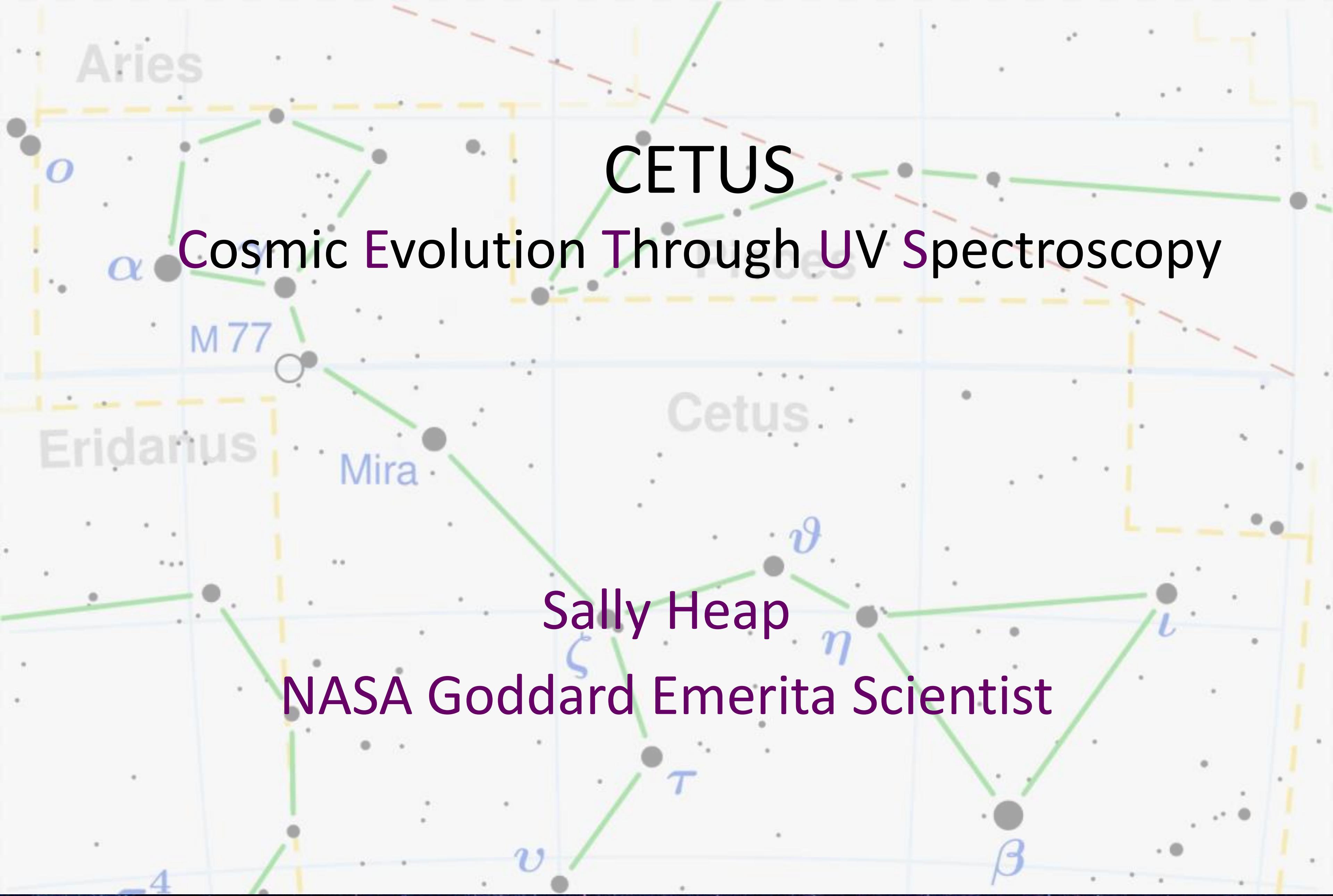


CETUS

Cosmic Evolution Through UV Spectroscopy

Sally Heap

NASA Goddard Emerita Scientist

What is CETUS?

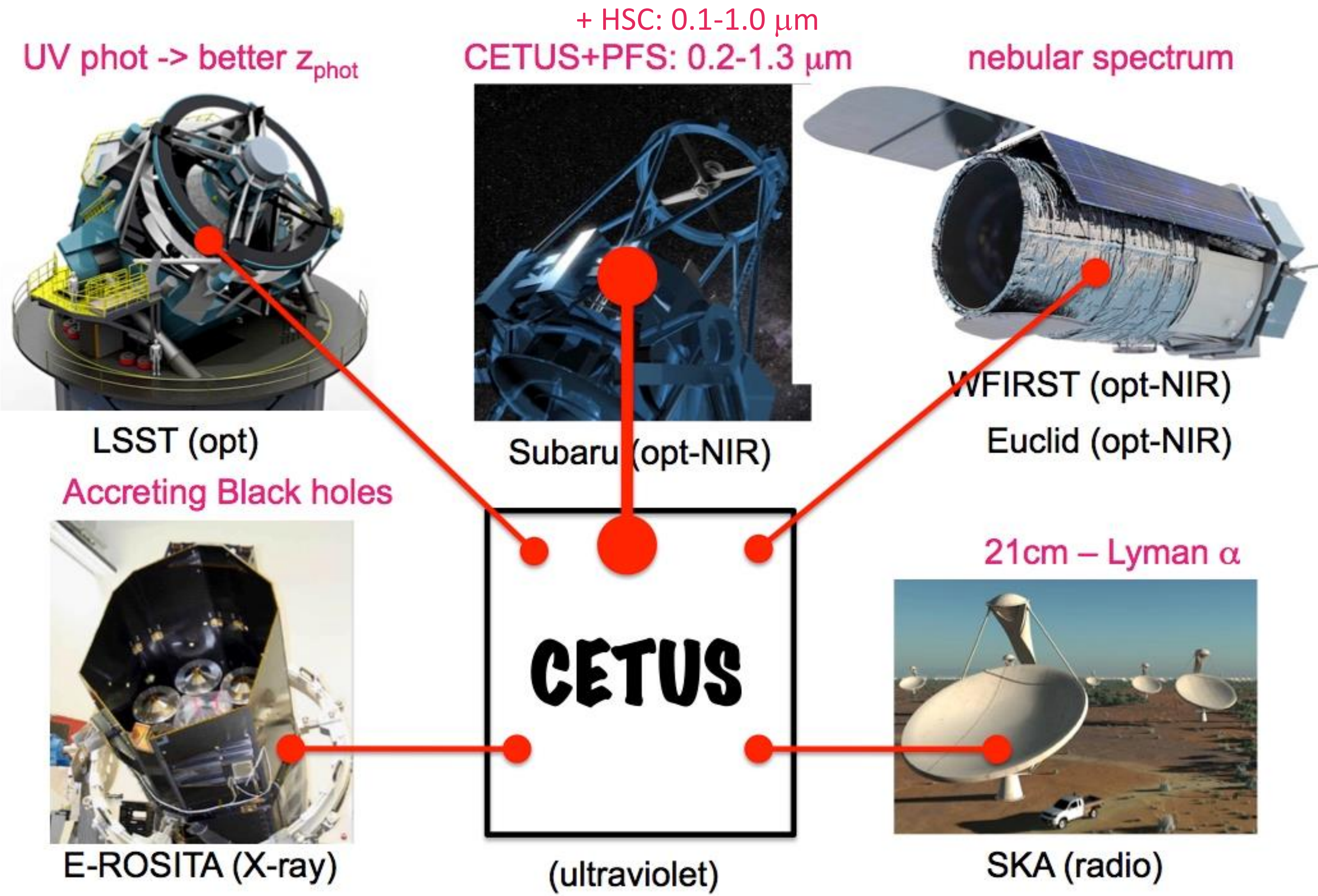
- CETUS: wide-field 1.5m telescope with 3 powerful UV instruments

    - ***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

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

With CETUS, the 2020's will be a golden age of surveys



In collaboration with other telescopes, CETUS will address outstanding questions left over from the 2010's

- How did galaxies come to look like the ones we see today?
- What explains the co-evolution of galaxies and black holes?
- What explains the turnover in the star-formation history and growth history of black-holes at $z<2$?
- How did the heavy elements form?

