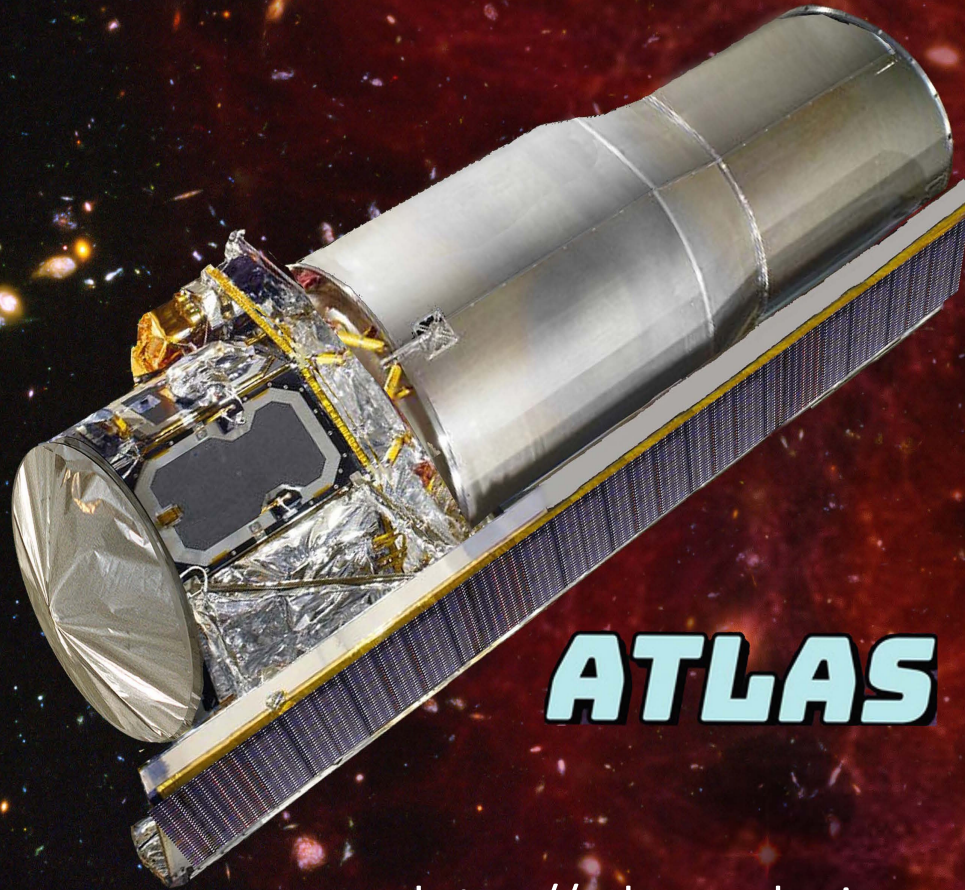


Astrophysics Telescope for Large Area Spectroscopy

Yun Wang (Caltech/IPAC)

on behalf of the ATLAS Probe Team

Presentation to Astro2020 EOS-1 Panel, March 18, 2020



ATLAS

<https://atlas-probe.ipac.caltech.edu/>

ATLAS Probe Overview

- 1.5m aperture telescope with 0.4 deg² FoV
- R = 1000 slit spectroscopy over 1-4 μ m
- 6,000 spectra simultaneously
- Slit selectors: Digital Micromirror Devices
- Launch Ready Date: < 2030
- Cost within NASA probe-class envelope



- Map the cosmic web to shed light on the physics of galaxy evolution.
- Trace large scale structure densely to illuminate the nature of dark energy.
- Probe the Milky Way's dust-shrouded regions, reaching the far side of the Galaxy.
- Explore Kuiper Belt Objects in the outer Solar System.

PI: Yun Wang (Caltech/IPAC)

Primary Partner: JPL

Instrument Lead: Massimo Robberto (STScI & JHU)

Ref.: Wang et al. (2019), PASA, 36, e015, arXiv:1802.01539

Open collaboration: <http://atlas-probe.ipac.caltech.edu>

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- **Mission Science Goals**
- Mission Implementation
- Cost and Schedule Estimates
- Community Support
- Summary

ATLAS Probe Science Goals

ATLAS Probe addresses fundamental questions in astrophysics:

(1) How have galaxies evolved? What is the origin of the diversity of galaxies?

ATLAS will trace the relation between galaxies and dark matter with less than 10% shot noise at $1 < z < 7$, and probe the physics of galaxy evolution in the cosmic web.

(2) What is driving the accelerated expansion of the Universe?

ATLAS will obtain definitive measurements of dark energy & tests of General Relativity.

(3) What is the 3D structure and stellar content in the dust-enshrouded regions of the Milky Way?

ATLAS will penetrate the dust & map the inner Milky Way to a distance of 25 kpc.

(4) What is the census of objects in the outer Solar System?

ATLAS will detect & quantify the composition of 3,000 Kuiper Belt Objects (KBOs) in the outer Solar System.

ATLAS Probe and Galaxy Evolution

Spectroscopic redshifts of galaxies over **large areas** & at **high number densities** are required to connect galaxy properties (e.g., stellar masses and star formation rates) to the underlying dark matter halo masses and environments that are key to understanding galaxy formation physics.

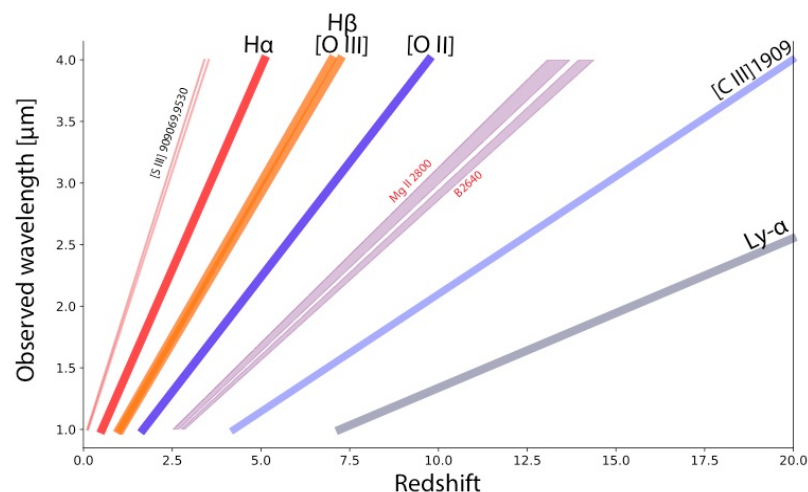
ATLAS Probe will

- Trace the cosmic web in detail over cosmic history.
- Reveal how the evolution of galaxies depends on their environments.
- Connect galaxy properties to statistical measurements of dark matter halo masses.
- Extend the redshift baseline of all SDSS-like galaxy science (high number density and all spectral types) to $z \sim 3$ and in many cases to $z \sim 7+$.

ATLAS Notional 3-tiered Galaxy Survey

Survey	Area / deg ²	Depth		N _{gal}
		Line	Cont.	
Wide	2000	5e-18	23	183M
Medium	100	1.2e-18	24.5	17M
Deep	1	4.6e-19	25.5	.31M

*Line Flux in $\text{erg/s/cm}^2 (5\sigma)$, Continuum in AB mag (3σ)



(see Astro2020 science white paper, Dickinson et al.)

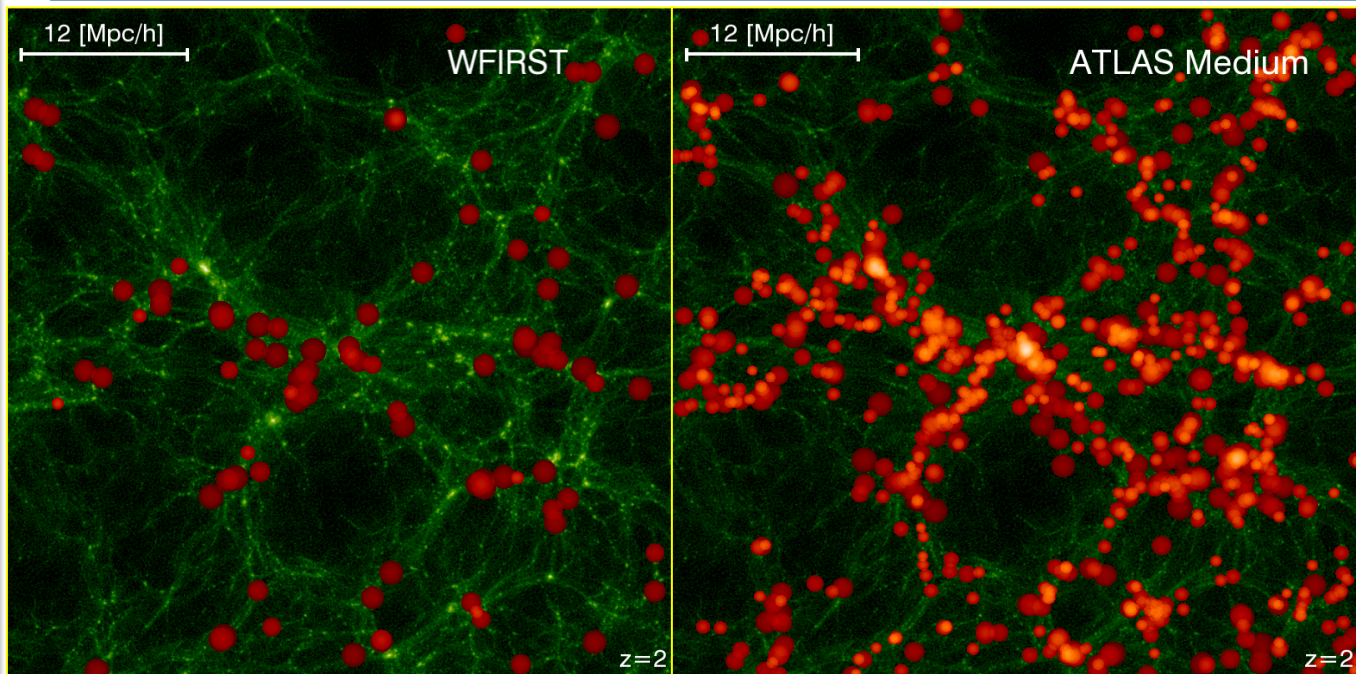
ATLAS Probe Maps the Cosmic Web

How does the evolution of galaxies depend on their environment?

