The *Sub Lyman-alpha Explorer*: Mapping the Most Massive Stars and their Environmental Feedback in the Low-redshift Universe

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Abstract –

We present the scientific and mission overview of a Small Explorer (SMEX) mission concept designed to map the spatial distribution and luminosity function of the most massive stars in the low-redshift universe. The *Sub Lyman-alpha Explorer* (*SubLymE*) provides ~ 2 arcsecond resolution imaging in the Lyman ultraviolet (LUV: 100 - 120 nm) bandpass, the most sensitive portion of the electromagnetic spectrum for thermal emission from hot stars and star clusters. LUV luminosities allow us to break existing color degeneracies in star-forming populations to identify the most massive stellar components (O star-dominated, age < 10 Myr). Combining SubLymE LUV imaging with existing galaxy surveys at UV, optical, and IR wavelengths, we will characterize the high-mass end of the stellar mass distribution and compare the spatial distribution of O stars with detailed maps of metallicity, dust content, H II regions diagnostics, and radio CO and HI 21 cm maps that trace the fuel for star-formation; determining the influence of O stars on the mass-chemical-energy cycle of star-forming galaxies. *SubLymE*'s Local Galaxy Survey will map well-studied nearby galaxies (d < 30 Mpc; from SINGS, KINGFISH, LEGUS, etc), provide LUV imaging of the 11 Mpc volume limited 11 HUGS survey, Galactic star-formation regions, and the Magellanic Clouds.

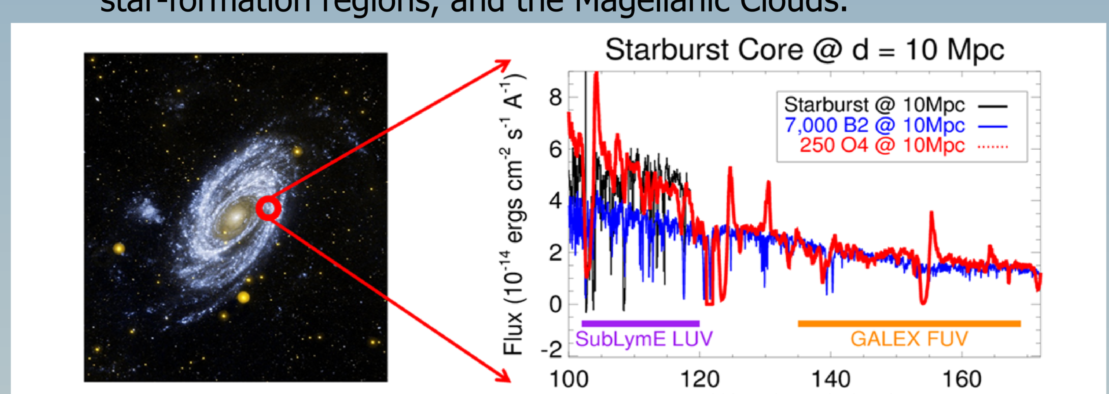


Fig 1 Left: GALEX FUV (blue) + NUV (yellow) image of nearby star-forming galaxy M81. Right: A hypothetical stellar decomposition of the flux from an individual star-forming cluster, comparing a stellar population of ~250 early O stars (red curve) and a stellar population of ~7,000 B stars (blue curve). While these two stellar populations have a very similar flux output in the GALEX FUV band, they are well-separated in the SubLymE LUV. A FUSE LUV starburst galaxy spectrum is shown for comparison (black curve). The environmental impact of an O star-dominated cluster from its ionizing radiation and wind/supernova kinematic input is much greater than the comparable B-star dominated cluster; SubLymE enables us to distinguish these clusters and understand their relation to the local physical and chemical properties of their host galaxies.

SubLymE Instrument –

Light is collected with a 0.5 meter diameter afocal telescope (Gregorian concentrator), which includes a 7′ X 7′ square field stop at the focus of the primary mirror. The collimated beam passes to a flat, uniform line density grating. The dispersed light is then reconstructed by a second grating, parallel to the first, with the same line density. The technique is referred to as "crossed grating reconstructive imaging" (Green & France 2014). Each wavelength/field point creates a footprint on the second grating; the footprint of Lyα is completely blocked. The rays that are transmitted are imaged by a camera mirror onto a 40 mm round micro-channel plate detector. By choosing where to locate the object in the FOV (via offset pointing), a specific bandpass can be selected with a long wavelength cutoff. Alternatively, by scanning an object across the FOV, color differences can be formed if there is sufficient S/N.

