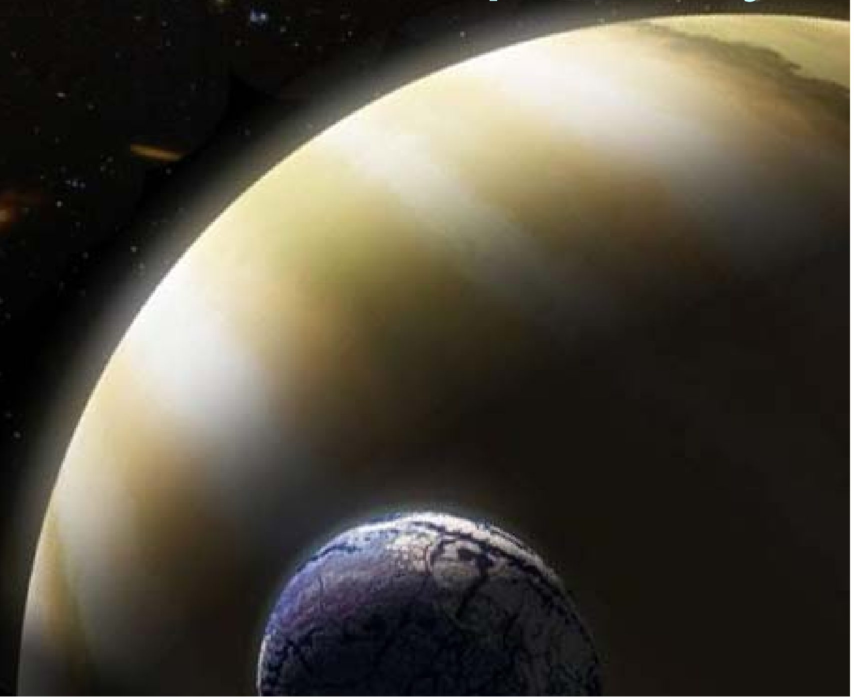
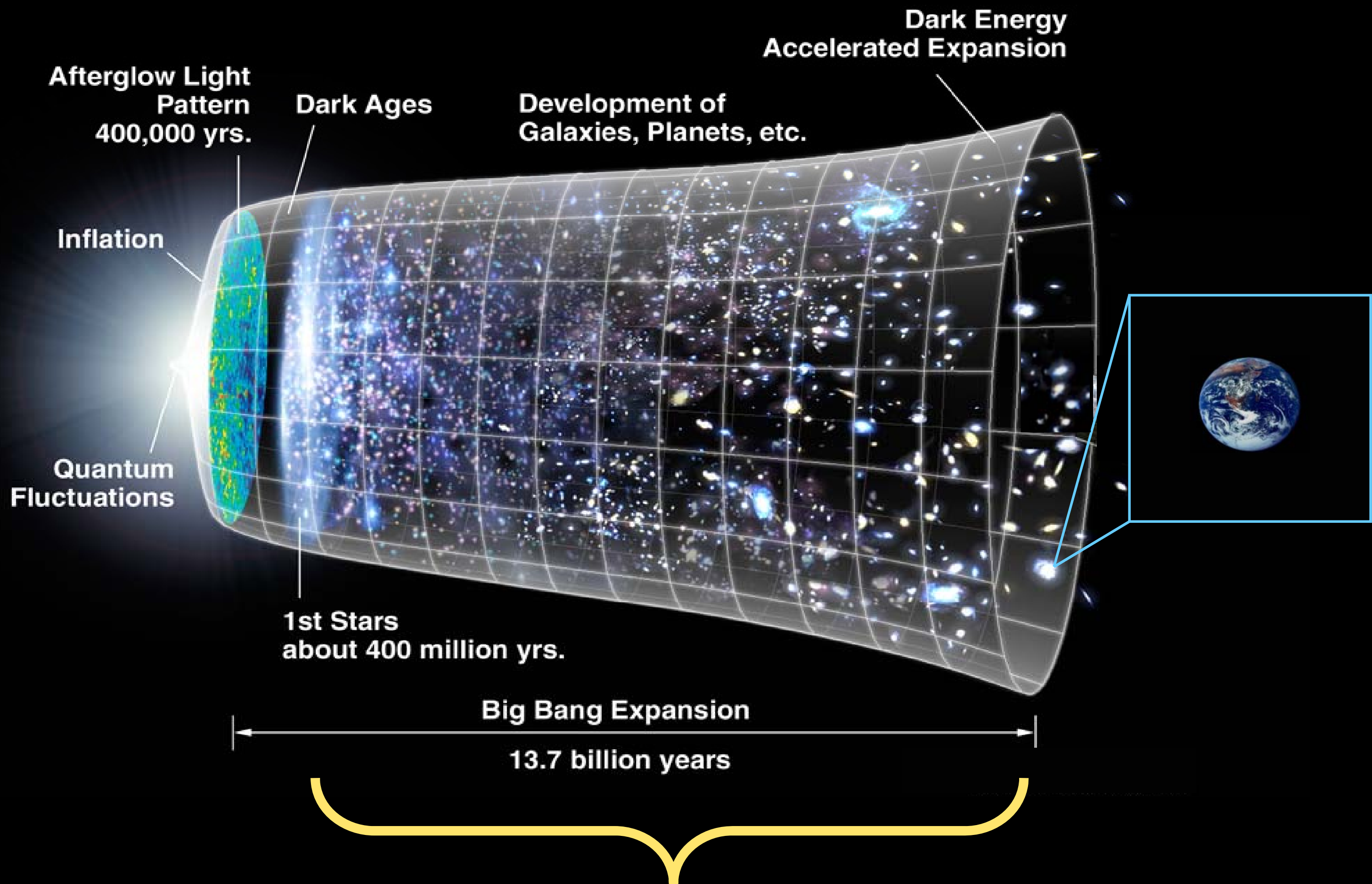
Galaxies, Black Holes and Exoplanets:

Scientific Drivers for a Large UV-Opt-NIR Space Telescope / “ATLAST” concept study



Dr. Anton M. Koekemoer *(STScI)*

The story of life, the universe, and everything…



21st Century astronomers should be uniquely positioned to study "*the evolution of the universe in order to relate causally the physical conditions during the Big Bang to the development of RNA and DNA*"

- Riccardo Giacconi, 1997

The Imperative for a larger UV/Optical Space Telescope

How did the present Universe come into existence and what is it made of?

- How do galaxies assemble their stars?
- How are baryons distributed in intergalactic space?
- How does the mass of galactic structures increase with time?

Requires velocity and brightness measurements of very faint objects. Requires UV/optical spectra of faint sources in crowded fields.

What are the fundamental components that govern the formation of galaxies and black holes?

- How do super massive black holes evolve?
- Why is their mass correlated with that of their host galaxies?

Requires UV/optical spectra in central 200 pc of galactic nuclei. Needs high angular resolution & sensitivity.

How does the Solar System work?

- What are the connections between the Solar System's Interplanetary Medium and the Local Interstellar Medium?
- What are the physical processes driving the weather on the outer gas giant planets in the Solar System?

Requires UV spectroscopy of faint sources and high angular resolution UV/optical/NIR narrow band imaging.

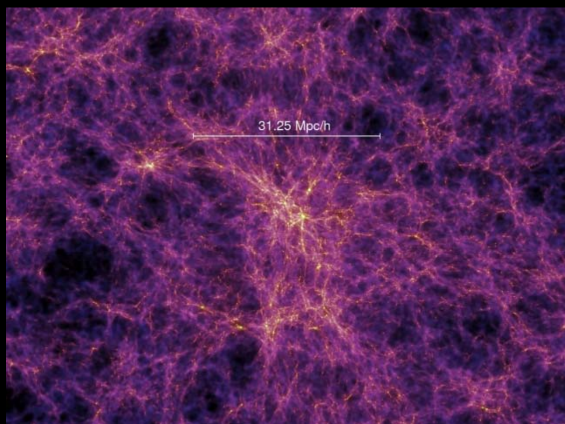
What are the conditions for planet formation and the emergence of life?

- What fraction of circumstellar disks form planets?
- Are there detectable biosignatures on exoplanets in the Habitable Zones of their host stars?

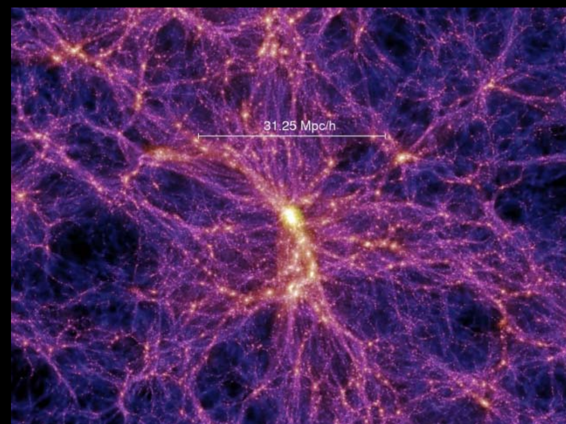
Requires high-contrast optical and NIR imaging and spectroscopy of very faint point sources

“Modern” Galaxy Evolution

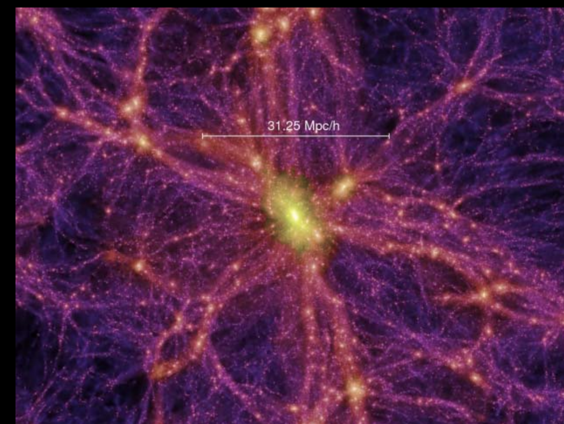
Structure in the Universe is predicted to grow (in mass) as time progresses



12.5 Gyr ago
(z = 5.7)



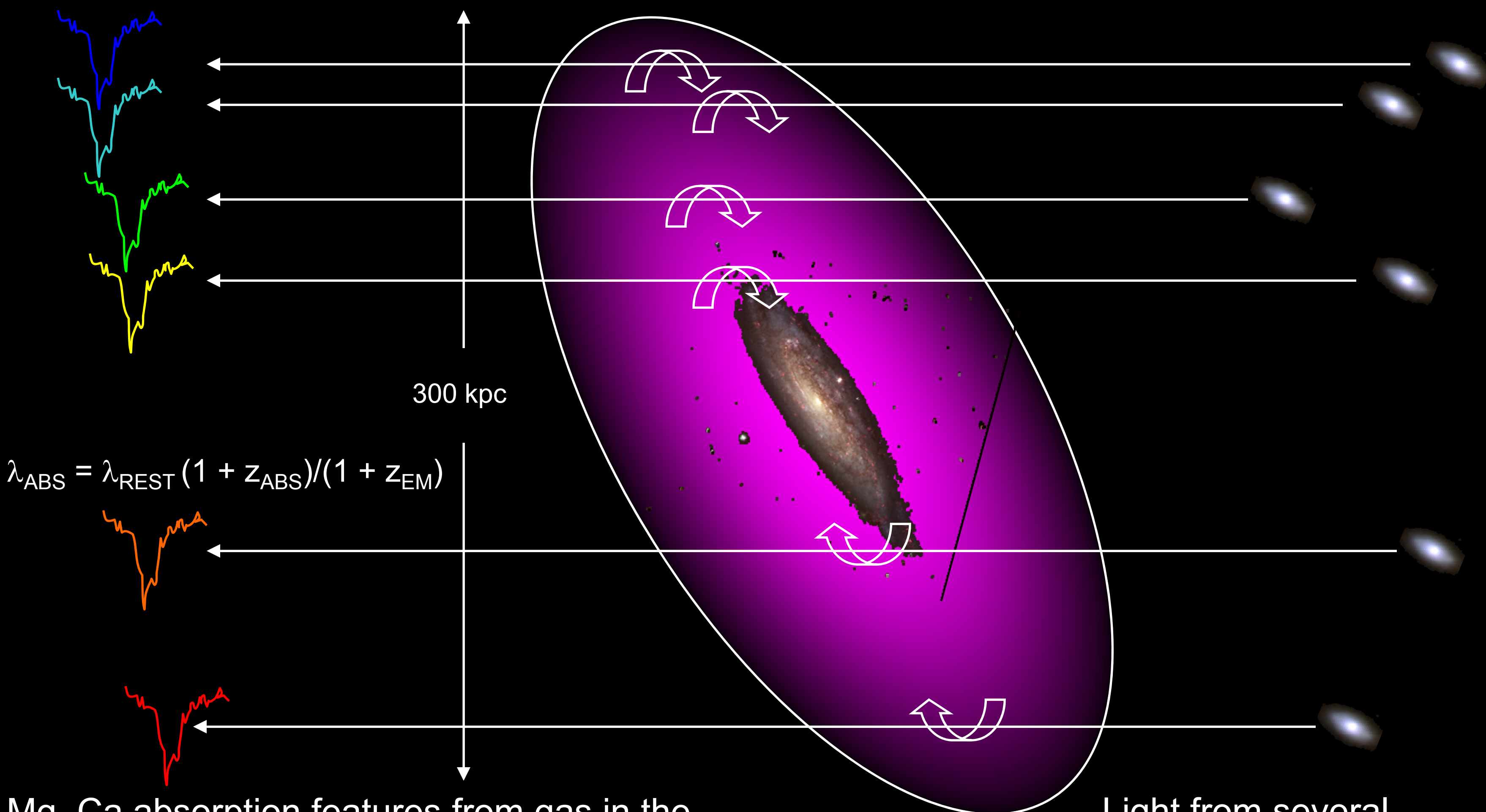
9.0 Gyr ago
(z = 1.4)



Now
(z = 0)

To date, we have only inferred this growth of mass with time via indirect means. ATLAST will allow us to measure the growth of galactic structures vs. time directly.

