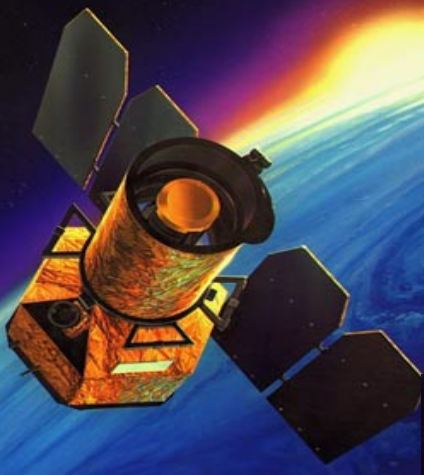


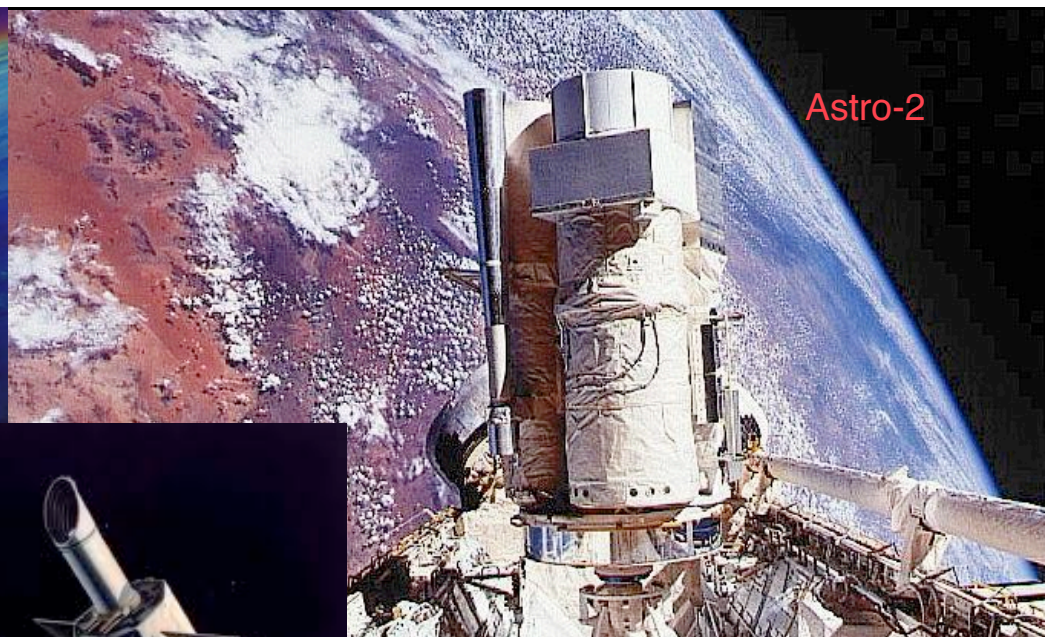


*The Once and Future
World of
Ultraviolet Astronomy*

GALEX



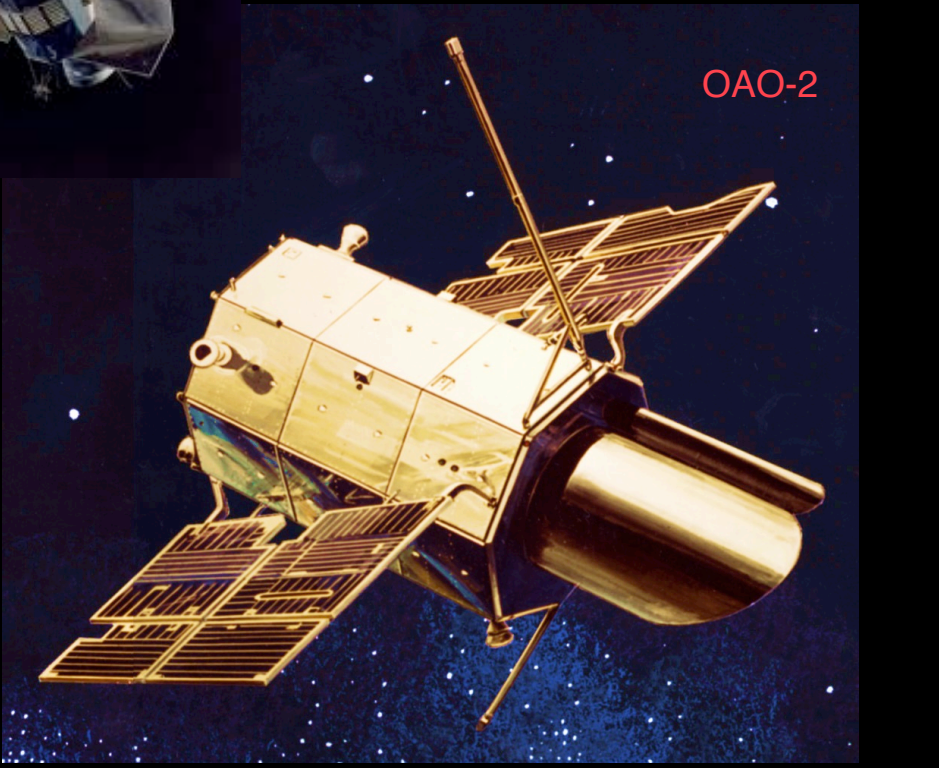
Astro-2



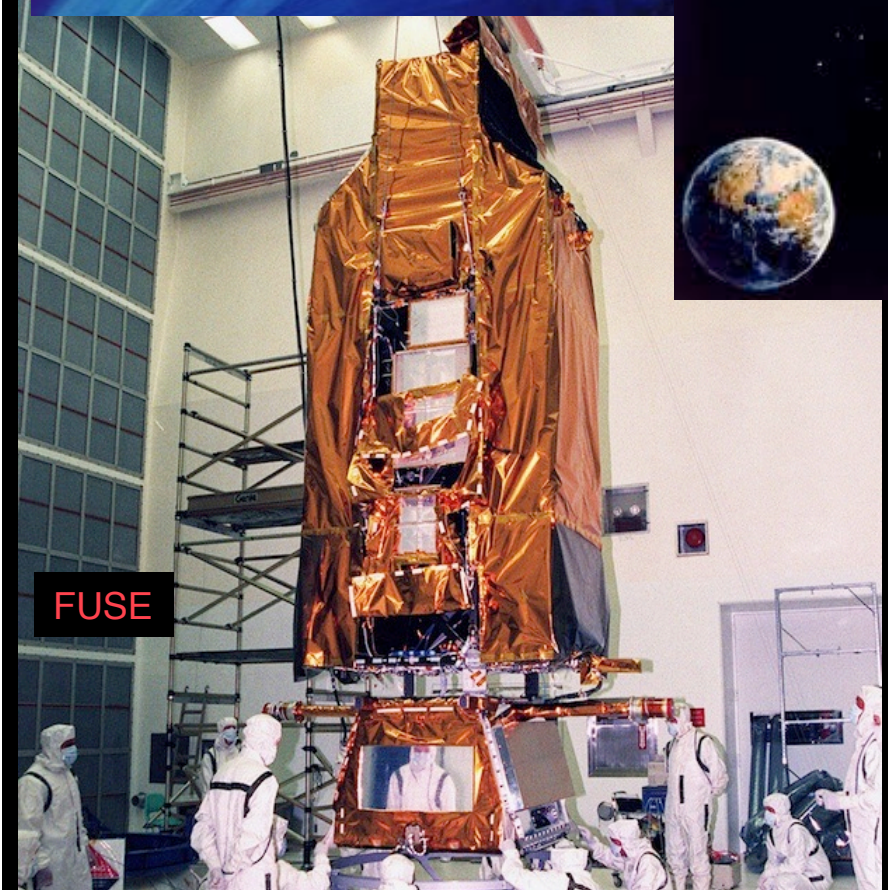
IUE



OAO-2



FUSE



HST: 1990 – 2018(?)



Era of Giant Telescopes (2020 --)



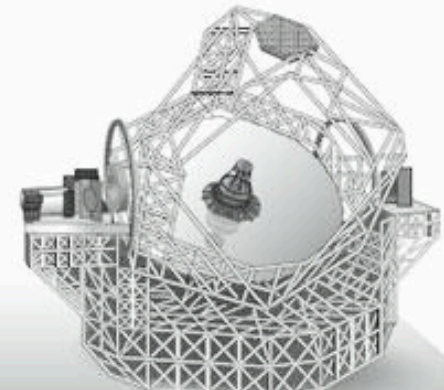
Big Ben clocktower
(96.6 metres) for scale



Giant Magellan Telescope



Thirty-Meter Telescope



European Extremely Large Telescope

Telescope diameter	25.2 metres	30 metres	42 metres
Component mirror segments	7 (8.4-metre segments)	492 (1.44-metre segments)	984 (1.45-metre segments)
Cost	US\$600 million	US\$754 million	€900 million (US\$1.37 billion)
Planned location	Chile	Candidates: Hawaii; Mexico; three sites in Chile	Candidates: Canary Islands; Morocco; Argentina; two sites in Chile
Planned construction period	2010-2017 (First mirror already cast)	2009-2016	2010-2017
Technical advantages	Adaptive optics integrated within secondary mirror Shortest focal length means it has the smallest and cheapest structure	Mirror segments are comparatively cheap and more easily replaced Similar scaled-up version of the existing Keck telescopes	Five-mirror design results in a flat focal plane and better images Similar mirror-segment size to the TMT, so greater vendor choice
Financial advantages	Potential support from \$34-billion Harvard endowment or Texas billionaire George Mitchell	\$200-million gift from Intel founder Gordon Moore	Steady European funding stream
Disadvantages	Only one place can make the mirrors Gaps in mirror limit the effective aperture to 21.5 metres	Adaptive optics performed after the light leaves the telescope, so the 'natural seeing' mode cannot benefit from adaptive corrections to wind effects	Biggest and most expensive design No similar design experience Reflections through five mirrors reduce light levels

Era of Giant Telescopes (2020 --)



Big Ben clocktower
(96.6 metres) for scale

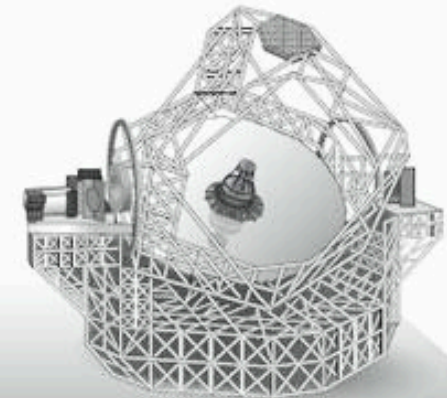
HST Mirror



Giant Magellan Telescope



Thirty-Meter Telescope



European Extremely Large Telescope

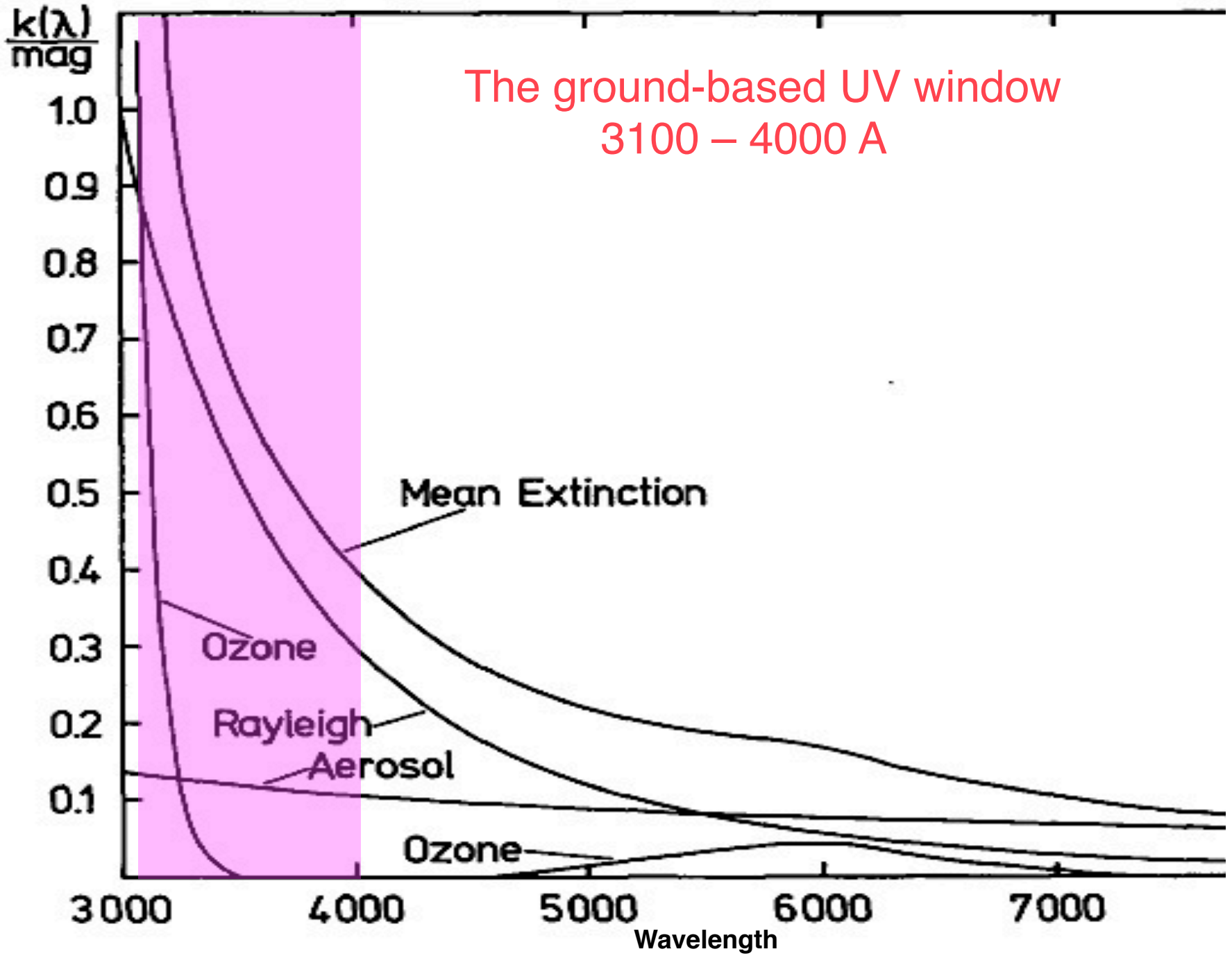
Telescope diameter	25.2 metres	30 metres	42 metres
Component mirror segments	7 (8.4-metre segments)	492 (1.44-metre segments)	984 (1.45-metre segments)
Cost	US\$600 million	US\$754 million	€900 million (US\$1.37 billion)
Planned location	Chile	Candidates: Hawaii; Mexico; three sites in Chile	Candidates: Canary Islands; Morocco; Argentina; two sites in Chile
Planned construction period	2010-2017 (First mirror already cast)	2009-2016	2010-2017
Technical advantages	Adaptive optics integrated within secondary mirror Shortest focal length means it has the smallest and cheapest structure	Mirror segments are comparatively cheap and more easily replaced Similar scaled-up version of the existing Keck telescopes	Five-mirror design results in a flat focal plane and better images Similar mirror-segment size to the TMT, so greater vendor choice
Financial advantages	Potential support from \$34-billion Harvard endowment or Texas billionaire George Mitchell	\$200-million gift from Intel founder Gordon Moore	Steady European funding stream
Disadvantages	Only one place can make the mirrors Gaps in mirror limit the effective aperture to 21.5 metres	Adaptive optics performed after the light leaves the telescope, so the 'natural seeing' mode cannot benefit from adaptive corrections to wind effects	Biggest and most expensive design No similar design experience Reflections through five mirrors reduce light levels

Where is the UV *indispensable* (or nearly so)?

1969-1974

- UV upturn in old populations (UVX)
- Multiphase ISM
- IGM $z < 2$

- Galaxy SFR's and SFH's
- YSO star-disk-planet interactions
- Exoplanets
- Globular clusters
- AGN's



