General Astrophysics Science Drivers
Ultraviolet-Visible Passband
Paul Scowen

- Input received for a tentative 4-6m class Observatory
- Input from the COPAG SIG2 – UV-visible astronomy from space
- Membership consists of 87 scientists and 41 technologists, both US and International

Galaxy Leakiness and Reionization

- The first stars and galaxies:
  - Small assemblies
  - No metals – no cooling channels
  - No metals – no scattering and absorption
  - How much H-ionizing (LyC) radiation escapes?
  - From where? SF galaxies, AGN and QSOs
  - How does this change over cosmic time?
  - What do Pop-III stars do to the ISM of such galaxies when they end their lives?
  - Can we simulate / analogize the problem to the local Universe?

Definitive Determination of Lyman Continuum Luminosity Functions for 0 < z < 3

Project Lyman

(white paper for astro2010 McCandliss et al. 2009)

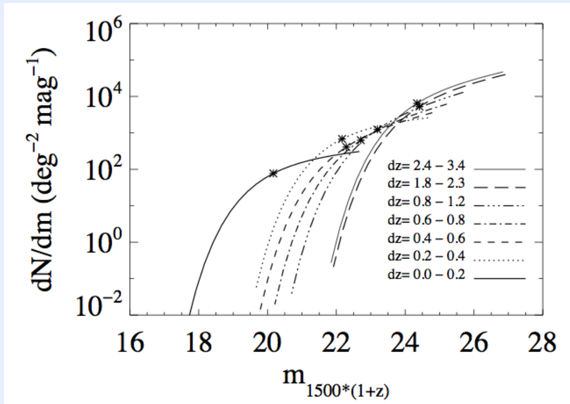
- If we are to understand why most of the universe is ionized, then we must characterize how much ionizing radiation* escapes from star-forming galaxies
  - *Rest frame continuum emission below the Lyman edge at 911.75 Å
- No "direct" low column density sightlines for z > 3
  - UV observations required to measure fraction of LyC photons that escape (f^e_{LyC})

Major LyC Science Questions

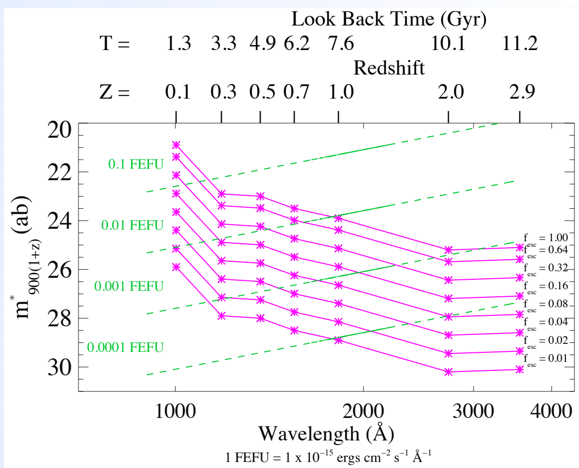
1) What are the relative contributions of star-forming galaxies, AGN and quasars to the ionizing background over the past 11 Gyrs (z < 3)?
2) How does f^e_{LyC} evolve with redshift?
3) What local and global environmental factors aid LyC escape?
   - Gas, dust, metallicity, clumpiness of interstellar medium, velocity fields, intergalactic neighborhood, star formation history, luminosity, mass
4) Are there local relic analogs to the sources of reionization?
   - High escape fraction at EoR
   - Low escape fraction before EoR is complete
5) What is the relation between Lyα and LyC escape?
   - This is critical to the JWST key project seeking the source(s) of reionization.
6) How is reionization initiated and sustained?

Requirements Flowdown for Determining Evolution of the LyC Luminosity Function

Far- UV Galaxy number density (Arnouts ea 2005 luminosity functions).
***Characteristic magnitude**



LyC fluxes (magnitudes) for L^*_{uv} gal as functions of redshift and escape fraction, (f^e_{LyC})

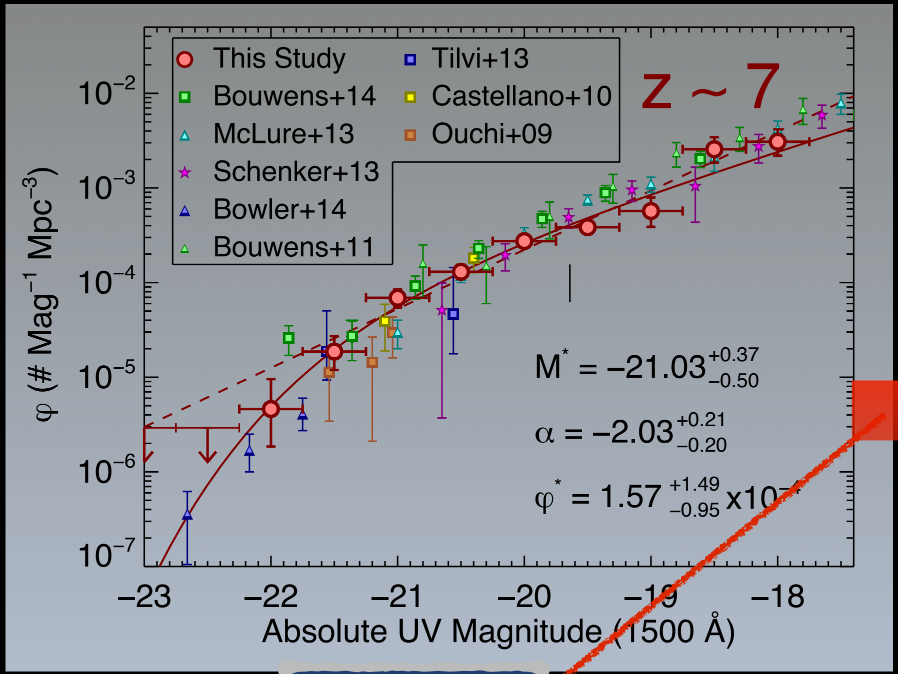


(McCandliss et al. 2008, 2012)

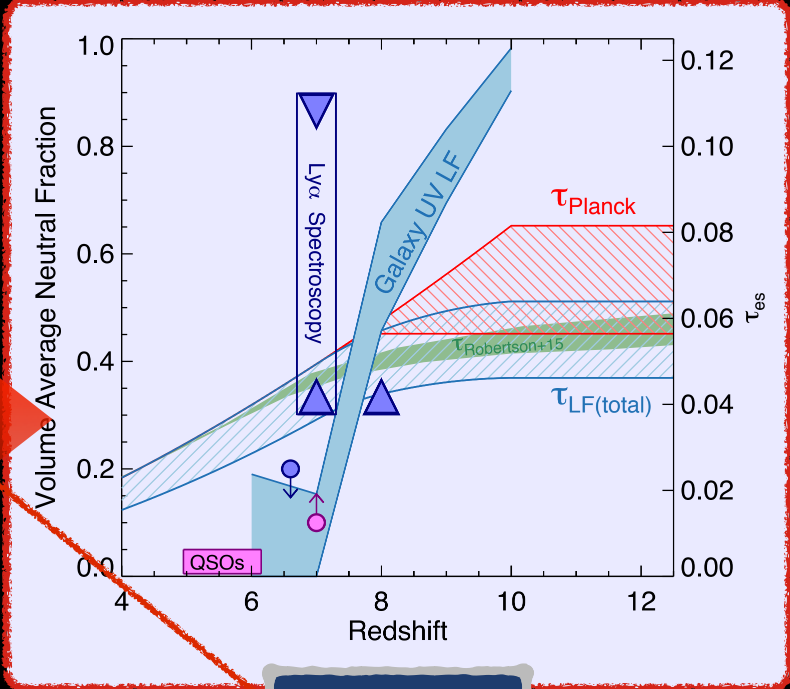
Science requirements for defining technical flowdown

- Objects $0 < z < 3$, so $912 < \lambda < 3500$ Å
- Example Goal f^e_{LyC} = 1% for L^* at 2000 Å
  - $f_{900(1+z)} = 10^{-19}$ erg cm^{-2} s^{-1} Å^{-1} representative flux
    - Requires $A_{eff} T\ \Delta\lambda \approx 2.5 \times 10^9$ **cm² s Å at 2000 Å** for S/N = 5
    - A_{eff}=14000 cm^2, T= 5 hrs, $\Delta\lambda$=10Å
  - 25 objects per mag bin per redshift interval yields rms deviation for each point ≈ 20%
- Angular sample > 1 degree
  - Beat down cosmic variance
- Angular resolution on star-forming cluster scales ~ 30 pc, to examine environment. Typical galaxy size ~ 1''
- Redshifts for all objects
- Detect Lyman "drop-ins" spectroscopically
  - High fidelity f^e_{LyC} determination!
- These criteria can be met with a large diffraction limited 8 meter aperture at f/24 (~ 1'' mm^{-2})
  - Multiobject imaging UV spectrograph(s?)
  - *R* = 200, 4 arcmin FOV
  - Detector 225 x 225 mm^2
  - Very low background
- Require Spectroscopic and Photometric Trade Studies to determine overall time allocation

IMPROVING OUR UNDERSTANDING OF REIONIZATION



SF+2015A



SF+2015C

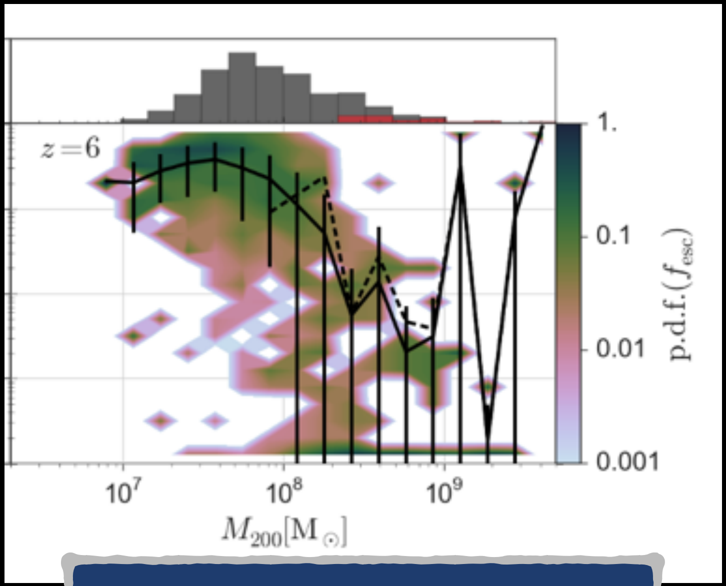
<u>ASSUMPTIONS</u>:

1) LIMITING MAG

2) IONIZING PHOTON ESCAPE FRACTION

ESCAPE FRACTION

- Nearly *all* observations at $z < 4$ result in non-detections, with typical limits on f_{esc} of less than a few percent (Siana+10), though there are isolated cases of some galaxies have f_{esc}~20-30% (Nestor+11).
- Most simulations show very low escape fractions in the galaxies we see, and imply that only very low-mass halos have conditions which promote ionizing photon escape.



PAARDEKOOPER+15

THIS COULD CREATE A PHOTON "CRISIS"

WE NEED TO MEASURE, EVEN AT LOWER REDSHIFT, WHAT THE ESCAPE FRACTION IS FROM GALAXIES OF ALL MASSES

THIS WOULD BE POSSIBLE WITH THE ATLAST/HDST DESIGN, BUT COULD ALSO BE POSSIBLE WITH A LOWER-COST UV-ONLY SPACE TELESCOPE, OPTIMIZED FOR HIGH UV THROUGHPUT

Observational goal:

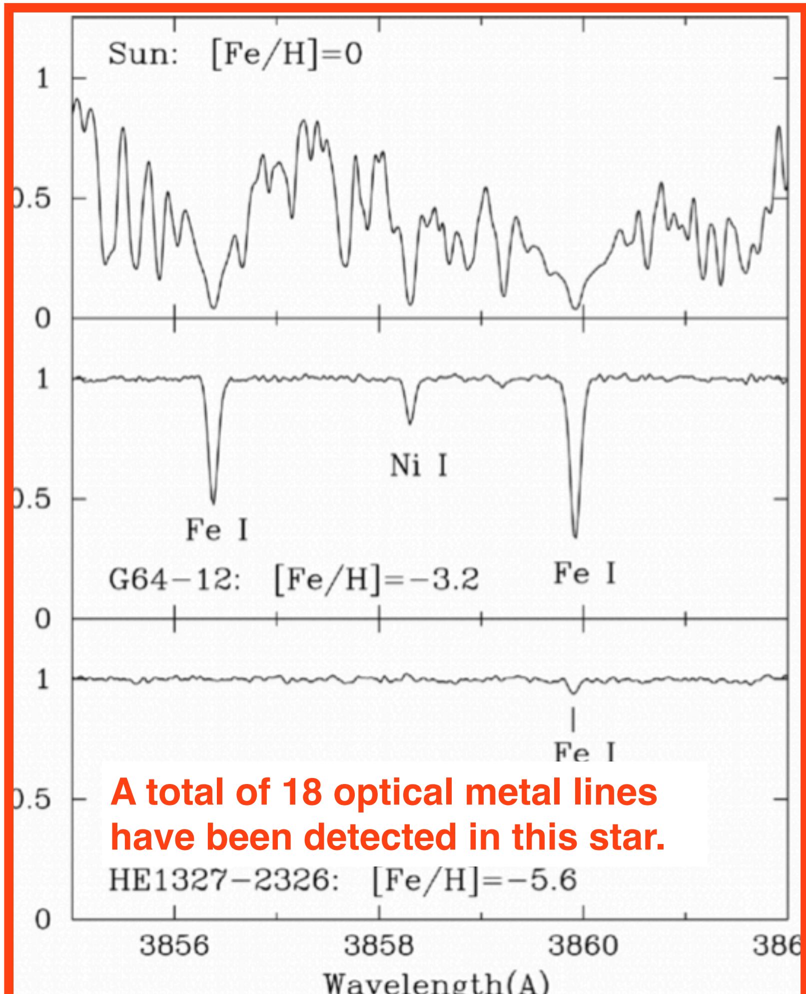
Directly observe rest-frame 900 Å at z=0.5-3
=> Observed λ = 1200-3600 Å

Assuming m_{AB}=30 limit, can reach M = -12 (z=0.5), -15 (z=3)

In low-metallicity stars in the Galactic halo, metal lines in the optical nearly disappear at the lowest metallicities.

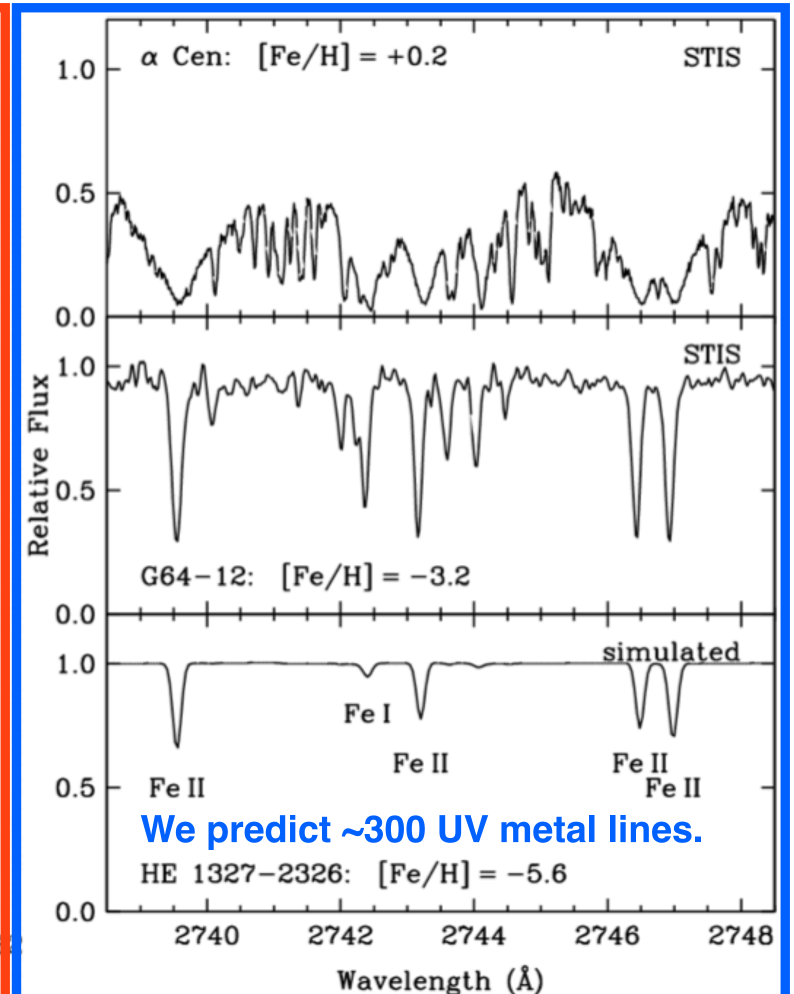
In the UV, there are expected to be hundreds of metal lines.

OPTICAL



Aoki et al. (2006, ApJ, 639, 897)

UV



G dwarf at solar metallicity

G subgiant at low metallicity

G subgiant at *ridiculously-* low metallicity

I. Roederer (U. Michigan)

SCIENTIFIC ADVANCE

The abundance patterns in the most metal-poor stars known ([Fe/H] < –4) provide a direct link to the very first stars. These reveal the nature of the first stars, the physics of their supernova explosions, and the flow of their metal yields into the nearby ISM/IGM.

A 4-6 m space telescope could obtain high-quality spectra for nearly all of the lowest-metallicity stars known and for most expected in future surveys. Approximately ~20 stars are known today, and hundreds more are expected to be found in the next few decades. (For comparison, only ~1-2 such stars can be observed with HST.)

TECHNICAL REQUIREMENTS

High spectral resolution: R~60,000 optimal (R ~ 15,000 minimum acceptable)

High signal-to-noise: S/N ~ 60-100 after co-adding exposures

Broad wavelength coverage (1700 to 3100 Å) in a single exposure (or covered in no more than two exposures)

Multi-object capability would be nice but is not required for the science case presented here.

EXAMPLE REFERENCES

"Hubble Space Telescope Near-Ultraviolet Spectroscopy of the Bright CEMP-no STAR BD+44 493"
Placco et al. (2014, ApJ, 790, 34)

"Detection of Phosphorus, Sulphur, and Zinc in the Carbon-Enhanced Metal-Poor star BD+44 493"
Roederer, Placco, & Beers (2016, ApJL, submitted)

I. Roederer (U. Michigan)

Understanding how galaxies reionized the Universe

- Ionizing (LyC) photons produced in galaxies were likely responsible for Reionization at z>6, but
  - The physical mechanism for LyC escape is not well understood
  - Interactions? Feedback?
- Requires UV / Uband observations to interpret JWST high-z results
  - Direct detection of LyC photons only possible at z<3.5, due to intervening HI,
  - Extensive searches by our team and others with HST, GALEX, FUSE and Keck
  - Likely to remain an open question by the end of HST's lifetime
  - Requires high spatial resolution to mitigate foreground contamination
- Average Lyc escape fraction appears very low or undetected at all z
  - No conclusive evidence of which galaxies have most LyC escape
  - Search for trends with SFR, metallicity, ionization, mergers, environment
  - Need to focus on observations of rare, faint objects
- Our Relevant Papers
  - Rutkowski+16; Siana+15; Teplitz,+13; Bridge+10; Siana+10; Siana+07

Requirements for HabEx

- UV sensitivity
  - Detect <0.1 L* without lensing
    - About 10x--20x HST sensitivity at <3000 AA
  - Substantially improved CTE if using CCDs
    - This is a major limitation of HST deep UV surveys
- Low spectral resolution
  - Narrow-band imaging or low-resolution spectroscopy
  - Measure the continuum at λ_{rest} < 912 AA
  - For imaging, strict red-side filter cutoff required
- High spatial resolution
  - Matched to JWST at e.g. 1 μm would yield maximum physical information about LyC escape
  - Needs to be as good as HST at comparable wavelengths

HabEx Science Case:
Ionizing photon escape at moderate redshift

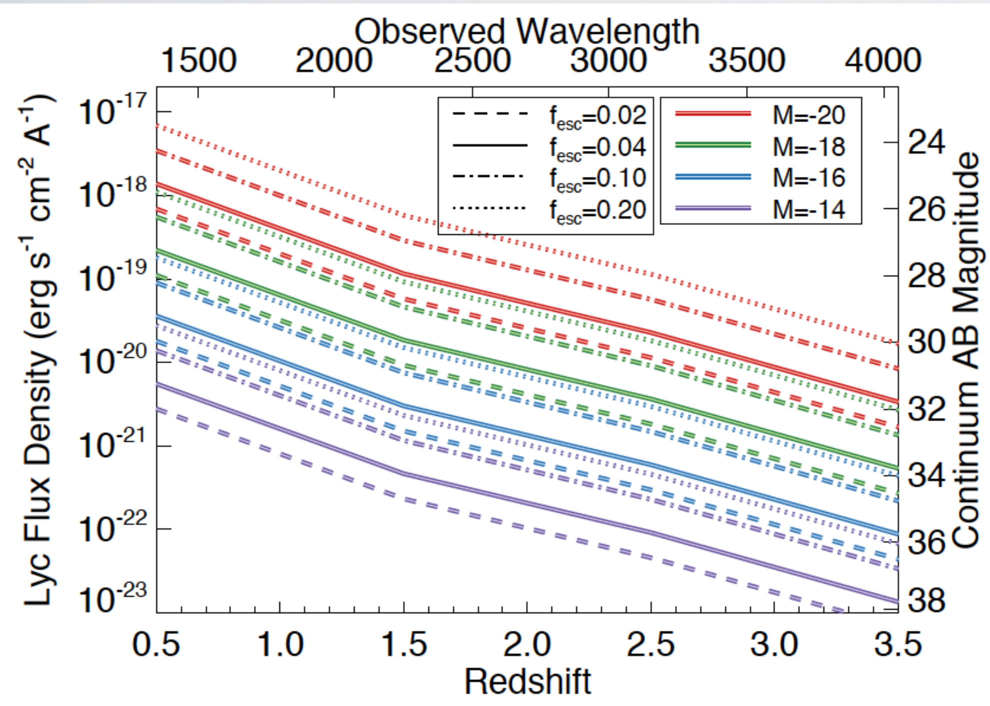
- The major uncertainty for the contribution of galaxies to reionization is the fraction of ionizing (Lyman continuum) photons which escape galaxies, and thus can reionize the IGM.