None of the currently planned space missions can provide a definitive answer.

The cosmic web of dark matter plays a central role in galaxy evolution. A galaxy's relative position in the cosmic web may determine its star formation history and ultimate fate.

ATLAS Probe traces the cosmic web of dark matter in sufficient detail over large areas, to reveal how the evolution of galaxies depends on their environment, and enable fundamental understanding of how galaxies have evolved.



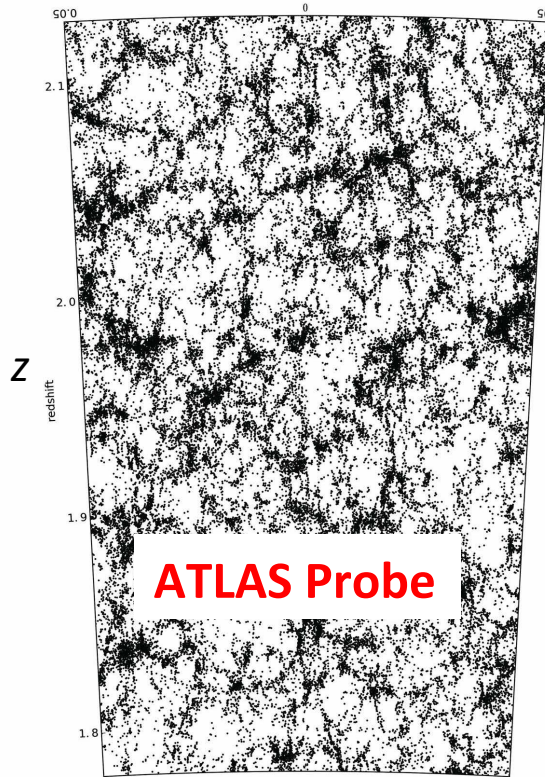
Cosmic web of dark matter (green) at $z=2$ traced by galaxies with spectroscopic redshifts (red) from WFIRST (left) & ATLAS Probe (right).

(Credit: Alvaro Orsi)

Why Slit Spectroscopy?

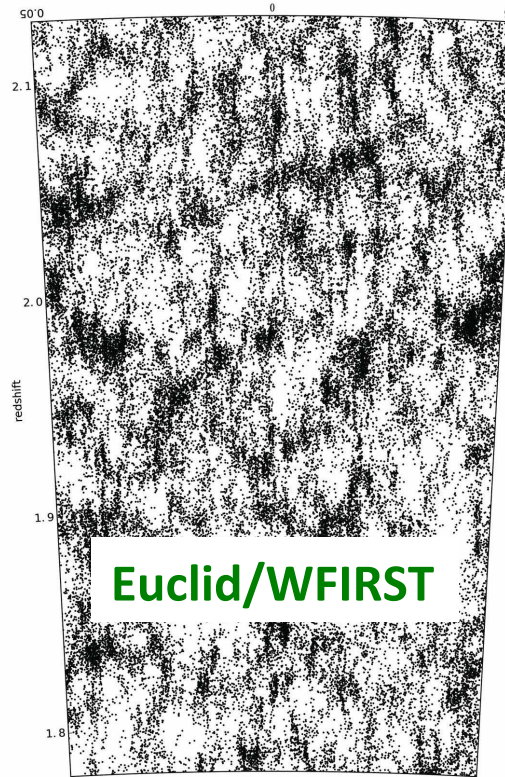
Slit spectroscopy is required to trace the cosmic web in sufficient detail to discover how environment determines a galaxy's physical properties.

Slit: $\sigma_z/(1+z)=10^{-4}$



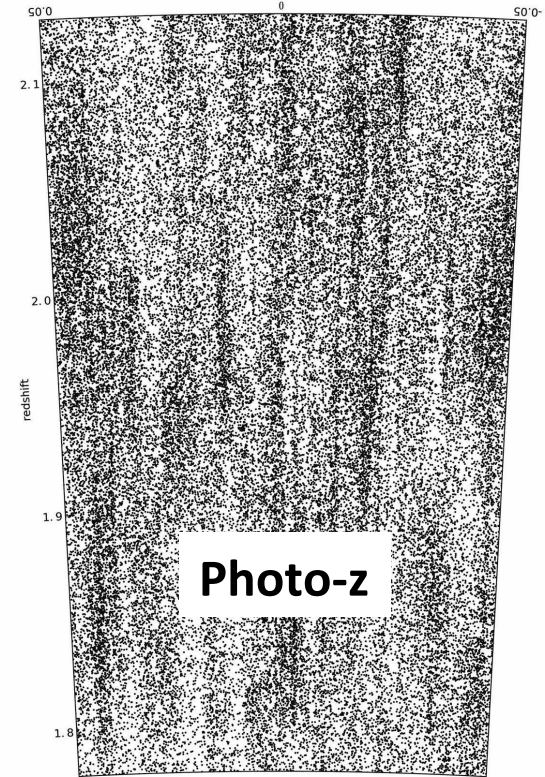
Angular position in radians

Slitless: $\sigma_z/(1+z)=10^{-3}$

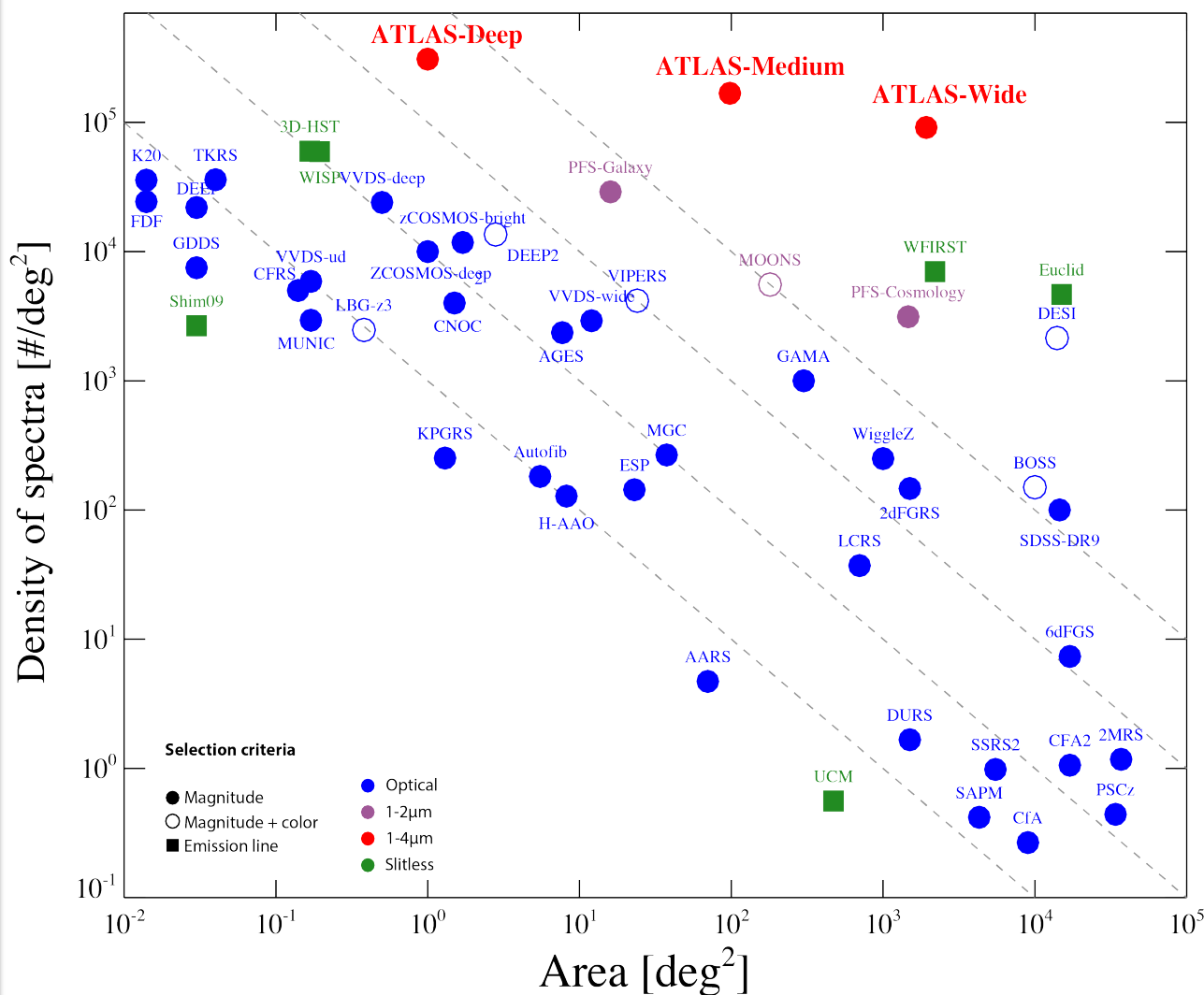


(Figures by Alvaro Orsi)