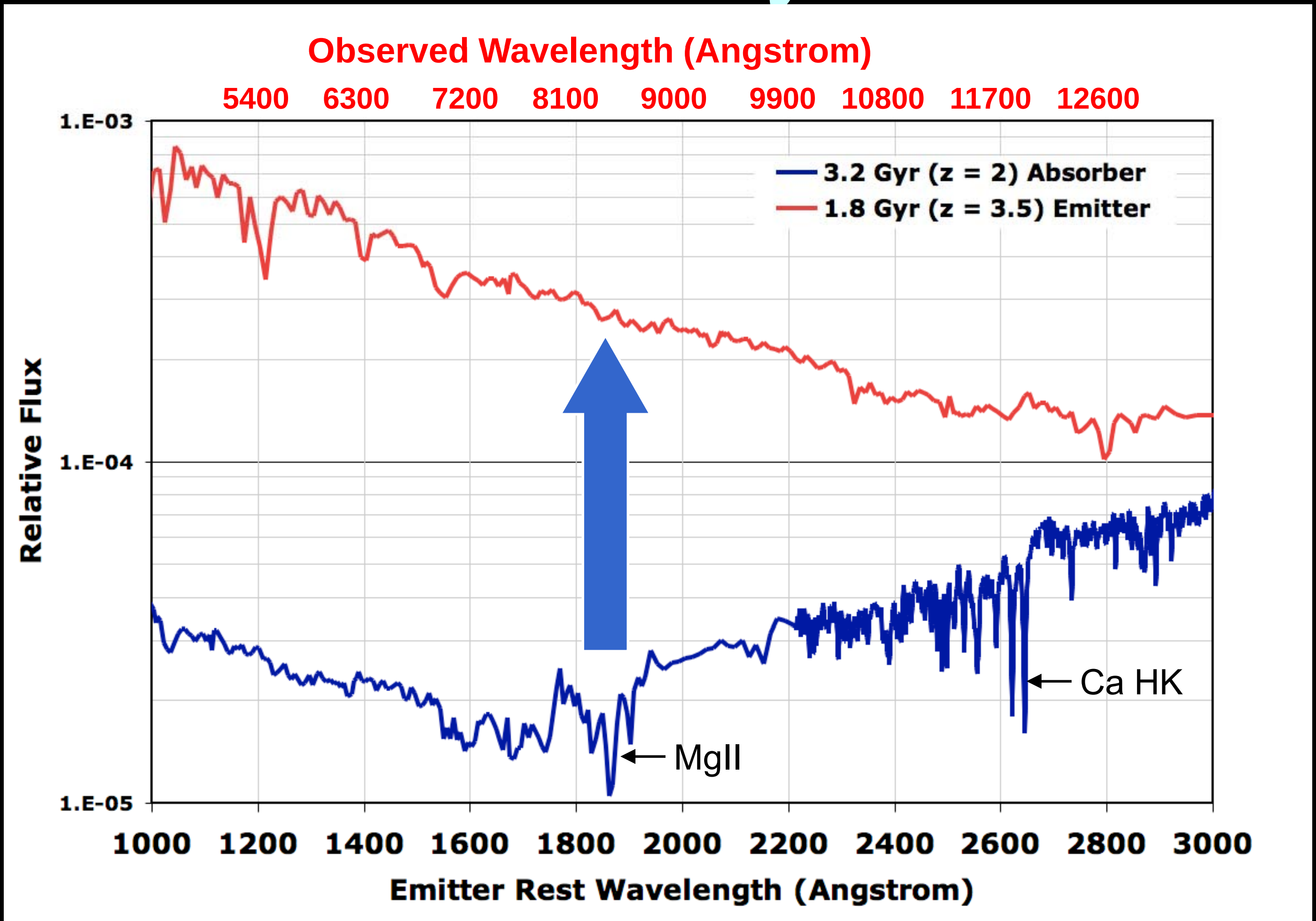
“Modern” Galaxy Evolution



Mg, Ca absorption features from gas in the foreground galaxy’s halo are superposed on the spectra of the background galaxies, enabling the direct determination of the halo mass within the radius probed by the light beam.

Light from several background galaxies can be used as probes of the galactic halo of a foreground galaxy

“Modern” Galaxy Evolution



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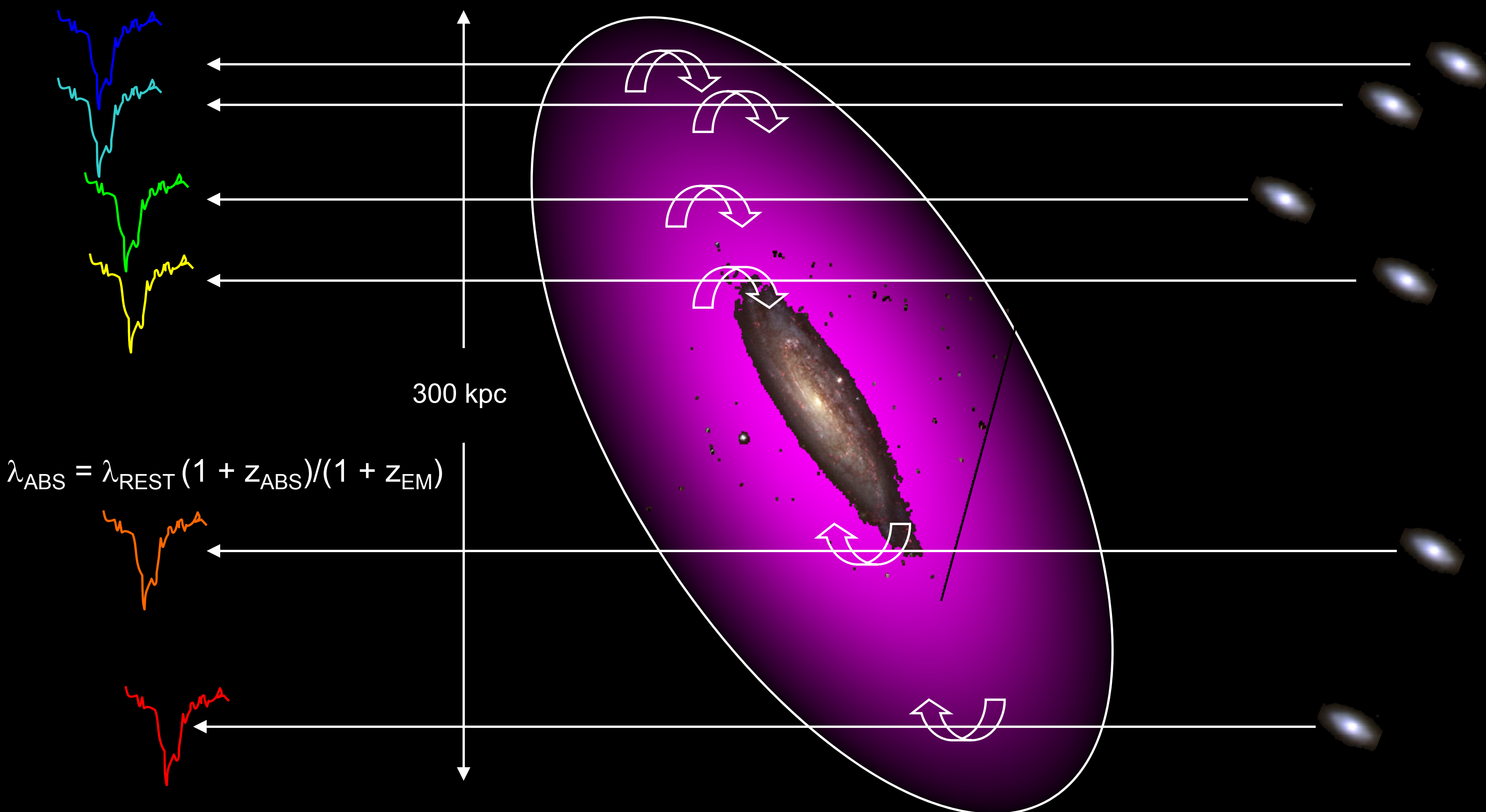
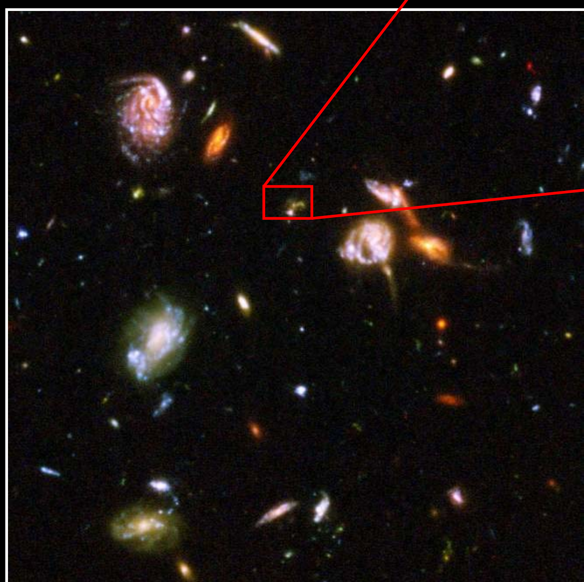
"Modern" Galaxy Evolution

