Estallidos 8, WS XIV
“Extreme Star Formation”

Madrid 5-7 February 2024

Bruce Elmegreen

Common Theme of *Estallidos 8*: Extreme star formation

Local Dwarfs (BCD, GPs, EELG, …) → high z analogues …
low metallicity, clumpy, high gas/star, high sSFR, low gas consumption times, …
supernovae, super star clusters, supershells, ISM blowout, …

What is extreme star formation?

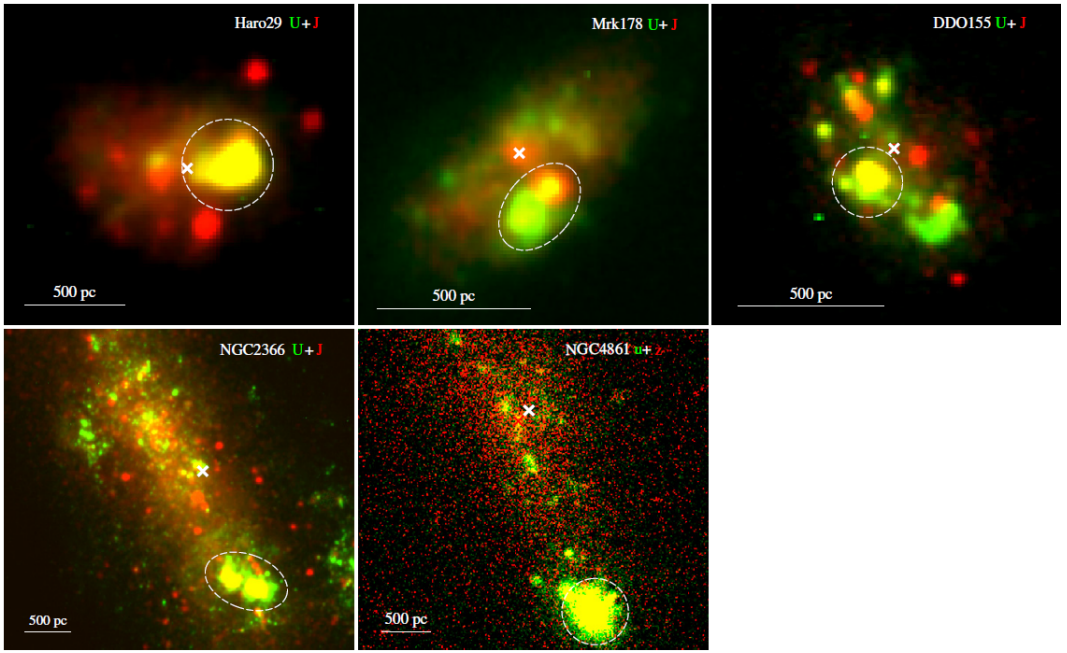
1. High sSFR needs high density: sSFR (in inverse years) corresponds to $(G \rho)^{1/2}$
2. For high SFR also, need a high gas mass → high surface density: $\Sigma \sim M^{2/3} \rho^{1/3}$
3. High surface density means high pressure: $P \sim G \Sigma^2$ and high $\Sigma_{SFR} \sim \Sigma^{1.5}$
4. High Σ also means high gas-to-star ratio (local dwarfs ~ high redshift galaxies)
5. High gas/star ratio means highly unstable disks (low Toomre Q) because the gas is dissipative
   → irregular disk structure
   → forming big clumps of gas and SF by gravitational instabilities
   → big torques in the disk
   → high turbulent speeds
   → relatively thick disks
   → fast secular evolution (in-spiraling)

THE ASTROPHYSICAL JOURNAL, 747:105 (9pp), 2012 March 10 doi:10.1088/0004-637X/747/2/105
© 2012. The American Astronomical Society. All rights reserved. Printed in the U.S.A.

