General Astrophysics Landscape in the 2030s

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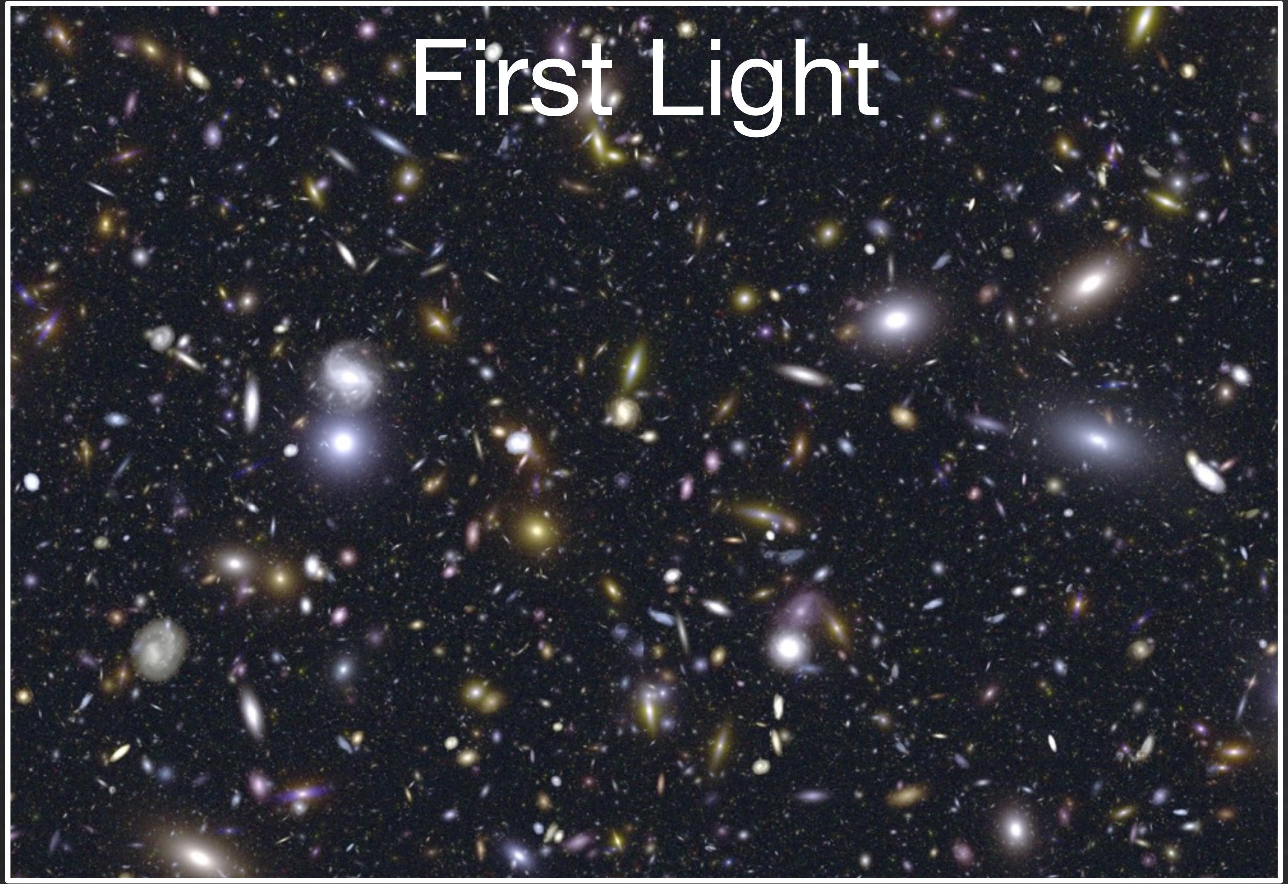
STScI | SPACE TELESCOPE SCIENCE INSTITUTE

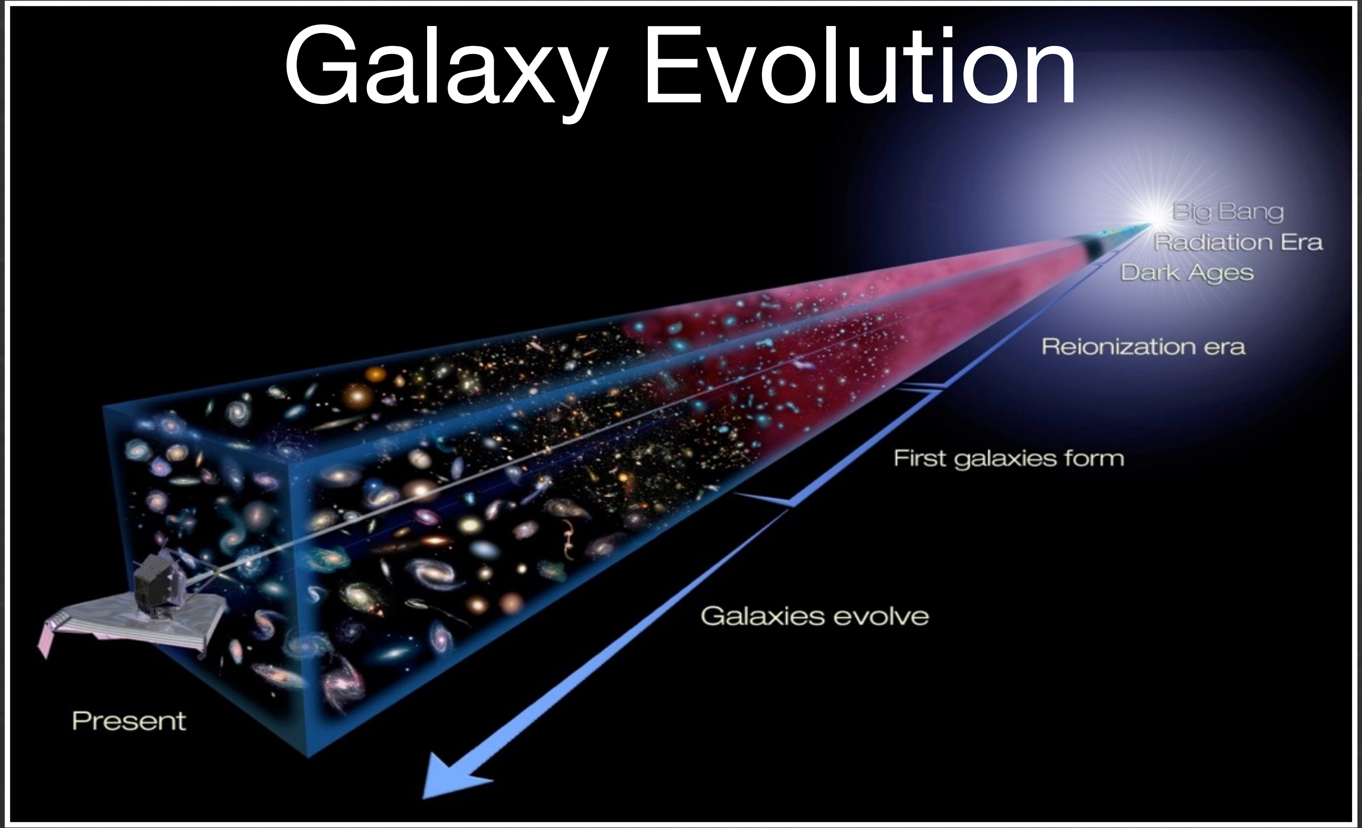
Tracing our Cosmic Origins

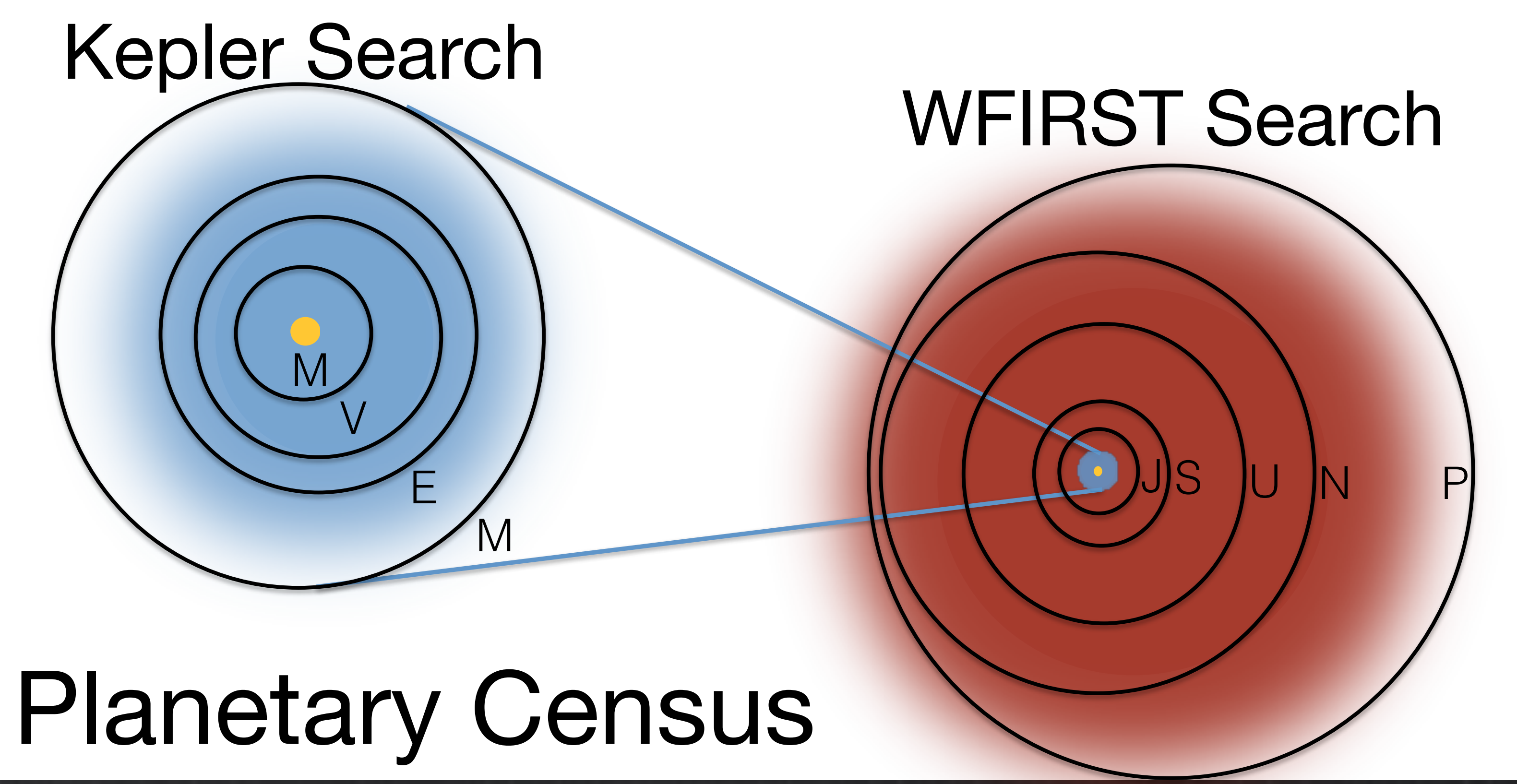
How did we get here?

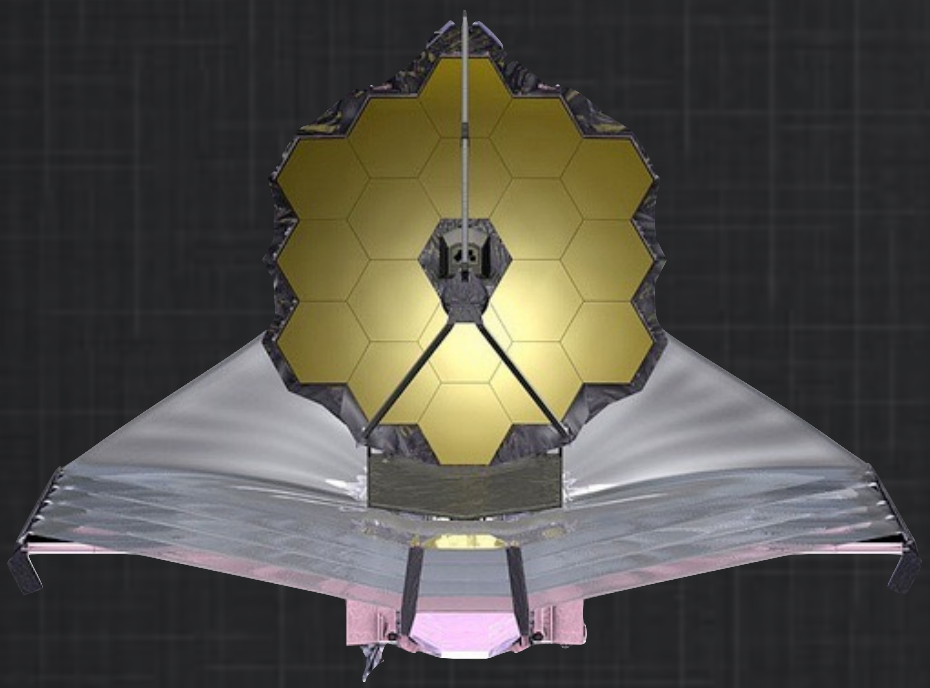
- When and how did the first stars form?
- What were the earliest galaxies like?
- How did galaxies grow over cosmic time?
- What is the process by which life came to be on Earth?
- How do Solar Systems like our own form and evolve?
- What is the influence of dark matter and black holes in shaping galaxies?

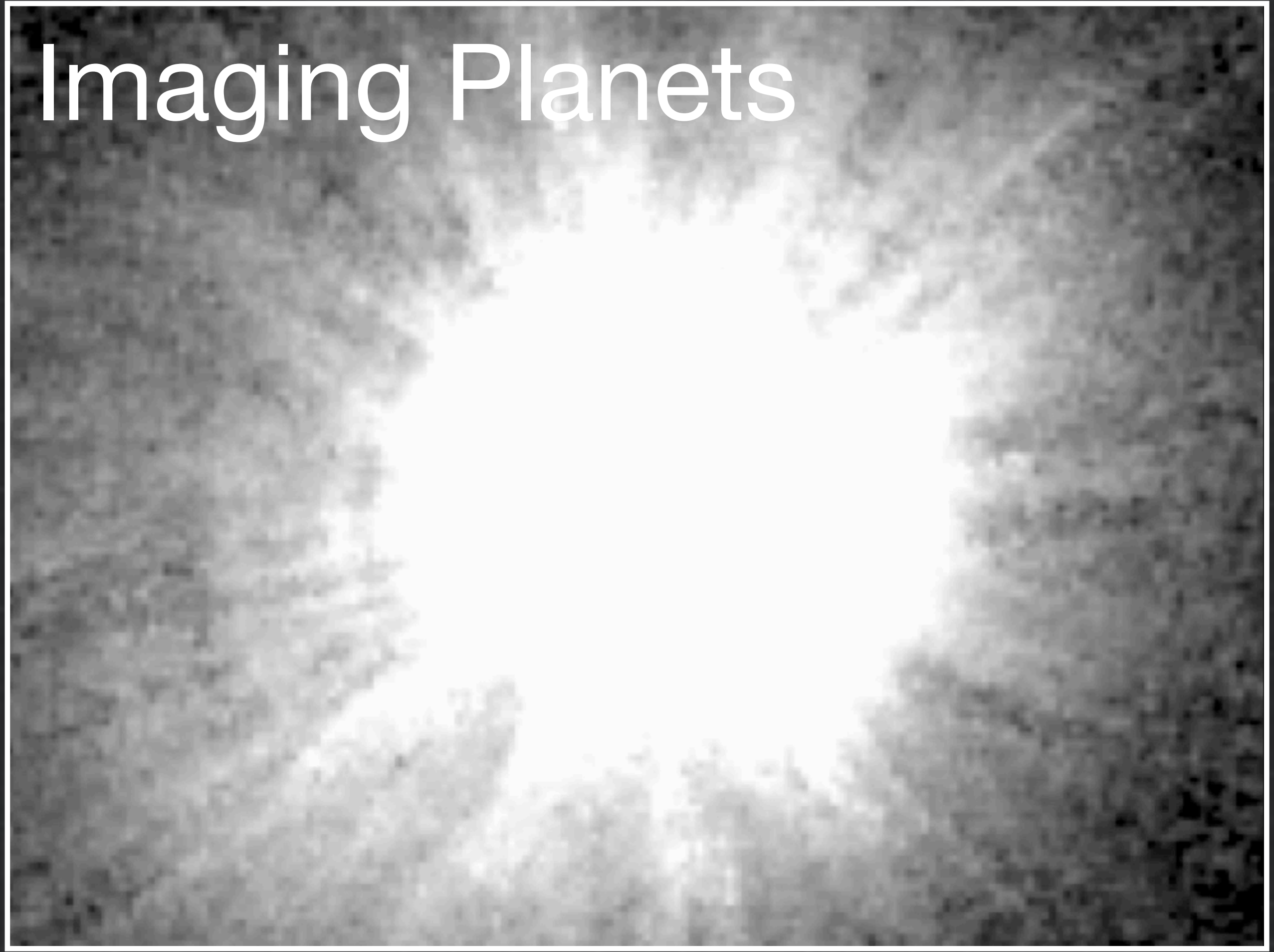
These Enduring Questions are the Foundation of JWST and WFIRST



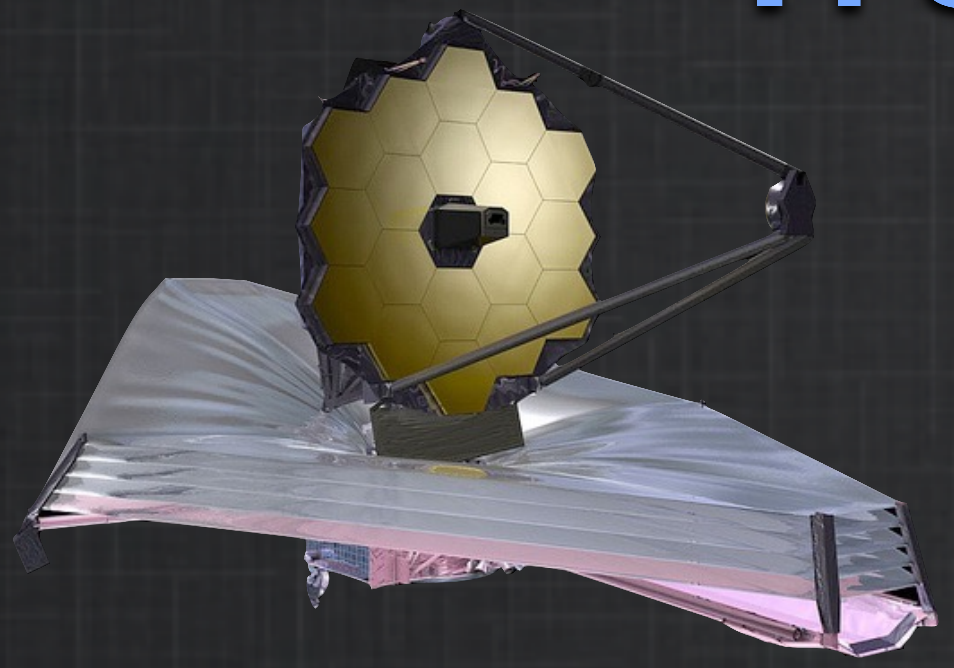








Tracing our Cosmic Origins



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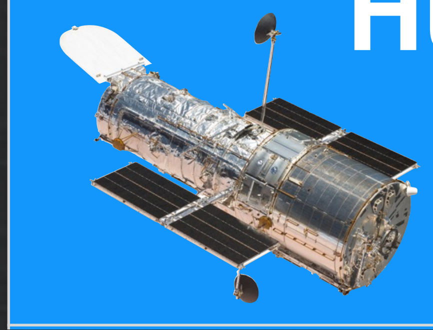
Enabling the next frontier in NASA Cosmic Origins science requires us to place these enduring questions into a post JWST and WFIRST context.