CETUS Scientific Objectives

[1] Understand galaxy evolution in the critical era (z~1-2) by:

- Obtaining rest far-UV spectra and images of z~1-2 galaxies
- Deriving distributions & correlations in concert with other telescopes,
  e.g. galaxy outflow rate vs. stellar mass
- Understanding the distributions through massive simulations /models

[2] Provide access to the UV for a myriad of GO programs

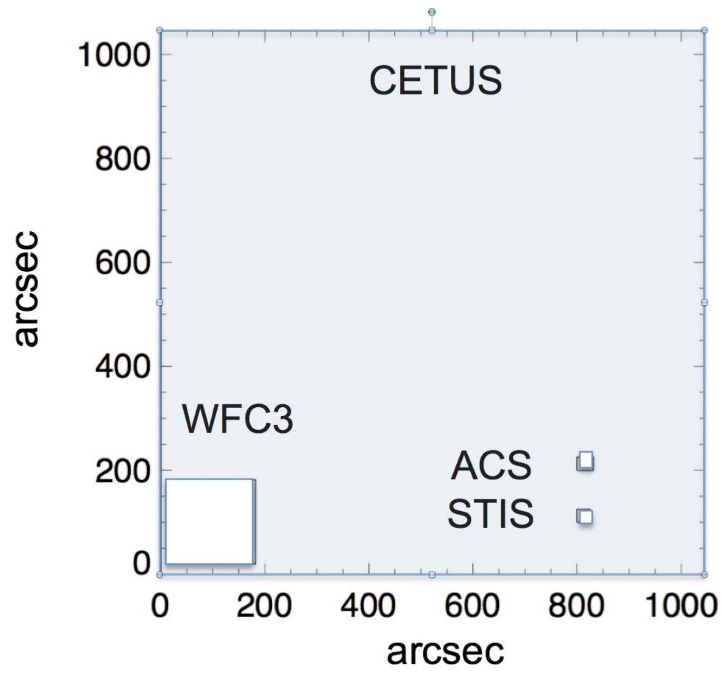
- Continuation of Hubble programs
- Follow-up observations of discoveries
  e.g. UV observations of aftermath of neutron-star mergers

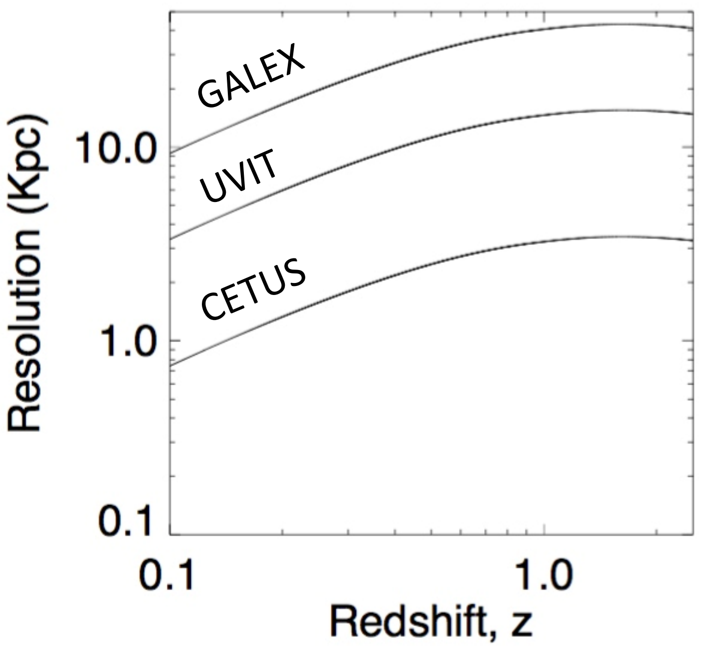
CETUS' Strengths

Much larger FOV field than Hubble

Much finer resolution than GALEX

- Wide-field (>1000"), high-resolution (~0.5") imaging filter photometry in the near-UV and far-UV
- Near-UV wide-field, high-resolution (~0.4") multi-object *slit* spectroscopy





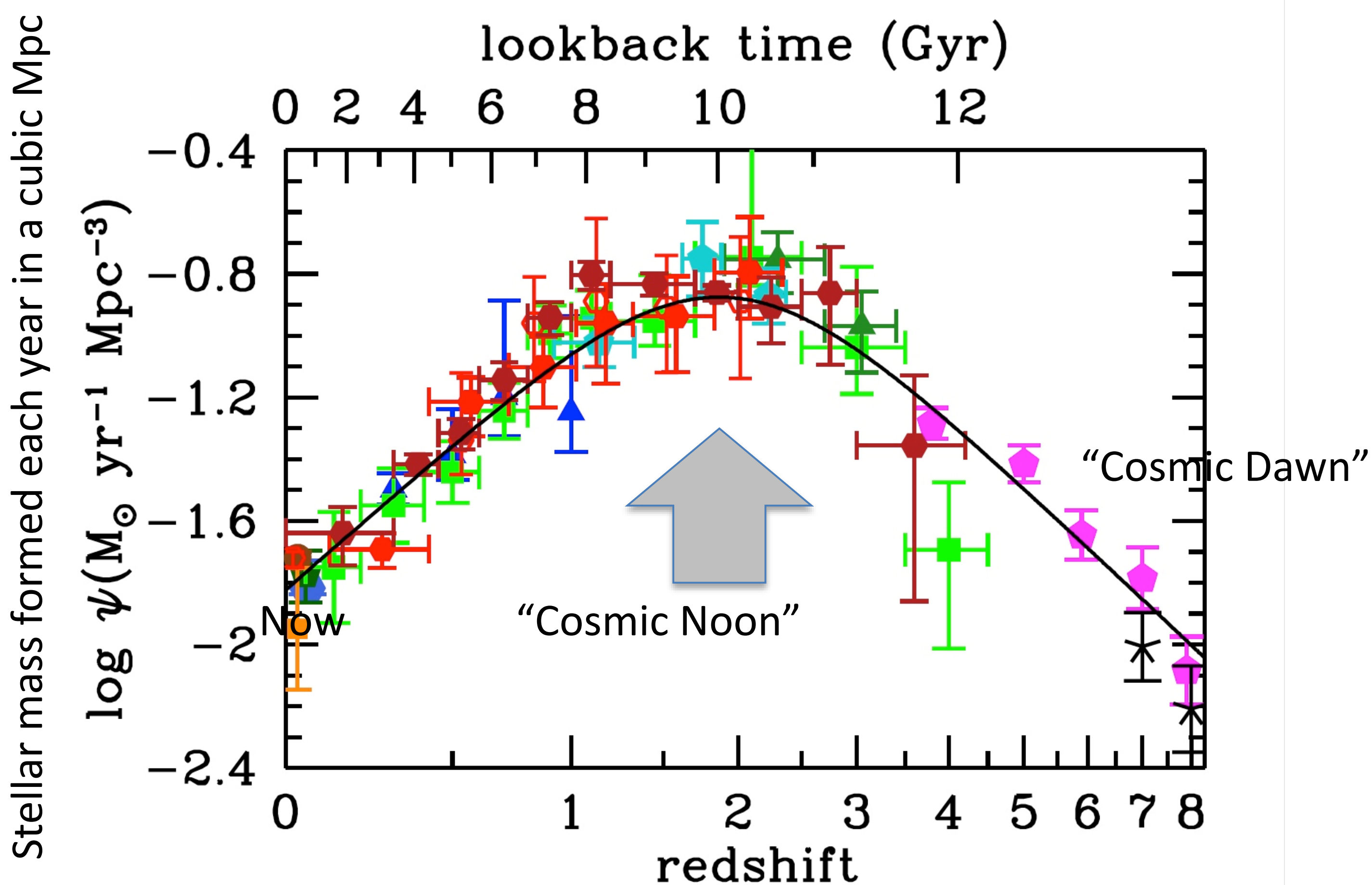
Near-UV Multi-Object Spectroscopy

Telescope: 1.50-m f/5 three-mirror anastigmat (TMA)

MOS

- Slit device: next-generation microshutter array at focal plane
  - ~390 x 185 shutters
  - shutter: 100 um x 200 um, 2.75”x5.50”
- Spectrograph: Offner relay with a convex grating
  - Tip/tilt/focus mechanism for dithering, subsampling
- Detector: e2v CCD 231

