Star Clusters as Astrophysical Clocks
Building an Age Ladder for Robust Cluster Ages

Janice C. Lee
STScI & Laboratorie Lagrange, U.
Cote de Azur

NASA COPAG @AAS
Jan 3 202 SIX!

The utility of star clusters

Star clusters

- Trace the densest peaks of the star formation hierarchy
- Bright and observable to large distances*
- Cosmic clocks - (effectively) single-age populations

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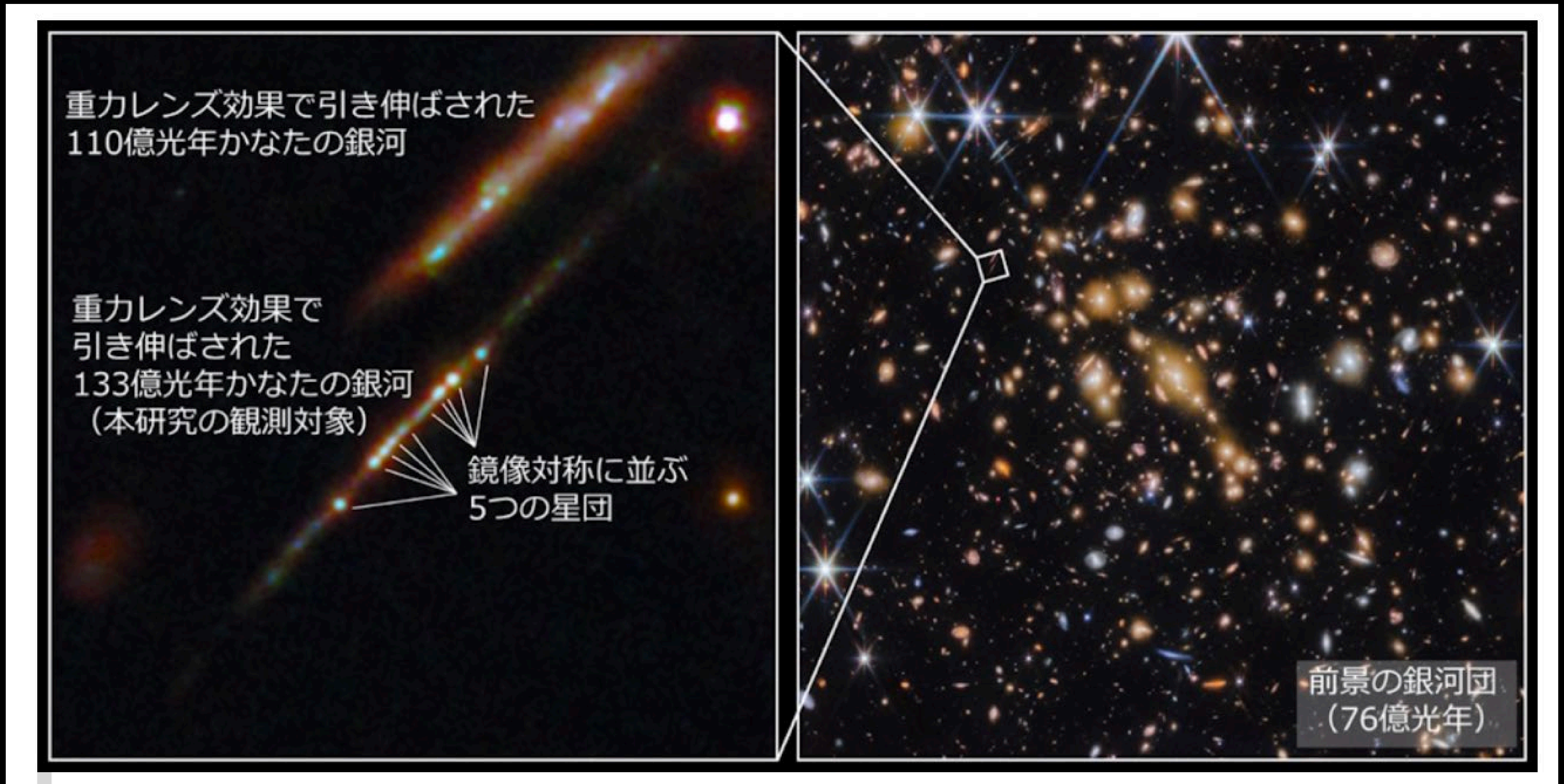
** to z~10 with lensing! "Cosmic Gems"*
(Adamo+24; Mayer+25)



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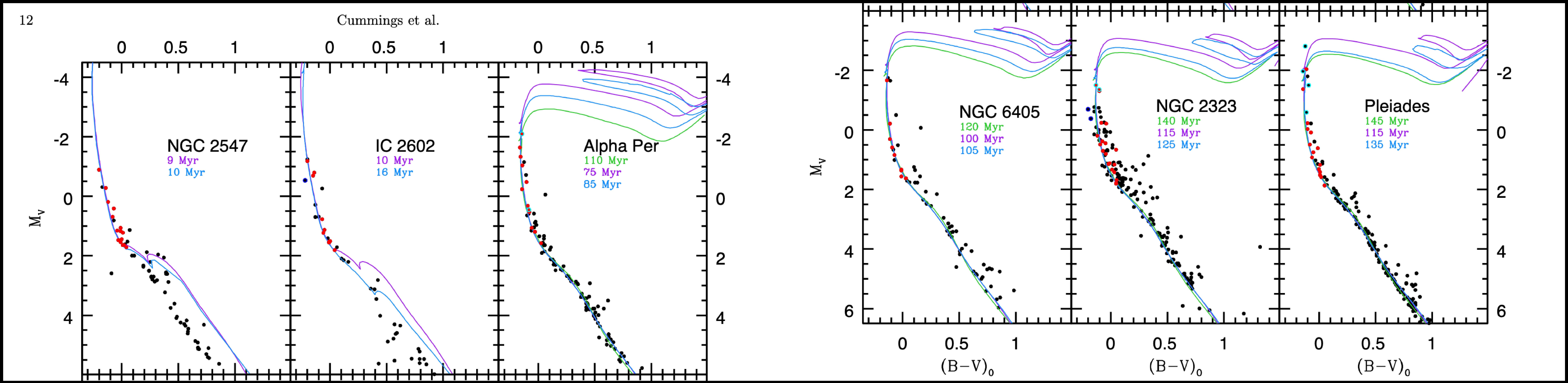


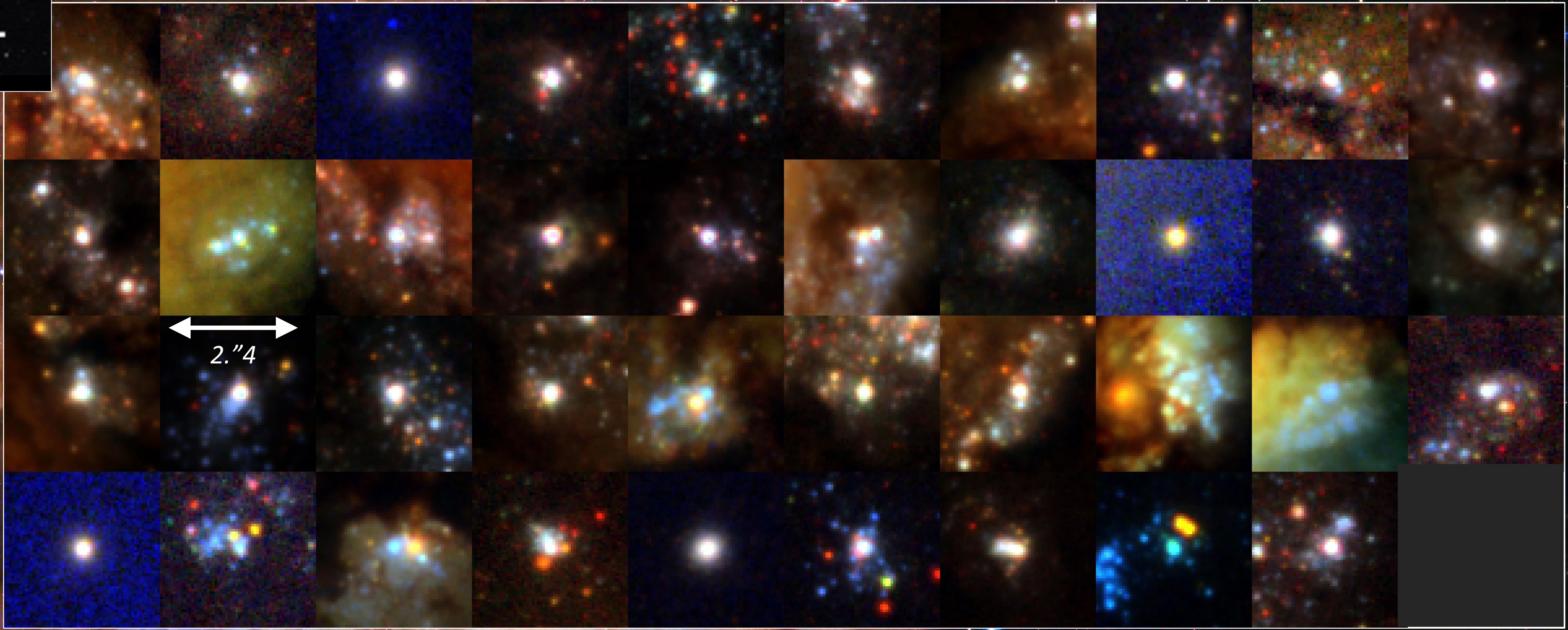
Isochrone fitting of MW open clusters
Cummings+18

Hubble imaging of a MW star cluster 6000 pc away

Hubble 25th Anniversary Image - NASA, ESA, Hubble Heritage Team (STScI/AURA), A. Nota (ESA/STScI), Westerlund 2 Science Team

Beyond Local Group: Hubble resolution required to identify star clusters in nearby galaxies

HST



Brightest star cluster in each of the 38 PHANGS galaxies (5-23 Mpc).

Postage stamps span 50-270 pc.

JCL+22, Maschmann, JCL+24, Thilker, JCL+25

NGC 1087 PHANGS
JWST & HST

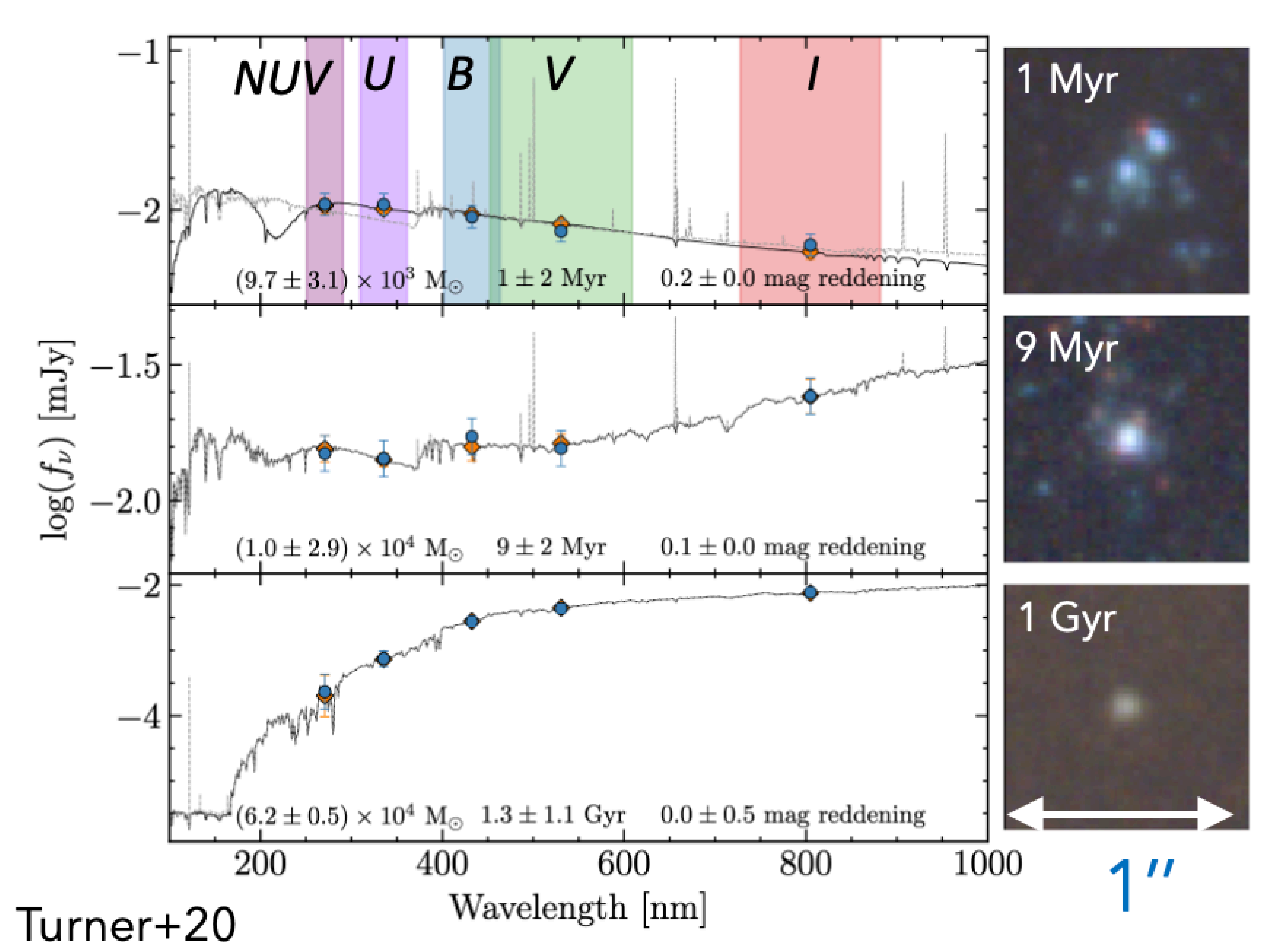
PHANGS HST & JWST Stellar Pops Group

Janice Lee (STScI, PI)
Brad Whitmore (STScI)
David Thilker (JHU)
Rupali Chandar (U Toledo)
Daniel Dale (U Wyoming)
Aida Nava Wofford (U Ensenada)
Mederic Boquien (U Côte d'Azur)
Kirsten Larson (STScI)
Remy Indebetouw (Uva/NRAO)
Gagandeep Anand (STScI)
+Leonardo Ubeda (STScI)
+Oleg Gnedin (U Michigan)

Postdocs, *Grads*, *Interns*
M. Jimena Rodriguez (STScI)
Sumit Sarbadhicary (JHU)
Daniel Maschmann (U Wyoming)
Matthew Floyd (U Toledo)
Kiana Henny (U Wyoming)
Stephen Hannon (MPIA)
Sinan Deger (Cambridge)
Qiushi Chris Tian, Sophia Rivera (JHU)

Star Clusters as Clocks

SED fitting of 5-band UV-optical integrated photometry for cluster age, mass, dust reddening



Ages, M*, E(B-V) SED fits - CIGALE (Boquien+19)

Clusters as Clocks
HII region morphologies – cluster age distributions

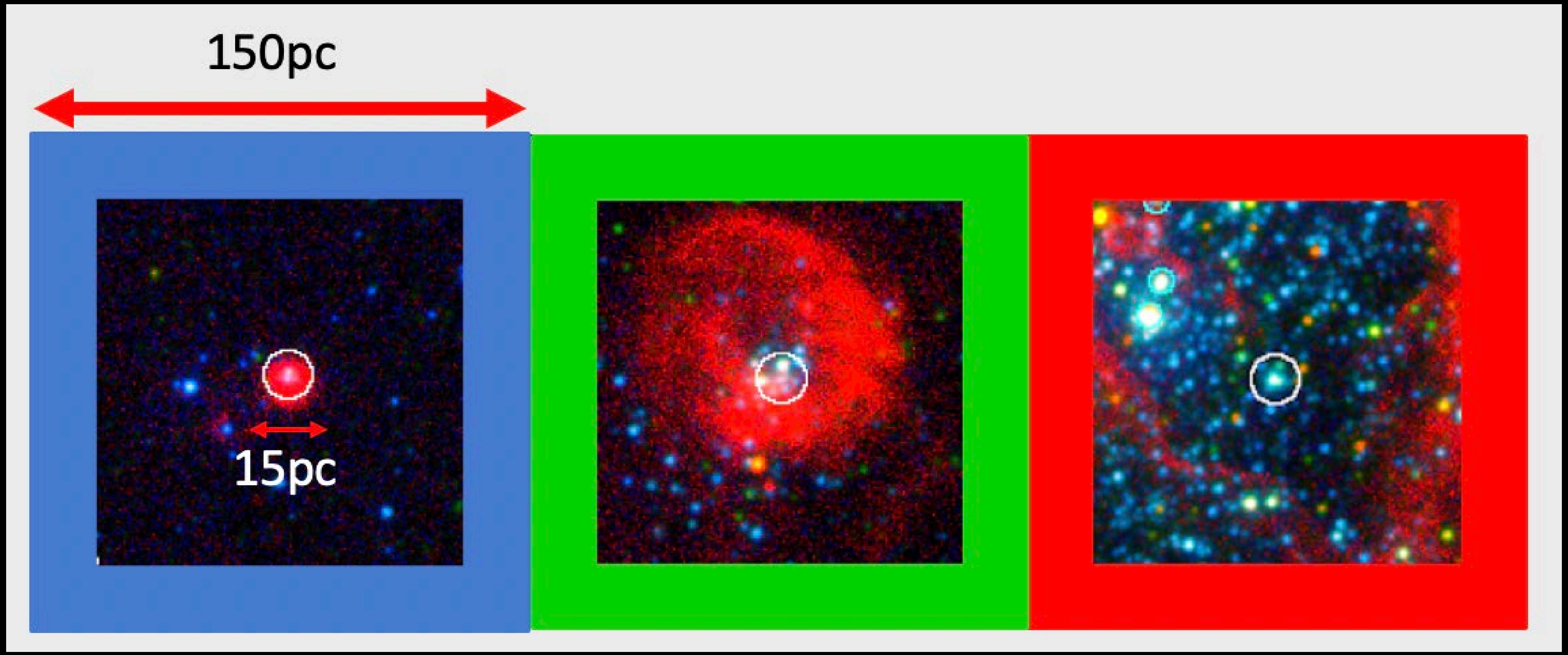
Results from 4000 visible star clusters in 16 galaxies with LEGUS (Calzetti, JCL+15) HST Halpha imaging

(Hannon, JCL+19, 22)

Also Whitmore+11, Hollyhead+15 for M83

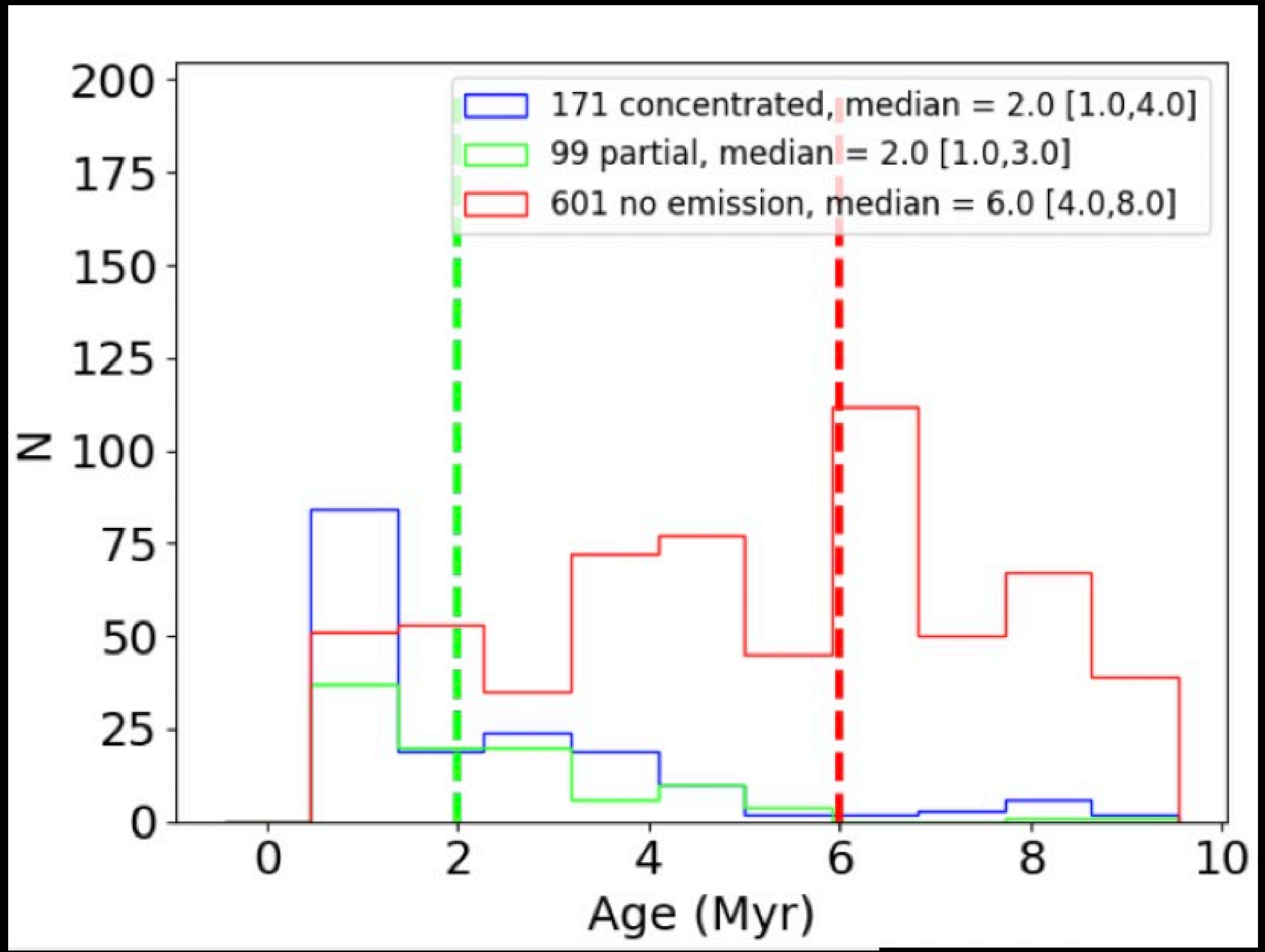
Partially exposed HII regions have clusters with median age of 2-3 Myr.

→ ISM clearing must begin before SNe



Concentrated Partially Exposed Exposed

Age distributions of parent star clusters



Clusters as Clocks
GMC-Cluster Correlation Analysis

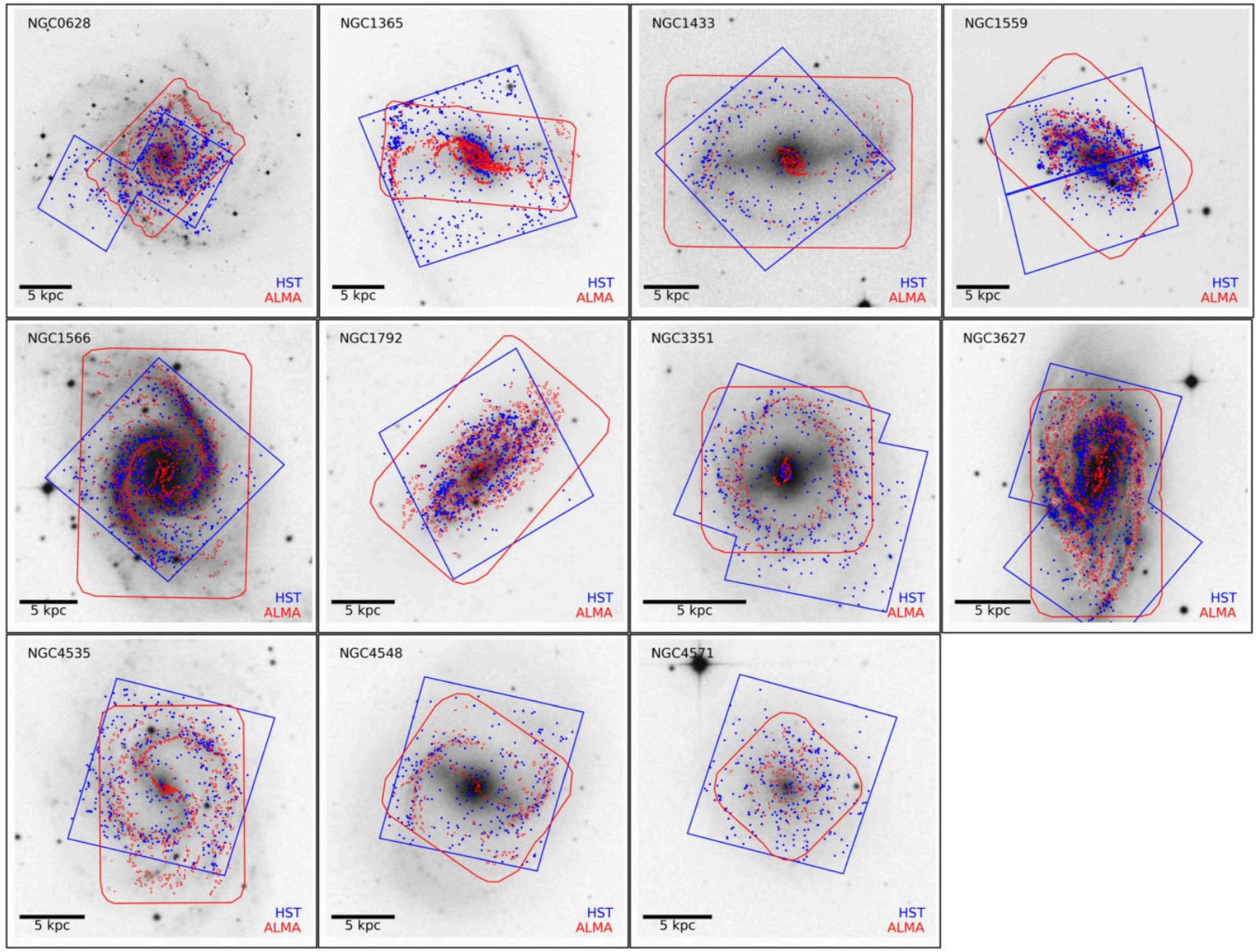


Figure 1. The PHANGS–ALMA footprints and the size and location of GMCs are shown in red. PHANGS–*HST* F336W observation footprints and the location of Classes 1, 2, and 3 star clusters are shown in blue. Background images are from the Digitized Sky Survey.

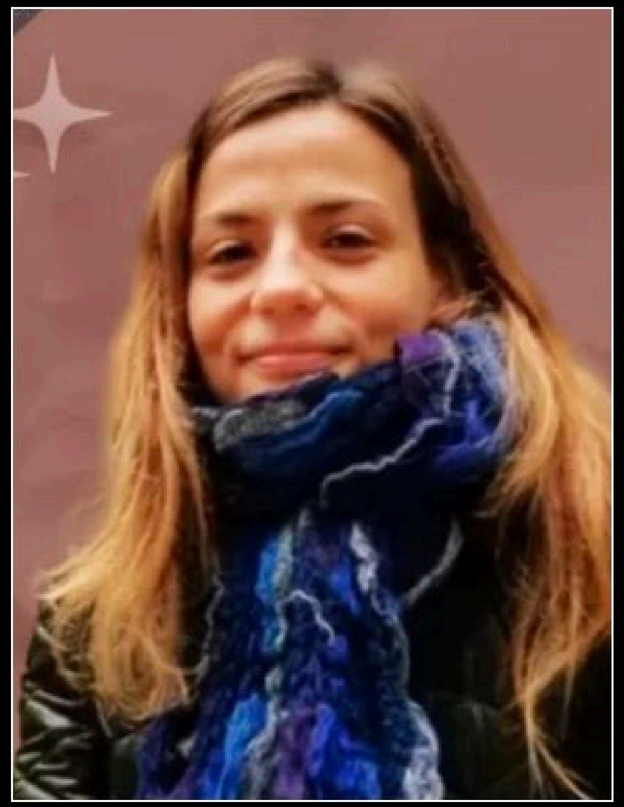
Median age of clusters:

- *within GMC radius ~1 Myr*
- *Between 2-3 radii 4-6 Myr*

11 PHANGS Galaxies: Turner+22 (also M51: Grasha+19 NGC7793: Grasha+18)

Clusters quickly lose association with GMCs (~6 Myr)

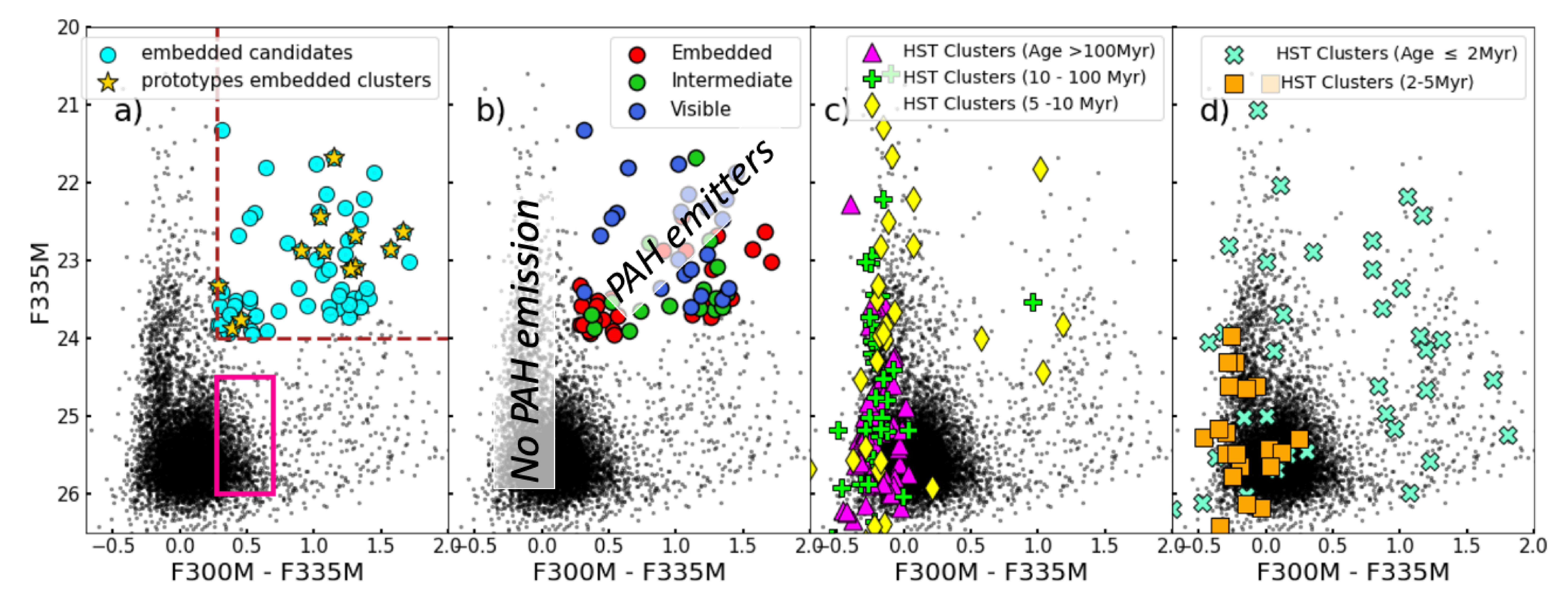
Clusters as Clocks
Embedded Clusters & Compact 3.3 um PAH emission timescales



MJ Rodriguez, JCL, Whitmore+23

MJ Rodriguez, JCL, Indebetouw+25

Compact 3.3 mircon PAH emission undetected in vast majority of Hubble optical clusters older than ~3 Myr



And many subsequent studies, incl.

NGC1365: Whitmore+23
NGC3256: Linden+24,
NG628: Pedrini+24, Whitmore+25
M83: Kuntas+25
….

Compact 3.3 um PAH emission is short-lived: ≲3 Myr

SL25: [The data] suggest a period of cloud collapse on the order of the free-fall or turbulent crossing time (~10–30 Myr) followed by forming massive stars and subsequent rapid (<5 Myr) gas clearing after the onset of star formation.

Meanwhile, the short gas-clearing timescales suggest a large role for presupernova feedback in cloud disruption.