The ground-based UV window
3100 – 4000 Å

Mean Extinction

Ozone

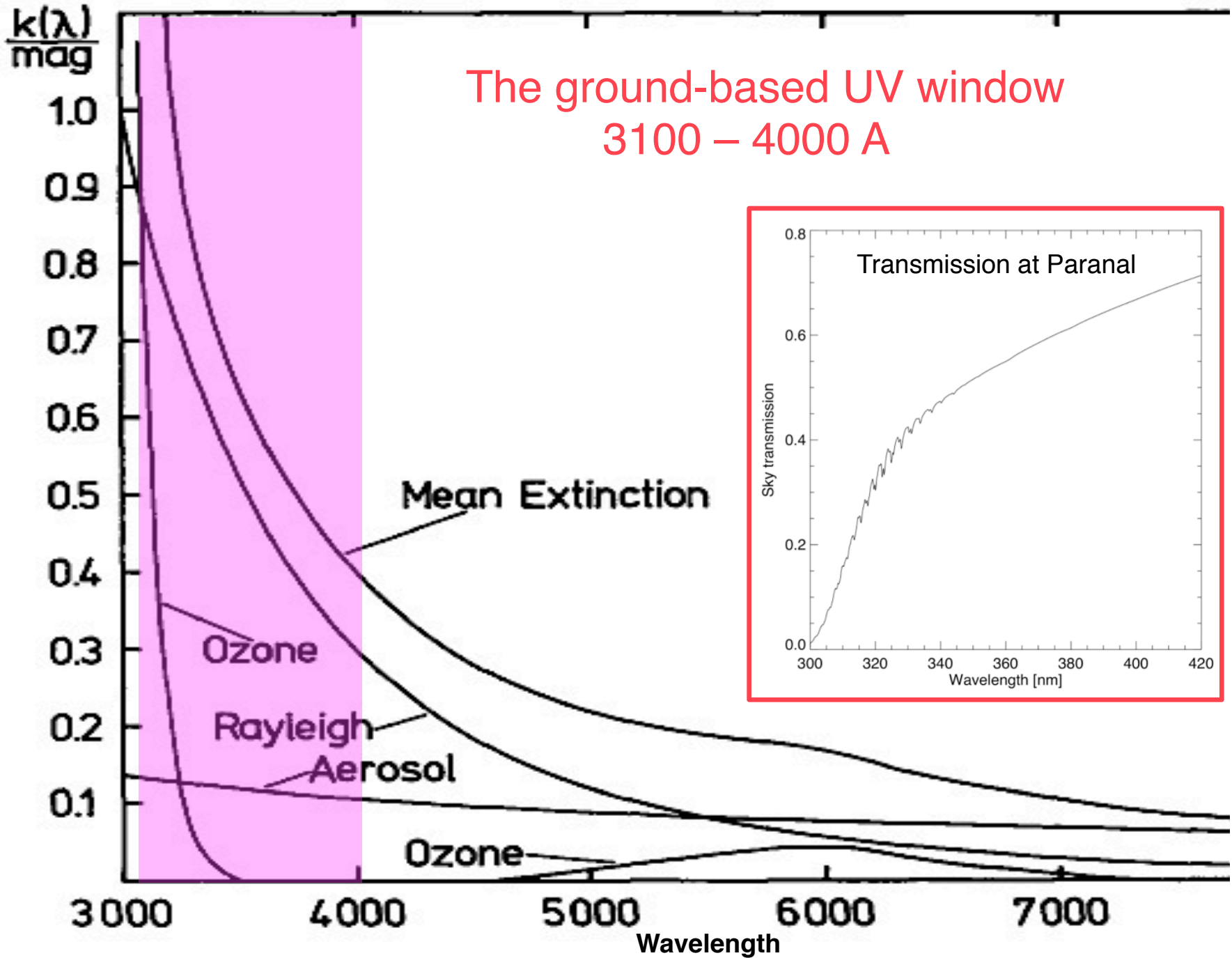
Rayleigh

Aerosol

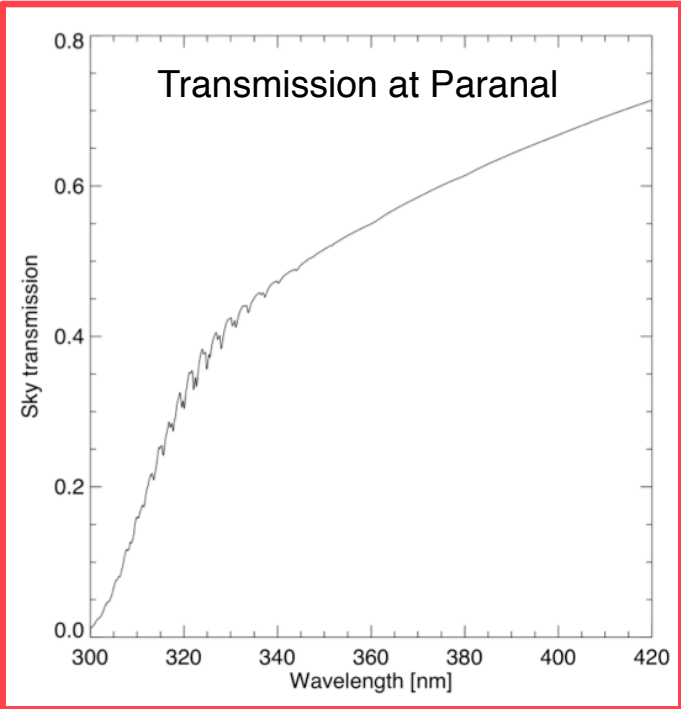
Ozone

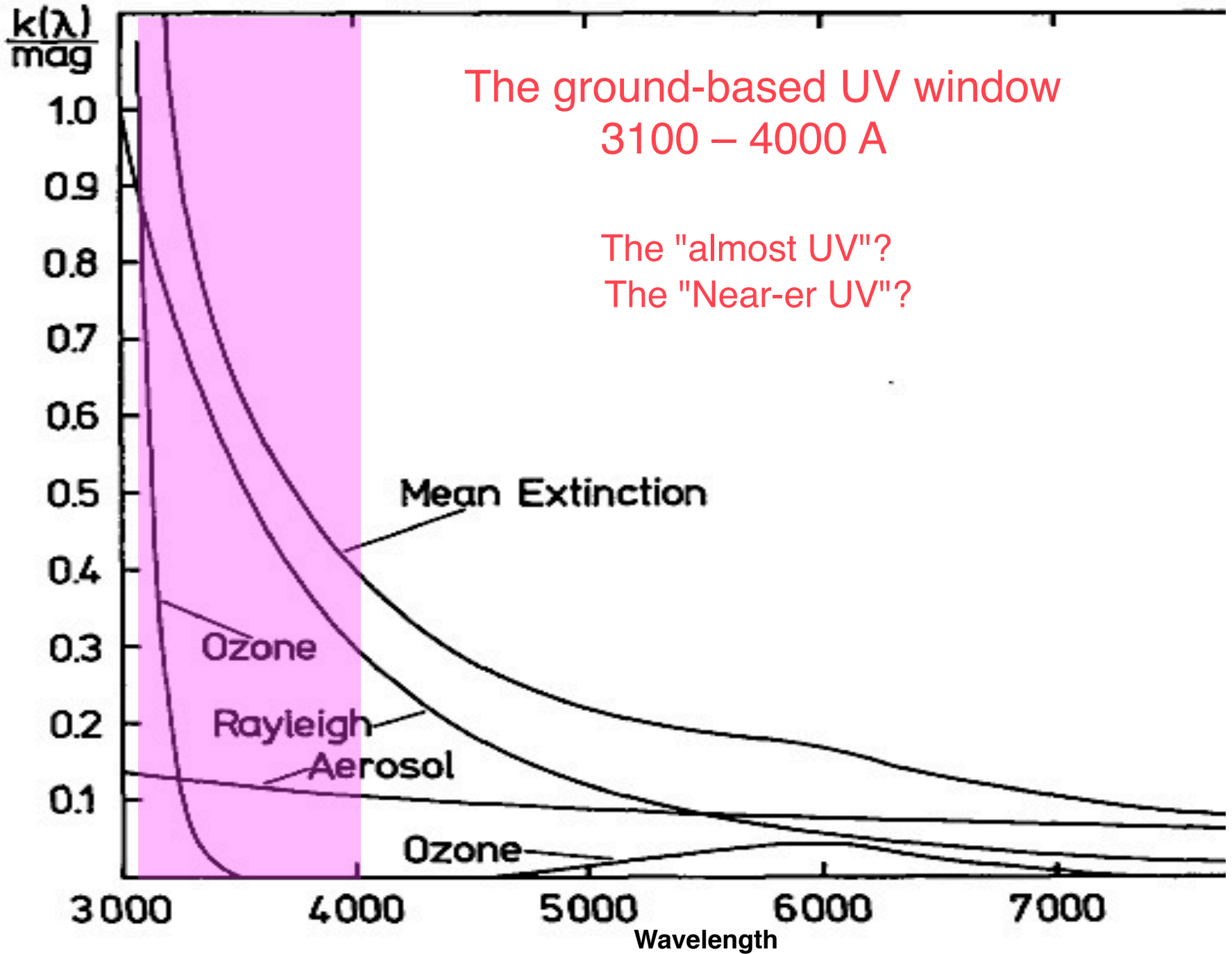
$k(\lambda)$
mag

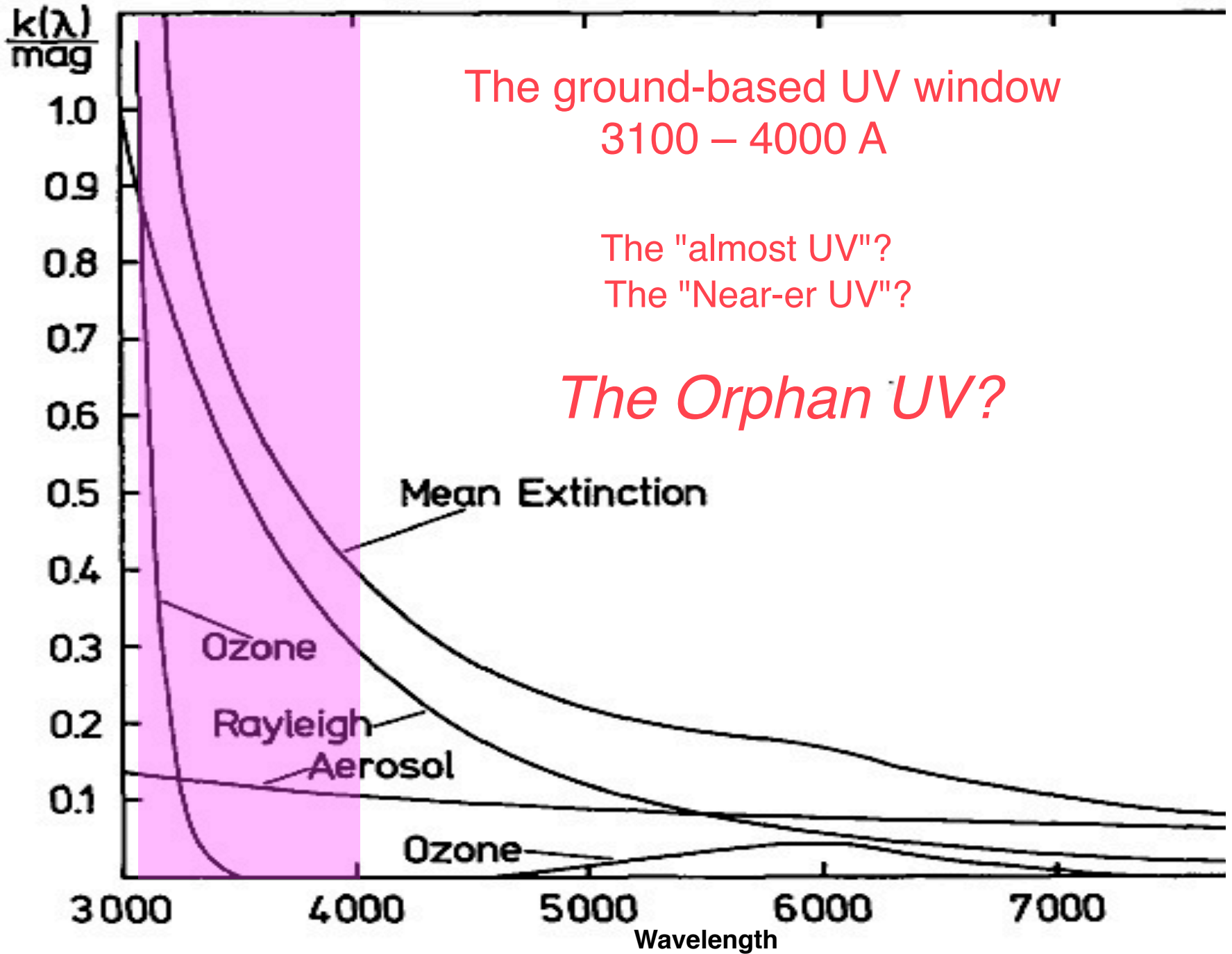
Wavelength

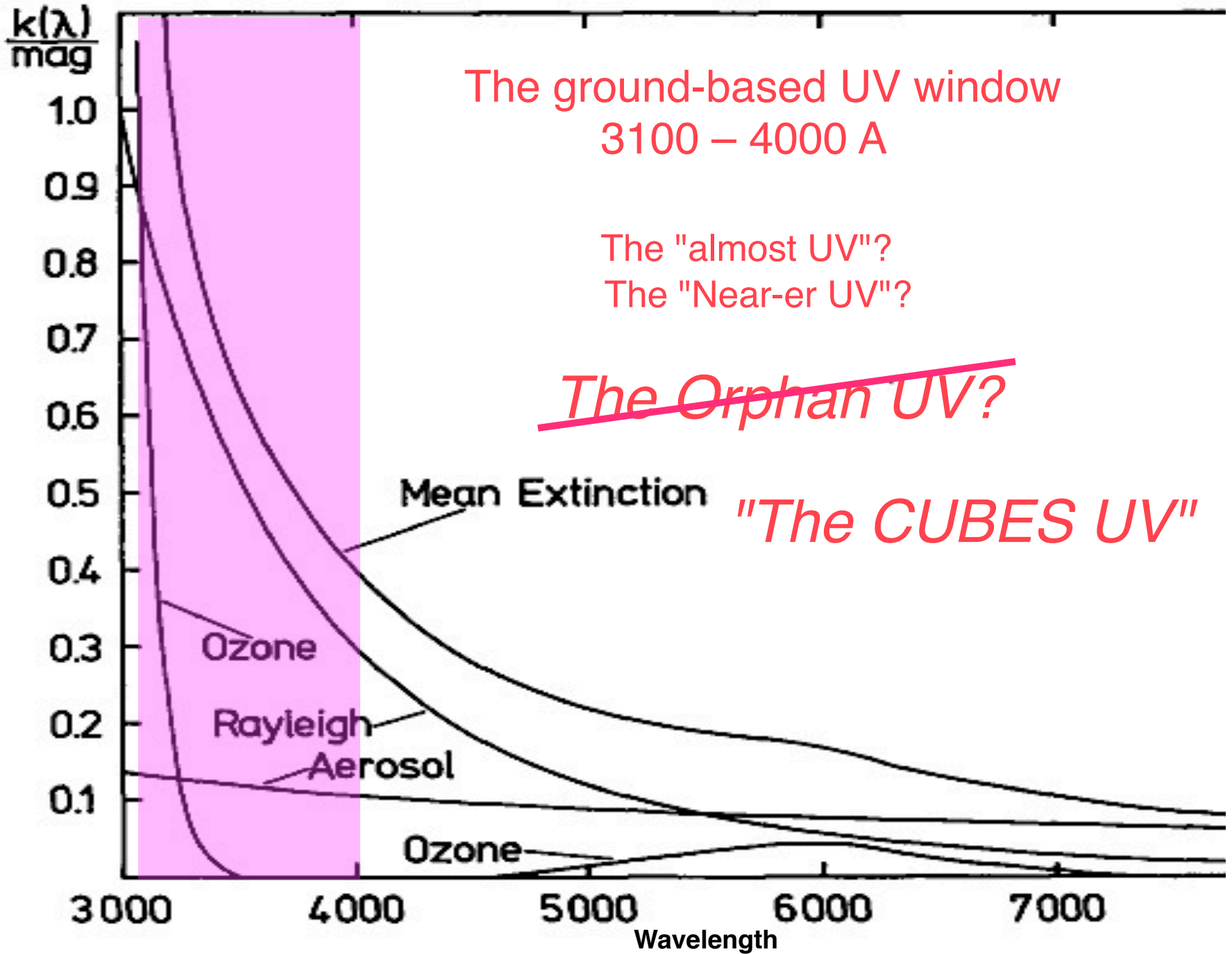


The ground-based UV window
3100 – 4000 Å









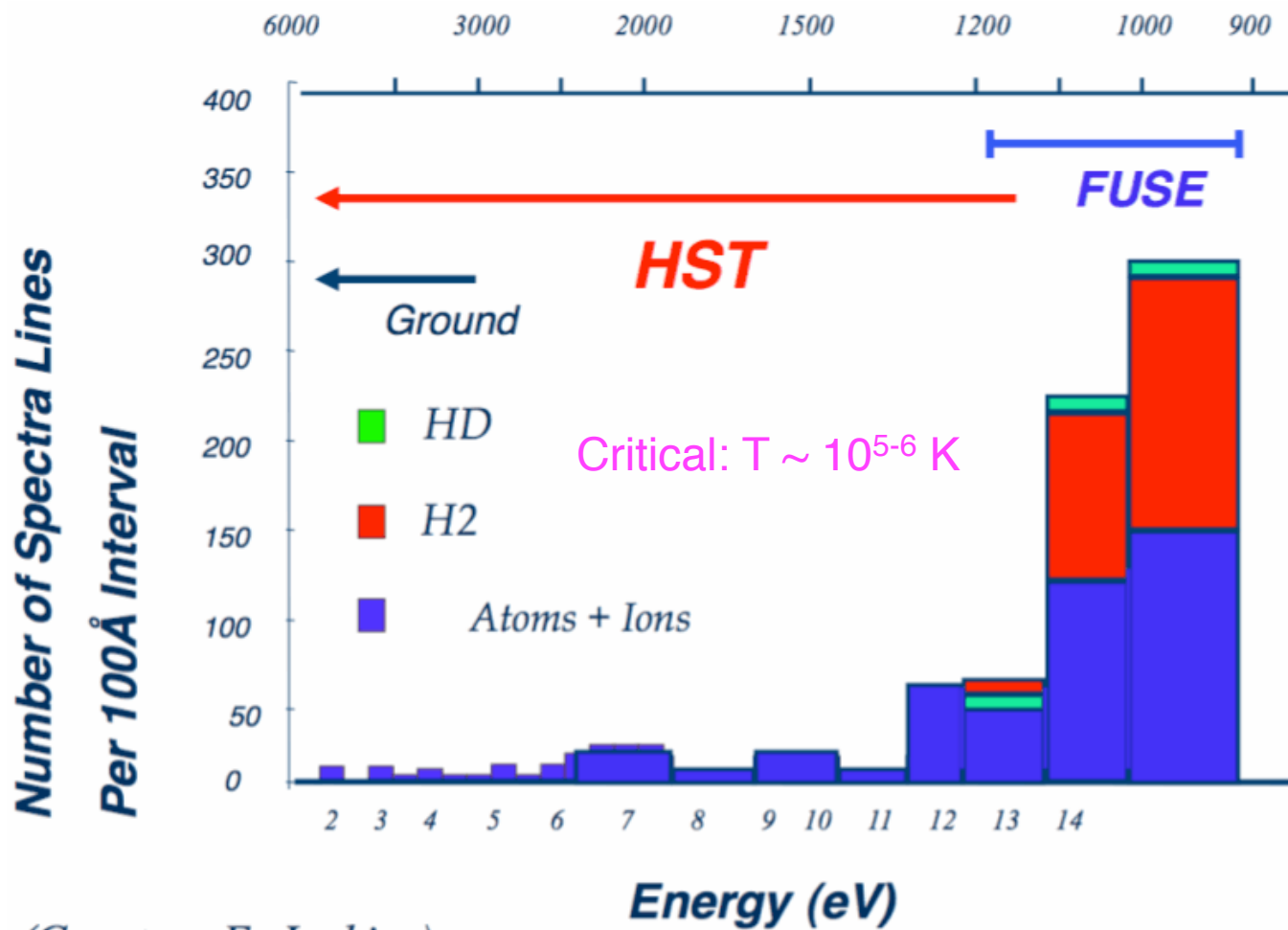
The ground-based UV window
3100 – 4000 Å

The "almost UV"?
The "Near-er UV"?

~~The Orphan UV?~~

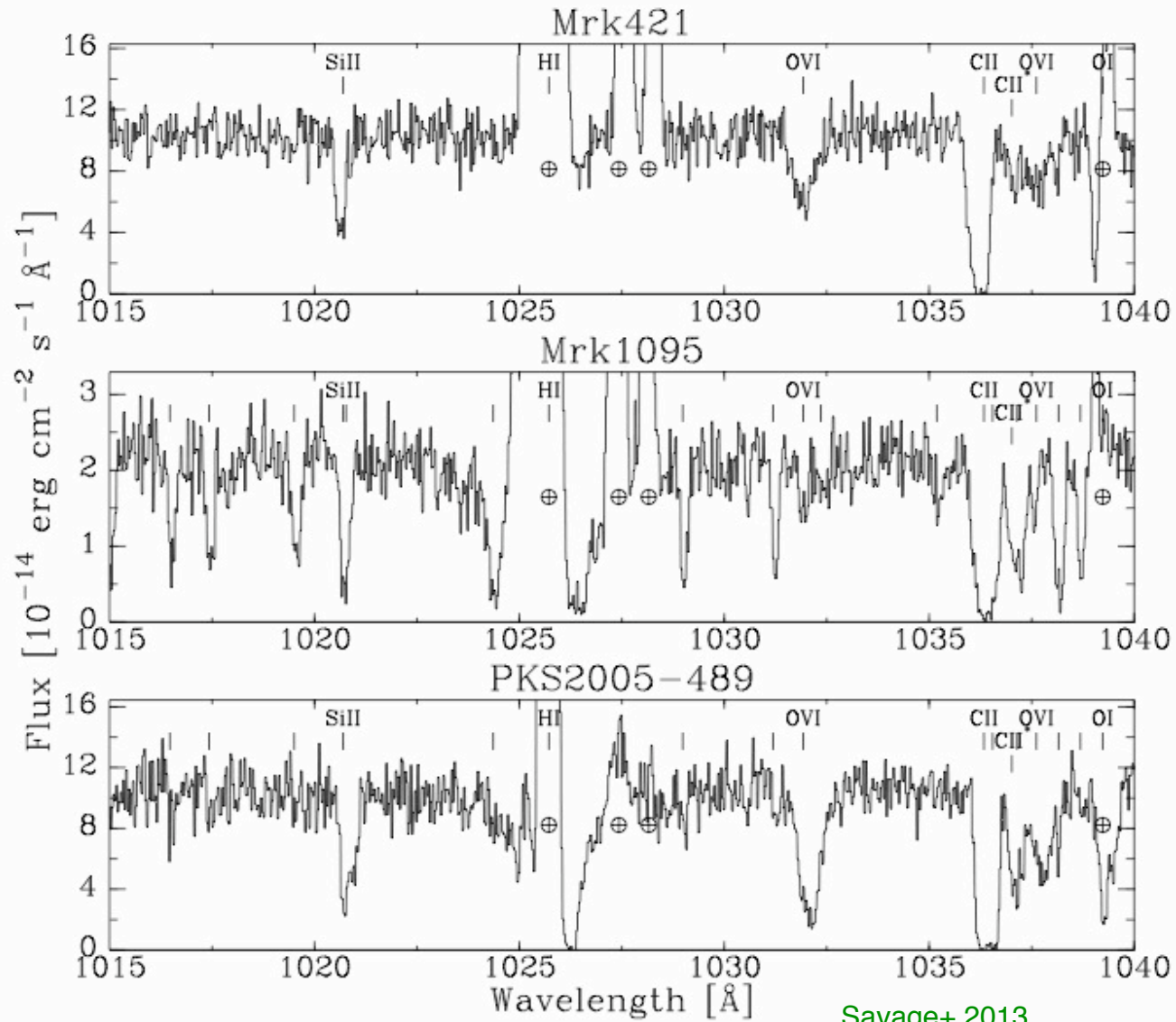
"The CUBES UV"

ISM/IGM/CGM



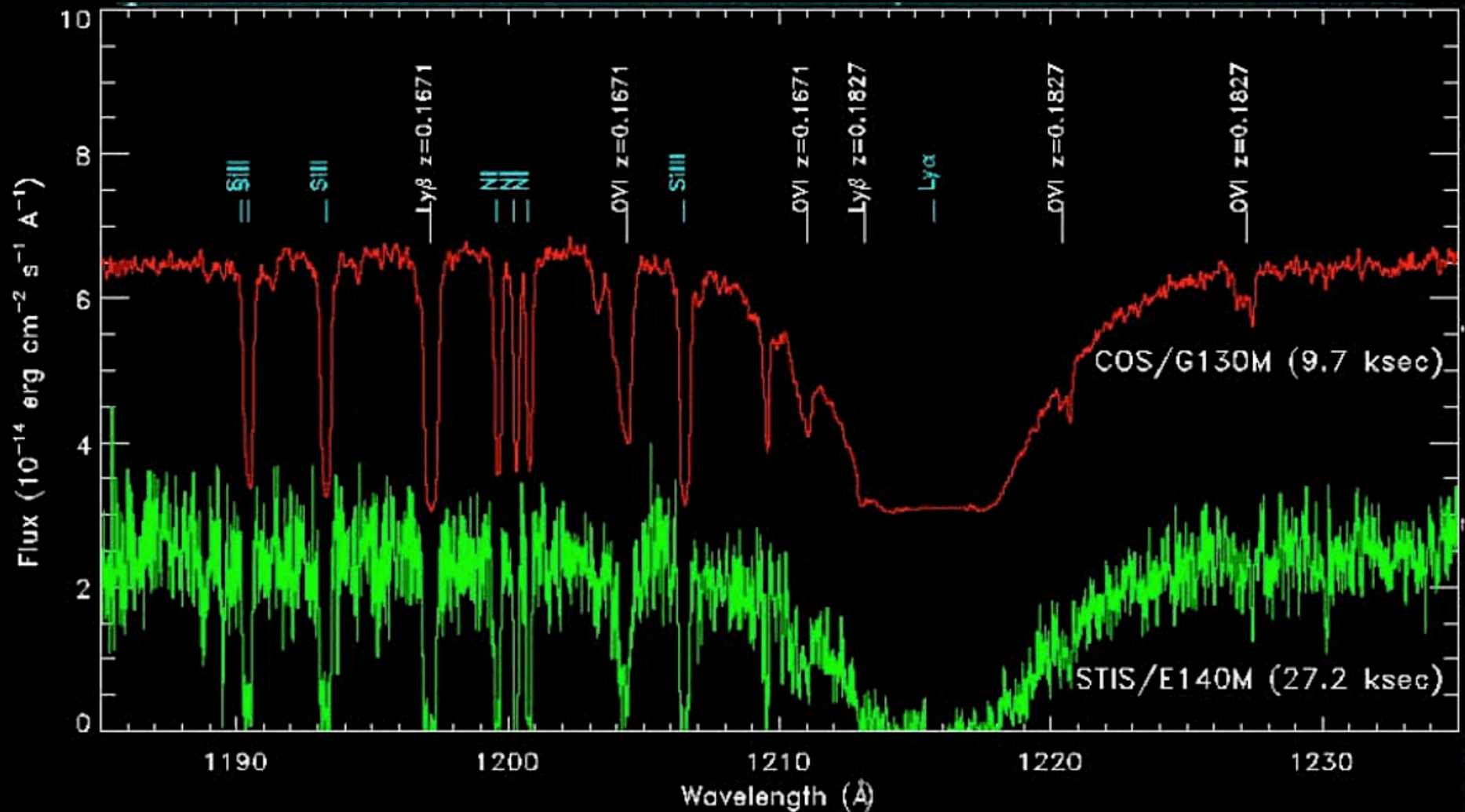
(Courtesy E. Jenkins)

Hot Milky Way ISM seen against distant AGN (FUSE)



Savage+ 2013

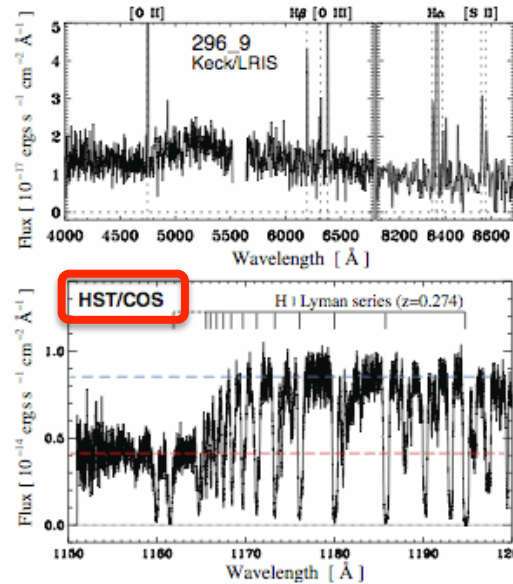
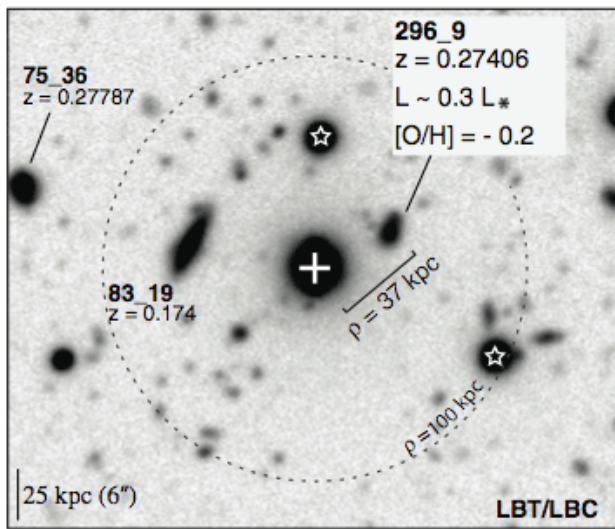
IGM Absorption Spectrum (HST/COS)



Danforth, Keeney, France, et al.

