RFI Response Summaries

7 Rapid Science Summaries

Topic: Star Formation / Nearby Galaxies

Paul Scowen (twice)

Aida Wofford

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UNDERSTANDING GLOBAL GALACTIC STAR FORMATION

Paul Scowen (ASU)

Rolf Jansen, Matthew Beasley, Daniela Calzetti, Steven Desch, John Gallagher, Mark McCaughrean, Robert O'Connell, Sally Oey, Deborah Padgett, Aki Roberge, Nathan Smith

MOTIVATION

- Meteoritic evidence indicates that the Solar System was exposed to a SN blast wave during its formation – statistically this points to the Sun forming as part of a large cluster that had massive stars
- Statistically the majority of stars form in massive stellar environments
- Understanding the formation mechanisms and survival rates within massive stellar environments is therefore fundamental to understanding a large part of the star formation process within our and other galaxies
- We aspire to the development of an understanding of star formation (SF) as a large-scale, coherent and systematic process

METHODOLOGY

- To understand SF as a global process we need to design and engage in a systematic program that samples a large number of Galactic SF environments representing a wide range of environments and conditions
- We propose a widefield UVO imaging survey of star forming complexes to observe:
  - the interactions between gas and stars, between stars and stars and between stellar disks and their environment
  - Spatially resolve disks, multiple stars and clusters
  - Measure stellar and outflow motion and perform relative photometry to age-date young stars
- Requirements: widefield UVO imaging with diffraction limited resolution

SPECIFIC COMPONENTS

- YSO's: masses, rotation rates, variability, ages, multiplicity, clustering statistics, motions, brown dwarf and free-floating planet detection
- Disks: sizes, masses, structure, mass-loss rates, photo-evaporation, density distributions, survival times
- Outflows: detection of microjets, wide-angle flows, winds, motions, momenta, mass-loss rates, turbulence, shocks
- Nebulae: excitation, motion, ionization fronts, triggered SF
- Massive stars: motions, variations, winds, interactions with siblings, HII regions
- Recycling: SNRs and PNe, bulk motions, excitation, shocks
- Superbubbles: cloud destruction, OB associations, T associations, global structure and evolution of SF regions
- Galactic Ecology: impact of spiral arms, cloud formation, Galactic gradients in properties

FOUR CENTRAL QUESTIONS

- What is the formation and survival rate of Solar System class objects in massive star forming regions? There is a growing body of evidence that many stars form in these environments, and that our own Sun was one such system, based on meteoritic evidence concerning ^{60}Fe.
- What is the role of triggering and feedback in star formation propagation? A wide range of predictions from numerical simulations describe the role of triggering and feedback as being anything from dominant to negligible. What is the correlation between environment and the nature of the stellar population that forms in secondary and even tertiary star formation events?
- How is the distribution of star formation across a galactic disk managed? We see evidence that an increase in the efficiency or intensity of star formation occurs almost simultaneously across large distances – what is the source of these global modes – what environmental changes are necessary to initiate and support star formation at these levels?
- When considering global star formation, what are the determining factors that cause stars to form in one place as opposed to another? At the microphysics level, how does elevated or starburst star formation compare to the more common modes? What dictates the intrinsic efficiency of the star formation process? These latter questions will require comparison with observations from other nearby galaxies such as the LMC, but the database of observations from this program will be necessary to lay the groundwork to answer them.

Parameter	Specification	Justification
Field of View	At least 200 sq. arcmin	To allow a statistically complete survey of as many targets and environments as possible in a reasonable period of time
Resolution	Diffraction Limited to 300nm	To provide access to UV-blue stellar populations; to resolve structure in YSO jets, protoplanetary disks, ionization fronts, etc.
Aperture	1.5-4m	This is driven by the limiting surface brightnesses and magnitudes needed traded against the necessary exposure times to achieve them – the larger the better
Stability	A small percentage of a pixel	To allow the stable photometry and astrometric measurements necessary to achieve the science goals
Photometric Stability	Combination of gain, A/D conversion and QE need to be stable to better than 10^{-5}	Again to provide the photometric stability to achieve the science goals of the project
Filter Suite	F250W, F336W, F438W, F625W, F775W, F850W; F547M, F980M, F1020M, F1050M, F1080M; F280N, F373N, F469N, F487N, F502N, F631N, F656N, F673N, F953N	Dictated by both broad-band colors needed to survey stellar populations and the narrow-band diagnostics necessary to probe the resolved gas structure and dynamics
Optical Design	Efficient design offering a wide, well-corrected field of view to be populated by a large focal plane	The science program can only be achieved by an efficient design that offers parallel observing in the red and blue, with little field distortion, and as large an objective as possible
Detectors	High yield, efficient detectors, customized in their response to the passbands needed	Tiling the large focal plane will be challenging – we need an efficient manufacture and testing process, combined with the ability to match response to the optical channels

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THE MAGELLANIC CLOUDS SURVEY

Paul Scowen (ASU)

Rolf Jansen, Matthew Beasley, Daniela Calzetti, Alex Fullerton, John Gallagher, Mark McCaughrean, Robert O’Connell, Sally Oey, Nathan Smith

MOTIVATION

- To address 2 key Cosmic Origins questions:
  - How are chemical elements distributed in galaxies and dispersed into the circumgalactic and intergalactic medium?
  - How does baryonic matter flow from the intergalactic medium to galaxies and ultimately into planets?
- The Magellanic Clouds (MCs) represent the closest external galaxies available to us and represent a wide range of star formation (SF) from the pedestrian to starburst-like (30 Dor)
- There is well-documented interactions between material streams and the Clouds allowing study of mass-exchange between the IGM and the galaxies, and the impact on their SF
- The Magellanic Clouds are known to be metal-poor allowing comparison of SF modes with Galactic analogs

METHODOLOGY

- A 3-phase survey of the Clouds, composed of:
    - A complete-area, high resolution multi-band UVOIR broadband survey
    - A narrowband survey in 7 key nebular filters to cover a statistically significant sample of HII regions, and to also cover a large-area survey of the diffuse, warm ISM (WIM)
    - A comprehensive FUV spectroscopic survey of 1300 early-type stars
- This allows:
    - Assessment of massive star feedback in both HII regions and the diffuse warm ISM
    - Completion of a comprehensive study of 30 Dor – the closest example of a giant extragalactic HII region (GEHR)
    - Development and quantitative parameterization of stellar clustering
    - Extensive FUV studies of early-type stellar atmospheres and energy distributions
    - Extensive FUV absorption-line studies of molecular cloud structure and ISM properties

SPECIFIC COMPONENTS

- Feedback from Massive Stars
  - Massive stars destroy molecular clouds, produce ionizing radiation, galactic superwinds and heavy elements that drive evolutionary processes
  - MCs offer a high resolution, unobstructed opportunity to study triggering and feedback over micro- and macro-scopic scales
  - Access to the WIM – association with SF regions, correlation and properties of the gas
- 30 Doradus – the nearest GEHR
  - Represents a single starburst-like SF event 2-3 Myr ago
  - Is the closest such example
  - Contains over 300 OB and WR stars
  - Provides an “in situ” look at these large structures and insight into their structure, evolution and impact on their environment and host galaxy
  - Is regarded as a likely working model for how you make a globular cluster

SPECIFIC COMPONENTS

- Stellar Clustering:
  - Unobstructed view of entire system allows study of coherence length that could indicate the mode SF follows to propagate - ground-based studies indicate a strong correlation between age and separation in the LMC over degree scales
  - Hierarchical clustering – clustering of massive stars has a length scale, but the determination is a strong function of resolution and sensitivity
- Massive Stellar Atmospheres:
  - Some fundamental aspects of massive stellar atmospheres are not well modeled - clumpy winds, underestimated ionization fluxes, wind-blanketing, loss of angular momentum
  - FUV spectroscopic survey of 1300 massive stars (down to B2V) will provide unprecedented diagnostics to address these issues
  - Use of sight lines to study absorption by hot gas, cool molecular gas and dust properties

FOUR CENTRAL QUESTIONS

- What is the nature of the interrelation between the formation, evolution and destruction of massive stars and the energization of the WIM? How does the formation of massive stars in a particular locale affect and dictate the subsequent star formation across that region?
- What is the fundamental difference between starburst star formation and the more common disk modes we see in disk star forming regions in our own Galaxy? What causes the several orders of magnitude increase in star formation efficiency as well as the almost instantaneous formation of thousands of stars at once?
- What is the correct density and velocity structure associated with the stellar winds from massive stars? How does inhomogeneity and clumping in these winds affect the transfer of energy and material to the ISM and the process of recycling of material from the stellar to the gas phase for the next generation of stars?
- What are the global processes that govern the assembly and evolution of giant molecular clouds? Since these nurseries host the most dominant modes of star formation in galaxies, we need to understand the nature of their formation and development if we are to understand the underlying process of stellar assembly.

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Detectors	High yield, efficient detectors, customized in their response to the passbands needed	Tiling the large focal plane will be challenging – we need an efficient manufacture and testing process, combined with the ability to match response to the optical channels
Coatings	Development of stable, high-reflectivity FUV mirror coatings	To provide high throughput access to the FUV (below 115nm) while minimizing risk to the optical reflectivity of an optical system
FUV Detectors	Development of next generation MCP technology	To provide a low-cost, high QE, robust solution to allow efficient observations of FUV emission, below 115nm to as low as 100nm
FUV Spectroscopic Resolution	R > 30,000	To enable sufficient resolution to see structure and dynamics of emission from science targets

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Massive stars: key to solving the cosmic puzzle

Wofford A.; Leitherer C.; Walborn N. R.;
Smith M.; Peña-Guerrero M.; Bianchi L.;
Thilker D.; Hillier D. J.; Maíz Apellániz J.;
García-García M.; Herrero-Davó A.

Massive stars: key to solving the cosmic puzzle.
Science context.