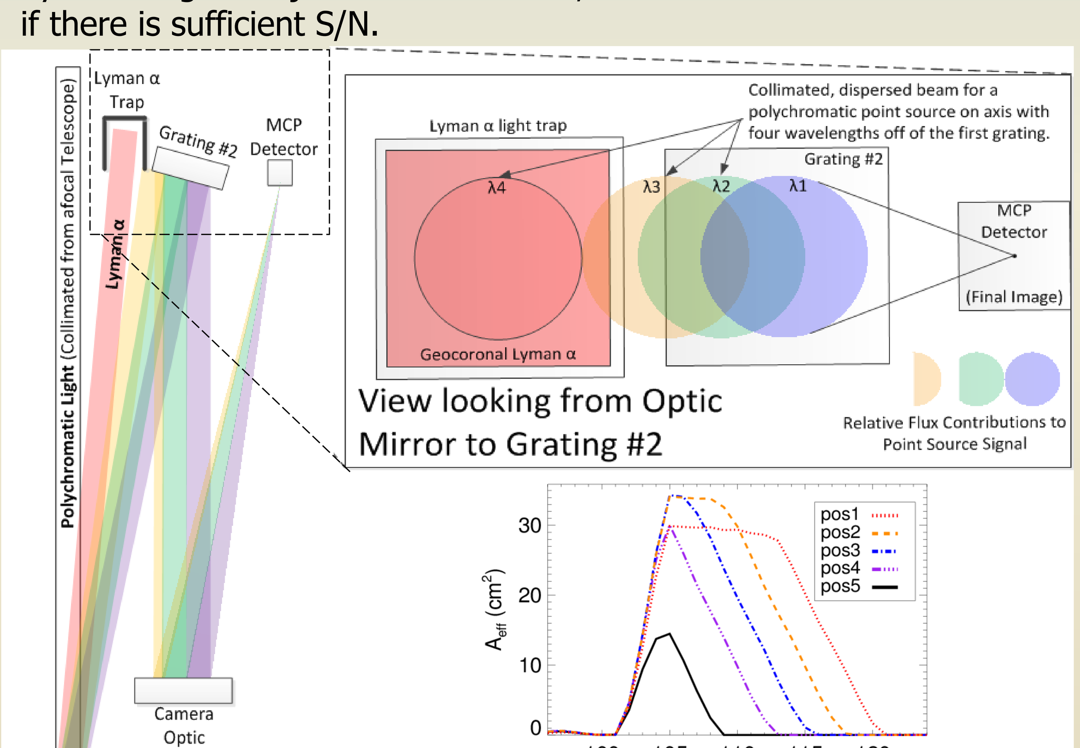
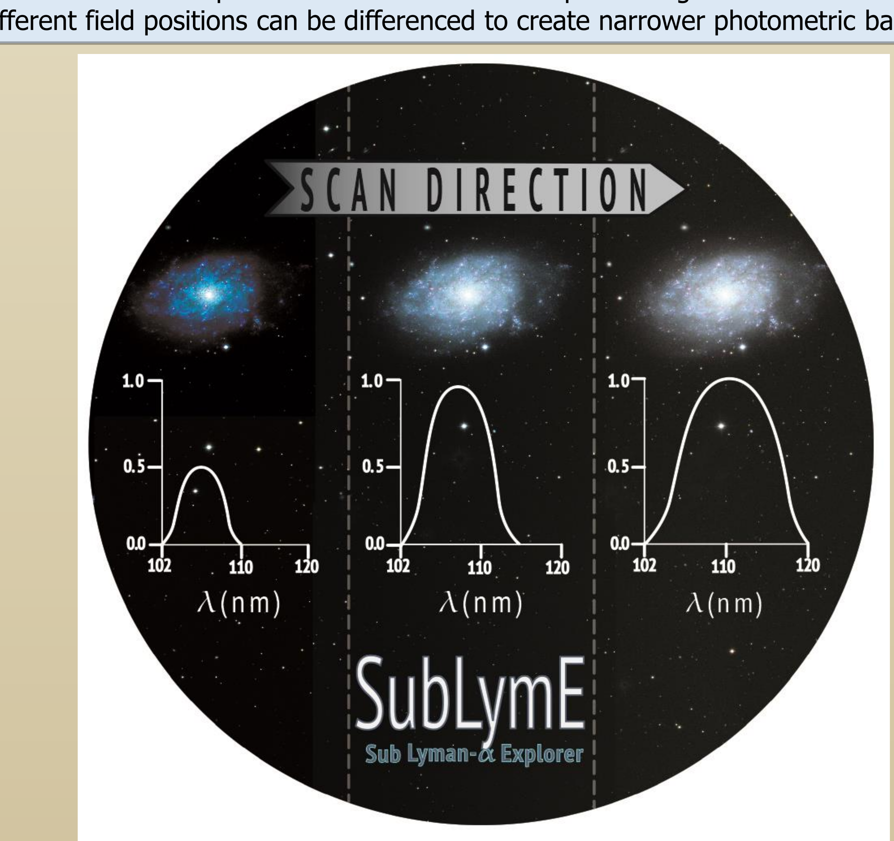