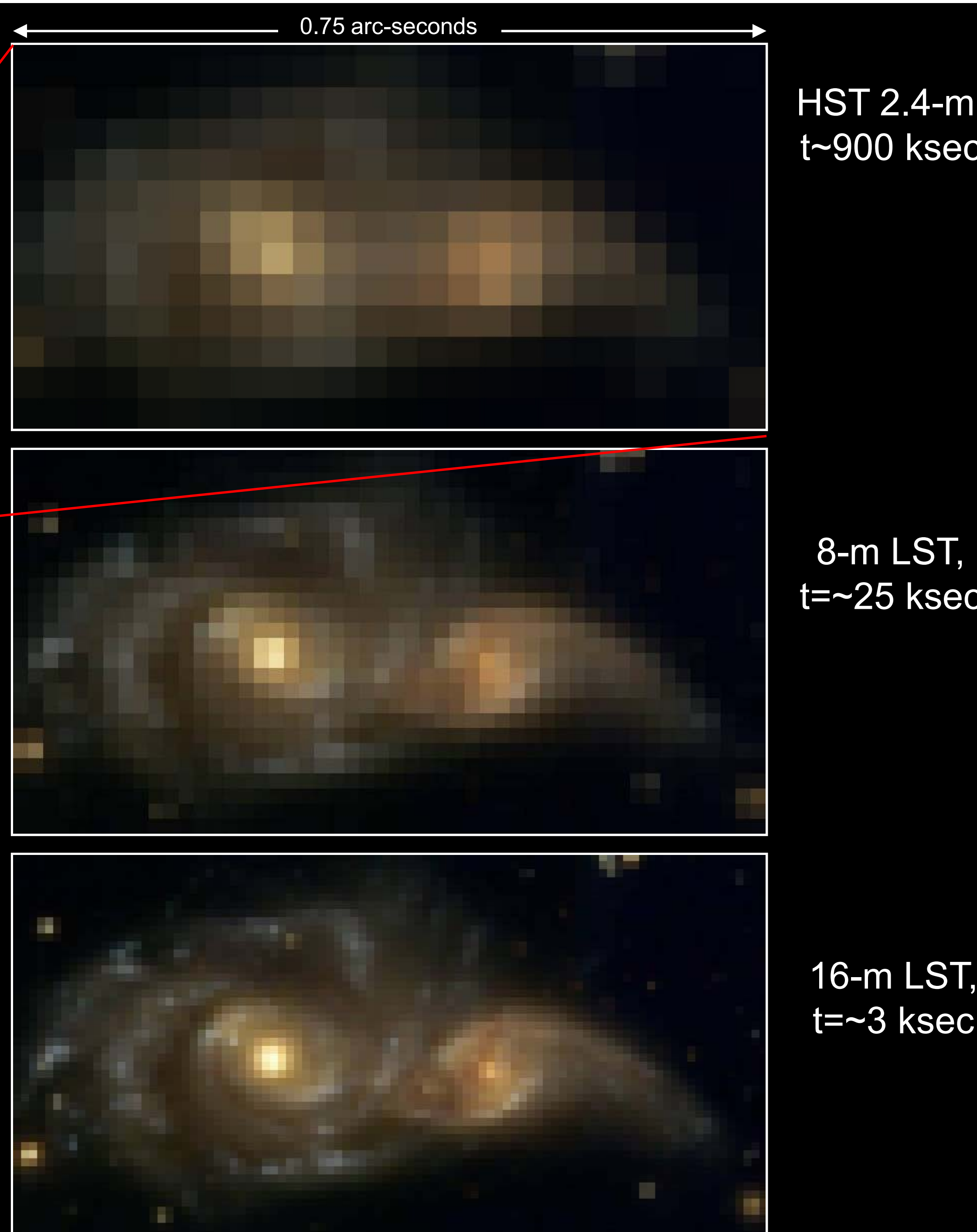


To find a sufficient number of background sources (~500 galaxies per square arcminute) and to be able to measure these spectral features across many lines of sight in each foreground galaxy requires

- **Extensive light-gathering power (typical bkgd source is between ~28 - 30 AB mag)**
- **UV/optical sensitivity to access usable regions of the galaxy spectrum**

“Modern” Galaxy Evolution





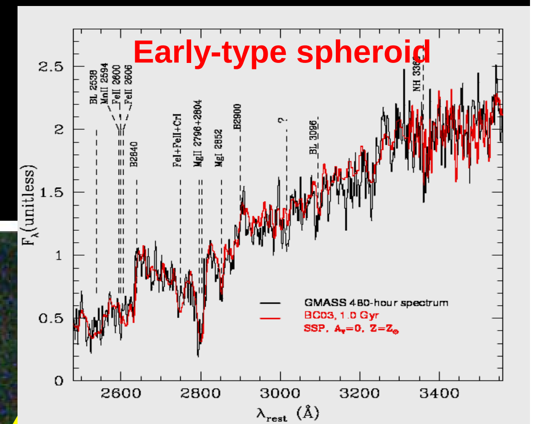
HST Ultra Deep Field

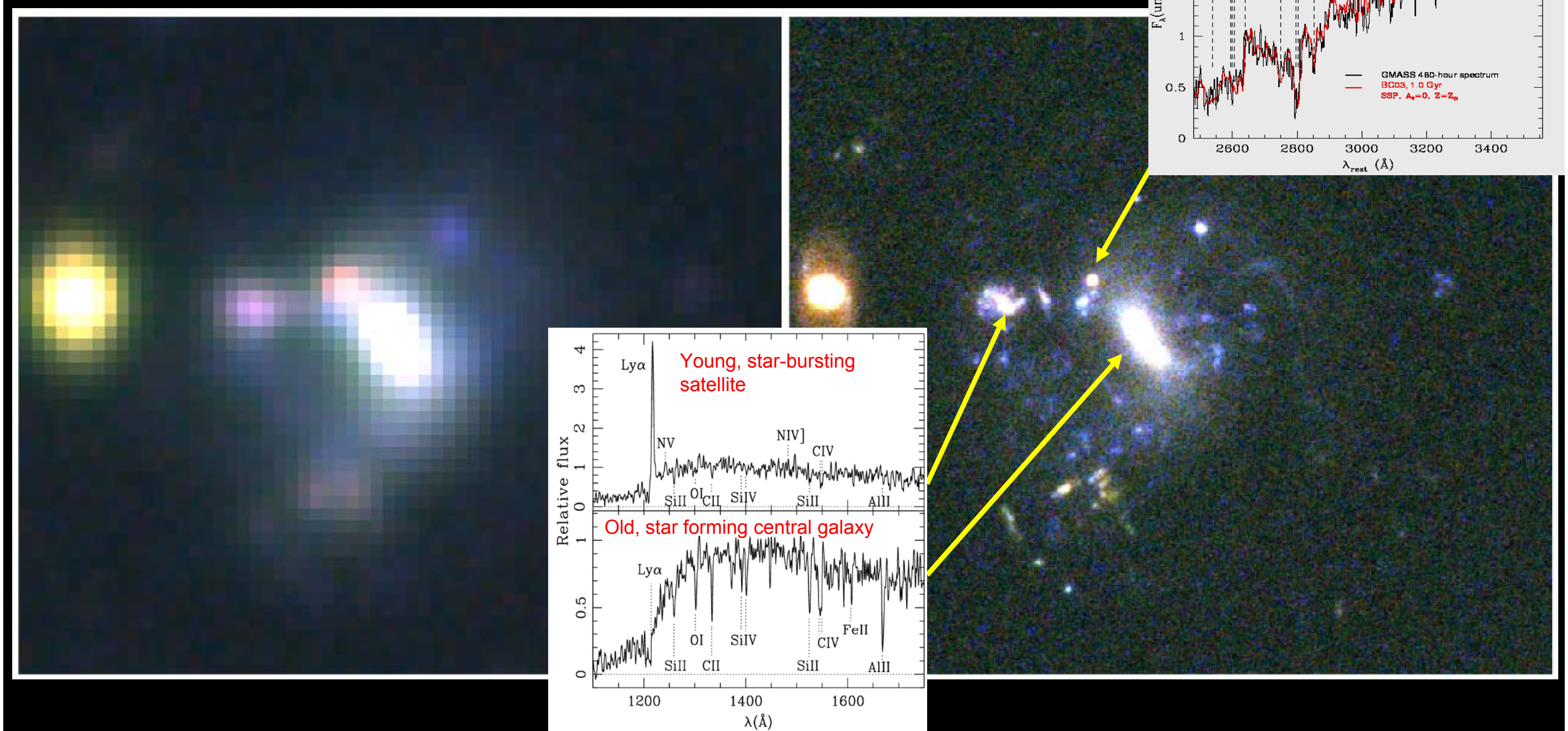
Faint Galaxy:
- 25.1 AB mag (330 nJy) in I-band
- 0.75 arc seconds across
- 2 “peaks” in light distribution
- Morphology unknown

“Modern” Galaxy Evolution

ATLAST will track how and when galaxies assemble their present stars
ATLAST will investigate why galaxies start to evolve passively.
ATLAST will test the hierarchical formation of structure

We require high ang. resolution & hi-sensitivity access to UV-Vis diagnostics





Galaxy at z~3 with HST (100 mas FWHM)

Galaxy at z~3 with ATLAST (10 mas FWHM)

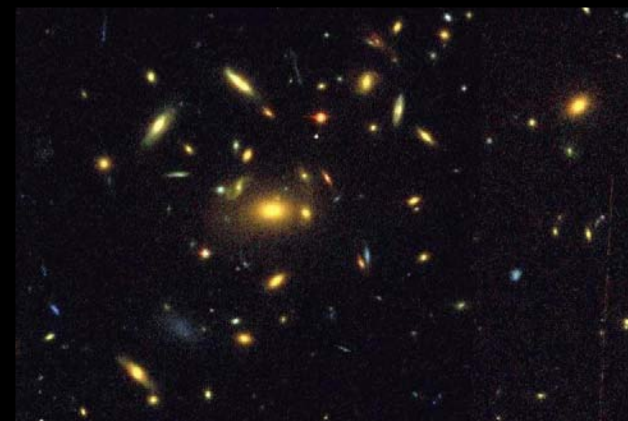
Re-tracing the Star Formation History of Galaxies *in High Definition*

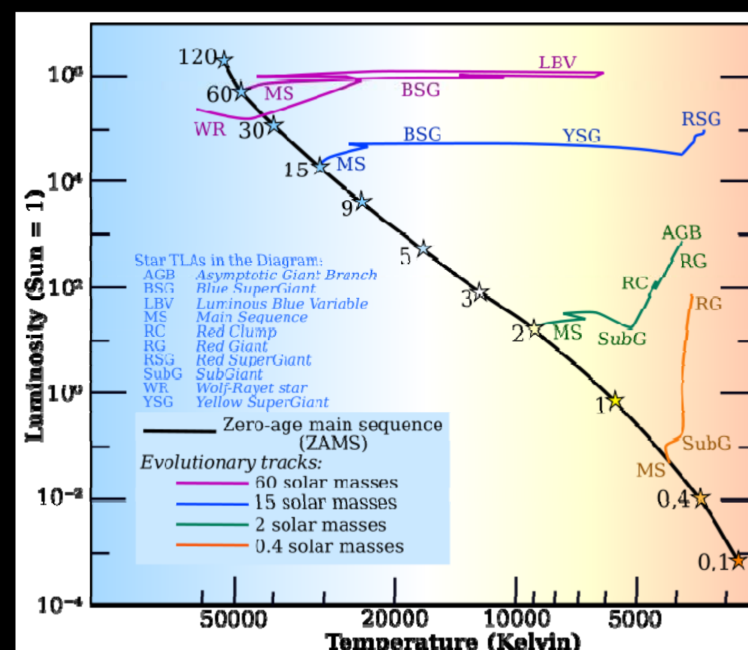
Age & Metallicity (elemental abundances) of galaxy are sensitive indicators of its star formation history and the physical processes that govern the star formation.

Constraints on the ages of stellar populations in distant galaxies can only be inferred statistically (from large galaxy samples) using broadband photometry. Their precise SFH's cannot be reconstructed but one can access very high look-back times with even modest-sized telescopes.

In nearby galaxies, the stellar populations can be resolved with a sufficiently large telescope. This enables the individual components of the stellar population (e.g., MS, AGB, RGB) to be studied, yielding a complete SFH.

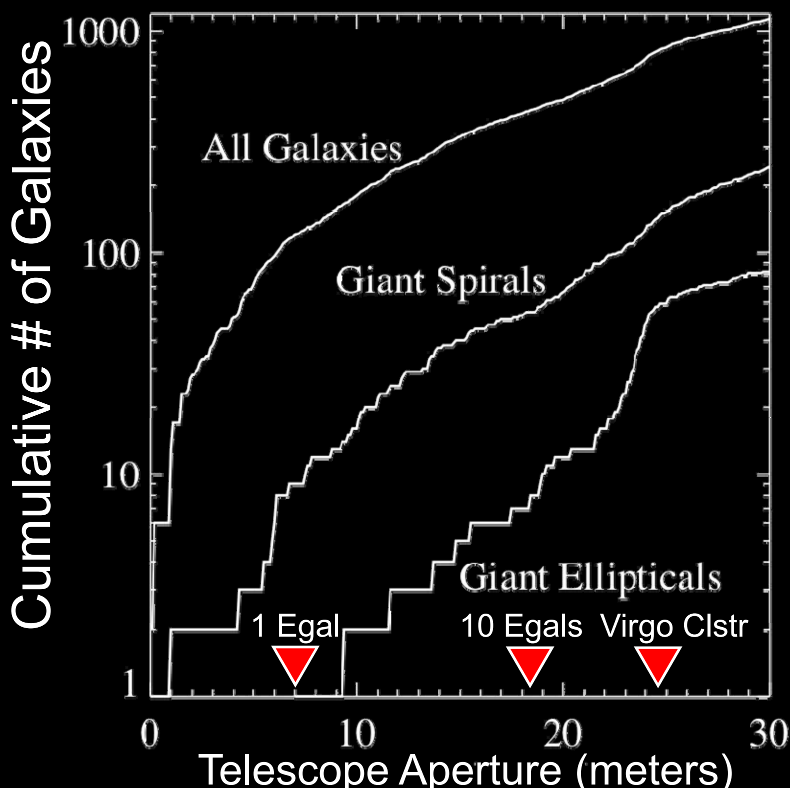
The two approaches are complementary and will allow us to definitively establish the detailed cosmic history of star formation in the universe.

