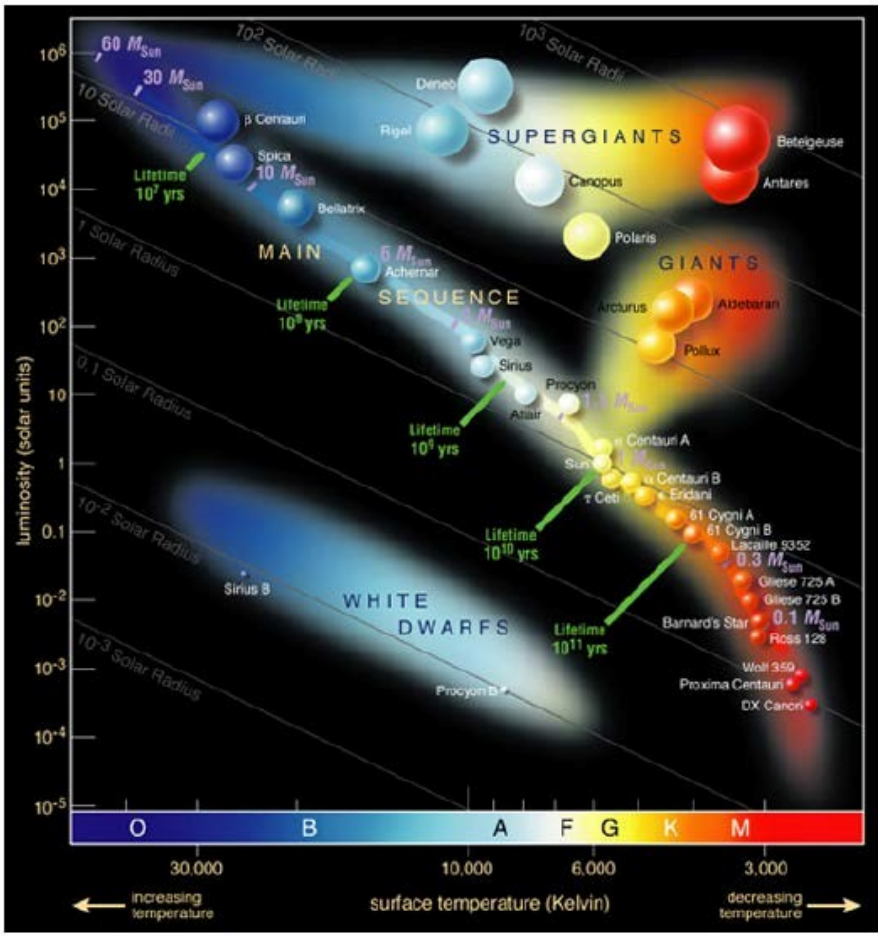
Galaxy Evolution



Hubble classification of galaxies is based on morphology.
Credit: Karen L. Masters.

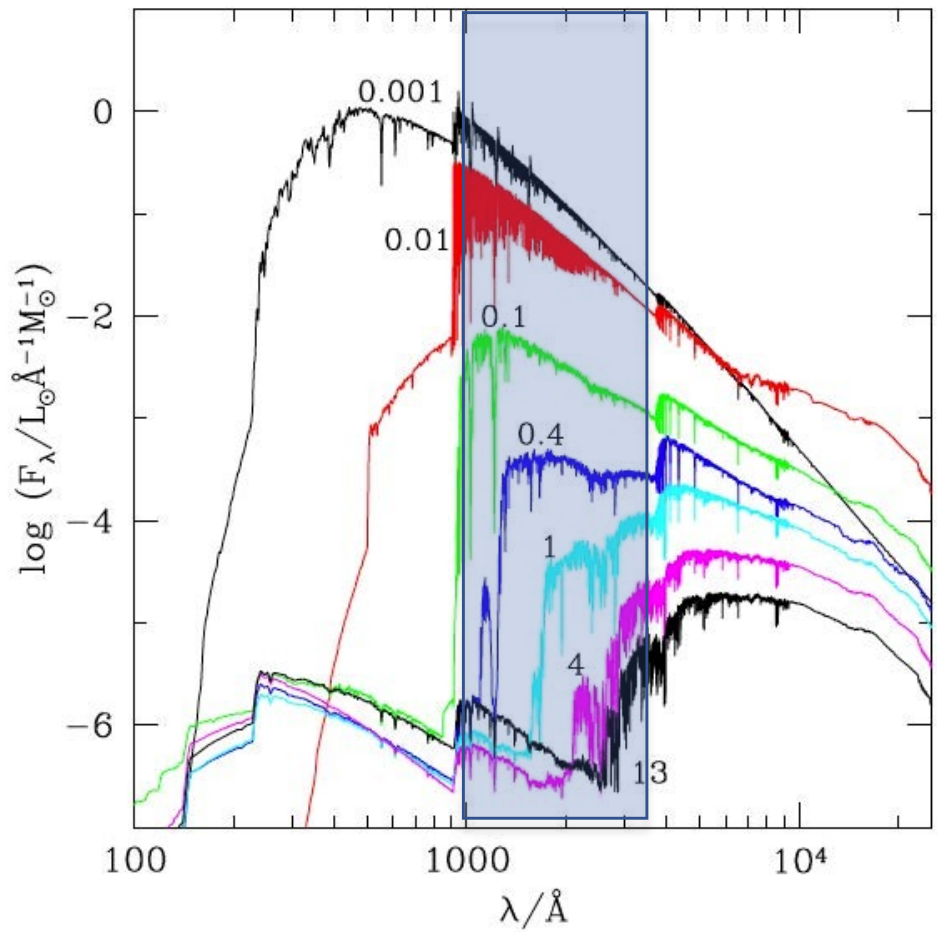
Classification of galaxies based on star-formation activity.
Credit: Brian Koberlein.

To understand galaxy evolution we need UV spectroscopy



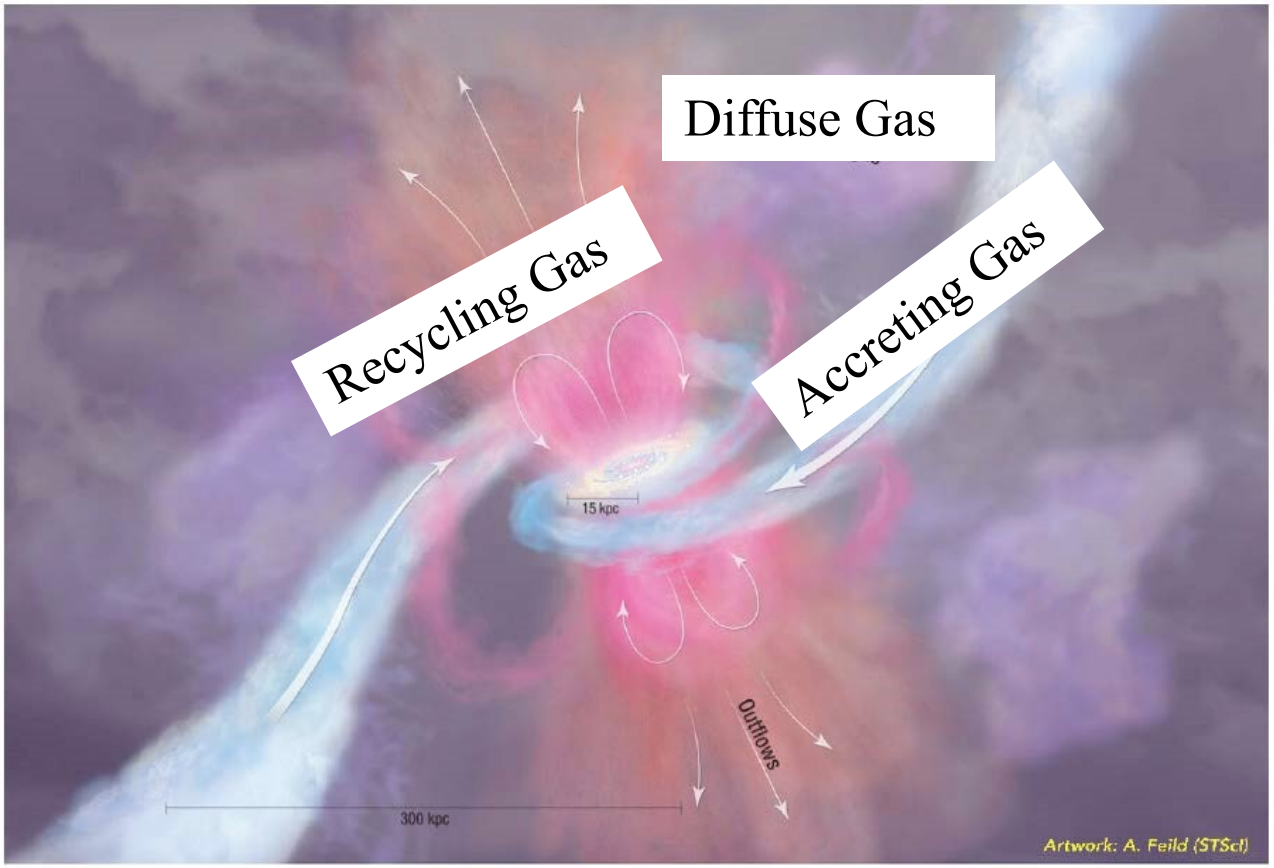
Hertzprung-Russell (HR) diagram.
Credit: Wikipedia

CETUS UV Bands



Spectral evolution of the standard single-metallicity single-age simple stellar population (SSP) model for solar metallicity. Ages are indicated next to the spectra (in Gyr). Credit: Bruzual & Charlot (2003).

Understanding the Circumgalactic Medium (CGM) is an important driving force for CETUS



Normal galaxies are surrounded by massive reservoirs of diffuse gas, a factor of 10 larger in size than the galaxy itself, e.g., 300 kpc compared to 15 kpc. These reservoirs are fed by accretion out of the cosmic web and by outflows from the galaxy. Recent evidence indicates that the CGM is a major factor in galaxy evolution. Adapted from Tumlinson, Peeples, & Werk (2017), and from the LUVOIR Final Report.

Possible drivers of galaxy evolution

Dark Energy

At z~1-2, dark energy became influential in accelerating the expansion of the universe, so that:

- The distances between galaxies grew
- Galaxy mergers became less frequent
- Merger-induced star formation decreased

Feedback from active galactic nuclei (AGN'S)

AGN-induced outflows from galaxy & AGN jets made the galaxy inhospitable for further star formation

CETUS UV Spectra:

CETUS will observe the rest frame far-UV of z~1-2 galaxies,
which is rich in spectral diagnostics of Star Forming galaxies

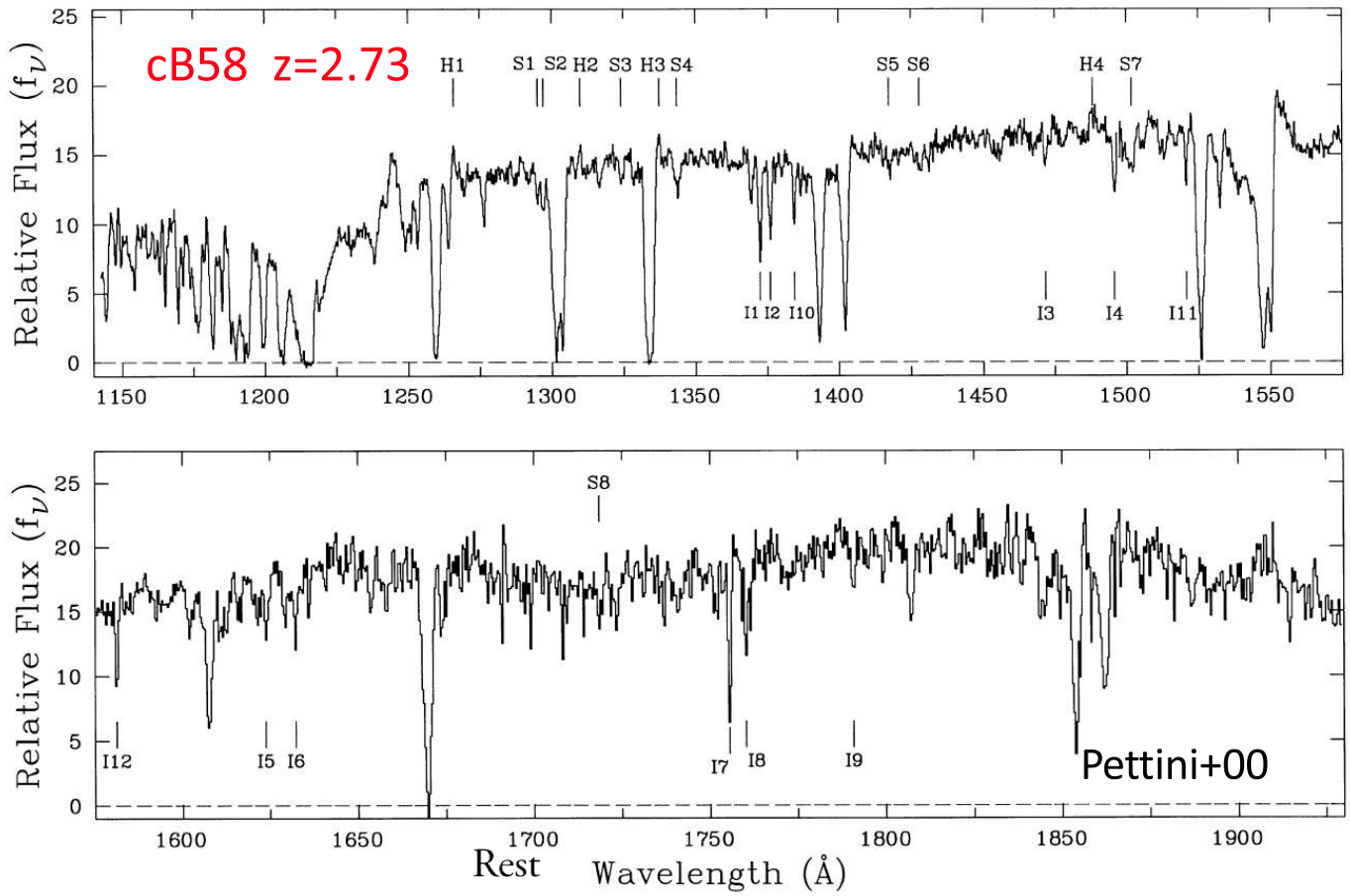


FIG. 1.—LRIS spectrum of MS 1512−cB58 reduced to the systemic redshift of the galaxy, $z_{stars} = 2.7268$. Tick marks above the spectrum identify weak stellar lines (labeled S*n*) listed in Table 1 and weak emission lines (labeled H*n*—see Table 4) that we attribute to H II gas. Tick marks below the spectrum (labeled I*n*) mark the positions of the intervening absorption lines listed in Table 6. The numerous interstellar lines in MS 1512−cB58 have not been marked

12/30/12

This far-UV spectrum yielded: SFR~40 $M_\odot$, galactic wind with mass-loss rate ~60 $M_\odot$/yr,
protracted SF with a Salpeter IMF with M_u>50 $M_\odot$,
Z~1/4 $Z_\odot$ (both stars & gas), N_{HI}=7.5x10^{20} cm^{-2}, dust E(B-V)~0.1-0.3

Measurements to be performed with a massive UV spectrocopic survey

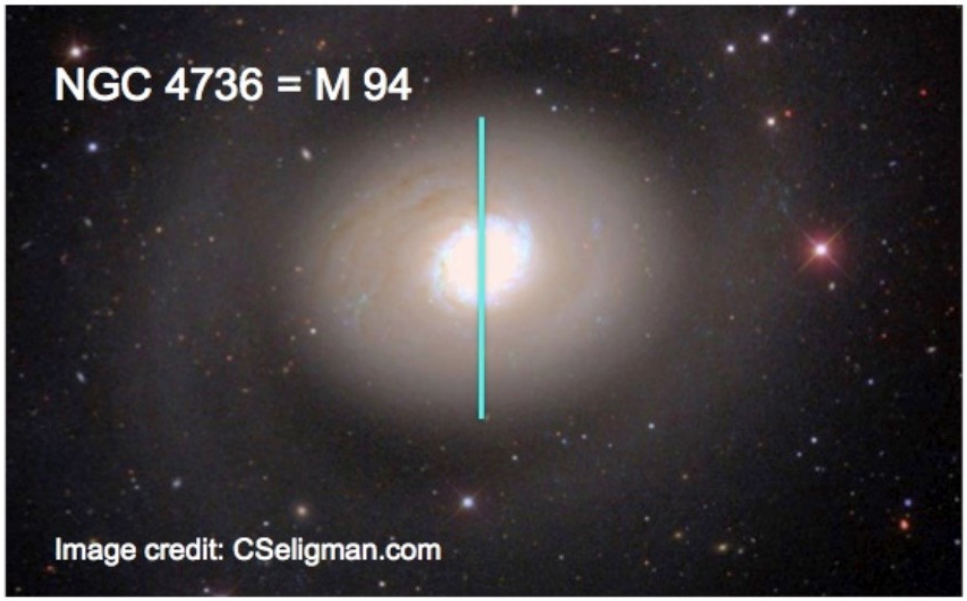
Far-UV spectra will give:

- Accurate redshifts for coaddition, identification of clustering
- Clean separation of continuum & emission-line flux
- Direct view of stellar feedback (ionization, heating, winds & outflows)
- Build-up of stellar mass (mass-loss vs. star-formation)
- Kinematics of galaxies
- Dust properties (extinction curve)
- Physical conditions of the ISM (HI and HII) and CGM
- Evolution of the mass-metallicity relation
- Co-evolution of galaxies & black holes

Why?

- To distinguish among the effects of accretion, mergers, star formation and feedback, growth of black holes, etc.;
- To cover a wide variety of environments that govern star formation
- To construct stacked spectra

CETUS will also take long-slit UV spectra of host galaxies of the CGM



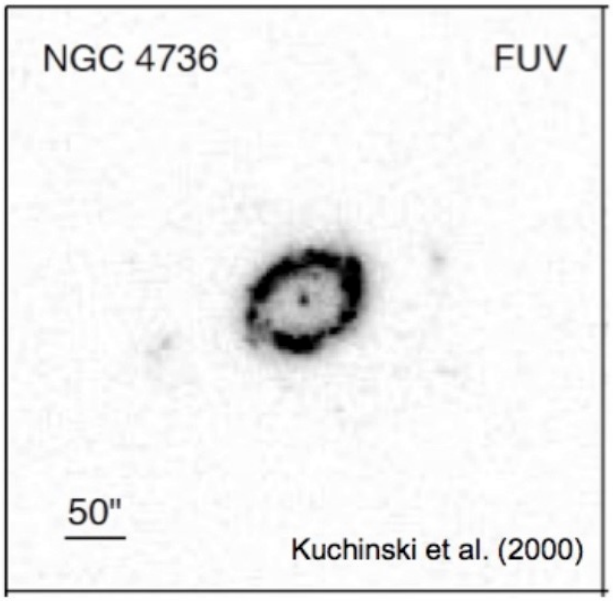
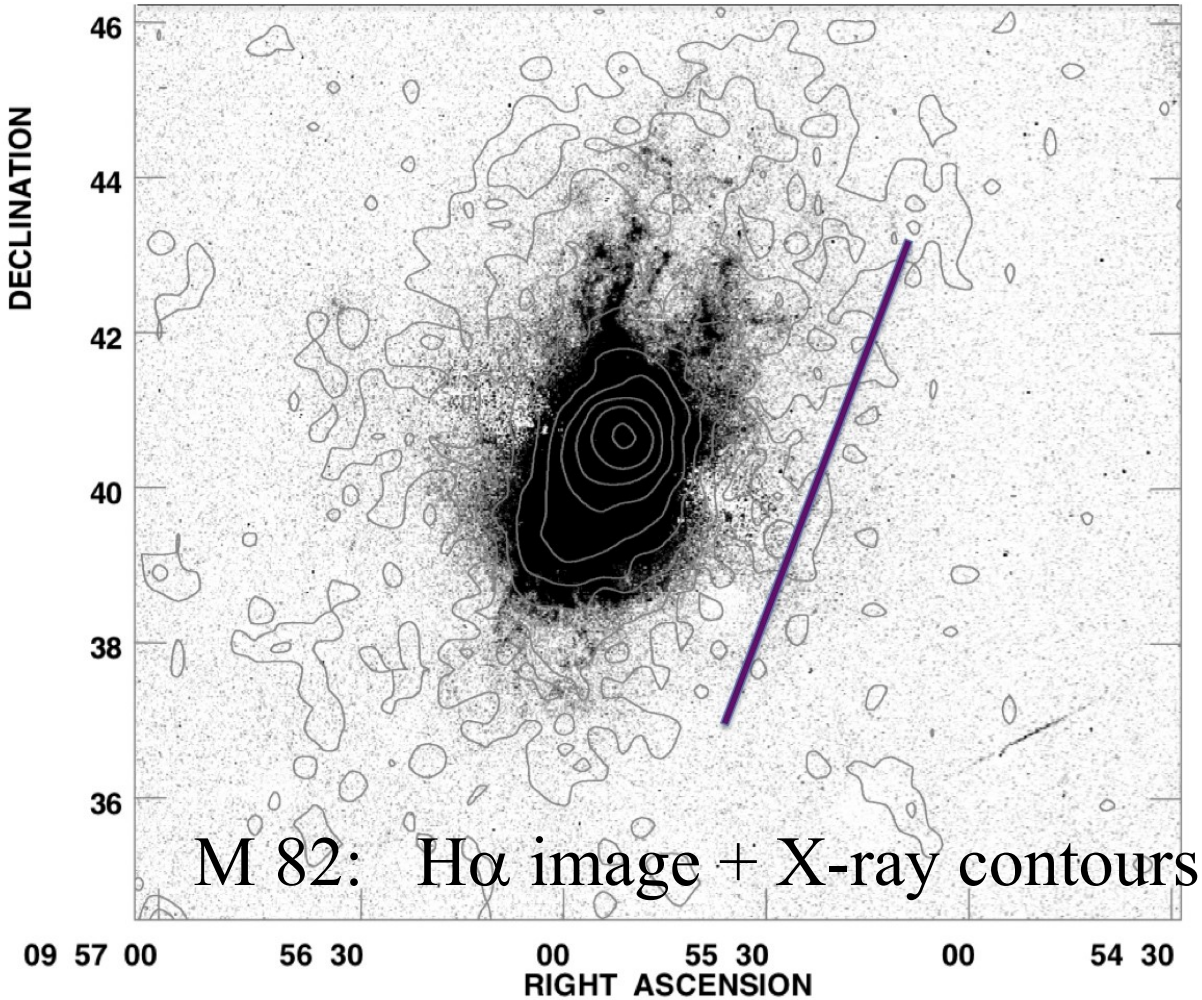


Figure 12. Left: The CETUS far-UV spectrograph will obtain UV spectra of nearby galaxies like NGC 4736 covering 1000-1800 Å over a 6'-high slit (shown in turquoise). The R_{25} radius of the galaxy is 3.86 arcmin, while the QSO-galaxy separation is 64 arc min. Right: A long-slit far-UV spectrum along the diameter of NGC 4736 would include the nucleus, which is bright in the far-UV and soft-Xrays and classified a low-luminosity AGN, and a starburst ring composed of stars less than 10 million years old.

The CETUS optical design allows far-UV long-slit spectroscopy (6')

CETUS will probe galaxy outflows directly



M 82: Hα image + X-ray contours

Lehnert +1999

CETUS will probe gas & dust halos

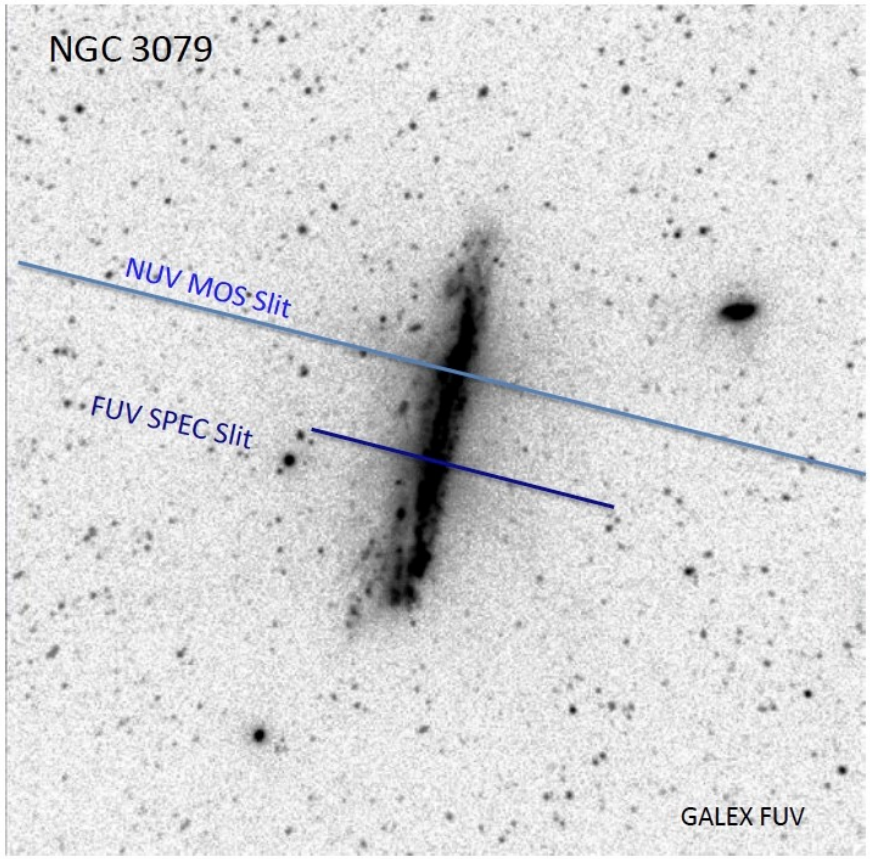
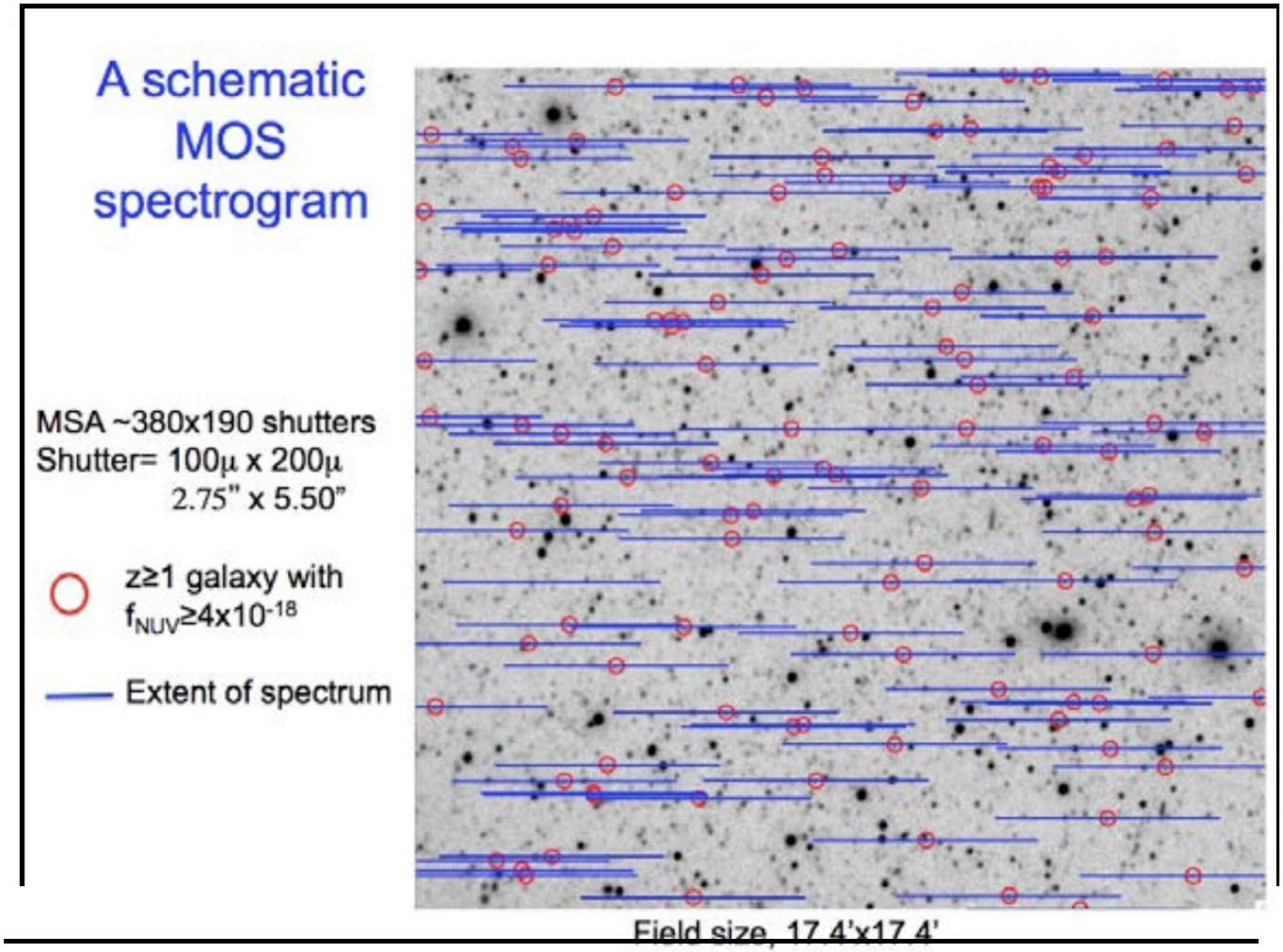


Figure 2-10: CETUS can obtain imaging spectra of gas and dust in halos of galaxies such as NGC 3079.