Fig 2 – *Above:* Schematic representation of the *SubLymE* optical system. Panchromatic light is collected by the afocal Gregorian telescope. Wavelengths are discriminated, and geocoronal Lyα is removed, by the crossed-grating design. The schematic shows the optical layout and the field-dependent effective area of the system. *Below:* SubLymE uses a scanning observing mode for most science observations to sample the entire 102 - 120 nm spectral region. Observations at different field positions can be differenced to create narrower photometric bands.



Mission Overview and LUV Imaging Surveys -

SubLymE is proposed in response to NASA's 2014 SMEX AO, as a general purpose observatory opening a new imaging bandpass for astronomical investigations. *SubLymE*'s baseline science program addresses the following key questions in astronomy, as identified by the Astro2010 Decadal Survey and the 2013 NASA Astrophysics Roadmap:

1) How do galaxies inject ionizing radiation to the intergalactic medium?
2) What controls the mass, energy and chemical flows within galaxies and into their circumgalactic media?
3) How do circumstellar disks evolve and form planetary systems?
4) What is the ultraviolet radiation environment of low-mass exo-planet host stars?

Sublyme Survey	Baseline (Predicted) Targets	Baseline (Predicted) Orbit Allocation	Science Traceability Matrix (STM)
Escape Fraction Survey	75 (125) low-redshift (0.22 < z < 0.50) star-forming galaxies	1500 (2500)	1.1 1.2 1.3
Local Galaxy Survey	250 (450) galaxies at distances of ≤ 30Mpc: 1) Legacy galaxies, 2) 10 Mpc local volume survey	1200 (1800)	2.1
SNR and Magellanic Cloud Survey	Cygnus, Vela, Magellanic Cloud superbubbles and star-forming regions	600 (900)	2.3 2.2
Nearby Star-forming Region Survey	Targeted regions or complete scans of Orion, Chameleon, and Carina	800 (1100)	2.2 3
Exoplanet Host Star Survey	All G, K, and M exoplanet host stars within 30 pc	300 (450)	4

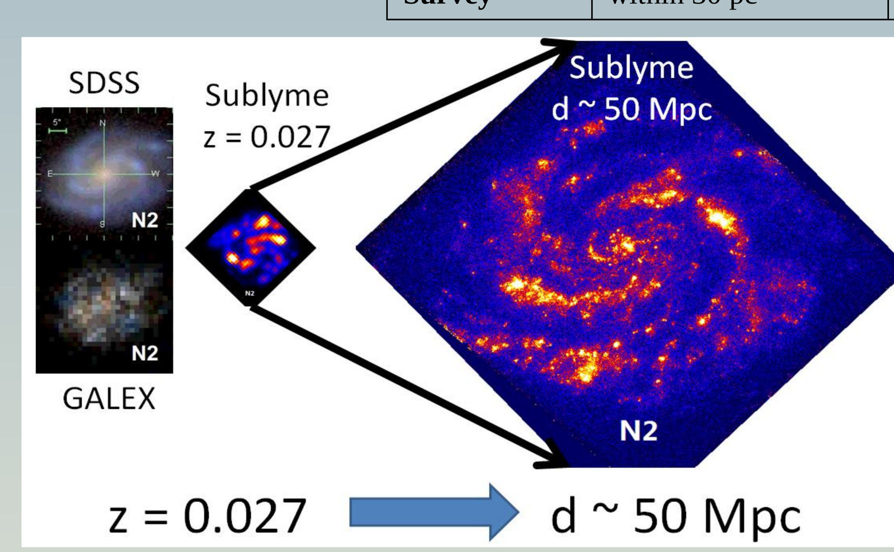


Fig 3 – Simulated image of low-z Lyman Break Galaxy Analog at z = 0.027, compared with SDSS and GALEX. At right, this same galaxy moved to d ~ 50 Mpc, the outer extent of the SubLymE Nearby Galaxy Survey. (original image from ACS/SBC 125nm; Fleming et al. 2014)

