

Ardua

UV Instrument Technology and Design Trades for Wide-Field,
Ultra-Low-Surface-Brightness Circumgalactic Medium Mapping

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Desired Capability from Science

- Ultra-high Sensitivity, large FoV UV + X-ray imaging spectroscopy

SCIENCE GOAL	OBSERVABLE	DESIRED CAPABILITY
How does the CGM regulate galaxy growth?	Comprehensive multiphase gas maps around 50+ nearby galaxies; gas kinematics/turbulence; outflow vs. inflow structure	Surface-brightness sensitivity <100 photons s ⁻¹ cm ⁻² sr ⁻¹ (UV) <0.01 photons s ⁻¹ cm ⁻² sr ⁻¹ (X-ray) Field of view >15' × 15' Δv ≈ 6 km s ⁻¹ (UV) Δv ≲ 50 km s ⁻¹ (X-ray)
How do galaxies connect to the cosmic web?	Metal enrichment of CGM/IGM; hot gas tracing cosmic web filaments on degree scales	
How do stars and black holes shape their environments?	Energy partition b/w ISM, superbubbles, and CGM; stellar/planetary-host environment characterization for HWO targets	

Ardua ASTRA Submission →



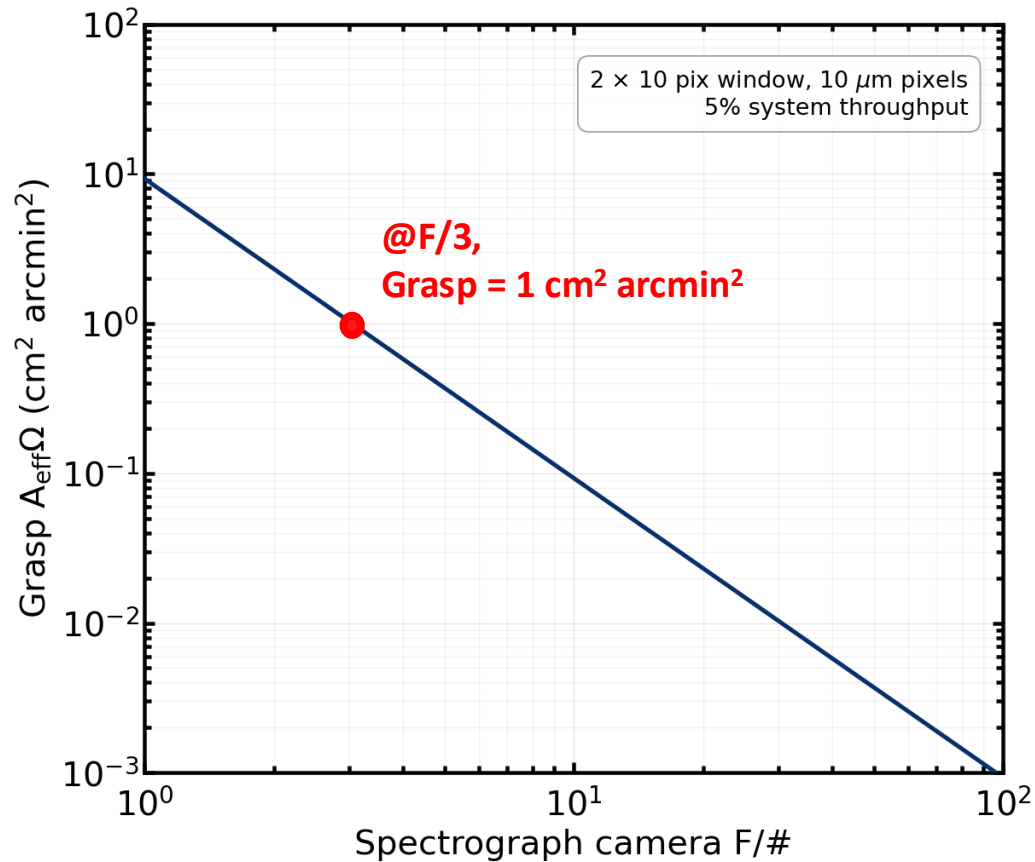
- Ultra-high Sensitivity, large FoV UV + X-ray imaging spectroscopy

Astronomer's Wishlist

Parameter	Value [desired]	Note
Sensitivity (Diffuse source)	< 100 LU [10 LU]	counts/s/cm ² /sr T_{exp}=10-100 hrs per res. element
Wavelength Coverage	100 – 200 nm [100-400 nm]	Not instantaneous coverage
Spectral Resolution (Diffuse source)	R=50,000 @103.2 nm	$\Delta V = 6 \text{ km/s}$
Target <i>Angular Coverage</i>	15' x 15'	Not instantaneous field of view; could be divided
Spatial Resolution	20"-40" [4"]	4" ~ 1 pc at Magellanic cloud

How do we achieve the sensitivity?

- *Is it possible to reach 10 LU line sensitivity with single aperture/slit in FUV?*