Annual Review of Astronomy and Astrophysics

Molecular Gas and the Star-Formation Process on Cloud Scales in Nearby Galaxies

E. Schinnerer[1] and A.K. Leroy[2]

[1]Max Planck Institute for Astronomy, Heidelberg, Germany; email: schinner@mpia.de

[2]Department of Astronomy, The Ohio State University, Columbus, Ohio, USA; email: leroy.42@osu.edu

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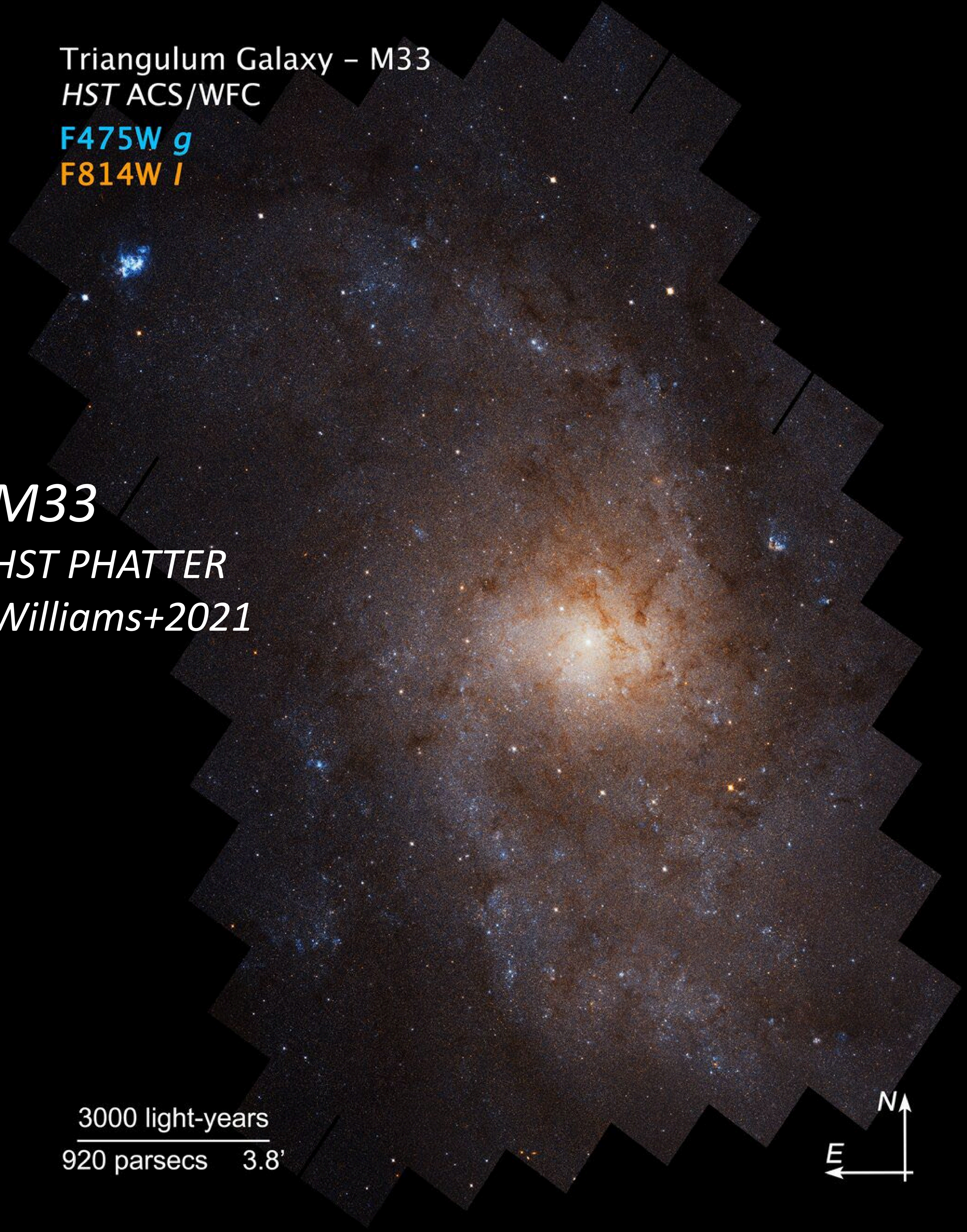
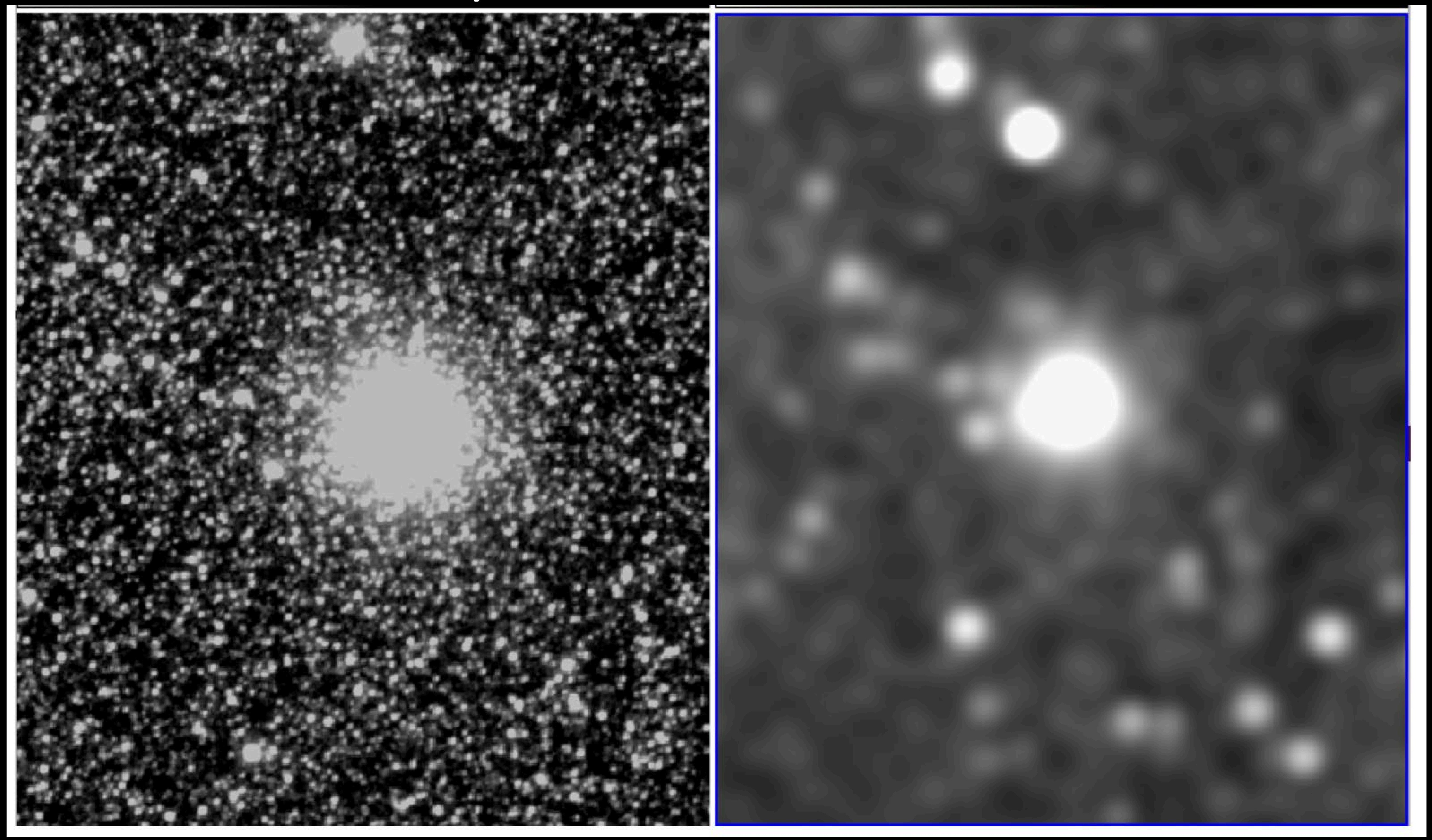
HOW GOOD IS AGE DATING OF UNRESOLVED CLUSTERS?



M33
HST PHATTER
Williams+2021

A cluster in M33
D~0.84 Mpc

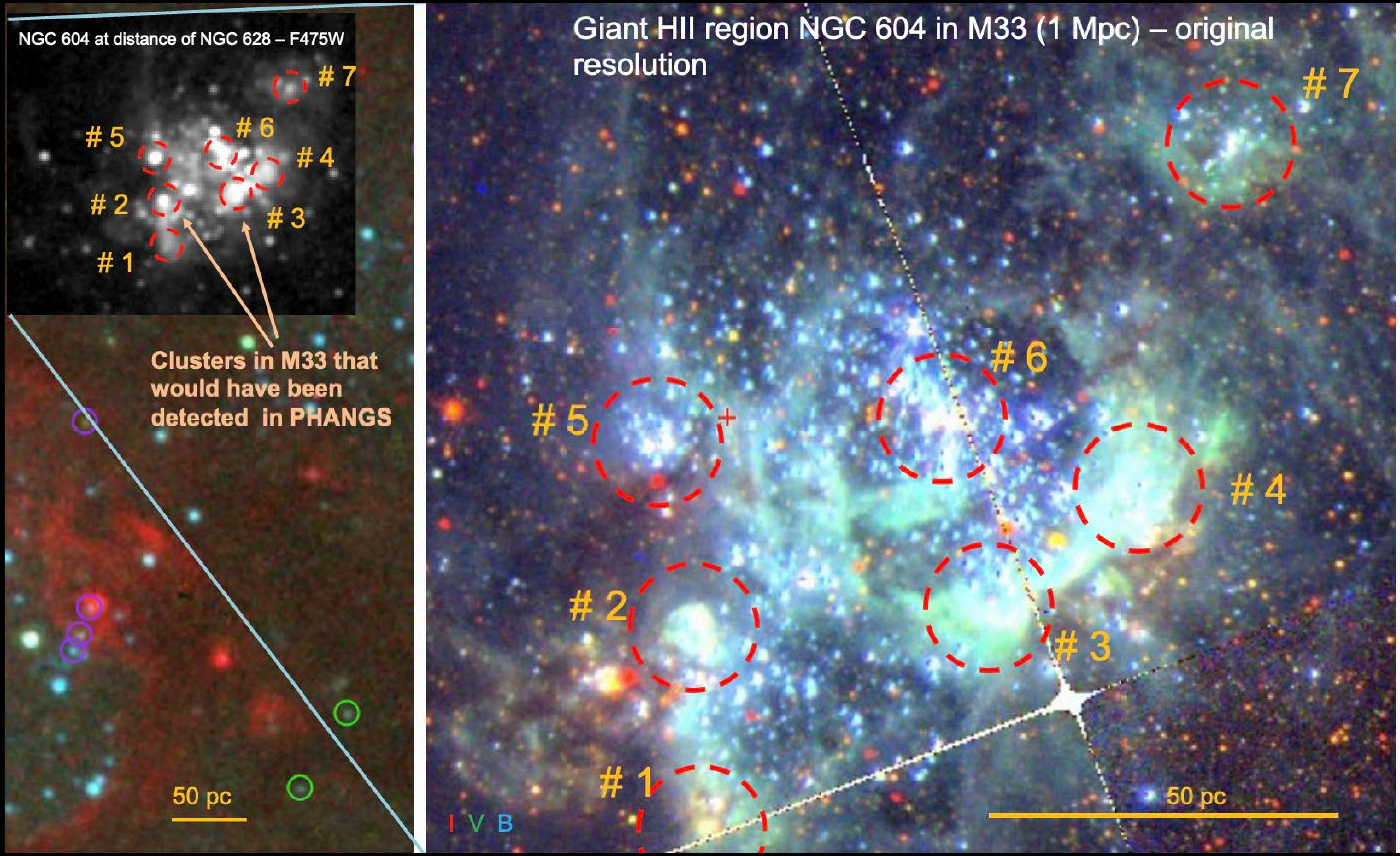
Convolved to 10 Mpc



Age Ladder I: Comparison of Isochrone and SED model ages for Clusters in M31+M33

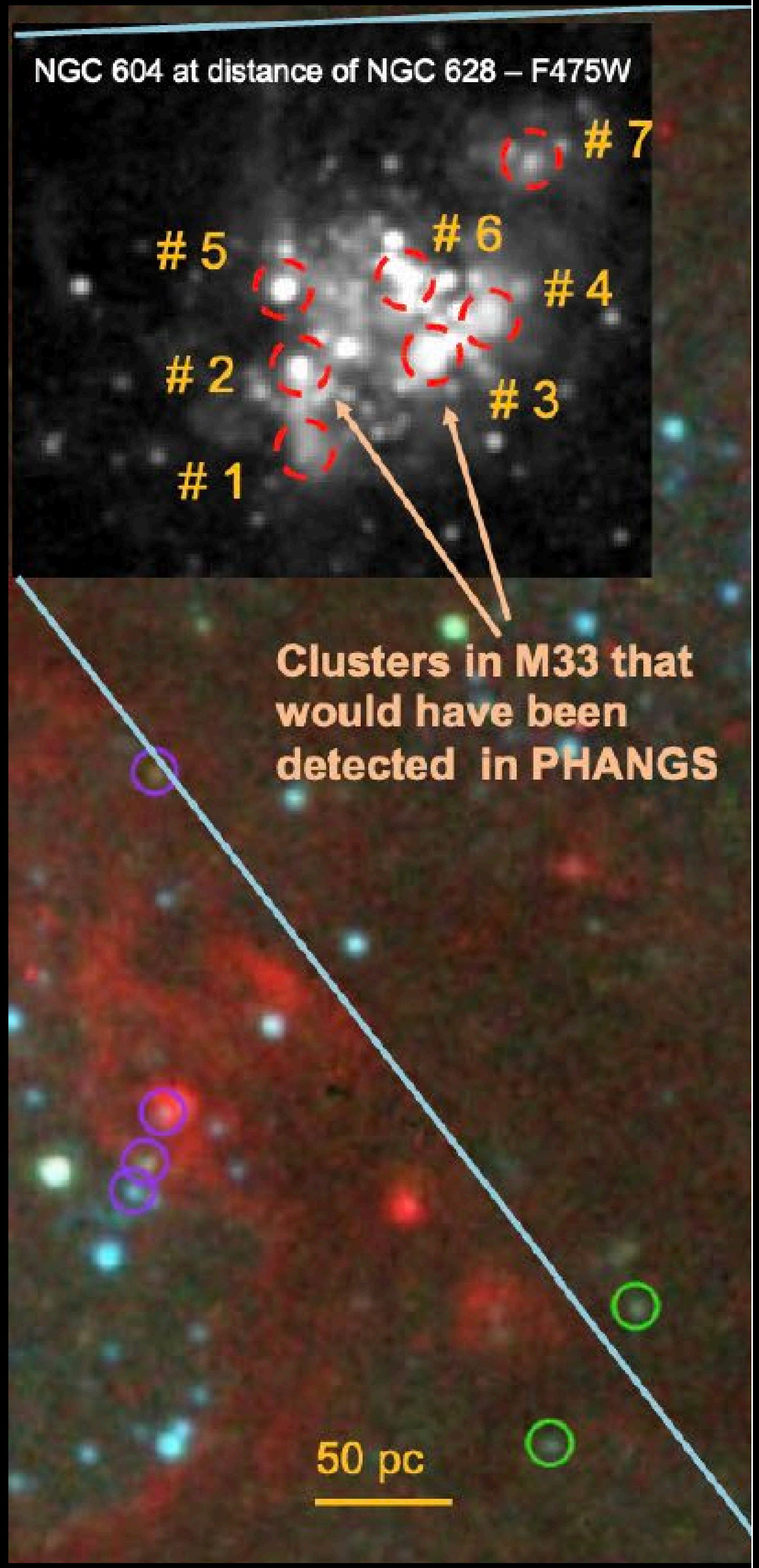
K. Henny (U. Wy)
PhD Thesis

Age Ladder II: Age dating of NGC 604 with multiple methods at native and 10 Mpc resolution



Age dating at 1 Mpc

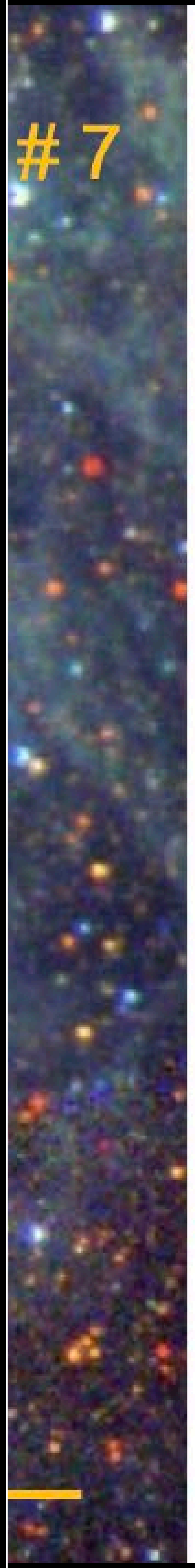
1. SED-fitting
2. Color-color diagrams
3. Halpha bubble sizes
4. Halpha + PAH EW
5. Expansion velocities
6. Surface brightness RMS
7. Red/Blue star fraction
8. **CMD of stars (MS turnoff)**
9. Spectra of individual stars
10. % of YSOs (~1 Myr)
11. % of O stars (~2 Myr)
12. % of Wolf-Rayet stars (~4 Myr)
13. % of Red Super Giants (~5 Myr)
14. % of X-ray stars (~? Myr)



Other ways of age dating (e.g., fitting of UV spectra for young clusters)?

How can we mobilize the community to build an age ladder for clusters?

- *Use multiple, local age-dating methods to calibrate cluster ages at larger distances*
- *Quantify random/systematic (model) uncertainties*



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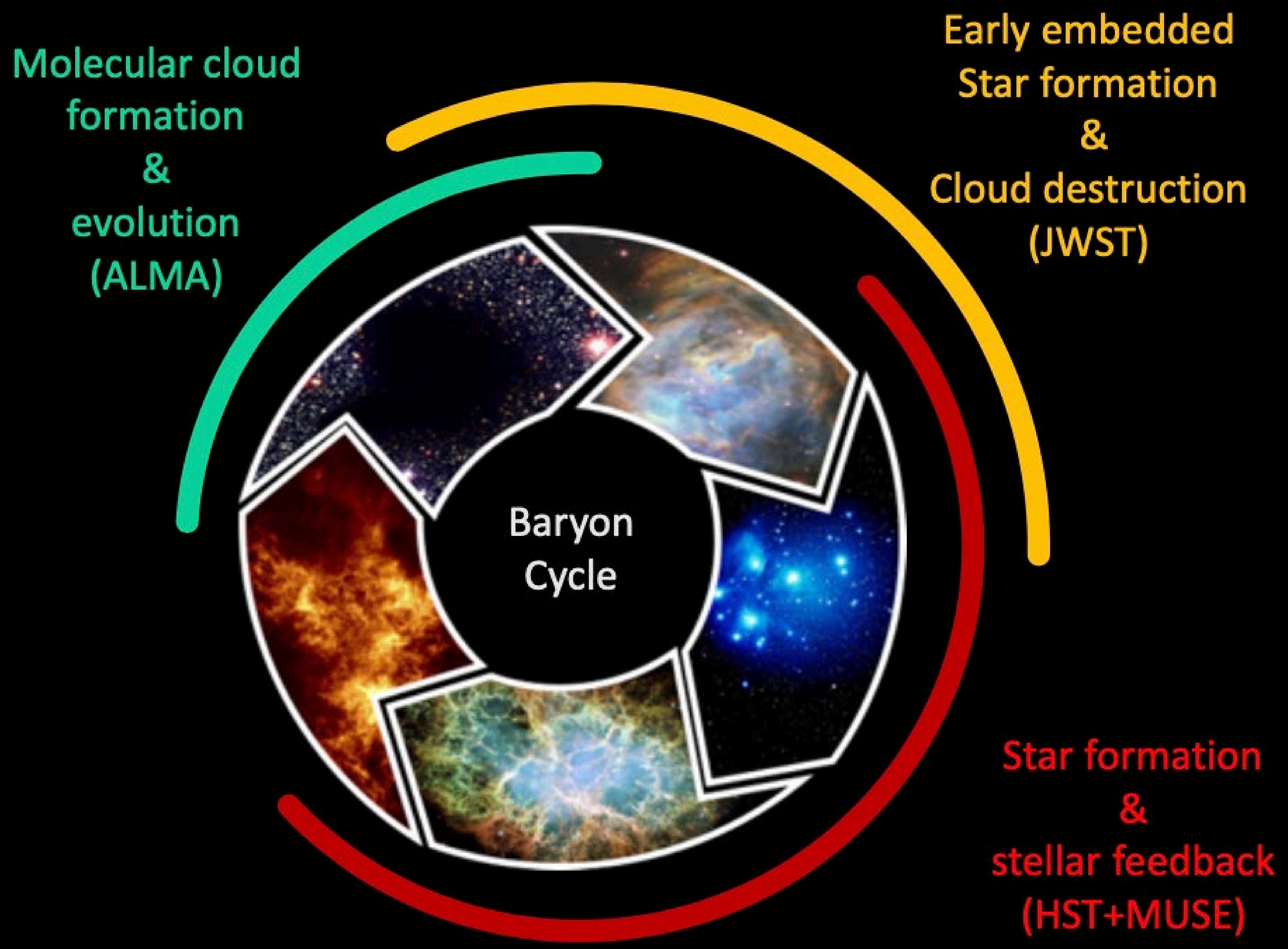
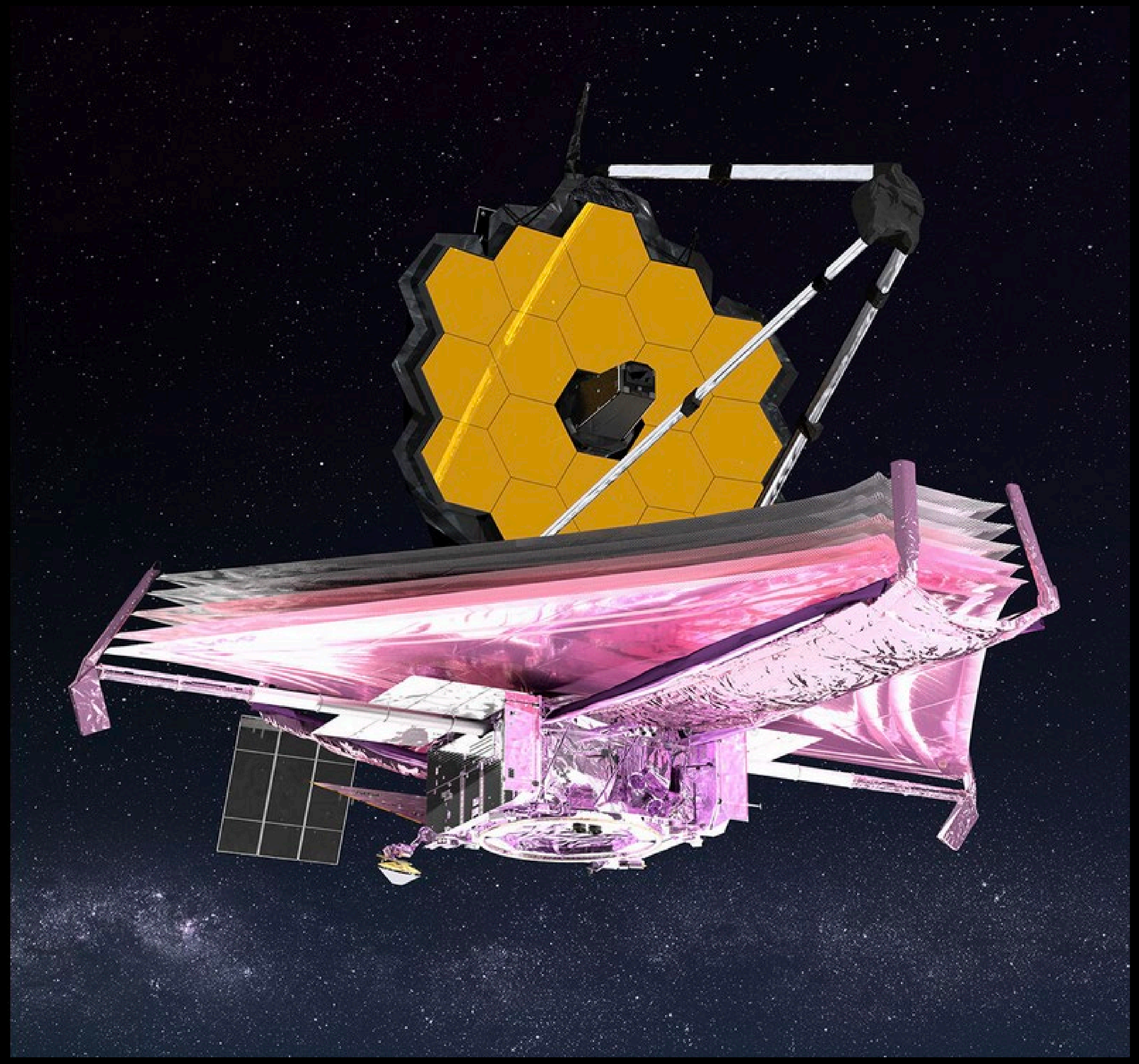
Phangs

Missing from census:
dust embedded stars and clusters → earliest stages of star formation



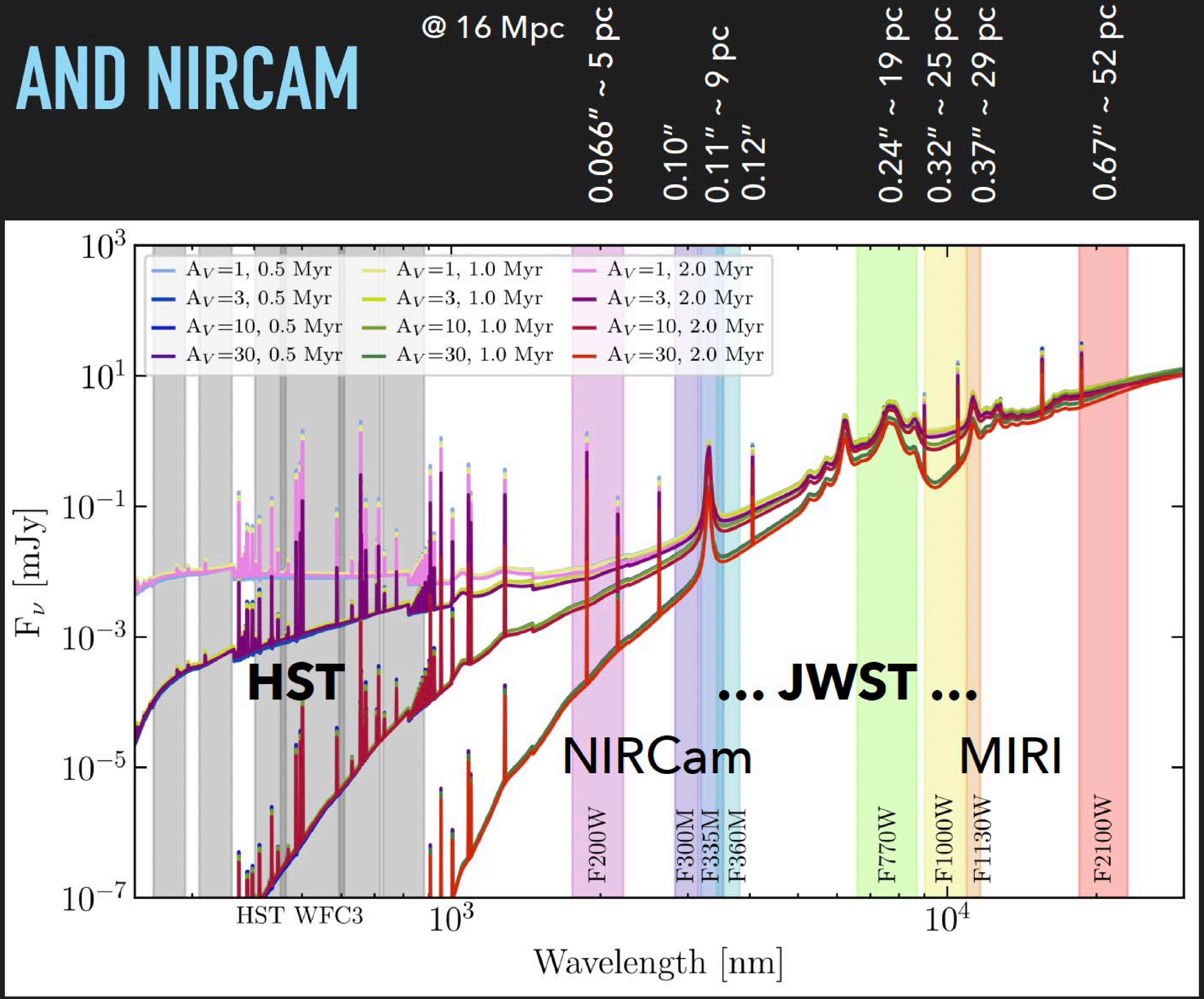


JWST Cy 1 Treasury

Co-PIs: JC Lee, K Larson, A Leroy, E Rosolowsky, K Sandstrom, E Schinnerer, D Thilker

JWST IMAGING IN 8 BANDS WITH MIRI AND NIRCAM

- F200W-F360W: Low obscuration views of photospheric emission (clusters, stars)
- F335M, F770W, F1130W: PAH emission, tracing a combination of size and charge
- F1000W, F2100W: Dust continuum em.
- F1000W: Silicate absorption
- S/N>10 for ~2×10^3 $M_\odot$ clusters with A_V<10
- S/N = 3 for 0.3 MJy/sr (diffuse/"M33 goal")



JC Lee+23

A color composite: PHANGS Hubble UV-optical images for the nearby spiral galaxy NGC 7496 (D=18.7 Mpc).

Typical spiral
SFR~SFR(MW)
Barred Sy2

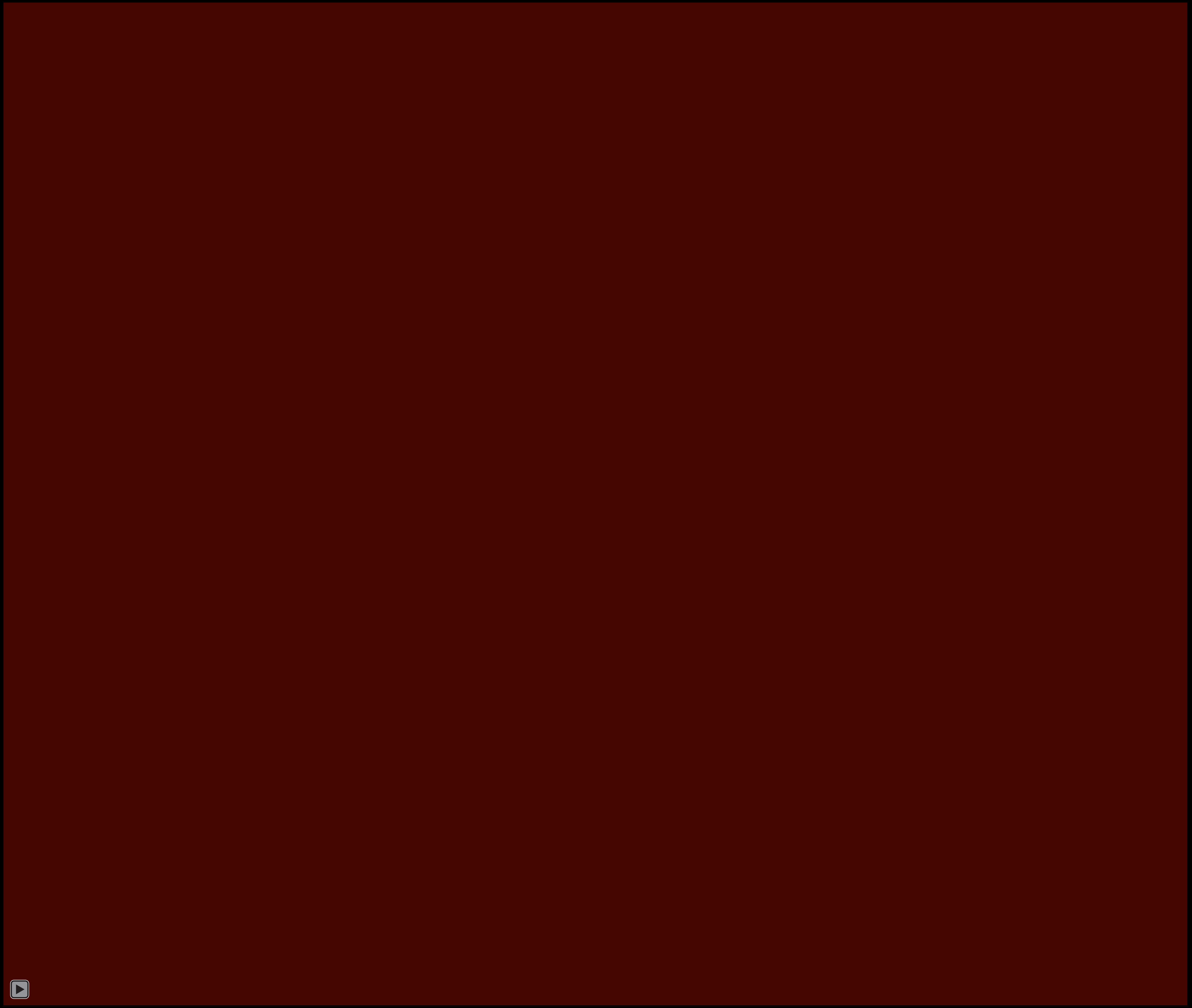
blue: young stellar clusters & assns
dark: dust

HST UV-optical (r:F814W/F555W/F438W; g:F336W; b:F275W) JWST MIRI (red hue: F1000W/F1130W/F2100W)
Image Credit: NASA / ESA / CSA / J. Schmidt

With JWST, dark dust lanes light up in emission, *revealing the earliest stages of star formation and impact of feedback.*

Complex network of filaments, bubbles, shells, compact sources in context of visible young stellar pops

compact IR sources -invisible embedded star cluster population



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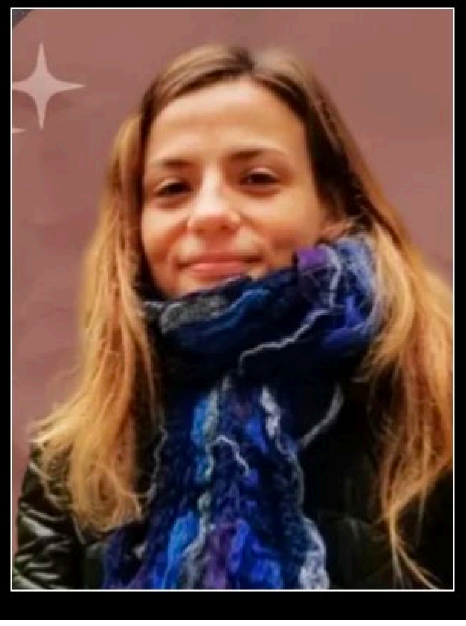
Clusters as Clocks
Embedded Clusters & Compact 3.3 um PAH emission timescales