- The number of "Lyman leaking" galaxies known is only a handful, and nearly all studies result in non-detections, with typical upper limits of <10%.

- For galaxies to be the dominant source of reionzing photons, the escape fraction needs to be on average at least 4%, if not ~10%.

Steven Finkelstein The University of Texas at Austin
stevenf@astro.as.utexas.edu

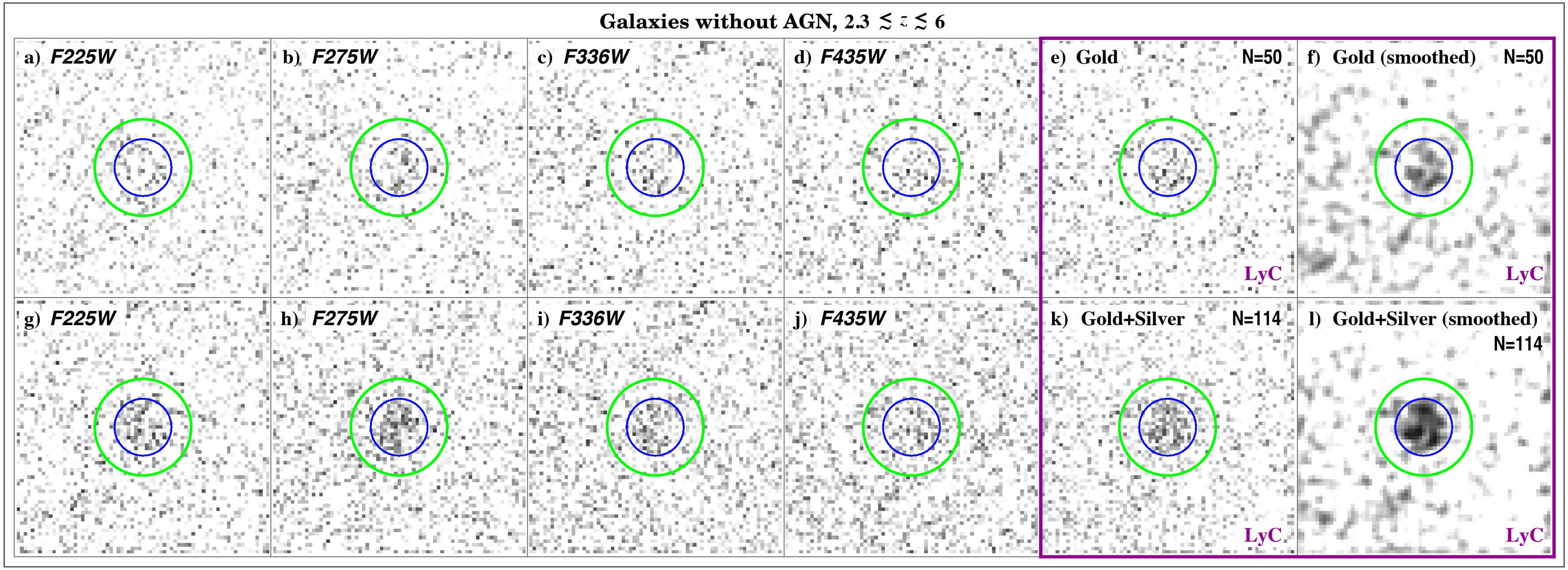
HabEx Science Case:
Ionizing photon escape at moderate redshift



- Results based on Bruzual and Charlot (2003) stellar population models, assuming $Z_{\odot}$ and an age of 100 Myr.
- The lines show how the Lyman continuum flux density (calculated as the average rest-frame flux at 860-910 A) changes with redshift, with the different colors denoting different absolute magnitudes, and the line styles denoting different escape fractions.

- Transforming this science area requires *detections* in modestly faint galaxies. A possible goal could be the f_{esc}=0.04 line for M=-16 galaxies (solid blue line), covering 1000-4000 A over this redshift range.

Steven Finkelstein The University of Texas at Austin
stevenf@astro.as.utexas.edu



z=2.26–2.47 z=2.47–3.08 z=3.08–4.35 z=4.35–5.5 WEIGHTED ALL: z=2.26–5.5.

[*Top Row*]: All galaxies in combined Gold Galaxy sample: N=50;

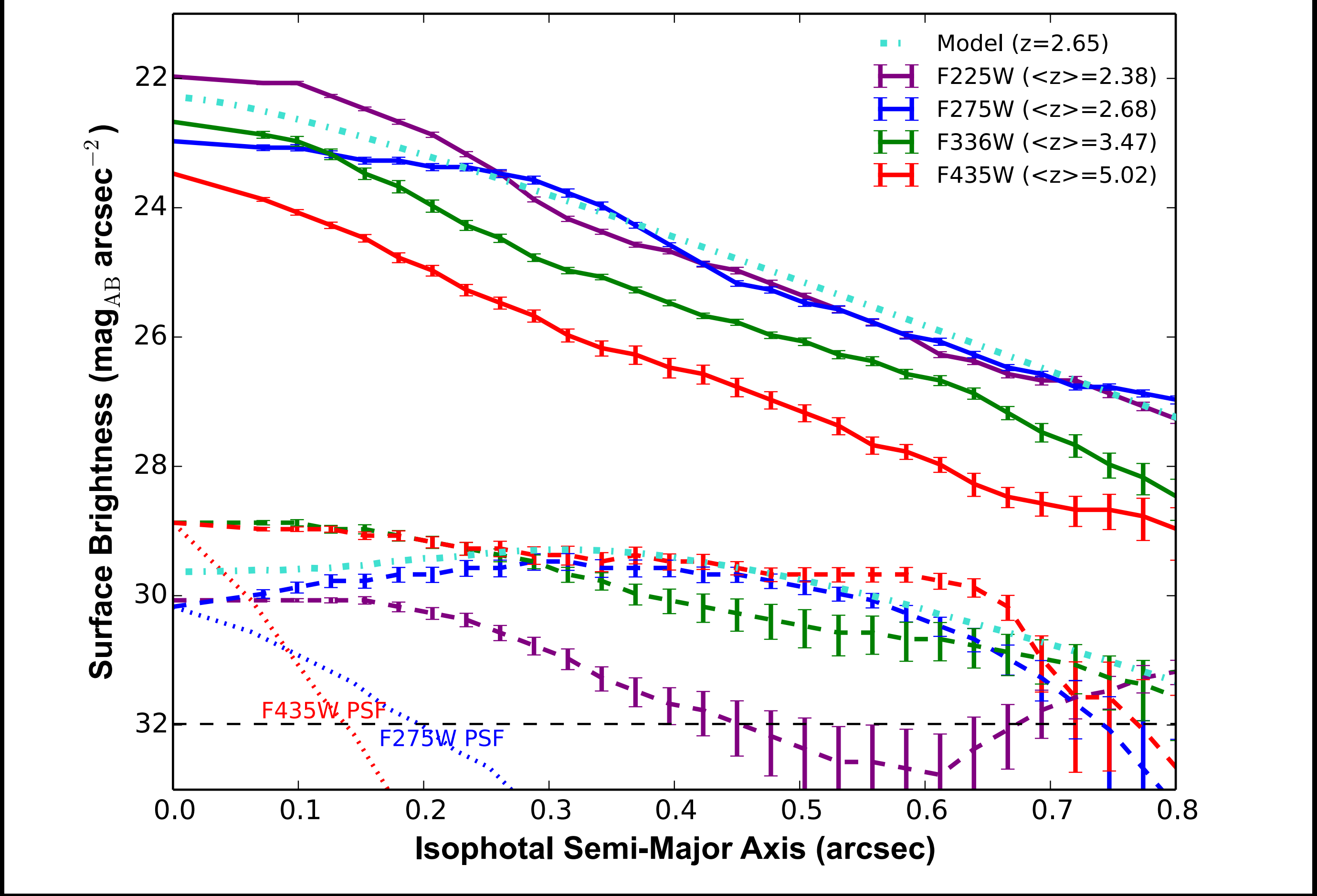
[*Bottom Row*]: All galaxies in combined Gold+Silver sample: N=114.

[Right 2×2 panels]: Weighted "stack-of-stacks" over all 4 LyC filters: best visualizes LyC of galaxies at z≃2.3–5.5. Formal detection S/N-ratios:

$\gtrsim 7\sigma$ ($\sim\sqrt{50}\times 1.0\sigma$ above sky), $\gtrsim 13\sigma$ ($\sim\sqrt{114}\times 1.2\sigma$ above sky).

- Equivalent to 22–228 orbit UV stacks with HST, respectively.

Circles: r=8 ($0''.72$), 13 pix ($1''.17$), centered on the UVC emission.

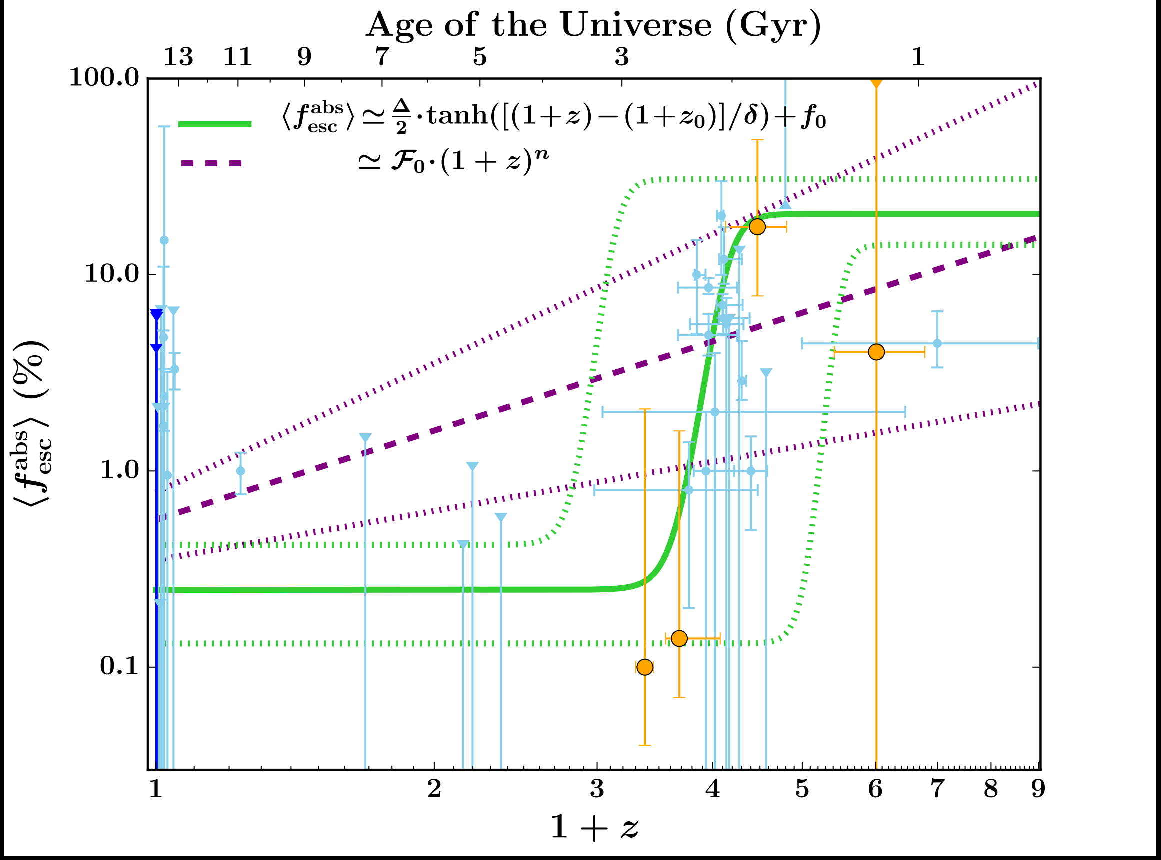


[*Top Curves*]: radial SB-profiles of stacked non-ionizing UVC (*solid*).

[*Bottom Curves*]: Radial SB-profiles of stacked LyC signal (*dashed*):

- All LyC SB-profiles are extended compared to the PSFs (dotted).
- Horizontal black dashed line is the 1σ SB-limit of ∼32 mag arcsec^{-2} .

Light-blue dot-dash: Dijkstra's z=2.68 UVC-scattering model with ISM porosity + escaping LyC increasing as: $f_{\rm cov}(r) = \mathcal{N} \exp\{-(r/10\,{\rm kpc})^x\}$.



Absolute f_{esc} -z: Published + ERS Gold & Gold+Silver samples.

Power-laws: $f_{esc} \simeq (0.006 \pm 0.002) \cdot (1+z)^{1.5 \pm 0.7}$ do not fit well.

Simple tanh[log(1+z)] captures more sudden f_{esc} -increase at z$\gtrsim$2.5–3.

- f_{esc} of galaxies just high enough to cause reionization at z$\gtrsim$3.
- LyC of 17 weak AGN in ERS ∼1.0 mag brighter than for galaxies.
- Weak AGN may dominate and maintain reionization at z$\lesssim$3.

Review Articles

- Frebel & Norris, 2015: http://www.annualreviews.org/doi/abs/10.1146/annurev-astro-082214-122423
- Sommerville & Dave, 2015: http://www.annualreviews.org/doi/abs/10.1146/annurev-astro-082812-140951
- Madau & Dickinson, 2014: http://www.annualreviews.org/doi/abs/10.1146/annurev-astro-081811-125615
- Bromm & Yoshida, 2011: http://www.annualreviews.org/doi/abs/10.1146/annurev-astro-081710-102608

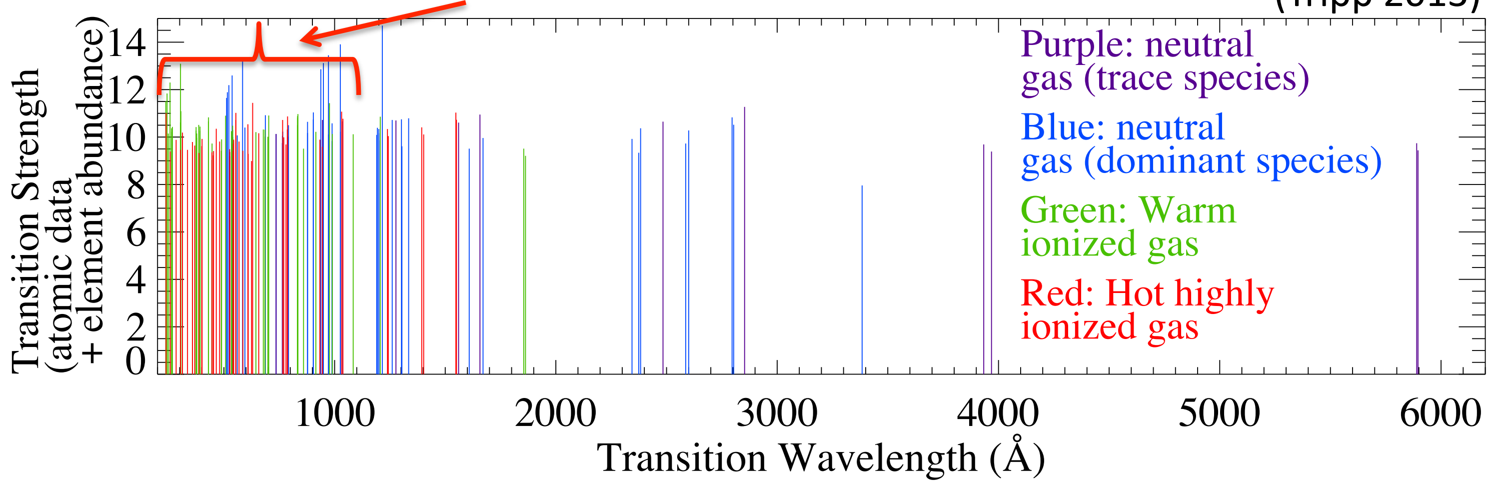
The Interface between Galaxies and the IGM – the Life Cycle of Baryons

- How does primordial material make it into galaxies?
  - Inner Disk vs. Outer Disk
  - Corotation Radius
  - Cooling & SF Enhancement
- How is material returned?
- What effect does such cycling have on the chemical evolution of galaxies?
- What is the role of the halo in this interface?
- The idea of tracking material from the primordial IGM into stars, planets, life
- Assessing the ecology of various processes - the rate of infusion and return affects:
  - energy
  - metallicity
  - the efficiency of SF
  - the conditions for planet formation
  - the conditions for life

Probing the Circumgalactic Medium and The Baryon Cycle with **High-Precision Diagnostics**

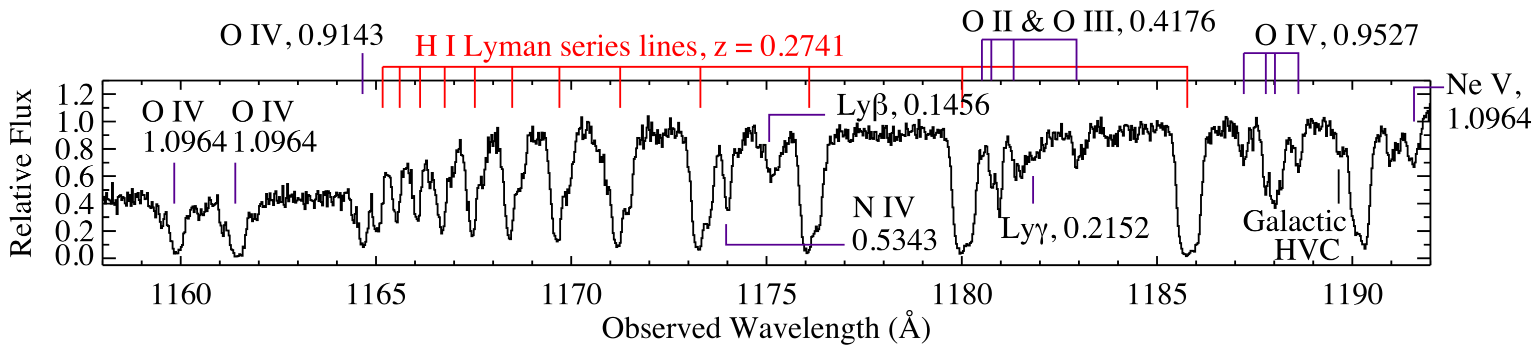
- Astro2010 key science: ***What controls the mass-energy-chemical cycles within galaxies? What are the flows of matter and energy in the circumgalactic medium (CGM)?***
- Explosive growth area in astrophysics: The term "circumgalactic" was first used by Lyman Spitzer in 1948 and appeared in 60 abstracts between 1948 and 2010 (1 per year); in 2015 alone, this appeared in 71 abstracts (70x higher).
- **Ultraviolet spectroscopy is, by far, the most effective tool for probing the CGM because (1) low gas densities make emission difficult/impossible to detect, (2) UV offers a rich array of diagnostics (see below), (3) compared to X-ray instruments, UV spectroscopy has orders of magnitude higher resolution, superior S/N, and vastly more targets.**
- The figure below shows resonance absorption lines that are detectable with a HabEX-class telescope. By observing intermediate-redshift QSOs/AGN, transitions from a tremendous suite of elements and ions are redshifted into the UV band.

