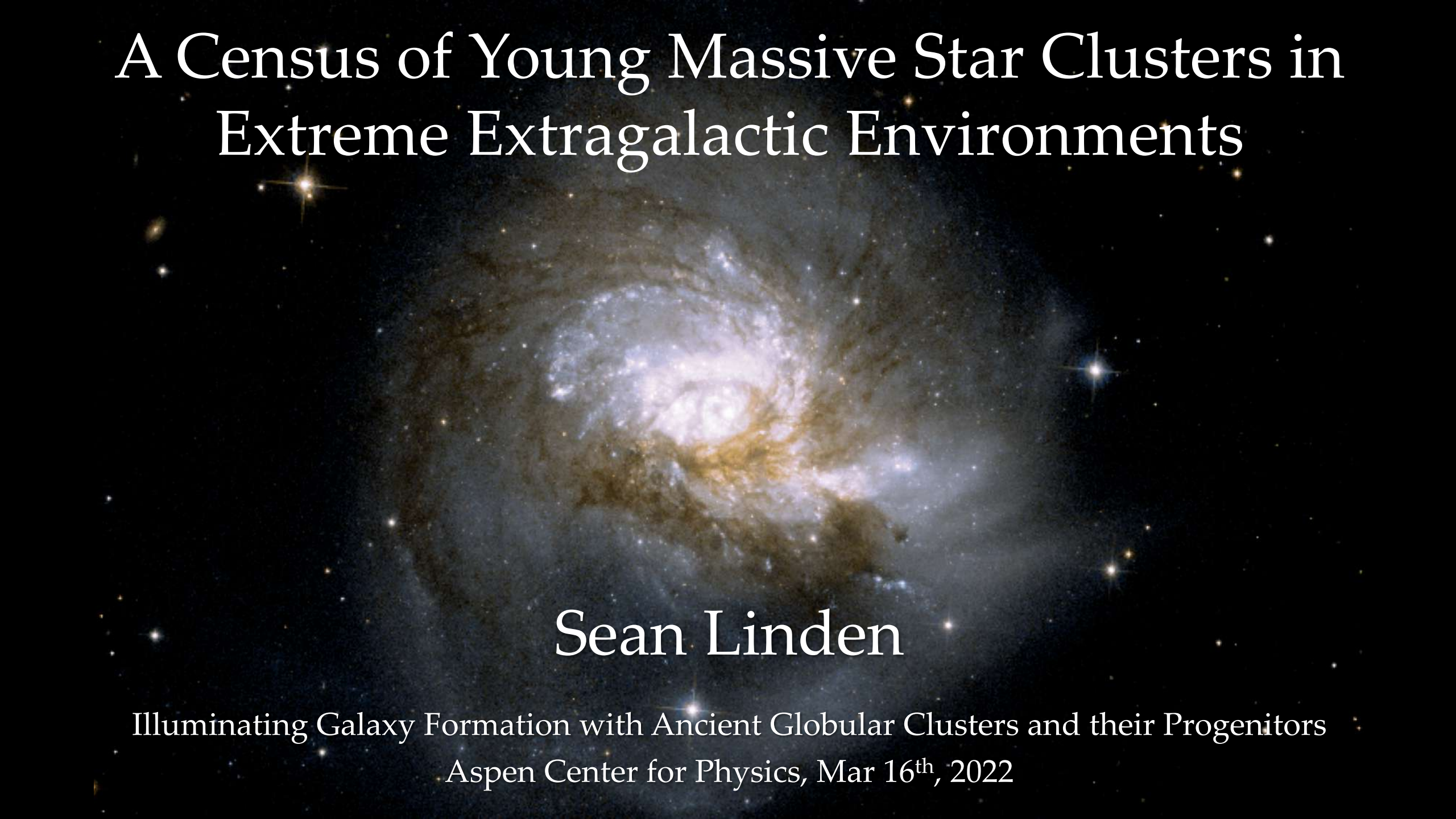
A Census of Young Massive Star Clusters in Extreme Extragalactic Environments

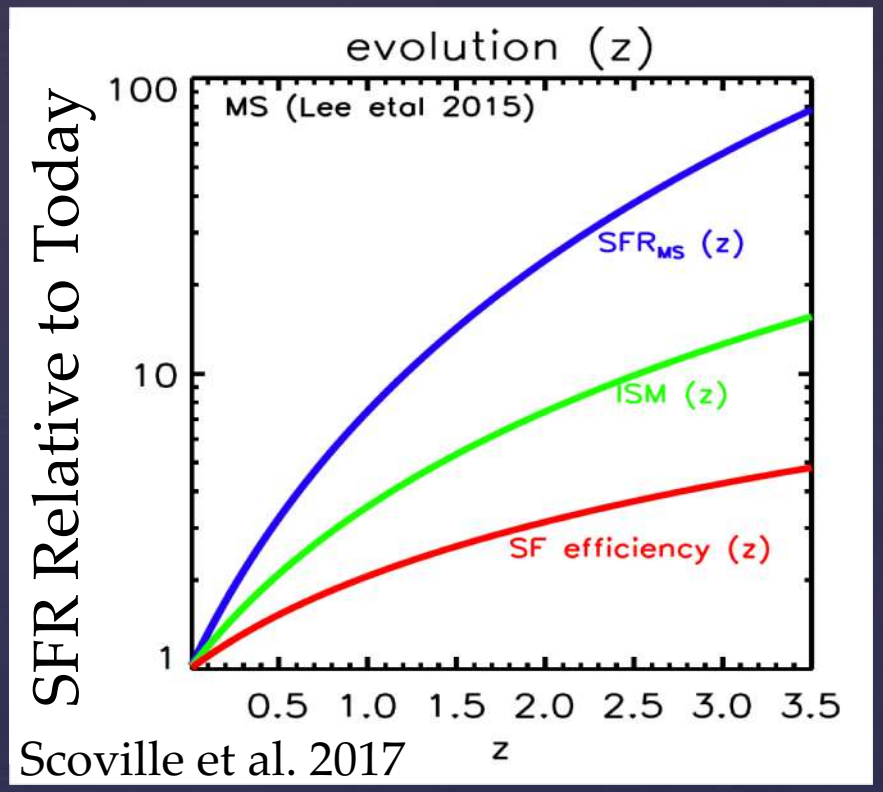


Sean Linden

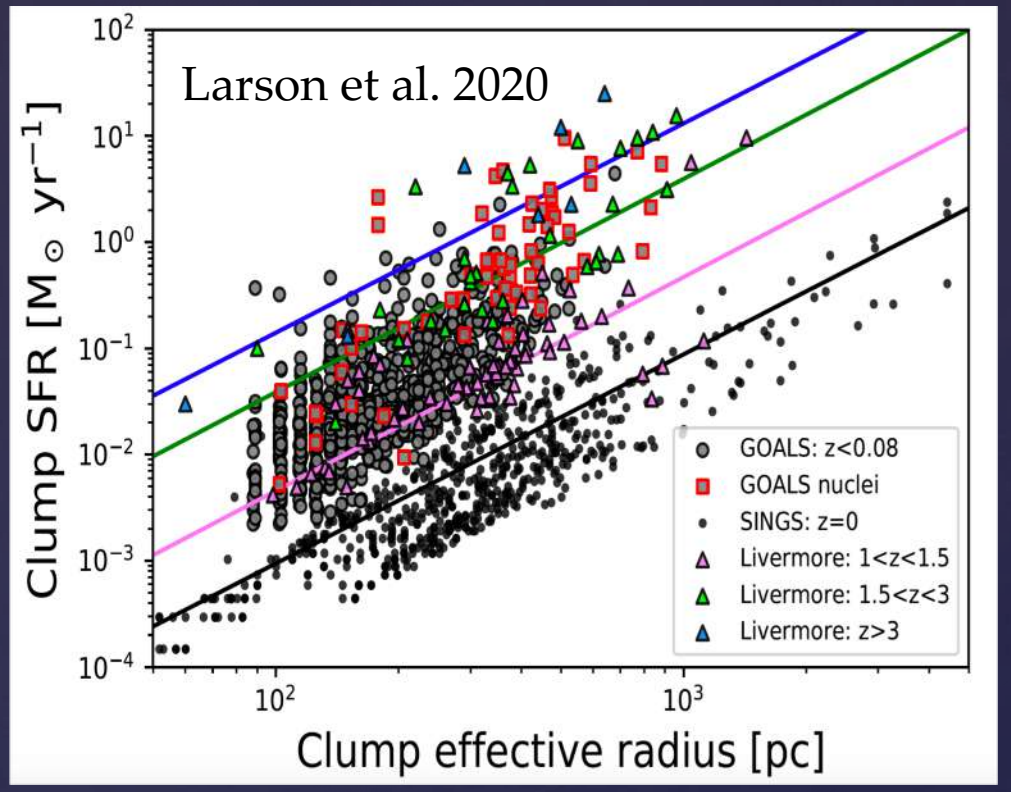
Illuminating Galaxy Formation with Ancient Globular Clusters and their Progenitors

Aspen Center for Physics, Mar 16th, 2022

The Evolution of Star Formation Activity



Scoville et al. 2017



- Galaxies at the peak epoch of SF activity (z~2: Madau & Dickinson) formed stars at 10-100 times higher rates than galaxies today
- Local luminous infrared galaxies (LIRGs) are gas and dust-rich (<fgas> = 33 % - Larson et al. 2015) and contain clumps comparable to high-redshift galaxies