- **What is the question? Why is it important?**
  - How do mass, composition, convection, mass-loss, rotation rate, binarity, magnetic fields, and cluster mass affect massive stars and their radiative, mechanical, and chemical feedbacks.
  - Massive stars are the cosmic production site of atoms that are essential for life.
- **What has been done up to now? What have we learned?**
  - few x 10 OB stars in MW & MCs from 900-1200 Å with FUSE
  - ~200 OB stars in MW at $R\sim10^4$ from 1200-1900 Å with IUE
  - Only a few x 10 OB stars in MCs with HST ☹
  - Lesson 1: we need at least a few x 100 OB stars to separate all the effects that affect massive star evolution
  - Lesson 2: we need to probe lower metallicities than in the MCs

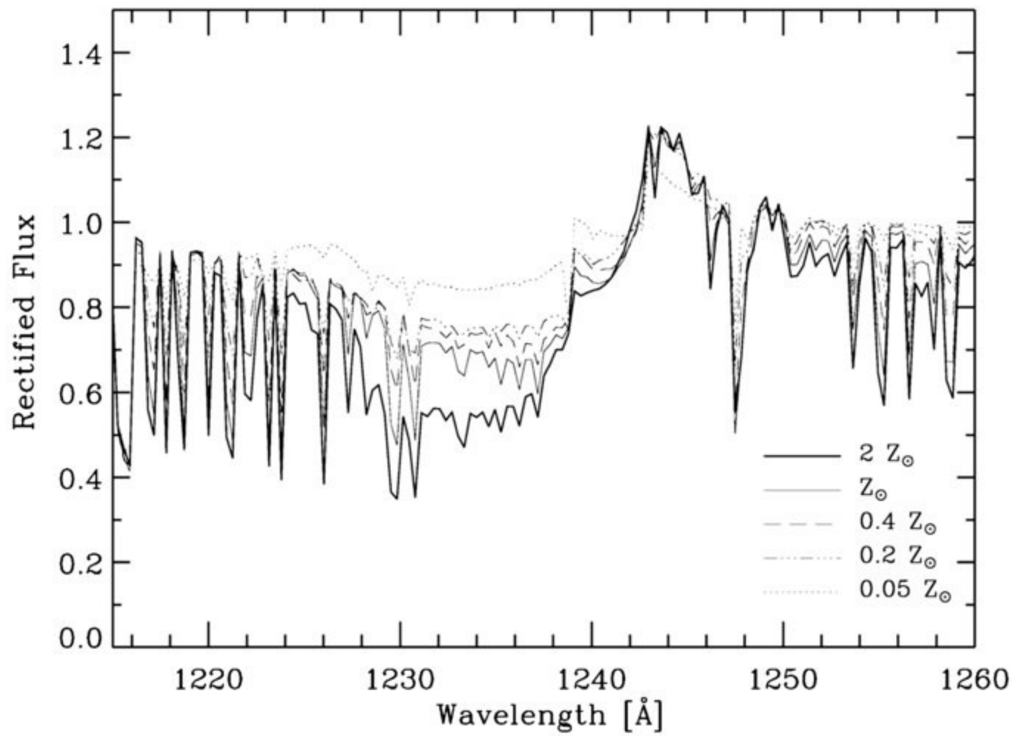
Massive stars: key to solving the cosmic puzzle.
Specific Scientific Investigation.

- **What cannot be done now? Why not?**
  - Too-expensive to obtain HST high-resolution spectroscopy for a statistically significant sample of OB stars in the MCs.
  - 1/30 solar metallicity galaxy I Zw 18 is 18 Mpc away
  - Too-expensive to obtain HST imaging and spectroscopy of a statistically significant sample of SF galaxies within a few x100 Mpc for studying the escape of Lyα photons from SF galaxies. 1200-1600 Å spectroscopy / UV +optical imaging are necessary.
- **What is the next step?**
  - Observe hundreds of massive stars in the MCs.
  - Detailed observations in I Zw 18 (see next slide).
  - Continue the ~100 Mpc study of the escape of Lyα photons but using hundreds of SF galaxies.

I Zw 18

A large (> 10m) space –based telescope will provide:

- Complete CMDs of star-forming regions down 1 solar mass
- High-resolution UV/optical spectra of individual OB stars
- Low-resolution SEDs of individual stars
- Emission- and absorption spectra of the ISM
- A 20 m telescope at 1500 Å will resolve 0.1 pc in I Zw 18; comparable to resolution in 30 Doradus in V from ground.



Massive stars: key to solving the cosmic puzzle.

Science Requirements

- Imaging / Spectroscopy / Multi-slit spectroscopy
- At least 25”x25” (size of a KISS face-on disk galaxy at 100 Mpc)
- Physical / angular resolution(s)
  - 0.1” required / <0.1” desired
- Spectral resolution(s)
  - Similar to COS/G130M for studying ISM flows using UV absorptiosn lines.
- Wavelength band(s)
  - redshifted Lyman-alpha (λc=1242 Å, $\Delta\lambda$=30 Å)
  - 900 Å / 9000 Å (upper/lower limits)
- Sensitivity
  - We need better sensitivity than COS to reach massive stars beyond the Magellanic Clouds. Currently, 5 orbits are needed to get COS mid-resolution data for V~19.5 O-stars in IC1613, which is still Local Group, and most O-stars in the same galaxy are fainter.
  - Resolved O-stars in Izw18 will probably have V>25 .

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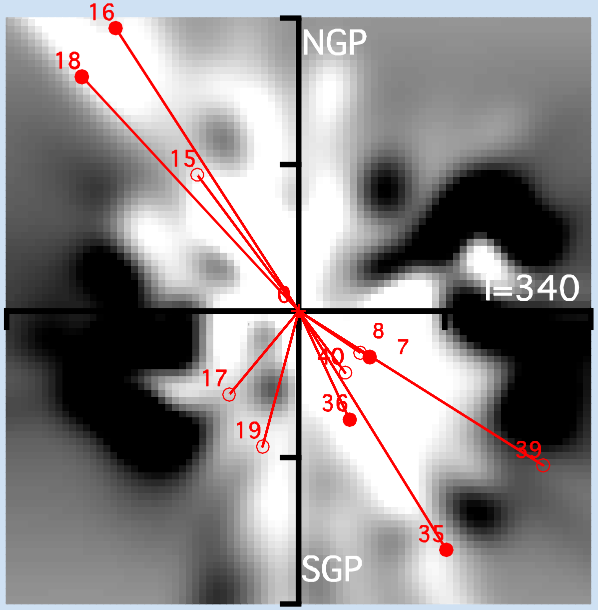
Conditions for Life in the Local Universe

M.A. Barstow and members of the European Network for UV Astronomy



Science Context

- How does cosmic feedback influence habitability in the Galaxy
  - Physics of hot atmospheres and coronae
  - Resulting interplanetary environment
- Small scale studies with HST and FUSE
  - Patchy data on general structure of local region (various research groups)
  - Revealed significant complexity

Specific Science Investigation

- Target samples far too small
  - Objects too widely distributed in space for multi-object spectroscopy
  - Obs. times too long at required $\lambda/\delta\lambda$
- What is needed
  - Improvements in sensitivity… mirrors, detectors, gratings and filters

University of Leicester

Science Requirements

- Highest poss. λ/δλ (R>100,000)
  - Resolve multiple IS/CS components
- High effective area
  - Low T_{exp} > large samples (100s to 1000s)
- High resolution imaging
  - capable of studying 10s of parsec size structures in local group galaxies
- Wavelength range 100-300nm

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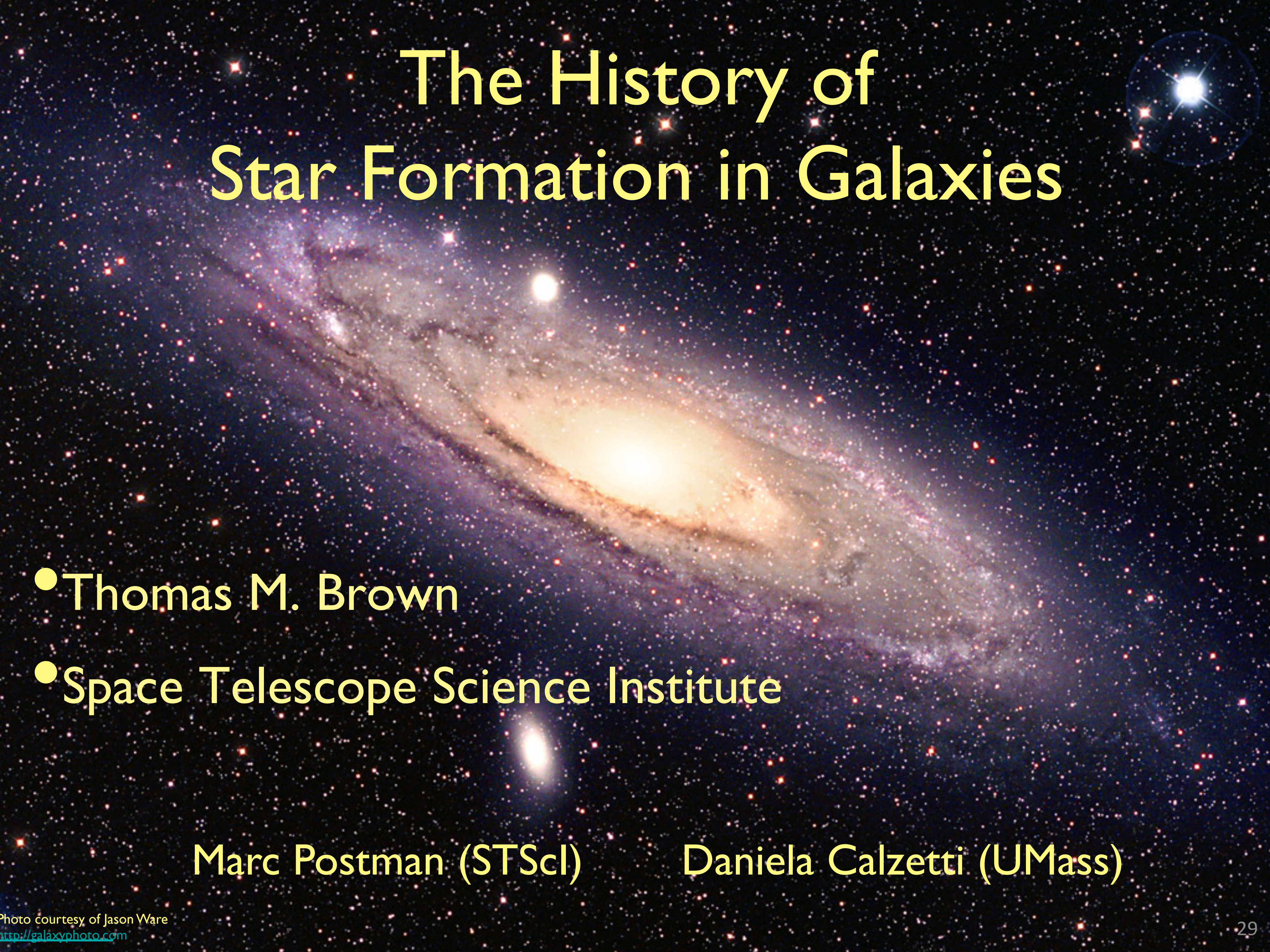