IN-SPIRALING CLUMPS IN BLUE COMPACT DWARF GALAXIES

BRUCE G. ELMEGREEN[1], HONG-XIN ZHANG[2,3,4], AND DEIDRE A. HUNTER[2]
[1] IBM Research Division, T. J. Watson Research Center, 1101 Kitchawan Road, Yorktown Heights, NY 10598, USA; bge@watson.ibm.com
[2] Lowell Observatory, 1400 West Mars Hill Road, Flagstaff, AZ 86001, USA
[3] Purple Mountain Observatory, Chinese Academy of Sciences, 2 West Beijing Road, Nanjing 210008, China
[4] Graduate School of the Chinese Academy of Sciences, Beijing 100080, China
Received 2011 October 19; accepted 2012 January 5; published 2012 February 22

"If the clump mass fraction exceeds a few percent, then these torques can drive an inflow of the clump's amount of mass in less than 1 Gyr"

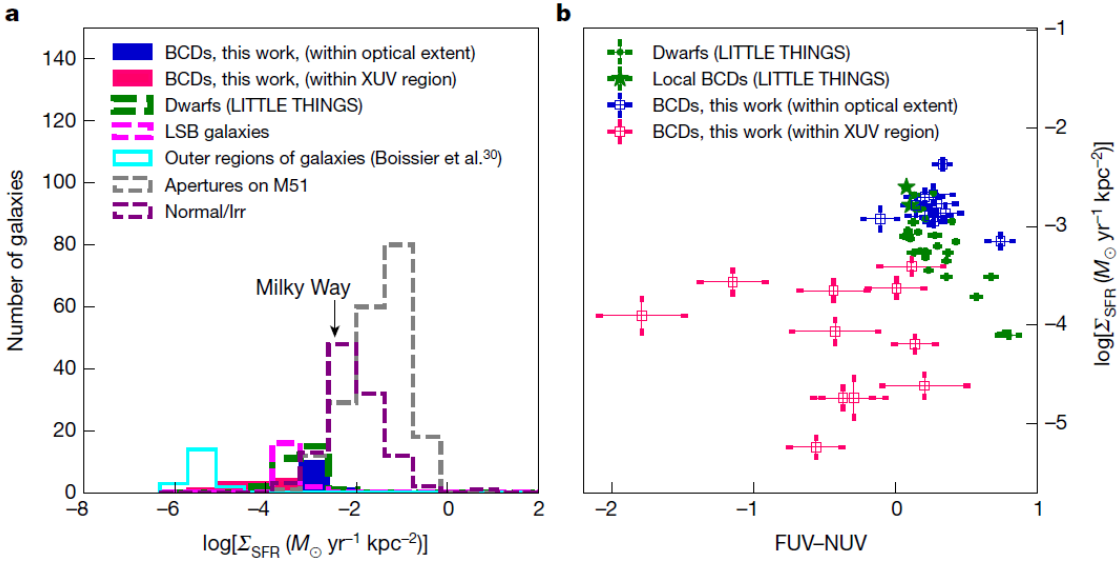


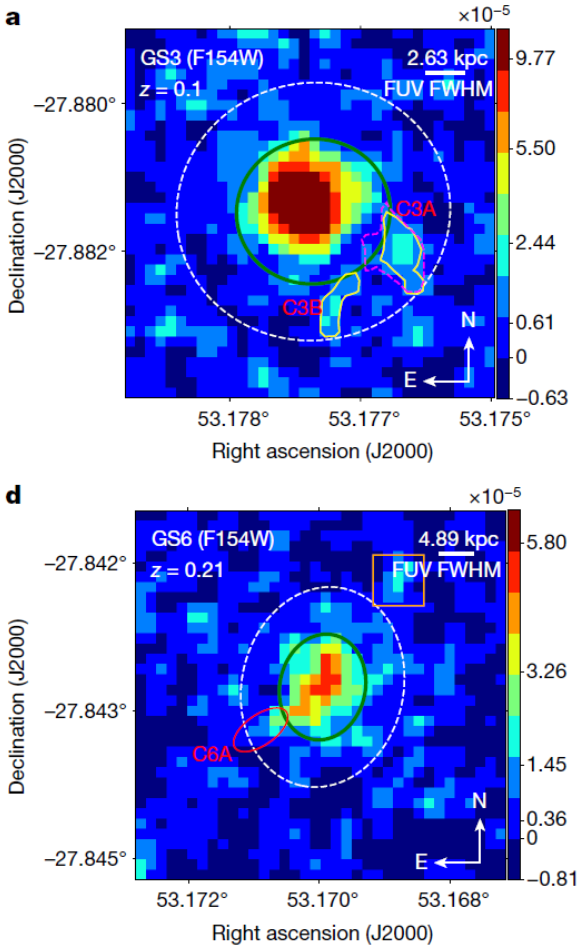
Article Nature | Vol 607 | 21 July 2022 | 459

