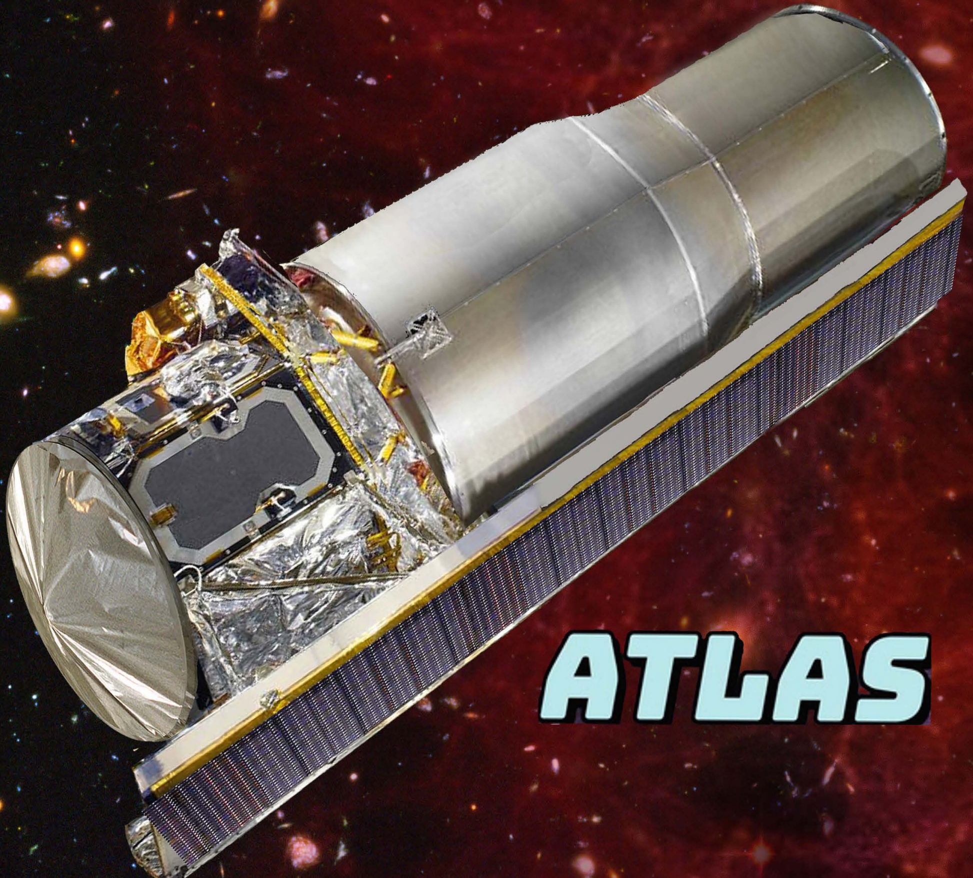
# Astrophysics Telescope for Large Area Spectroscopy


Yun Wang (Caltech/IPAC)

on behalf of the ATLAS Probe Collaboration


Presentation to Snowmass 2021, September 9, 2020

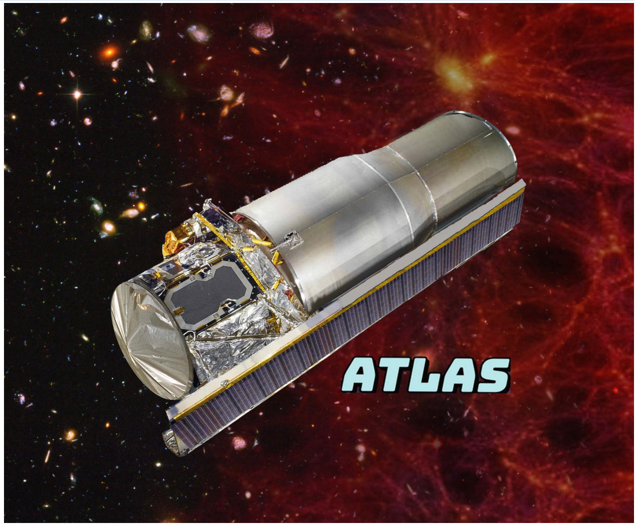


ATLAS

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](http://atlas-probe.ipac.caltech.edu)