Finding Local Analogs of High-Redshift Galaxies

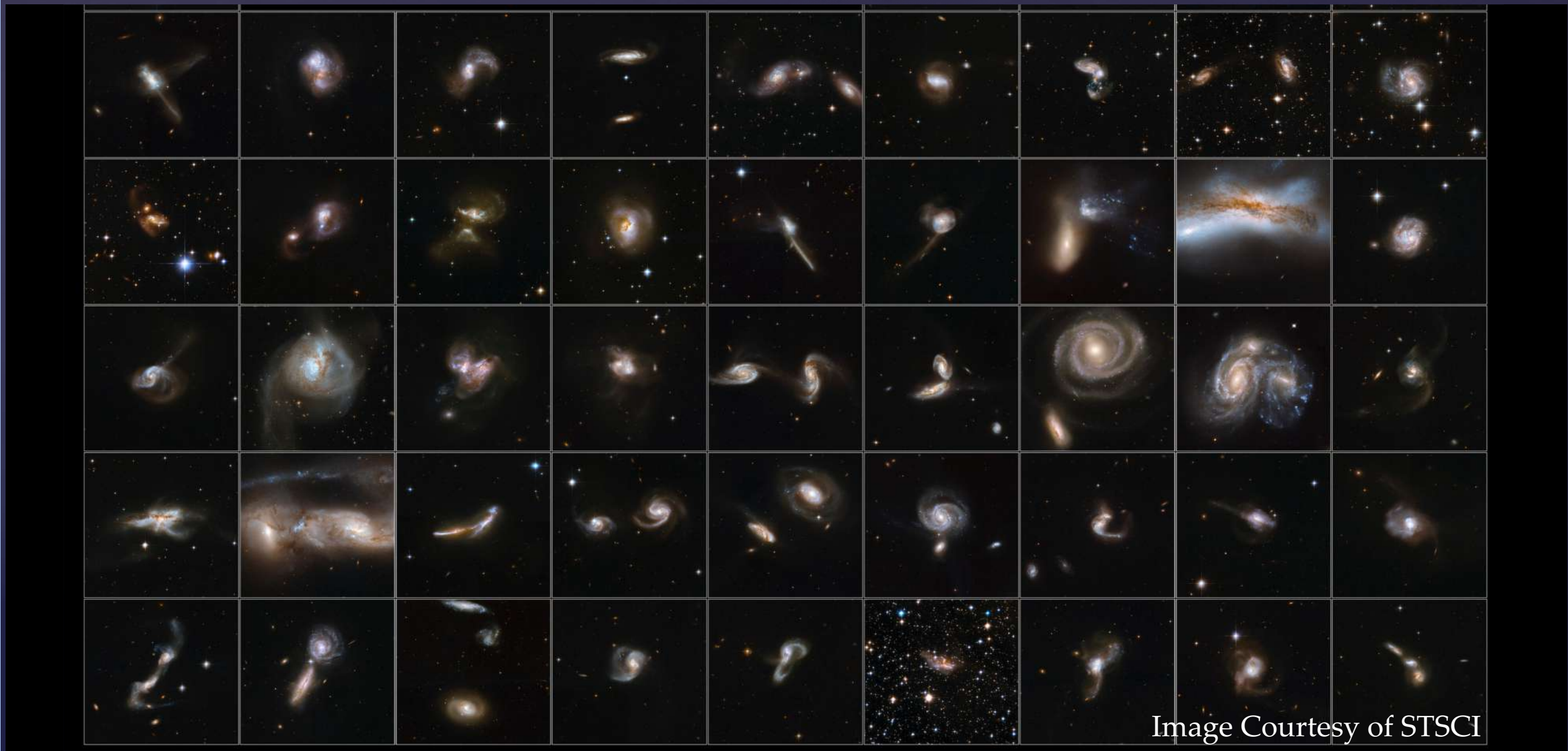


Image Courtesy of STSCI

Finding Local Analogs of High-Redshift Galaxies

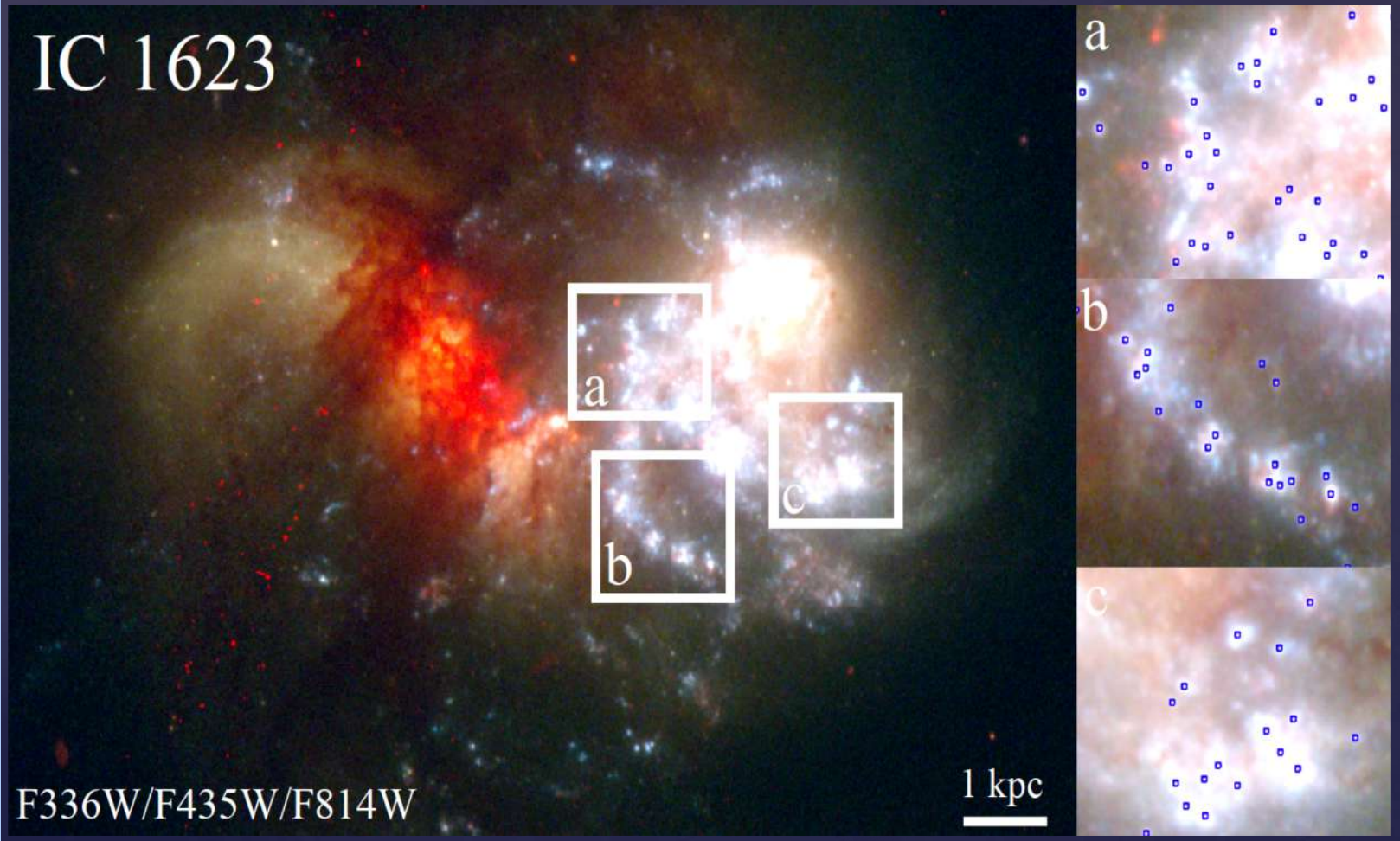
The Great Observatories All-Sky LIRG Survey (GOALS)

- The 201 brightest galaxies in the Revised Bright Galaxy Sample (Sanders et al. 2003, Armus et al. 2009)
- Survey includes a combination of space- and ground-based imaging and spectroscopic data from Chandra, GALEX, HST, JWST (soon!), Spitzer, Herschel, Keck, ALMA, JVLA, and more

Image Courtesy of STSCI

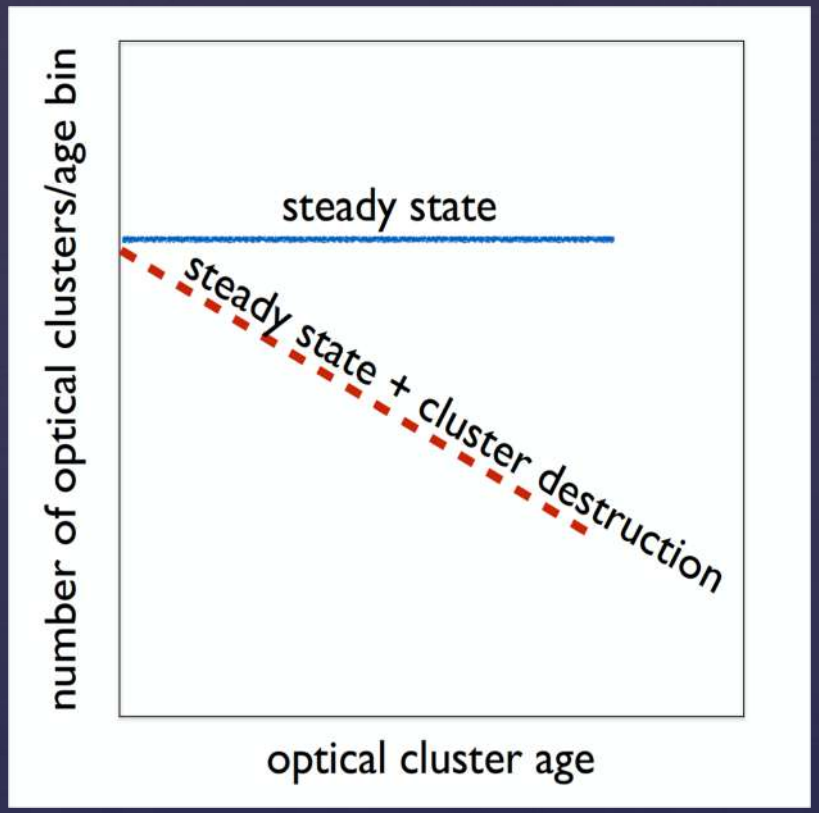
Massive Star Cluster Formation and Destruction in Luminous Infrared Galaxies in GOALS