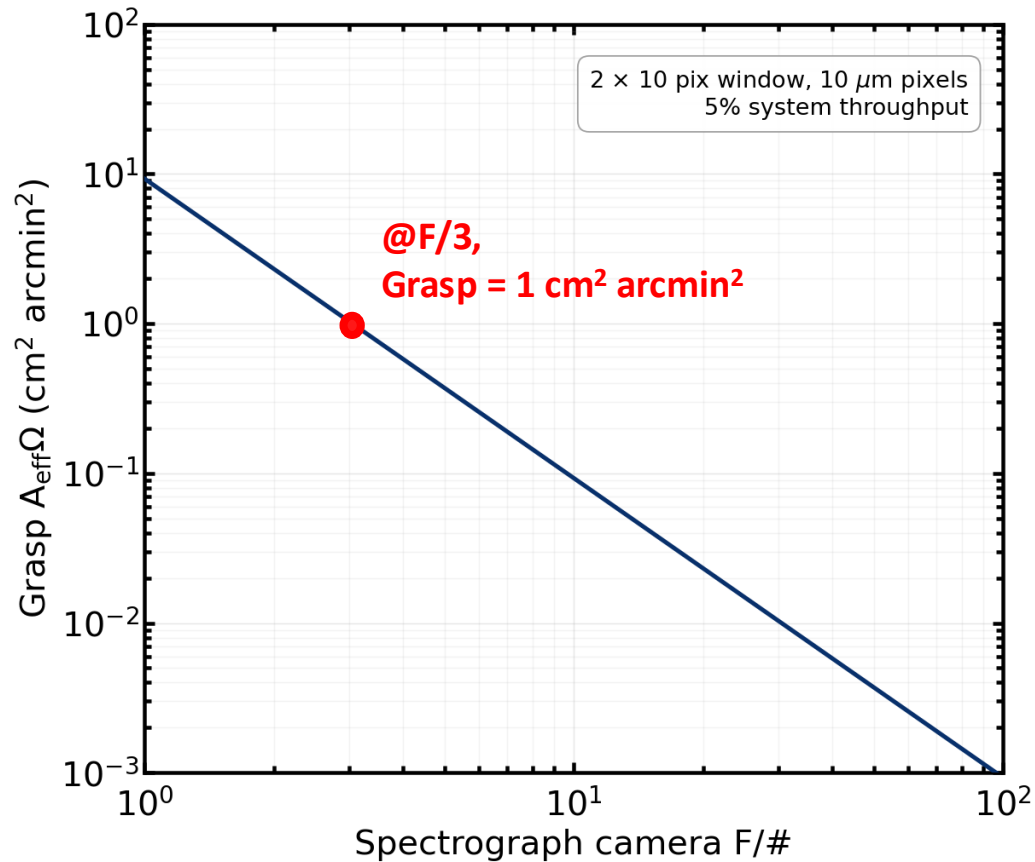


Case Study

How long does it take to collect 100 photons at 103.2 nm, from 10 LU line?

How do we achieve the sensitivity?

- *Is it possible to reach 10 LU line sensitivity with single aperture/slit in FUV?*
-> **Not really. Nearly impractical** (unless dramatically sacrificing nominal spatial resolution)



Case Study

How long does it take to collect 100 photons at 103.2 nm, from 10 LU line?

- F/3, $\Delta\Omega \propto 2 \times 10$ pixels (10 um pixel): Grasp ~ 1 [cm² arcmin²]

-> **3.8 years**

For mapping, spatial binning is not a desired options/knobs

Grasp per resolution element is **independent of telescope diameter**
– with fixed physical extraction window size (~detector pixel size)

- How do we increase the grasp?
 - Multi-Aperture
 - Multi-Slit
 - Wider-Slit (while sacrificing spectral res.) (effectively the same as multi-slit)

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$$SNR = \frac{Signal}{Noise}$$

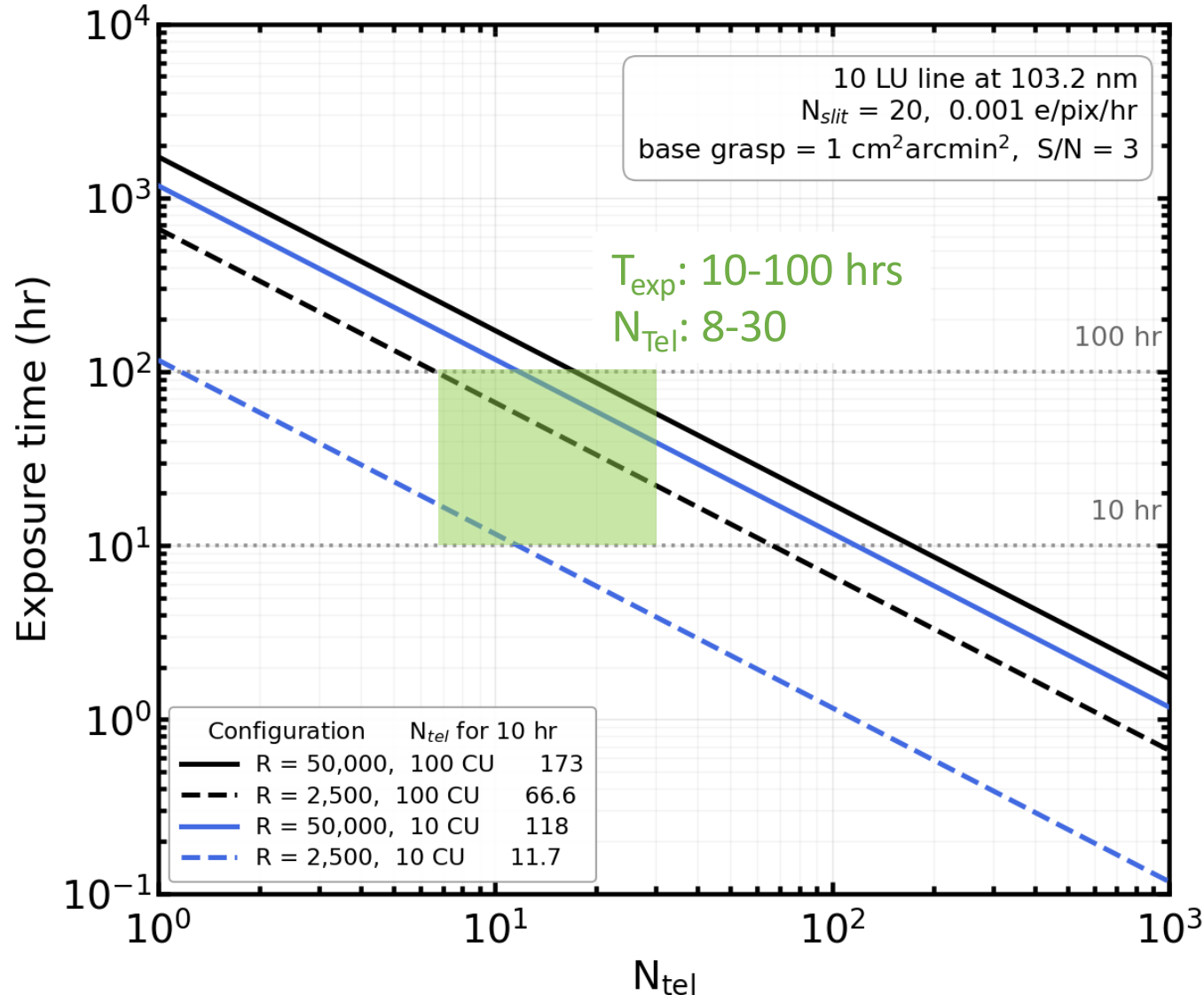
$$t_{exp} = \frac{SNR^2}{\mu_S N_{tel}} \times \left[\frac{1 + \frac{\mu_{B,detector}}{\mu_S}}{N_{slit}} + \frac{\mu_{B,UV}}{\mu_S} \right]$$