Near-UV long-slit spectroscopy (17.4') is possible with the multi-object spectrograph

CETUS will make a massive spectroscopic survey of z~1 galaxies thanks to its wide field and microshutter array

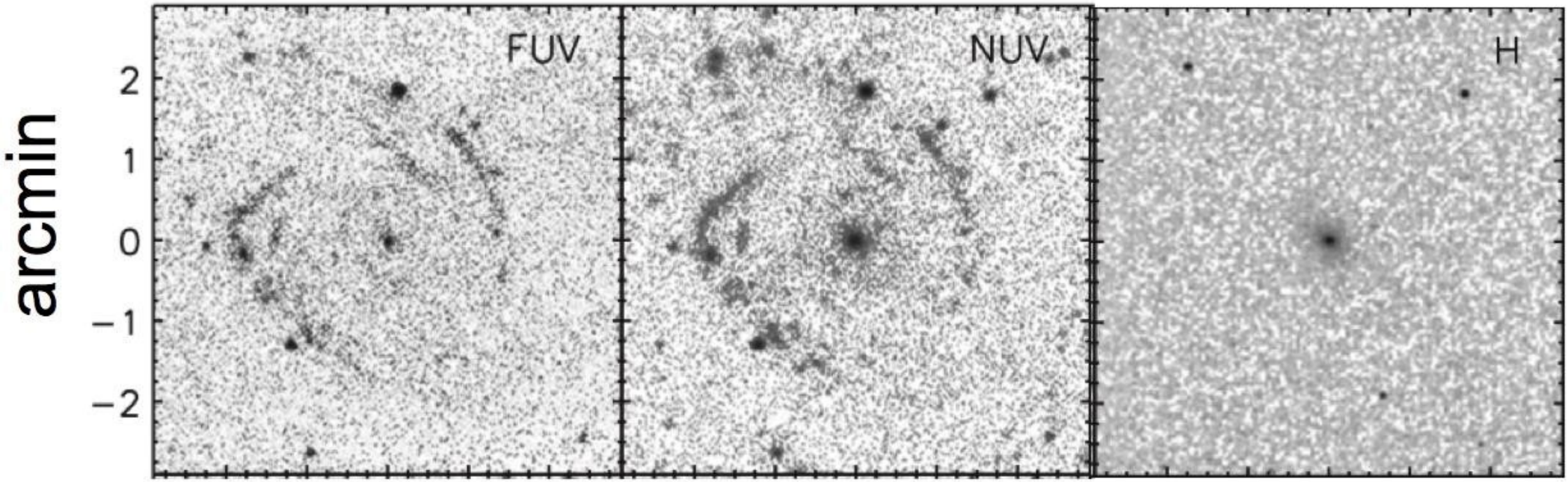


~100 z~1 galaxies are available to CETUS for simultaneous spectroscopy
The MSA blocks astronomical background (e.g. zodiacal light, spectra from nearby sources)

Also UV Imaging is needed

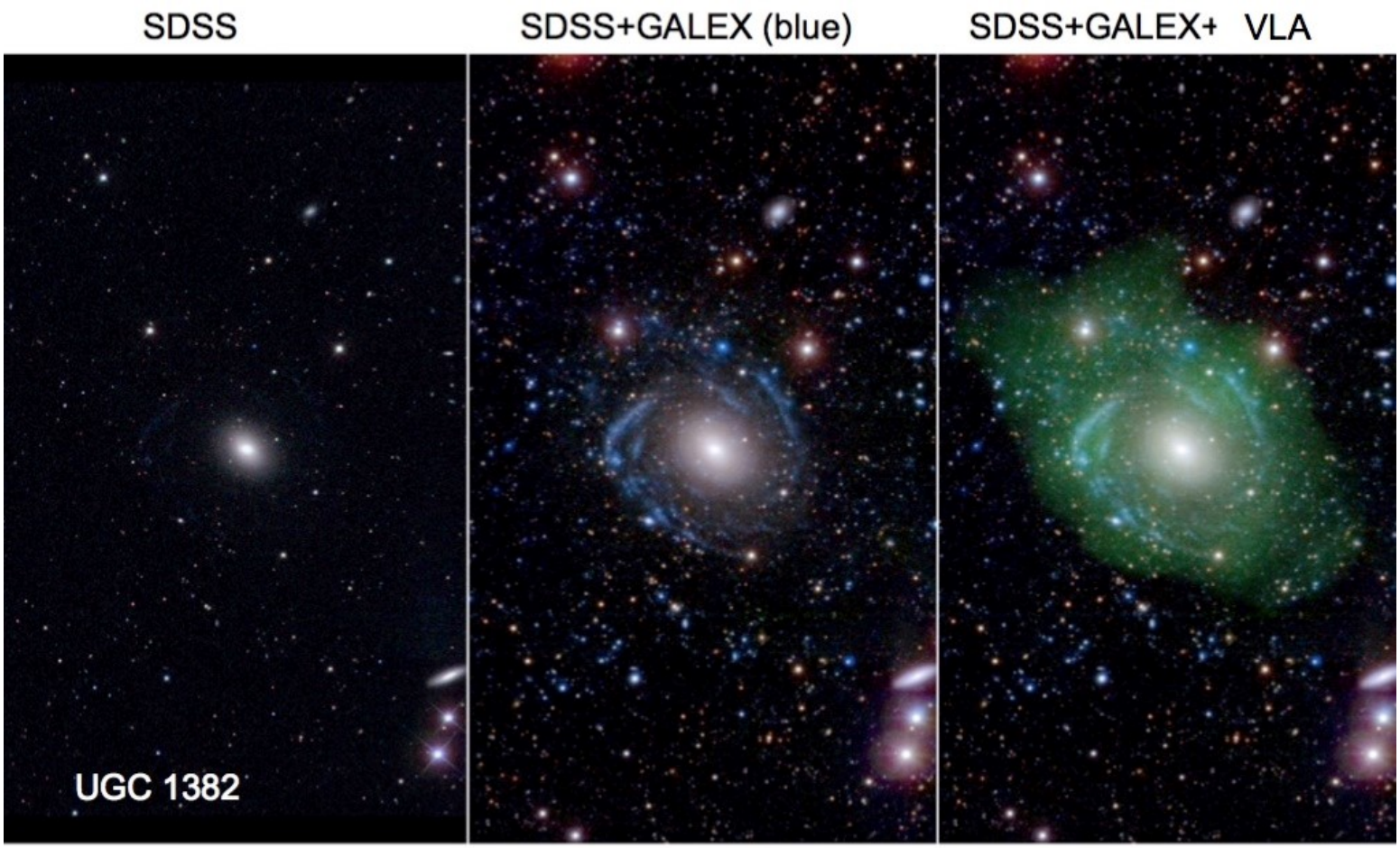
CETUS will conduct UV morphology studies

The far-UV is uniquely sensitive to extended star formation in galaxies



NGC 1382, classified as an elliptical galaxy, is actually a lenticular system with a low surface-brightness disk (R_{eff}~38 kpc) .... Hagen+2016

Multi-wavelength observations are important



Credits: NASA/JPL/Caltech/SDSS/NRAO/L. Hagen and M. Seibert (2016)

CETUS UV data will complement data at other wavelengths in the 2030's to solve major problems in astrophysics

CETUS

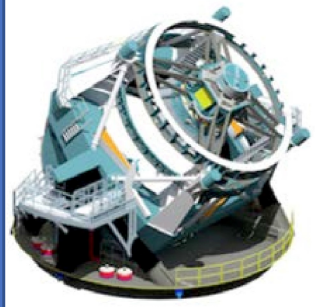
X-Ray E-ROSITA

CETUS will provide UV spectra of selected stellar black holes and massive, accreting black holes (AGN's) detected by E - ROSITA.

UV?

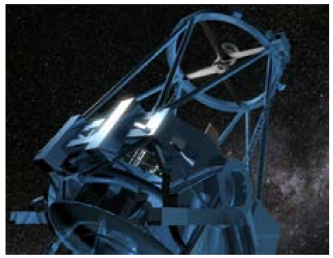
CETUS

Visible LSST



CETUS's cameras will help to refine photometric redshifts and preventing catastrophic redshift errors for sources detected by the LSST.

Visible/NIR Subaru

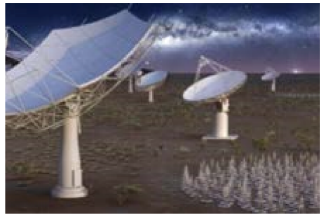


CETUS's MOS will observe z~1-2 galaxies based on optical-IR spectral energy distributions and galaxy stellar masses from Subaru PFS.

Visible/NIR WFIRST

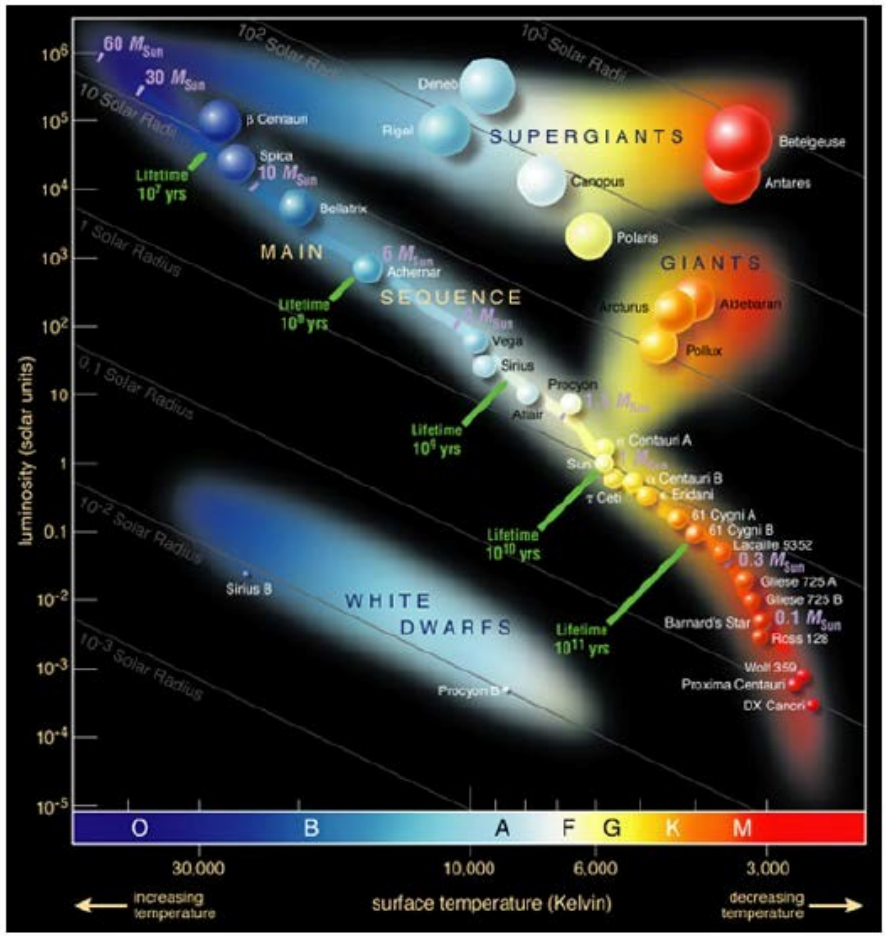
CETUS's cameras will observe objects in the far-UV and near-UV from WFIRST IR surveys, which may reveal phenomena first seen by GALEX such as extended star formation, UV halos around galaxies produced by dust reflection of stellar light, and Lyman alpha emission in the circumgalactic medium

Radio SKA



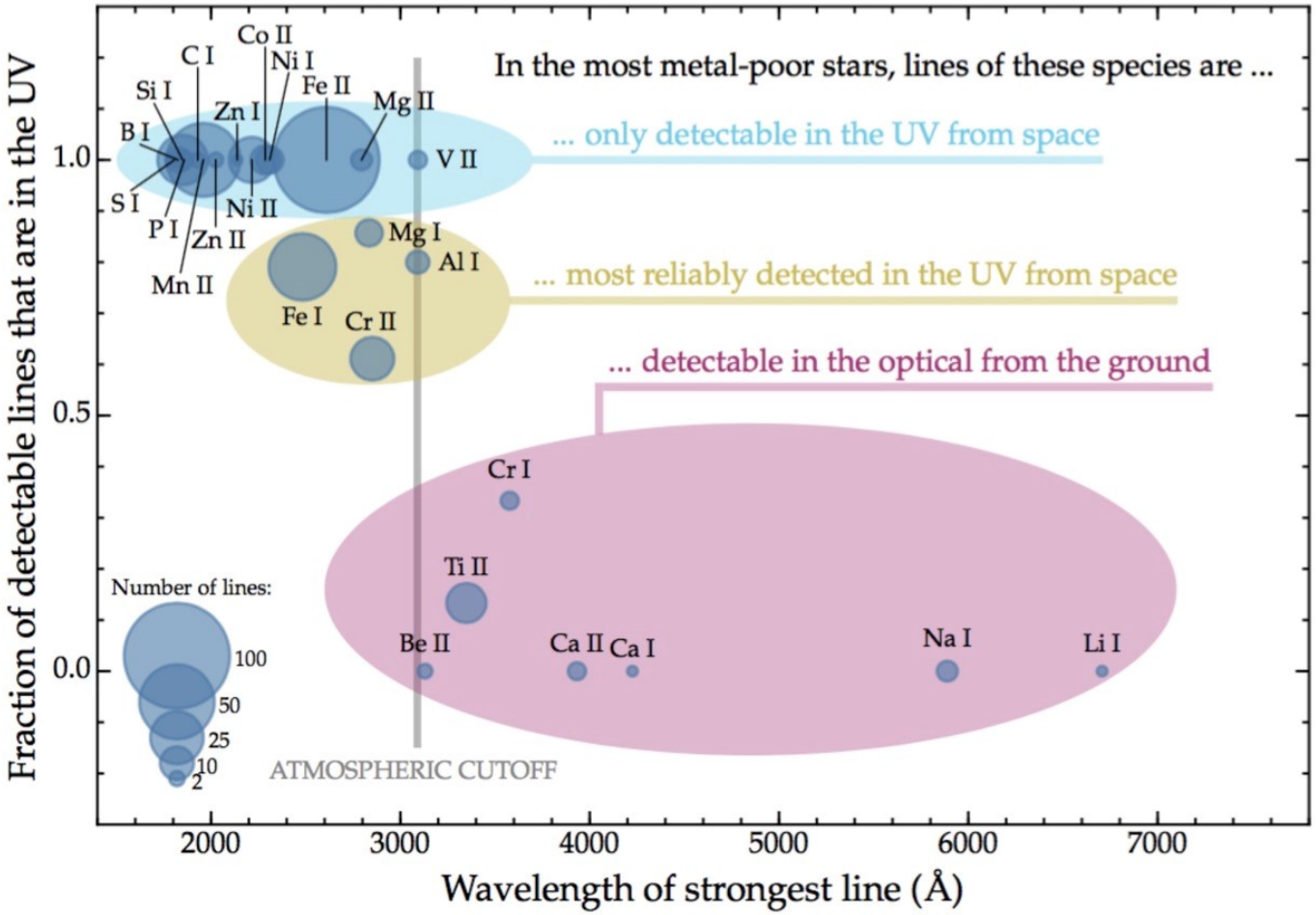
CETUS will obtain UV imagery of some galaxies mapped in the 21-cm line of neutral hydrogen, and will find Lyman alpha in emission, indicating ionized hydrogen to learn how star formation proceeds in galaxies.

Stellar Astrophysics and Exoplanets



Hertzprung-Russell (HR) diagram.
Credit: Wikipedia

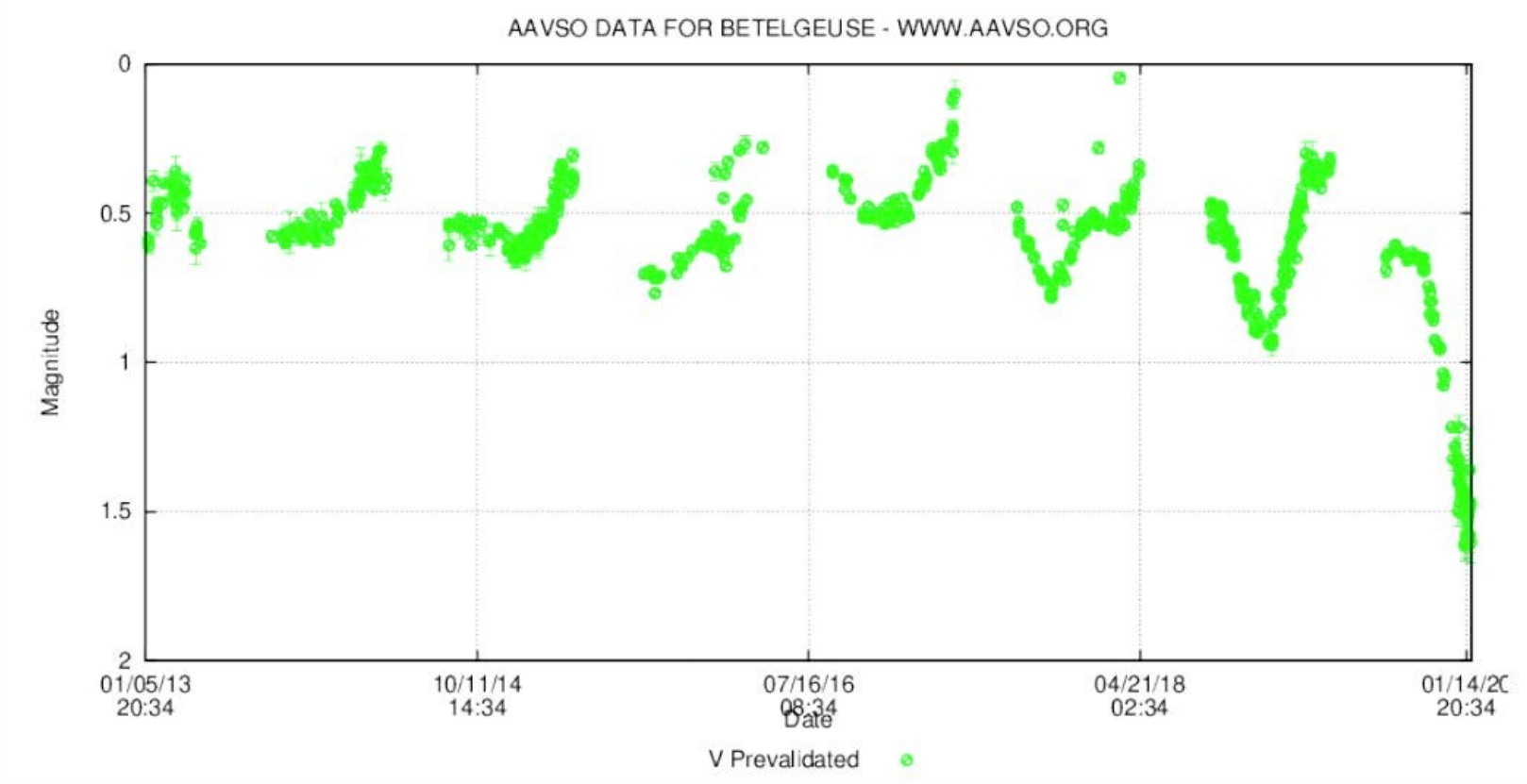
Improved metal detections in the most metal-poor stars is enabled by UV spectra



Typically ~8-10 elements can be detected in the optical alone, but UV spectra can enable the detection of ~20 elements, probing supernova physics (carbon through zinc, 6 ≤ Z ≤ 30) and Big Bang nucleosynthesis, stellar evolution, and spallation reactions (lithium, beryllium, and boron, 3 ≤ Z ≤ 5).

(Figure credit: Ian Roederer)

Chromospheres in giant stars -- the curious case of Betelgeuse, aka Alpha Orionis mysterious drop in V magnitude Will Betelgeuse become a Supernova in the near future??

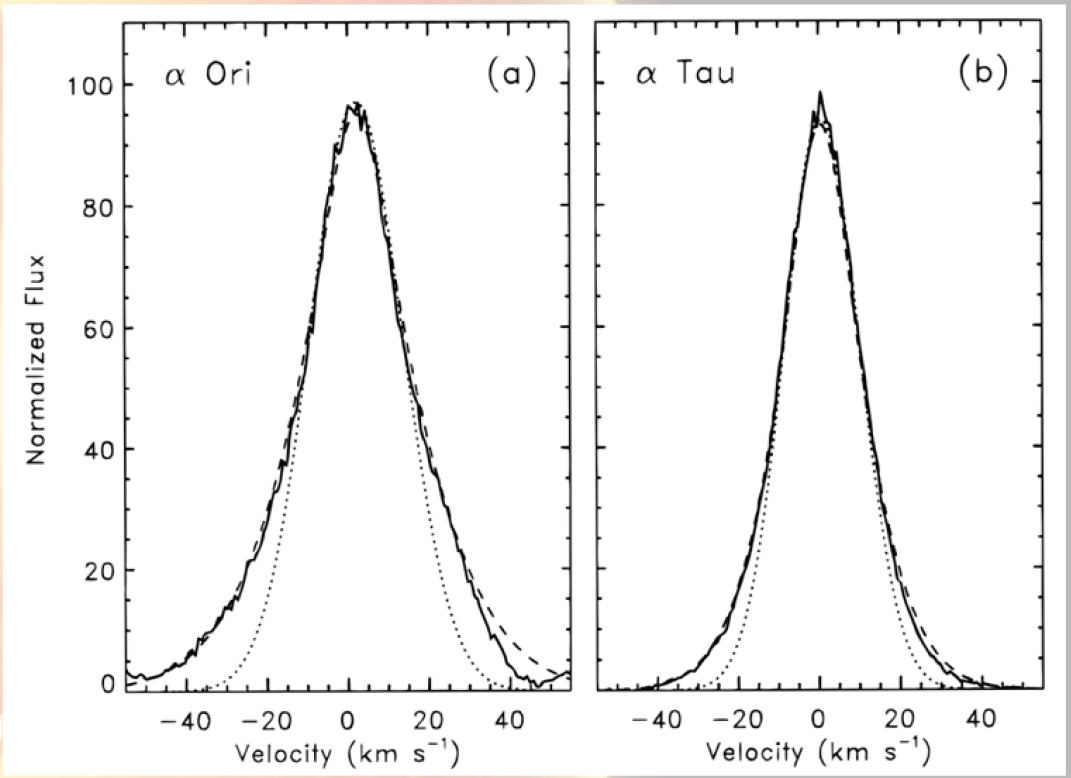


Stars of all types are variable, having pulsations, flares, coronal mass ejections, mass loss, and other types of activity. Future observations with UV space observatories like CETUS with improved capabilities will help to solve longstanding mysteries of stars and their evolution across the HR diagram.

CHROMOSPHERES IN GIANT STARS

- Chromospheric signature in the atmosphere of red giant and red supergiant stars (Carpenter et al 1995, Carpenter et al. 1999)
- Anomalous Widths of CII] Lines – The Signature of Alfven Waves?

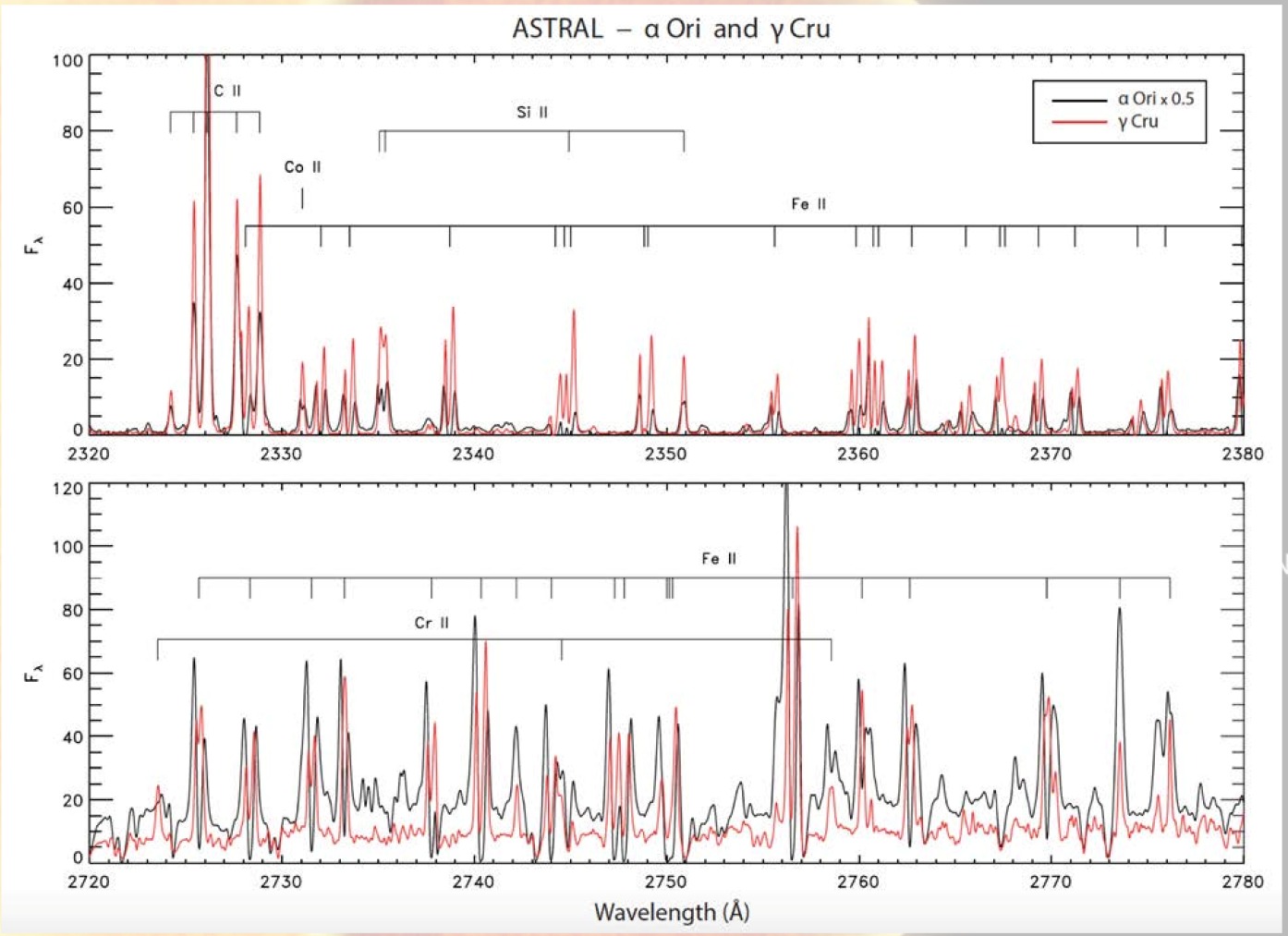
C II profiles (2325.398 Å) of α Ori and α Tau.



