

Cosmic Evolution Through UV Surveys

OUTLINE OF TALK

Introduction to CETUS

Science Goal and Science Program

- The low-redshift universe: galaxies & circumgalactic medium

- The universe at $z \sim 1$

- Transients

- Surveys & complementarity with other missions

Implementation

- Description

- Technical status and risks

- Schedule & cost

- Differences between CETUS Surveys (us) and Spectroscopy (GSFC)

Cosmic Evolution Through UV Surveys (CETUS)

Science Goal: To advance our understanding of the universe through UV observations and science-ready data available to all

Sources of Inspiration and Ideas

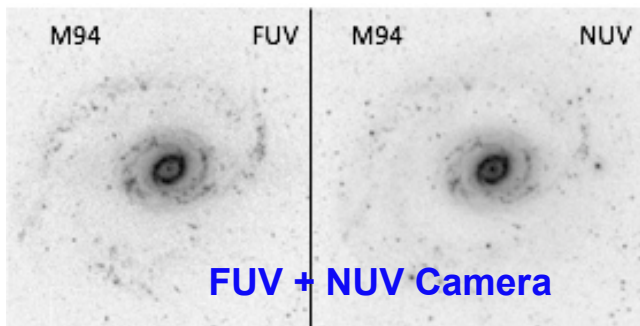
- Hubble, GALEX, FUSE for instrumentation
- Sloan Digital Sky Survey (SDSS) for maximizing science impact

ACS/SBC

WFC3/UVis

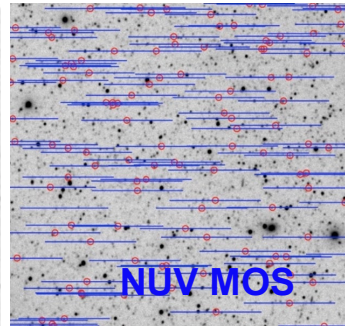
COS/FUV

STIS/E230M



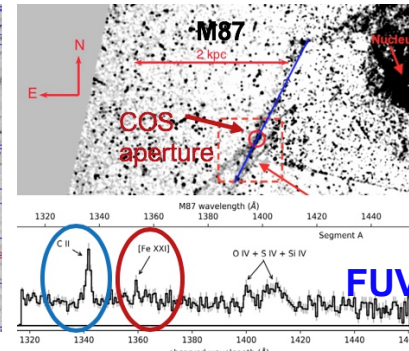
FUV + NUV Camera

GALEX



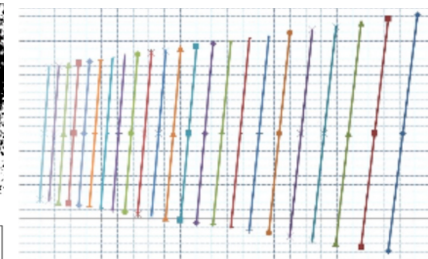
NUV MOS

JWST



FUV + NUV spectrograph

FUSE



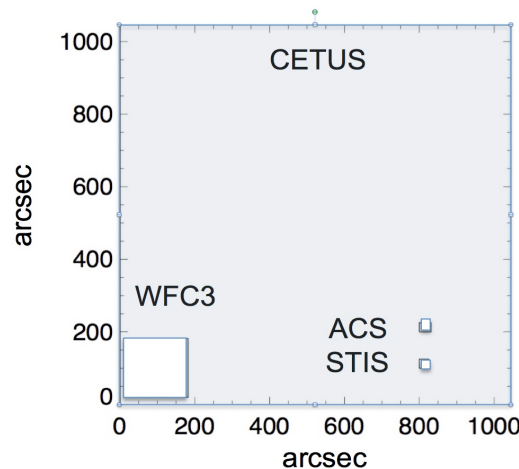
IUE, GHRS, STIS

New Capabilities → New Science

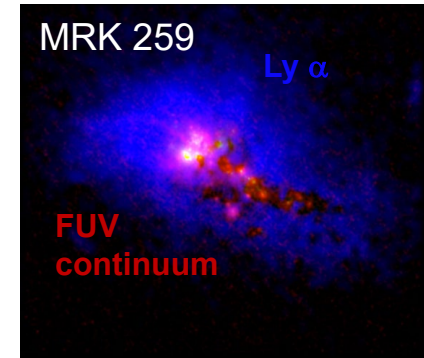
Fast Facts

- CETUS telescope: $D=1.5\text{m}$, $f/5$
- 3 instruments: Camera, MOS, and spectrograph
- Field of view of wide-field instruments
 - FUV&NUV Camera: $1044'' \times 1044''$
 - NUV MOS: $1044'' \times 1044''$
- Wavelength Coverage
 - LUV/FUV: 1000-1800 Å
 - NUV-Optical: 1800—4000 Å
- Spectral Resolution
 - LUV/FUV: 20,000
 - NUV: 1000 (MOS), 40,000 (Echelle Spec)
- Spatial Resolution: $0.40''$ (FUV), $0.33''$ (NUV)

Wide field of view to study physical processes in nearby galaxies

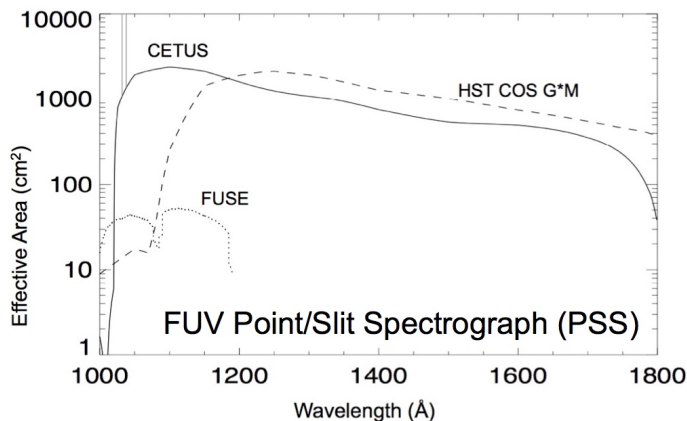


Sensitivity to diffuse sources to detect what's out there

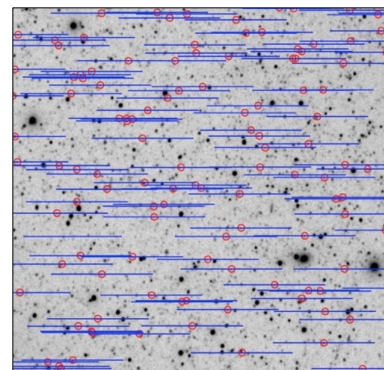


Hayes + 2016

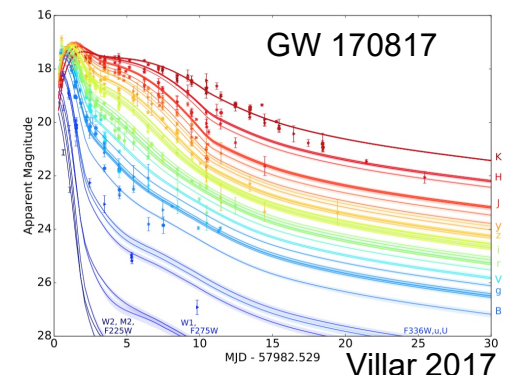
LUV (1000-1150 Å) sensitivity to study the nearby WHIM



MOS/MSA Spectroscopy to study $z=1$ galaxies, Ly α



Rapid response to catch GW sources, SNe



Villar 2017

Astro2020 Science White Paper

“Imprint of Drivers of Galaxy Formation

in the Circumgalactic Medium”

CETUS will:

- Make sensitive & reliable census of baryons in the CGM at low redshift
- Observe the CGM around galaxies in all masses
- Closely study galaxies to evaluate the role of the CGM- in galaxy evolution
- Be sensitive to diffuse gas in all phases - cold, warm, hot
- Directly observe main feedback modes

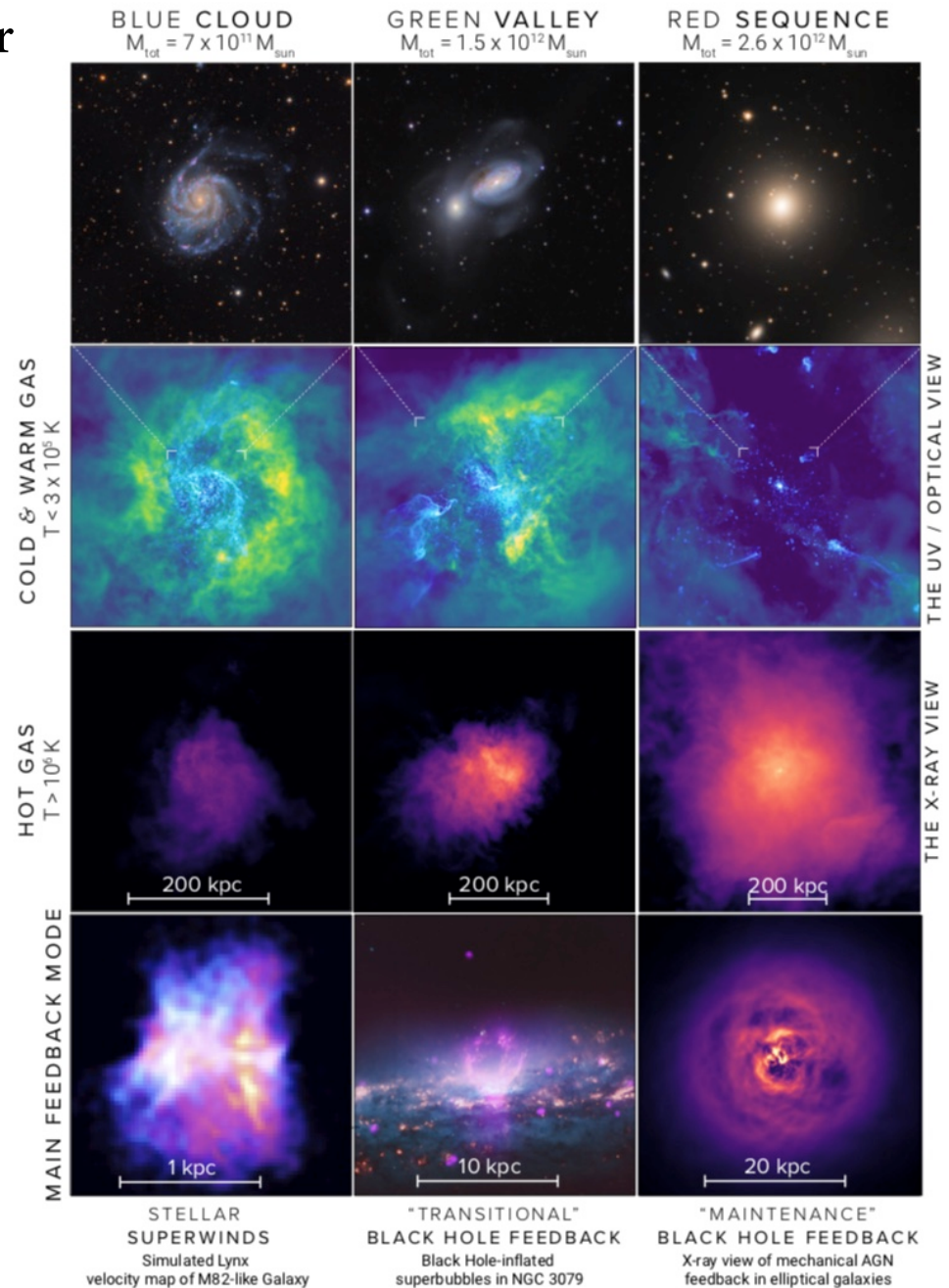
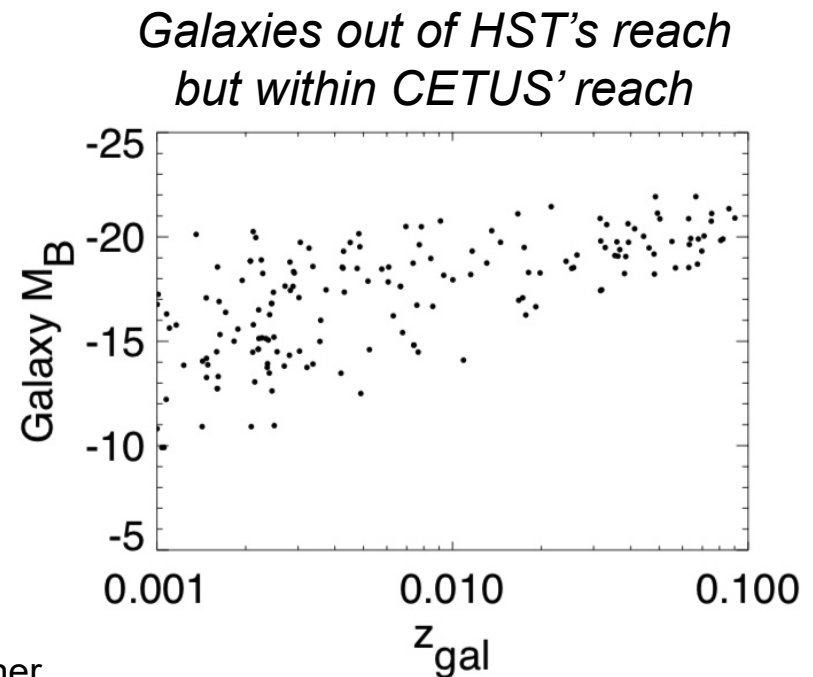
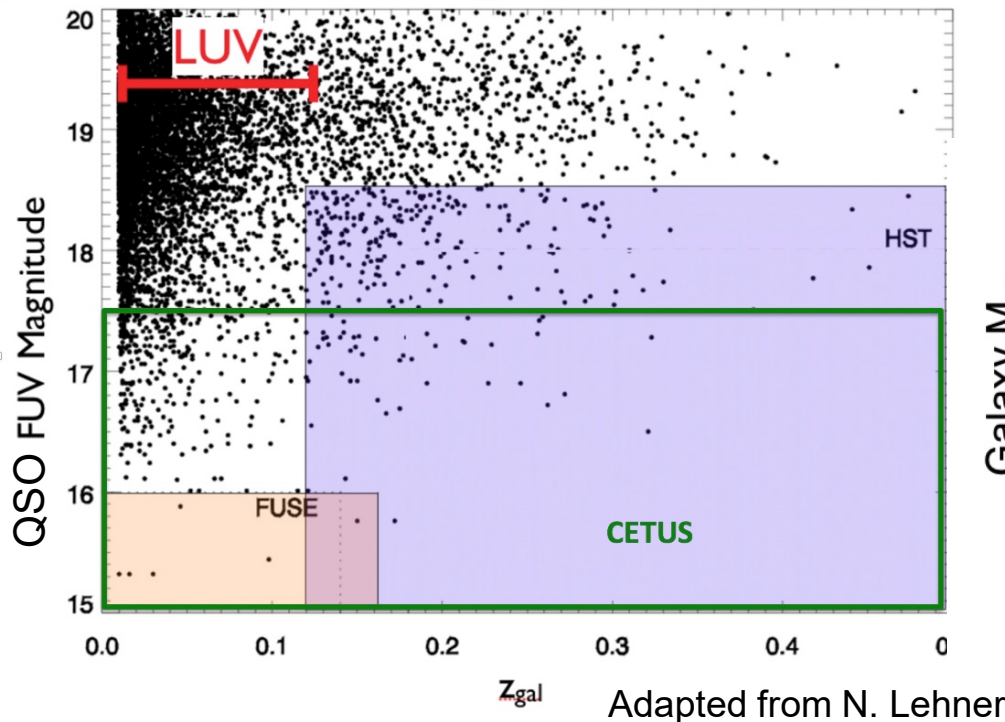