$\mu_S = SA_{eff}\Delta\Omega$, **Signal rate (cnt/s)**. S in LU [cnt/s/cm²/sr] or erg/s/cm²/arcsec²

$\mu_{B,UV} = BA_{eff}\Delta\Omega$, **Total background rate (cnt/s)**. B in CU [LU/Å] or erg/s/cm²/arcsec²/Å

$\mu_{B,detector} = Noise\ per\ pixel \times N_{pixel\ per\ resolution\ element}$, Dark current, Clock-induced-charge

Feasibility Study: Deep-Dive Sensitivity Calculation

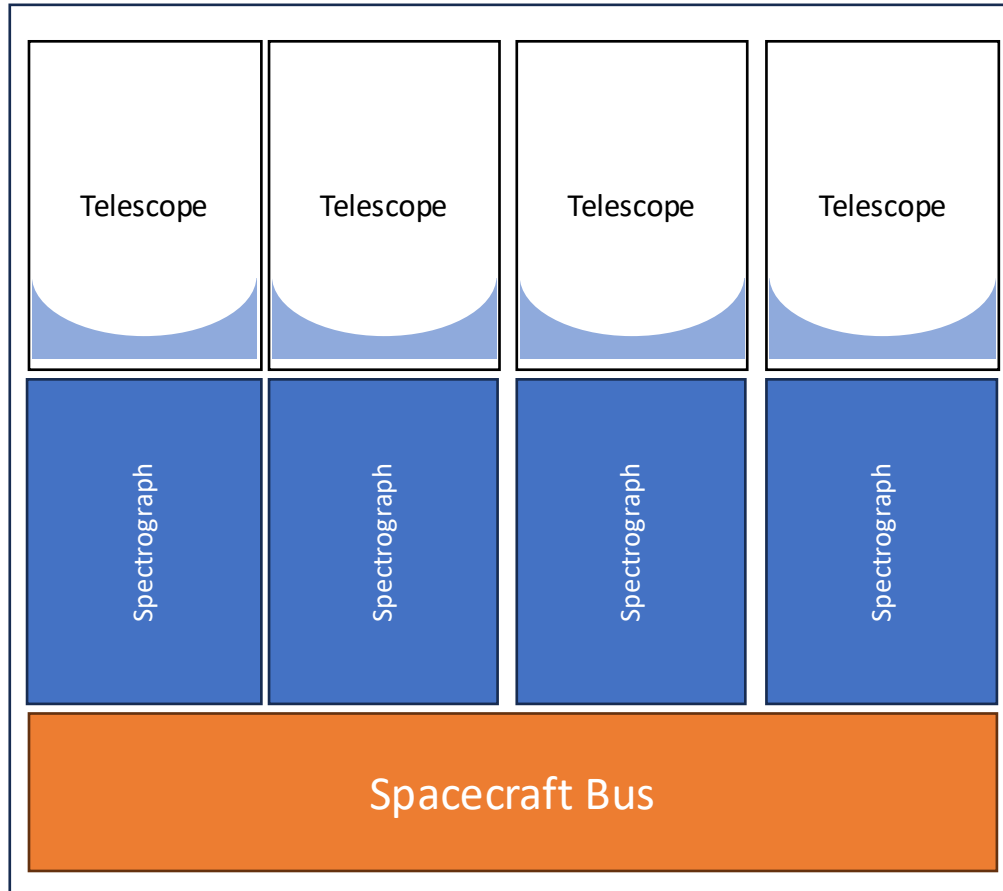


- Target sensitivity: 10 LU @103.2 nm (O VI)
- Target S/N (SNR) = 3
- F/3 telescope & spectrograph
- Base grasp per resolution element from 2 pixel x 10 pixel sampling
 - Angular size depends on M1 diameter
 - 2.8" x 14" with 36 cm diameter
- Dark current: 0.001 e-/pix/hr
- UV background: 10 CU & 100 CU
- Multi slit (20 long slits)