Next Generation Science Capabilities

Missions	Capabilities
 Hubble	High resolution and high throughput UV and visible light imaging UV spectroscopy High resolution NIR imaging and grism spectroscopy

Next Generation Science Capabilities

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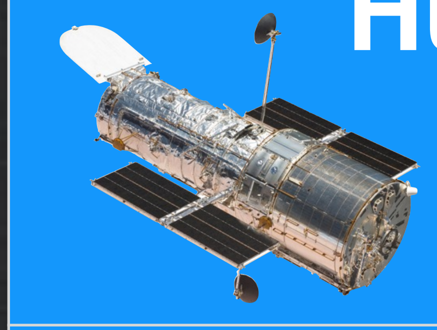
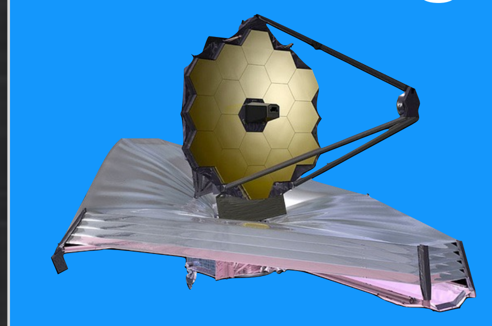
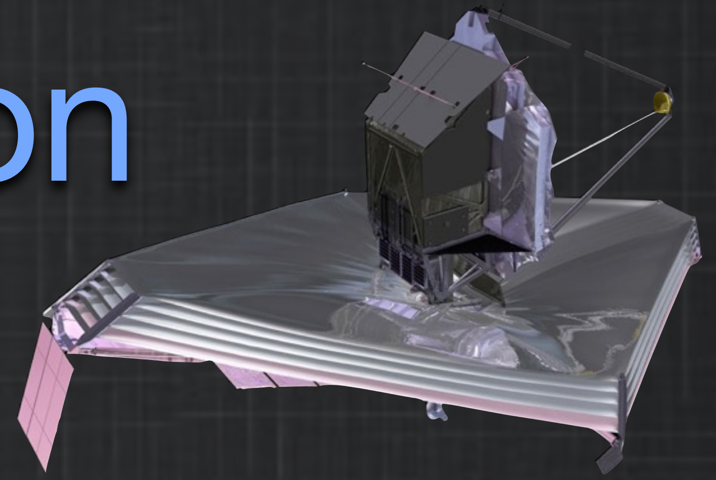
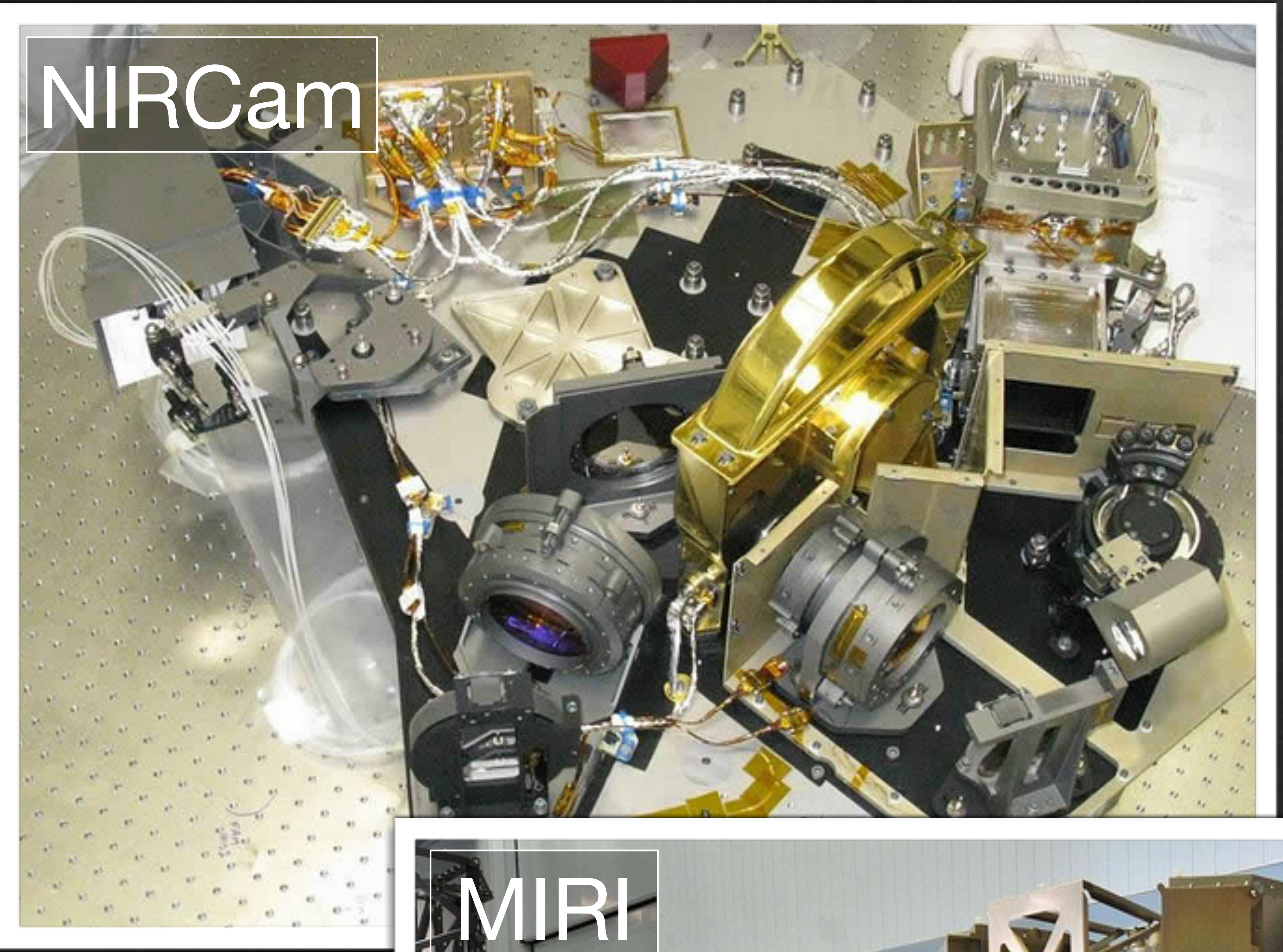
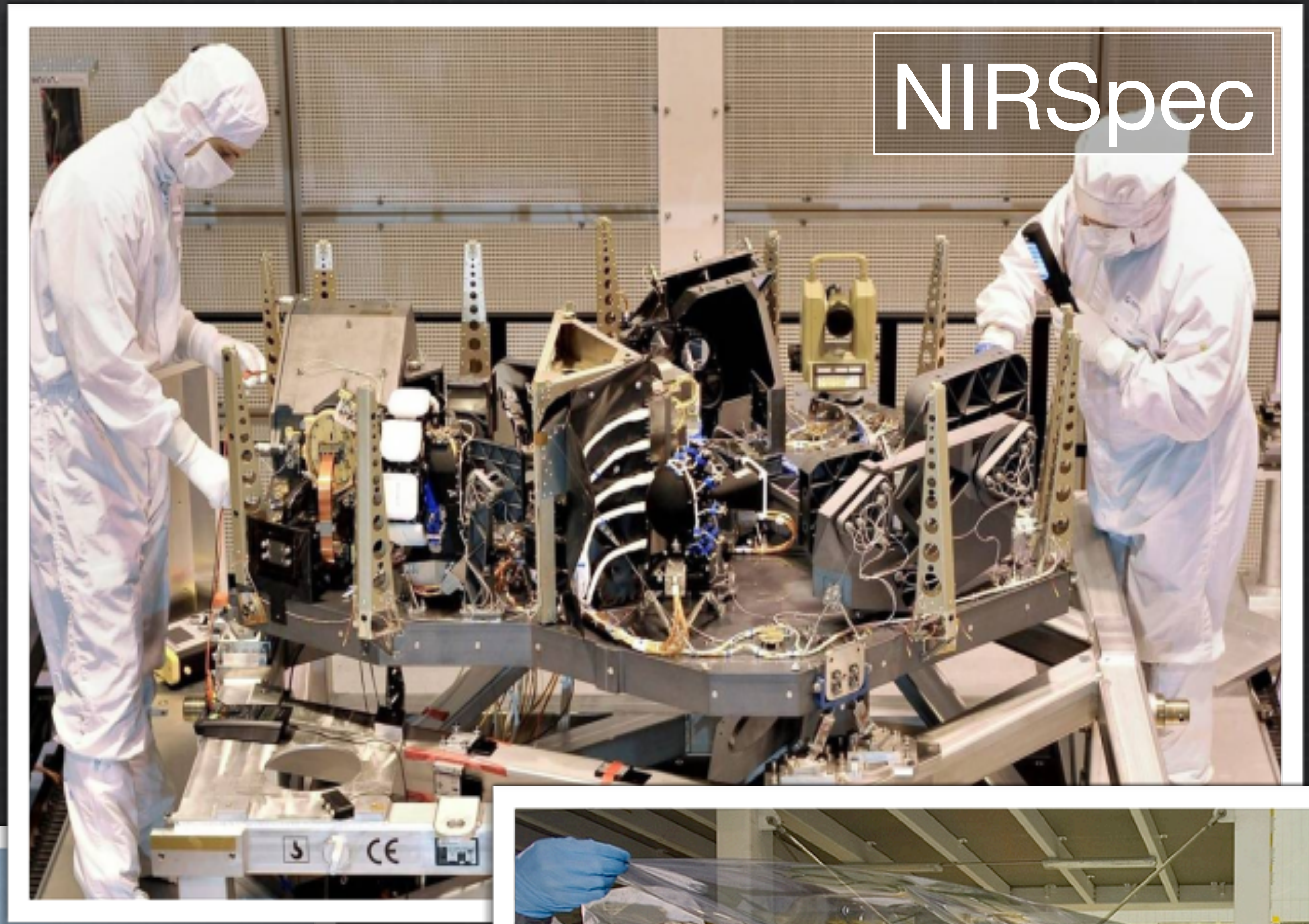
Hubble 	High resolution and high throughput UV and visible light imaging UV spectroscopy High resolution NIR imaging and grism spectroscopy
JWST 	High resolution and high throughput NIR and MIR imaging High throughput and medium resolution multiplexed NIR spectroscopy NIR and MIR IFUs NIR and MIR coronagraphy

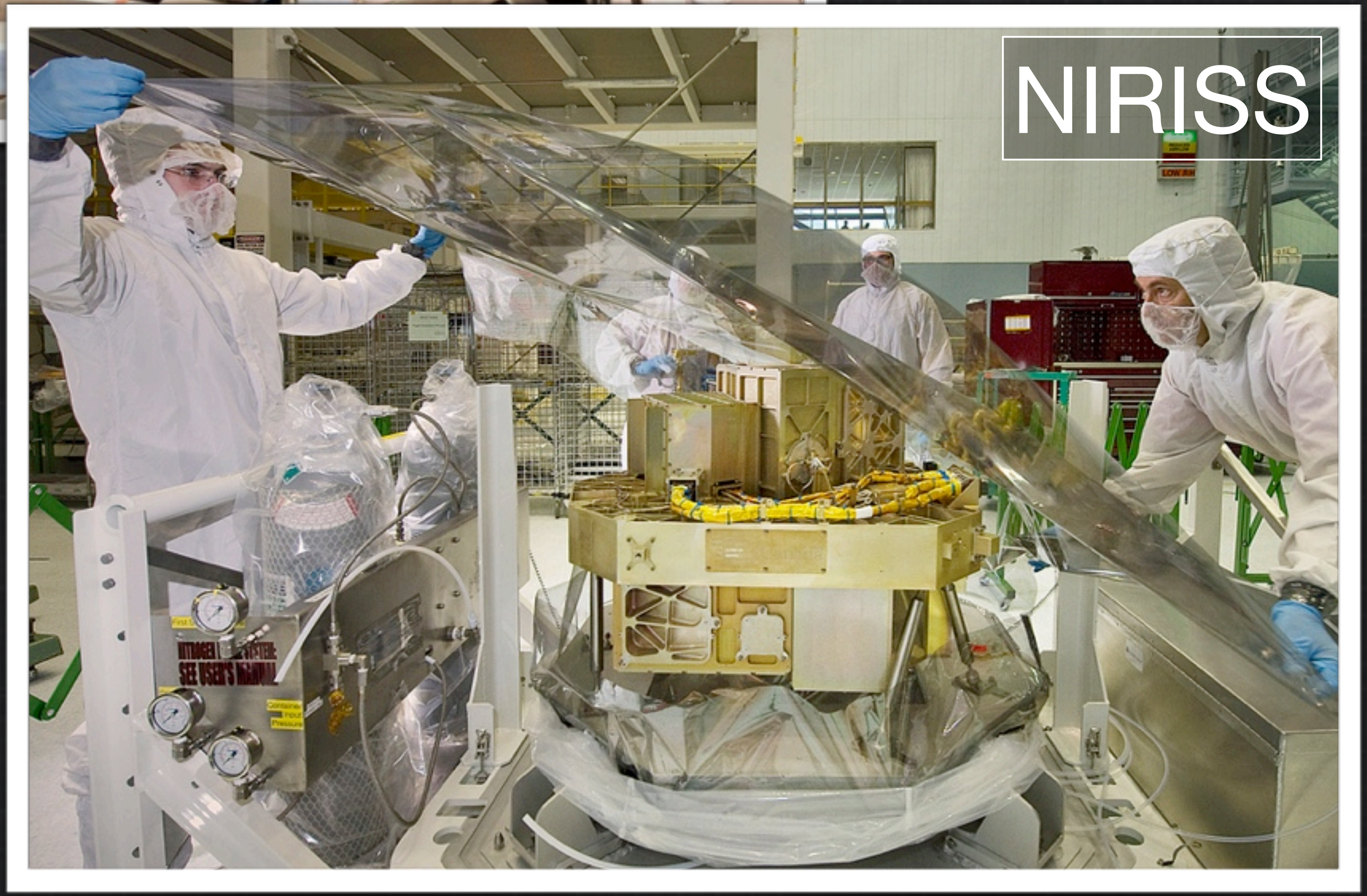

Ultra Sensitive and High Resolution Imaging
Mid IR IFUs
Single Object and Wide-Field Slitless Spectroscopy
Big Bang
Radiation Era
Dark Ages
Reionization era
First galaxies form
Present
m=1
m=2
m=3
Space Based MOS
Science Capabilities
Moving Target Support
Bright Object Modes
λ
JWST/NIRSpec 25 Transits
10x Earth mass (and hot)
Thick Atmosphere
Water & Methane
Water
Near IR IFUs
0.8″ ~ 5200 km
image at 0.94 microns (Cassini mission 2009)
exoplanet beta pictoris b
beta pictoris
NIR and MIR Coronagraphy

General Astrophysics Demands Diverse Instrumentation









Next Generation Science Capabilities

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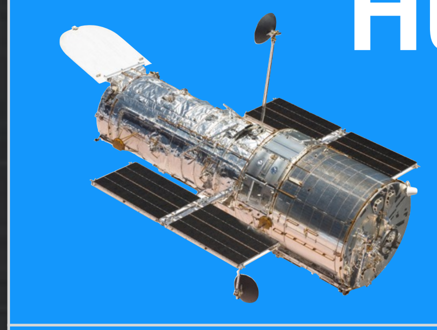
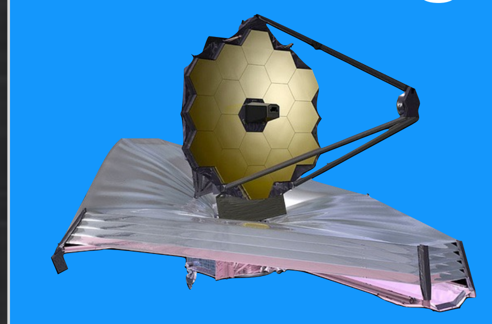
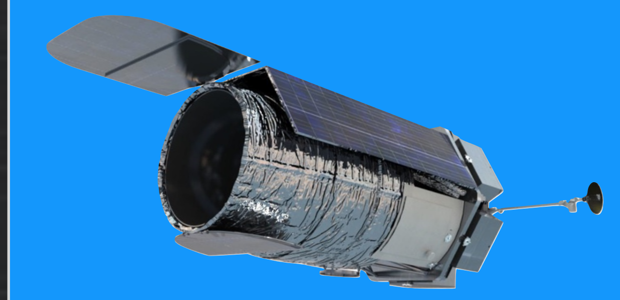
Hubble 	High resolution and high throughput UV and visible light imaging UV spectroscopy High resolution NIR imaging and grism spectroscopy
JWST 	High resolution and high throughput NIR and MIR imaging High throughput and medium resolution multiplexed NIR spectroscopy NIR and MIR IFUs NIR and MIR coronagraphy
WFIRST 	Very wide field, high resolution NIR imaging Very wide field NIR grism spectroscopy Visible light IFU High performance coronagraph