Photo-z: $\sigma_z/(1+z)=0.01$



ATLAS: Large Area & High Number Density Game-Changer in Galaxy Redshift Surveys

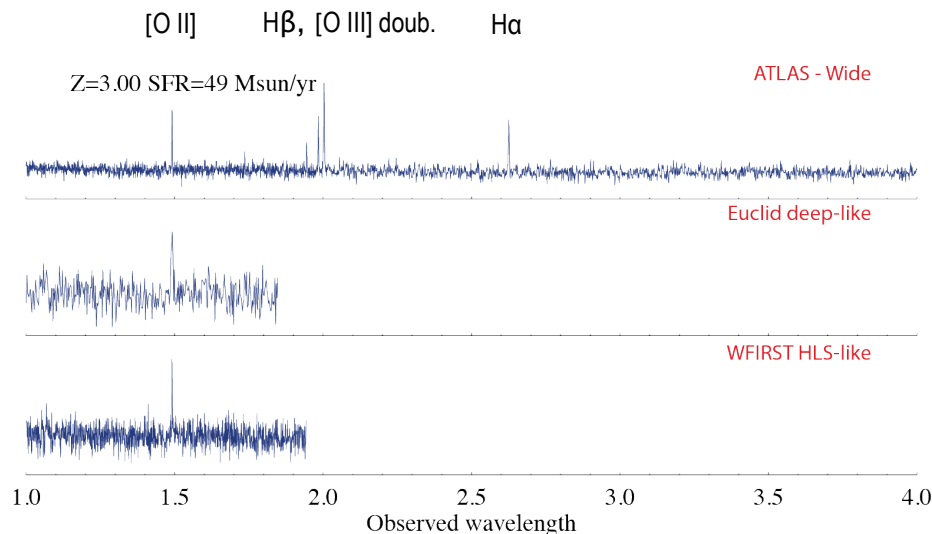
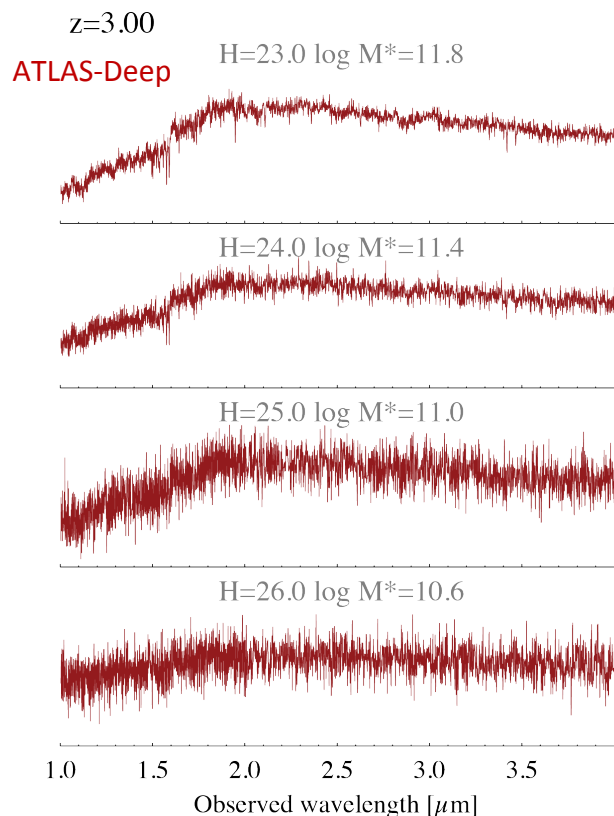


Massively parallel large area high density slit spectroscopy will be pioneered in space with ATLAS. This will revolutionize our understanding of the Universe.

(Figure by Jarle Brinchmann, adapted from Ivan Baldry's original figure)

Understanding Galaxy Evolution Requires Spectra for All Types of Galaxies

Atlas Probe will measure complete IR spectra of passive galaxies, essential for understanding ages and star formation histories.

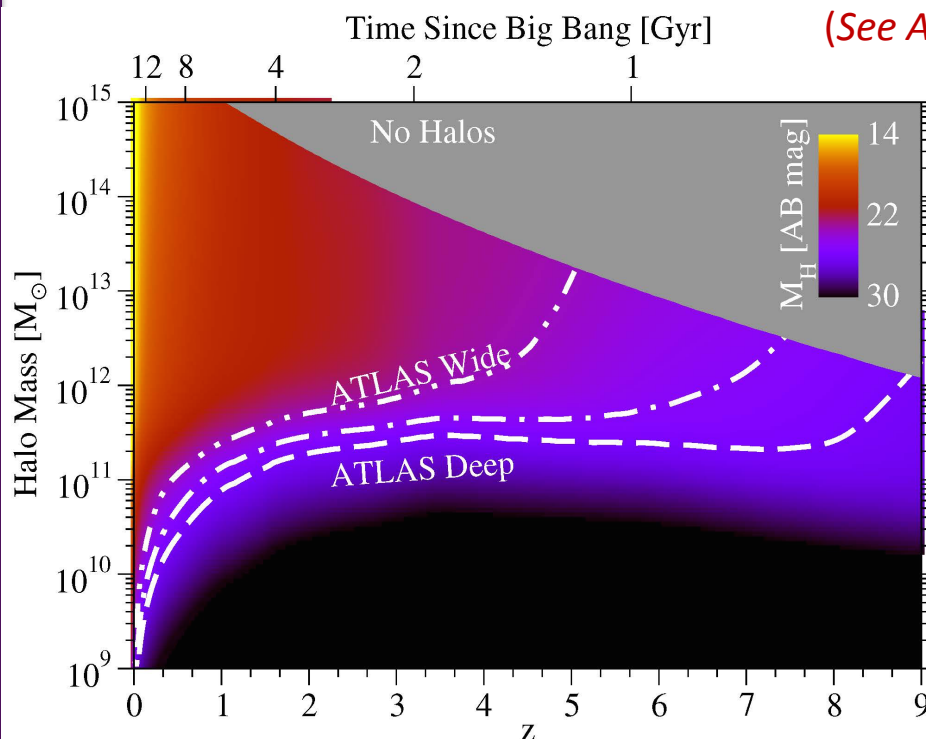


ATLAS Probe will measure spectra of star-forming galaxies with multiple emission lines, indicators of physical properties of the galaxies.

(Figures by Jarle Brinchmann)

Notes: How ATLAS Probe Decodes the Physics of Galaxy Evolution

- Decode the physics of galaxy evolution by probing the clustering of dark matter halos over a wide dynamical range.
- Allow robust statistical measurement of dark matter halo masses and other fundamental galaxy properties.
- Many open questions in galaxy formation concern how halo assembly affects galaxy properties and supermassive black hole activity.

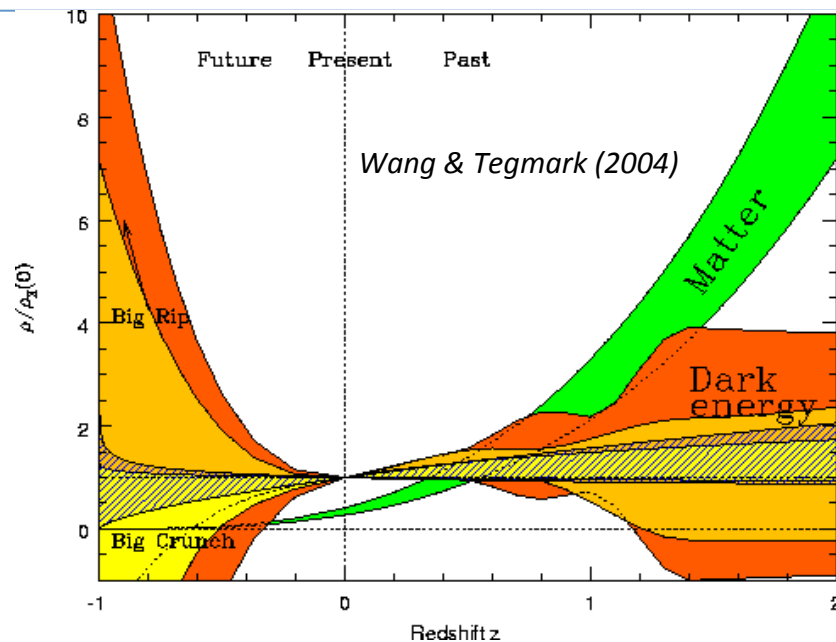
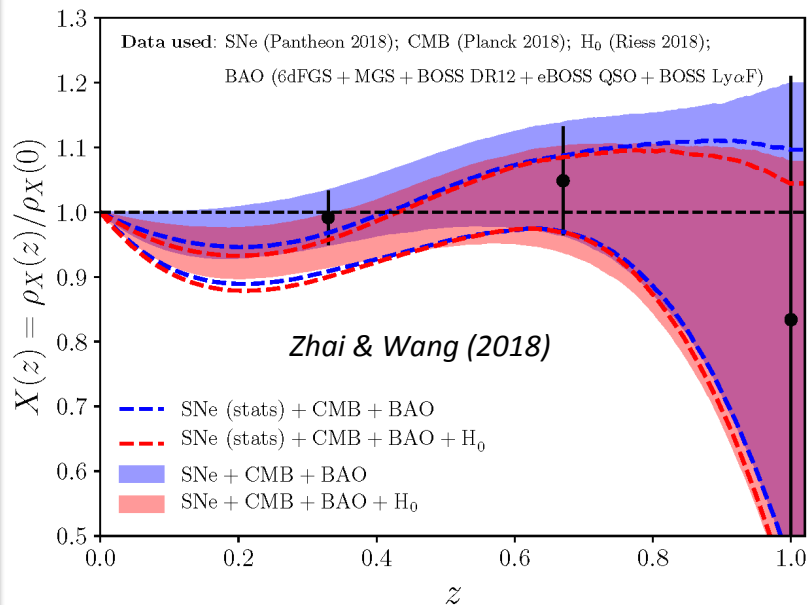


(See *Astro2020 science white paper*, Behroozi et al.)