- Alfven waves reflect and propagate to drag material (Airapetian et al. 2000, 2010, 2015) and might drive the winds in those stars

HST: STUDYING CHROMOSPHERES IN GIANT STARS

Carpenter, Rau, et al. (2018), ApJ, 869, 157



ASTRAL

program on

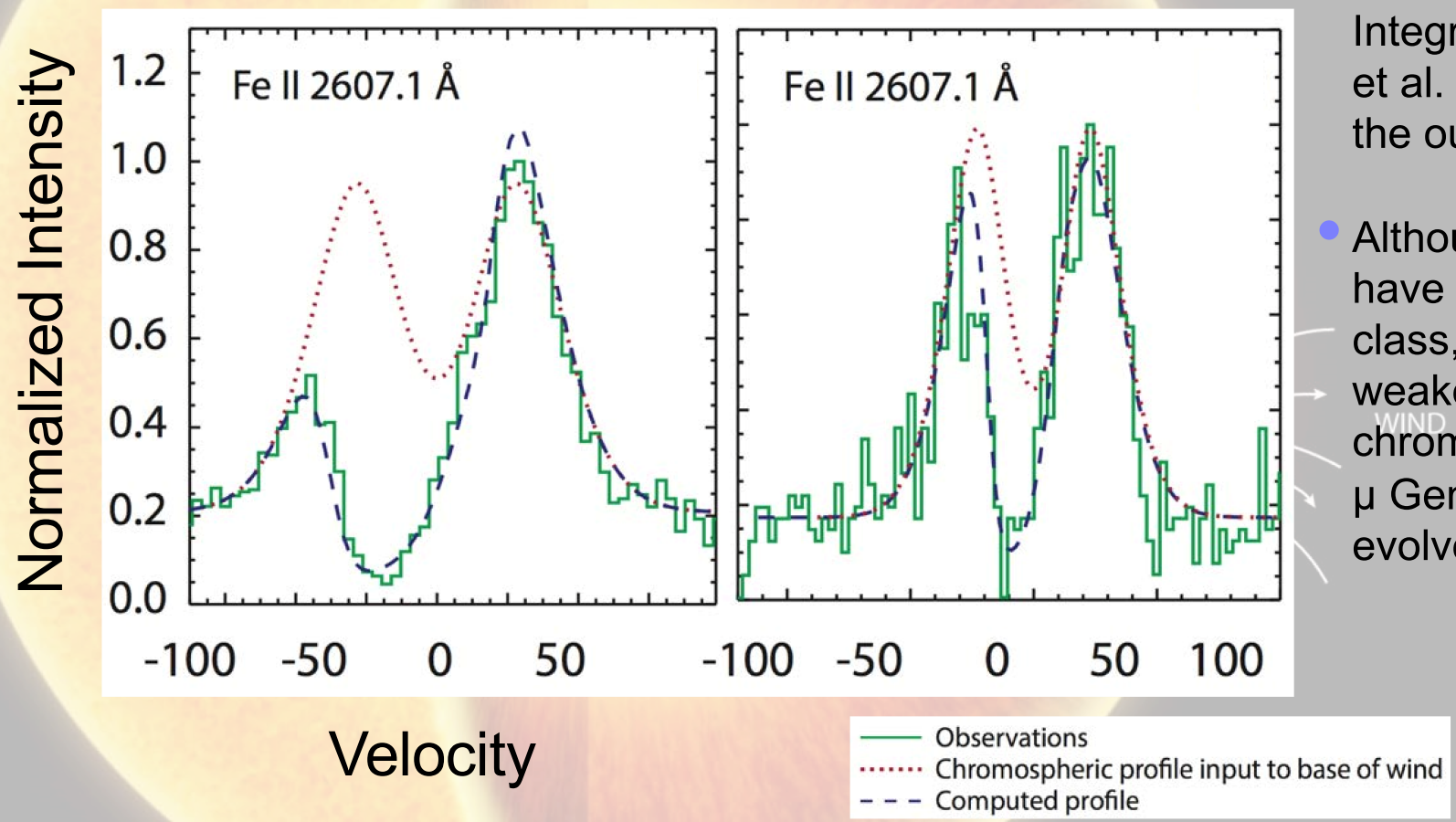
HST/STIS data

HST: STUDYING CHROMOSPHERES IN GIANT STARS

Rau et al. (2018), ApJ, 869,1

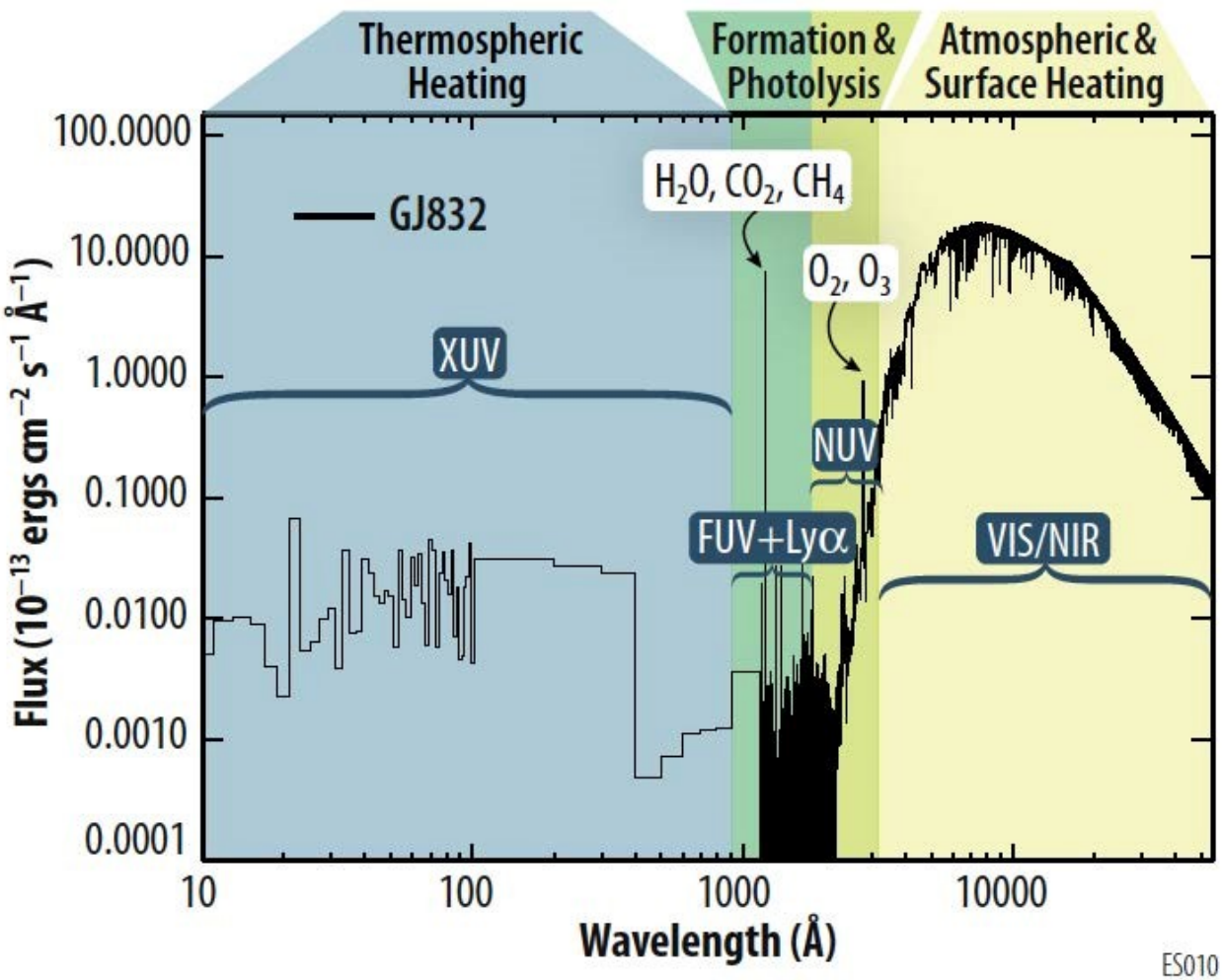
γ Cru

μ Gem



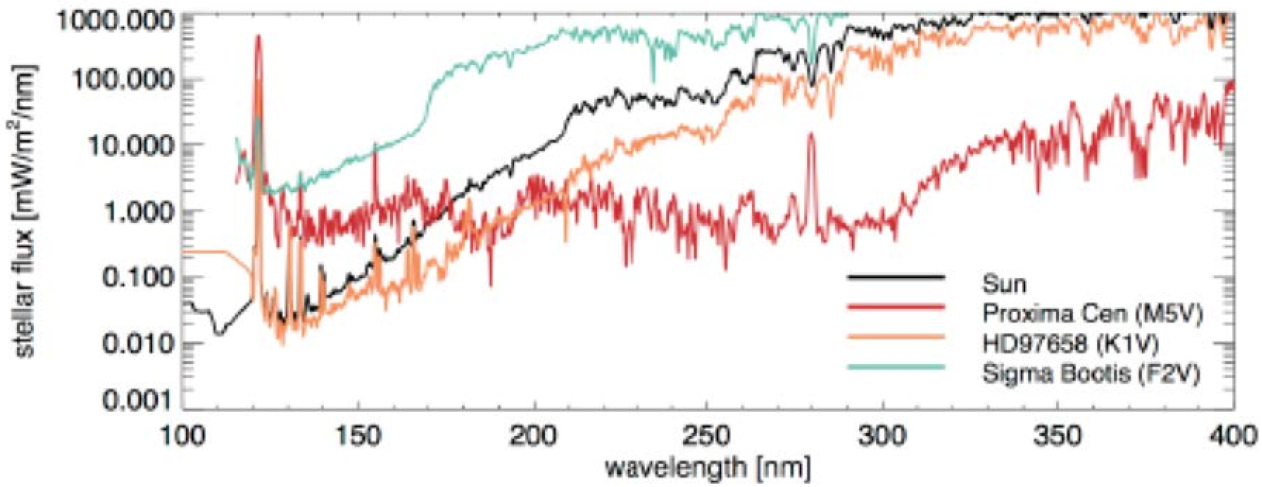
- Sobolev with Exact Integration (SEI, Lamers et al. 1987) modeling of the outflowing winds
- Although the 2 stars have ~same T_{eff} and L class, μ Gem has weaker wind and chromosphere —> μ Gem could be more evolved than γ Cru.

NUV and FUV characterization of host stars is vital to studies of exoplanet habitability, particularly for K and M dwarfs

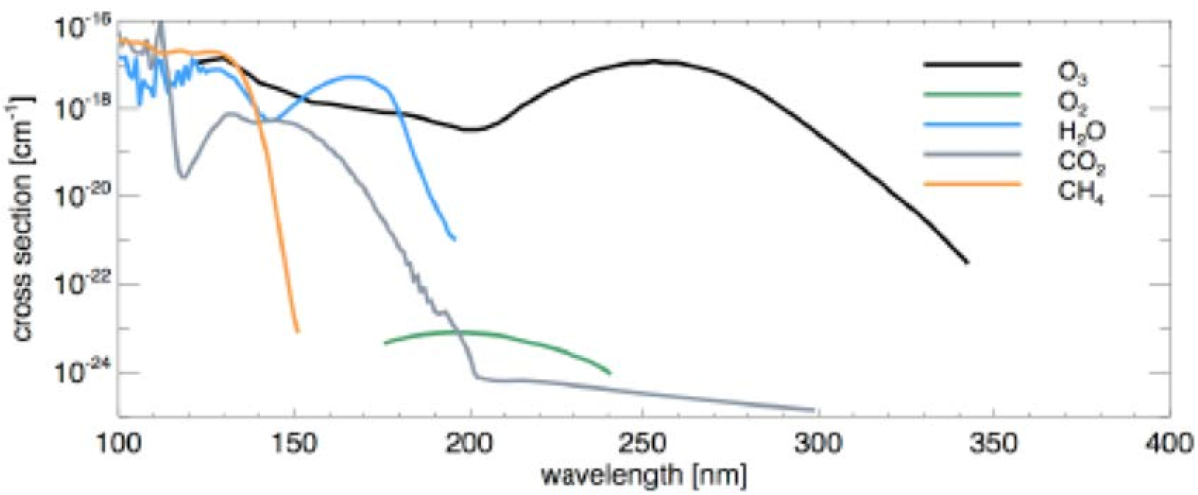


Panchromatic spectrum of GJ 832, illustrating the influence of each spectral bandpass on an Earth-like planet orbiting this star [France et al. 2016]. GJ 832 has a super-Earth mass planet located in the HZ [Wittenmyer et al. 2014].

UV Spectra are key to understanding exoplanet atmospheres and potential habitability



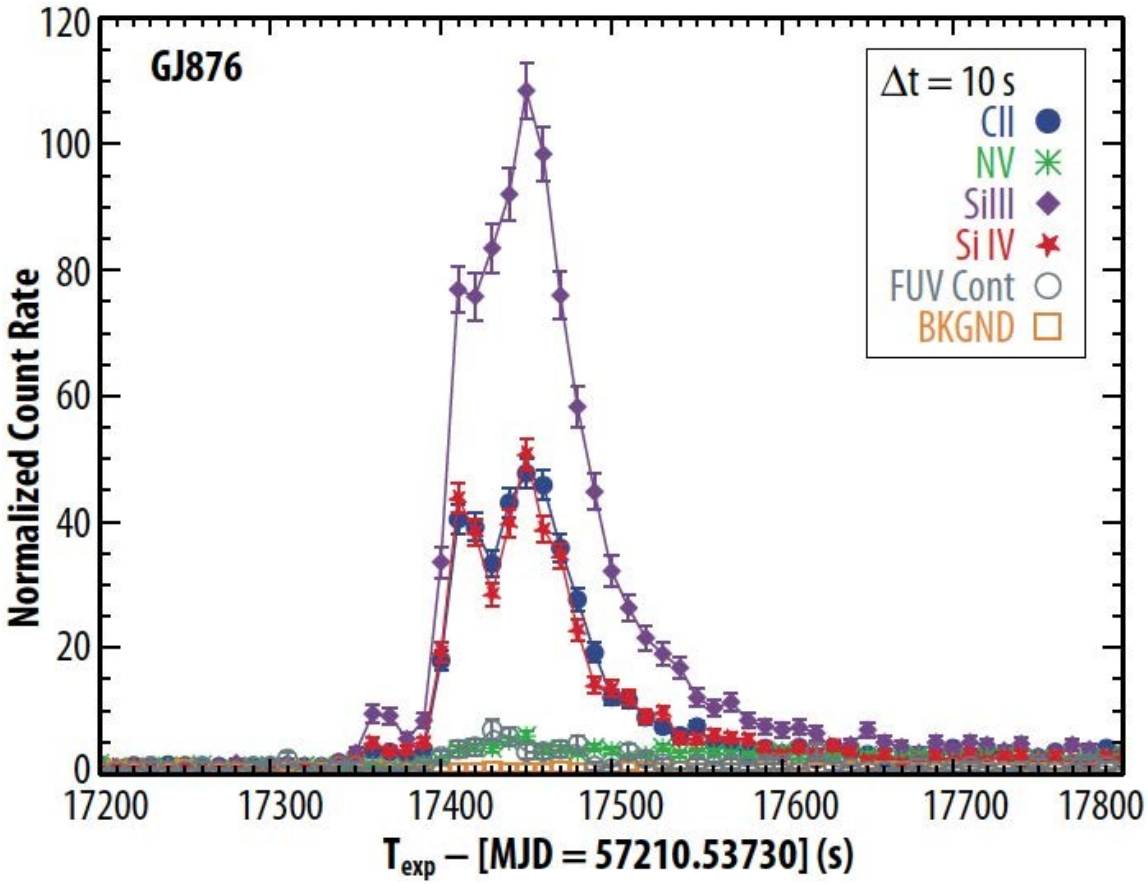
UV spectra of the Sun, Proxima Centauri, a K1V dwarf, and a F2V dwarf.



UV absorption cross-sections for key gases.

Atmospheric photochemistry of exoplanets is effectively controlled by the product of the stellar UV and molecular absorption cross-sections. Credit: G. Arney (NASA GSFC) / Proxima Cen: Meadows et al. (2018); HD97658: France et al. (2016), Youngblood et al. (2016), Loyd et al. (2016); Sigma Bootis: Segura et al. (2003), adapted from the LUVOIR Final Report.

Example of UV flux enhancement during a flare



A strong UV flux enhancement is observed on the “optically inactive” M dwarf GJ 876 [France et al. 2016]. The peak flare/quiescent flux ratio for the Si2+ ion is ~110, making this one of the most extreme disk-integrated UV flares ever detected. These types of flares, which occur roughly twice a day on GJ 876, have the equivalent X-ray output of an X40 class solar flare, and are associated with high-energy proton fluxes higher than 2000 protons cm-2 s-1 sr-1 [Youngblood et al. 2017].

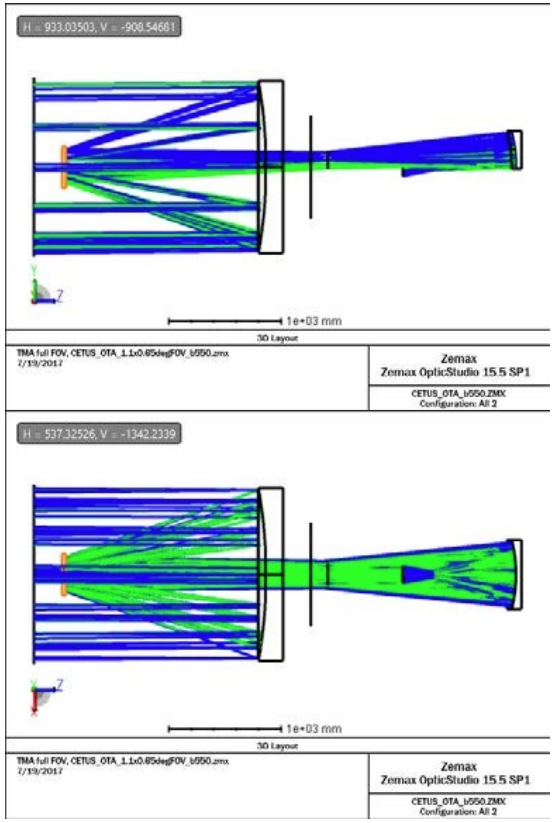
Implementation

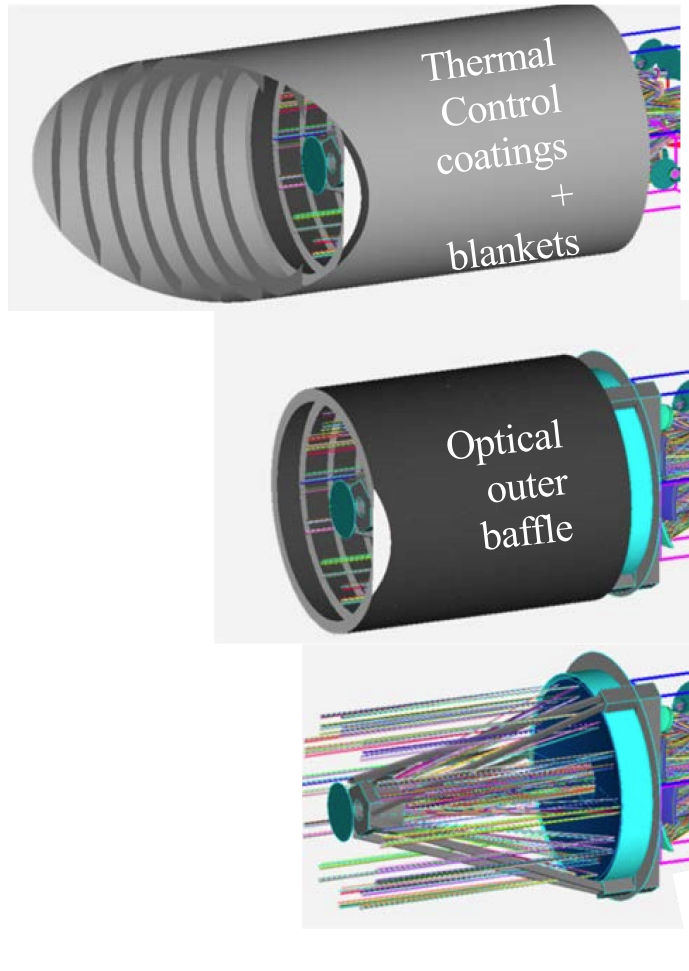
- Only a single point design was developed during the Probe study
- No time & funds were available to optimize the science and concept design to fit into a particular cost bucket

CETUS Implementation Satisfies Science Objectives

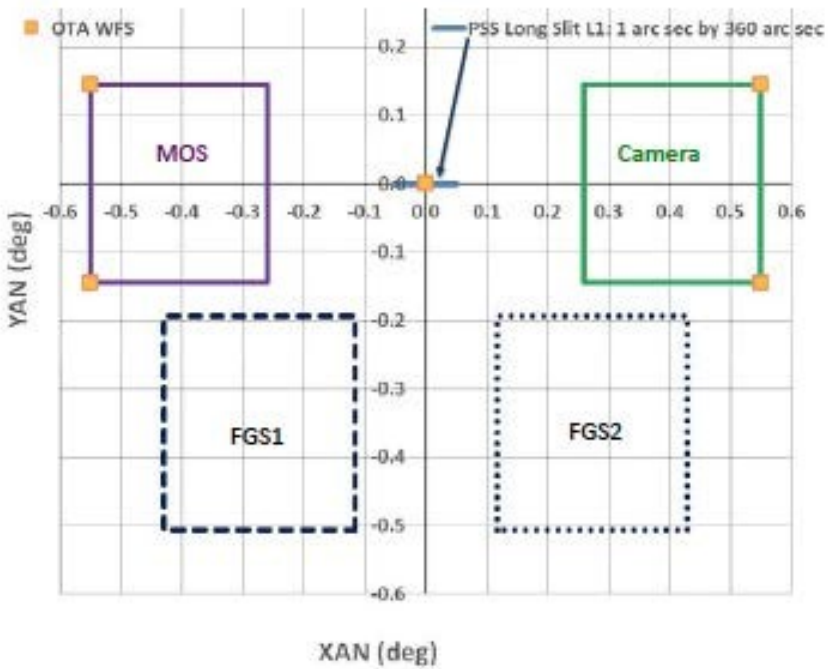
	Objectives	2.1 Understanding the evolution of galaxies, stars, planets			2.2 The Modern Universe		2.3 Transients; 2.4 Surveys: CETUS prime, Multi-Telescope		
Science	Principal Targets	z~1 galaxies	Primitive stars	M-star Flares	Galaxies & Outskirts	The CGM	UV Surveys	Rapid Transients	Multi-λ surveys
	Measurement Types	Spectral lines	Spectral lines	Emission lines, continuum	Spectral lines, continuum	Spectral lines	Spectral lines	UV light curves	UV SED
	Observations by Prime Science Instrument	NUV MOS	NUV SPEC	NUV, FUV SPEC	FUV SPEC, FUV CAM	FUV SPEC	FUV SPEC	VARIOUS	NUV. FUV CAM
OTA/Obs	Aperture diameter 1.5 m	✓	✓	✓	✓	✓	✓	✓	✓
	Mirror coatings Al/LiF/MgF_2				✓	✓			
	λλ 100-1000 nm (>400 nm for guider only)				✓	✓			
	FoR > anti-solar hemisphere							✓	
	Pointing stability 64 mas 1σ							✓	
	Slew time < 15 min for 180 deg							✓	
	Parallel Operation of SI's	✓	✓	✓	✓	✓	✓	✓	✓
NUV MOS	λλ 180-350 nm; RP ~ 1000@300 nm; MSA ~ 190x380 shutters; Shutter=100x200 micron (2.75" x 5.50"); FOV=17.4' x 17.4'	✓							
FUV SPEC	λλ 100-180 nm; Slit 0.2" x 3"; RP~20,000			✓	✓	✓	✓	✓	
	Slit-LS 2" x 360"; RP~2000 (ext. sources)				✓	✓	✓	✓	
NUV SPEC	λλ 180-350nm; Slit 0.2"x3"; RP 40000 @ 300 nm		✓	✓	✓			✓	
FUV CAM	λλ 115-180 nm; 5 long-pass filters; FOV 17.4' x 17.4'; Res 0.55" (22 mm); Sub-pix sampling	✓			✓			✓	✓
NUV CAM	λλ 180-400 nm; 5 filters; FOV 17.4'x17.4'; Res 0.33" (12 mm); Sub-pix sampling	✓						✓	✓