SubLymE Local Galaxy Survey -

The SubLymE Local Galaxy Survey focuses on galaxies out to distances d ≤ 30 Mpc. The first focus is detailed LUV mapping of the best-studied galaxies in the nearby universe, "Legacy Galaxies" (SINGS, KINGFISH, LEGUS, etc). The second focus is a volume-limited survey of star formation in the nearby universe, out to d ~ 10 Mpc, galaxies in the UV-to-IR Local Volume Legacy survey (Kennicutt et al. 2008). SubLymE provides the first maps of Galactic SNRs and the MCs at LUV wavelengths to study the distribution of 300,000K gas (O VI) in remnants and superbubbles.

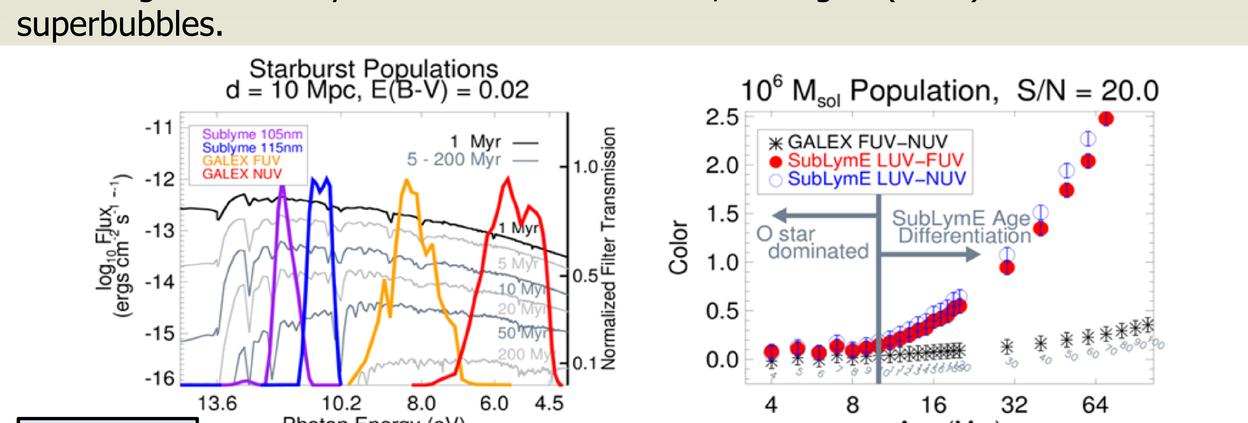


Fig 4: *SubLymE will provide the first LUV (100 – 120 nm) images, in two colors (as shown in purple and blue in the left figure), of low-z star-forming galaxies. Left: Several model stellar populations from a hypothetical star forming region (Leitherer et al. 1999; 2010), where the age of each model stellar population is displayed in Myr. These population models demonstrate the break in GALEX FUV-NUV colors vs. LUV-FUV and LUV-NUV colors between 8 – 10 Myr (right panel), when the O star populations begin to die out. We display the ultraviolet colors as a function of age for an instantaneous starburst (Salpeter IMF, 10^6 M_{solar}, Z = 0.04). Continuous burst models show flatter ultraviolet color distributions and different color-magnitude behavior, making the LUV colors a powerful discriminator for instantaneous vs. continuous models of star-formation.*