Limiting halo masses as a function of redshift. Note that SFR (& thus luminosity L) increases nonlinearly with halo mass. Low-mass halos: a small increase in halo mass is a large increase in L , & the slope of the halo mass vs. z contour is shallow. Halo masses above $10^{12} M_{\odot}$: SFR increases much more slowly with halo mass (if at all), a large increase in halo mass leads to a small increase in L , & the slope of the halo mass vs. z contour is steep.

The Dark Energy Problem: Its Fundamental Nature & Current Status

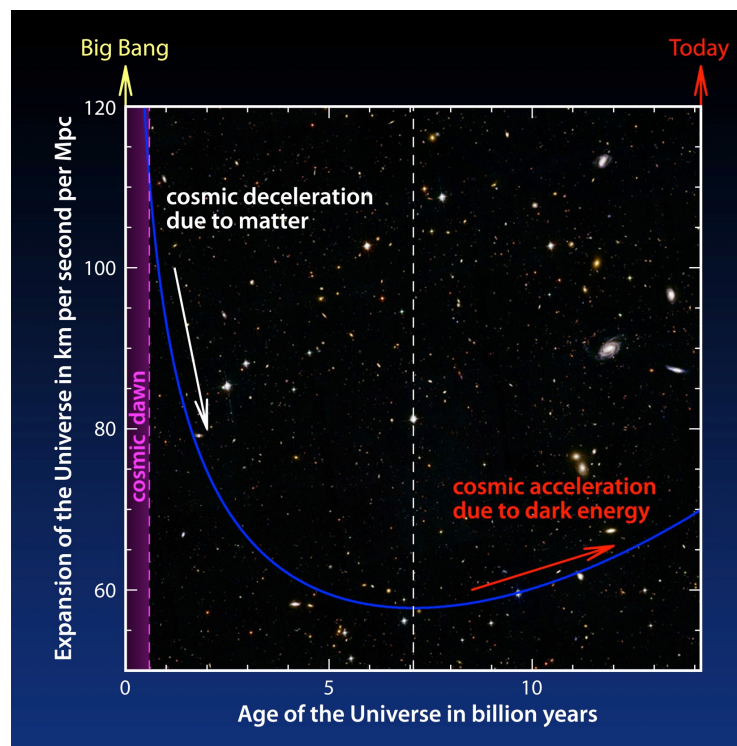
The nature of dark energy, i.e., the physical cause for the observed cosmic acceleration, will determine the ultimate fate of the Universe.



The simplest model for dark energy, the cosmological constant model, i.e., constant dark energy density $\rho_X(z)$, is consistent with current observational data, but uncertainties are large. Deviations from it have come and gone over the last two decades.

Dark Energy: a Fundamental Problem in Cosmology Today

- WFIRST, Euclid, Rubin Observatory, & DESI will significantly advance our understanding of the nature of dark energy, but do not provide definitive measurements for its resolution, due to limits inherent to each.
- A very high number density galaxy redshift survey, e.g., ATLAS Wide, is the most efficient way to illuminate the nature of dark energy (shot noise $\propto 1/n_{\text{gal}}$ for 2 pt & $\propto 1/n_{\text{gal}}^2$ for 3 pt statistics).
- ATLAS will measure dark energy definitively, with a level of precision and over a range of cosmic history not achievable with planned future surveys.



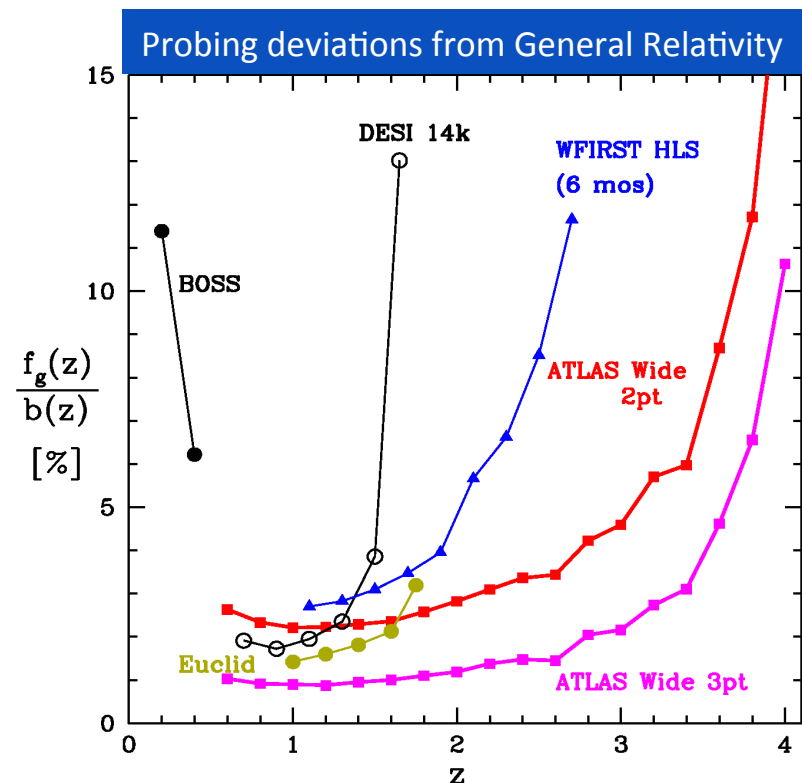
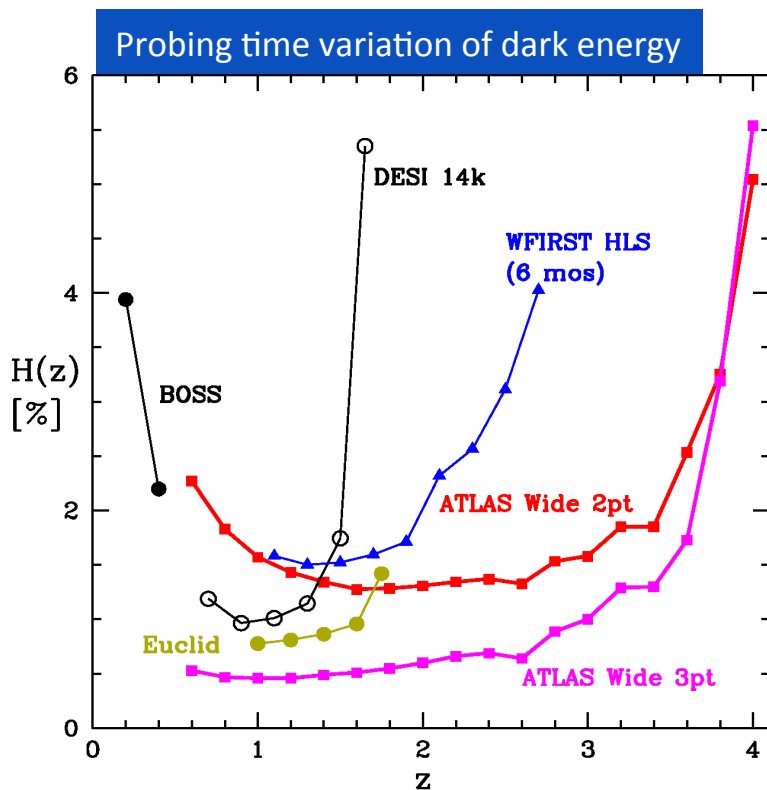
Time derivative of the cosmic scale factor $a(t)$, da/dt , vs cosmic time t .

(See Astro2020 science white paper, Wang et al.)

ATLAS Probe and Dark Energy

ATLAS Wide Survey, a high number density galaxy redshift survey, will definitively measure cosmic expansion history $H(z)$ & growth history of large scale structure $f_g(z)$, to discover whether dark energy is an unknown energy component, or the modification of General Relativity.

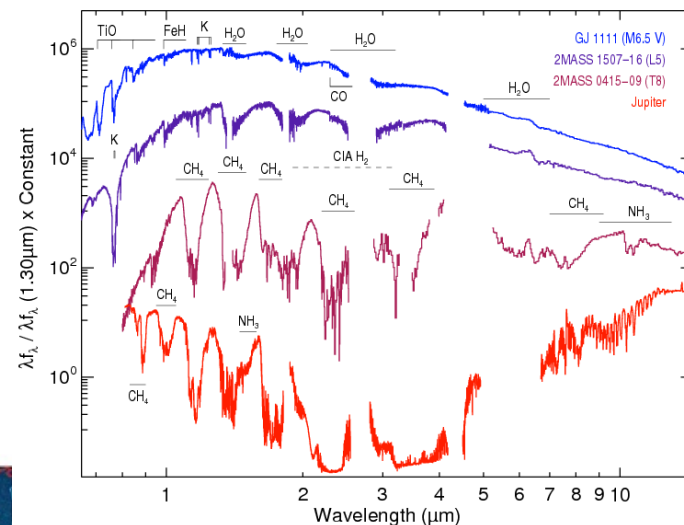
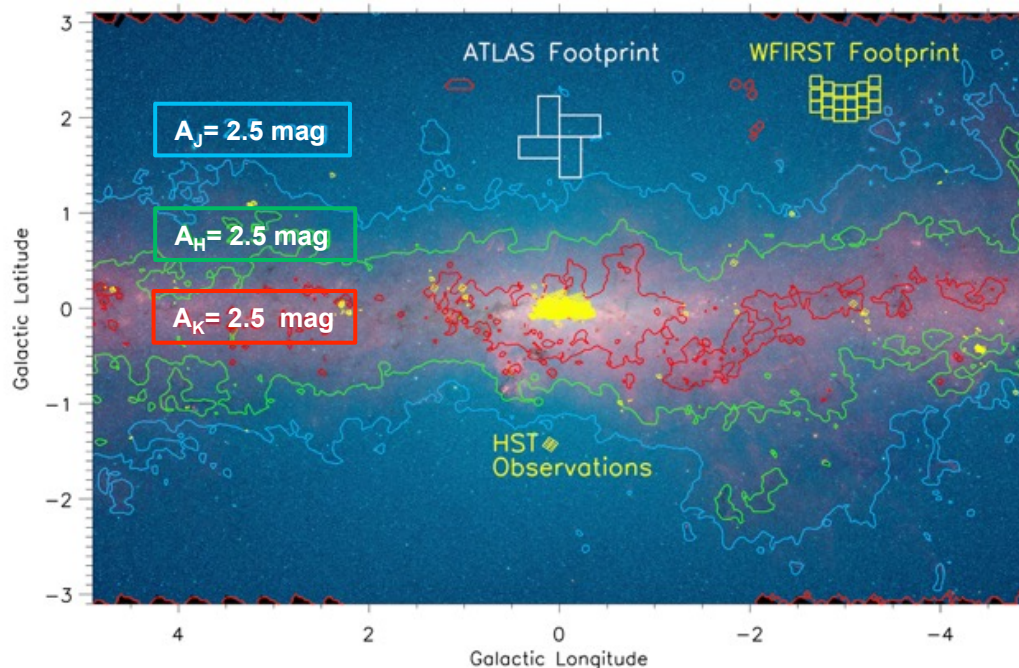
(See Astro2020 science white paper, Wang et al.)