Extended far-ultraviolet emission in distant dwarf galaxies

Anshuman Borgohain, Kanak Saha, Bruce Elmegreen, Rupjyoti Gogoi, Francoise Combes & Shyam N. Tandon

→ Astro-Sat imaging of 11 BCDs at z=0.1 to 0.24; M_{star}~few x$10^8 M_O$





Dynamical friction on the FUV clumps (~10^6 M_O) drives them in at an average rate of ~10^6 solar masses per Gyr

Other aspects of extreme star formation

→ ***Highly efficient*** *formation of* ***massive bound*** *clusters* (B. Elmegreen 2018 ApJ 869: 119)

First, some interesting observations:

1. Space density of GCs today ~ 8 Mpc^{-3} (Portegies-Zwart & McMillan 2000; Boylan-Kolchin 2017)

2. Forming one ~10^6 M_O GC requires a total SF mass of 50x10^6 M_O as much (other clusters, Γ~25% cluster fraction)
   → this alone gives a universe stellar density of ~4x10^8 M_O Mpc^{-3},
   … which **equals the average stellar density in the universe by z=1** (Madau & Dickinson 2014)

   → a high fraction of star-forming regions included at least one GC before about half the age of the universe.

3. If the duration of this star formation is the time from z=7 to z=2, i.e., 2.6 Gyr, then the average SFR of GC-forming events is 0.15 M_O yr^{-1} Mpc^{-3},
   → which **equals the peak value of the comoving cosmic SFR density in the universe at z~2**
   → GC formation involved **whole galaxy starbursts**

4. the current mass density of GCs is only 0.26% of the stellar mass density
   → **the universe "commonly" produced GCs before z~2 and "rarely" produced GCs afterwards.**

Other evidence for *Whole Galaxy Starbursts*: (B. Elmegreen 2018 ApJ 869: 119)

1. WLM has an old metal-poor GC whose luminosity suggests that it contains ~10^6 M_O of stars. The mass of other stars at the same age and metallicity is comparable to this (Leaman et al. 2012; Larsen et al. 2014), suggesting that the GC was a high fraction of the total WLM mass when it formed (Elmegreen et al. 2012).

… Old GCs in the Fornax dwarf spheroidal totaled 25% of the galaxy stellar mass when they formed (Larsen et al. 2012). For IKN and NGC 147, these fractions are 50% and 6% (Larsen et al. 2014, 2018).

These are **enormously high fractions** considering the additional cluster mass that should have been present in the full cluster mass function plus the and unbound stellar mass that formed at the same time.

→ These were **whole-galaxy starbursts**

2. The specific frequency of GCs in local dwarfs is ~100 per 10^9 M_O of stellar mass at 3×10^8 M_O (Zaritsky et al. 2016).

… for $M_{GC} \sim 2\times10^5$ M_O, the current mass fraction is 2%.

… At 10% of the age of the universe these GCs were there, but M_{star} was only 0.1 as much → $f_{GC} \sim 20\%$

... For more massive initial GCs (evaporation and an escaped population to make 2 generations [Bastian & Lardo 2018], plus the accompanying star formation in the same burst, the **GC-events involved the whole galaxies**.