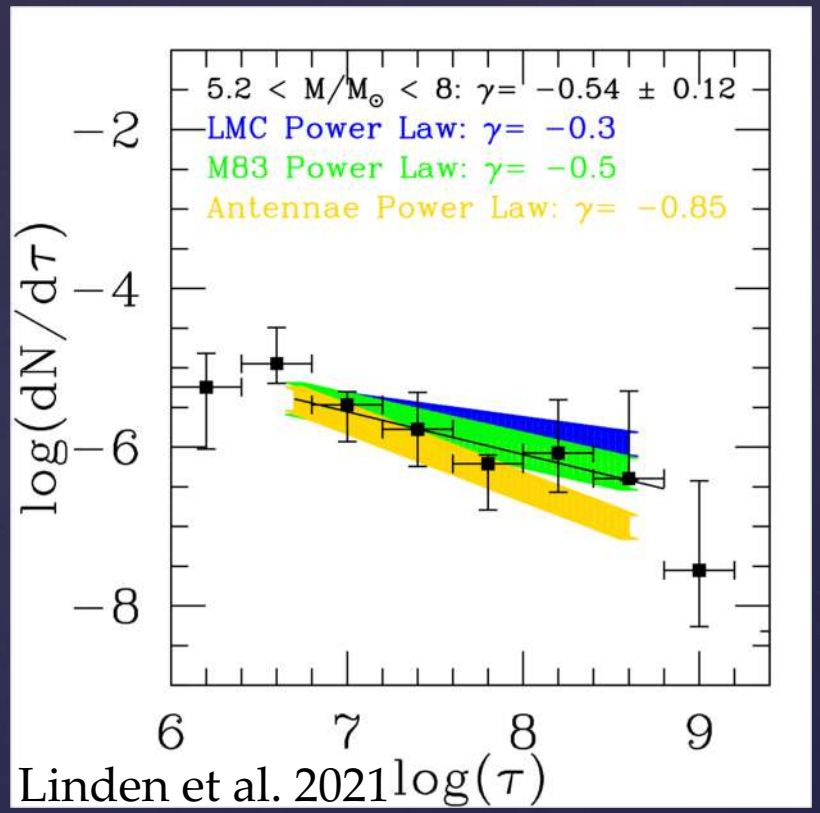
Linden et al. 2021



- HST WFC3 F336W for 10 galaxies in the GOALS JWST ERS + approved GTO targets – Cycle 25 program
- Star clusters identified with sextractor after local background subtraction
- Chi^2 minimization to derive age/mass/extinction with BC03 and SB99 models along with starburst dust attenuation law (Calzetti et al. 2000)

Massive Star Cluster Formation and Destruction in Luminous Infrared Galaxies in GOALS

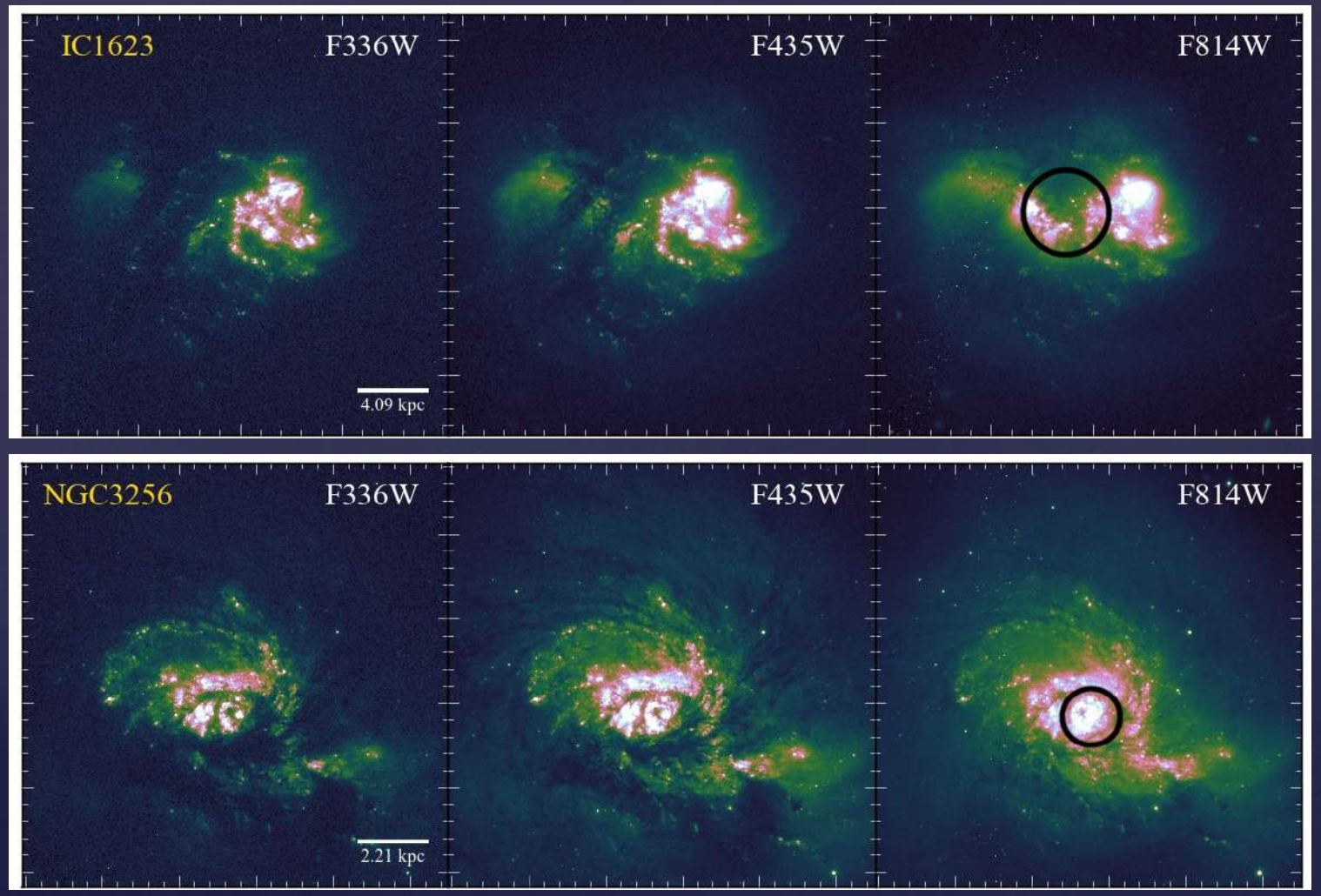




Linden et al. 2021

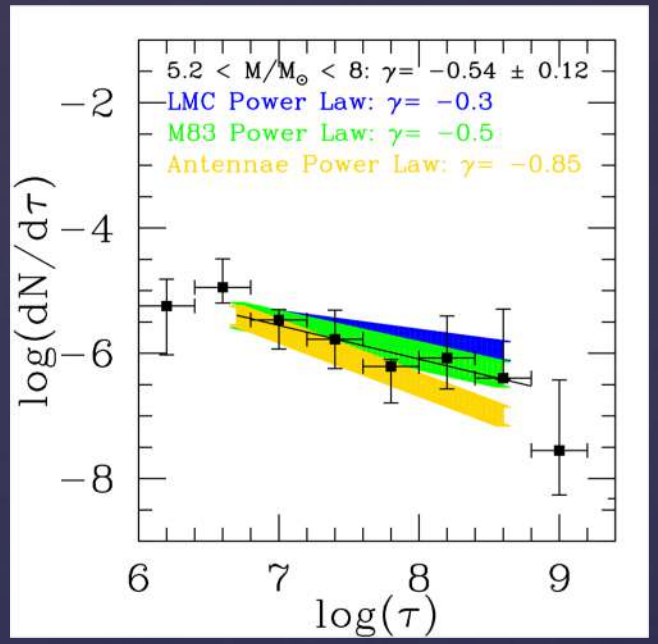
- Clusters in the centers of $L_{IR} > 10^{11.4}$ L_{sun} LIRGs suffer a higher rate of cluster destruction relative to normal star-forming galaxies in LEGUS and PHANGS
- Results are also consistent with Hi-PEEC survey of 5 LIRGs (Adamo et al. 2020)

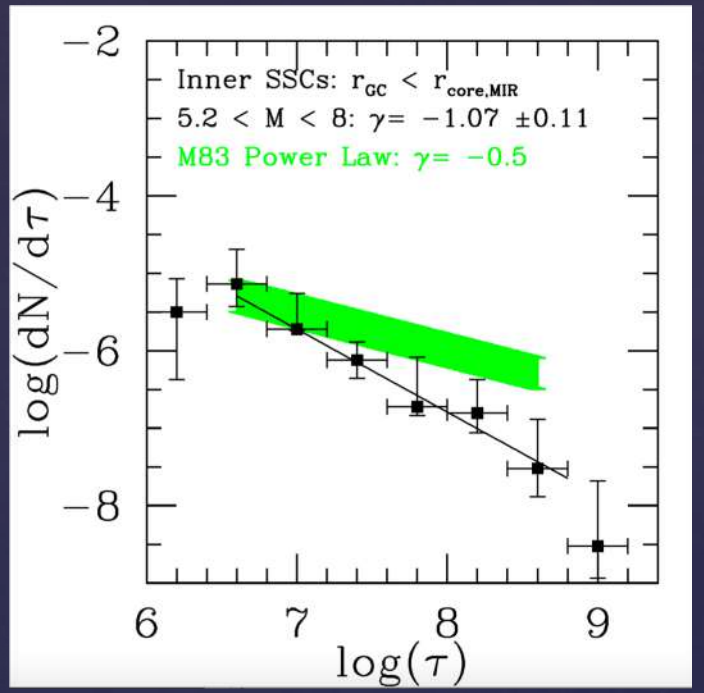
Massive Star Cluster Formation and Destruction in Luminous Infrared Galaxies in GOALS

