

MUSTI: A Massive stars far-Ultraviolet, Spectroscopic and Time-domain mission

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ABSTRACT

MUSTI is a 40 cm-aperture high-resolution spectroscopic mission concept meeting the requirement of an ESA FAST mission. MUSTI is optimized for far-ultraviolet (FUV) time-domain astrophysics and is driven by the need to solve massive stars physics if we are to obtain reliable cosmic models. MUSTI therefore aims to obtain the observational breakthroughs needed to alleviate uncertainties in massive stars internal structure, stellar winds and (binary) evolution. The spacecraft architecture relies on a heritage platform and a secondary high-precision pointing system. The payload is a fixed-format échelle spectrograph covering the wavelength range 120–210 nm at a resolving power of $R = \lambda/\delta\lambda \approx 20,000$. By combining high throughput, broad FUV coverage, and dedicated time-domain operations, MUSTI anticipates a strategic knowledge gap that will become acute in the next decade. Beside its main science aim, complementary surveys will cover classical Be stars, hot subdwarfs, young stars, and the Galactic interstellar medium.

Keywords: Space instrumentation, Ultraviolet astronomy, Far-ultraviolet spectroscopy, Time-domain astrophysics, Massive stars, Stellar winds, Binary evolution

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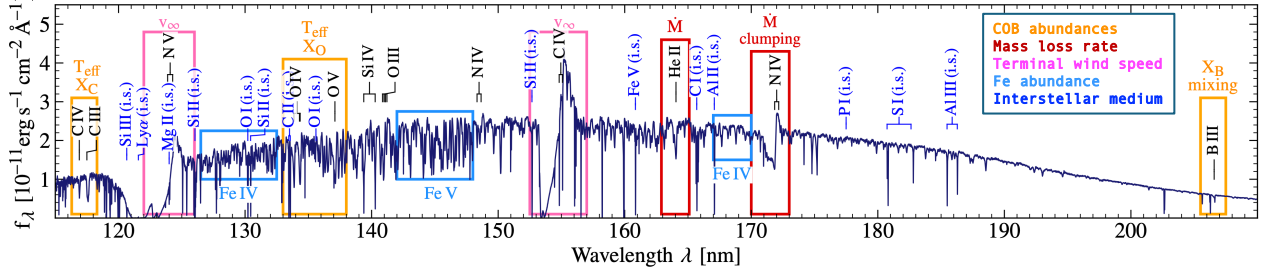


Figure 1. Representative FUV spectrum of a massive star showing the principal diagnostics used by MUSTI across the 120–210 nm wavelength range. Based on an HST/STIS spectrum of HD 46223 (O4 V), degraded to the resolution of MUSTI.

1. INTRODUCTION

Massive stars are major drivers of cosmic evolution. Through their ionizing radiation, their radiatively-driven winds, and their end-of-life explosions, they dominate the stellar feedback, drive the nucleosynthesis enrichment, and define the appearance of star-forming galaxies. Massive stars also seed neutron-star and black-hole populations relevant to transient and gravitational-wave astrophysics. Given their central role as cosmic engines, the reliability of cosmic models are limited by persistent uncertainties in their internal mixing, mass loss properties, and overall (single and binary) evolution.^{1,2} Addressing these open issues is becoming even more pressing. With the number of predicted Gravitational Wave Transients (GWT) nearing 10,000 by mid-2035,³ uncertain massive star physics will become a dominant source of uncertainties in the interpretation of the GWT distributions.^{4,5}

The far-ultraviolet (FUV) provides a unique observational window to resolve some of the main uncertainties affecting our understanding of massive star physics. The FUV spectral lines of massive stars encode atmospheric abundances and wind structure, and provide more prominent signatures of stripped stars produced by binary evolution. Many of these observations are either weak or degenerate in the optical wavelengths, or they are simply inaccessible, making FUV observations an absolute must-do.^{6,7}

In this context, MUSTI is designed to deliver FUV high-resolution spectroscopy of massive stars through a dedicated 40 cm-aperture mission delivering $R \sim 20,000$ spectroscopy over the 120–210 nm wavelength range with sufficient sensitivity for repeated observations of Galactic targets.