We can detect 10 LU line emission in reasonable time frame

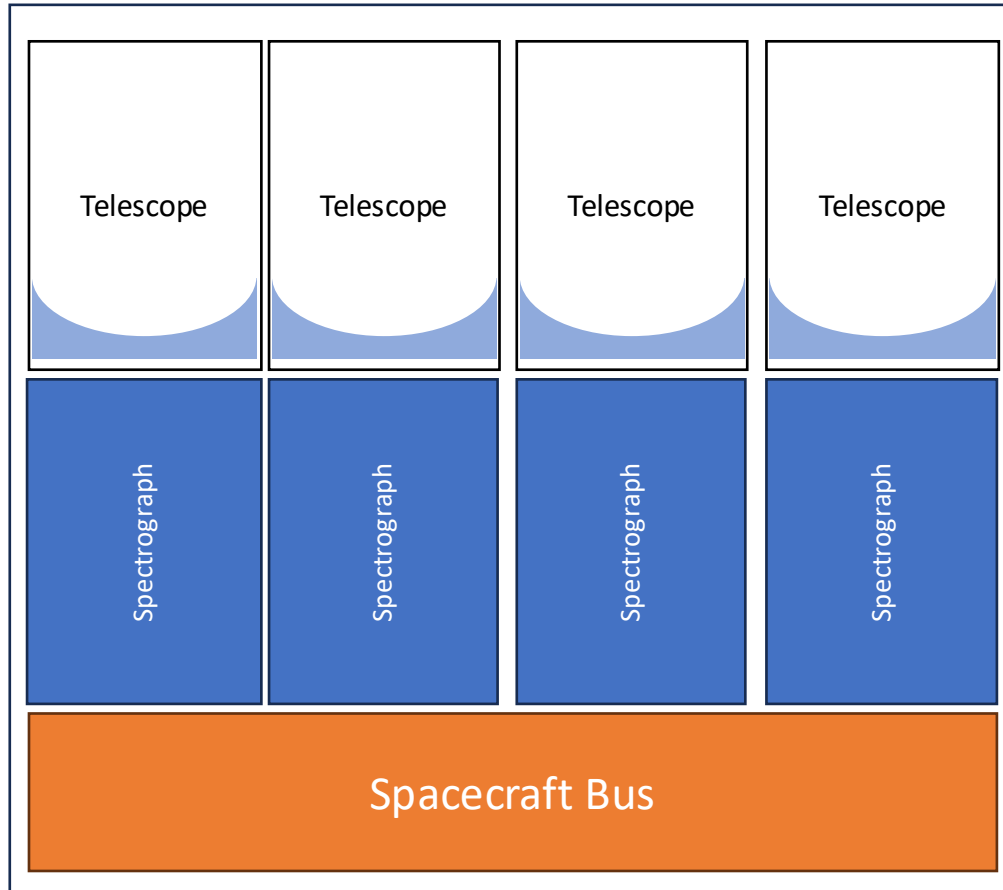
Ardua UV Instrument Concept – Multi-Aperture, Multi-Slit CGM Mapping Machine

N telescopes & N spectrographs



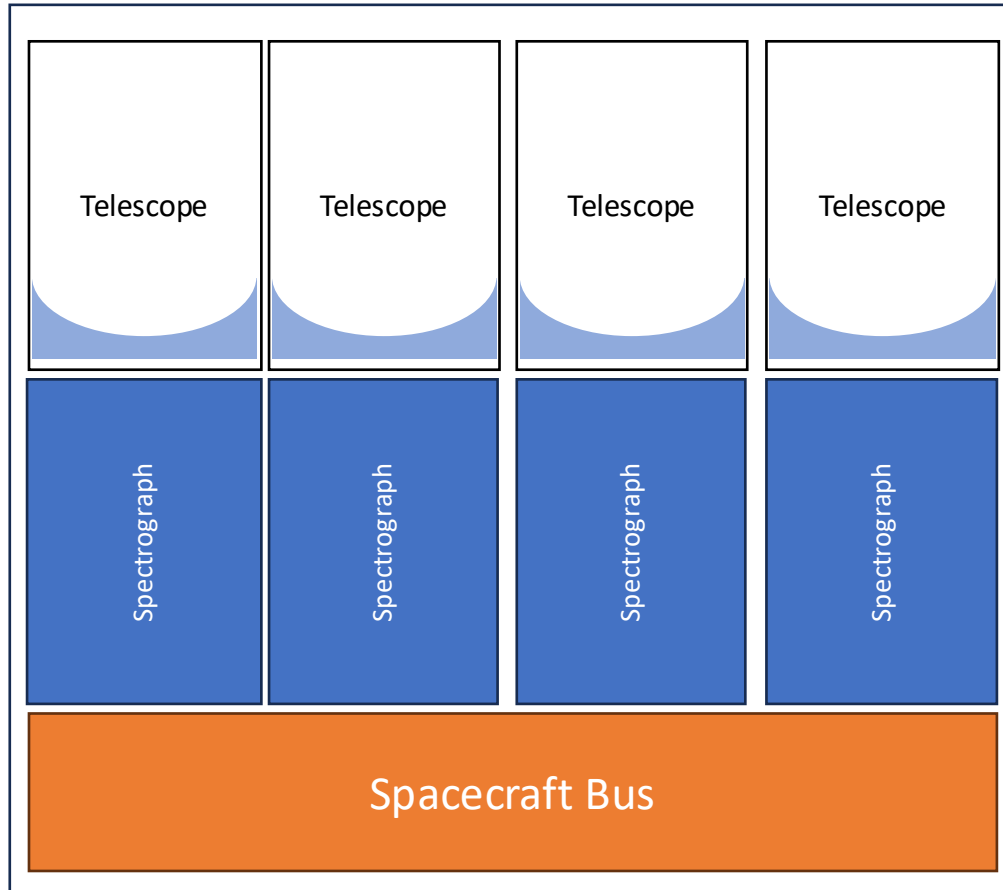
- Concept Maturity Level 2-3
- Fast Telescope/Spectrograph -> High Etendue (Grasp)
- Multi-telescope on a single S/C bus
 - Multiply Grasp (Grasp is a function of F/#, not dia.)
 - Diameter: 30-50 cm