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



Madau & Dickinson 2014

...or the accretion history of black holes

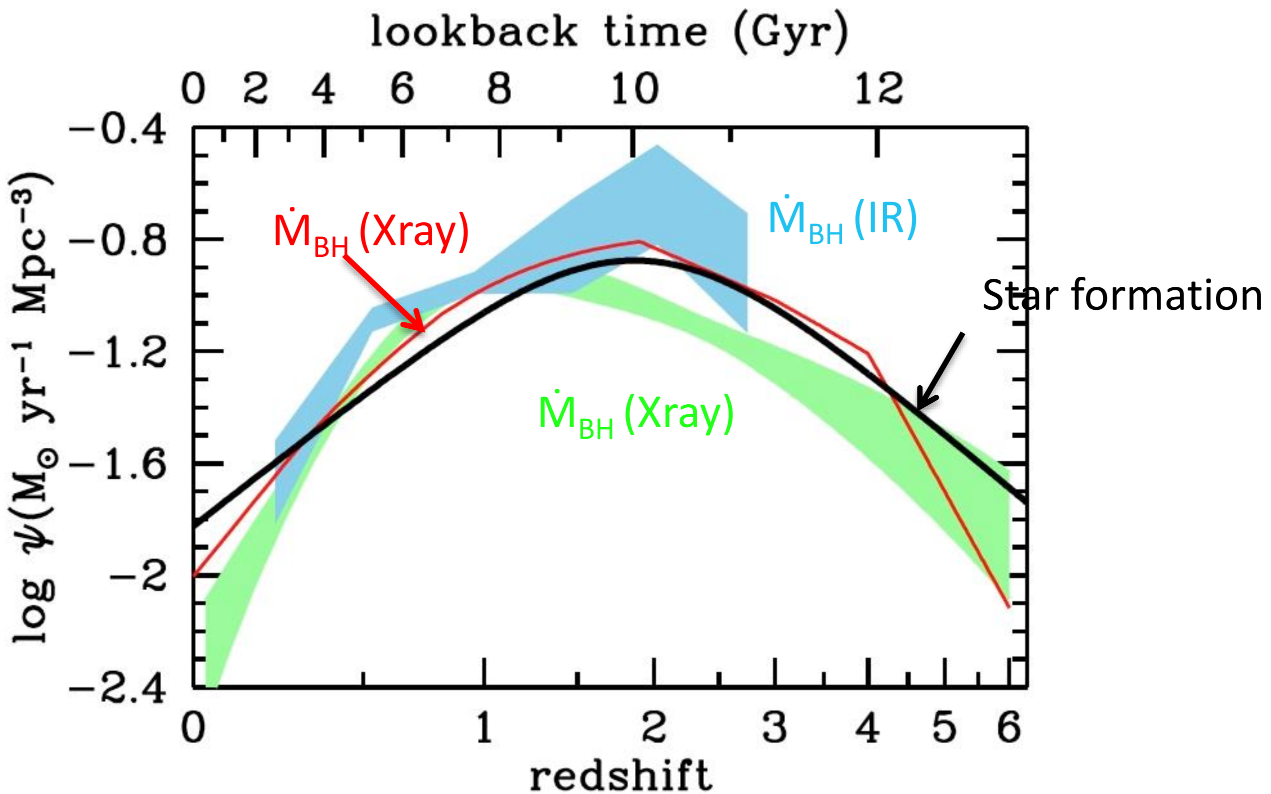
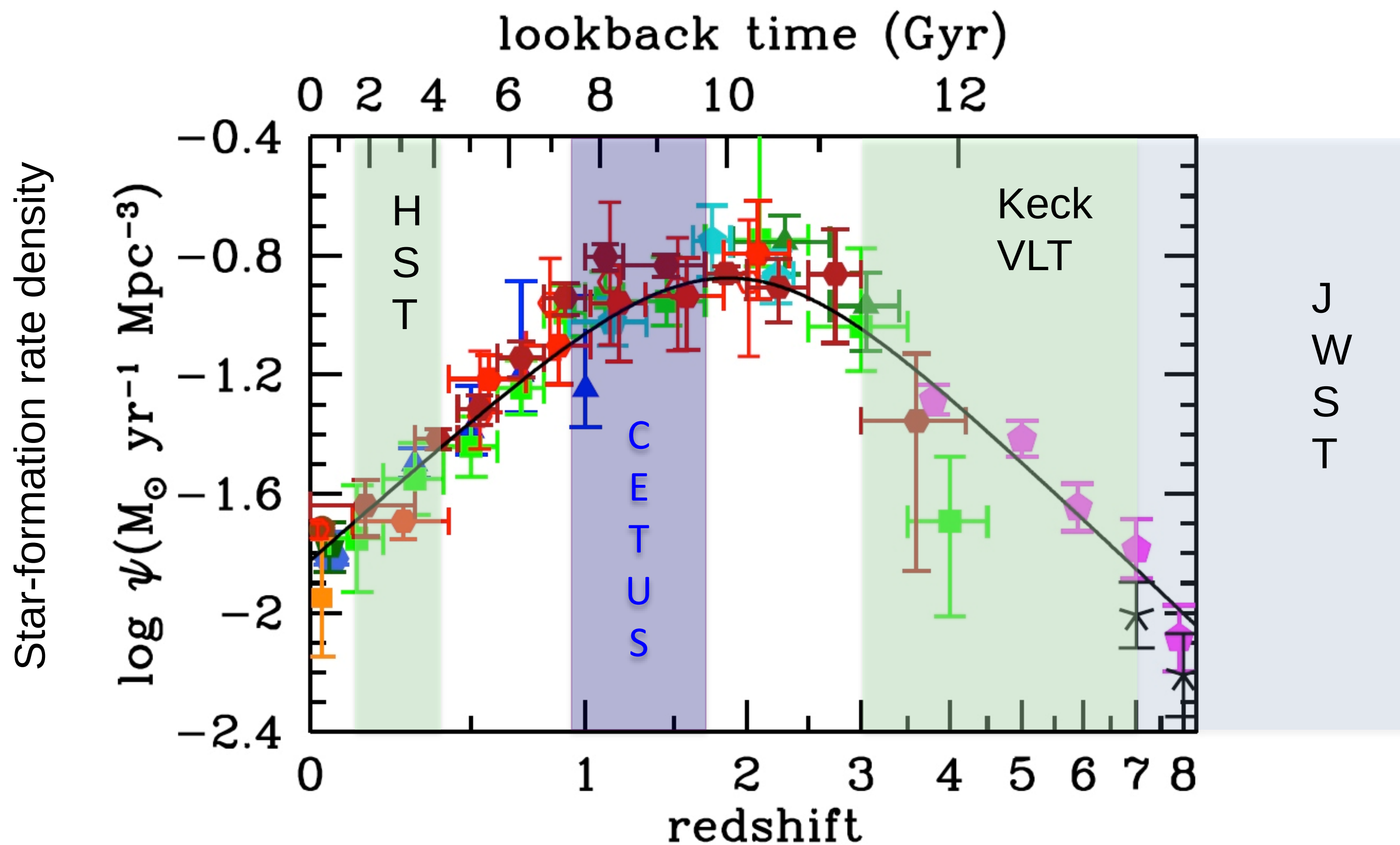


Figure 15: Comparison of the best-fit star formation history (*thick solid curve*) with the massive black hole accretion history from X-ray [*red curve* (Shankar et al. 2009); *light green shading* (Aird et al. 2010)] and infrared (*light blue shading*) (Delvecchio et al. 2014) data. The shading indicates the $\pm1\sigma$ 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.

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

Possible drivers of evolution

Dark Energy

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

How CETUS UV Spectra will Help

CETUS will observe the restframe far-UV of z~1-2 galaxies, which is rich in spectral diagnostics of SF galaxies

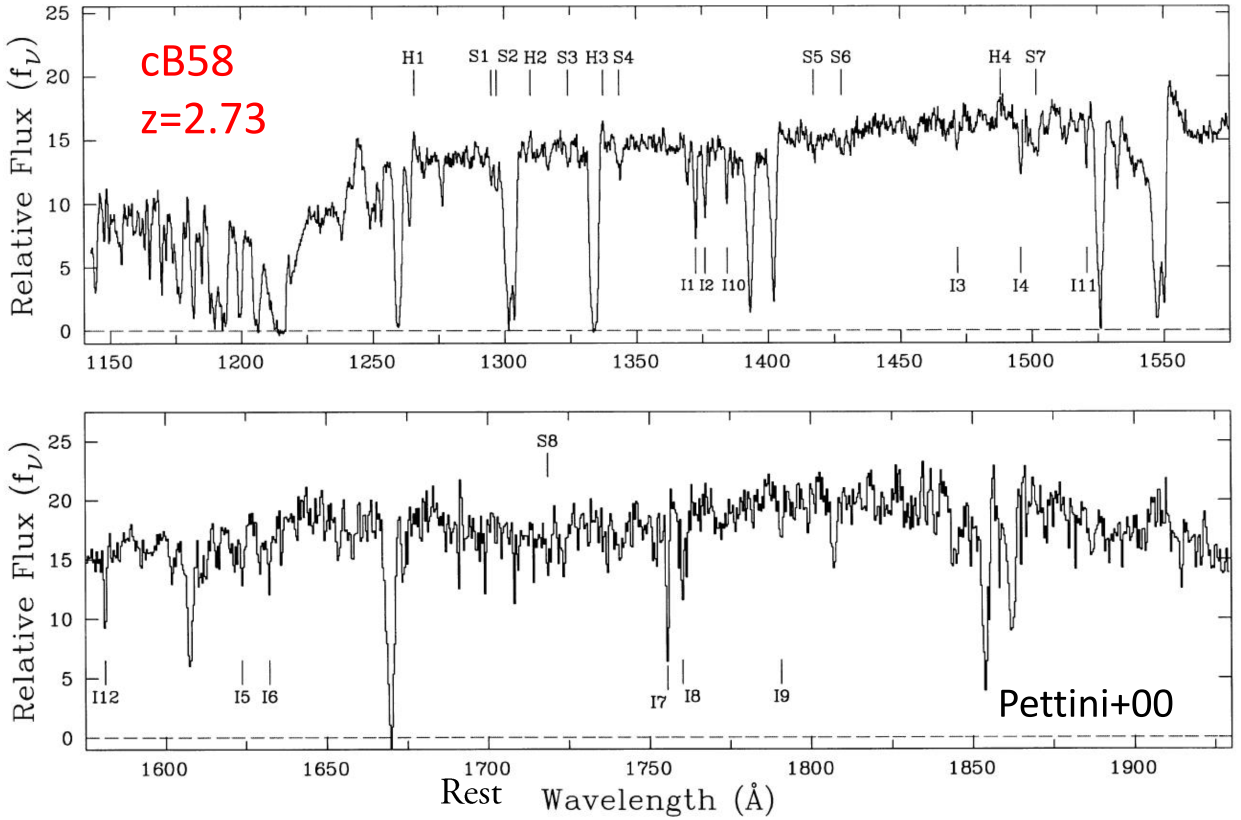


FIG. 1.—LRIS spectrum of MS 1512−cB58 reduced to the systemic redshift of the galaxy, $z_{stars} = 2.7268$. Tick marks above the spectrum identify weak stellar lines (labeled S*n*) listed in Table 1 and weak emission lines (labeled H*n*—see Table 4) that we attribute to H II gas. Tick marks below the 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), $N_{HI}=7.5\times10^{20}$ cm^{-2}, dust E(B-V)~0.1-0.3

Measurements to be made:
a massive UV spectrocopic survey

Far-UV spectra can provide:

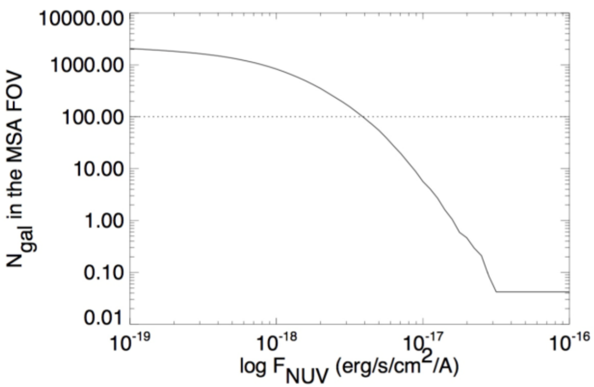
- accurate redshifts for coaddition, identification of clustering
- clean separation of continuum & emission-line flux
- direct view of stellar feedback (ionization, heating, winds & outflows)
- build-up of stellar mass (mass-loss vs. star-formation)
- kinematics of galaxies
- dust properties (extinction curve)
- physical conditions of the ISM (HI and HII) and CGM
- evolution of the mass-metallicity relation
- co-evolution of galaxies & black holes

Why a Massive Survey?