ATLAS Probe and Milky Way Science

ATLAS Galactic Plane Survey will measure spectra of 95M stars over 700 deg² imaged by Spitzer, to map the dust-enshrouded 3D structure (via spectroscopic parallax calibrated using Gaia) and stellar content of the Milky Way to a distance of 25kpc.

ATLAS will pierce through the Galactic plane highly obscured by dust.



1-4 μm spectrum becomes richer going from M stars to brown dwarfs spectral types. Notes gaps in ground-based data in the main H₂O bands.
(Burgasser 2009)

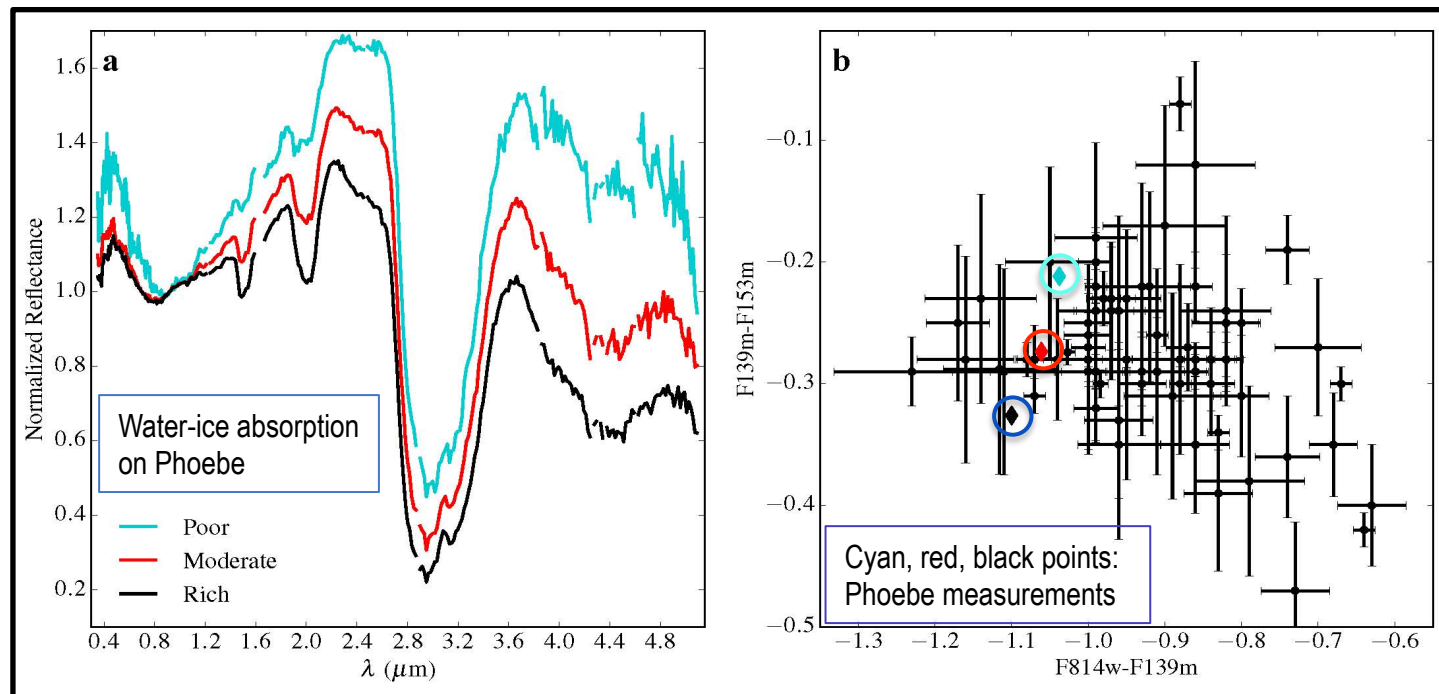
Spectroscopic information allows firm derivation of the extinction and effective temperature of the sources, and hence their position in the HR diagram.

ATLAS Probe & Outer Solar System Science

ATLAS will probe the formation history of the outer Solar System through the composition of 3,000 Kuiper Belt Objects (KBOs) from spectroscopy.

*KBOs are distributed at distances 30-50 AU from the Sun & move $\sim 1''$ - $4''$ per hour. ATLAS can take slit spectra of moving targets with regular guiding, as the $0.75'' \times 0.75''$ micromirrors can either form long slits or switch on in sequence as the target drifts across the field.

ATLAS Probe will measure the key features in the spectra of KBOs, similar to the water-ice absorption feature seen in the spectra of Phoebe.



* Phoebe is a good KBO analog, based NIR colors of KBOs from HST WFC3

ATLAS Science Traceability Matrix

Flow-down of ATLAS Science Goals to Science Objectives, to Science Requirements, to Instrument Requirements, to top level Mission Functional Requirements.

ATLAS Probe Science Traceability Matrix

Science Goals	Science Objectives	Science Requirements		Instrument Requirements		Mission Functional Requirements (Top-Level)
		Science Observable	Measurement Requirement	Technical Parameter	Technical Requirement	
1. Discover how galaxies have evolved in the cosmic web of dark matter from cosmic dawn through the peak era of galaxy assembly	1A. Trace the relation between galaxies and dark matter with less than 10% shot noise on relevant scales at $1 < z < 7$ 1B. Probe the physics of galaxy evolution at $1 < z < 7$	1A. Galaxy bias as a function of clustering length scale 1Ba. Galaxy metallicity 1Bb. Star formation rate (SFR) in galaxies 1Bc. Galaxy kinematics	1A. Measure redshifts for 200M galaxies in 3 tiered surveys at $1 < z < 7$ using H α or [OIII] 1Ba. Detect the main optical diagnostic lines (H α when available, H β , [O III]5007, [O II]3727) 1Bb. Measure emission line flux for 300k galaxies down to 5×10^{-19} erg/s/cm 2 (SFR $\sim 0.1 M_{\odot}$ /yr at $z = 2$) 1Bc. Measure the emission line widths and/or stellar velocity dispersion of galaxies with mass $> \text{TBD}$	Wavelength range	1-4 μm	Telescope aperture: 1.5m Observing strategies: TBD Launch Window: TBD Mission Life to complete Science Requirements: 5 years Desired Mission Life or Extended Mission Life: 10 years Observatory will orbit L2
				Spatial resolution	$\theta_{\text{pix}} < 0.5''$ at 1 μm	
				Spectral resolving power	$\lambda/\Delta\lambda = 1000$	
				Spectroscopic multiplex	> 5000	
				Spectroscopic sensitivity	5×10^{-18} erg/s/cm 2 in < 1.5 hrs	
				Field of view	$> 0.15 \text{ deg}^2$	
				Survey area and depth	$z < 4 : 2000 \text{ deg}^2$ to AB=23 (3 σ) $z < 5.5 : 100 \text{ deg}^2$ to AB=24.5 (3 σ) $z < 7 : 1 \text{ deg}^2$ to AB = 25.5 (3 σ)	
2. Discover how the dark matter filaments have grown in the cosmic web, and the nature of cosmic acceleration	2A. Measure the mass of dark-matter-dominated filaments in the cosmic web on the scales of 5-50 Mpc/h over $2,000 \text{ deg}^2$ at $0.5 < z < 3$ 2B. Obtain definitive measurements of dark energy and tests of General Relativity	2. Redshifts of massive galaxies from the WFIRST High Latitude imaging survey	2. Measure redshifts for galaxies with dark matter halo mass $\geq 10^{13} M_{\odot}$ in the 2000 deg^2 WFIRST weak lensing imaging sample	Wavelength range	1-2.5 μm	Observatory will accommodate 4 identical spectrographs, each with an imaging mode for calibration and target verification
				Spatial resolution	$\theta_{\text{pix}} < 0.5''$ at 1.6 μm	
				Spectral resolving power	$\lambda/\Delta\lambda > 600$	
				Spectroscopic multiplex	> 5000	
				Field of view	$> 0.15 \text{ deg}^2$	
				Survey area	2000 deg^2 to AB=23 (3 σ)	
3. Probe the Milky Way's dust-enshrouded regions, reaching the far side of our Galaxy	3. Measure the dust-enshrouded 3D structure and stellar content of the Milky Way to a distance of 25 kpc	3. Spectral types and radial velocities of stars in the inner Galaxy	3. Measure spectra of stars toward the Galactic Center	Wavelength range	1-4 μm	
				Spectral Resolving power	$\lambda/\Delta\lambda = 1000$	
				Spectroscopic multiplex	> 1000	
				Field of view	$> 0.1 \text{ deg}^2$	
				Survey area	700 deg^2 to AB=18.2 (30 σ)	
4. Discover the bulk compositional building blocks of planetesimals formed in the outer Solar System	4. Detect and quantify the composition of 3,000 planetesimals in the outer Solar System	4. Spectra of Kuiper Belt Objects (KBOs)	4. Measure the spectral features for KBOs: silicates (olivine 1 μm & 3.3 μm); pyroxene (0.9 & 3.3 μm); water ice (1.6 μm , 2.0 μm , 3.2 μm); PAH materials (C-H vibration bands and overtones (2.1-2.4 μm , 1.8 μm , 1.6 μm); ethane, methane (~2.5 μm)	Wavelength range	1-4 μm	
				Spectral Resolving power	$\lambda/\Delta\lambda = 100-500$	
				Slit tracking	4" per hour	