Next Generation Science Capabilities

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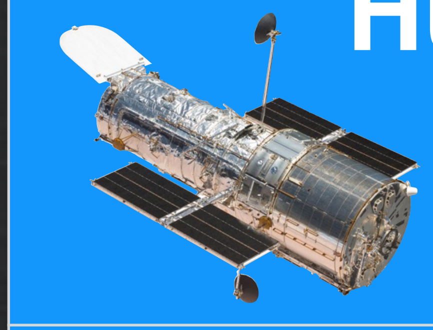
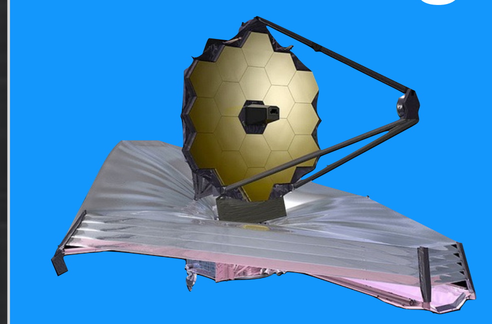
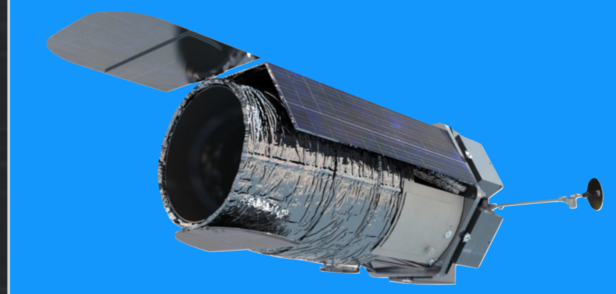
Hubble 	High resolution and high throughput UV and visible light imaging UV spectroscopy High resolution NIR imaging and grism spectroscopy
JWST 	High resolution and high throughput NIR and MIR imaging High throughput and medium resolution multiplexed NIR spectroscopy NIR and MIR IFUs NIR and MIR coronagraphy
WFIRST 	Very wide field, high resolution NIR imaging Very wide field NIR grism spectroscopy Visible light IFU Very high performing coronagraph
LSST 	Very wide field UV and visible imaging Cadence observations Specialized deep observations with customized setups

Next Generation Science Capabilities

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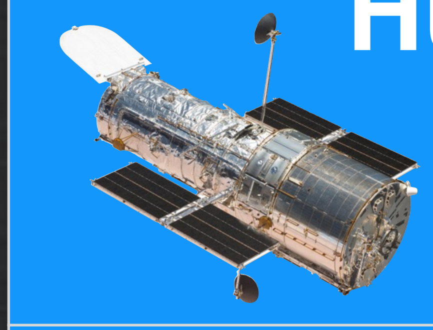
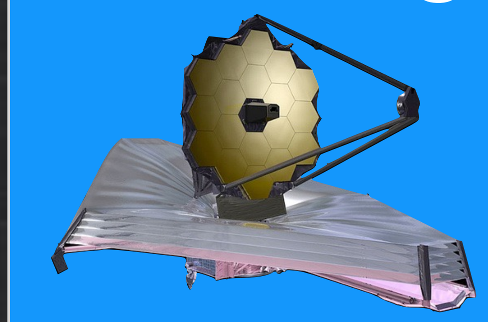
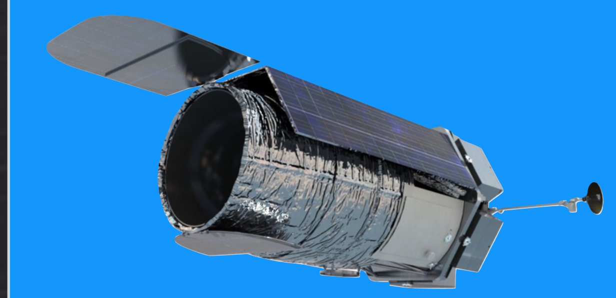
Hubble 	High resolution and high throughput UV and visible light imaging UV spectroscopy High resolution NIR imaging and grism spectroscopy
JWST 	High resolution and high throughput NIR and MIR imaging High throughput and medium resolution multiplexed NIR spectroscopy NIR and MIR IFUs NIR and MIR coronagraphy
WFIRST 	Very wide field, high resolution NIR imaging Very wide field NIR grism spectroscopy Visible light IFU Very high performing coronagraph
LSST 	Very wide field UV and visible imaging Cadence observations Specialized deep observations with customized setups
GSMTs 	Very high resolution (small field) imaging Very high resolution visible spectroscopy Multiplexed visible and NIR spectroscopy Coronagraphy

European Extremely Large Telescope

www.eso.org

Thirty Meter Telescope

First Generation Instruments

★**Wide Field Optical Spectrometer (WFOS)**

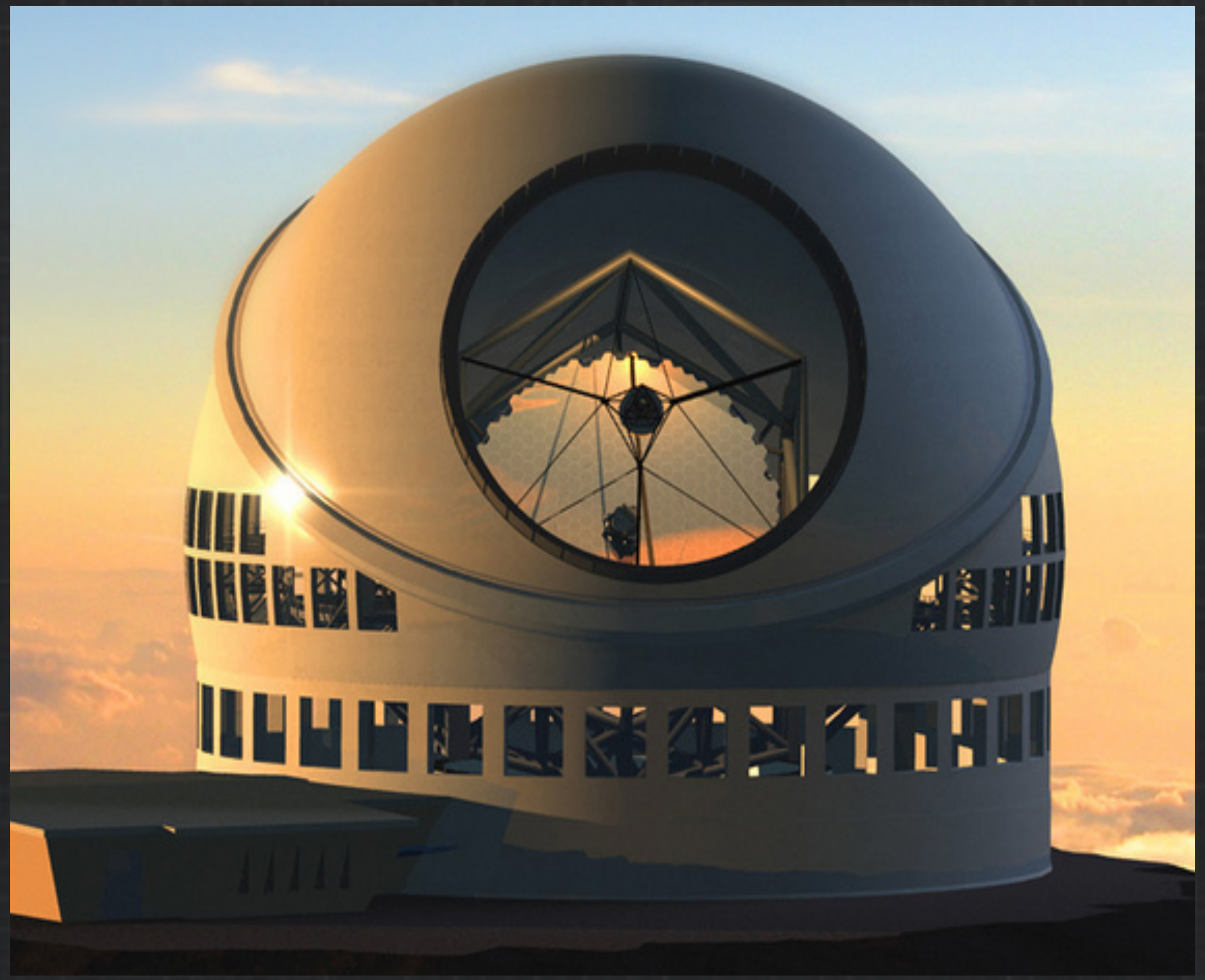
- near UV and optical (0.3 - 1 micron) imaging and spectroscopy over 40 sq arcmin
- long slit and MOS modes

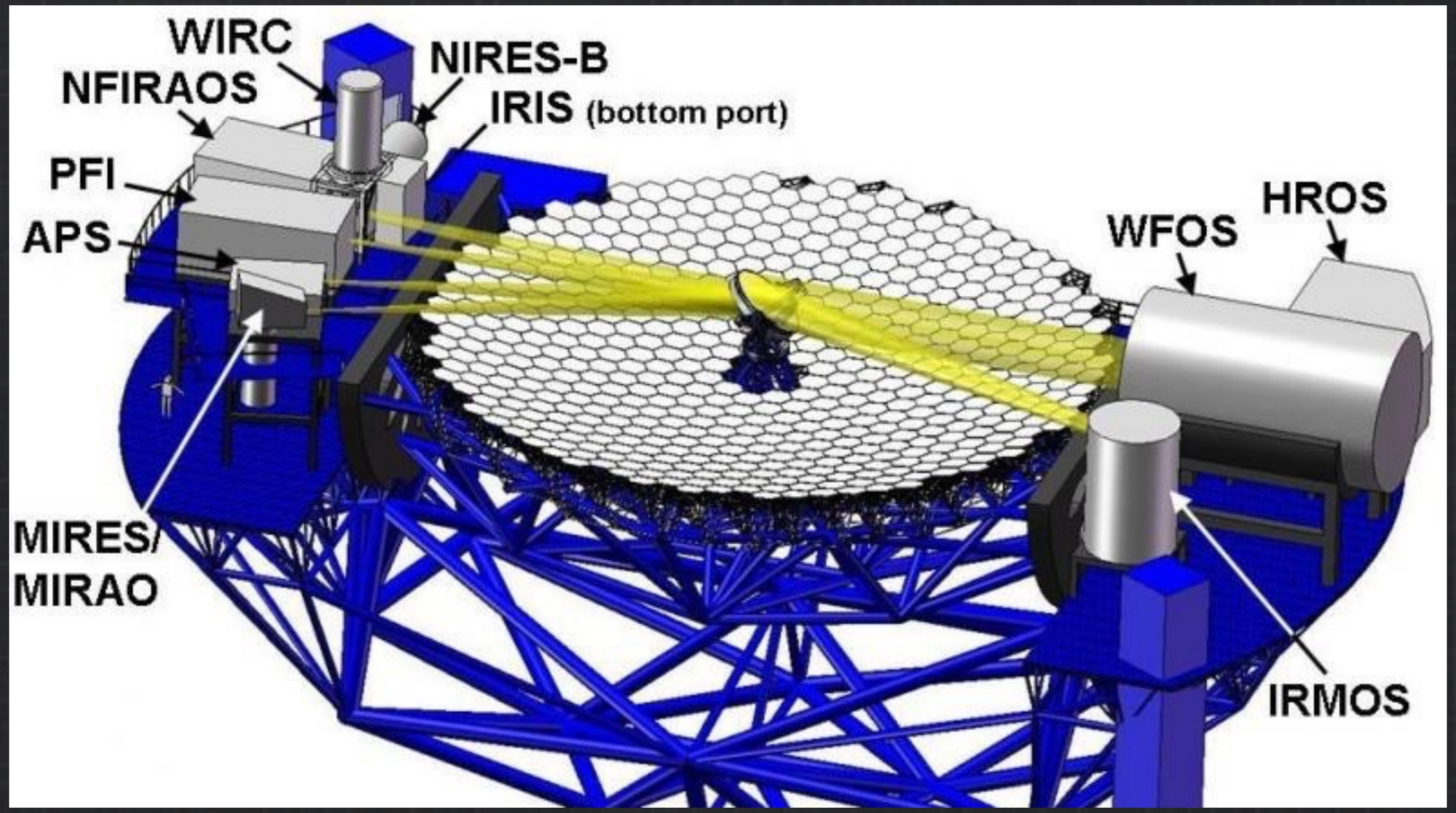
★**Infrared Imaging Spectrometer (IRIS)**

- diffraction limited (through MCAO) imaging and integral field spectroscopy (0.8 - 2.5 micron)

★**Infrared Multi-object Spectrometer (IRMS)**

- diffraction limited imaging and slit spectroscopy over a 2 arcmin field (0.8 - 2.5 micron)

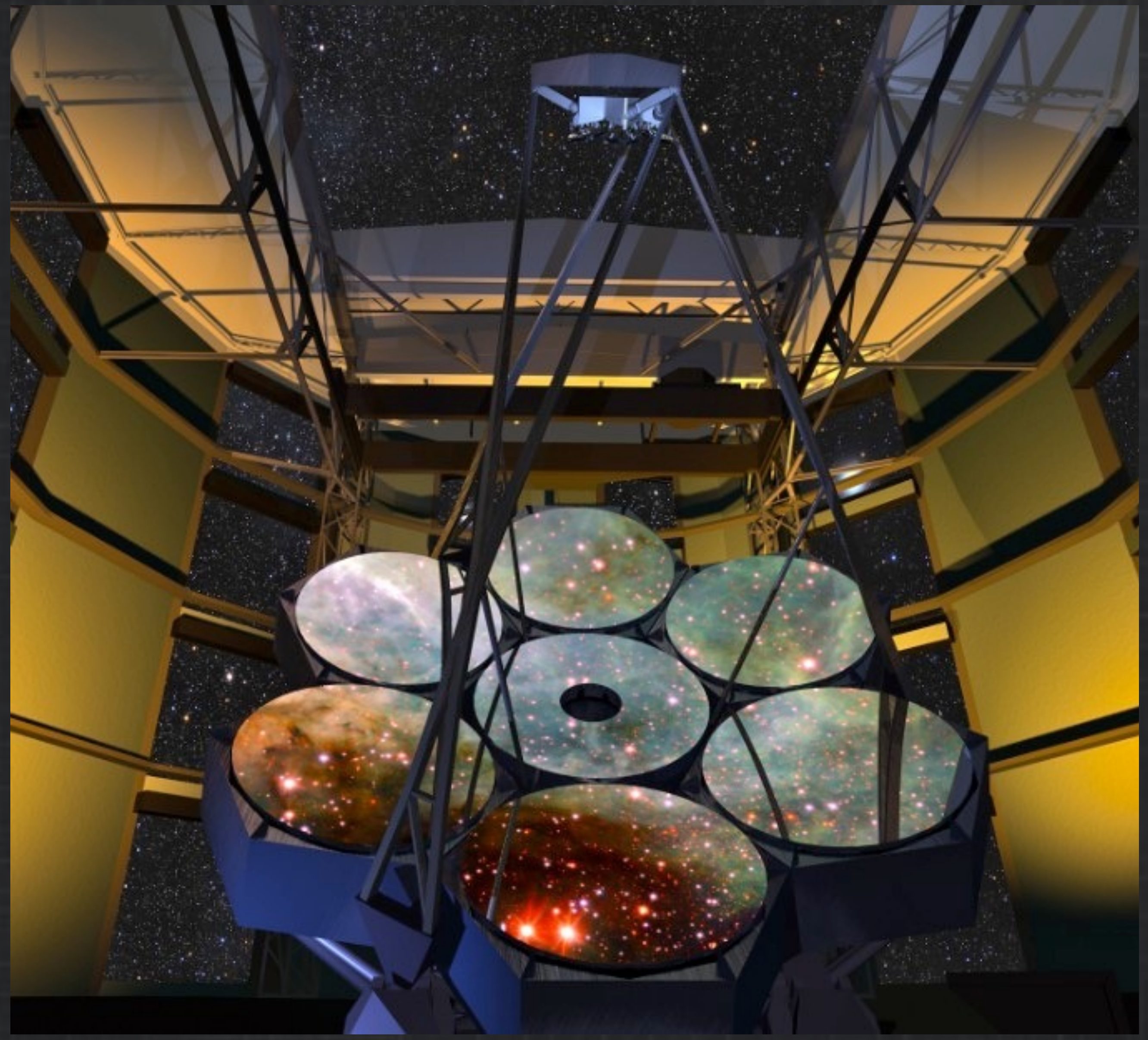


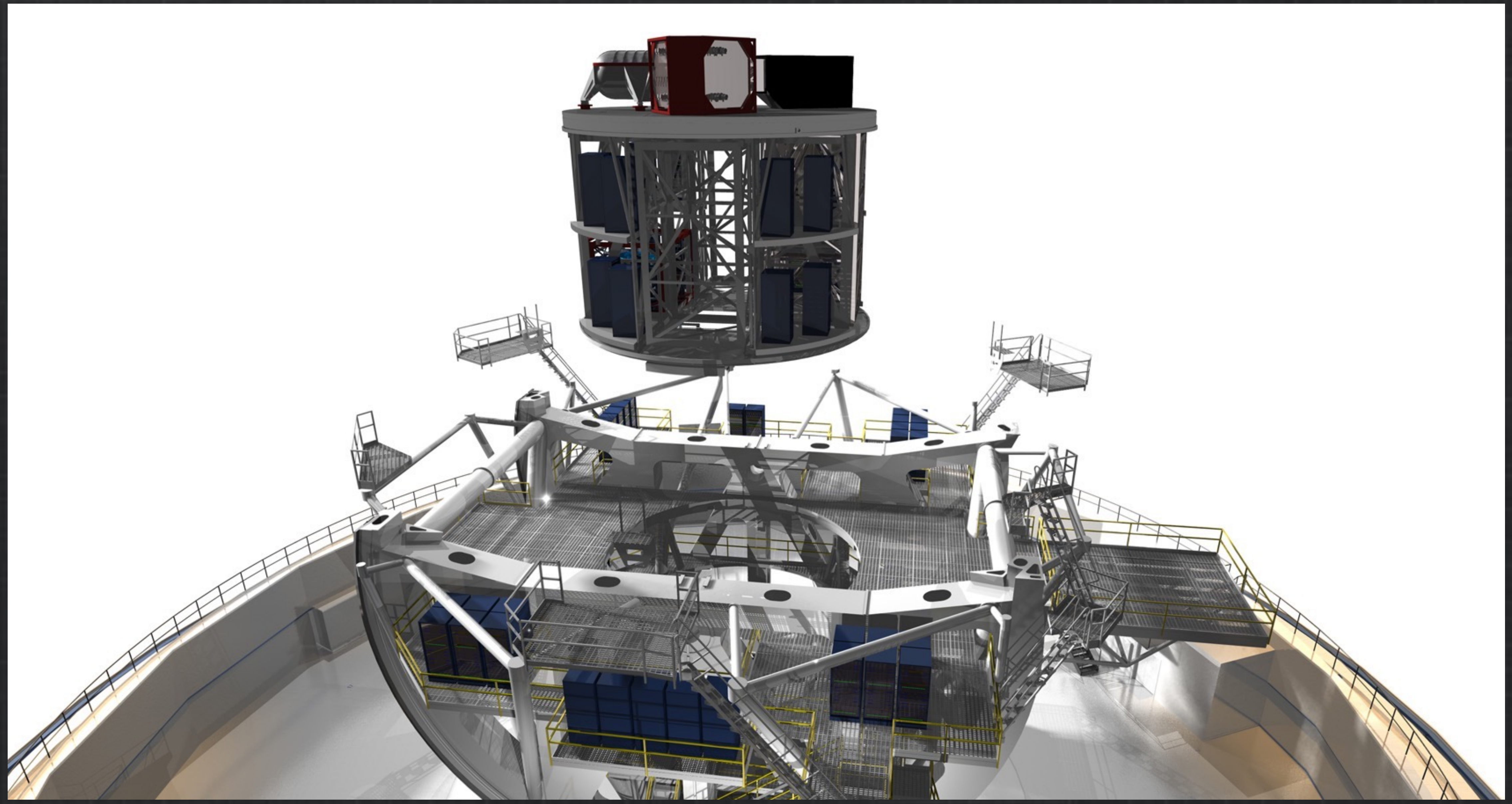


Giant Magellan Telescope

First Generation Instruments

- ★ **Visible Echelle Spectrograph (G-CLEF)**
  - single object optical high resolution spectrometer / PRV (0.35 - 0.95 micron; R = 20 - 100,000
- ★ **Visible Multi-Object Spectrograph (GMACS)**
  - optical multiobject spectrometer with 40 arcmin field (0.36 - 1.0 micron; R = 1500-4000; 10,000)
- ★ **Near Infrared IFU and Adaptive Optics Imager (GMTIFS)**
  - near infrared AO-fed IFU and imager (0.9 - 2.5 micron; R = 4000 -10,000; 10/400 arcsec)