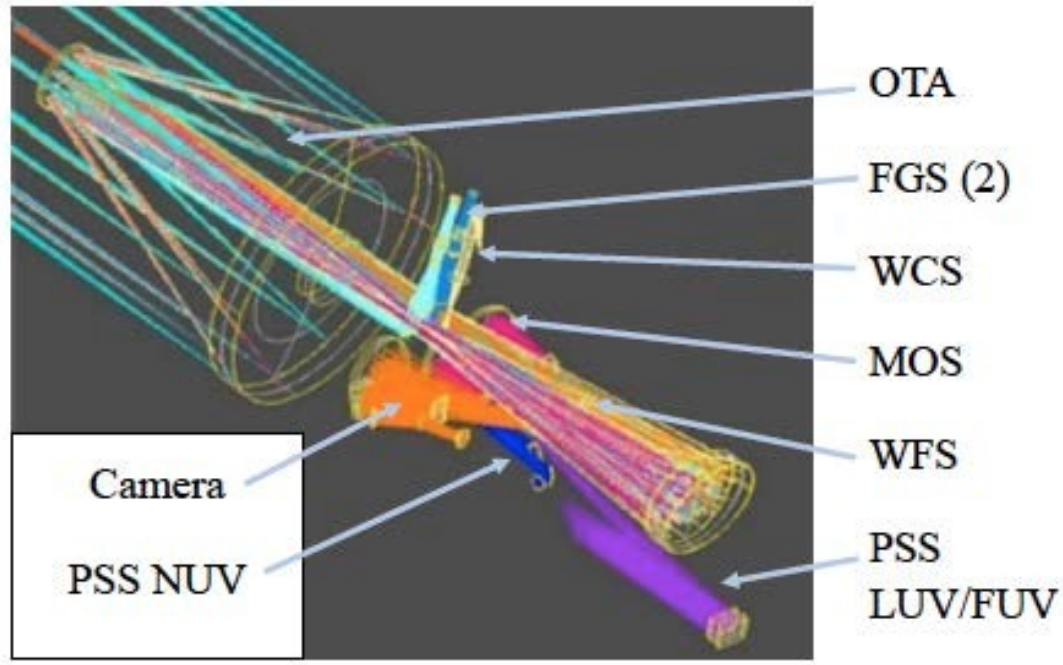
CETUS 1.5-m Wide Field-of-View Three-Mirror Anastigmat Telescope



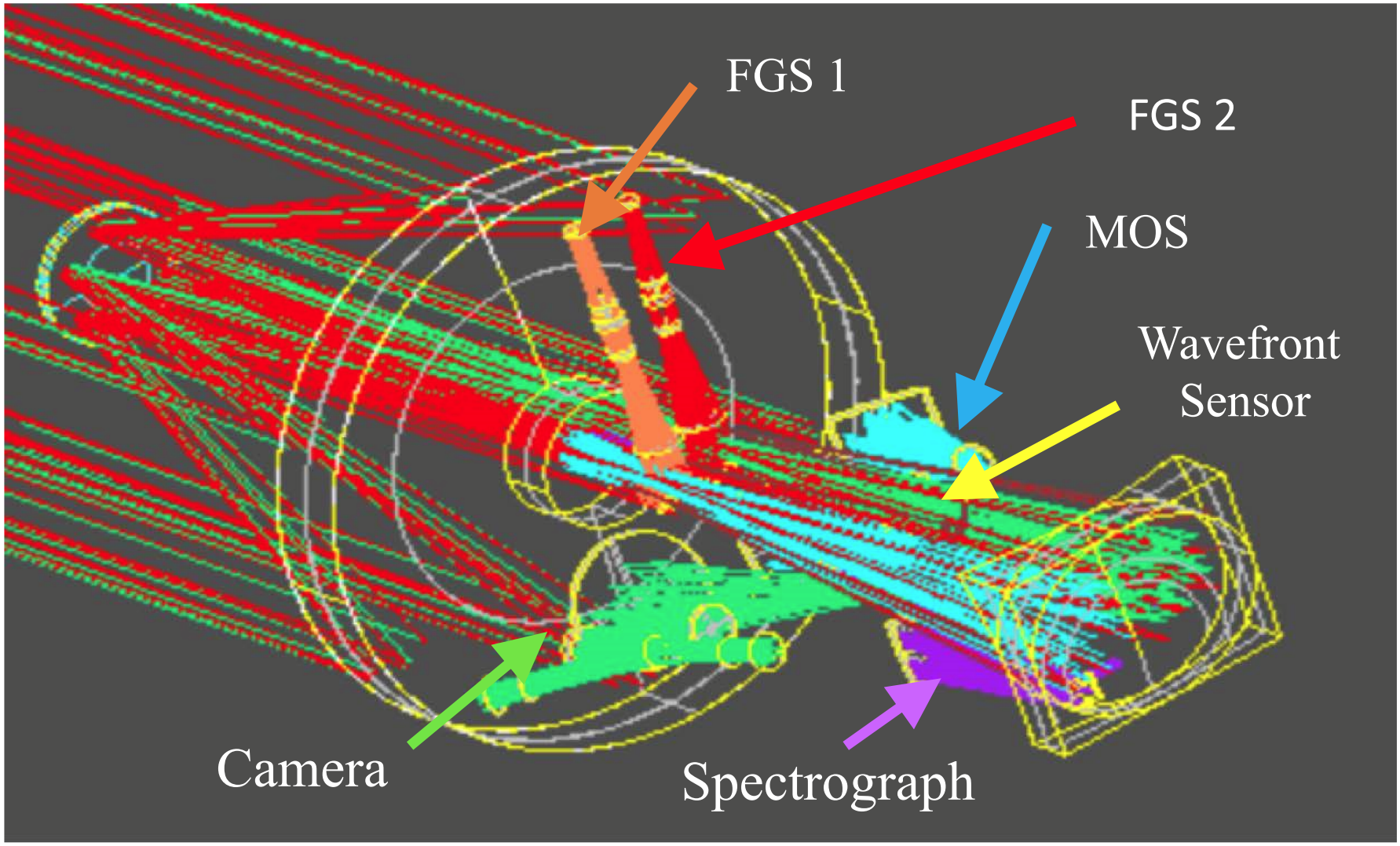


Shared-splitting of CETUS OTA Field-of-View Allows Simultaneous Operation of the Three Instruments





Ray Trace View of Instruments

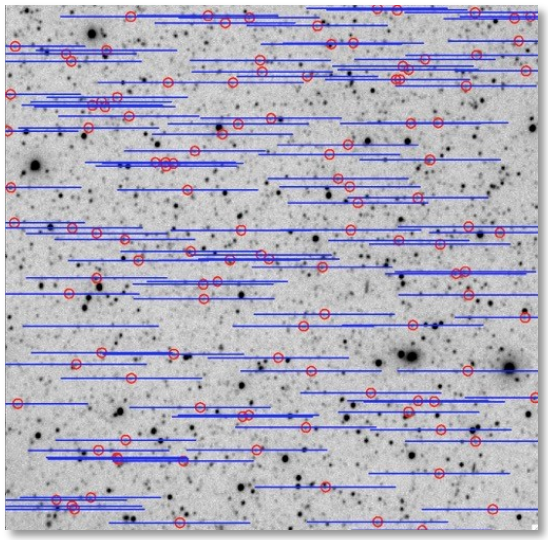


Trade Studies

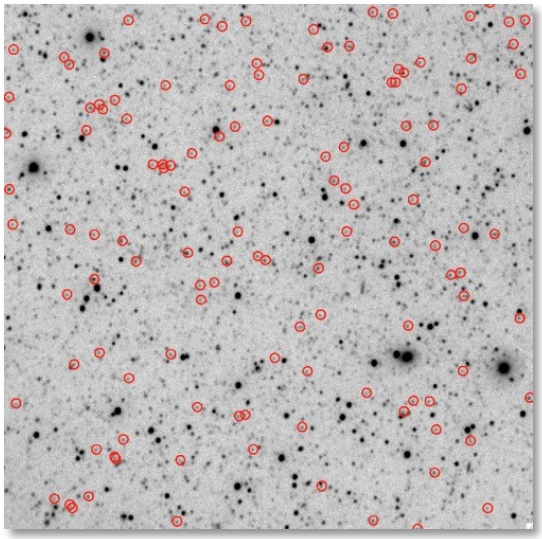
Trade	Design Choices	Rationale
Layout of Science Instruments	JWST – Integrated science module	
	CETUS -- Modular	Potential cost savings on AI&T
A-Omega of wide-field instruments (Cam & MOS)	D=1.5 m	For faint objects
	FOV = 17.4' x 17.4'	FOV of MOS to include ~100 z~1 galaxies
Resolution: 1=pixel vs. diffraction-limit Res.	0.40'' -- CETUS	Relaxes optical error budget & ACS error budget
	0.04'' -- Diffraction Limited	Requires an array of CCDs to cover wide field
Sampling & Dithering	Some observatories use many observations	
	Others require precise changes in telescope pointing	
	CETUS – Tip/Tilt/Focus mechanism on grating	Low cost, enhancement in productivity
Telescope & PSS mirror coatings	HST – Al/MgF2	
	FUSE – Al/LiF	
	CETUS – Al/LiF/MgF2 (ALD overcoat)	Protection from humidity – lowers cost
Rapid Response	No – CETUS for surveys and normal pointed observations	
	Yes – for important transient events Core-Collapse SN, neutron star mergers	Needed only if ASTRO2020 does not recommend another observatory for this need

CETUS MOS and CAMERA Simultaneously Observe Adjacent Fields

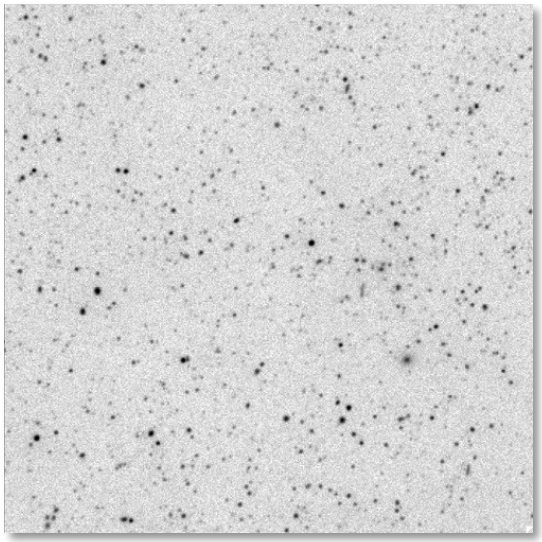
CETUS MOS



CETUS CAMERA



NUV



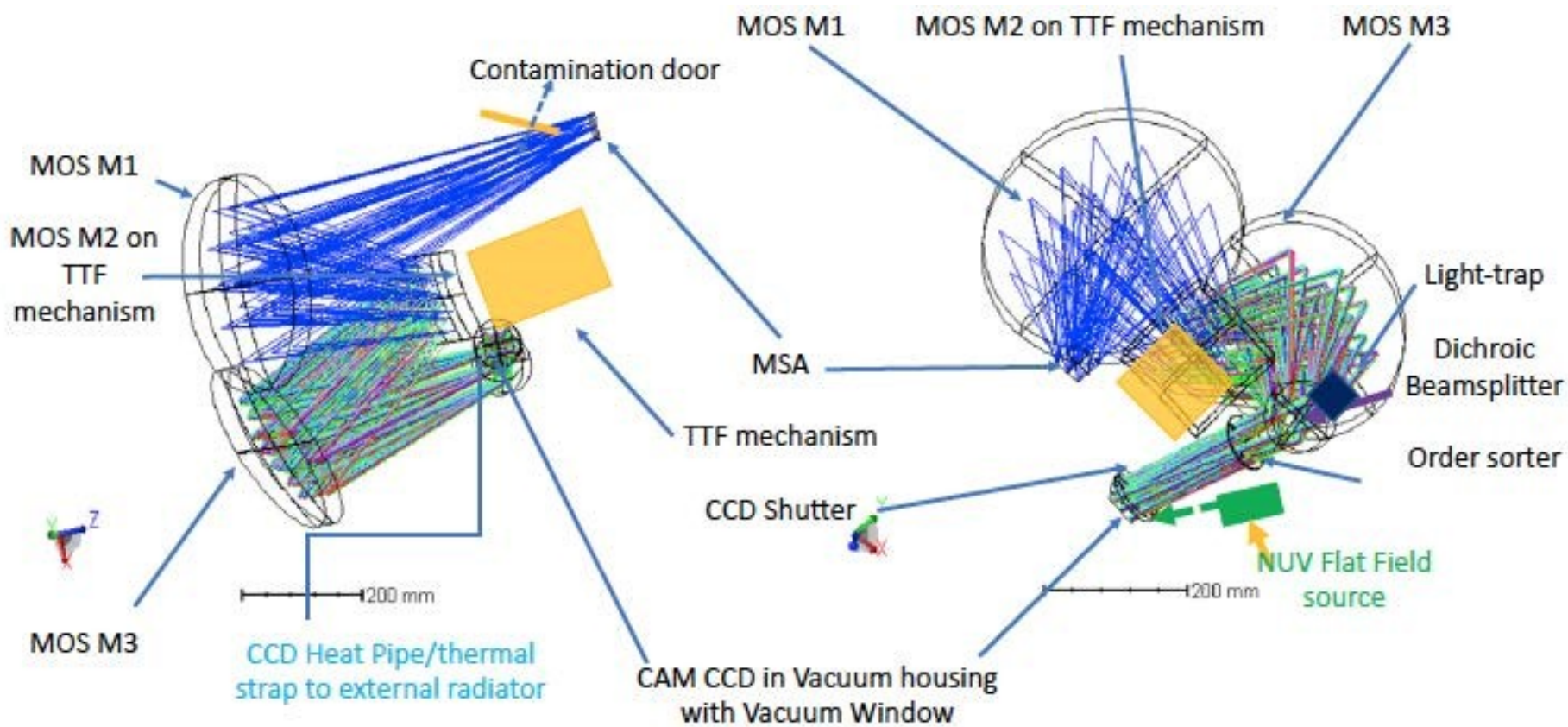
FUV

Each survey observation produces:

- one NUV spectrogram with ~100 spectra
- a NUV image } of an adjacent field
- a FUV image

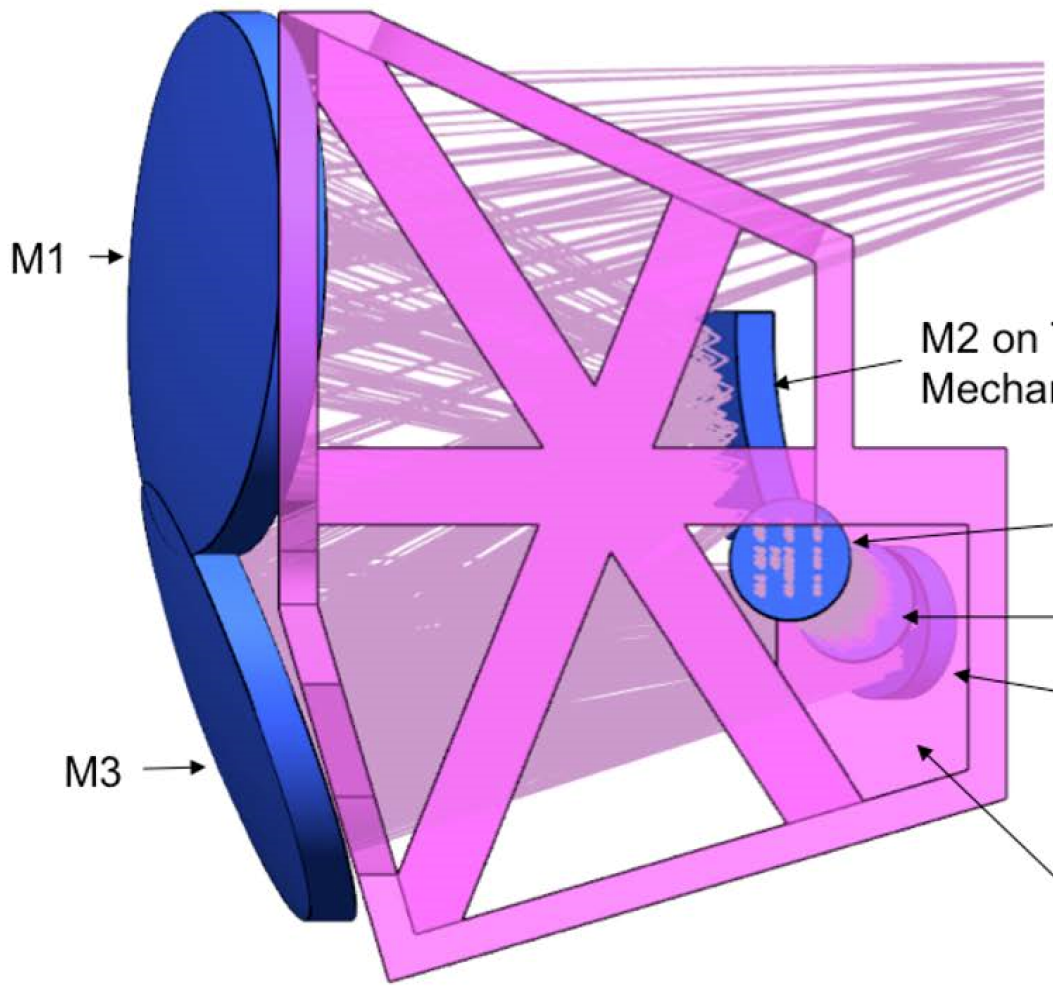
Each image is 1045” on a side

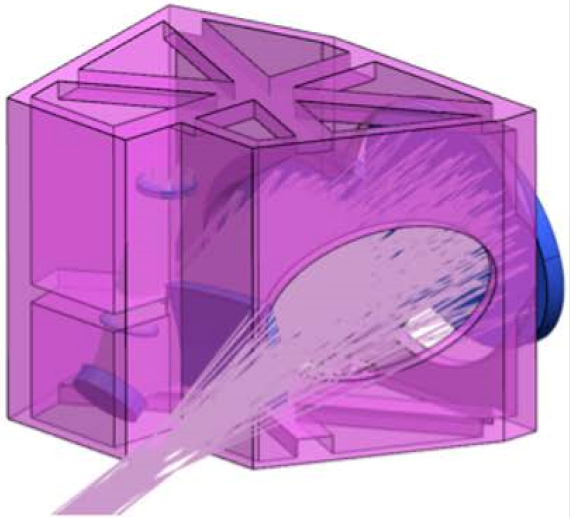
The Multi-Object Spectrograph (MOS)



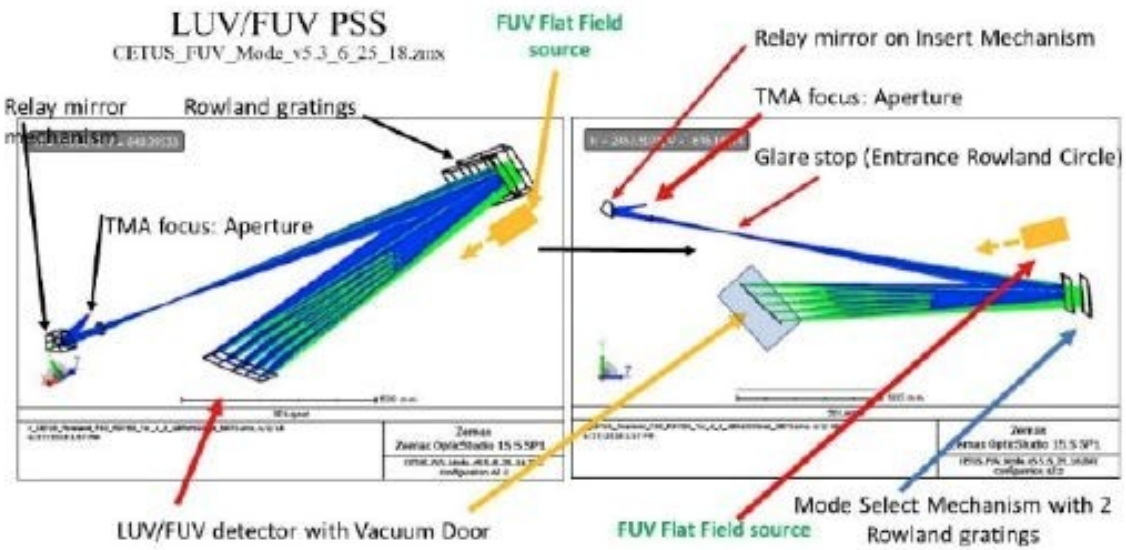
CETUS Multi Object Spectrograph Packaged

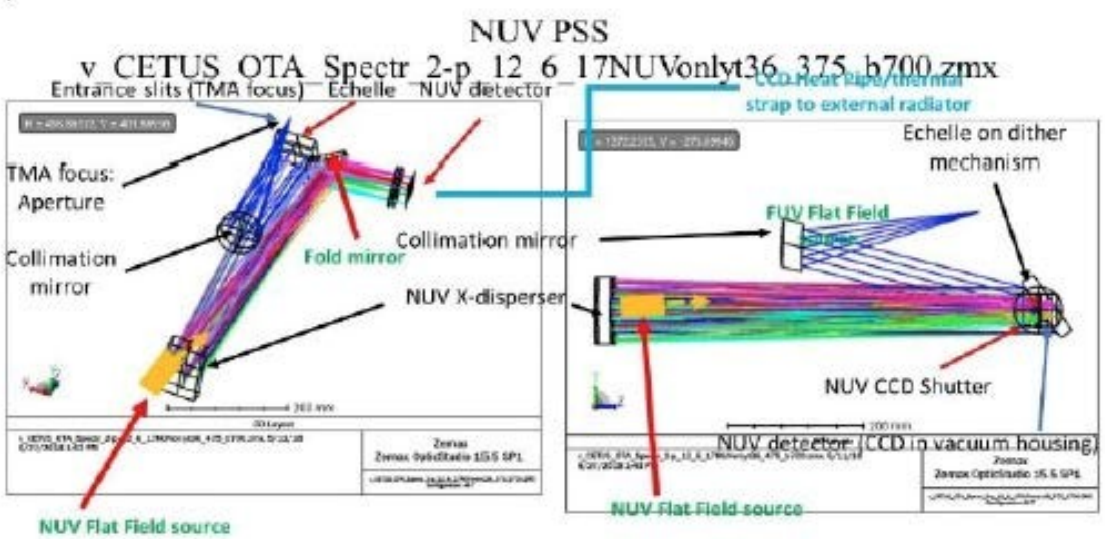
- Overall Size 25.3” X 19” X 18”





The CETUS LUV/FUV and NUV Spectrographs

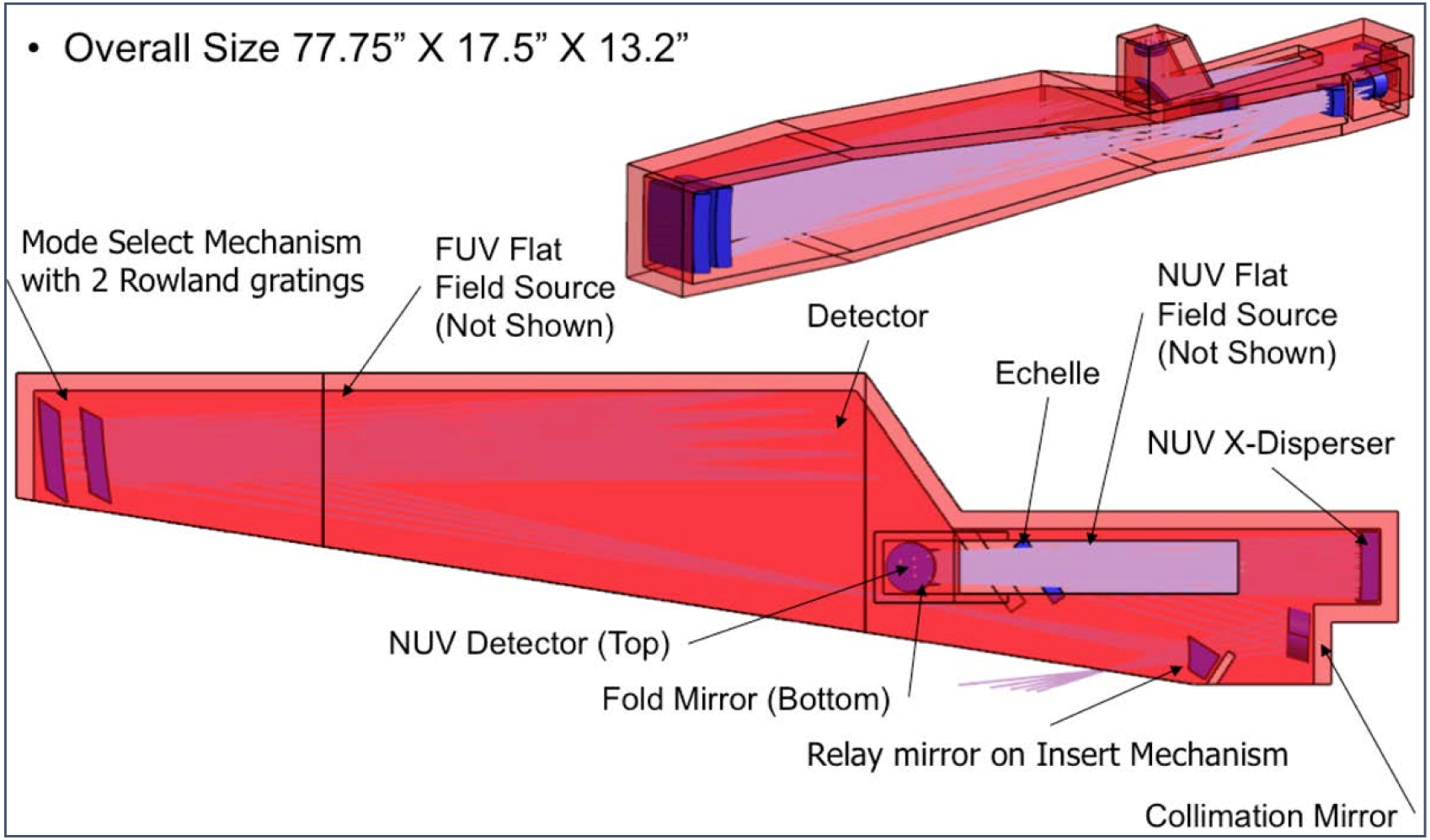




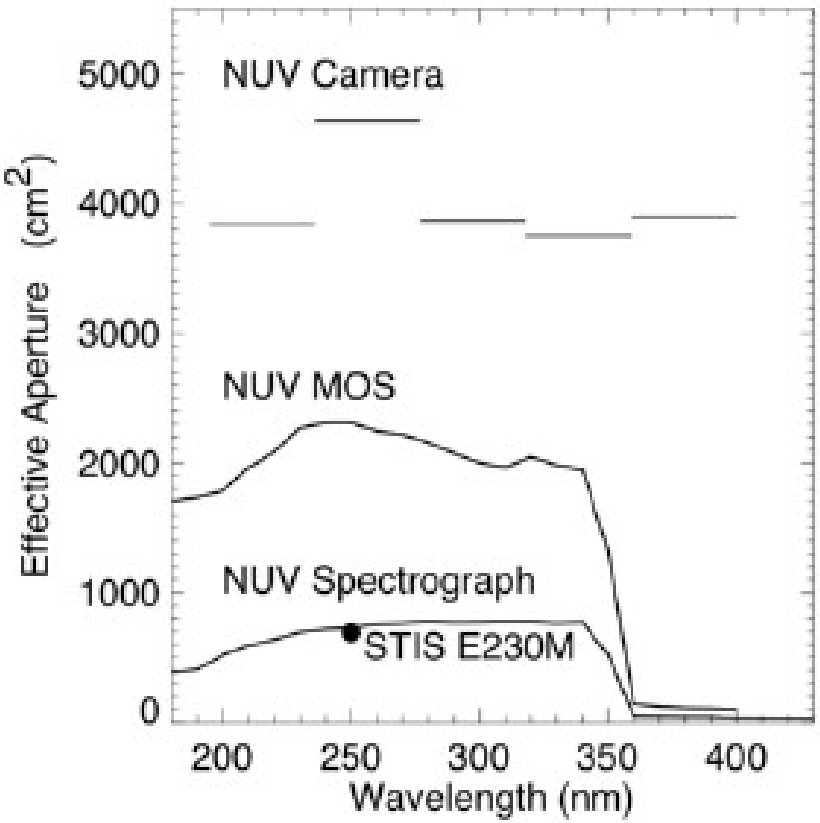
Upper diagram: The Lyman UV / Far-UV Spectrograph is a Rowland grating spectrograph.