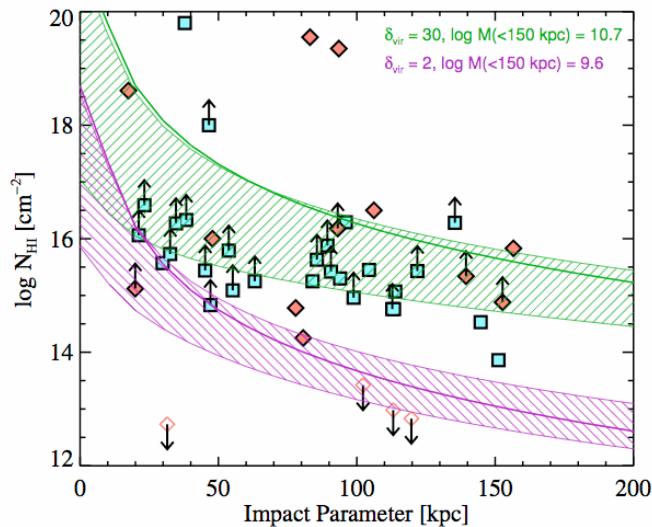
Courtesy Jim Green

Spectroscopic evidence for circumgalactic cold accretion



Low metallicity Lyman limit system at $z = 0.27$

Ribaudo+ 2011



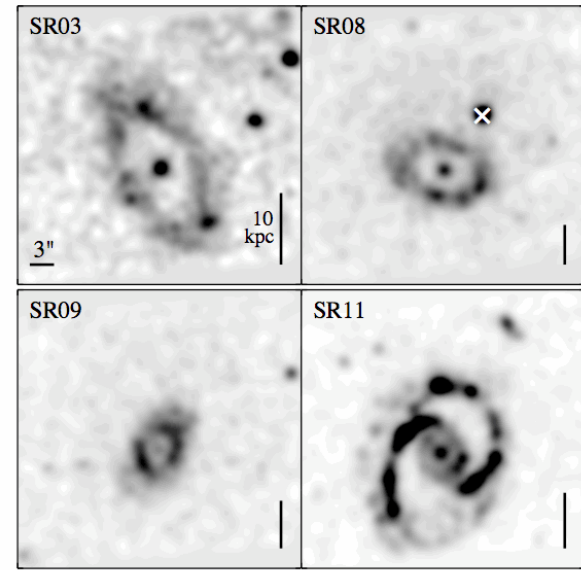
HI features (HST/COS) in halos of distant galaxies: $M_{\text{gas}} \sim M_{\text{stars}}$

Tumlinson+ 2013



GALEX/Bigiel+ 2010

UV imaging evidence
for CGM: "XUV"
star formation



HST/Fang+ 2012

STAR FORMATION IN EARLY-TYPE GALAXIES

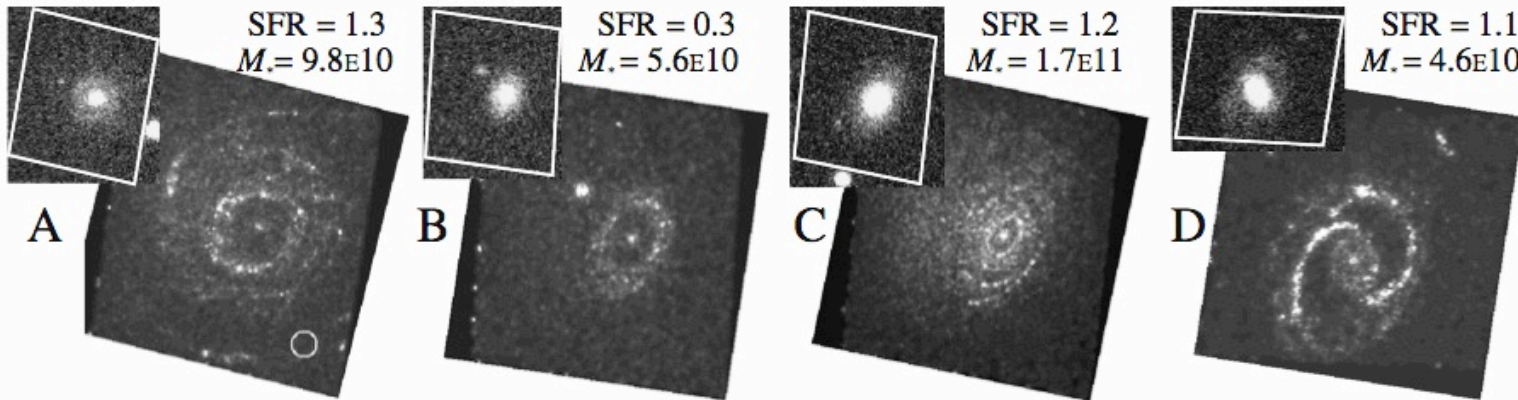
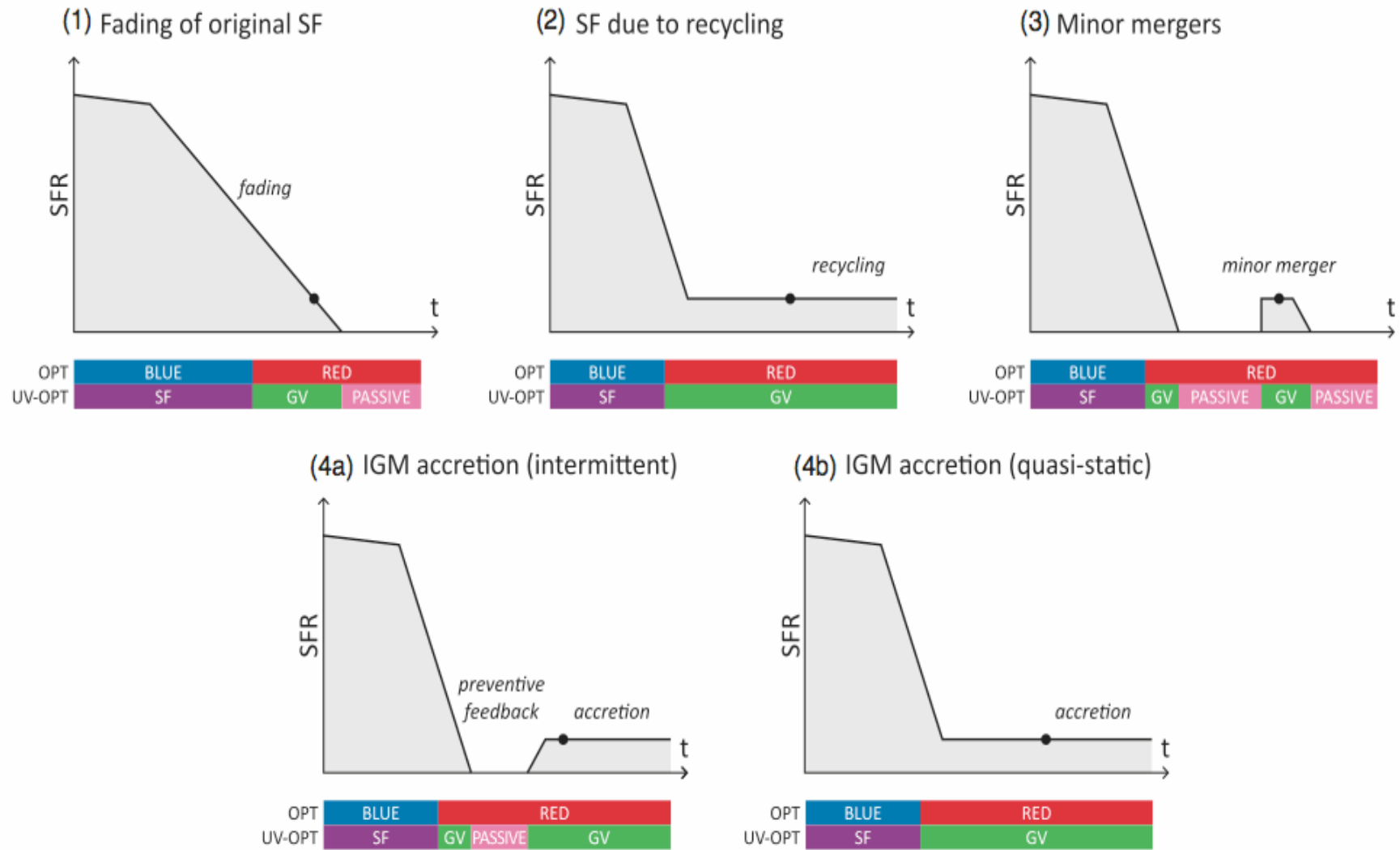


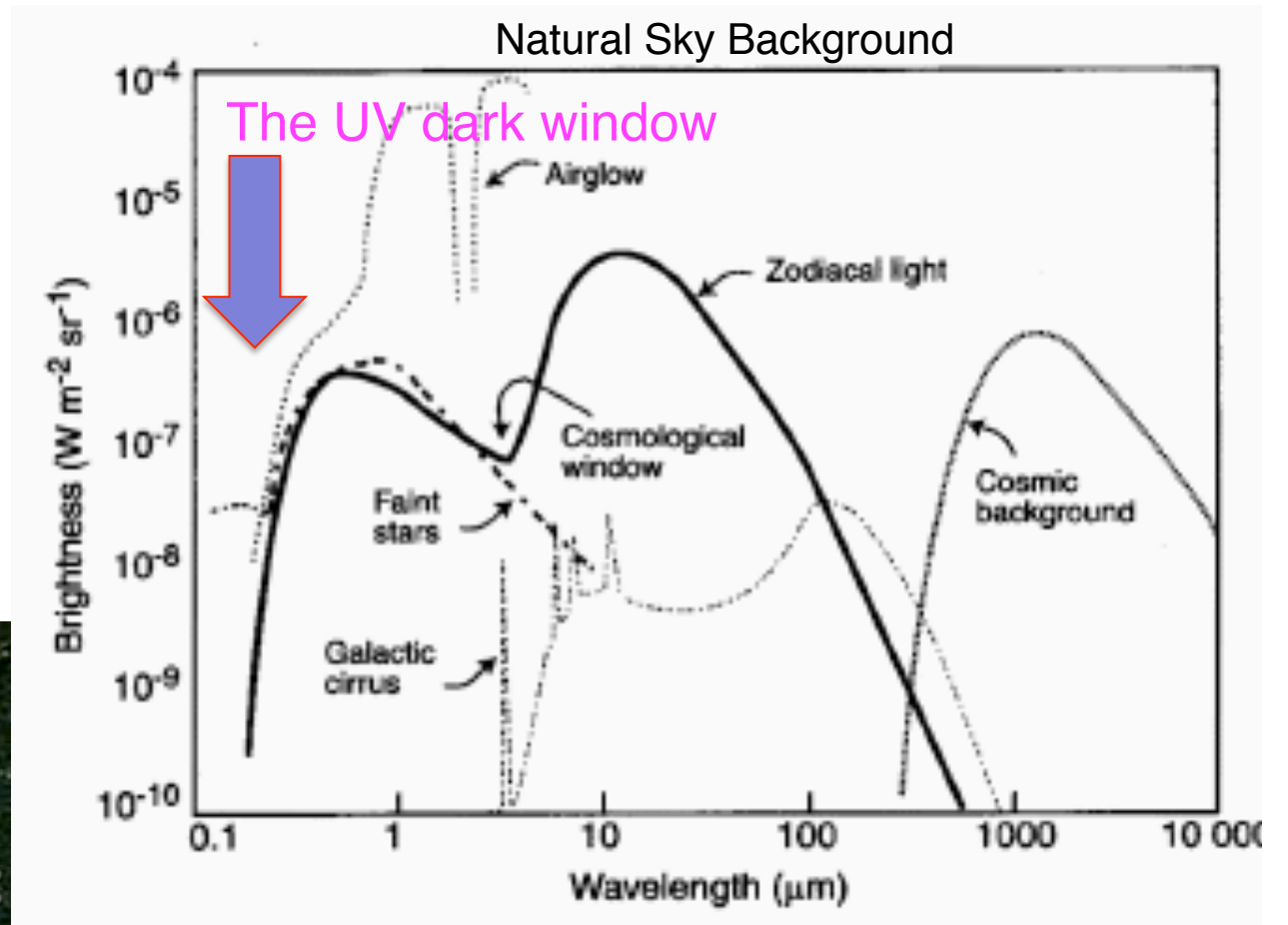
Figure 3. *HST* ACS/SBC far-UV images of several strong UV-excess galaxies. Insets show SDSS *g*-band image. ACS images are $\sim 33''$ across (~ 63 kpc). SFRs are given in $M_{\odot}\text{yr}^{-1}$ and stellar masses in M_{\odot} .

Salim & Rich 2010

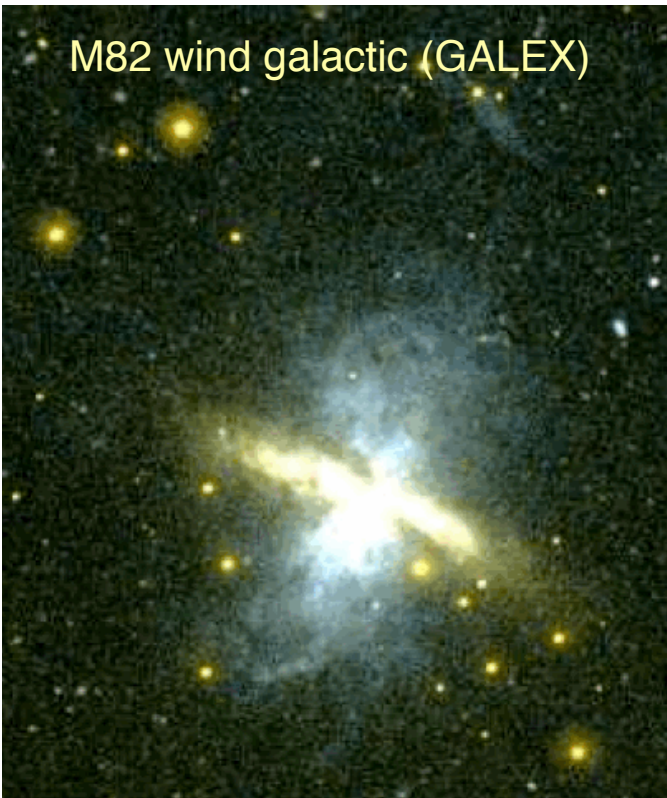
UV/optical discrimination between late epoch star formation histories in early-type galaxies (Salim+ 2012)



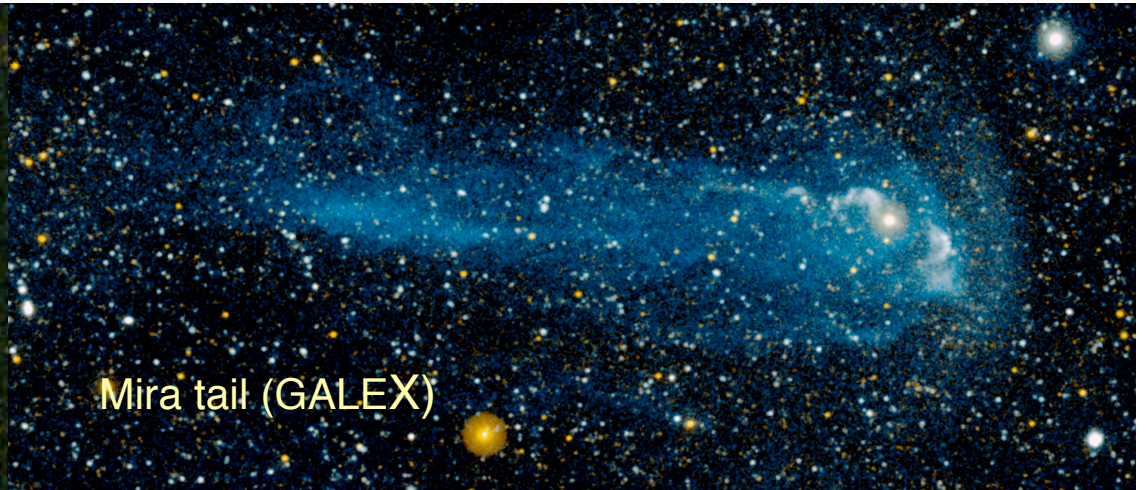
Low-surface
brightness
UV science



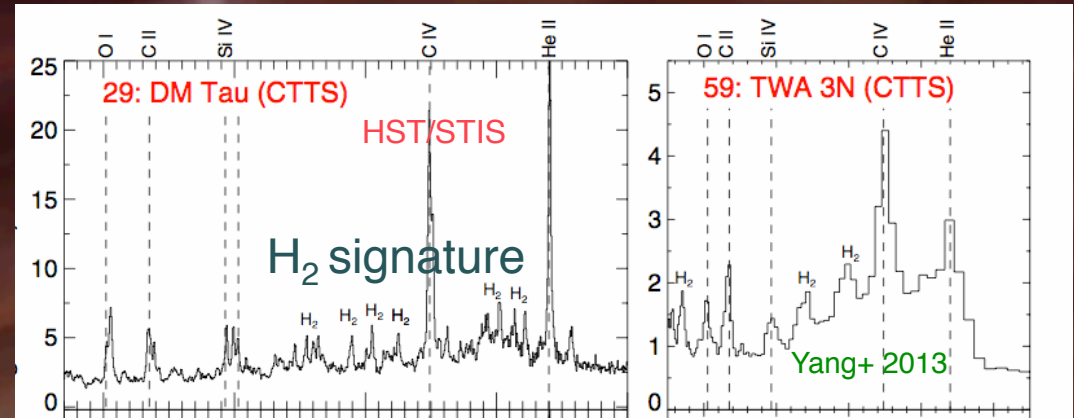
M82 wind galactic (GALEX)



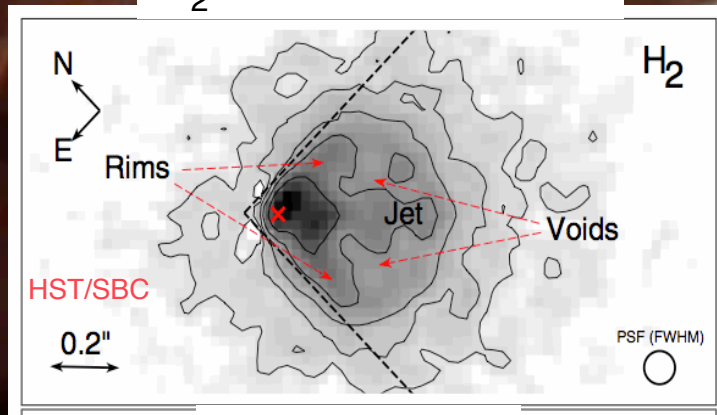
Mira tail (GALEX)



Assembly and physics of protoplanetary disks

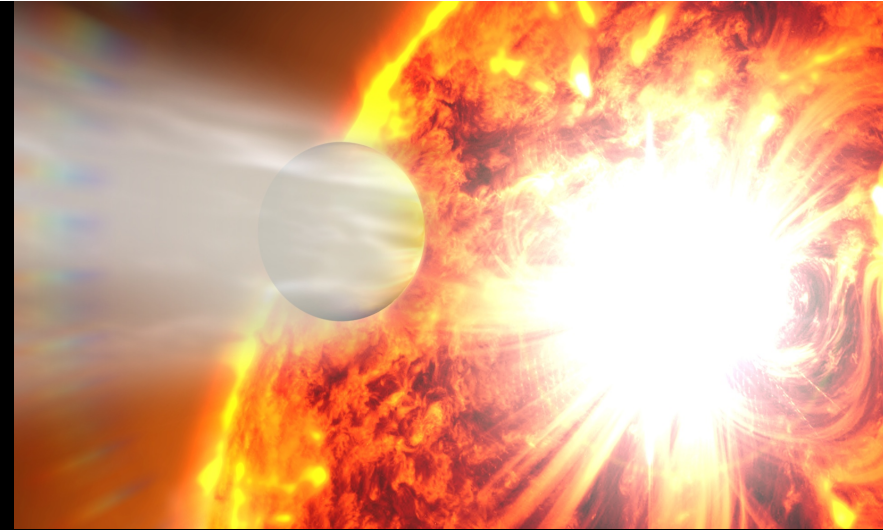


H₂ outflow in DG Tau

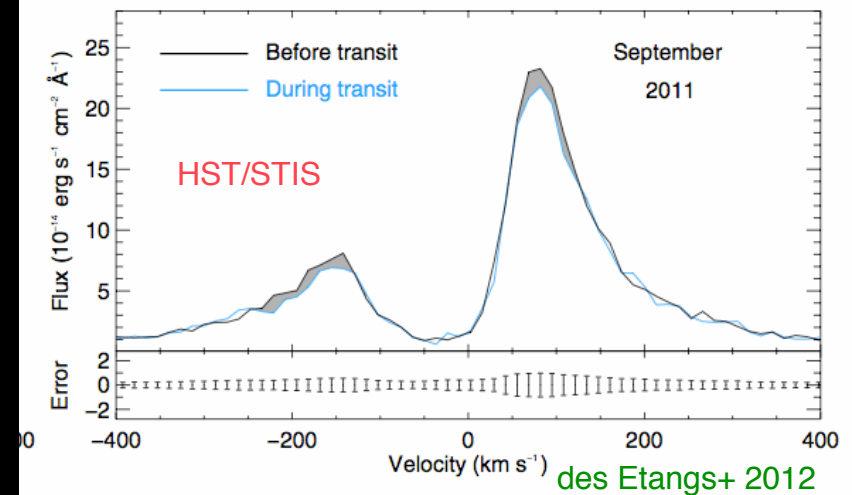
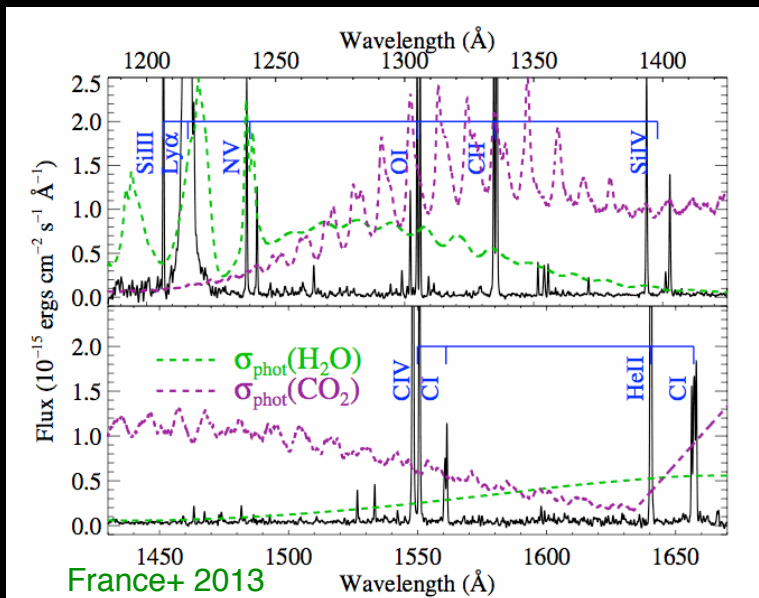