ATLAS PROBE

# Outline

ATLAS PROBE

- **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

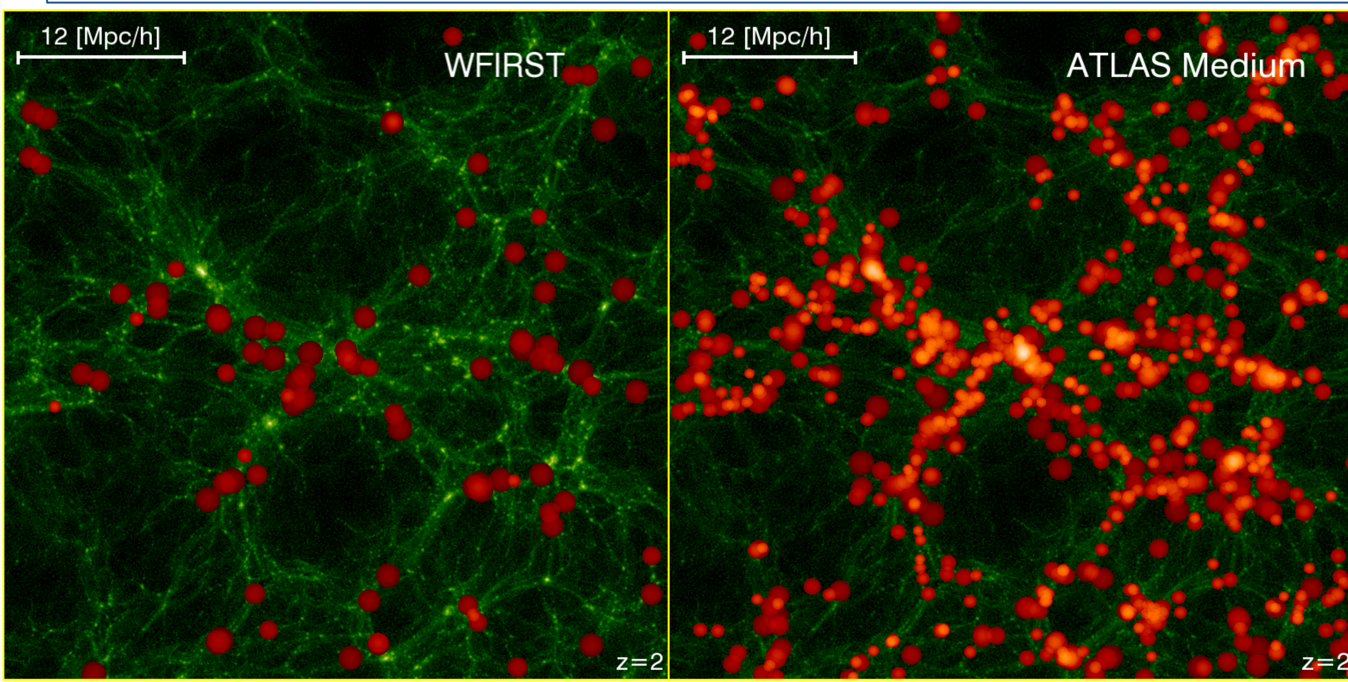
# ATLAS Probe Maps the Cosmic Web

*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.