MJ Rodriguez,
JCL,
Whitmore+23

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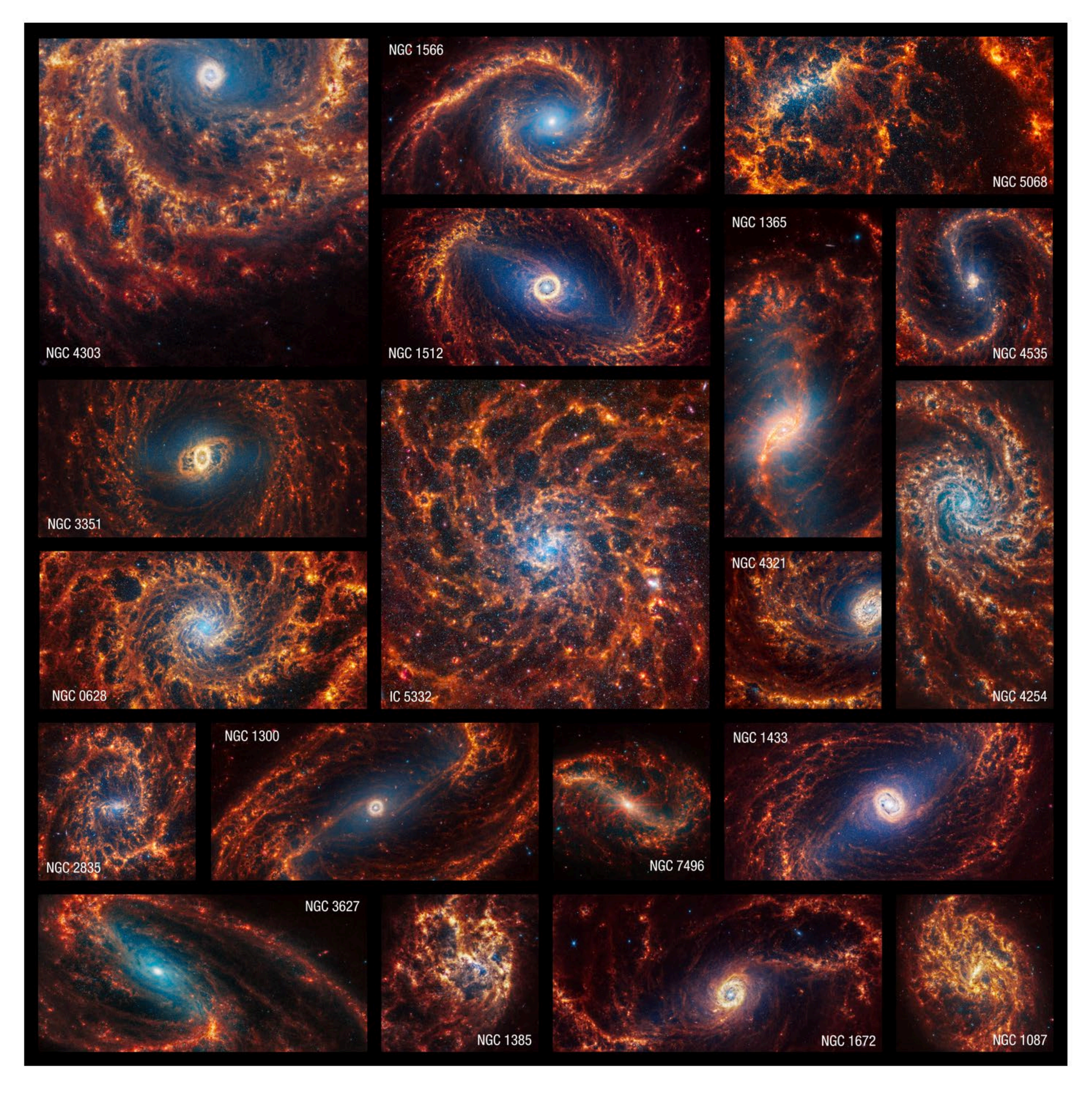
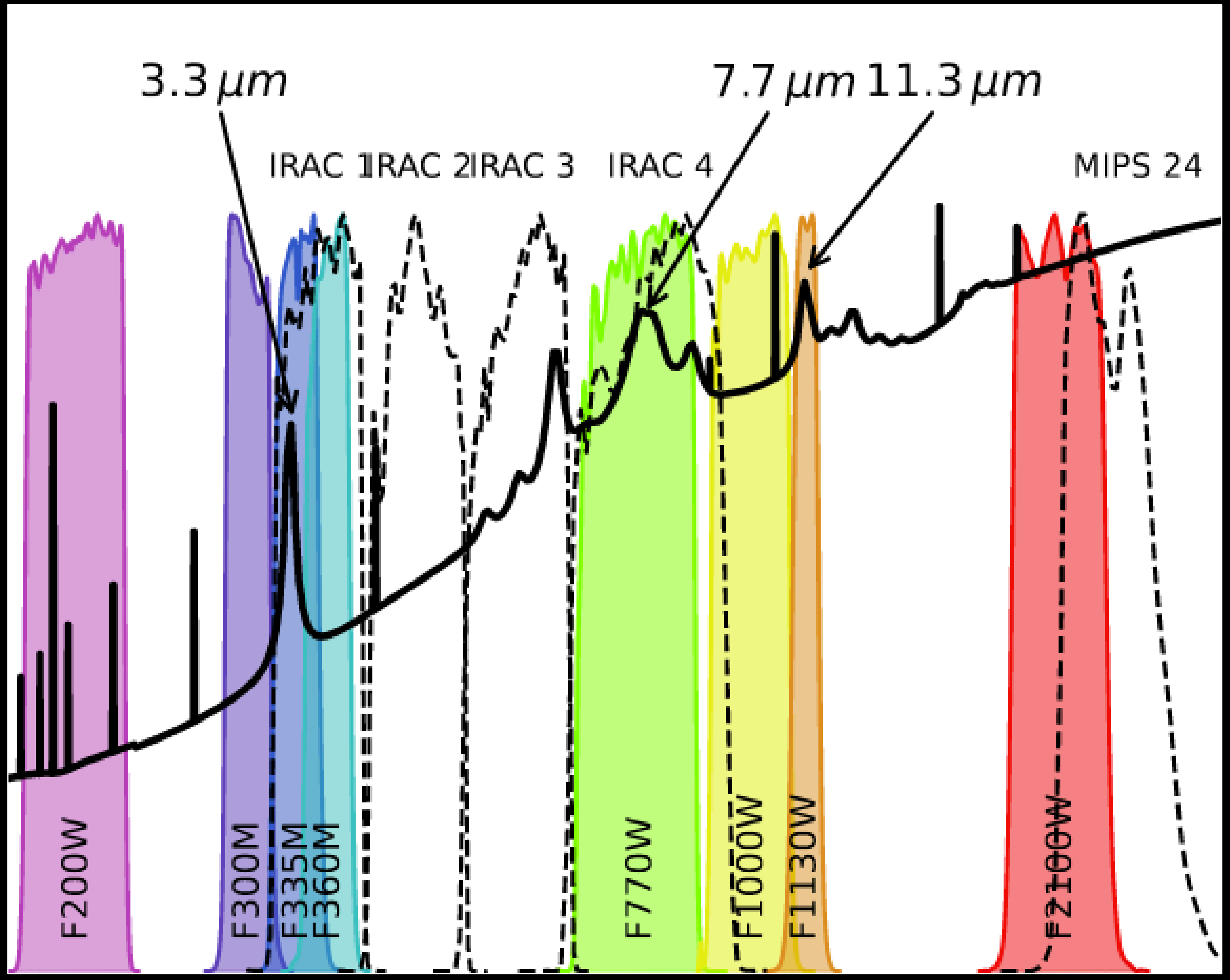


JWST detection of compact 3.3 um PAH emission provides a new way of finding dust embedded star clusters in nearby galaxies.

→ Census of embedded clusters across 19 PHANGS galaxies.

Why is this new?

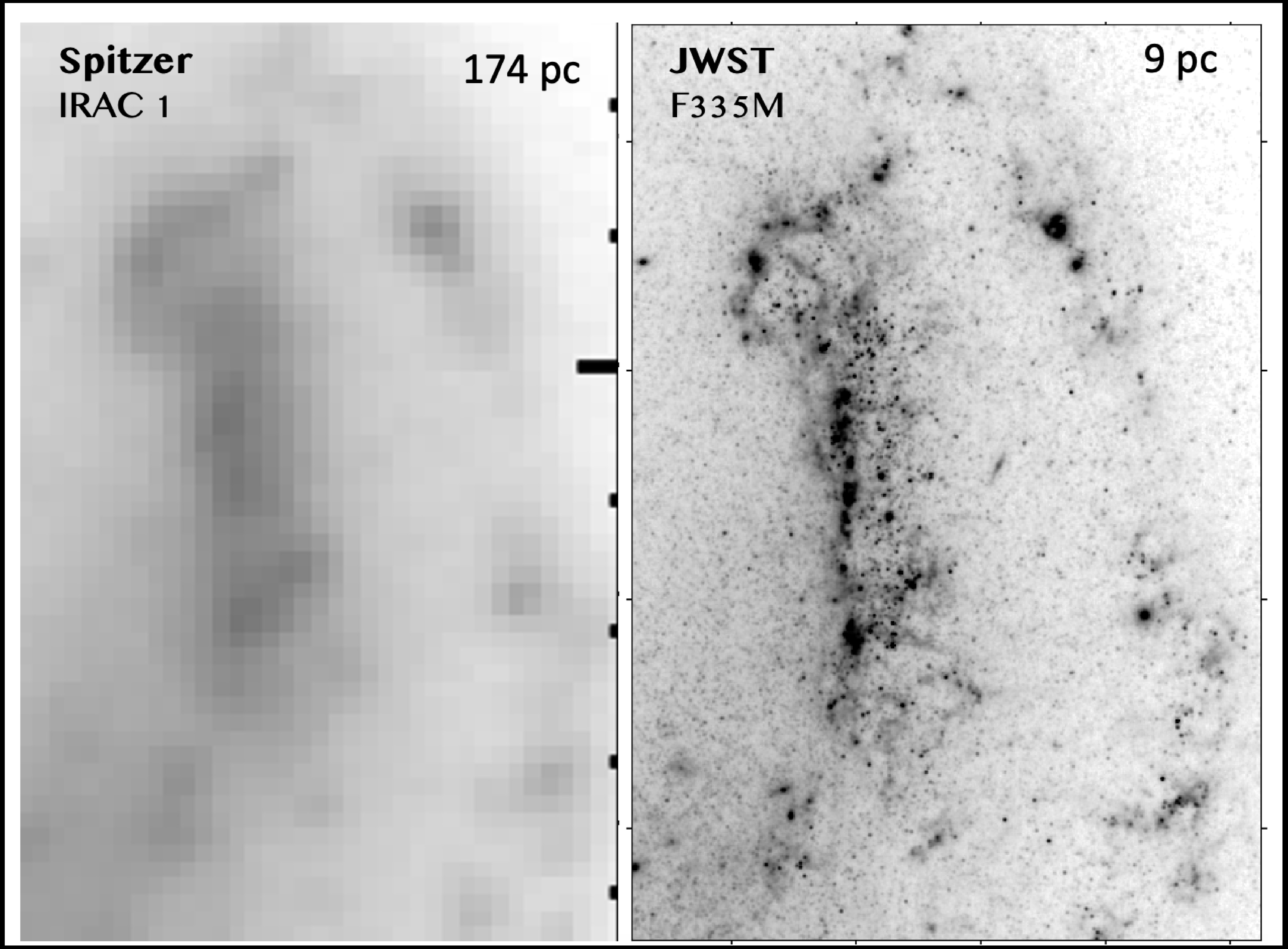
- *3.3um PAH (not extensively studied (e.g. Spitzer IRAC1)*
- *highest resolution dust dominated NIRCam band (PSF FWHM 0.”11)*



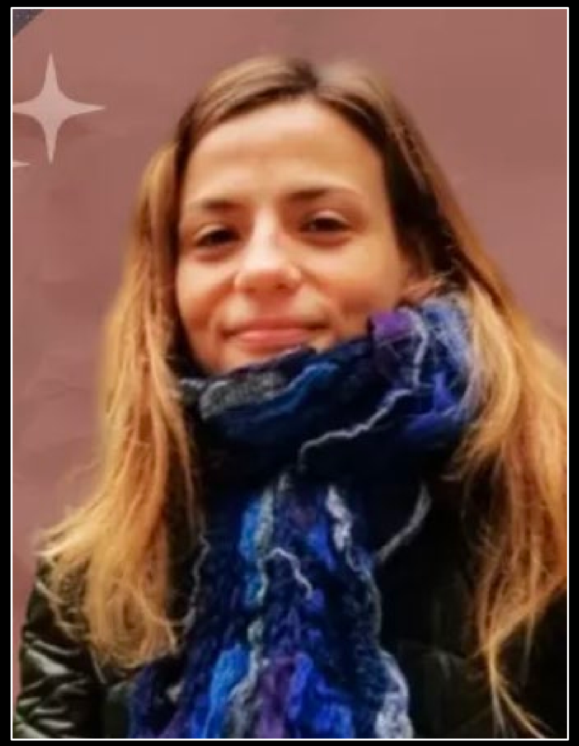
0.”066 0.”11 0.”24 0.”32 0.”37 0.”67

Spitzer & JWST 3.3um Comparison

NGC 7496 at 19 Mpc



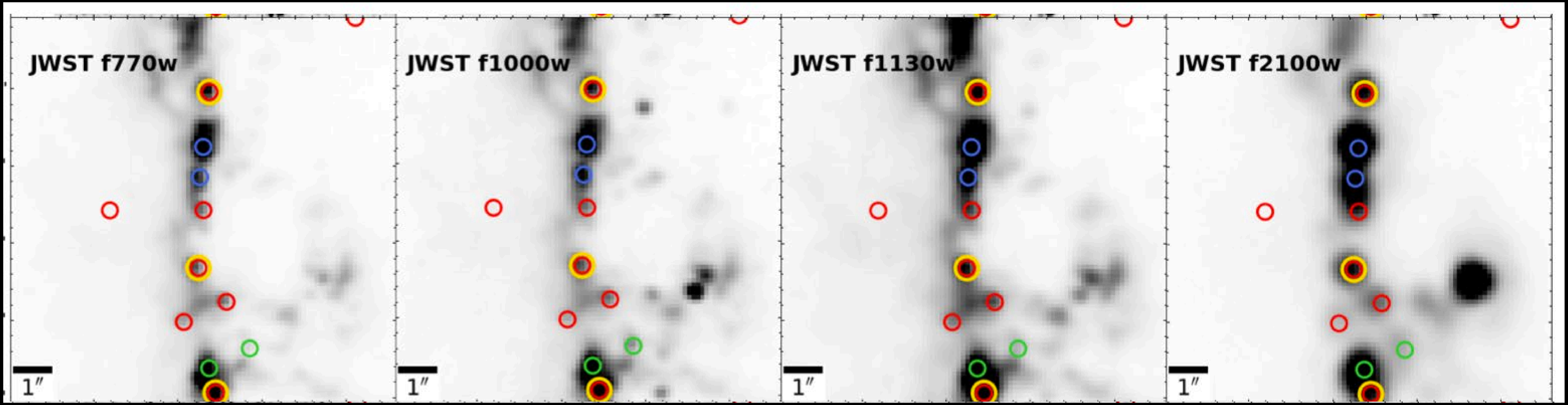
Lee+PHANGS-JWST 23

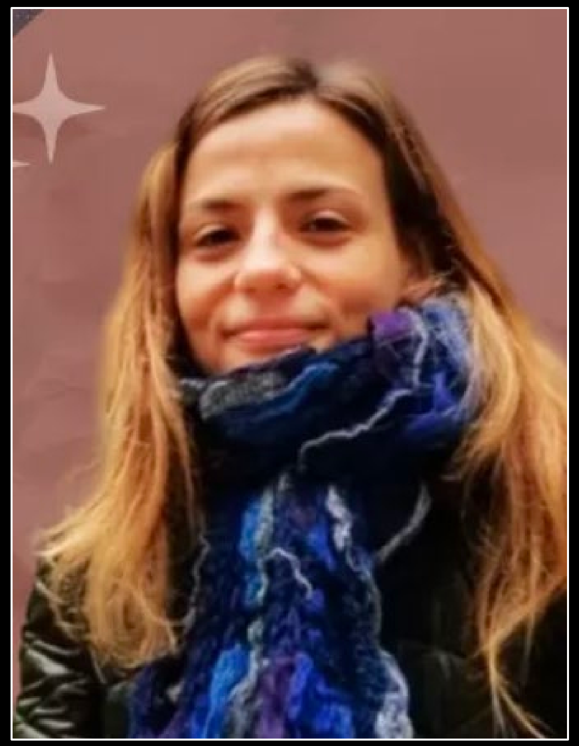


MJ Rodriguez,
JC Lee,
Whitmore+23

How do we know that compact 3.3um PAH emission is a good tracer of embedded star clusters?

- *Visually identify dust embedded cluster "prototypes" (yellow)*
- *Use prototypes (N=12) to identify selection criteria.*





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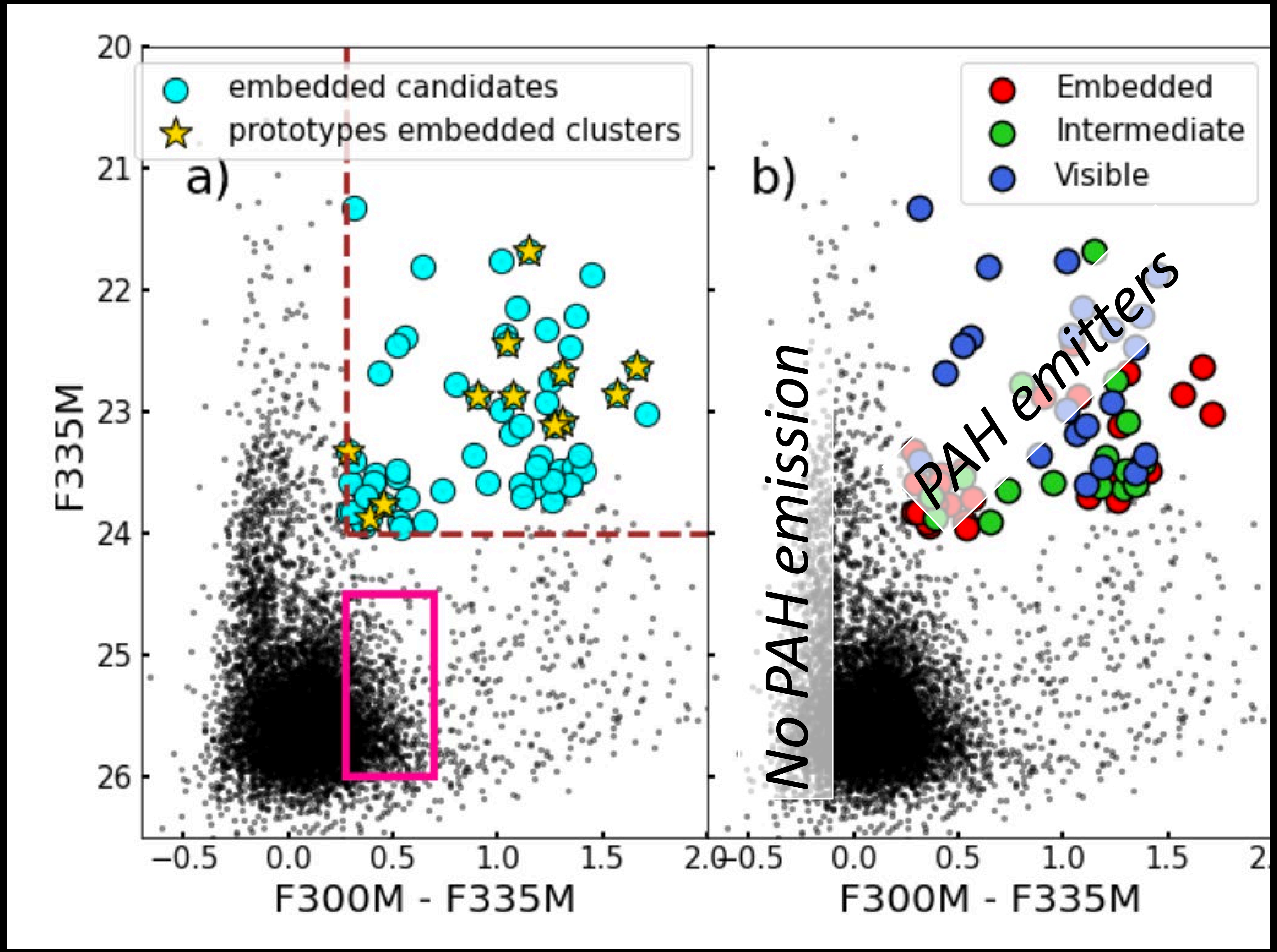
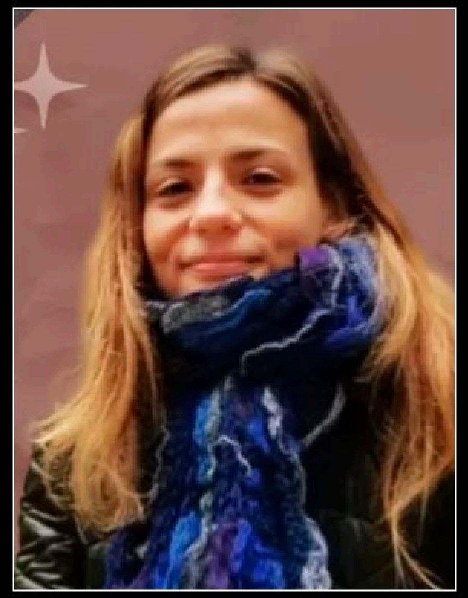


All show F300M-F335M color excess
→ PAH emission

Clusters as Clocks
Embedded Clusters & Compact 3.3 um PAH emission timescales



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And many subsequent studies, incl.

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M83: Kuntas+25
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Compact 3.3 um PAH emission is short-lived: $\lesssim$3 Myr

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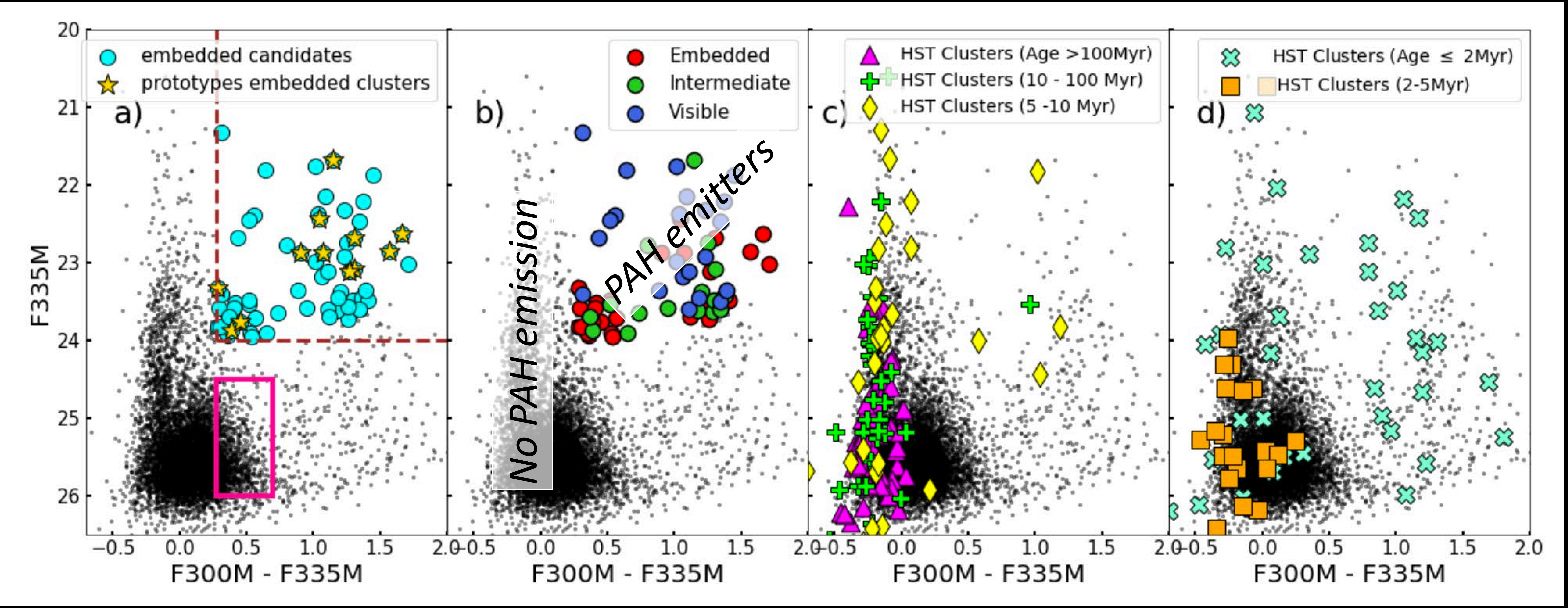
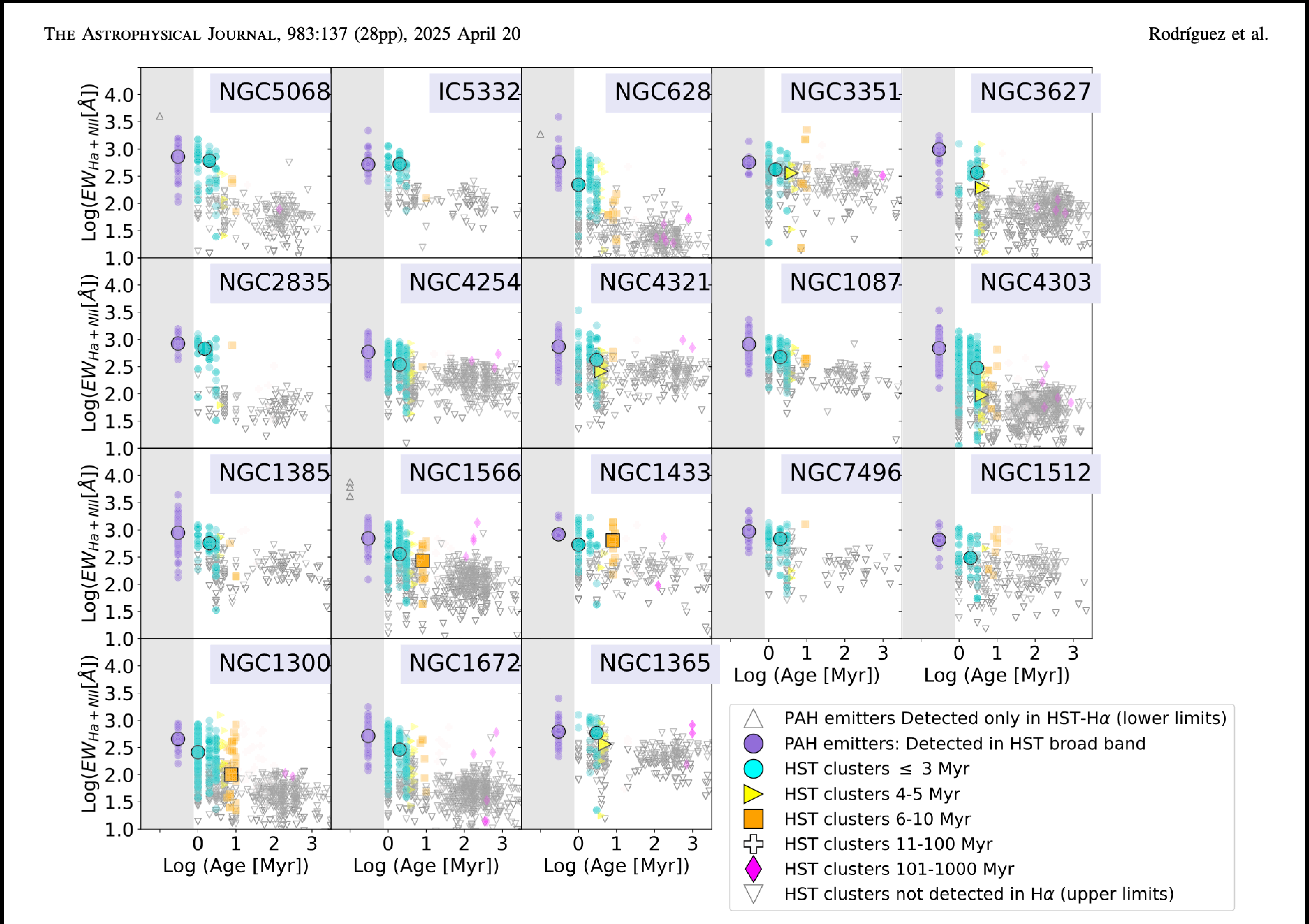
Compact 3.3 mircon PAH emission undetected in vast majority of Hubble optical clusters older than ~3 Myr



Hα equivalent width of compact PAH emitters up to 2.8 times higher compared with young PHANGS-HST clusters → PAH emitters are on average younger.



