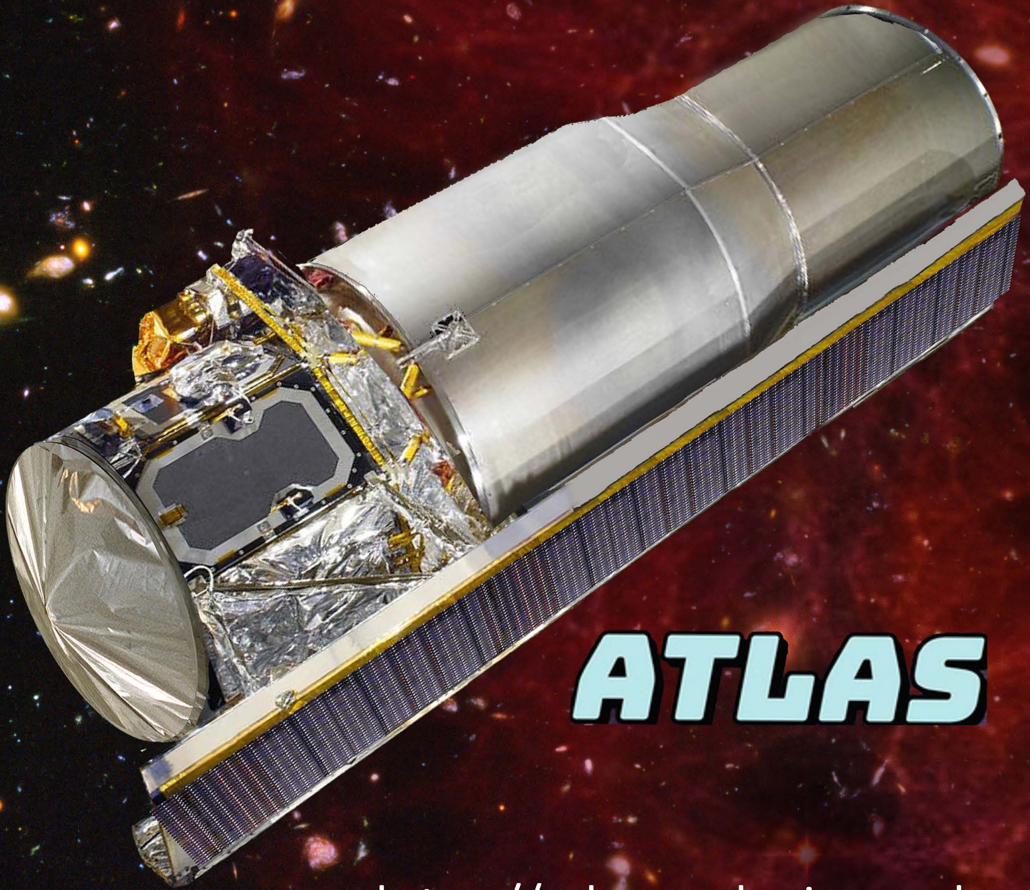
Astrophysics Telescope for Large Area Spectroscopy

Yun Wang (Caltech/IPAC)
on behalf of the ATLAS Probe Team

2nd ATLAS Probe Community Workshop, June 21, 2021

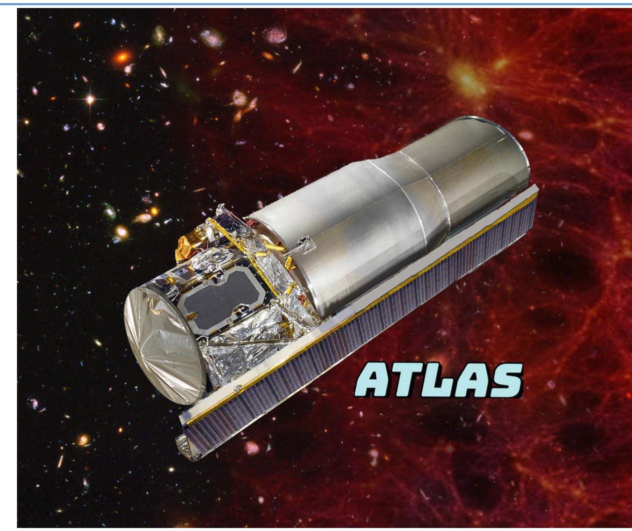


ATLAS

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

ATLAS Probe Overview

- 1.5m aperture telescope with 0.4 deg^2 FoV
- R = 1000 slit spectroscopy over 1-4μm
- 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

ATLAS Probe Team

PI: Yun Wang (Caltech/IPAC)

Instrument Lead: Massimo Robberto (STScI)

Science Leads: Mark Dickinson (NOAO), Lynne Hillenbrand (Caltech)

Deputy Science Leads: Lado Samushia (Kansas State), Claudia Scarlata (Umin)

Core Team: Lee Armus (IPAC), James Bartlett (JPL), Peter Behroozi (UA), Robert Benjamin (UWW), Jarle Brinchmann (Porto/Leiden), Ranga Chary (IPAC), Andrea Cimatti (Bologna), Charlie Conroy (Harvard), Robert Content (AAO), Emanuele Daddi (CEA), Megan Donahue (MSU), Olivier Dore (JPL), Peter Eisenhardt (JPL), Andreas Faisst (Caltech/IPAC), Harry Ferguson (STScI), Wesley Fraser (NRC/Canada), Karl Glazebrook (Swinburne), Anthony Gonzalez (UF), Varoujan Gorjian (JPL), George Helou (IPAC), Chris Hirata (Ohio State), Michael Hudson (Waterloo), Davy Kirkpatrick (IPAC), Sangeeta Malhotra (GSFC), Lauro Moscardini (Bologna), Zoran Ninkov (RIT), Michael Ressler (JPL), James Rhoads (GSFC), Jason Rhodes (JPL), Andrew S. Rivkin (JHU), Michael Seiffert (JPL), Alice Shapley (UCLA), Stephen Smee (JHU)

Collaborators: Mario Ballardini (Western Cape), Andrew Benson (Carnegie), Chia-Hsun Chuang (Stanford), Pablo Arrabal Haro (NOAO), Andrew Hearin (ANL), Jon Lawrence (AAO-MQ/Australia), Simona Mei (Paris), Chirag Modi (Flatiron), Jeffrey Newman (Pittsburgh), Alvaro Orsi (CEFCA), Alice Pisani (Princeton), Alvise Raccanelli (Padova), Russell Ryan (STScI), Daniel Scolnic (Chicago), Zachary Slepian (UF), Francesco Valentino (Copenhagen), Dmitry Vorobiev (Colorado), Risa Wechsler (Stanford), Zhongxu Zhai (Caltech/IPAC), …