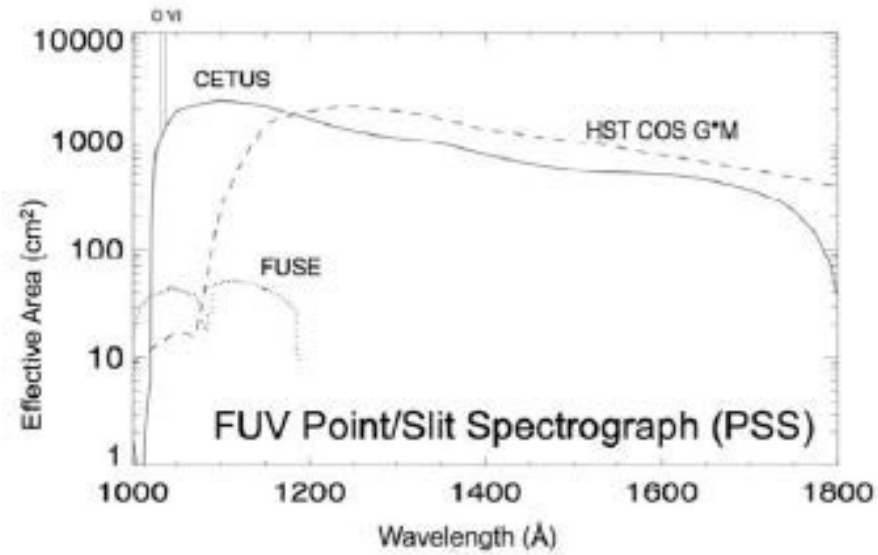
Lower Diagram: The Near UV Spectrograph is a Czerny-Turner configuration.

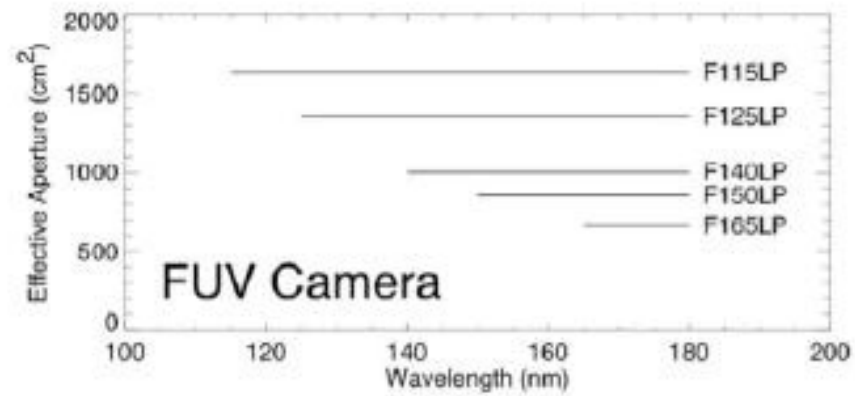
Packaged View of CETUS LUV/FUV/NUV Spectrograph



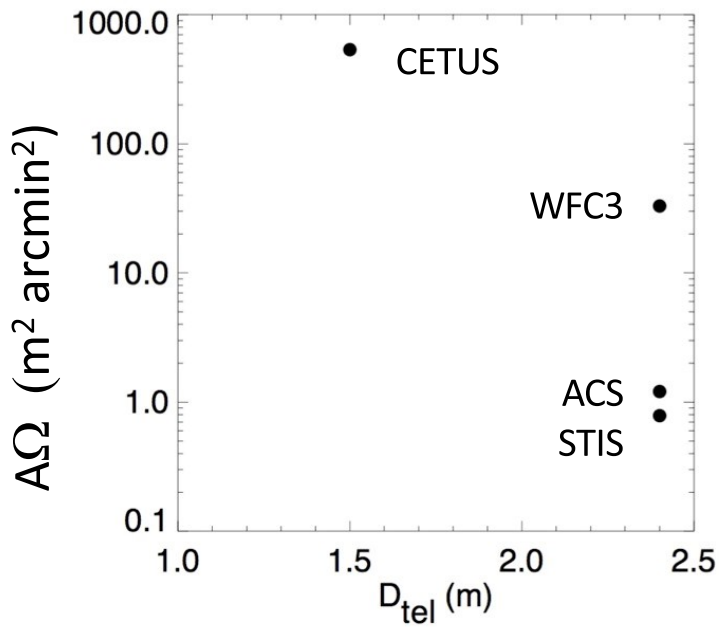
Effective Area of CETUS Compared to Hubble Instruments

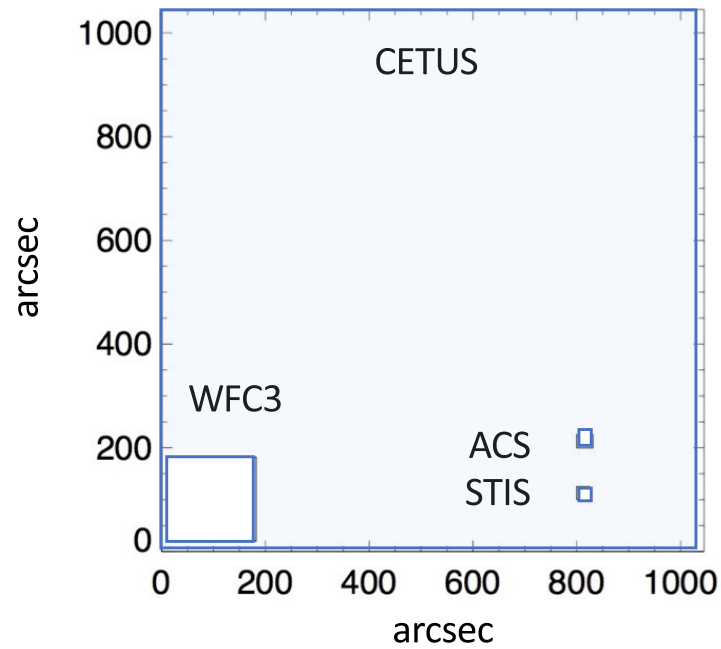




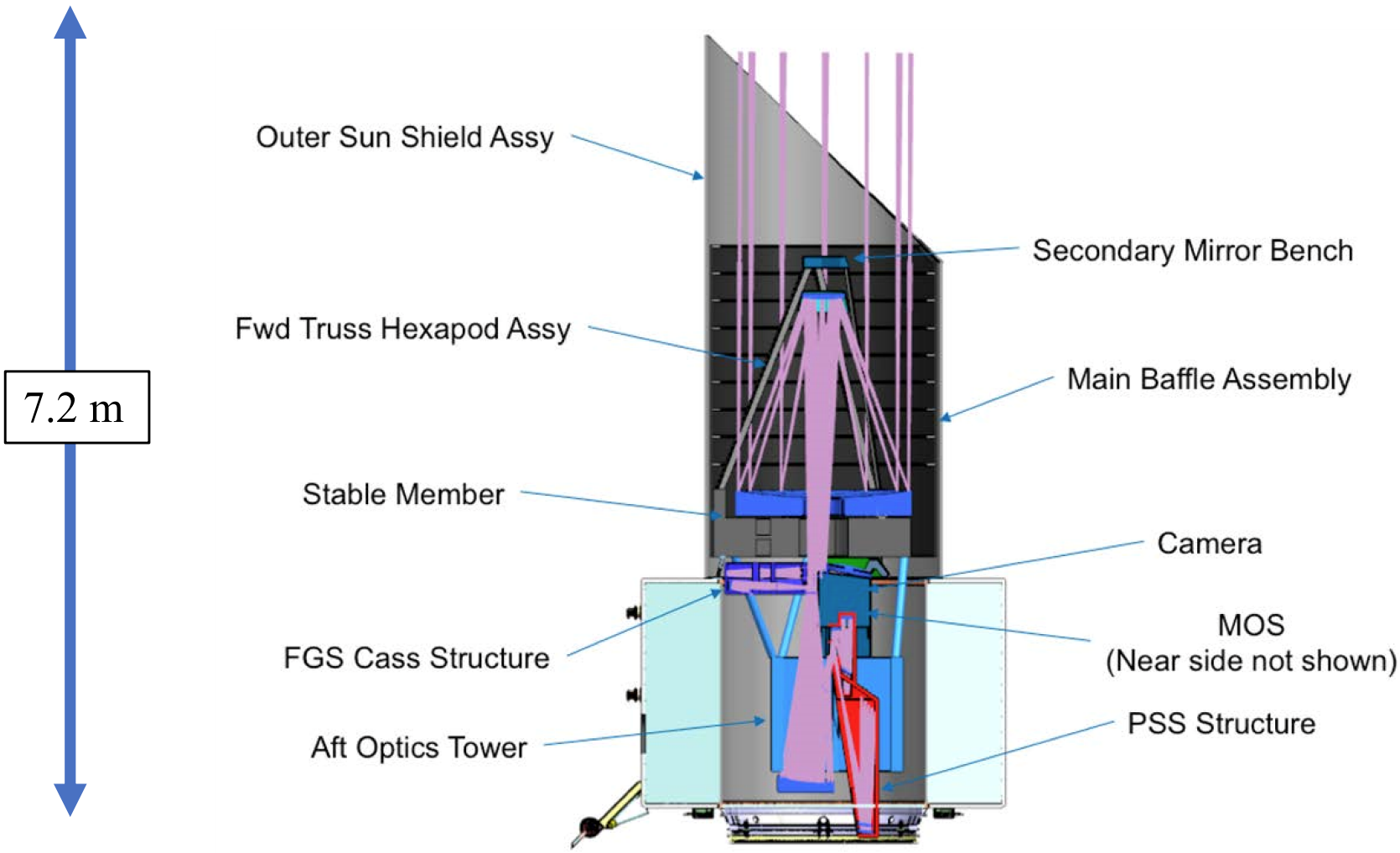


CETUS easily outscores Hubble's UV cameras in the figure of merit, A*Omega = Aperture x FOV



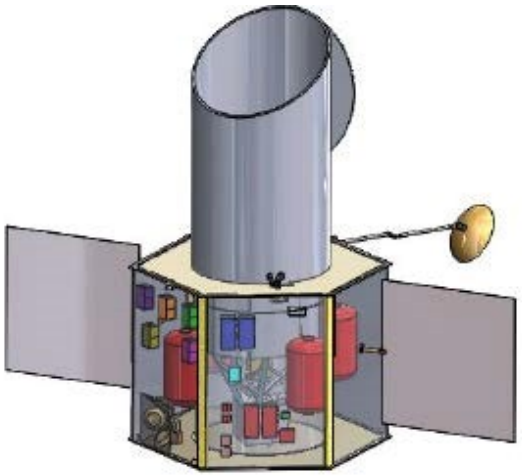


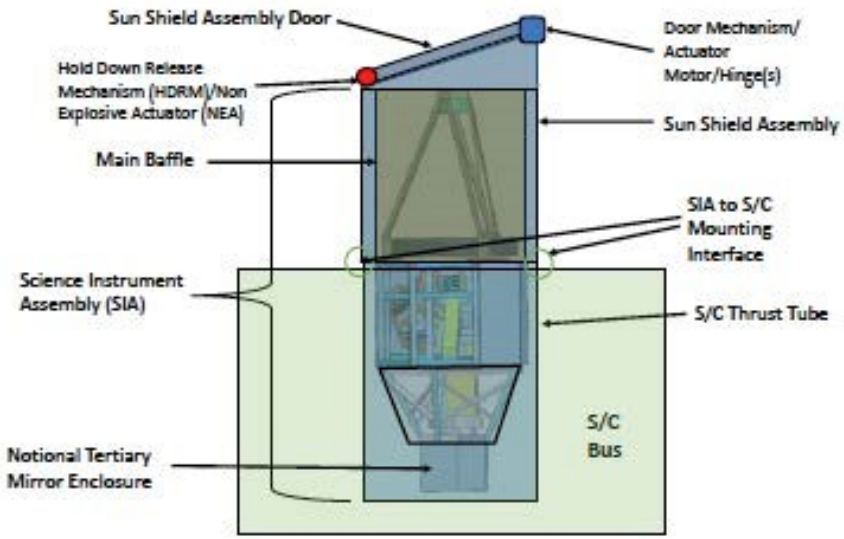
Side View of CETUS w/ Packaging of Instruments



Key Features of CETUS mission design rationale

CETUS Mission Feature	Rationale
Orbit about the Sun-Earth L2	• ~2 π steradians of sky visible at any one time • 4 π steradians visible over any 12 month period • Relatively easy to reach and maintain orbit • Reasonable cost of communications • Thermally benign with Sun/Earth light always from roughly the same relative direction
5-year mission design life with consumables for 10 years	• Longest mission duration that avoids significantly more expensive design
Dual wing solar arrays (SAs) with single axis articulation	• Supports Field of Regard (FOR) over 2 π steradians of sky • Keeps Cp near Cg, minimizing rate of momentum buildup
Oversized Reaction Wheel Assemblies (RWA's)	• Slew to view any transient in FOR within 15 minutes after commanded
Two-axis articulated High Gain Antenna (HGA)	• Can communicate with ground at high data rates while CETUS is observing anywhere in FOR
On-board Celestial Navigation for onboard Orbit Determination	• Eliminates costs of tracking by ground system
Near-Earth Network Ground System	• Adequate performance and less expensive than Deep Space Network
Recoverable Falcon 9 Launch Vehicle	• Adequate and proven performance, adequate fairing size, low price

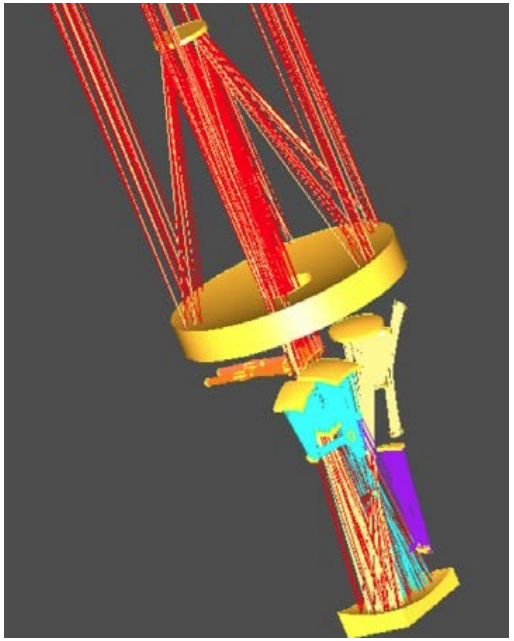


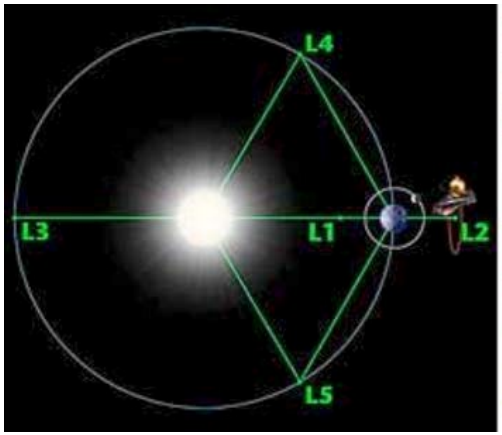


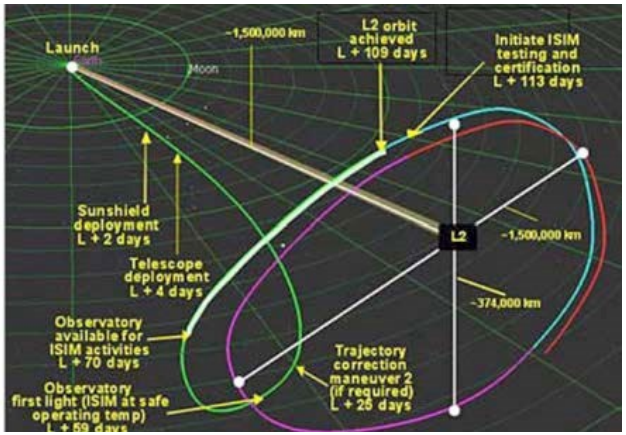
Note: The bus is essentially the same as the commercial LEOstar-3 bus from NGIS used on other NASA missions.

CETUS Systems: Mission Overview

- Probe Class (Class B)
- Instrument envelope: ~5 m long and ~2 m in diameter
- Instrument mass and power ~1084 kg and ~1200 W
- Operating temperature environment ~293 K
- Science Data Downlink: ~27 Gbit/day
- Command uplink: Anytime to initiate a slew and quickly observe a transient event
- Instrument slew speed ~180 degrees in less than 15 minutes
- Instrument pointing accuracy: ~0.1 arcsec
- Mission Life: 5 Years
- Mission orbit: L2, similar to JWST
- Instruments: FUV/NUV Camera, UV Spectrograph, MOS
- Objectives: Obtain >10^5 spectra of galaxies (z=0.8 – 1.3)
  With SNR > 7
- Launch vehicle: Falcon 9 (Appx. 3400 kg payload mass capability)



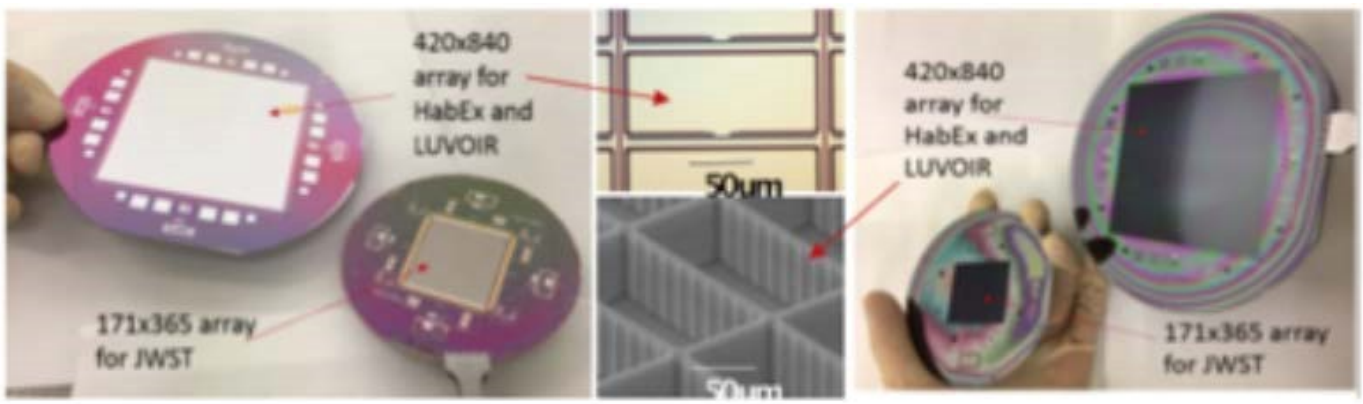




Technologies

Microshutter Technology Development

Technology	Heritage/ Comments
Next-Generation Micro-Shutter array • 380x190 shutters baselined • With 100x200 micrometer rectangular shutters	• JWST NIRSpec MSA space qualified with 365x172 array with 100x200 micrometer shutters [TRL 8 which will be baseline if NGMSA not TRL 6 at Phase A] • NG MSA pilot demonstrated with 128x64 array so current TRL is 3-4; NASA/JHU sounding rocket experiment with MSA planned for July 2019. • GSFC currently has 3-year SAT grant which is maturing NGMSA to TRL 5 by 2021 and developing 840x420 array for LUVOIR and HabEx (scale-up applicable to CETUS - though CETUS can accept an even smaller, simpler design).



NGMSA 840x420 and JWST arrays size comparison: front (left) and back (right) side of array.

A pilot design NG-MSA array with 128x64 shutters on a PC board with integrated drivers has been fabricated.

Detectors – FUV MCPs

Technology	Heritage/ Comments
Micro channel Plate (MCP) detectors with high quantum efficiency in the FUV	• The CETUS FUV MCP detectors made by U.C. Berkeley Space Sciences Lab are the same technology as flown on the Hubble COS spectrograph. • CETUS FUV Camera MCP uses CsI photocathode (~50x50mm) with MgF2 window – TRL 6+ • CETUS PSS FUV MCP uses CsI photocathode (200x70 mm) windowless - a 200x200mm MCP has recently flown on a University of Colorado rocket experiment. CsI in windowless MCP detectors have flown many times – this is just a scale-up requirement • Sounding rocket programs have and continue to provide verification of comparable MCPs – CU's DEUCE (2017, 2018) and NASA/JHU.

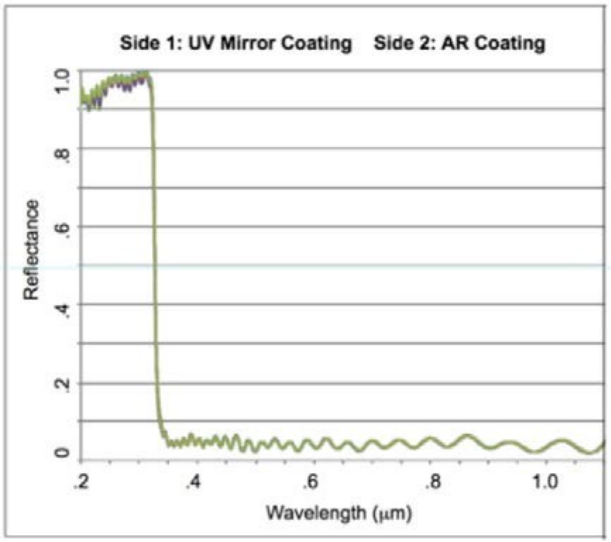
	FUV CETUS MCP	FUV HST/COS MCP
Detector type	XS (cross-strip), CsI photocathode	XDL, CsI photocathode
Spatial resolution	20 micron FWHM	35 micron FWHM (dispersion); 65-550 micron FWHM (X-disp)
Low gain operation	10^6	10^7
Higher dynamic range	Multi-MHz rates	60,000 global count-rate limit
Ultra low MCP background	<0.05 event/sec/cm^2	<1 event/s/cm^2
High UV QE	50% @115nm, 30%@200 nm	26% @ 133 nm, 12% @ 156 nm
Solar-blind cutoff	~350 nm	> 239 nm
Long stable lifetimes	>4x10^{13} events/cm^2	4 lifetime positions due to gain sag
Format size	up to 200 mm x 200 mm; no gaps	2x85mm x 12 mm; 9-mm gap

NUV Detectors:

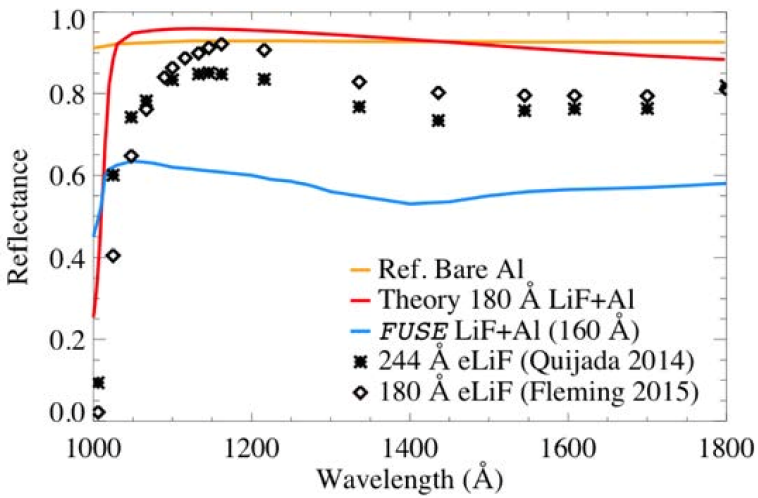
- Originally considered using e2v CCD 43 with high TRL
- Newer CCDs, better for CETUS – CCD 273-84, 4K x 4K with 12 micron pixels were developed by Euclid and space qualified.
- Recently, CCD 272, a variant of the above CCD was developed for the Solar UV Imaging Telescope (SUIT), optimized for UV.
- Delta-doped detectors also a possibility.

High Reflectivity Coatings

Technology	Heritage/ Comments
High UV-reflectivity coatings on mirrors	• Telescope optics – LiF coatings from 100 nm+ are the baseline at TRL9 (Copernicus, FUSE). Potential future option of more robust LiF coating which is protected by thin ALD layer – SAT in-progress and another just awarded being monitored as protected Al/LiF coatings progress. Collins has large coating chamber planned which could be modified to apply ALD coating on CETUS OTA PM. • Optics in instruments requiring NUV & FUV coatings - Materion (Barr) and ZeCoat are proficient in making special multi-layer UV coatings at these wavelengths and applicable coatings have been demonstrated on small samples. Facilities exist for coating CETUS-size optics.



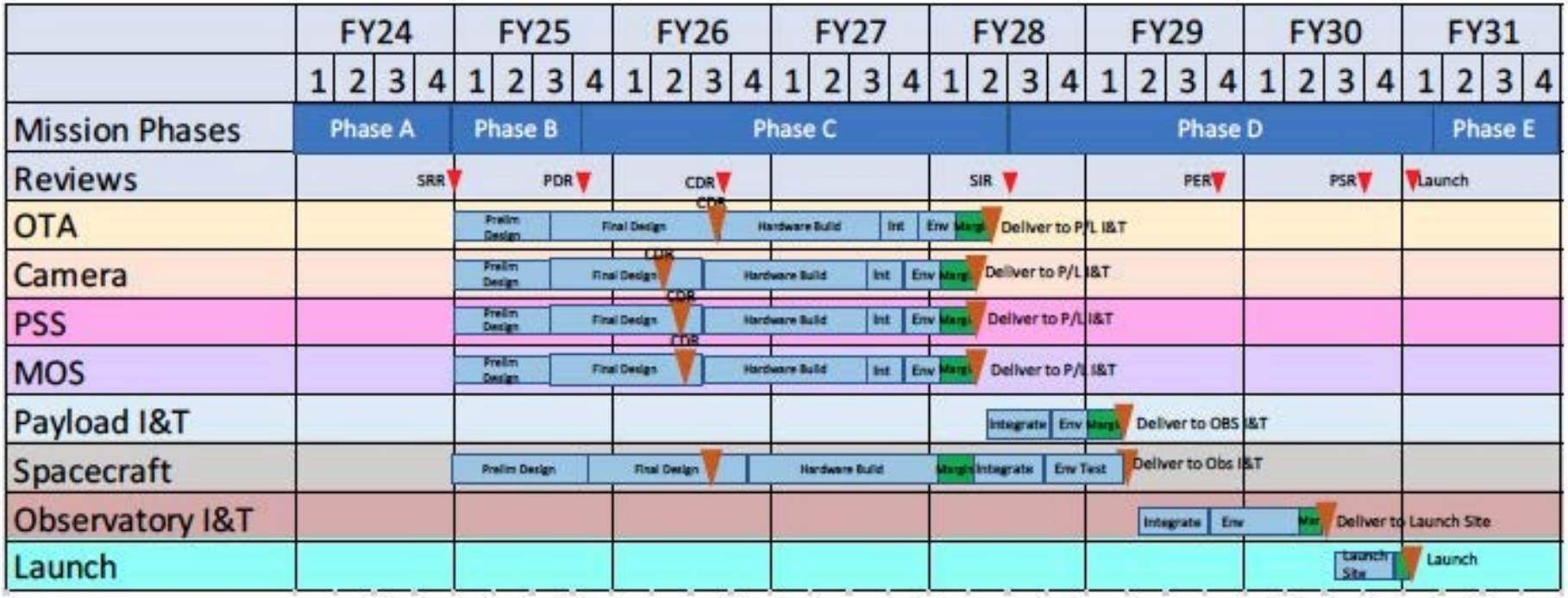
The coatings are designed to sharply reduce reflectance of light longer than 320nm. (Reflectance data adapted from MacKenty, J., 2016)



The theoretical reflectivity of LiF+Al coatings (red) relative to the best realized conventional coating (Blue). eLiF mirror coatings improve LiF+Al reflectivity to closer to the theoretical limit.