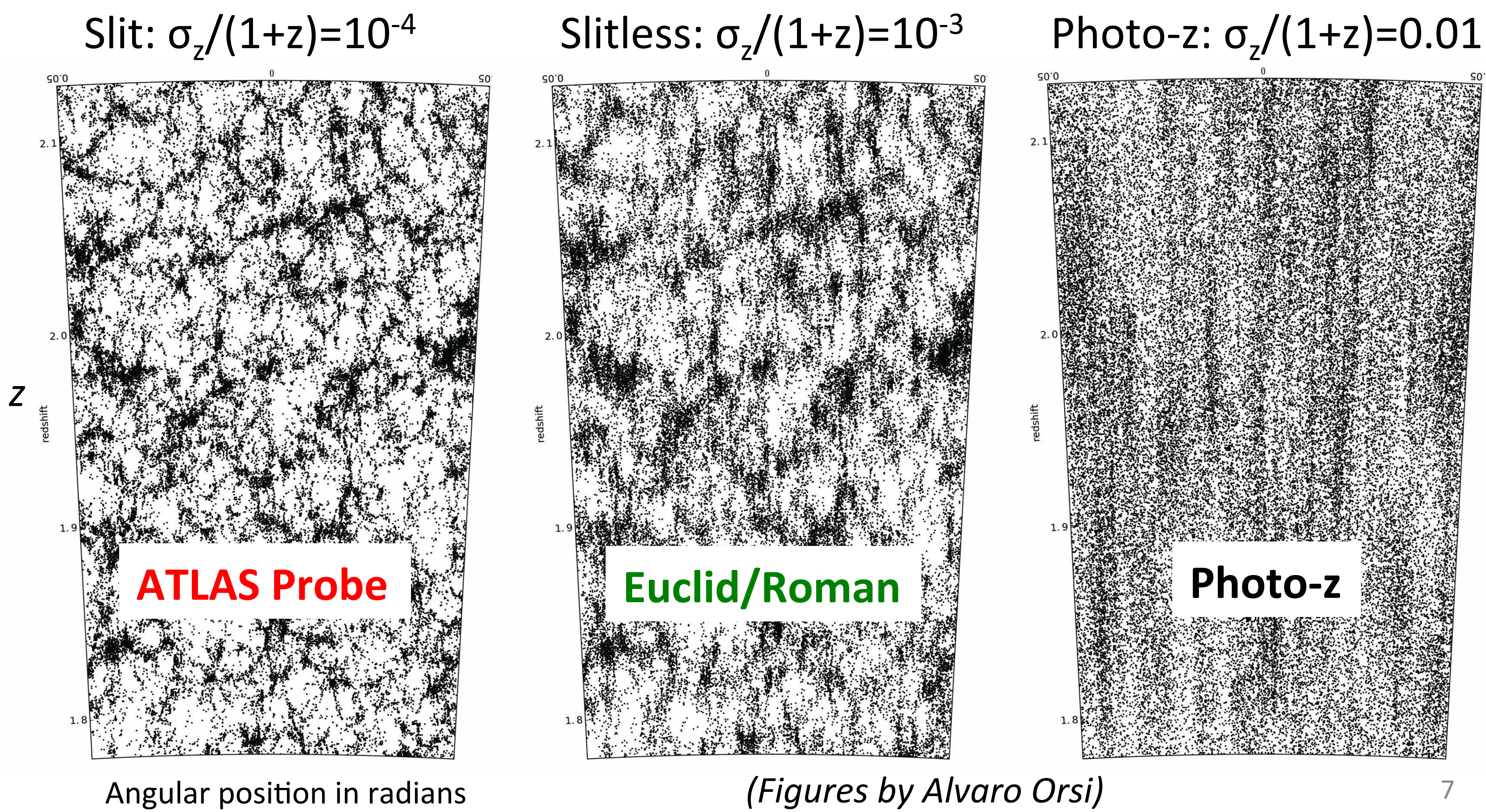



*Cosmic web of dark matter (green) at z=2 traced by galaxies with spectroscopic redshifts (red) from Roman (left) & ATLAS Probe (right).*

*(Credit: Alvaro Orsi)*

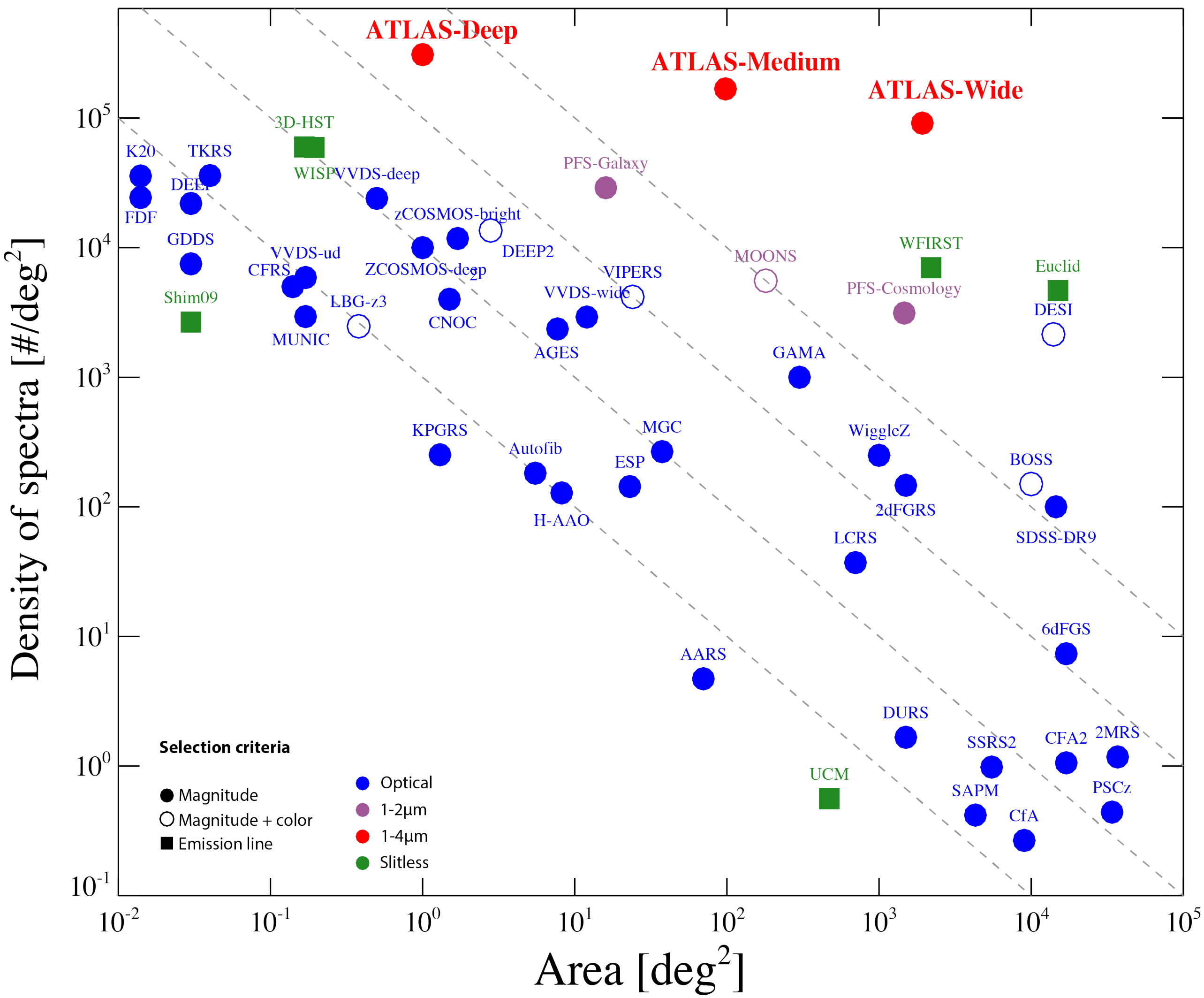
# Why Slit Spectroscopy?