The History of Star Formation in Galaxies

- Thomas M. Brown
- Space Telescope Science Institute

Marc Postman (STScI) Daniela Calzetti (UMass)

Photo courtesy of Jason Ware
http://galaxyphoto.com

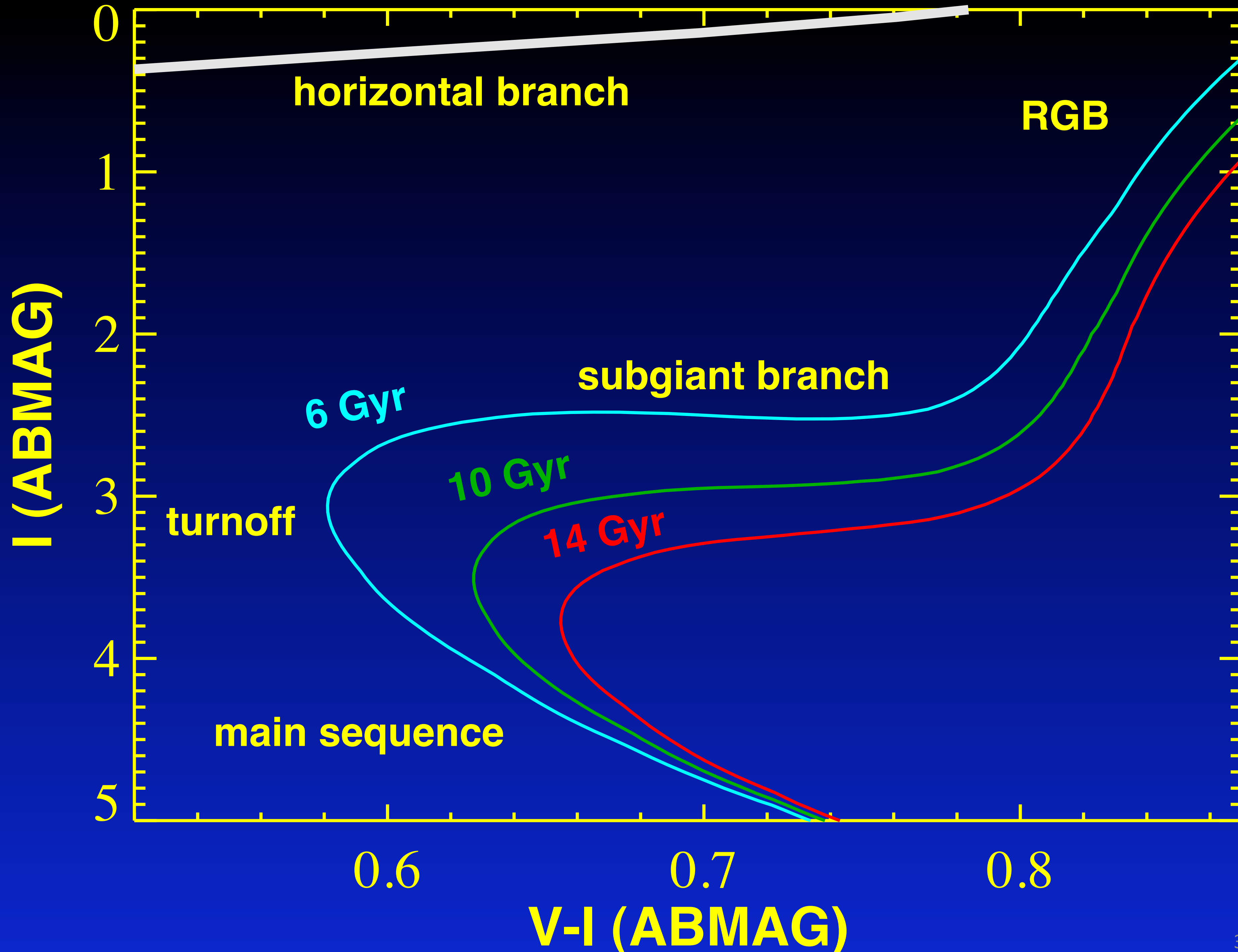
Photometry of resolved stellar populations in nearby galaxies:

- Provides the most accurate measurement of star formation history
- Can probe individual components and structures within each galaxy

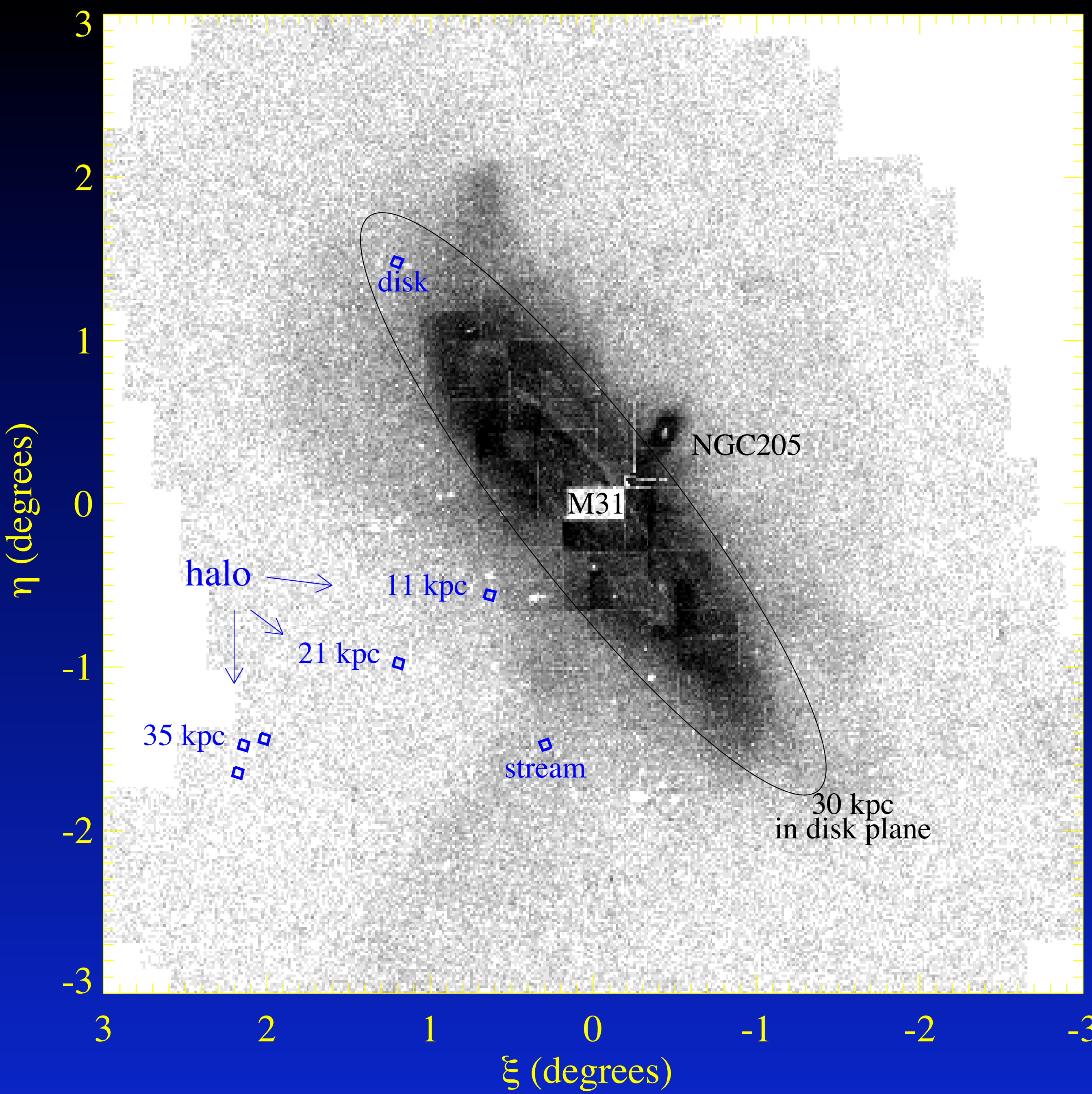
However:

- Often limited to a few pencil-beams within each galaxy
- Local Group is cosmological backwater (small number of galaxies and not representative of all types)