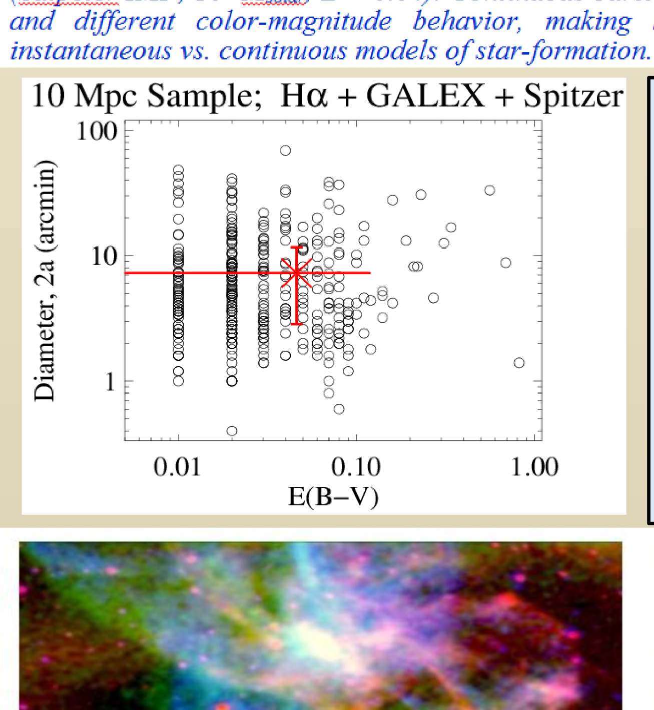


Fig 5 – *Left:* Distribution of angular size and reddening from the 11HUGS volume-limited sample (Lee et al. 2011). 60% of the sources are smaller than the *SubLymE* FOV. Larger galaxies will be observed in multiple scans. **Signal-to-noise** in two photometric bands (102-110 nm and 110 - 120nm) will be between **10 - 30 per resolution element** (2″ PSF) for hot stellar clusters in the *SubLymE* Nearby Galaxy Survey. *Below:* *SubLymE* will also carry out a survey of Galactic and MC supernova remnants and star-forming regions in narrow-band O VI.

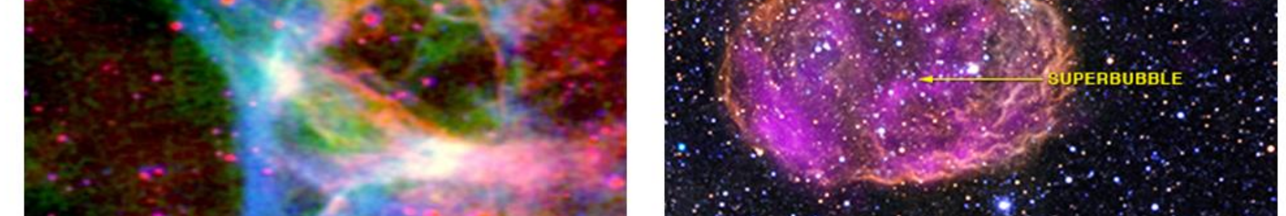
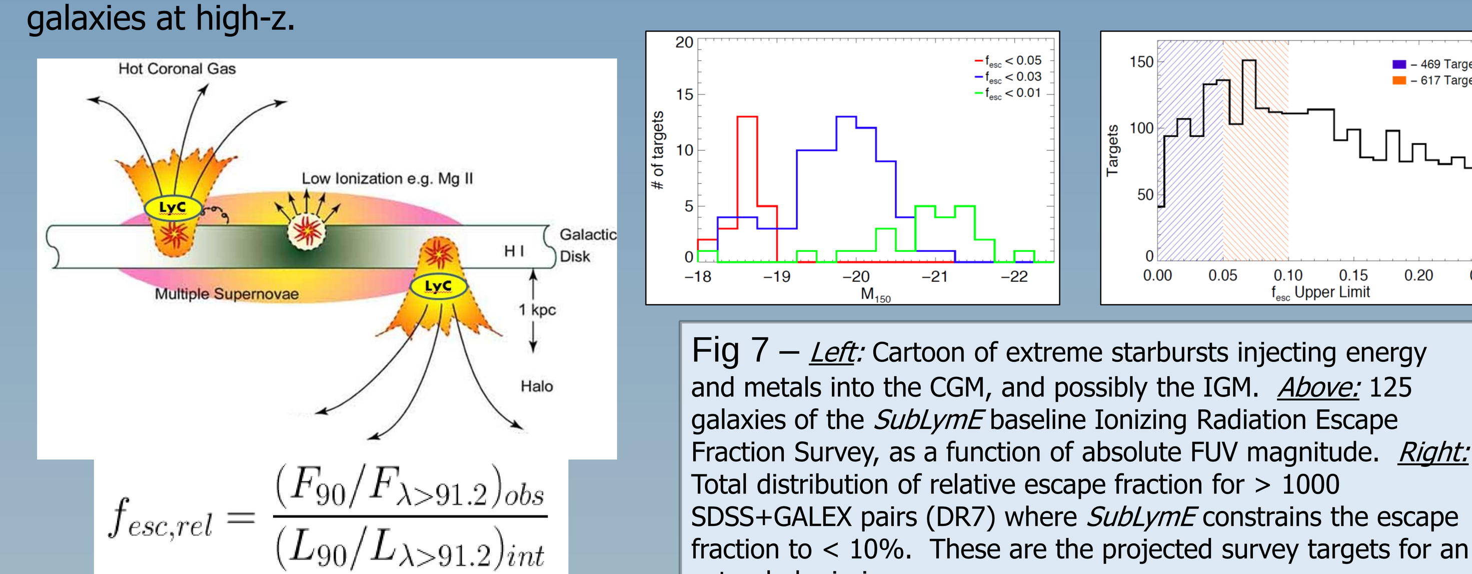