FIG. 2 A drastic transformation of galaxies from star-forming blue cloud to green valley galaxy and further to red sequence happens in a relatively narrow range of masses around $M_{\text{tot}} = 1 \times 10^{12} M_{\odot}$. The diverse optical appearances

CETUS will make a sensitive & reliable census of baryons in the CGM of nearby galaxies



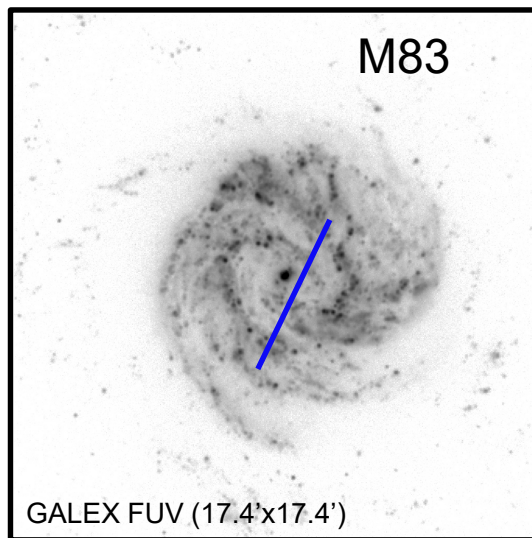
*CETUS will observe >160 nearby galaxy-QSO pairs including many dwarf galaxies (based on David Bowen's *Pairs* catalogue)*

CETUS will make systematic study of galaxy

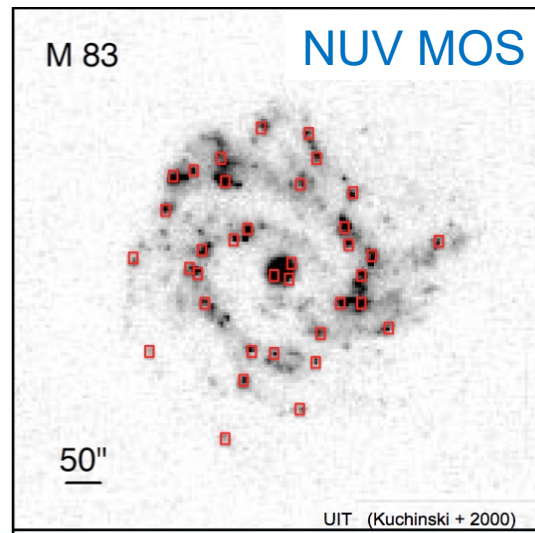
- properties - stars, gas, and dust,
- processes - star formation & feedback

via:

FUV filter imagery
FUV long-slit spectra



NUV filter imagery
NUV MOS spectra



UV long-slit spectra

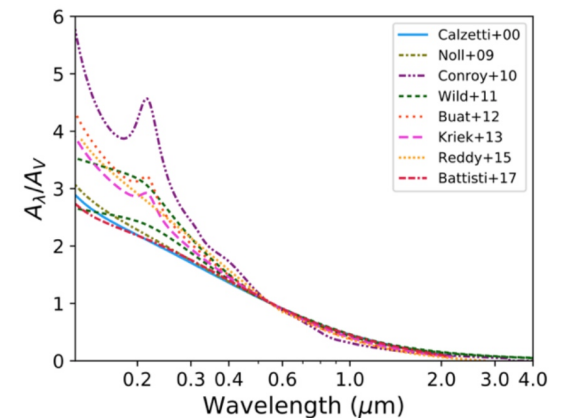
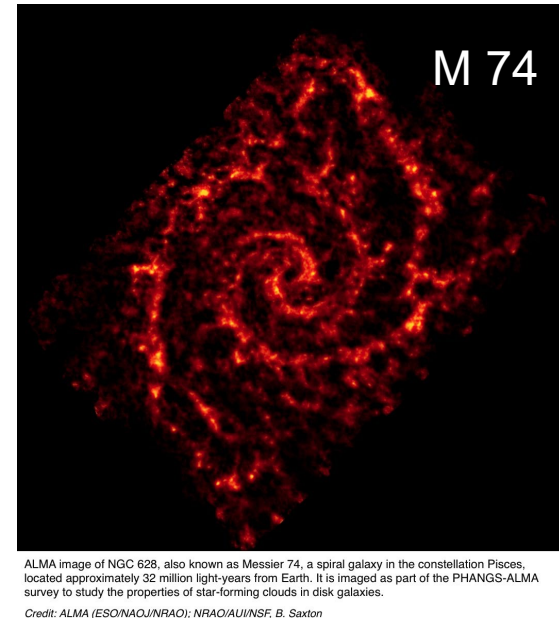
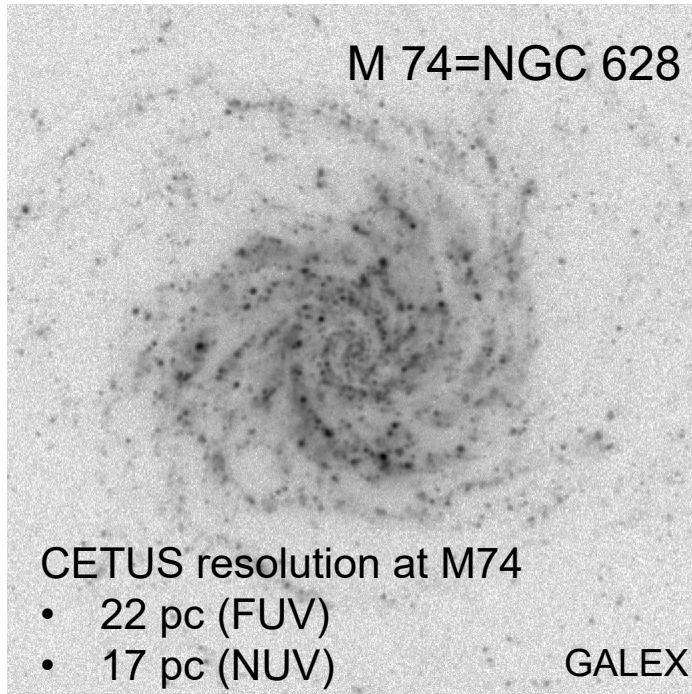


Figure 2-1. A collection of measured dust attenuation curves in galaxies illustrates the range in the 2175-Å bump and the UV slope, β_{uv} . From Hagen #593

and collaboration with multi-wavelength telescopes

CETUS will discern the role of dust and H₂ on star formation and stellar feedback



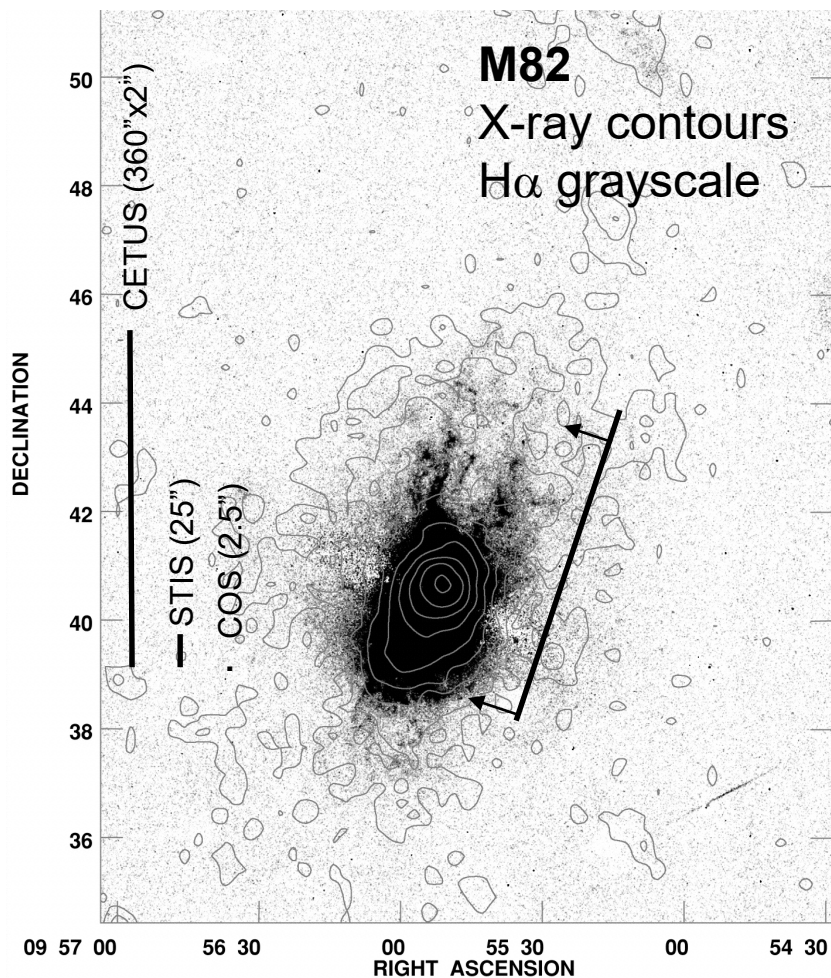
ALMA / PHANGS CO (2-1)

*PHANGS survey will observe “100,000 star factories in 74 galaxies”
CETUS will follow suit as soon as it is launched.*