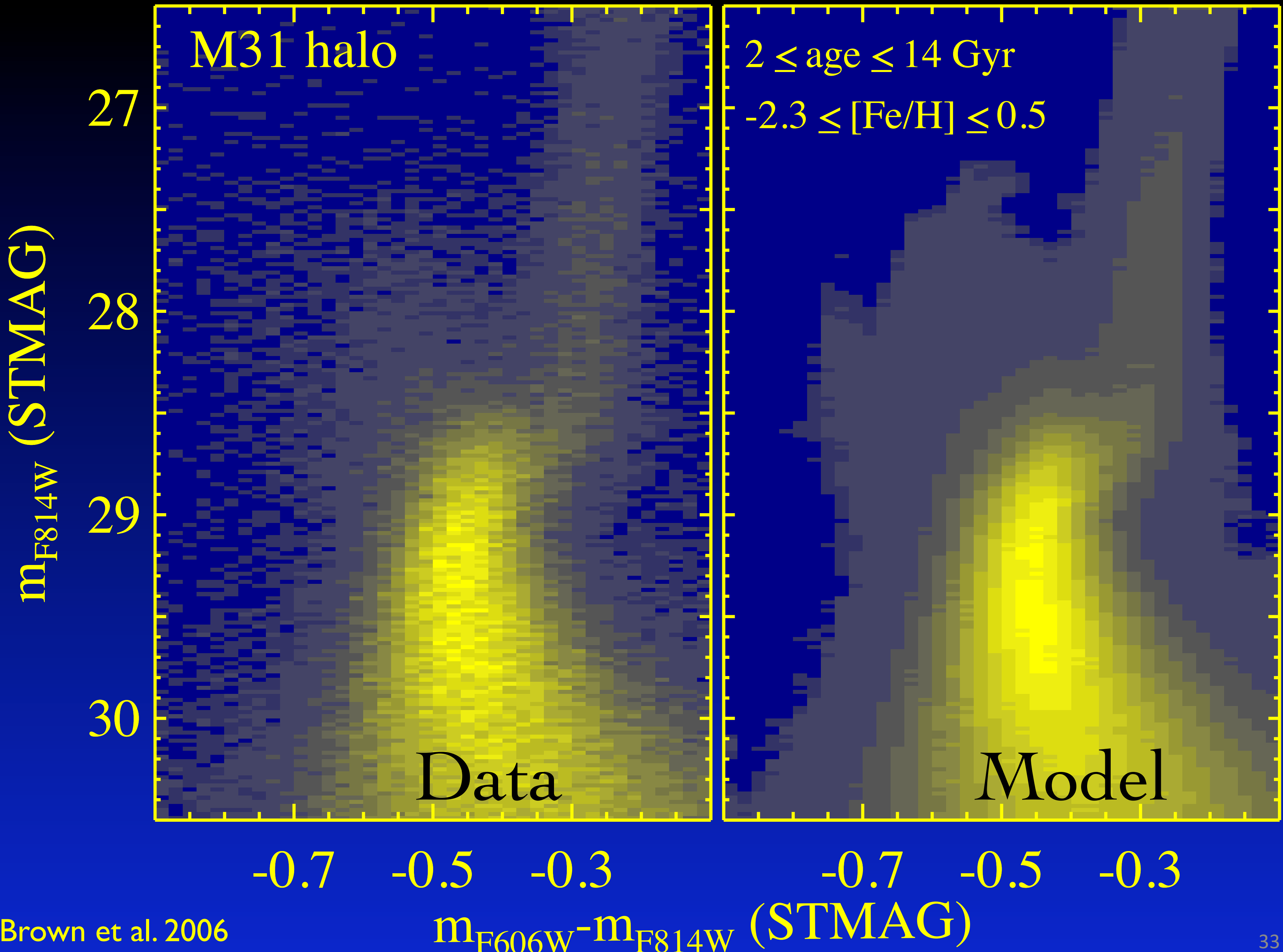
Progress requires reaching larger galaxy groups beyond the Local Group


0
1
2
3
4
5
I (ABMAG)
horizontal branch
RGB
subgiant branch
6 Gyr
10 Gyr
14 Gyr
turnoff
main sequence
0.6
0.7
0.8
V-I (ABMAG)

In several large HST programs, we have mapped the star formation history in various M31 structures (Brown et al. 2003, 2006, 2007, 2008)

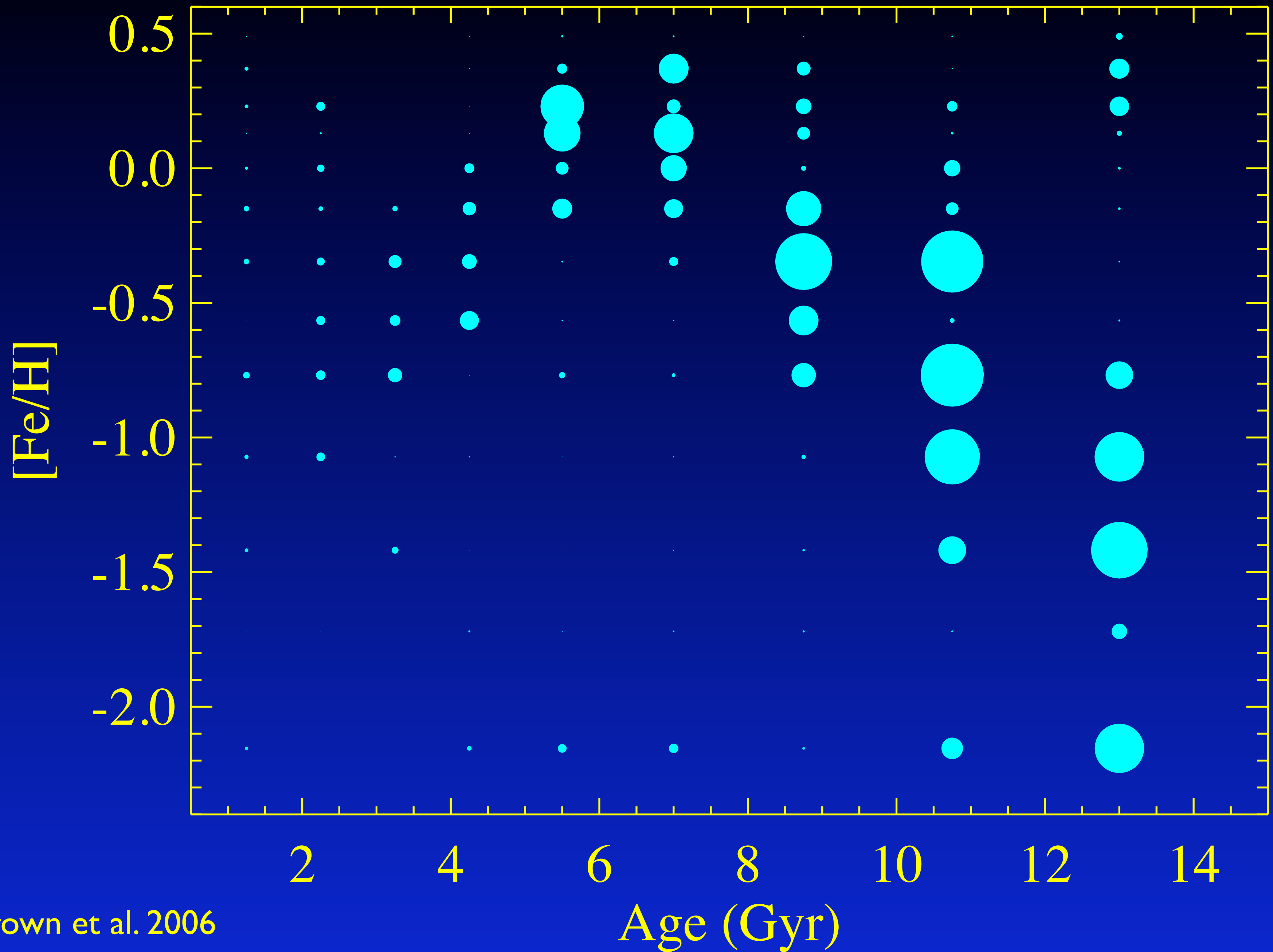


(star count map from Ferguson et al. 2002)