Compact 3.3 um PAH emission, no Hα **<1 Myr**

Compact 3.3 um PAH emission & Hα **<2-3 Myr**

Hα+UV+optical, but no compact 3.3 um PAH emission **>~3Myr**

ISM clearing must begin before SNe; radiation pressure, winds etc important on cluster scales

Decoding Galaxies & Star Formation Feedback with 100,000 Star Clusters

Summary (more conventional)

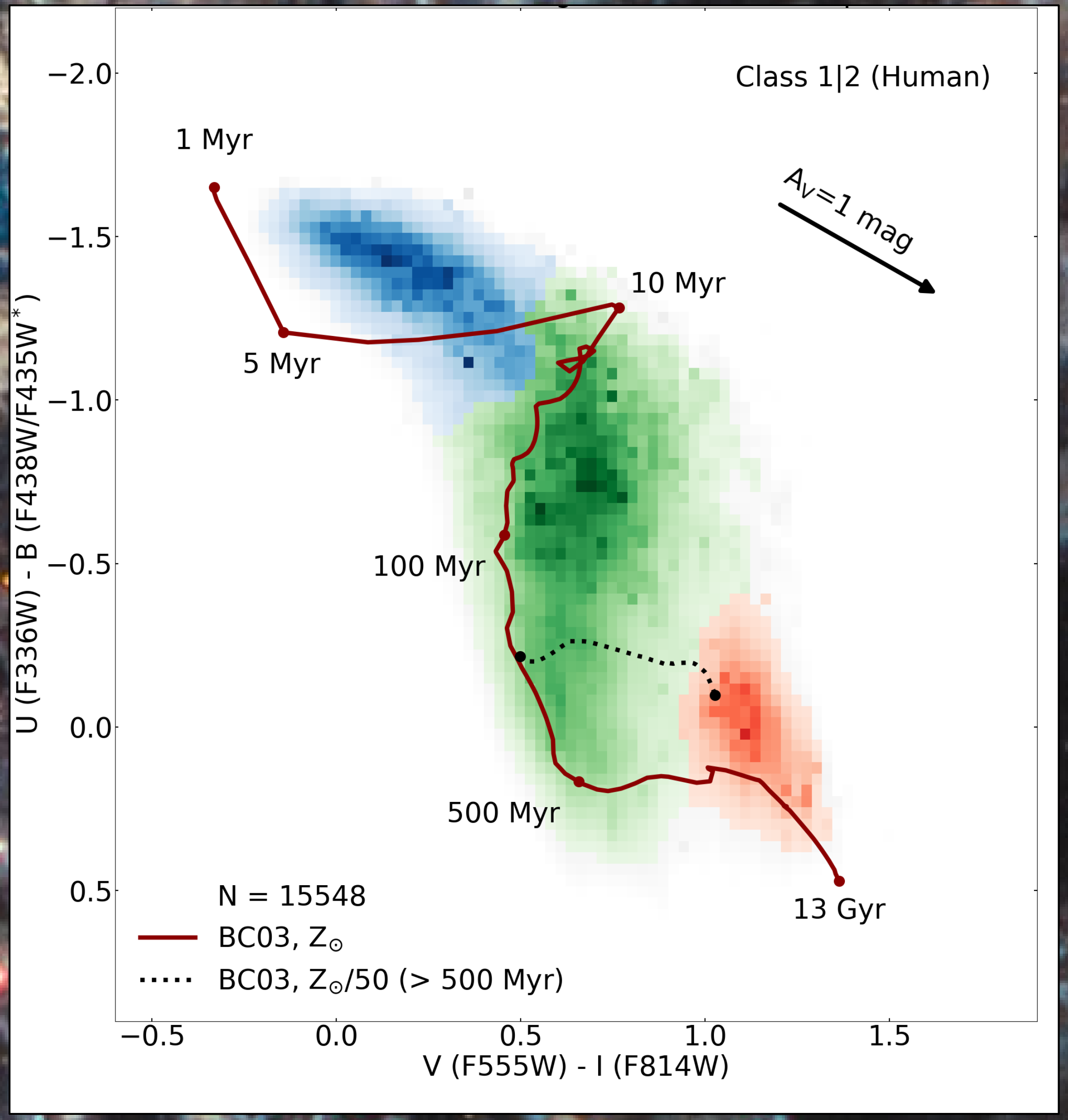
- *Largest census of ~100,000 optically selected clusters across 38 galaxies; images & catalogs publically available*
- *First census of embedded clusters with compact 3.3 micron emission across 19 galaxies*

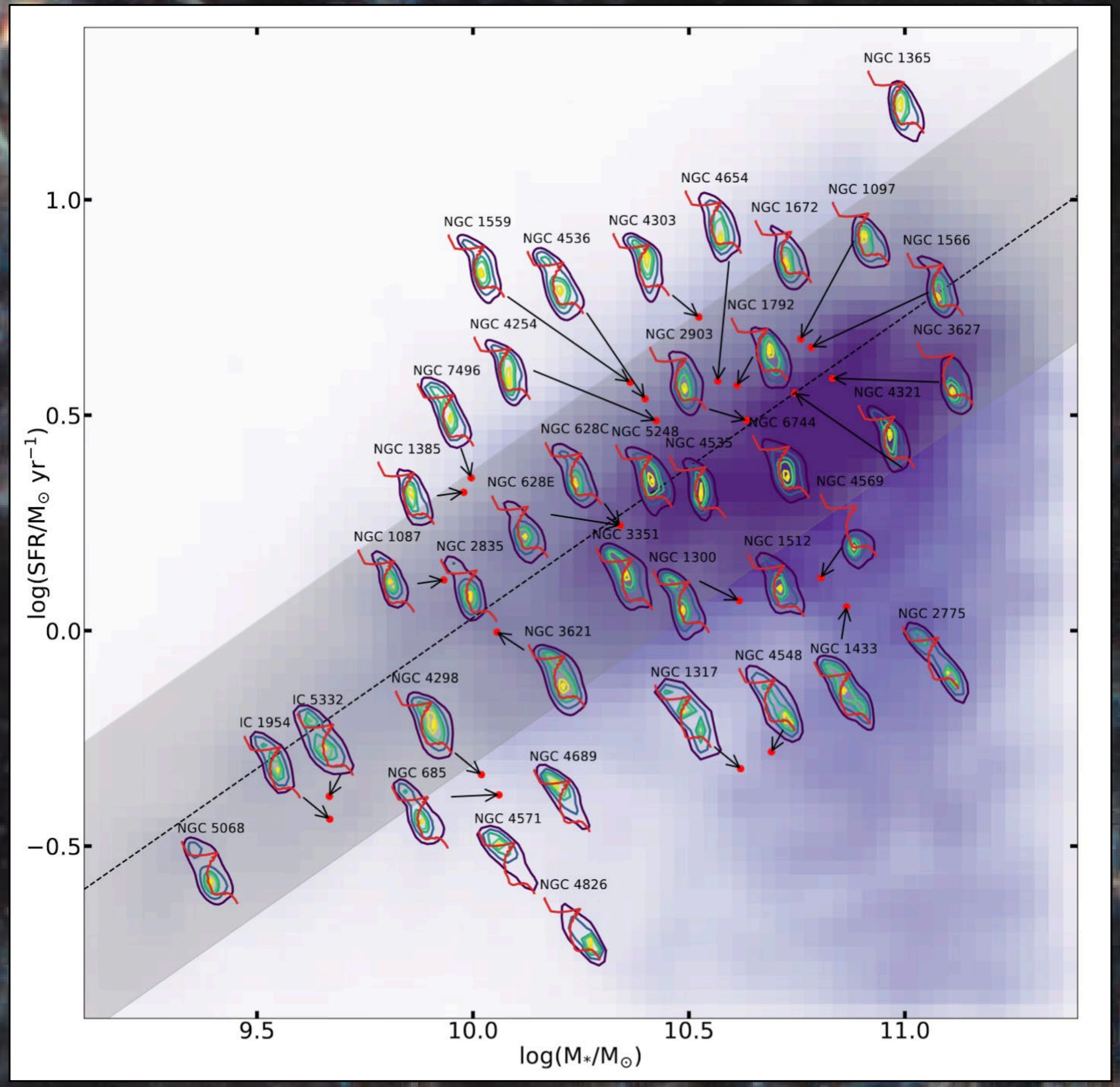
Clusters as clocks to time ISM processes on pc-scales

- *HII regions with bubble features have median age of 2-3 Myr*
- *compact 3.3 micron emission disappears quickly, few clusters older than ~ 3 Myr are emitters*
- *pre-SNe feedback important for clearing ISM on pc-scales*

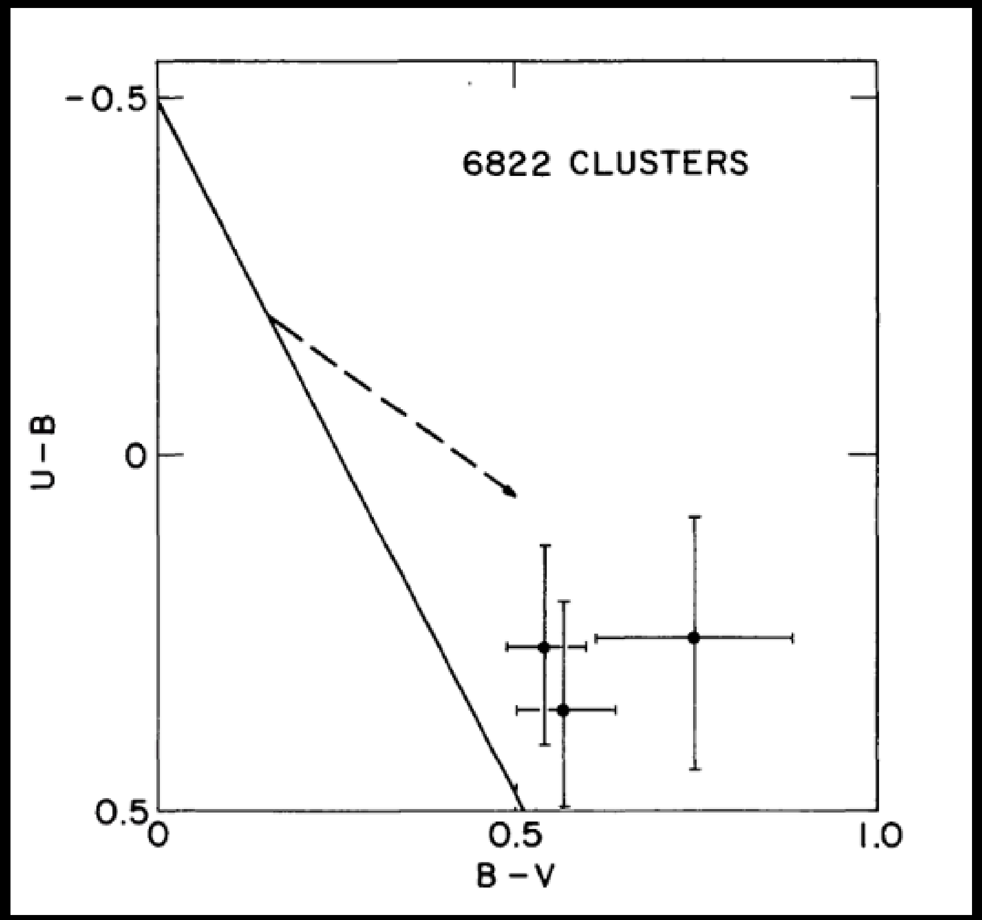
Exploratory work enabled by large cluster catalogs

Many uses for the UBVI color-color diagram as model-independent, multi-scale observational diagnostic for star and cluster formation and evolution, and for the evolutionary status of galaxies.

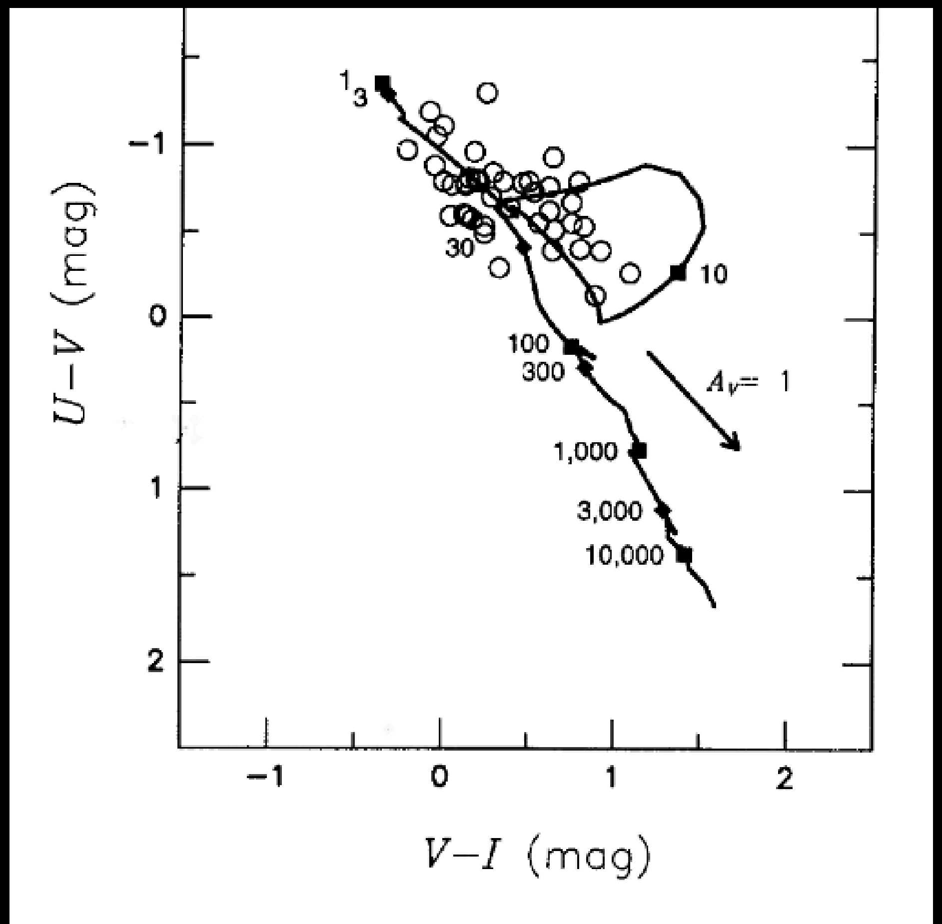




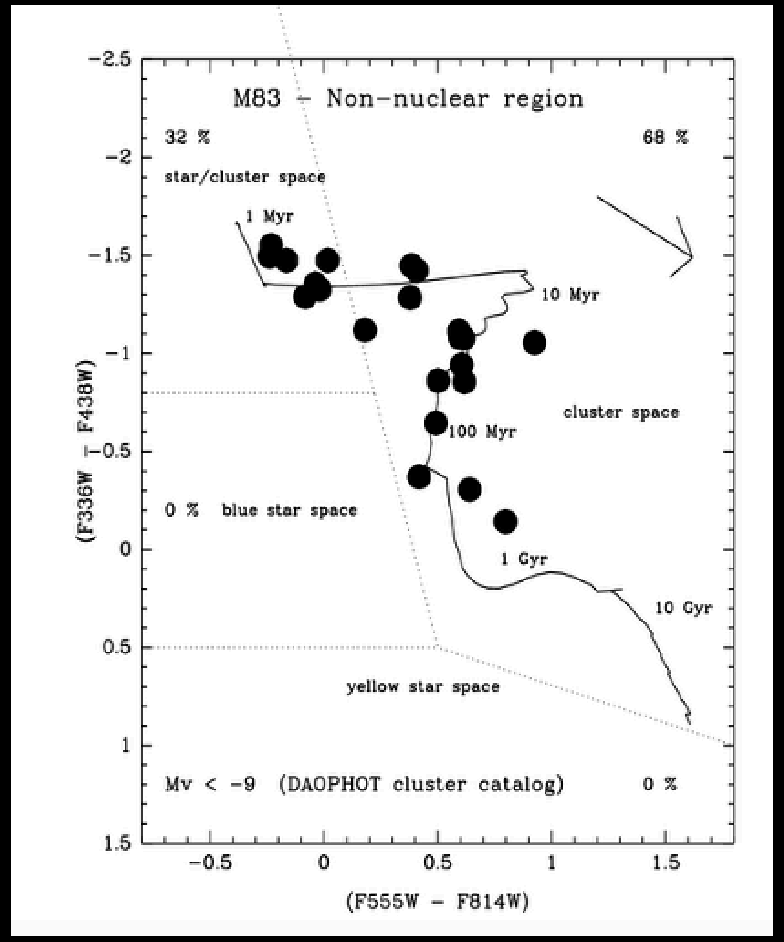
Decoding Galaxies & Star Formation Feedback with 100,000 Star Clusters



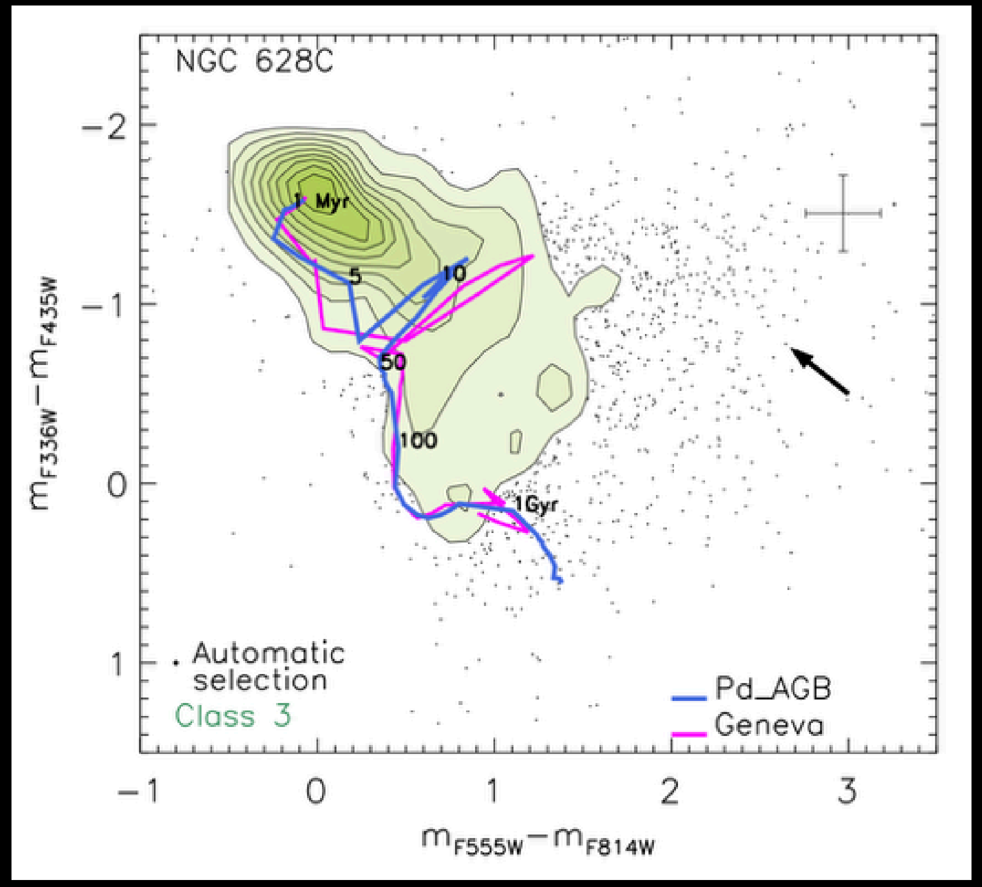
NGC6822
Hodge77



Antennae
Whitmore&Schweizer95



M83
Chandar+10



NGC 628 center
Adamo+LEGUS17

Exploratory work enabled by large cluster catalogs: factor of 10 increase over last decade

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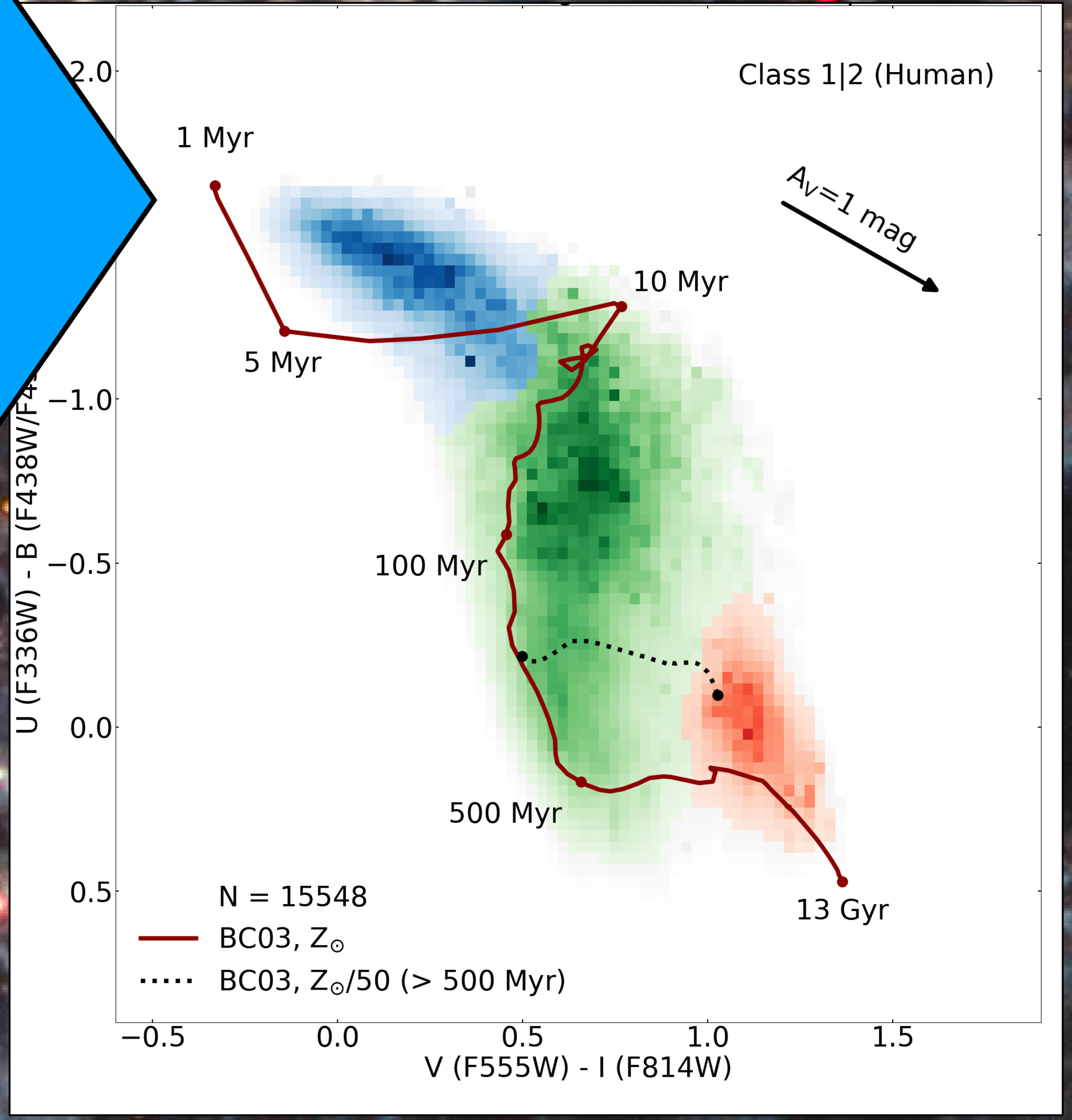
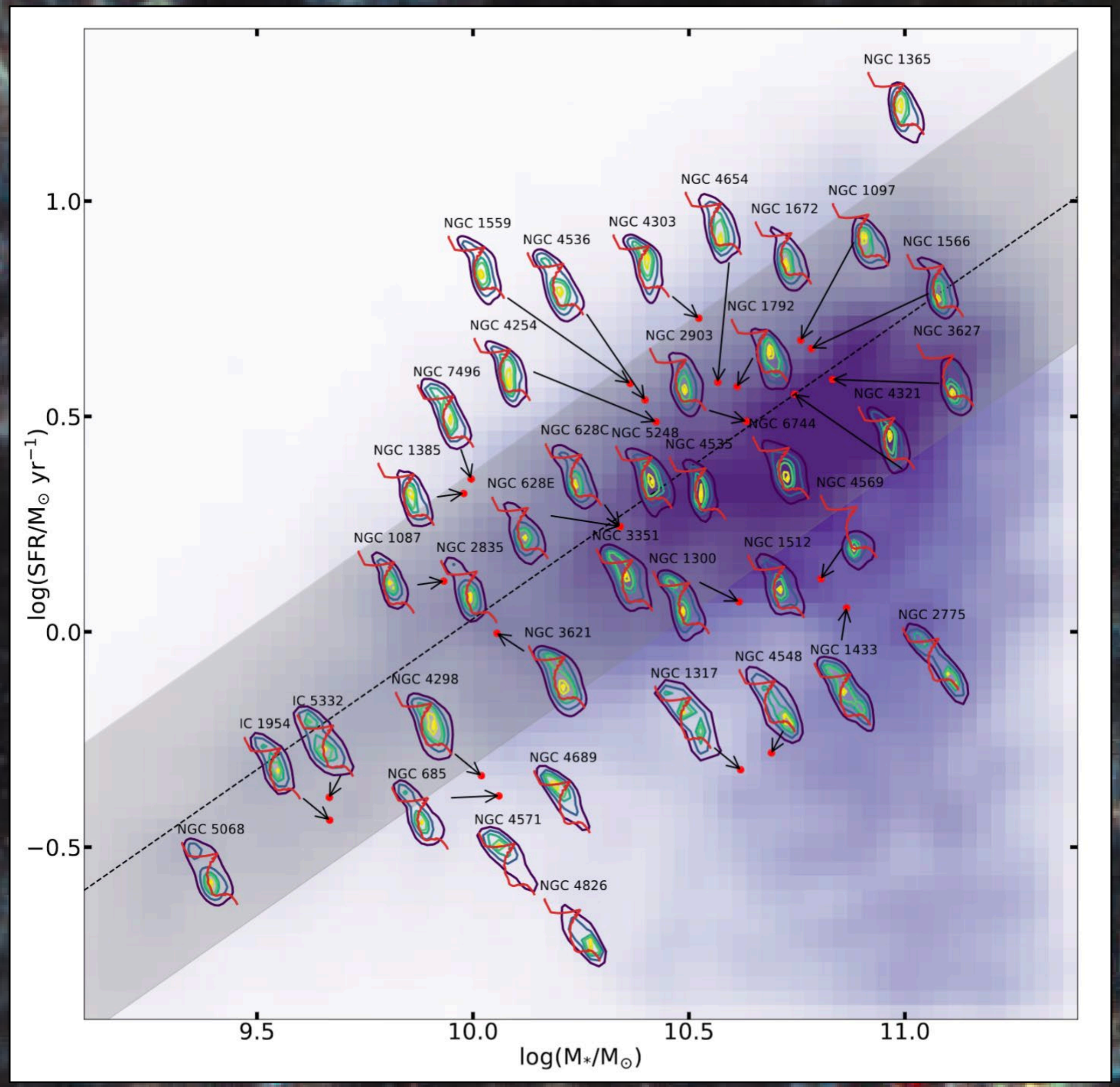
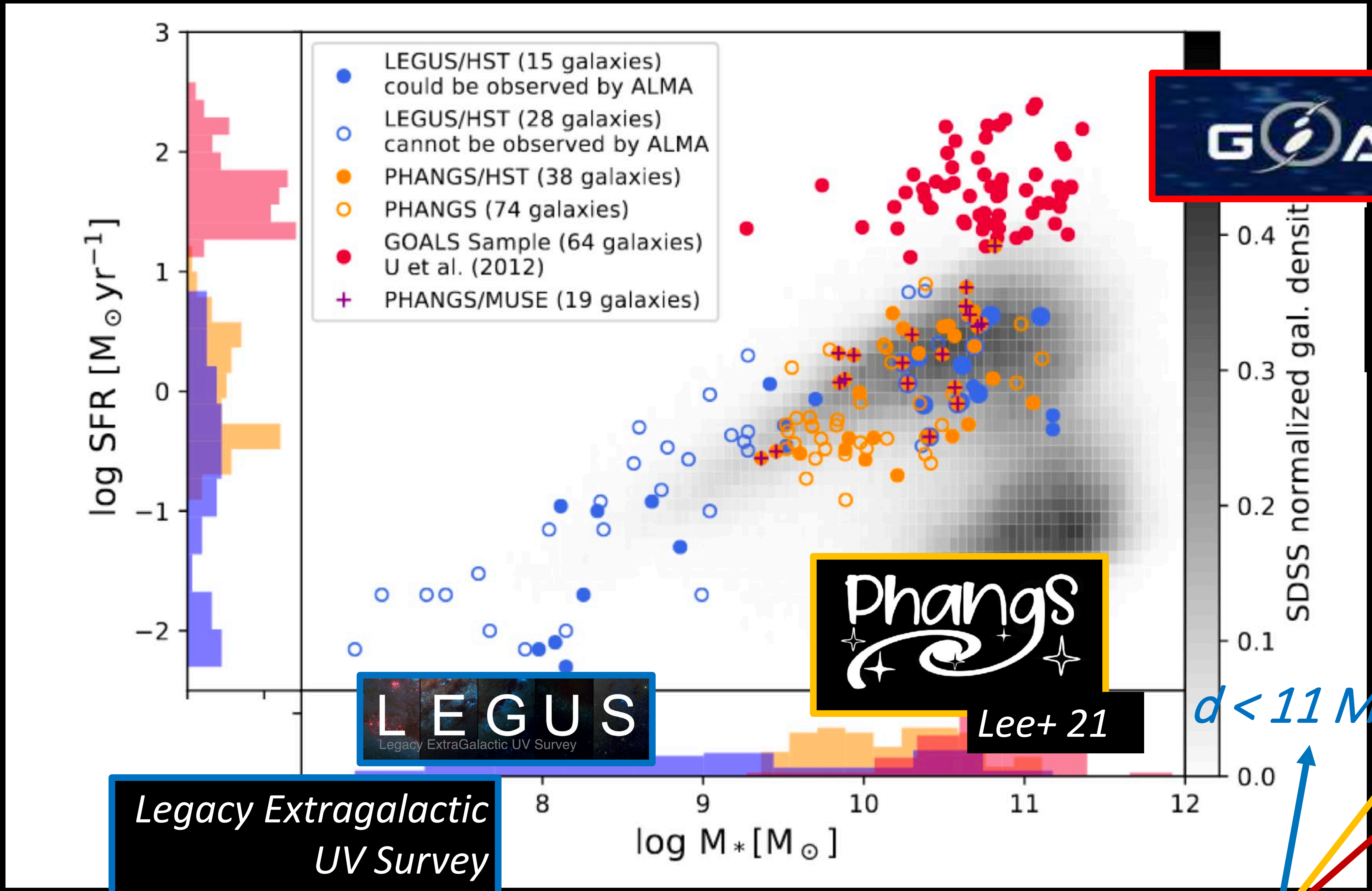




The Future with Habitable Worlds Observatory
Isn't a sample of ~100,000 star clusters enough?

HWO needed to increase the volume available for star cluster studies to:

- capture galactic environments, rare in the present-day universe
- Increase the sample of massive young clusters >1e5 Msun (<1% of current census)



Great Observatories All-sky LIRG Survey (Armus+09)

Legacy Extragalactic UV Survey (Calzetti, Lee+15)

50-100 Mpc

d < 25 Mpc

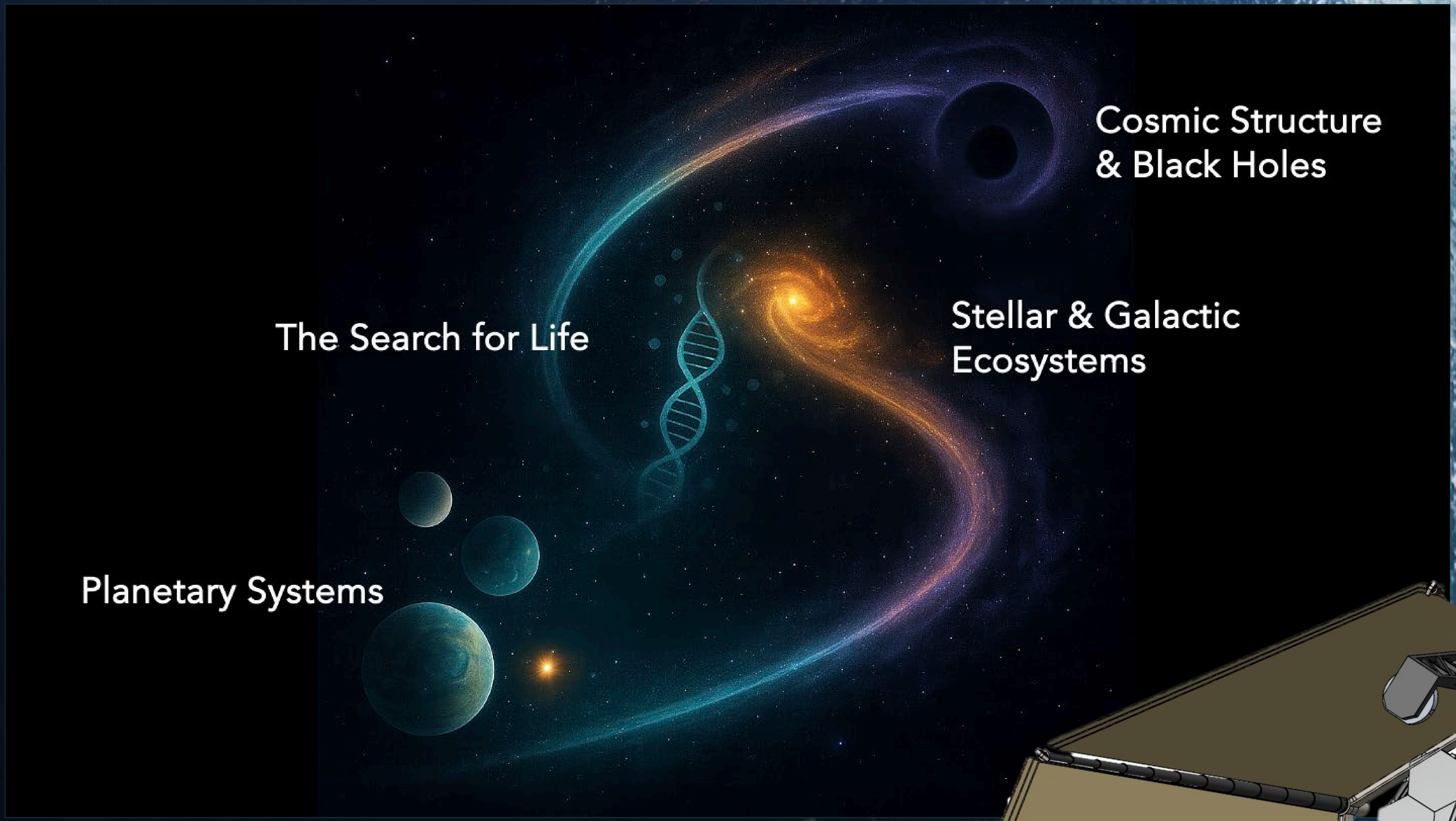
d < 11 Mpc

Ultimately, analysis of all programs together needed to fully understand impact of galactic environment on star formation

What is HWO?