Schneider+ 2013

The dangerous lives of exoplanets



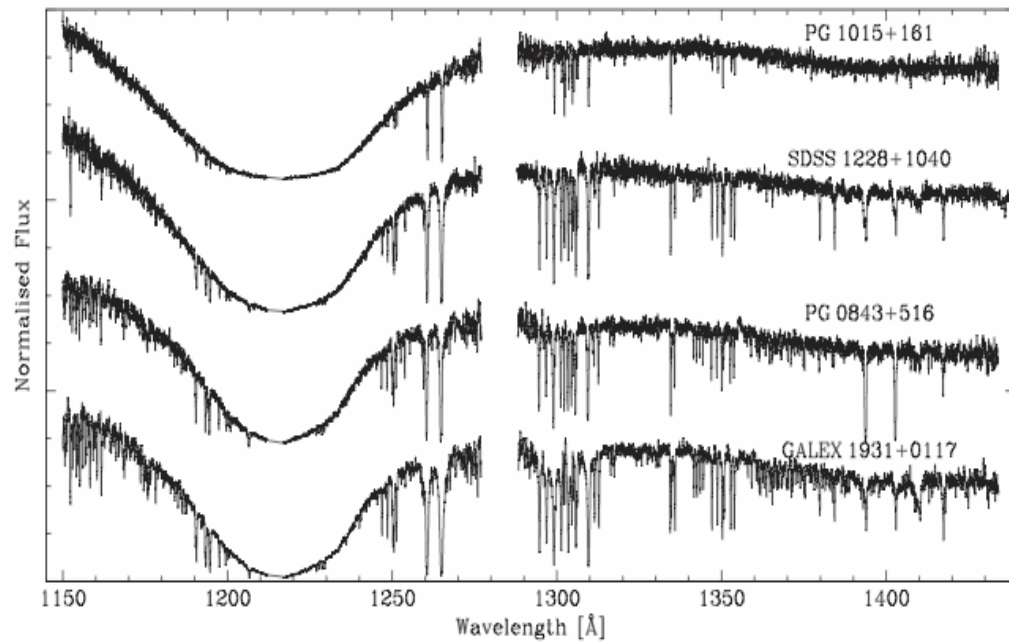
Ly-alpha traces evaporation of a hot Jupiter atmosphere



H_2O and CO_2 photo-dissociation by dM UV flares

Probing terrestrial exoplanets by their pollution of white dwarf atmospheres

Planetary metallic features in far-UV spectra of white dwarfs (HST/COS)

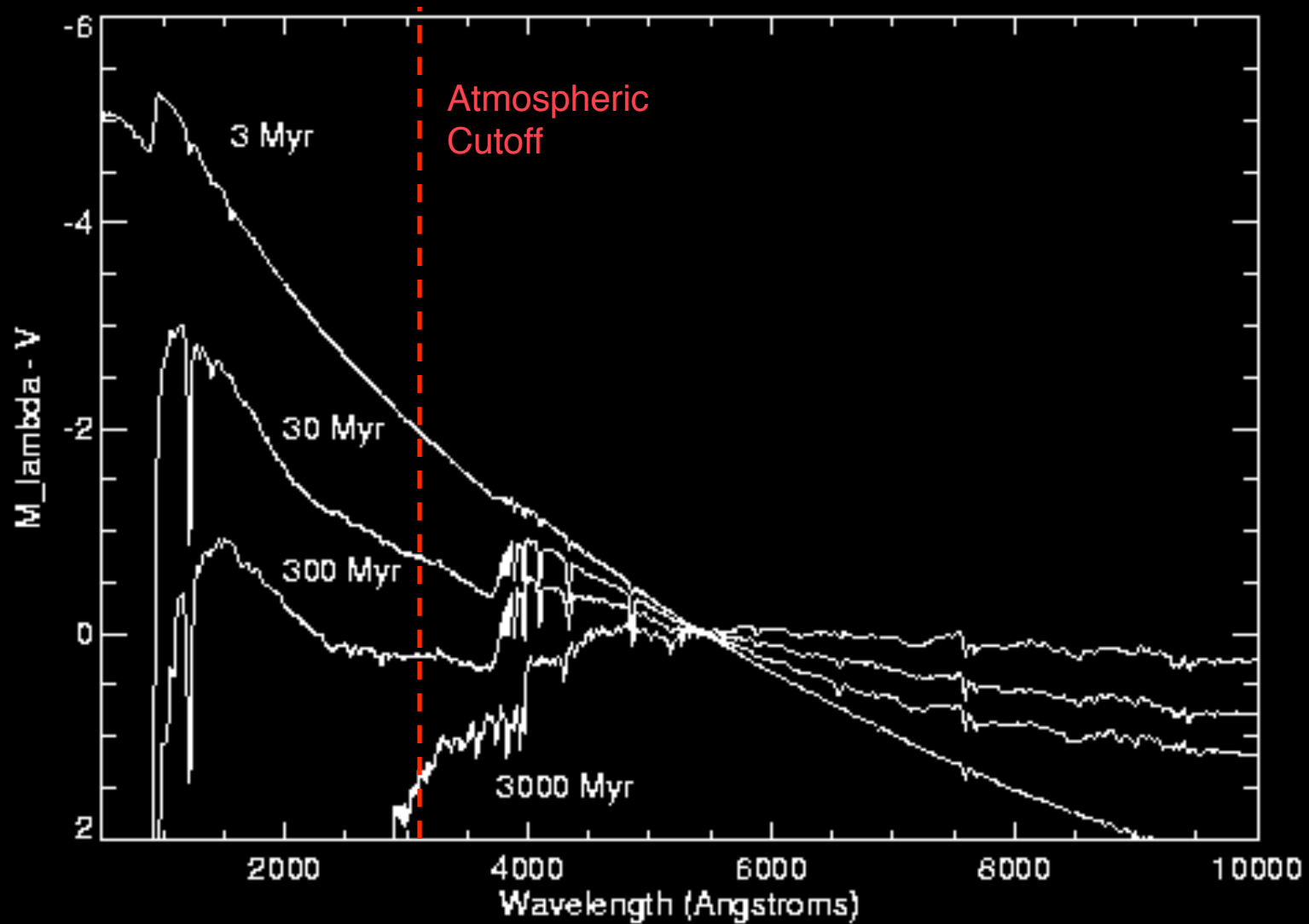


Gaensicke+ 2012

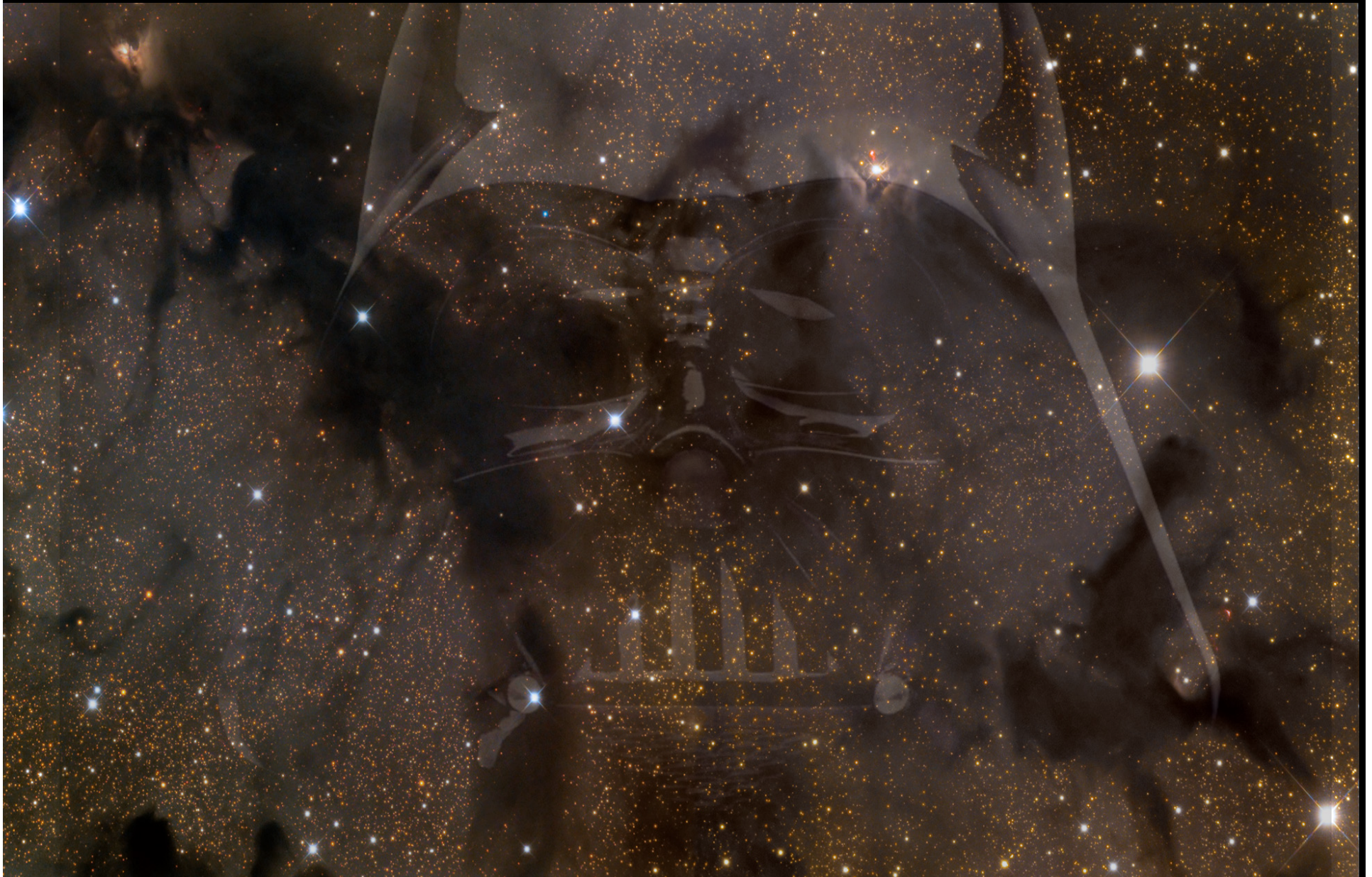


UV Determination of Galaxy Star Formation Rates and Histories

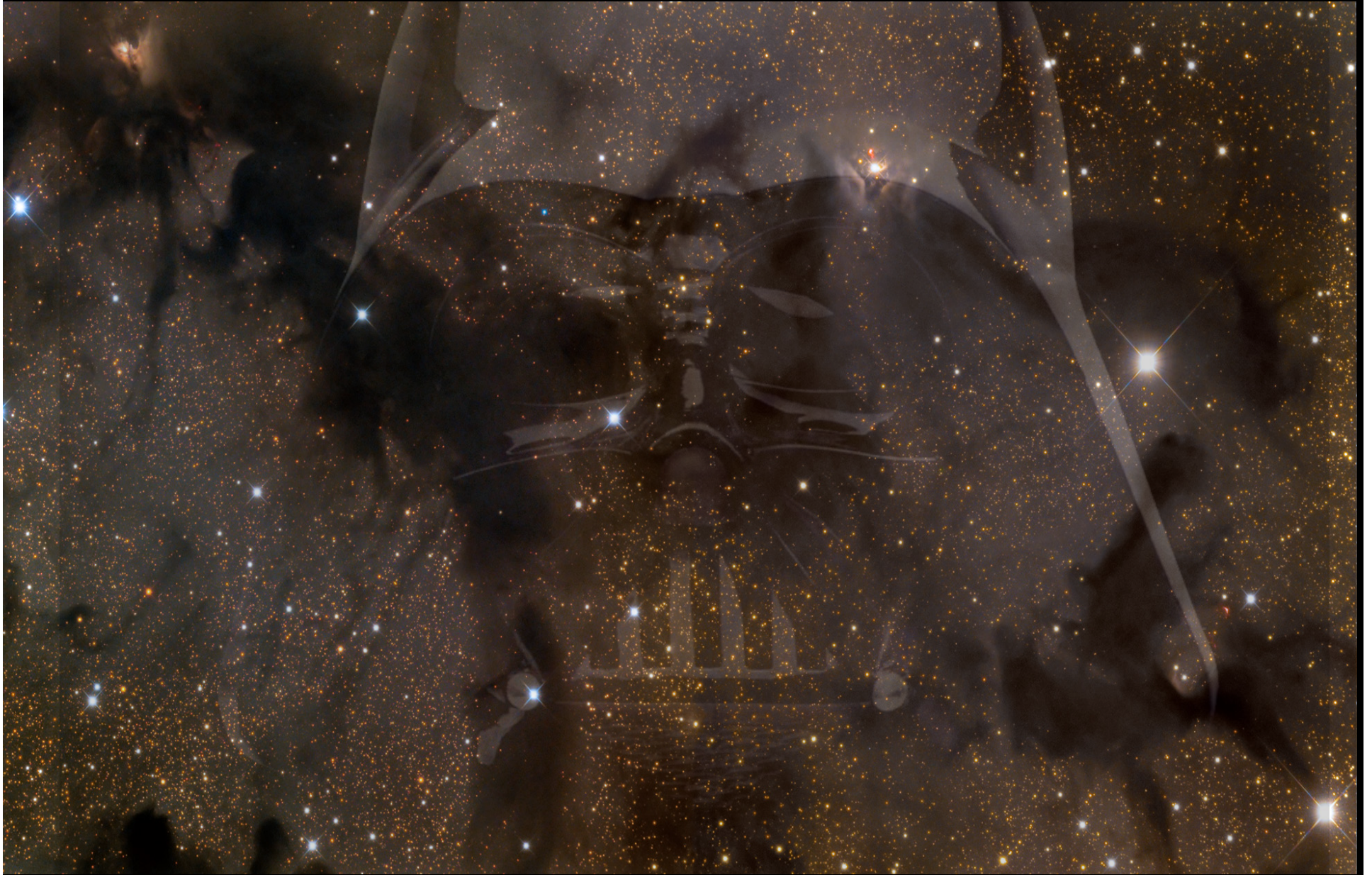
Integrated energy distributions of stellar populations: UV sensitivity to age



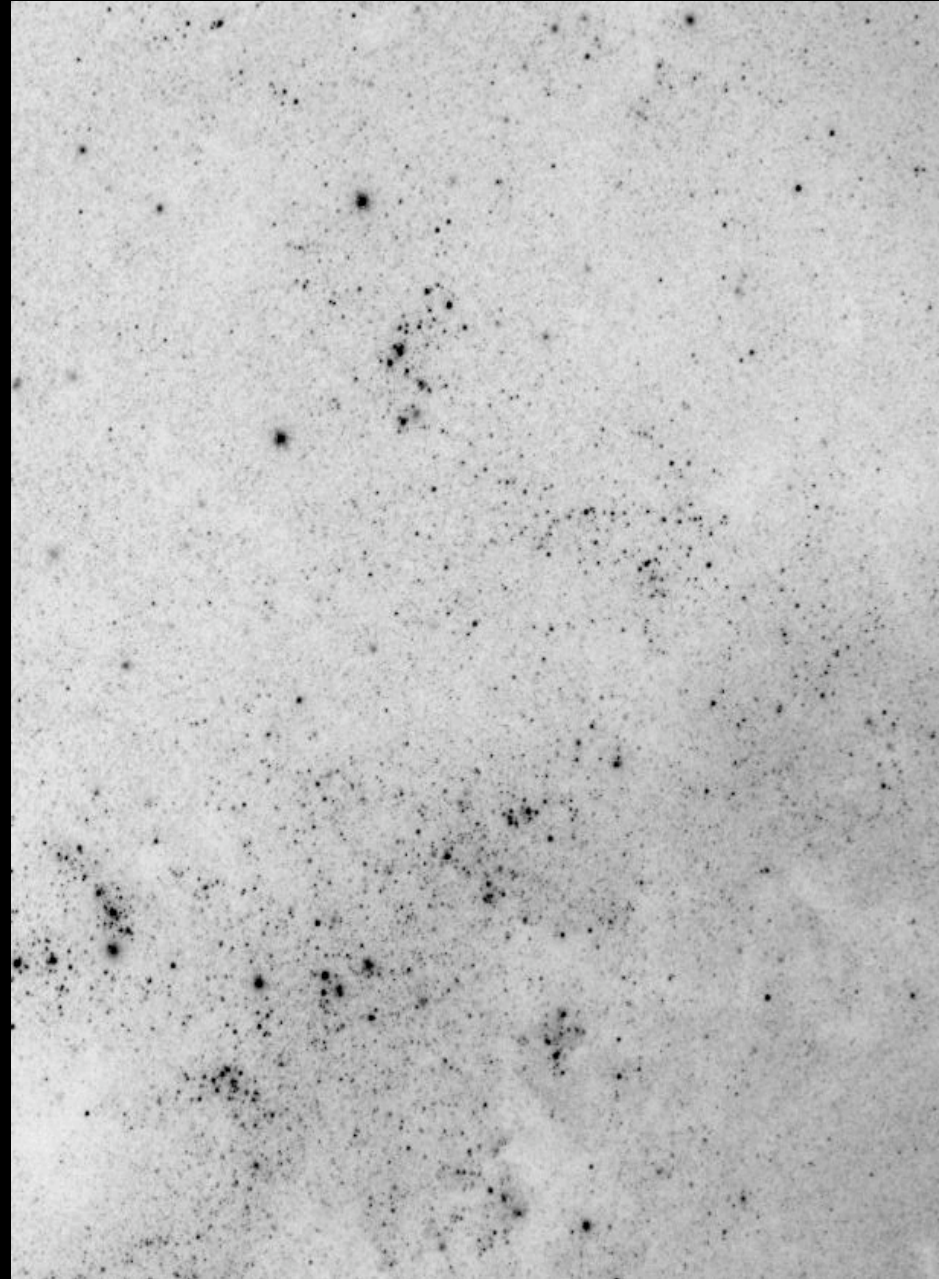
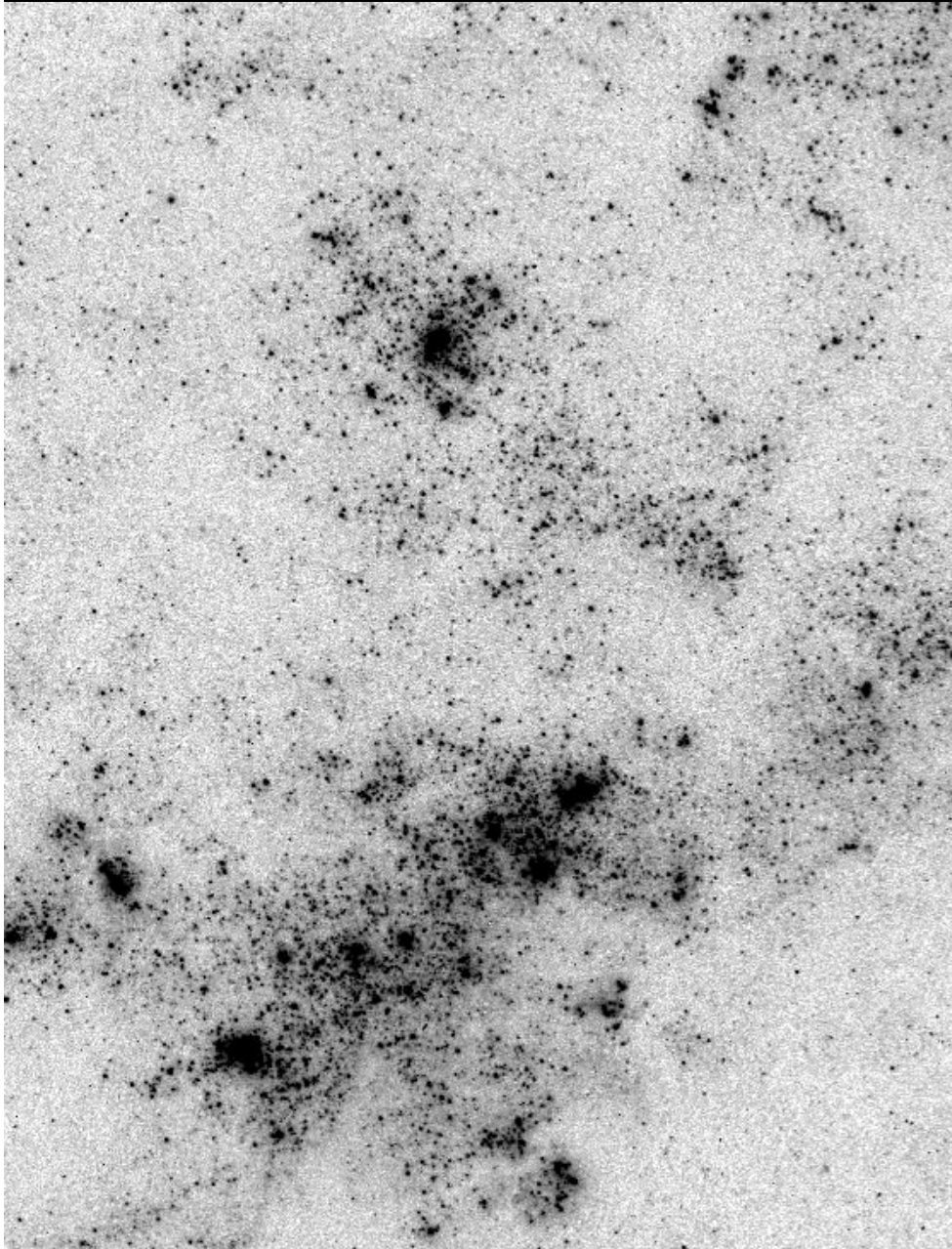
Dust: the bane of UV studies of star formation