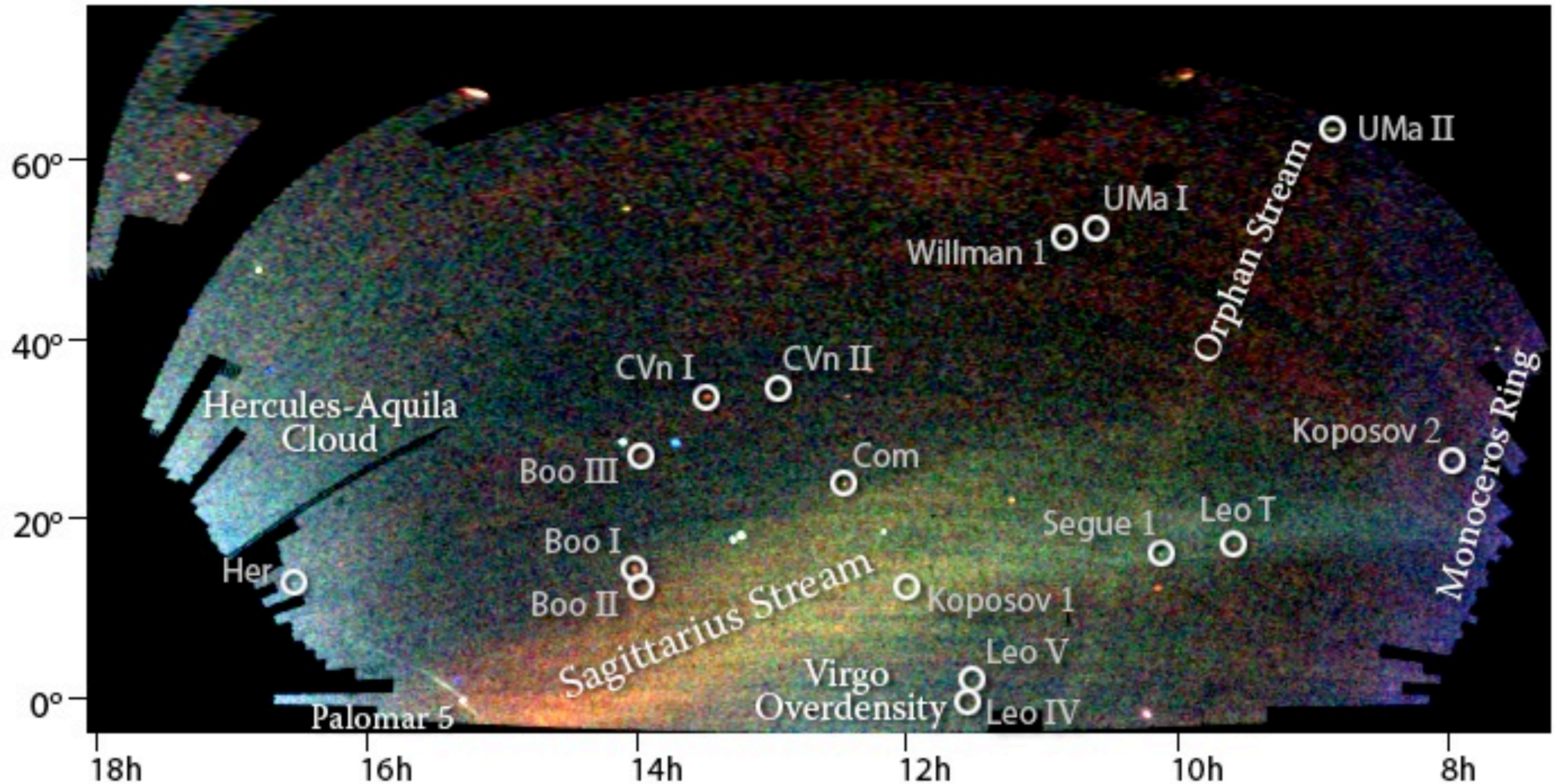
Brown et al. 2006

Halo Distribution in Age and Metallicity

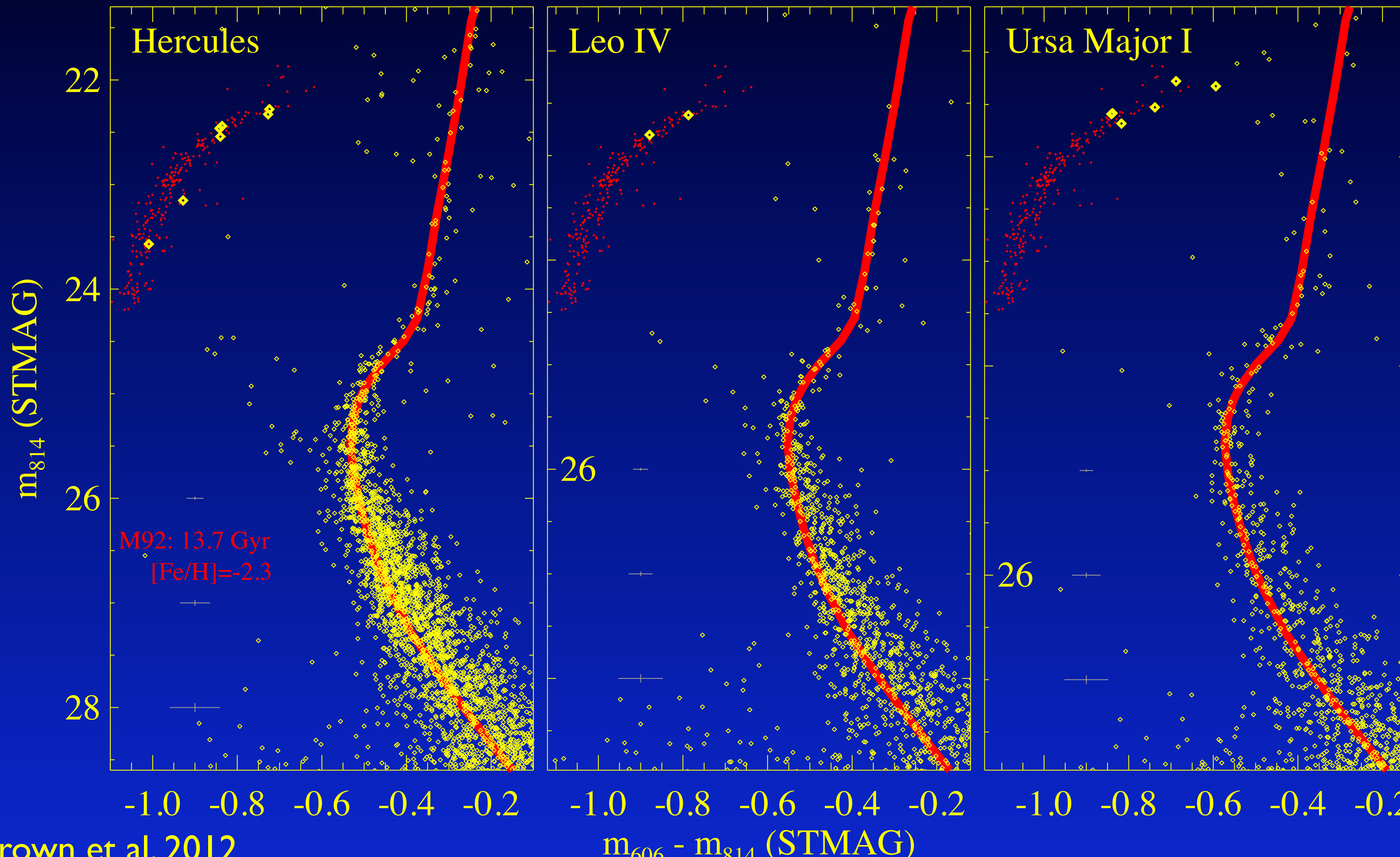


Brown et al. 2006

HST has also targeted the recently-discovered “ultra-faint dwarf galaxies” to measure their star formation histories and determine if they are true fossils from the early universe



These faint Milky Way satellites exhibit purely ancient populations, each at 13.6 Gyr, suggesting their star formation was truncated by the reionization of the universe



Brown et al. 2012

Enabling Breakthroughs

- Groundbreaking progress usually comes from two avenues:
  - Order-of-magnitude gains in sample or signal
  - Crossing new thresholds
- Background-limited observations of faint stars make enormous gains with aperture:

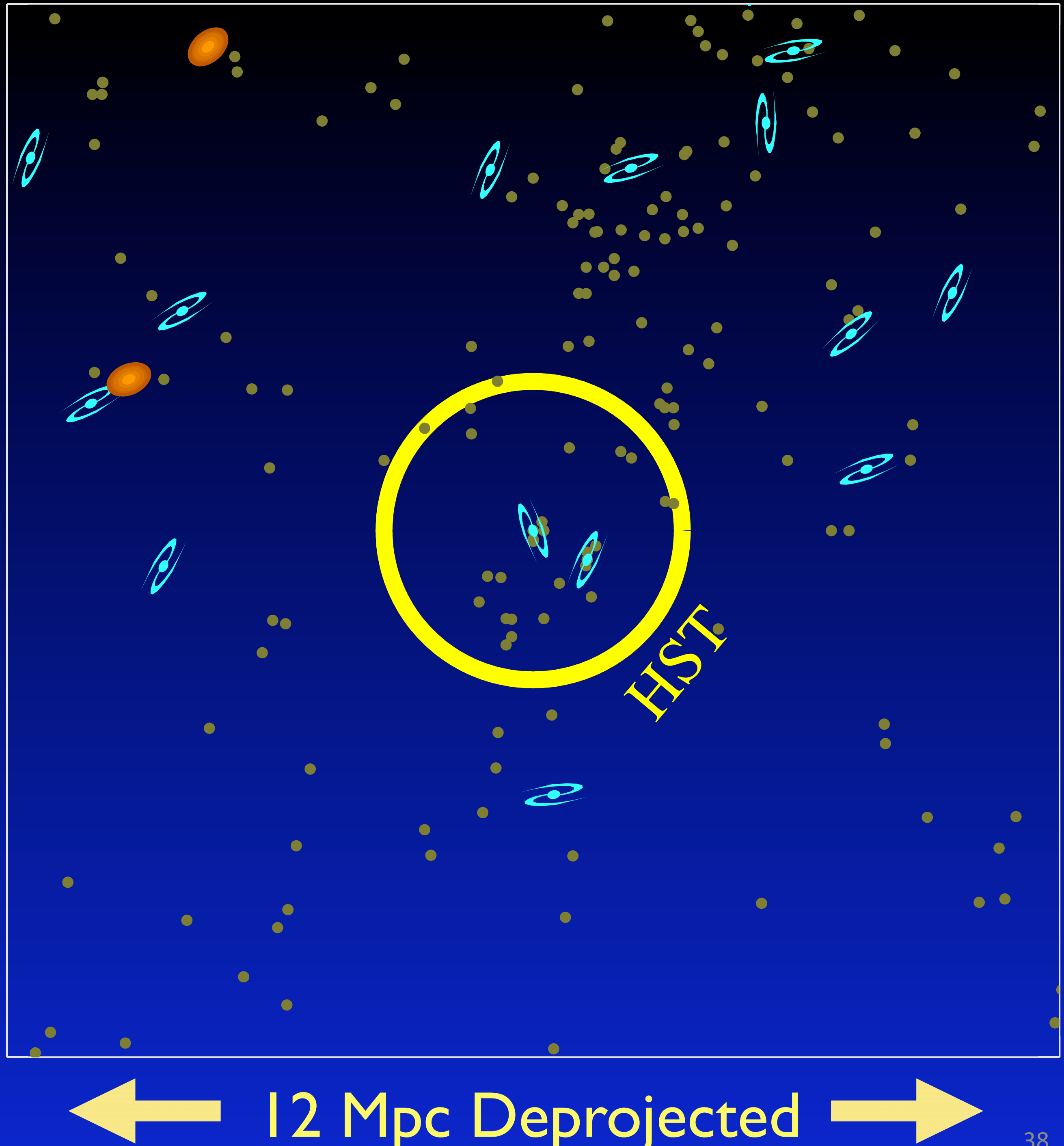
$$\text{Exposure time} \propto \text{aperture}^{-4}$$

(for fixed luminosity & distance)

$$\text{Volume} \propto \text{aperture}^{3}$$

(for fixed luminosity & exposure time)