(Tripp 2013)

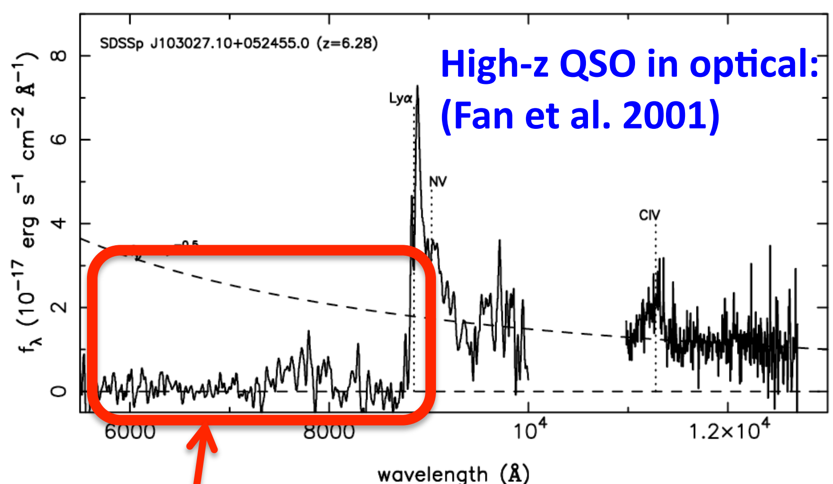


HST has started to do this, but only with tiny samples (e.g., Tumlinson et al. 2011; Tripp et al. 2011; Lehner et al. 2013; Meiring et al 2013). **These far-UV lines cannot be studied effectively from the ground or space-based optical band (see below); this is only possible in the ultraviolet**

- z = 1.47 QSO observed with HST+COS (from Tripp 2013); species and redshifts labeled:



- At higher redshifts, these lines are shifted into the optical, but the lines cannot be measured because they are embedded the Lyman alpha forest (Lya redshift density increases *rapidly* with z). Moreover, high-z QSO spectra are often black and useless due to optically thick Lyman limit and damped Lya absorbers.
- **This science requires deep coverage of the far UV (at least to 1150 A), high spectral resolution, and good sensitivity**



Lya forest ruins the spectrum for exploiting the far-UV CGM diagnostics

James Lauroesch (Louisville)

- I think what is compelling is that the UV universe is half the universe, not just what has happened since the Earth but what happened for 2+ Gyr before the Earth. Where do elements come from, where can planets with life form, how common can these planets be in the Universe.

- QSOALS let us trace the build up of the gas rich portion of the universe, this is complimentary to imaging studies which show us the evolution of the stellar portion. Spectra of QSOs allow us to measure the abundance, ionization state, pressure. temperature, density, and spatial structure in distant galaxies. Studies have shown (Som 2015, ApJ, 806, 25 and references there in) that apparently more gas rich systems have lower abundances. Such studies also allow us to study the Circum-Galactic Matter which allows us to trace how the influx of primordial material occurs and how enriched material is injected into the halo and how the feedback between these processes affects the abundance of elements which can form planets and potentially life.

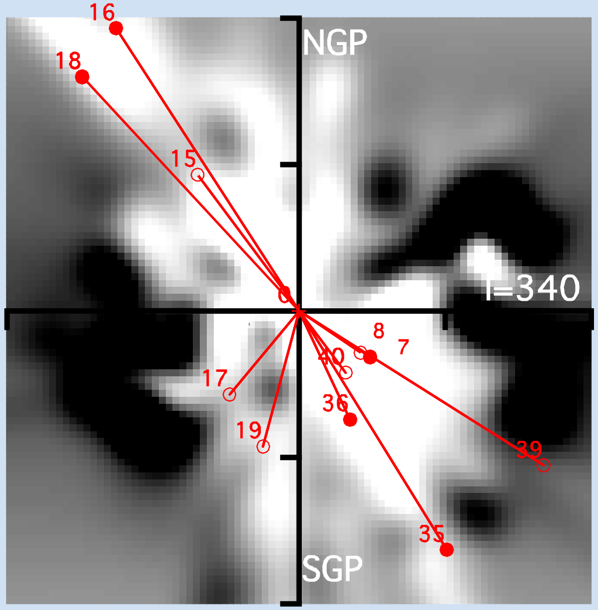
- UV imaging observations allow us to measure the rate of massive star formation over the last 1/2 of the age of the universe, which allows us to trace the build up of the elements over this time.

Conditions for Life in the Local Universe

M.A. Barstow and members of the European Network for UV Astronomy

University of Leicester

Science Context



- How does cosmic feedback influence habitability in the Galaxy
  - Physics of hot atmospheres and coronae
  - Resulting interplanetary environment
- Small scale studies with HST and FUSE
  - Patchy data on general structure of local region (various research groups)
  - Revealed significant complexity

Specific Science Investigation

- Target samples far too small
  - Objects too widely distributed in space for multi-object spectroscopy
  - Obs. times too long at required λ/δλ
- What is needed
  - Improvements in sensitivity… mirrors, detectors, gratings and filters

University of Leicester

Science Requirements

- Highest poss. $\lambda/\delta\lambda$ (R>100,000)
  - Resolve multiple IS/CS components
- High effective area
  - Low T_{exp} > large samples (100s to 1000s)
- High resolution imaging
  - capable of studying 10s of parsec size structures in local group galaxies
- Wavelength range 100-300nm

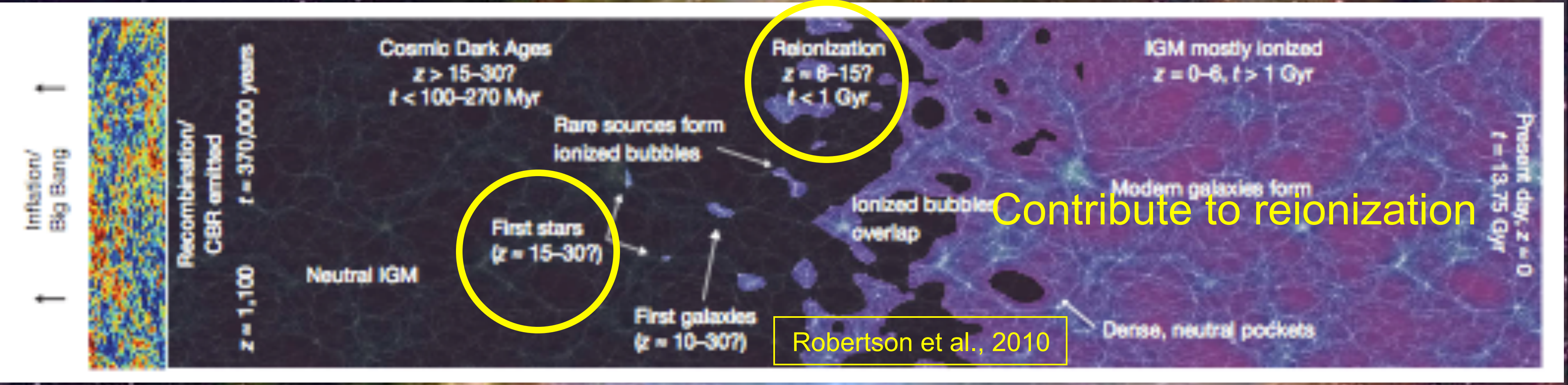
Massive stars as tool to understand the Universe

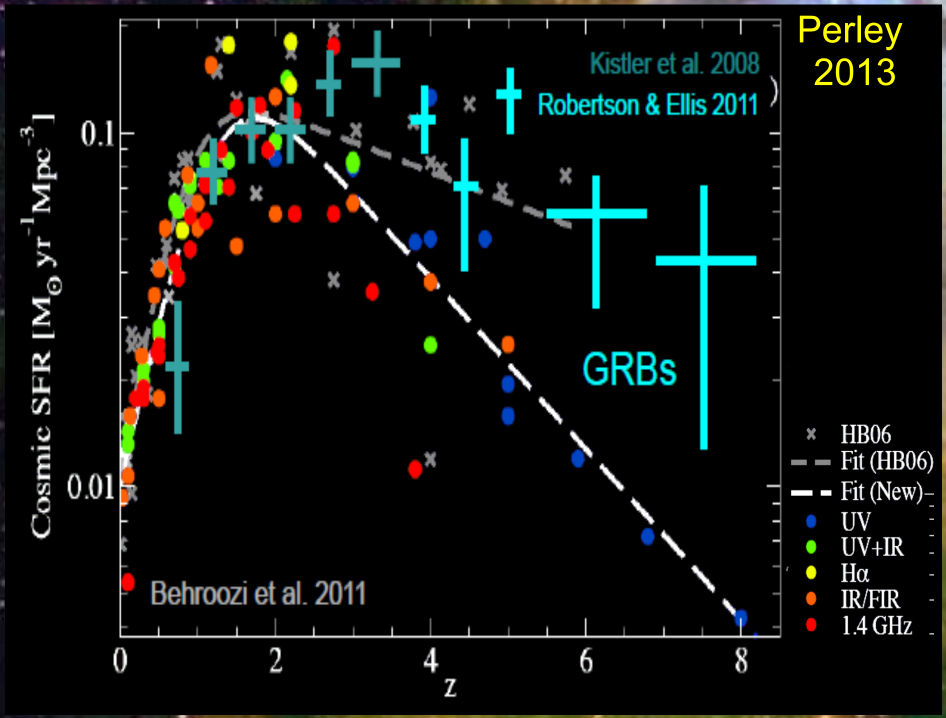
- Massive stars are the agents ionizing the regions of intense Star Formation that can be seen at huge distances. They have also been proposed as responsible of the re-ionization of the Universe (Aoki et al., 2014, Science 345, 912)
- They are progenitors of extreme objects (Langer, 2012, ARA&A 50, 107), like SNe, long-duration GRBs, black hole and neutron stars (often in binary systems, like in the gravitational wave system GW150914, Abbott et al., ApJL 818, L22)
- They contribute to the chemical and dynamical evolution of their host galaxy by returning metal-rich matter to the surroundings and injecting large amounts of mechanical and radiative energy
- The details of all these processes are still poorly understood. Understanding the phyiscs of massive stars under different local conditions (e.g., metallicity) is crucial to understand the Universe
- Fortunately, massive stars are very luminous and can be individually studied in galaxies up to 10 Mpc with current telescopes
- For most of its life, its energy is radiated in the FUV and they are often born in crowded systems. Moreover, when metallicity decreases (approaching conditions in the early Universe) stellar winds, a crucial physical process, can only be studied in the UV
- All these conditions make UV space-based observations of massive stars unavoidable

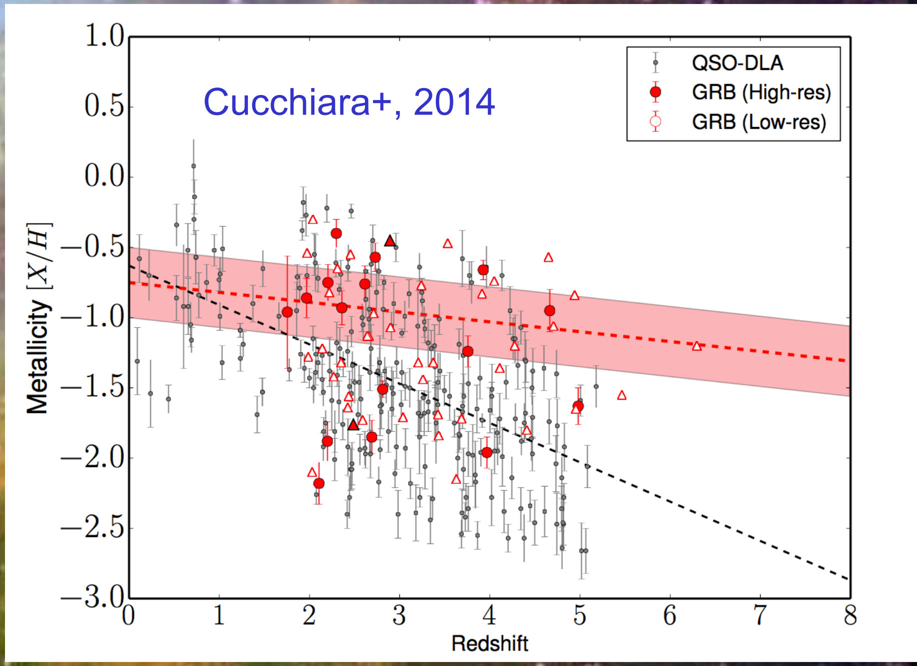
UV observations of massive stars in the Local Universe

- We want to observe the UV spectrum of massive hot stars in the Local Universe (ideally, up to 20 Mpc).
- The FUV spectrum of massive hot stars is crowded. And at low metallicities the spectral features will be shallow.
- We require
  - High spectral resolution (for a good contrast with the continuum and good line separation in a crowded spectrum). R= 10,000
    - More than that is not required here because of the stellar line broadening
  - High throughput (we want to obtain good spectra of individual stars at large distances; $m_v > 23$; presently with HST we may reach ; $m_v = 20$ with very limited R and S/N, at ~1,5 Mpc)
  - High spatial resolution and small apertures (target overlap is one of the big issues in extragalactic stellar spectroscopy; the PSF FWHM should be less than 0.05 arcsec).
    - (The 0,05 arcsec number is set to get a resolution of ~3 pc at 10 Mpc)

1.- Massive stars: tools to understand the Universe

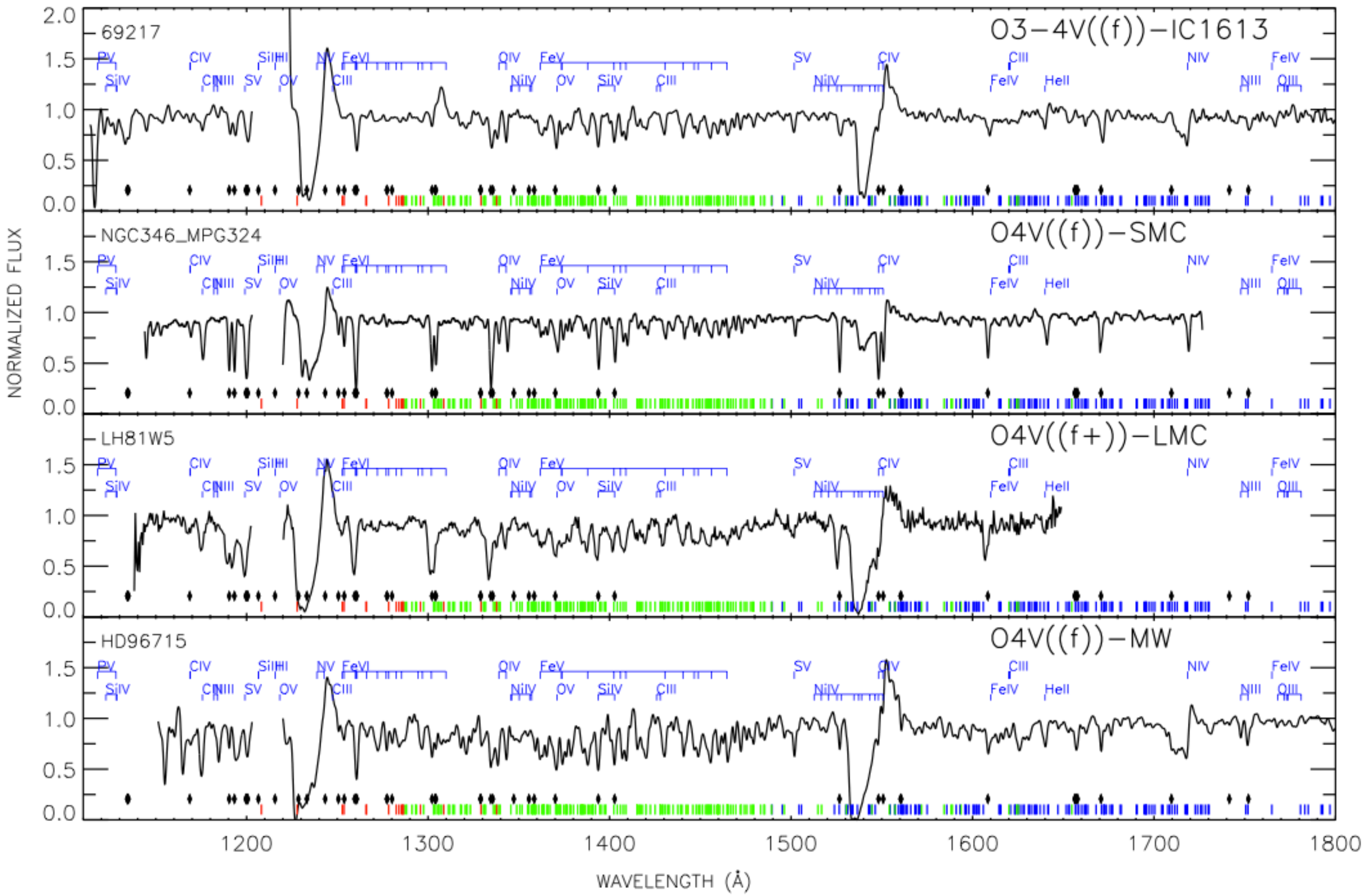






UV observations of massive stars in the Local Group

Garcia et al., 2014, ApJ 78, 64



The eventful life of ETGs in low density environments

UV working group **Rampazzo R.**, Marino A., Mazzei P.,(INAF) Bianchi L. (JHU)

Groups contain ~60% of galaxies in the nearby Universe and the transition between galaxy properties typical of field and clusters (SF vs. passive) happens at the characteristic densities of groups. Spirals dominate the UV LF in poor groups, Early-Type Galaxies in the evolved, rich ones (Fig. 1). We used GALEX to reaveal that a residual SF is stil present in ETGs members of rich, viralized groups, in particular, but not only, in the dwarf E population.

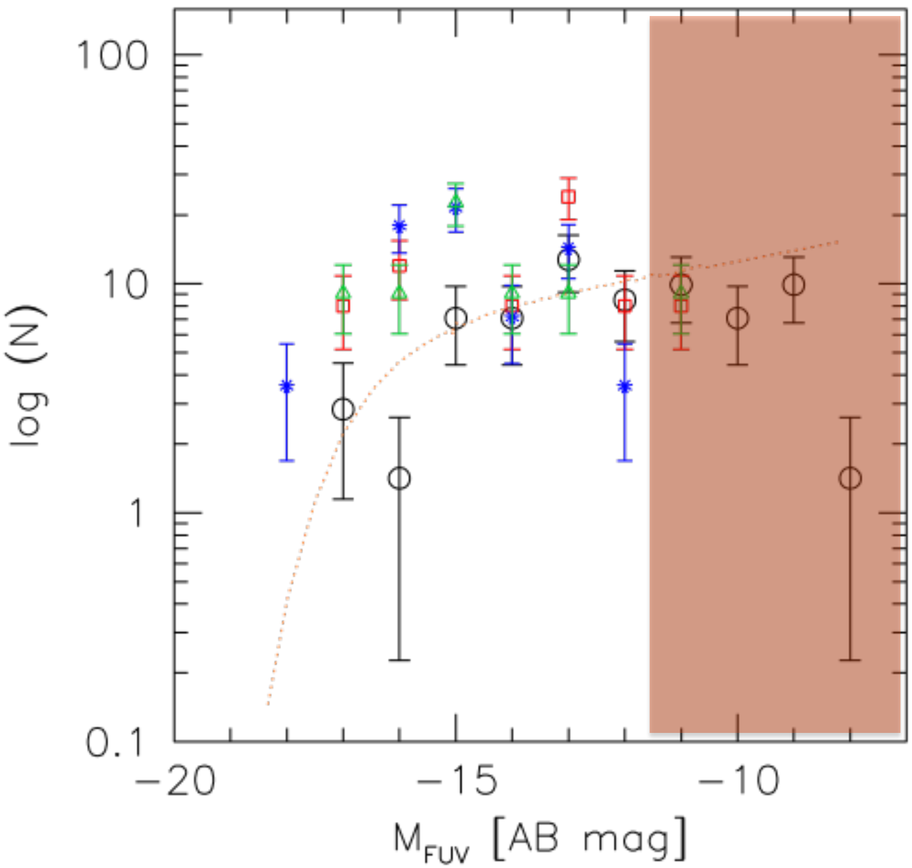
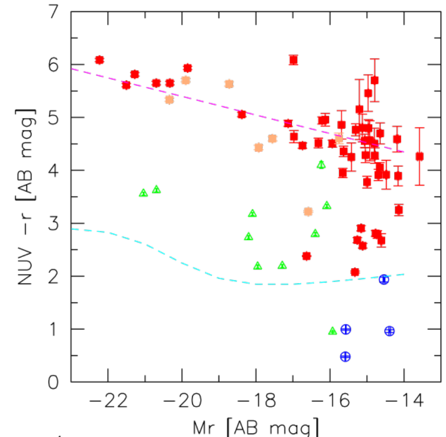


Fig. 1 The FUV LF of NGC 5846 group (circles) compared to those of the Virgo cluster (dotted line Boselli+ 2014, A&A Rev, 22, 74) and of the poor groups U376 (red squares), U268 (blue asterisks) and LGG 225 (green triangles) (Marino+ 2016).