Outline

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

ATLAS PROBE

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

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

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

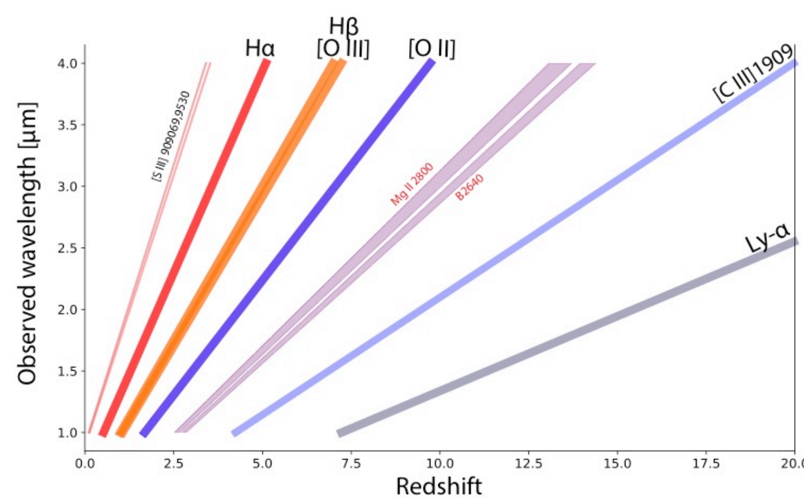
- Trace the cosmic web in detail over cosmic history.
- Reveal how the evolution of galaxies depends on their environments.
- Connect galaxy properties to statistical measurements of dark matter halo masses.
- Extend the redshift baseline of all SDSS-like galaxy science (high number density and all spectral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

ATLAS notional 3-tiered Galaxy Survey

Survey	Area / deg^2	Depth*		N_{gal}
		Em. Line	Cont.	
Wide	**2000****	**5×10^{-18}**	**23.0**	**183M**
Medium	**100**	**1.2×10^{-18}**	**24.5**	**17M**
Deep	**1**	**4.6×10^{-19}**	**25.5**	**.31M**

**Line Flux in erg/s/cm^2 (5σ), Continuum in AB mag (3σ)*

*** **ATLAS-Wide** would cover the Roman Space Telescope High Latitude Wide Area Survey*



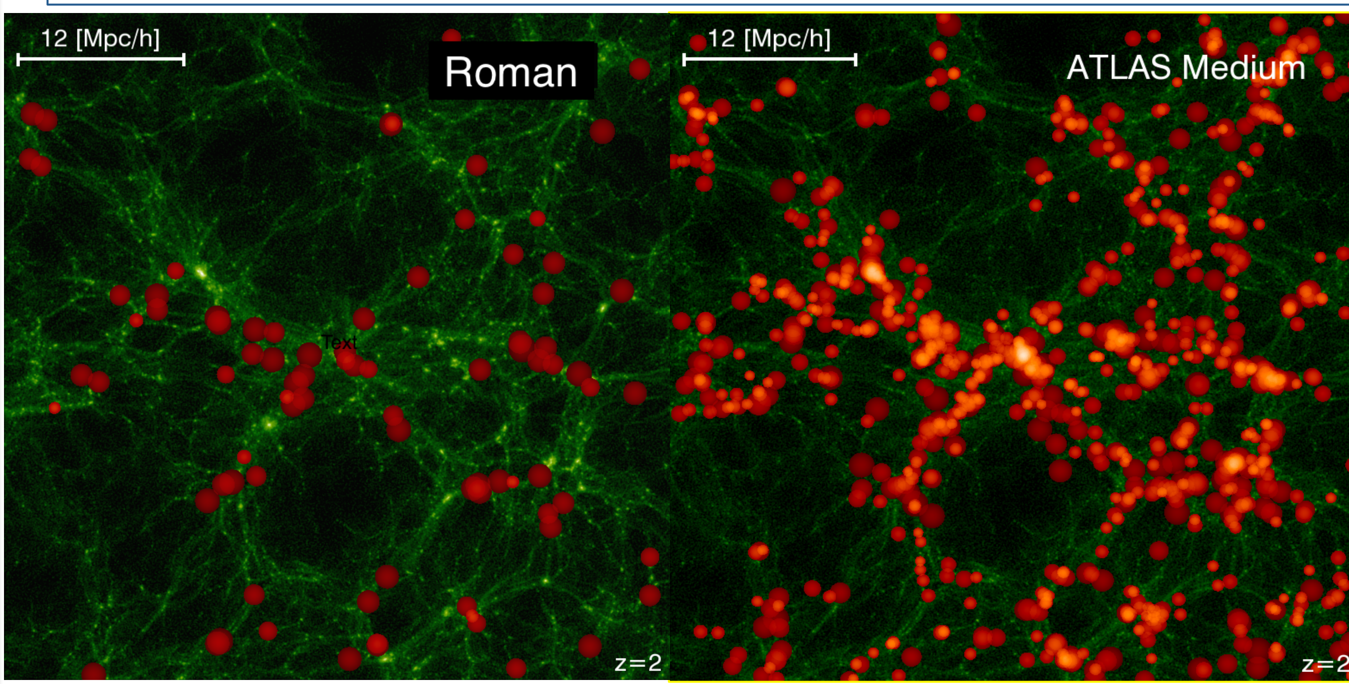
ATLAS Probe Maps the Cosmic Web

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.



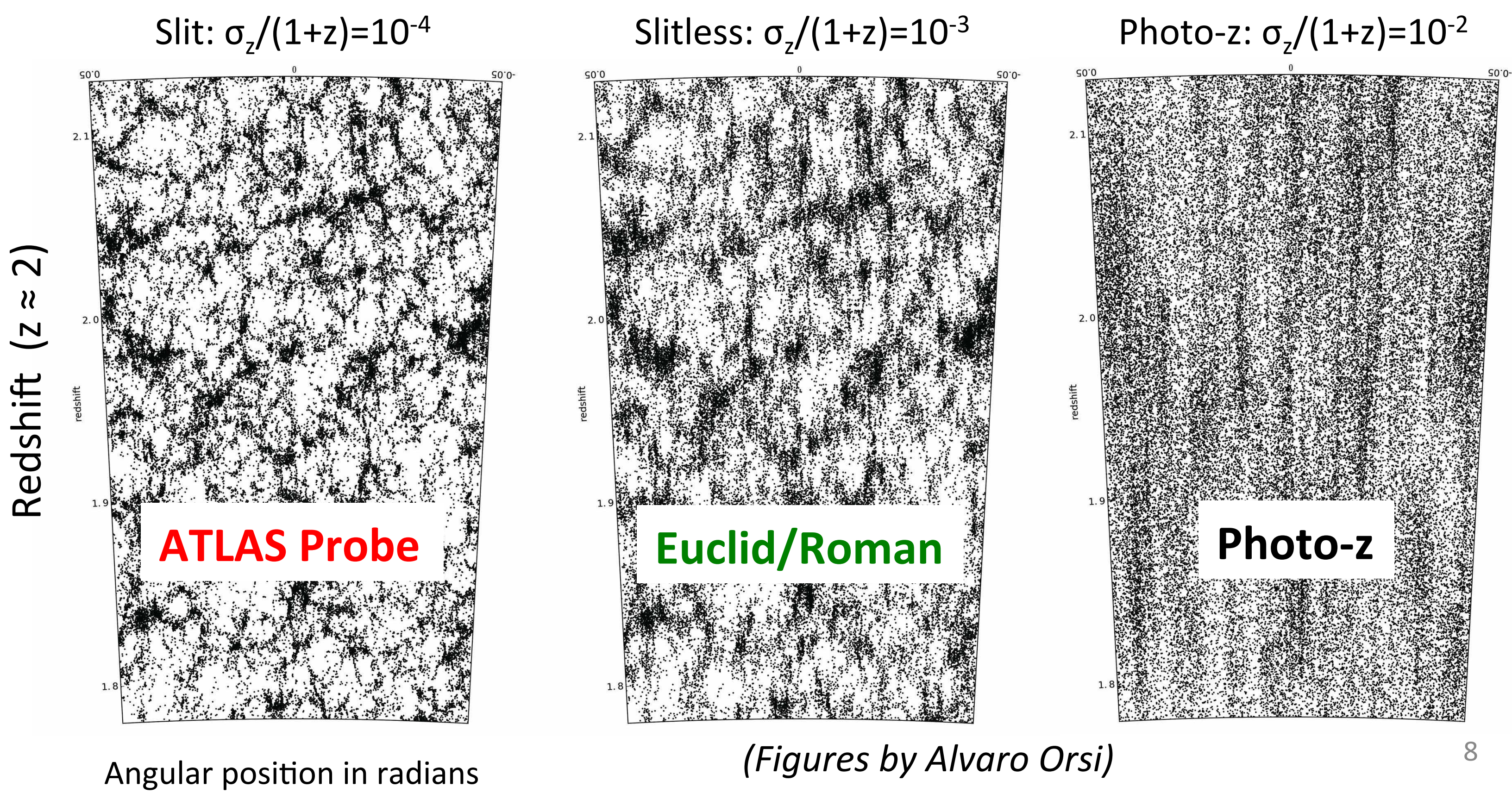
Green: *Dark Matter at z = 2*

Red: *Galaxies at z=2 with spectroscopic redshifts from Roman (left) & ATLAS Probe (right).*