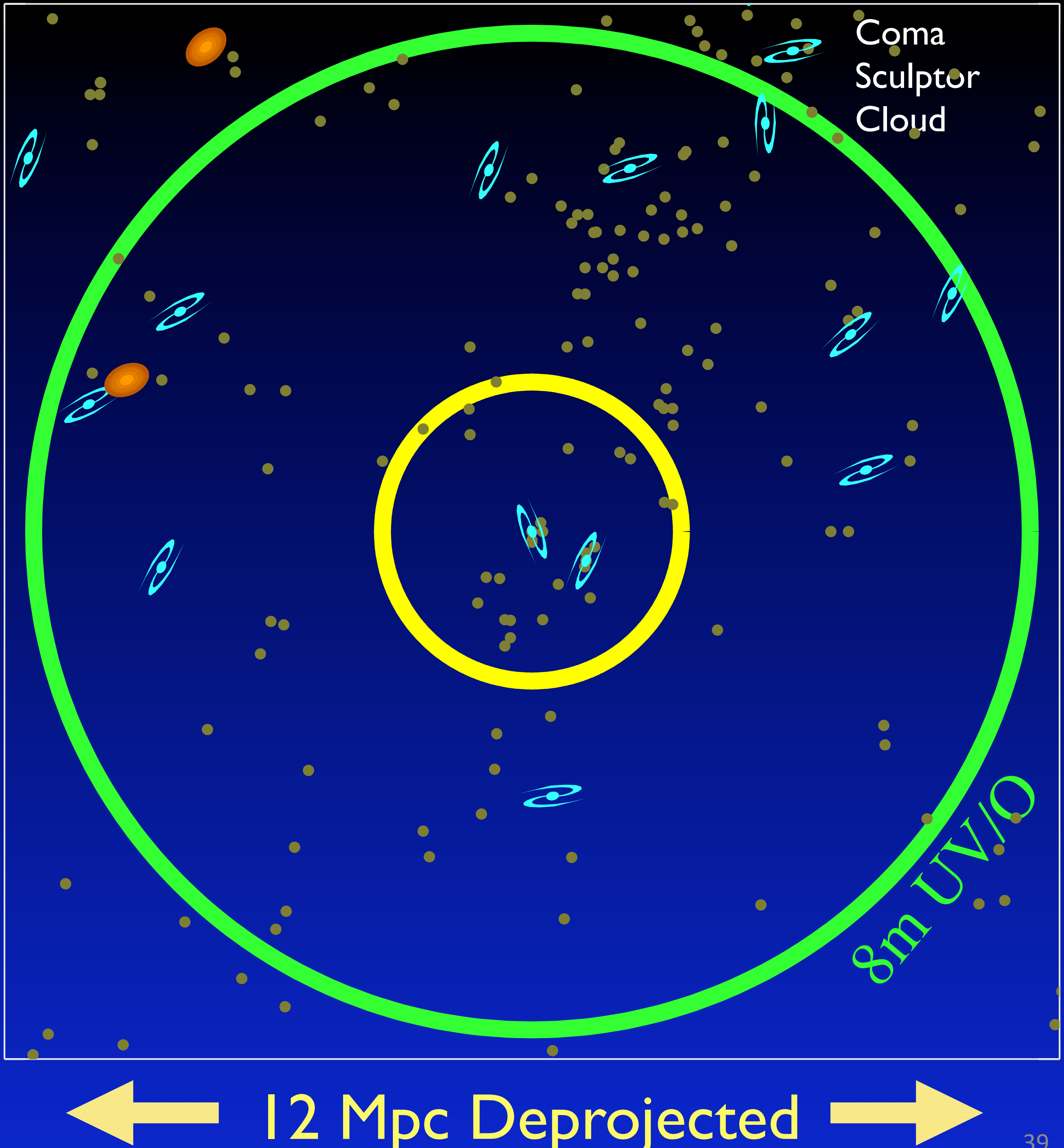
In 100 hours of observations split between two wide bands, HST can measure star formation histories in the outskirts of Local Group galaxies



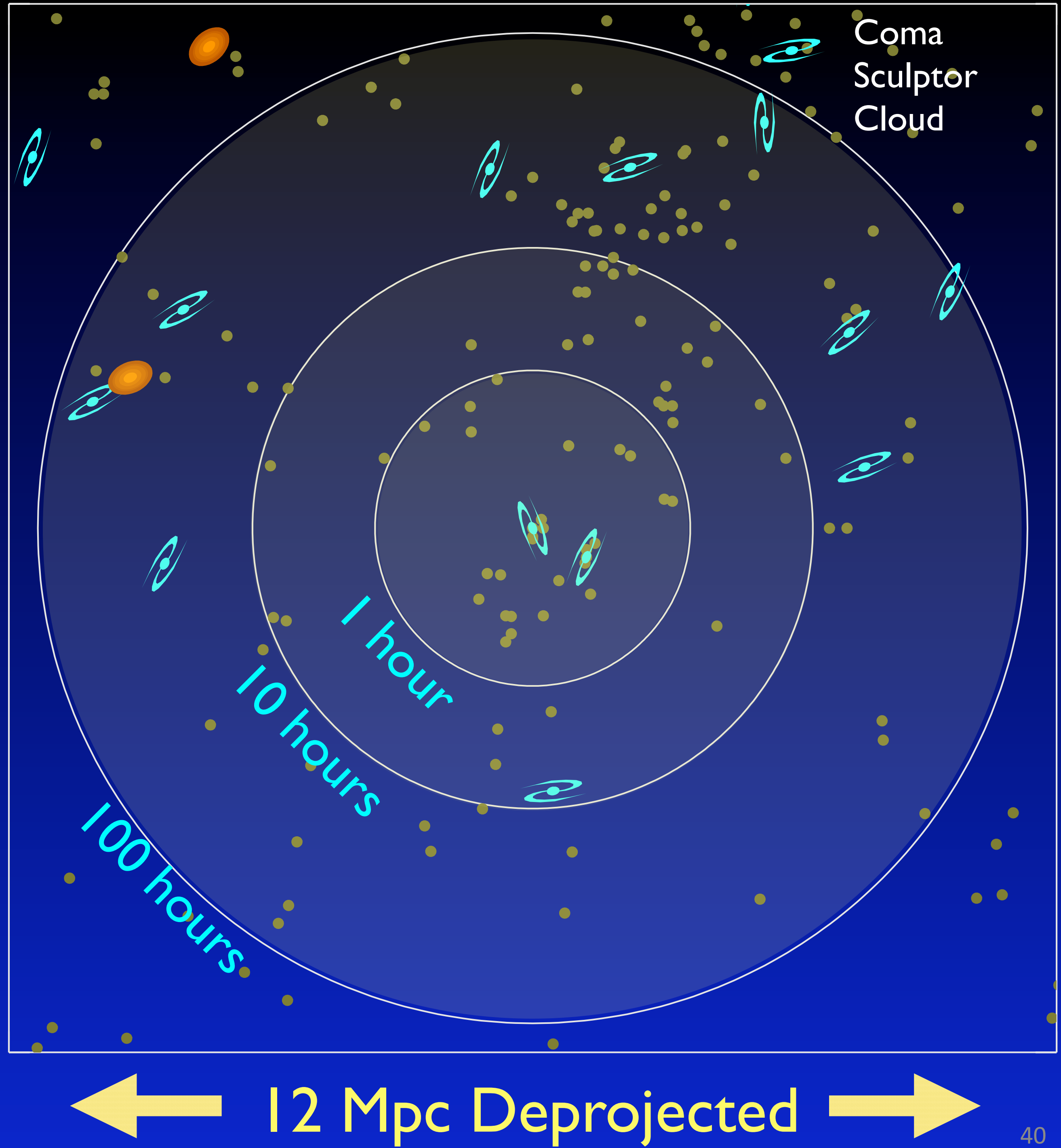
Large UV/Optical space telescopes begin making enormous gains

An 8m telescope could measure star formation histories in:

- 100s of dwarfs
- dozen giant spirals
- giant elliptical



An 8 meter UV/Optical space telescope could very quickly explore many sightlines through nearby galaxies, and probe more crowded regions in these galaxies



Need for space platforms

- Much of this work requires
  - ✦ stable high-precision photometry & astrometry
  - ✦ diffraction limited at 500 nm
  - ✦ tens of thousands of stars per pointing
  - ✦ crowded fields several arcmin across
  - ✦ low sky backgrounds (V ~ 22.3 mag/arcsec^2)
  - ✦ dynamic range: $5 > M_v > -2$ mag ($33.8 > V > 26.8$ mag for 8m case)
  - ✦ access to the optical & UV (Johnson U B V I)
- Ground telescopes can provide high-resolution imaging, but not with the contrast & stability over wide fields achieved from space, not yet in the optical, and never in the UV
- Large ground telescopes (e.g., TMT) will not be competitive with large space telescope for photometry of faint stars, but will provide synergistic spectroscopy of brightest stars (much like HST & Keck synergy today)

Summary

- Much of the work on local stellar populations is limited to small samples due to prohibitively expensive observations
- An 8m UV/O telescope makes enormous gains:
  - ~120x faster observations in HST-sampled volume
  - ~35x larger volume sampled in a given time
  - Star formation histories throughout the Local Group and reaching into the Coma Sculptor Cloud
  - Star formation histories in a galaxy sample that is representative of all galaxy classes in the universe

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Space-Based UV/Optical Wide-Field Imaging and Spectroscopy:

Near-Field Cosmology and Galaxy Evolution Using Globular Clusters in Nearby Galaxies

Paul Goudfrooij (STScI)

with

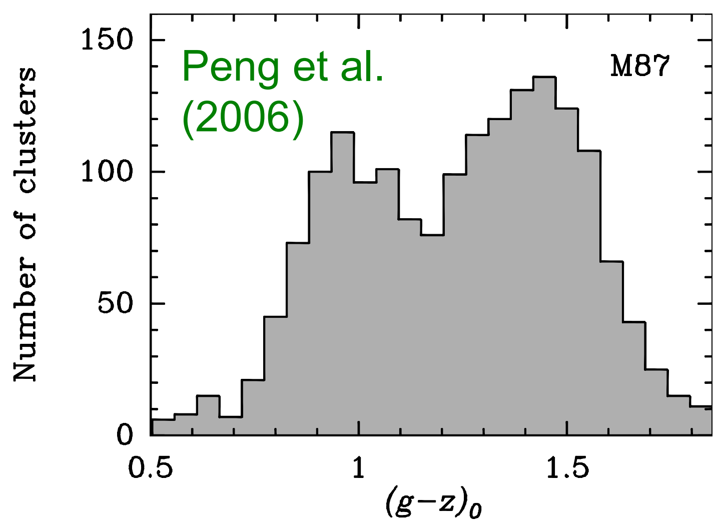
J. P. Brodie (UCSC), R. Chandar (U. Toledo), O. Y. Gnedin (U. Michigan), K. L. Rhode & E. Vesperini (Indiana U.), F. Schweizer (Carnegie Obs.), J. Strader & S. E. Zepf (Michigan State U.), & B. C. Whitmore (STScI)

Globular Clusters (GCs) in Nearby Galaxies - Science Context

- ***Stars are Formed in Star Clusters***
  - Majority of star clusters disrupt relatively soon after formation, building up field star population
  - The most massive clusters (i.e., GCs) survive for Hubble time; luminous enough to observe out to ~10^2 Mpc (right now)
  - GCs constitute excellent examples of Simple Stellar Populations (as opposed to diffuse galaxy light), thus providing unique fossil record of star formation era
  - Need to build coherent picture of star cluster formation, assembly, and evolution to understand galaxy building