European Extremely Large Telescope

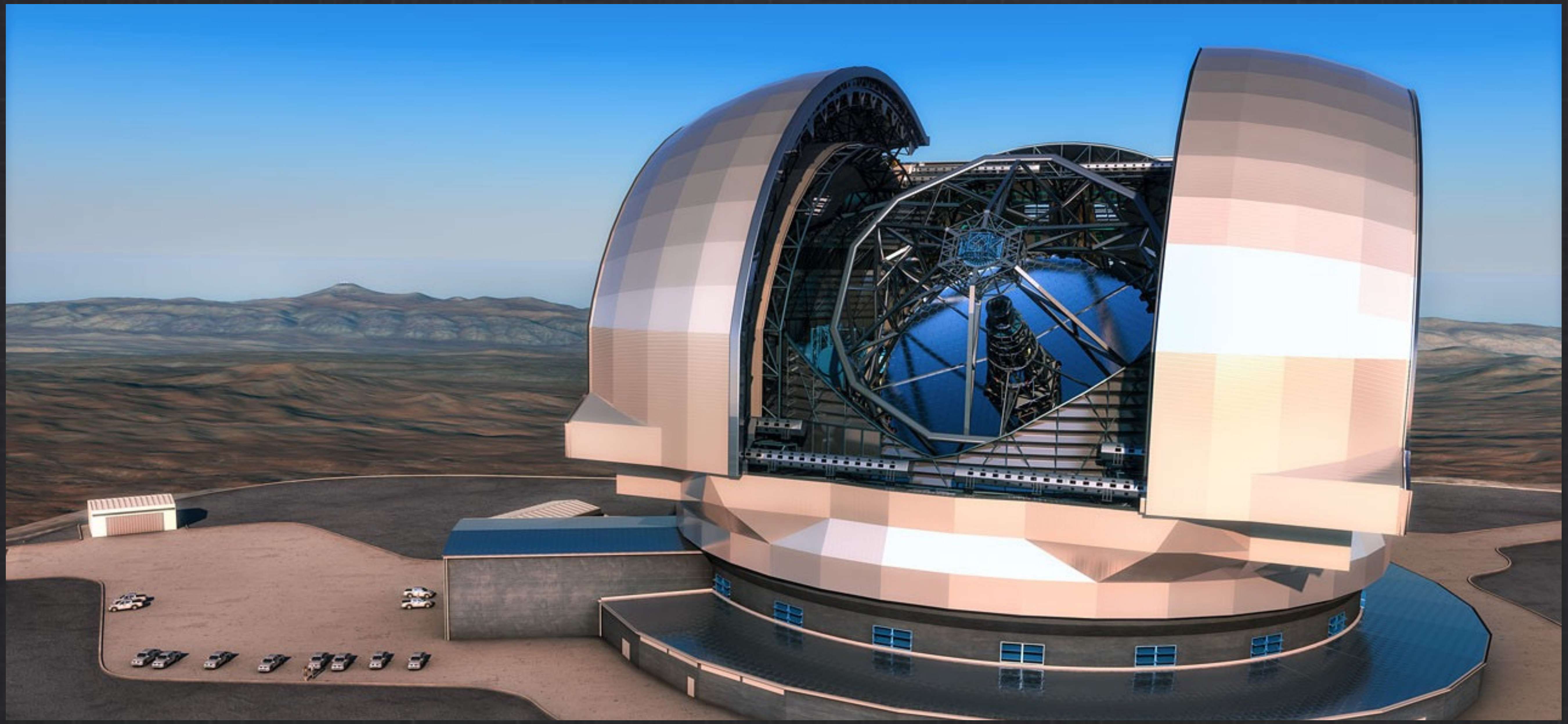
First Generation Instruments

★ **ELT-CAM**

- diffraction limited near-infrared imager w/ high throughput slit spectroscopy and coronagraph
- 50 microarcsec presicion; 0.8 - 2.5 micron

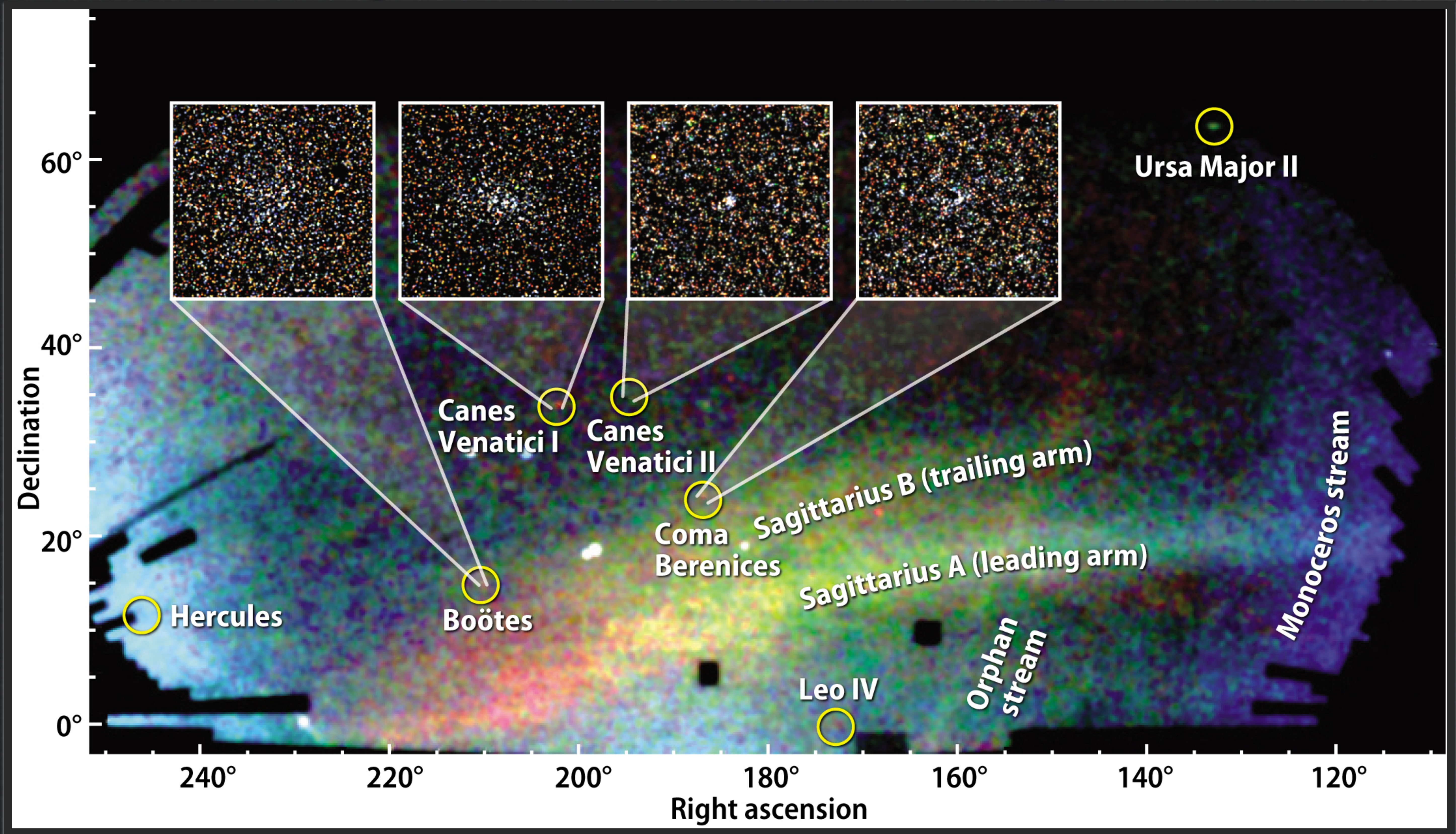
★ **ELT-IFU**

- Single field near-infrared wide band IFS, including adaptive optics system
- very high strehl ratios, 4-40 mas pixel scale; 0.2-10 arcsec field of view; 0.5 - 2.4 micron

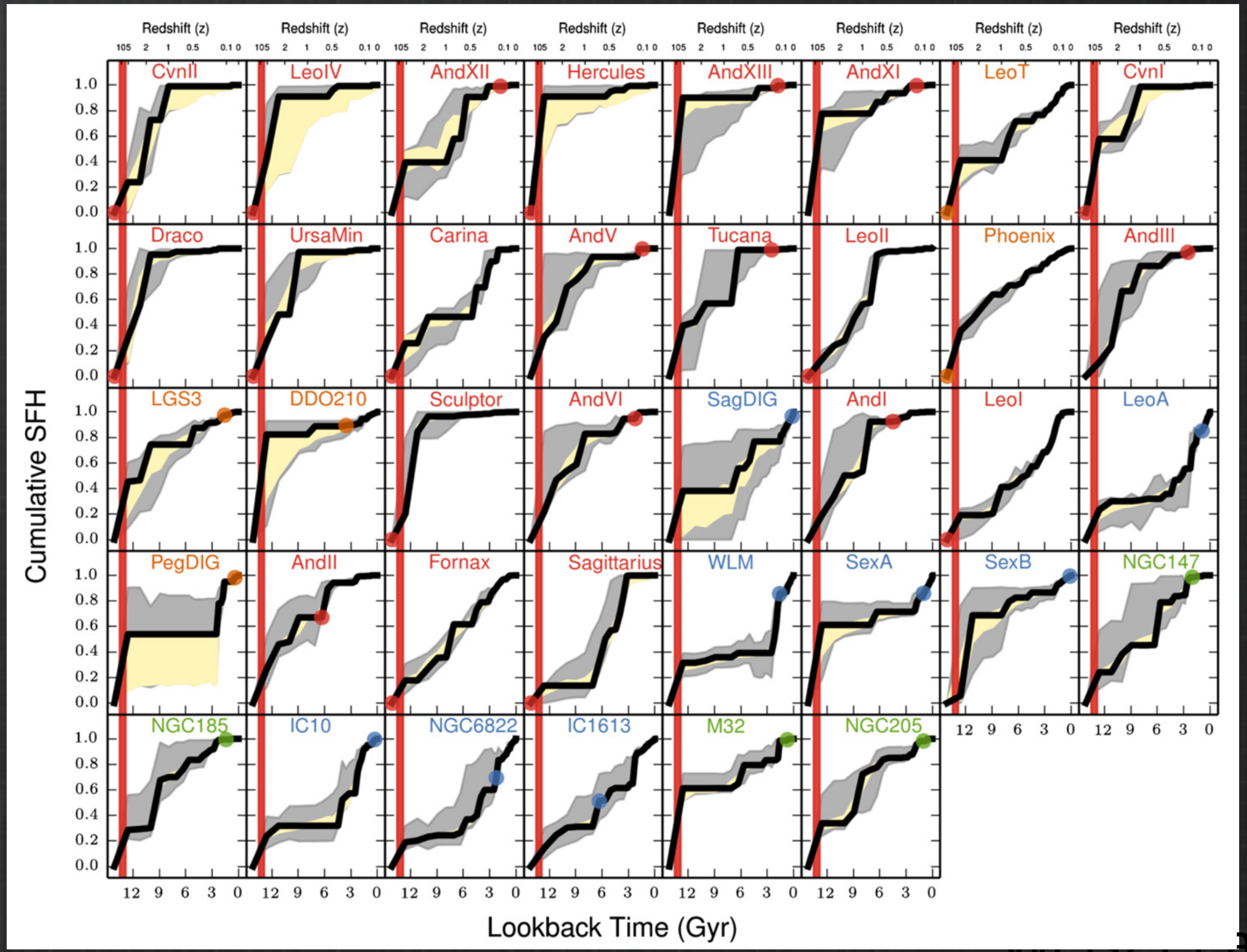


Dark Matter and our Milky Way Galaxy

Nearby Galaxies: High-Resolution Tests to LCDM



Belokurov et al.



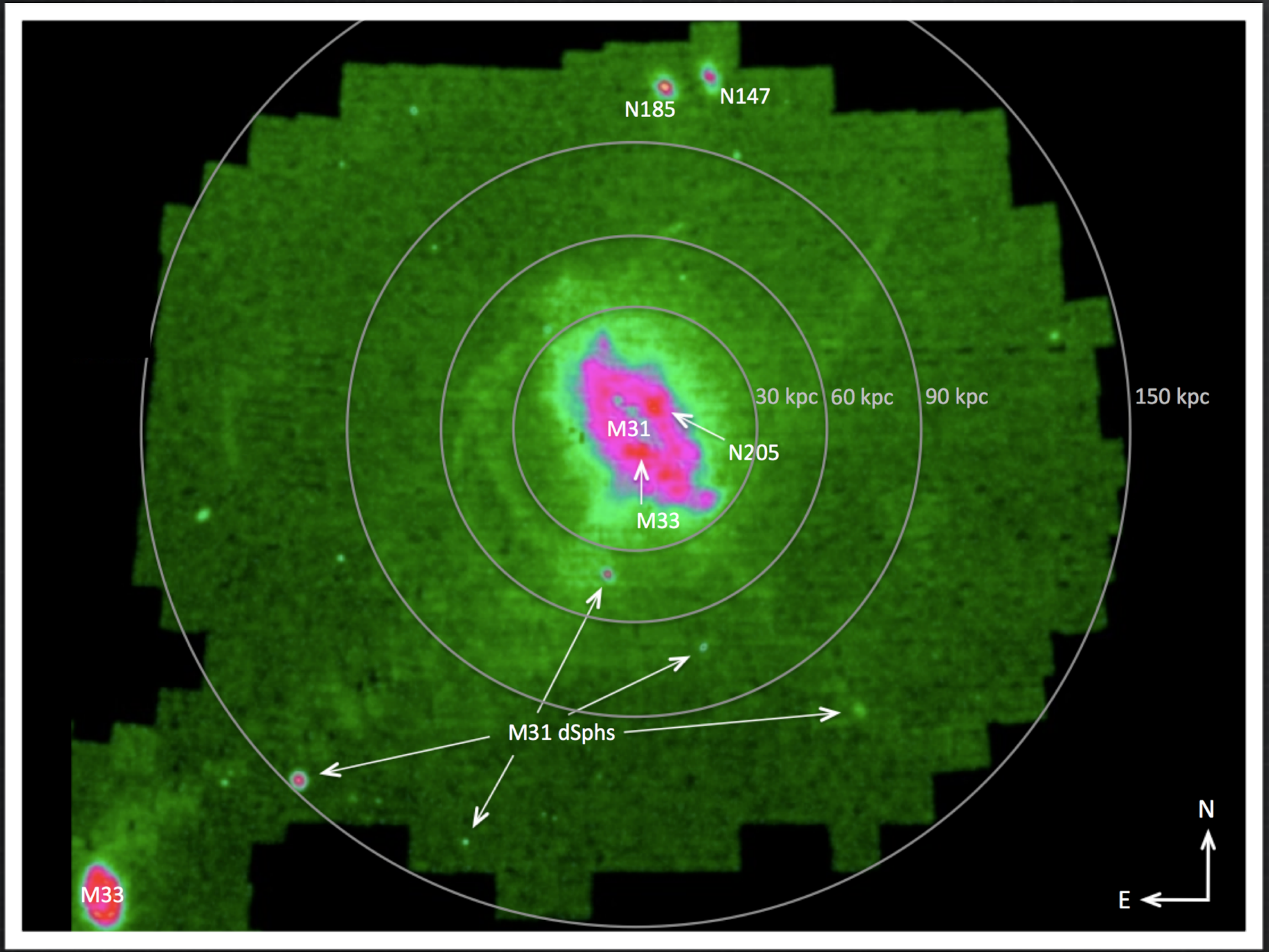
Weisz et al. (2014)

Many Outstanding Problems

1.) Is the census of small satellites consistent with CDM predictions on galactic scales?
2.) Is there a low luminosity threshold for galaxy formation?
3.) Is the spatial distribution of dSphs (planar vs spherical) consistent with CDM?
4.) Can we test different DM models with 3D resolved velocities?
5.) Do sub-Gyr age measurements reveal any cosmologically-driven synchronization in the SFHs?
...