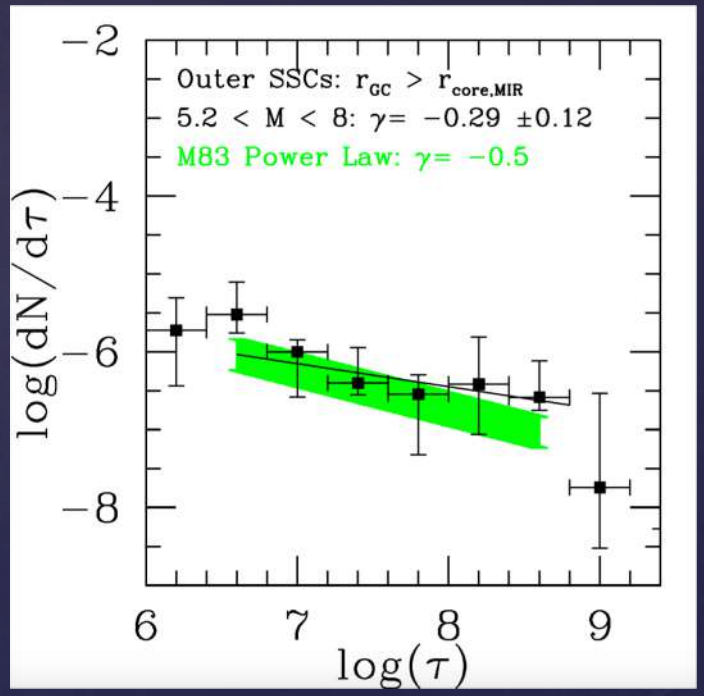


- Spitzer 2D IRS Spectra are used to estimate the center and total size of the MIR dominant region in each system. This size serves as our best estimate for the size (upper-limit) of the central starburst
- For each cluster the de-projected galactocentric distance from the center is calculated. Clusters which fall within the FWHM of the MIR core are “inner-disk” clusters

Massive Star Cluster Formation and Destruction in Luminous Infrared Galaxies in GOALS







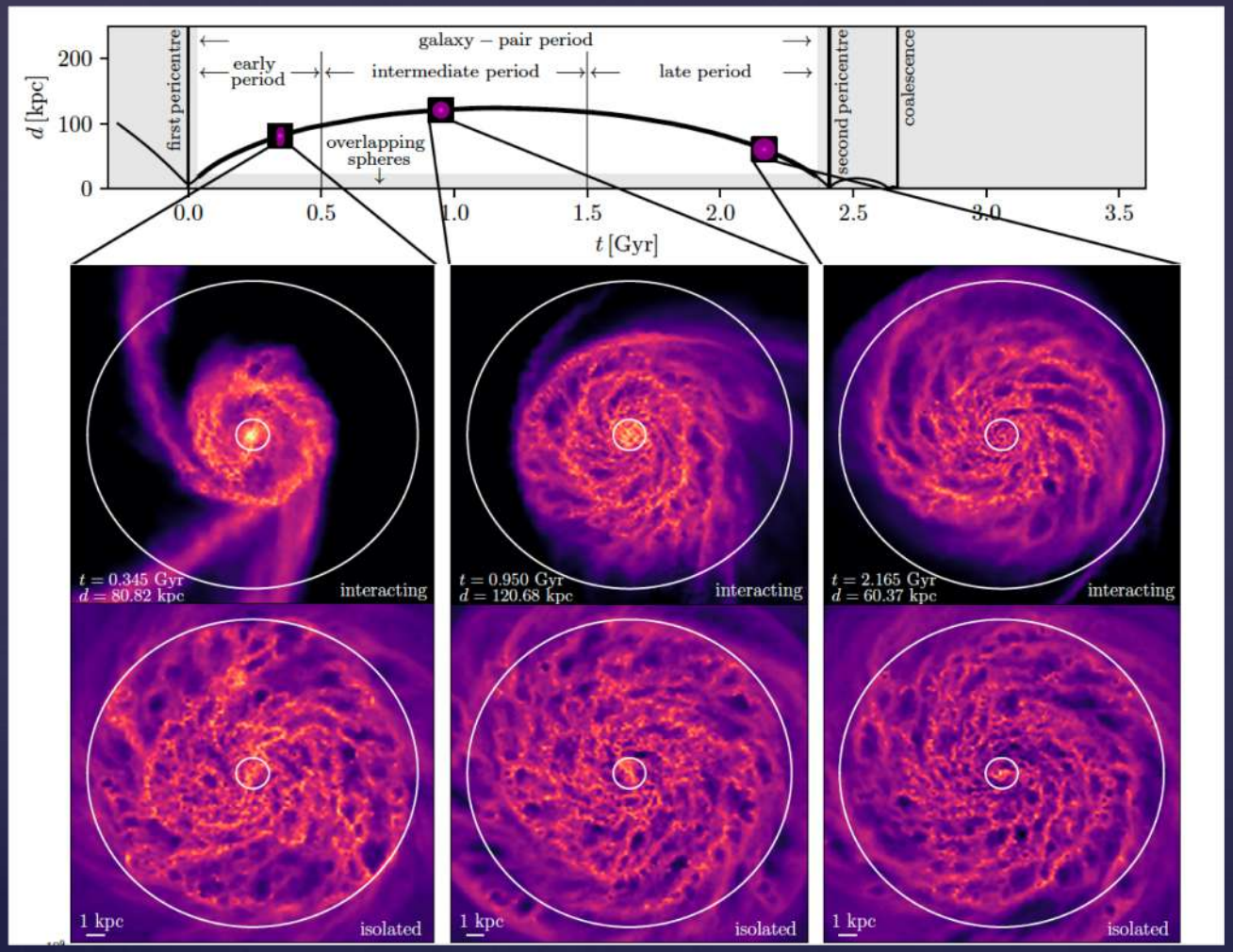
$$\gamma_{\rm GMC} \simeq 6.5\,{\rm Gyr}\,\frac{\sigma_{\rm rel}}{10\,{\rm km\,s^{-1}}}\,\frac{10\,{\rm M_\odot^2\,pc^{-5}}}{\Sigma_{\rm GMC}\rho_{\rm ISM}}.$$

$$\tau_{\rm sh} = \gamma_{\rm GMC}\,\frac{\rho_{\rm h}}{10^2\,{\rm M_\odot\,pc^{-3}}}.$$

Gieles & Renaud (2016)

- For 3 mid-stage mergers (NGC 3256, IC1623, and NGC 7469) we separate clusters as inner- and outer-disk
- Disruption appears location-dependent: SSCs found in the inner-regions of LIRGs show greater disruption rates relative to SSCs identified in their outer-disks.

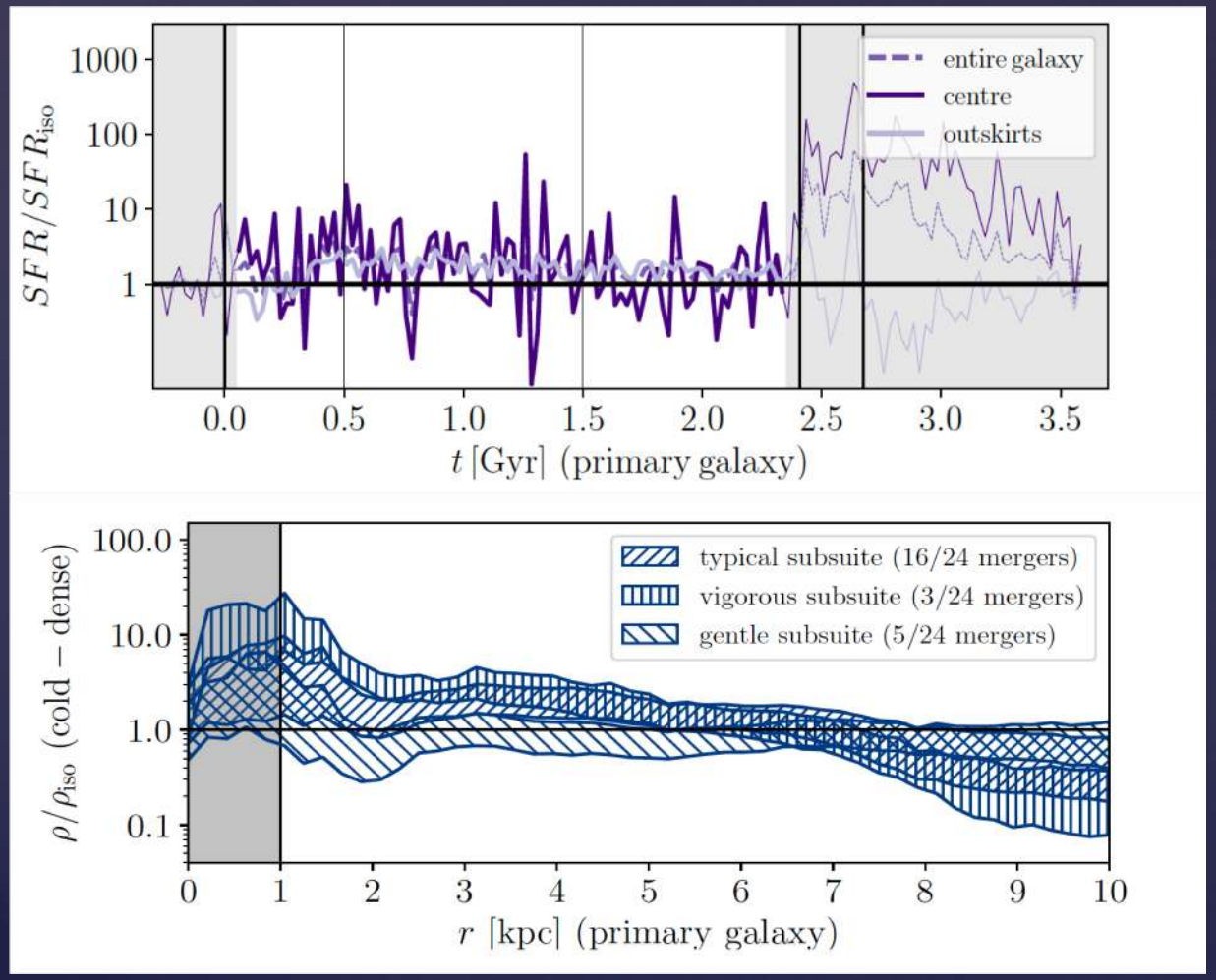
Comparisons with Hydrodynamic Simulations



- Suite of *merging* and *isolated* parsec-scale galaxy simulations which employs the "Feedback In Realistic Environments-2" model (FIRE-2): Moreno et al. 2020)
- This framework resolves star formation, feedback, and the multiphase structure of the ISM in galaxy-pairs at each stage of their interaction relative to isolated galaxies