(Credit: Alvaro Orsi)

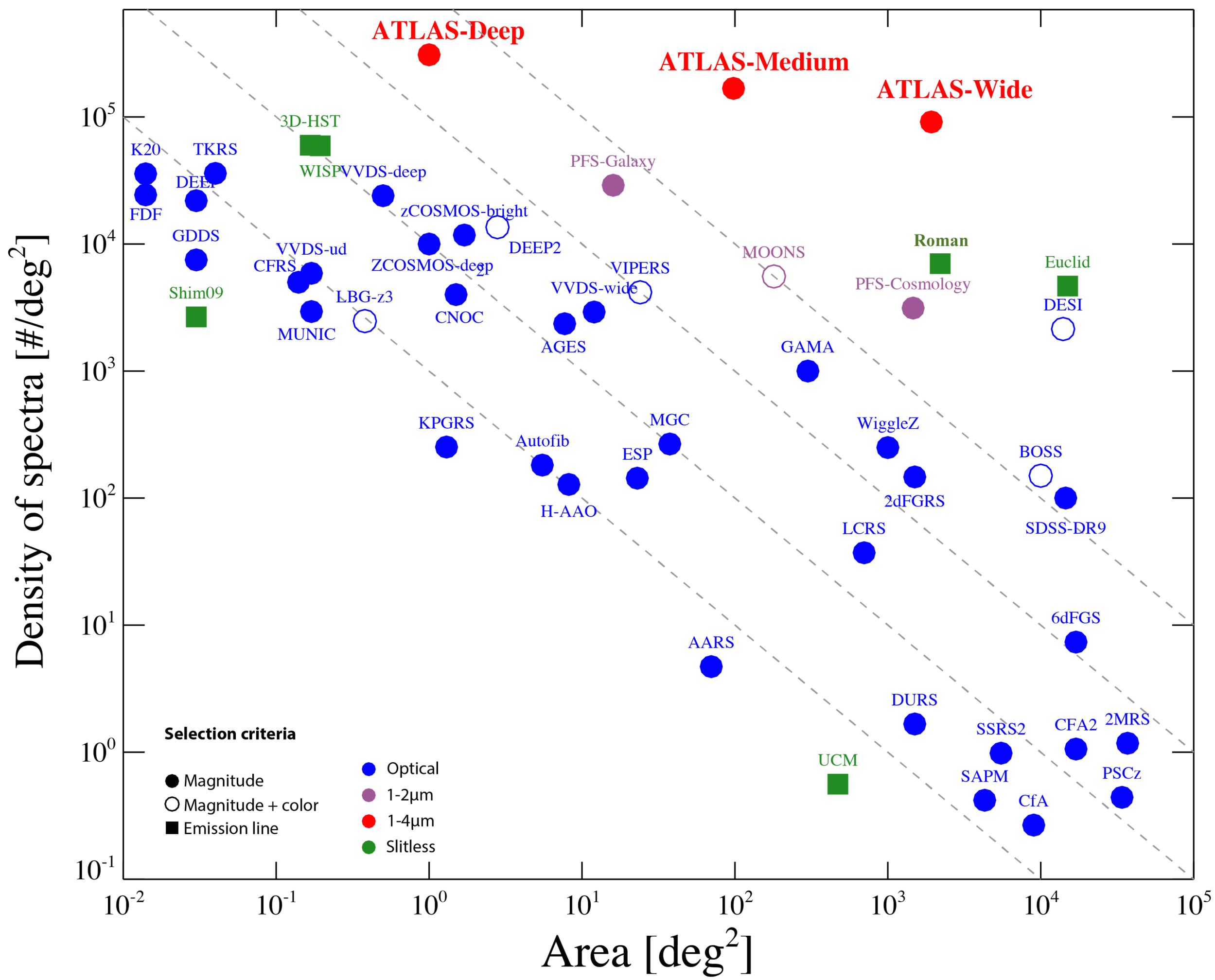
Why Slit Spectroscopy?

- Reduce background → Increase spectroscopic SNR
- Enable high spectral resolution to trace the cosmic web with sufficient fidelity to place galaxies into their environmental context



(Figures by Alvaro Orsi)

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

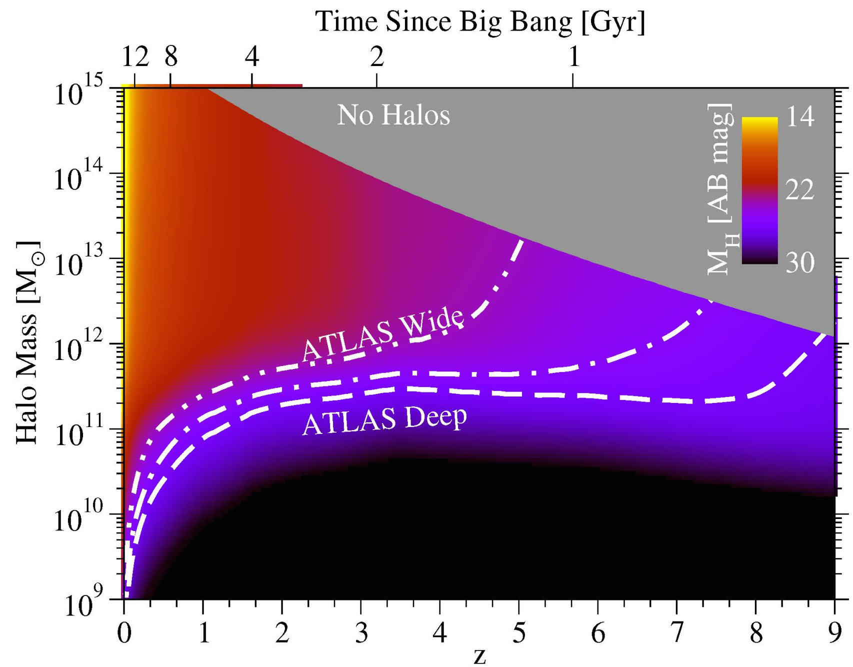


Massively parallel large area high density slit spectroscopy will be pioneered in space with ATLAS. This will revolutionize our understanding of the Universe.