- 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

Performance Requirements

1. Multiplexing – Multi-object slit spectrograph
   - Slit generator – Micro-shutter array
   - Large field of view – 0.29º x 0.29º



2. High UV Sensitivity
   - Telescope aperture 1.5-m
   - Optical throughput – min. # of reflections e.g. no fold mirrors
   - Detector UV QE – UV-enhanced e2v CCD 231; low noise
   - Exposure time – 5+ hours
3. High Observing Efficiency
   - Orbit – sun-earth L2
   - Use of Subaru HSC images and PFS spectra for target selection and target acquisition

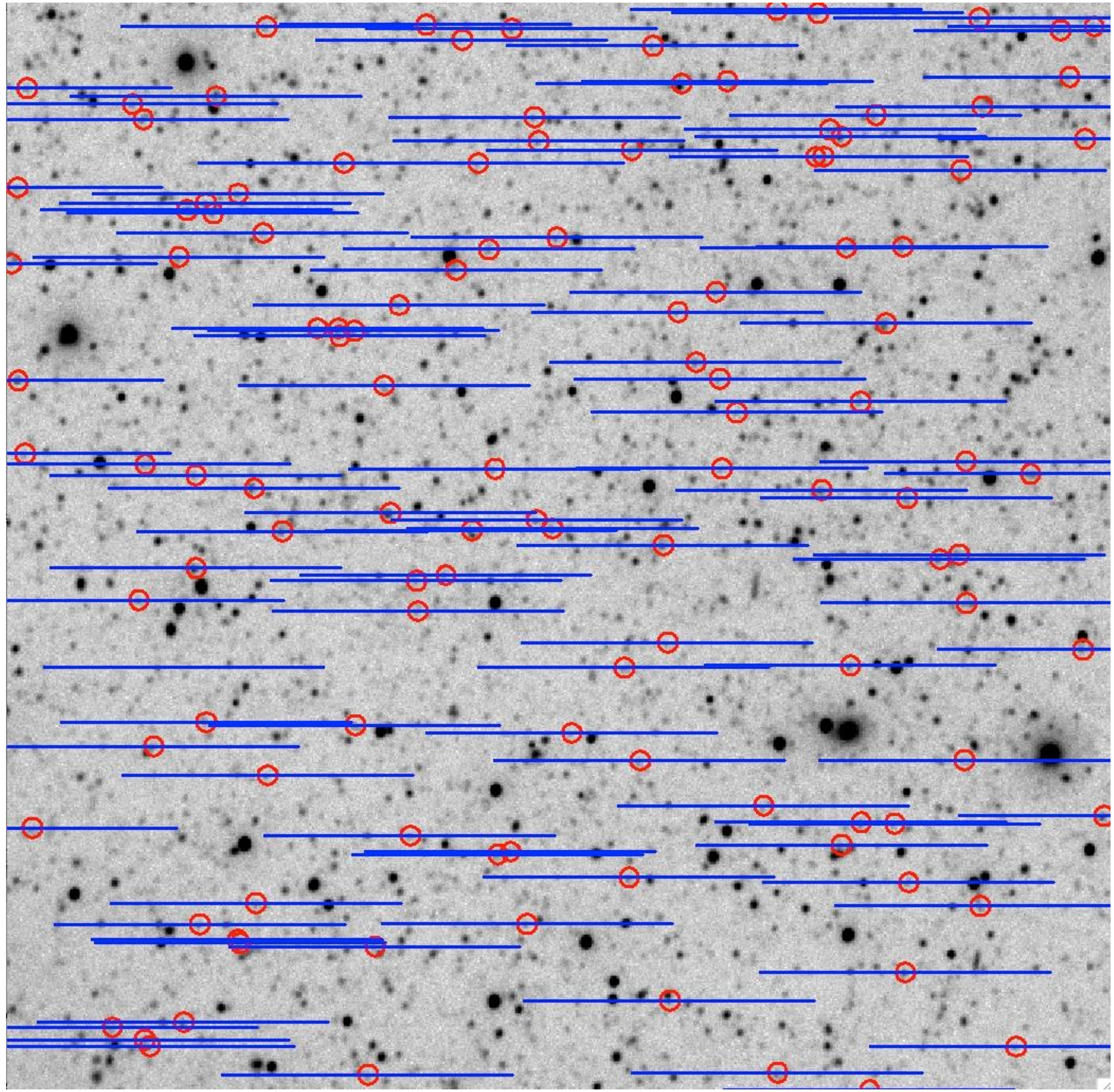
A typical CETUS Field
17.4’x17.4’

Field size set by MSA and 1.5m f/5 telescope

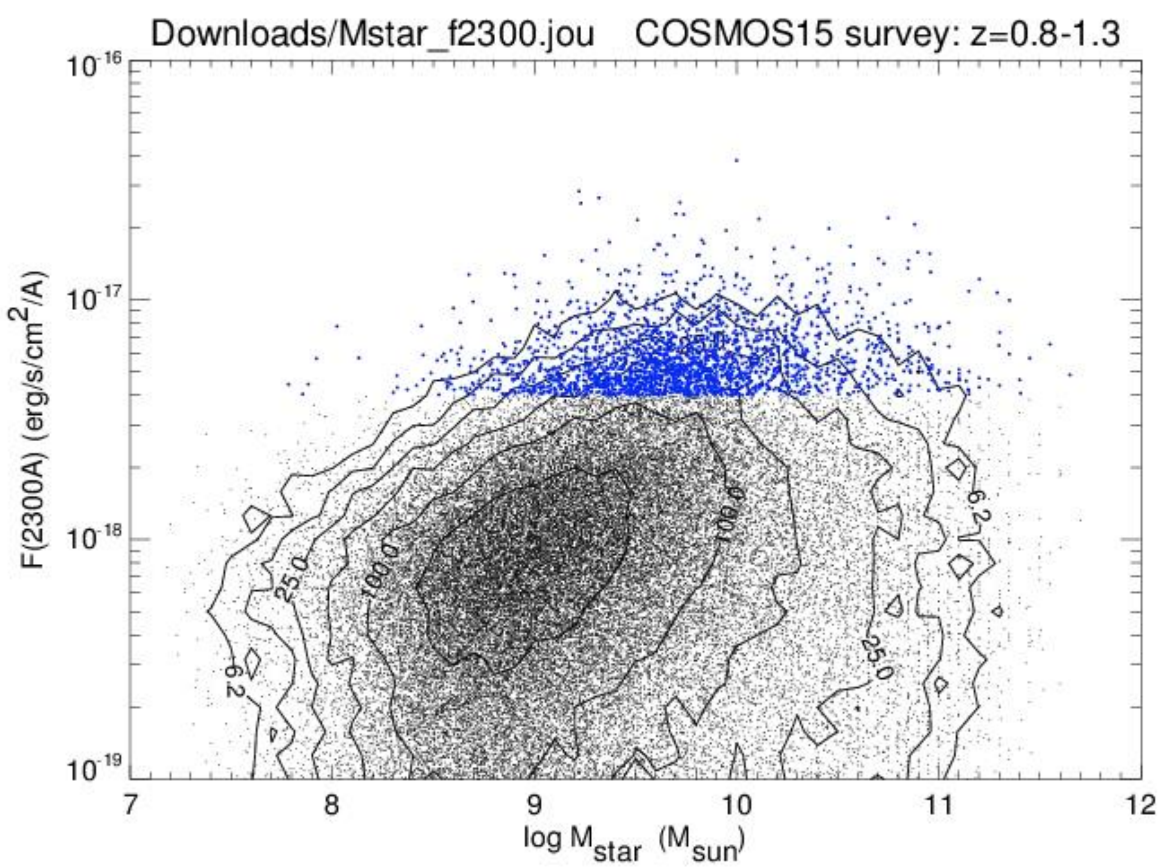
MSA ~380x190 shutters
Shutter 100μ x 200μ
2.75□ x 5.50”

○ z≥1 galaxy with $f_{NUV} \geq 4\times10^{-18}$

— Extent of spectrum



A NUV Sensitivity = $4x10^{-18}$ yields spectra of galaxies over a wide range in stellar mass



94 Galaxies in MSA FOV

14 Galaxies with log $M_\star$>10.3 in MSA FOV

CETUS/MOS + Subaru/PFS
= spectra covering 0.2-1.3μ

	CETUS	Subaru/PFS
Scientific Goal	Galaxy evolution	Galaxy evolution (1 of 3 goals)
Primary targets	z~1-2 galaxies	z~1-2 galaxies
Wavelength coverage	~0.2-0.4μ (MOS)	0.4-1.3μ PFS
Coverage of Lyman α	z~0.6 -2.3	z>2.3
Telescope	1.5 m	8.2 m
Orbit/Location	Sun-Earth L2	Hawaii
MOS survey	~25,000 hr over 4 years	100 nights/yr
Exposure time	5-10 hr	~0.3-3 hr
Spectra per expos.	Up to 100	2000
Spectra density	600-1200 spectra/deg^2	1800 spectra/deg^2
Sensitivity	4 x10^{-18} erg/s/cm^2/A	few x10^{-18} erg/s/cm^2/A