N telescopes & N spectrographs



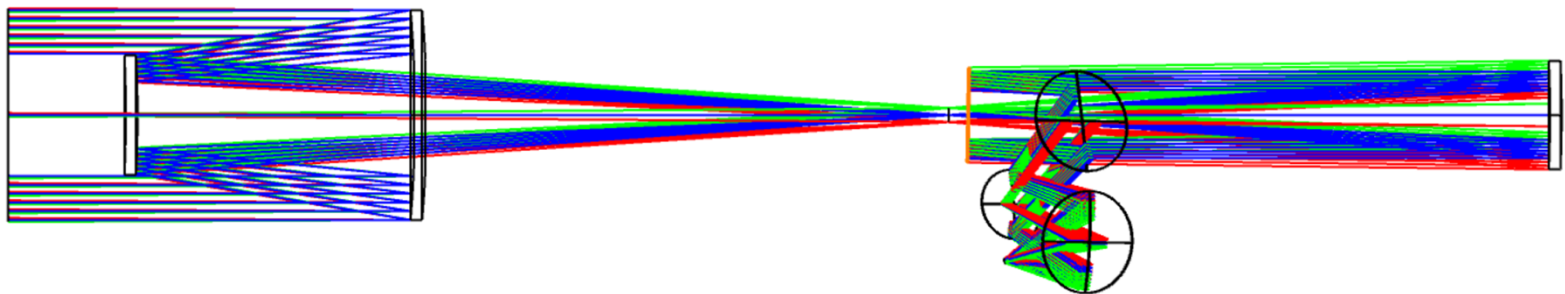
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- Simple long slit spectrograph, but with
 - High-spectral resolution ($R > 50k$)
 - Wide FoV: > 30 arcmin in length (4-40 arcsec in width)
 - Slit mask changing mechanism
 - Multi-slit or single slit. (Multi-slit + Multi-Aper.: **pseudo-IFS**)
 - Slit-width options: Sensitivity $\leftrightarrow$ spectral resolution
- Grating changing mechanism
 - Wide wavelength coverage (100 nm – 400 nm)
 - Central wavelength selection (LOS velocity)

N telescopes & N spectrographs



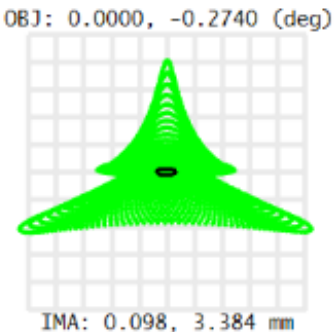
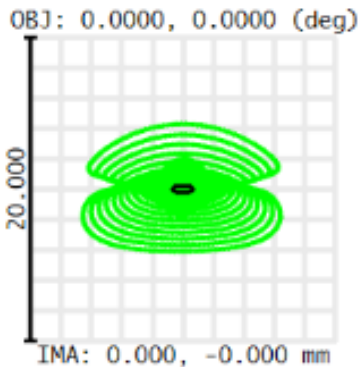
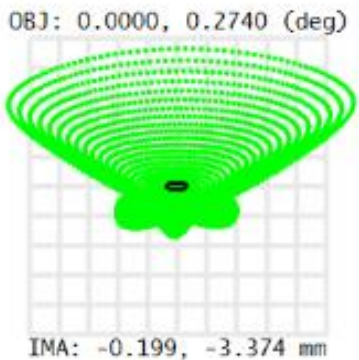
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Optical Design Requirement Trace Matrix