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




*(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 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.

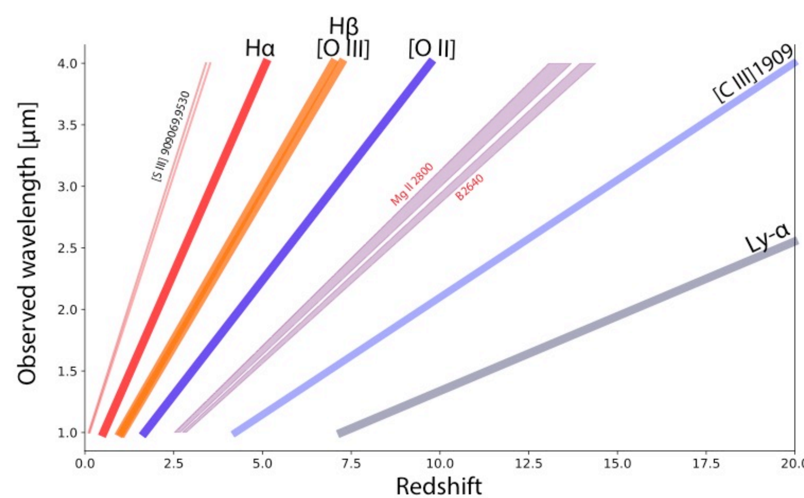
ATLAS Probe will

- 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 ~ 3-4 and in many cases to z ~ 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** |

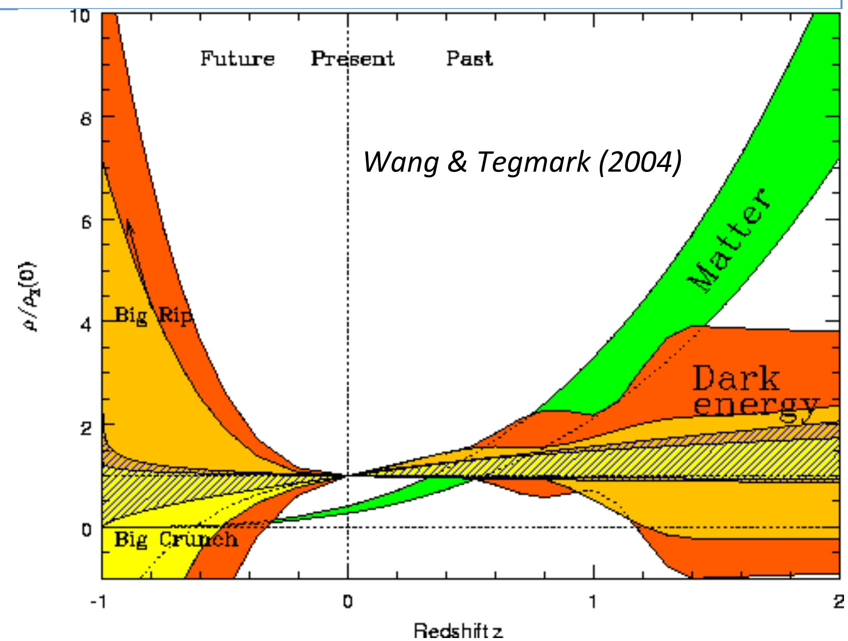
**Line Flux in erg/s/cm$^2$(5σ), Continuum in AB mag (3σ)*