3. Sollima & Baumgardt (2017) suggest 2×10^8 M_O of stars escaped from Milky Way GCs, which is 20% of all the stars in the halo (~10^9 M_O in the halo; Morrison 1993; Bell et al. 2008; Deason et al. 2011).

→ the **MW GCs alone were 20% of all the stars that came in with them.**

What does it take to make a super star cluster (or one of today's globular clusters)?

1. **The SF rate required to make a 10^6 M_O cluster is ~1 M_O yr^{-1} :**
    1. Integrate the cluster mass function up to a maximum mass of 10^6 M_O and the total mass is 12.5×10^6 M_O.
    2. For a cluster mass fraction of $\Gamma \sim 0.25$, the total SF region mass is $\sim 50 \times 10^6$ M_O
    3. For a SF region size of ~ 1 kpc and a turbulent speed of ~20 km/s, the duration of SF is ~50 Myr,
        1. → 50 Million solar masses in 50 Myr is **1 M_O yr^{-1}**

… But not all galaxies with SFR = 1 M_O yr^{-1} make SSCs because **a second condition is needed**:

B. Elmegreen 2018 ApJ 869: 119

2. A high mass cluster needs a high-pressure (high Σ_{gas}, high Σ_{SFR}) environment.

From the virial theorem:

$$M_{\rm cloud} = (2\pi)^{3/2}(3/4\pi)^2(P_{\rm cloud}/G)^{3/2}\rho_{\rm cloud}^{-2}$$

Define $M_{cluster} = \varepsilon_M M_{cloud}$ and $\rho_{cluster} = \varepsilon_\rho \rho_{cloud}$, and define $\varepsilon=\varepsilon_M\varepsilon_\rho^2$, then

$$M_{\rm cluster} = 0.9\epsilon\,(P_{\rm cloud}/G)^{3/2}\rho_{\rm cluster}^{-2} \quad \rightarrow \quad P_{\rm cloud} = G(1.1M_{\rm cluster}\,\rho_{\rm cluster}^2/\epsilon)^{2/3}$$

For a 10^6 M_O inside a half-mass radius of ~2.3 pc, $\rho_{cluster} \sim 10^4$ $M_O pc^{-3}$.

Then setting ε~0.5 for $M_{cluster}=10^6$ M_O, $\mathbf{P_{cloud} \sim 8x10^{10}\ k_B}$. This is the cloud core.

Locally, $P_{ISM} \sim 10^{-4}$ $P_{cloud\text{-}core}$ (i.e., Radius of a cloud core is about 1% of the disk thickness), so