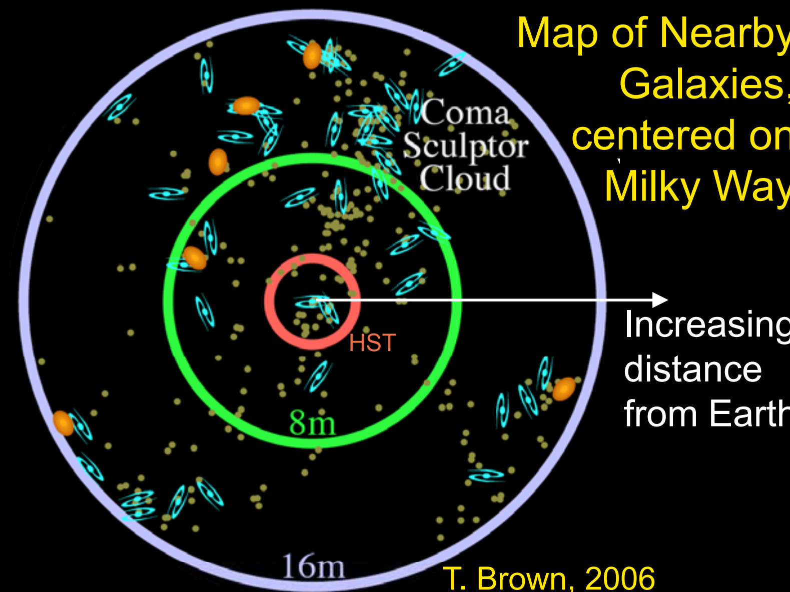




Re-tracing the Star Formation History of Galaxies *in High Definition*

Resolved Stellar Populations: An 8-m to 16-m space telescope will bring about a major revolution in the study of stars, enabling observations of solar-luminosity stars outside the Local Group of galaxies. Observations of solar-luminosity stars on the main sequence are essential to reconstructing the star formation history over the entire lifetime of a galaxy.





Map of Nearby Galaxies, centered on Milky Way

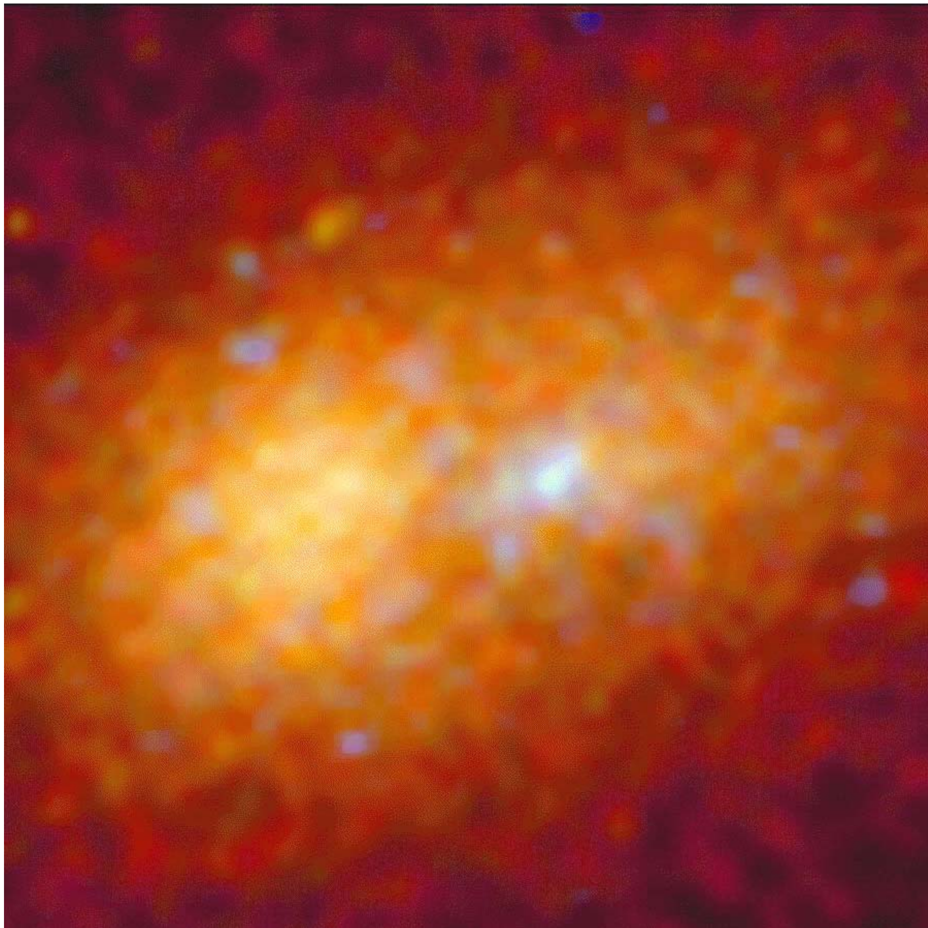
T. Brown, 2006

ATLAST will open up the entire Hubble sequence of elliptical and spiral galaxies to study, revealing their detailed star formation histories. These histories hold fundamental (but as yet unknown) information about galaxy formation. JWST will observe the integrated populations of stars at high redshift but will not reconstruct their detailed star formation histories. We will need the capabilities of ATLAST to understand the detailed evolutionary history of nearby galaxies to obtain a comprehensive understanding of how stars form.

We require S/N = 5 photometry of ~thousands of 33 - 35 m_V stars.

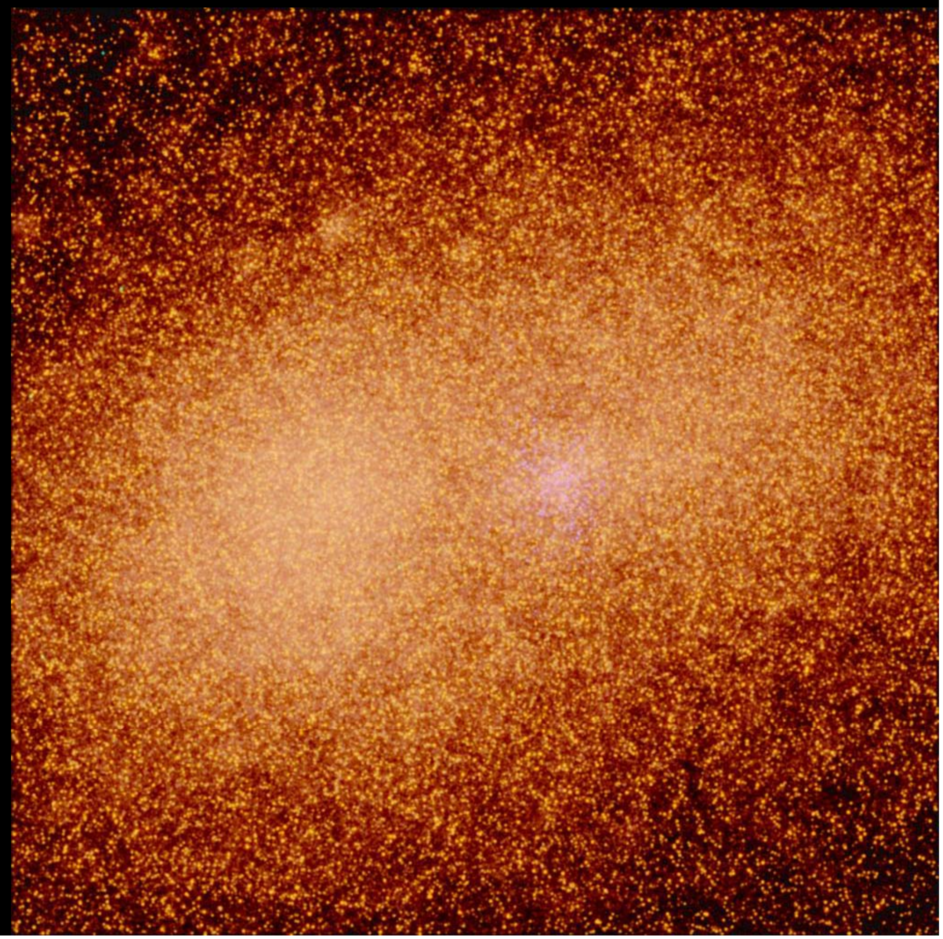
We also require high-resolution spectroscopic capabilities in the near UV - optical to study the distribution of stellar masses in nearby galaxies.

M31



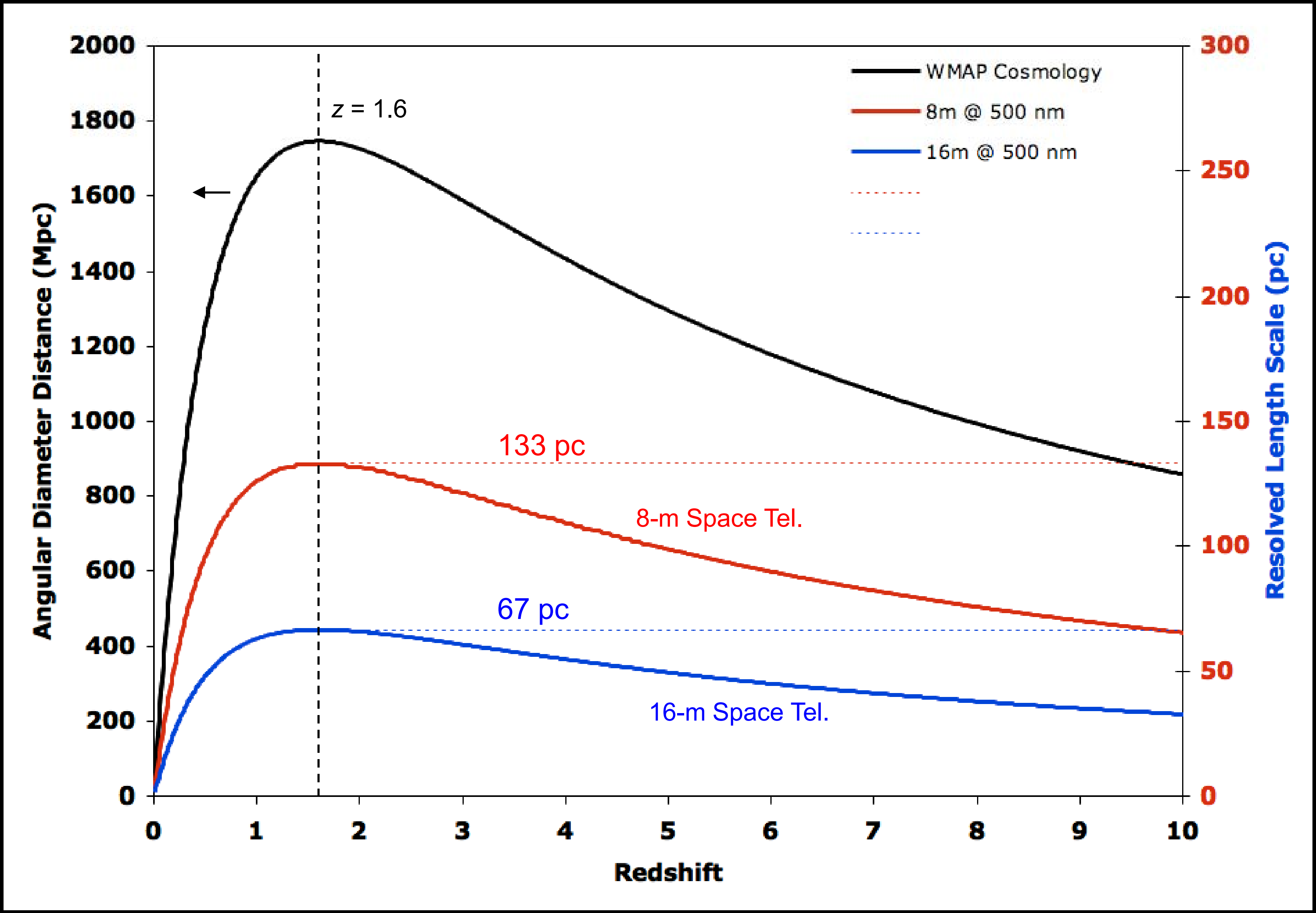
HST (~100 mas)

16-m ST (~8 mas)