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

ATLAS: Galaxy Evolution in the Cosmic Web of Dark Matter

- Derive DM halo masses statistically from clustering for galaxies binned by properties such as stellar mass, SFR, morphology
- Measure the Stellar Mass – Halo Mass Relation as a function of galaxy properties and redshift
- Derive individual halo masses from Group Catalogs, spectroscopically identifying central + satellite galaxies
- Measure environmental densities to z ~ 3
  - These correlate with halo assembly properties, e.g., concentration, spin, mass accretion rate



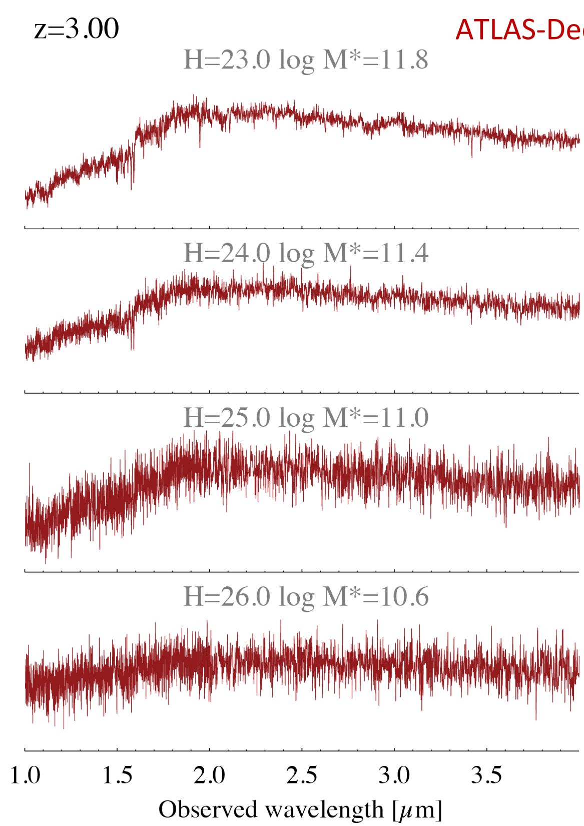
Limiting halo mass vs. redshift accessible for study with a 3-tiered ATLAS Probe survey (fig. by Peter Behroozi)

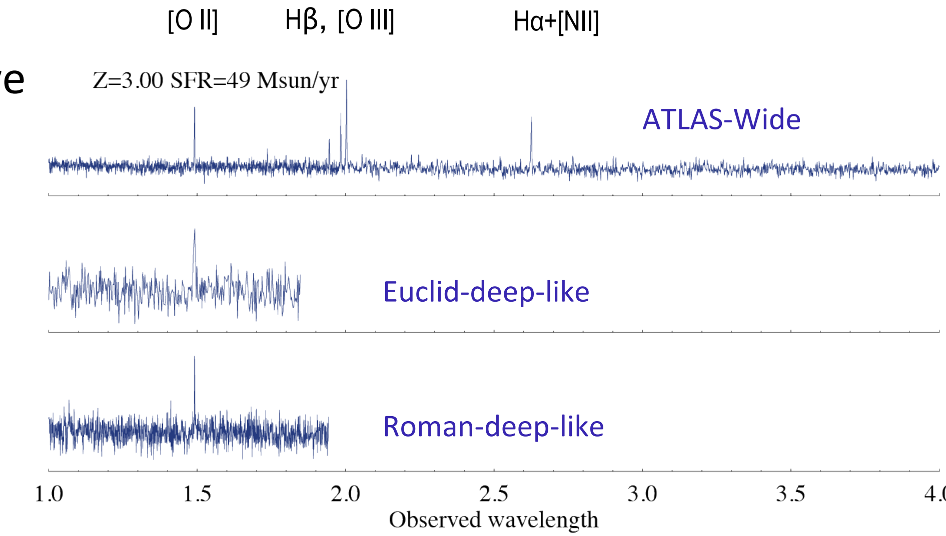
- Measure average dark matter accretion rates via detection of the splash-back radius of satellites (More+2016)
- Spectroscopically identify galaxy pairs to measure the evolution of merger fractions and merger rates

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

ATLAS: Diagnostic Spectroscopy for Galaxies

Atlas Probe will measure stellar continuum / abs. line spectra of passive galaxies, essential for understanding ages and star formation histories.





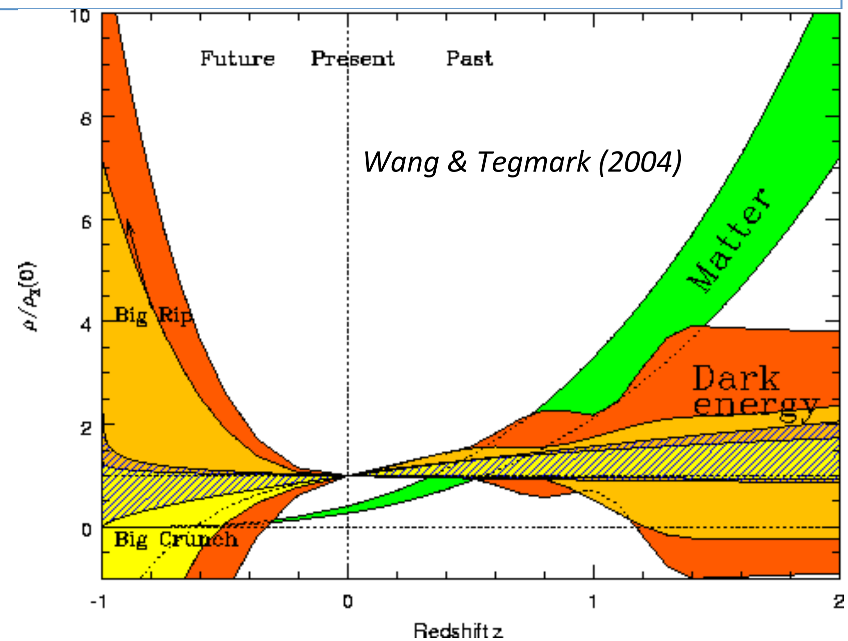
ATLAS Probe will measure multiple emission lines for star-forming galaxies and AGN – diagnostic indicators of ISM abundance, excitation, physical conditions.

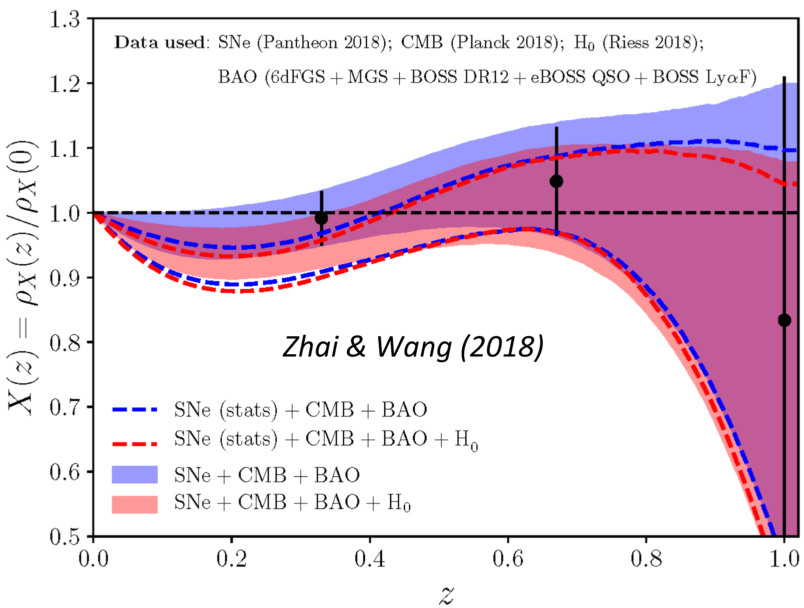
- $H\alpha$ + [NII] at $0.5 < z < 5$
- $H\beta$ + [OIII] at $1 < z < 7$
- [OII] at $1.7 < z < 9.7$

(Figures by Jarle Brinchmann)

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.