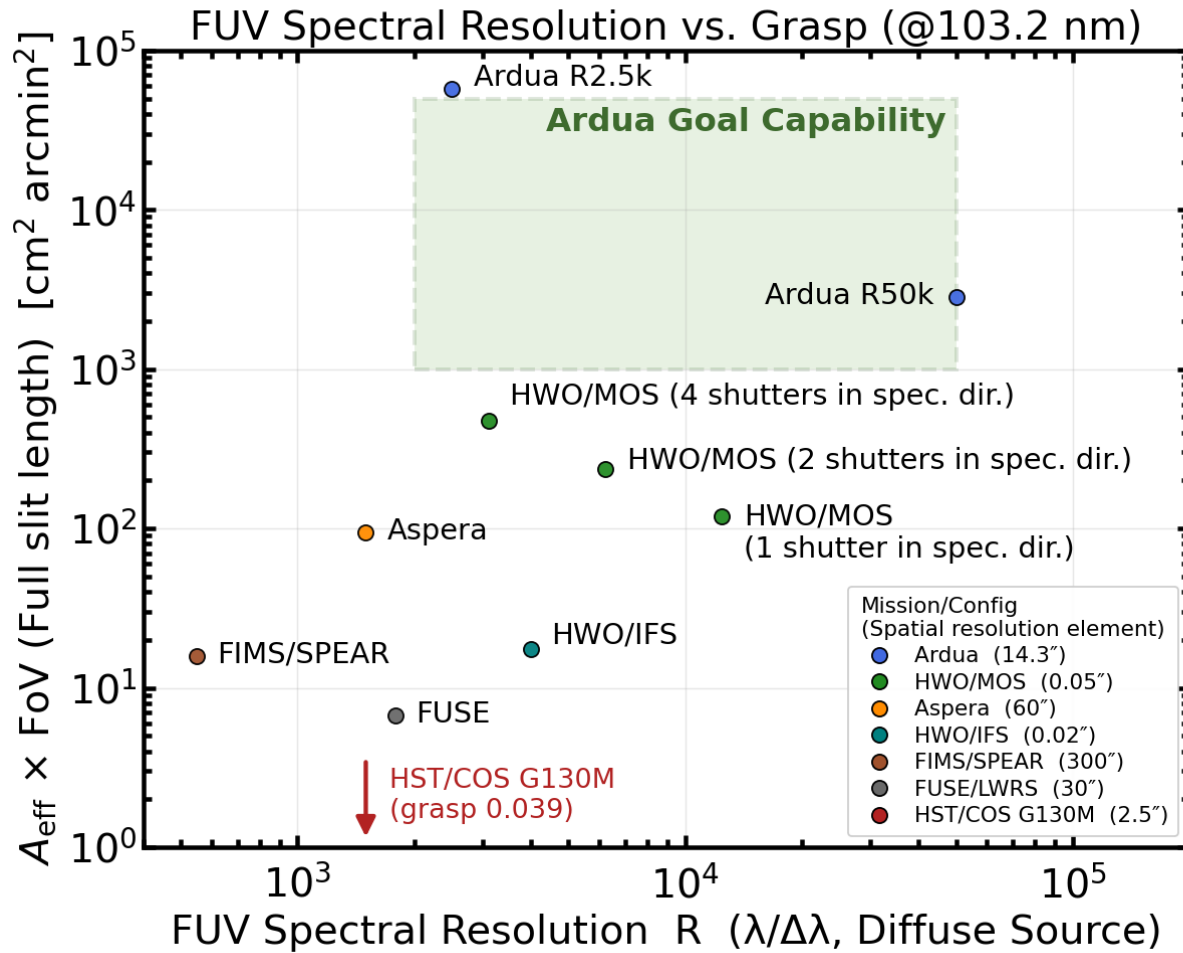


ID	Requirement / driver	Trace to Current design	Verification method	Status
R-01	Surface-brightness sensitivity $10^{-20} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$	F/7 Cassegrain Telescope design	Zemax, Sensitivity equation: $N_{\gamma} = I_{\gamma} A_{geo} \Omega_{slit} \eta t$ $A_{geo} \Omega_{slit} = \frac{\pi}{4} (206265)^2 \frac{w_{slit} L_{slit}}{(F/\#)^2}$	CALC PASS
R-02	$R \approx 50,000$ $\Delta v \approx 6 \text{ km s}^{-1} \lesssim 30 \text{ km s}^{-1}$	$R \approx 48,300 \sim 51,750$ for 103-104 nm	Zemax Optical design	PARTIAL
R-03	Field of view $>15' \times 15'$ (Multi aperture)	FoV: $33' \times 1.6''$ and slit size: 24.1mm * 20 μm design for 103-104 nm (TBD)	Zemax Optical design	PARTIAL
R-04	Broad FUV coverage with controlled calibration	103-104 nm for O VI, will have more coverage with multi-aperture or Beam splitter approach	Zemax Optical design multi-configuration	OPEN