2. SCIENCE DRIVERS FOR A TIME-DOMAIN FUV MISSION

The mission is shaped by one main goal: unraveling the relevant uncertainties of massive star physics that currently hinder our understanding of the cosmic roles of massive stars. To this aim, MUSTI will address three main areas where progress is critically needed: (i) calibrating internal physics through accurate atmospheric abundances and establishing precise wind and mass-loss properties for a large Galactic sample of OB and Wolf-Rayet stars, (ii) measuring the time-dependent structure of massive-star winds, and (iii) characterizing Galactic massive stripped stars. These three goals drive the wavelength range, spectral resolution, sensitivity, and calibration stability of the payload, and the cadence of the observations. The MUSTI dedicated operational concept is essential. The required observations span bright targets, short cadences, and repeated revisits over hours to months which cannot be executed efficiently with general-purpose observatories.

2.1 Massive star atmospheres

The first primary science driver is a quantitative characterization of massive-star atmospheres through high-resolution FUV spectroscopy. Radiatively driven winds remove a substantial fraction of the stellar mass, and the FUV contains the most direct diagnostics of both atmospheric composition and outflow properties. MUSTI is designed to provide the Galactic benchmark required to anchor abundance analyses and the metallicity dependence of wind physics for a large sample of OB and Wolf-Rayet stars.^{8,9}

A key objective is to measure the elements which are most sensitive to internal mixing and binary interaction. Optical surveys constrain helium (He) and nitrogen (N), but these alone do not uniquely separate rotational

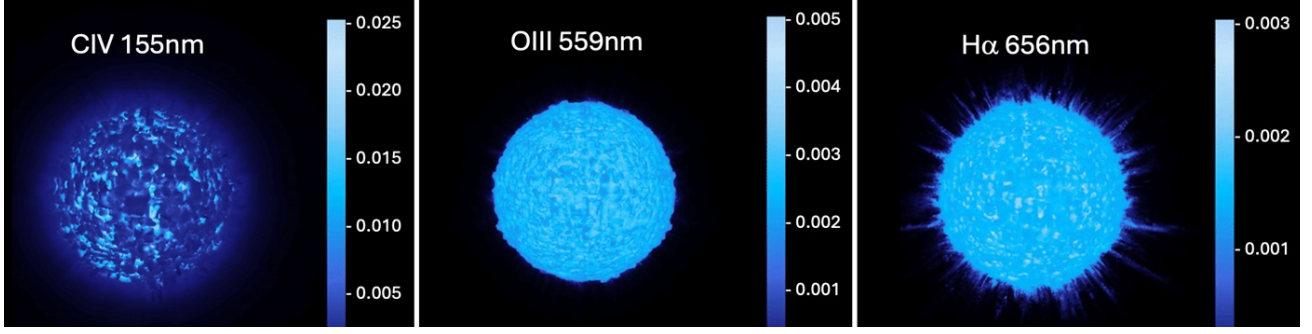


Figure 2. 3D simulations of surface structures in the winds of massive stars. The panels compare the line emissivity of clumps in the CIV 155 nm FUV line (left), and in the O III 559 nm and H α optical lines (center, and right).²³ Colour bars provide the respective line emissivity relative to the continuum flux. The contrast of the signal is over 10 times larger in FUV than in optical observations.

mixing from mass transfer or merger signatures. The combination of FUV and optical spectroscopy gives access to carbon (C), nitrogen (N), oxygen (O), and boron (B) diagnostics that can distinguish internal mixing from binary evolutionary processes. FUV resonance profiles of C and N further provide wind-sensitive diagnostics (Fig. 1).^{6,10–12}

2.2 Dynamics of massive star winds

The second primary science driver is the time-domain characterization of structured winds. Massive-star winds are not smooth: clumping and large-scale structures alter line profiles and introduce systematic uncertainty in mass-loss rates, terminal velocities, and even abundance measurements when only single-epoch spectra are available.^{16,17} Repeated revisits are needed to average-out these effects, calibrate the mass-loss rates *vs.* stellar parameters relations, and provide a reliable solar metallicity anchor for extra-galactic, low-metallicity environments studies.^{18,19}