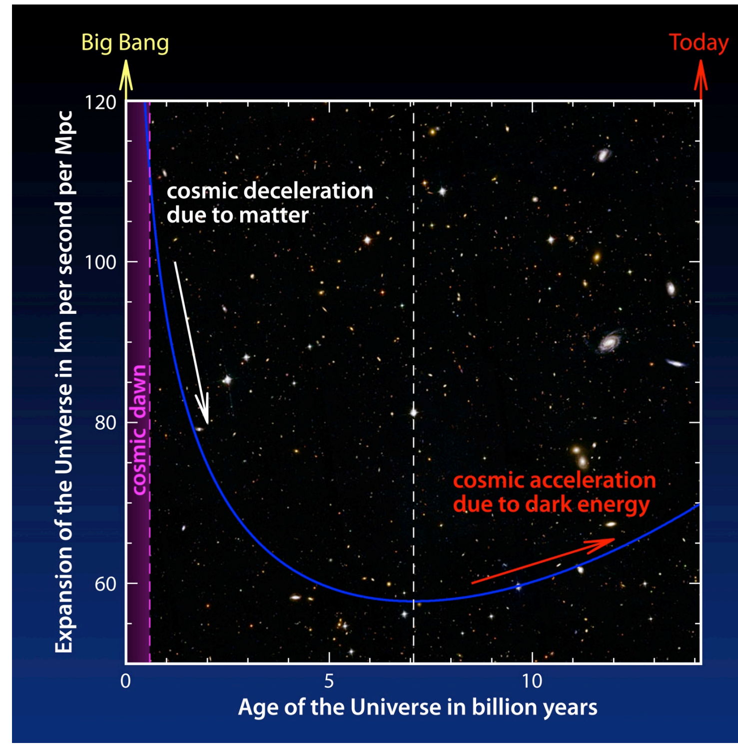
The simplest model for dark energy, the cosmological constant model, i.e., constant dark energy density $\rho_X(z)$, is consistent with current observational data, but uncertainties are large. Deviations from it have come and gone over the last two decades.

Dark Energy: a Fundamental Problem in Cosmology Today

- Roman, 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 $\propto 1/n_{gal}$ for 2 pt & $\propto 1/n_{gal}^2$ 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.

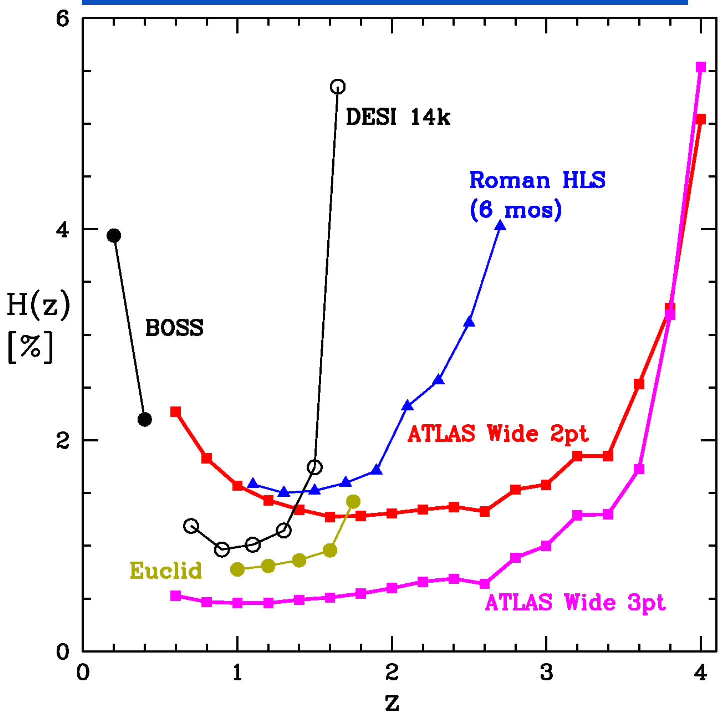
(*See Astro2020 science white paper, Wang et al.*)

ATLAS Probe and Dark Energy

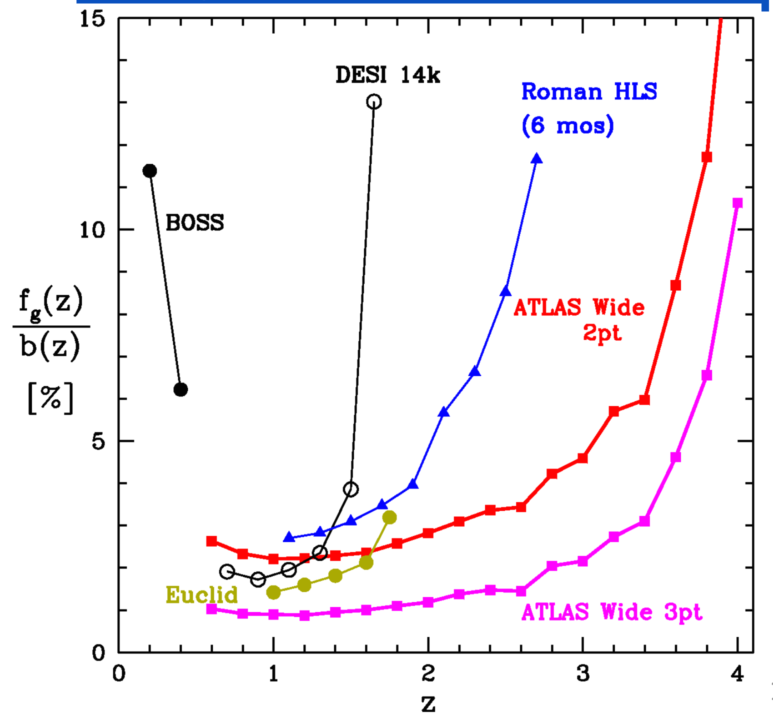
ATLAS Wide Survey, a high number density galaxy redshift survey, will definitively measure cosmic expansion history H(z) & growth history of large scale structure $f_g(z)$, to discover whether dark energy is an unknown energy component, or the modification of General Relativity.