(With input from Ball Aerospace)

ATLAS Probe Capability Meets Science Objectives

ATLAS Probe science requires massively parallel slit spectroscopy from space with a wide FoV, at high galaxy number densities, to cover a large redshift range over a large area:

ATLAS Parameter		Notes
Aperture	1.5m	Probe-class mission, can launch in 2030
Field of View	0.4 sq deg	Slitsize 0.75"× 0.75", 0.38" detector pixels
Wavelength range	1-4 μm	Near and mid IR spectroscopy & imaging, PSF (FWHM) = 0.14"($\lambda/\mu\text{m}$)
Spectral Resolution	$R \sim 1000$	Heritage of mature designs
Multiplex factor	6,000	Uses Digital Micromirror Devices (DMDs)
# of galaxy spectra	200M in 4 yrs	3-tiered galaxy surveys: 23, 24.5, 25.5 AB (3σ)
Redshift range	$0.5 < z < 7+$	Emission line and passive galaxies
Estimated cost	< \$1B	DMDs can reach TRL 6 within Phase A

ATLAS Probe Capability: Unique & Powerful

- The big gap in current and planned future space missions is massively parallel slit spectroscopy from space over a wide FoV. It is filled by ATLAS with an unprecedented spectroscopic capability.
- In addition to meeting its science goals, ATLAS will be a powerful Guest Observatory for a wide range of additional science, e.g., exoplanet spectroscopy, transients monitoring, and resolved object spectroscopy of nearby galaxies.

Mission	λ (μm)	R	FoV/ (deg) ²	Cont. AB mag	line flux erg/s/cm ²	N _{gal}	Aper (m)	cost	Launch date
ATLAS	1-4	1000	0.4	23 (3σ) 24.5 (3σ) 25.5 (3σ)	5e-18 (5σ) 1.2e-18 (5σ) 4.6e-19 (5σ)	183M 17M .31M	1.5	<\$1B	2030
WFIRST	1-1.9	460/slitless	0.281	20.5 (7 σ)	1e-16 (6.5 σ)	~10M	2.4	\$3.2B	2025
SPHEREx	0.75 -5	41-130 slitless	39.6	19.1-19.6 (5 σ) R=41	N/A	[6" pix]	0.2	\$250M +ELV	2023
Euclid	0.92 -1.85	380 slitless	0.53	20, 21.3 (3.5 σ)	2e-16, 6e-17 (3.5 σ)	~20M	1.2	1B Euros	2022
JWST NIRSpec (10 ⁵ s)	0.6 -5.3	100, 1000, 2700	.0034	25.3 (10 σ)	3.5e-19 (10 σ)	< 1M	6.5	\$10B	2021

- Mission Science Goals
- **Mission Implementation**
- Cost and Schedule Estimates
- Community Support
- Summary

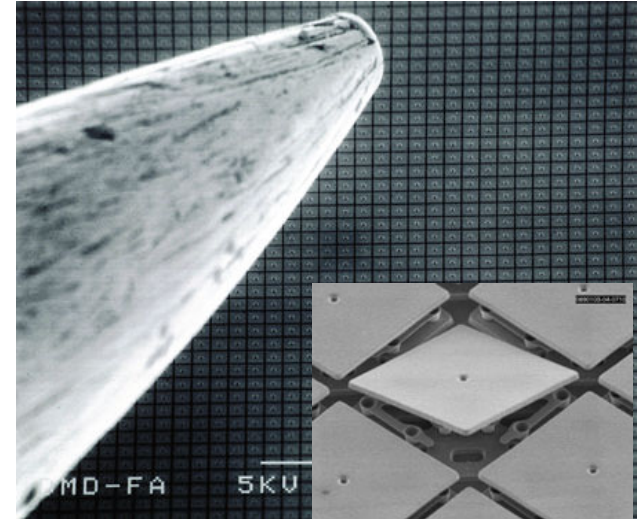
Overview of Implementation

- ATLAS Probe has a single spectroscopic instrument with 4 identical modules
- ATLAS Probe system is simple & straightforward for a probe mission
- ATLAS Probe has a low level of technical risk, with its least mature technology at TRL 5 (DMDs)

ATLAS Probe Enabling Technology: Digital micromirror Devices

DMD Facts:

- A microelectrical mechanical system (MEMS) built on the top of a memory array, as a spatial light modulator
- Each micromirror tips about the diagonal $\pm 12^\circ$ (“On” and “Off” positions). “On” selects target for spectroscopy; “Off” sends the light to the light dump.
- DMDs come in different formats.
- Tens of millions of units have been produced for the consumer market, e.g., for use in overhead projectors.



ATLAS DMDs:

- Texas Instrument Cinema 2K model, TRL 5
- 2048×1080 elements
- Square mirrors, 13.7 μ m side
- 92% filling factor

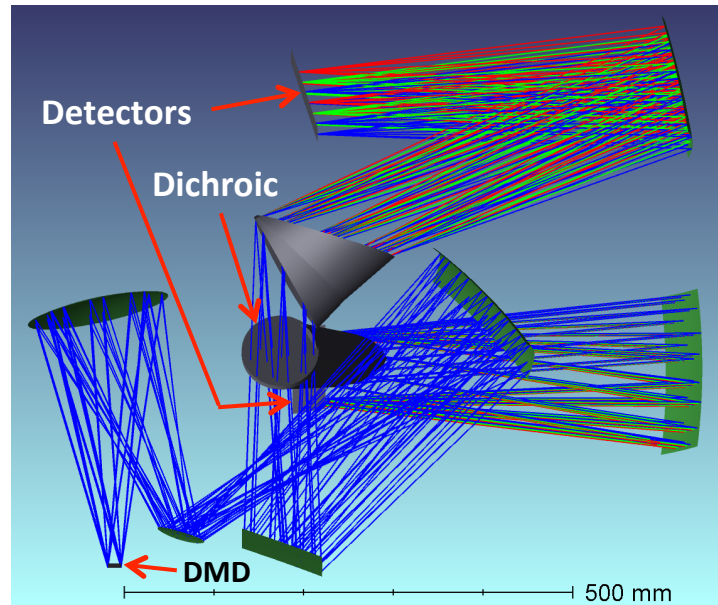
Each DMD consists of >2M micromirrors, providing great capacity for multiplexed “slit” spectroscopy.



Promising Technology: Digital Micromirror Devices (DMDs)

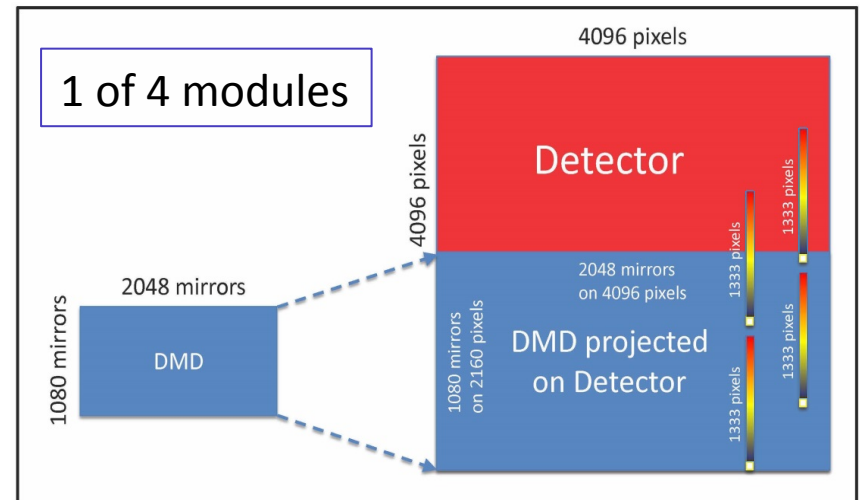
- **Commercial Off-the-Shelf (COTS) product by Texas Instrument**
 - Candidate slit selector (new devices, not COTS) studied in 2002 for JWST
 - DMD-based multi-object spectrographs (MOS) have been built for ground-based telescopes: RITMOS (Mees Observatory 24 inch, 2003) and IRMOS (0.8-2.5 microns on KPNO 4m, 2004), both with 848x600 TI DMD
 - Gemini funded study in 2015 for a \$15M Gemini MOS with 2048x1080 TI DMDs
 - NSF funded a \$1.5M project (9/2016-8/2018) to build a MOS for SOAR (4.1m), with 2048x1080 TI DMD (PI Robberto, ATLAS Probe Instrument Lead)
 - **NASA funded Strategic Astrophysics Technology (SAT) programs (PI Ninkov, ATLAS Probe core team member), which raised the TRL level of DMDs to TRL5-6, as input to 2020 decadal survey.**
- **COTS 1024x768 DMDs: TRL 6.**
 - Tests Passed: Vibration, EM Interference, Radiation (protons, heavy ions & gamma), Low T (63K-77.2K)
 - **COTS 2048x1080 DMDs (identical in architecture) used by ATLAS: TRL 5**