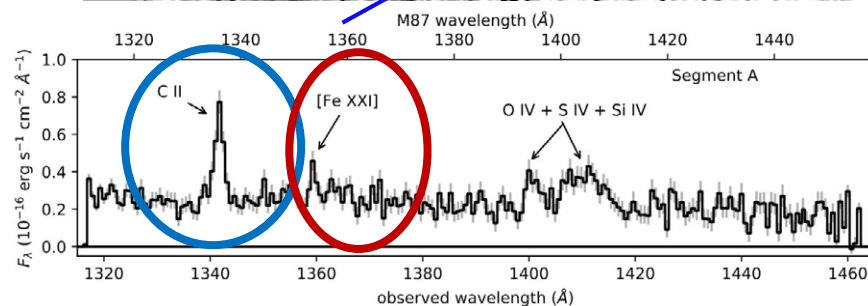
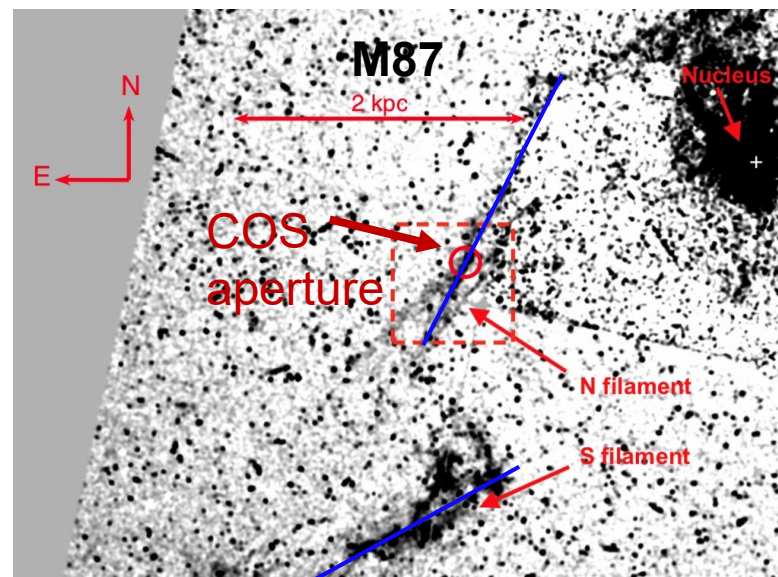
Formation of H₂ on dust grains – cooling – star formation – dust removed by stellar feedback

ALMA CETUS Spitzer, JWST CETUS

CETUS will directly observe feedback from stars, SN, SMBH



Lehnert, Heckman & Weaver 1999

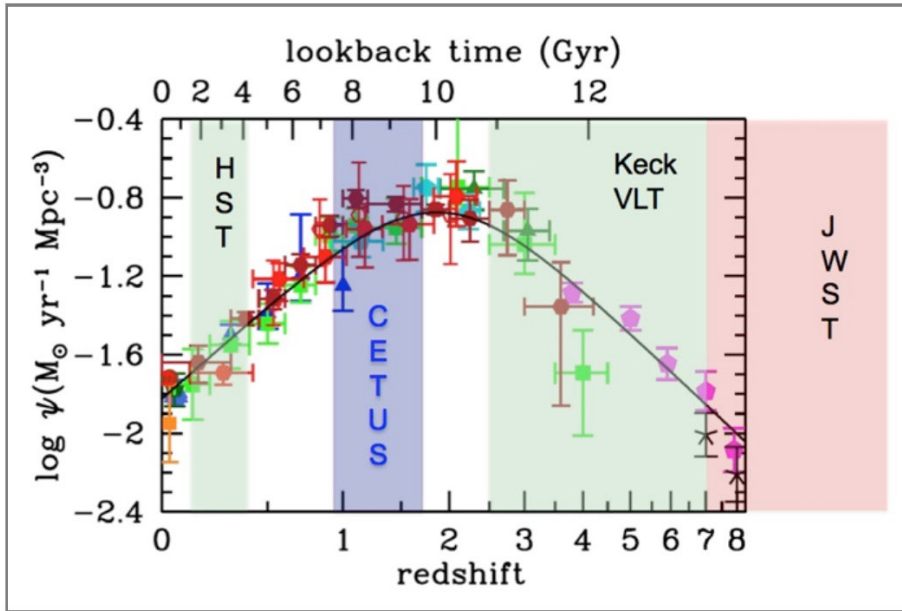


Anderson & Sunyaev 2018

COOL TO WARM-HOT GALAXY OUTFLOWS

COOL TO HOT FILAMENTS

CETUS will make the first spectroscopic survey of $z \sim 1$ galaxies in the rest far-UV



Using its NUV MOS, CETUS will obtain $>10^4$ NUV (rest FUV) spectra of $z \sim 1$ galaxies to compare with HST UV spectra at low z . Figure adapted from Madau & Dickenson (2014)

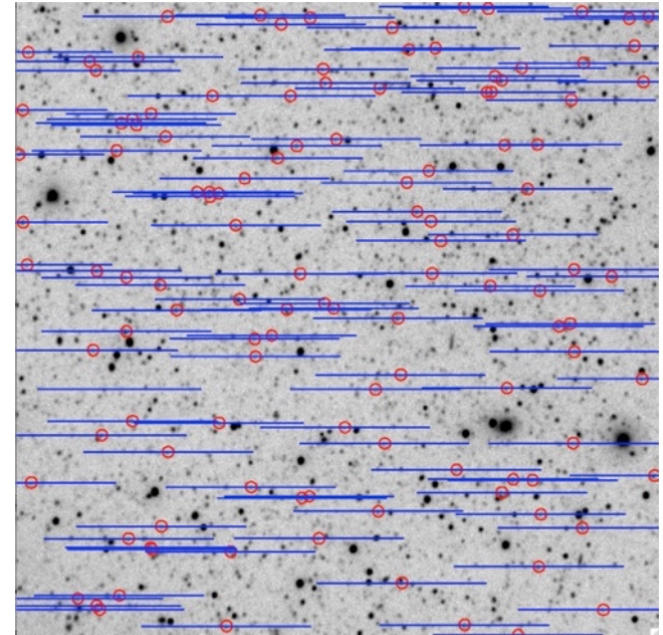
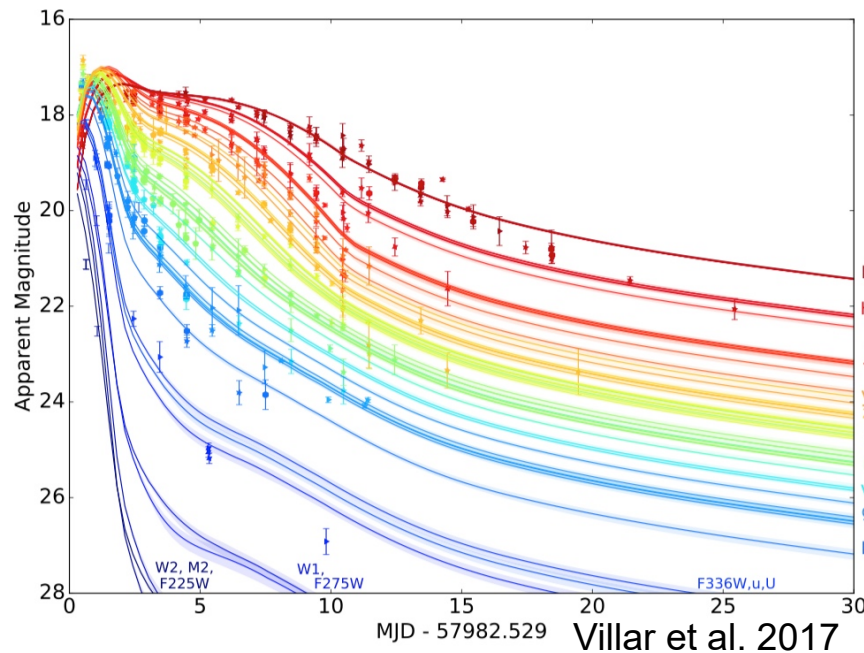


Figure 2-17. The CETUS MOS will obtain spectra (blue lines) of up to ~ 100 galaxies brighter than $m=24.3$ AB (circled in red) in the field of view of the MSA.

CETUS will have rapid response (<15-min slew to target) to catch and monitor transients in the UV

Light curves of GW 170817



FUV Light curves of CCSN

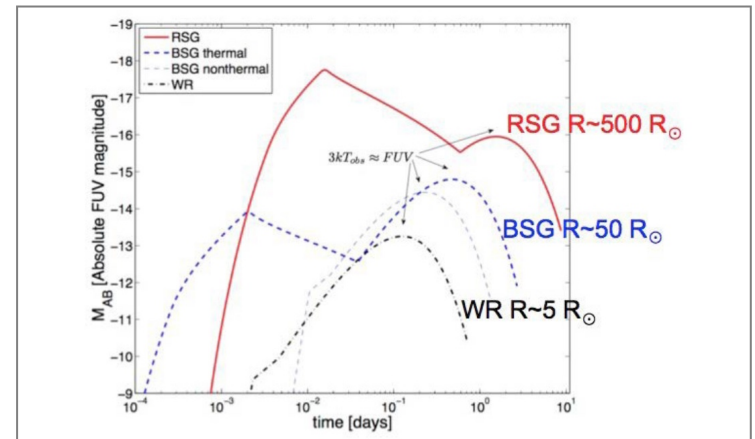
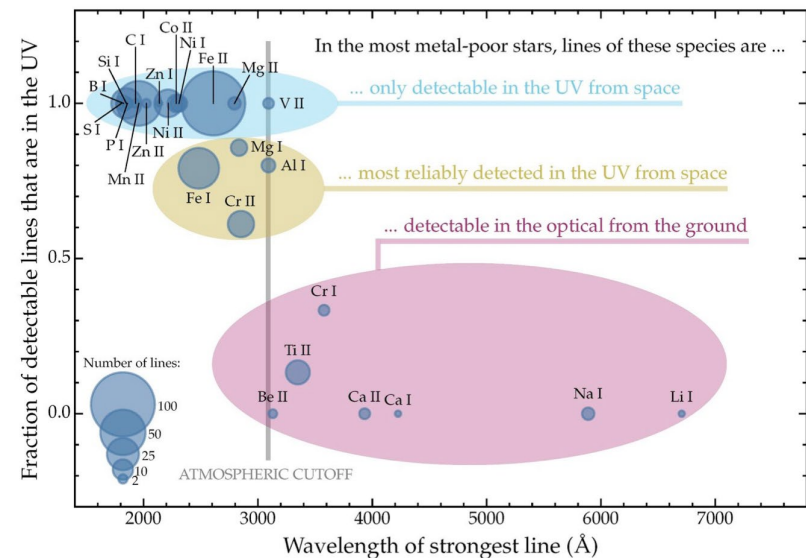
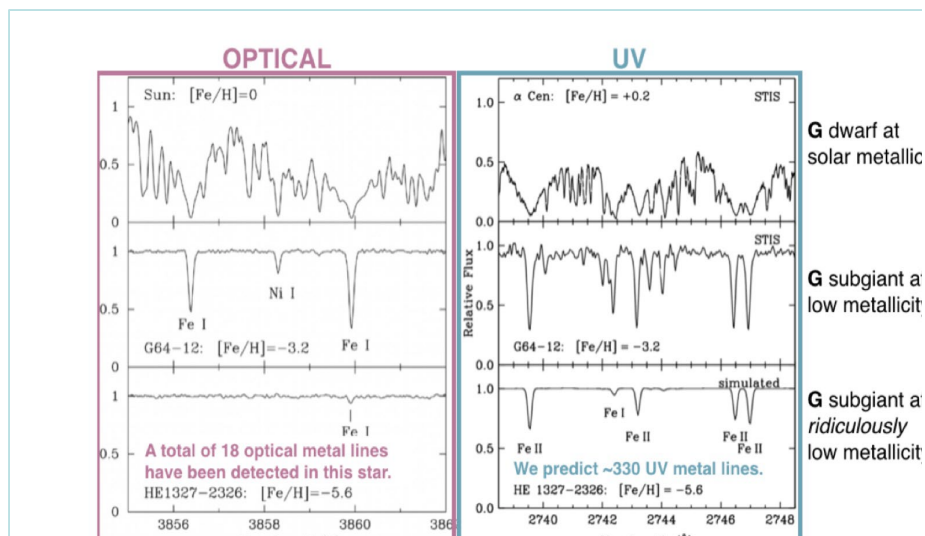
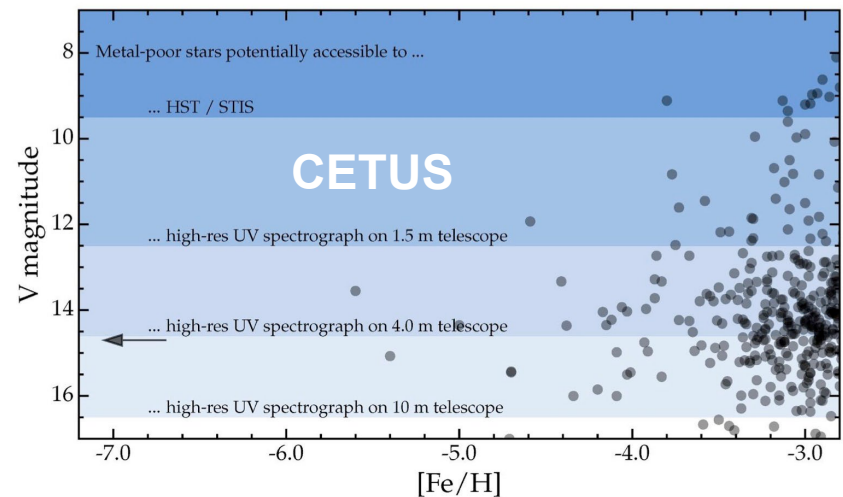


Figure 2-23. CETUS will infer the progenitors of core-collapse supernovae from their FUV light curves. (Figure credit: Nakar & Sari, 2010)

CETUS will chart the metal enrichment in the early universe



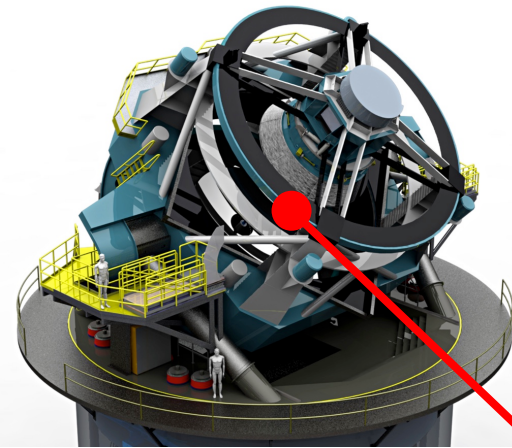
The near-UV is rich in spectral diagnostics of metals (top-L) which enable detection of many more metal lines in the most metal-poor stars (top-R). CETUS will observe a larger sample of metal-poor stars than is available to HST's STIS spectrograph (bottom-R).