A <u>Super Hubble!</u>

…to search for life in the universe and perform transformative astrophysics



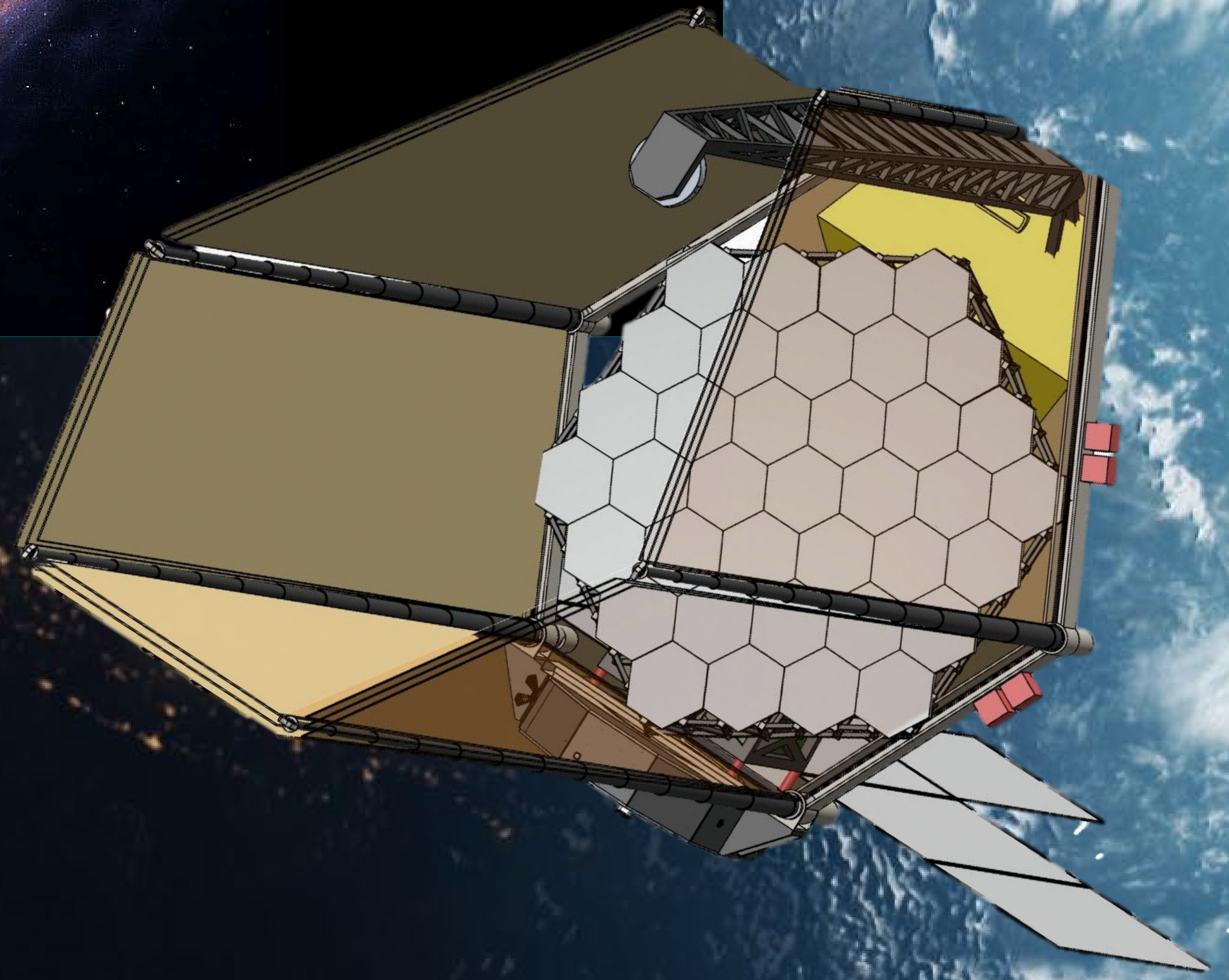
largest concept:

Off axis telescope, 10 m outer diameter

Volume dual rocket compatible

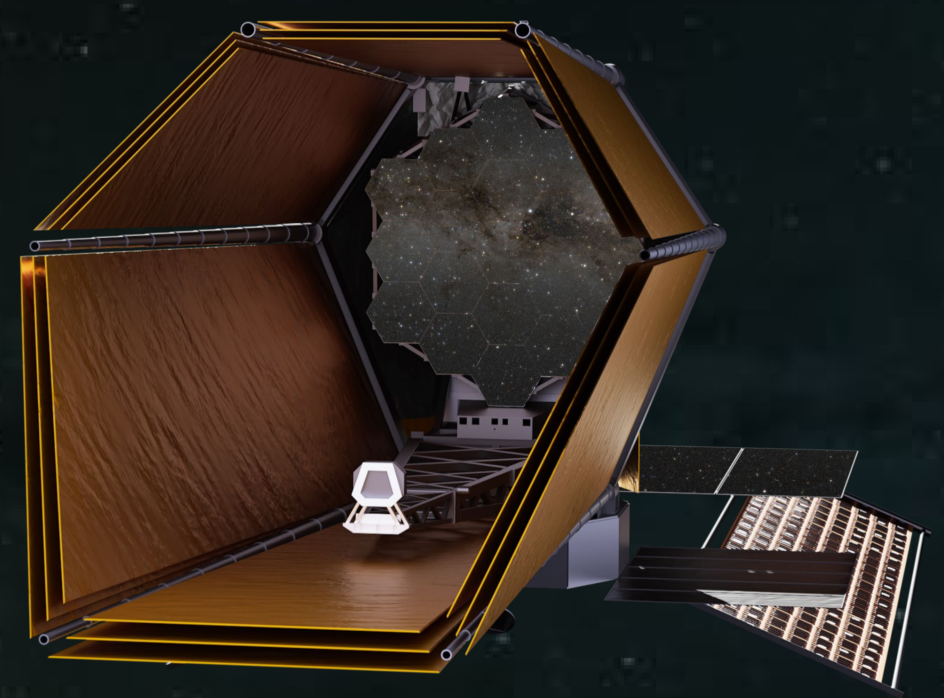
5 science instruments

3 channel UV/Vis+NIR coronagraph



Telescope

Diameter	~6-8 m (inner)
Bandpass	~100–2500 nm



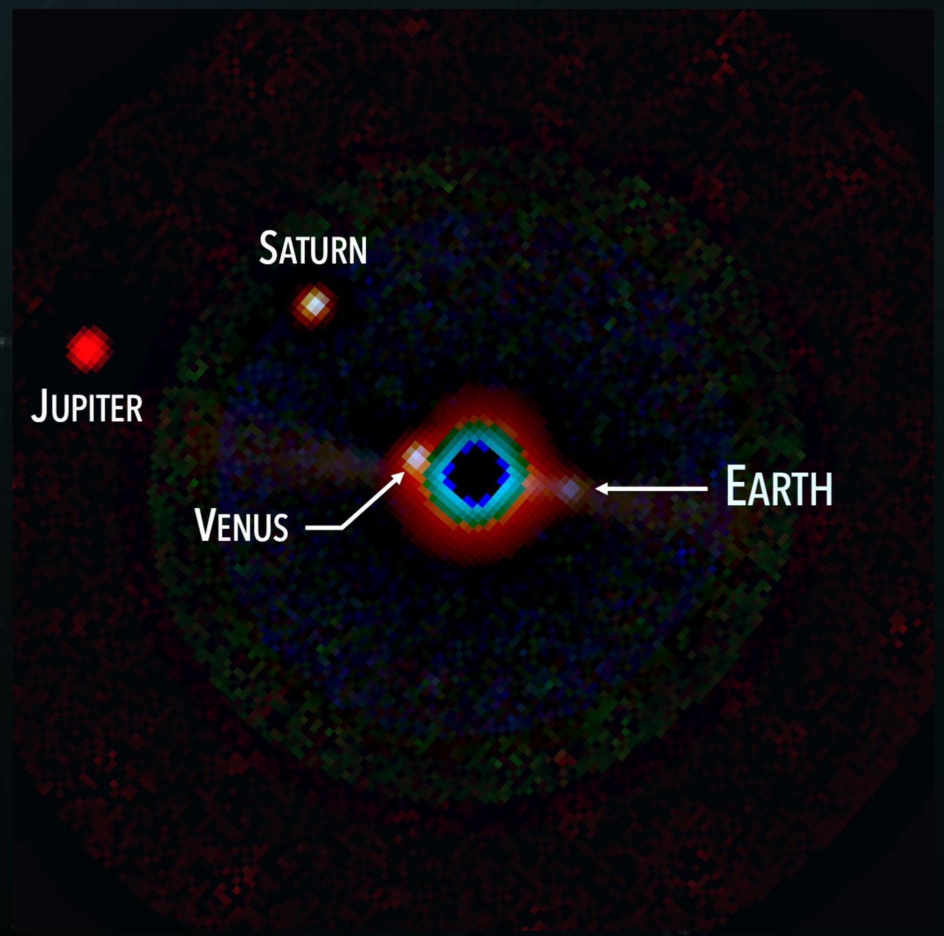
Other Possible Instrument(s)

include NUV coronagraph, NUV starshade, UV/VIS IFS, Spectropolarimeter

Coronagraph

High-contrast imaging and imaging spectroscopy

Bandpass	~450 - 1700 nm
Contrast	$\lesssim 1 \times 10^{-10}$
R $(\lambda/\Delta\lambda)$	Vis: ~140 NIR: ~40



High-Resolution Imager

UV/Vis and NIR imaging

Bandpass	~200–2200 (TBD) nm
Field-of-View	$\sim 3' \times 2'$

60+ science filters & grism

High-precision astrometry?

UV Multi-Object Spectrograph

UV/Vis multi-object spectroscopy and FUV imaging

Bandpass	~90 – 700 nm
Field-of-View	$\sim 2' \times 2'$
Apertures	$\sim 840 \times 420$
R $(\lambda/\Delta\lambda)$	~500–60,000

Potential international contributions.

HWO25 | JULY 28 – 31, 2025

Towards the

HABITABLE WORLDS OBSERVATORY

VISIONARY SCIENCE AND TRANSFORMATIONAL TECHNOLOGY

HWO25 | JULY 28 – 31, 2025

Towards the

HABITABLE WORLDS OBSERVATORY

VISIONARY SCIENCE AND TRANSFORMATIONAL TECHNOLOGY

HWO25 International Partnerships Panel

NASA
USA

Shawn Domagal-Goldman
Astrophysics Division Director (Acting)

UKSA
United Kingdom

Caroline Harper
Head of Space Science

JAXA
Japan

Keigo Enya
HWO Study Task Force Lead

ESA
Europe

Paul McNamara
Astronomy & Astrophysics Coordinator

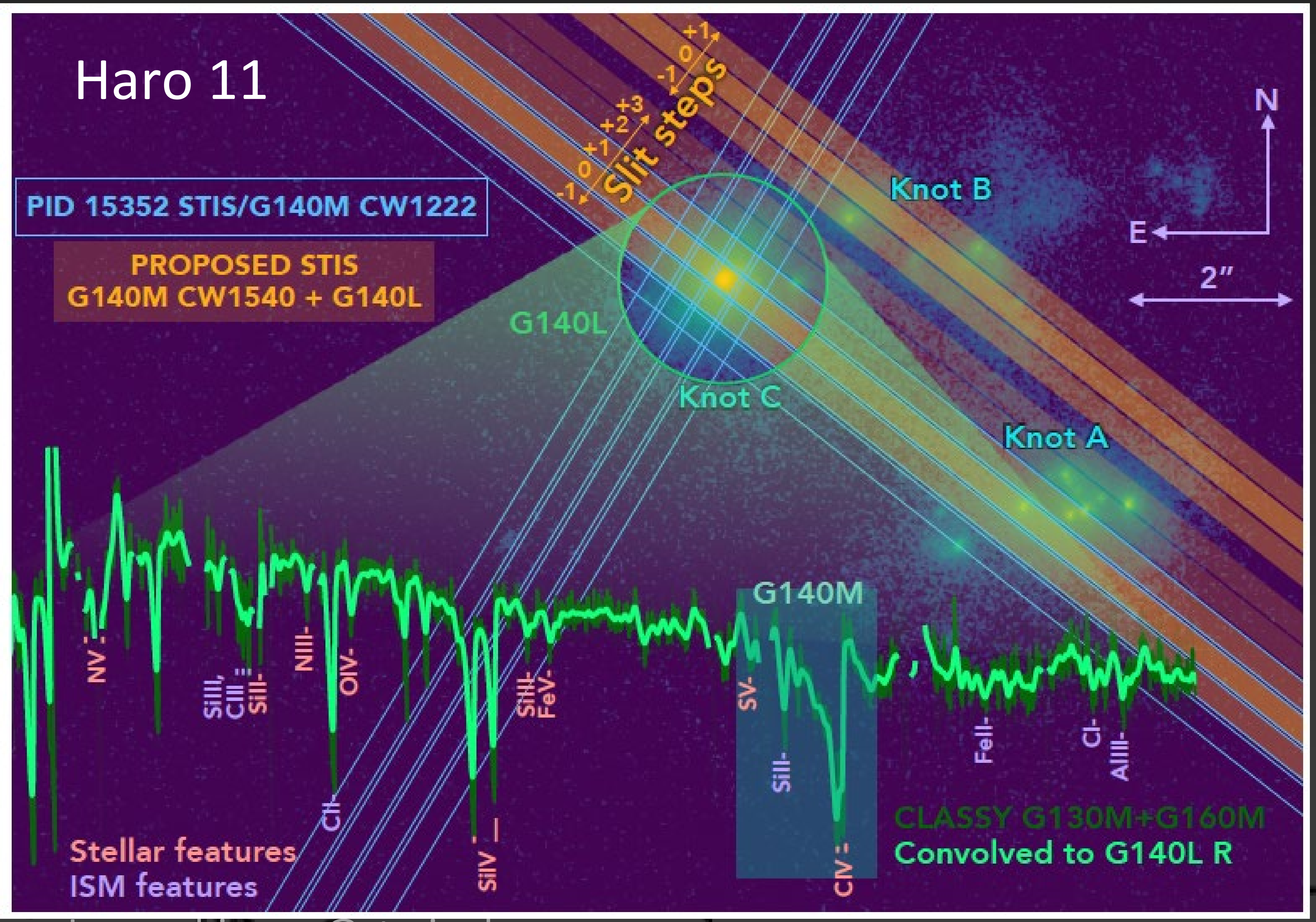
CSA
Canada

Jean Dupuis
Space Astronomy Senior Mission Scientist

(Slit)-Stepping into the future:
Simulating a UV-IFU with HST/STIS

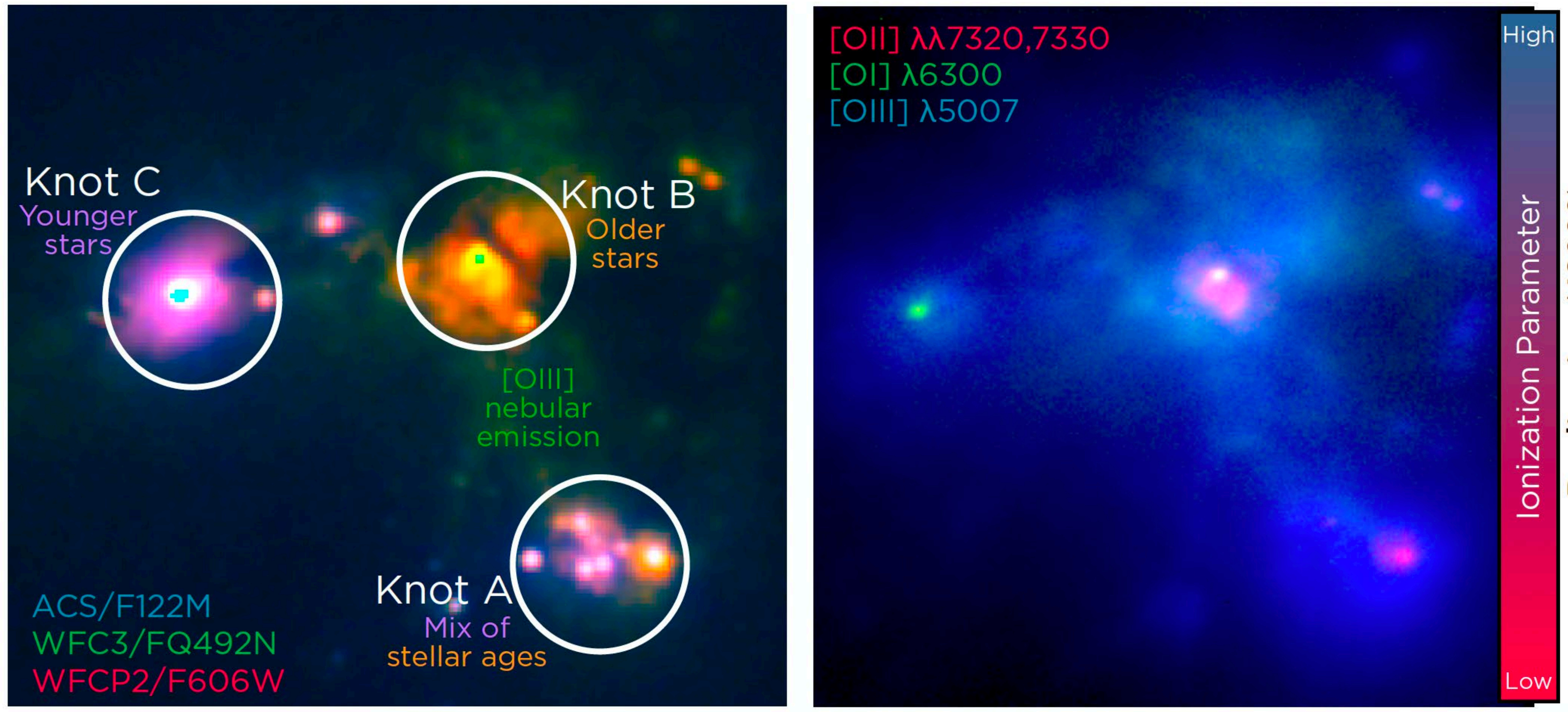
65 Orbits with HST/STIS (PI: B. James, STScI)

High-R UV cube + low-R UV cube
0.2” x 0.2” spaxels (0.2”=86pc)



Haro 11

archival optical MUSE-AO (0.13"/spaxel) data



(a) Three-colored image highlighting range of stellar ages.
(b) Three-colored MUSE spectral cube showing range of gas ionization.

Science Objectives:

- map the structure and content of cold neutral ISM
- characterize multi-phase outflows
- directly map the effects of young massive stars
- decipher the conditions for nebular CIV emission

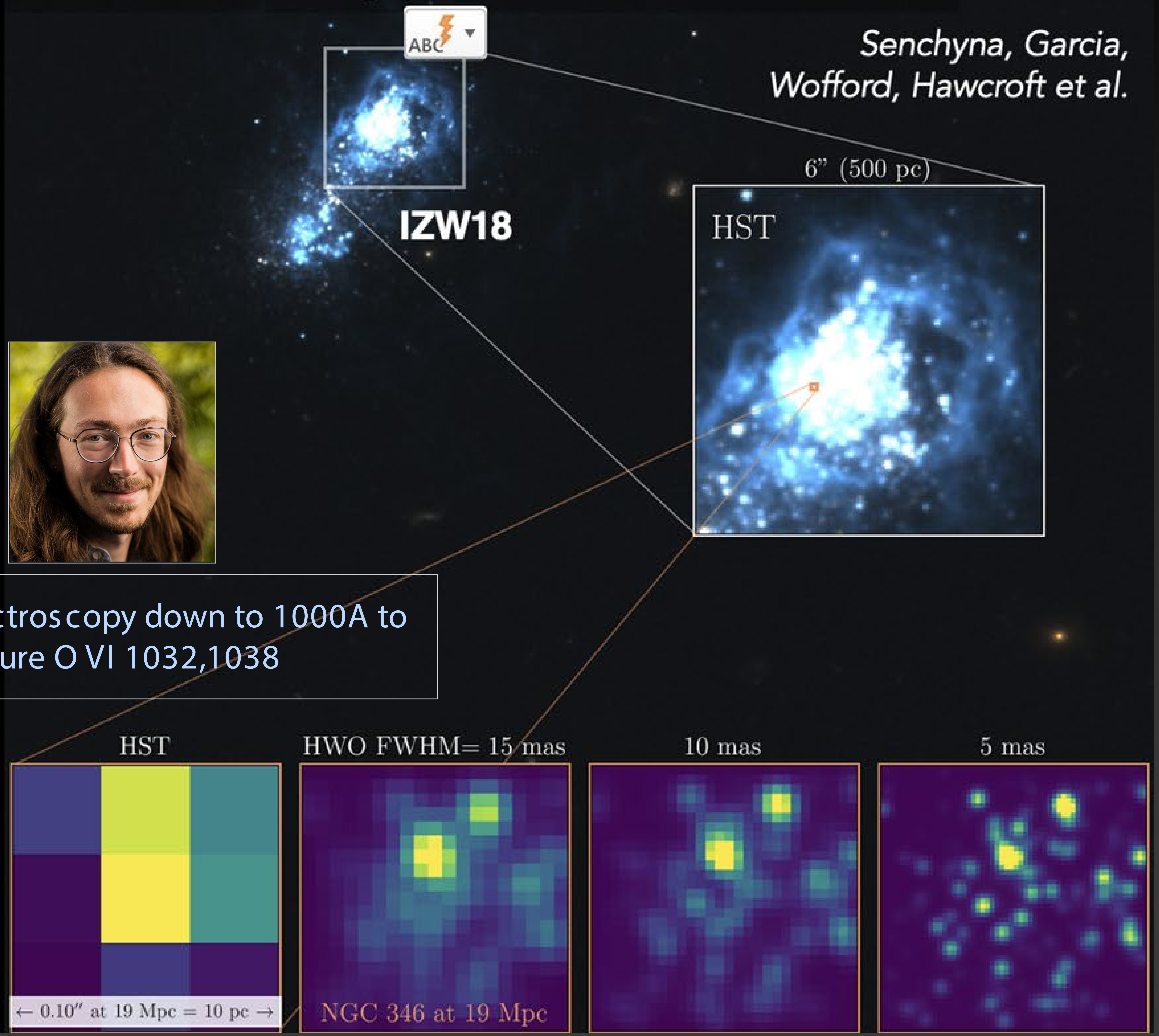
Data in July 2026 → UV-IFU design for HWO

Bethan James: bjames@stsci.edu

Pathfinder science case: The most chemically primitive massive stars

- Massive stars dominate production of common heavy elements (C, N, O) & feedback of momentum and energy into the ISM
- Early-universe massive stars may be distinct from their modern counterparts
- The nearby galaxy I Zwicky 18 is one of a few places where we may be able to observe individual chemically primitive massive stars

Senchyna, Garcia, Wofford, Hawcroft et al.



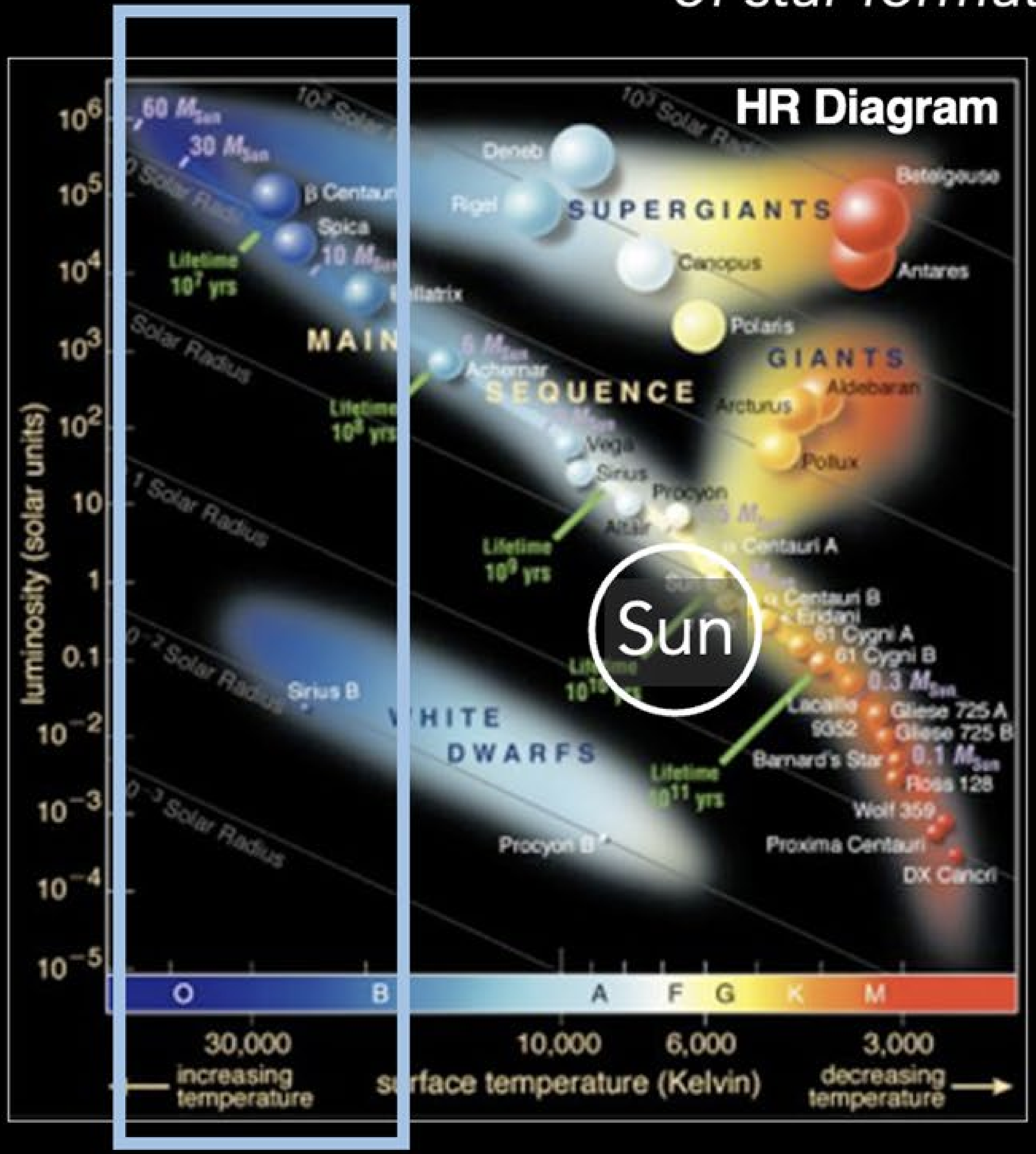
Only HWO

- can resolve massive, clustered stars at UV wavelengths where they emit most of their radiation
- measure temperature, mass, metal content, and age for these key stellar populations
- Hubble lacks the resolution and JWST & Roman lack the UV sensitivity to perform these observations

Spectroscopy down to 1000A to capture O VI 1032,1038

~15-20 mas

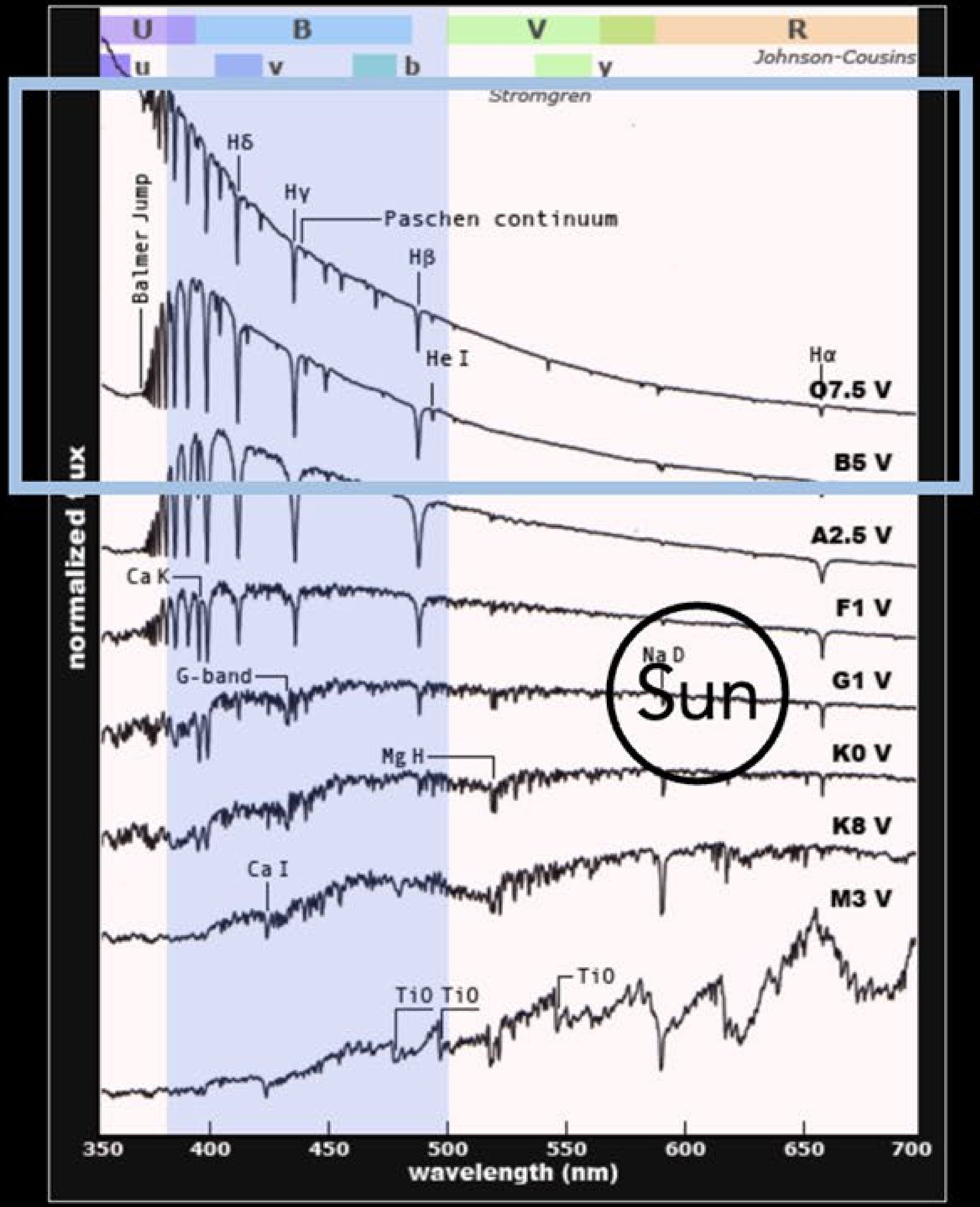
Blue/UV observations are critical for the study of star formation & massive (HOT) stars



O & B stars photospheric emission peaks in UV

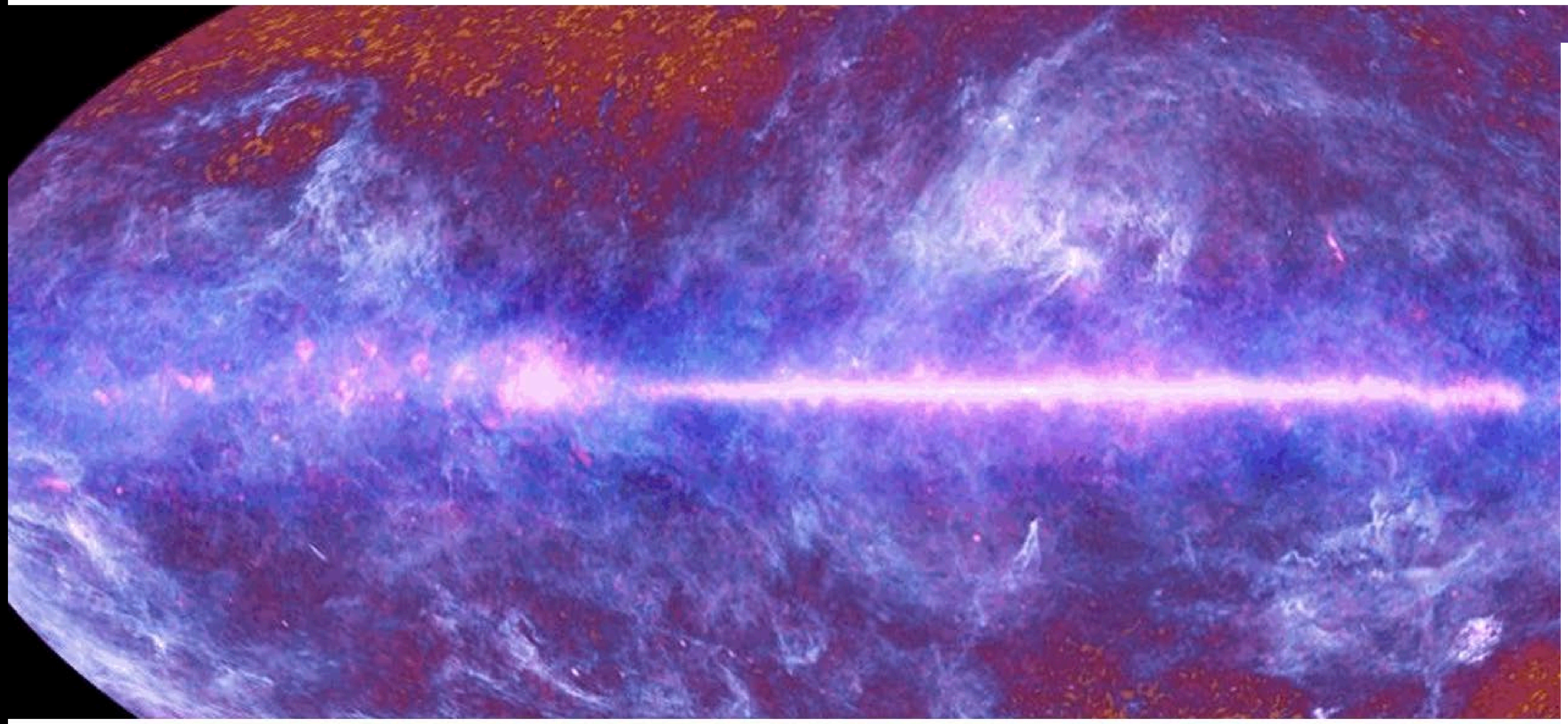
UV flux is a principle SFR tracer

*esp for low metallicity dwarf galaxies (Lee+09ab)



Characterizing Gas Flows at the Disk-CGM Interface

SCAN ME



Sanch Borthakur

Arizona State University

In collaboration with

Joseph Burchett, Frances Cashman, Andrew Fox, Yong Zher

Rongmon Bordoloi, Brad Koplitz, & the IGM-CGM working

Tracers

- A wide array of lines is available to probe the multi-phase nature of the flows.

Cold/neutral molecular

Cool/low ion

Warm/medium ion

Hot/high ions

Table 1 Lines of interest and their associated phenomenon.

Transitions	Wavelength (Å)	Importance
H I[a]	Lyman series (1215 to 920)	Traces neutral gas content at low and intermediate temperatures ($T = 10^{1-5}$ K). The most common set of absorption lines.
Lyman α[a,e]	1215	Strongest emission line tracing neutral hydrogen and the bulk of the cool gas mass in the CGM.
C II[a]	1036, 1334	One of the strong metal lines suitable for probing low metallicity or low column density gas at low-ionization states.
C III[a,e]	977	One of the strong metal lines suitable for probing low metallicity or low column density gas at intermediate ionization states. Expected to be one of the strongest metal emission lines.
C IV[a]	1548, 1550	Strong lines tracing higher ionization states. Together with O VI and N V can be a powerful tool to identify non-equilibrium processes. Also, known to trace interactions of galactic winds and the CGM.
N V[a]	1238, 1242	Coronal lines with powerful diagnostic power to identify young (1 to 5 Myr) stellar population and non-equilibrium processes.
O I[a]	1025, 1039, 1302	Strong tracer of primarily neutral gas and is coupled to neutral hydrogen.
O VI[a,e]	1031, 1038	Tracer of (1) gas at the viral temperature of 0.1 to 1 $L_\star$ galaxies, (2) energetic interactions expected between the cool CGM clouds and hot winds/outflows, (3) photoionized gas; and (4) non-equilibrium processes. Suitable for high-resolution ($R > 50,000$) absorption and low-resolution ($R \approx 5000$) emission spectroscopy. One of the most powerful high-ionization diagnostic transitions.
Si II[a]	1190, 1193, 1260, 1304, 1526	Commonly observed species with five lines of different intrinsic strength that enable characterization of the saturation level and hence accurate estimation of column densities.
Si III[a]	1206	The most common metal line seen in absorption in the halos of galaxies. Together with Si II and Si IV allows for accurate measuring of the ionization state of the gas.
Si IV[a]	1393, 1402	Together with Si II and Si III enables accurately measuring the ionization state of the gas.
S II[a]	1250, 1253, 1259	Weak lines associated with a low-depletion species that enable accurate metal measurement for high column density systems such as damped Lyα systems.
Mg II[a,e]	2796, 2803	Commonly traced species associated with extended gas disks and cool outflowing material. Extensive literature on this line at $z > 0.5$. Expected to be detectable in emission.
H_2[a]	Bands from 1150 to 912	Traces the bulk of the cold molecular gas. Critical for accurate estimation of the baryon budget and gas flows that may support short-term star formation.