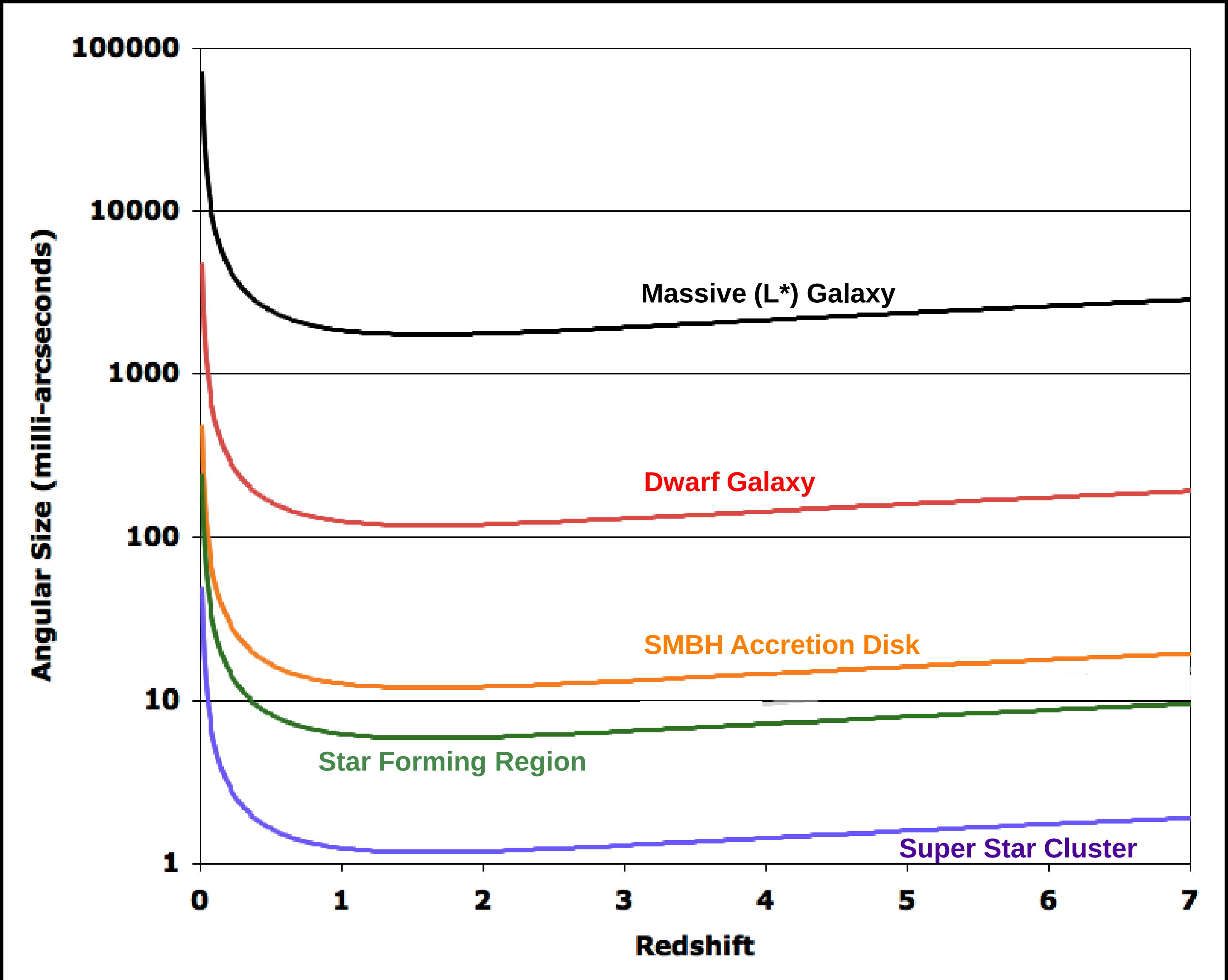


Simulation by T. Lauer, 2004

The Astrophysics of Resolution



The Astrophysics of “Resolution”

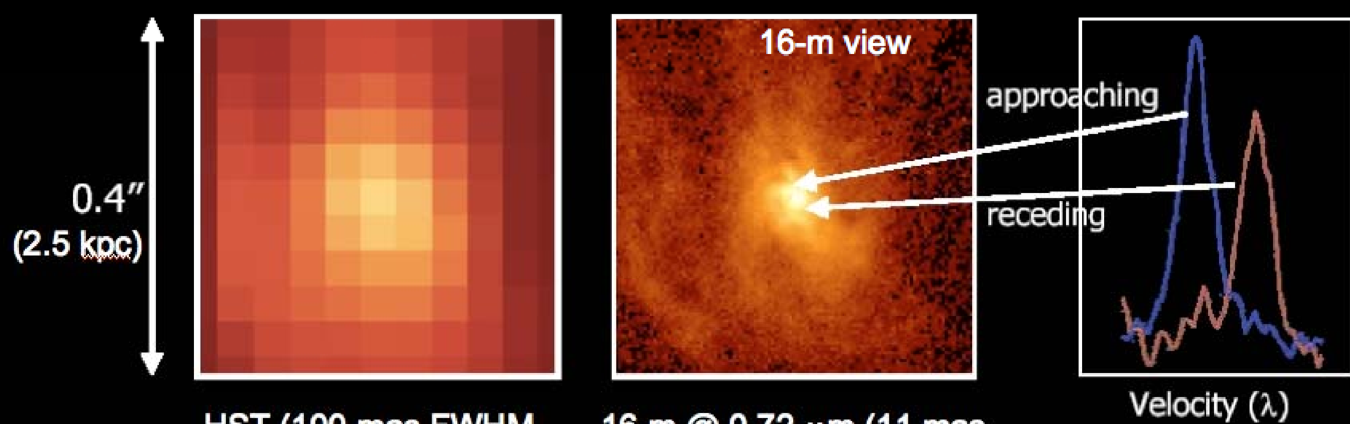


Super Massive Black Holes Across Cosmic Time

Most galaxies have massive black holes in their centers. The mass of the central black hole is highly correlated with the mass of the host galaxy. Understanding the origins of this fundamental relationship is one of the key unsolved problems in astrophysics. ATLAST enables us to measure the SMBH mass over a large range in cosmic time.

SMBH Candidates vs. Telescope Aperture

D_{TEL} (meters)	Highest z at which 100 pc can be resolved in UV/Opt	Number of SMBH Candidates
2	0.06 (Univ age 94%)	10
4	0.10 (Univ age 90%)	50
8	0.36 (Univ age 71%)	1,740
16	7.00 (Univ age 6%)	43,500



HST (100 mas FWHM, 16-m @ 0.72 µm (11 mas

Need to sample velocity field within gas accretion disk to get accurate BH mass: ~200 pc for typical SMBH.

A. Koekemoer (2008)

A large space telescope is unique in providing the required combination of:

- **high resolution and extensive light-gathering power**

to provide the required high spectral dispersion and mass measurements for black holes well beyond the local universe, up to cosmological distances.

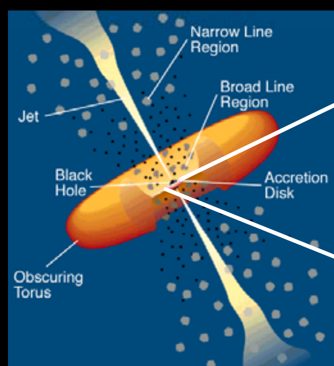
Probing Black Holes, continued …

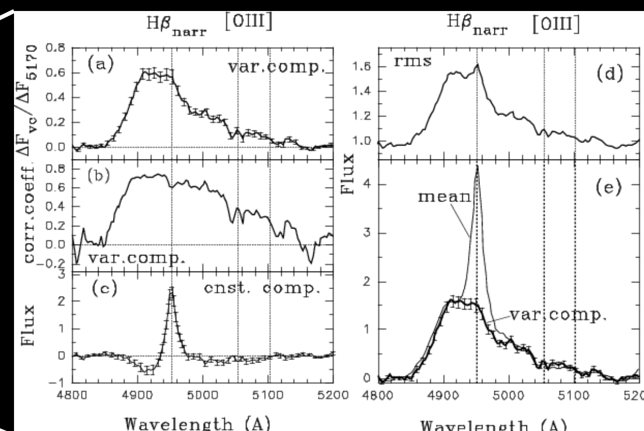
"Dissecting" gas immediately around the black hole using reverberation mapping:

The very innermost regions of the accretion disk, within a few gravitational (Schwarzschild) radii of the black hole itself, provide the most direct insight into:

- the properties of the black hole;
- the effects of strong gravitational relativistic effects on the infalling gas.

These regions are so close to the black hole that they probe light travel times of only a few hours to a few days at most, and can only be studied by time-resolved spectroscopy at very high dispersions (R ~ 30,000 or more).





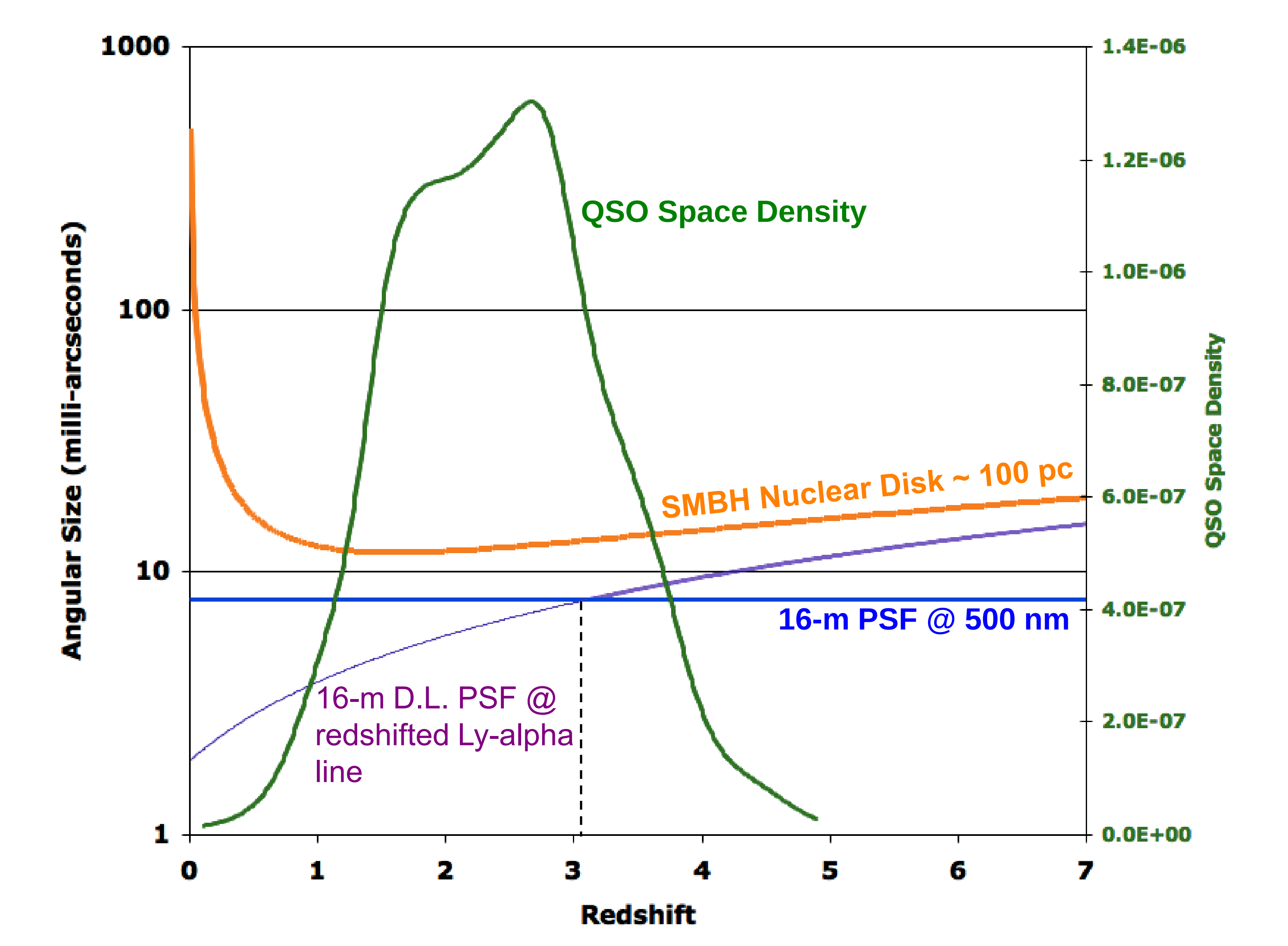
To date, only a few local AGN can be studied to this level of detail since high contrast observations are required. For more distant sources, the light from the surrounding galaxy overwhelms the emission from the central source and washes out the signal.