Credit: Ian Roederer, Astro2020 Science WP.

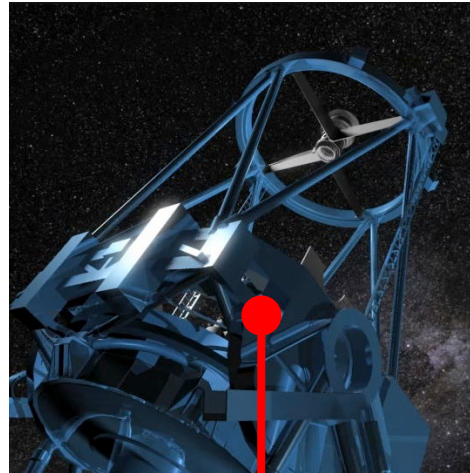
Survey mode: CETUS will work with other telescopes of the 2020's to solve major problems in astrophysics

Transient Science



LSST (opt)

Cosmic Evolution



Subaru, Euclid, WFIRST

Star formation, gas, dust



ALMA mm--sub-mm)

Accreting BHs, hot CGM

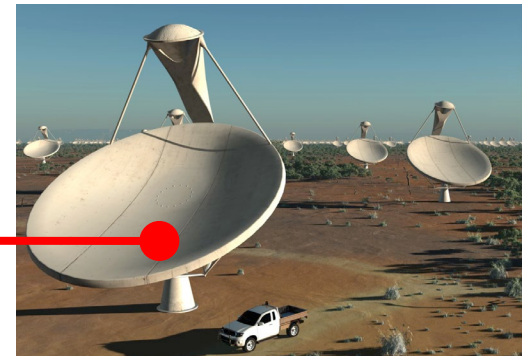


E-Rosita (X-ray)
Chandra, XMM

CETUS

(ultraviolet)

21cm at $z < 0.4$

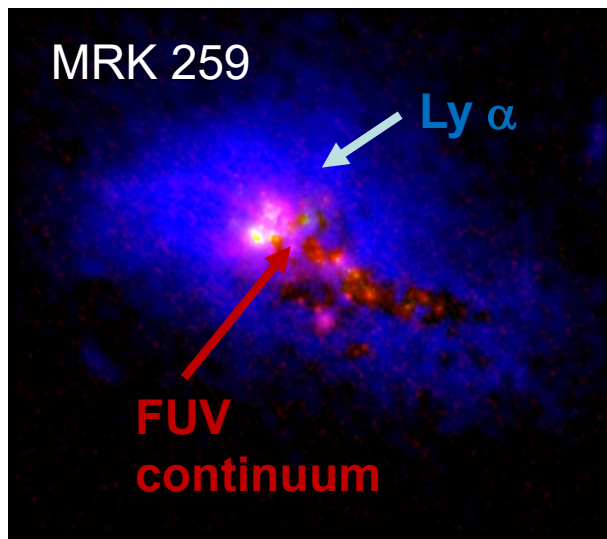


VLA, SKA etc. (radio)

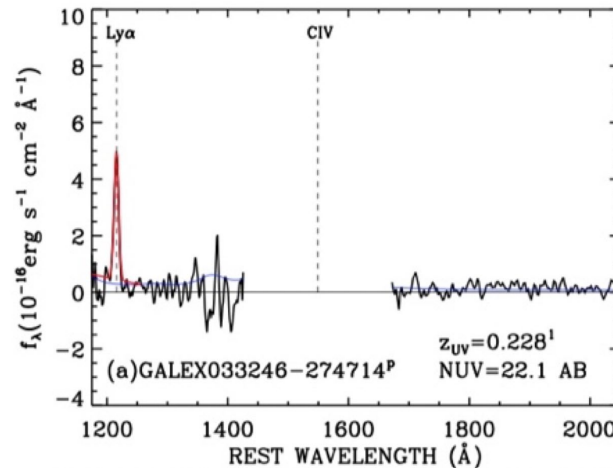
Discovery mode: CETUS will find "what's out there"

All observations can be done in parallel

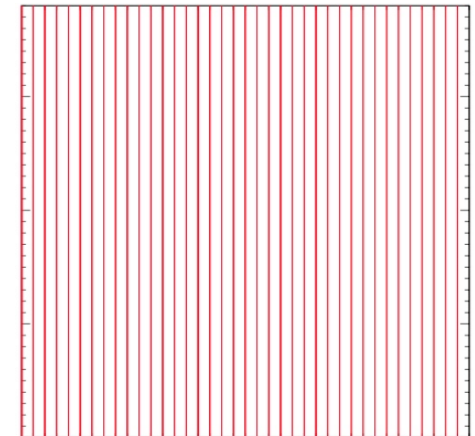
FUV filter imagery



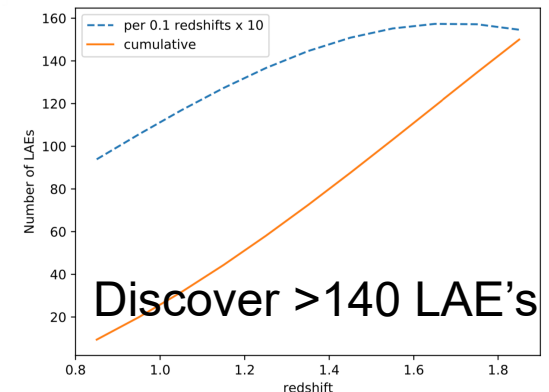
FUV long-slit spectra



NUV MOS long-slits



Discover {25,35,30}
new galaxies at
 $\langle z \rangle = \{0.05, 0.15, 0.27\}$
with 1000X FOV



Credit: M. Hayes (priv. comm.), I. Wold+ (2017)

CETUS science-ready data will be available to all

Published online 6 February 2009 | Nature |
doi:10.1038/news.2009.81

News

The world's top ten telescopes revealed

The best observatories ranked by their scientific impact.

Eric Hand

It doesn't take a big mirror to have a big impact. The Sloan Digital Sky Survey, a project conducted with a modest 2.5-metre-wide telescope in New Mexico, performed the most highly cited science in 2006, according to a new analysis of the top ten 'high impact' astronomical observatories¹.

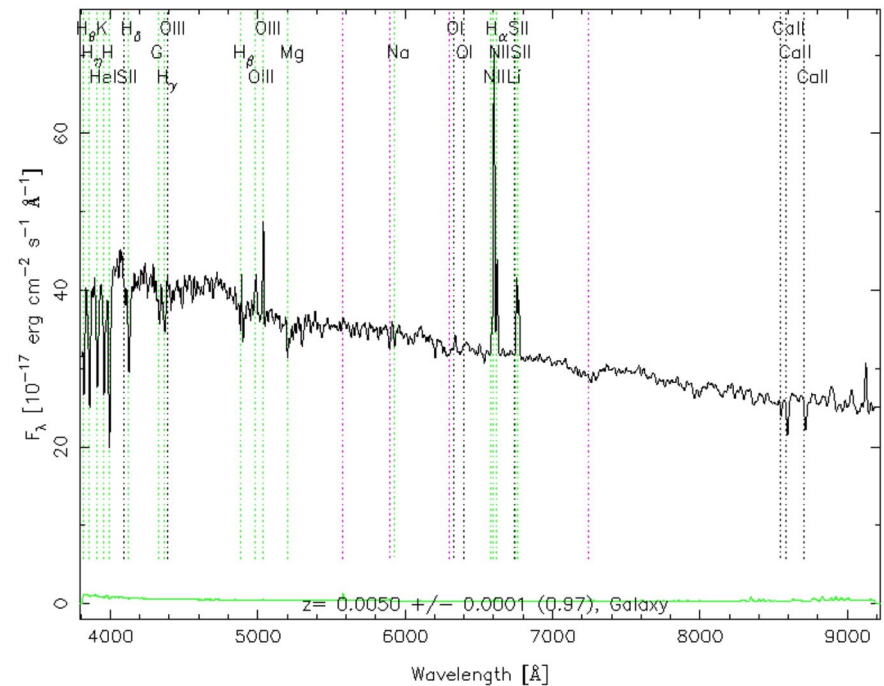


SDSS image of Messier 51, the Whirlpool Galaxy.

Sloan Digital Sky Survey

SDSS J011530.44-005139.5

RA=18.87684, DEC=-0.86095, MJD=51789, Plate= 398, Fiber=282



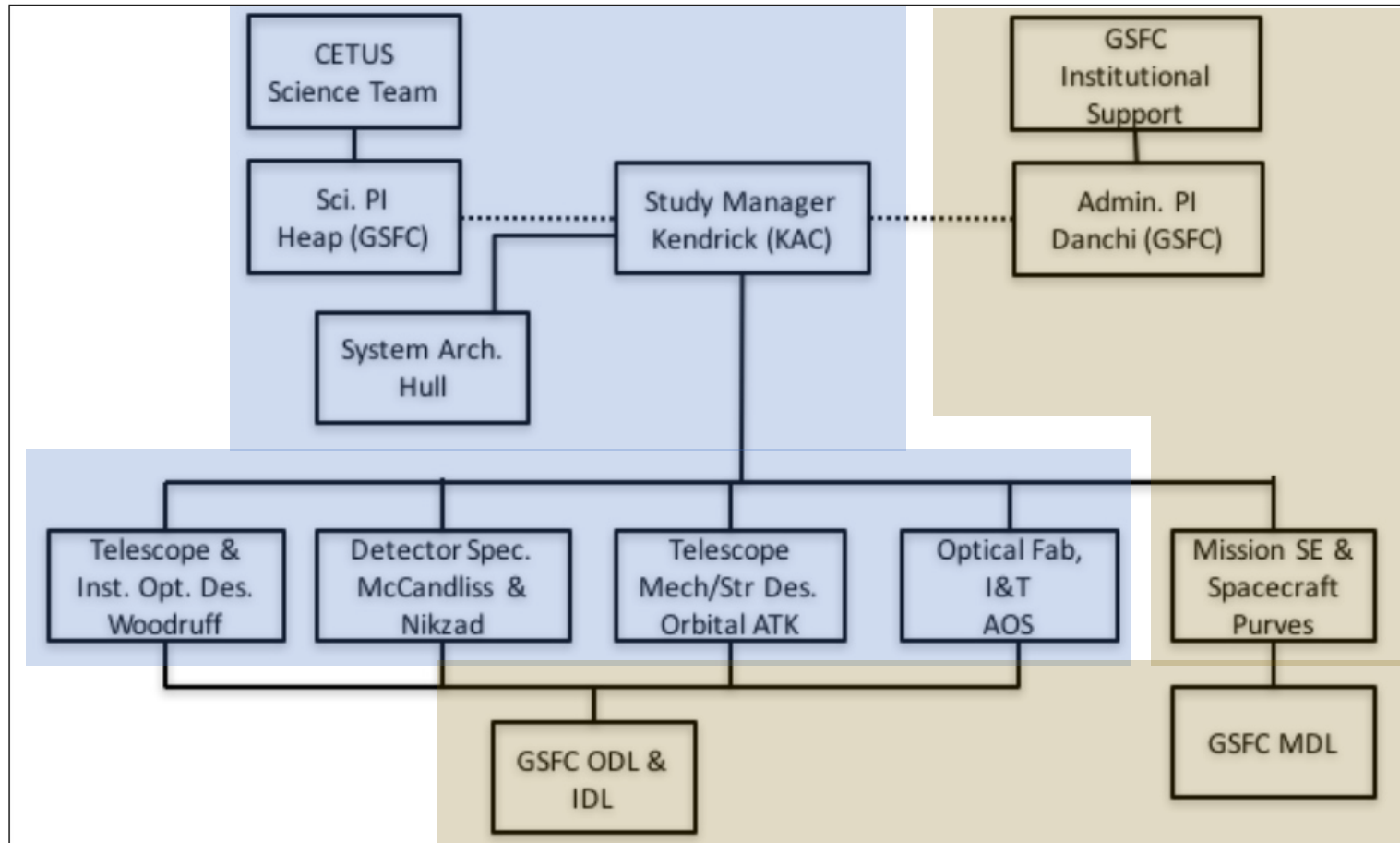
CETUS Surveys (us) vs. CETUS Spectroscopy (Goddard)