Schedule

CETUS instruments are developed, fabricated, and tested in parallel. Each has built in margin.



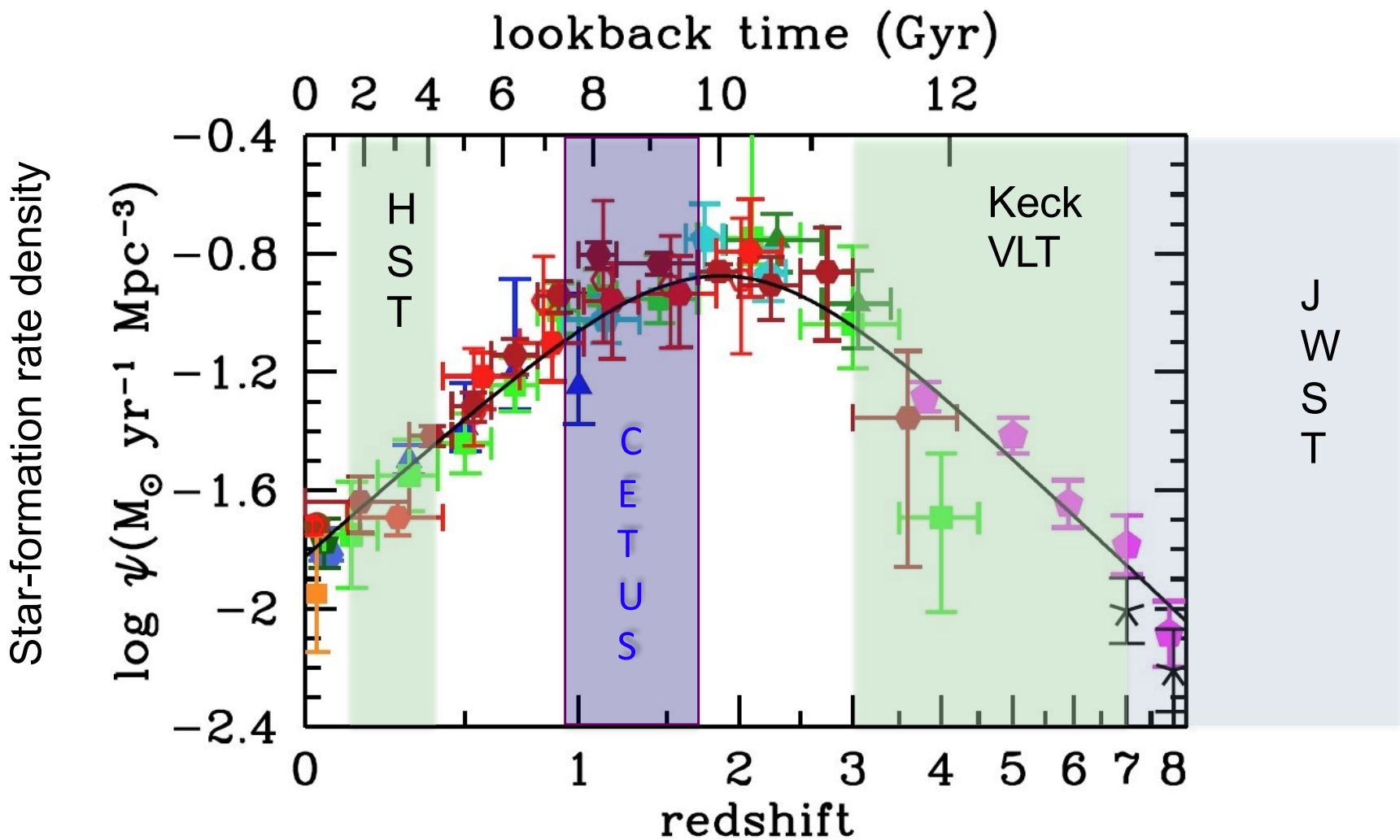
The three technologies currently being matured will be ready in time for a Phase A start at the beginning of FY20. Other programs/projects require these technologies in addition to CETUS, reducing technology risk.

CETUS Summary

- Fulfills Decadal 2010 desire for a broadly capable UV space telescope to follow HST
- Maintains access to UV for the gap between HST and LUVOIR or HabEx
- Broad Science Reach
  - Galaxy Evolution
  - Transient Events
  - Cosmic Origins, Stellar Astrophysics, and Exoplanet Science
- Wide FoV UV 3 mirror anastigmat telescope
  - NUV/FUV Camera
  - LUV/FUV/NUV Point Source Spectrograph -- actually also has a long slit mode (6 arcmin length)
  - NUV Multi-Object Spectrograph with new microshutter arrays (2nd generation)
- 2 PI steradian field of regard, slew in 15 minutes
- Five year mission lifetime, propellent for 10 years
- Efficient for surveys, ability to quickly observe transient events
- General purpose instruments with plenty of discovery potential
- High flight heritage of all instruments and spacecraft bus

Backup Slides

What is driving galaxy evolution in the critical era of z~1-2?



CETUS will fill the hole in rest far-UV coverage at z~1-2

Madau & Dickinson 2014

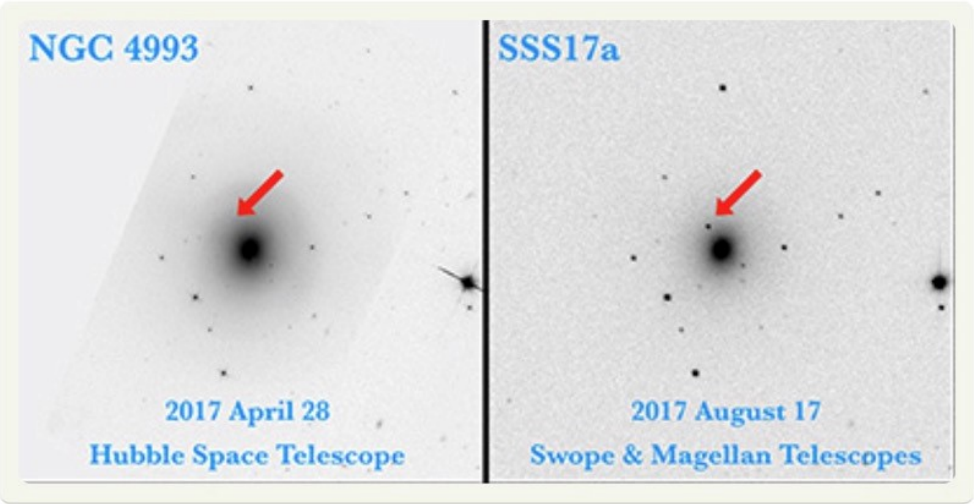
CETUS Spacecraft has appropriate margin for early stages of the conceptual study.

Requirement Description	Rqmt Value	Perf.	Margin	Comment
CETUS Observatory Wet Mass	3375 kg	2640 kg	22%	Falcon 9 capability to L2
CETUS SC Dry Mass	1252 kg	1074 kg	16%	Uncertainty based on status
S-Band Command UL using HGA w/ranging	2 kbps	2 kbps	18 dB	18m NEN GT and at L2
S-Band Telemetry DL using HGA w/ranging	2 kbps	2 kbps	14 dB	18m NEN GT and at L2
Ka-Band Wideband Downlink Using HGA to NEN	15 Mbps	15 Mbps	6.8 dB	18m NEN GT and at L2
Mission Delta V	102 m/s	102 m/s	NA	Fuel based on 3375 kg mass
Fuel	224 kg	272 kg	18%	Tank size margin
Slew and settle within 2p FOR	15 min	5 min	67%	Six RWAs
Jitter and Drift over 30min observation (1 sigma)	40mas	29mas	27%	Preliminary 1 axis analysis
SC Pointing Knowledge (1 sigma)	2 arcsec	1.5 arcsec	25%	2 for 3 star trackers
RWA Desaturation	7 days	TBD	TBD	Six RWAs
7 Days of Science Data Storage	183 Gb	512 Gb	180%	Flash Memory in PIE
Solar Array Size	2562 W	3290 W	22%	w/15% SC and 30% payload uncertainty

Transient Events

CETUS will observe important transient objects like the gravitational wave source in NGC 4993

Ramirez-Ruiz (UCSC) has calculated that a single neutron-star merger can generate an amount of gold equal to the mass of Jupiter. The team's calculations of heavy element production by SSS17a suggest that neutron star mergers can account for about half of all the elements heavier than iron in the universe.



The UCSC team found SSS17a by comparing a new image of the galaxy N4993 (right) with images taken four months earlier by the Hubble Space Telescope (left). (Image credits: Left, Hubble/STScI; Right, 1M2H Team/UC Santa Cruz & Carnegie Observatories/Ryan Foley)

Observing the aftermath of a merger of a neutron-star binary

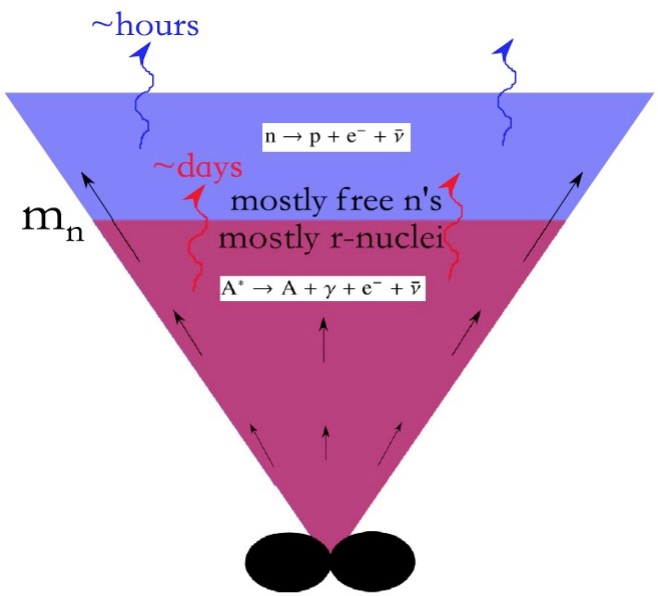
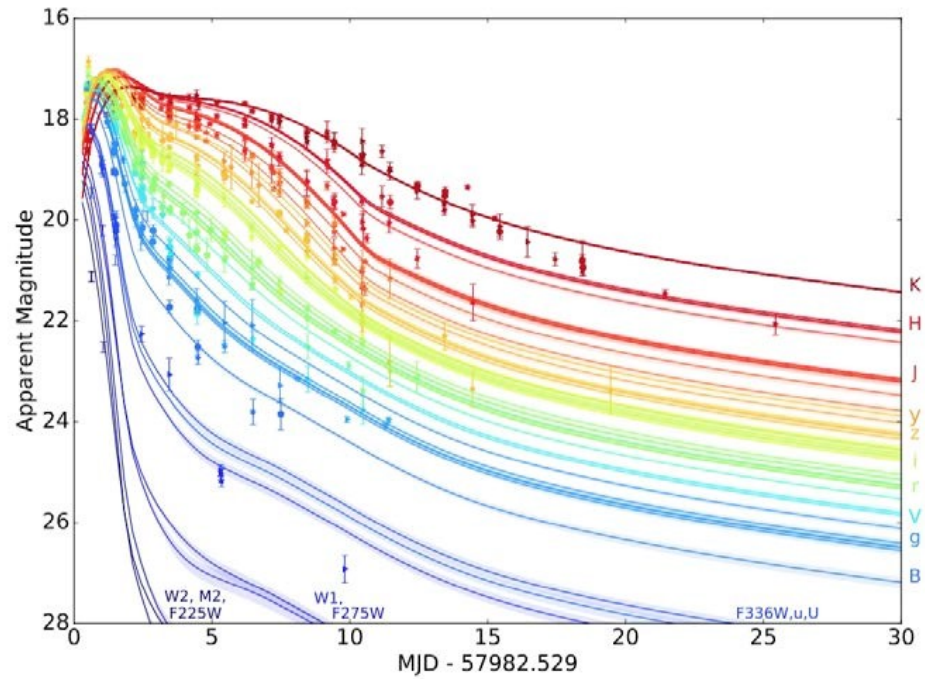


Figure 2. Schematic illustration of the ejecta from a binary NS merger leading to a neutron-powered precursor. Matter ejected from the shock-heated interface between the merging NSs expands outwards with a range of velocities $v(m) \propto m^{-\beta}$ (equation 4; Fig. 1) where $\beta \approx 3$. A small quantity of mass ejected first (mass coordinate $m < m_n \sim 10^{-4}\,M_\odot$; blue) expands sufficiently rapidly that neutrons avoid capture into nuclei, while for the bulk of the ejecta ($m > m_n$; maroon) neutrons are captured into nuclei during the r-process. Energy released by the decay of free neutrons escapes the outer layers over a short time-scale $t \lesssim$ hours, powering the precursor emission, which is relatively blue due to the high photosphere temperatures. Radioactive energy released by r-process nuclei throughout the bulk of the ejecta (including that ejected by tidal tails and disc winds) escapes over a longer time-scale $\sim$ days, with redder colours.

Metzger et al.

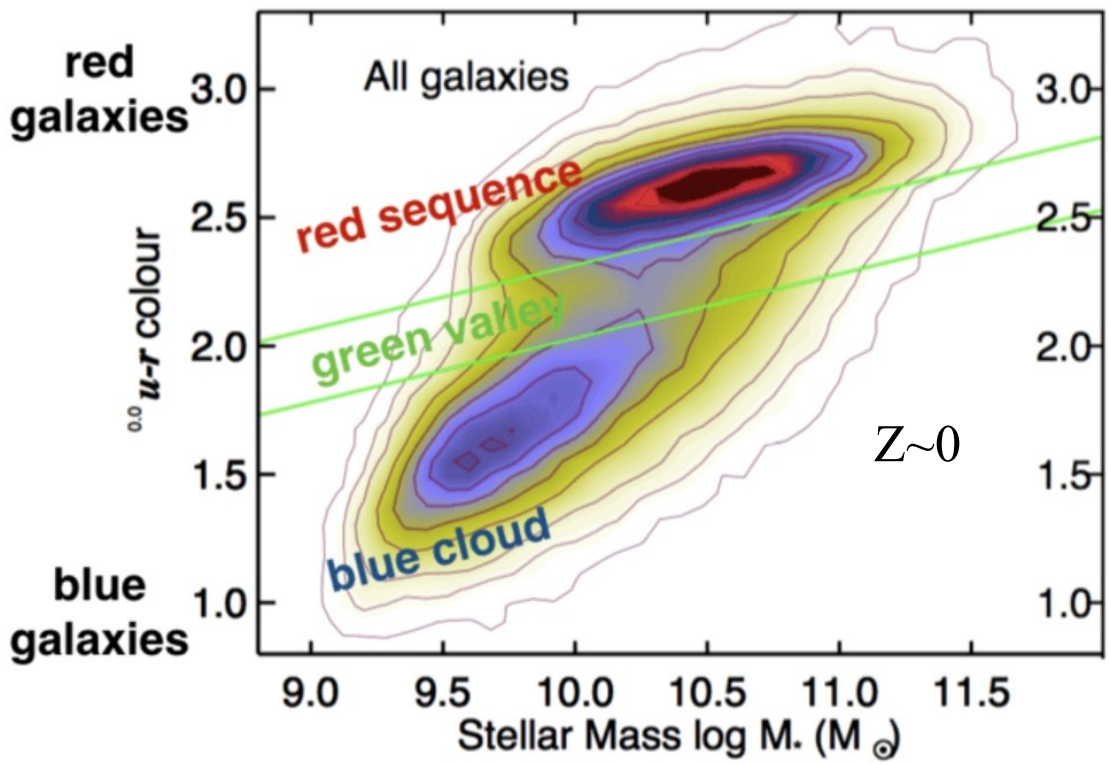


Villar + 17

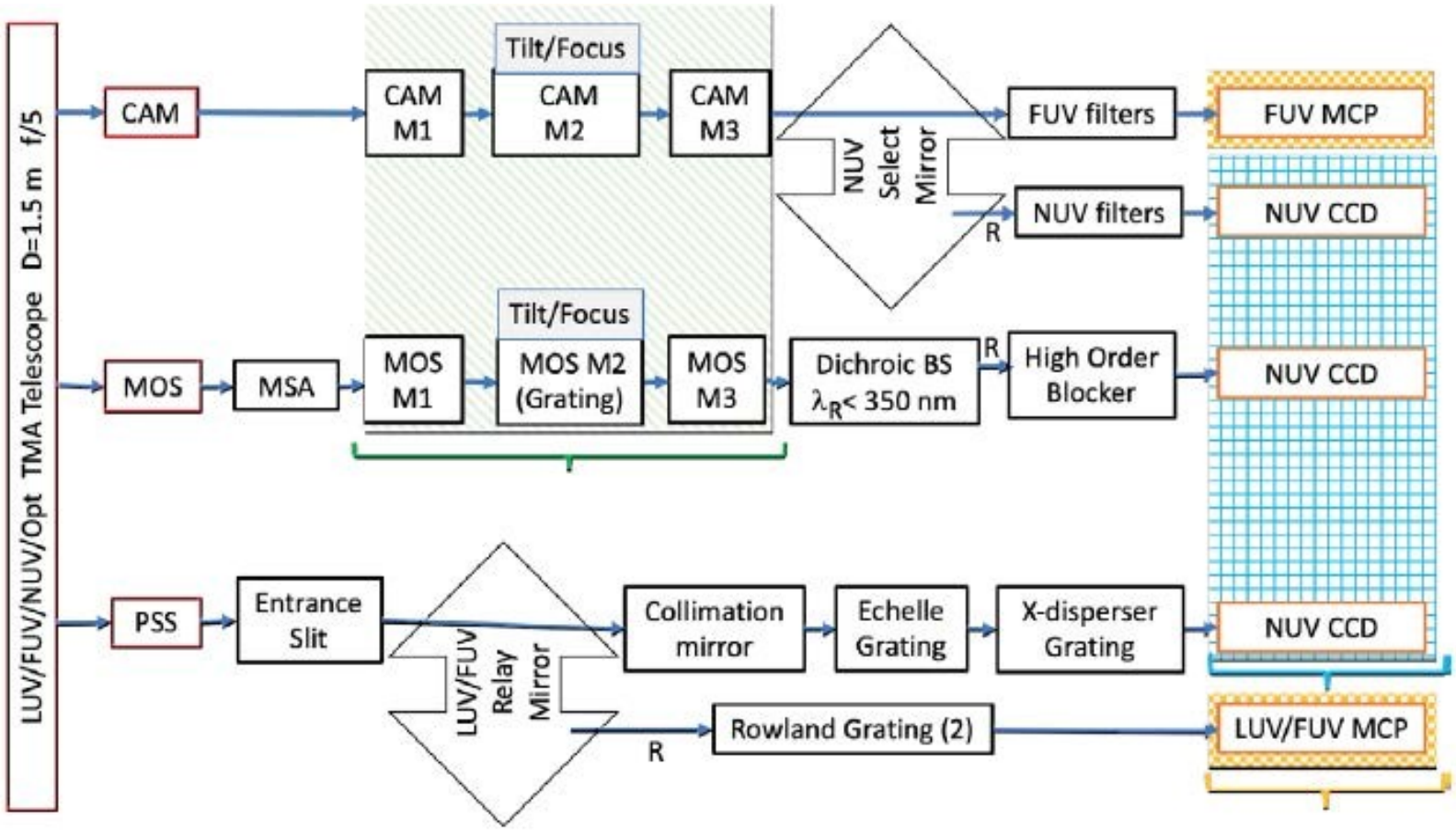
CETUS will be on constant alert from the ground and will slew to the target in 15 min.

The near-UV camera will pinpoint what kind of z~1-2 galaxies have slowed down or stopped stopped making stars

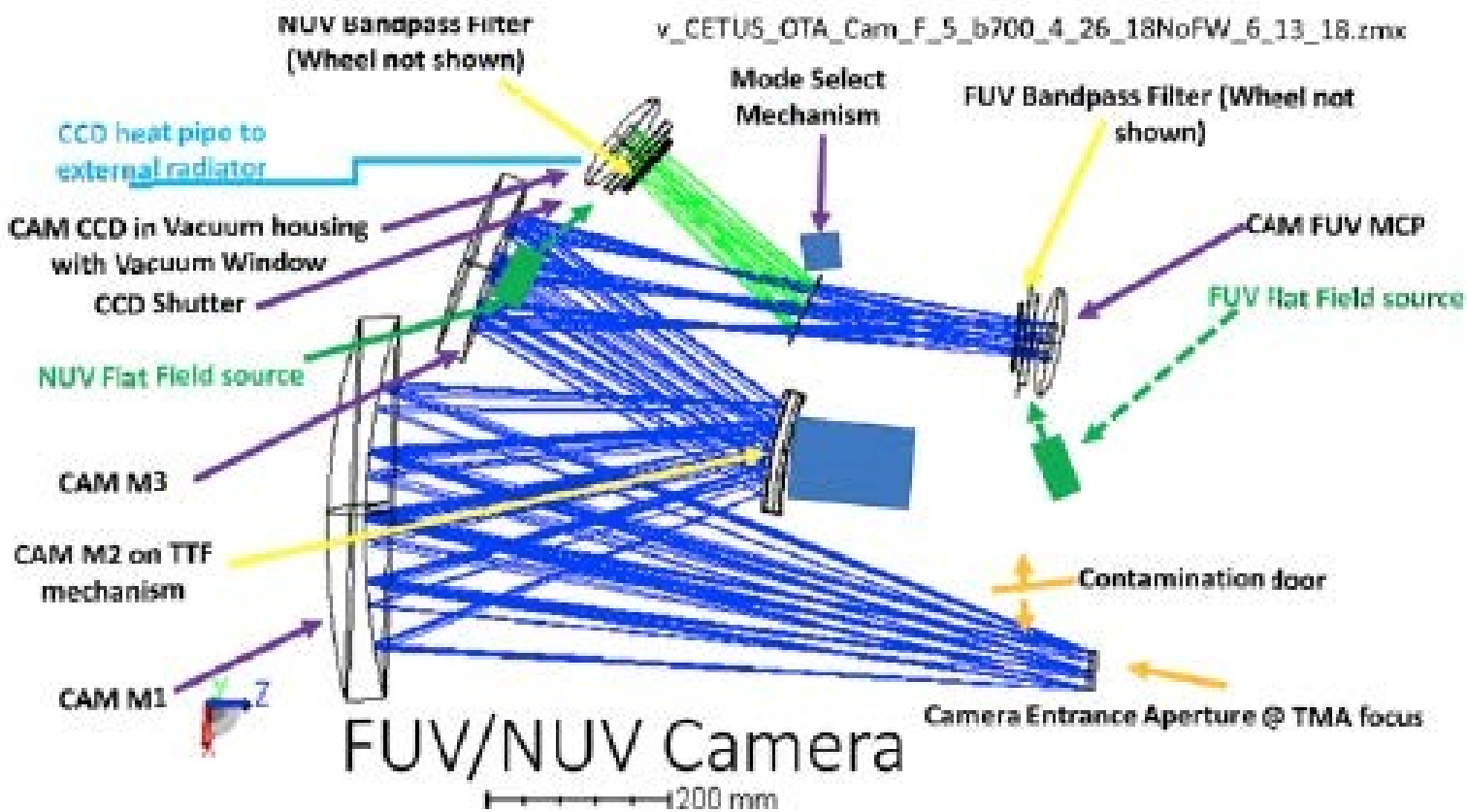
•via rest-frame (far-UV – optical/IR) color
•via high-resolution imagery (morphology)