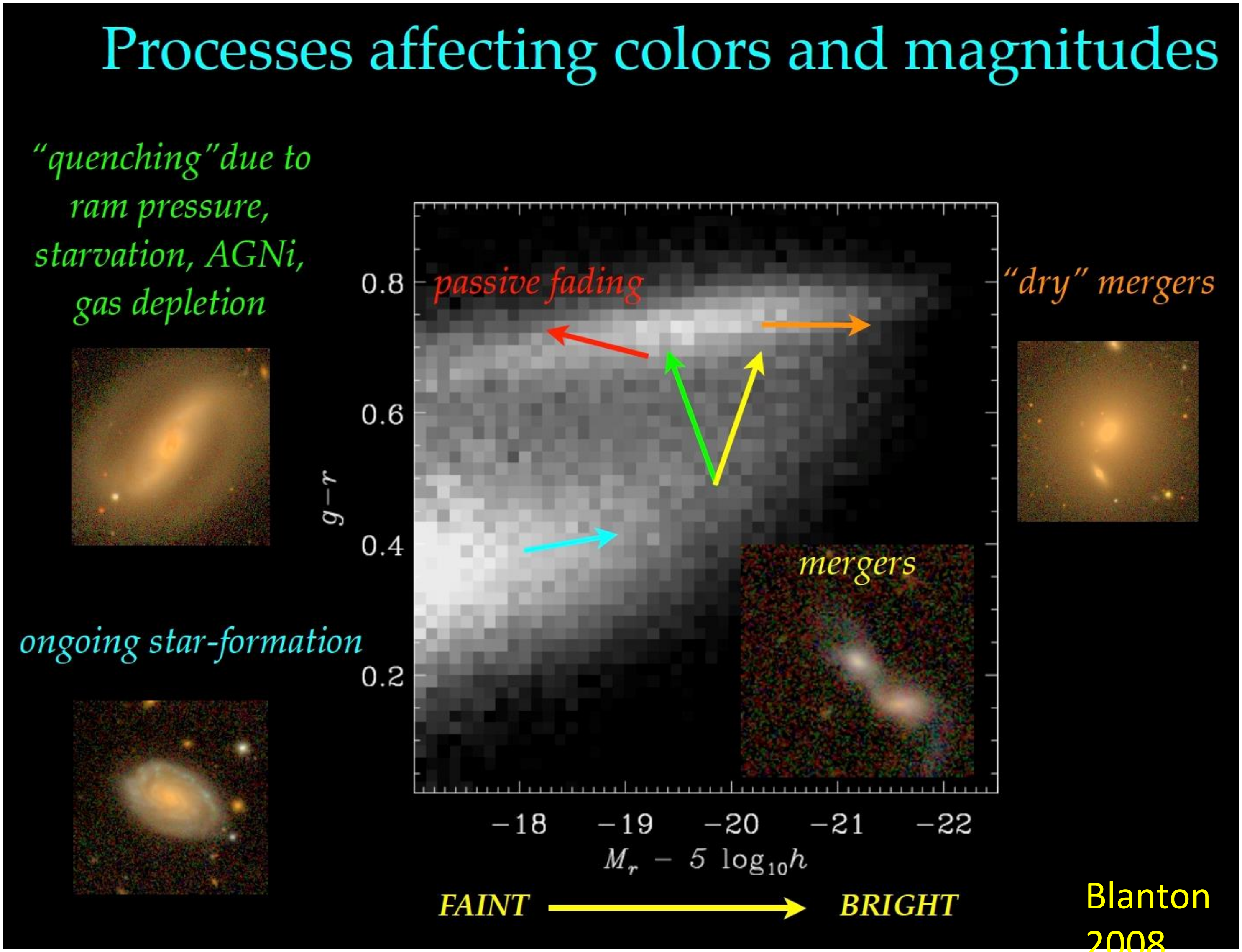
Far-UV/Near-UV Camera

NUV/FUV Camera Requirements

Parameter	Requirement	Design
Field of View	>1000”	1044”
Resolution Far-UV Near-UV	≤0.60”	 0.55” 0.42”
Spectral Range Far-UV Near-UV	~1150-4000 Å Continuity preferred	 1150 -1800 Å 1800?-4000 Å
Filter bandpass Far-UV Near-UV	 ≥5 LP filters, $\Delta\lambda$=100–300 Å >5 filters, $\Delta\lambda$=300–500 Å	 $\Delta\lambda$=100–150 Å * $\Delta\lambda$=410 Å à la SDSS

* By subtraction of adjacent filter fluxes

SDSS Color-$M_\star$ Diagram for z~0



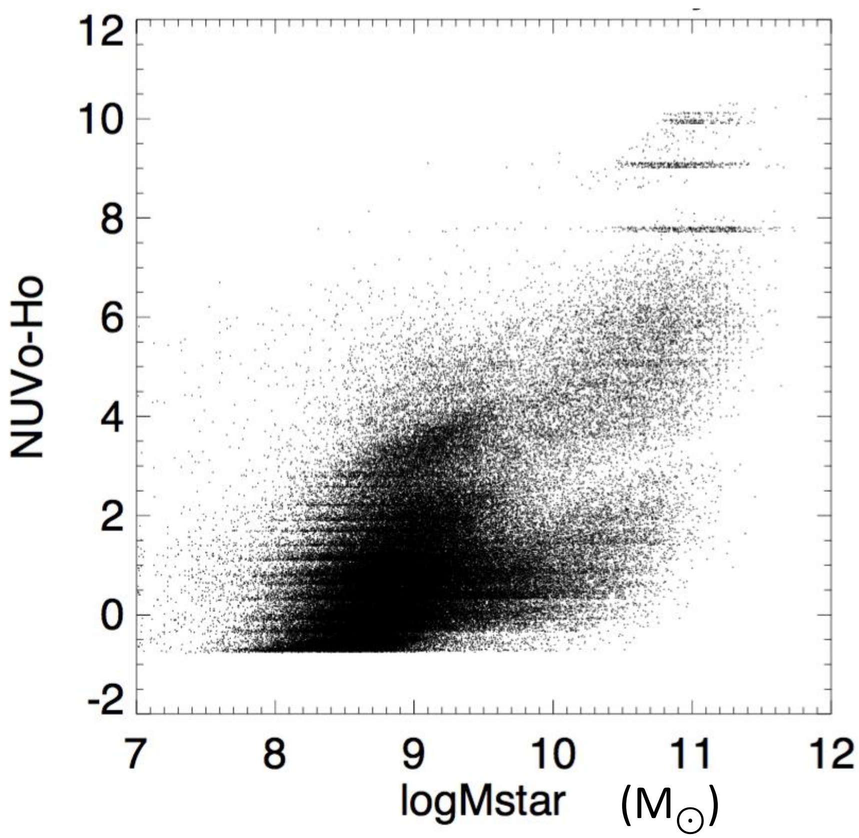
Blanton 2008

Galex data* suggest multiple evolutionary paths Are they real? Probably not

Problems

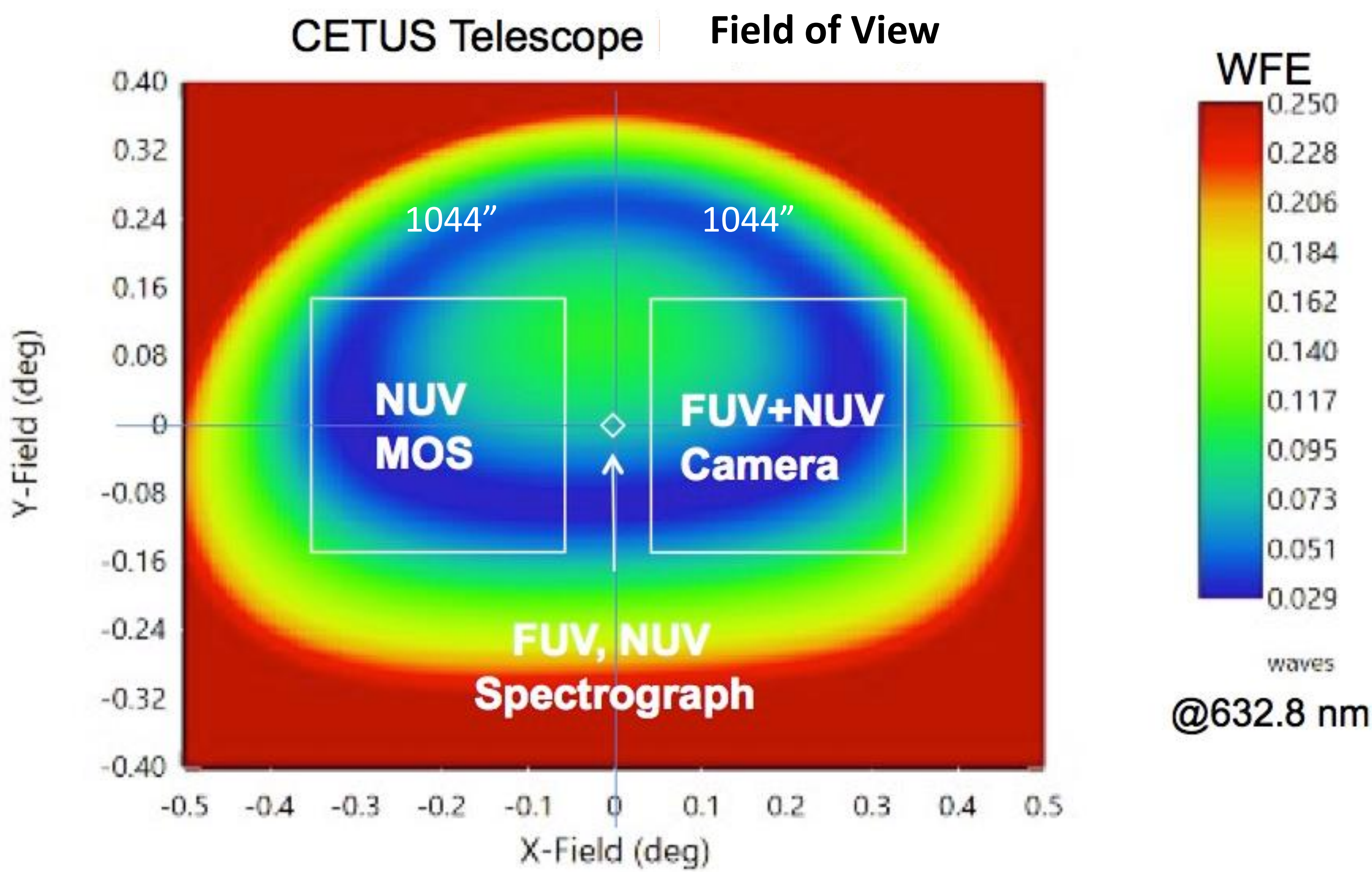
- UV photometry hampered by source confusion
- Systematic errors in photo-z's
- Uncertainties in extinction