"a" lines suitable for absorption-line spectroscopy.
"e" lines suitable for emission-line spectroscopy.

Web Portal for HWO Science Cases

Released June 22

4 Science Working Groups, ~60 science cases

The Next Era for Star Formation, ISM, CGM Cosmic Ecosystem Studies

The Habitable Worlds Observatory (HWO) Science Case Development Documents (SCDDs) are central to building a transf
the priorities of the scientific community and the Astro2020 US Decadal Survey. Science cases sourced from the research
science objectives, instrument needs, and overall mission architecture for HWO.

The portal hosts all 60 current SCDDs, with documents being added through May 30. A subset of the authors are inviting
endorsement from members of the broader community. This open, transparent process ensures shared ownership of HWC
supports future planning by the HWO Technology Maturation Project Office and the forthcoming Community Science and

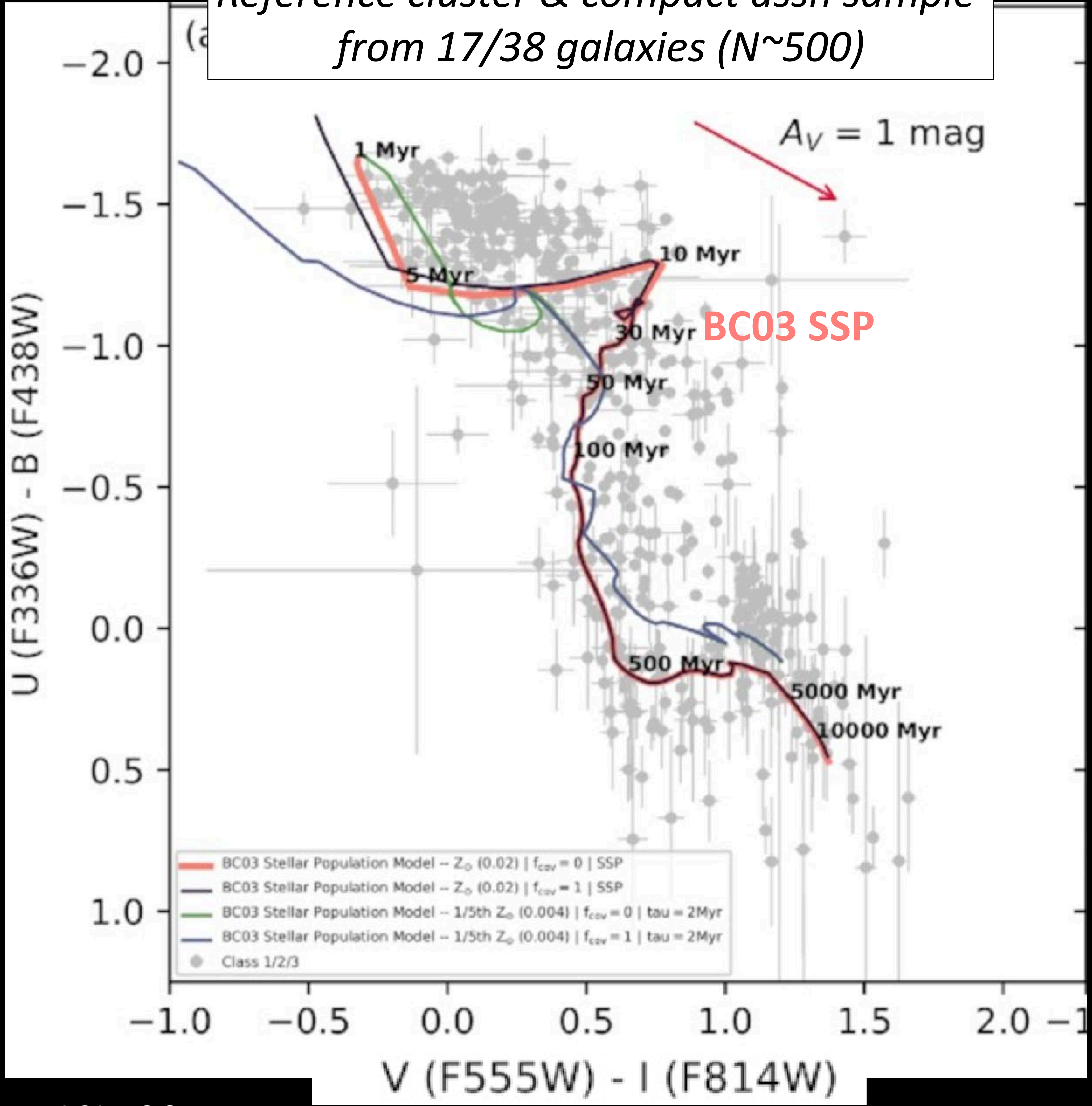
SCDD Portal Table External

Working Group	Sub Working Group	Science Case Title	Principal Authors	Signatory and Feedback Form	
Evolution of the Elements	Stars & Stellar Populations	Massive stars in extremely metal-poor environments	Peter Senchyna, Miriam Garcia, Aida Wofford, Calum Hawcroft	https://forms.gle/znixjbUvg4T9CwbA9	
Evolution of the Elements	Star Formation & ISM	Dust extinction curves in the Milky Way and Local Group galaxies	Roberta Paladini, Samir Salim	https://forms.gle/kDQM3f5DqfFExUad8	NEW!
Evolution of the Elements	Cosmic Explosions	The Final Moments of Massive Stars	Jen Andrews, Eric Burns	https://forms.gle/qvqjk7VuTeahXk2k9	
Evolution of the Elements	Cosmic Explosions	R-process elements	Eric Burns, Jen Andrews	https://forms.gle/RzBbnSH3VxH82nKU8	
Evolution of the Elements	Stars & Stellar Populations	Very Massive Stars	Fabrice Martins, Aida Wofford	https://forms.gle/o5Q73kDdRtKF8vjV7	
Evolution of the Elements	Stars & Stellar Populations	Resolved Stellar Populations in Large Nearby Galaxies	Adam Smercina, Tara Fetherolf	https://forms.gle/KbMDtKfe6R1uuDuX7	
Evolution of the Elements	Stars & Stellar Populations	White dwarfs as probes of extrasolar planet compositions and fundamental astrophysics	Siyi Xu, Martin Barstow	https://forms.gle/3GmJb6PUnMac8NrJ9	
Evolution of the Elements	Stars & Stellar Populations	The Nature of the First Stars	Ian Roederer, Rana Ezzeddine, Jennifer Sobeck	https://forms.gle/LSvJ3N6my2PxwFJZ8	
Evolution of the Elements	Stars & Stellar Populations	Origin of the elements all across the periodic table	Ian Roederer, Rana Ezzeddine	https://forms.gle/mH2LYcJ5kVqCWK3JA	
Evolution of the Elements	Stars & Stellar Populations	Distance Ladder 3.0	Gagandeep Anand, Meredith Durbin, Rachel Beaton	https://forms.gle/3K7HUCve1BEtEsxd8	
Evolution of the Elements	Stars & Stellar Populations	New Frontiers in the Study of Magnetic Massive Stars	A. David-Uraz et al.	https://forms.gle/ZxxEa3GngrbGhoebA	NEW!
Evolution of the Elements	Star Formation & ISM	Probing the variations of interstellar dust abundance and properties within and between galaxies with HWO UV spectroscopy in the Local Volume	Roman-Duval, Julia	https://forms.gle/THDcqrwM7YUkoGzu5	
Evolution of the Elements	Star Formation & ISM	Probing the Full Depth of ISM Properties with a UV-IFU	Bethan James, Danielle Berg	https://forms.gle/i4tks1LihSQTvf9eA	

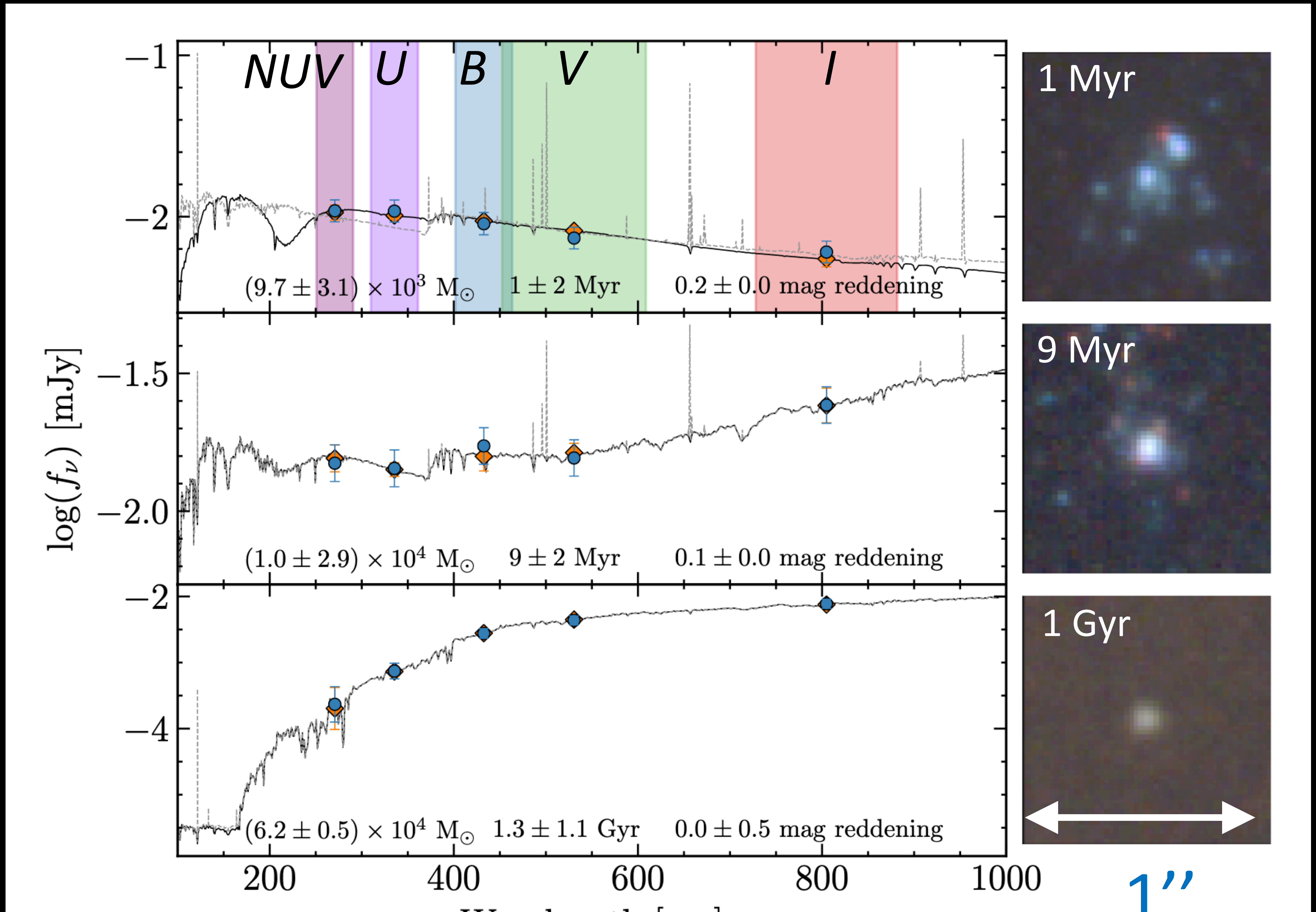
Evolution of the Elements | Galaxy Growth | Living Worlds | Solar Systems in Context

What can we do with a much larger cluster sample?

Reference cluster & compact assn sample from 17/38 galaxies (N~500)



Deger, JCL+22

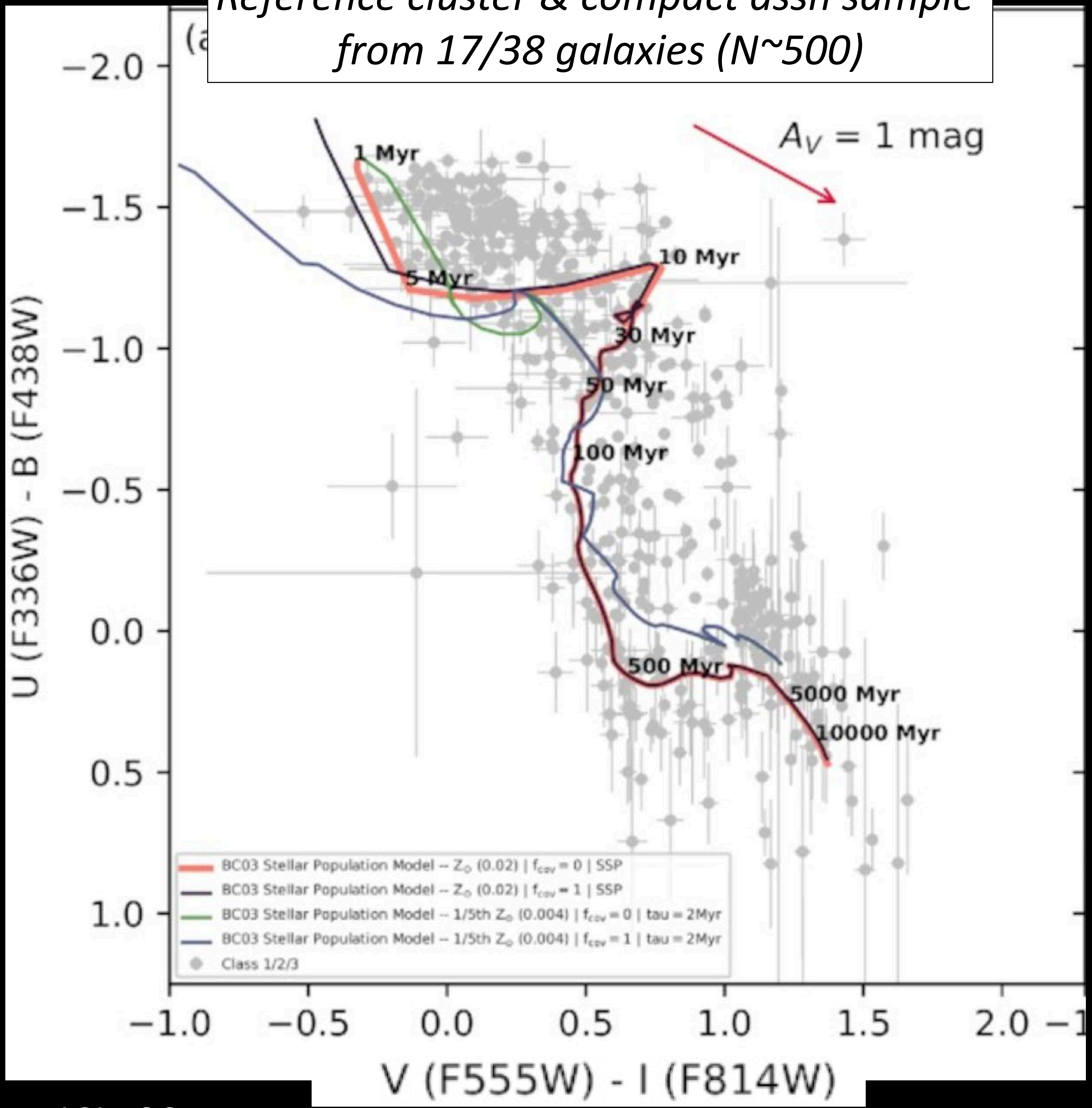


Turner+20

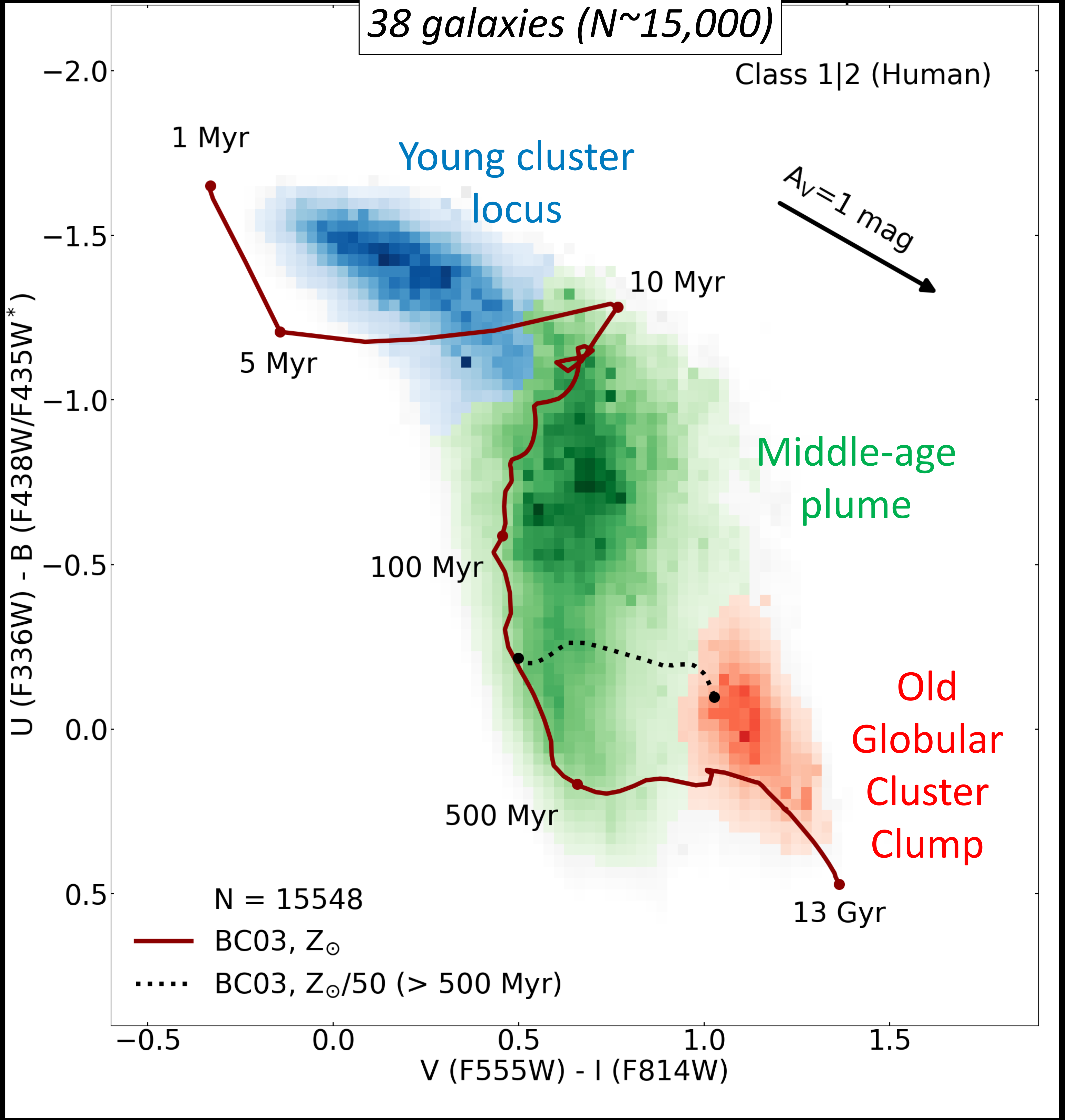
Ages, M*, E(B-V) SED fits - CIGALE (Boquien+19)

What can we do with a much larger cluster sample?
Color distribution reveals three features

Reference cluster & compact assn sample from 17/38 galaxies (N~500)



Bright cluster sample 38 galaxies (N~15,000)



Deger, JCL+22

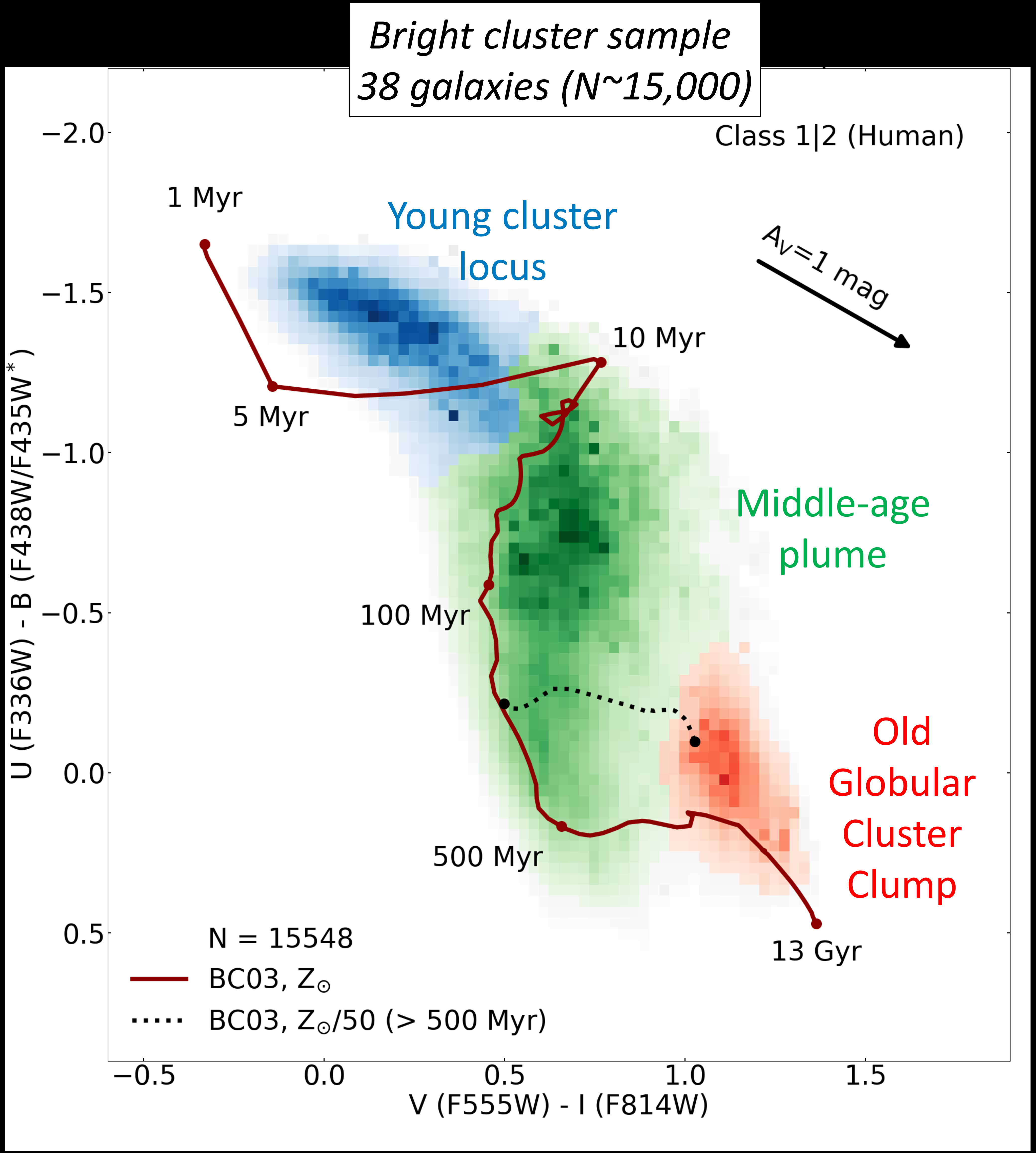
What can we do with a much larger cluster sample?
Color distribution reveals three features

3 principal features observed
- young cluster locus (YCL)
- middle-aged plume (MAP)
- old globular cluster clump (OGC)

slope of the YCL consistent with reddening vector

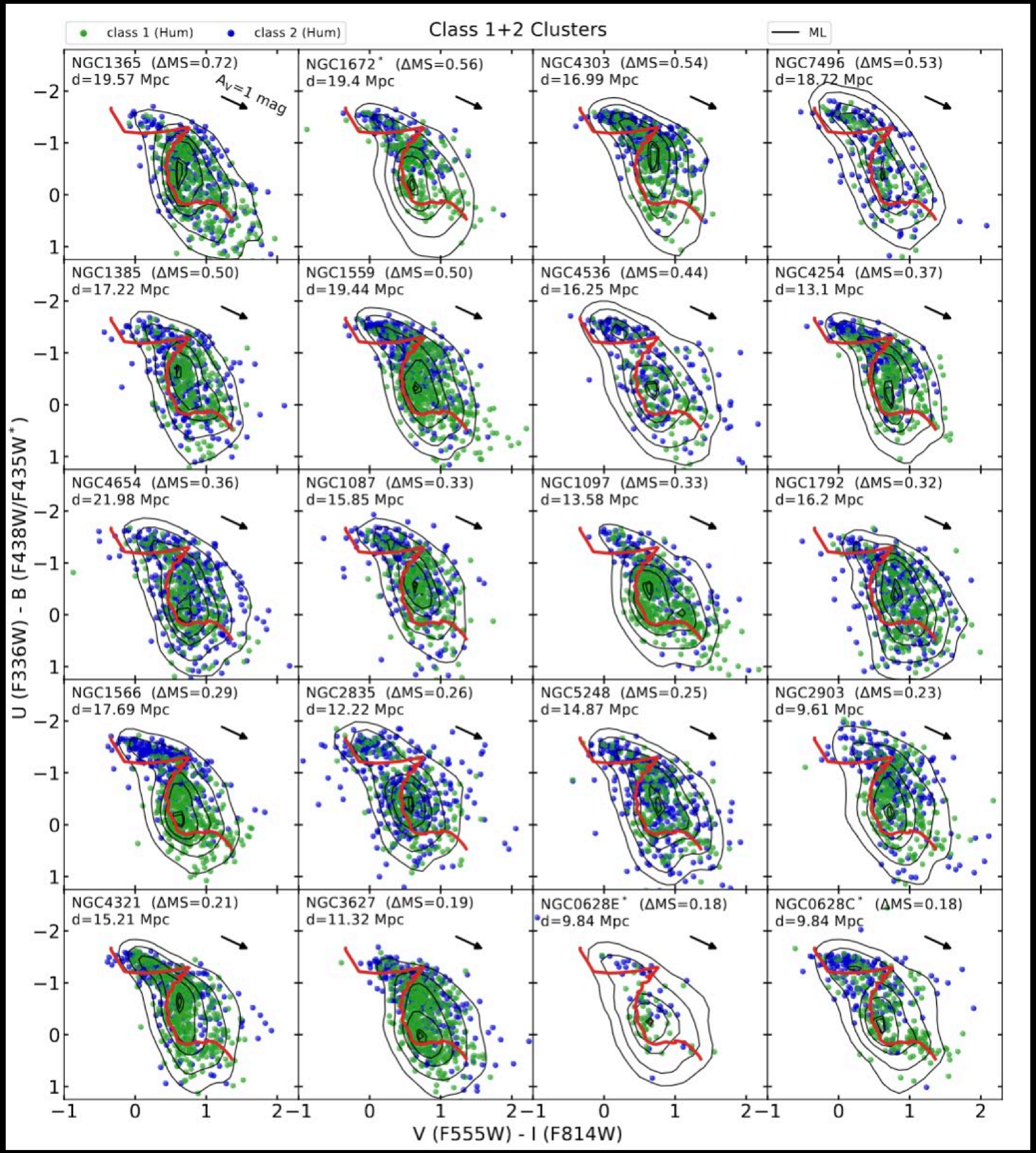
MAP left edge show remarkable consistency with solar metallicity BC03 SSP

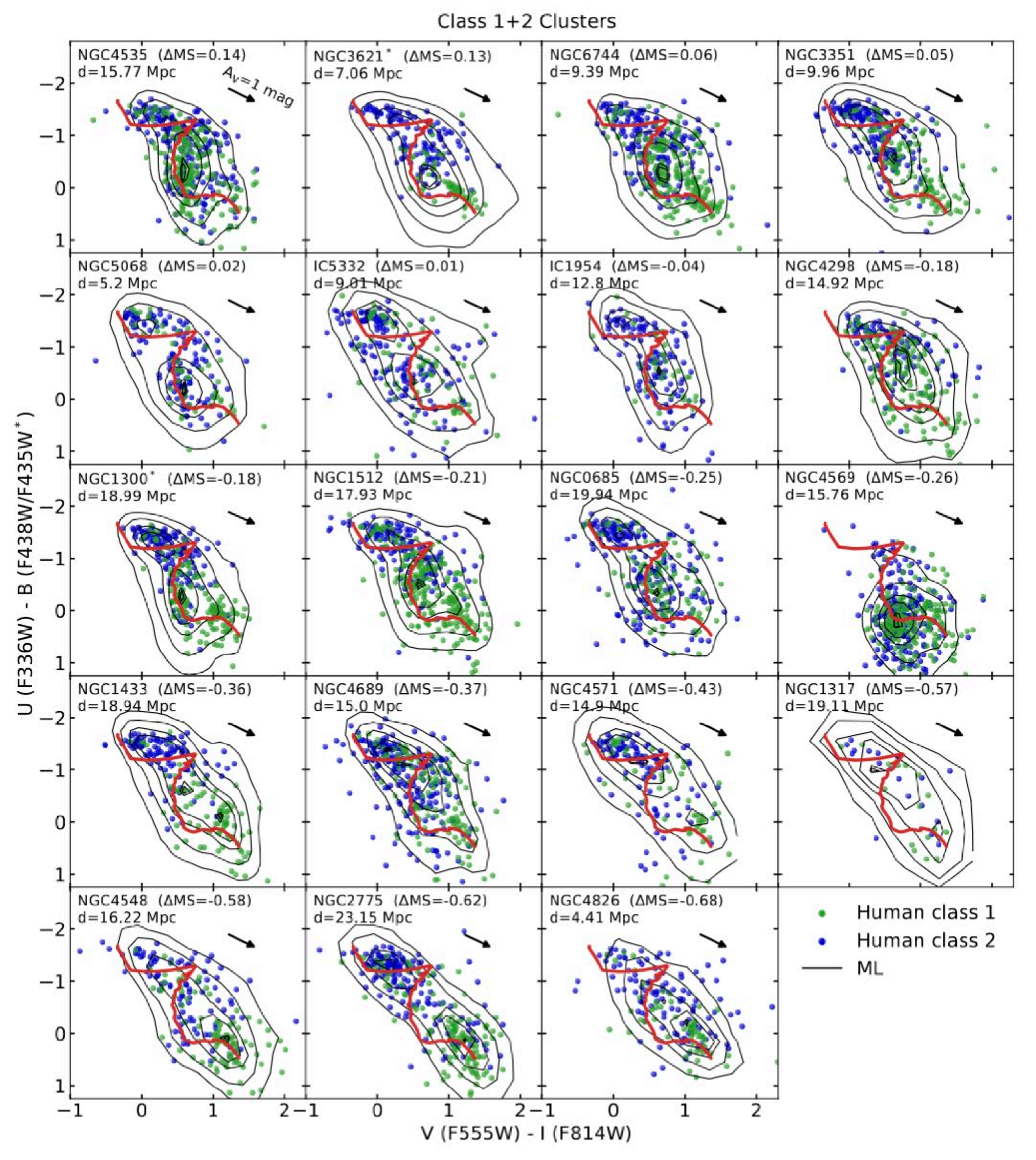
OGC separate into a distinct clump, consistent with their metal-poor nature



DM, JCL, DT, BCW, SD + 24

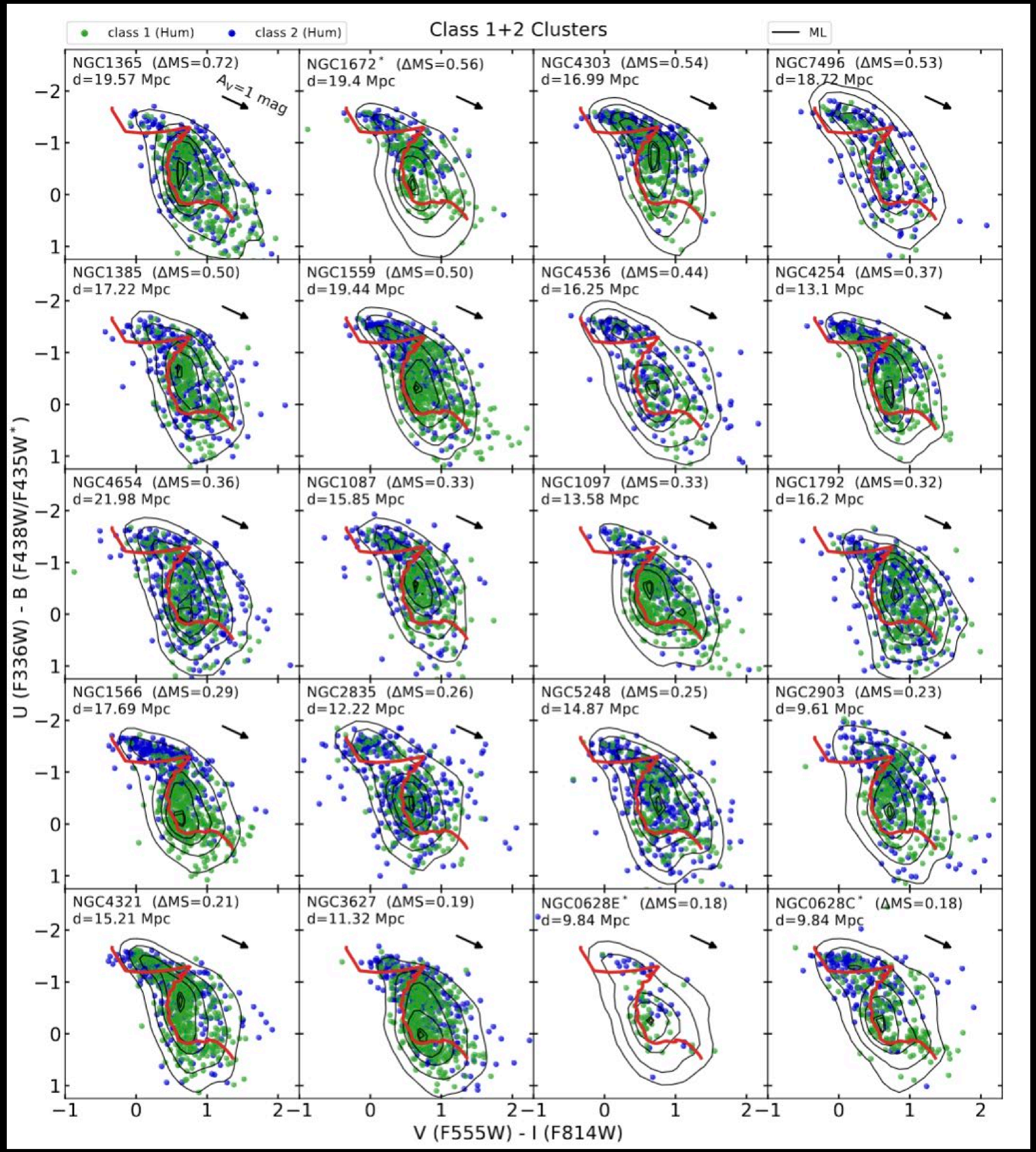
Color distribution of clusters in individual galaxies