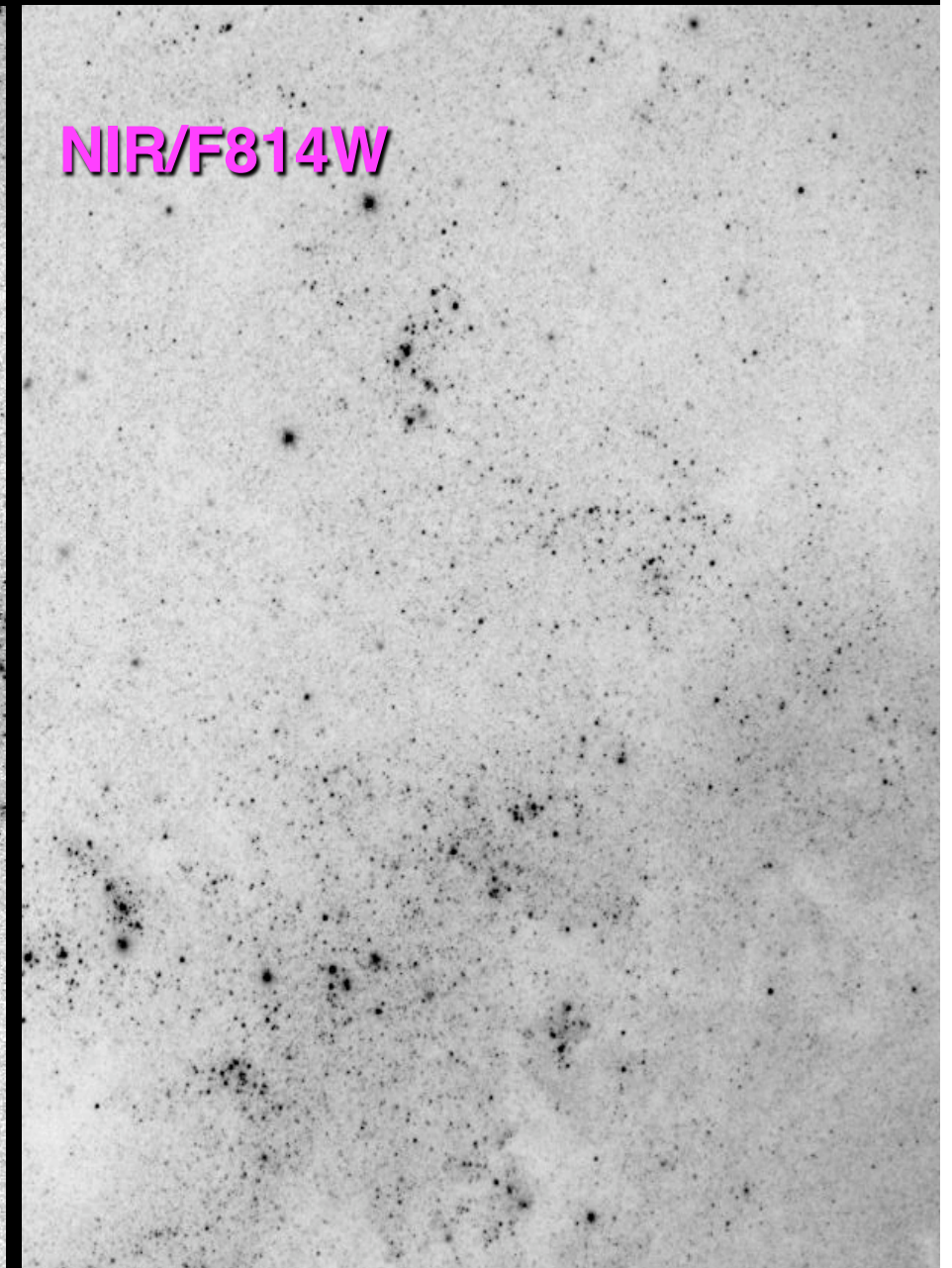
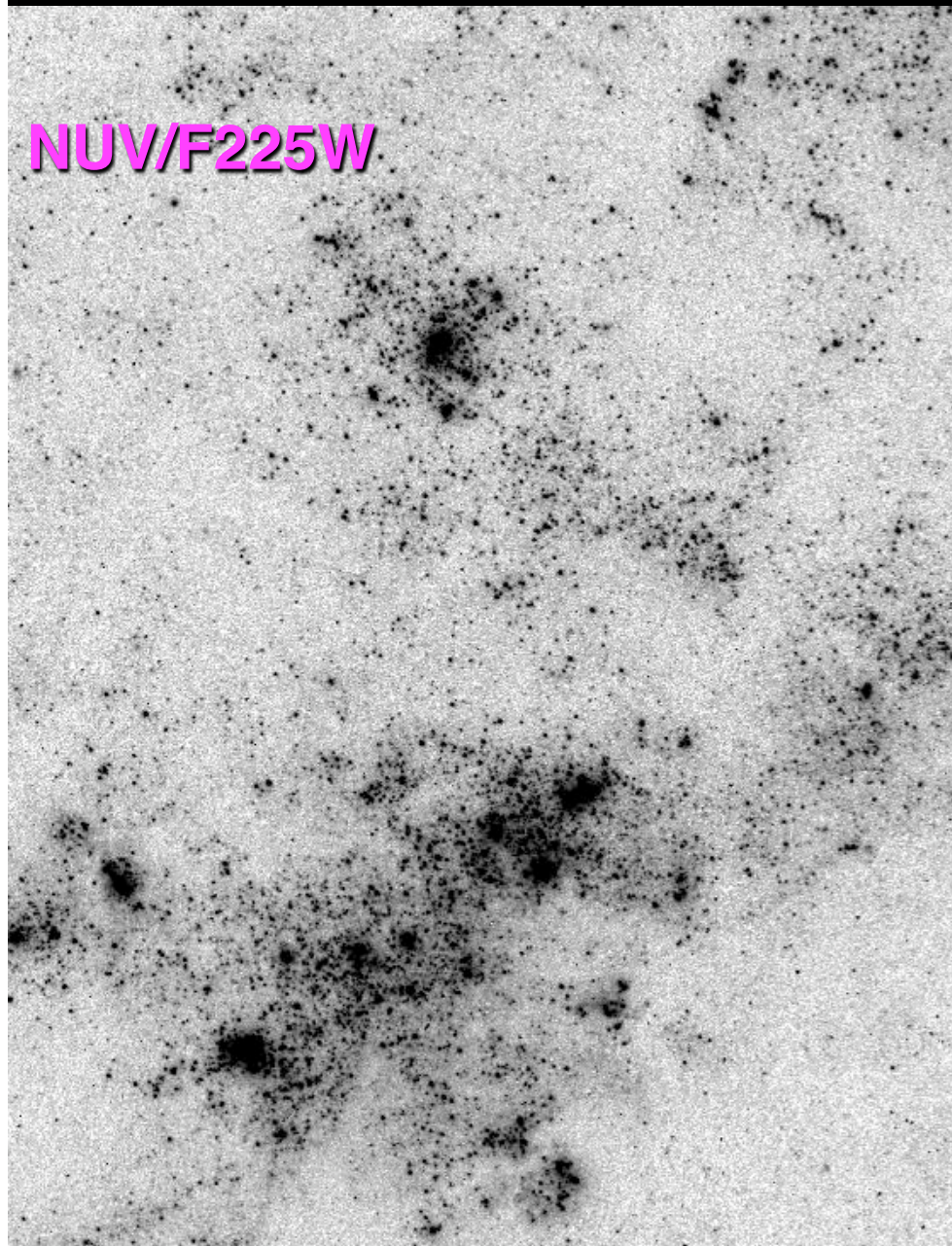
Dust: the bane of UV studies of star formation?

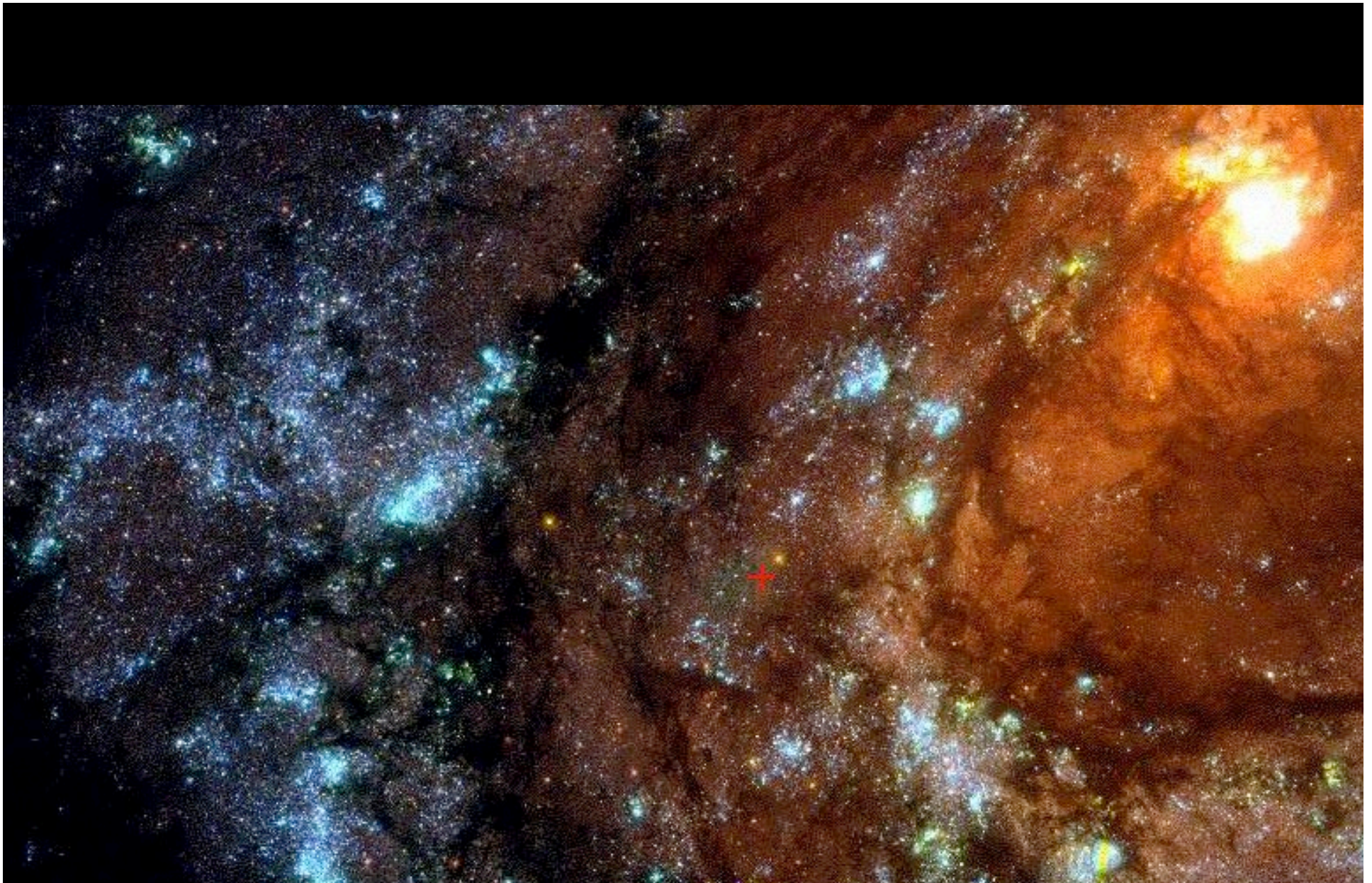


M83: NUV vs NIR bands (HST/WFC3)

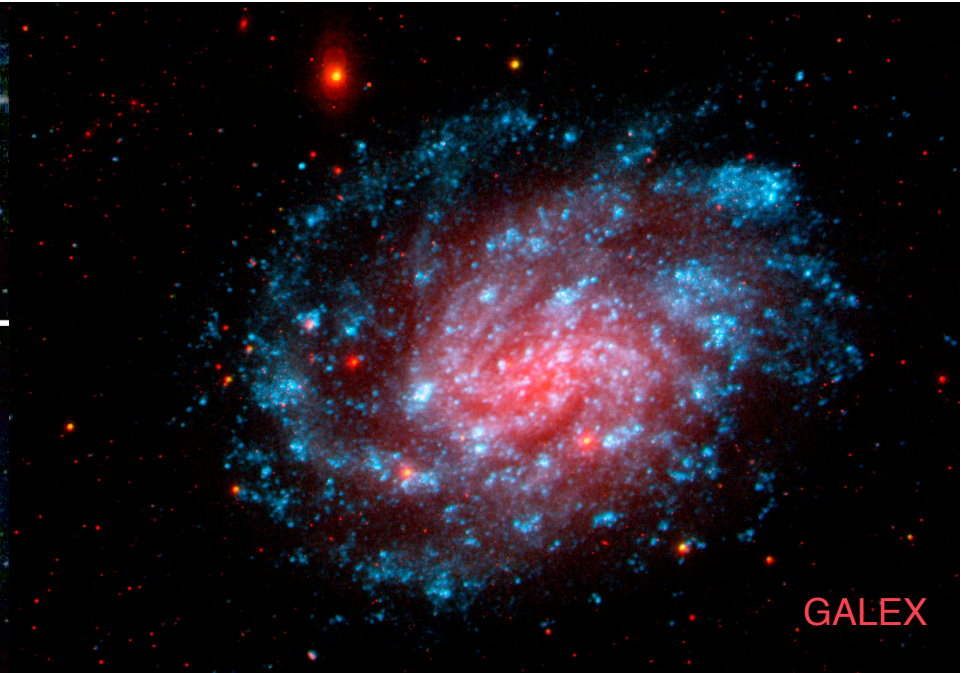
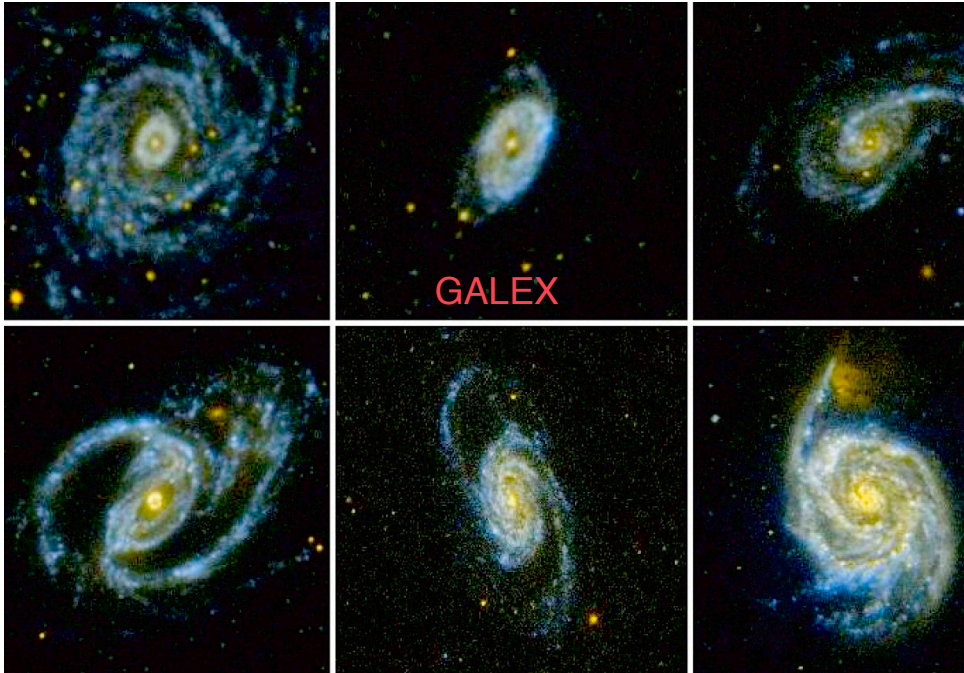


M83: NUV vs NIR bands (HST/WFC3)

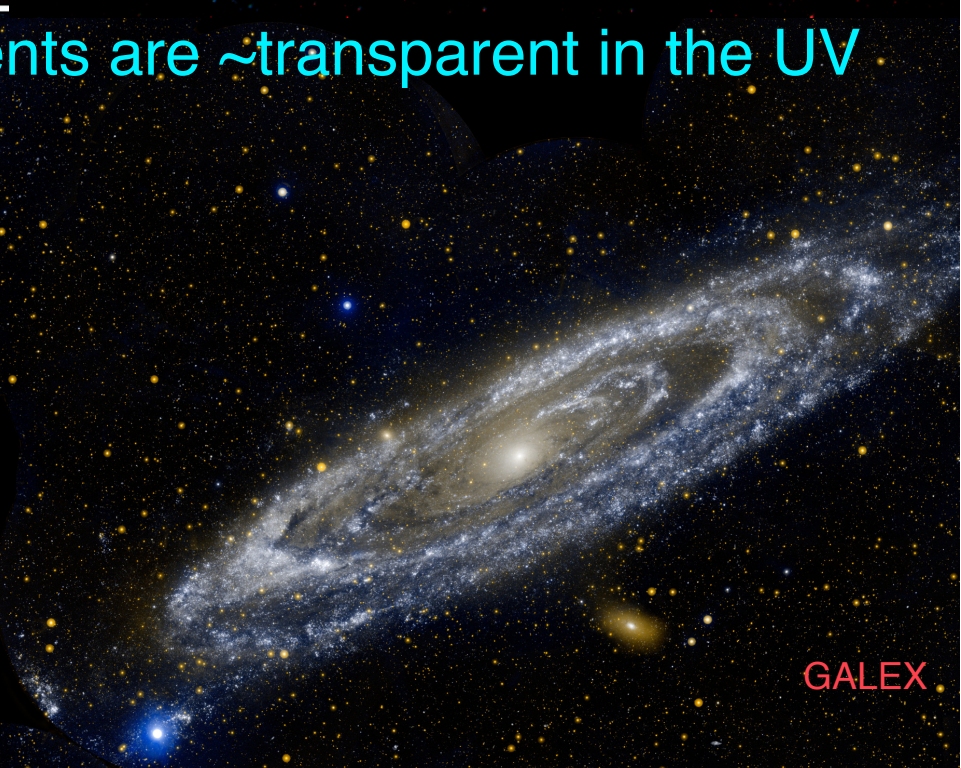
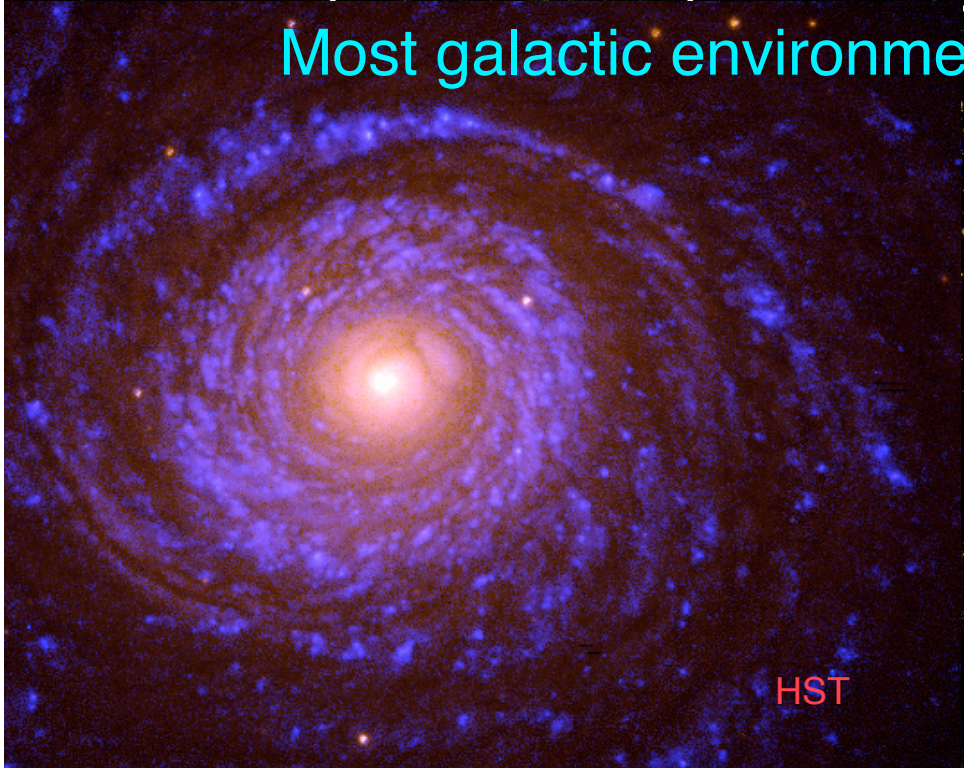


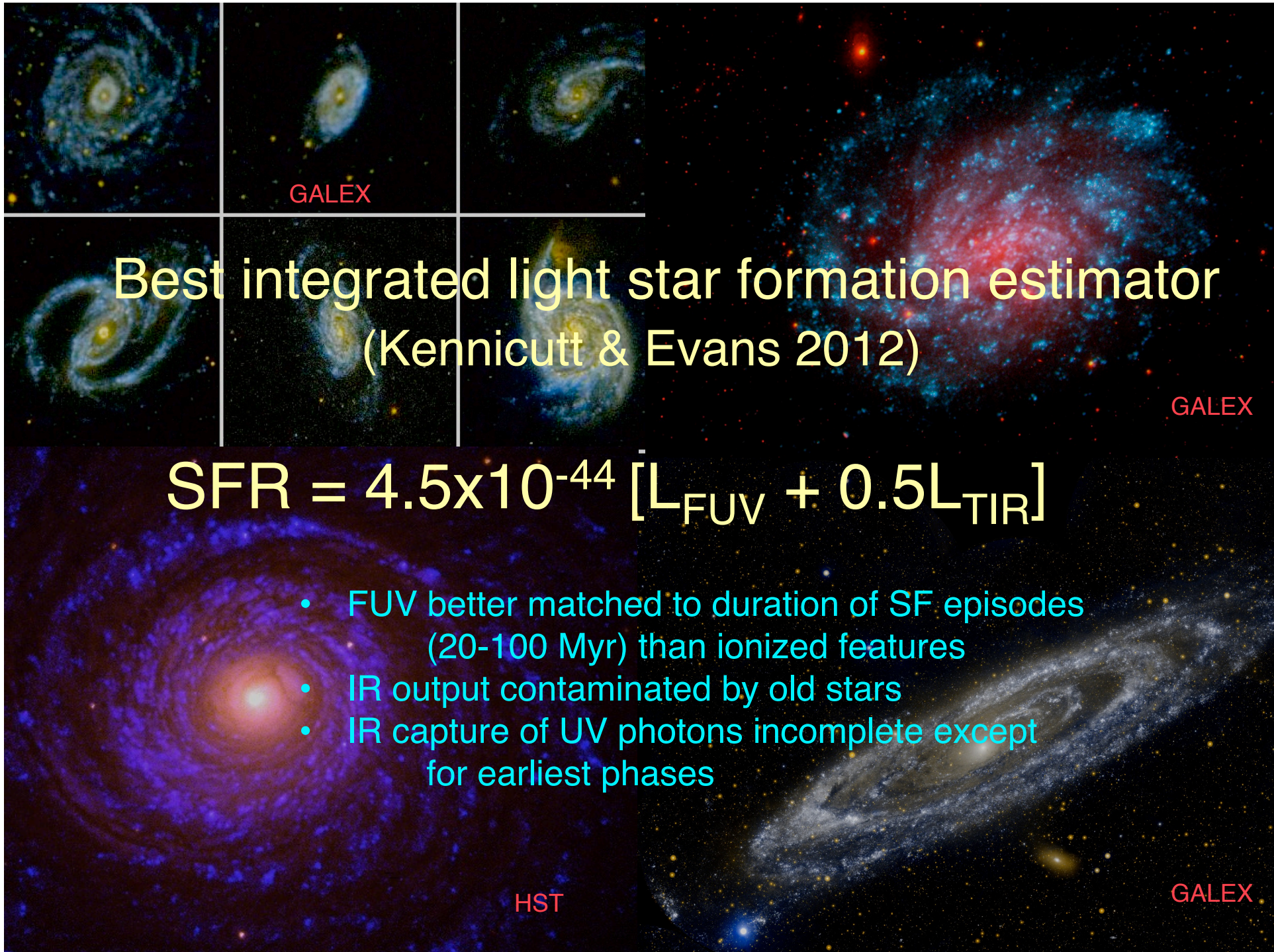


M83: NUV-to-blue band composite (WFC3)



Most galactic environments are ~transparent in the UV





Best integrated light star formation estimator
(Kennicutt & Evans 2012)