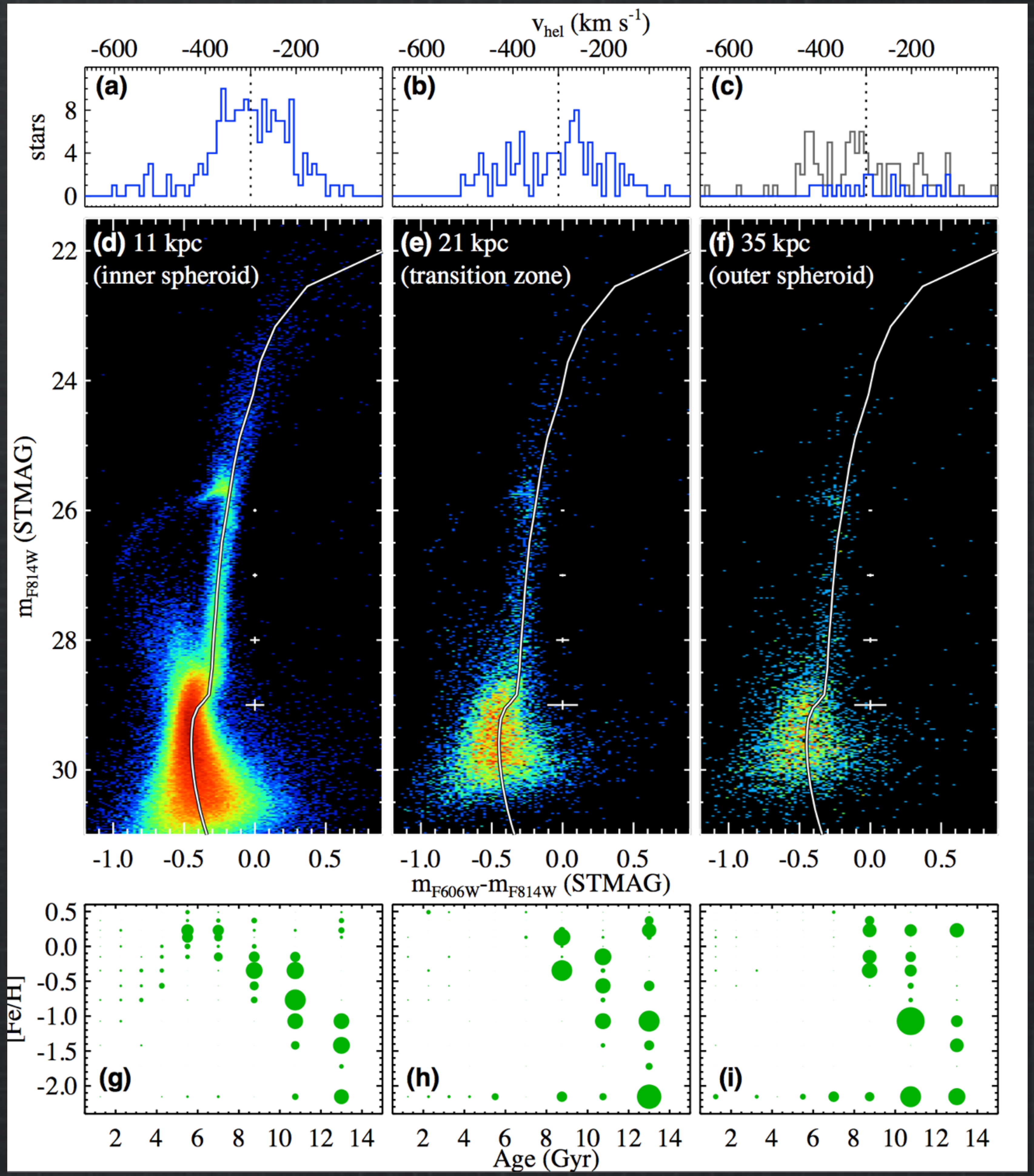
Current Strategy to Measure Detailed Galaxy Properties

CFHT, SDSS, DECam, Pan-STARRS



McConnachie et al. (2009)

Hubble and 8-10m's

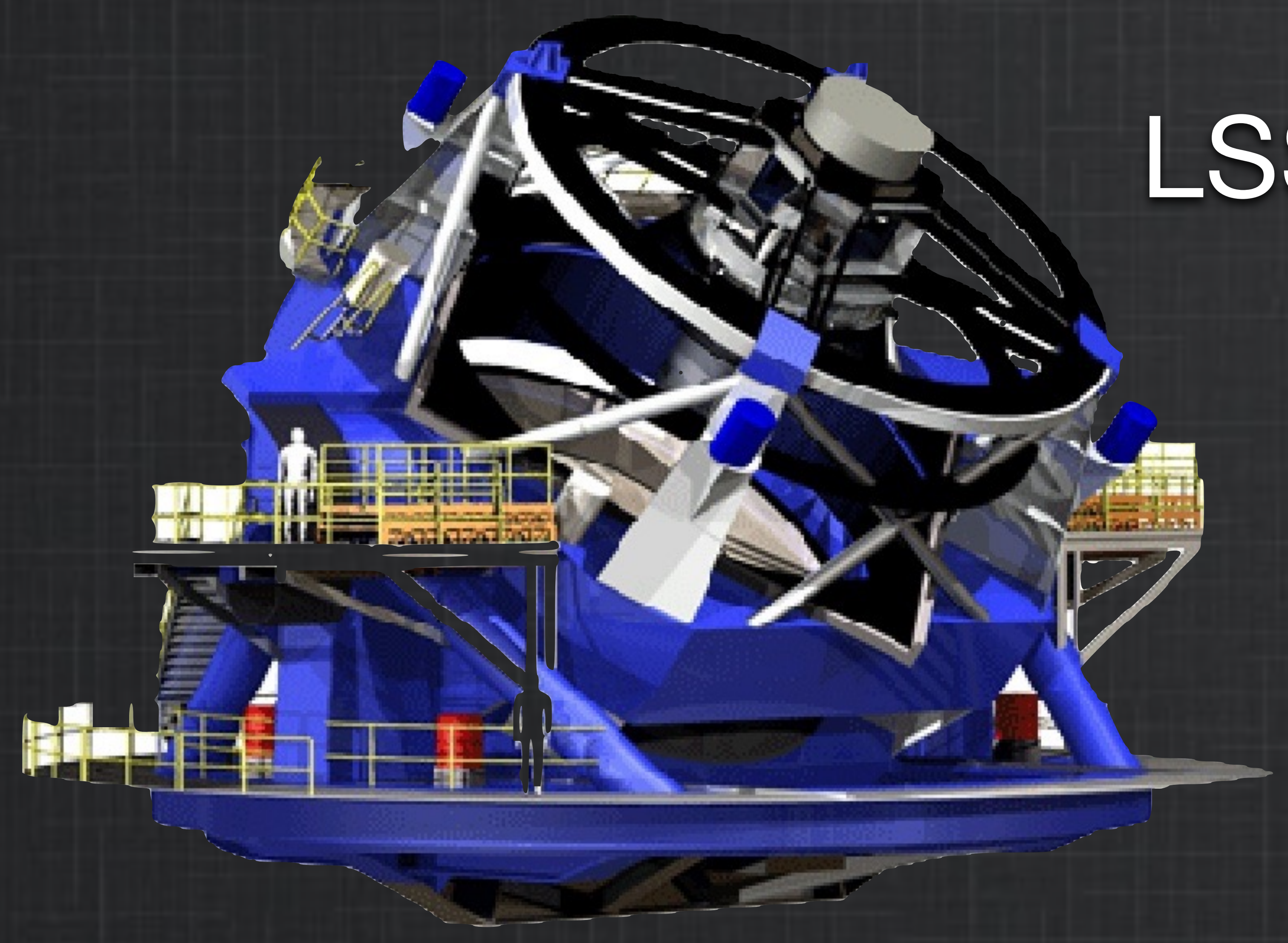


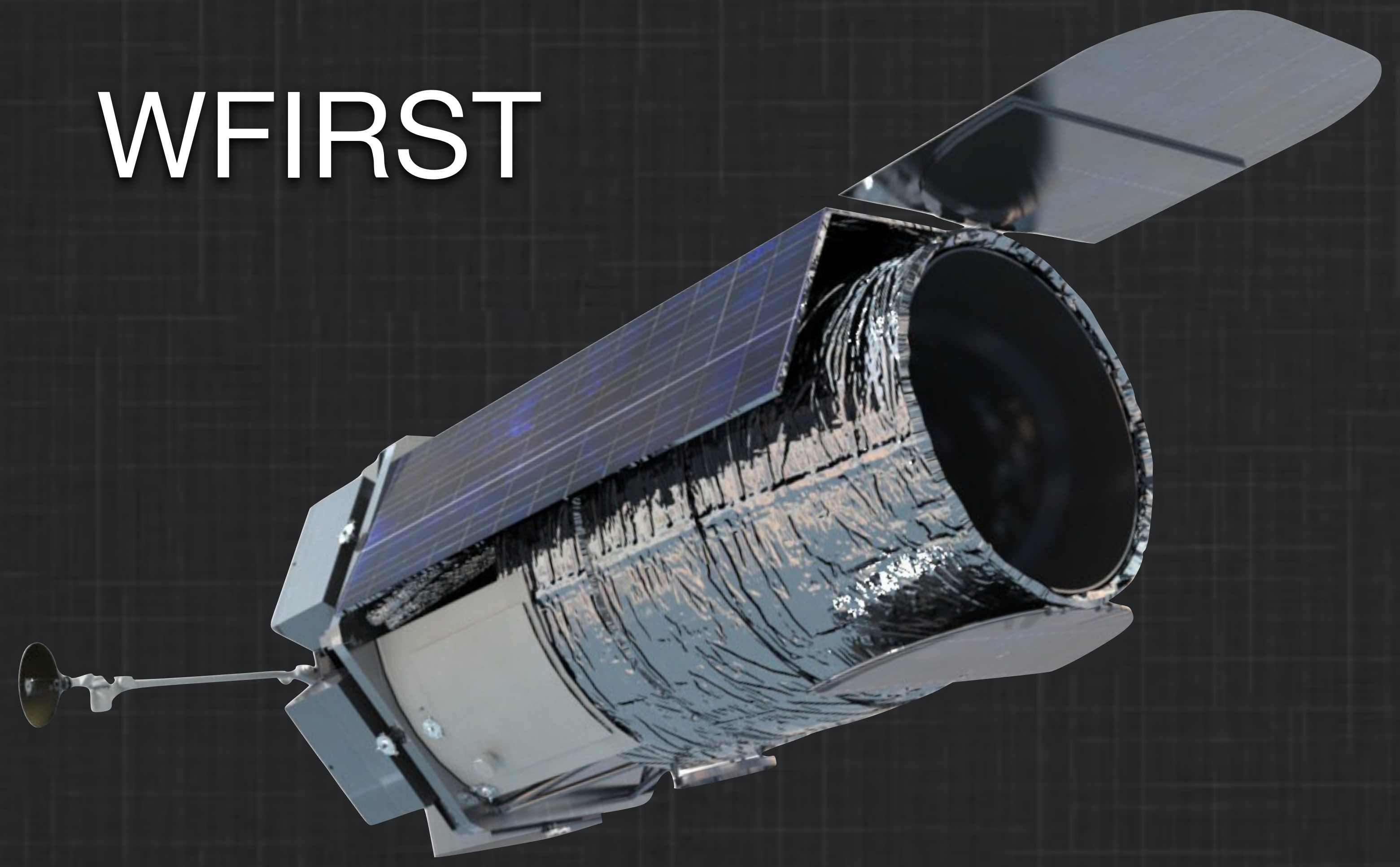
Brown et al.

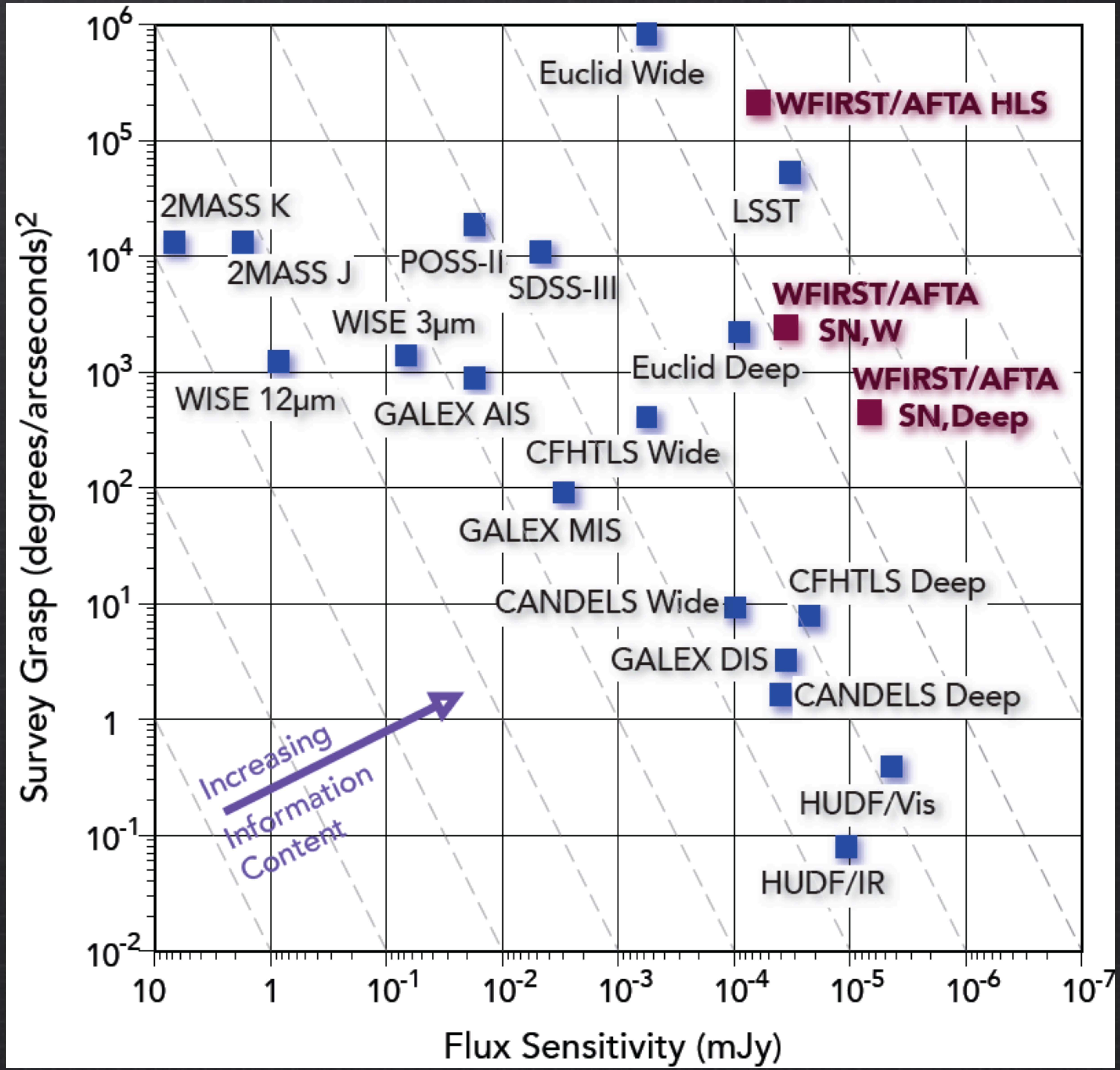
We have a detailed, resolved characterization of two large galaxies

- Hubble can not see Sun-like stars beyond the Local Group (no direct SFHs based on ancient stars)
- Observations of M31 (surface brightness profile, chemistry, SFH) show strong differences w/ MW