The FUV is especially sensitive to this problem because FUV resonance-line variability is stronger than at optical wavelengths (Fig. 2). Recent multidimensional hydrodynamical calculations reveal line profile variability on timescales from hours to weeks (Fig. 3), motivating dense short-term monitoring.^{20–23}

2.3 Galactic massive stripped stars

The third primary science driver is the identification and characterization of Galactic massive stripped stars as key benchmark diagnostics of the binary evolution of massive stars toward GW mergers. These helium-core stars are important contributors to the ionizing budget of stellar populations and they are likely progenitors of hydrogen-poor supernovae and compact-object binaries. Yet they remain poorly characterized because they are hot, FUV-bright, and often optically hidden by a companion.^{24–27} High-resolution FUV spectroscopy is therefore essential because the FUV contains the strongest diagnostic lines and the spectral lines of the stripped component are more reliably isolated from that of its companion only at the shorter wavelengths. In particular, high-resolution spectroscopy offers the perspective of FUV-based orbital determination of stripped stars with degenerate and non-degenerate components alike.

2.4 Complementary science return

The MUSTI high-resolution FUV spectrograph and its time-domain approach further open up a rich discovery space, extending well beyond the primary science case on massive stars. This includes the origin and disk properties of classical Be stars, the largest homogeneous survey of hot subdwarfs (sdOs/sdBs), the physical processes affecting young stars and the formation of their planetary systems, and the study of the galactic interstellar medium and its dust content.^{31–38} Recognizing that, in the mid-2030s, the observational capability of MUSTI will be relevant for a large community, an estimated 20% of the available time will also be offered on a competitive basis.