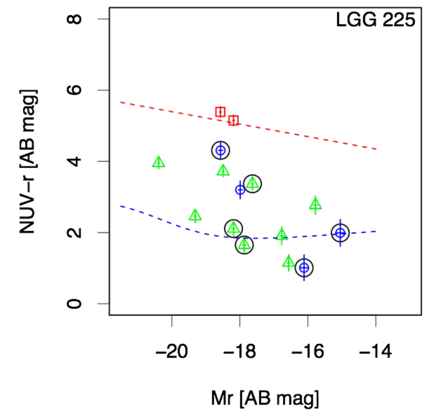


Fig. 2 M_r vs. NUV-r of NGC 5846 (top left) and of LGG 225 group (top right); over-plotted the Wyder+ (2007, ApJS, 173, 293) fits to the red and blue galaxy sequences. Green triangles mark Spirals, Ellipticals and S0s are red and orange squares respectively, blue circles show Irregulars (Marino+ 2014, 2016).

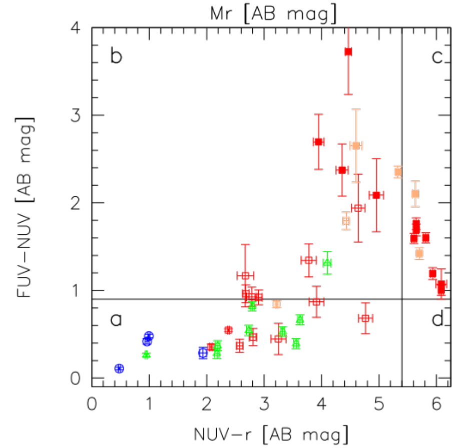


Fig. 3 The FUV-NUV vs NUV-r C-C diagram of the NGC 5846 group. Symbols are as in the Fig.2. Solid lines mark the conditions FUV-NUV< 0.9, i.e UV rising slope, and NUV-r>5.4, i.e. a galaxy devoid of young massive stars (Yi+ 2011, ApJS, 195, 22). These conditions separate passively evolving ETGs (region b) from star forming galaxies (region a). Filled symbols are for galaxies with FUV-r>6.6 mag (Marino+ 2016).

The eventful life of ETGs in low density environments

Wants in UV range (down 200nm) 4-6m telescope

- N.B. multi-wavelength coverage not only UV (normal and narrow band filters) required
- high spatial resolution (0.02”/px) → resolve stars up to and beyond Virgo
- MOS spectroscopy (50-100 slits) → gas/stellar kinematics/chemistry, properties of UV LF tail
- IFU capabilities: FoV>=4’; R_{spec} >5000 → mechanisms of triggering/quenching SF

N.B. need for a Wide Field, High resolution far UV companion space mission

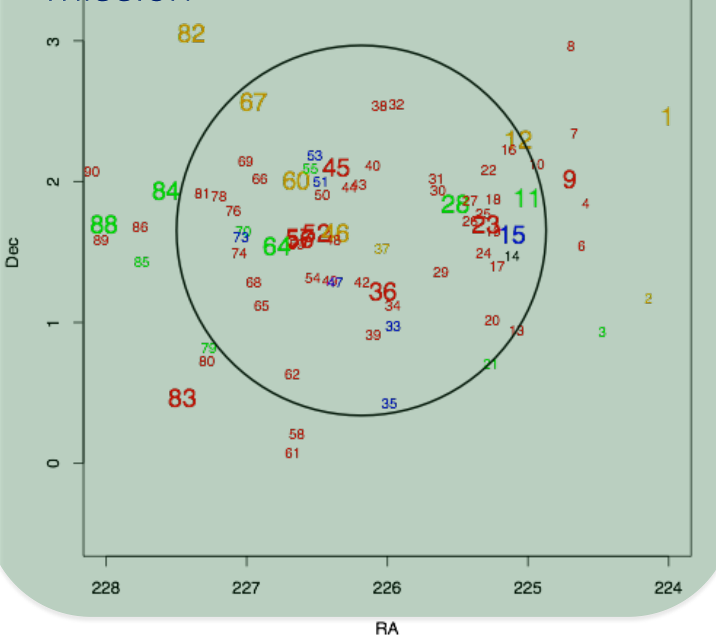
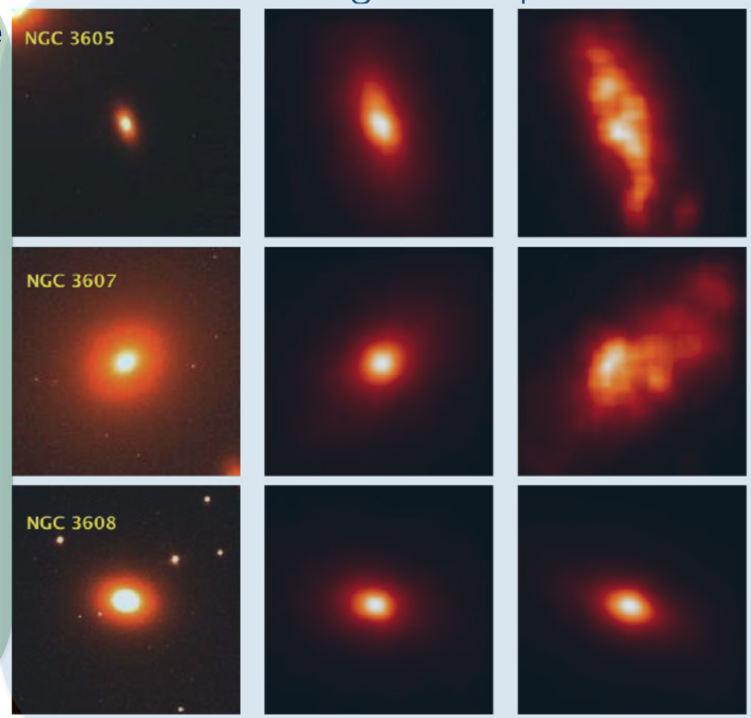


Fig. 4 Projected distribution of the galaxy members of the NGC 5846 group, the third more massive group in the Nearby Universe. Galaxies with B magnitude <15.5 are labeled with bigger numbers. The circle (solid line) corresponds to the virial radius centred on the centre of mass of the group. Colors as in Figure 1 (Marino+ 2016).

Constraining chemophotometric SPH simulations



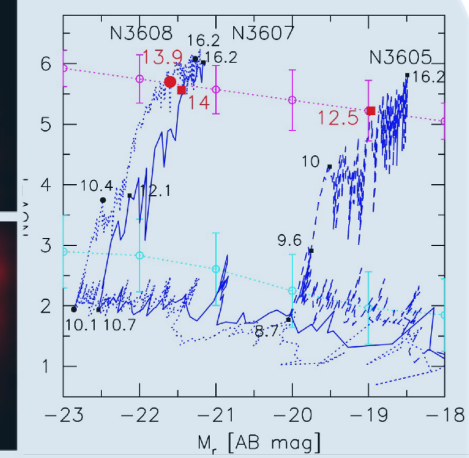
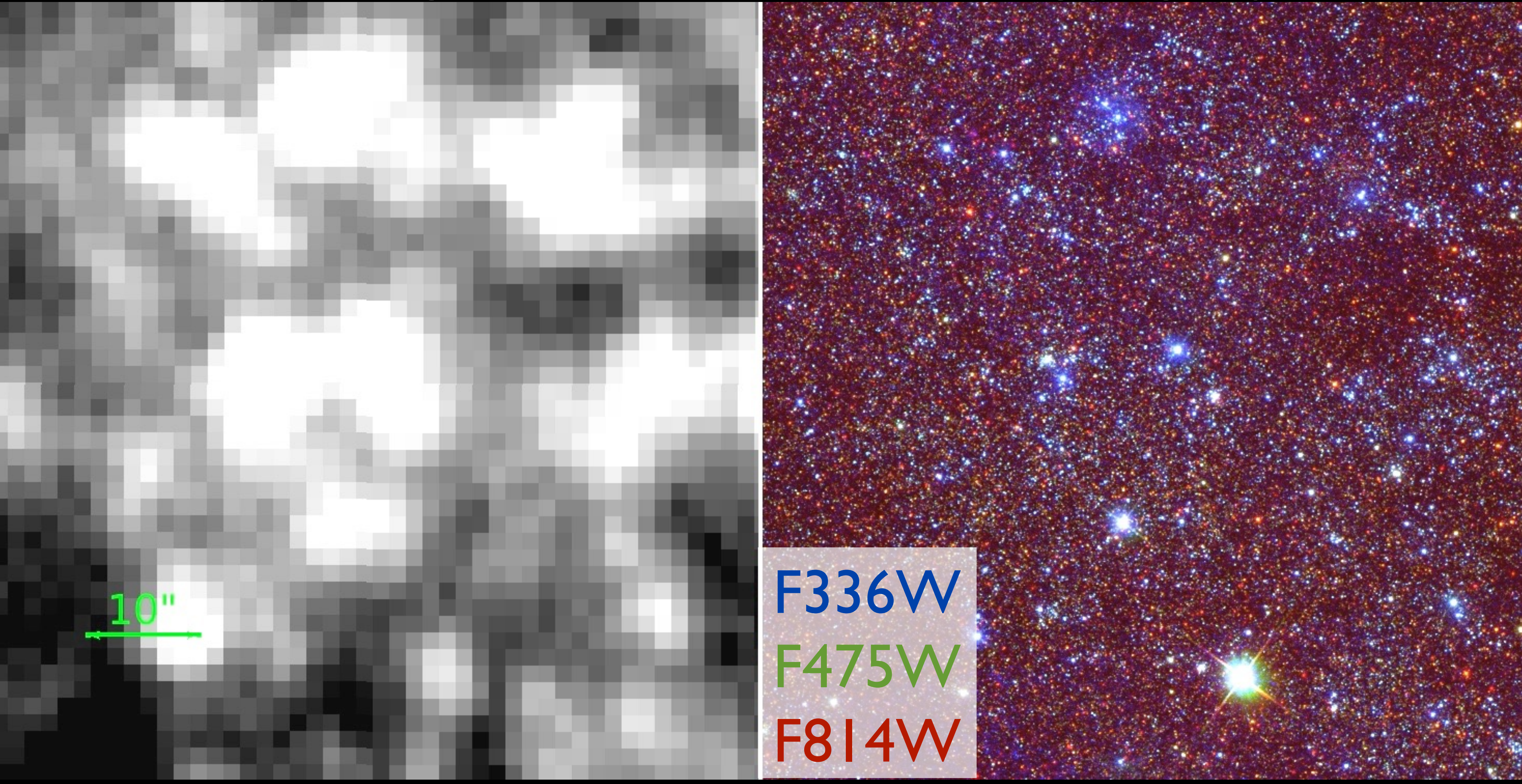


Fig. 5 (left panel) SDSS r-band images (left), our simulated maps at the current age (middle) and the at the age corresponding to brightest Mr in the top CMD panel (Mazzei+ 2014)

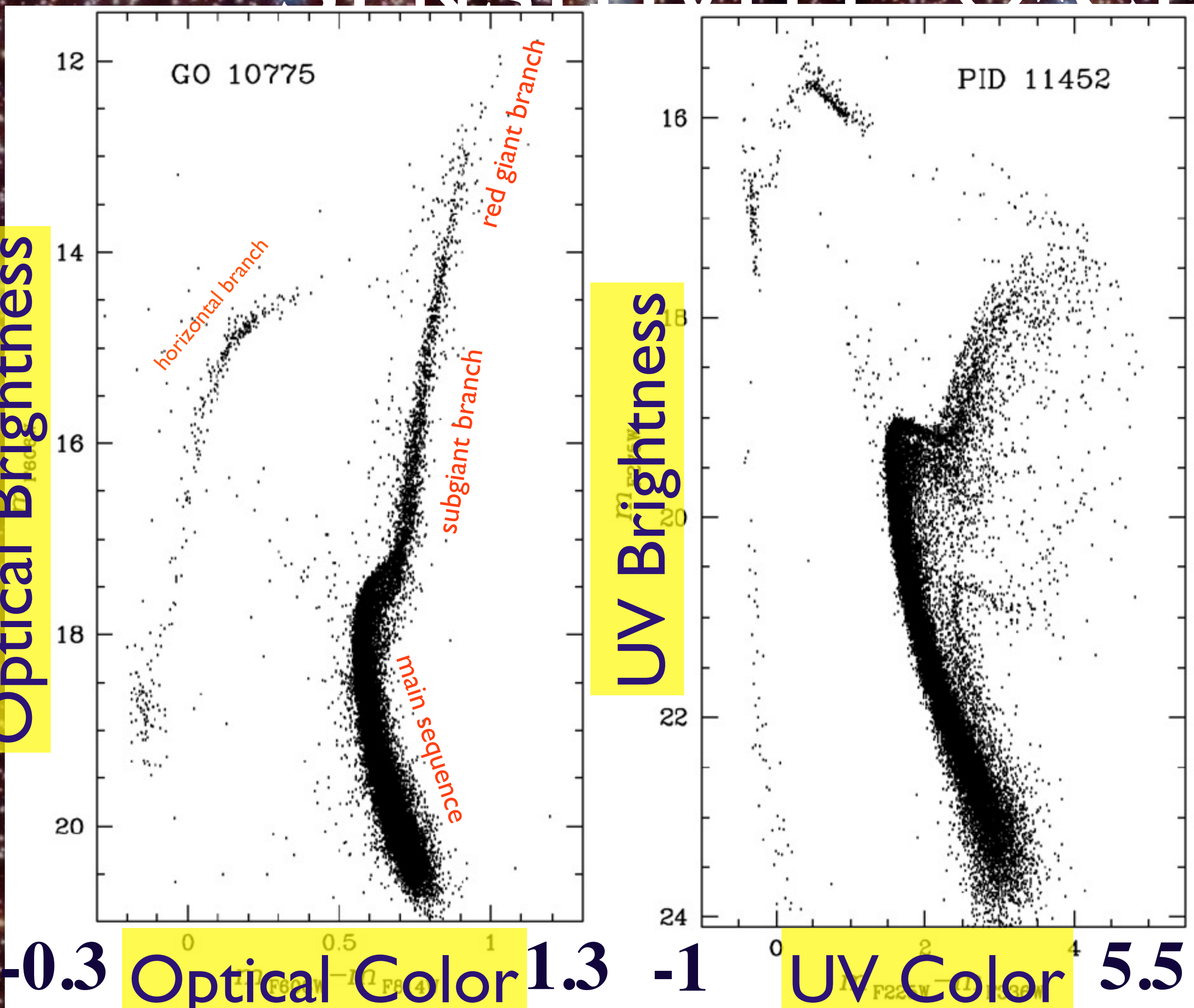
Our References
Marino, Bianchi, Rampazzo+ 2010, A&A, 511, A29
Marino, Plana, Rampazzo+ 2013, MNRAS, 428, 476
Marino, Bianchi, Mazzei+ 2014, AdSpR, 53, 920
Mazzei, Marino, Rampazzo+ 2014, AdSpR, 53, 950
Mazzei, Marino, Rampazzo 2014, ApJ, 782,53
Marino, Mazzei, Rampazzo & Bianchi 2016 MNRAS, in press

Galex flux Comes from stars Requires High Spatial Resolution

Galex NUV ACS+UVIS



Old Population Sensitivity: O-Cen

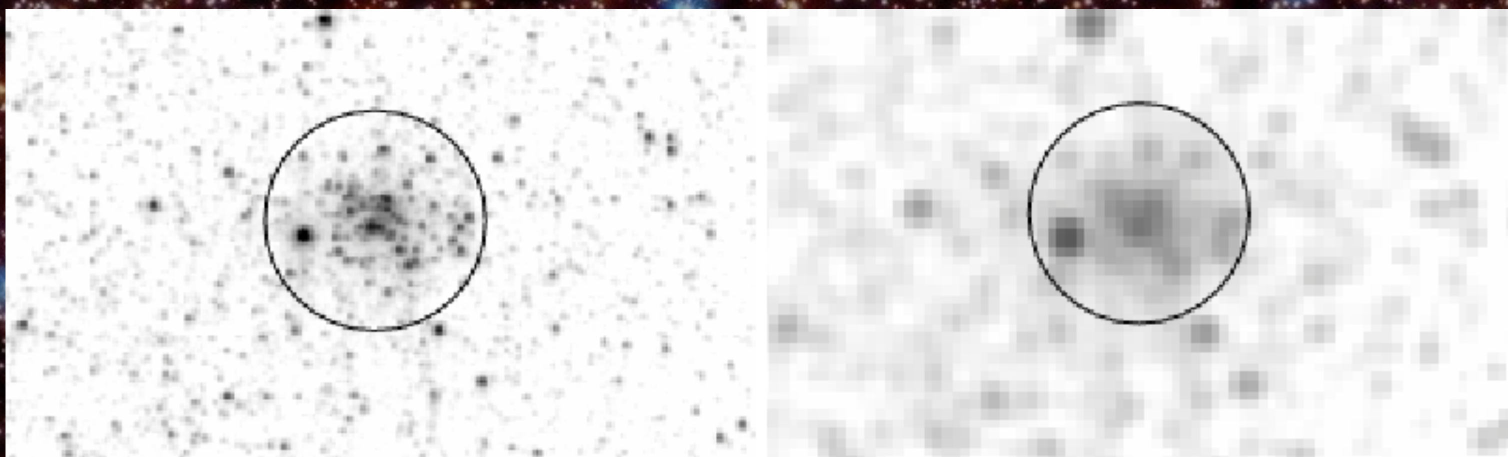


Color → Temperature

Bellini et al. 2010

Need improved resolution and sensitivity in Clusters

M31 (0.8 Mpc) Convolved to 3 Mpc



Barely capable of this in M31
with current technology

Review Articles

- Frebel & Norris, 2015: http://www.annualreviews.org/doi/abs/10.1146/annurev-astro-082214-122423
- Sommerville & Dave, 2015: http://www.annualreviews.org/doi/abs/10.1146/annurev-astro-082812-140951
- Madau & Dickinson, 2014: http://www.annualreviews.org/doi/abs/10.1146/annurev-astro-081811-125615
- Kennicutt & Evans, 2012: http://www.annualreviews.org/doi/abs/10.1146/annurev-astro-081811-125610
- Putman, Peek & Joung, 2012: http://www.annualreviews.org/doi/abs/10.1146/annurev-astro-081811-125612
- Beers & Christlieb, 2005: http://www.annualreviews.org/doi/abs/10.1146/annurev.astro.42.053102.134057
- Veilleux, Cecil & Bland-Hawthorn, 2005: http://www.annualreviews.org/doi/abs/10.1146/annurev.astro.43.072103.150610