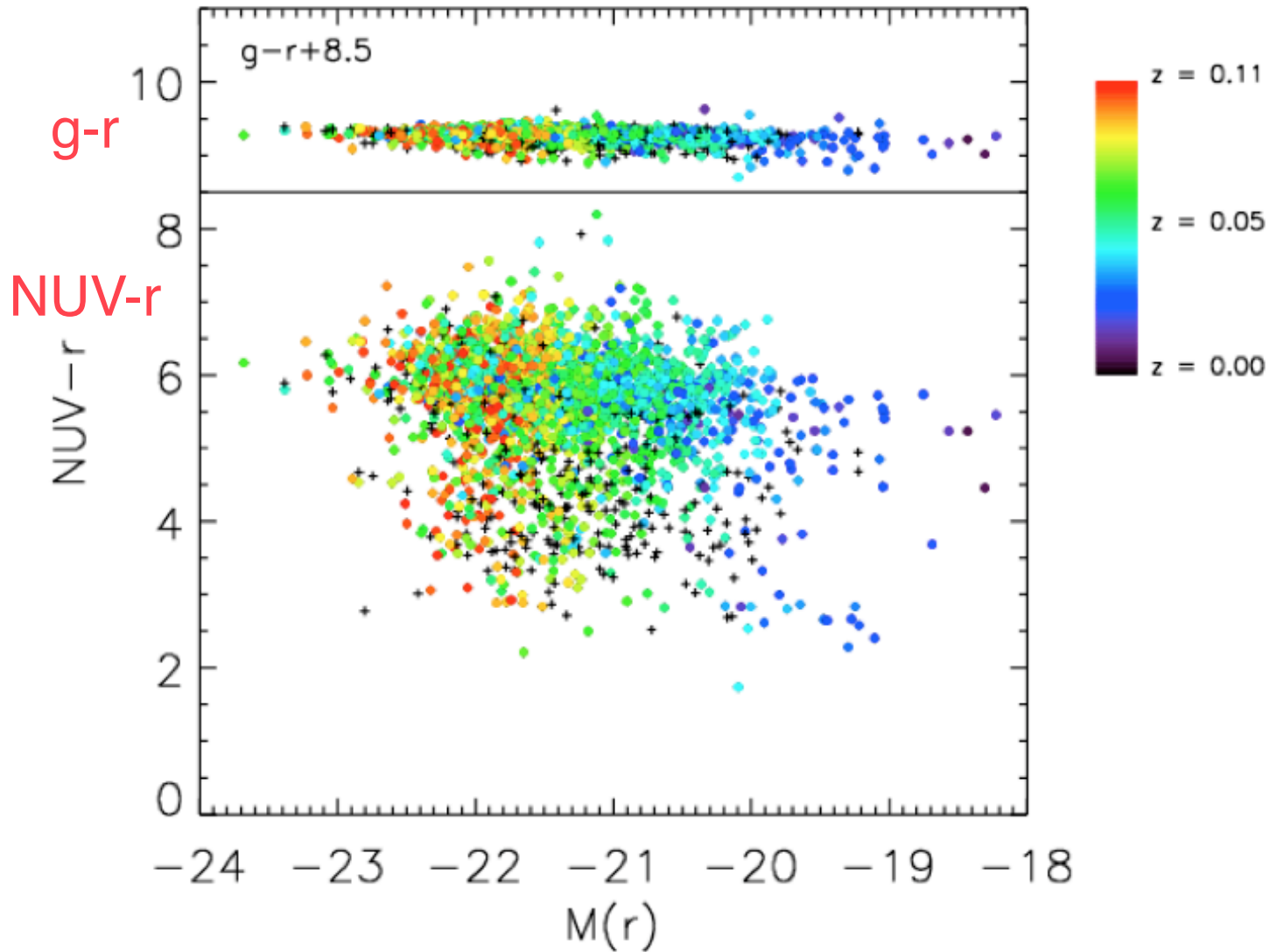
$$\text{SFR} = 4.5 \times 10^{-44} [L_{\text{FUV}} + 0.5 L_{\text{TIR}}]$$

- FUV better matched to duration of SF episodes (20-100 Myr) than ionized features
- IR output contaminated by old stars
- IR capture of UV photons incomplete except for earliest phases

HST

GALEX

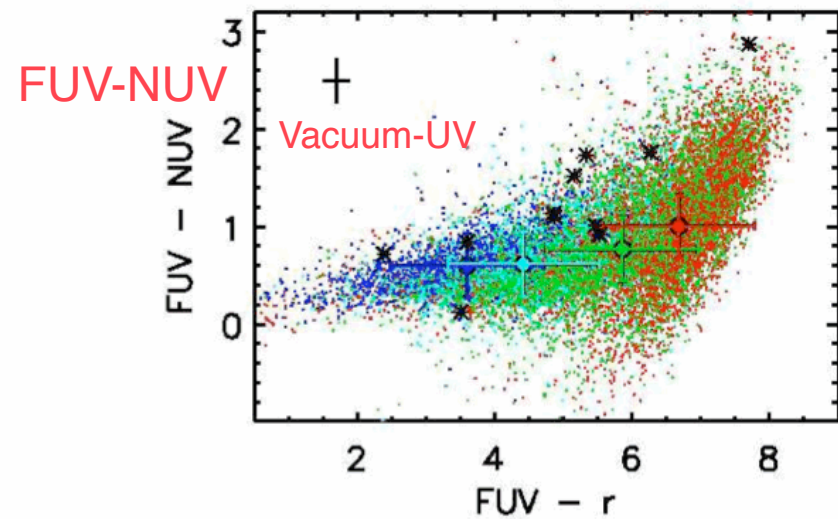
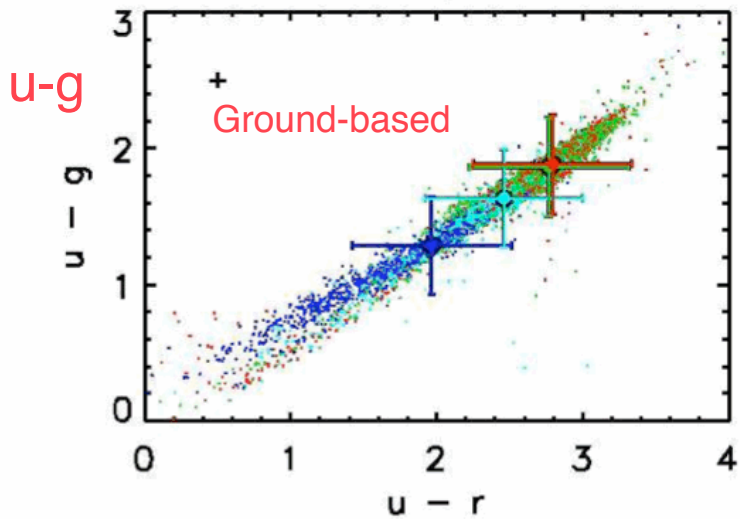
GALEX/UV revelation of complex star-formation histories
(0.1-1 Gyr) in ETG's ($\sim 30\%$)



Kaviraj et al., *ApJS*, 173, 619 (2007)

Early-type galaxies: dispersion in (GALEX + SDSS) colors

Vacuum-UV contains new/independent information on stellar populations
(even CUBES UV won't help)



Ree+ (2011)

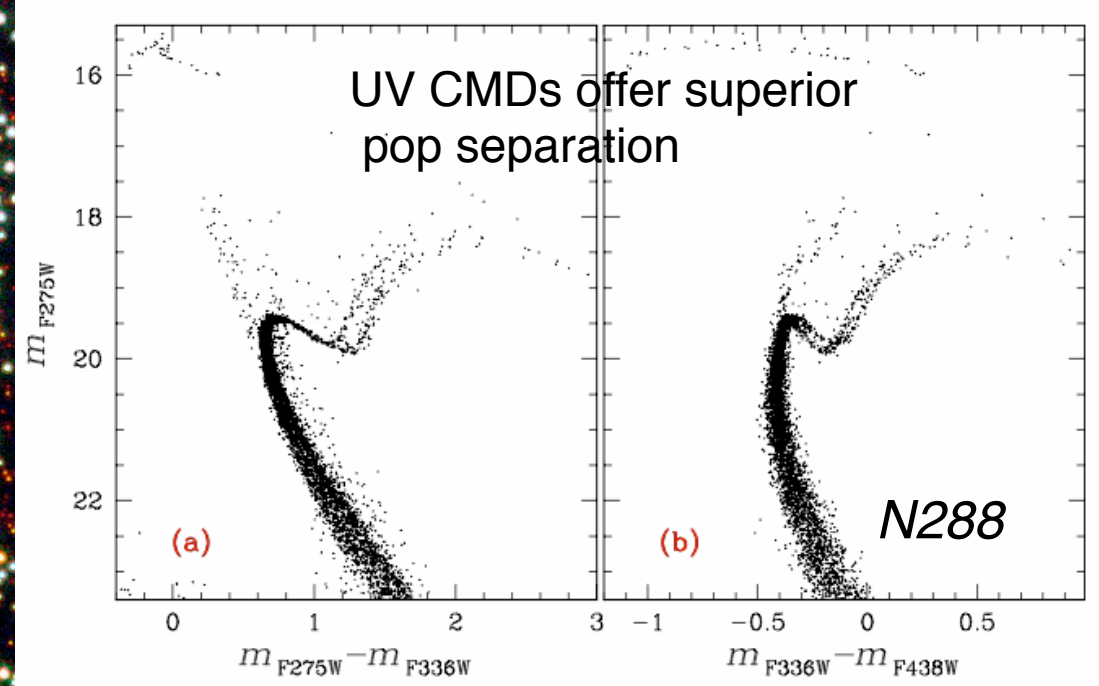
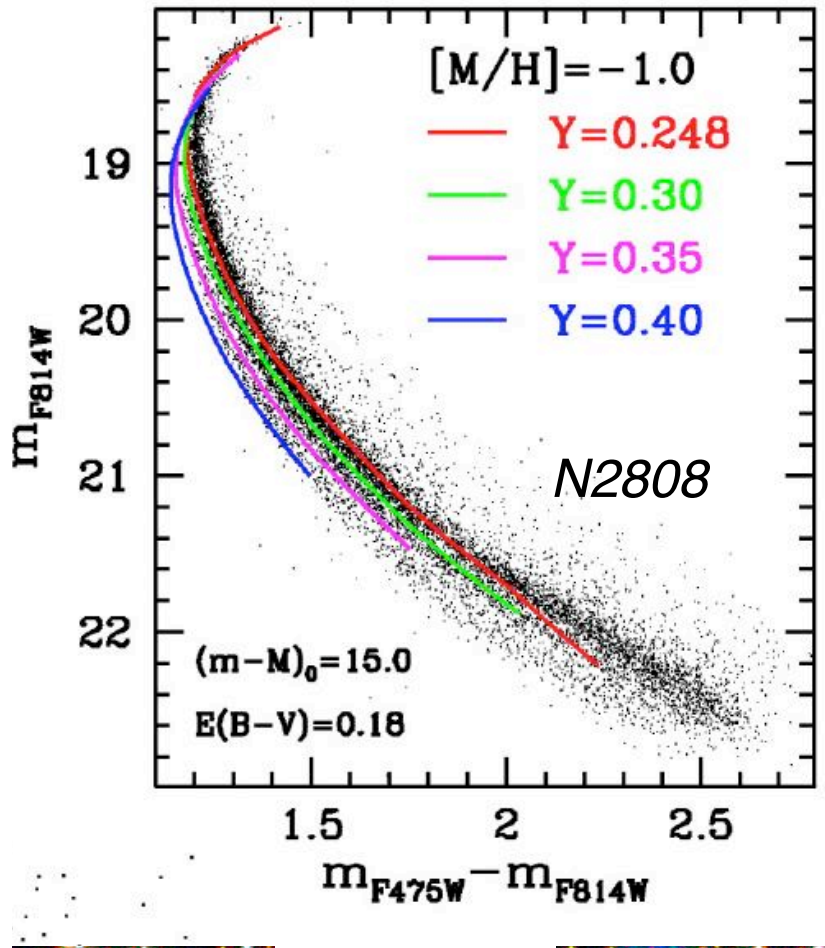


The UV perspective on globular clusters

Omega Centauri – HST/WFC3
225W, 336W, 814W

Multiple Populations in Globular Clusters

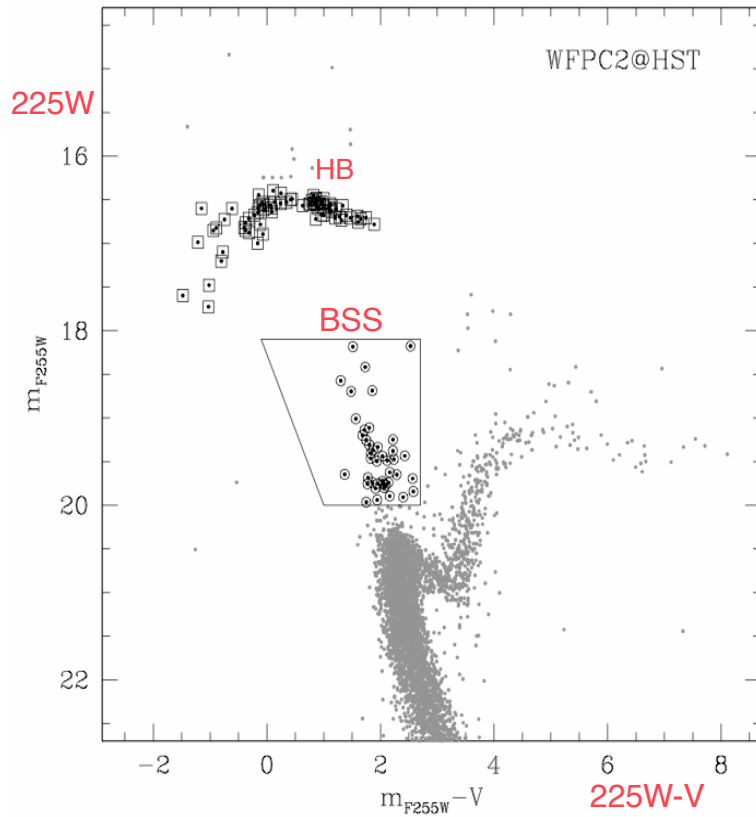
M4
M5 MF



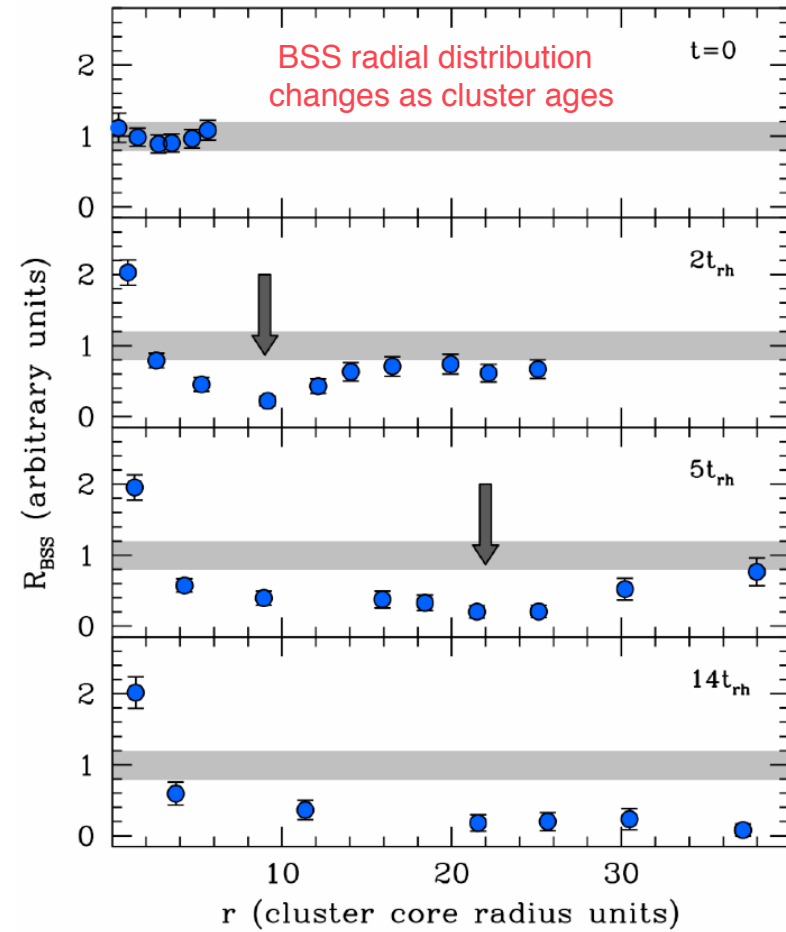
(Piotto+ 2013)

(Piotto+ 2007)

UV identification of (binary) Blue Stragglers as tracers of cluster dynamical evolution



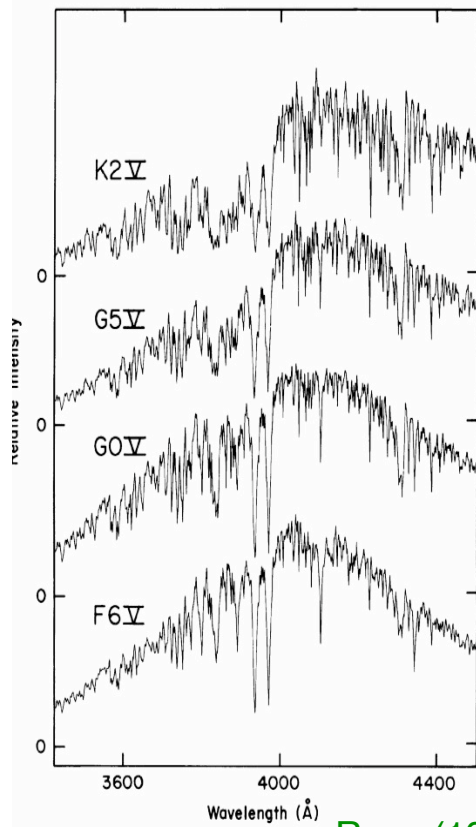
Dalessandro+ (2013)



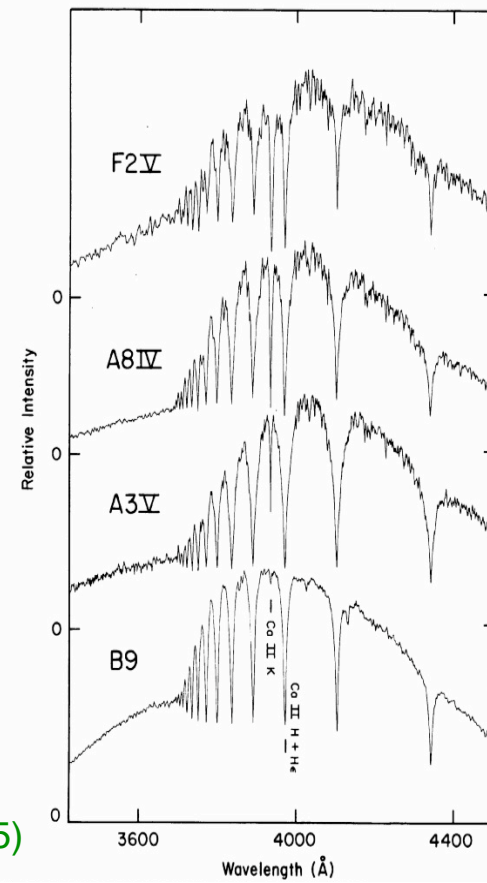
Ferraro+ (2012)

Dynamical "chronometer"

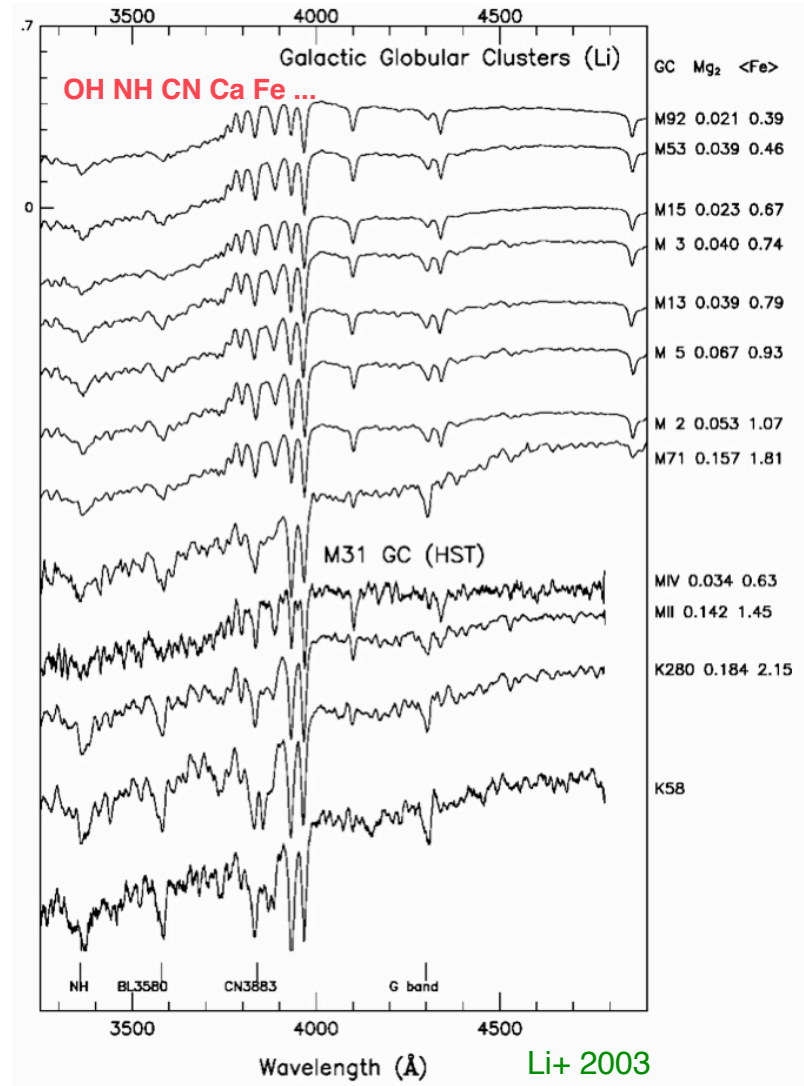
Old stellar population integrated light discriminants in the CUBES UV



Rose (1985)