FIRE Simulations: Moreno et al. 2019

Comparisons with Hydrodynamic Simulations

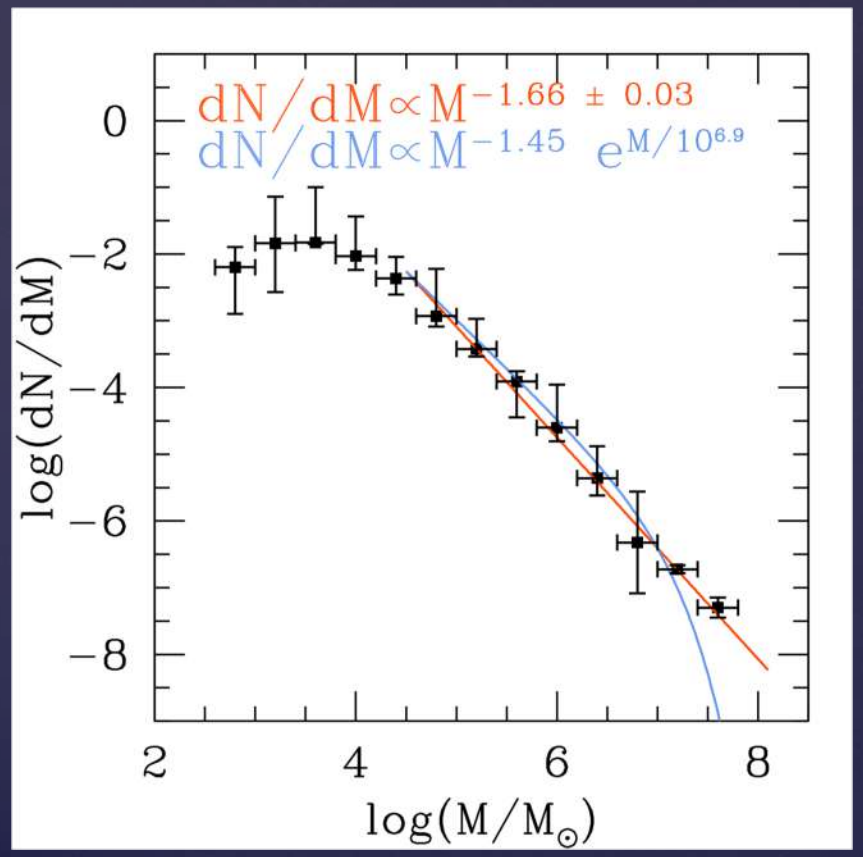


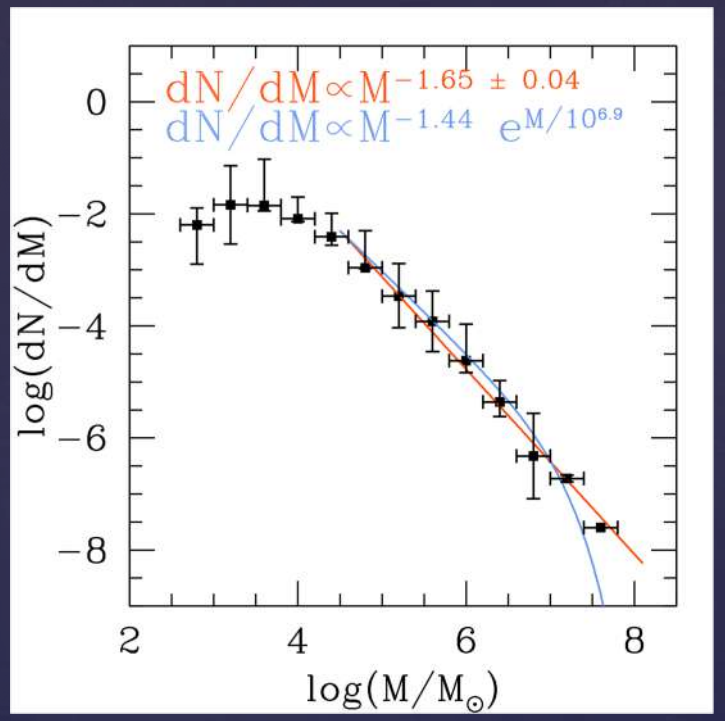
- SFR enhancements appears nearly constant between first and second passage, and no sharp increases are seen in center vs outskirts.
- Caveat with these simulations is that only a small fraction reach a total IR luminosity that would qualify them as "LIRGs"

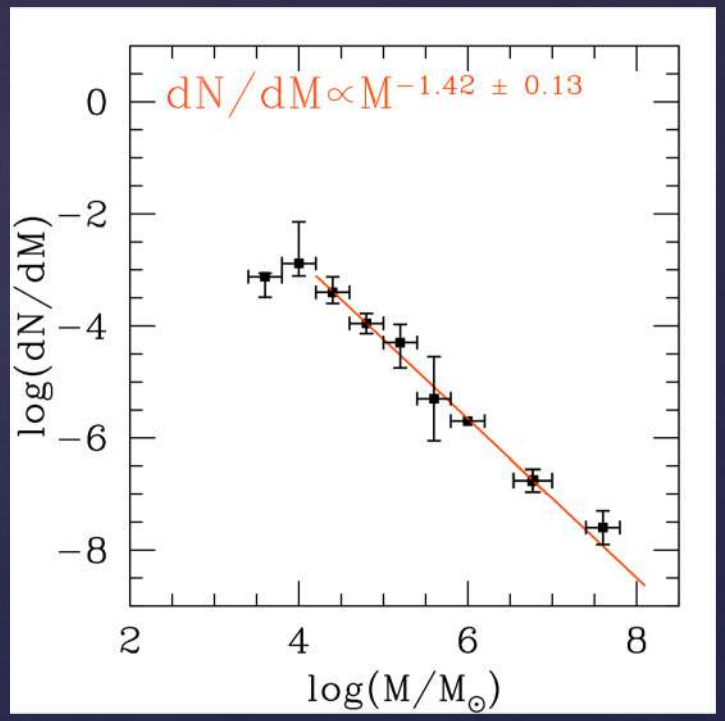
FIRE Simulations: Moreno et al. 2019

Massive Star Cluster Formation and Destruction in Luminous Infrared Galaxies in GOALS

Linden et al. 2021

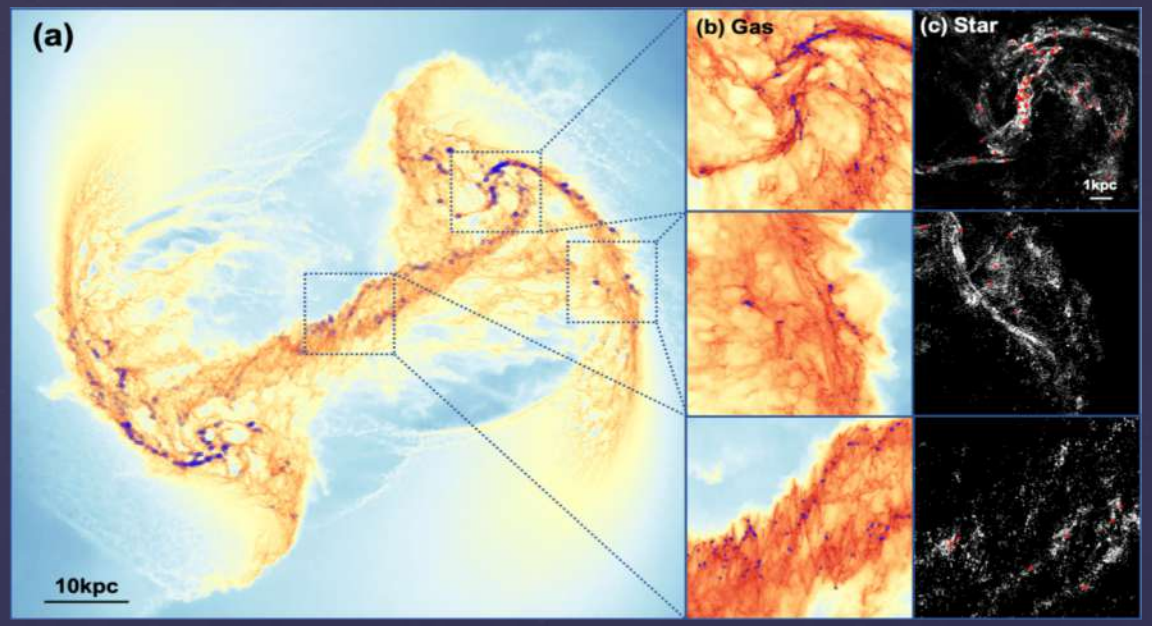


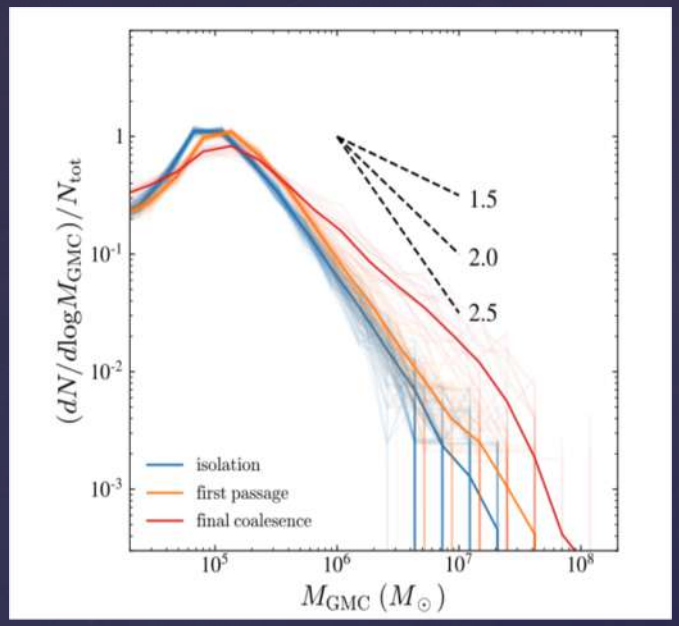


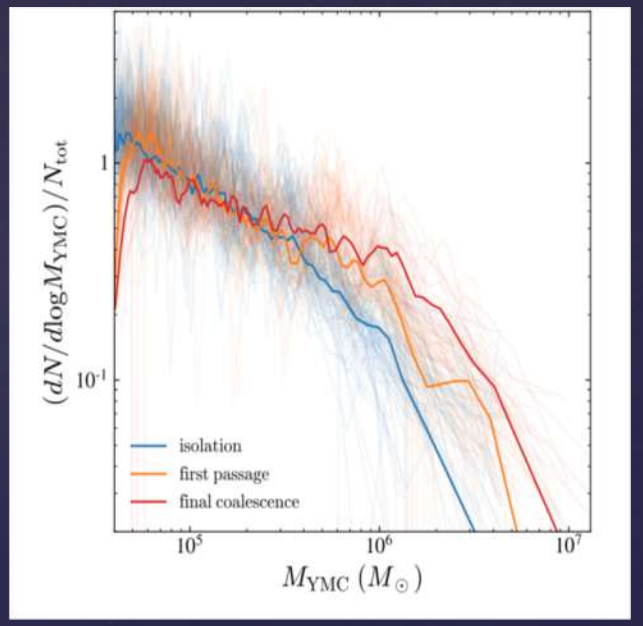


- Mass Function of young clusters consistent with L20 slope. Marginal evidence for cutoff in full sample, but constrained at 10^7 Msun. Similar results found in Adamo et al. (2020)
- Flattening of late-stage MF which we attribute to cluster destruction? – Caveat this is only based on 2 late-stage mergers!