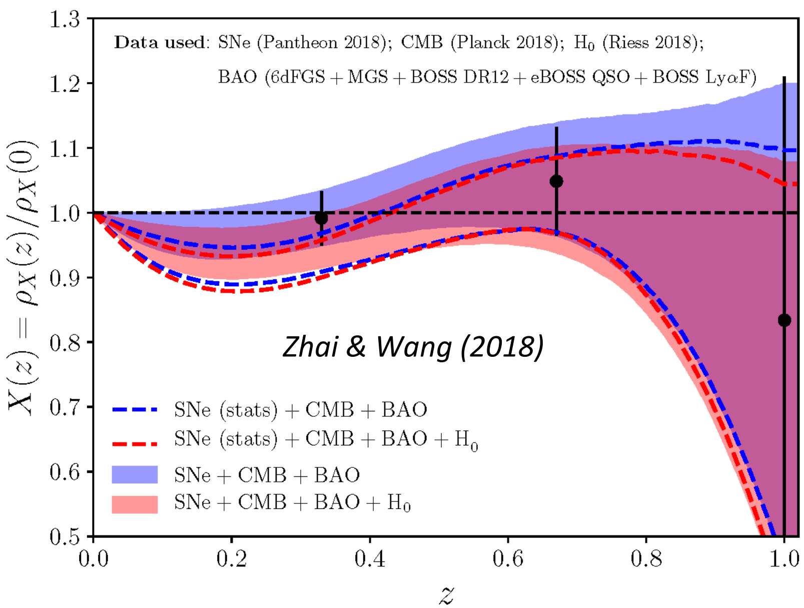



*(see Astro2020 science white paper, Dickinson et al.)*

# 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.

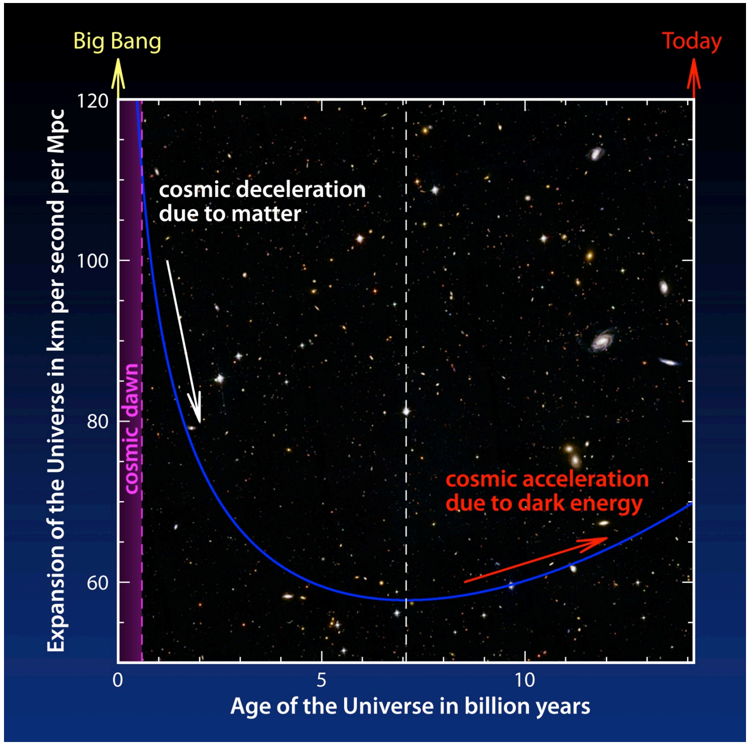



The simplest model for dark energy, the cosmological constant model, i.e., constant dark energy density $\rho_X(z)$, is consistent with current observational data, but uncertainties are large. Deviations from it have come and gone over the last two decades.

# 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 Probe 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.*)

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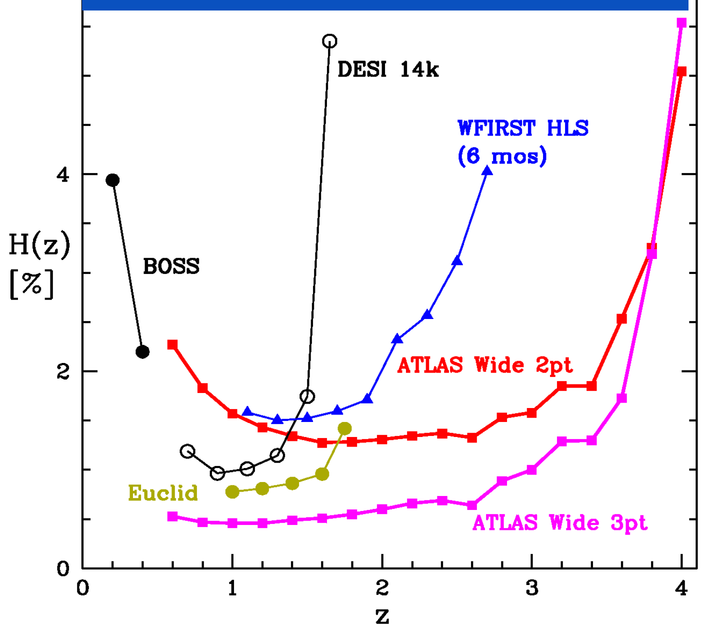
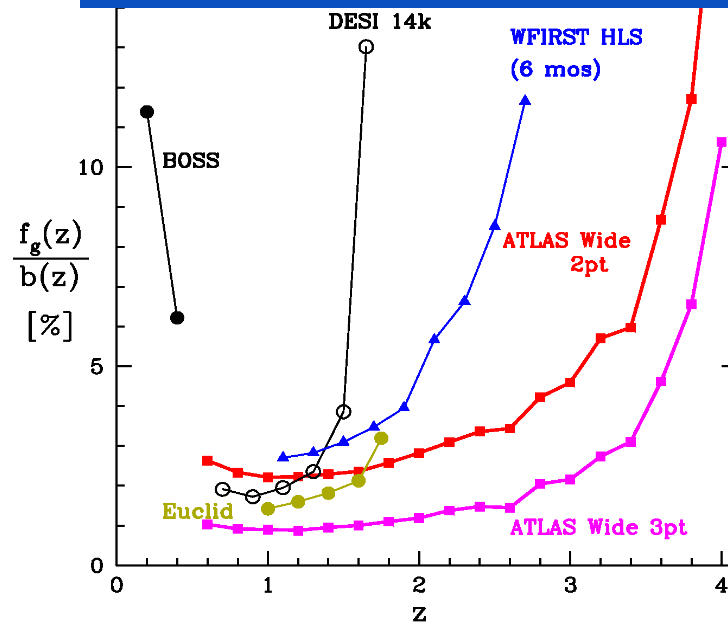
# ATLAS Probe and Dark Energy