- **Same science** during formal Probe study period (ended March 4, 2019) since CETUS Spectroscopy adopted our science goals and program
- **Same optical design**, since our design was adopted by CETUS Spectroscopy team
- **Different implementation** due to:
 - Different team members, roles and responsibilities
 - Different technical approach
- **Different implementation yielding:**
 - Different cost estimates based on different methodologies
 - Different schedule

Different team members, roles and responsibilities (1/2)

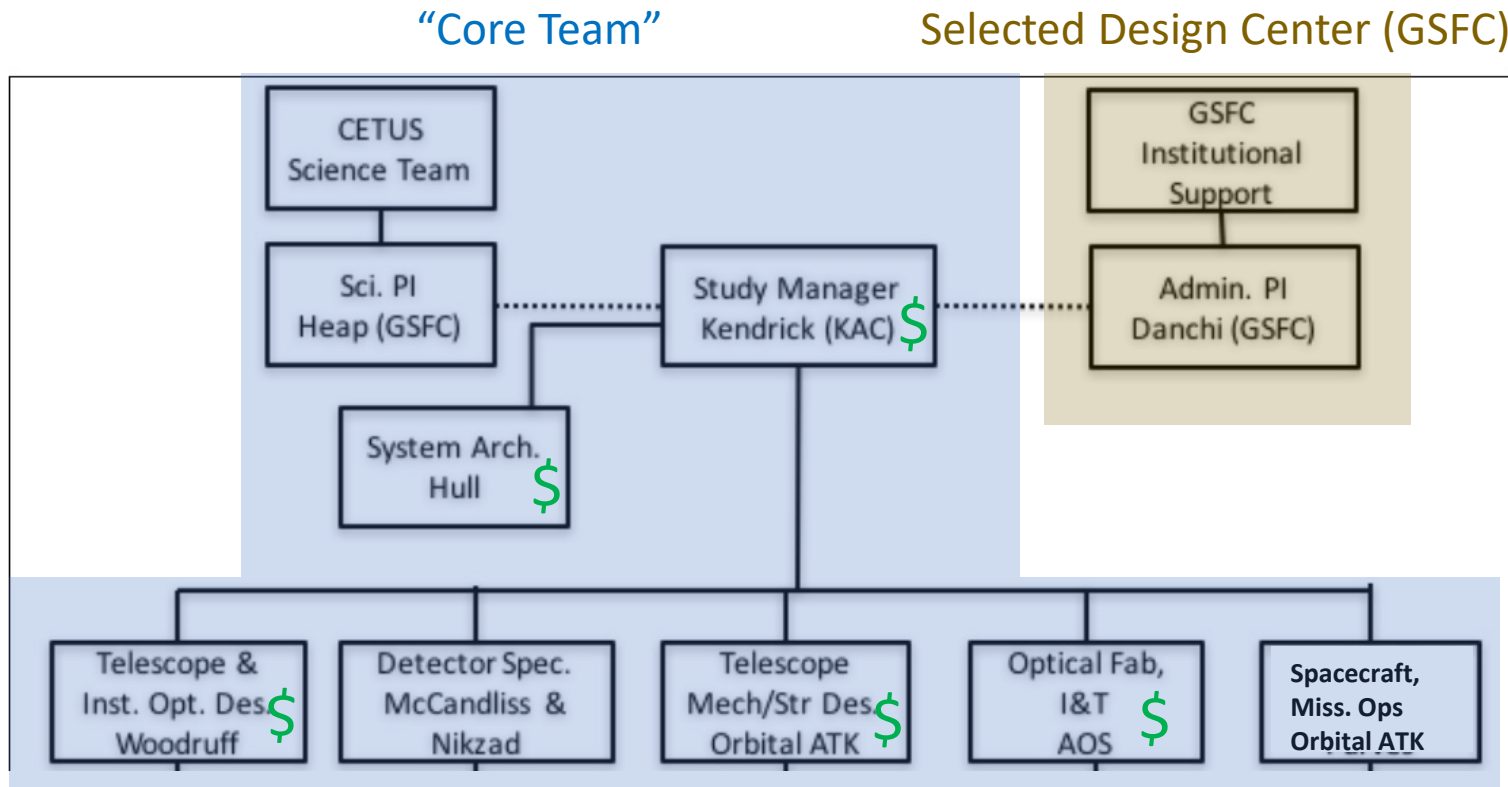
“Core Team”

Selected Design Center (GSFC)



Proposed CETUS Org Chart (Nov. 2016)

Different team members, roles and responsibilities (2/2)



\$ Partially funded by NASA HQ for study

CETUS Surveys Org Chart 2018-

Different technical approach

Our technical approach (from CETUS Proposal, 15 November 2016)

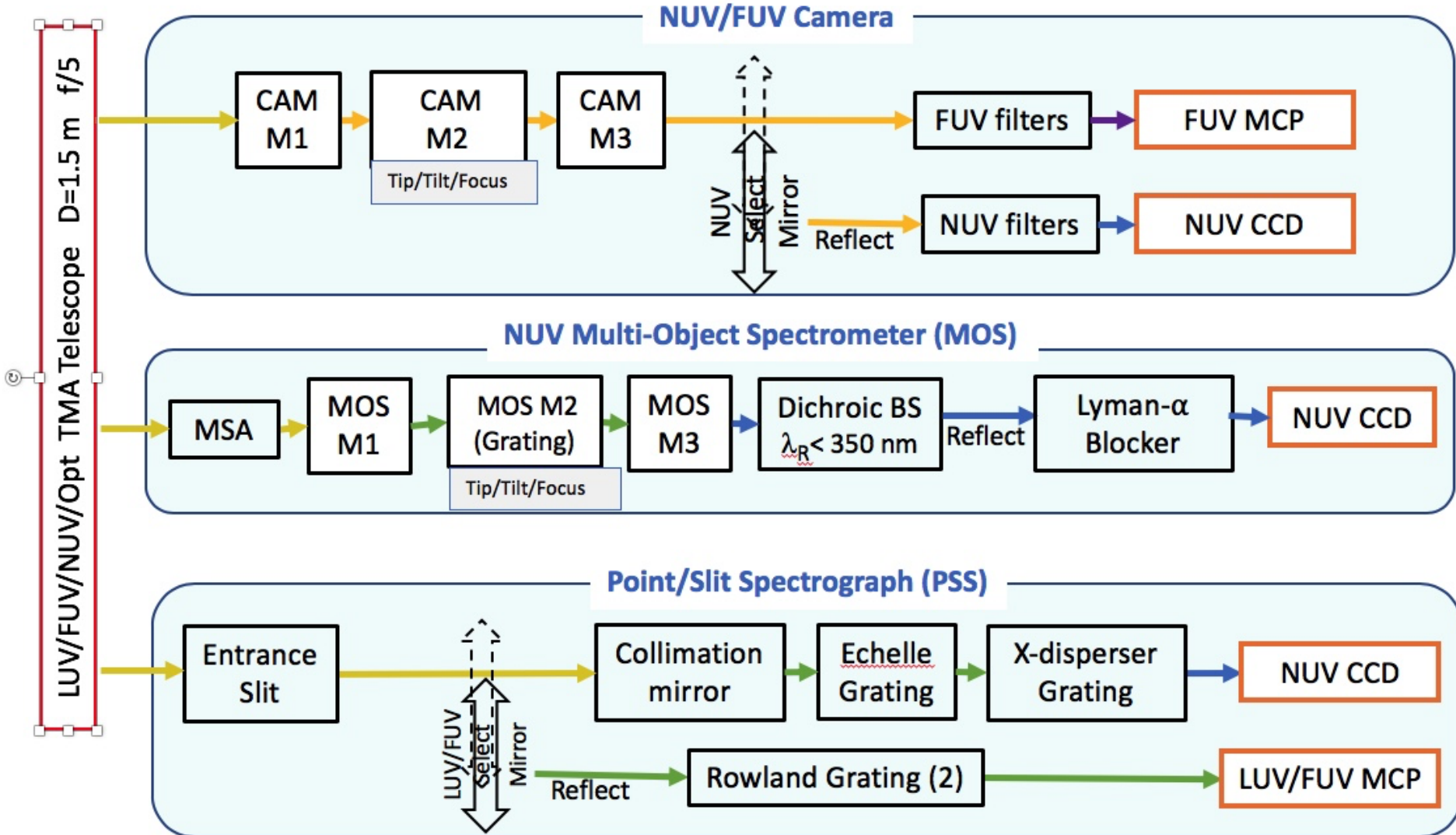
- “In order to be useful, a paper study like this must be realistic.
- To be realistic, we must go about our study with the mindset of people actually developing the CETUS mission.
- **Our technical approach in a nutshell is: Go to the Experts**, who have developed numerous space missions similar to CETUS.”
- We will develop the CETUS mission concept for both performance and cost”.

... And go to the experts we did!

The CETUS Core Team has world-class industrial partners

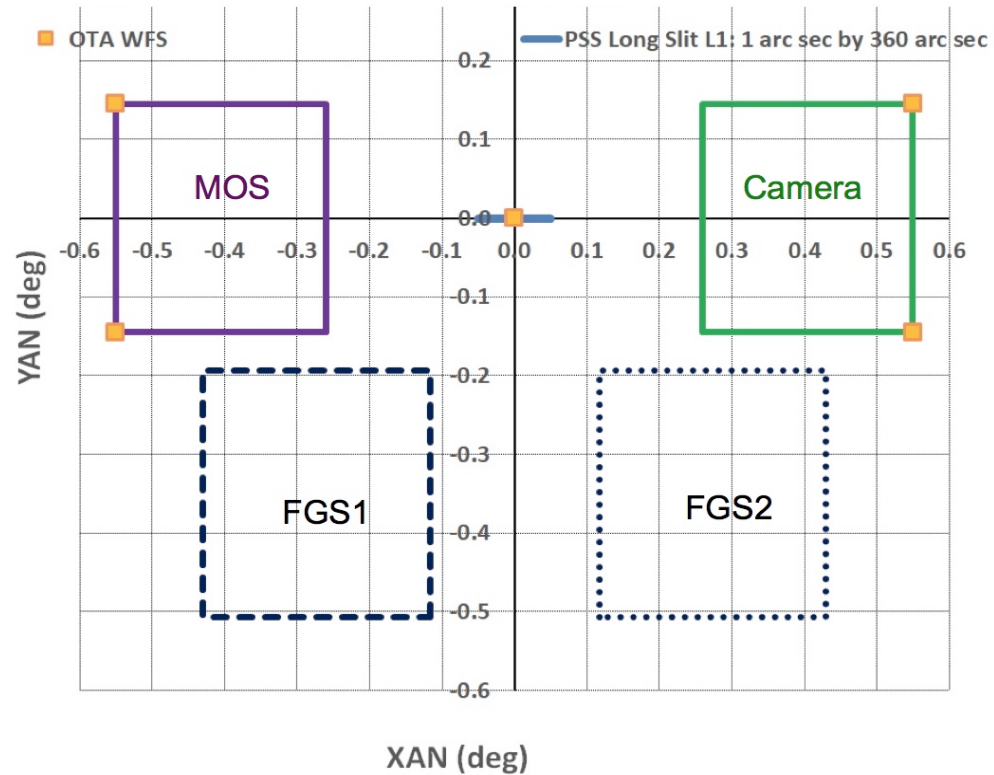
- There is nothing in CETUS that they haven't done before
- They carried out the study based design-to-cost methodologies using space-flight comparables
 - Optics, opto-mechanics and structures a concurrent effort of highly regarded, experienced designers : Greg Mehle & Kelly Dodson of NGIS San Diego with Bob Woodruff (Woodruff Consulting), Jim Burge, Marty Valente (AOS), Steve Kendrick (Kendrick Aerospace Consulting), and Tony Hull (UNM)
 - Spacecraft & Mission Ops by Chip Eckles and John Dyster (NGIS Gilbert, AZ) closely follows the recent heritage of TESS