An ATLAS telescope is unique in providing the required combination of:

- **high contrast**
- **extensive light-gathering power**

to provide the required high dispersion measurements for black holes well beyond the local universe, up to cosmological distances.

Combining Spectroscopy with high-angular resolution



Galactic science with ATLAST

Space-based observations at UV/optical/nearIR wavelengths offer:

- Low background
- Stability
- Diffraction limited imaging

Ground-based AO-assisted observations at UV/optical/nearIR wavelengths offer

- Large collecting area
- High Strehl point-source imaging (in near-IR)
- But low stability and high background

➔ Space offers significant advantages for low surface brightness, extended objects

➔ Propose to focus on circumstellar material, particularly protoplanetary disks and debris disks

Key issue: How many stars form planets ?

Disks and planet formation

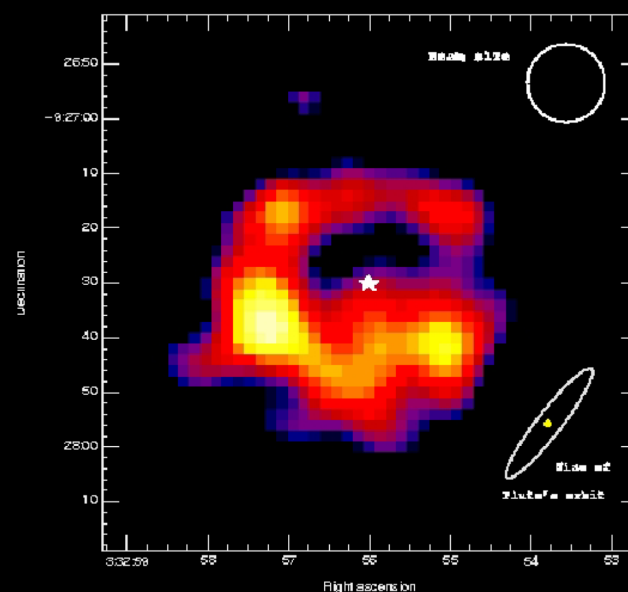
Disk structure can provide important clues concerning planet formation

- Central holes
- Gaps, rings & radial structure
- Asymmetries

May be only way of detecting very low mass (sub-terrestrial) and/or large semi-major axis planets

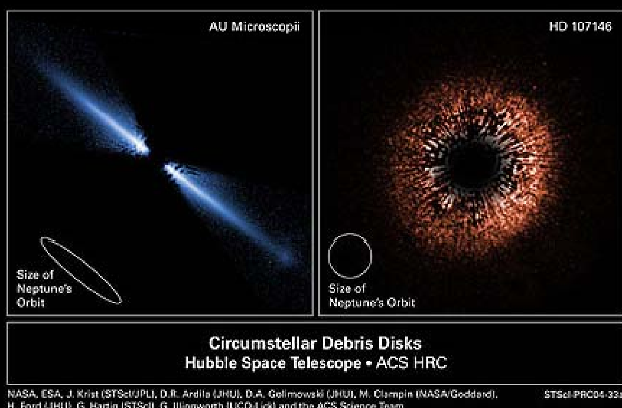
Solar system zodi has $\Sigma \sim 27$ mag arcsec^{2}

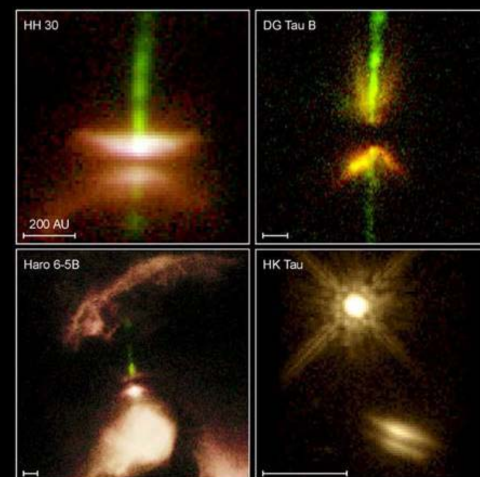
→ comparable in brightness to Earth at 10 pc



Detecting circumstellar disks

Current observations are limited to disks with fractional luminosities $f_{disk}/f_{star} > 10^{-4}$ → young stellar systems, $\tau < 1$ Gyrs, ~2% of nearby stars





Achieving suppression of 10^{-9} would allow detection of disks with $f_{disk}/f_{star} > 10^{-7}$ → ~10 zodi level, increase detection rates to 30-40%

Also probe gas structure (density/temperatures/kinematics) in young disks/HH objects

Characterizing Exoplanets

“Does life exist elsewhere in the Galaxy?”

If terrestrial mass (<10 M_{earth}) planets lie within the habitable zones of nearby stars, they may harbor life as we know it.

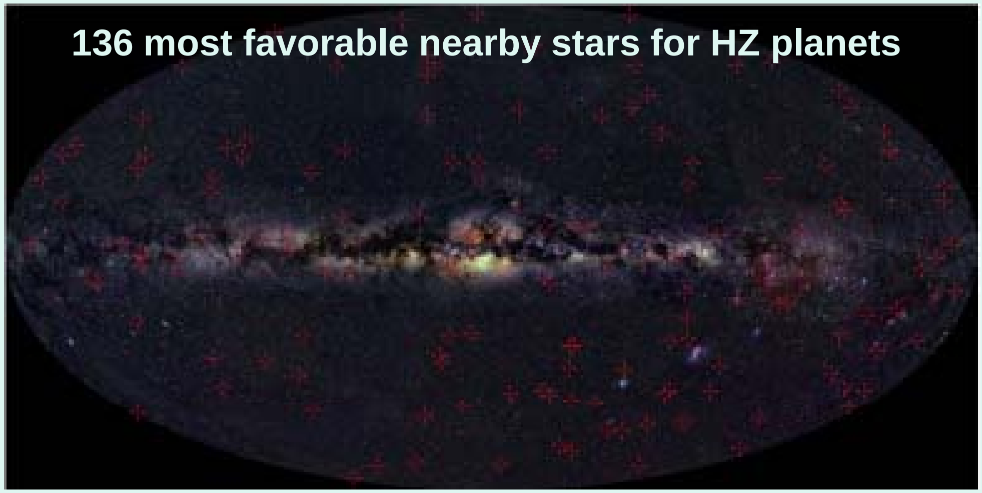
If that life alters the atmospheres of other planets as it has on Earth through the production of oxygen and carbon dioxide, for example, we could detect these chemical signatures in spectra of the planets.

We require R ≥ 100 spectra of ~30 m_v sources

Earth at 10 pc is V ~ 29.1
Earth at 20 pc is V ~ 30.6

Large space telescopes (~8-m or more) ***are required*** to greatly enhance the likelihood of detecting biosignatures from terrestrial exoplanets in the Habitable Zone.
This is not a problem that can be readily addressed even with the largest (20 - 40m) telescopes on the ground due to tough limitations imposed by Earth’s atmospheric absorption and emission and photon statistics within speckles. (Lunine et al. ExoPTF, 2008)

How big a telescope do we need to solve the Observable Drake Equation?

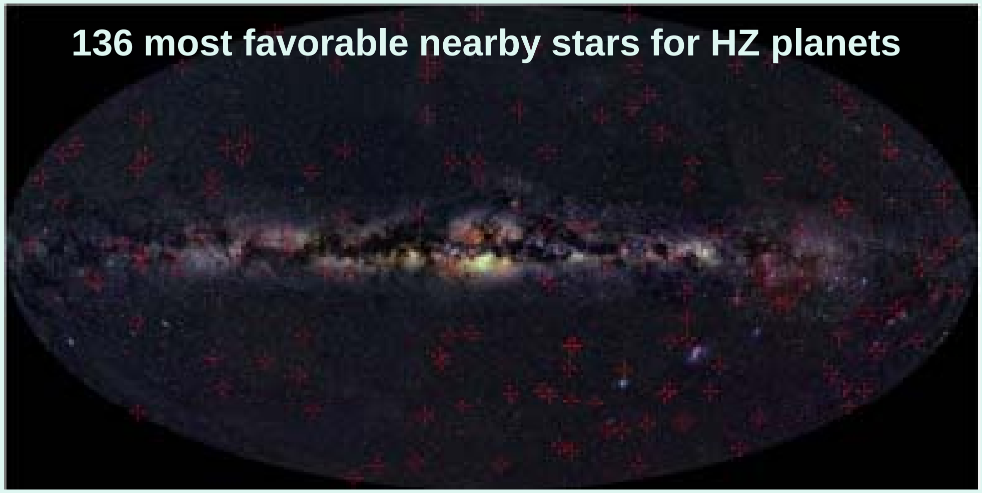


$$N_{L,t} \sim D_{Tel}^{\,2.5} \cdot \eta_{\,earth} \cdot \; p_L$$

EXOPLANET HOST STAR SAMPLE SIZE vs. TELESCOPE DIAMETER (For Realistic Telescope Performance)		
Primary Mirror Diameter (Meters)	**# Coronagraphic Candidates**	
	All Stellar Types	**Solar Type Stars**
2	**4**	**0**
4	**35**	**13**
8	**280**	**101**
16	**2240**	**1417**

From Beckwith 2008

How big a telescope do we need to solve the Observable Drake Equation?



$$\boxed{N_{L,t} \sim D_{Tel}^{\ 2.5} \cdot \eta_{\ earth} \cdot \ p_L}$$

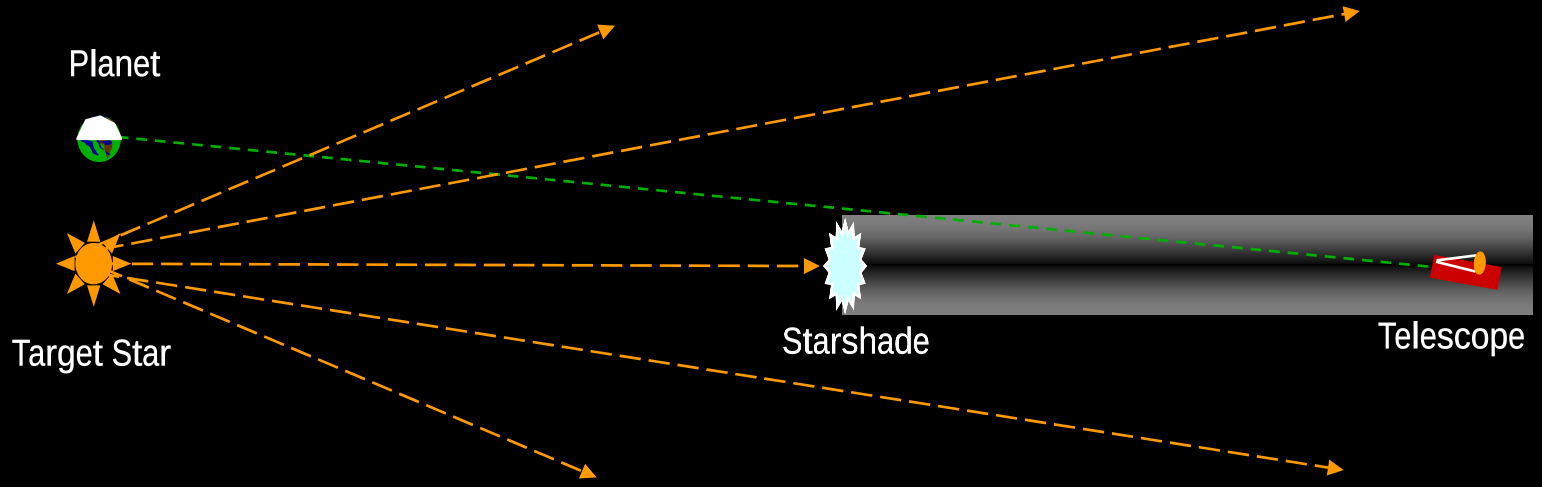
If: $p_L * \eta_{\ earth} \sim 1$ then $D_{tel} \sim 4m$