Fig 6 *Left: A 6' square region on the eastern limb of the Cygnus Loop, shown in Hα (red), UIT B5 filter (primarily C IV 155nm, green) and in [Ne V] 342.5 nm (blue). The varying spatial distributions of each ion show the progression of the primary shock wave through an inhomogeneous ISM (travelling from right to left in this picture). HUT and FUSE spectra at isolated locations show strong O VI emission, but its overall spatial distribution is unknown. Right: Superbubble DEM L50 in the LMC, with SNR N186D on the northern limb. Magenta is Chandra 0.35 – 0.9 keV X-ray emission, orange is MCELS Hα emission. Field of view is ~12' in the vertical extent. See Jaskot et al. 2011.*

Ionizing Radiation Escape from low-z Star-Forming Galaxies

SubLymE carries out the first uniform survey of ionizing radiation escape in the low-z universe to directly measure small escape fractions from individual galaxies (f_{esc} > 3% for the mean survey galaxy), to characterize the fraction of "high-escape" (f_{esc} > 10%) galaxies, and to measure the ensemble average escape fraction from star-forming galaxies in the z < 0.5 universe. The brightest galaxies (~30 sources) will be observed to a depth that allows precise measurements of the escape fraction (3-σ escape faction limits of f_{esc} ≤ 1%, detections at f_{esc} > 1 %). The main body of the *SubLymE* Escape Fraction Survey targets (~75 sources, $M_{AB,150}$ ≈ -19.5 to -21.5) are probed down to f_{esc} > 3 % and a portion of the survey is dedicated to observations of star-forming dwarf galaxies (~20 sources, $M_{AB,150}$ > -19) to 3σ escape fraction measurements f_{esc} > 5 % in order to characterize the relative contribution of low-luminosity galaxies, those likely to be the best local analogs to dwarf galaxies at high-z.



$$f_{esc,rel} = \frac{(F_{90}/F_{\lambda>91.2})_{obs}}{(L_{90}/L_{\lambda>91.2})_{int}}$$

Fig 7 – *Left:* Cartoon of extreme starbursts injecting energy and metals into the CGM, and possibly the IGM. *Above:* 125 galaxies of the *SubLymE* baseline Ionizing Radiation Escape Fraction Survey, as a function of absolute FUV magnitude. *Right:* Total distribution of relative escape fraction for > 1000 SDSS+GALEX pairs (DR7) where *SubLymE* constrains the escape fraction to < 10%. These are the projected survey targets for an extended mission.