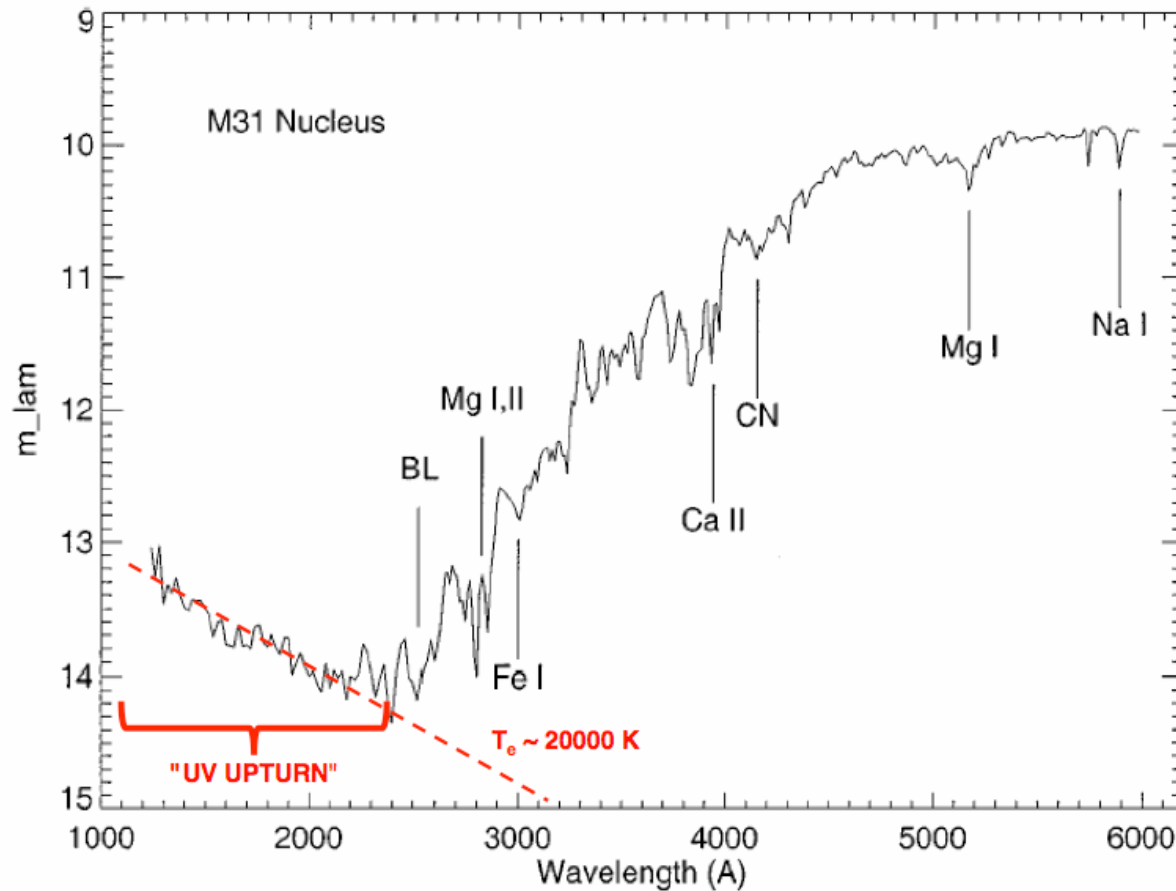


Most of the information on older stellar populations is at wavelengths < 4500 Å



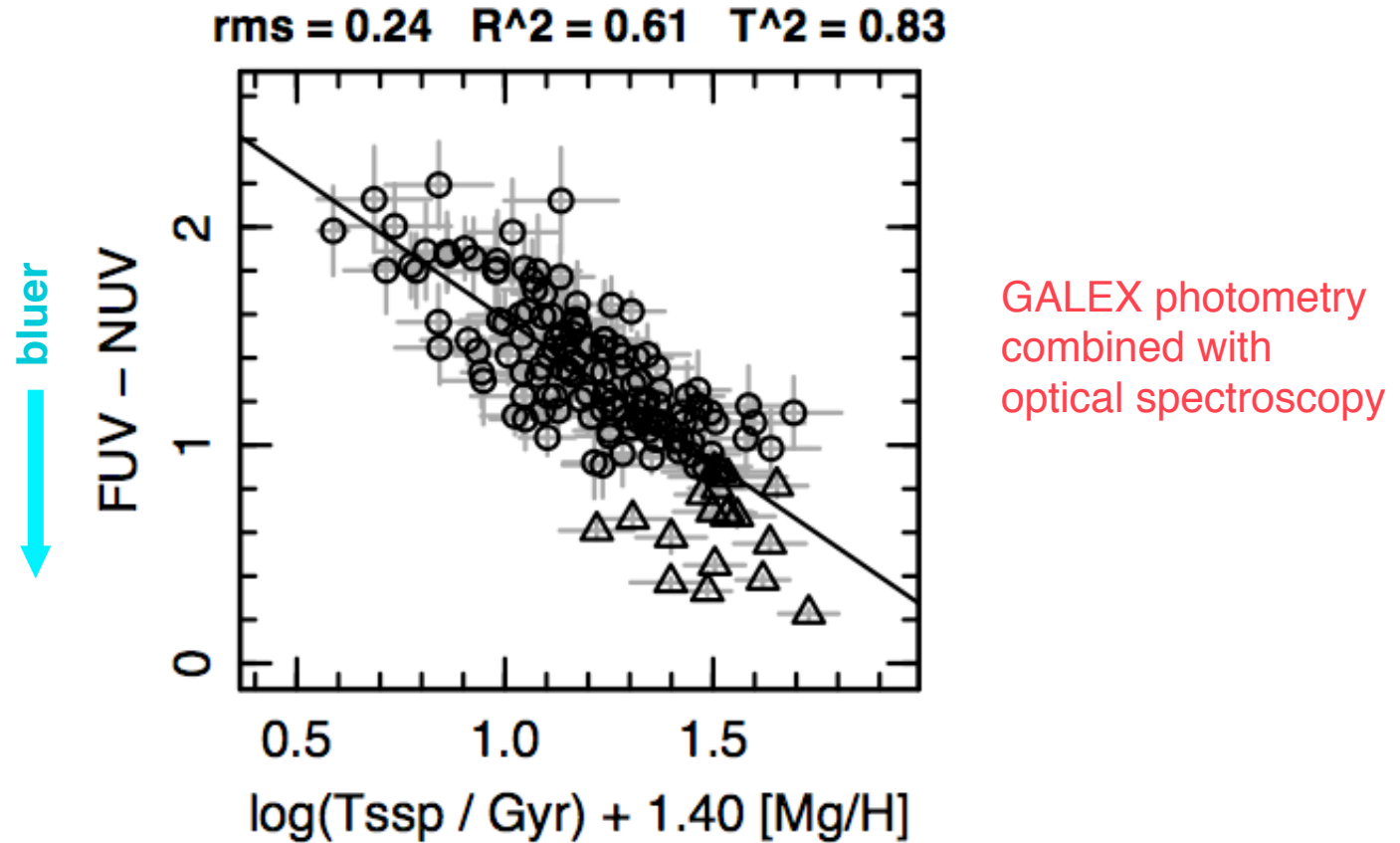
Li+ 2003

The "UV Upturn" in early-type galaxies: recent results



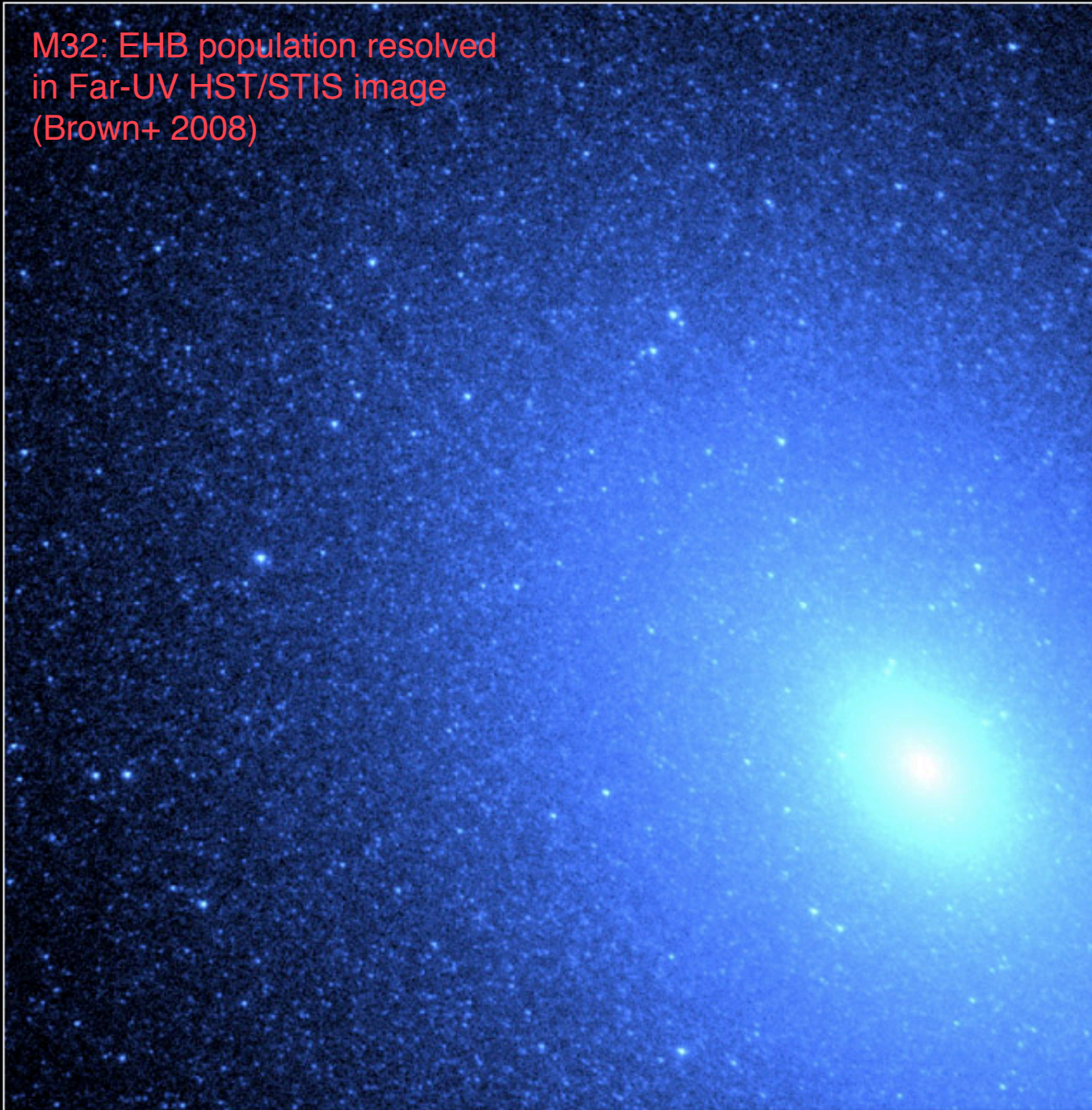
Accepted interpretation: extreme horizontal branch (EHB) & related He-burning stars in the dominant, old, metal-rich population

UVX: Confirm correlation with properties of old population (Coma Cluster)



Smith+ MNRAS, 421, 2982, 2012

M32: EHB population resolved
in Far-UV HST/STIS image
(Brown+ 2008)



UV CMD for M32 (Brown+ 2008):
EHB confirmed as source of UVX

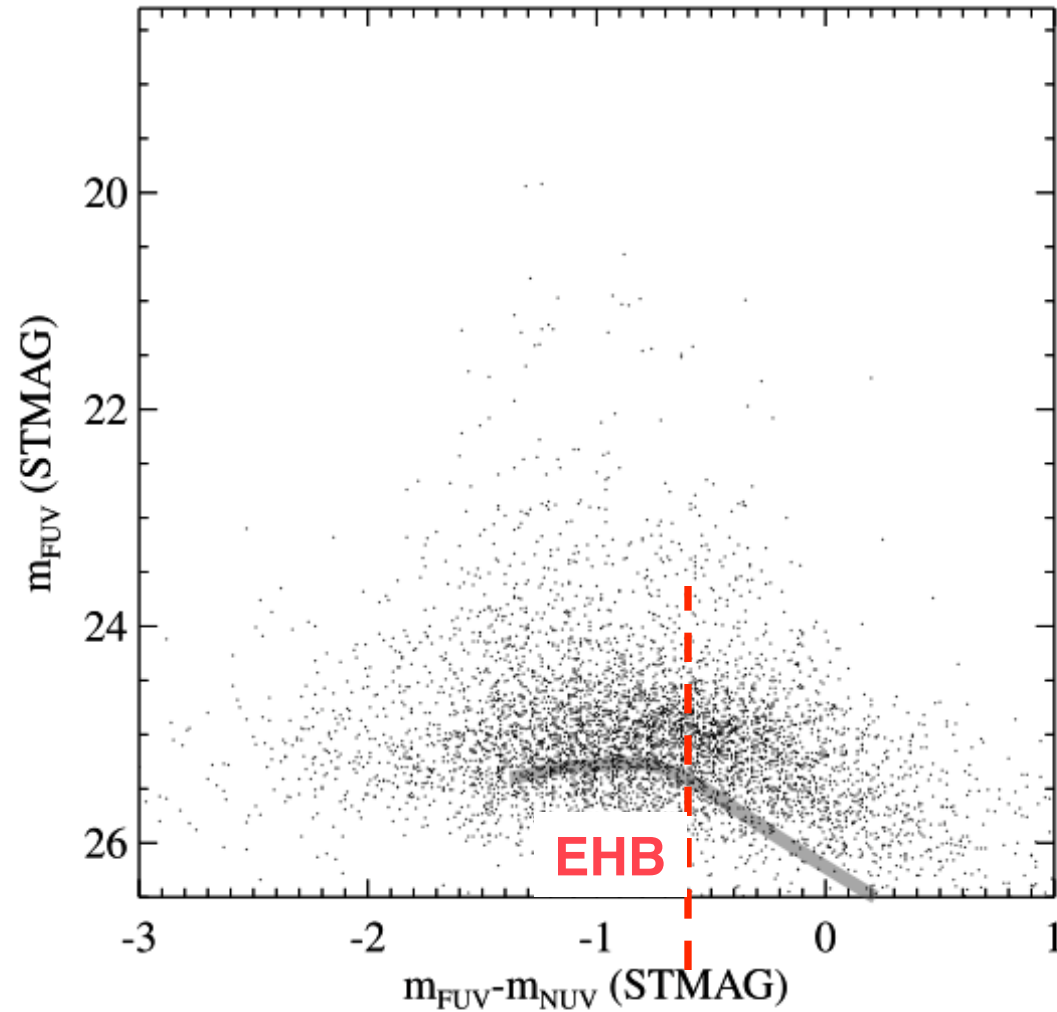


FIG. 3.—UV CMD of M32. The EHB and UV-bright post-HB stars are clearly resolved. A solar metallicity ZAHB is plotted for reference (*gray curve*).

UV CMD for M32 (Brown+ 2008):
But....

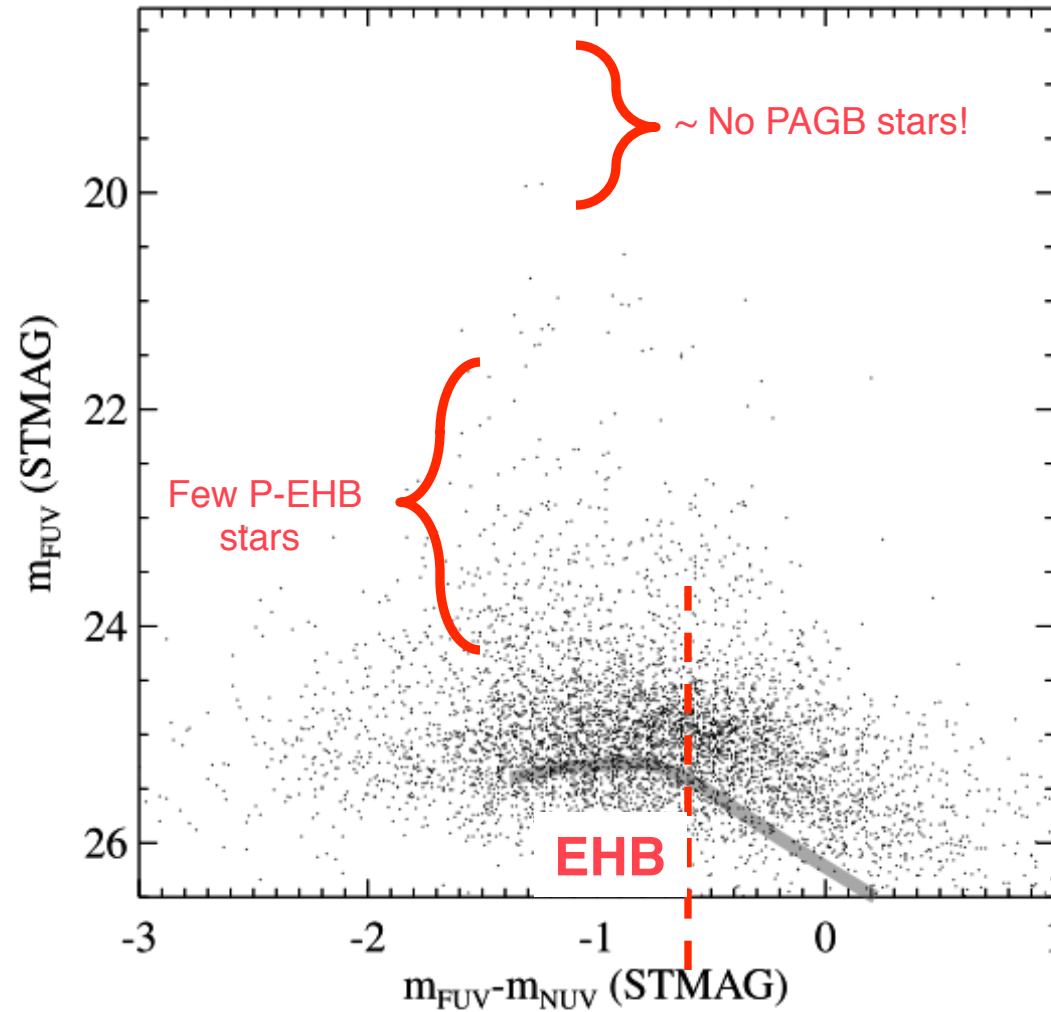
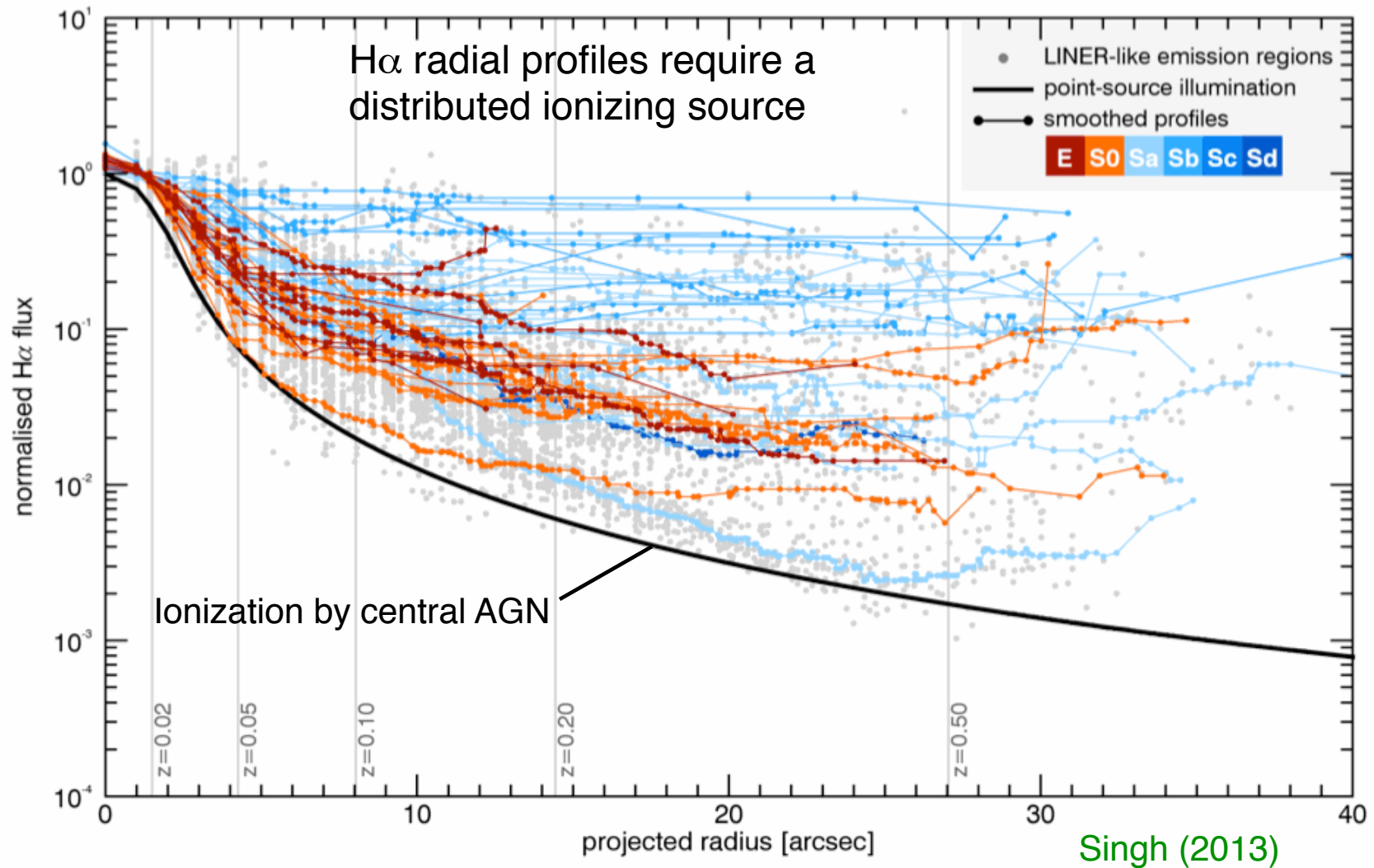


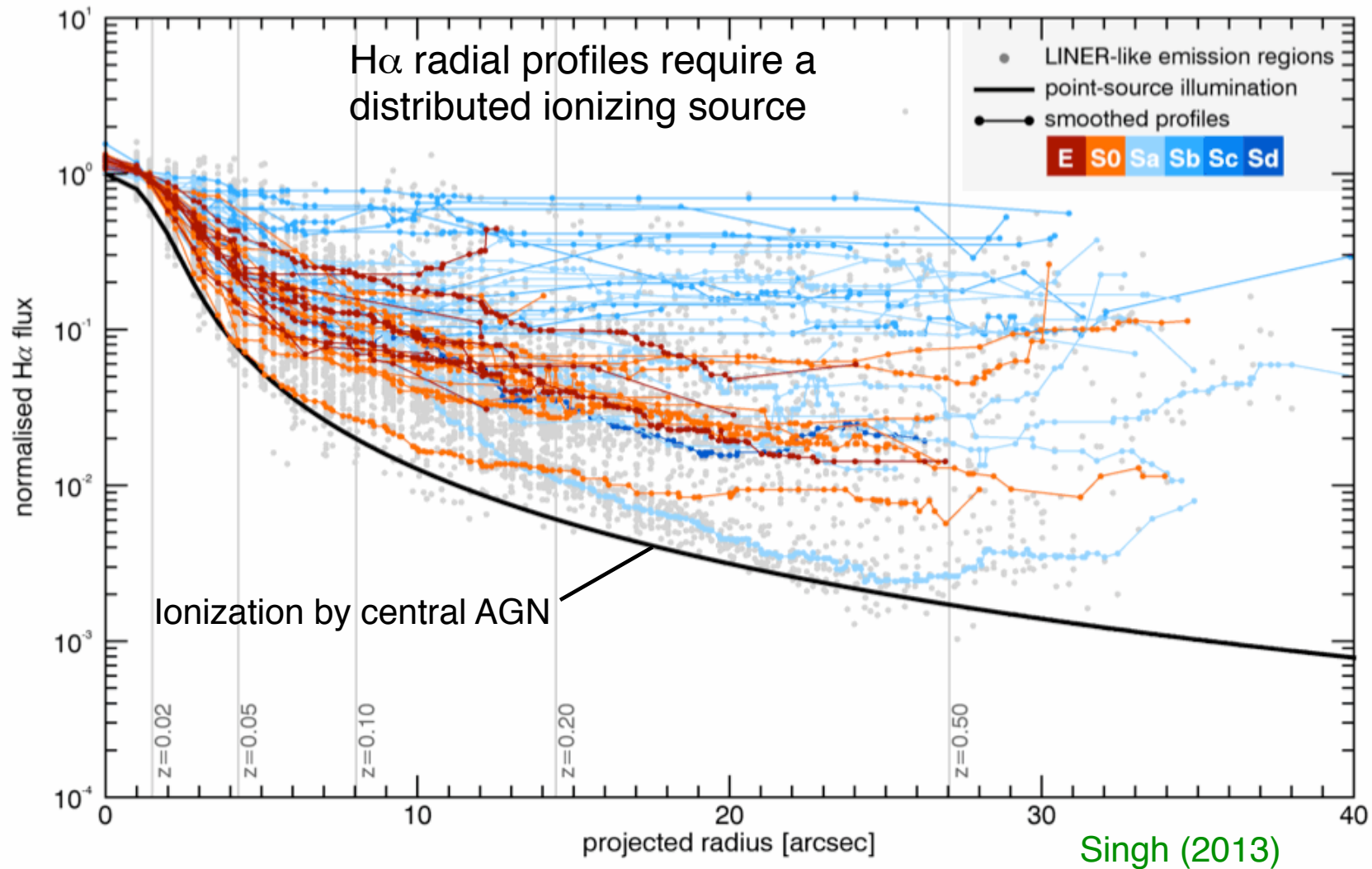
FIG. 3.—UV CMD of M32. The EHB and UV-bright post-HB stars are clearly resolved. A solar metallicity ZAHB is plotted for reference (*gray curve*).