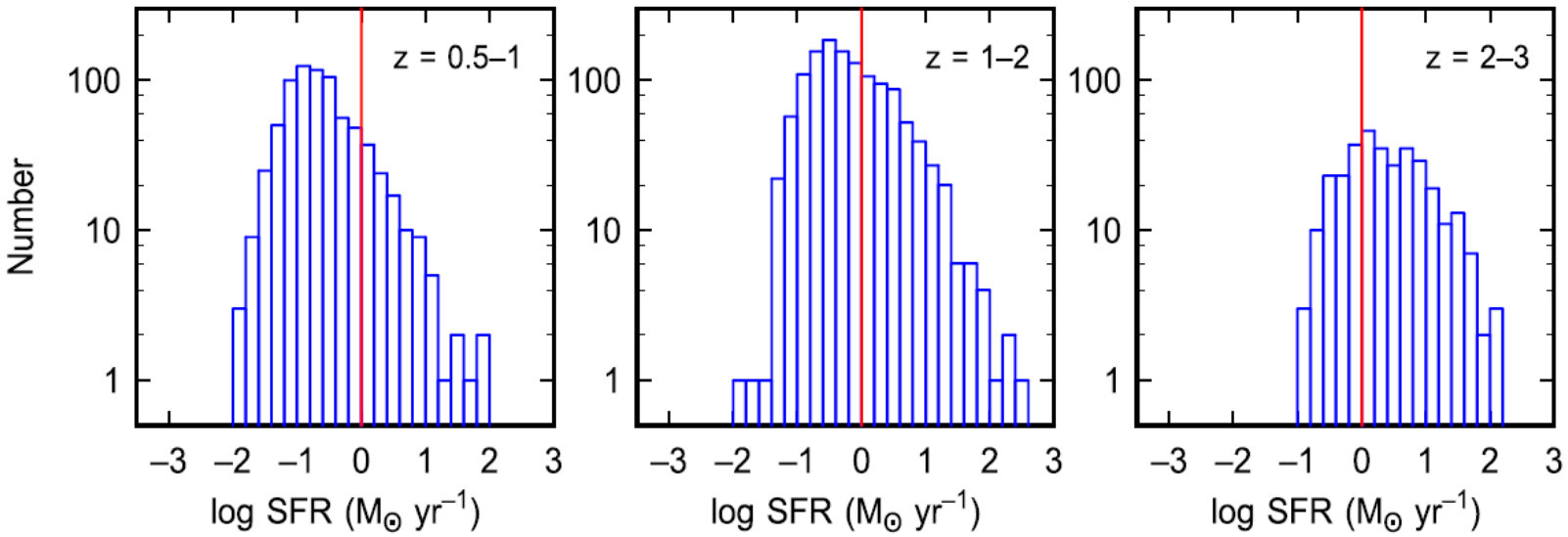
→ require $\mathbf{P_{ISM} \sim 10^7\ k_B}$. (x1000 local P_{ISM})

→ require Σ_{ISM} ~ 30 x local value ($P \sim G\Sigma^2$) ~ **500-1000 $M_O pc^{-2}$**

→ require $\mathbf{\Sigma_{SFR} \sim 1\ M_O\ pc^{-2}\ Myr^{-1}}$ (=1 M_O kpc^{-2} yr^{-1}) from the KS relation

B. Elmegreen 2018 ApJ 869: 119

This is the SFR and Σ_{SFR} in high redshift clumps:



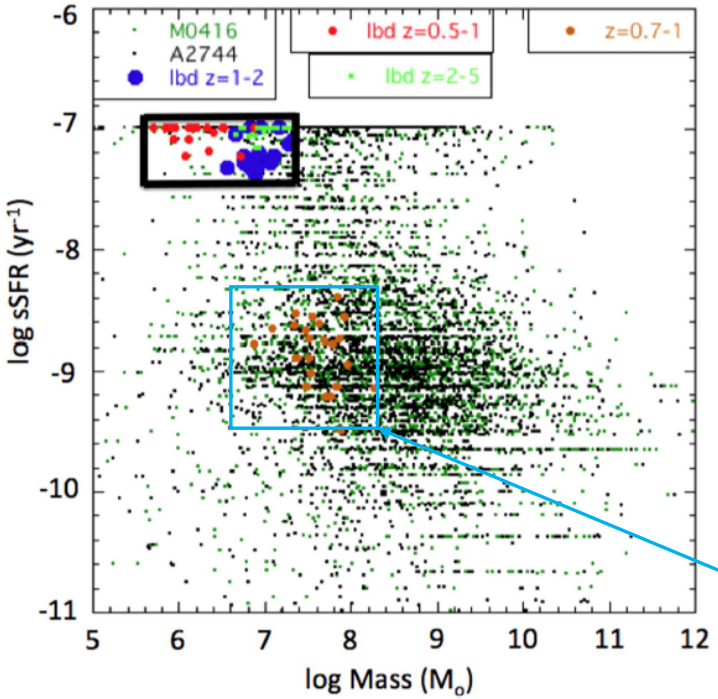
Distribution function for SFRs in the giant clumps of galaxies studied by Guo et al. (2018), divided into three redshift bins. Approximately half the clumps exceed 1 M_O yr^{-1} (first condition) and since most clumps are ~1 kpc big, they also satisfy the second condition, $\Sigma_{SFR} > 1$ M_O kpc^{-2} yr^{-1}

B. Elmegreen 2018 ApJ 869: 119

The Astrophysical Journal Letters, 851:L44 (5pp), 2017 December 20 https://doi.org/10.3847/2041-8213/aaa0ce
© 2017. The American Astronomical Society. All rights reserved.