$p_L * \eta_{\ earth} < 1$ then $D_{tel} \sim 8m$

$p_L * \eta_{\ earth} << 1$ then $D_{tel} \sim 16m$

Characterizing Exoplanets

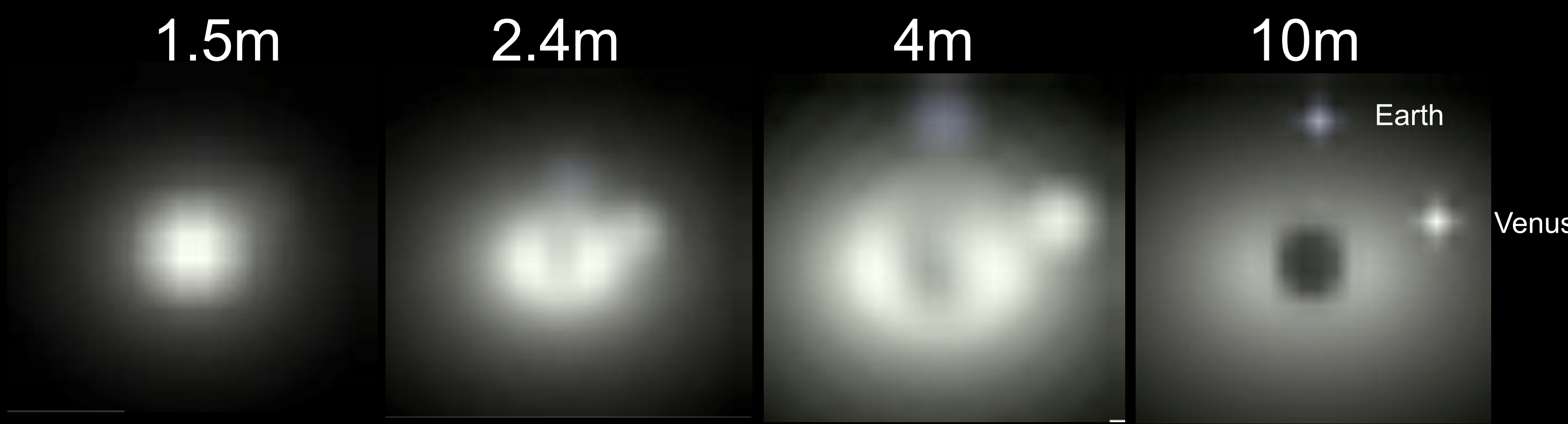
Credit: Web Cash 2008



Characterizing Exoplanets: Via the use of an external occulter, one can suppress the light of the central star, enabling the detection of any orbiting exoplanets. Detecting and characterizing these, however, becomes progressively easier with increasing telescope aperture.

Characterizing Exoplanets

Credit: Web Cash 2008



Above: a simulation of our solar system at a distance of 10 pc observed with an external occulter and a telescope with the indicated aperture size. The two planets are Earth and Venus. The challenges of deploying and maneuvering the star shade, however, also increase with increasing telescope aperture. Using a combination of an internal coronagraph and an external occulter may be the optimal solution.

Characterizing Exoplanets: Via the use of an external occulter, one can suppress the light of the central star, enabling the detection of any orbiting exoplanets. Detecting and characterizing these, however, becomes progressively easier with increasing telescope aperture.

Discriminating terrestrial scale planets from their parent star *also* requires angular resolution

Many Other Scientific Drivers …

- Galaxy and stellar kinematics enabled by precision astrometry. Yields fully 3-D kinematic model of gravitationally bound structures.
  - Local Group tangential velocities 50 - 250 km/s: 10 to 50 micro-arcseconds per year.
  - Virgo cluster tangential galaxy velocities ~400 - 800 km/s: 5 to 10 micro-arcseconds per year.
  - Centroid accuracy: 0.1 pixel easy, 0.01 pixel challenging but feasible, 0.001 pixel very difficult but (perhaps) not impossible.

Astrometric Precision in micro-arcseconds

Centroid Accuracy (pixels) ↓	Telescope Primary Diameter			
	2.4-m	8-m	16-m	20-m
0.1	**5000**	**1570**	**785**	**628**
0.01	**500**	**157**	**78.5**	**62.8**
0.001	**50**	**15.7**	**7.9**	**6.3**

LG Kinematics: 50 - 250 μ-asec in 5 years
Virgo Kinematics: 25 - 50 μ-asec in 5 years

Long time baseline requires high focal plane stability

Q: What Requirements Flow From These Science Goals?

ATLAS-T Specific Question:	ATLAS-T Requirements
Are there detectable biosignatures on exoplanets in the Habitable Zones of their host stars?	WL: 0.4 - 2.4 μ (various atmospheric bands and features from O_2, H_2O, CO, and CH_4), R~100 - 500 spectroscopy, ~2 nJy sensitivity over above range, high-contrast (~10^{-10}) imaging, Ang. Resol. ~8 mas (1 AU at 100pc), FOV ~1 - 2 arcseconds
What are the physical processes driving the weather on the outer gas giant planets in the Solar System?	WL: 0.6 - 2.2 μ, Spatial Resol. ~20 km on Jupiter, narrow and medium band imaging; W.L. 0.11 - 0.6 μ - medium band imaging (aurora and lightening on Jupiter), FOV ~ 30 arcsec
What are the properties of the Solar System's Interplanetary Medium and the Local ISM?	Imaging of diffuse Ly-α emission; Ly-α spectroscopy with R ~10,000 to 100,000. FOV ~up to few arcminutes.
How do galaxies assemble their stars? What is the standard path to assembling the stellar mass in giant galaxies?	WL: 0.2 - 1 μ, ~0.2 nJy sensitivity at 0.4 μ (1 Lsun at 10 Mpc), broad-band imaging, Ang. Resol. sufficient to accurately photometer crowded field of Solar mass stars at ~10 Mpc, FOV ~ few arcminutes
How does the IGM evolve? How are the baryons in the IGM distributed in space?	WL: 0.11 - 1 μ (various H and metal lines), ~10 nJy sensitivity at 0.2 μ, R ~ 1000 - 10,000 spectroscopy, broad-band imaging, Spatial Resol. ~kpc scales, FOV ~ few arcminutes
What is the precise relation between the dynamics of baryons and dark matter in galaxies?	WL: 0.3 - 1.6 μ (various H and metal lines), ~few nJy sensitivity at 0.5 μ, R ~ 1000 - 10,000 spectroscopy, broad-band imaging, sub-kpc spatial resolution, FOV ~ few arcminutes
How do super massive black holes evolve and why is their mass correlated with that of their host galaxies?	WL: 0.5 - 1.2 μ (various metal lines), ~10 nJy sensitivity at 0.5 μ, R ~ 10,000 - 30,000 spectroscopy and broad-band imaging, Spatial Resol. ~few pc at all redshifts out to z ~ 5, FOV ~1 arcminute

ATLAS Telescope Strategic Mission Concept Study Goals

- Define viable technology roadmap to enable a phase A start for a 8-m to 16-m UV/Opt/NIR space telescope in ca. 2020 - 2025. Draw upon existing heritage where possible but must identify and develop “cost-breaking” technologies as well.
- Design objective: an observatory that can *<u>both</u>* characterize terrestrial mass planets in hundreds of stars AND address fundamental problems in astrophysics by providing up to 10x the resolution of JWST and up to 300x the sensitivity of HST.
- Recognize that large space optics have broad potential uses (e.g., Earth Science, National defense).

The Evolving Synergy between Ground and Space Observatories

High Angular resolution coupled with high sensitivity is increasingly a science-driven requirement for astronomy.

Extremely Large ground-based telescopes + next generation Adaptive Optics Systems will redefine the capabilities of ground-based imaging and spectroscopy.

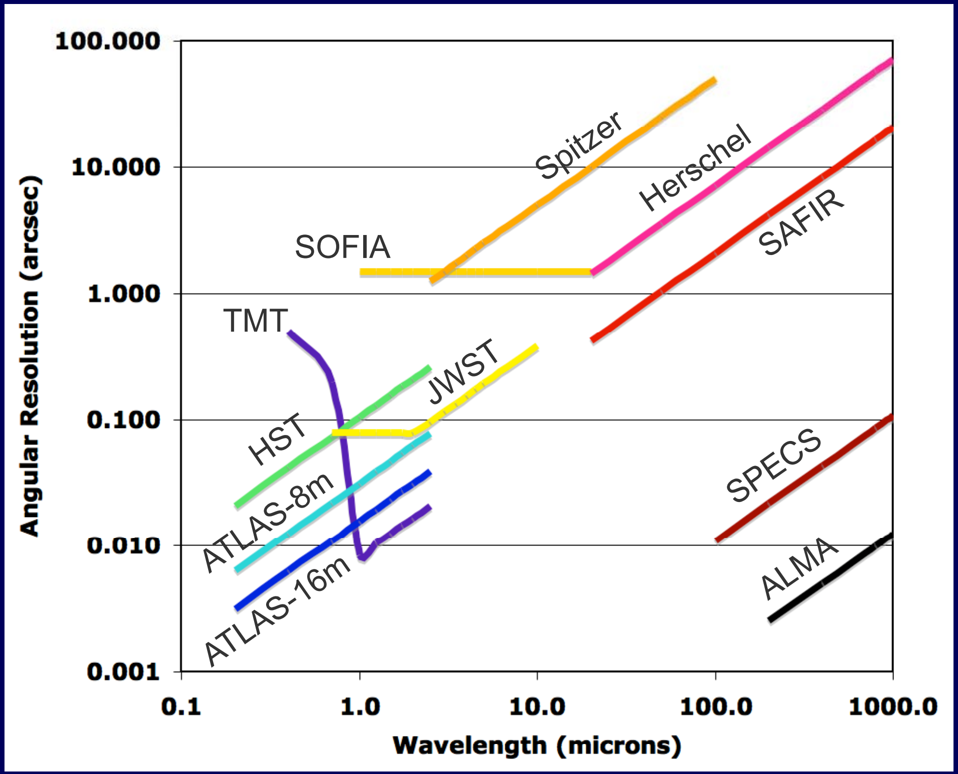
But there remain unassailable advantages of space in the UVO+NIR range:

- Wide-fields (several arcmin) or panoramic imaging (tens of arcmin)
- Stable, high Strehl ratios (>90%)
- Precise wavefront sensing and control
- Highly stable PSFs (<2% variability spatially and temporally)
- Ultra precise photometry (<0.0001 mag) and astrometry

If we want to pursue the compelling scientific issues we imagine today (and the many we cannot imagine), we will need a large UV/optical space telescope as part of our astronomical tool kit.

Making it affordable is the strong motivation for a focused technology development roadmap for the coming decade.