ATLAS Probe Preliminary Optical Design

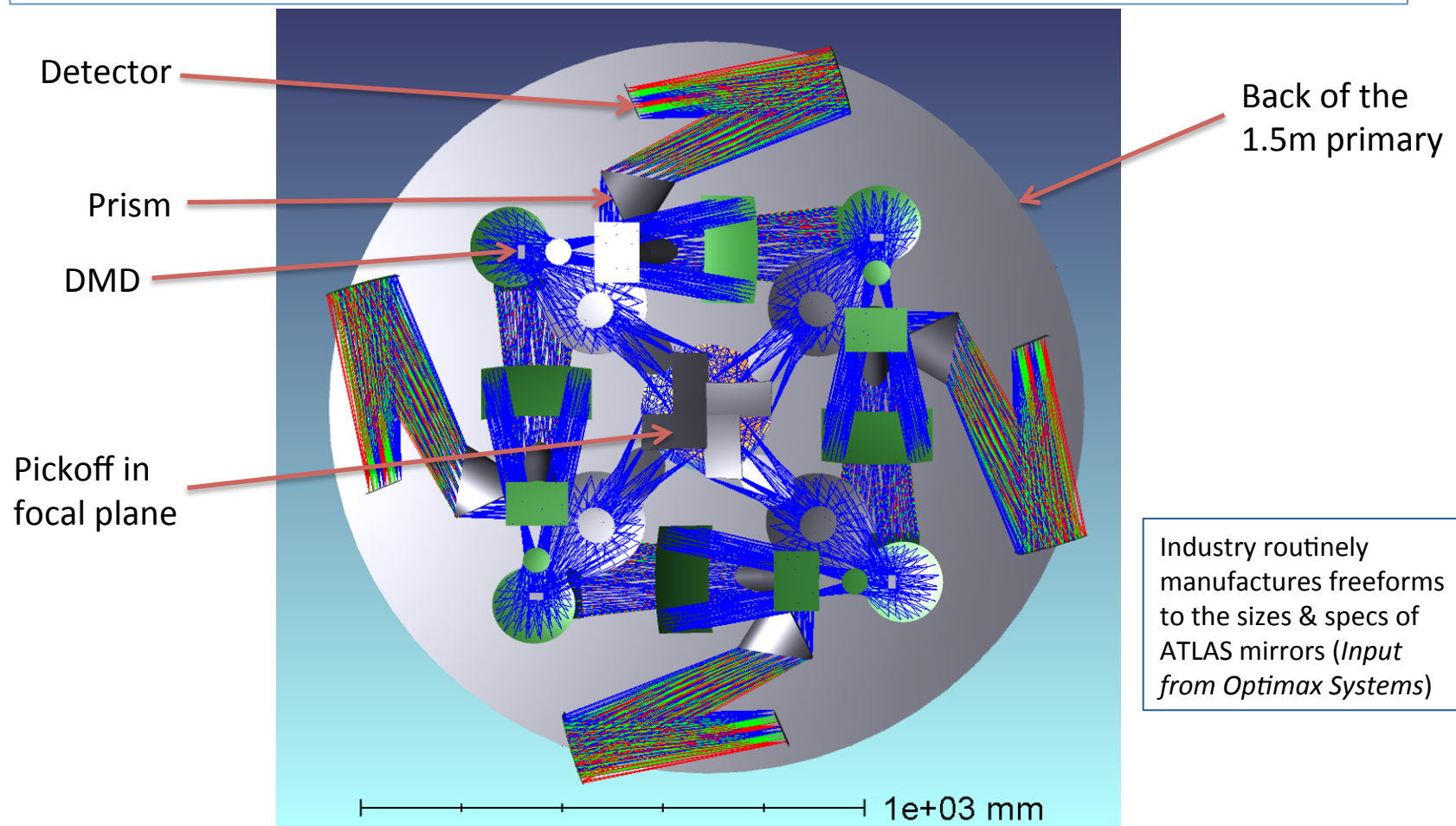


- A single instrument with 4 identical modules
- Each module has two channels (1-2 μ m & 2-4 μ m). The dichroic reflects the blue channel & transmit the red channel.
- Imaging (calibration & targeting) via use of a zero dispersion grism in the blue channel.
- Each DMD maps to an IR H4RG detector in a spectrograph channel. Spatial sampling: 2x2 pixels per micromirror.

Spectroscopic multiplex factor is determined by detector pixel count & spectrum length (~1333 pixels at R=1000, 2 pix/per spec res element), and the avoidance of opening micromirrors in adjacent columns (to avoid overlap between parallel spectra):
 $[2048/2 \text{ mirror col}] * 1.5 * [4 \text{ modules}] \sim 6000$



ATLAS Probe Preliminary Optical Design



This preliminary optical design (by Robert Content) meets all ATLAS science requirements.

ATLAS Probe Mission Profile

ATLAS Probe: 5 Year Prime Mission

Surveys	Observing Time	Area (deg ²)	Number of sources	Per-target Exp. Time*	Trackback to Science Objectives
ATLAS Wide	32%	2000	183M	5000s	Objectives 1 & 2
ATLAS Medium	42%	100	17M	7.7×10^4 s	Objective 1
ATLAS Deep	4%	1	0.3M	4.7×10^5 s	Objective 1
ATLAS Galactic Plane	8%	700	95M	800s	Objective 3
ATLAS Solar System	4%	1200	> 3000	2500s	Objective 4
Guest Observers	10%				

*Per-target exposure time at the faint limit. Bright targets are rotated off in successive visits to a field.

ATLAS Probe: 5 Year Extended Mission

Surveys	Observing Time
Guest Observers	100%

ATLAS Probe Mission Architecture

- Mission:
 - Astrophysics pointed IR spectroscopic observatory
 - L2 Orbit
 - Class B Mission
 - Dual string spacecraft bus
- Constraints:
 - Tight pointing stability
 - Driven by slit size of 0.75"
 - Requires $< \pm 0.375''$ 3-sigma over $\sim 200s^*$
 - $< \sim 80$ K detector temperature (in family with other passively cooled probes)
 - Sunlight cannot contact telescope
 - Long dwell time (up to days)
- Measurement:
 - 4 identical spectrometers to cover 1-4 microns
- Data Volumes
 - ~ 600 Mb every 500 seconds, for 170 samples/day
 - ~ 186 Tb over 5 years
- Commanding Requirements
 - Weekly commanding cycle once on orbit

**Spitzer achieved an in-flight absolute pointing accuracy of 0.45" (1σ , radial) & 0.02" stability (1σ , radial) over 500s*

Notes: ATLAS Probe Design Assumptions

- Assume thermal solutions for other Probe-class missions will be sufficient for ATLAS's 4 spectrometers
- Observation requirements may mean that required thermal shields and solar panels could be limited by the fairing size
- Assume that solar panels can be integrated with bottom sun shield / bottom deck of spacecraft. If instrument power requirements are too high there could be cost/mass penalties.

Notes: ATLAS Probe Ground System

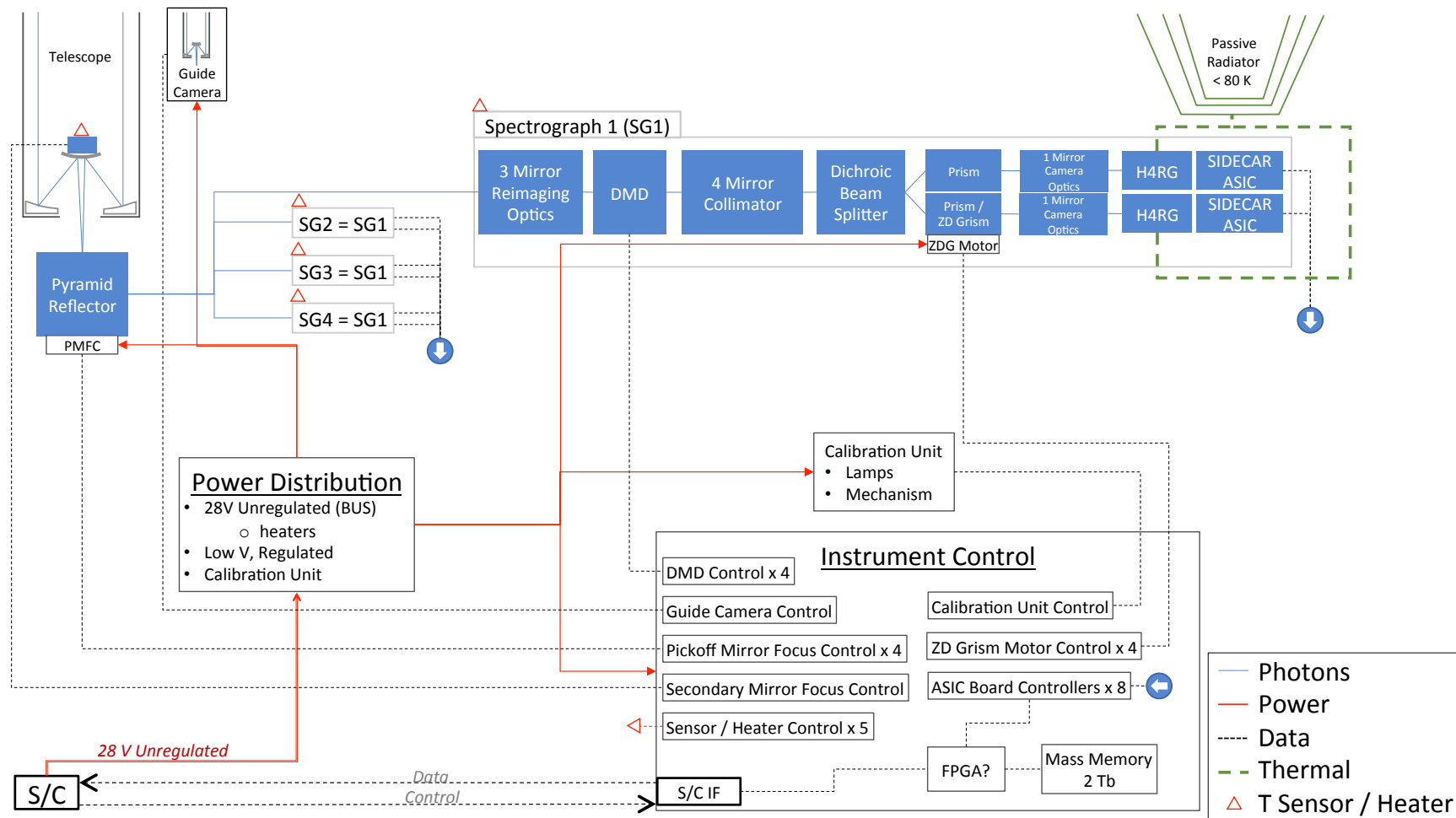
- DSN 34m BWG subnet
- Near Earth Ka-band for High Rate science downlink, 150 Mb/s data rate, including protocol overhead this becomes effectively 130 Mb/s science downlink
- Uplink and engineering data can be X-/S-band via S/C LGA
- During cruise, assume 2-3 passes per week