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.

Probing time variation of dark energy




Probing deviations from General Relativity




*If early dark energy remains viable in the 2020s, it can be measured by enhancing ATLAS Wide with a high redshift only ATLAS GRS, targeting Hα emission line galaxies at 3 < z < 5 selected from Roman imaging beyond that of the WL sample. Galaxy redshifts at z > 5 can be measured using other emission lines, as needed.

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

# Additional Dark Energy Constraints from ATLAS Probe (I)

**3D Weak Lensing with Spectroscopic Redshifts**

Replaces photometric redshifts with spectroscopic redshifts for ~70% of the lensed galaxies in the Roman WL sample. This will

- Eliminate the photo-*z* calibration ladder as a major source of systematic uncertainty in WL.
- Dramatically suppressing the systematic error from intrinsic galaxy alignments, by enabling the identification of every close pair of galaxies in 3D space for 70% of the sample.
- Enables the production of a super data set of 183M galaxies over $0.5 < z < 4$ with both WL shear and 3D galaxy clustering data for the same galaxies.

(*Wang et al. 2019*)

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# Additional Dark Energy Constraints from ATLAS Probe (II)

**Type Ia Supernovae (SNe Ia)**

ATLAS Wide will easily include the host galaxy redshifts of nearly all 30,000 SNe Ia that will have lightcurves measured by the Rubin Deep Drilling Fields and Roman SN surveys, over the redshift range of $0.2 < z < 2.0$.

- These will provide a powerful measurement of $H(z)$, and the matter clustering amplitude $\sigma_8$ via SN Ia weak lensing magnification measurements.
- Without the host galaxy redshifts, SN analyses will be forced to rely on photometric redshifts, which for the full SN sample degrades the cosmological precision by introducing a series of systematic uncertainties and reducing the statistical precision as well.

(*Hounsell et al. 2019; Zhai, Wang, & Scolnic 2020*)

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# Additional Dark Energy Constraints from ATLAS Probe (III)

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**Clusters**

The abundance of mass-calibrated galaxy clusters provides complementary measurements of cosmic expansion history and growth rate of large-scale structure. ATLAS Wide will include spectroscopy for the 40,000 clusters with $M>10^{14}M_{\odot}$ expected to be found by Roman HLS imaging.

- Cluster sample with mass accurately measured by the deep 3D WL data, and cluster membership precisely determined by spectroscopic redshifts.
- Independent cluster mass function evolution measurements using infall amplitude rather than lensing, eliminating degeneracies that affect weak lensing and clusters the same way. (*Wang et al. 2019*)

**Voids**

Cosmic voids are underdense patches of the Universe. Voids can be used to test for modifications of gravity from GR: in many models modifications are stronger where the matter density is low. ATLAS Wide void data set will be ideal: the dense sampling means that we will pick up many galaxies close to the void centers, which contain the most information. (*Pisani et al. 2019*)

# Cosmology With ATLAS Probe

- In addition to probing cosmic acceleration, ATLAS Wide Survey will provide invaluable constraints on dark matter by tracing the cosmic web of dark matter, and enable the measurement of dark matter filament mass, as well as high precision measurements of neutrino mass and other cosmological parameters.
- ATLAS Probe's wide area spectroscopy at 1-4μm will be powerfully complementary to future ground-based facilities limited to < 1μm due to absorption by the Earth's atmosphere.
- **ATLAS Probe will be a game changer in providing spectroscopic coverage of cosmological surveys not accessible from the ground, providing a useful reference for optimizing ground-based facilities.**