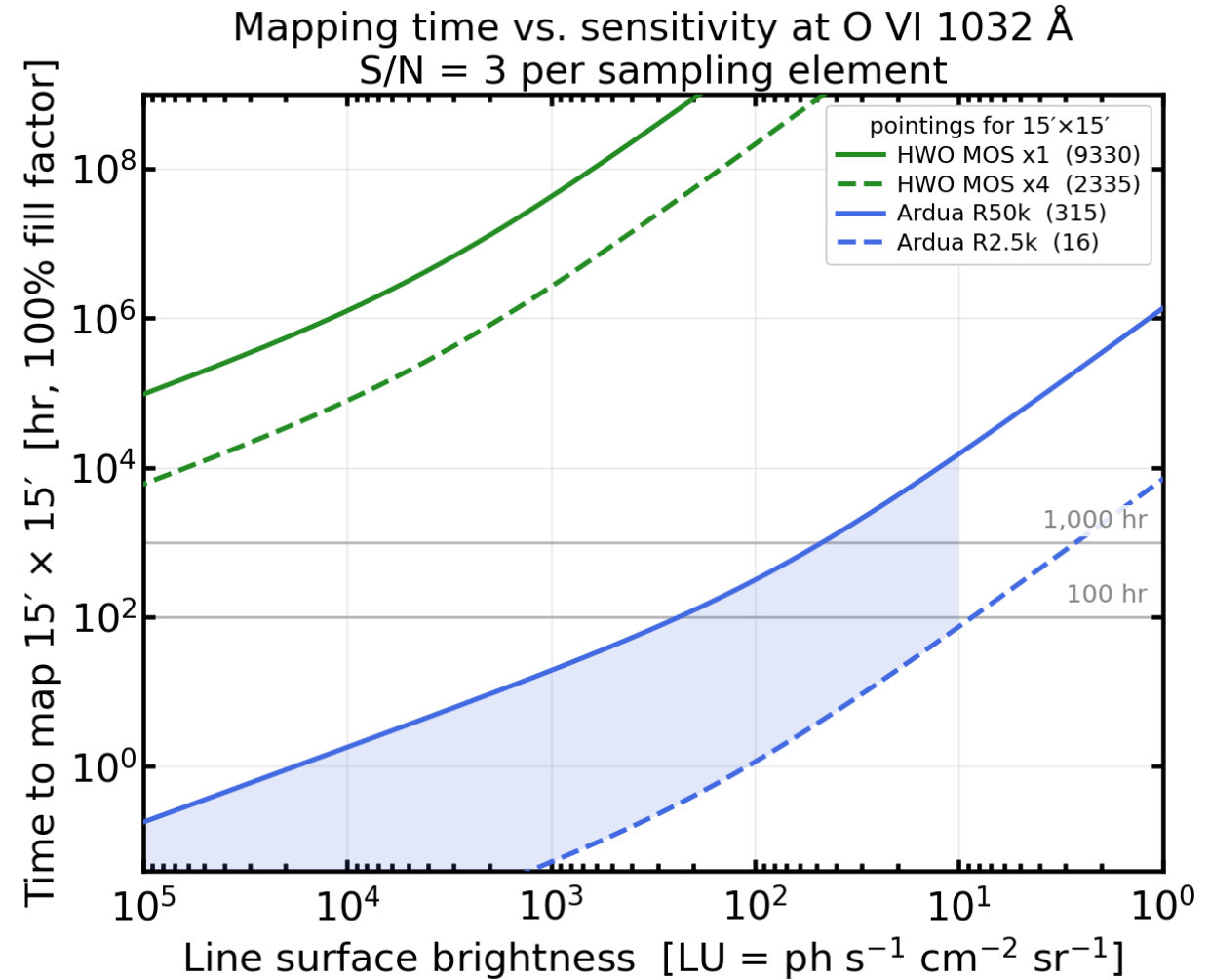
Spot diagram on detector



Comparison with Current / Planned State of Art



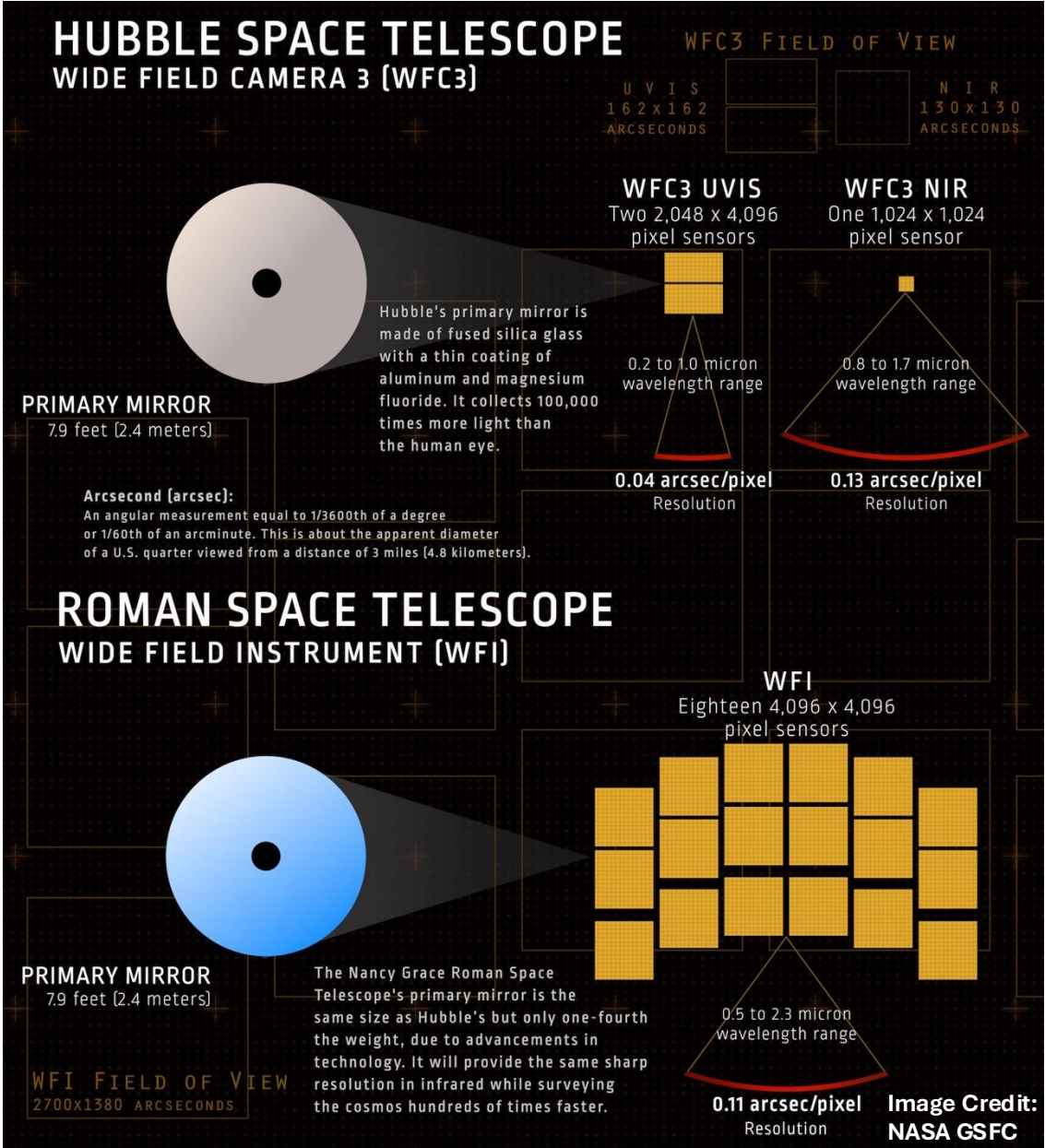
Ardua: Single telescope grasp $\times N_{\text{Tel}}$



HWO (3%): 1 MOS shutter base (0.12" $\times$ 0.24" element)

Ardua (8%): $N_{\text{Tel}}=30$, $N_{\text{Slit}}=20$ (2.9" $\times$ 14" element)