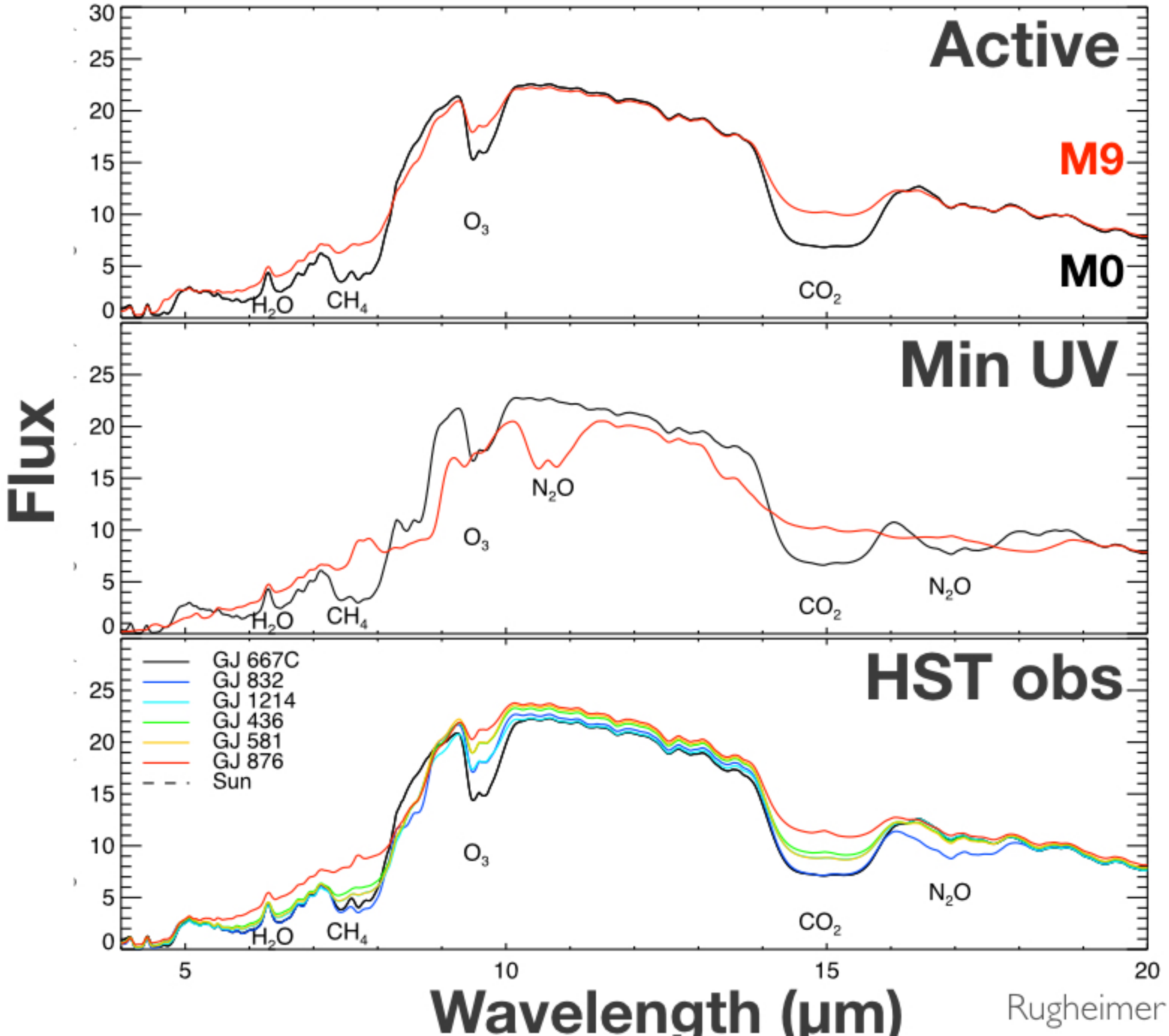
Understanding the Environment Around Young Stars using the UV

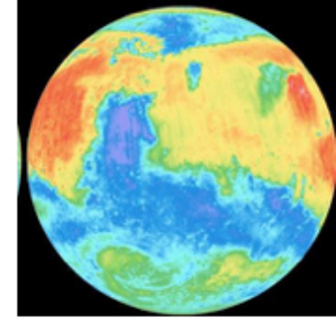
- The spectrum of the host star intimately affects:
  - The conditions for planet formation
  - The formation and evolution of planetary atmospheres
- The UV deposits a larger energy per photon
- UV Spectral diagnostics to trace the accretion processes and gas dynamics in young stellar objects
- Physics of accretion disks – jet energy, accretion shocks, disk abundances and grain assembly
- Following the life cycle of planet formation –
  - tracing the nature of planetesimals to understand aggregation
  - tracing water and other volatiles

Sarah Rugheimer (Harvard)

- I am working on actually modeling the UV transit spectrum right now for different stellar types. This was more just the UV's impact on the photochemistry and atmosphere.   Characterizing the UV environment of host stars is of vital importance and after HST we won't have a way to do so. We will only understand (and be able to use our retrieval models accurately) the planet as well as we know the UV of the star.
- I think this shows that characterizing the UV of stars is vital. We don't have models that can predict the UV for stars, particularly M stars. And we don't even have very many M stars characterized in the UV. AND we don't know the floor of UV flux possible for M stars yet. All of which could be done with a future UV mission like HabEx. This is all motivated by atmosphere modeling (see below).
- As well I'll say that pushing as far into the IR as possible is vital for detecting biosignatures since without a constraint on the reducing potential of the atmosphere a detection of oxygen is meaningless.
- http://adsabs.harvard.edu/abs/2015ApJ...809...57R
  - Title: Effect of UV Radiation on the Spectral Fingerprints of Earth-like Planets Orbiting M Stars
  - Authors: Rugheimer, S.; Kaltenegger, L.; Segura, A.; Linsky, J.; Mohanty, S.

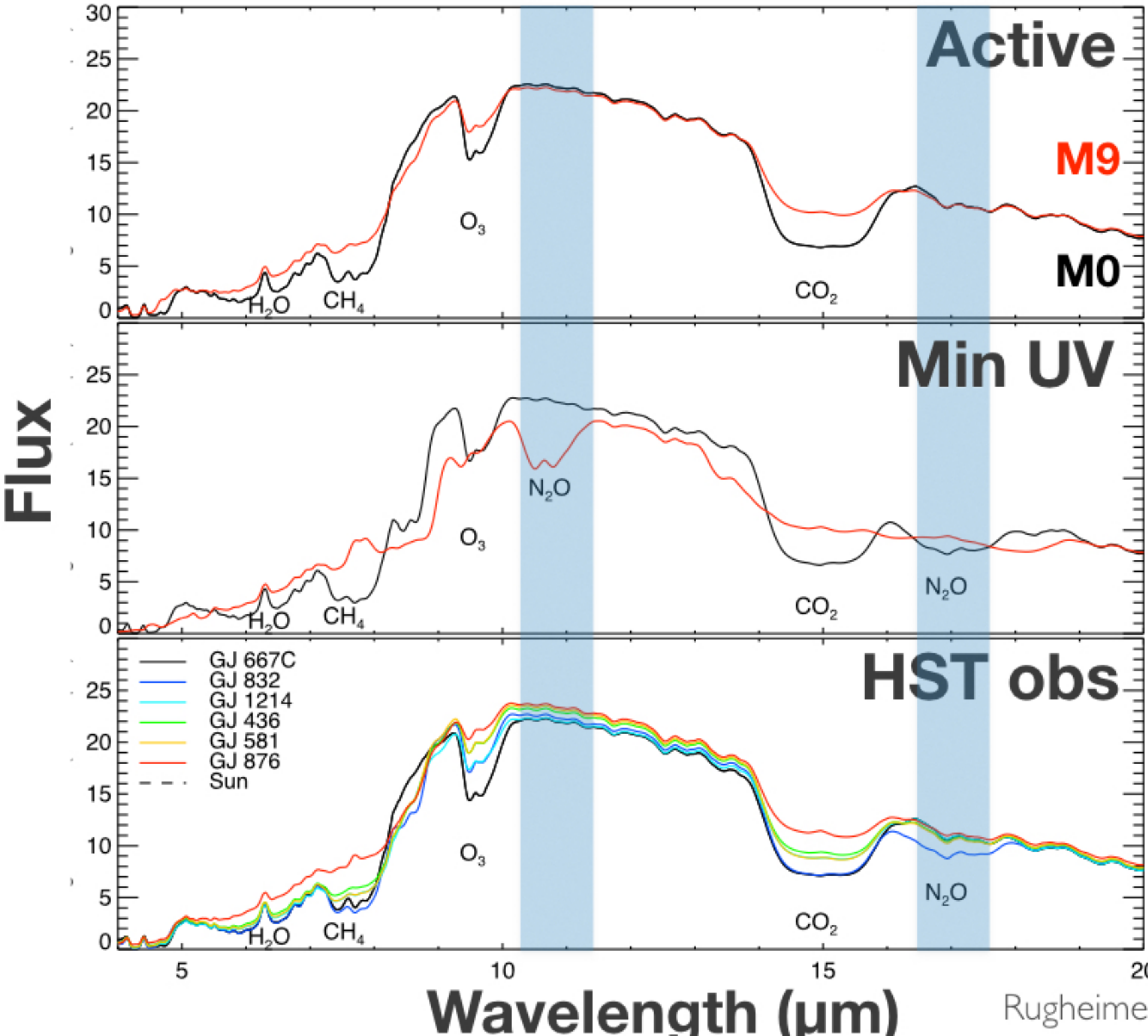
Simulated Planet IR Spectra

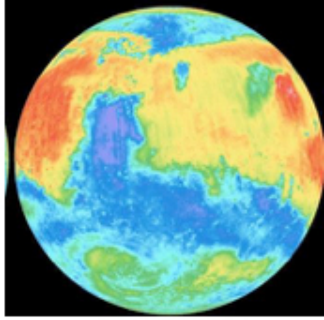




Rugheimer *et al.*, 2015b

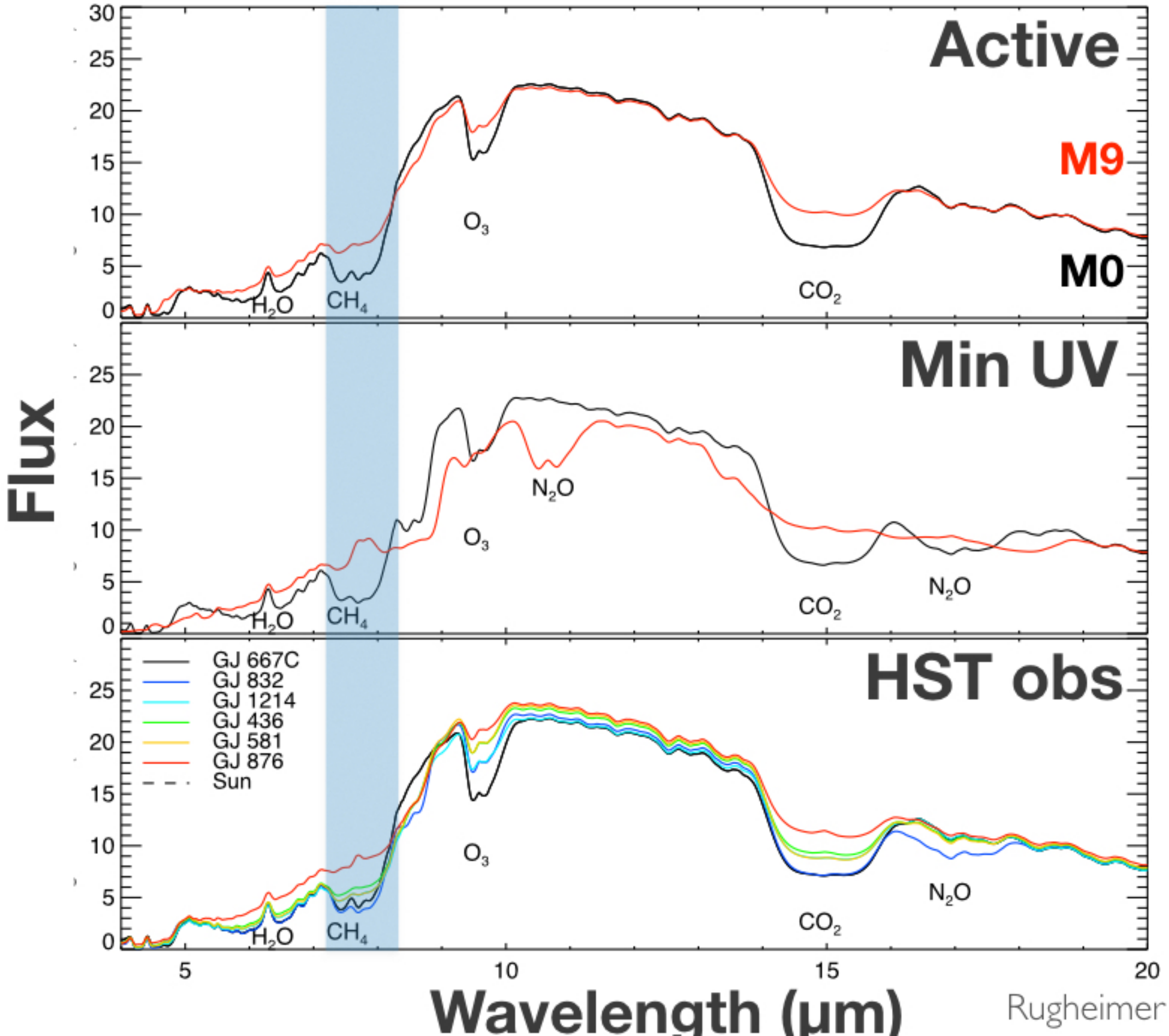
Simulated Planet IR Spectra

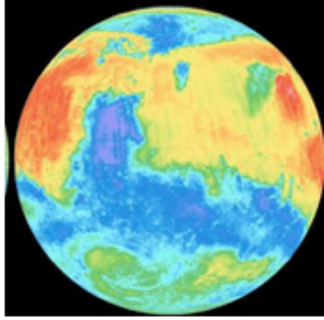




Rugheimer *et al.*, 2015b

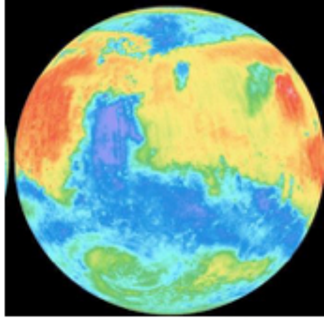
Simulated Planet IR Spectra

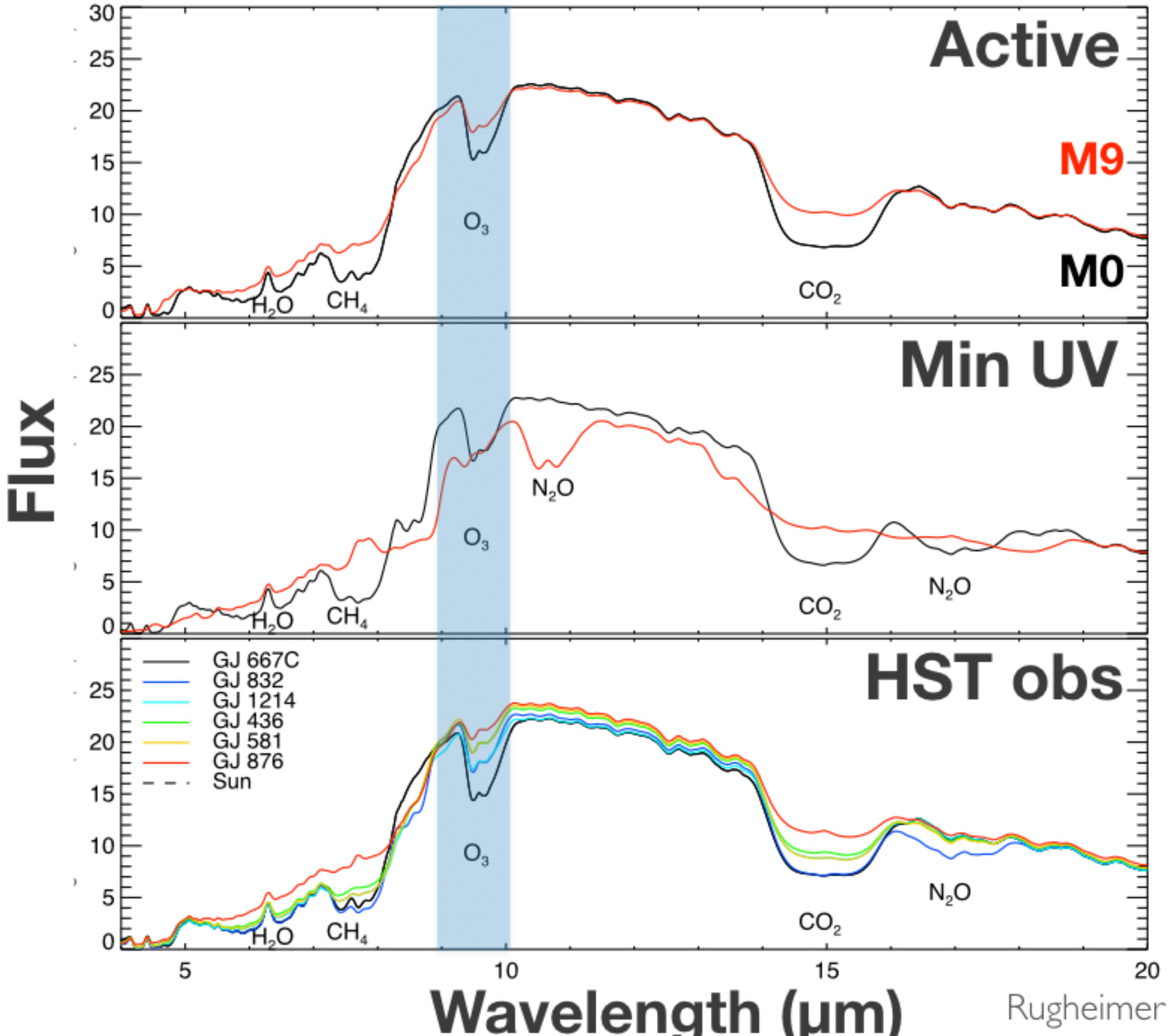




Rugheimer *et al.*, 2015b

Simulated Planet IR Spectra

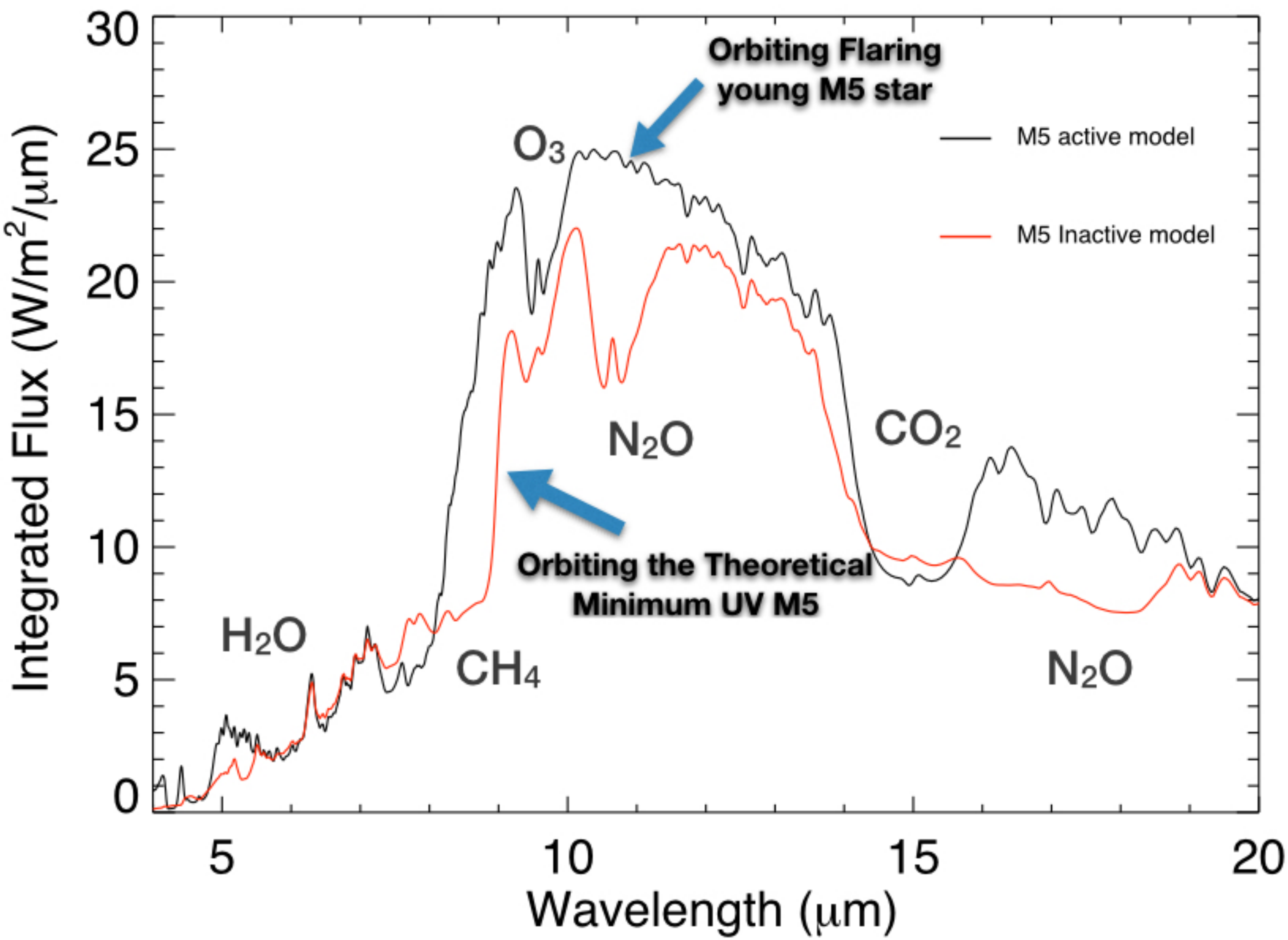




Rugheimer *et al.*, 2015b

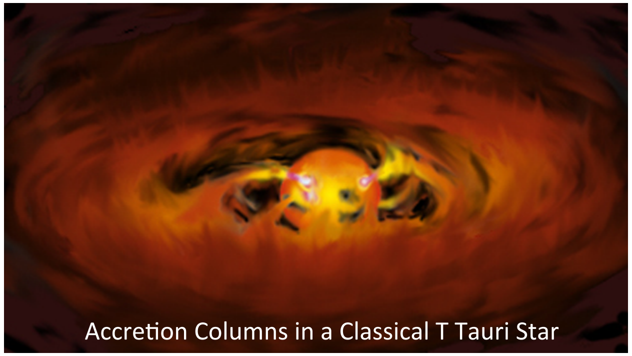
Compare two extremes - Earth-like planet orbiting M5