Notes: ATLAS Mission Design & Navigation

- Delta V Budget
 - TCM 1 Clean up 25m/s
 - Halo orbit insertion + Clean up 25m/s
 - Station Keeping /year 4m/s
 - **Total over 5 years 70m/s**

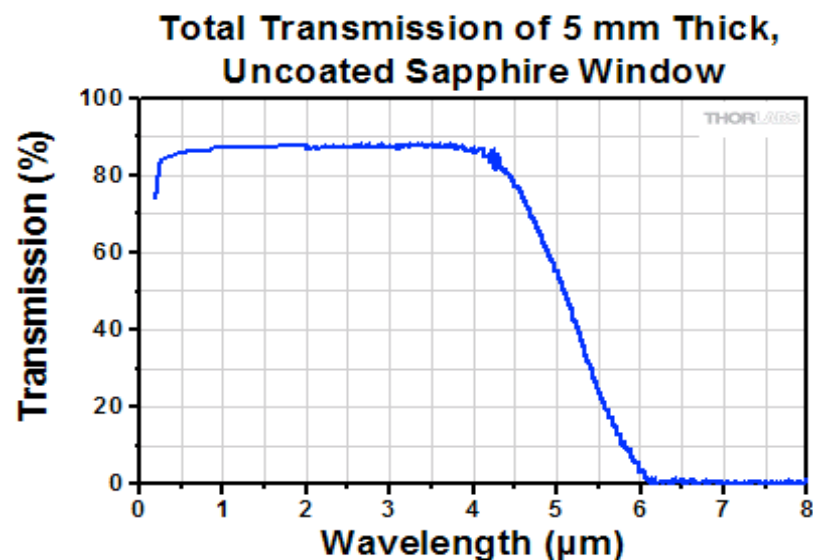
ATLAS Probe Block Diagram

**ATLAS Probe system is simple & straightforward for a probe mission*



ATLAS Probe Technical Risks

- **ATLAS has a low level of technical risk, with its lowest TRL technology at TRL5 (DMDs), and a clear path forward to advance it to TRL 6 within Phase A.**
 - The COTS DMD is adequate for the 1-2 μm channel
 - The 2-4 μm channel requires re-windowing of the COTS DMD, a procedure already developed by the RIT group lead by ATLAS Probe Co-I Ninkov.



Single-pass transmission for sapphire window. This window would also be AR coated to optimize throughput in the ATLAS band of interest (2-4 μm).

- ATLAS detectors are HgCdTe H4RGs, with wavelength cutoffs similar to that of WFIRST & JWST detectors respectively. Input from industry indicates that ATLAS H4RG detectors should be straightforward to manufacture.

- Mission Science Goals
- Mission Implementation
- **Cost and Schedule Estimates**
- Community Support
- Summary

ATLAS Cost Estimation Methodology

- Telescope OTA from Stahl Model
- Spectrometer(s) cost distribution scaled from other Probe class missions and JPL rules of thumb
- Spacecraft based on triangular distribution of Probe class spacecraft buses
- Mission Operations and Ground Data System costed by JPL subsystem engineers
- WBS elements 1-4 (Project Mgmt., Project Sys. Eng., Safety & Mission Assurance, Science) and 10 (Project Sys. I&T) based on their historical relationship to WBS 5 (Payload Sys.) & 6 (Spacecraft Sys.)
- Standard schedule used for all Probe class missions applied

ATLAS Instrument Mass Estimation Methodology

- Scale results from previous Astrophysics Probe study results
 - Single spectrometer mass and costs scaled by number of detectors
 - Total 4 identical Spectrometers using 2 H4RG detectors each
 - Scale focal plane mass/costs from similar study with H2RG detectors
 - Rules of thumb applied to calculate spectrometer mass and costs from focal plane mass/cost
 - Telescope mass calculated from telescope diameter
 - Linear fit calculated on previous study results to get mass as function of diameter
 - Error in fit used to calculate max and min probable mass
- Payload mass sum of 4 spectrometers plus telescope
 - Given are estimated minimum, mode, and maximum payload mass (backup slide #48)

ATLAS Spectrometer Cost Estimate

- Focal plane costs scaled off # of detectors compared to similar study
- Rules of thumb applied to get from Focal Plane costs to First unit Spectrometer cost
- Other 3 spectrometers assumed to be 40% of initial unit costs
- Estimates for minimum, mode, and maximum cost are given

Focal Plane Cost (NICM Detector)	4 Spectrometers min cost (\$M)	4 Spectrometers mode cost (\$M)	4 Spectrometers max cost (\$M)
5.9	75.5	116.7	213.9

The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

ATLAS Probe Cost Estimate

WBS No.	WBS Title	Cost Estimate Method	MIN	A-D MODE	MAX	E-F
01	Project Mgmt.	% Wrap based on other studies	\$9.5	\$14.0	\$22.5	\$4.3
02	Project Sys. Eng.	% Wrap based on other studies	\$12.5	\$18.5	\$29.7	
03	S&MA	% Wrap based on other studies	\$12.9	\$19.2	\$30.7	
04	Science	% Wrap based on other studies	\$12.5	\$18.5	\$29.7	\$31.8
05	Payload Sys.	Subtotal of below	\$105.2	\$147.6	\$247.7	
05.01	Payload Sys. Mgmt.	% Wrap based on other studies	\$1.7	\$2.4	\$4.0	
05.02	Payload Sys. Eng.	% Wrap based on other studies	\$1.4	\$1.9	\$3.2	
05.04	Optical Instrument	Instrument ROT	\$75.5	\$116.7	\$213.9	
05.05	Telescope	Stahl Model	\$26.6	\$26.6	\$26.6	
06	Spacecraft Sys.	\$/kg from other studies	\$140.1	\$216.4	\$335.8	
07	MOS	% Wrap based on other studies	\$18.6	\$18.6	\$18.6	\$16.4
08	LVS	AO provided				\$150.0
09	GDS	% Wrap based on other studies	\$19.5	\$19.5	\$19.5	\$6.7
10	Project Sys. I&T	% Wrap based on other studies	\$15.1	\$22.4	\$35.8	
	Reserves	% Wrap based on other studies	\$103.7	\$148.4	\$231.0	\$8.9
	Total	Total of above	\$449.4	\$643.1	\$1,001.0	\$218.1
Total A-F			\$667.5	\$861.2	\$1,219.1	
Cost Target (incl LV)			\$1,000.0	\$1,000.0	\$1,000.0	
A-D Reserves	30%	Difference	\$332.5	\$138.8	-\$219.1	
E-F Reserves	15%					

Cost estimates indicate that ATLAS is in-family with other Probe Class missions

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ATLAS Probe Schedule

- The schedule is estimated from JPL schedule reference model, based on prior successful missions of similar scope.
- The schedule includes one month schedule reserves for each year in development with 2 months held in ATLO which are fully funded reserves and included in the cost estimate.

Schedule in Months	
Phase A	12
Phase B	12
Phase C	22
Design	10
Fabrication	6
Subsystem I&T	6
Phase D	18
System I&T	14
Launch Operations	4
Phase E	60
Phase F	4

- Mission Science Goals
- Mission Implementation
- Cost and Schedule Estimates
- **Community Support**
- Summary

ATLAS Probe Community Support

- Core team including leading scientists and instrumentalists
- Open collaboration: Anyone can propose to join the ATLAS Probe Collaboration and contribute to the science investigation
- Participation of prominent European scientists
- Possibility of becoming an ESA Mission of Opportunity (\$50M)
- Current optical design funded by Australian Astronomical Optics at Macquarie University
- Current mission study funded by JPL
- First community workshop, “Massively Parallel Large Area Spectroscopy from Space”, was held at Caltech in October 2018, with ~80 US and foreign participants (the majority of them from the community)

- Mission Science Goals
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ATLAS Probe Summary

- **ATLAS mission addresses fundamental questions in astrophysics**
 - Decodes the physics of galaxy evolution in the cosmic web (science driver)
 - Delivers definitive measurements of dark energy
 - Probes dust-enshrouded Inner Galaxy & the uncharted Outer Solar System
- ATLAS mission implementation is expected to be straightforward
 - Simple concept for a probe mission: a single spectroscopic instrument with 4 identical modules
 - Key technology: DMD, at TRL 5, can reach TRL 6 within Phase A
 - No significant technical risks
 - Launch ready < 2030
- Cost and schedule estimates are compliant with a probe class mission
- Community support for ATLAS Probe is strong and broad
- **Ready to develop & submit the ATLAS Probe mission proposal if NASA issues the AO for probe missions**