Comparisons with Hydrodynamic Simulations





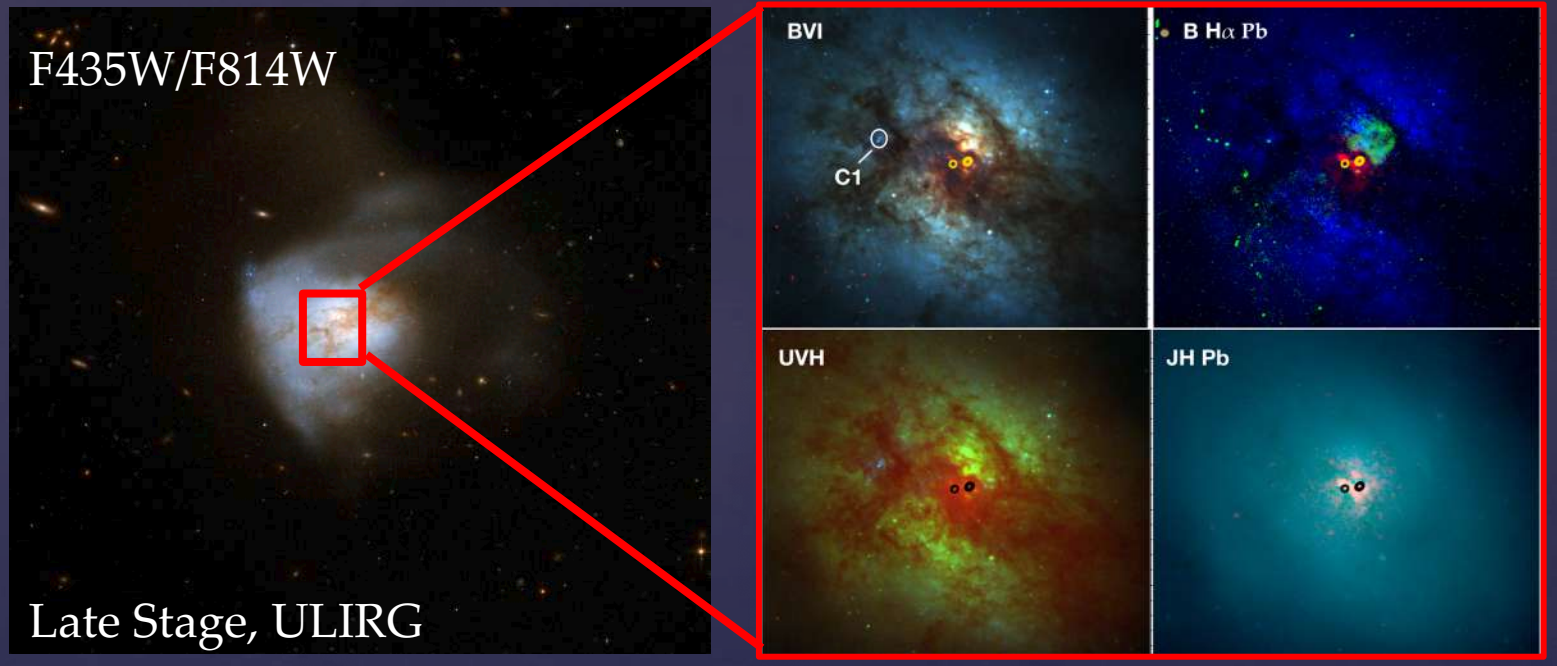


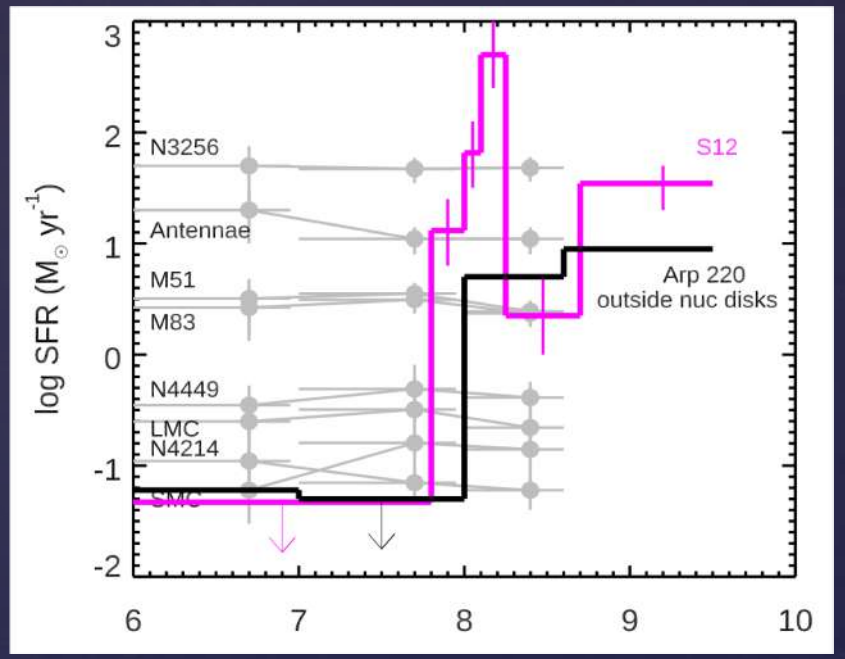
SMUGGLE Zoom Simulation: Li et al. 2021

- The latest simulations of MW-MW like merging system shows that as mergers progress from early to later stages the slope of the GMC and YMC mass functions become more shallow
- Likely as a result of further increases in SFE and destruction of lower mass clusters over the course of the interaction

Arp 220: No Current Star Formation Over 99.9% of it's Area!

Chandar et al. 2022, submitted

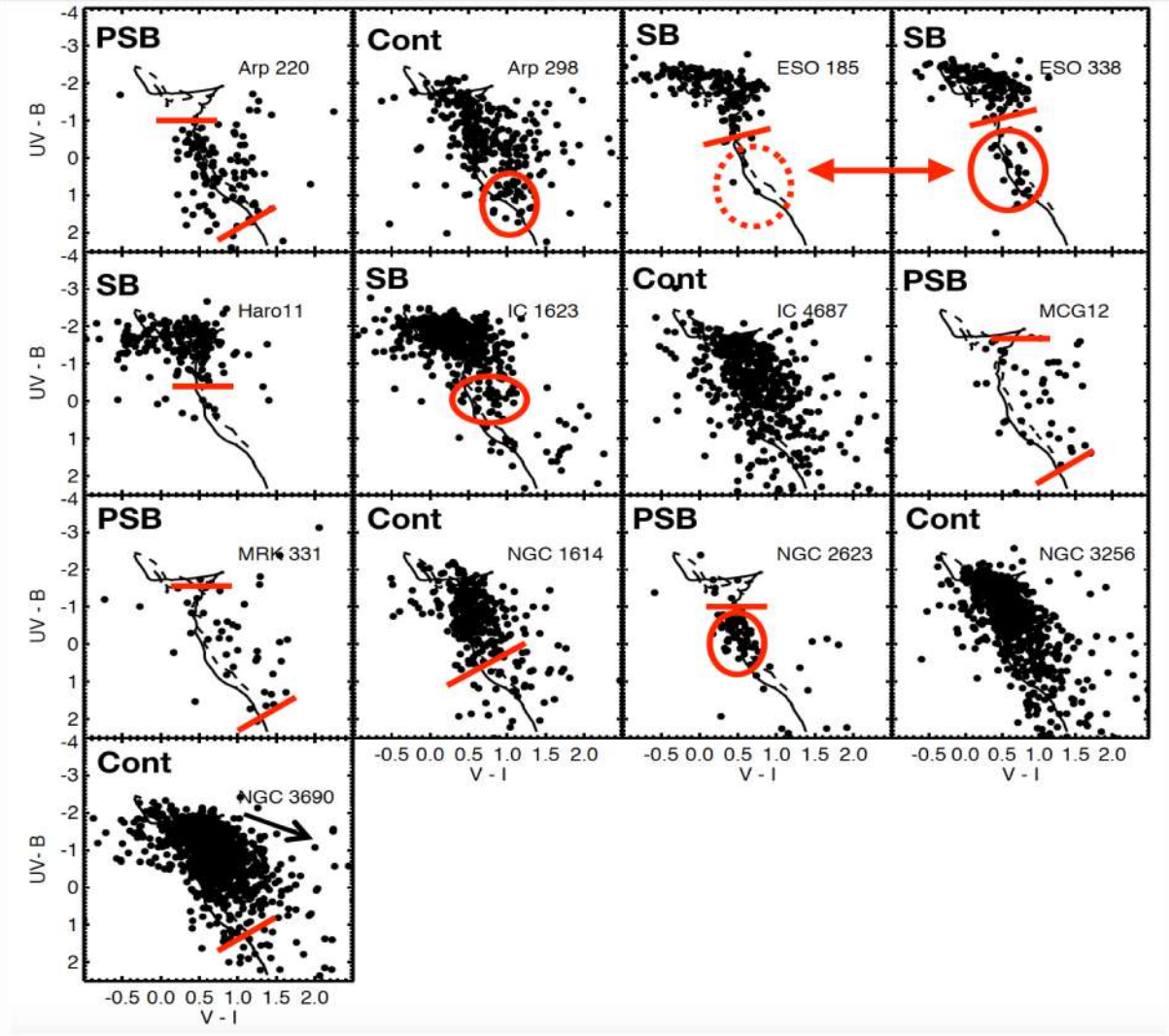




- Star formation outside the two nuclear disks halted abruptly approximately 100 Myr ago
- We estimated a star formation rate between ≈100 −400 Myr ago of ≈3 −9, which is typical of that found in nearby spiral galaxies, and not as high as that found in many actively merging systems