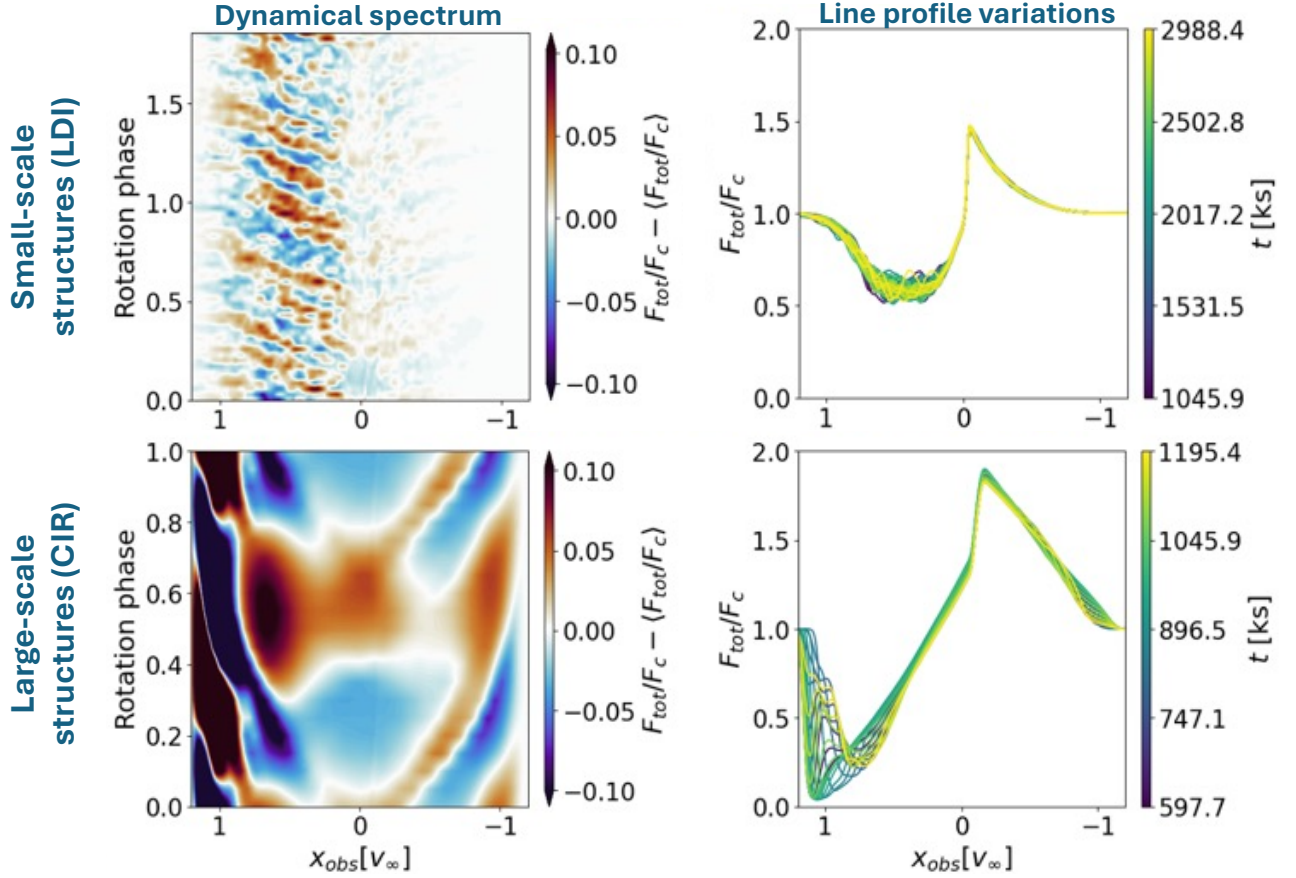


Figure 3. Time-dependent 3D radiative models of CIV 155 nm line profile variations resulting from: (Top) wind line driving instabilities (LDI) and (Bottom) co-rotating interaction regions (CIR) (Simulations performed by MUSTI col F. Driessen).

3. SCIENCE REQUIREMENTS AND OBSERVING PROGRAM

The science objectives translate into a compact set of mission requirements. MUSTI must deliver broad FUV wavelength coverage to sample the main spectral diagnostics, sufficient spectral resolution for radial velocity work, sufficient sensitivity to reach the required S/N in a fraction of the wind variability time scale, and operational flexibility to support cadences from hours to months. Table 1 shows the overview of the principal science drivers defining the mission requirements.

3.1 Wavelength coverage and spectral resolution

The wavelength range is fixed at 120–210 nm by the need to access the principal diagnostic lines of OB, Wolf-Rayet, and stripped stars. The NV 124 nm line is a crucial temperature, mass-loss and abundance diagnostic for the hottest stars and sets the low end of the wavelength coverage. The BIII 207 nm is key to differentiating the evolutionary history (single star *vs.* binary interaction)¹⁰ and sets the red edge of the wavelength coverage. The baseline resolving power for abundance work is $R > 15,000$, which balances precision and throughput. These requirements are also sufficient for terminal wind-speed measurements and time-domain sampling of broad FUV line profiles.

For stripped stars, the relevant diagnostics lie largely between 120 and 170 nm, and the required velocity precision is at the level of a few km s^{-1} , implying accurate wavelength calibration. $R \sim 20,000$ is sufficient for velocity and atmospheric work across plausible target and binary configurations and sets the MUSTI resolving power.^{7, 28, 29}