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

Probing time variation of dark energy



Probing deviations from General Relativity

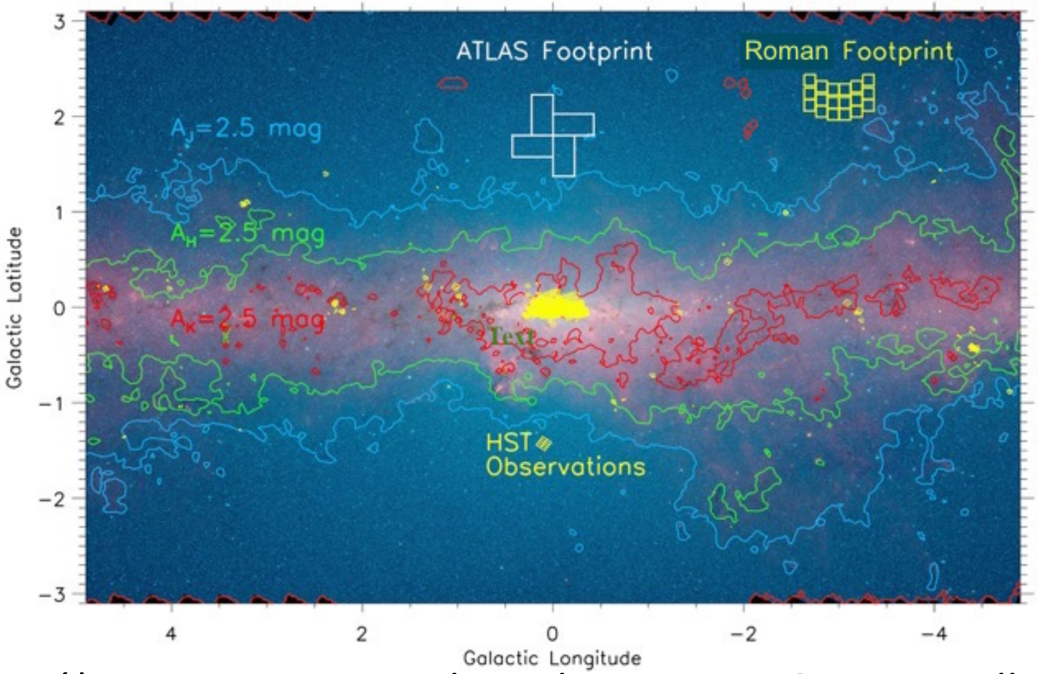


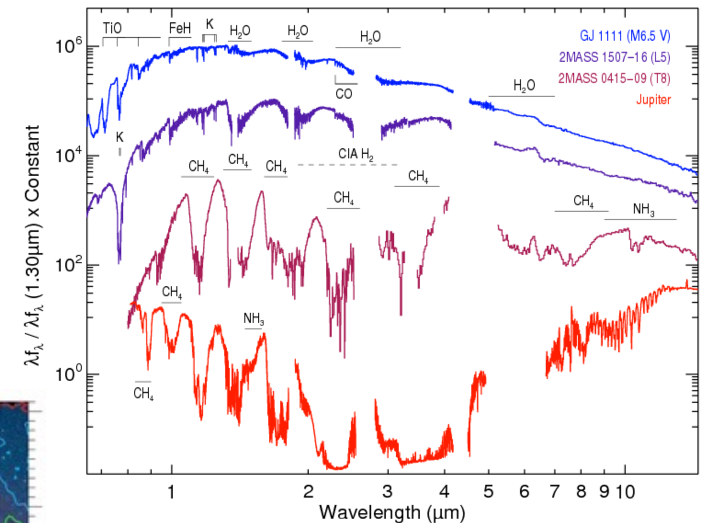
ATLAS PROBE

ATLAS Probe and Milky Way Science

ATLAS Galactic Plane Survey will measure spectra of 95M stars over 700 deg^2 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.





1-4μm spectrum becomes richer going from M stars to brown dwarfs spectral types. Notes gaps in ground-based data in the main H_2O 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.

*(*See presentations by Bob Benjamin & Lynne Hillenbrand at this workshop)*

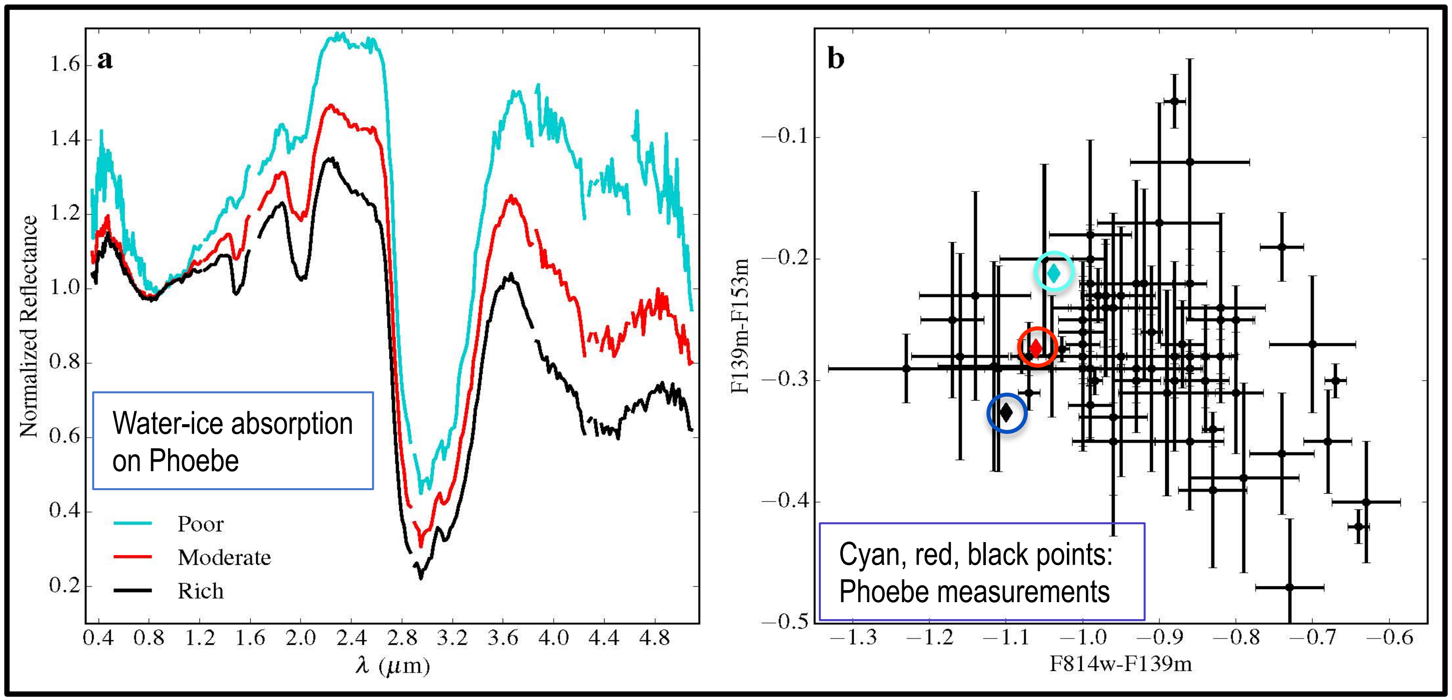
ATLAS PROBE

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 ~ 1”-4” per hour. ATLAS can take slit spectra of moving targets with regular guiding, as the 0.75”×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.



(*Figures by Wes Fraser*)

* *Phoebe (Saturn’s moon): good KBO analog, based NIR colors of KBOs from HST WFC3*

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”(λ/µm)
Spectral Resolution	R ~ 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**
Roman	1-1.9	460/slitless	0.281	20.5 (7σ)	1e-16 (6.5σ)	~10M	2.4	$3.2B	2026
SPHEREx	0.75 -5	41-130 slitless	39.6	19.1-19.6 (5σ) R=41	N/A	[6"pix]	0.2	$250M +ELV	2024
Euclid	0.92 -1.85	380 slitless	0.53	20 (3.5σ) 21.3 (3.5σ)	2e-16 (3.5σ) 6e-17 (3.5σ)	~20M	1.2	1B Euros	2022
JWST NIRSpec (10^5 s)	0.6 -5.3	100, 1000, 2700	.0034	25.3 (10σ)	3.5e-19 (10σ)	< 1M	6.5	$10B	2021

ATLAS PROBE

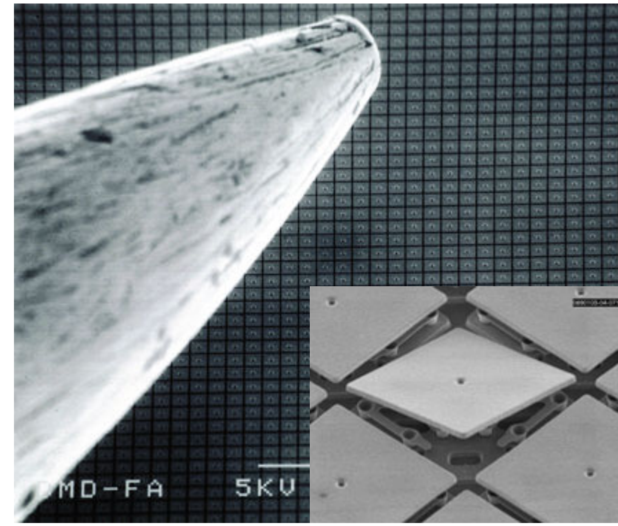
Overview of Implementation

- 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 ±12° ("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.