The Landscape is About to Change





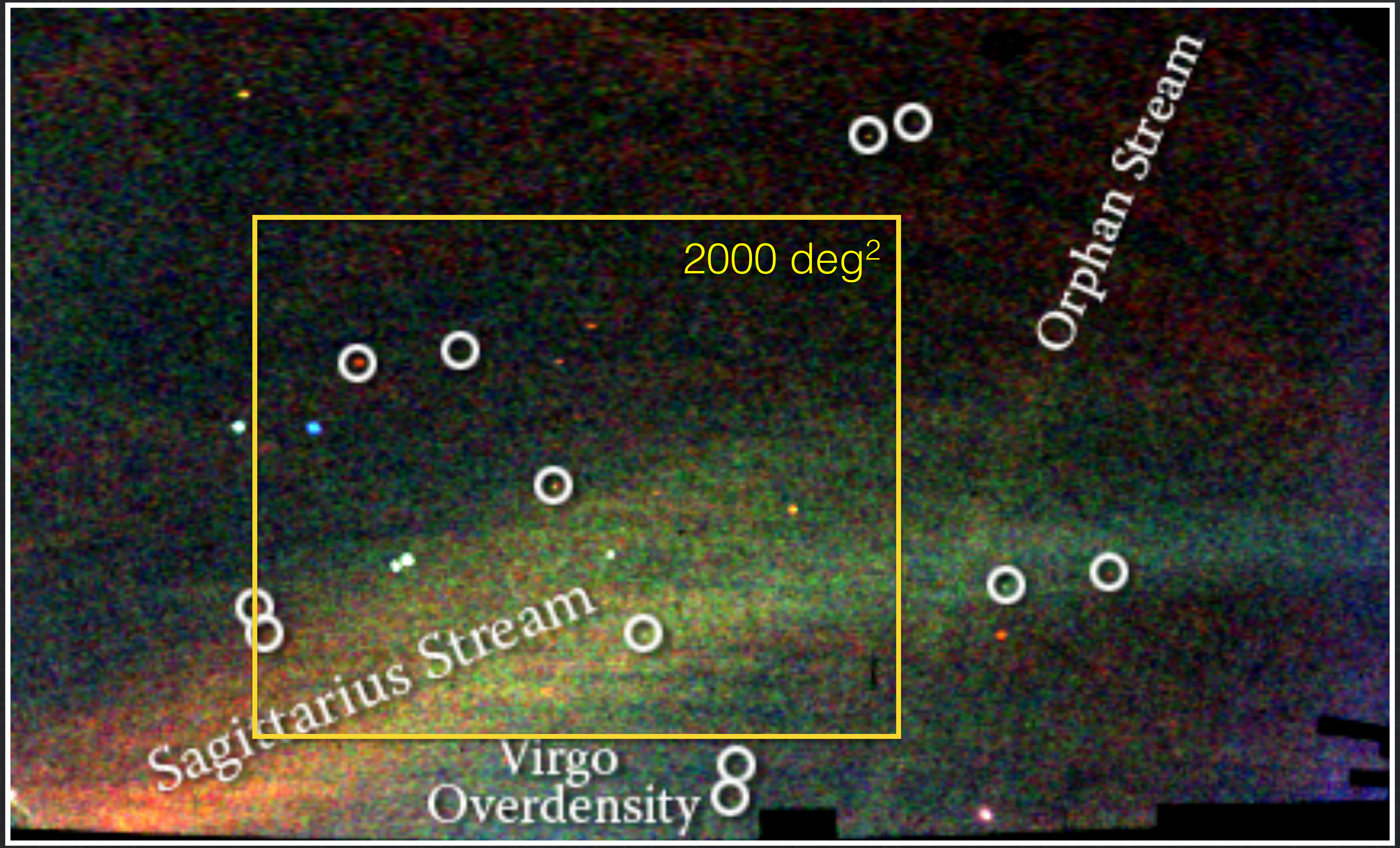


P. Cote & D. Benford

The Landscape is About to Change

Substructure and Dwarf Galaxies with WFIRST and LSST

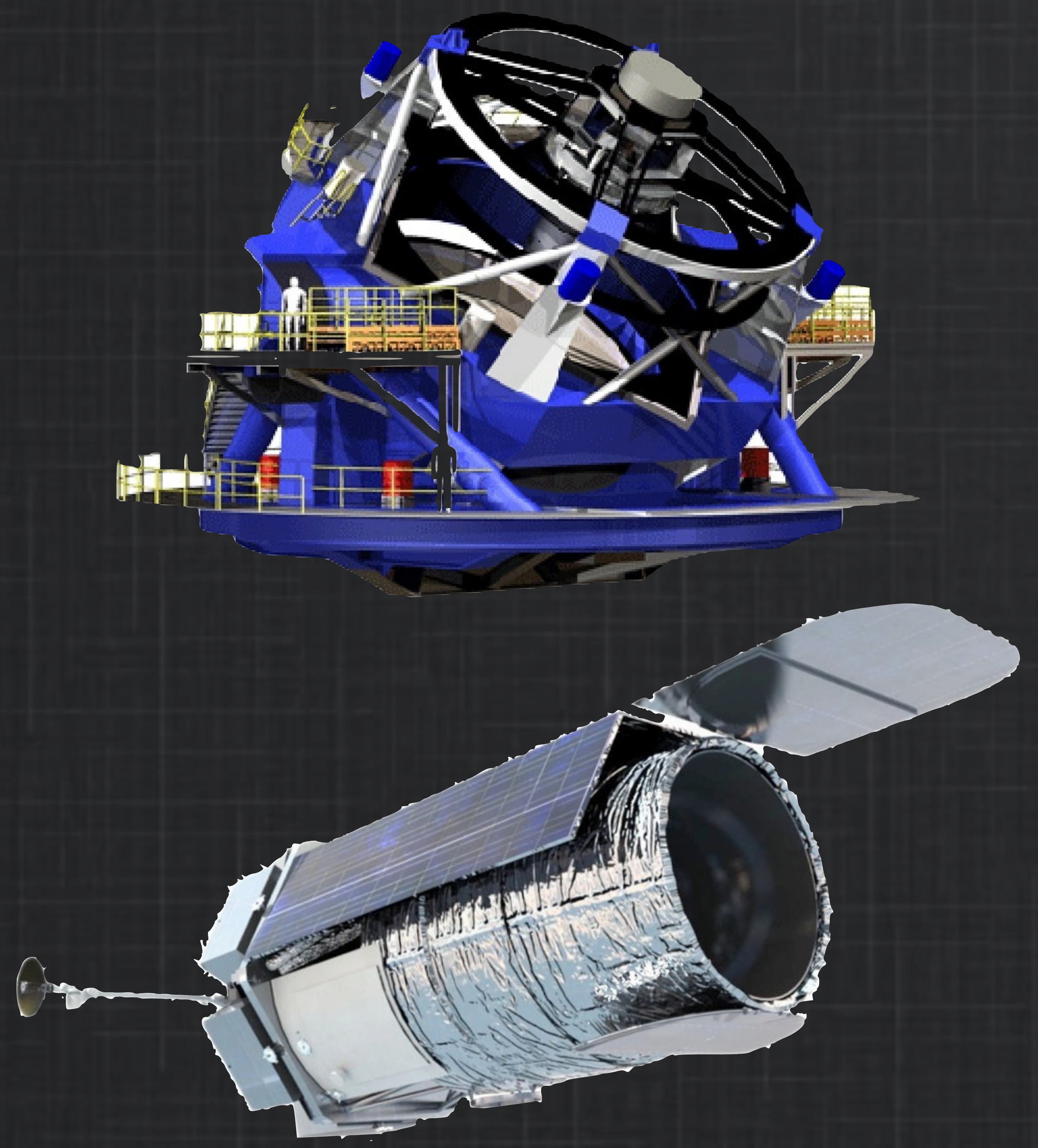
Dramatically increase the contrast of Milky Way streams and UFDs enabling detection through the halo
- SDSS Field of Streams detects the faintest substructure to merely 1% of the MW Volume
- WFIRST HLS will enable structure detection throughout the full volume of the 2000 sq deg
- LSST will be orders of magnitude more sensitive than SDSS, and survey 18,000 sq deg every 3 days
- LSST and WFIRST surveys of nearby galaxies will fully characterize their halo substructure, **except for timescales**



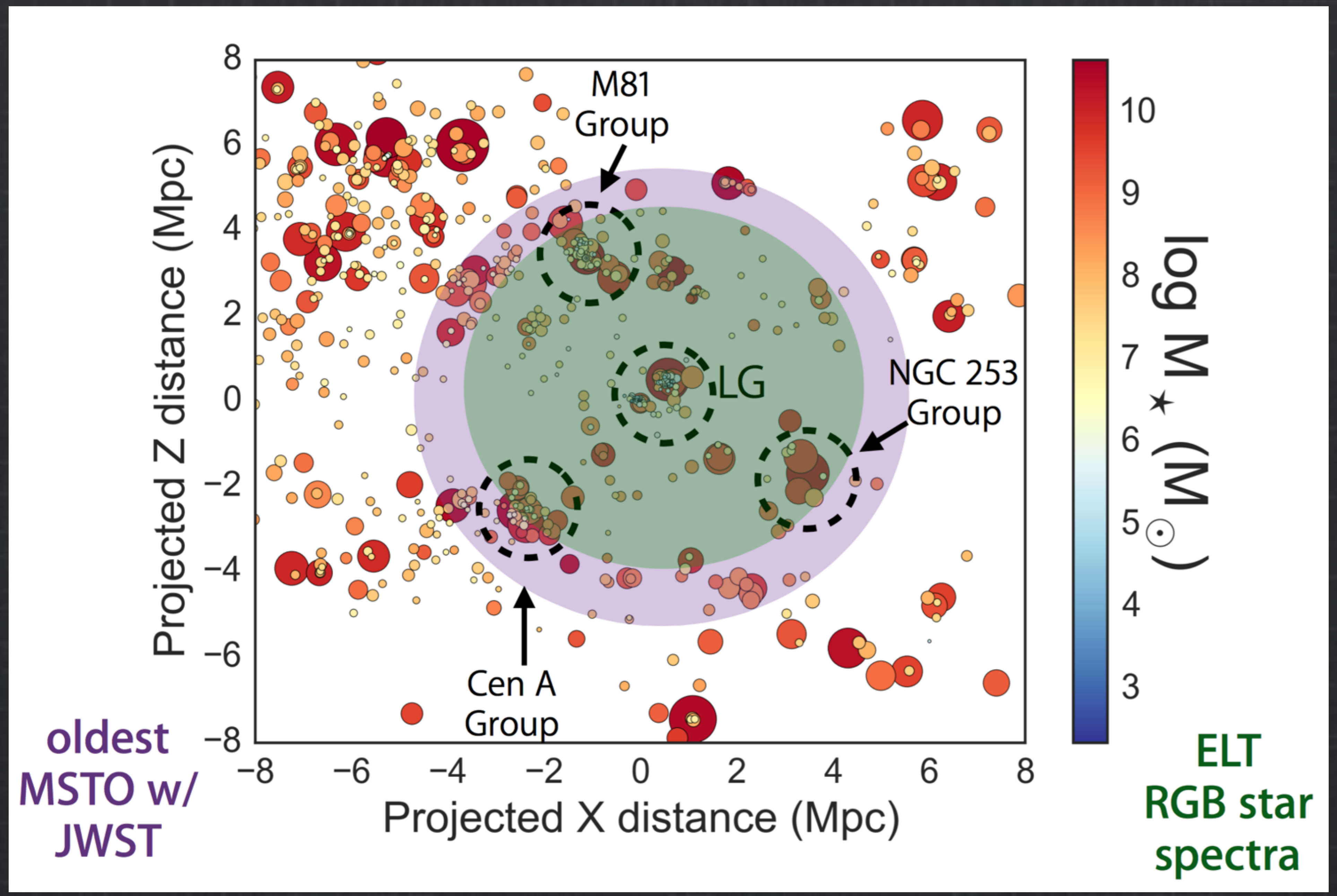
SDSS Field of Streams - Belokurov et al. (2006)

The 2020s - Strategies with LSST, WFIRST, JWST, and ELTs

LSST + WFIRST
Exquisite Maps of Galaxy Halos

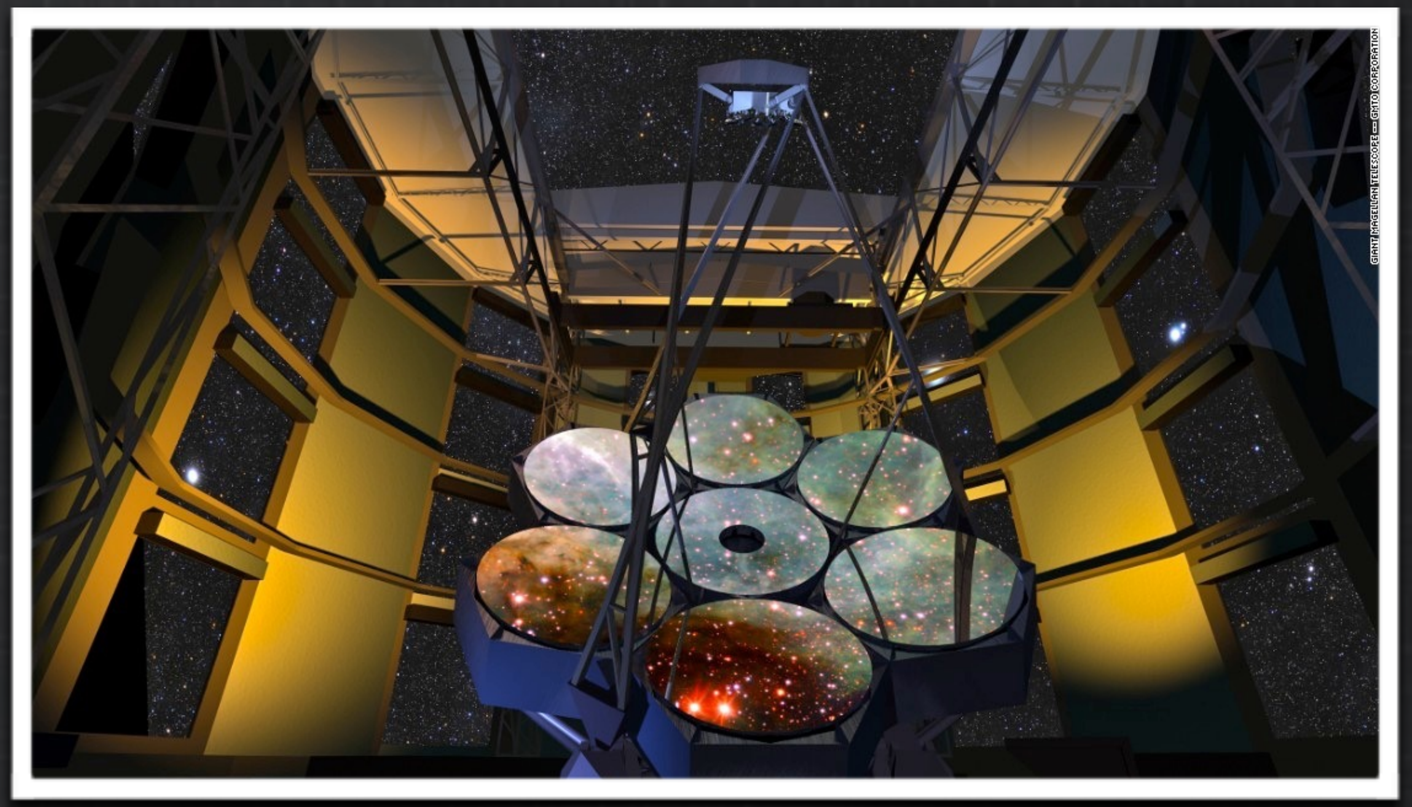


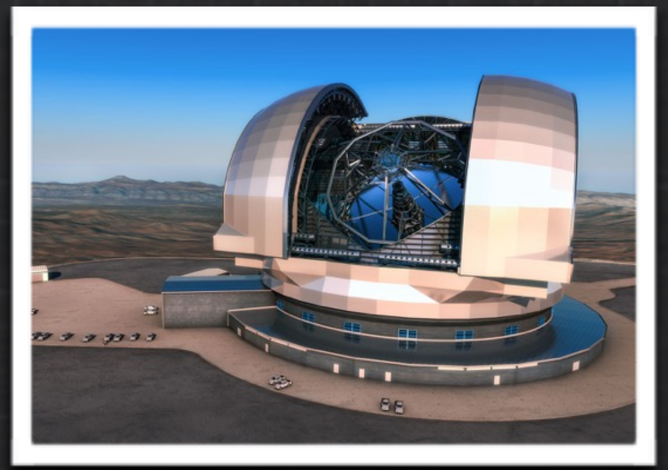
JWST
SFHs Just Beyond the LG

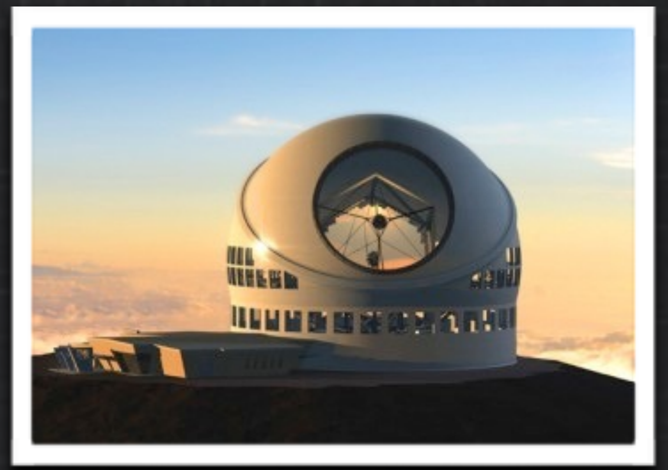


D. Weisz, priv. comm.

ELTs
Chem. + Kin. Beyond the LG







We have a detailed, resolved characterization of two large galaxies

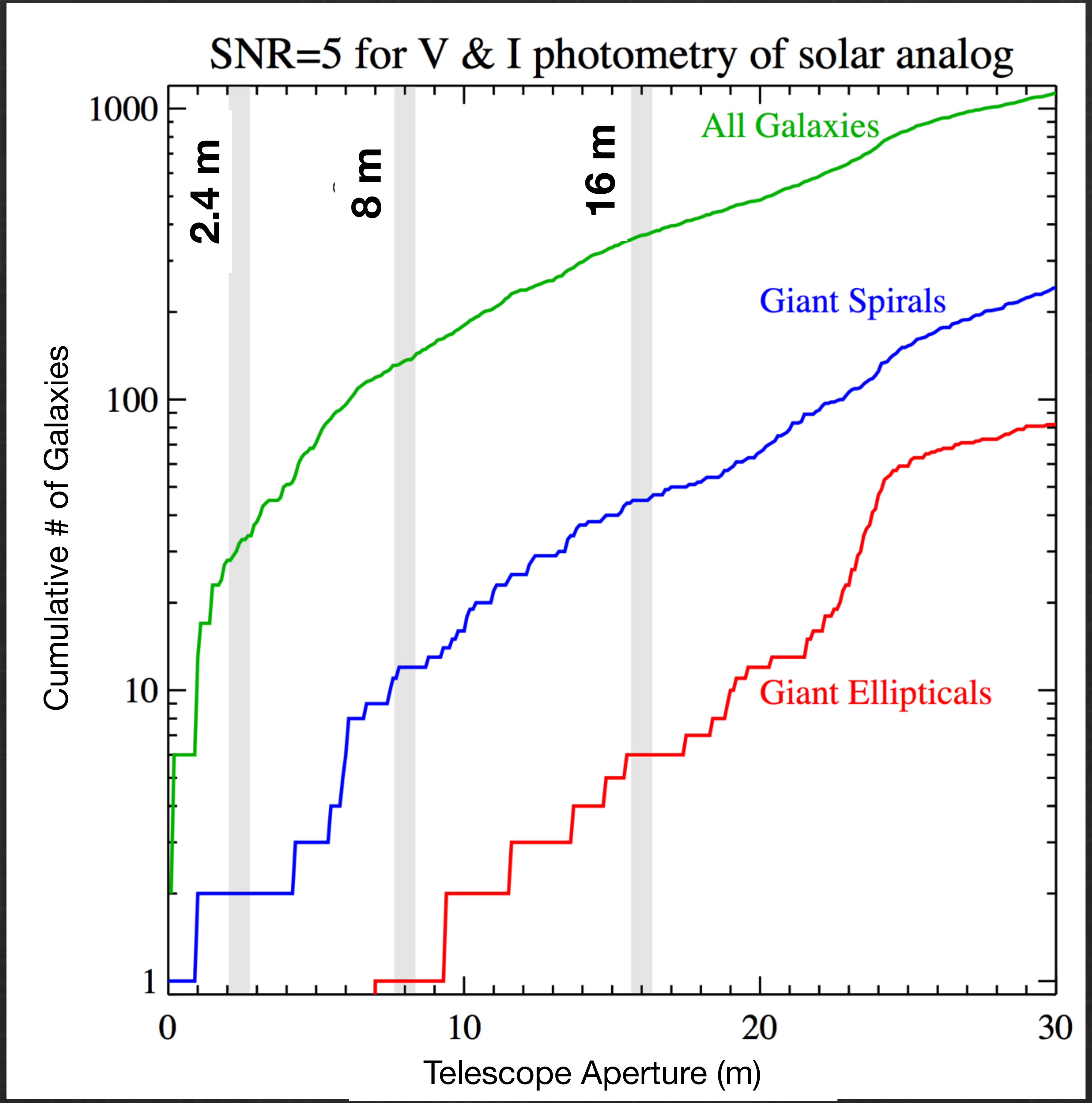
- Hubble can not see Sun-like stars beyond the Local Group (no direct SFHs)
- Observations of M31 (surface brightness profile, chemistry, SFH) show strong differences w/ MW
- **JWST will extend this into the nearby Local Volume (smaller spirals), but not out to ellipticals**