Little Blue Dots in the *Hubble Space Telescope* Frontier Fields: Precursors to Globular Clusters?

Debra Meloy Elmegreen[1] and Bruce G. Elmegreen[2]
[1] Department of Physics and Astronomy, Vassar College, Poughkeepsie, NY 12604, USA; elmegreen@vassar.edu
[2] IBM Research Division, T.J. Watson Research Center, 1101 Kitchawan Road, Yorktown Heights, NY 10598, USA; bge@us.ibm.com
Received 2017 November 15; revised 2017 December 6; accepted 2017 December 7; published 2017 December 21



Looking for GC precursor galaxies:

Pick high sSFR and low M for galaxies in the HST Frontier Fields Parallels for Abell 2744 and MACS J0416.1-2403

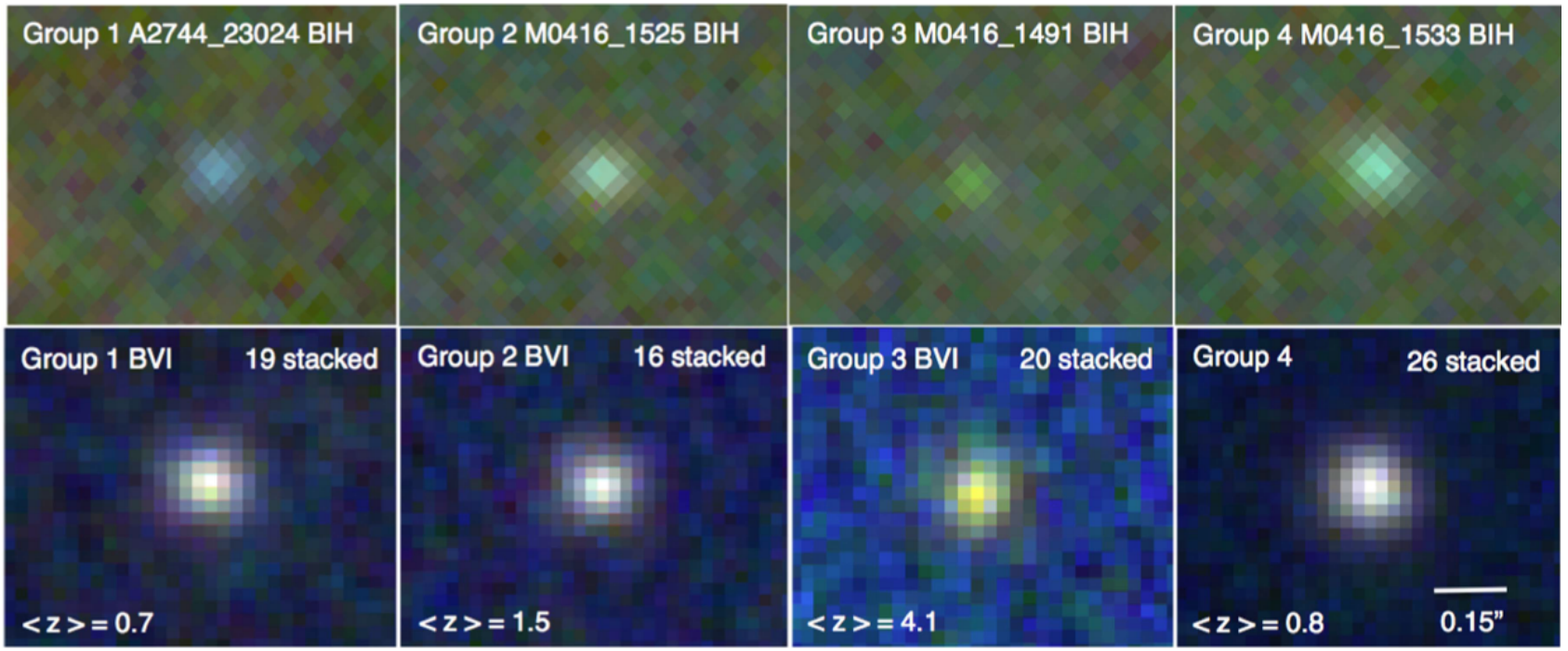
… high sSFR means high density, SFR, gas/stars…
… low M means low metallicity