**Instruments are much simpler than Hubble instruments,
yet fulfill CETUS science requirements (and more)**

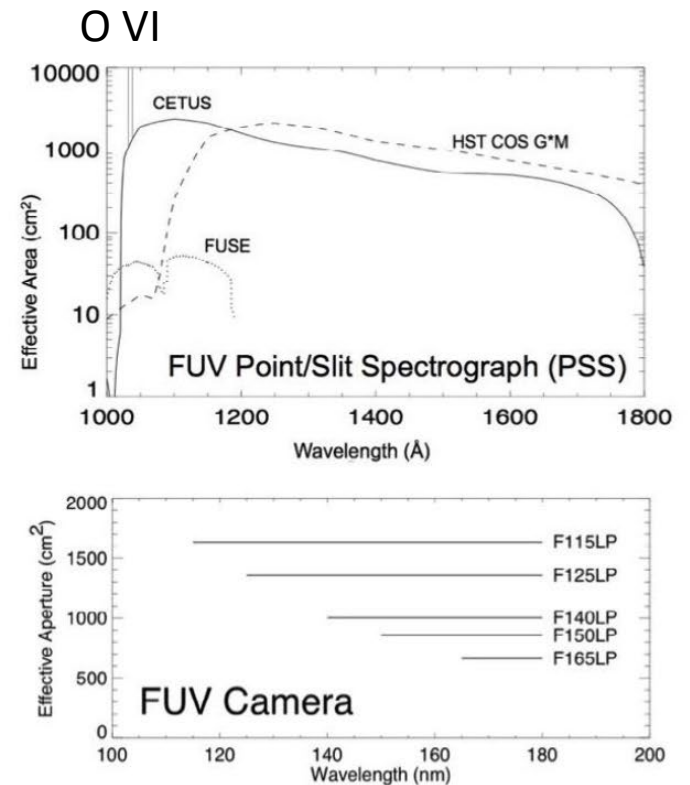
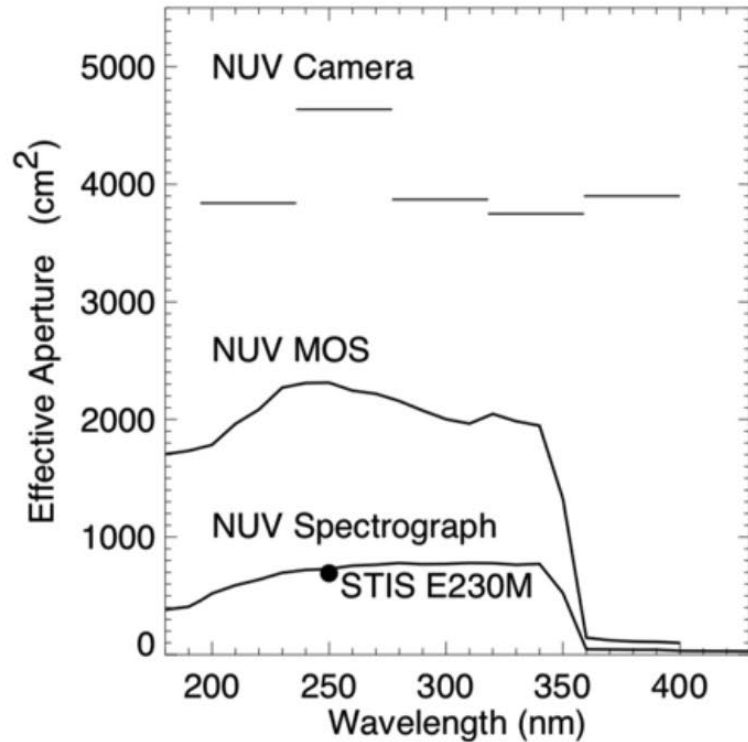


Global design of science instruments yields complementarity, ease of build up, and consistency through a common Interface Control Document (ICD)

- Each instrument has its own aperture
- An instrument can be inserted or removed from the instrument bay without disturbing the others
- Instruments can operate in parallel with the others
- Prime instrument sets the telescope pointing, roll angle, and time on target
- The NUV MOS can scan the sky while the telescope pointing stays fixed



Effective Apertures of the Science Instruments



The CETUS Core Team has selected excellent suppliers of high-heritage components (1/2)

Instrumentation - Source	Needed by CETUS	TRL/NOTES
1.5-m ZERODUR telescope with greatly reduced MSF artifacts of HST <i>Source: Collins (or L3HARRIS)</i>	Telescope	TRL 7-8
Broadband FUV coating: Al + eLiF+MgF2 <i>Source: Collins-JPL collaboration</i>	- LUV/FUV spectrograph 1.5-m telescope	TRL 7 for <0.5-m mirrors TRL 3 for 1.5-m telescope PM Path to TRL 6 in planning stage, plan expected in 2021
Next-generation micro-shutter Array (NG-MSA) <i>Source: GSFC</i>		TRL 7 for 128x64 NG-MSA (rocket) TRL 5 for 840x420 NG-MSA by Dec. 2021 (SAT) TRL 6 (Dec 2022) extended SAT?
Large-format CsI MCP <i>Source: Berkeley SSL</i>	50 mm x 50 mm CsI MCP 200 mm x 70 mm CsI MCP	TRL 7+ multiple space flights including extreme radiation environment in planetary exploration TRL 7 Rocket (200mm X 200mm)
Large-format 4kX4k CCD <i>Source: Teledyne-e2v</i>	NUV MOS NUV camera NUV R~40,000 spec'graph	TRL 8 (Euclid CCD, e2v CCD273-84) Euclid camera design/qualification available to us too

CETUS will be better than Hubble. It will find and make reliable measurements of the missing baryons at low-z

HST mirror surface errors

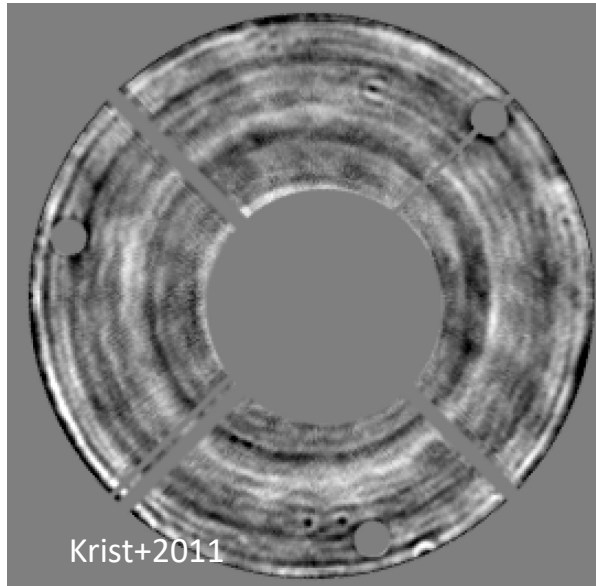


Figure 2. Map of the combined primary and secondary mirror surface errors left from polishing obtained using phase retrieval on highly defocused star images. Shown between ± 30 nm surface error. The HST and WFPC2 obscuration patterns are superposed.

HST/COS line spread function

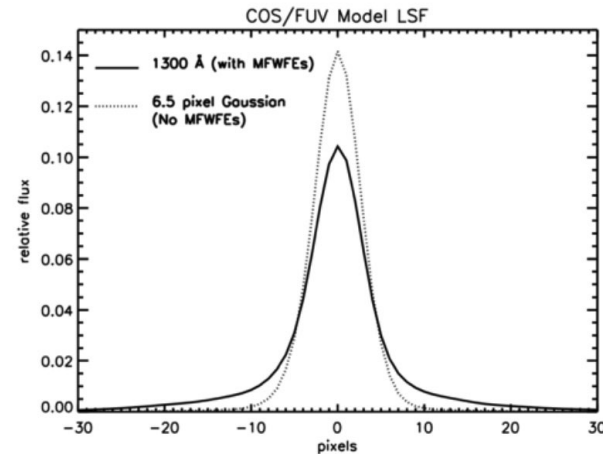


Figure 2-15: Spectral lines in CETUS spectra will have Gaussian profiles leading to accurate measurements of line strengths.

Ghavamian
COS ISR 2009-1

O VI absorption lines in CETUS spectra will be free from systematic error (underestimate of line strength)

5. ASSESSMENT OF MATURITY AND RISK

Operation	Description	TRL *	Residual Risk
Substrate Manufacture	Schott machining of lightweight substrate and passivation of machines surfaces	9 Multiple lightweight machined zerodur mirrors	Dependent on details of mirror design, but expectation is to specify features within proven capabilities
Optical Fabrication and Metrology	Polishing and verification of optical surface to required figure spatial frequency content	9 Mature, proven processes	Specific manufacturing sequence and details to achieve desired low mid-spatial frequency errors
Edge Mounting	Danbury	9 Multiple space borne mirror using this approach	Selection of epoxy compatable with coating processes
Coating	Application of durable coating providing desired end-of-life performance across required wavelenths	Unknown NASA to assess	Danbury silver coating is TRL 9, but does not provide required UV reflectivity. Unsure of maturity of UV coatings.

*Cannot be verified because it is not in the public domain

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The CETUS far-UV detector will be much better than Hubble's

	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 (cross-dispersion)
Low gain operation	10^6	10^7
Higher dynamic range	≥ 5 MHz count rates	60 KHz global count-rate limit
Ultra low MCP background	< 0.05 events/sec/cm ²	1-2 events/s/cm ²
High UV QE	60% @ 115nm	26% @ 133 nm, 12% @ 156 nm
Solar-blind cutoff		
Long stable lifetimes	$> 5 \times 10^{13}$ 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

The CETUS Core Team has selected excellent suppliers of high-heritage components (1/2)

Instrumentation - Source	Needed by CETUS	TRL/NOTES
1.5-m ZERODUR telescope primary mirror <i>Source: Collins (or L3Harris)</i>	Telescope	TRL 7-8
Broadband FUV coating: Al + eLiF+MgF2 <i>Source: Collins-JPL collaboration</i>	- LUV/FUV spectrograph 1.5-m telescope	TRL 7 for <0.5-m mirrors TRL 3 for 1.5-m telescope PM Path to TRL 6 in planning stage Plan expected in ~2021
Next-generation micro-shutter Array (NG-MSA) <i>Source: GSFC</i>	NUV R~1000 MOS	TRL 7 for 128x64 NG-MSA (rocket) TRL 5 for 840x420 NG-MSA by Dec. 2021 (SAT) TRL 6 (Dec 2022) extended SAT?
Large-format CsI MCP <i>Source: Berkeley SSL</i>	50 mm x 50 mm CsI MCP 200 mm x 70 mm CsI MCP	TRL 7+ multiple space flights TRL 7 Rocket (200mm X 200mm)
Large-format 4kX4k CCD <i>Source: Teledyne-e2v</i>	NUV MOS NUV camera NUV R~40,000 spec'graph	TRL 8 (Euclid CCD, e2v CCD273-84) Euclid camera design/qualification available to us too

The CETUS Core Team has selected excellent suppliers of high-heritage components (2/2)

Instrumentation - Source	Needed by CETUS	TRL/NOTES
Spacecraft <i>Source: NGIS (Gilbert AZ) (formerly Orbital ATK)</i>	CETUS Observatory	TRL 7+ All components are TRL 7-9, heritage from TESS



<https://www.nasa.gov/content/tess-images>

In our plan, CETUS will be obtaining important observations 10 years from today!