Two extremes - M5 case

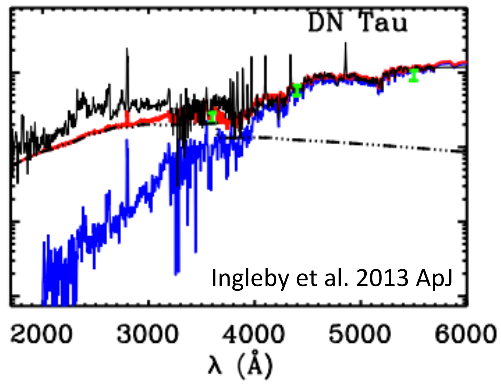


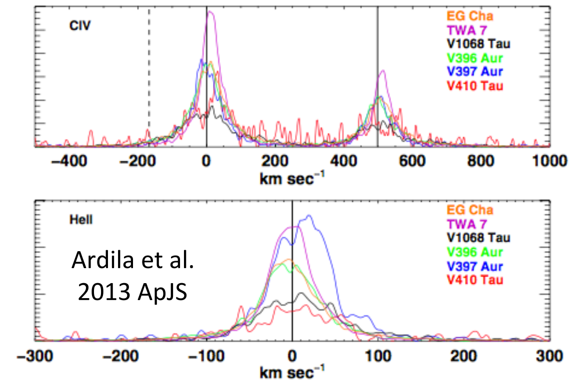
Physics of Accretion Phenomena in Young Stars

Most energy from accretion onto young stars is released in the UV
Spectra show continua and broad emission lines



P. Hartigan





Understanding accretion flows requires resolving line profiles (R > 10000)
Different emission lines trace the full range of temperatures

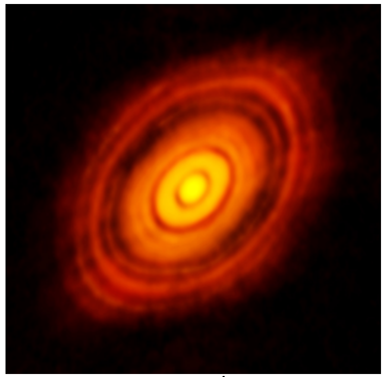
- S II, NII etc. optical 10^4 K
- O III 5007A $3x10^4$ K
- C IV 1550A $1x10^5$ K
- N V 1240A $6x10^5$ K
- OVI 1038A $4x10^5$ K
- X-rays 10A $2x10^6$ K

- *Having spectroscopic capability in 1000A – 1250A range bridges 10^5 K and 10^6 K gas*
- *A long-slit option will allow for diffuse hot gas to be traced (e.g. along jets)*

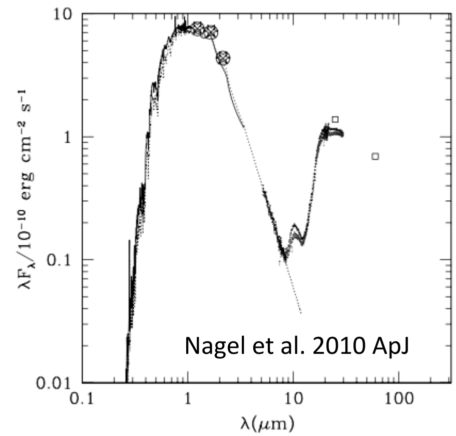
Gas in Protoplanetary Disks

ALMA images show gaps in Protoplanetary Disks

IR Spectral Energy Distributions imply inner holes in older T Tauri disks and in binaries



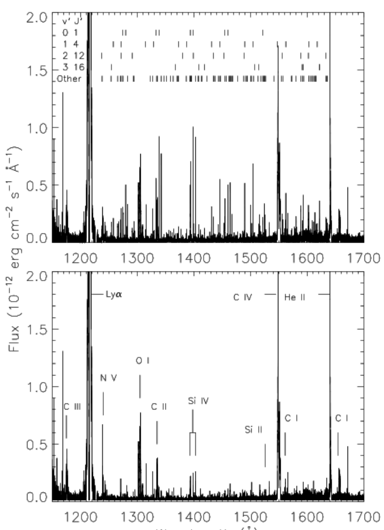
ALMA Press Release 2014



Nagel et al. 2010 ApJ

But mm-wave and IR continuum trace only dust. What about the gas?

Best way to trace H_2 is via UV fluorescence



Herczeg et al 2002 ApJ

Spectroscopy and Imaging are complimentary:

- More difficult to image small spatial scales
- Easier to resolve orbital motions at smaller r

6-m class telescope at 1400A with d=140pc resolves 0.8AU

For d < 0.8AU, V_{orbit} > 30 km/s

With both imaging (or long slit) and high-res UV spectroscopy one can probe gas dynamics at all scales in these disks

UV Science with a HabEX-like telescope

May 4, 2016

David R. Ardila

Activity in exoplanet hosts

Science: Stellar activity in the UV dominates the chemistry of exoplanetary atmospheres and the long-term habitability of the planets. Energy proxies analogous to those used as inputs to the Earth's Jacchia-Bowman model are not available for other stars. *Consistent with "Formative Era" Astrophysics Roadmap activities.*

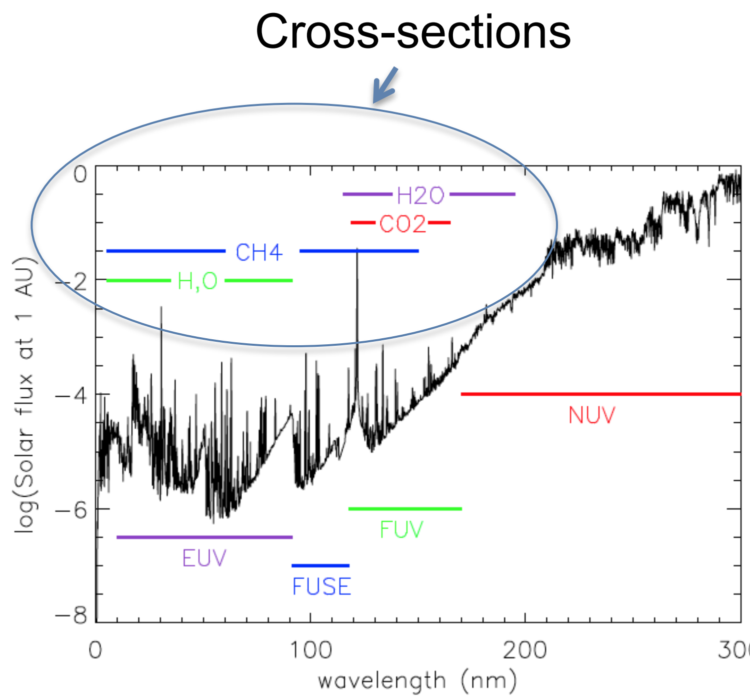
Project:

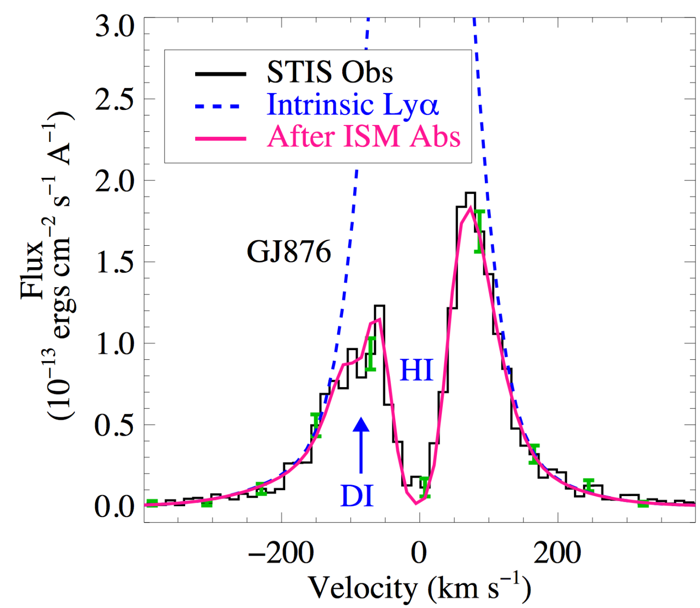
- Measure UV variability of exoplanet host stars, due to flares, rotation, and activity cycles. Focus on photochemically important UV lines for GKM stars: LyAlpha: 122 nm; CIV: 156 nm; MgII: 280 nm
- Same instrument can be used to do exoplanet transits

Targets: Planetary hosts plus GKM dwarfs within 10 pc: ≈100s of objects. Emphasis on M dwarfs.

Procedure: Long-term (3 mo to 5 yrs) spectroscopic observations.

Instrument: D=5 m telescope, UV longslit spectrograph with R=10,000 at 1216 A, HST-like throughput





France et al. (2013)

Imaging of earth-like exoplanets in the UV

Based on Cook et al. submission to the 2012 RFI on Scientific Objectives for UV/Visible Astrophysics Investigations

Science: The UV contains a host of exoplanet atmosphere diagnostics, providing information about upper atmosphere processes and heating. UV albedo is >1 in places due to fluorescence. *Consistent with "Formative Era" Astrophysics Roadmap activities.*

Project: Coronagraphic imaging and spectra of extrasolar earth-like planets

Targets: Earth-like planets

Procedure: Long-term (3 mo to 5 yrs) spectroscopic observations.

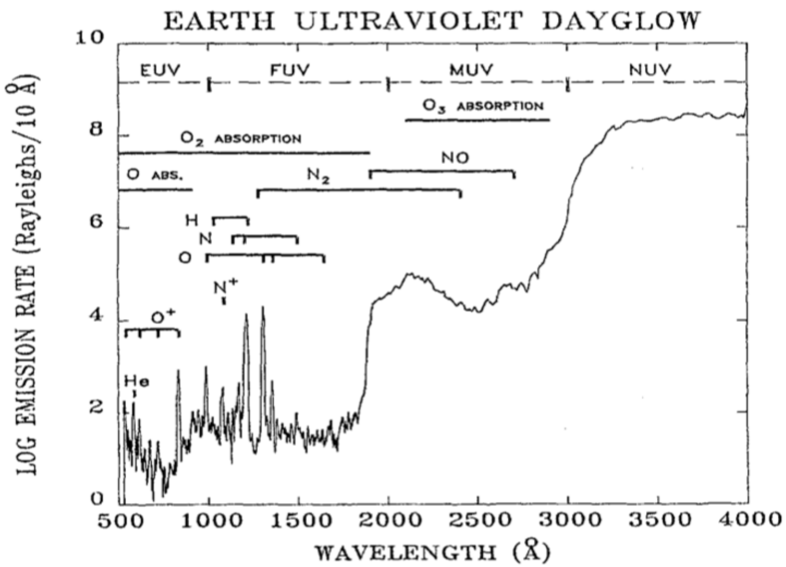
Instrument:

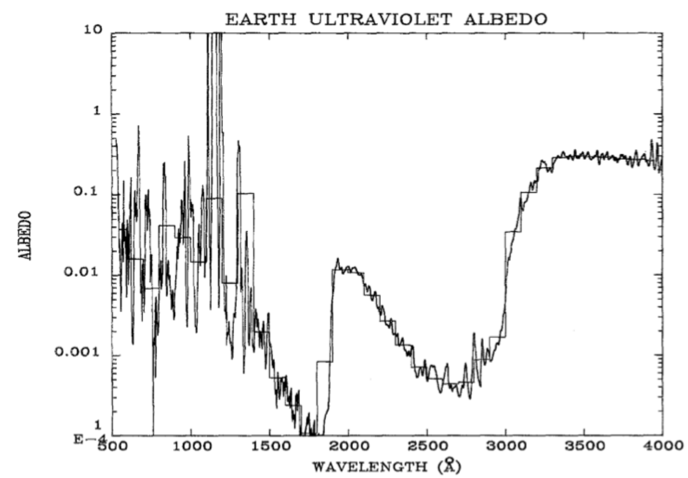
Coronagraph: IWA: $3\lambda/D$=100 mas; Contrast: 3σ~1e-10 – 1e-7

IFU: R~100, 1200-3500 A

Telescope: D ~ 4 m (assuming diffraction limit at 6000 A)

Reference: Cook et al. 2012; http://cor.gsfc.nasa.gov/RFI2012/docs/29.Cook.pdf





AEROSPACE

Protoplanetary disk structure and evolution

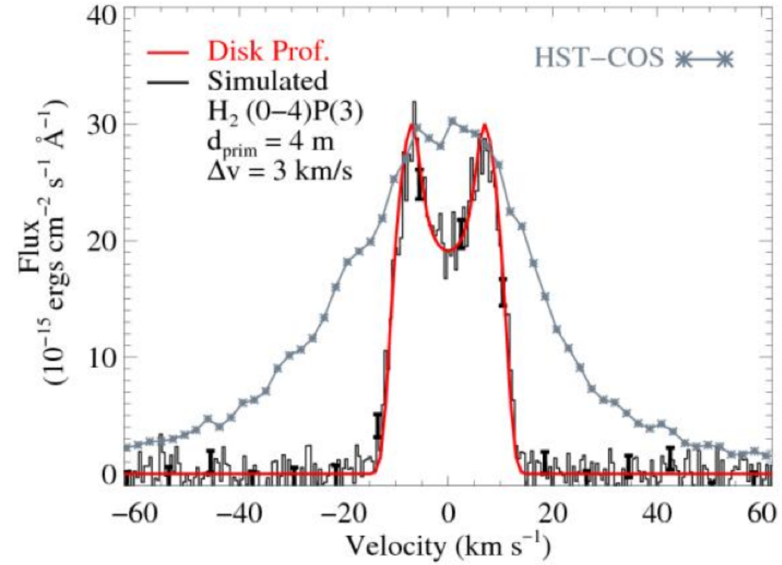
Based on France et al. submission to the 2012 RFI on Scientific Objectives for UV/ Visible Astrophysics Investigations

Science: To determine radial structure, abundance, and lifetimes of circumstellar disks. UV spectroscopy samples disk composition at the terrestrial planets region. The strong H2 lines provide a very sensitive probe of the gas content in disks. *Consistent with "Formative Era" Astrophysics Roadmap activities.*

Project: UV spectroscopy of protoplanetary disks.

Instrument: D=4 m, High-resolution ($\Delta v < 3$ km s^{-1}), high-throughput ($\leq$ 10-17 erg cm^{-2} s^{-1} $Å^{-1}$ in 100 sec) spectroscopy; 1000 – 1700 Å bandpass

Reference: France et al. (2012); http://cor.gsfc.nasa.gov/RFI2012/docs/30.France.pdf



France et al. (2012)

FROM PROTOPLANETARY DISKS TO PLANETARY SYSTEMS

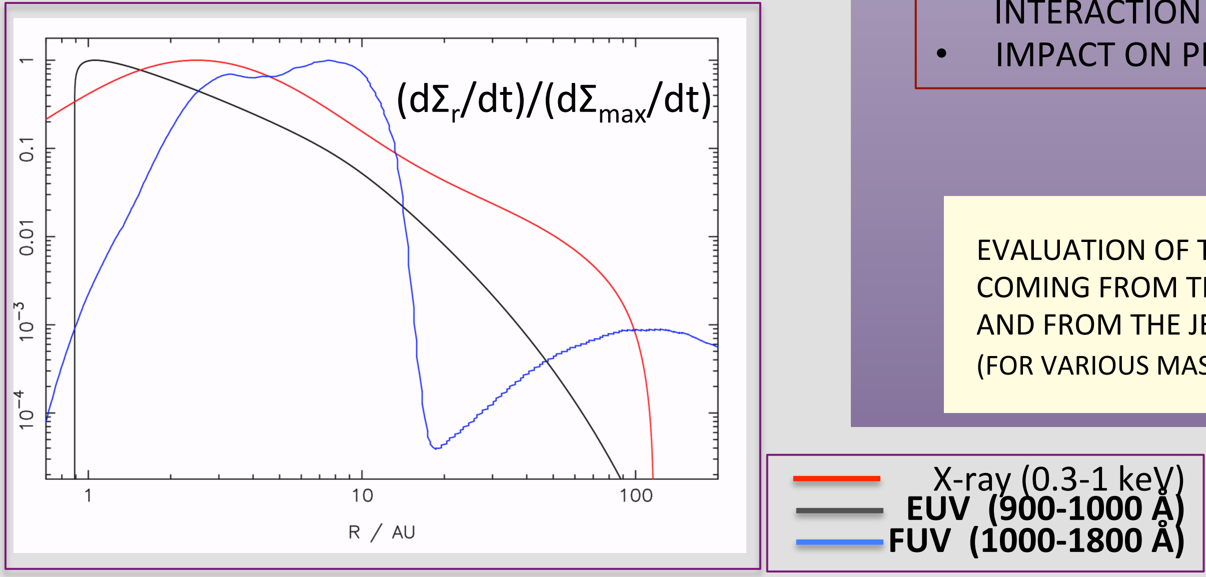
Ana I Gómez de Castro/Universidad Complutense, Spain

THE GAS IN THE DISK ABSORBS THE STELLAR RADIATION AND GAINS ENOUGH KINETIC ENERGY TO ESCAPE FROM THE DISK ATMOSPHERE.