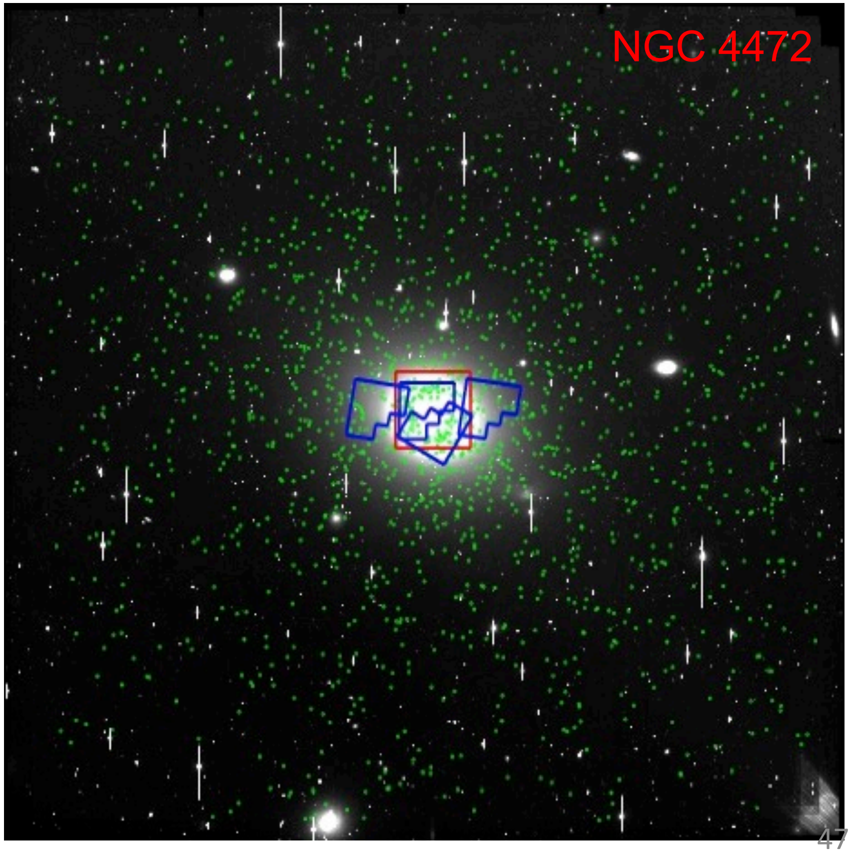
Space-based Imaging (HST) Revolutionized Extragalactic Globular Cluster Science

- **Size of GCs (2-3 pc) marginally sampled by diffraction-limited optical imaging of 2.4-m telescope**
  - Allows robust measurements of GC radii and hence their dynamical status (i.e., half-mass density, mass loss rate)
  - Allows high S/N even in bright inner regions of galaxies
- **Episodic History of Star Formation in Early-Type Galaxies**
  - Bimodal optical color distribution (e.g., Whitmore+95; Peng+06; Goudfrooij+07)
  - Mainly due to metallicity
  - Blue GCs show extended distribution ("halo"?), red GCs follow "bulge"
  - Number of red GCs in HST FOV $\propto L_{gal}$



Remaining Burning Questions in Extragalactic Globular Cluster Science

- ***Probe Halos of Massive [Early-Type] Galaxies***
  - HST covered very small fraction of GC candidates
  - Wide FOV required to determine "total" properties of GC systems, trends with galactocentric radius
  - Outer halos thought to hold unique clues Re: early assembly history
  - GCs unique probes in halo



KPNO 4-m+MOSAIC
36' x 36'; Zepf 2005

Remaining Burning Questions in Extragalactic Globular Cluster Science

- **Assembly _History_ of Massive (Early-Type) Galaxies**
  - Optical colors alone do not significantly constrain GC ages
    - Age-Metallicity Degeneracy
  - Need addition of:
    - Wide-Field Near-IR Imaging from Space
      - Near-IR colors only sensitive to metallicity
      - Can catch hundreds of GCs per image
      - **Ground-based GC imaging in Near-IR limited to brightest ~dozen of GCs at sufficient S/N** (e.g., Puzia+02; Chies-Santos+11; Georgiev+12)
    - Optical Multi-Object Medium-Dispersion Spectroscopy from Space
      - Currently infeasible (2.4-m/HST is too small)
      - Yield metallicities and star formation timescales (from [α/Fe] ratios)
      - **Ground-based GC spectroscopy limited to outer regions of galaxies** (e.g., Cohen+03; Puzia+04; Cenarro+07)

Globular Clusters in Nearby Galaxies: Science Requirements for Future Space Facilities

Requirement	Wide-Field Imaging	Multi-Object Spectroscopy
Field of View (Optical)	1000 $arcmin^2$ (desired) / 200 $arcmin^2$ (required)	500 $arcmin^2$ (desired) / 100 $arcmin^2$ (required)
(near-IR)	700 / 200 $arcmin^2$	N/A
Angular Resolution (optical)	0.05 / 0.15 arcsec	0.10 / 0.20 arcsec
(near-IR)	0.10 / 0.40 arcsec	N/A
Spectral Resolution (optical)	N/A	R = 3000 / 1000
Wavelength Coverage (optical)	>= 200 / >= 550 nm	>= 150 / >= 400 nm
(near-IR)	<= 5 μm / <= 2 μm	N/A
Sensitivity (optical)	S/N = 20 for V = 26.5 (26.0) at μ_V = 20 mag/ $arcsec^2$ in 1 hour (~ HST)	S/N = 30 for V = 22.5 at μ_V = 20 mag/$arcsec^2$ in 10 (20) hours (8-m tel. can do it)
(near-IR)		N/A
Multiplicity	N/A	~100 / 30 targets per config

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Ben Williams

The Crucial Role of High Spatial Resolution, High Sensitivity UV Observations to Galaxy Evolution Studies

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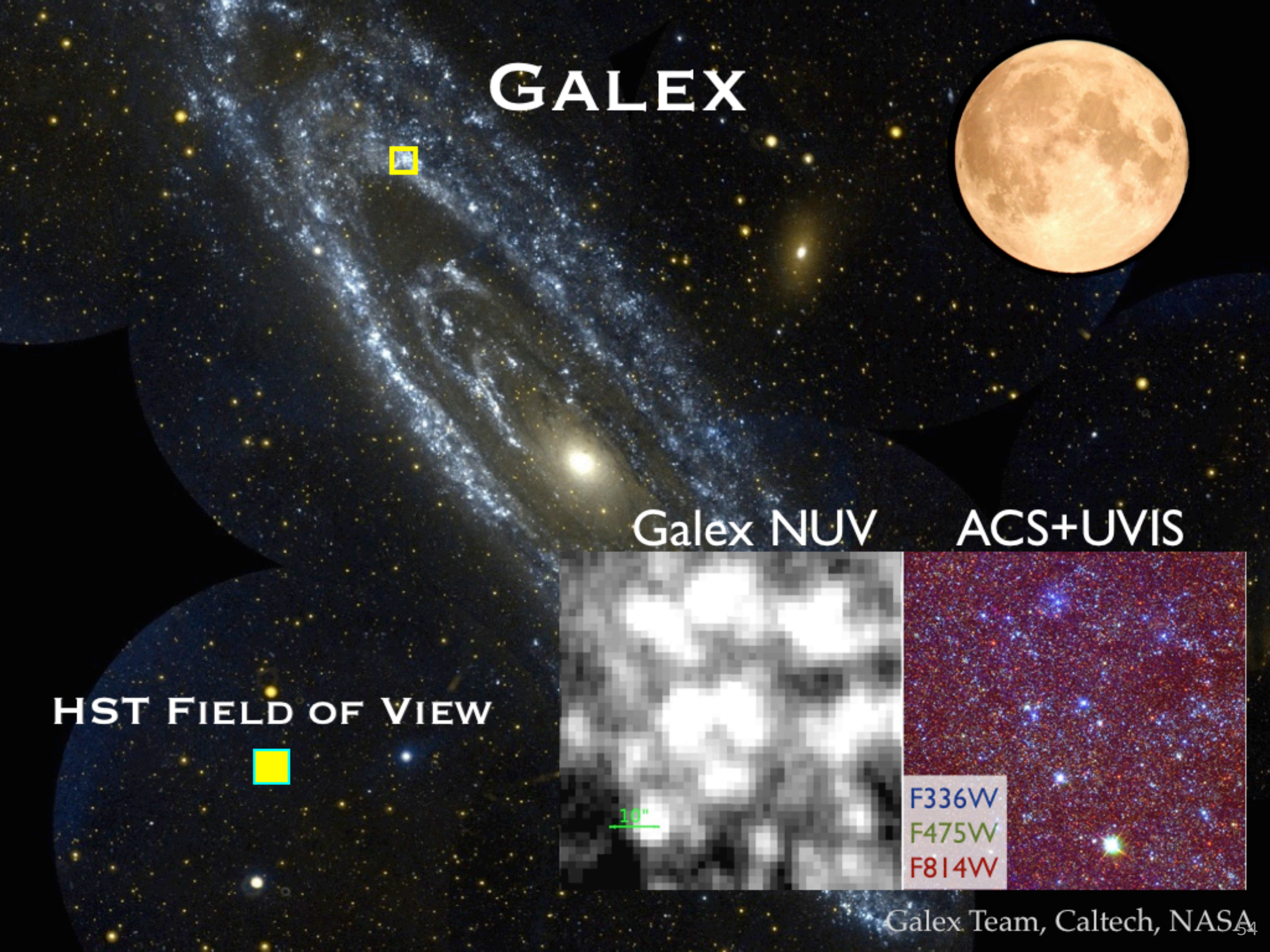
How did the diverse array of galaxies in the present epoch come to be?