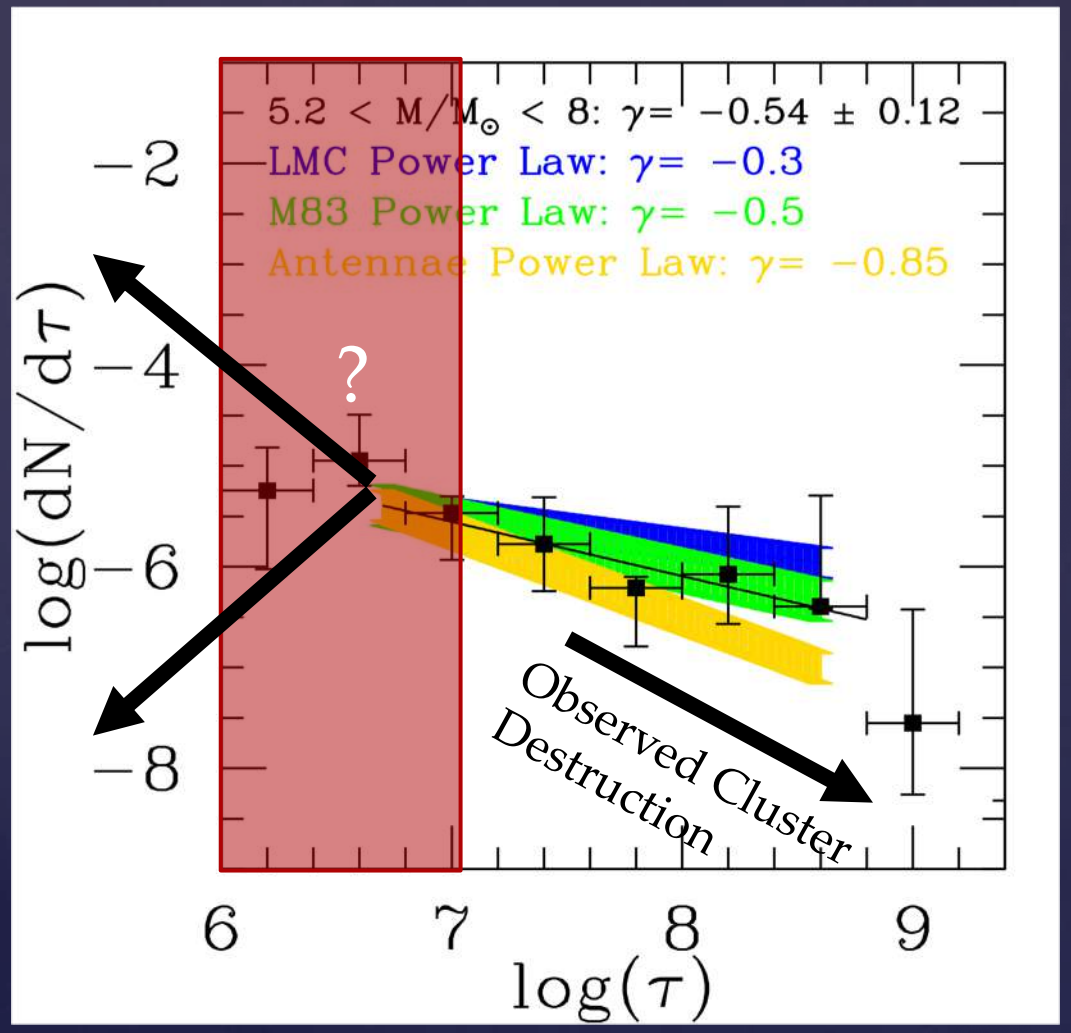
The Clusters, Clumps, Dust, and Gas Survey (CCDG)

Chandar et al. 2022, in prep



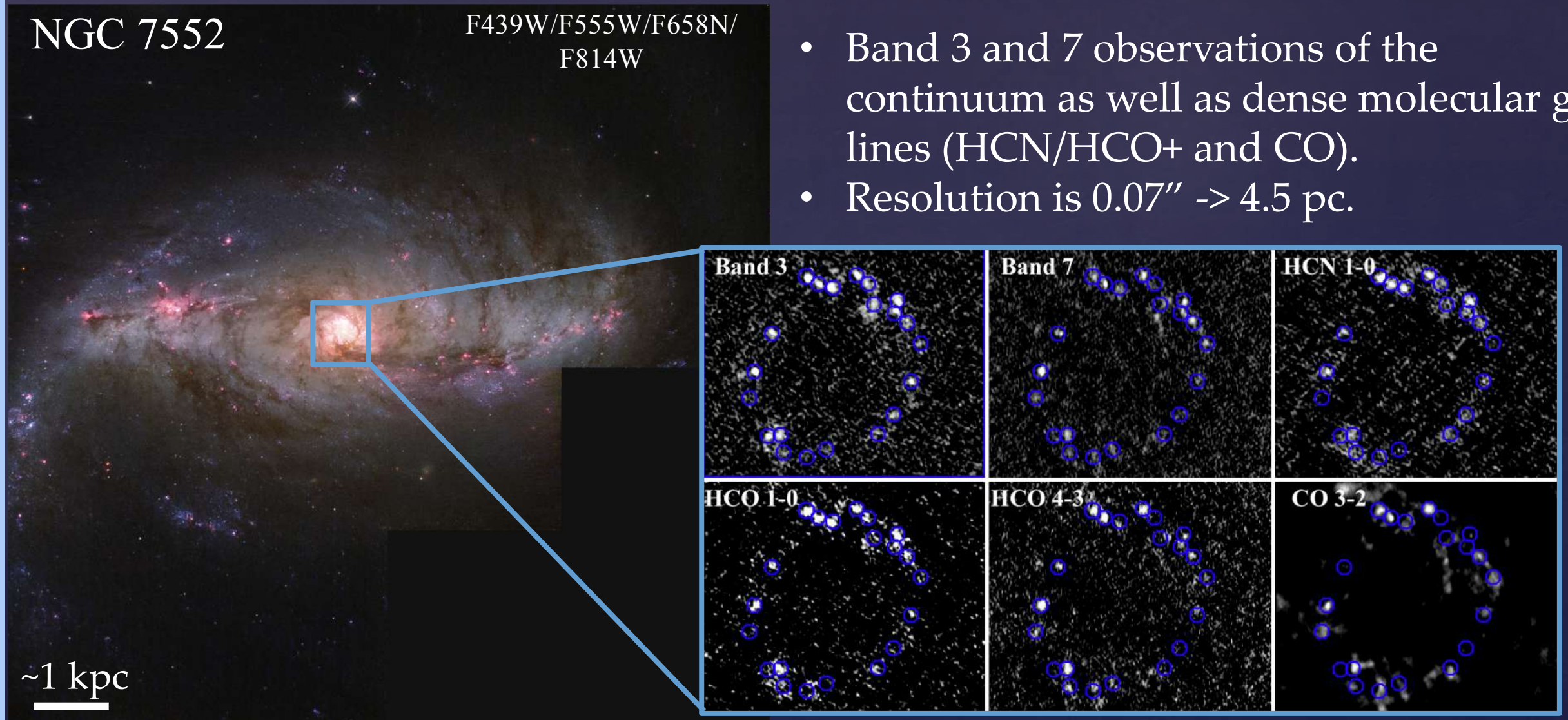
- Cycle 26 UV-IR HST NUV-NIR survey of 13 extreme star-forming galaxies with SFRs and ΣSFRs 1-2 orders of magnitude larger when compared to LEGUS galaxies
- The galaxies are all within 100 Mpc, ensuring we can identify and study older stellar clusters even as they fade rapidly with age

Embedded Cluster Formation and Early Evolution in LIRGs



- The majority of the star formation activity occurring in LIRGs is enshrouded in obscuring dust, and increases as a function of increasing LIR (SFR) - Howell et al. 2010
- Are star clusters destroyed before drifting out of their prenatal cocoons?
  - F_missed (FUV) ~60-80%
  - F_missed (U-band) ~20-30%