Block Diagram of CETUS Instruments

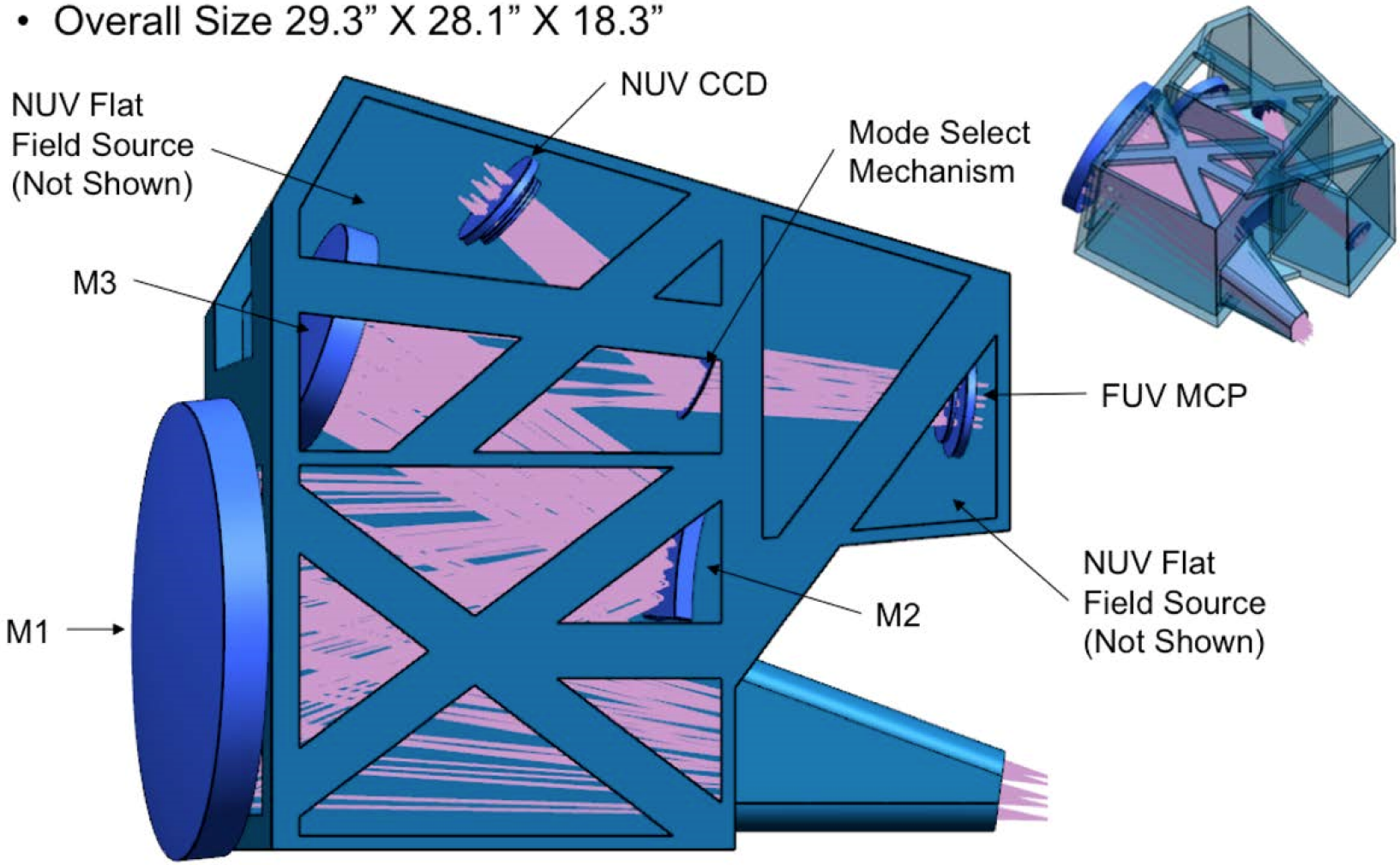


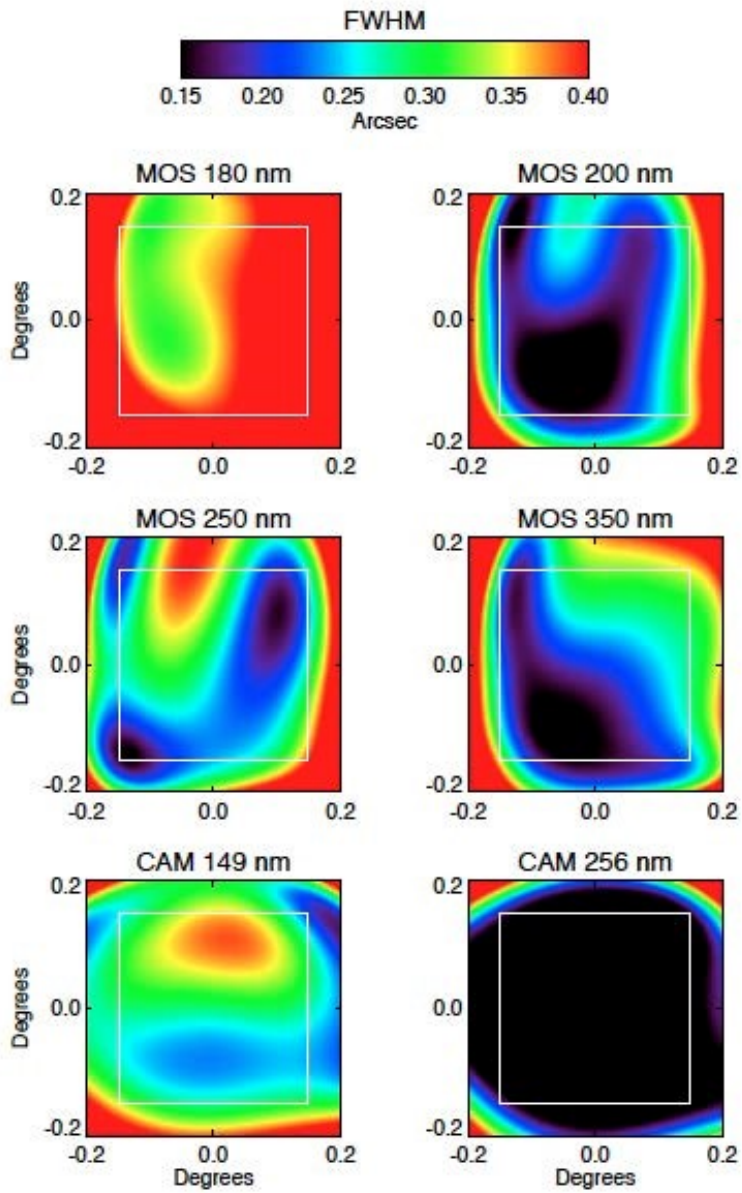
The CETUS Camera (CAM)



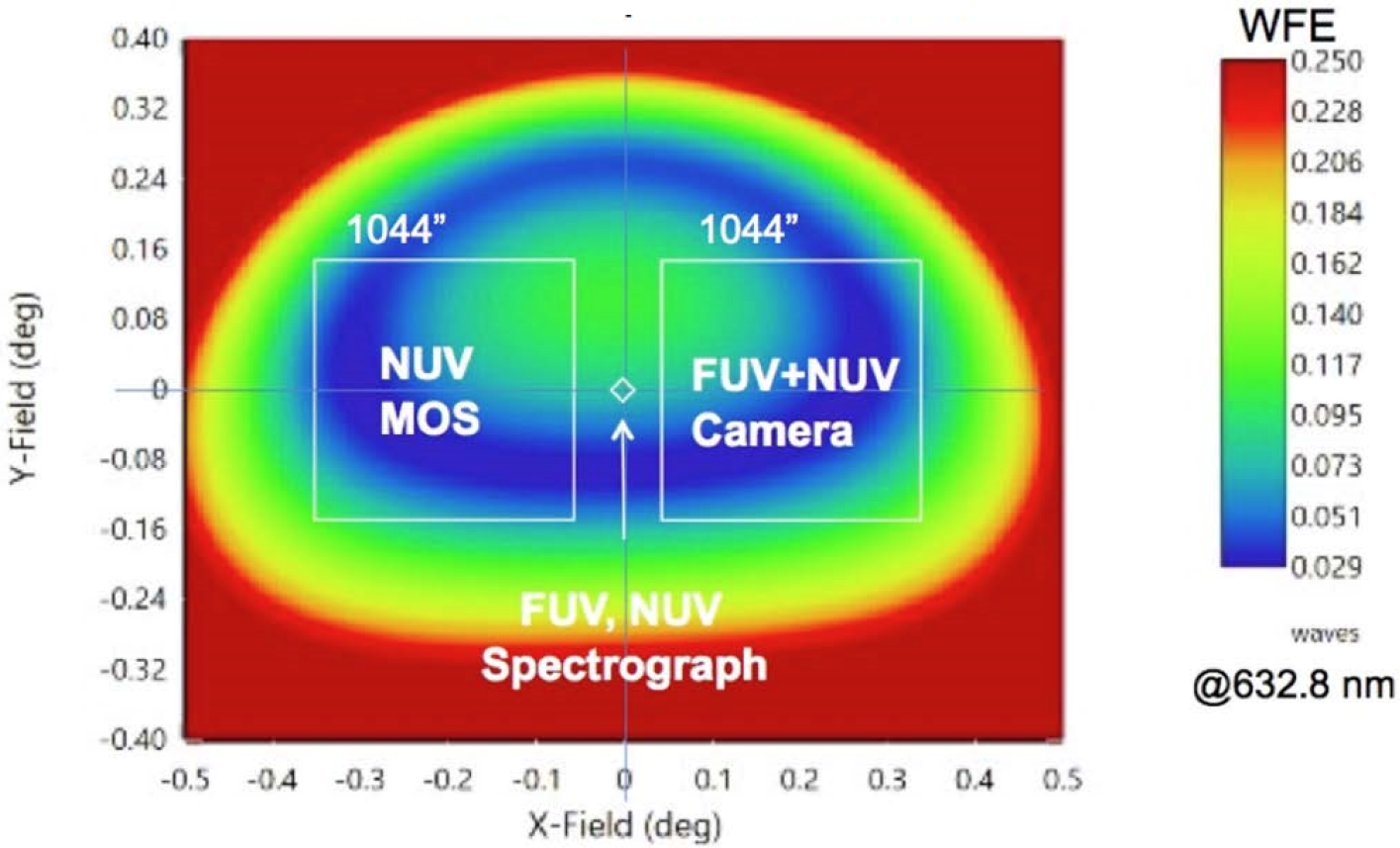
Packaged View of CETUS Camera

- Overall Size 29.3” X 28.1” X 18.3”




FWHM
0.15
0.20
0.25
0.30
0.35
0.40
Arcsec
MOS 180 nm
MOS 200 nm
MOS 250 nm
MOS 350 nm
CAM 149 nm
CAM 256 nm
Degrees
0.2
0.0
-0.2

The telescope field of view is large enough to accomodate all three scientific instruments working in parallel



The observations will be definitive because of CETUS' high image quality

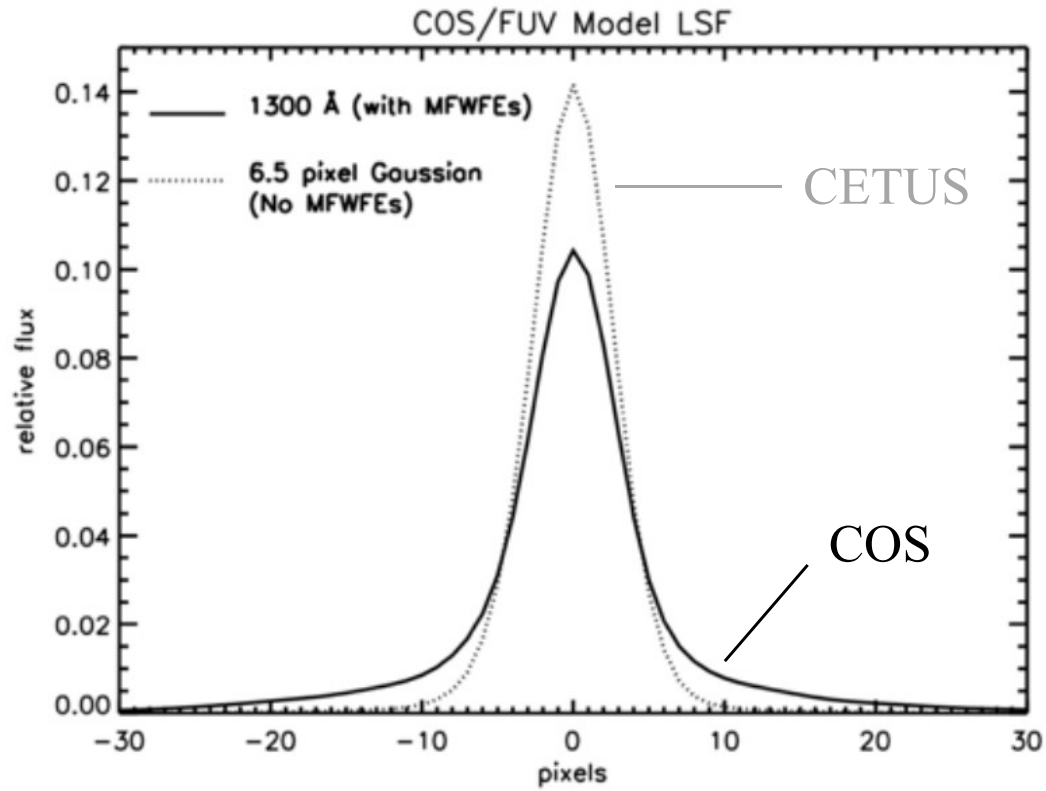
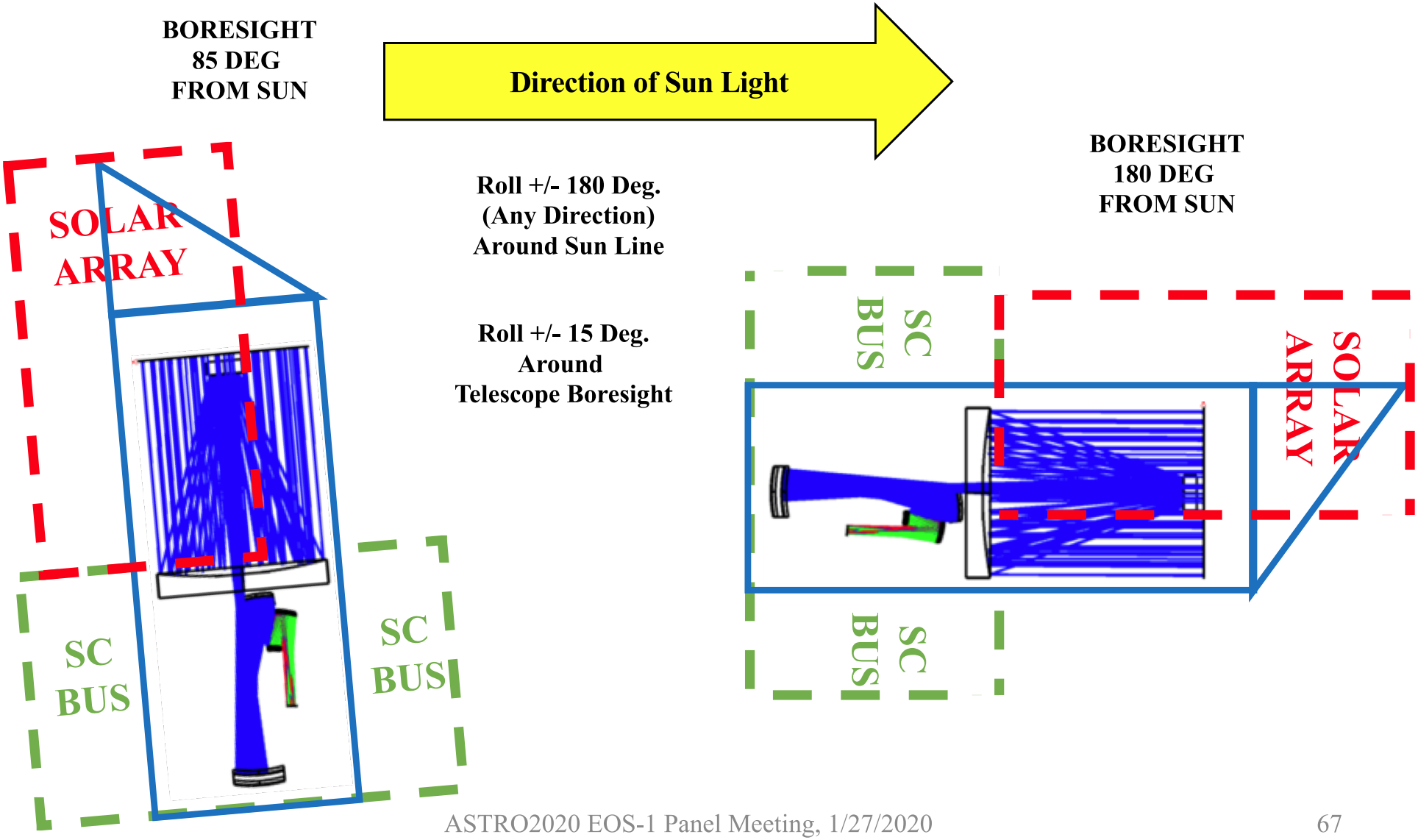


Figure 2-15: Spectral lines in CETUS spectra will have Gaussian profiles leading to accurate measurements of line strengths.

Modern techniques of mirror polishing will make CETUS better than Hubble!

CETUS Field of Regard (FoR)
(2 Pi Steradians of Sky in SEL2 Orbit



Mitigated Risks

A1: Grav. Rel.

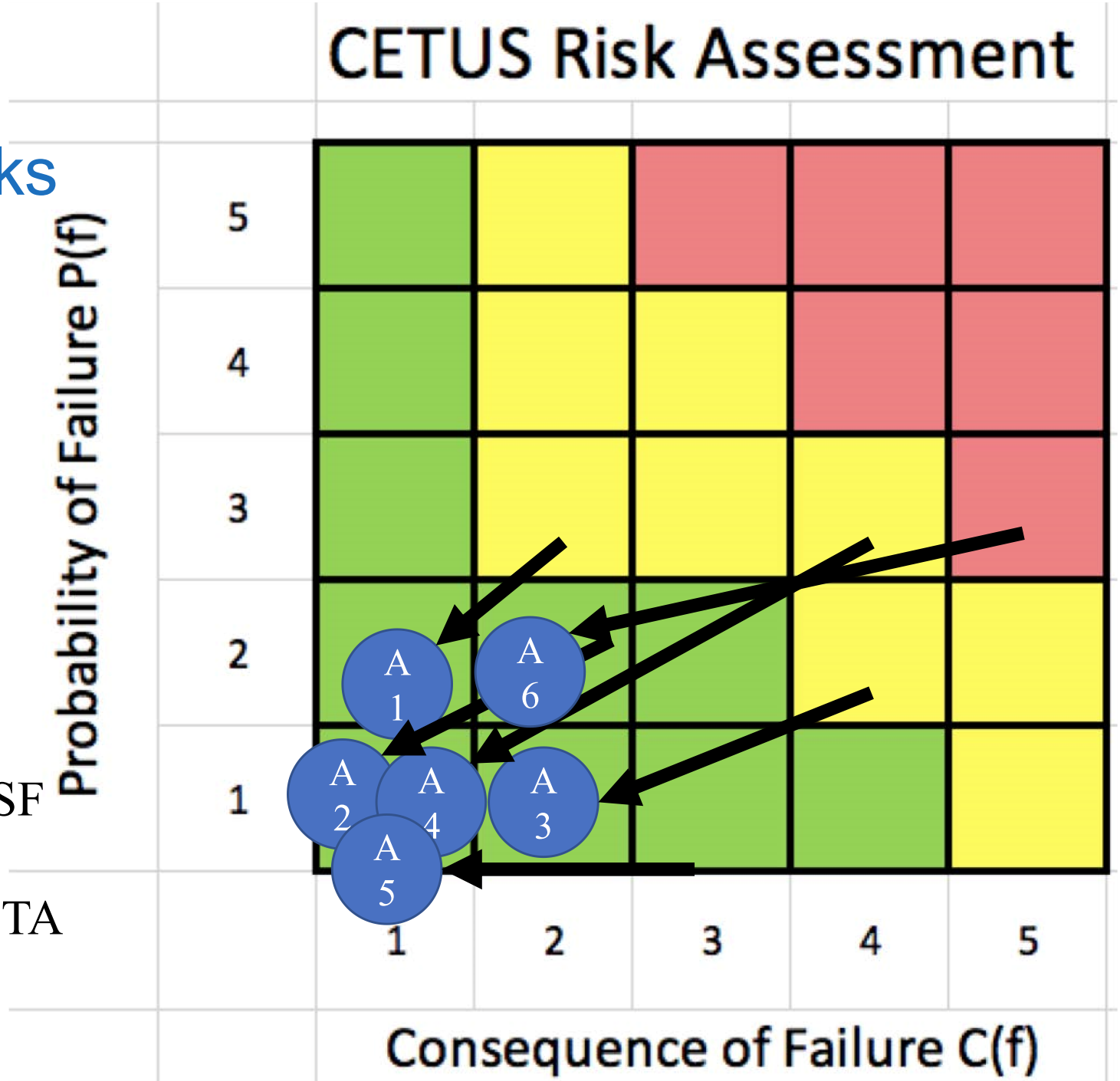
A2: T Stab. Optical

A3: Contam. Build

A4: Contam. Flight

A5: Low MSF→ LSF

A6: Cost of 1.5m OTA



Mitigated Risks in Study

	#	Failure catagories	Pf	Cf	Mitigations	Mit Pf	Mit Cf
A1	GR	Gravity release and launch load OpPerf error budget	3	3	Hexapod adjustment at OTA M2 WFS&C Shack Hartmann sensors	2	1
					In plan to do		

	#	Failure category	Pf	Cf	Mitigations	Mit Pf	Mit Cf
A2	T & C	Change of Thermal BC and/or material relaxiation	2	2	Hexapod adjustment at OTA M2 WFS&C Shack Hartmann sensors	1	1
					In plan to do		

	#	Failure category	Pf	Cf	Mitigations	Mit Pf	Mit Cf
A3	Comtam PreLaunch	Loss of light due to molecular contamination from part build through contamfor fabrication, AI&T through Space commissioning	3	4	Cleanliness program... dry N2 storage Pre-baking all parts P/L capping shutter Decontam heaters proximate to optics	1	2
					In plan to do		

	#	Failure category	Pf	Cf	Mitigations	Mit Pf	Mit Cf
A4	Comtam PostLaunch	Loss of light due to molecular contamination in observatory service	3	4	Warm biased optics Decontam heaters proximate to optics P/L capping shutter	1	1
					In plan to do		

	#	Failure category	Pf	Cf	Mitigations	Mit Pf	Mit Cf
A5	CETUS PM MSF << HST MSF	HST level MSF responsible for >40% degrdation of LSF	1	3	High TRL determanistic OpFab techniques have emerged after HST Leading candidate is Collins Aerospace (Danbury) Strong response from Harris Aerospace (Rochester) Coherent (ne. Tinsely) also candidate.	1	1
					In plan to do		

	#	Failure category	Pf	Cf	Mitigations	Mit Pf	Mit Cf
A6	Is a 1.5m OTA affordable?	Cost models may parameterize a 1.5m OTA as too large for a Probe Class Mission cap	3	5	Faster Better Cheeper lightweight mirror substrates of ZERODUR Supurb stability agaist thermal transients easing thermal management Excellent thermal match of mirrors with CFRP with metering materials Evolved OpFab methods in last 3 decades --> faster better cheeper finished optics	2	2
					In plan to do		

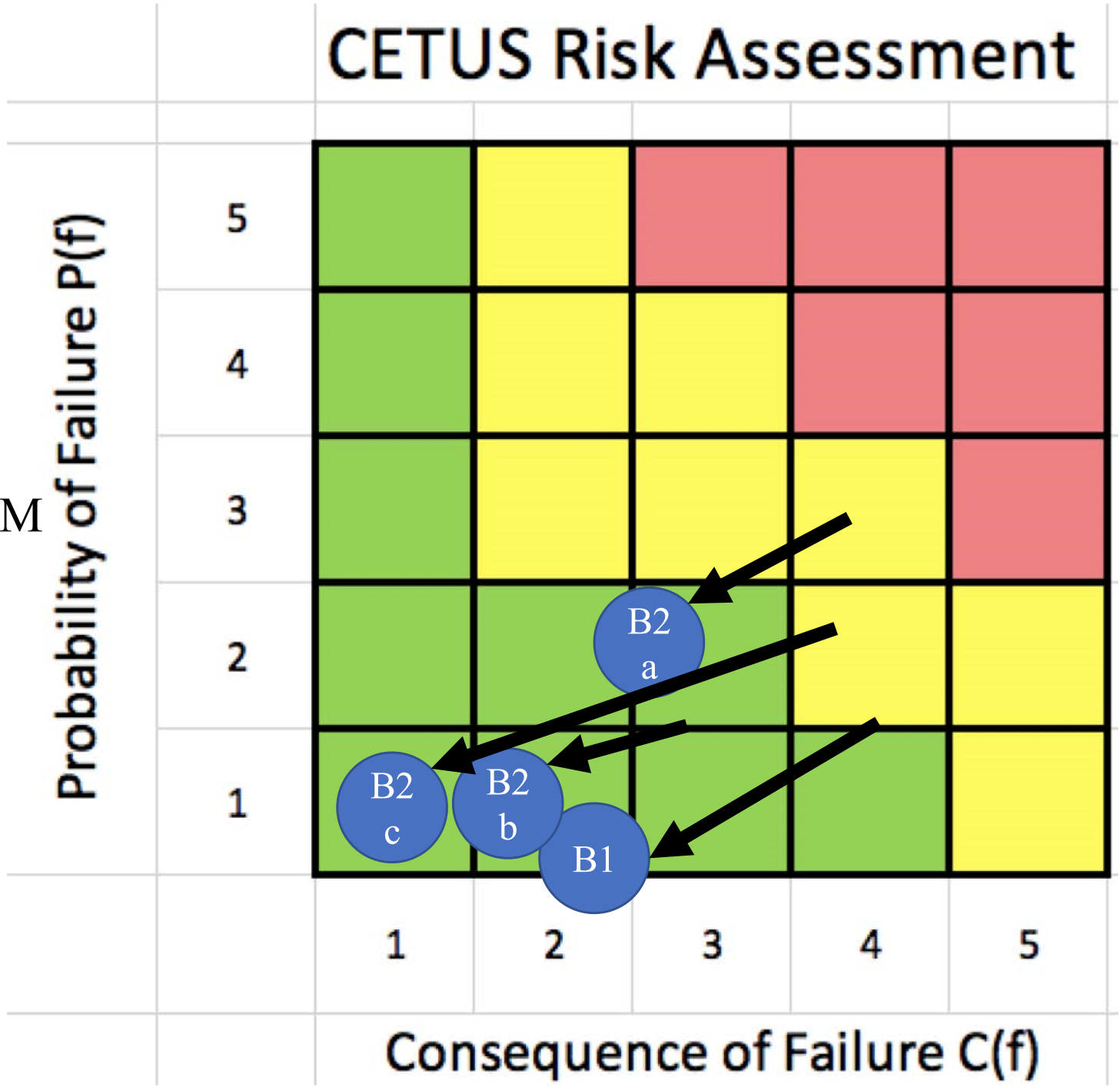
Risks to be Mitigated

B1: Next Gen MSA

B2a: Al:LiF:ALD PM

B2b: Al:LiF PM

A4: Al:MgF_2 PM



Risks to be Mitigated

	#	Failure category	Pf	Cf	Mitigations	Mit Pf	Mit Cf
B1	MSA	Next Gen MSA not available	2	4	SAT work for LUVOIR applicable to CETUS Can relax to use Gen 1 MSA as used on JWST	1	2
					In plan and Available to do		

	#	Failure category	Pf	Cf	Mitigations	Mit Pf	Mit Cf
2a	Coat PM Al:LiF:ALD	Facilities to coat with Al:LiF:ALD are presently available up to 0.5m aperture, while CETUS PM is 1.5m aperyure --> I no facility is available at Phase A... PM size (1.5m)	3	4	Collins Aerospace is ready to coat Al:LiF:ALD for $5-10M ZeCoat may be willin to do LiF coat	2	3

	#	Failure category	Pf	Cf	Mitigations	Mit Pf	Mit Cf
B2b	Coat PM LiF	ALD protective overcoat is unavailable for 1.5m PM	2	3	LiF degradation prevention protocols w/o ALD have been demonstrated Collins Aerospace willing to be facilitied to do LiF coating	1	2

	#	Failure category	Pf	Cf	Mitigations	Mit Pf	Mit Cf
B2c	Coat PM w. MgF2	If cleanliness routine for Al:LiF coatings not available OTA PM size (1.5m) --> revert to HST-like MgF2 with loss of	2	4	This is the HST coating, widely available from multiple sources, though loose science at $\lambda < 125nm$	1	1