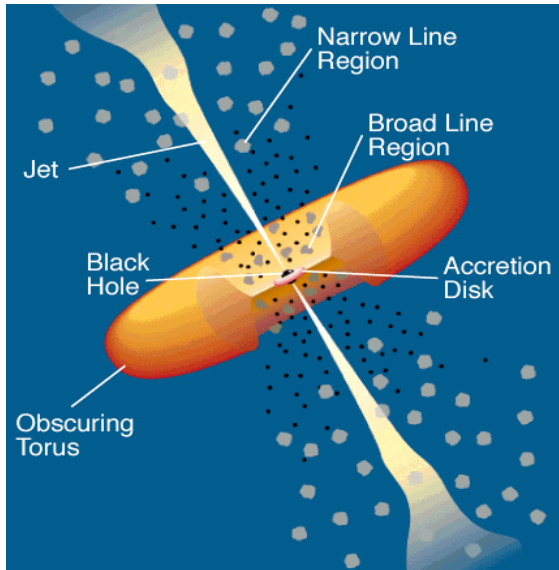
Most ionization in "LINERS" originates not from AGN but instead from hot, low-mass EHB and PAGB stars



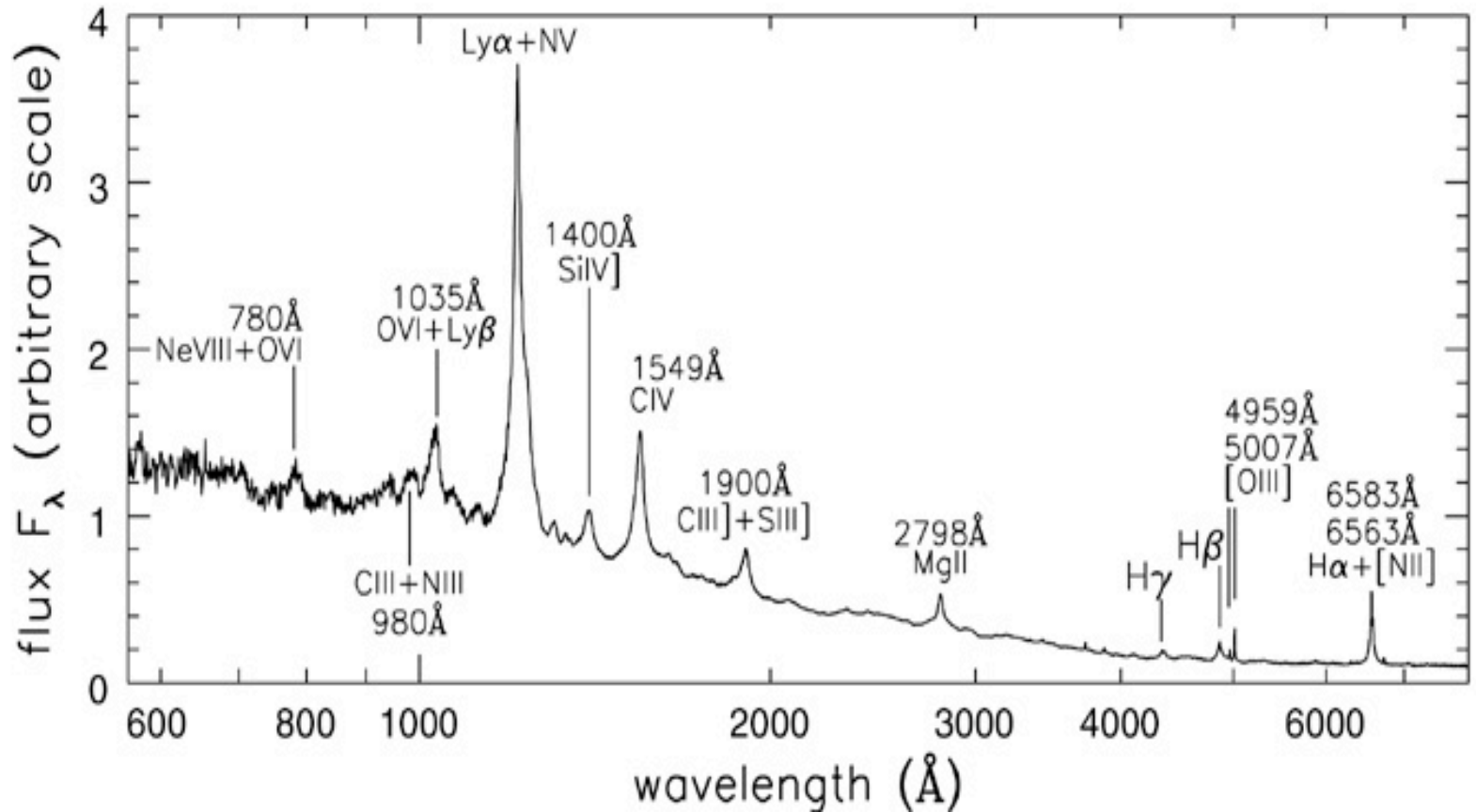
"LIERS"

Most ionization in "~~LINERS~~" originates not from AGN but instead from hot, low-mass EHB and PAGB stars

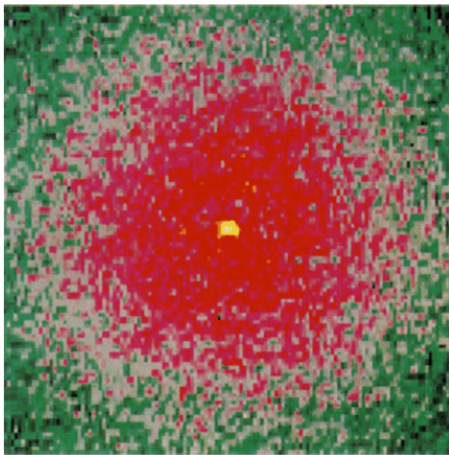




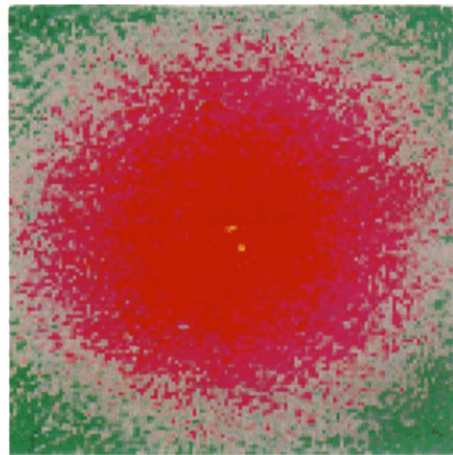
AGN: rich UV spectra are prime diagnostics of physical properties



UV Nuclear Flares: Tidal Disruption Events



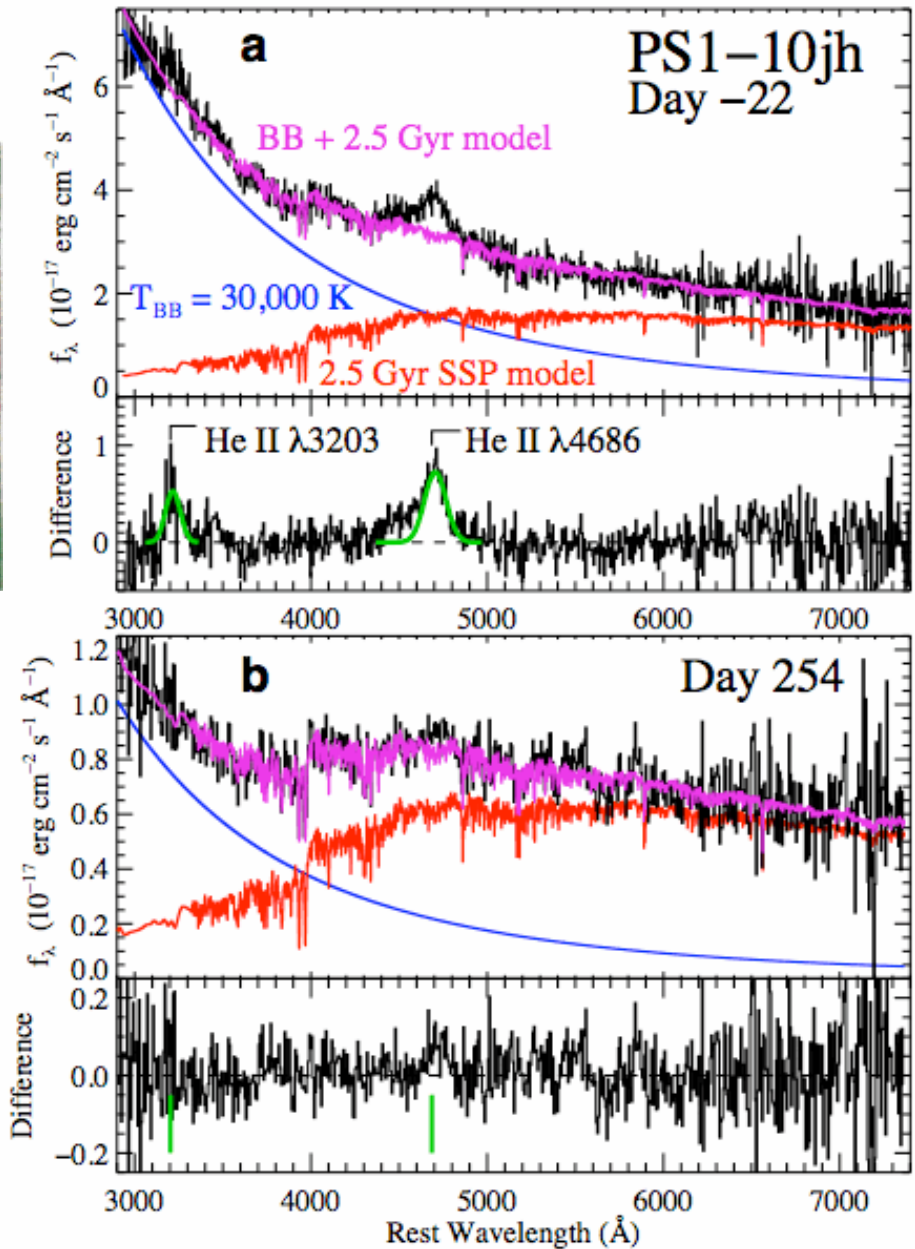
1993



1991

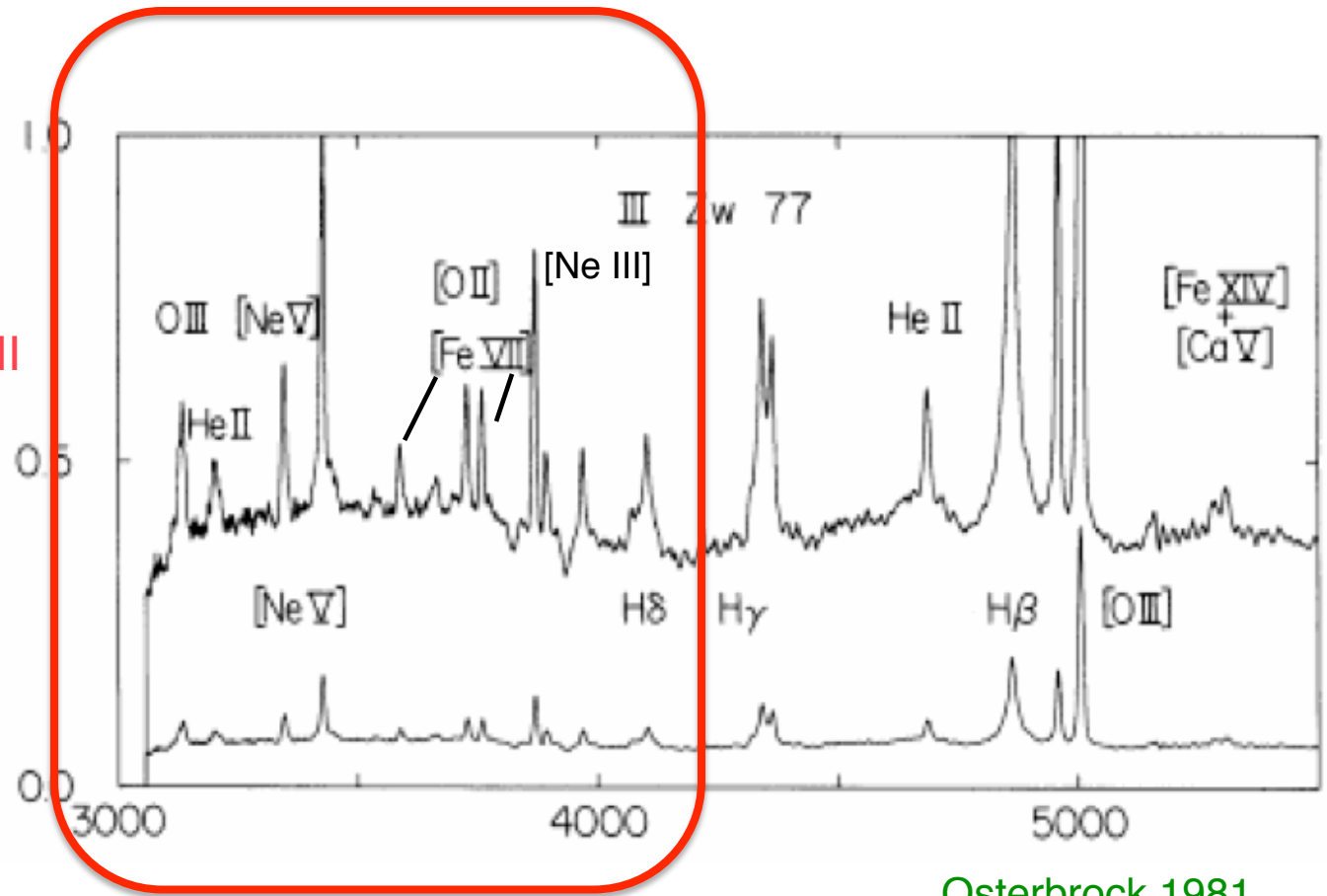
First detection: NGC 4552 (Renzini+ 1995)

UV flare from tidal disruption of a He-rich stellar core (Gezari+ 2012)



Potential UV flare diagnostic features in CUBES UV

High excitation (Ne III, Ne V, Fe VII, He II);
Bowen fluorescence OIII



Prognostication?



Shifting Scientific Tides

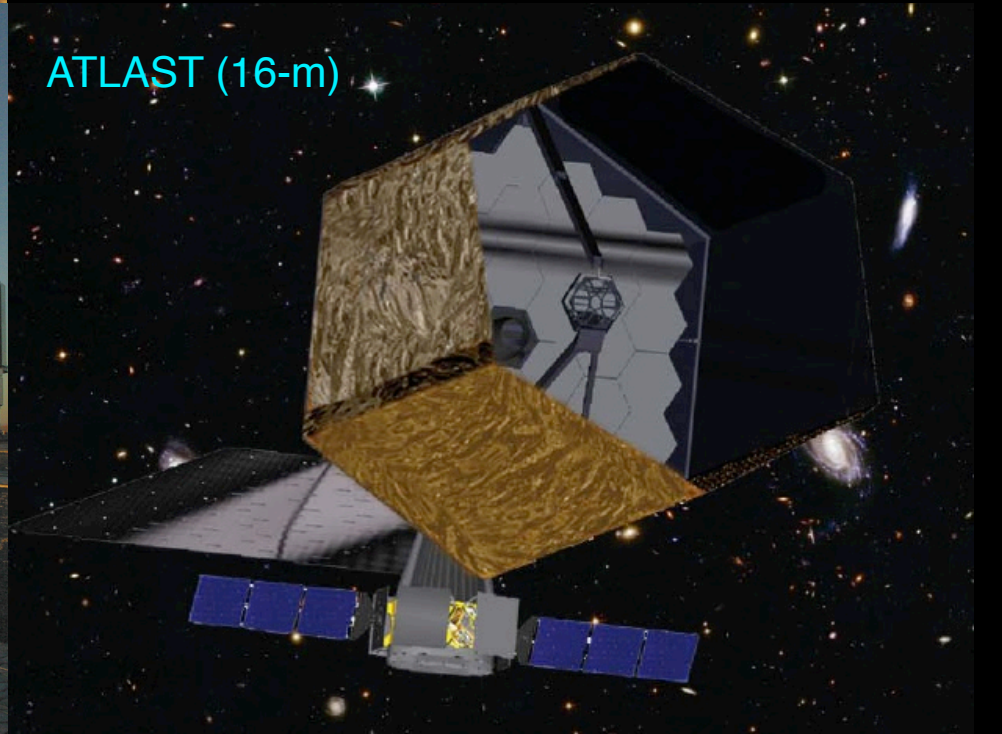
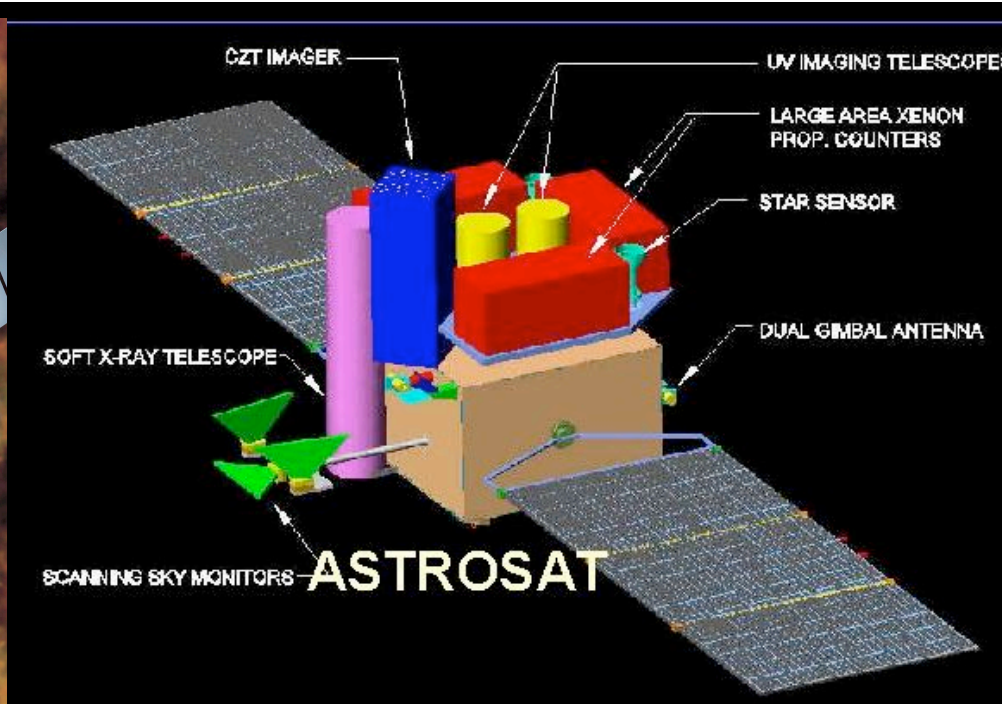
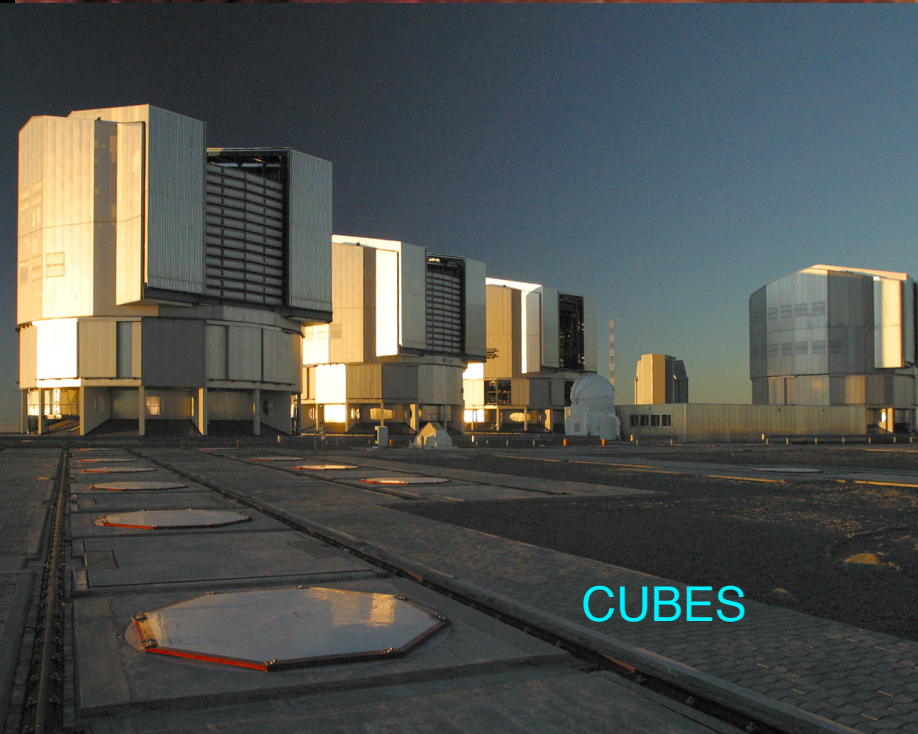
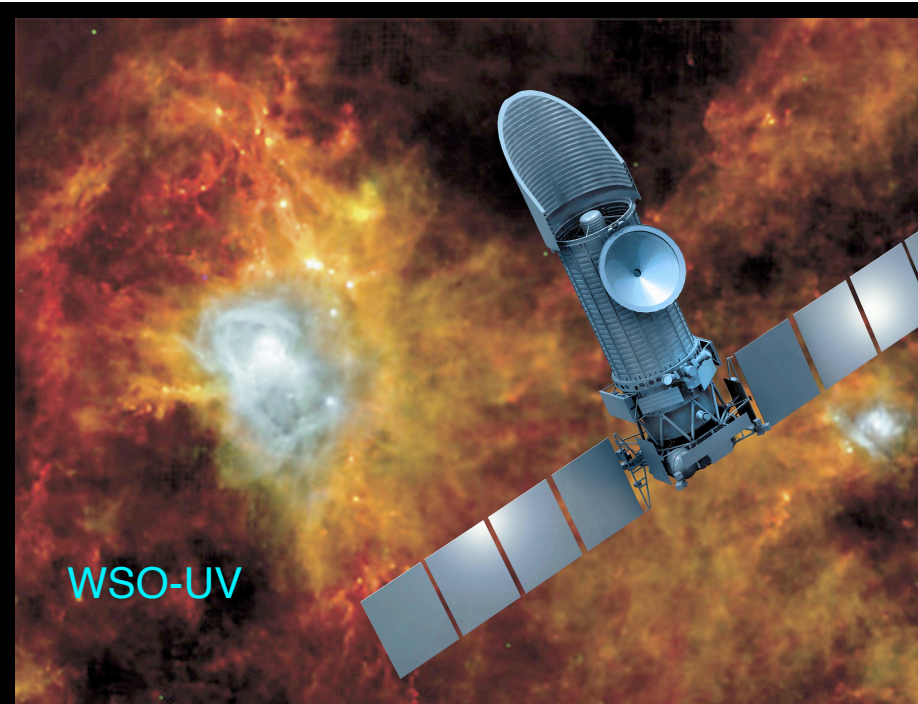
- Leading non-UV areas: cosmology, early universe, molecular clouds, obscured star formation (ALMA, JWST).....IR interest may begin to saturate.
- Transients (LSST)
- Exoplanets and planetary formation
- CGM and related low-SB problems
- Stellar astronomy, including binaries

Shifting Scientific Tides

- Leading non-UV areas: cosmology, early universe, molecular clouds, obscured star formation (ALMA, JWST).....IR interest may begin to saturate.
- Transients (LSST)
- Exoplanets and planetary formation
- CGM and related low-SB problems
- Stellar astronomy, including binaries (despite Princeton)

Technical Priorities (not new!)

- Detector QE to $> 80\%$ 90-320 nm
- Successful flight tests/astronomy from candidate detectors.
- Single mirror coating with high performance 90-320 nm







"Terrifying puzzles"

--- END ---