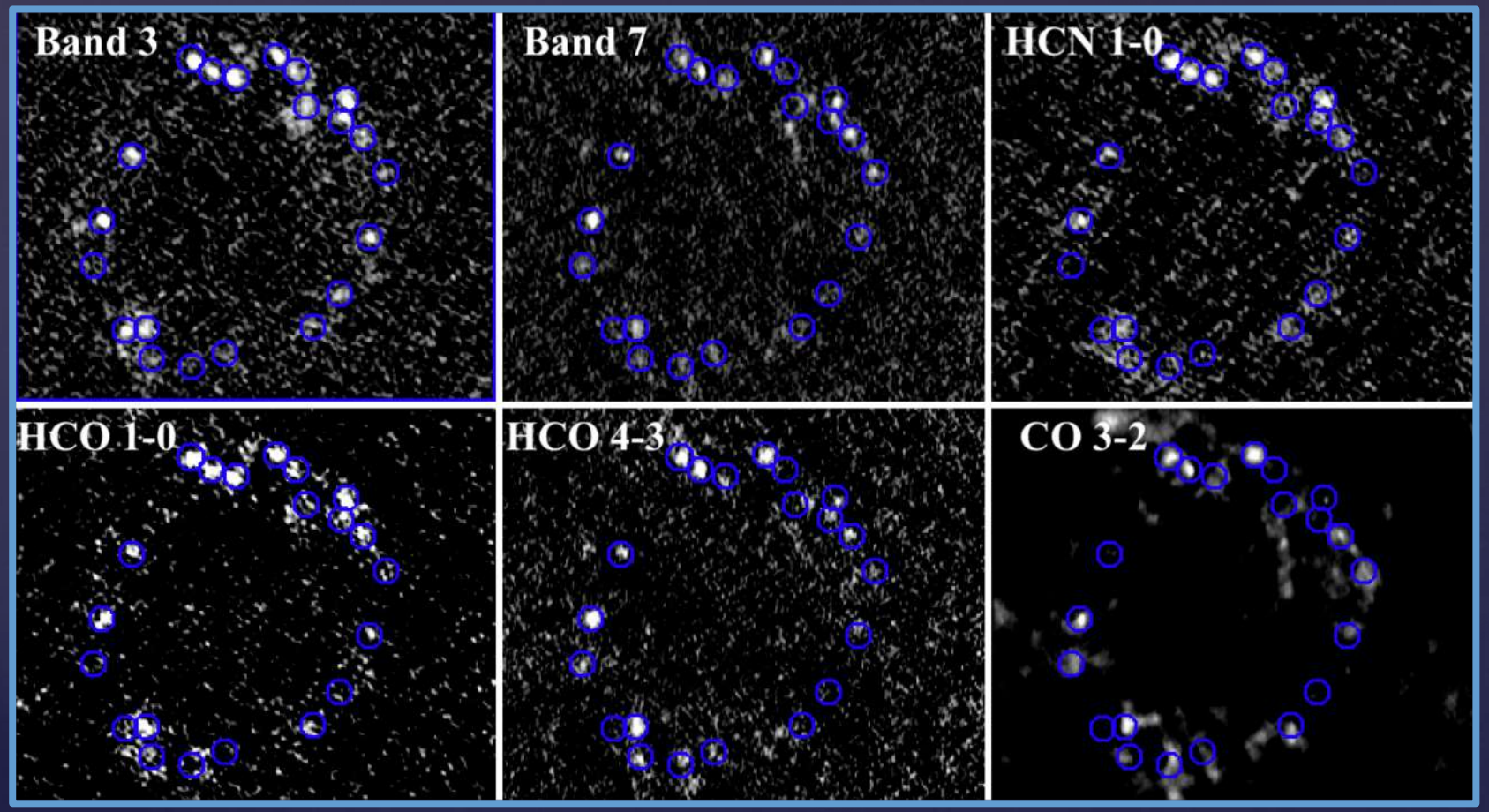
Embedded Cluster Formation and Early Evolution in LIRGs: NGC7552



- Band 3 and 7 observations of the continuum as well as dense molecular gas lines (HCN/HCO+ and CO).
- Resolution is 0.07” -> 4.5 pc.

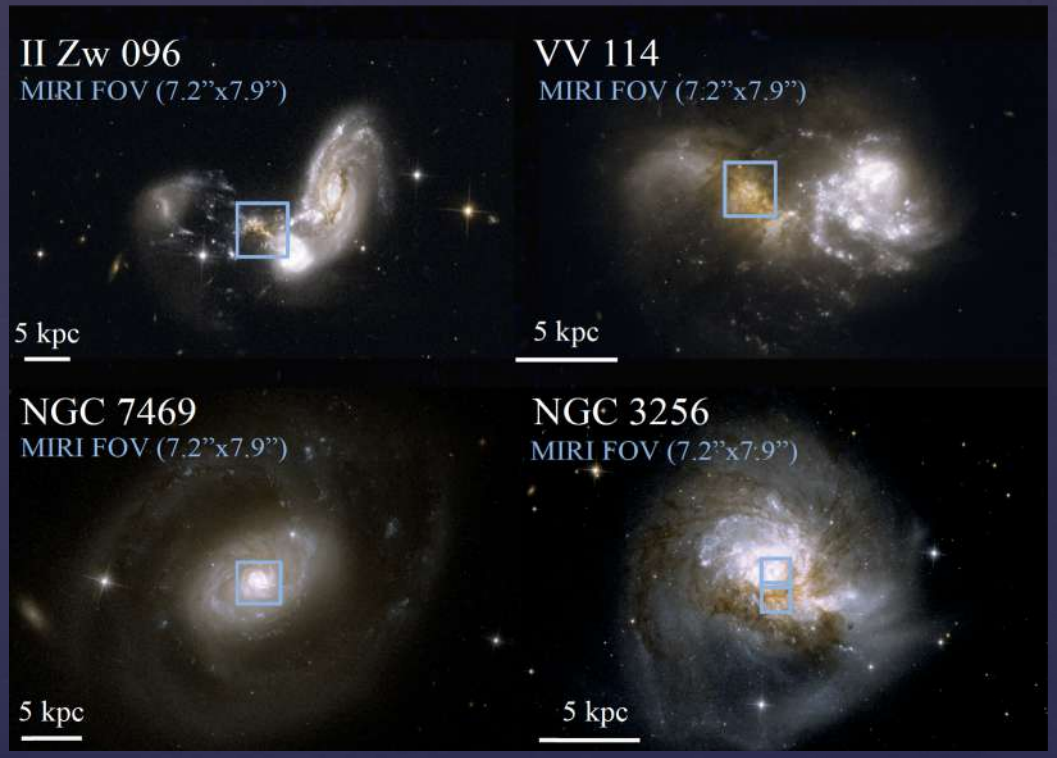
Embedded Cluster Formation and Evolution in LIRGs: NGC7552

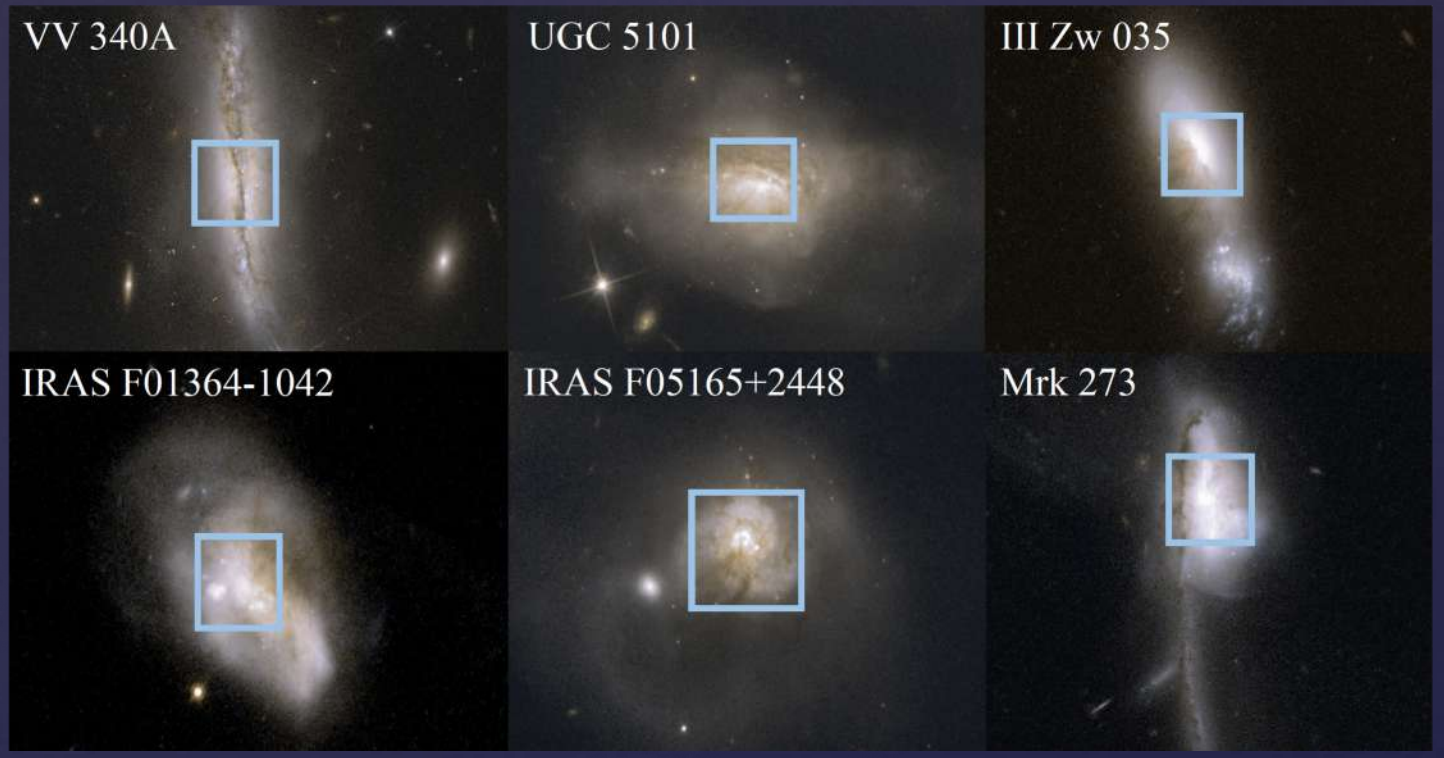
Linden et al. 2022, in prep



- Measurements of the Band 3 and 7 continuum reveal that these clusters span a range in physical size from 4 – 15 pc
- They also span a range of free-free emission fractions
- All clusters are very massive (1-5 x 10^6 Msun)

UPCOMING: JWST-HST Studies Cluster Formation and Evolution in LIRGS





- Approved ERS program to study 4 galaxies in GOALS using both NIRCAM and MIRI IFU and imaging modes (Left) Approved Mid-Cycle 29 program to obtain F336W for all JWST GO1 LIRGs with IFU pointings in the center (right)

Final Summary

- Studying local Luminous Infrared Galaxies provides us a unique laboratory for studying star formation under conditions which may seed the production of globular clusters

- We have made fundamental conclusions about the nature and fate of star clusters in nearby LIRGs, demonstrating that the merging environment produces both more massive clusters, and destroys them at a much more rapid rate in their centers

- We have begun a survey into the clusters, clumps, and dust properties of young, massive super star clusters in nearby LIRGs, demonstrating that the clusters in outer-region of Arp 220 appear consistent with normal star-forming galaxies

- Broadband infrared + narrow-band imaging from future JWST programs in combination with HST will allow us to search for the youngest, most highly embedded clusters in LIRGs

Acknowledgements

Thank you to my wonderful collaborators who have made all this work possible:

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- Matteo Messa
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