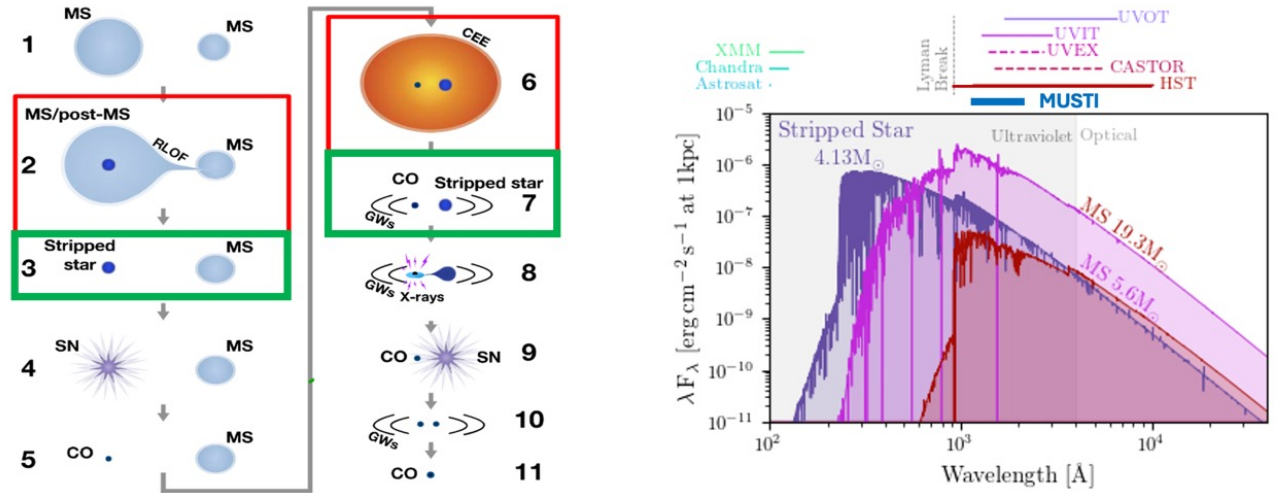


Figure 4. (Left) Binary evolution scenario highlighting two main channels to produce stripped stars (red boxes) and the stripped stars' evolutionary stages targeted by MUSTI (green boxes). (Right) Spectral energy distribution of a $4 M_{\odot}$ stripped star (dark blue) compared to a B (red) and O (pink) star (with wavelength coverage of ongoing and future missions indicated on top of the graph). Adapted from¹ and²⁷.

3.2 Sensitivity

The sensitivity requirement is driven by two cases. The atmospheric and wind-variability programs require $S/N \gtrsim 50$ per resolution element for representative OB and Wolf-Rayet targets, while the stripped-star survey requires typical single-epoch $S/N \gtrsim 20$ for fainter targets. The most demanding cadence is to reach $S/N \sim 50$ at 150 nm in about one hour for a representative O star.^{14,20}

3.3 Core surveys and cadence

MUSTI will reach its science goals through six core surveys. Three of these are dedicated to the primary science cases: (i) a Galactic atmospheric benchmark survey of more than 200 OB stars and more than 50 Wolf-Rayet stars, (ii) a time-domain wind survey of about 50 OB and Wolf-Rayet stars, and (iii) a multi-epoch survey of more than 50 Galactic stripped stars. The atmospheric survey establishes the reference abundance and wind dataset at Galactic metallicity; the wind program samples variability on timescales from hours to weeks; and the stripped-star survey addresses multiplicity and binary evolution on timescales from days to months.

Three additional core surveys are gathering the data required to meet the complementary science goals: Be stars, hot-subdwarf spectroscopy, one coeval southern star-forming region. In addition, interstellar-medium studies will capitalize upon the hundreds of new sight-lines.

3.4 Observing strategy and data products

MUSTI is a single-object, fixed-format spectroscopic mission with a simple observing concept. Working groups for each core survey will be assembled combining experts from the community and members of the MUSTI consortium. The working groups will select the individual targets and tune the observational strategy within the constraints of the mission. Targets are scheduled by visibility and cadence, with observations executed within one or several consecutive spacecraft orbits as long as the elapsed time remains short relative to the intrinsic variability timescale. A fraction of the mission time is reserved for community-driven investigations. A breakdown allocation of the observing time shows that MUSTI can meet its science objectives in a 4-yr duration mission (Fig. 5). The data will be reduced by the MUSTI team. Validated core-survey products will be released publicly on regular time intervals within the mission duration.