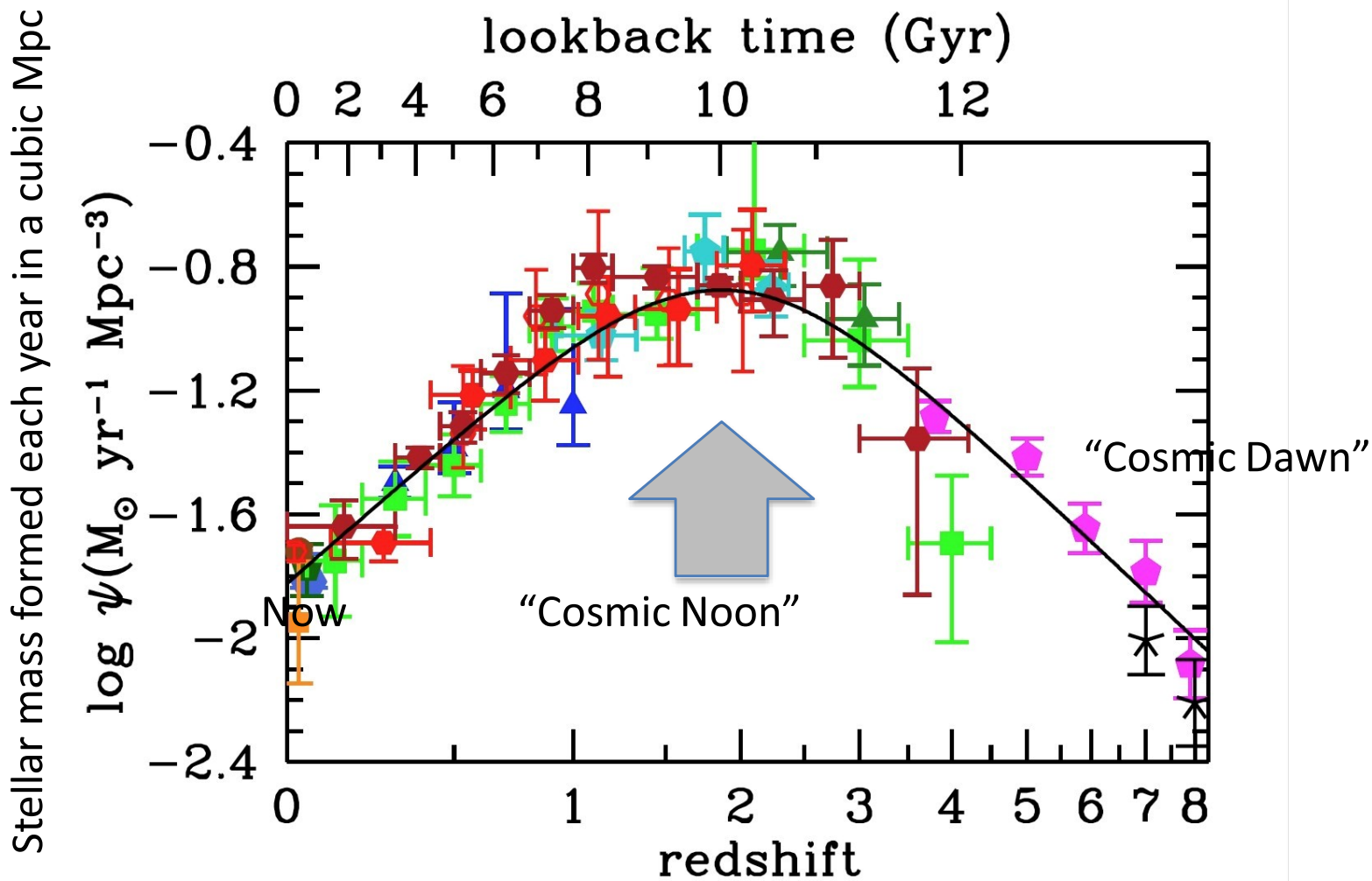
Derived Requirements for the CETUS MOS & Camera

Parameter	Requirement	Design
Field of View	>1000”	1045”
Angular Resolution	≤0.70”	0.55” (FUV) 0.55” (NUV)
Spectral Range	Far-UV and near-UV	1150-1750 Å (FUV) 2000-4000 Å (NUV)
Spectral Bandpass	LP filters, λ_{min}>1150 Å 300-500 Å	100-150 Å (FUV) ~410 Å (NUV)

IN THE CONTEXT OF THE CETUS SYSTEM CONCEPT

Requirement	Derived Requirement
MOS requirement: 100 S/N>7 spectra in a single exposure	MOS FOV 1045” square Tel. diameter = 1.50 m
Camera requirement: Observe in parallel with the MOS	Cam FOV 1045” square
Detector realities: NUV: CC pixel = 0.42” FUV: MCP resolution elements	Resolution = 0.55” for both MOS and CAM (not diffraction limited!)
Nyquist sampling requirement	Dither a pixel on the MOS and CAM
MOS requirement: no dithering of telescope	Dithering of MOS and CAM images via mechanism on M2 optic
Camera requirement: 5 spectral filters for higher spectral resolution & calibration filters	8-position filter wheel for both FUV and NUV camera

We don't understand the Star Formation History of the Universe



Madau & Dickinson 2014

...or the accretion history of black holes

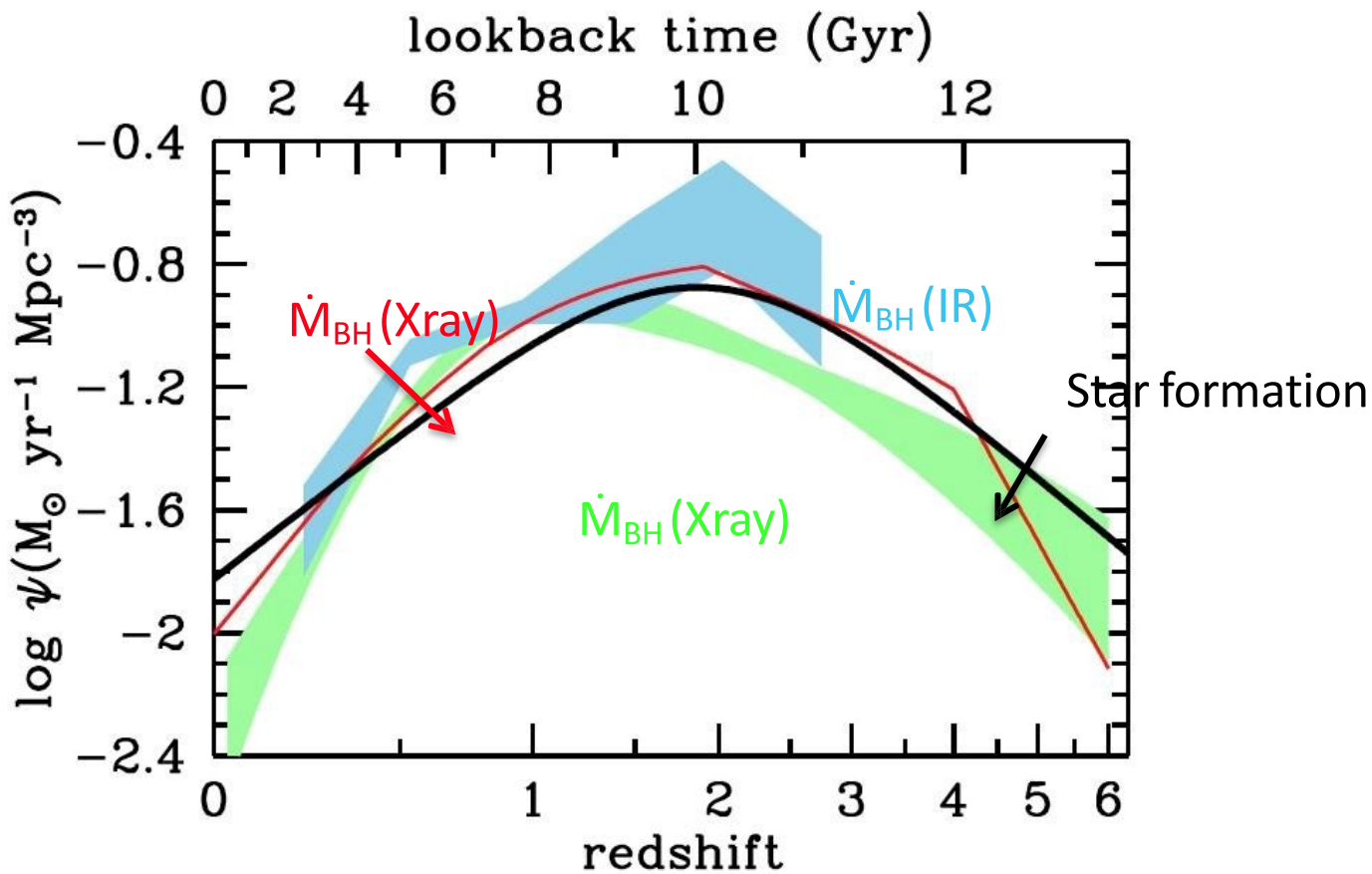
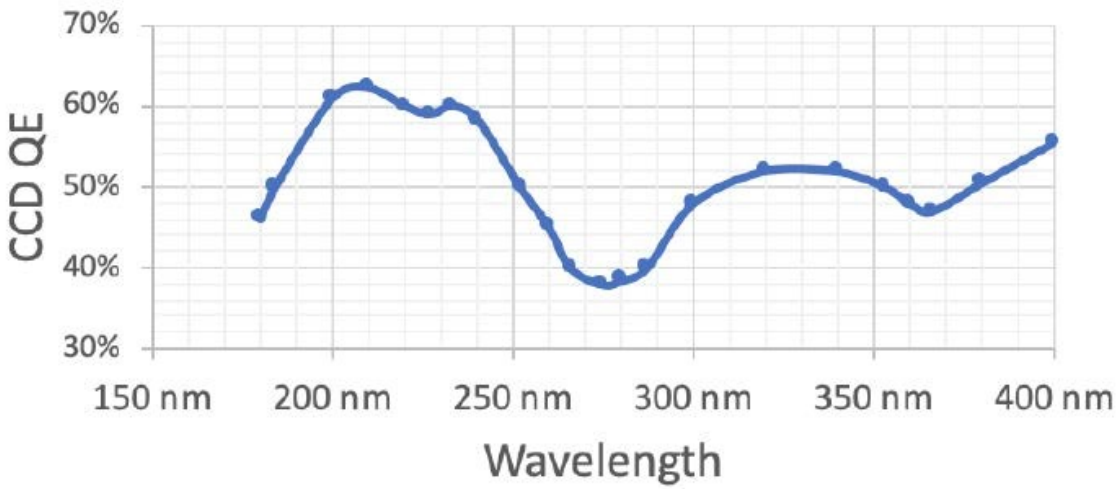


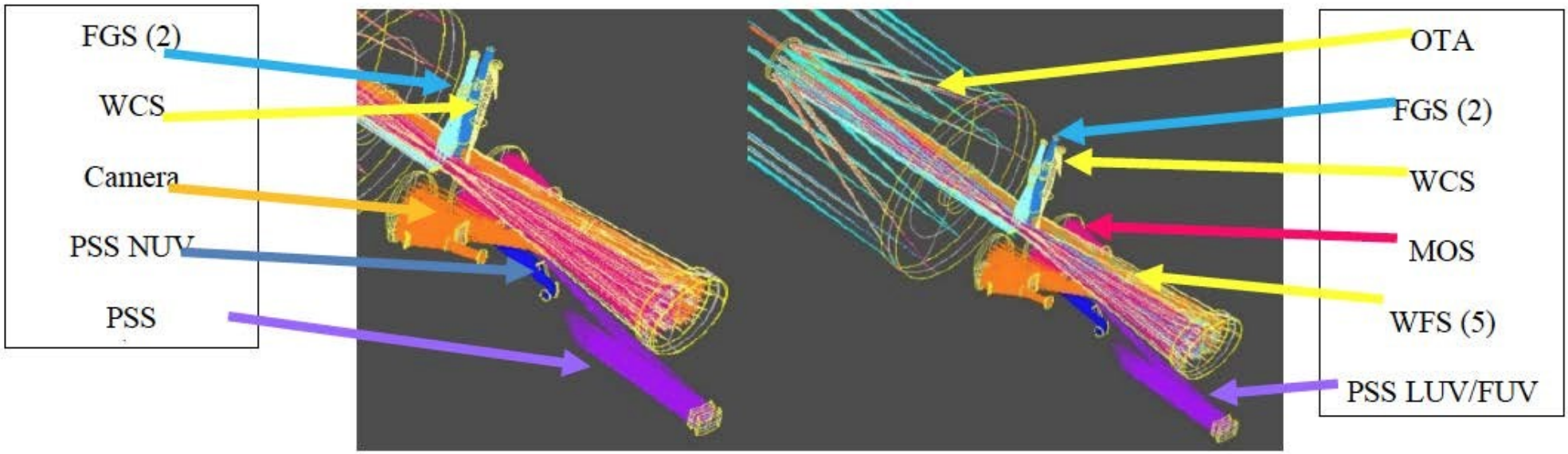
Figure 15: Comparison of the best-fit star formation history (*thick solid curve*) with the massive black hole accretion history from X-ray [*red curve* (Shankar et al. 2009); *light green shading* (Aird et al. 2010)] and infrared (*light blue shading*) (Delvecchio et al. 2014) data. The shading indicates the $\pm 1\sigma$ uncertainty range on the total bolometric luminosity density. The radiative efficiency has been set to $\epsilon = 0.1$. The comoving rates of black hole accretion have been scaled up by a factor of 3,300 to facilitate visual comparison to the star-formation history.


70%
60%
50%
40%
30%
CCD QE
150 nm
200 nm
250 nm
300 nm
350 nm
400 nm
Wavelength

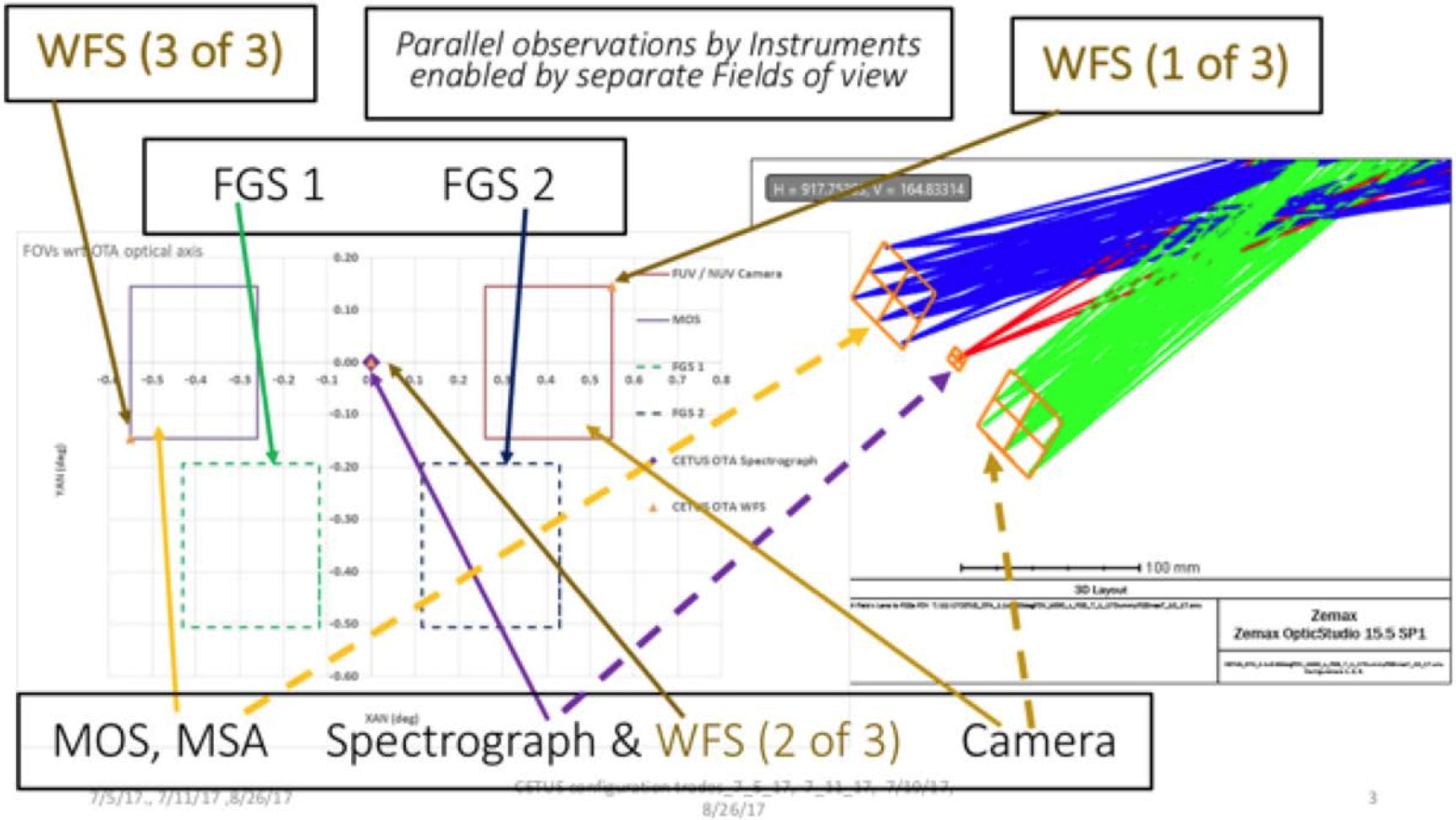
Overview of Improvements of CETUS FUV detectors over those from COS

	FUV CETUS MCP	FUV HST/COS MCP
Detector type	XS (cross-strip), CsI photocathode	XDL, CsI photocathode
Spatial resolution	20 micron FWHM	35 micron FWHM (dispersion); 65-550 micron FWHM (X-disp)
Low gain operation	10^6	10^7
Higher dynamic range	Multi-MHz rates	60,000 global count-rate limit
Ultra low MCP background	<0.05 event/sec/cm^2	<1 event/s/cm^2
High UV QE	50% @115nm, 30%@200 nm	26% @ 133 nm, 12% @ 156 nm
Solar-blind cutoff	~350 nm	> 239 nm
Long stable lifetimes	>4x10^{13} events/cm^2	4 lifetime positions due to gain sag
Format size	up to 200 mm x 200 mm; no gaps	2x85mm x 12 mm; 9-mm gap

Another Ray Trace View



Parallel observations by instruments are enabled by separate Fields of View



Key Requirements

- CETUS shall make a targeted UV survey of galaxies via a UV camera and multi-object spectrograph (MOS) utilizing a Micro-shutter array (MSA)
- The CETUS MOS shall obtain > 10^5 near-UV (rest frame far-UV) spectra of redshift z~1-2 galaxies already observed by Subaru's Hyper Suprime Camera and Prime Focus Spectrograph
- The CETUS MOS shall enable R~1000 spectroscopy of 50-100 redshift, z~1-2 galaxies simultaneously
- The CETUS cameras shall observe in parallel with the MOS, so target galaxies observed by the MOS will have additional observations supplied by the cameras
- Each CETUS camera will include 5 spectral filters and will have angular resolution of 0.41" for the near-UV and 0.55" for the far-UV, approximately a factor of ten better than GALEX (~5")
- The single object near-UV with R~2000 and R~40,000 and Lyman-UV far-UV spectrographs shall operate with R~2000 and R~20,000

What is CETUS?

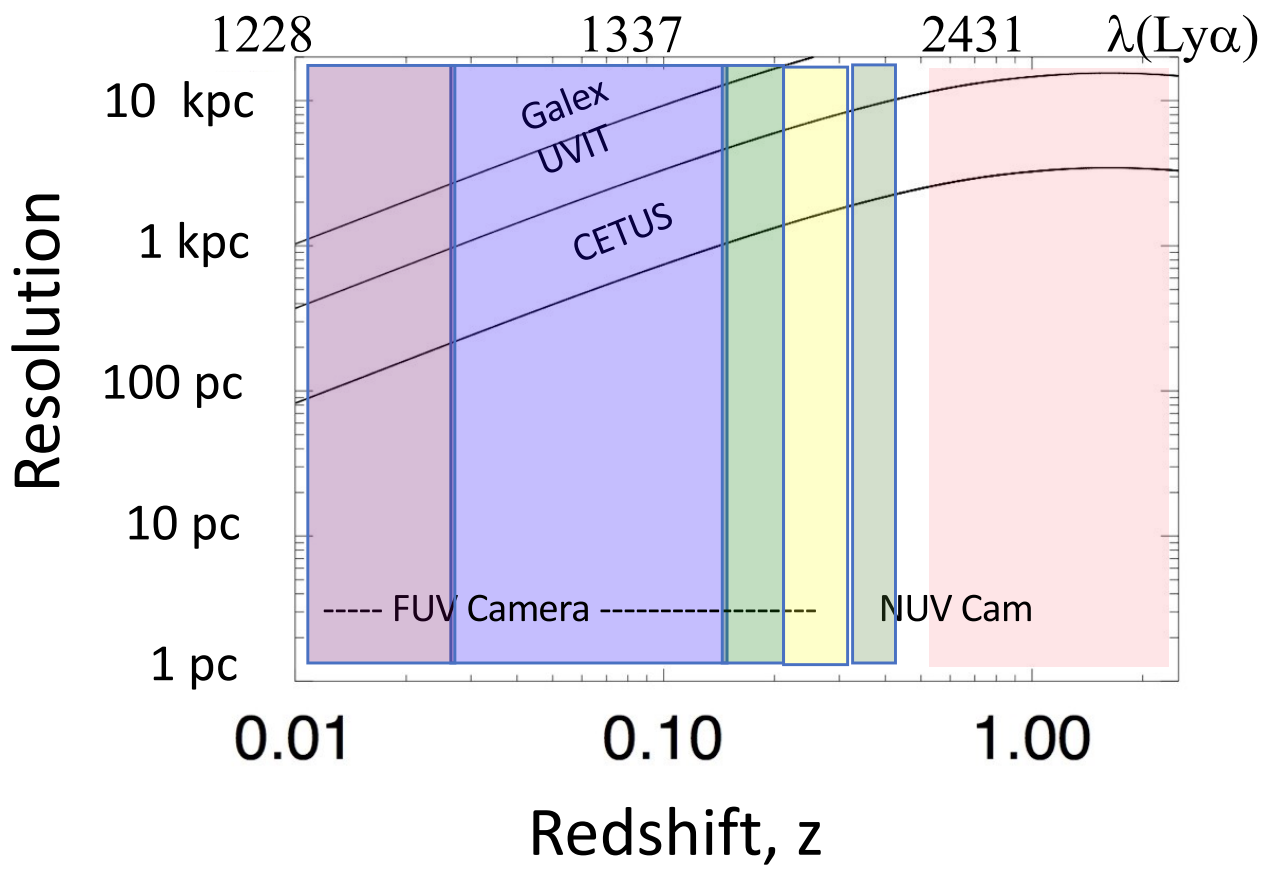
- CETUS: wide-field 1.5-m telescope with 3 powerful UV instruments

  - ***Near-UV multi-object slit spectrograph*** *(MOS)* utilizing a next-generation micro-shutter array (NG-MSA)

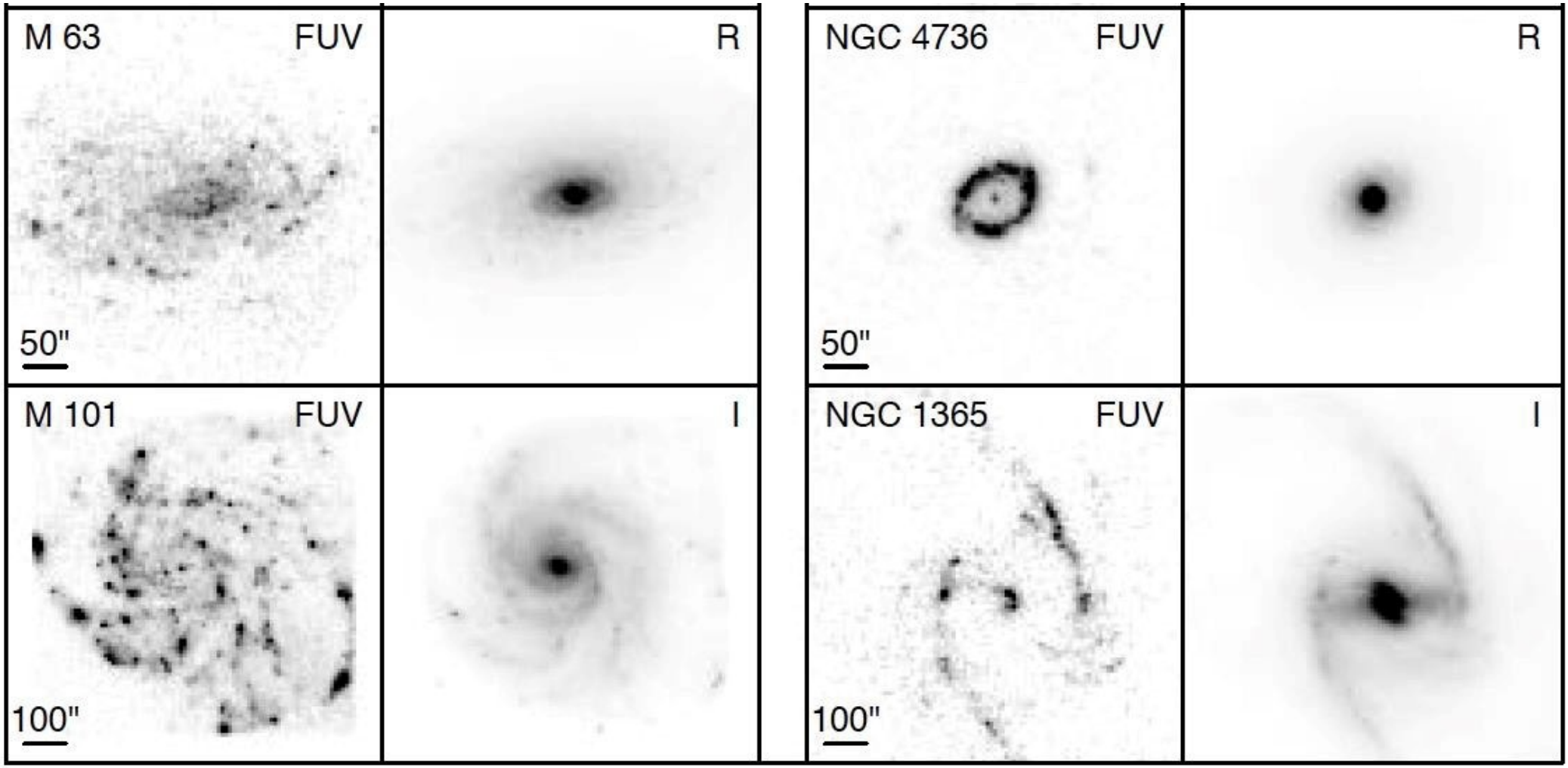
  - ***Far-UV & Near-UV cameras*** *(CAM)* each with 5 filters, resolution of 0.5" (GALEX resolution ~5");
    operates simultaneously with the MOS

  - ***Lyman-UV, Far-UV*** (with selectable resolving power R~2000 or R~20,000) ***& Near-UV spectrographs***, (with R~2000 or R~40,000)

The cameras will reveal Lyman a galaxies (LAE's) and show where in galaxy the emission comes from



UV morphology of galaxies in transition between the Blue Cloud and the Red Sequence will be especially informative



Selected Probe Mission Concept Studies

PI	Affiliation	Short title	Design Lab/Prog Office
Camp, J.	NASA's GSFC	Transient Astrophysics Probe	IDC/PCOS-COR
Cooray, A.	Univ. California, Irvine	Cosmic Dawn Intensity Mapper	TeamX/ExEP
Danchi, W.	GSFC	Cosmic Evolution through UV spectroscopy	IDC/PCOS-COR
Glenn, J.	Univ. of Colorado	Galaxy Evolution Probe	TeamX/ExEP
Hanany, S.	Univ. of Minnesota	Inflation Probe Mission Concept Study	TeamX/ExEP
Mushotzky, R.	Univ. of Maryland	High Spatial Resolution X-ray Probe	IDC/PCOS-COR
Olinto, A.	Univ. of Chicago	Multi-Messenger Astrophysics	IDC/PCOS-COR
Plavchan, P.	Missouri State Univ.	Precise Radial Velocity Observatory	No design lab funded/HQ grant
Ray, P.	Naval Research Lab	X-ray Timing and Spectroscopy	IDC/PCOS-COR
Seager, S.	MIT	Starshade Rendezvous	TeamX/ExEP