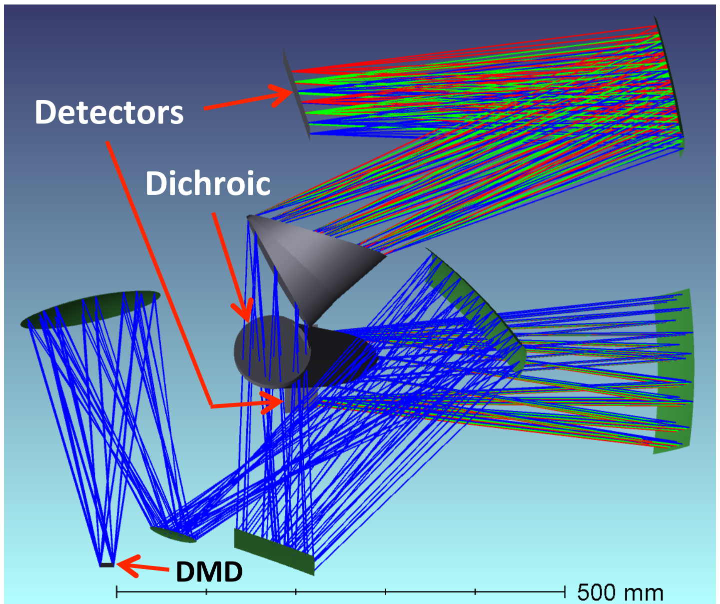
ATLAS DMDs:

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

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

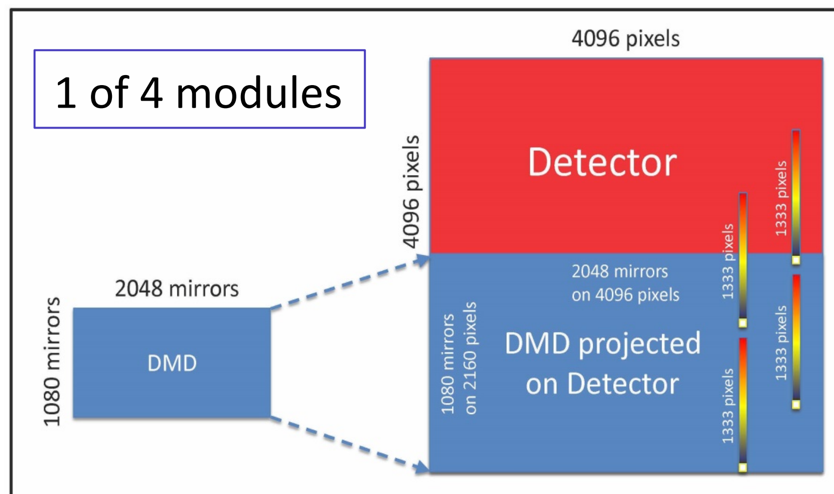
(*See Massimo Robberto's presentation at this workshop)*

ATLAS Probe Preliminary Optical Design



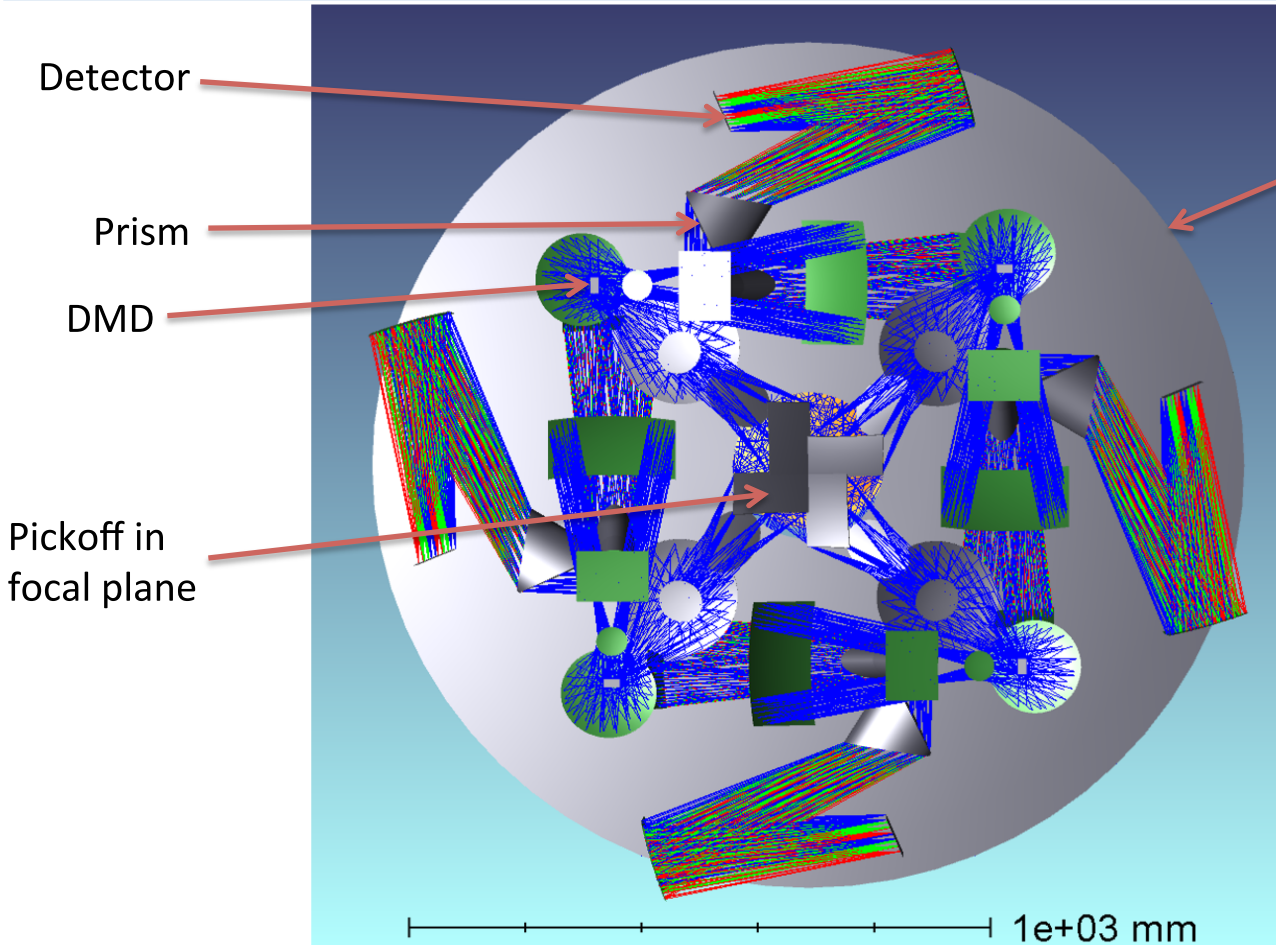
- A single instrument with <u>4 identical modules</u>
- Each module has two channels (1-2µm & 2-4µm). The dichroic reflects the blue channel & transmit the red channel.
- Imaging (calibration & targeting) via use of a zero dispersion grism in the blue channel.
- Each DMD maps to an IR H4RG detector in 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 mirror col] *1.5*[4 modules] ~ 6000