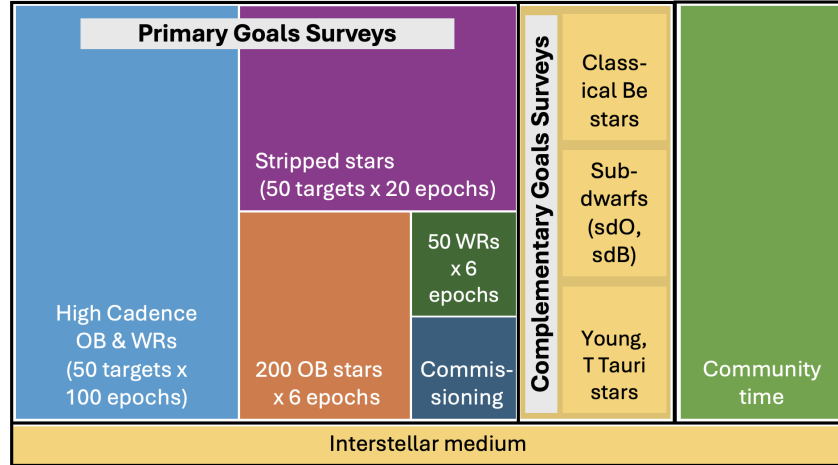


Figure 5. Conceptual distribution of various categories of observations that would allow MUSTI to meet its primary and complementary goals over a 4-year mission duration.

4. PAYLOAD AND INSTRUMENT CONCEPT

The payload is a compact, fixed-format, cross-dispersed échelle spectrograph, combined with a 40 cm-diameter Cassegrain telescope and a UV-optimized CMOS detector (Fig. 6). The payload includes internal flatfield and wavelength calibration capabilities, and a secondary high-precision pointing system. The architecture is intentionally simple in order to maximize throughput, to reduce mechanism count (hence to maximize robustness), and to preserve calibration stability. The overall payload is estimated to fit within a $50 \times 50 \times 60 \text{ cm}^3$ volume, which is compatible with several heritage low-Earth-orbit (LEO) platforms.

4.1 Overall payload architecture

At system level, the telescope feeds the slit spectrograph through a fine-steering optics chain. The optical payload assembly includes the telescope, fine steering mirror, spectrograph optics, focal plane, and calibration injection path. Detector and guidance front-end electronics remain close to the optics, while the main payload control electronics are accommodated remotely in the spacecraft avionics bay. This arrangement limits optical complexity while preserving clear subsystem interfaces.

The fixed-format concept is central to the mission. Recording the full science band in a single exposure simplifies operations and calibration and is particularly advantageous for time-domain work, where repeatability matters as much as raw sensitivity.

4.2 Telescope and spectrograph

The telescope is based on a 40 cm-class Cassegrain concept compatible with heritage European know-how. Its coatings are based on the flight-proven AlMgF₂ technology.³⁹ The design must also accommodate contamination control, straylight rejection, and potentially a protective aperture cover.

The spectrograph is a cross-dispersed échelle covering 120–210 nm in a single exposure. The baseline optical train comprises a slit, a collimator, a plane échelle grating, and a concave cross-disperser. Only reflective optics are used in the science path in order to preserve ultraviolet efficiency and simplify chromatic behavior.

4.3 Detector subsystem

The detector concept is based on a UV-optimized back-illuminated CMOS architecture with a $2k \times 2k$ format and $10 \mu\text{m}$ pixels. This balances ultraviolet quantum efficiency, readout simplicity, and compatibility with the two-dimensional échelle format. Compared with a CCD, the CMOS approach reduces front-end complexity; compared with microchannel plates, it avoids wavelength-coverage and sampling constraints across the full MUSTI band.^{40–42}

Table 1. Traceability between the principal science drivers of *MUSTI* and the resulting payload and mission requirements.

Mission requirements	Massive star atmosphere	Wind dynamics	Stripped stars
Wavelength coverage	120–210 nm	120–210 nm	120–180 nm
Spectral resolving power	>15 000	>15 000	>20 000
Wavelength calibration accuracy	<20 km s ^{−1}	<20 km s ^{−1}	<5 km s ^{−1} (2 σ)
S/N @150nm (per resolution element)	50	50 in ~1h	20
Typical target flux density at 150 nm [erg s ^{−1} cm ^{−2} Å ^{−1}]	5 10 ^{−11} to 10 ^{−12}	5 10 ^{−11} to 10 ^{−12}	10 ^{−12} to a few 10 ^{−14}
Number of epochs / covered time scales	1 / –	5 to 99 / hours to months	20 per orbital period (P <1 day to months)
Sky visibility	All sky but OB and WR targets typically close to the galactic plane		

The detector is passively cooled to about -50°C to suppress dark current and stabilize noise. This regime is expected to be compatible with radiator-based thermal control. Thermoelectric augmentation is available as contingency if characterization requires it later.