CETUS UV photometry and morphology will yield greatly improved constraints on galaxy evolution

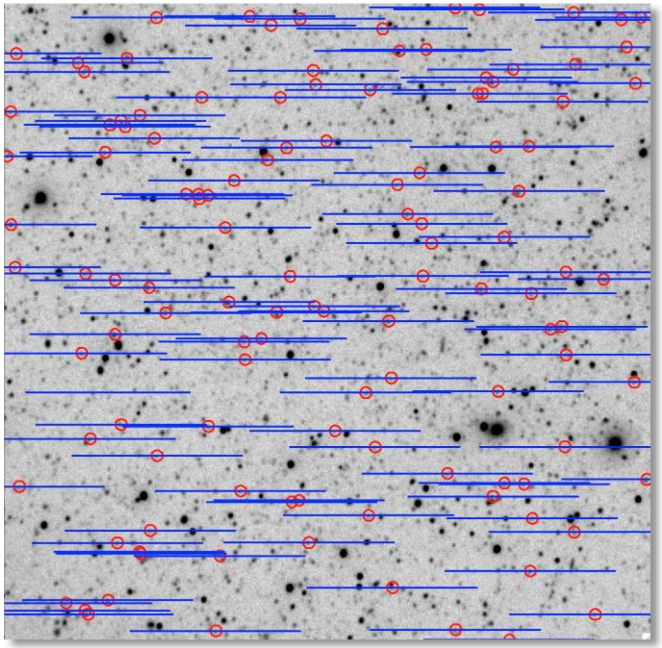


* source: Cosmos Mock Catalog (Jouvel+ 2009, 2011)

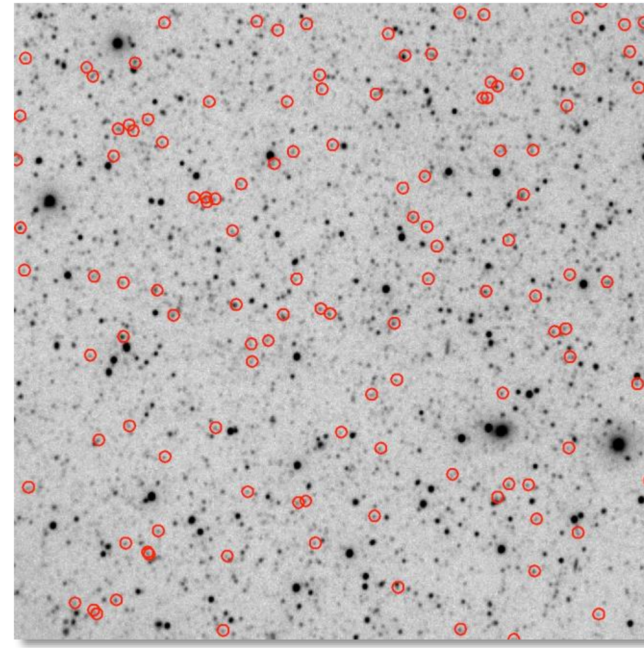
The FUV-NUV camera observes in parallel with the near-UV MOS (and/or spectrograph)



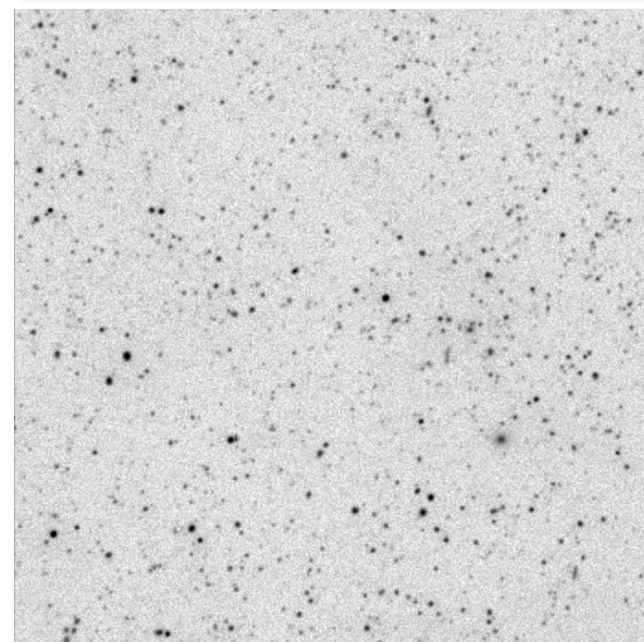
CETUS MOS



CETUS CAMERA



NUV



FUV

Each survey observation produces:

•a NUV spectrogram with ~100 spectra

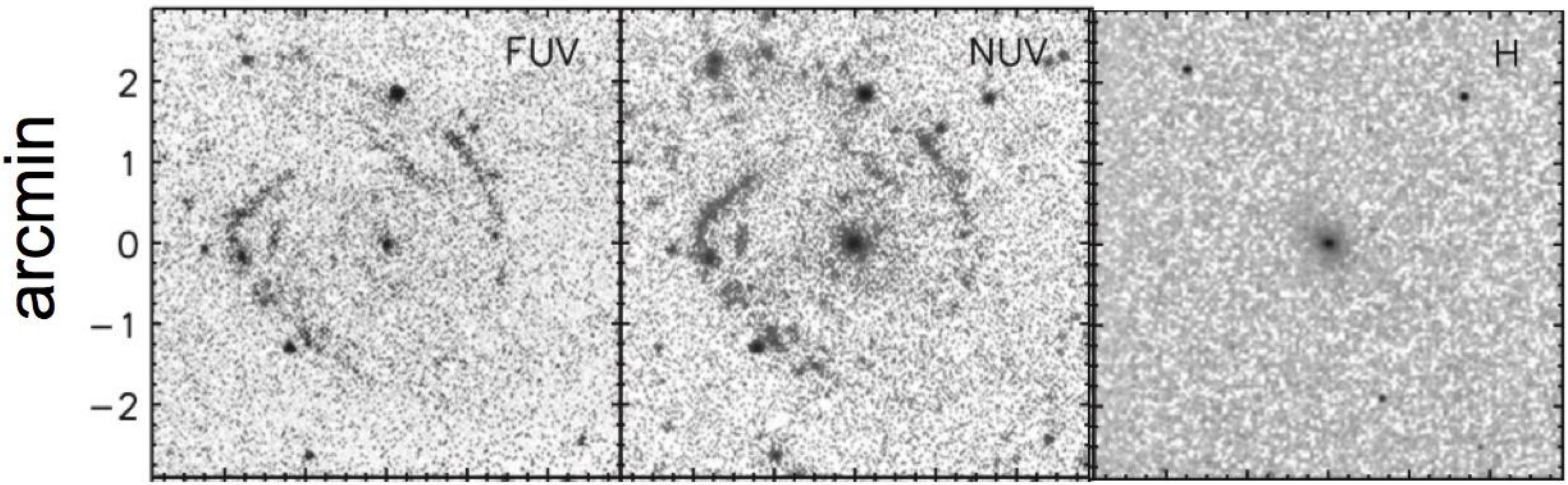
•a NUV image } of an adjacent field

•a FUV image } of an adjacent field

Each image is 1044” on a side

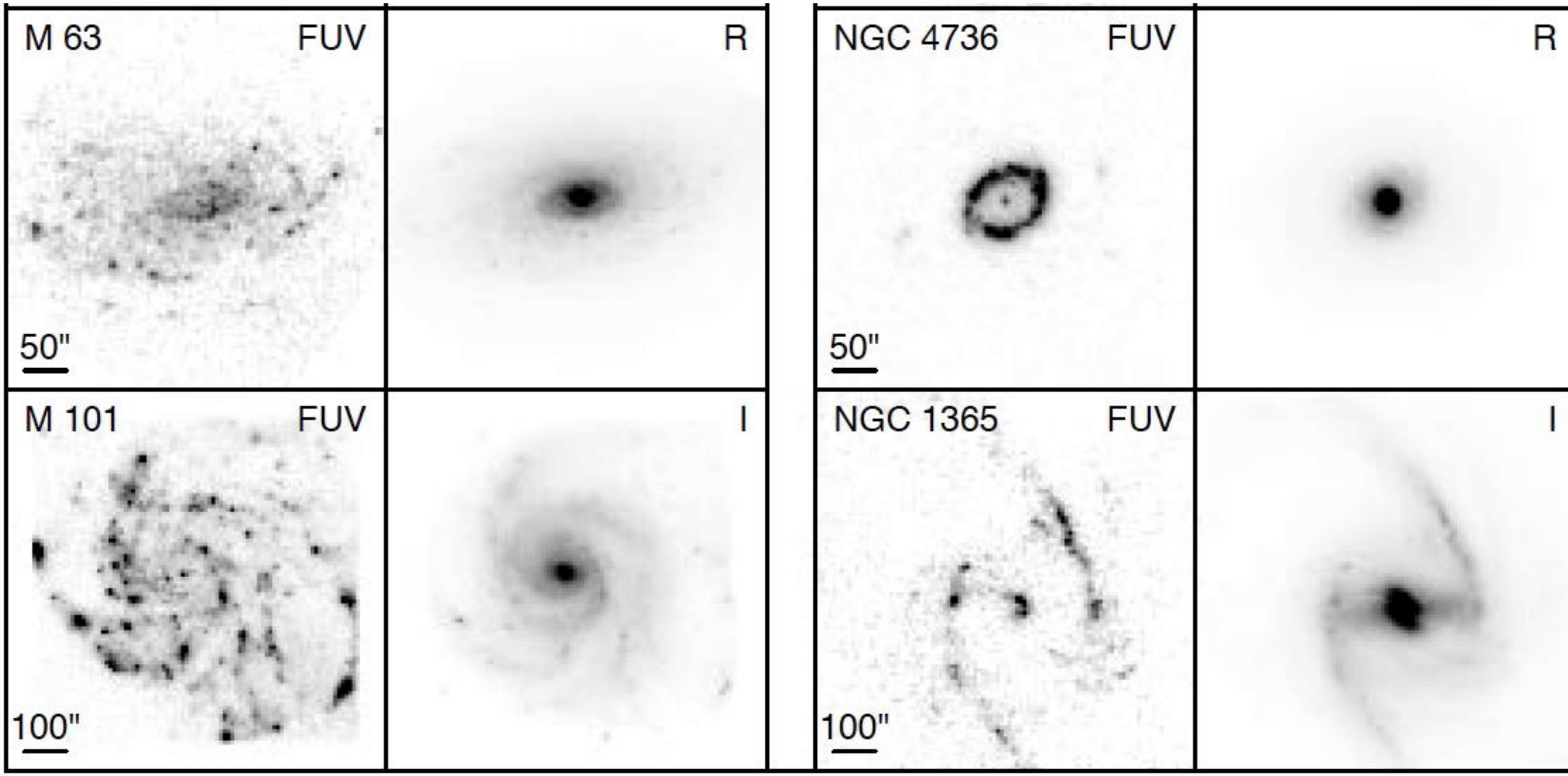
CETUS will conduct UV morphology studies

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

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



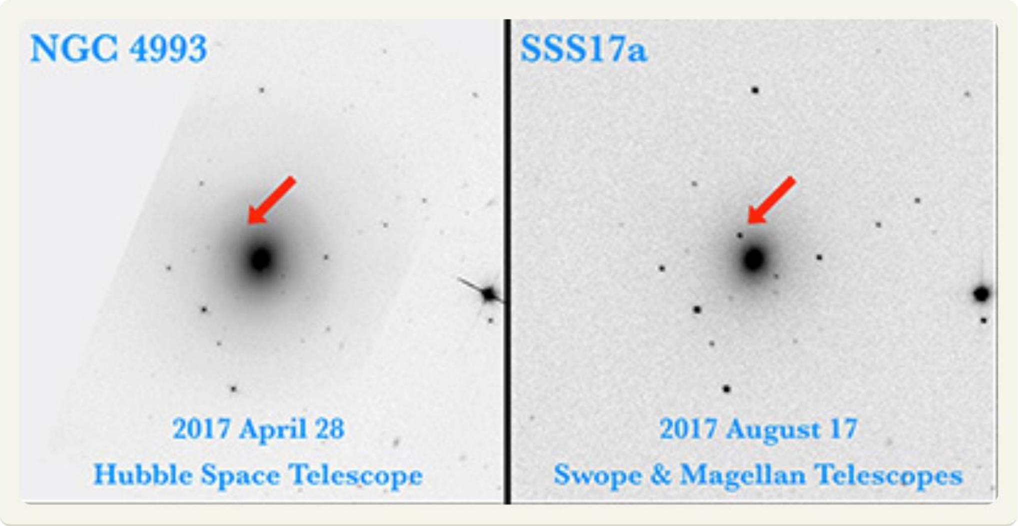
UV Observations of Selected Sources

- Far-UV/Near-UV imagery
- Far-UV/Near-UV spectroscopy at R= 2,000 or 40,000

CETUS will observe important transient objects like the neutron-star merger in NGC 4993
= GW 180817
= EM 180817 = SSS17a

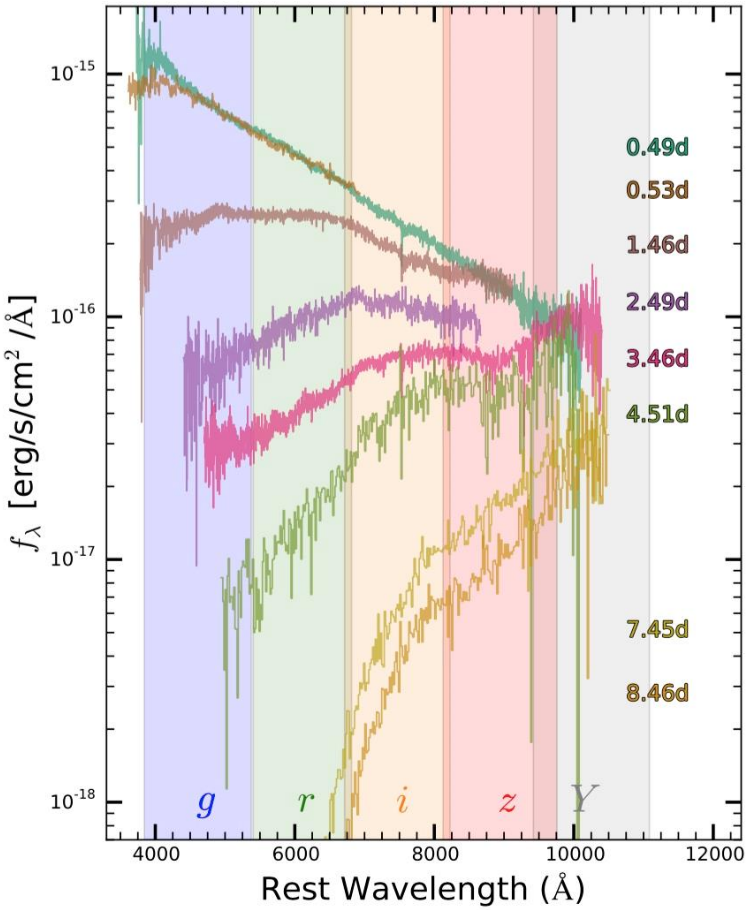
A single neutron-star merger can generate an amount of gold equal to the mass of Jupiter.

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.



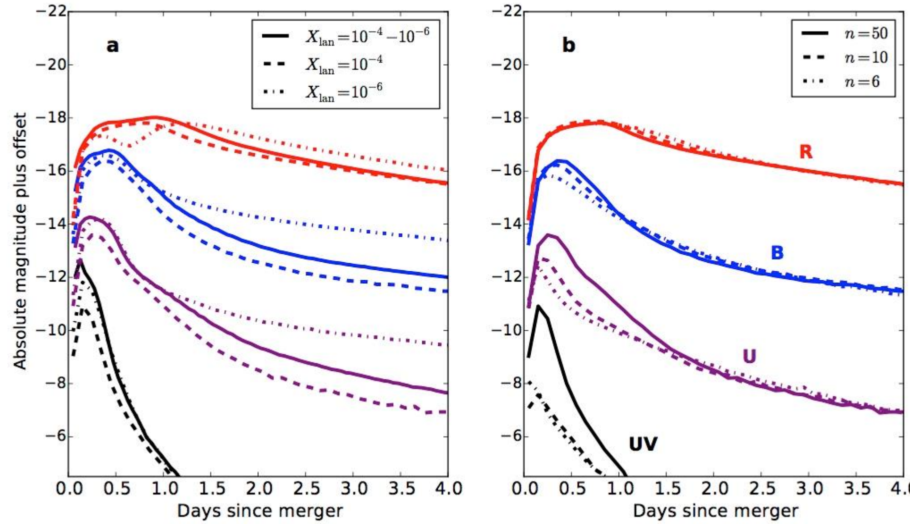
The UCSC team found SSS17a by comparing a new image of the galaxy N4993 (right) with images taken four months earlier by the Hubble Space Telescope (left). (Image credits: Left, Hubble/STScI; Right, 1M2H Team/UC Santa Cruz & Carnegie Observatories/Ryan Foley)

CETUS UV observations will help us understand the production sites of heavy elements



ure 2. **Spectroscopic time series of SSS17a.** The vertical axis is observed flux (f_λ).