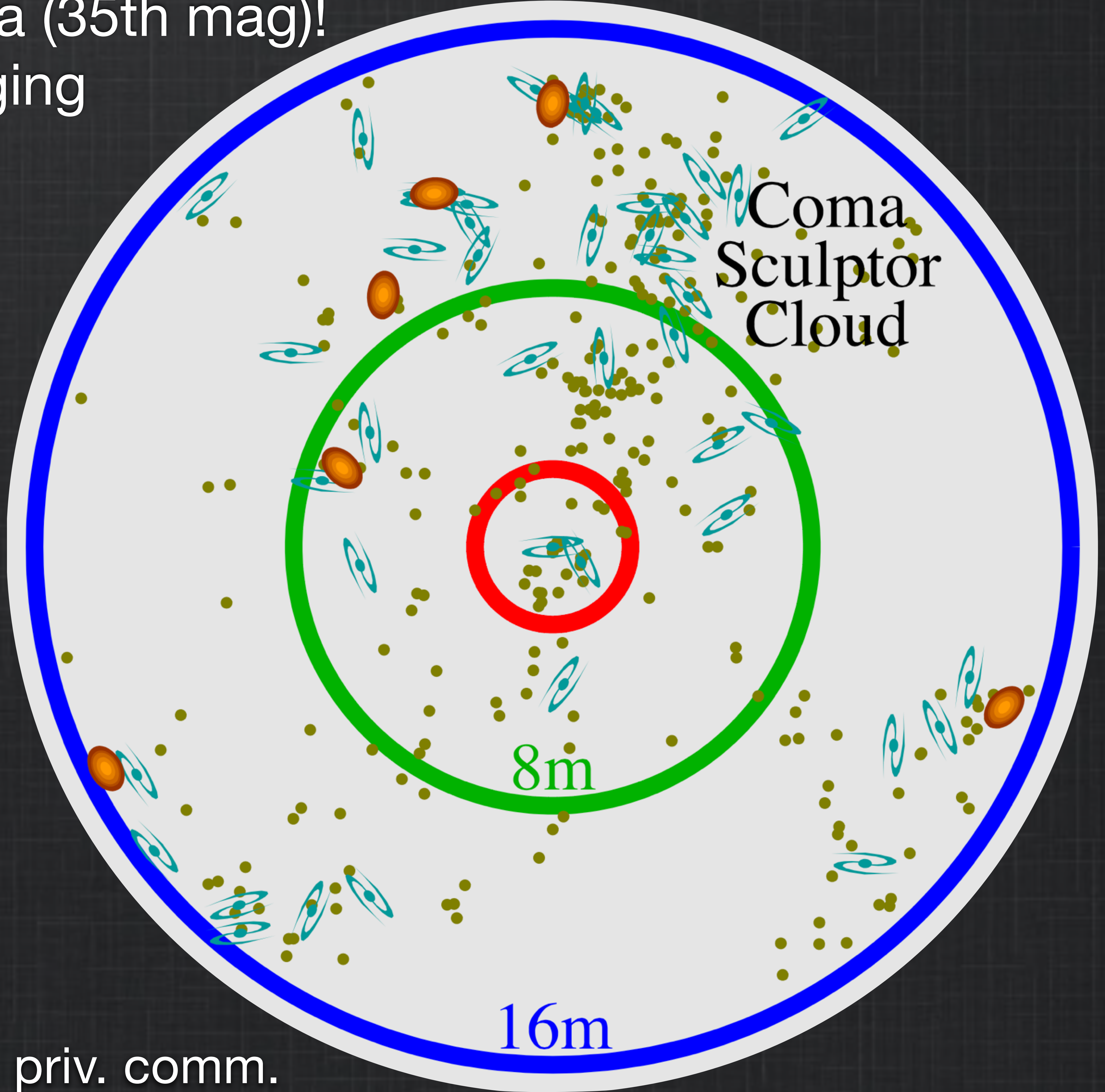
The Next General Astrophysics Opportunity Beyond LSST, WFIRST, and JWST

Measure the Full Chronology of Galaxies Across **all** Hubble Types

This is the only way to understand the context of our Milky Way Galaxy's assembly history

- Requires reaching the old main sequence turnoff out to Coma (35th mag)!
- High precision and stable diffraction-limited visible-light imaging





T. Brown, priv. comm.

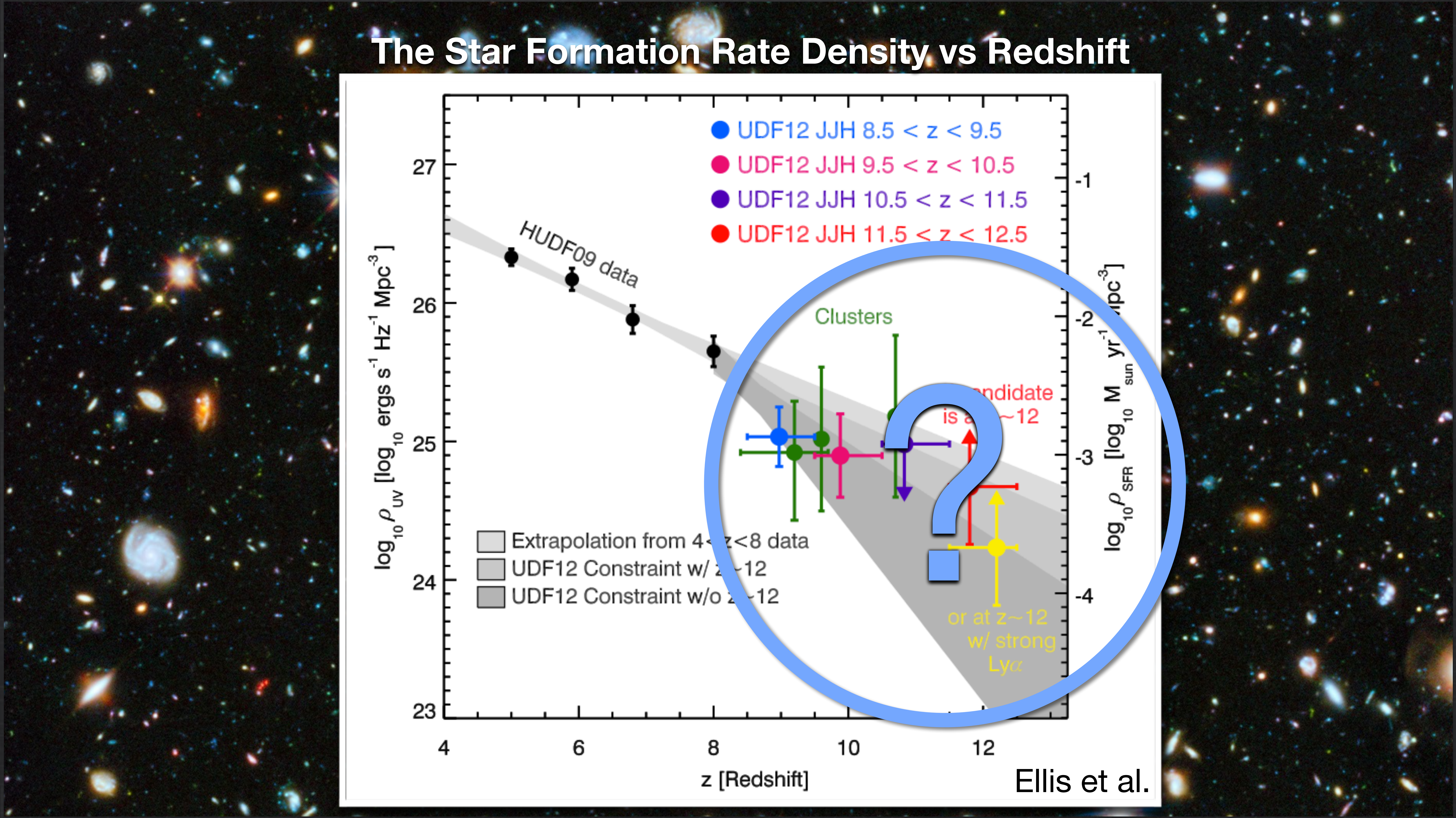
General Astrophysics Studies of Nearby Galaxies Anchor our Knowledge of Global Astrophysical Relations

Progress Will Require

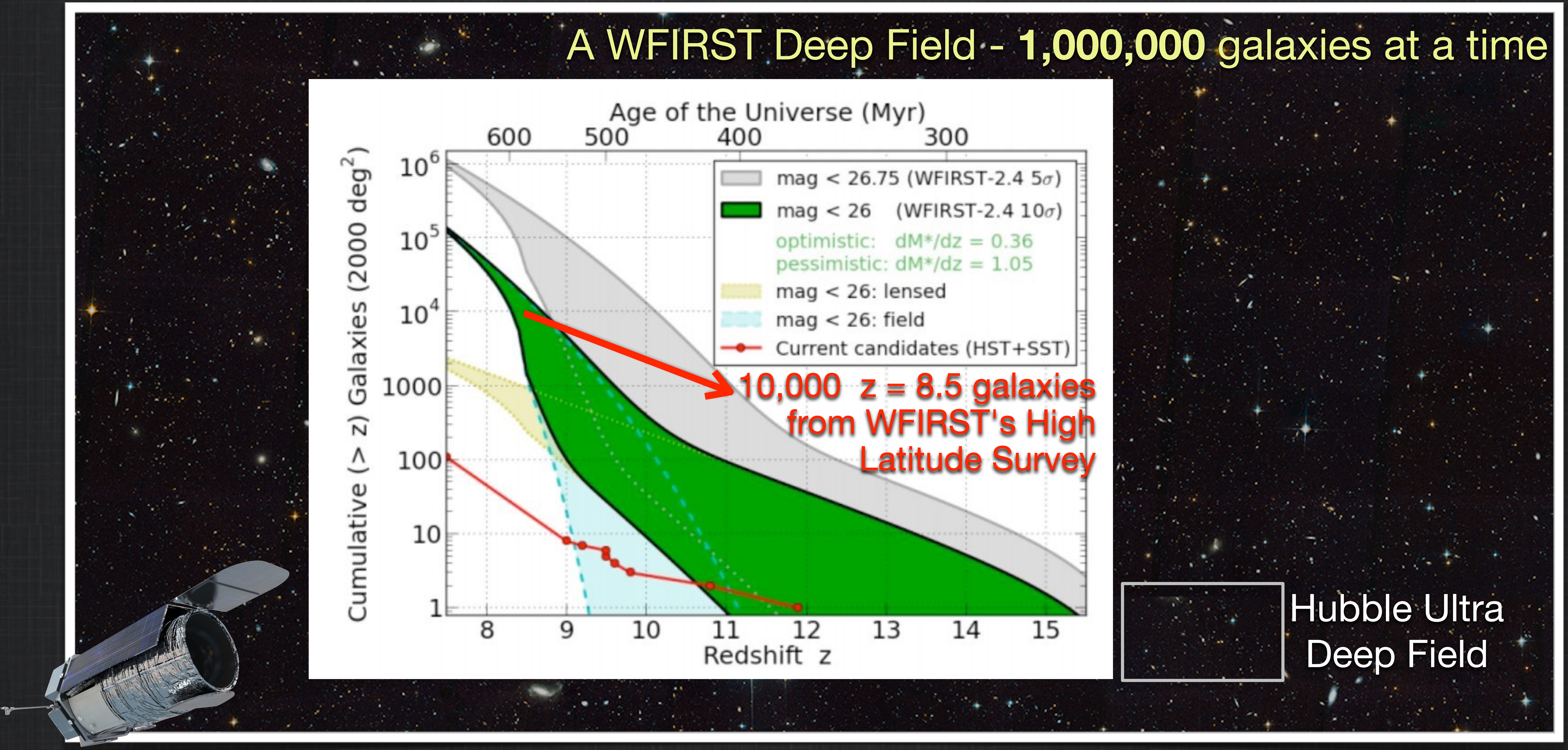
Breakthroughs in **sensitivity, resolution, astrometry, field of view**

First Light and Galaxy Evolution Through Cosmic Time

Searching for First Light



Searching for First Light - 100 Hubbles at a Time



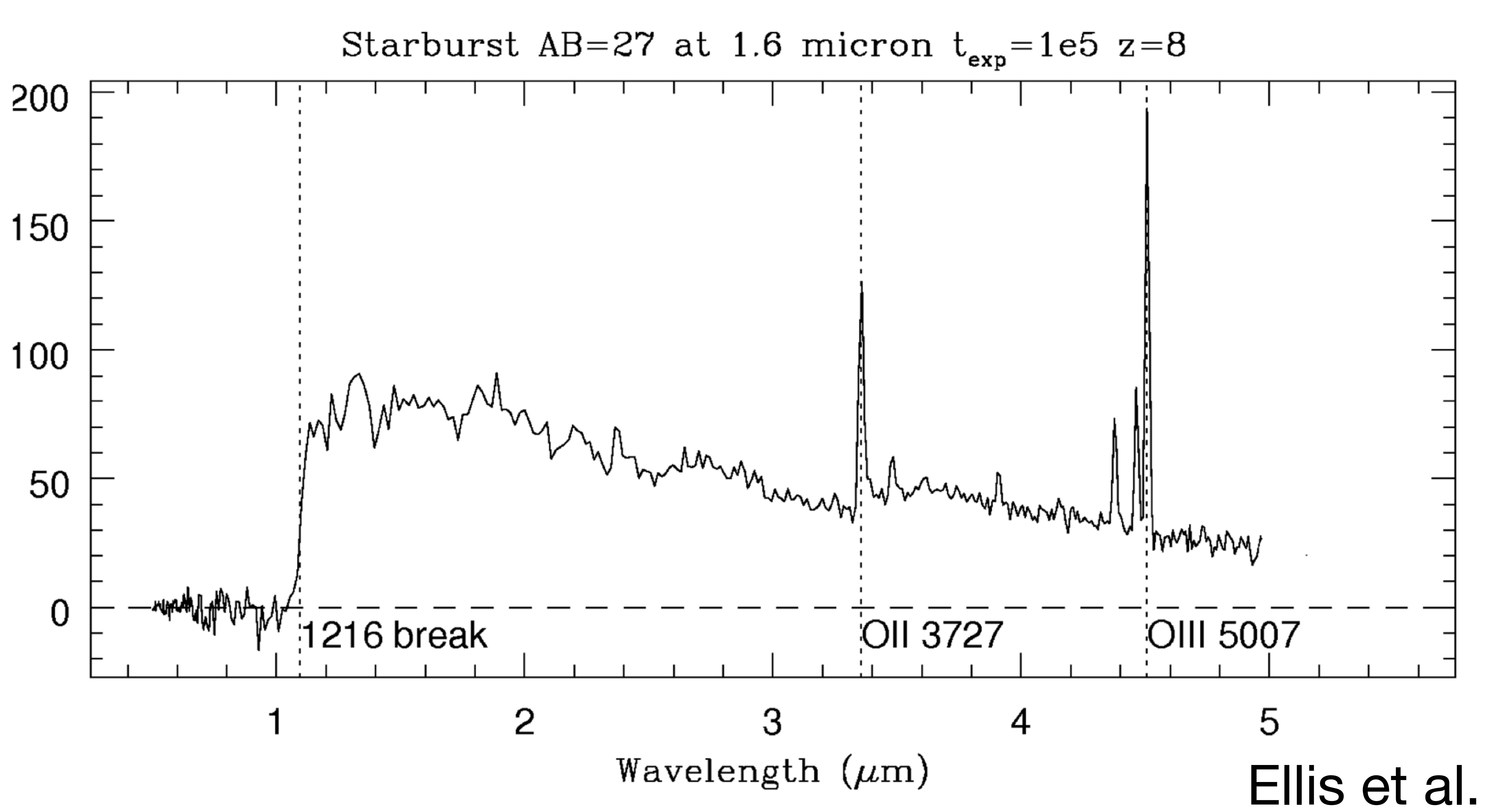
Searching for First Light

z = 8 Galaxy **Spectra** w/ JWST

WFIRST deep field imaging will contribute to demographics of early galaxies (#s, LFs, colors)

JWST spectroscopy will address detailed astrophysics

- nature of star formation: regular or burst-like (feedback).
- ionizing spectrum (stellar pops, role of AGN)
- escape fraction of Lyman limit photons
- chemical composition: O/H, C/O ratios (early nucleosynthesis)
- is there dust?



Ellis et al.

The Frontier Beyond JWST and WFIRST

A Breakthrough in **Image Resolution**

- Finding redshift 10 galaxies in the post WFIRST era will cease to be interesting
- JWST will obtain high throughput infrared spectroscopy of the brightest high redshift galaxies
- But, Hubble z = 8 galaxies show multiple clumps, and z = 10 galaxies are not resolved
- WFIRST will have similar image quality
- Possible that <100 pc scales of highest redshift galaxies will still not be resolved by JWST
- GSMTs with AO will help for galaxy morphologies