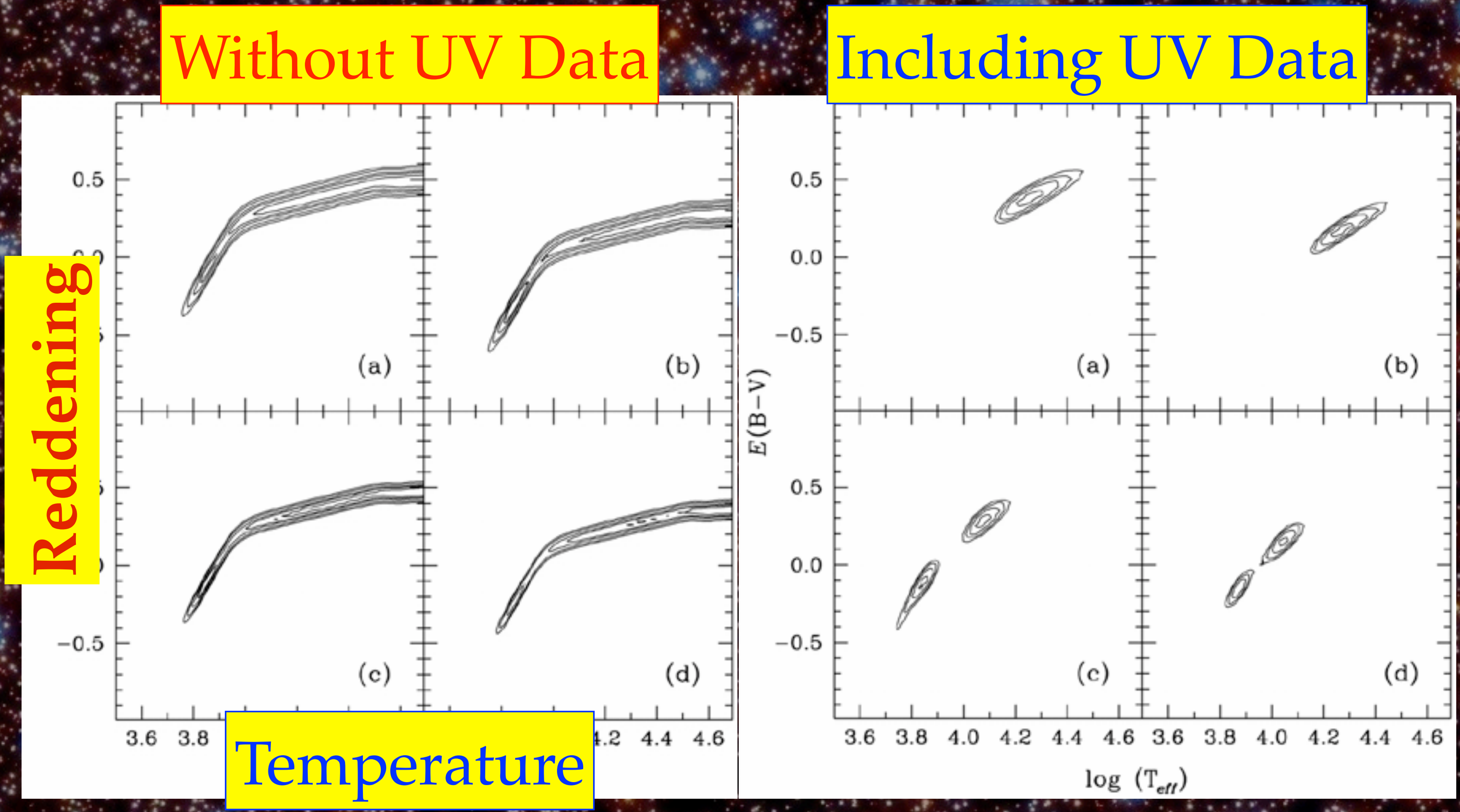
- How does star formation proceed in different environments?
- What role has the formation of stars played in the evolution of galaxies?
- How can we test our understanding of the fundamental physics that control galaxy formation in the universe?

State of the Field

- Large HST programs and ground-based surveys to find and measuring star formation in distant galaxies.
  - We can resolve individual (and measure temperature, radii, masses for) UV-bright stars only in the Local Group.
  - Current models have difficulty agreeing with observations of resolved populations in the UV (e.g., Johnson et al. 2013)
  - Dust corrections are complex and cause degeneracies in the optical. UV data are crucial (e.g., Bianchi et al. 2012)
  - Old populations also have UV-bright stars and UV observations are sensitive to their detailed age and composition (e.g., Milone et al. 2012)
  - Interpretation of integrated light requires reliable models of stellar atmospheres and evolution, as well as star formation in the rest-frame UV.


GALEX
HST FIELD OF VIEW
Galex NUV
ACS+UVIS
10"
F336W
F475W
F814W
Galex Team, Caltech, NASA

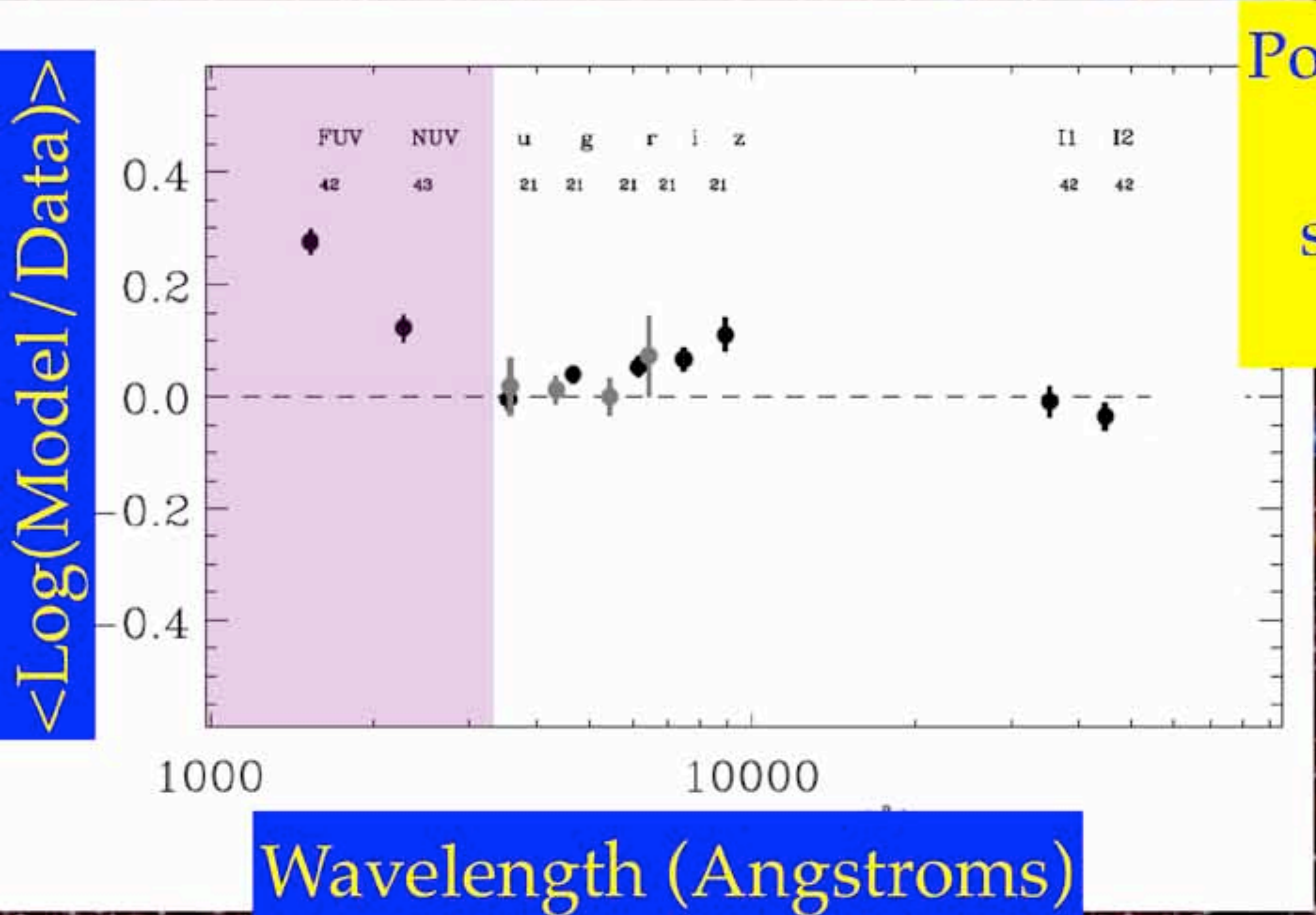
Breaking Degeneracies
SED Fitting



With UV: hot stars single valued

Romaniello et al. 2002

Limitations of UV Models



Population Synthesis models SED systematically off UV data

Mean and deviations of >40 low-mass galaxies

UV evolution at low metallicities not well-constrained

B. Johnson et al. in prep

Need to Study *Individual Stars* in Detail to Produce Reliable Models

- Massive stars that produce most of the UV emission are rare (wide FOV needed).
- They live in dense environments (high resolution needed).
- They live in dusty environments (UV sensitivity crucial)

B
V
Hα
I
Z

Orion-HST

Current Limitations

- UV stellar models are poorly constrained.
- High-mass initial mass function also poorly constrained.
- Interpretation of integrated light from distant galaxies depends strongly on these fundamentals.
- Small samples of resolved massive stars and resolved globular clusters in the UV (WFPC2 and WFC3 studies).
- Cannot resolve the star forming regions outside of the Local Group (spatial resolution).
- No good analogs for high-z galaxies in current samples.

Next Steps

- Obtain larger samples of many resolved star forming in wide range of galaxy types.
  - Measure high-mass initial mass function.
  - Constrain UV models for different metallicities, star formation rates, etc.
- Resolve dense, old populations
  - Account for old stars to integrated UV flux.
  - Reliable late-stage stellar evolution models.
- Learn detailed formation histories for stellar populations in many galaxies and clusters.

Science Requirements

- Every improvement over HST imaging helps us.
- Field of View: 30 arcmin; makes covering large numbers of star forming regions very efficient.
- Spatial Resolution: (0.007"); M82 and NGC253 at the current resolution of M31.
- Wavelength: 1100-6000 angstroms; gives best sensitivity for high-temperature stars, and gets blueward of extinction bump.

RFI Response Summaries

7 Rapid Science Summaries

Topic: Star Formation / Nearby Galaxies

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Open Discussion