(**See presentations at this workshop by Massimo Robberto & Robert Content*)

ATLAS Probe Preliminary Optical Design



Industry routinely manufactures freeforms to the sizes & specs of ATLAS mirrors (*Input from Optimax Systems*)

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

(**See Robert Content's presentation at this workshop)*

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	7.7×10^4s	Objective 1
ATLAS Deep	4%	1	0.3M	4.7×10^5s	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

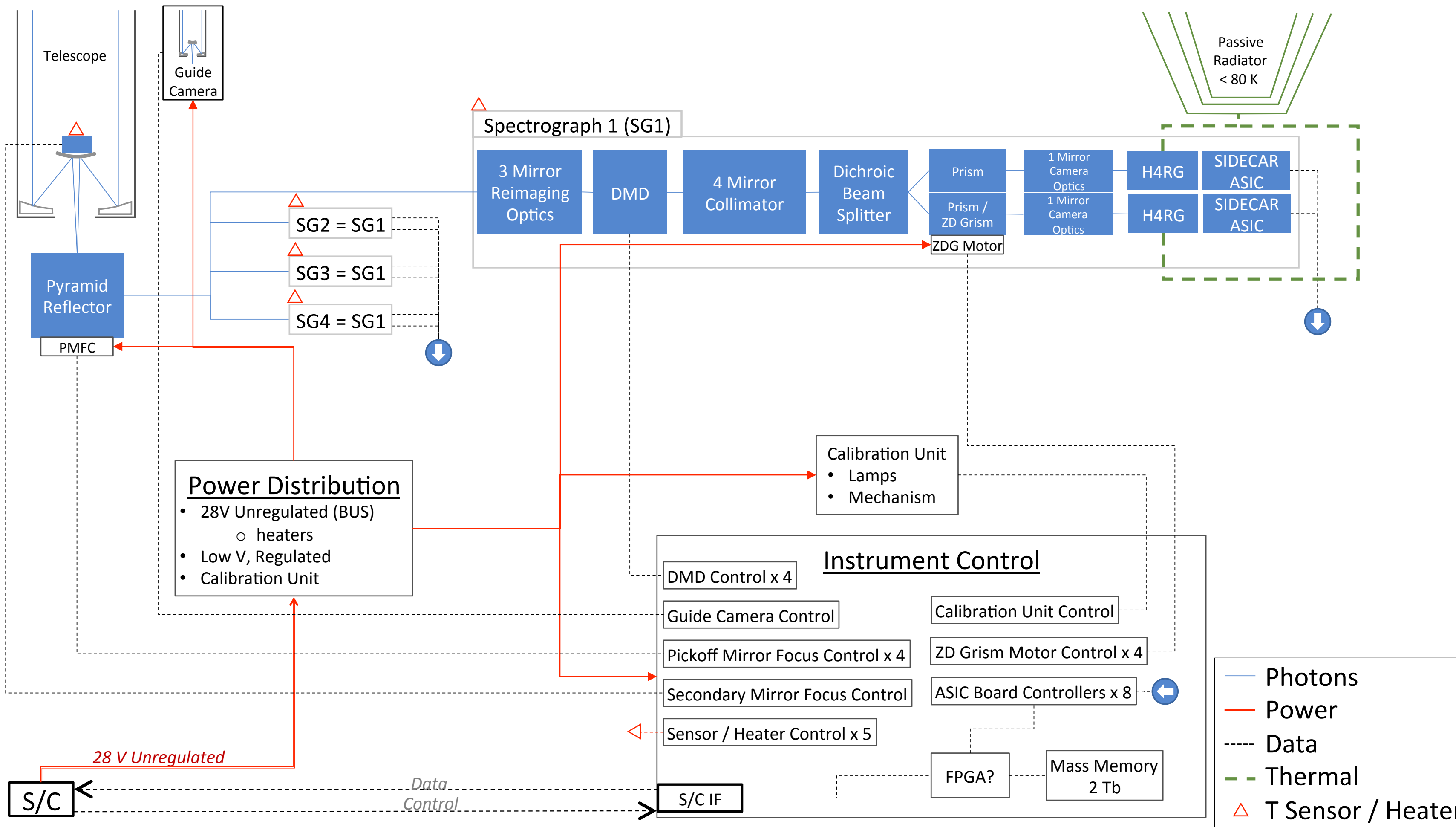
ATLAS Probe Mission Architecture

- 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 < +/- 0.375” 3-sigma over ~200s*
  - < ~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
  - ~600Mb 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*

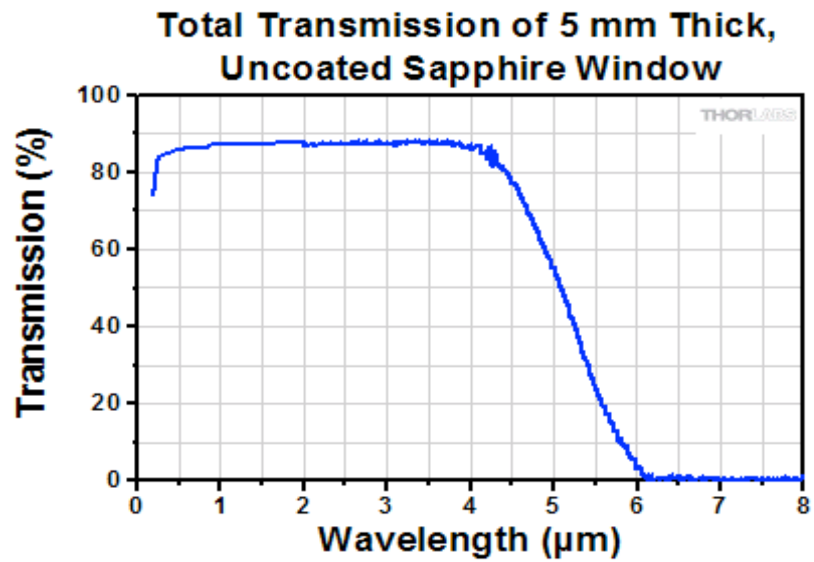
ATLAS Probe Block Diagram

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.**
    - ATLAS 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 (1-4µm).

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

ATLAS PROBE

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**

	MIN	A-D MODE	MAX
Total A-F	**$667.5**	**$861.2**	**$1,219.1**
Cost Target (incl LV)	**$1,000.0**	**$1,000.0**	**$1,000.0**
Difference	**$332.5**	**$138.8**	**-$219.1**

A-D Reserves	**30%**
E-F Reserves	**15%**

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

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 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

ATLAS PROBE

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

- Community workshops: "Massively Parallel Large Area Spectroscopy from Space",
  - 1st workshop: Caltech, October 2018, ~80 participants
  - 2nd workshop: Online (IA/Portugal), June 2021, 189 participants

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 (NASA is waiting for Astro2020 report)**
- **ATLAS Probe Collaboration is open to the community**