# 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,<br>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 ($3\sigma$) |
| 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)<br>24.5 (3σ)<br>25.5 (3σ)** | **5e-18 (5σ)<br>1.2e-18 (5σ)<br>4.6e-19 (5σ)** | **183M<br>17M<br>.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 | 2025 |
| SPHEREx | 0.75<br>-5 | 41-130<br>slitless | 39.6 | 19.1-19.6<br>(5σ) R=41 | N/A | [6” pix] | 0.2 | $250M<br>+ELV | 2023 |
| Euclid | 0.92<br>-1.85 | 380 slitless | 0.53 | 20, 21.3<br>(3.5σ) | 2e-16,<br>6e-17 (3.5σ) | ~20M | 1.2 | 1B<br>Euros | 2022 |
| JWST<br>NIRSpec ($10^5$ s) | 0.6<br>-5.3 | 100, 1000,<br>2700 | .0034 | 25.3 (10σ) | 3.5e-19 (10σ) | < 1M | 6.5 | $10B | 2021 |

ATLAS PROBE

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# Overview of Implementation

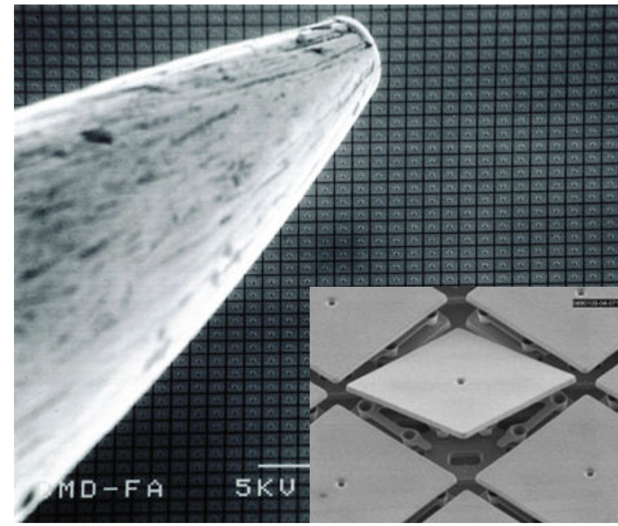
- ATLAS Probe has a single spectroscopic instrument with 4 identical modules
- ATLAS Probe system is simple & straightforward for a probe mission
- ATLAS Probe has a low level of technical risk, with its least mature technology at TRL 5 (DMDs)

ATLAS PROBE

# 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.

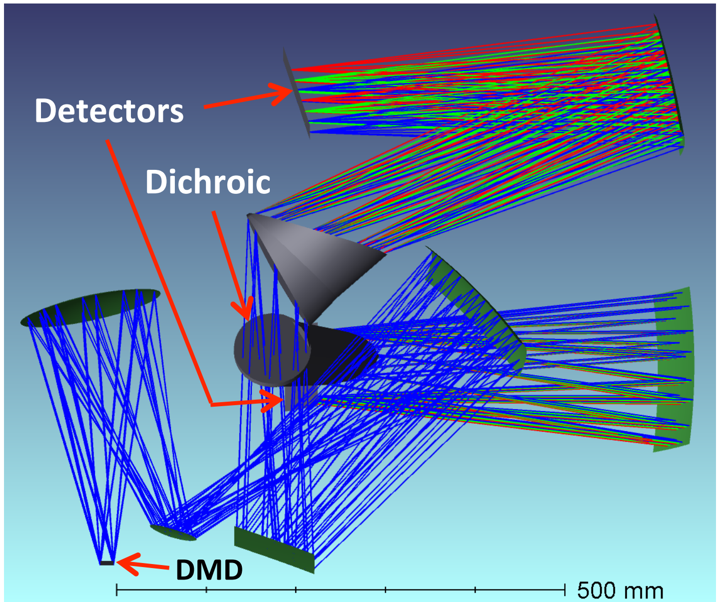
# Proven Technology: Digital Micromirror Devices (DMDs)

- **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 (flight qualified).**
- 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**