4.4 Fine guidance and calibration concept

Because the entrance slit is narrow on the sky, the nominal pointing performance of a generic LEO platform is insufficient by itself. *MUSTI* therefore employs a secondary high-precision pointing system based on a fine steering mirror and an optical fine-guidance sensor. This corrects residual platform jitter at payload level, enabling stable slit centering while relaxing spacecraft pointing requirements.^{43–45}

The same optical chain supports calibration. Internal calibration sources are injected through the payload optics to monitor wavelength stability and, where needed, instrument throughput. Repeated observations of astrophysical flux standards will complement internal reference measurements to preserve repeatability over many revisits.⁴⁶

5. EXPECTED PERFORMANCE AND FEASIBILITY

As a FAST mission concept, attention has been paid to the fact that *MUSTI*’s scientific and technical requirements can be largely met with heritage-based subsystems, or actively developed subsystems that will achieve TRL-9 in the next couple of years, i.e. well before the ESA F3 mission approval expected by 2030.

5.1 Throughput and signal-to-noise performance

The estimated end-to-end throughput is of the order of a few percent across the observed wavelength range, from about 2.2% at the edges of the band to a peak reaching 6.8% around 130 nm (Fig. 7). At 150 nm, this is sufficient to reach $S/N \sim 50$ per resolution element in about one hour for representative Galactic O stars, while still providing practical $S/N \gtrsim 20$ exposures for fainter stripped-star targets. The same throughput therefore meets both the bright-target cadence requirement and the fainter-target binary-evolution requirement.

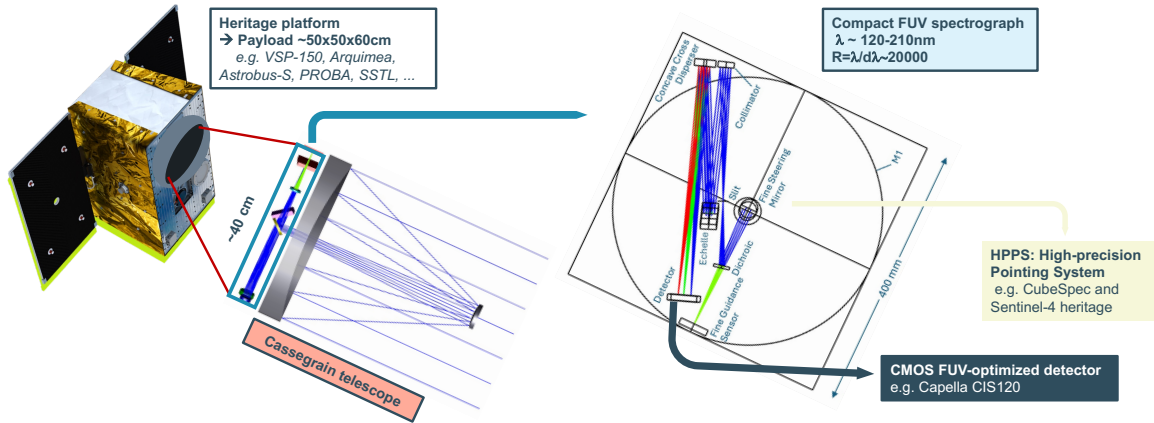


Figure 6. Key subsystems of the MUSTI mission concept.

5.2 Technology readiness and subsystem maturity

Most of the architecture relies on mature or heritage-derived subsystems. Telescope coatings, detector technology, guidance elements, and thermal-control building blocks all have strong lineage, while the main maturation effort is concentrated in the dedicated spectrograph implementation and aspects of the internal calibration chain. Specifically, MUSTI aims to explore the use of a FUV Fabry-Pérot étalon which can serve as a technology pathfinder de-risking technology development for the HWO FUV spectrograph.