THE MAIN COMPONENT OF THE PROTOPLANETARY DISK IS H_2 THAT ABSORBS EFFICIENTLY Lyα RADIATION; 80% OF THE FUV RADIATION FROM TTSs IS EMITTED IN Lyα

STATE OF THE ART:

IMPACT OF THE VARIOUS COMPONENTS OF THE **STELLAR** RADIATION FIELD ON DISK EVOLUTION

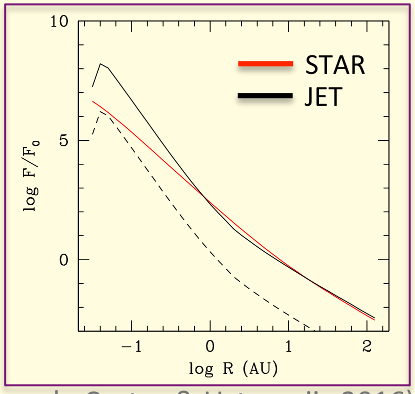


(from Alexander et al. 2014)

TO BE INVESTIGATED:

- LOCATION & CHARACTERISTICS OF THE SOURCES OF ENERGY IRRADIATING THE DISK
- STRUCTURE OF THE INNER REGION OF DISK AND ITS INTERACTION WITH THE STELLAR MAGNETOSPHERE
- IMPACT ON PLANET FORMATION

EVALUATION OF THE Lyα FLUX COMING FROM THE STAR AND FROM THE JET (FOR VARIOUS MASS LOSS RATES)



(from Gómez de Castro & Ustamujic 2016)

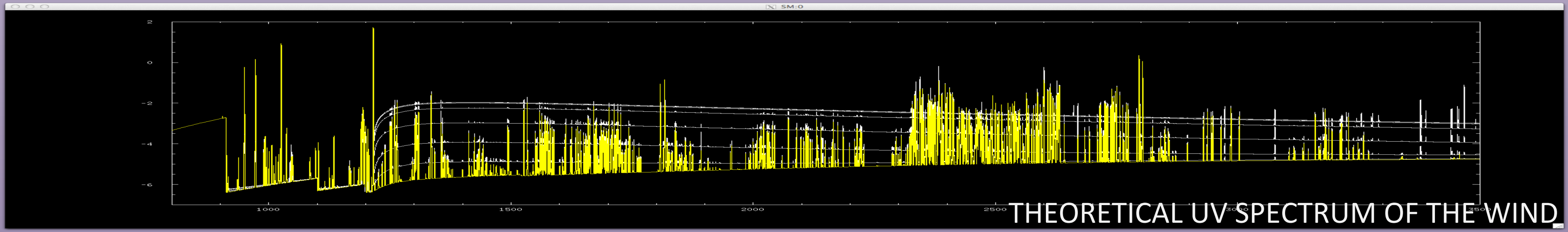
OBSERVABLES

BASE OF THE JET AND ITS RADIATION BUDGET (SiIII], CIII], MgII[uv1], CII], SiII]…
(Gómez de Castro & Verdugo 2001, Gómez de Castro & Verdugo 2005, López-Martínez & Gómez de Castro 2014)

ACCRETION SHOCKS AND ITS RADIATION BUDGET (HeII, CIV, NV, SiIII], CIII], OIII]…)
(Gómez de Castro & Lamzin 1999; Ingleby et al. 2011, 2013; Ardila et al. 2015; Gómez de Castro 2015)

MOLECULAR GAS COMPONENT IN THE INNER DISK (Herczeg et al. 2002, 2006, France et al. 2012; Schindhem et al. 2012)

ATOMIC COMPOUNDS (GAS) IN THE DISK and ABUNDANCES and GRAIN COAGULATION



FEASIBLE WITH AN EFFICIENT 4-6 M TELESCOPE

INSTRUMENTATION REQUIREMENTS

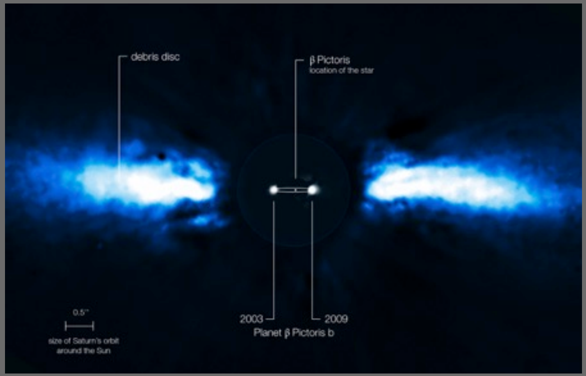
MID DISPERSION (25,000) SPECTROSCOPY WITH SIMULTANEOUS COVERAGE OF THE 900-3200 Å RANGE

MONITORING CAPABILITIES (HIGH EARTH ORBIT OF FURTHER)

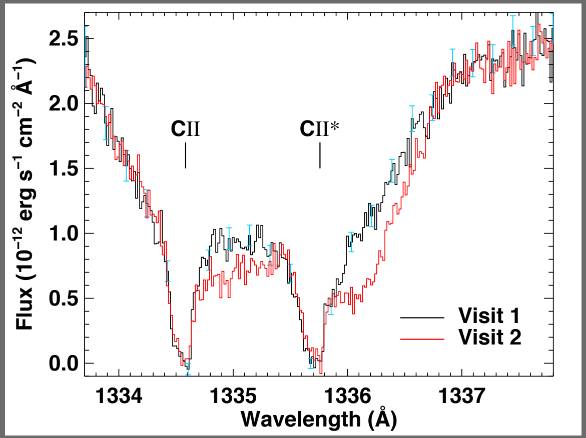
HIGH DISPERSION SPECTROSCOPY (>60,000) IN THE 1250-1700 Å RANGE AND IN THE 2300-3100 Å RANGE TO STUDY THE GAS KINEMATICS IN FEW YOUNG PLANETARY DISKS

Composition of extrasolar planetesimals

- Gas in debris disks reveals bulk composition of comets & asteroids
  - In two well-studied cases (Beta Pic and 49 Cet), gas looks strangely carbon-rich relative to metals (Roberge et al. 2006, Roberge et al. 2014)
- Why only two systems studied so far?
  - Optically thin gas is primarily atomic. Need FUV spectroscopy to access strong absorption lines of many elements
  - HST FUV absorption spectroscopy only possible for disks around UV-bright early A stars. Need more sensitivity to study later types
- Transits of star-grazing comets found in handful of young debris disks. Need FUV spectroscopy to probe composition



Beta Pic debris disk
Lagrange et al. (2010)



Star-grazing comet transit in 49 Cet
Miles, Roberge, & Welsh, submitted

Observation requirements

- UV absorption spectroscopy
  - FUV bandpass most important
  - High spectral resolution to separate circumstellar from interstellar absorption features
  - Spatially resolved spectroscopy not required

Parameter	Values
Wavelength	1300 A to 3000 A
Spectral resolution	R ~ 100,000
Sensitivity	TBD. A lot more than HST

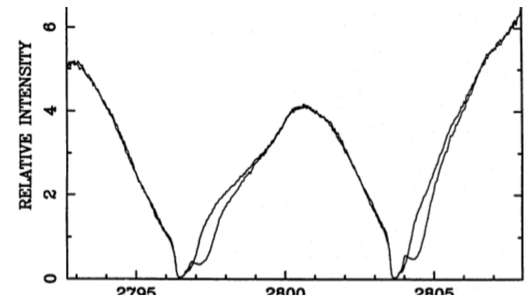
Transiting Exocomets at the Epoch of Terrestrial Planet Formation

C.A. Grady

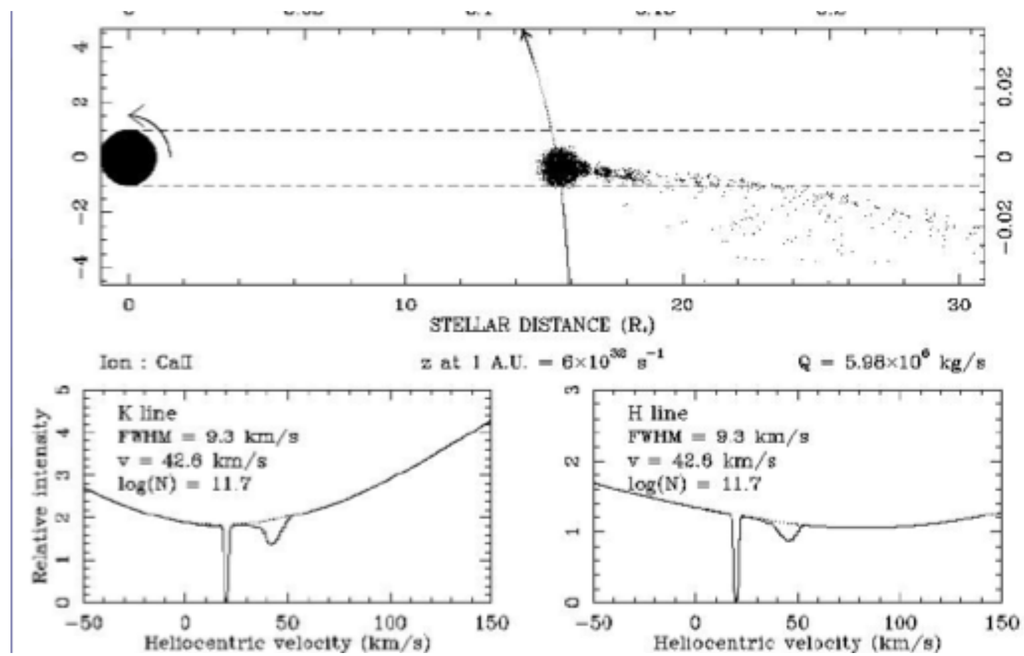
Eureka Scientific & GSFC

Time series studies of UV absorption features in Beta Pic

- Seen in wide range of atomic ions of abundant elements
- Interpreted as the comae of star-grazing bodies
- Carbon rich compared to surviving solar system bodies
- Parent bodies come from 2 families – probe of structure in warm debris belt
- Existence of beta Pic b predicted from these



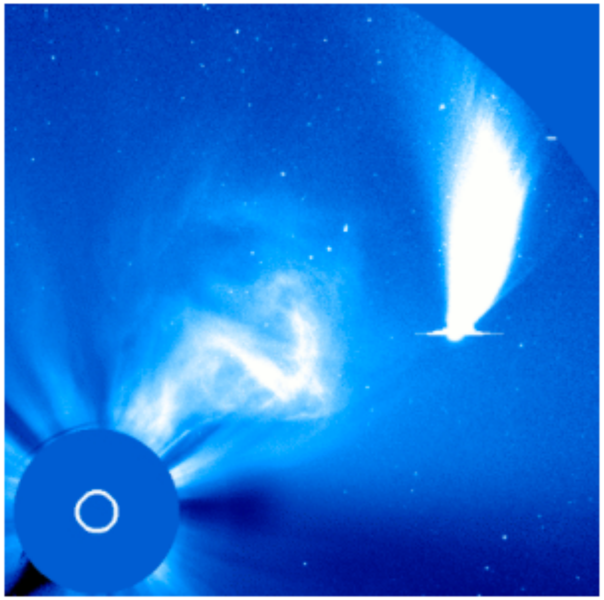
Mg II profiles Vidal-Madjar et al 1994



Simulations Beust et al. 2000

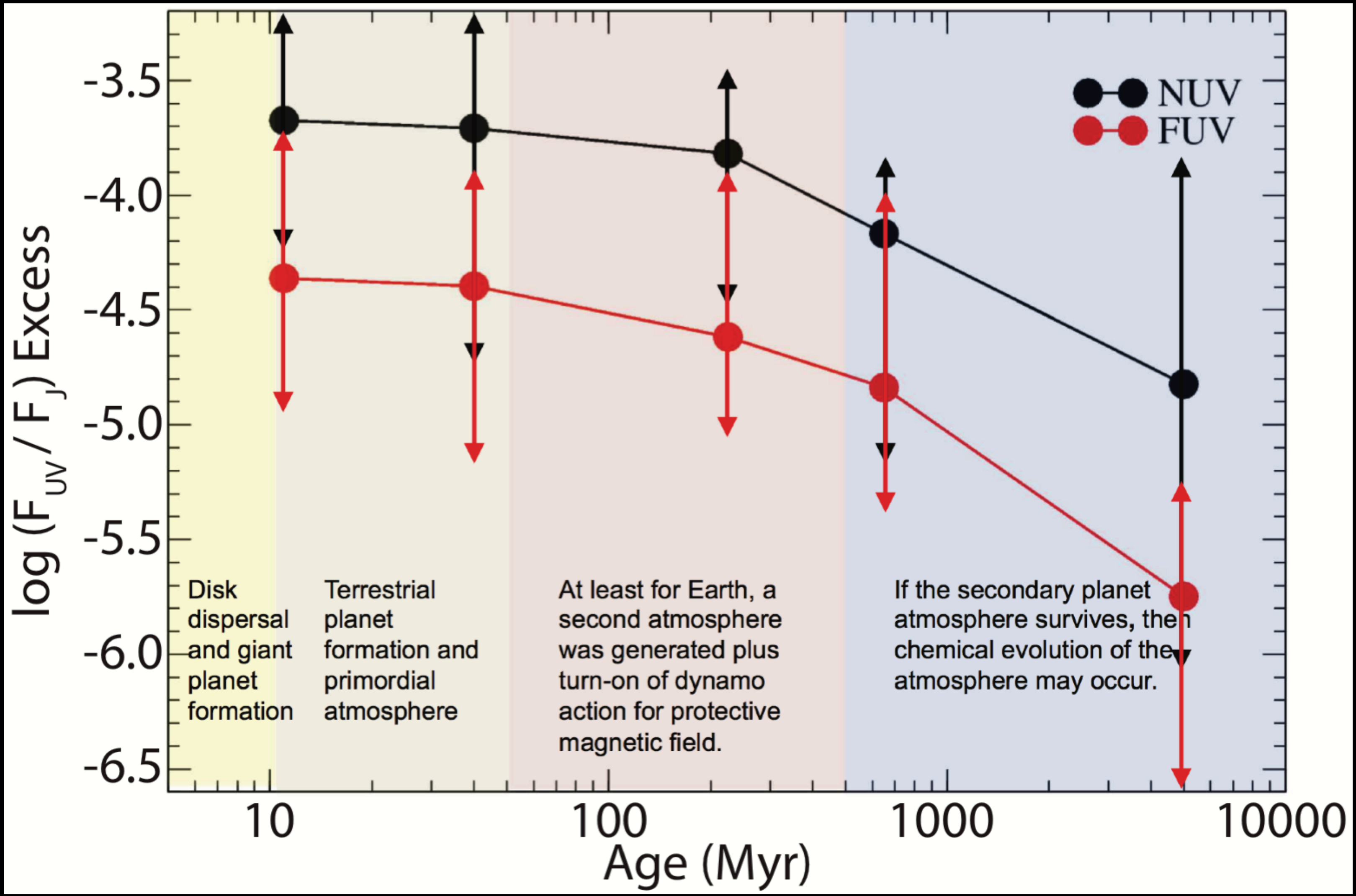
Beta Pic is not the only system with exocomet activity

- Similar activity now known in other, young systems, all with non-solar system abundance patterns (Roberge et al. 2014; Kiefer et al. 2014; Grady et al. 2016 (in prep).
- Access to the FUV, near Lyman alpha and O I probes water ice dissociation products and would be facilitated for systems with host star spectral types later than A7.
- Also offers a probe of stellar activity near the transition from stellar radiative to convective outer envelopes, analogous to the view provided by SOHO LASCO of sun-grazing exocomets in our solar system
- HST can do a few of these systems but NEED BIGGER telescope and more efficient UV spectrographs
- Synergy with high contrast imaging of disks
- Opportunity to see volatile delivery to terrestrial planet region which can make terrestrial planets life-bearing?



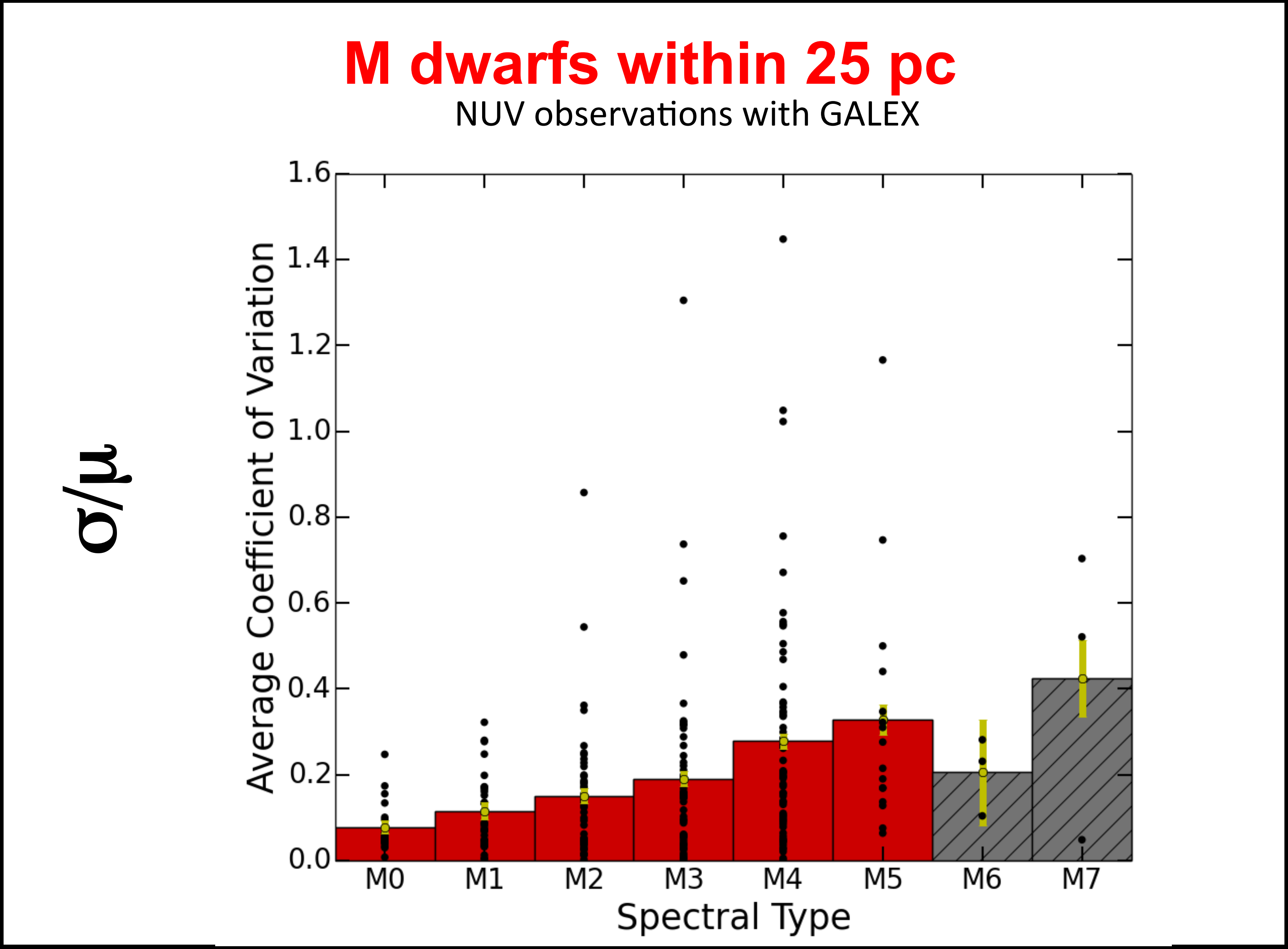
Comet C/2002 V1 (NEAT) in LASCO C3

UV Evolution over Planet Formation & Evolution Timescales



Shkolnik & Barman 2014

UV Variability Trends with Spectral Type



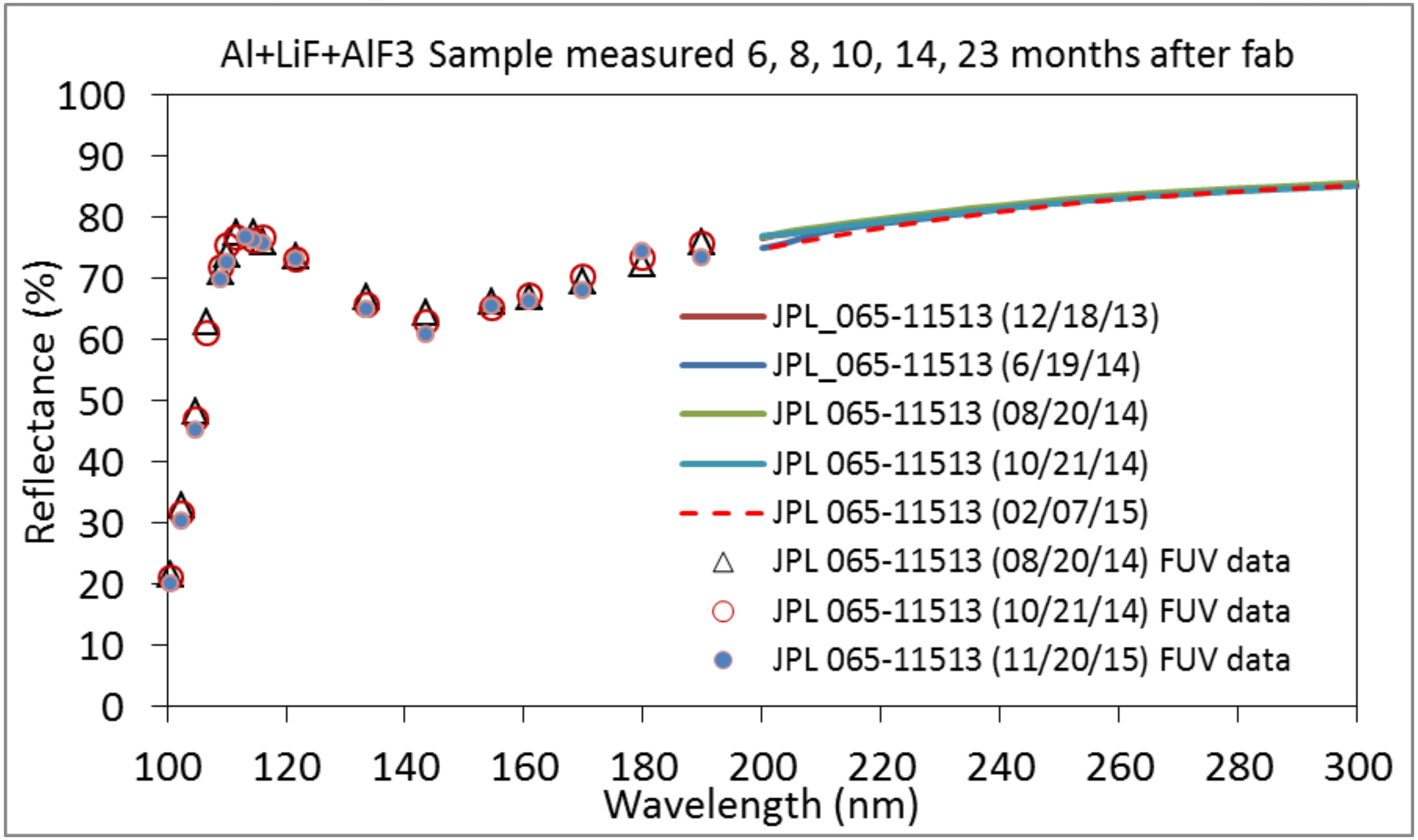
Miles & Shkolnik (in prep.)