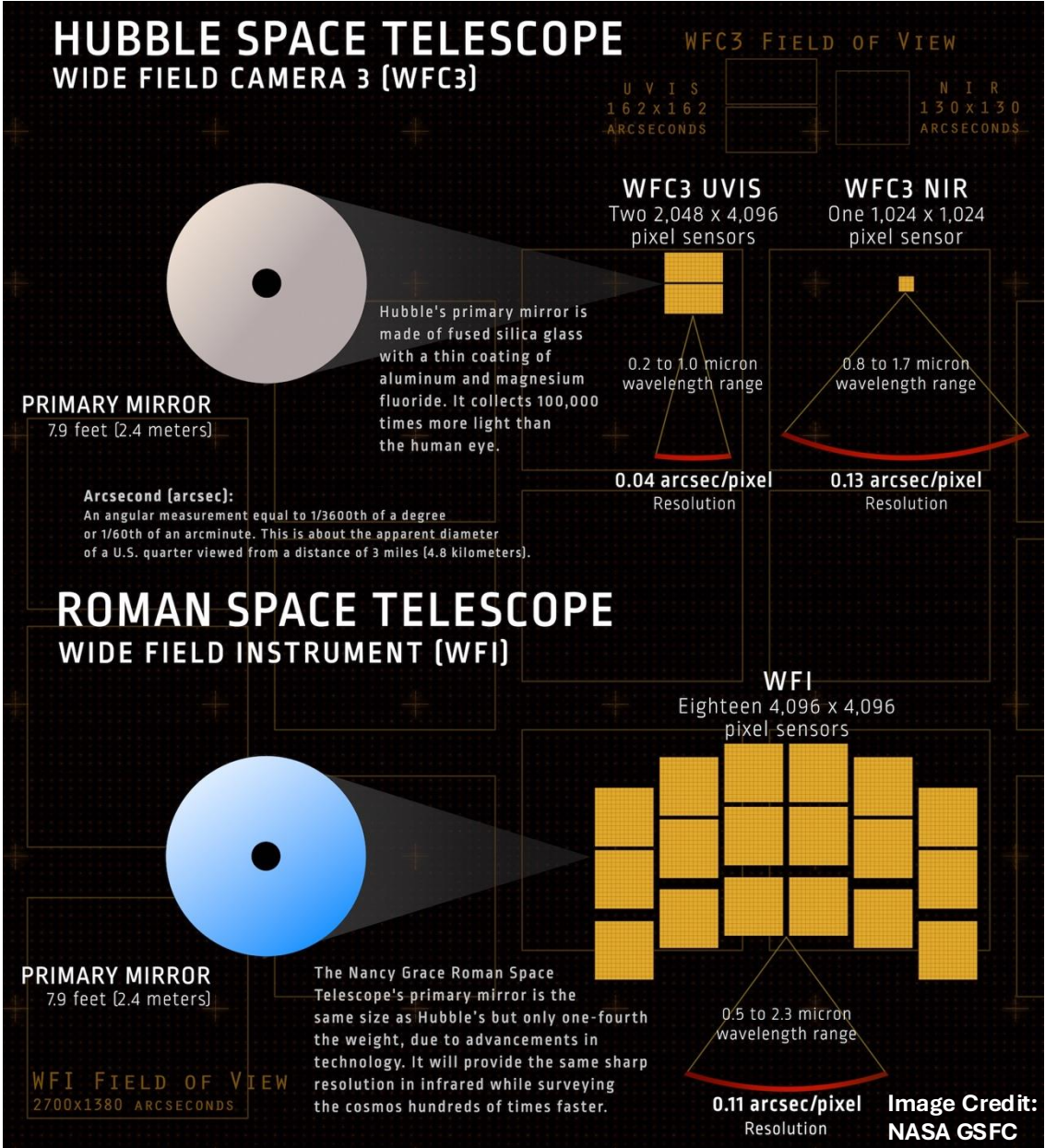
Roman is to HST, as Ardua is to HWO



	Hubble Space Telescope	Roman Space Telescope
FoV	WFC3 UVIS: 162" x 162" WFC3 NIR: 130" x 130"	WFI: 2700" x 1380"
F/#, N detector	WFC3 UVIS: ~F/32, Two 2k x 4k, 15 um WFC3 NIR: ~F/11, One 1k x 1k, 18 um	WFI: ~F/7.9, Eighteen 4k x 4k, 10 um
Other Instr.	ACS, COS, STIS	Coronagraph

	Habitable World Observatory (EAC 4/5)	Ardua (UV)
FoV	UV MOS as long slit: (0.12" - 2.4") x 180" UV IFS: 3" x 3"	(4" - 40") x 1500"
F/#, N detector	UV MOS: F/19 UV IFS: ~F/95 (?)	F/3 - F/6 Multi-Aperture, Multi-Slit
Other Instr.	5 others	

Roman is to HST, as Ardua is to HWO



	Hubble Space Telescope	Roman Space Telescope
	Slow F/#	Fast F/#
	Small Field of View	Wide Field of View, Multi-detector
	Multi-purpose, Multi instr./configs	Survey focus, Two instruments

	Habitable World Observatory (EAC 4/5)	Ardua (UV)
	Slow F/#	Fast F/#
	Small Field of View	Wide Field of View, Multi aperture/detector
	Multi-purpose, Multi instruments	CGM Survey focus (and more)

Technology		TRL [within 2 yrs]	Status / note
UV Coating	XeLiF coating	3-4 [6]	HWO dev., path, INFUSE sounding rocket
	eLiF coating	6-7 [9]	SISTINE, SPRITE & Aspera

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Detector	Skipper CCD	4-5 [6]	Sub e- noise shown, readout speed in dev. <i>[Flight-level characterization needed]</i>
	Micro Channel Plate	9	Flight-proven, multiple UV missions

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Grating	E-beam Lithography	4-6	Sounding rocket missions > 6,000 line/mm possible, low scatter. <i>[High ruling density needed for compact spectrograph]</i>
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Knowledge	UV Background, Interplanetary Airglow	N/A	Limited knowledge, galactic latitude dependent (UV Background), order of magnitude uncertainty. <i>[Actual measurement needed]</i>
	Straylight Control	N/A	<i>[Grating scatter characterization needed]</i>

- **UV CGM line emission is extremely faint.**
 - UV CGM emission at ~ 10 LU requires a fundamentally high-grasp observing architecture.
- **Ardua can cover large angular area with 10 LU sensitivity in reasonable time frame in UV.**
 - A fast, replicated multi-aperture/multi-slit spectrograph, while preserving useful spatial and spectral resolution.
- **Multi-Aperture is required, low detector/systematic noise is also required.**
 - CML 2-3
- **Key technologies are already coming along, *no entirely new* technology needed.**
 - Skipper CCD, E-beam grating, UV background needs further investments.