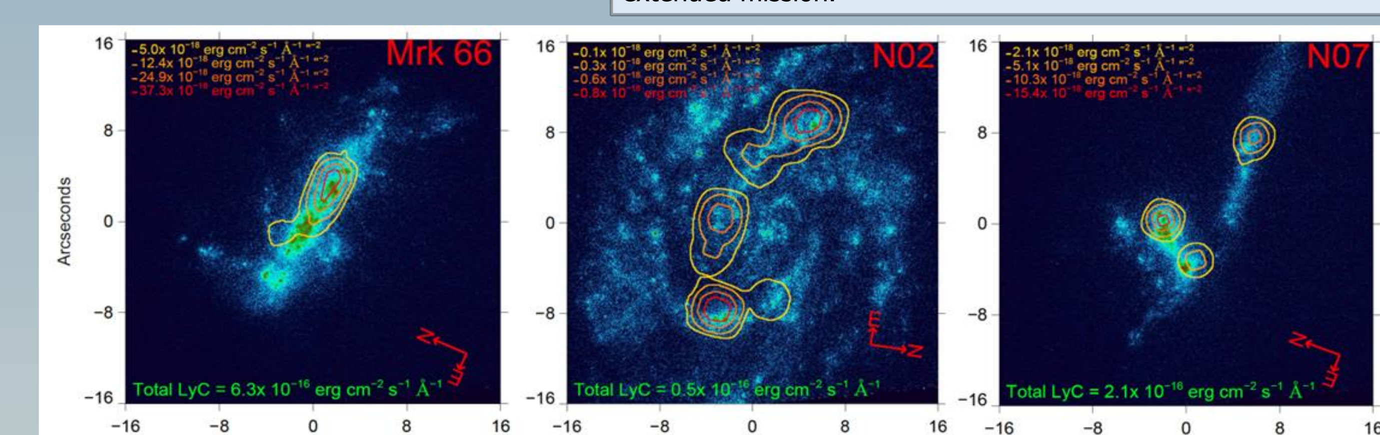


Fig 8 *Predicted Lyman continuum escape map (2″ resolution contours, the total LyC flux is the galaxy-integrated restframe 90 nm stellar flux) of low-z dwarf starburst galaxies overplotted on an FUV stellar continuum image (color map; Fleming et al. 2014). The predicted ionizing radiation escape locations are based on a combination of HST Lyman-α imaging and ground-based dust maps. SubLymE will provide the first maps of ionizing radiation escape from star-forming galaxies, enabling a better understanding of the physics governing the reionization of the Universe. This example shows that ionizing radiation escape is predicted for a variety of UV morphologies, from dwarf irregular galaxies (left) to spirals (center), to merging systems (right).*

Galactic Star-forming Region and Exoplanet Host Stars -

Mid-IR photometry and spectroscopy provide measures of the warm dust distribution inside of 20 AU. Sub-mm and radio wavelength disk tracers are mainly sensitive to gas and dust emission from the extended disk (r > 20 AU), while IR CO emission is typically sensitive to warm gas at r < 1 AU. However, the dipole-allowed LUV and FUV transition systems of H_2 are the most sensitive tracers of tenuous gas distributions (sensitive to disk surface densities Σ_{gas} < 10^{-6} g cm^{-2}) in low-mass protoplanetary disks, capable of probing trace amounts of gas in older disks where other gas tracers are no longer sensitive. The LUV fluorescent emission from H_2 probes the disk surface across the range of planet-forming radii (0.1 < r < 10 AU). *SubLymE* quantifies the characteristic timescale for gas disk dissipation by measuring the fraction of protostars in a given region with gas disks. Baseline target: Chameleon, Orion, Carina.