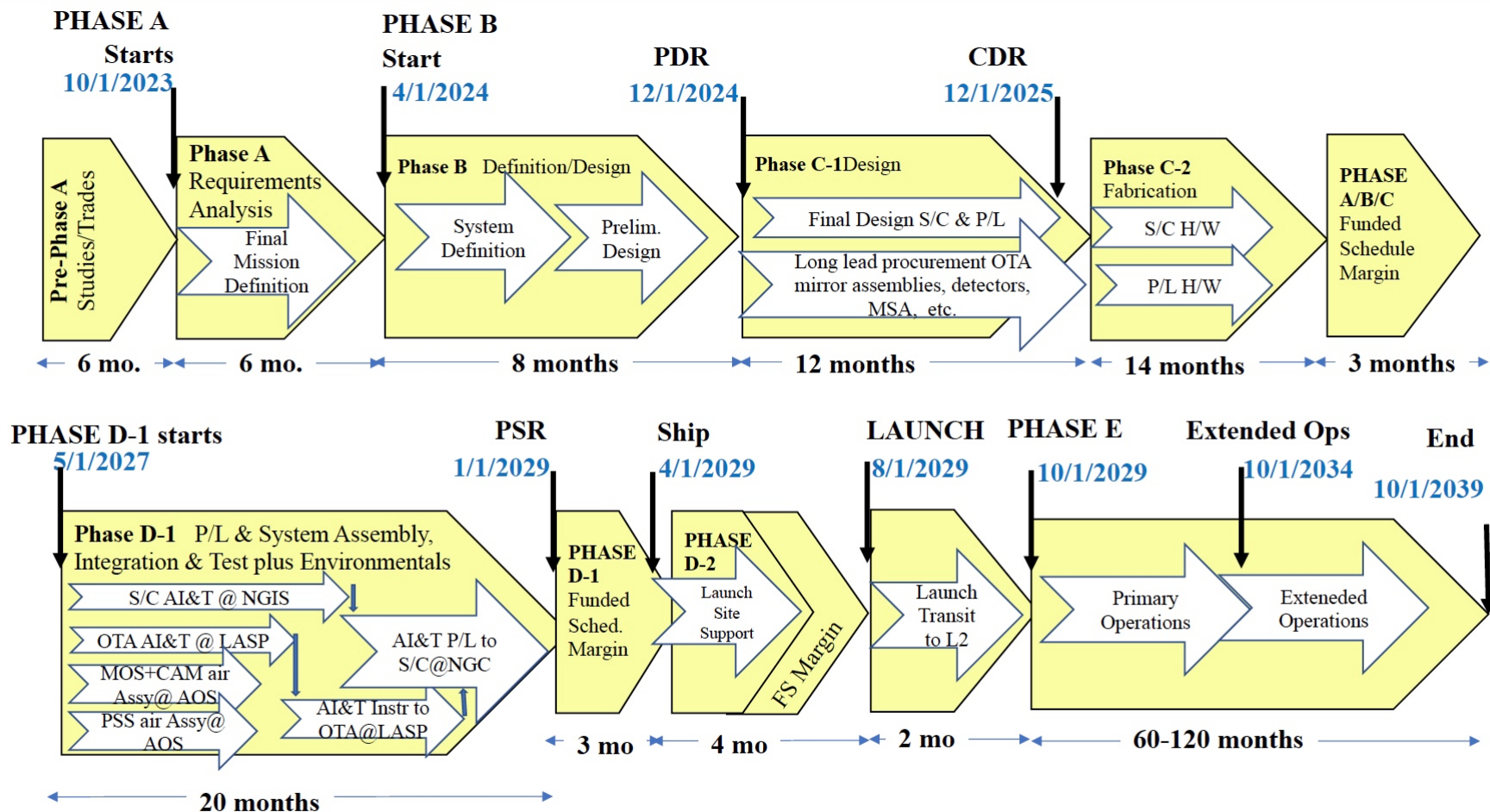
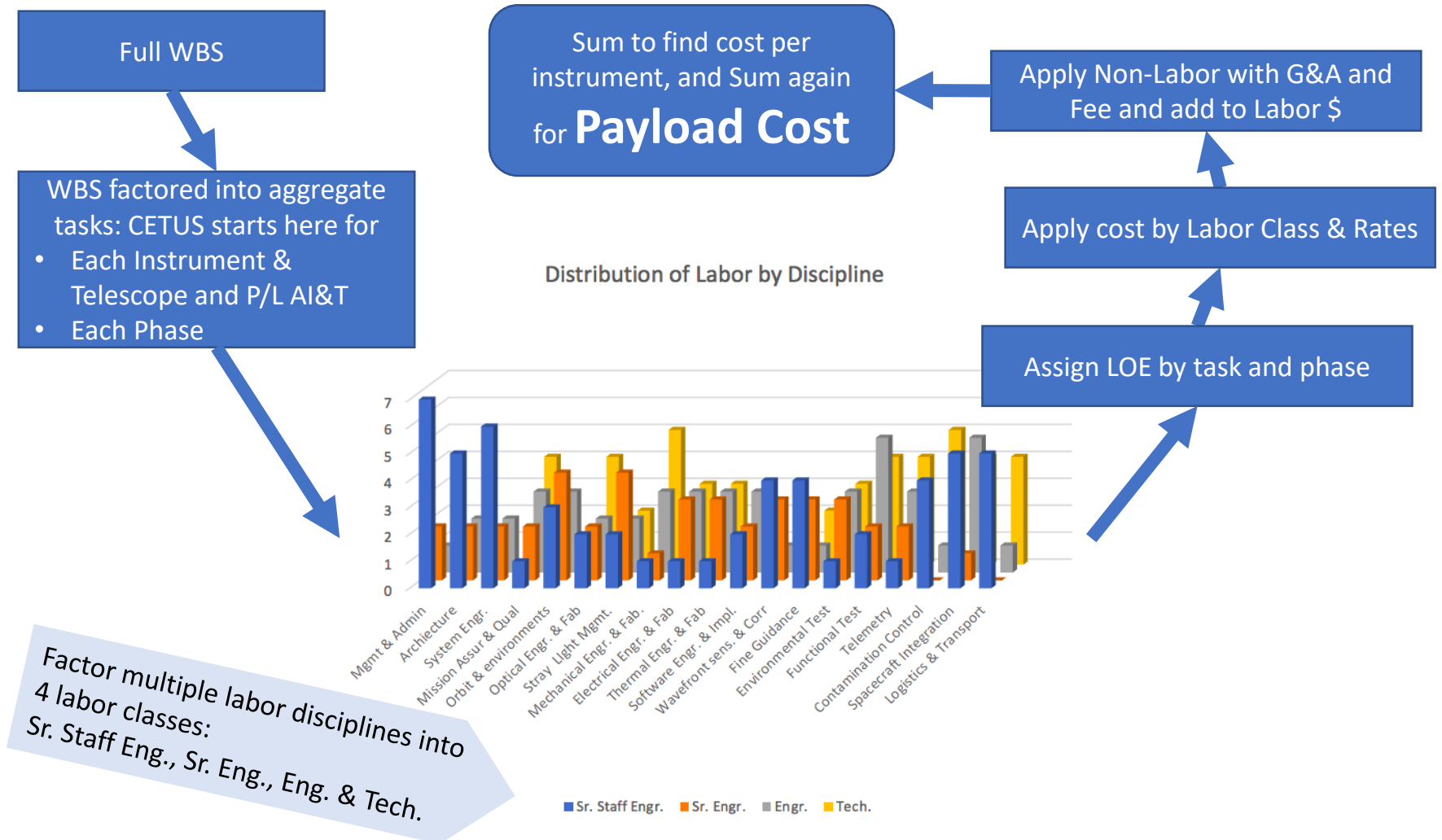


Figure 7-2. The CETUS schedule defines a realistic mission timeline for the 1.5-m telescope, scientific instruments, spacecraft, and AI&T at high-cleanliness UV-compatible facilities. It

Method of Deriving the Cost of CETUS Surveys



The cost of a CETUS 5-year mission is within the range of a Probe

WBS #	Phase	Cost Estimate	Notes
Phase A-D			
1.0-3.0	Management, SE, MA	\$60 M	
4.0	Science Preparation	\$8 M	Includes: monitoring CETUS hardware development; building/modifying s/w for levels 1,2,3 science data processing & s/w for measurement & on-line catalogs; participation in pre-launch test and calibration
5.0	Payload (Instruments, Telescope)	\$395 M	Based on industrial & institutional input from NGIS (Gilbert), NGIS (San Diego), Collins Aerospace, Harris Aerospace, SCHOTT, LASP (CU), Teledyne-e2v, JPL, GSFC, AOS, NGC. Multiple telescope cost models were used to derive the telescope cost estimate.
6.0	Spacecraft	\$164 M	NGIS (Gilbert) based on significant TESS similarities and TRL 7-9 hardware
10.0	Observatory I&T(ATLO)	\$20 M	NGIS (Gilbert)
	30% Reserve Phase A-D	\$194 M	
Phase E			
1.0 - 3.0	Management, SE, MA	\$2.4 M	
4.0	Science	\$30.0 M	Includes: planning & scheduling, post-observation data processing at Penn State Univ; archival & analysis center at JHU; measurements & catalogs by TBD
7.0	Mission Operations	\$15.0 M	NGIS (Gilbert); 5 yrs mission baseline; consumables for 10 yrs
9.0	Ground Data Systems	\$2.5 M	
	15% Reserve Phase E	\$7.5 M	
	Subtotal before Launch Vehicle	\$898 M	
	Launch Vehicle/ Launch Services	\$110 M	Space X Falcon 9 baselined in initial study, but to gain mass margin, we adopt the Falcon 9 Heavy (\$90M plus \$20M for launch services) https://www.spacex.com/about/capabilities
	15% Reserve on Launch Vehicle	\$16.5 M	
	CETUS Total Cost	\$1,025M	

Justification of CETUS as a Probe-Class Mission ($\leq \$1.0$ B) (1/2)

1) Design-to-cost decisions

- Telescope diameter ≤ 1.5 m co-optimizes science and cost
- Resolution set by 1 pixel on the sky (0.33") rather than the Rayleigh criterion $1.22 \lambda/D$, relaxing requirements on optics, pointing stability, thermal system, etc.
- Same detector for all 3 NUV instruments; same type of FUV detector (CsI MCP) for both FUV instruments
- Complicated STIS-like imaging spectrograph split into two simple instruments: camera and spectrograph
- The instrument suite is modular, tolerant of insertion or removal from instrument bay
- Instruments can observe in parallel

2) Highly successful industrial partners and component suppliers in areas relevant to CETUS science requirements

Justification of CETUS as a Probe-Class Mission ($\leq \$1.0$ B) (2/2)

3) Selection of high-TRL components or on their way to high TRL

4) Thorough, transparent cost estimate of CETUS yielding ~\$1.0B, **ready for analysis by Aerospace**

- Cost estimation by methods typically used by industry enabled by maturity of CETUS mission concept
- Technical, TRL, schedule, cost risk considered
- Redundancy between MOS and CAM, and reuse of CCD and MCP detector systems incorporated
- Use of NGIS (Gilbert AZ) design and cost estimate of spacecraft bus using TRL 7-9 parts

5) Confirmation of cost estimates and differences with GSFC through spot checks:

Item	\$ Goddard	\$ Core Team	\$ Goddard / \$ Core Team
IDL – Camera M1 mirror	\$ 3.3M	\$ 0.9M for 2 mirrors	3.6 X
MDL – Spacecraft bus	\$409M	\$198M (NGIS Gilbert)	2.1 X

Public Documents Available to Astro2020 / EOS-1:

Heap_CETUS_Cost_Guide.pdf

Heap_CETUS_Cost Workbook.xlsx

GUIDE TO CETUS COST WORKBOOK

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(1) U. New Mexico; (2) Kendrick Aerospace Consulting LLC

Contact: tonyhull@unm.edu, land +1 (505) 771-8566, cell +1 (510) 672-2499

1.0 Objective, Scope and Context

This document provides a guide to the cost estimate of CETUS as given by the accompanying Excel workbook, *CETUS Core Team Cost, Version 190620 C*. Our objective is to be a public, self-contained, readable description of CETUS costing by the CETUS Core Team, but auxiliary information may be obtained from other public documents such as the *CETUS Final Report* posted in September 2019 at ArXiv.org 1909.10437. To obtain proprietary information, please contact Tony Hull using the contact information given above.

We first digress to explain the meaning of CETUS "Core Team". It is shown graphically in Figure 1 by the blue shaded region of the CETUS organization chart. The Core Team comprises the proposers in response to an NRA for astrophysics Probe studies. It also includes Orbital ATK (now NGIS) in Gilbert AZ, which the Core Team engaged in February 2018. All NASA study funds went to members of the Core Team and industrial partners as indicated by the green dollar sign. The Core Team proceeded to carry out a study of the CETUS science payload, while NGIS (Gilbert) studied the spacecraft and mission operations.

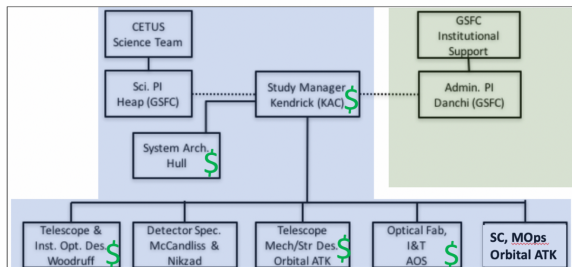


Figure 1. CETUS Organization Chart, valid from February 2018. The blue shaded region encompasses the CETUS "Core Team", while the green shaded region shows the institutional support by Goddard. The green dollar signs designate recipients of NASA HQ study funds.