5.3 Payload budgets and implementation margins

The payload remains compatible with heritage LEO platforms. Including system margin, the mass is about 83 kg and the power demand is about 58 W peak and 21 W average. The daily science-and-calibration data volume is of the order 6.5 Gbits, with housekeeping contributing about 1.7 Gbits. Both are compatible with a conventional X-band down-link strategy. These margins support the credibility of the MUSTI concept as a cost-effective ESA F-class realization.

6. MISSION PROFILE AND OPERATIONS

The mission concept is built around straightforward operations compatible with a compact heritage spacecraft. The baseline is a LEO implementation optimized for stable thermal behavior, broad sky access, and efficient operations.

6.1 Orbit and mission profile

The reference orbit is a high-inclination dusk/dawn Sun-synchronous low-Earth orbit above 600 km, with a period of roughly 90–100 minutes. This provides broad sky accessibility, favorable power conditions, and a manageable thermal environment. It also requires explicit treatment of ultraviolet observing constraints such as geocoronal contamination in selected lines and the effect of atomic oxygen on exposed surfaces.

The nominal mission duration is four years, with a review after two years. This duration is driven by the cadence and sample size of the reference surveys.

6.2 Observing concept and cadence implementation

MUSTI is a single-object, fixed-format spectroscopic observatory with minimal operational complexity. Science observations alternate with slews and regular calibration acquisitions. Targets may be observed within a single orbit or across consecutive orbits if the elapsed time remains short relative to the relevant variability timescale. This flexibility supports both short-timescale wind monitoring and longer-timescale binary monitoring.

The principal operations challenge is cadence control rather than mode complexity. Once the target is acquired and stabilized on the slit by the fine-guidance system, science acquisition will essentially be reduced to exposure sequencing.

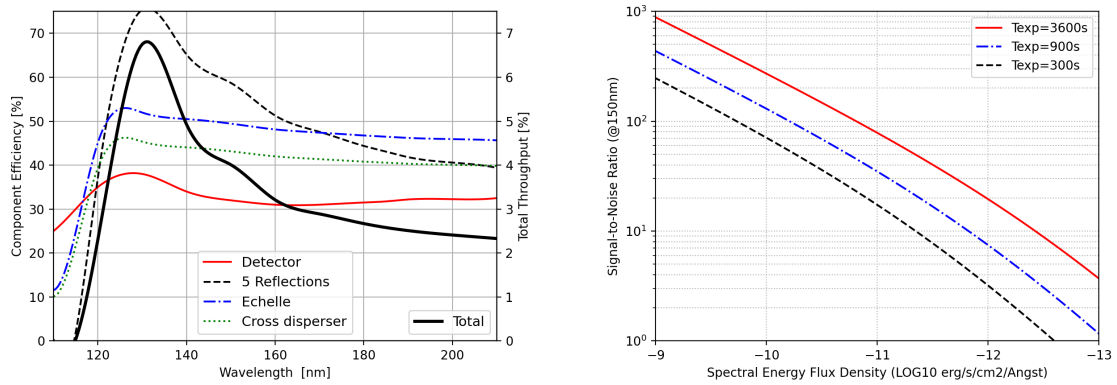


Figure 7. Predicted *MUSTI* performance: total system throughput across the science band (left) and representative signal-to-noise near 150 nm as a function of source brightness and exposure time (right).

7. CONCLUDING PERSPECTIVE

MUSTI is a science-driven mission primarily aiming at delivering observational breakthroughs in the field of massive stars, closing knowledge gaps that will become acute in the next decade. A dedicated mission is a necessity given the reality of the time-domain approach required by the variability of the phenomena at hands, being wind dynamics and orbital motion. The FUV, high-resolution capability is achieved through a relatively compact payload coupled to a heritage platform rather than a highly specialized spacecraft. This is an attractive position within the ESA F-class framework, where *MUSTI* offers the promise of a strong and timely science return balanced at a limited cost, by leveraging mature technologies and a simple payload design.

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