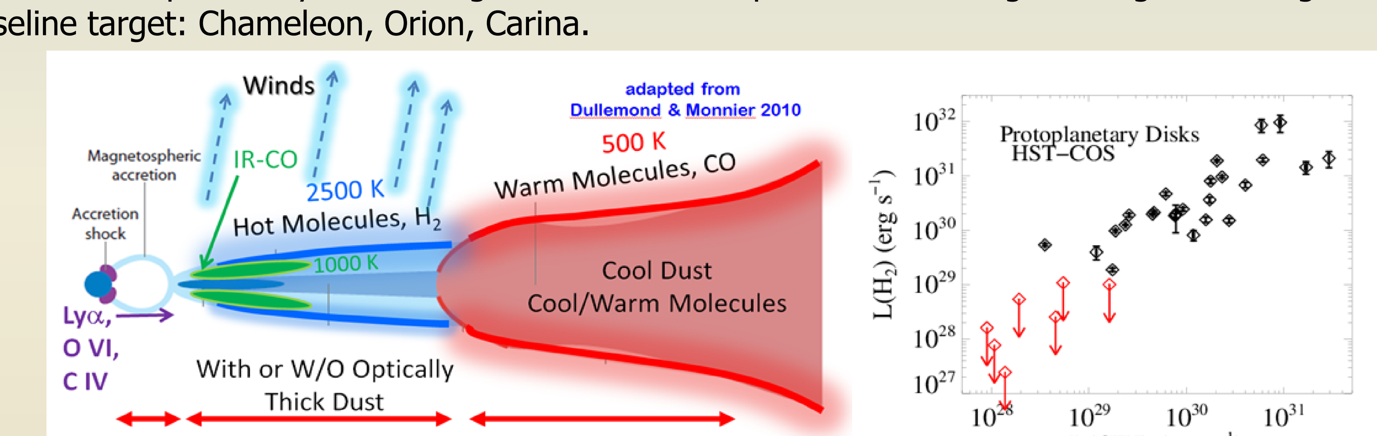


Fig 9 *(Left:) Schematic edge-on view of the inner, planet-forming region, around a Classical T Tauri Star. The gas-rich inner disk (in blue and green) is thought to feed magnetically channeled accretion onto the central star (blue loops). When the gas crashes into the region surrounding the stellar photosphere, high energy radiation is produced (Lyα, O VI, and C VI; shown in purple). Both the molecular disk and hot gas from the accretion region can be observed in the SubLymE bandpass, with O VI dominating the 100 – 110 nm region and photoexcited H_2 emission dominating the 110 – 120 nm spectral region (figure adapted from Dullemond & Monnier 2010). (Right:) Correlation between indirect (hot gas, C IV) and direct (H_2 fluorescence) tracers of disk gas from the HST-COS survey of CTTSs (adapted from France et al. 2012).*

The chemistry of molecules in the atmosphere of an Earth-like planet depends sensitively on the strength and shape of the UV irradiance of the host star. H_2O, CH_4, and CO_2 are most sensitive to LUV+FUV radiation (100 – 170 nm), the atmospheric oxygen chemistry is driven by a combination of LUV+FUV+NUV (100 – 320 nm) radiation. Observations of O VI emission provide both essential direct measurements of the LUV irradiance and a basis for estimating the EUV luminosity. *SubLymE* readily surveys all G, K, and M hosts at d < 30 pc is the Exoplanet Host Star Survey.

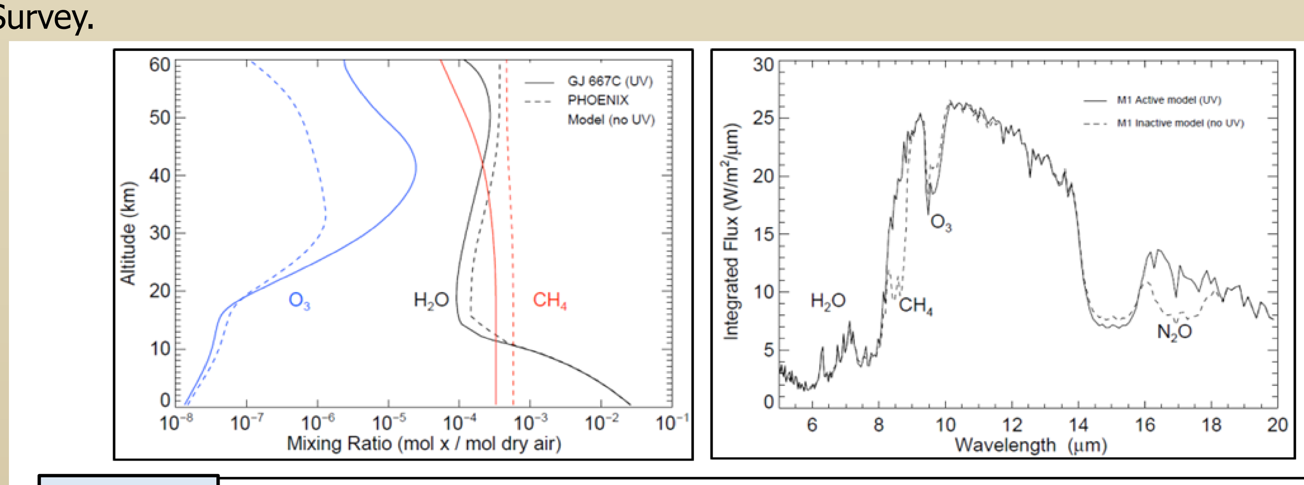


Fig 10 *- Mixing ratios of ozone (blue), methane (red), and water (black) for an Earth-like planet orbiting at the 1 AU equivalent distance for an active star model (UV from M1 dwarf star GJ 667C - solid) and photosphere only model (PHOENIX model with Teff=3600K - dashed). Fig 2 (right): Disk-integrated, R = 150 mid-IR spectra of an Earth-like planet around a chromospherically active M dwarf (solid) and photosphere only model (dashed). These simulations show that the use of empirically derived M dwarf spectra change the expected spectral signature from potentially inhabited planets around low-mass stars. Figures from Rugheimer et al. 2014-submitted.*