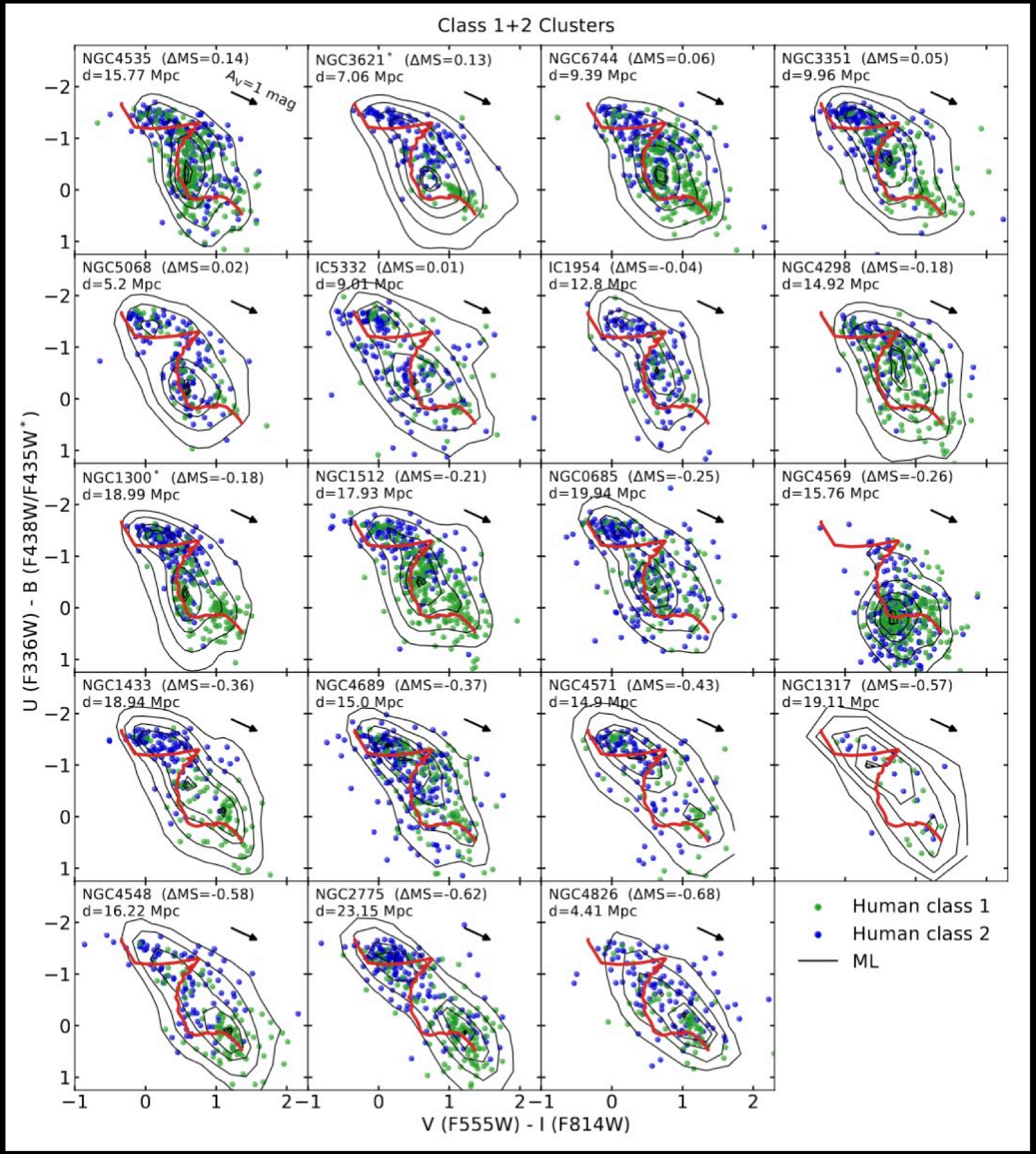




DM, JCL, DT, BCW, SD + 24

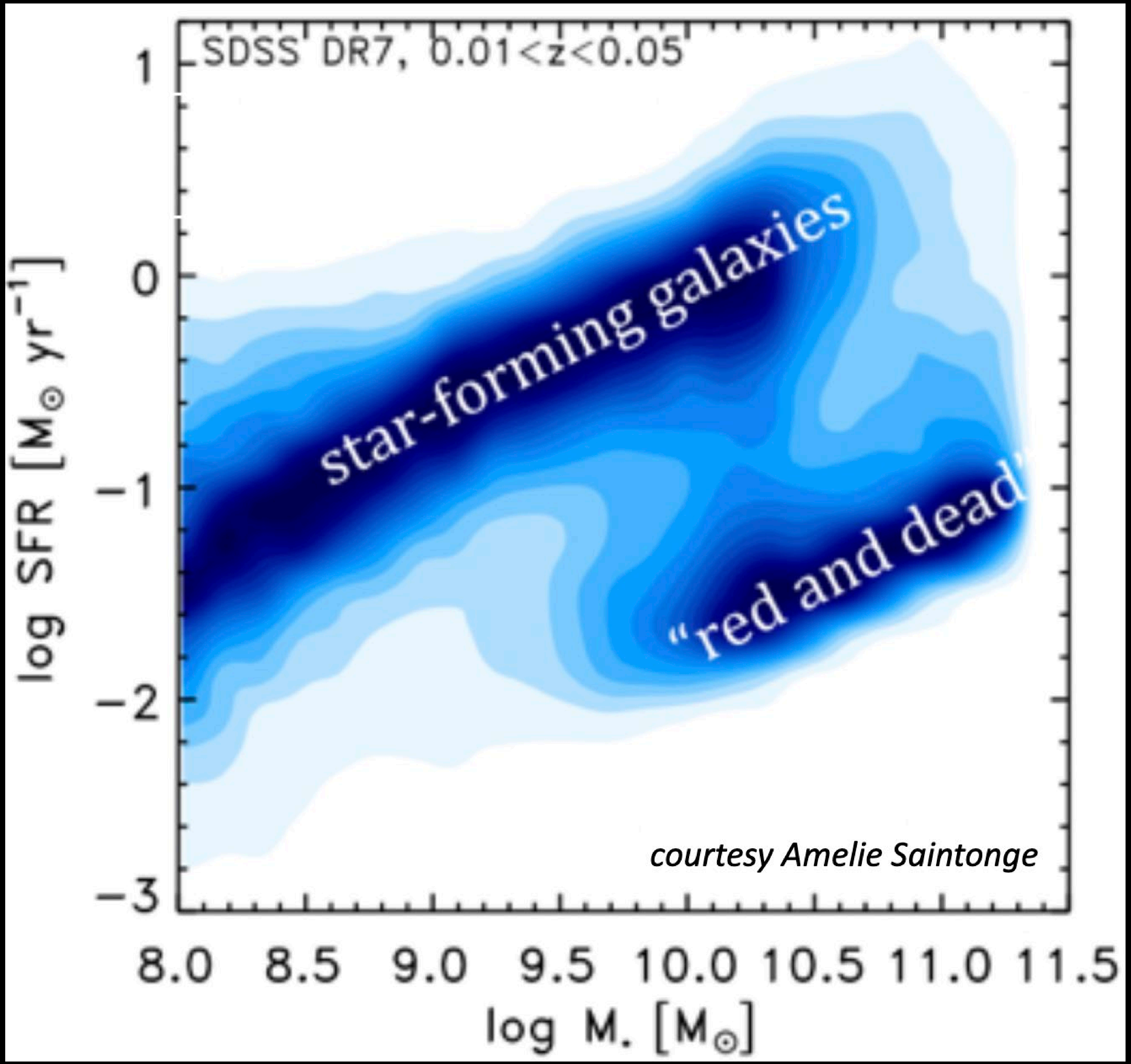
Theme 3: How can we connect small-scale physics to global galaxy properties?

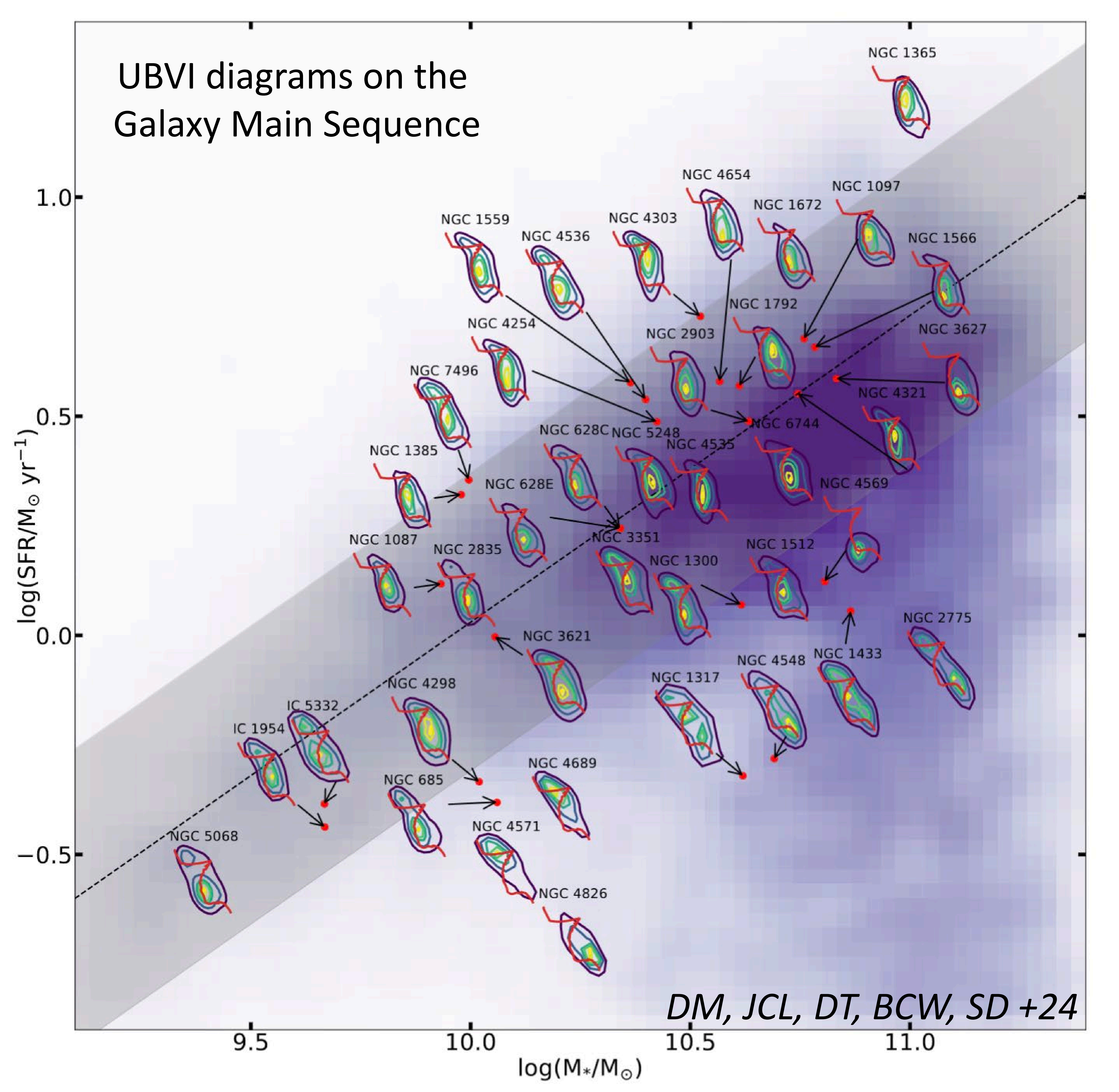




DM, JCL, DT, BCW, SD + 24

Color distribution of clusters in individual galaxies on the galaxy main sequence

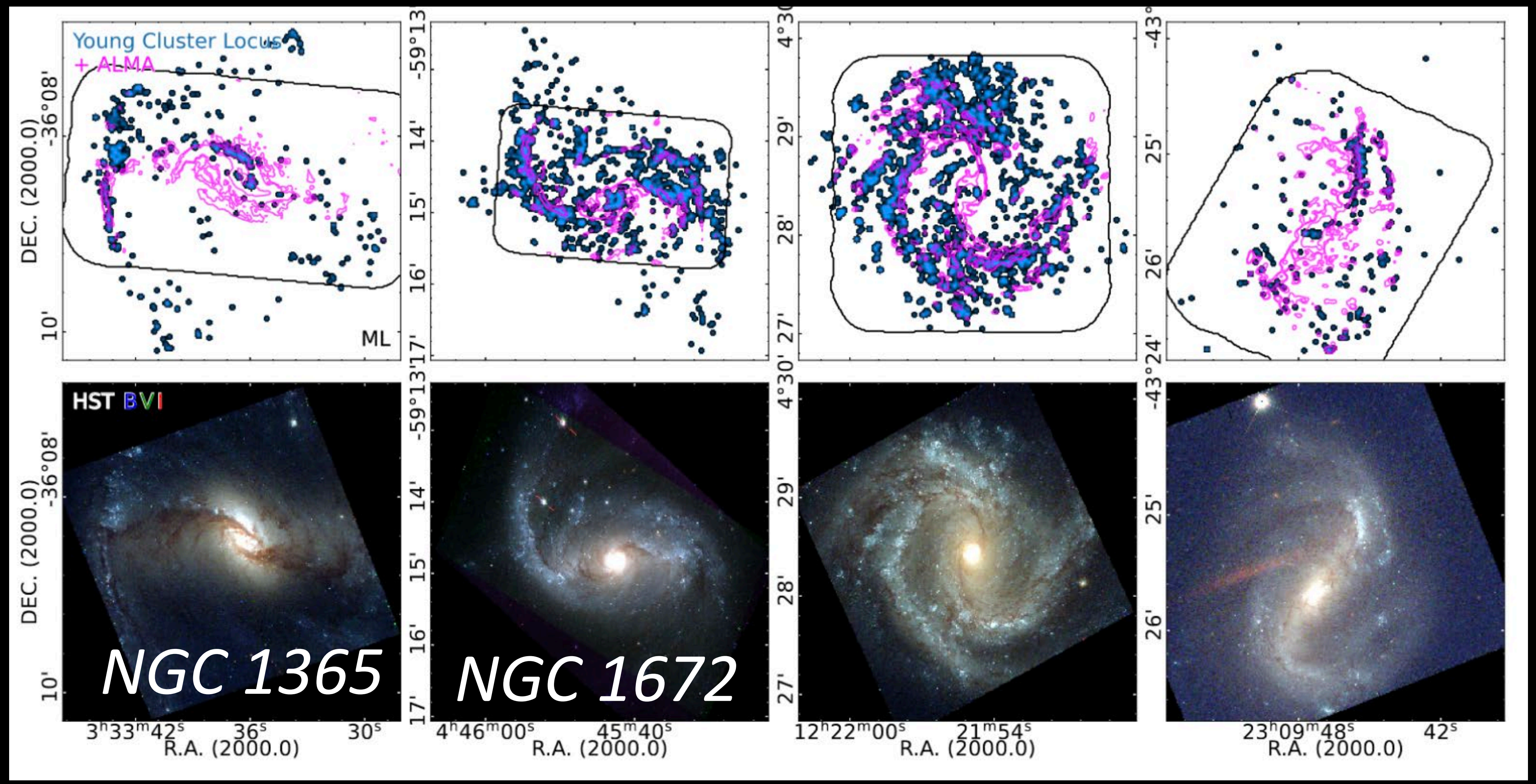


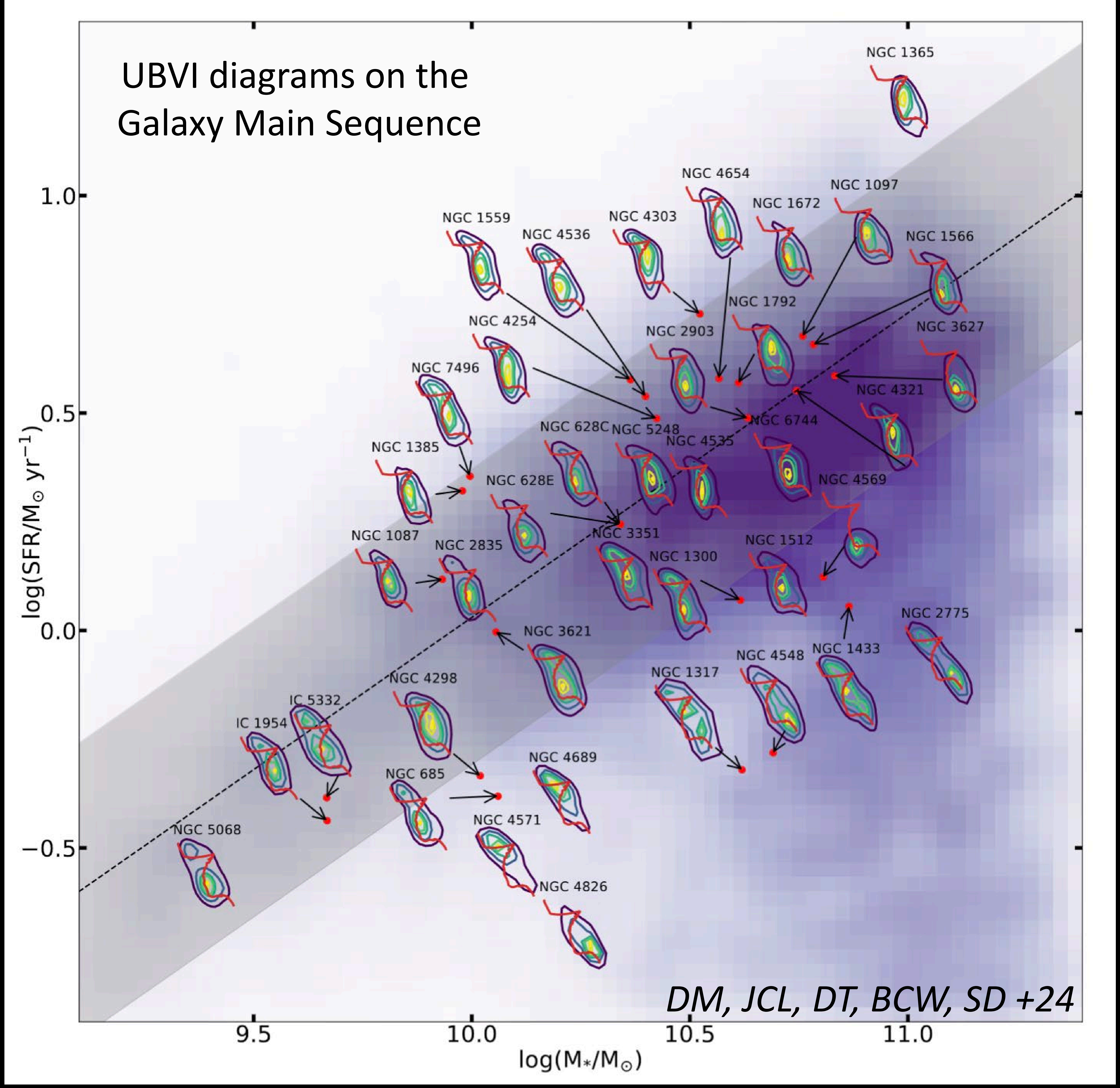


Above main sequence young cluster locus is weak
Clusters trace rings, bar ends; dusty

- strong bars feed central star forming rings, drive high SFR, promote cluster formation
- Clusters trace rings & bar ends
- Clusters tend to be dusty

Spatial distribution of young clsuters





Hubble census of star cluster and stellar associations

UBVI color-color diagram as a diagnostic tool

A reference sample for stellar, cluster, galaxy evolution

~15,000 Human classified clusters across 38 galaxies (C1+C2)

3 principal features observed

- young cluster locus (YCL)
- middle-aged plume (MAP)
- old globular cluster clump (OGC)

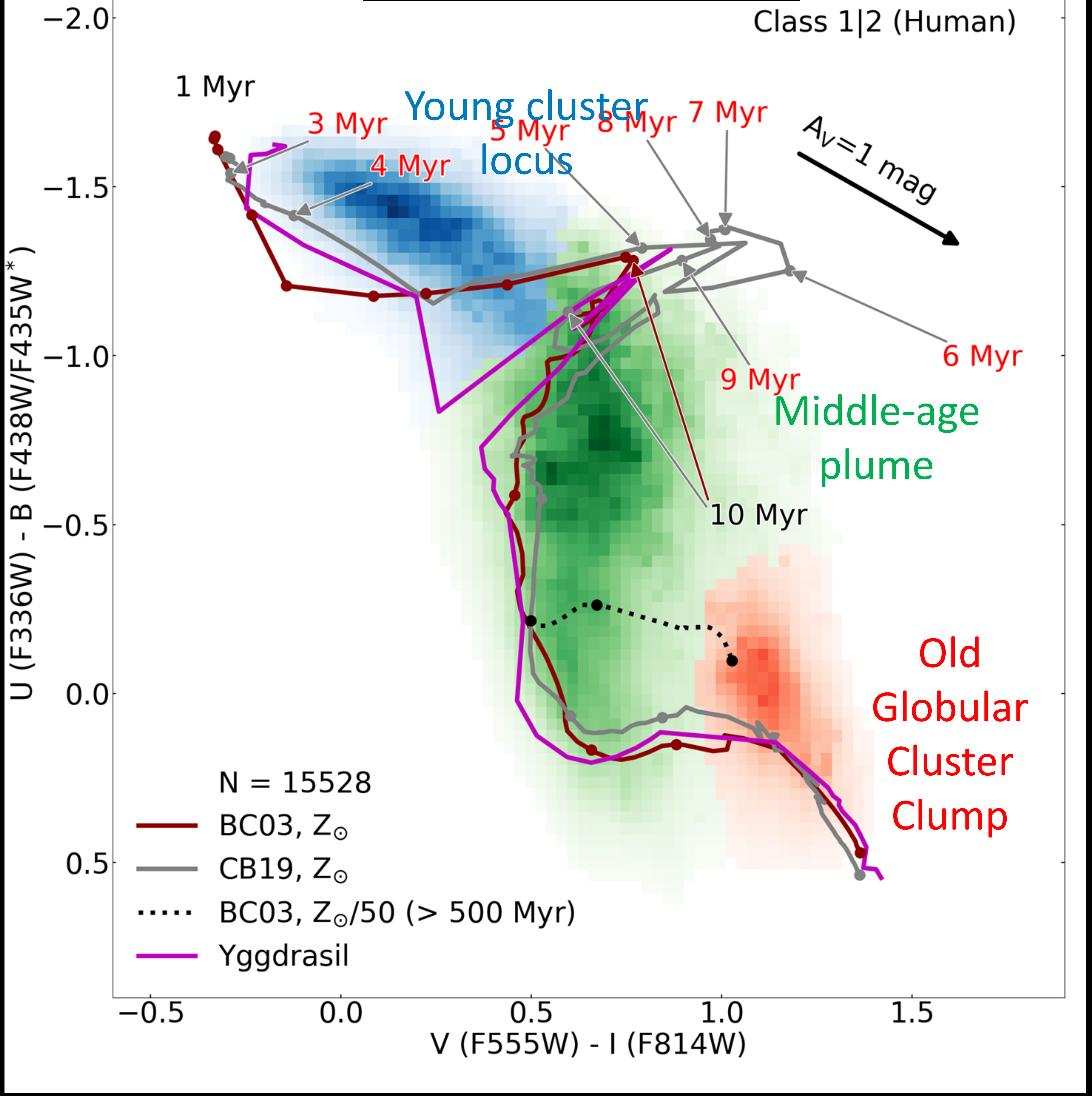
slope of the YCL consistent with reddening vector

MAP left edge show remarkable consistency with solar metallicity BC03 SSP

OGC separate into a distinct clump, consistent with their metal-poor nature

Provides a new test of SSP models

Bright cluster sample 38 galaxies (N~15,000)



DM, JCL, DT, BCW, SD + 24

The processes that drive, regulate, extinguish star formation operate together over stellar, interstellar, galactic, circumgalactic scales to help create the extraordinary structures in nearby galaxies.

The processes that drive, regulate, extinguish star formation operate together over stellar, interstellar, galactic, circumgalactic scales to help create the extraordinary structures in nearby galaxies.

PHANGS Hubble Treasury Survey (Lee+22)

Pictures of the Week (ESA)

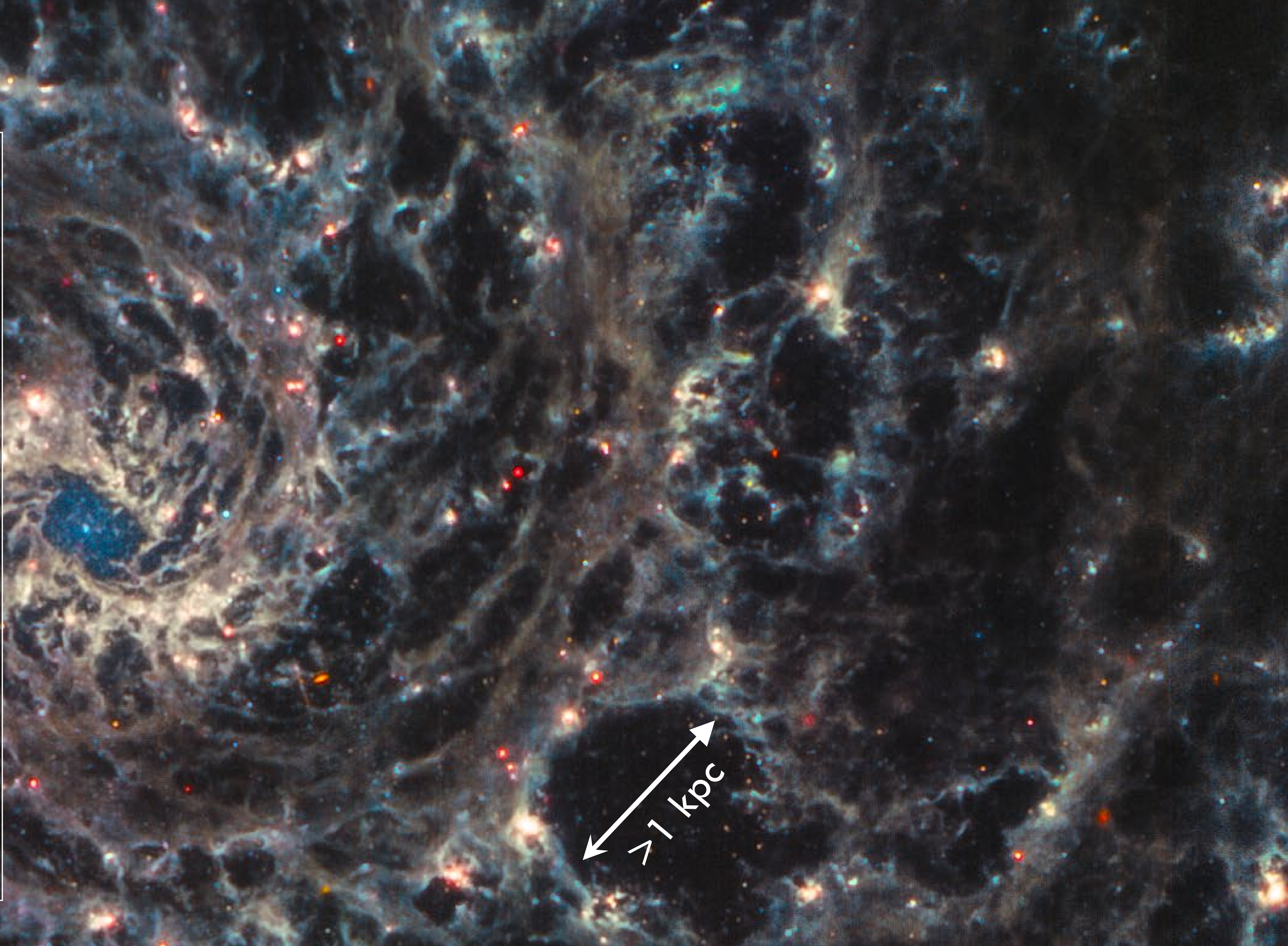
The processes that drive, regulate, extinguish star formation operate together over stellar, interstellar, galactic, circumgalactic scales to help create the extraordinary structures in nearby galaxies.

PHANGS JWST Jan 2024 NASA Release
Depasquale, Pagan, OPO/STScI (Lee+23)

Key Conclusion

SL25: [The data] suggest a period of cloud collapse on the order of the free-fall or turbulent crossing time (~10–30 Myr) followed by forming massive stars and subsequent rapid (<5 Myr) gas clearing after the onset of star formation.

Meanwhile, the short gas-clearing timescales suggest a large role for presupernova feedback in cloud disruption. This leaves the supernovae free to exert a large influence on the larger galaxy, including stirring turbulence, launching galactic-scale winds, and carving superbubbles.



Watkin, Barnes+23; Barnes, Watkins+23
Bubbles in JWST F770W imaging consistent with being feedback-driven incl "Phantom Void"

NGC 628 - MIRI F770W/F1000W/F1130W/F2100W
Image Credit: NASA / ESA / CSA / Judy Schmidt

Key Conclusion

SL25: [The data] suggest a period of cloud collapse on the order of the free-fall or turbulent crossing time (~10–30 Myr) followed by forming massive stars and subsequent rapid (<5 Myr) gas clearing after the onset of star formation.

Meanwhile, the short gas-clearing timescales suggest a large role for presupernova feedback in cloud disruption. This leaves the supernovae free to exert a large influence on the larger galaxy, including stirring turbulence, launching galactic-scale winds, and carving superbubbles.