Shappee+2017



Extended Data Figure 1 | Dependence of model light curves on the ejecta density profile and compositional stratification. The models all have mass $M = 0.025M_\odot$ and velocity $v_k = 0.25c$. **a**, Comparison of models with a homogenous composition to one where the lanthanide mass fraction varies from $X_{lan} = 10^{-6}$ at the outer ejecta edge to $X_{lan} = 10^{-4}$ in the interior (see equation (7)). **b**, Comparison of models with different density gradient in the outer layers. A shallower exponent ($n < 10$) leads to a cooler photosphere and suppresses the early ultraviolet and blue emission. The light curves at times $t \geq 1$ d and in redder bands are essentially independent of the outer density profile.

Kasen+2017

The CETUS Team

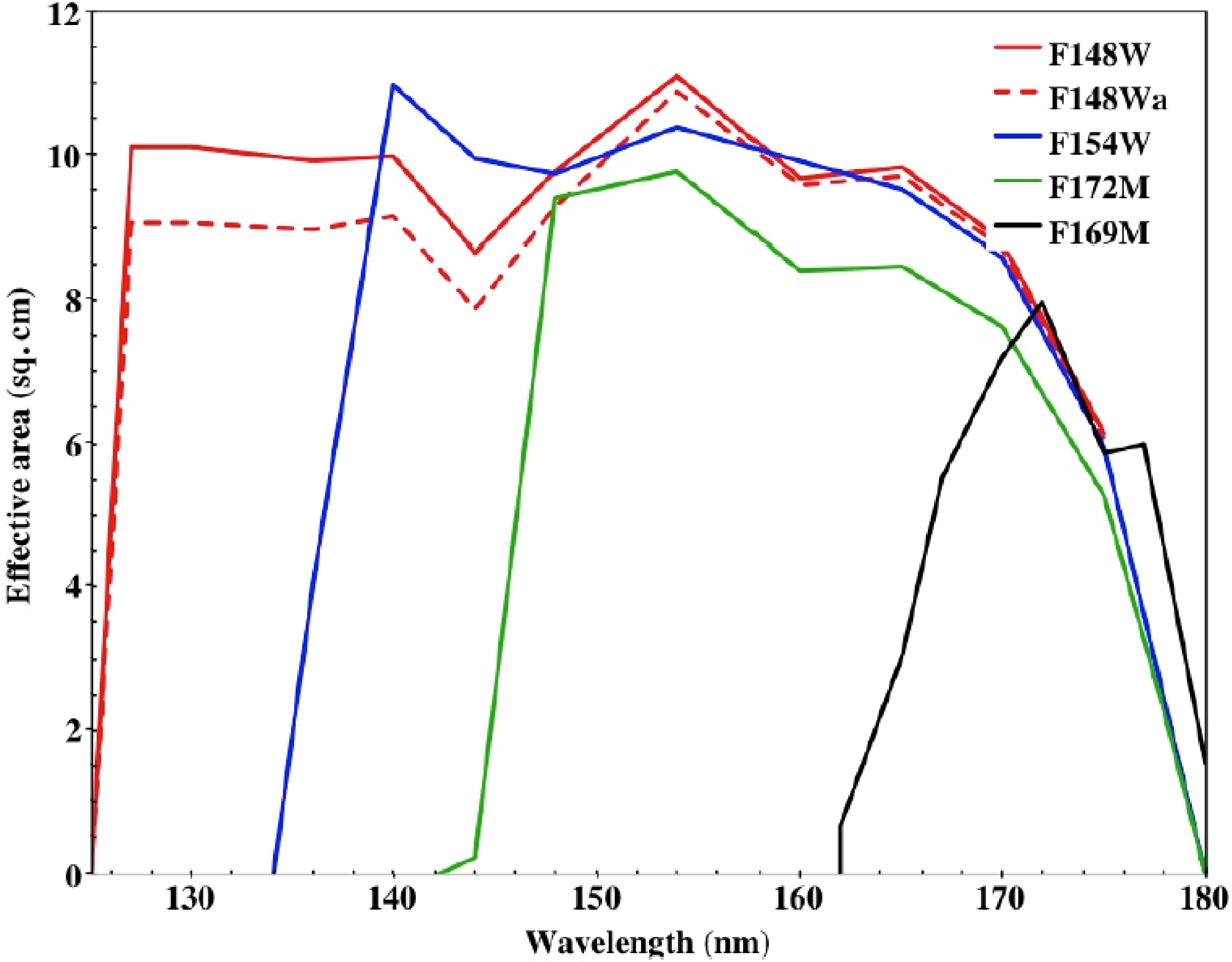
William Danchi (PI, GSFC), Sara Heap (Science PI, GSFC Emerita)

Co-Investigators: Steve Kendrick (Kendrick Aerospace Consulting), Tony Hull (Kendrick Aerospace Consulting, Univ. NM), Jim Burge & Martin Valente (Arizona Optical Sciences), Kelly Dodson & Greg Miehle (Orbital ATK), Steve McCandliss (Johns Hopkins Univ.)

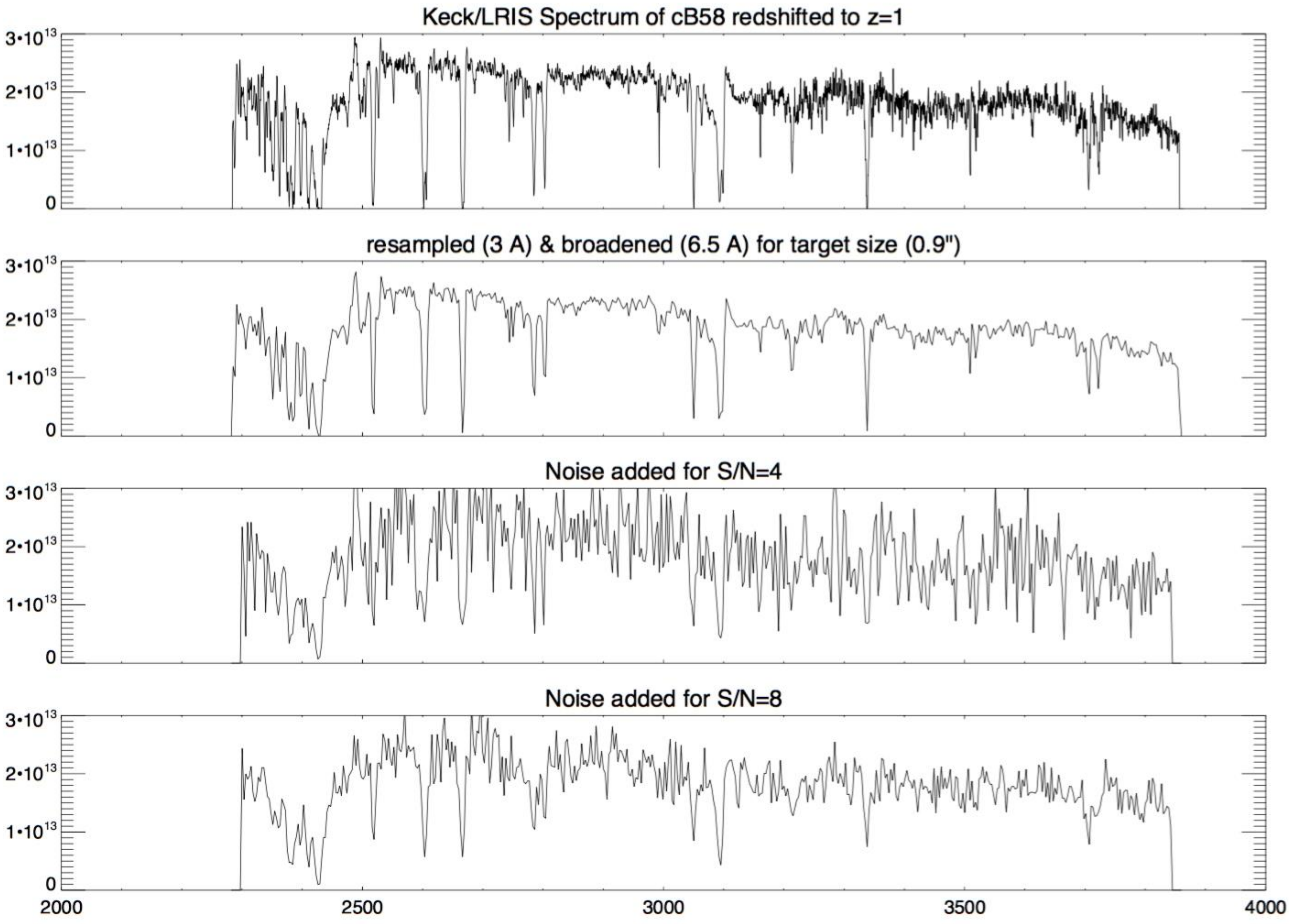
Science Team *(Collaborators)*: L. Bianchi, T. Heckman, A. Szalay, R. Wyse, (Johns Hopkins Univ.); E. Dwek, J. Rigby (GSFC); J. Greene, D. Spergel (Princeton); I. Roederer (U. Michigan); D. Stark (U. Arizona); J. Trump, K. Whitaker (U. Conn.)

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

Consultants: R. Woodruff (Woodruff Consulting)



F148W
F148Wa
F154W
F172M
F169M
Effective area (sq. cm)
Wavelength (nm)
0
2
4
6
8
10
12
130
140
150
160
170
180



Keck/LRIS Spectrum of cB58 redshifted to z=1
resampled (3 A) & broadened (6.5 A) for target size (0.9")
Noise added for S/N=4
Noise added for S/N=8
3•10^13
2•10^13
1•10^13
0
2000
2500
3000
3500
4000