CETUS (Surveys) Cost Workbook

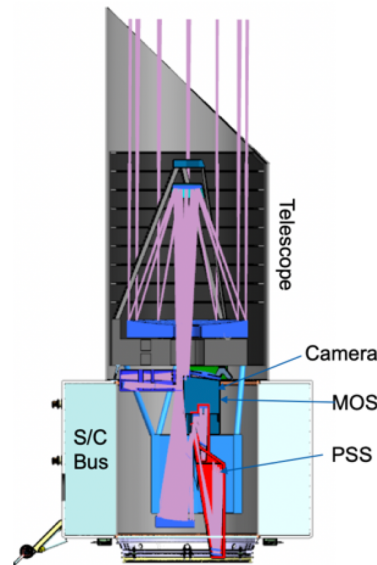
Document 190620 C3: CETUS Core Team COST

By Tony Hull & Steve Kendrick

tonyhull@unm.edu

With supporting data from:

- ✓ Arizona Optical Systems, Tucson
- ✓ Collins Aerospace, Danbury
- ✓ CU LASP, Boulder
- ✓ GSFC, Greenbelt
- ✓ Horiba JY, Piscataway
- ✓ JPL, Pasadena
- ✓ L-3HARRIS, Rochester
- ✓ MSFC Huntsville
- ✓ NGC, Redondo Beach
- ✓ NGIS, Gilbert
- ✓ NGIS, San Diego
- ✓ SCHOTT AG, Mainz
- ✓ SDL, Logan
- ✓ SSL, Berkeley
- ✓ Teledyne e2v UK
- ✓ ZeCoat, Los Angeles
- ✓ ZEISS Germany



DECADAL SURVEY ON ASTRONOMY AND ASTROPHYSICS 2020 STEERING COMMITTEE MTG. 1

02_Hertz_NASA_Astro2020_July2019

- *Probes are strategic missions...*
- *Project management [of strategic missions] is generally directed to a NASA Center*

Options for 2020 Decadal Survey

- *Do not recommend a medium mission in Astro2020*
- *Recommend specific probe(s) as medium-size strategic missions*
- *Recommend several specific science concepts for an AO (New Frontiers)*
- *Recommend an unconstrained AO (Super-Explorer)*

**If a UV Probe is recommended by Astro2020,
competition will lead to the most cost-effective solution**

Competition is good ...

From: **Mather, John C. (GSFC-6600)** <john.c.mather@nasa.gov>

Date: Thu, Jan 23, 2020 at 12:12 PM

Subject: Re: [EXTERNAL] competition

To: Sara Heap <sara.heap@gmail.com>

Hi Sally,

Glad you like the thought. Here's my quotable version:

Competition is good because it calls forth our creativity to reach as far and as high as we can imagine. It's also good to have a trustworthy process, so that people with resources can appreciate that the resources will be well used. When the Decadal Survey makes a recommendation, Federal agencies, private fund sources, international partners, and Congress all listen. When NASA chooses winners based on competition, we know that the results will be at least wonderful and maybe spectacular.

John

BACKUP SLIDES

Contributors to CETUS STUDY

Scientific Contributors: Maarten Baes, Rachel Bezanson, Luciana Bianchi, David Bowen, Brad Cenko, Yi-Kuan Chiang, Rachel Cochrane, Mike Corcoran, Paul Crowther, Simon Driver, Bill Danchi, Eli Dwek, Brian Fleming, Kevin France, Pradip Gatkine, Suvi Gezari, Lea Hagen, Chris Hayward, Matthew Hayes, Sally Heap, Tim Heckman, Edmund Hodges-Kluck, Alexander Kuttyrev, Thierry Lanz, John MacKenty, Steve McCandliss, Harvey Moseley, Coralie Neiner, Goren Östlin, Camilla Pacifici, Marc Rafelski, Bernie Rauscher, Jane Rigby, Ian Roederer, David Spergel, Dan Stark, Alexander Szalay, Bryan Terrazas, Jonathan Trump, Arjun van der Wel, Sylvain Veilleux, Kate Whitaker, Isak Wold, Rosemary Wyse

Technical Contributors: Jim Burge, Kelly Dodson, Chip Eckles, Brian Fleming, Jamie Kennea, Gerry Lemson, John MacKenty, Steve McCandliss, Greg Mehle, Shouleh Nikzad, Trent Newswander, Lloyd Purves, Manuel Quijada, Ossy Siegmund, Dave Sheikh, Phil Stahl, Ani Thakar, John Vallerger, Marty Valente, the Goddard IDC/MDL.

Options for lowering cost growth of CETUS

- International contributions (total=\$208M)
 - A science instrument: spectrograph (\$69M) or MOS (\$99M)
 - Telescope primary mirror assembly polished and coated (\$20M)
 - NUV detector assembly (e2v CCD) for all three science instruments (\$20M)
 - Software for CETUS science-data processing, calibration
- Descope (total=\$124M)
 - Loss of rapid-response capability (~\$25M)
 - Loss of multi-object spectrograph (\$99M)

Descope decisions may be made as late as PDR

Confidence in cost estimate from *CETUS Final Report*, Section 3.1

It is generally known that >70% of the cost of a product originates from decisions made during concept development and design. Hence, *a mature CETUS concept is essential for identifying and avoiding potential technical, schedule, or cost risk*. Among the cost risks we identified is complexity. We have worked to avoid complexity by:

- Imposing on the three science instruments a common technology in optical configurations, mechanisms, and detectors;
- Designing each instrument for installation in (or removal from) the payload with minimal interference to the other instruments;
- Establishing a single Interface Control Document (ICD) governing the entire space element including science payload and spacecraft including a shared electronic architecture for the detectors and devices used in CETUS; and
- Planning for contamination control starting with assembly of each component and continuing through subsequent AI&T stages and launch.

We have worked to avoid technical and hence, cost risk by:

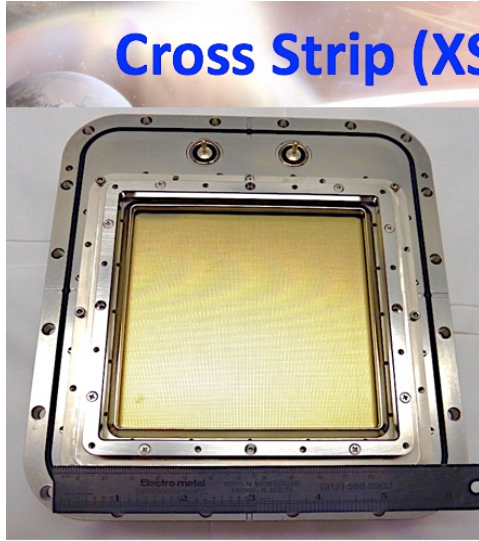
- Selecting high-TRL components, e.g. the space-qualified Euclid CCD. The only component below TRL 5 is the Next-Generation MicroShutter Array;
- Ensuring systems engineering is included in the conceptual design phase. The greater CETUS engineering team worked together, literally working side by side, to develop the optical- mechanical design of CETUS;
- Selecting materials known for their temporal and thermal stability. M55J structural material closely matches the coefficient of thermal expansion (CTE) of extremely stable ZERODUR® OTA mirror substrates. Thus, the design which is nearly athermal by passive means, requires only mild heater controls to ensure robust optical metering performance

Confidence in Cost Estimate. Slide 2

- High level of design and design approach, considering AI&T, provides end-to-end visibility
- Heritage traceable to industrial partners participating in study → High TRL, low developmental
- Team experience with substantial experience in costs of relevant instruments, including those for HST
- Concurrent design and design-to-cost employed from start of CETUS study. Science traceable... “better is the enemy of good enough!”
- Use of industrial element costs, even evaluated competitive costs (e.g. PMA)
- Test of major elements (e.g. OTA) against Aerospace costs (scaled from Exo-C), and against parametric models, and other analyzed OTA's up to 1.8m in diameter
- Full allocation of funded schedule reserve, and NASA prescribed cost margins
- Independence of instruments for AI&T, common ICD, and common sub-assemblies among instruments
- Payload bottom-up and independent top-down costs match to within 5%
- Top-down cost review by selected industrial partners
- Special cost allocations for future facilitation to coat PMA, GSE for AI&T, etc.

Input from Berkeley Space Science Lab. Slide 1

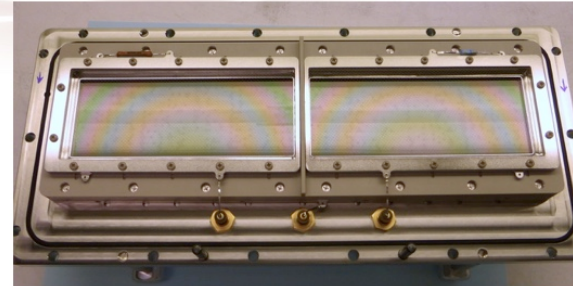
Cross Strip (XS) & ALD MCP Detector Evolution



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

“Open” 100 mm XS detector selected for sub orbital flight(s) in ~2022. Also selected for 100mm sealed tube XS fabrication 2020-3.

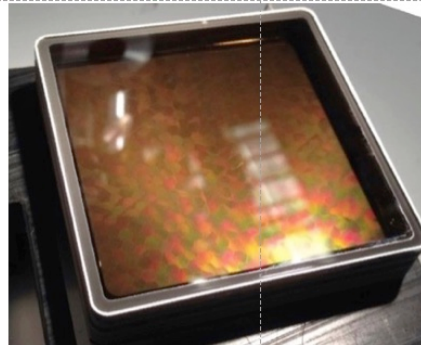
An open face 40 mm XS detector with CsI was flown successfully 4x on CHESS Rocket payload. $\sim 25\mu\text{m}$ resolution @ MHz rates.



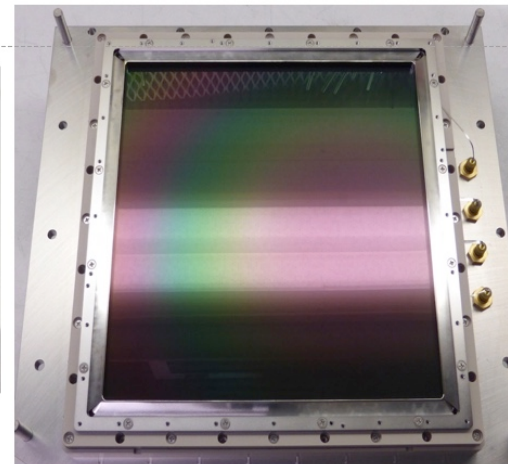
2 x 115mm x 45mm ALD MCP detector with CsI cathode & XDL successfully operated on SISTINE rocket flight in 2019.



SMT Electronics for 100mm XS achieves $<20\mu\text{m}$ FWHM spatial resolution 16k x 16k (digitized) pixel format $>5\text{ MHz}$ global count rate at low $\sim 1.5 \times 10^6$ gain.



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.



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

Input from Berkeley Space Science Lab. Slide 2

MCP Cross-Strip (XS) Detector Risk Reduction

50mm sealed tube. Planacon devices have 15+ year heritage and basis in established night vision practices. SAT program will qualify (TRL 6) the CETUS configuration by 2021 and sub-orbital (TRL 7) infusions are under consideration.

200mm x 70mm open face. Components, MCPs, cathode, have flown multiple times (TRL 7) in 200mm format, 50mm anodes flown 4 times. XS anodes in 100mm format are TRL 6 and selected for 2022 flight. 200 x 70mm format achieved with borderless abutted 2 x 100mm anodes.

Encoding & support Electronics. Existing electronics performs to CETUS specs and has flown 4x. Will need to update EEE component selections & verifications as parts availability changes over time. Same strategy as applied for successful electronics used on ROSETTA, New Horizons PLUTO, JUNO, JUICE & EUROPA UVS detectors. Only consider adoption of new ASIC technologies if TRLs established on CETUS timeline.

Personnel support. Small but highly experienced team with 30-year age spread, with hands-on experience from sub-orbital (BU, CU, JHU, CAL, etc.) missions, to planetary, heliospheric and HST implementations.

Outlines of Emergent CETUS Concept

- Telescope diameter ≤ 1.5 m
- Resolution set by 1 pixel on the sky (0.33") rather than the Rayleigh criterion, ~ 1.22 λ/D , relaxes requirements on optics, pointing stability, thermal system, etc.
- Same detector for all 3 NUV instruments; same type of FUV detector (CsI MCP) for both FUV instruments
- Complicated STIS-like imaging spectrograph split into two simple instruments: camera and spectrograph
- The instrument suite is modular, tolerant of insertion or removal from instrument bay
- All instruments can observe in parallel