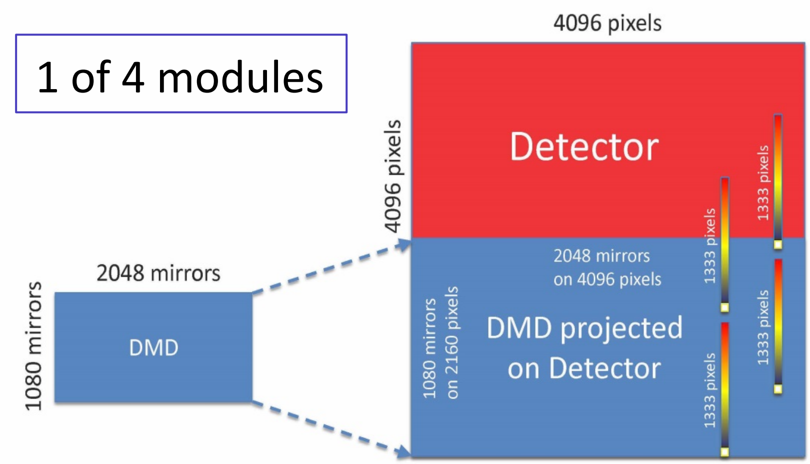
ATLAS PROBE

# ATLAS Probe Preliminary Optical Design



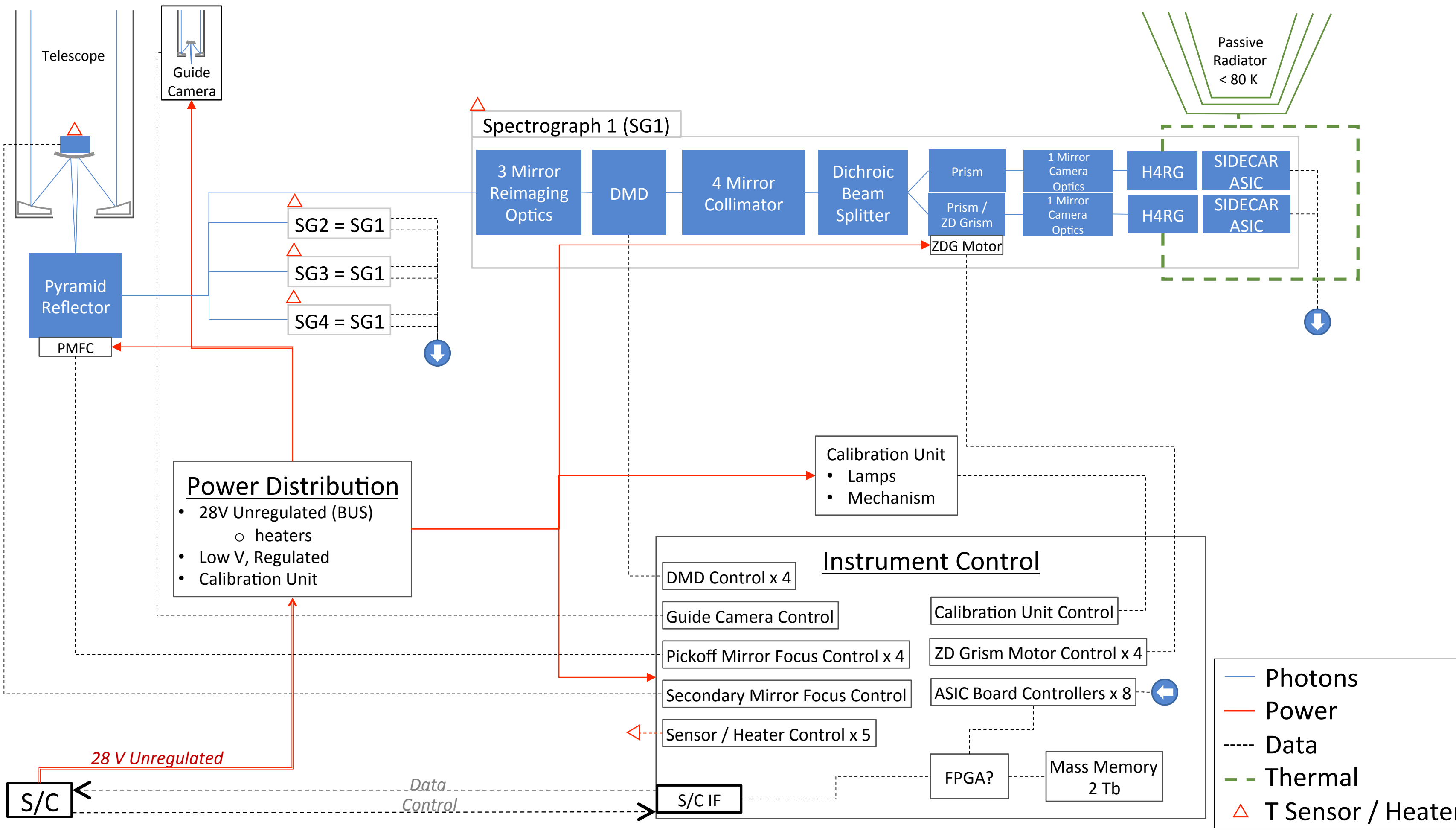

- A single instrument with <u>4 identical modules</u>
- Each module has two channels (1-2µm & 2-4µm). The dichroic reflects the blue channel & transmit the red channel.
- Imaging (calibration & targeting) via use of a zero dispersion grism in the blue channel.
- Each DMD maps to an IR H4RG detector in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



# ATLAS Probe Block Diagram

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



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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** |

| | | | | |
|---|---|---|---|---|
| | | **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**

*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.*

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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 |

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# 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” (Caltech, October 2018), had ~80 US and foreign participants (the majority of them from the community). Future workshops being planned.

- Invited presentation to Astro2020 Decadal Survey Program Panel on “Electromagnetic Observations from Space 1” (UV, optical & NIR) in March 2020

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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
- **ATLAS Probe (1-4µm) provides a useful reference for optimizing ground-based facilities (< 1µm). DOE scientists are welcome to contribute to ATLAS Probe.**