Performance Discriminators



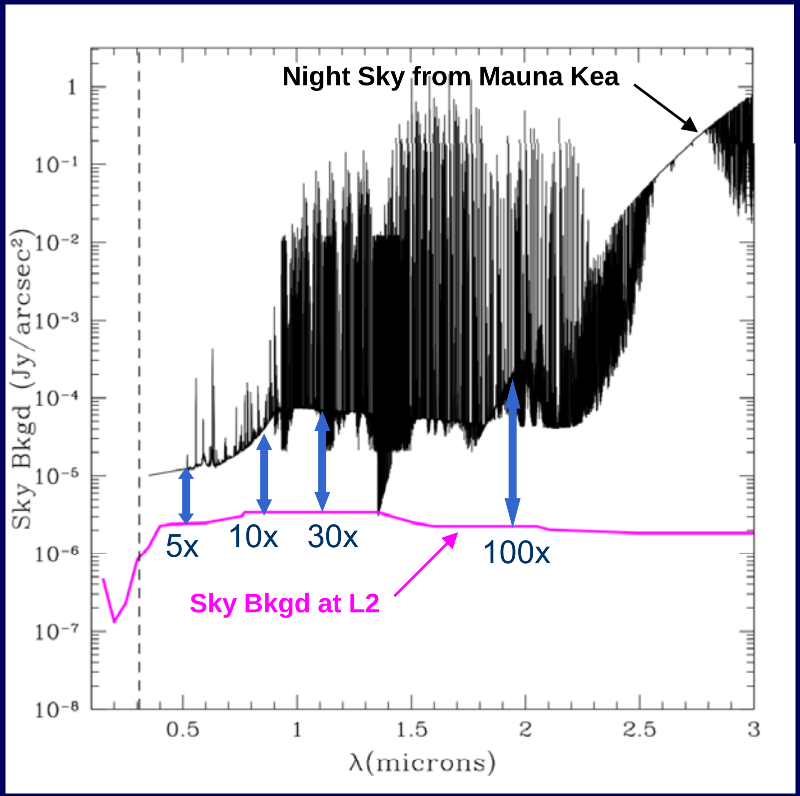
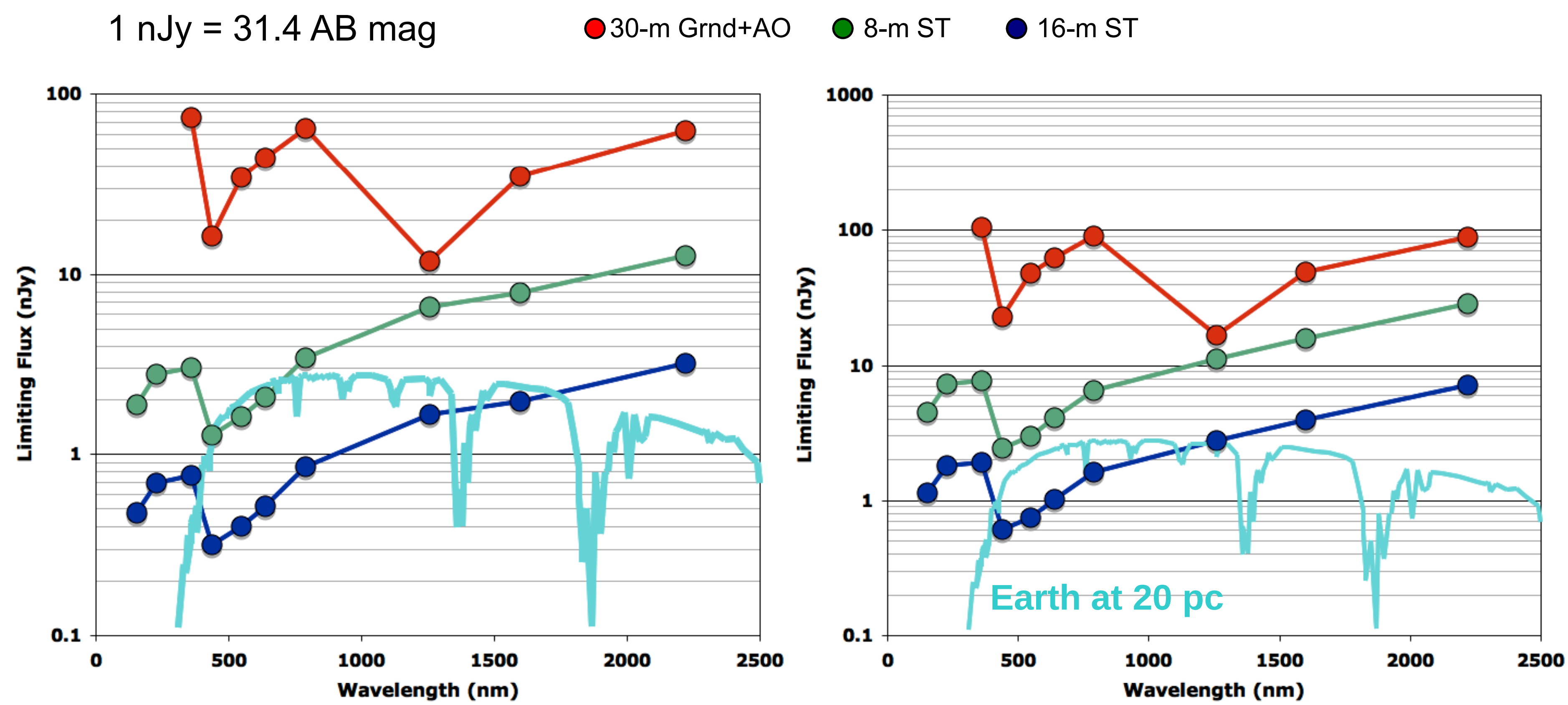


Figure derived from ExoPTF (Lunine et al. 2008)

Point Source Sensitivity

1 nJy = 31.4 AB mag



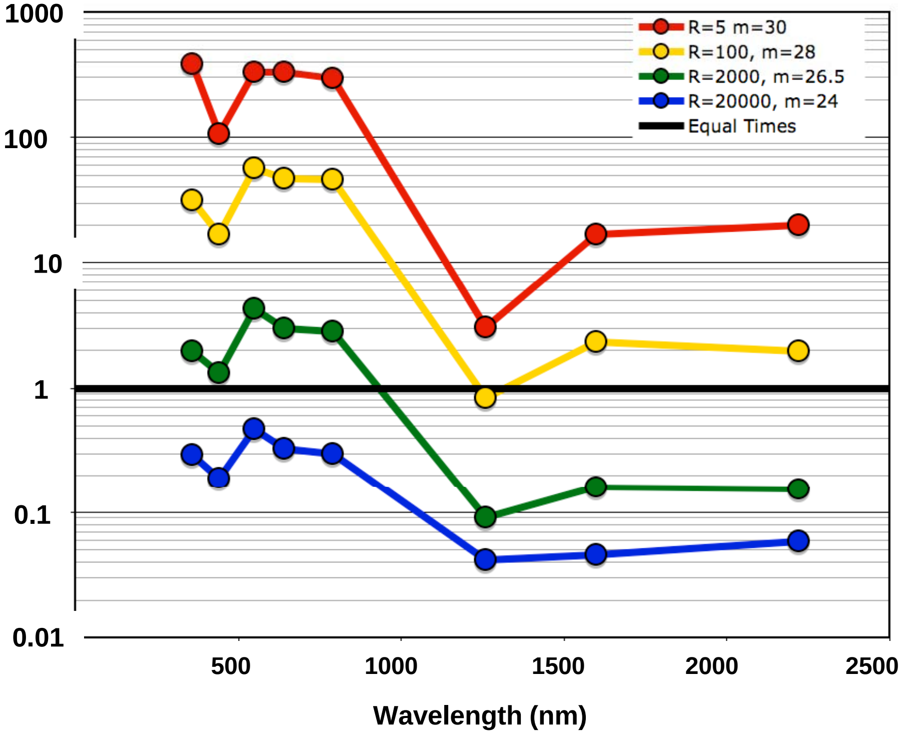
Imaging: R =5, S/N=10 limit in 10 ksec

Low-res spec: R =100, S/N=10 limit in 100 ksec

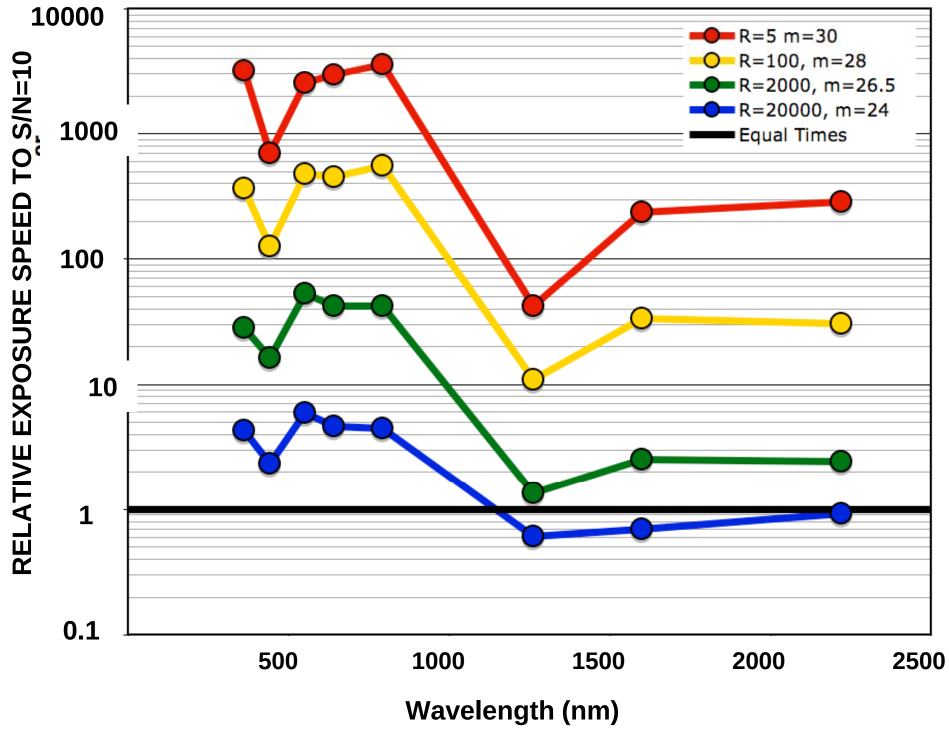
Assumptions (space): RN = 3-4 e^-, Dark = 0.001 sec^{-1}, Tot. Eff = 0.25, Zodi limited bkgd.
(ground): AO enables D.L. performance at >1 micron, seeing-limited (0.5”) below this.

Time Gain Factor

8-m ST vs. 30-m Ground-based+AO in NIR



16-m ST vs. 30-m Ground-based+AO in NIR

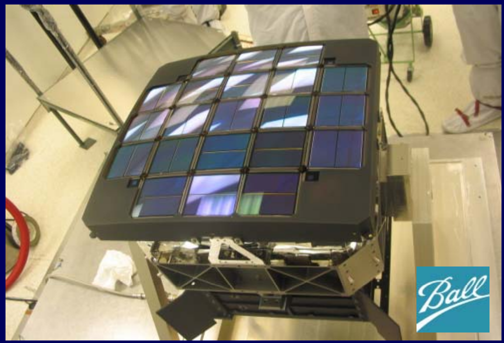


8-m ST faster than 30-m on ground for all imaging and for most R=100 low-res spectroscopy. 8-m also faster for med-resolution spectroscopy in optical band.

16-m ST faster than 30-m on ground for all imaging and spectroscopy except when R > few x 1000 in the NIR. Unique parameter space for hi-res spectroscopy in optical band.

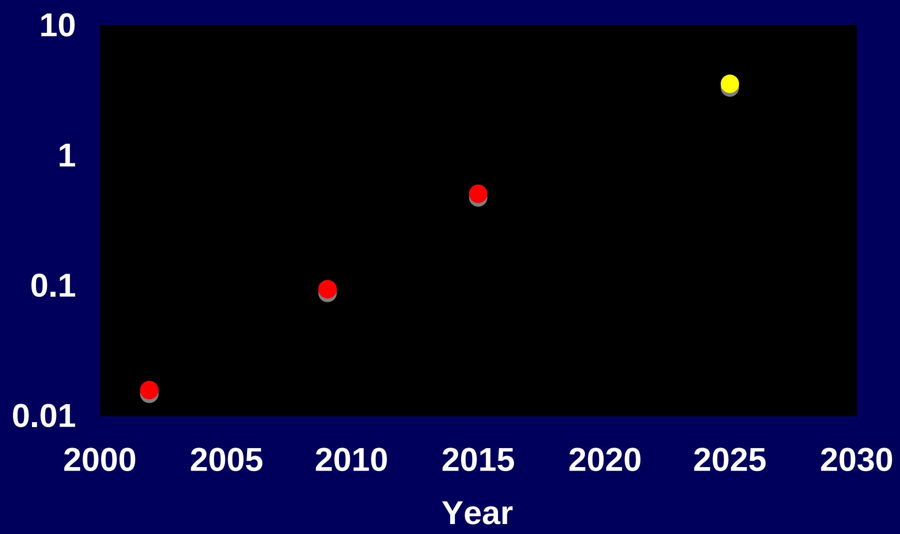
Gigapixel Cameras in Space

- Nominal “fully paved” FOV:
  - 8m: 9 x 18 arcmin
  - 16m: 5 x 5 arcmin
- Nyquist sampled at 500 nm:
  - 8m: 3.6 Gigapixels
  - 16m: 1.2 Gigapixels



Kepler Focal Plane Array (95 Mpix)

- Recent space heritage:
  - ACS/HST: 16 Megapix (2002)
  - Kepler: ~95 Megapix (2009)
- Near future space FPA:
  - JDEM: ~120 - 600 Megapix (~2014 - 2015)



Conclusions:

- The rationale for larger (8+ meters) UVOIR telescopes in space is strong:
  – Uniquely able to characterize Earth-mass planets to search for evidence of biological activity;
  – Establish the mass distribution of super-massive black holes over a substantial fraction of cosmic time, revealing the nature of their assembly and their role in the formation of galaxies;
  – Make direct measurements of the growth of mass of galaxies as a function of time;
  – Provide exquisite high-angular resolution images in a mere fraction of the time of even the largest ground-based telescopes (with MCAO) enabling much larger surveys;
  – Provide unique parameter space coverage in UV and optical high-resolution spectroscopy and low-res NIR spectroscopy;
  – Complement observations with large (20 - 40 meter) ground-based telescopes
  – Address as yet unimagined scientific problems
- Now is the time to develop the technology that will enable us to afford to build such telescopes in the 2020+ era.