High Throughput UV Coatings

- Conventional Thermal Evaporation (CTE) appears to be stable and using combinations of Fluorides able to deliver reflectivities above 60% down to 100nm
- Atomic Layer Deposition (ALD) is a chemical plasma-based process that can be done either hot or cold and deposits atomic mono-layers with great uniformity and higher optical throughput in the FUV than CTE
- Choice of the appropriate protective overcoat material, its oxygen content and layer thickness can produce remarkable increases in FUV reflectivity – and can provide performance below 100nm
- That said, the smaller the number of reflections, the better
- The effect of these new coating technologies on polarization has not been studied, but needs to be – control over specific refractive indices is critical and is possible – the angle of the reflection appears to be a critical factor – maximum angle of incidence of 19° (workers include Shaklan and Breckinridge)

Al+LiF+AlF_3 mirror aging performance

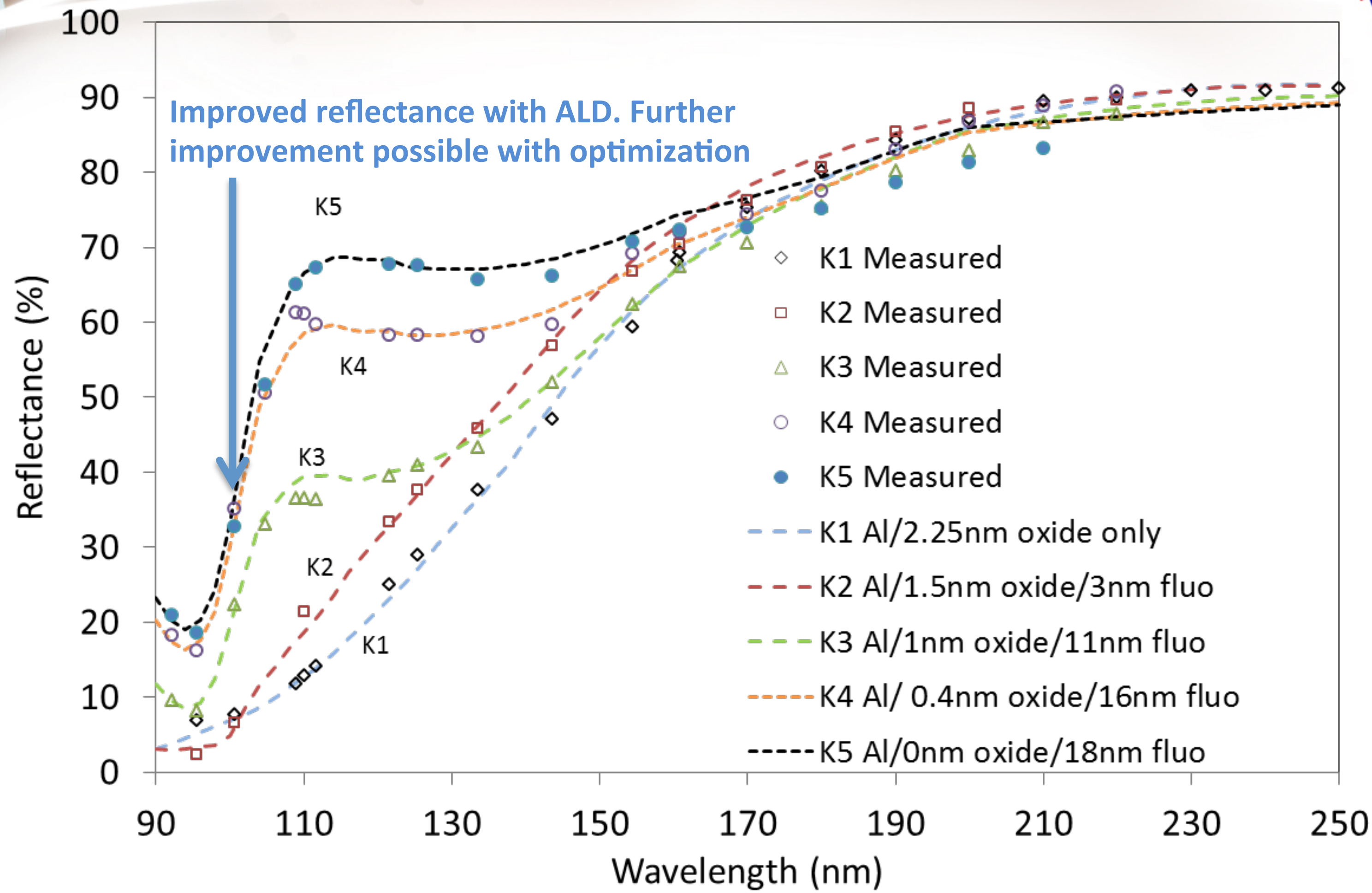
Conventional Thermal Evaporation



Measured reflectance of a tri-layer Al mirror sample measured 6, 8, 10, 14 and 23 months after fabrication showing excellent stability.

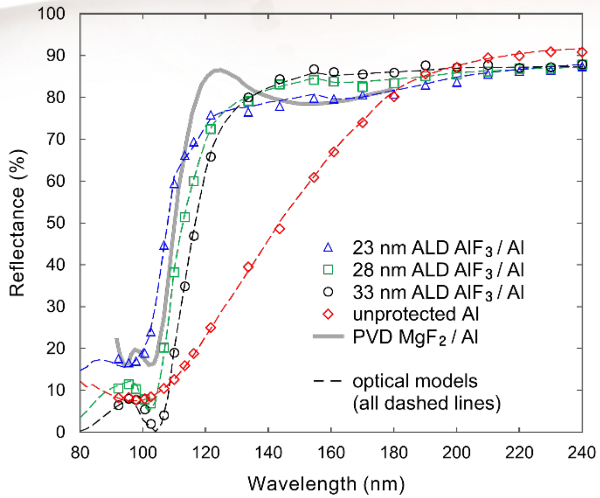
FUV reflectance has room for improvement which could be achieved with ALD processes

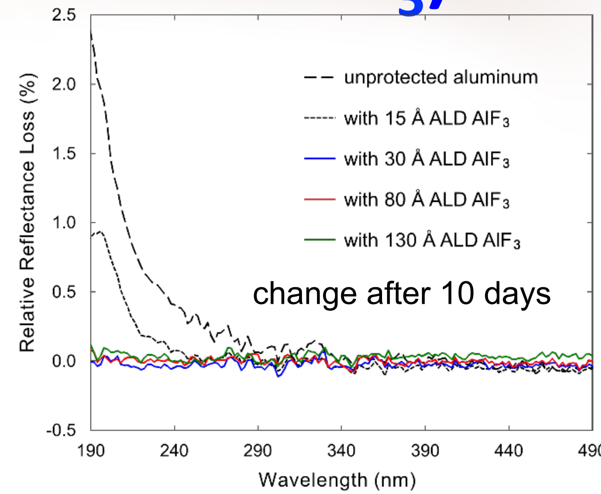
FUV performance of ALD AlF_3/Al mirror samples



Model fits (dotted lines) of measured (symbols) FUV reflectance of unprotected (sample K1) and AlF_3 protected samples (K2 to K5) in this early simple one layer study. Further optimization is underway.

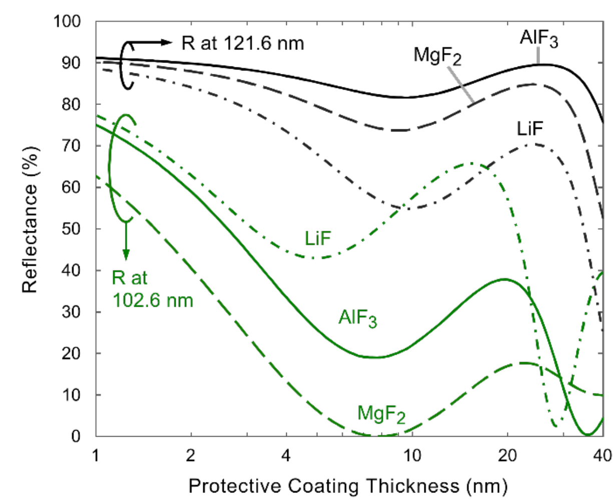
Mirror results (focus on AlF_3)





- **ALD MgF_2 processes have been developed and LiF ALD process development is underway.**

- **Al mirrors protected with ALD AlF_3 are competitive with state-of-the-art PVD MgF_2 protected mirrors (similar to HST coating) despite non-idealities in metal evaporation and exposure to air**
  - Can extend short wavelength cutoff over MgF_2
  - This will improve with removal of interfacial oxide
- **Ultrathin ALD ALF_3 have also shown good environmental stability for layers as thin as 3 nm**
  - Has potential to greatly improve performance near 100 nm compared to conventional thick coatings (~25 nm)
  - Theoretical calculations on the right based on our FUV optical model of ALD AlF_3 thin films



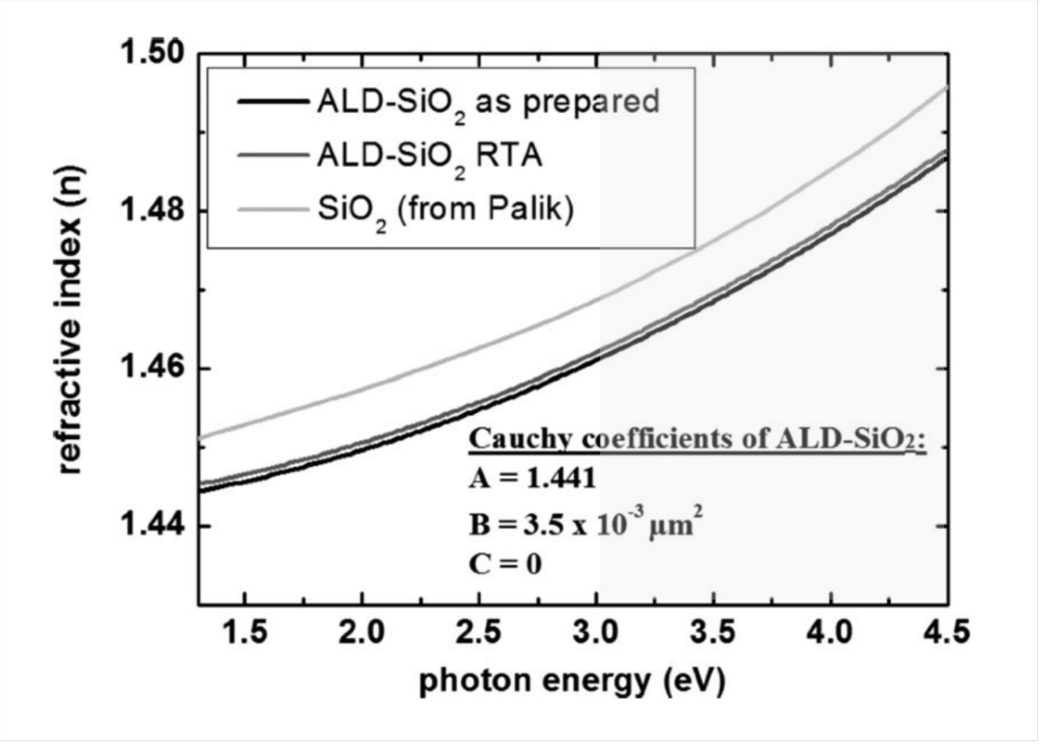
Throughput of a 3 mirror telescope system: with 60% R from each optic at 100nm, throughput will be 0.6^3 = 0.22

PLASMA-ENHANCED ATOMIC LAYER DEPOSITION

Refractive Indexes

material	thickness (nm)	refractive index
Cauchy model		
Al_2O_3	109 ± 3	**1.63 ± 0.02**
SiO_2*	--	**1.45***
Tauc–Lorentz model		
Er_2O_3	7.1 ± 0.3	1.78 ± 0.02
HfO_2	11.6 ± 0.4	2.00 ± 0.02
Ta_2O_5	56.4 ± 0.8	2.23 ± 0.02
Ti_2O_2	33.2 ± 0.6	2.42 ± 0.02
Ta_3N_5	48.5 ± 0.7	2.68 ± 0.02
Drude–Lorentz model		
TiN	11.7 ± 0.5	1.30 ± 0.02
$TaN_{x,x<1}$	33.2 ± 0.5	2.70 ± 0.02

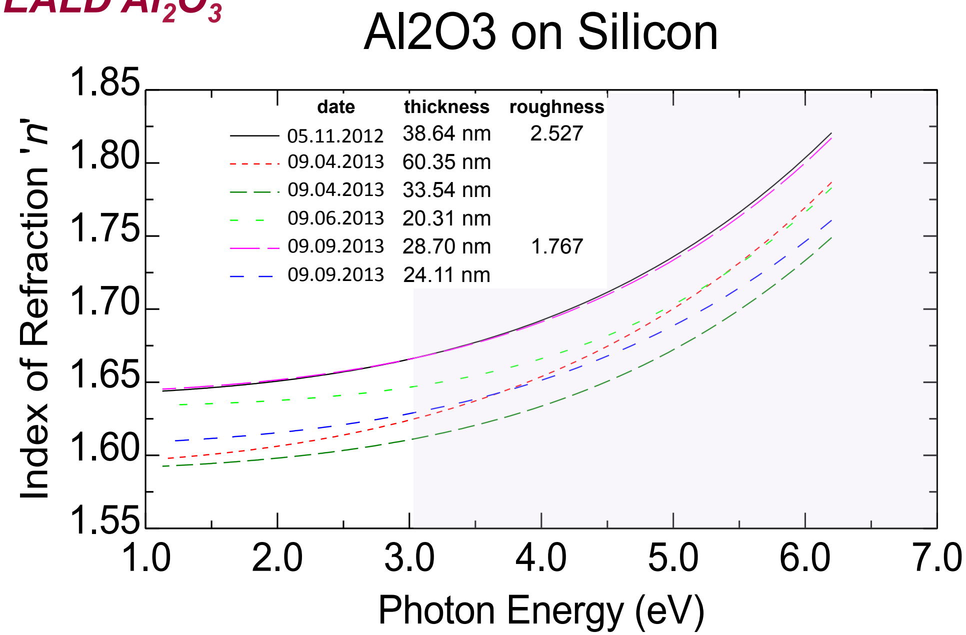
E. Langereis, S. B. S. Heil, H. C. M. Knoops, W. Keuning, M. C. M. van de Sanden and W. M. M. Kessels, *J. Phys. D: Appl. Phys.* **42,** 073001 (2009).

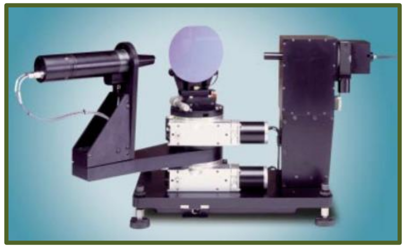


D. Hiller, R. Zierold, J. Bachmann, M. Alexe, Y. Yang, J. W. Gerlach, A. Stesmans, M. Jivanescu, U. Müller, J. Vogt, H. Hilmer, P. Löper, M. Künle, F Munnik, K. Nielsch, and M. Zacharias, *J. Appl. Phys.* **107**, 064314 (2010).

PLASMA-ENHANCED ATOMIC LAYER DEPOSITION

Refractive Index of PEALD Al_2O_3





PEALD	25 ºC	200 ºC
growth per cycle	1.5 Å/cycle	1.5 Å/cycle
Al atoms per cycle	3.9 ± 0.3 at.nm^{-2}cycle^{-1}	5.3 ± 0.3 at.nm^{-2}cycle^{-1}
mass density	2.69 ± 0.04 g/cm^3	2.96 ± 0.02 g/cm^3
O:Al ratio	2.1 ± 0.1	1.6 ± 0.1
refractive index (630 nm)	**1.61 ± 0.01**	**1.63 ± 0.02**
band gap	-	6.7 ± 0.1 eV
electron affinity	-	2.2 ± 0.1 eV

J. Yang, B. S. Eller, M. Kaur, and R. J. Nemanich, *J. Vac. Sci. Technol. A* **32**, 021514 (2014).

Capabilities Summary

Investigator	Area	Mode	Passband	Δλ	FoV	R	Mag Limit
McCandliss	Reionization	MOS	91-350nm	1nm	4 arcmin	200	
Finkelstein, Teplitz	Reionization	Imaging	120-360nm				M_{AB}~30
Roederer	IGM	Spectroscopy	170-310nm			15k-60k	
Windhorst	SMBH	Imaging	225-435nm				<32 mag/”
Tripp	CGM	Spectroscopy	115-200nm			High	
Barstow	Environment	Spect.+Imaging	100-300nm			>100k	
Herrero	Massive Stars	Spectroscopy	120-180nm			10k	mv>23
Rampazzo	ETGs	MOS	FUV+NUV		4 arcmin	5000	
Hartigan	Gas+Disks	Spect.+Imaging	100-140nm				
Ardila	Host stars + disks	Spect.+Coron.	100-300nm			10k	
Gomez	PP Disks	Spectroscopy	90-320nm			25k	
Roberge, Grady	Exocomets	Spectroscopy	130-300nm			100k	

Additional Papers to Read

- McCandliss et al, 2009, white paper http://adsabs.harvard.edu/cgi-bin/nph-data_query?bibcode=2009astro2010S.196M&link_type=ARTICLE&db_key=AST&high=
- McCandliss et al 2008, http://arxiv.org/pdf/0807.2295v1
- McCandliss et al 2012, http://arxiv.org/pdf/1209.3320v1
- Som et al 2015, http://arxiv.org/pdf/1502.01989v3
- Rugheimer et al 2015, http://arxiv.org/pdf/1506.07202v1
- Finkelstein et al 2015a, http://arxiv.org/pdf/1410.5439v2
- Finkelstein et al 2015c, http://arxiv.org/pdf/1504.00005v2
- Aoki et al 2006, http://arxiv.org/pdf/astro-ph/0509206v1
- Roberge et al 2014, http://arxiv.org/pdf/1410.6542v1
- Kiefer et al 2014, http://www.nature.com/nature/journal/v514/n7523/full/nature13849.html
- Shkolnik & Barman 2014, http://arxiv.org/pdf/1407.1344v1