Elliptical

Abell S0740
Blakeslee

Spiral

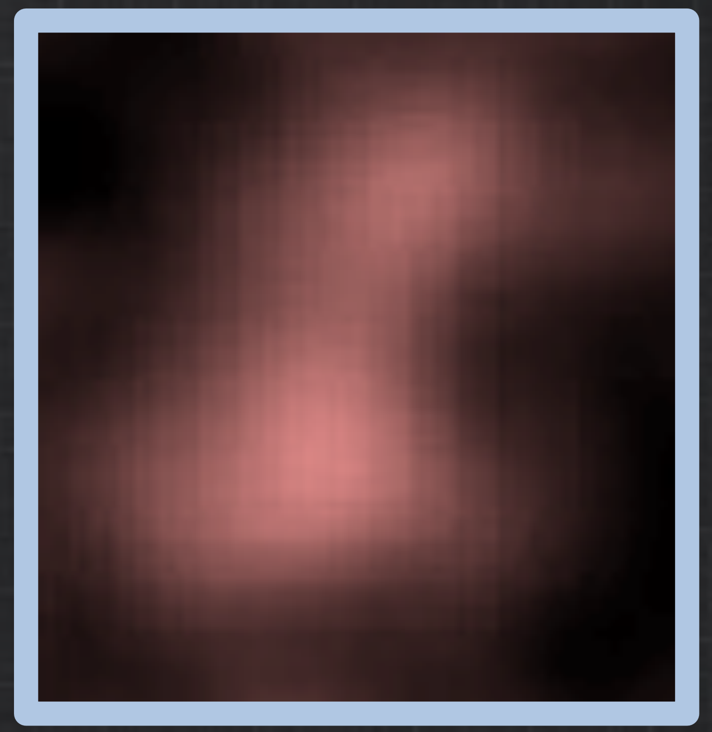
M74
Chandar

Irregular
Starburst

Antennae
Whitmore

Clump clusters, chains

in CANDELS
z = 2.05
Wuyts12



A1689-zD1*
z ~ 7.8
Bradley08

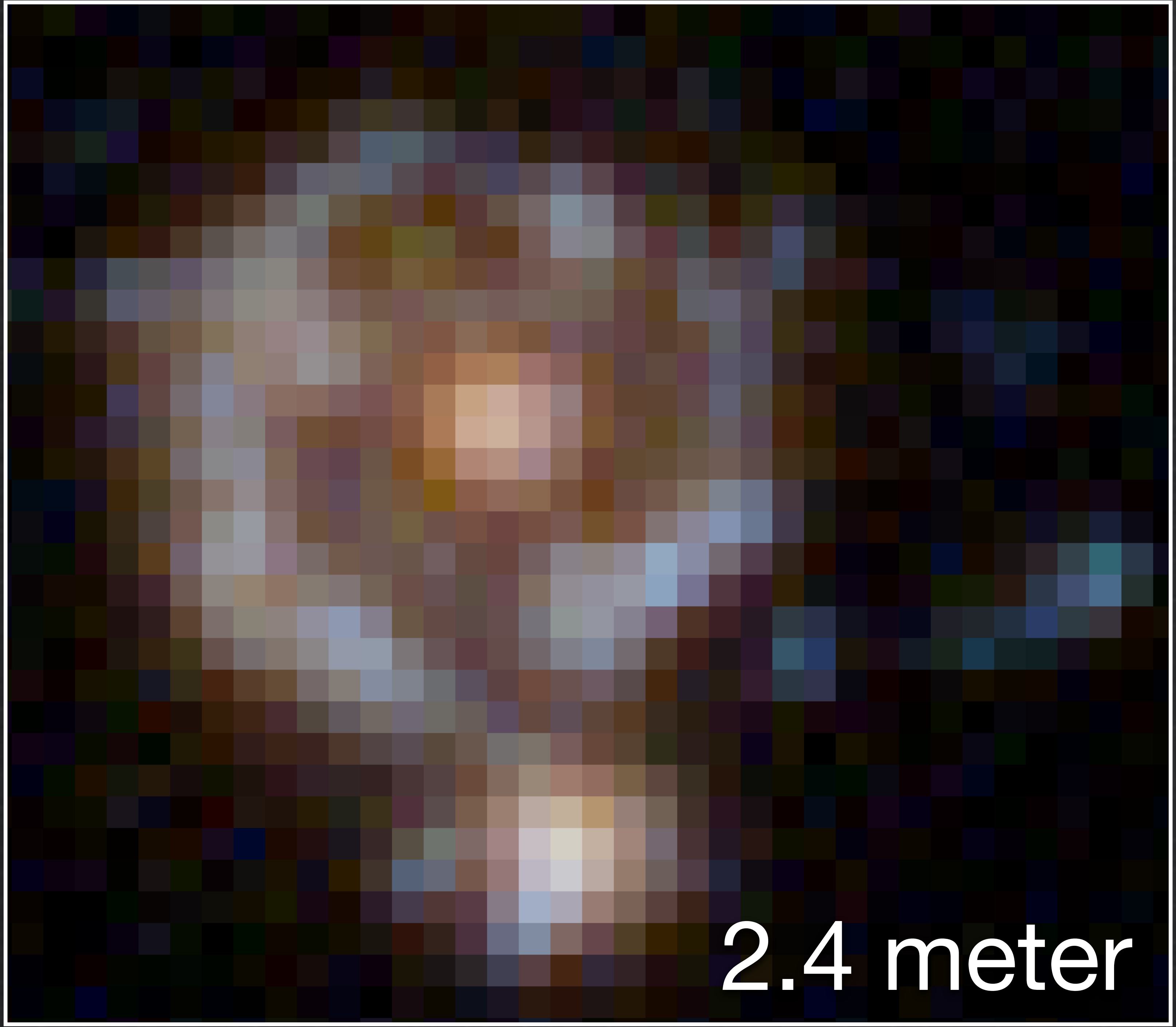
Single Clump?
r <~ 100 pc

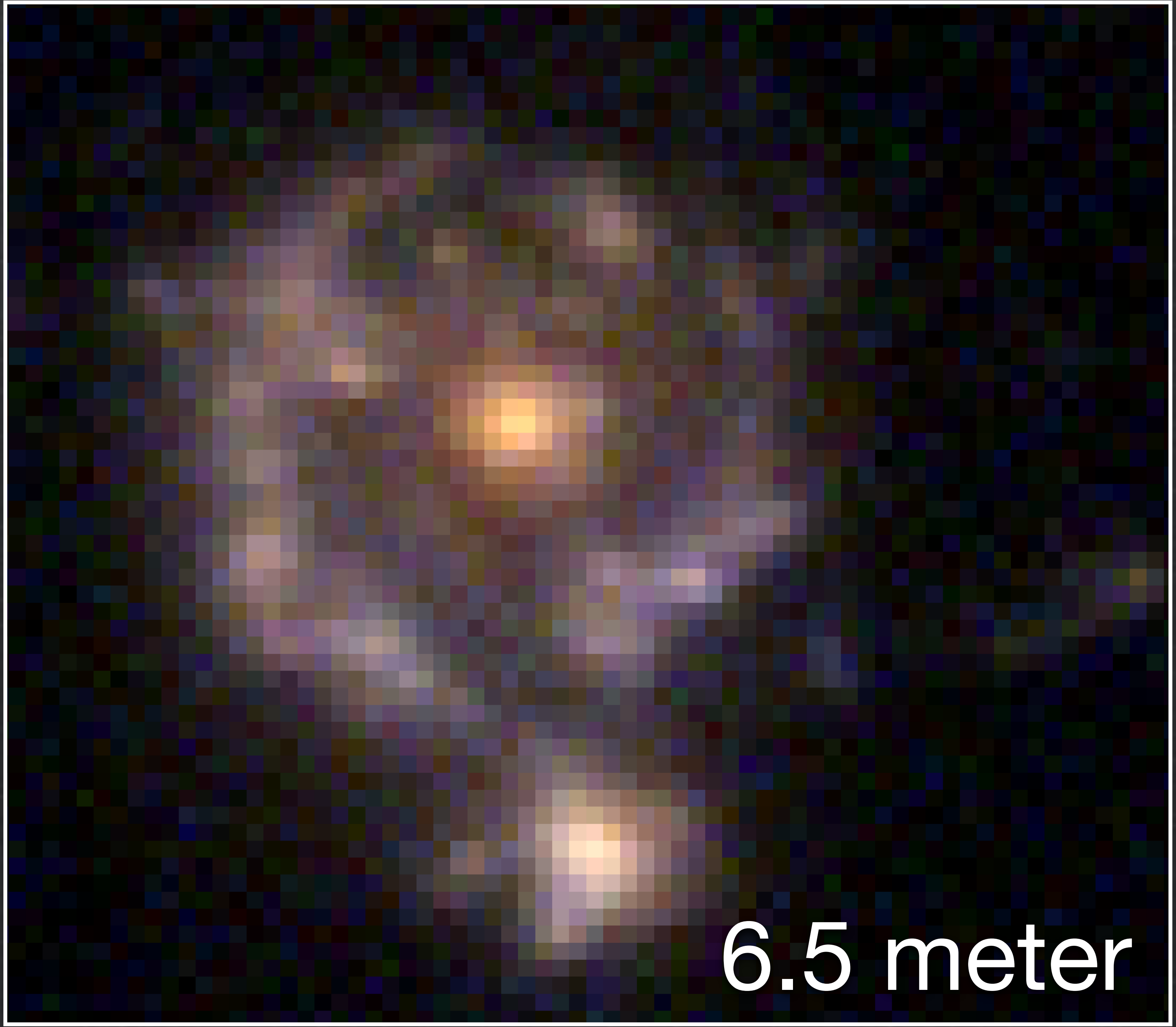
in CLASH*
MACS0647-JD
z ~ 10.8; Coe13

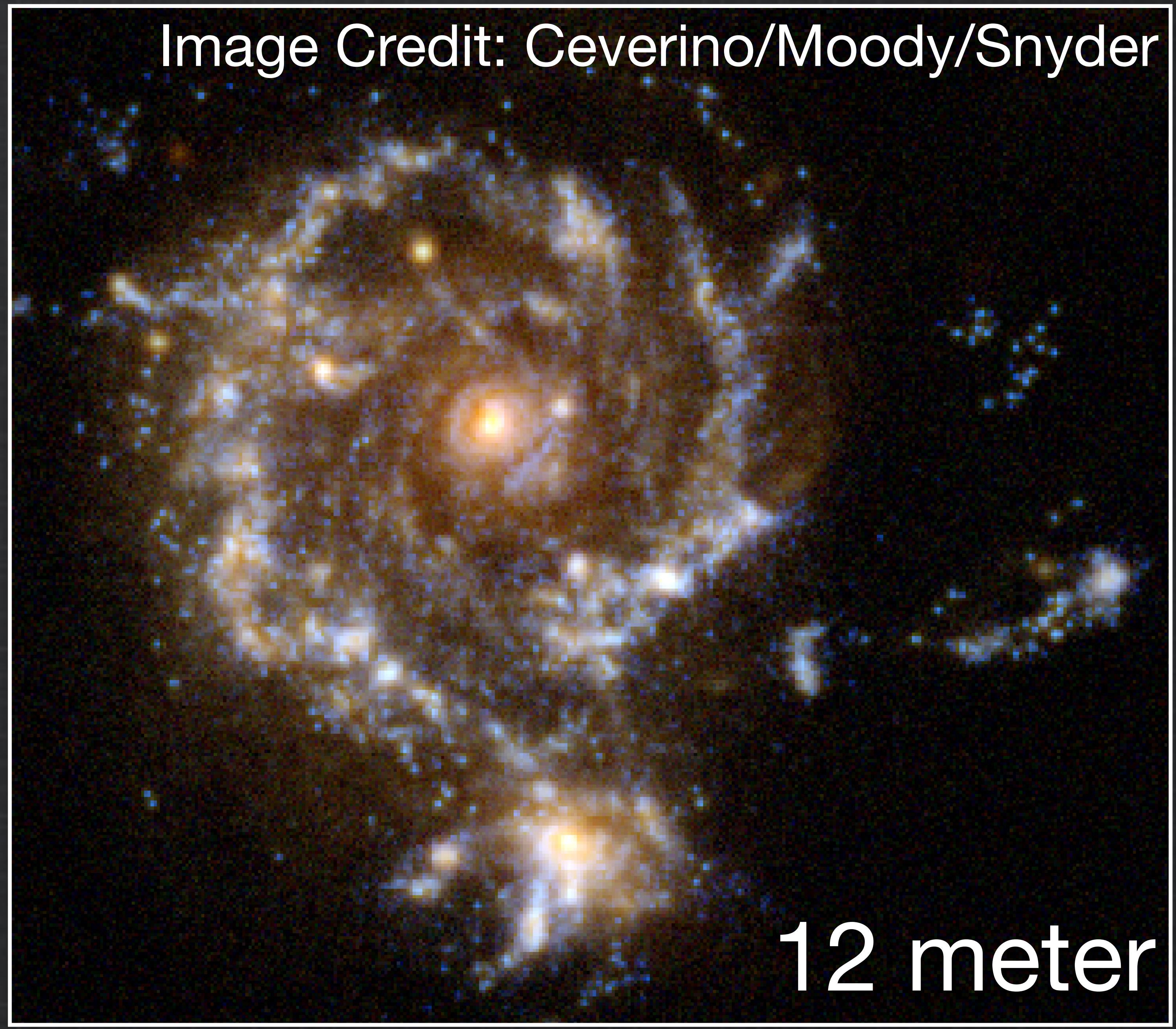
(graphic from D. Coe)

The Frontier Beyond JWST and WFIRST

IMAGE RESOLUTION







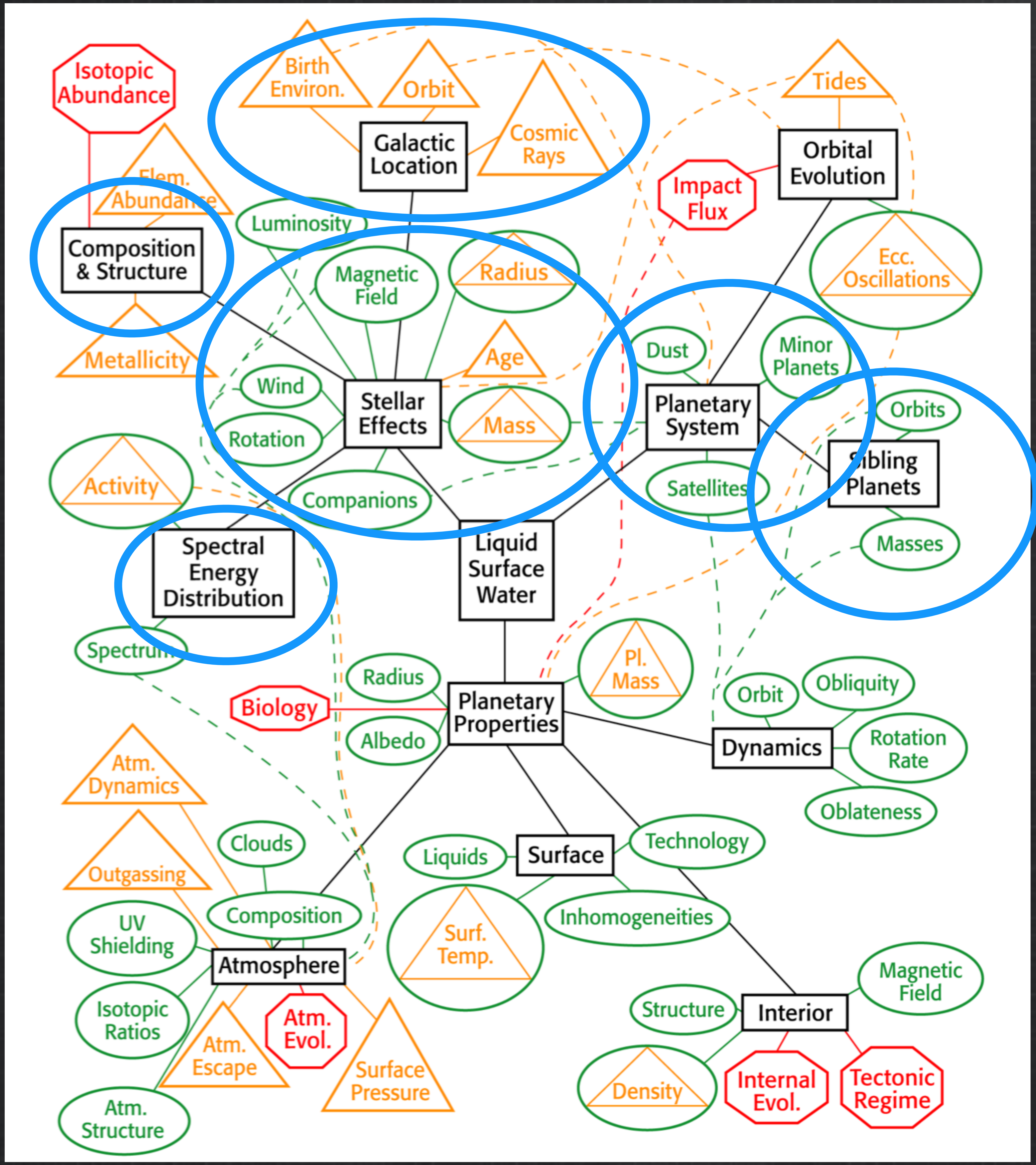
Resolving the Building Blocks of High-z Galaxies Discovered by JWST and WFIRST

- Star forming regions and dwarf galaxies have 100 pc scales
- Visible light space-based imaging can establish earliest galaxy morphologies
- Complements spectroscopy from GSMTs
- Complements molecular gas studies with ALMA

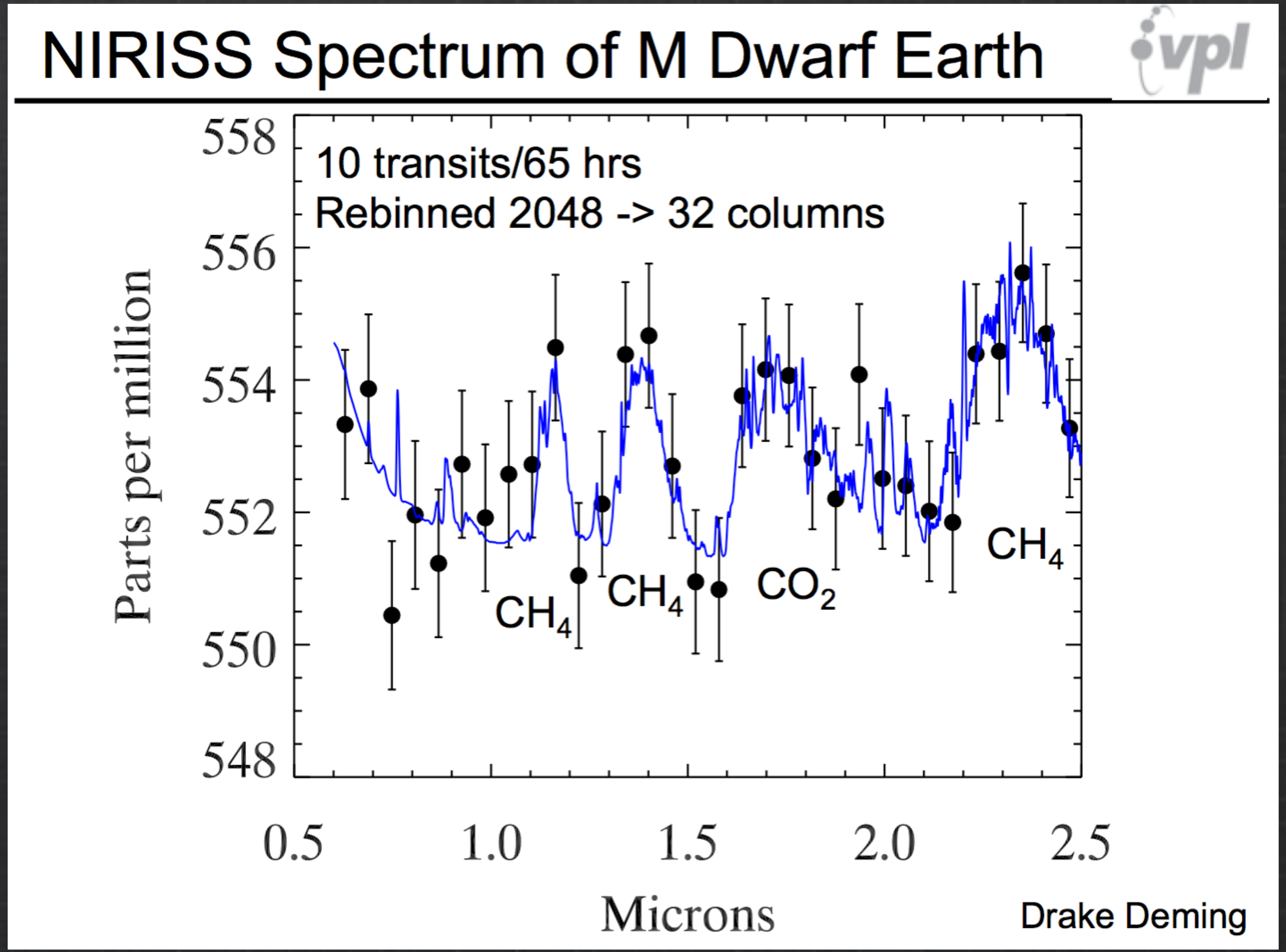
Life

…also a Cosmic Origins Pursuit

Cosmic Origins and Exoplanet Characterization



V. Meadows



Assessing Potential Habitability (V. Meadows)

K2 and TESS are (will) yield prime targets for JWST follow up

JWST provides our first opportunity to characterize habitable zone terrestrial planets

- JWST may be able to detect O4 dimer at 1.06 and 1.27 microns
- (Earth like planet at 5 pc)
  - requires ppm sensitivity, long integrations, & favorable conditions
- warm mini Neptunes will be straightforward for JWST (cloud and atmospheric composition)
- lots of exciting mid infrared exoplanet science also

Thank You