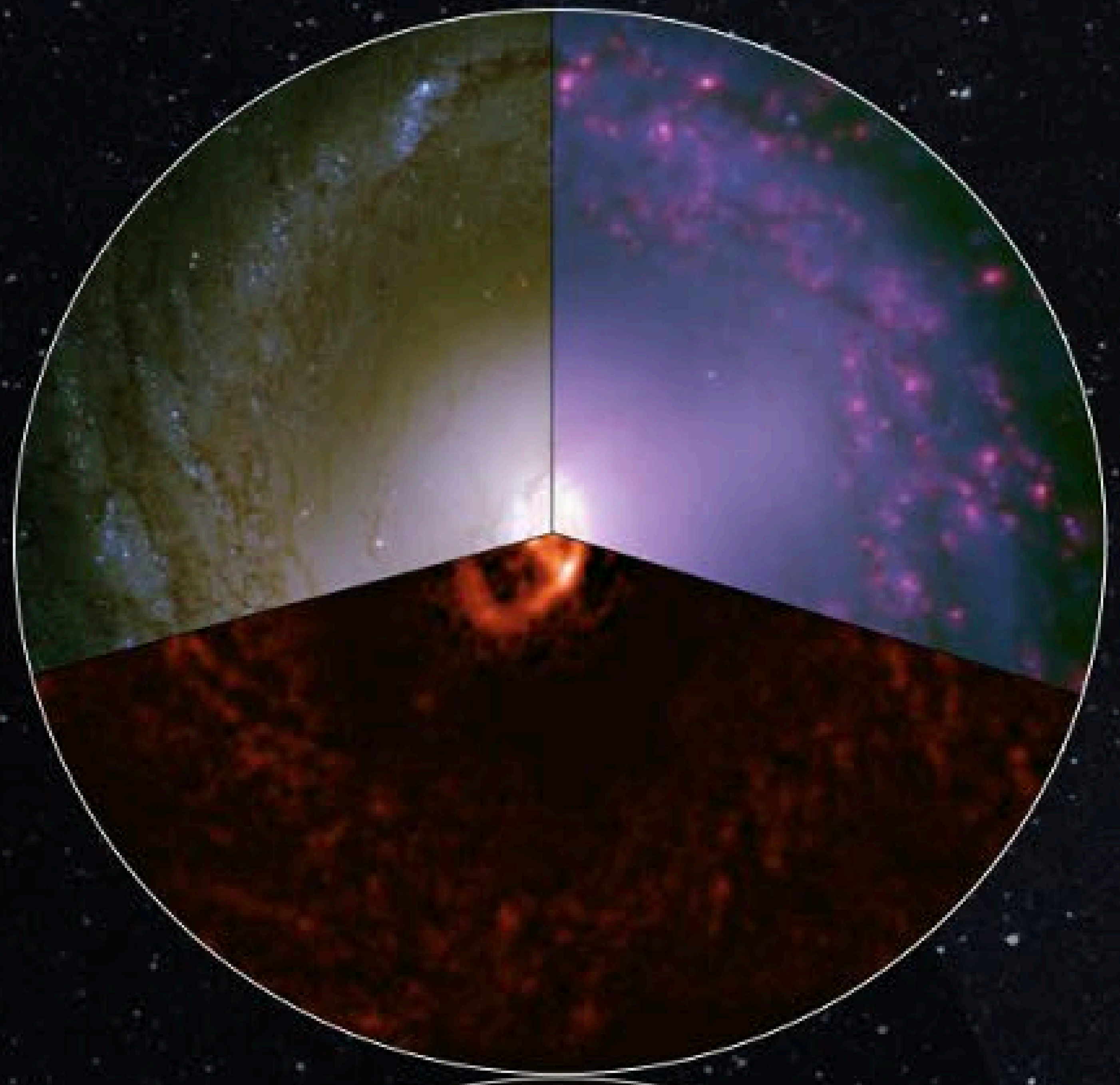
Today's talk: What's the evidence?
Leveraging star clusters as clocks

NGC 628 - MIRI F770W/F1000W/F1130W/F2100W
Image Credit: NASA / ESA / CSA / Judy Schmidt

PHANGS

Schinnerer+19

International collaboration of >100 members



Physics at High Angular resolution in Nearby GalaxieS

www.phangs.org

Lee+23

Leroy+21a

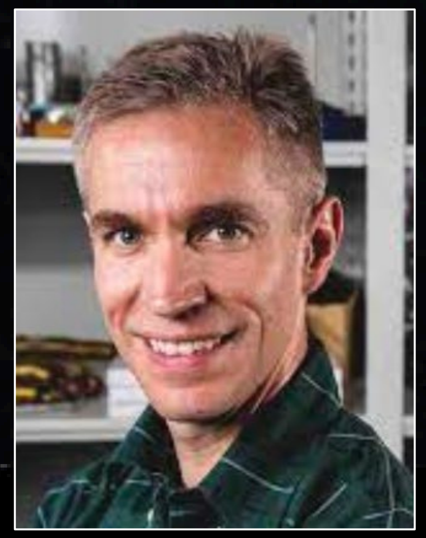
ALMA

MUSE
multi unit spectroscopic explorer

Emsellem+22

HST

Lee+22



Reference dataset for multi-phase, multi-scale study of star formation and ISM

gas & dust → clouds, stars & clusters → galaxy disks

A census of ~100,000 star clusters and associations across 38 galaxies

D. Maschmann

PHANGS-HST catalogs for ~100,000 star clusters and compact associations in 38 galaxies: I. Observed properties

Daniel Maschmann,[1] Janice C. Lee,[2,1,3] David A. Thilker,[4] Bradley C. Whitmore,[2] Sinan Deger,[5,6] Médéric Boquien,[7] Rupali Chandar,[8] Daniel A. Dale,[9] Aida Wofford,[10,11] Stephen Hannon,[12] Kirsten L. Larson,[13] Adam K. Leroy,[14] Eva Schinnerer,[12] Erik Rosolowsky,[15] Leonardo Úbeda,[2] Ashley T. Barnes,[16] Eric Emsellem,[16,17] Kathryn Grasha,[18,19,*] Brent Groves,[20] Rémy Indebetouw,[21,22] Hwihyun Kim,[3] Ralf S. Klessen,[23,24] Kathryn Kreckel,[25] Rebecca C. Levy,[1,†] Francesca Pinna,[26,27,12] M. Jimena Rodríguez,[1,28] Qiushi Tian,[29] and Thomas G. Williams[30]

[1] *Steward Observatory, University of Arizona, Tucson, AZ 85721, USA*
[2] *Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA*
[3] *Gemini Observatory/NSF's NOIRLab, 950 N. Cherry Avenue, Tucson, AZ, 85719, USA*

DM, JCL+24

D. Thilker

PHANGS-HST catalogs for ~100,000 star clusters and compact associations in 38 galaxies: II. Physical properties resulting from improved SED fitting methods

David A. Thilker,[1] Janice C. Lee,[2,3,4] Bradley C. Whitmore,[2] Rupali Chandar,[5] Daniel Maschmann,[3] Daniel A. Dale,[6] Sinan Deger,[7,8] Médéric Boquien,[9] Kiana Henny,[6] Aida Wofford,[10,11] Leonardo Úbeda,[2] Alessandro Razza,[12] Ashley T. Barnes,[13] Francesco Belfiore,[14] Frank Bigiel,[15] Kathryn Grasha,[16,17,*] Brent Groves,[18] Hwihyun Kim,[4] Ralf S. Klessen,[19,20] Justus Neumann,[21] Francesca Pinna,[22,23,21] M. Jimena Rodríguez,[3] Erik Rosolowsky,[24] Eva Schinnerer,[21] and Thomas Williams[25]

[1] *Department of Physics and Astronomy, The Johns Hopkins University, Baltimore, MD 21218, USA*
[2] *Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA*

DT, JCL+25

PHANGS HST & JWST Stellar Pops Group

Janice Lee (STScI, PI)

Brad Whitmore (STScI)

David Thilker (JHU)

Rupali Chandar (U Toledo)

Daniel Dale (U Wyoming)

Aida Nava Wofford (U Ensenada)

Mederic Boquien (U Côte d'Azur)

Kirsten Larson (STScI)

Remy Indebetouw (Uva/NRAO)

Gagandeep Anand (STScI)

+Leonardo Ubeda (STScI)

+Oleg Gnedin (U Michigan)

Postdocs, *Grads*, *Interns*

M. Jimena Rodriguez (STScI)

Sumit Sarbadhicary (JHU)

Daniel Maschmann (U Wyoming)

Matthew Floyd (U Toledo)

Kiana Henny (U Wyoming)

Stephen Hannon (MPIA)

Sinan Deger (Cambridge)

Qiushi Chris Tian, Sophia Rivera (JHU)

HST & JWST Stellar Populations Group

PHANGS-HST census of ~100,000 star clusters and compact assns

Technical pipeline efforts:

- *Survey, pipeline summary (Lee+22)*
- *Source detection & candidate selection (Whitmore+21, Thilker+22)*
- *Photometry & aperture corrections (Deger+22)*
- *CNN cluster morphological classification (Wei+20, Whitmore+21, Hannon+23)*
- *SED fitting with CIGALE (Turner+21)*
- *TRGB distances (Anand+21)*
- *Associations id (Larson+23)*
- *Catalogs (Maschmann+24, Thilker+25)*

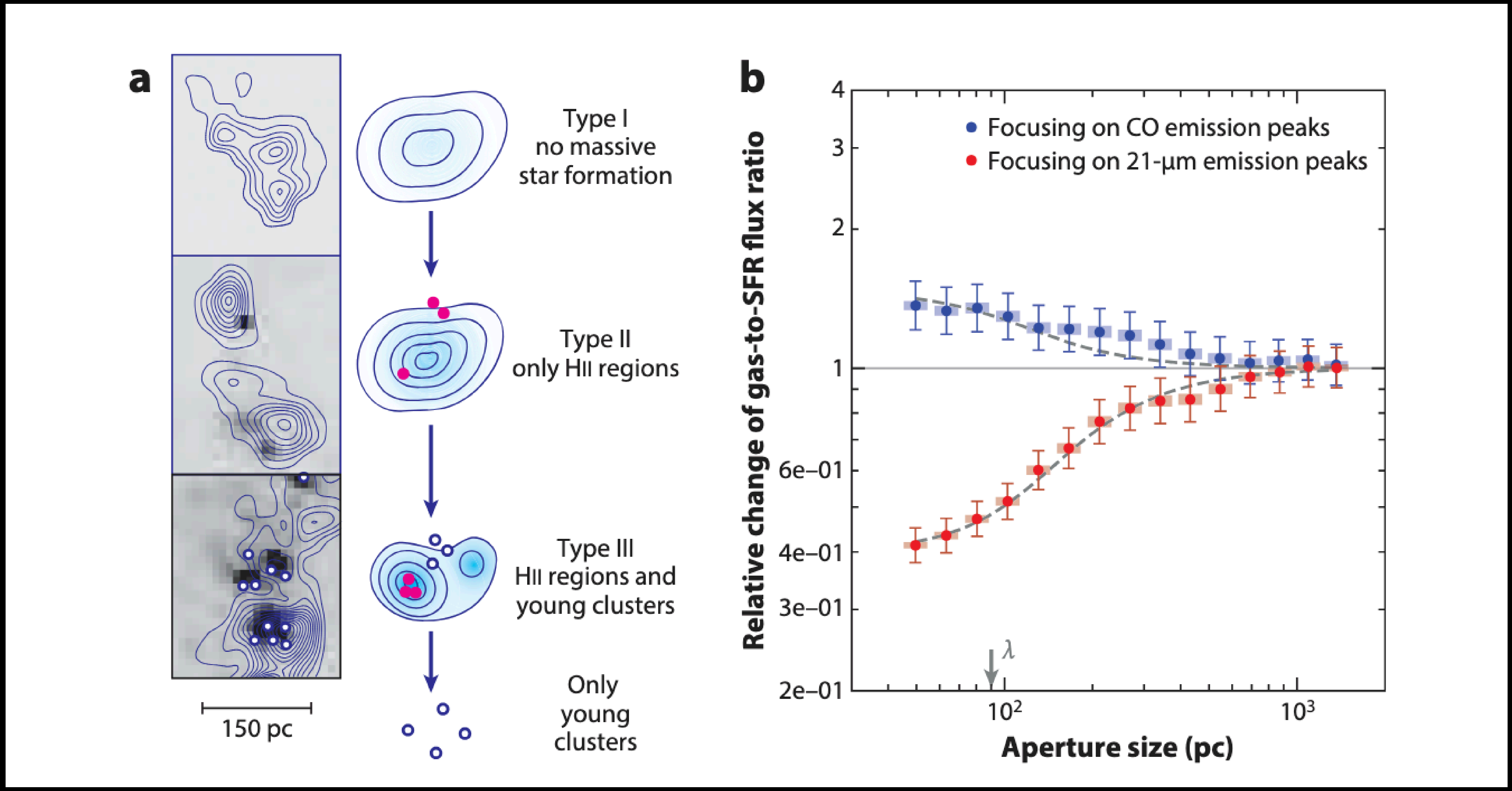
The utility of star clusters

Star clusters:

- Trace the densest peaks of the star formation hierarchy
- Bright and observable to large distances*
- Cosmic clocks - (effectively) single-age populations - connect stars to gas & time ISM processes**

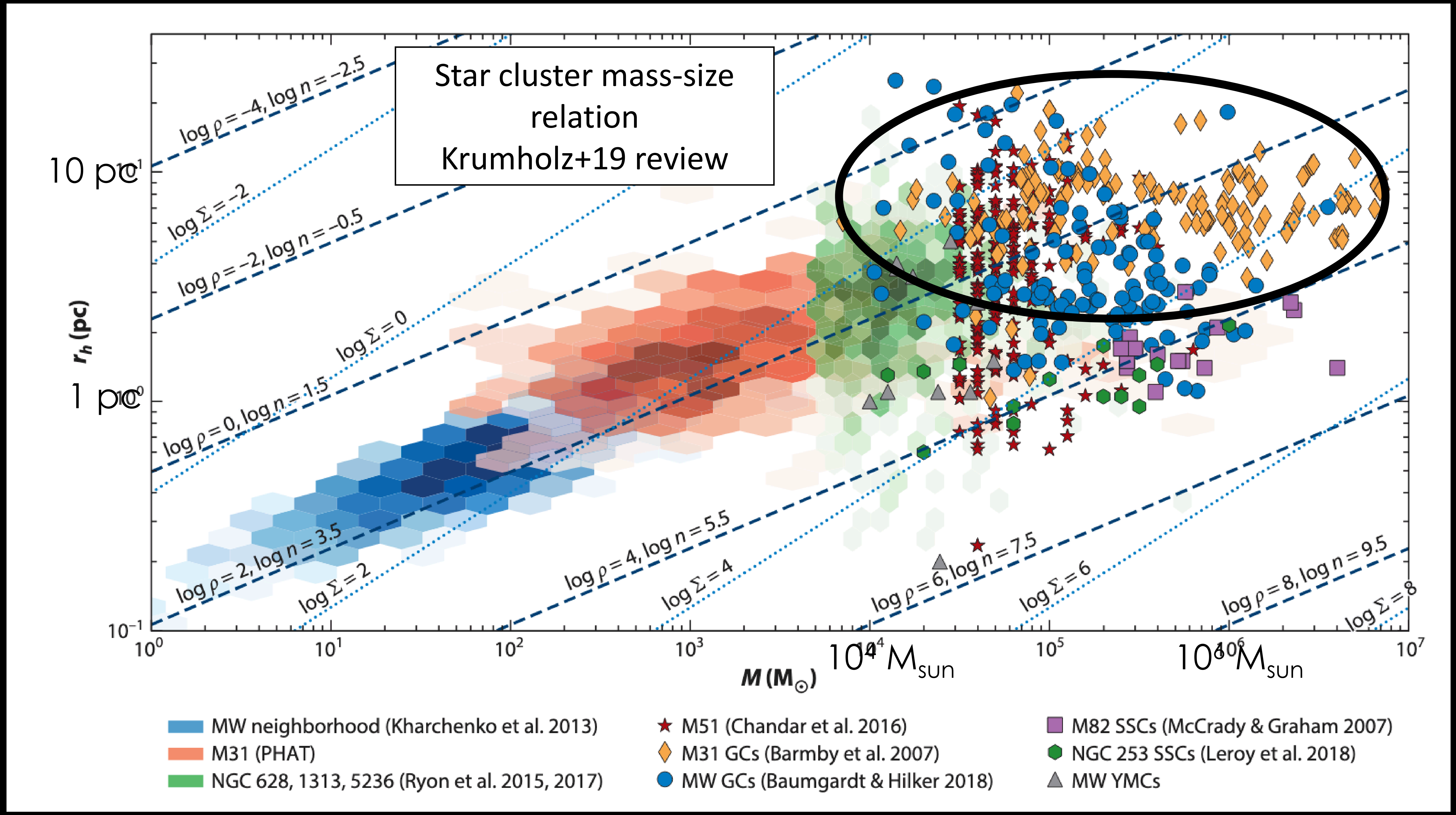
** to z~10 with lensing! "Cosmic Gems" (Adamo+24; Mayer+25)*

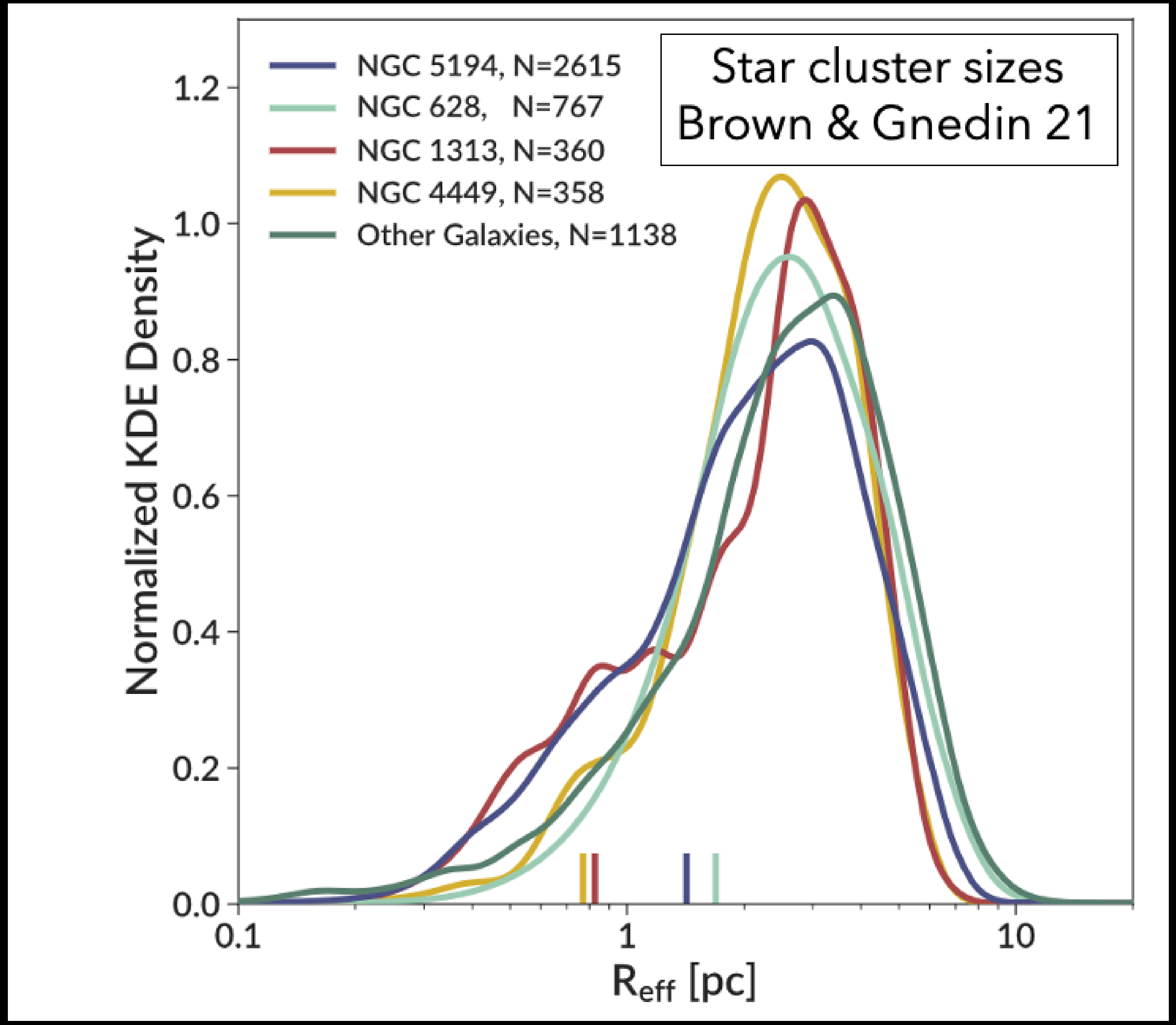
***clusters-as-clocks independent complement to "tuning fork" method on ~100pc cloud scale (e.g., Kruijssen+2018, Kim+25, Ramambason+25, Romanelli+21)*



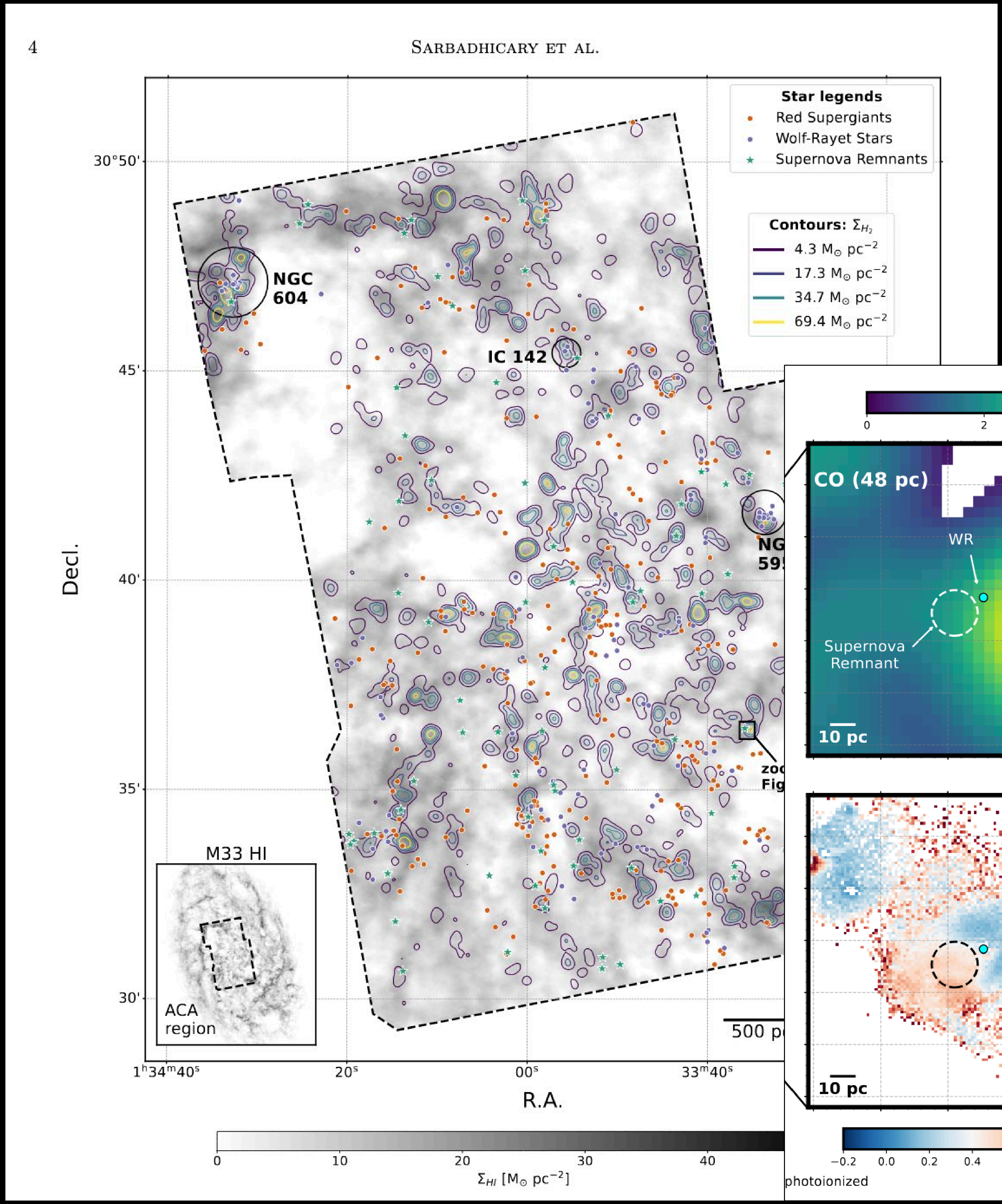
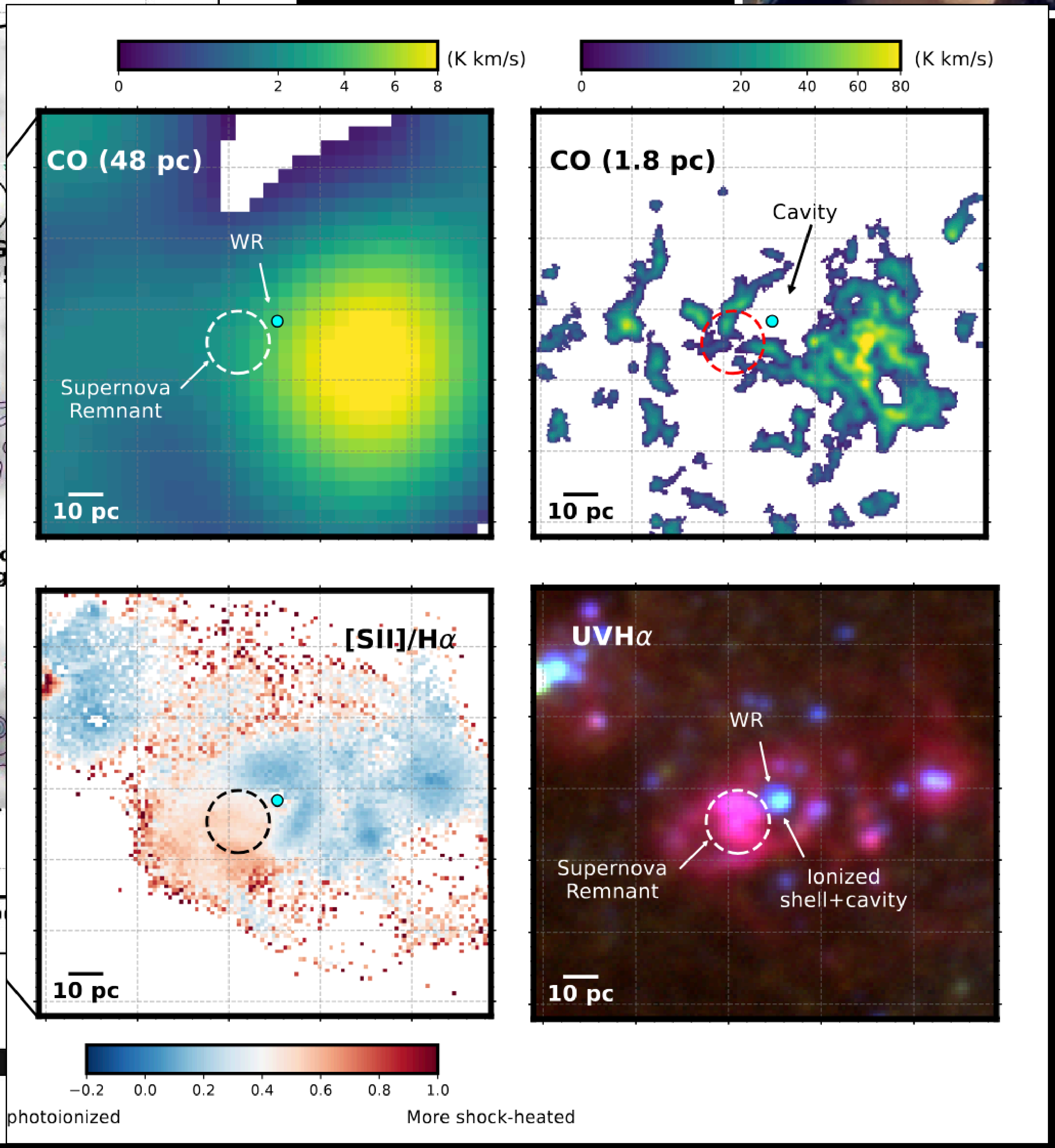
Kawamura+09 & Kim+23 reproduced in SL25

Probes smaller scales
star clusters sizes: ~few pc





Consistent picture from study of M33 RSG, WR, SNR

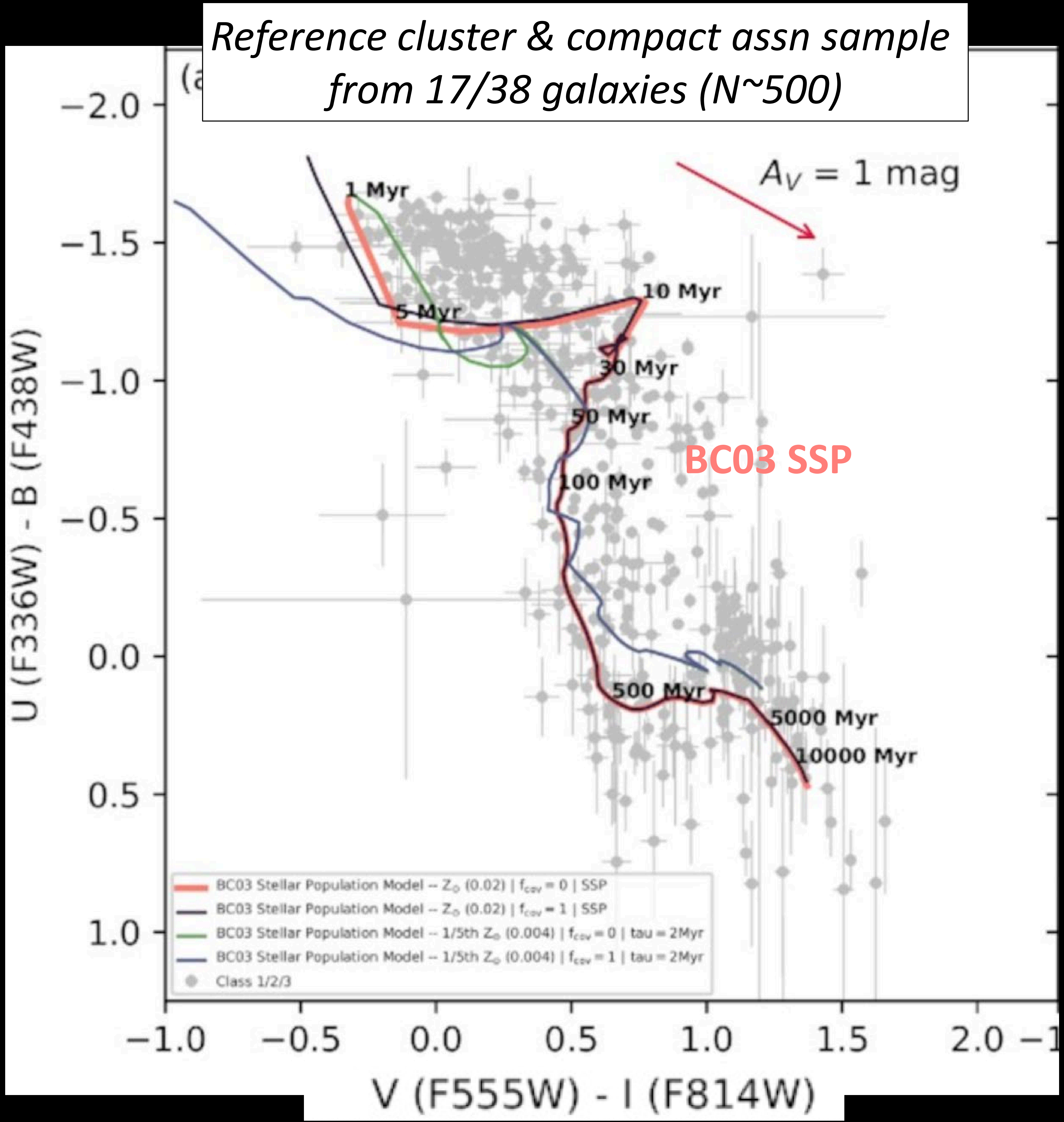



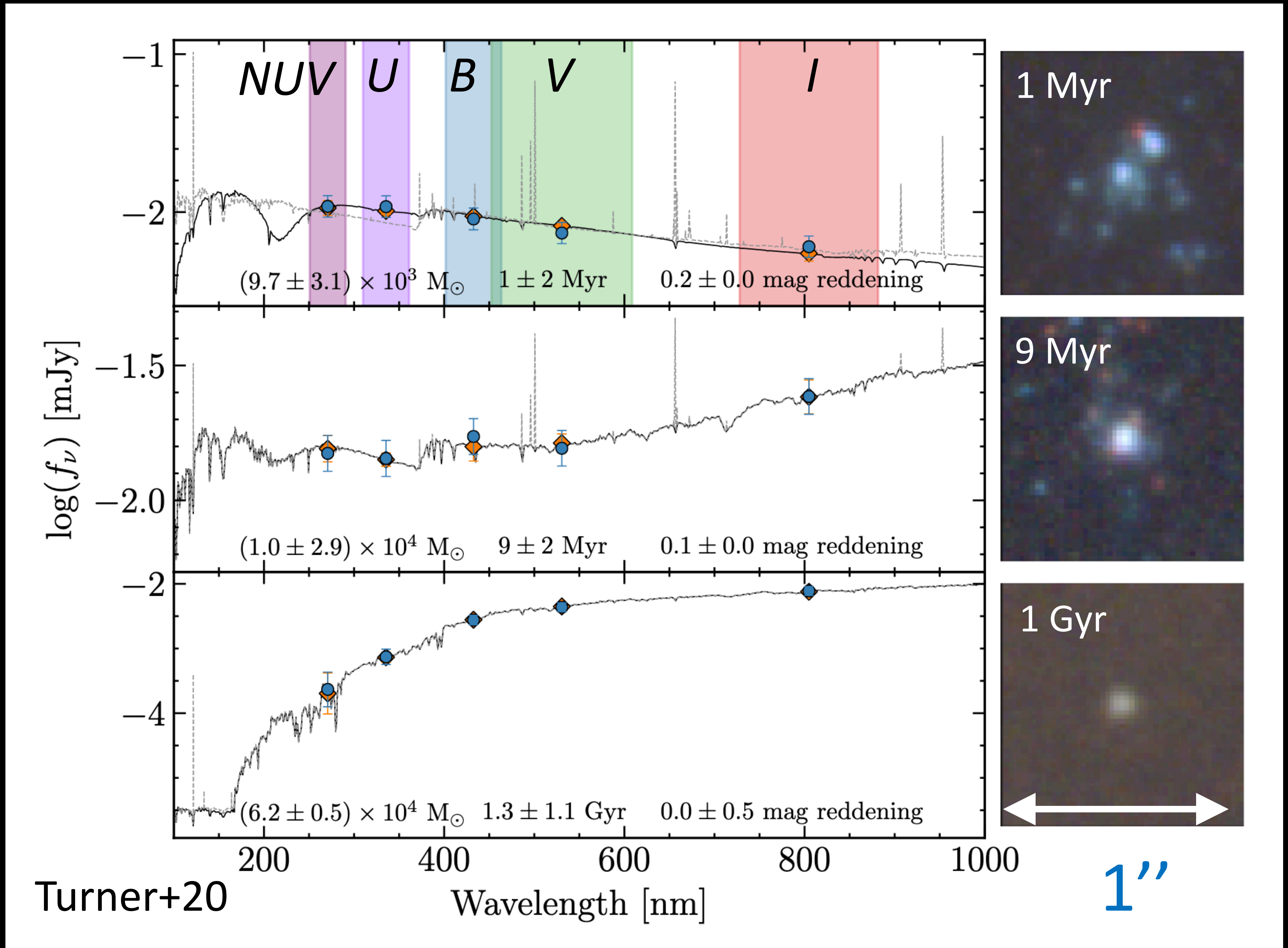
Sarbadhicary+23:

- *High fraction (~45% of WRs; higher for RSGs) in atomic-gas-dominated, inter-cloud media*
- *20-pc diameter molecular gas cavity around a WR revealed with high res (0."45) ALMA CO map*

importance of pre-SN feedback for evacuating the dense gas around massive stars before explosion & the high-res (pc-scale) surveys of multi-phase ISM in nearby galaxies

UBVI colors consistent with SSP (single age population)





Ages, M*, E(B-V) SED fits - CIGALE (Boquien+19)

Deger, JCL+22