(found by eye)

E&E 2017 ApJ 851:L44

Sample galaxies in redshift bins

All galaxies stacked from those redshift bins



Found by eye

E&E 2017 ApJ 851:L44

From M_{stars} , deconvolved radius, and SFR, can estimate M_{gas} using the KS relation, and then

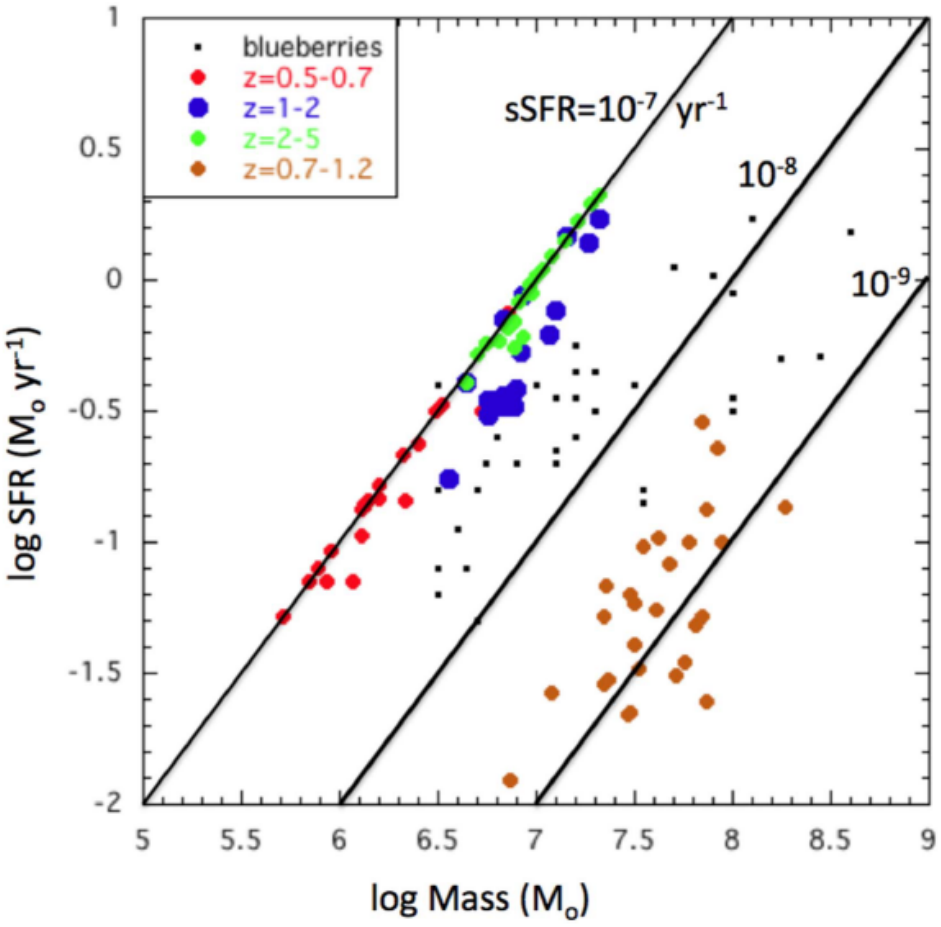
$$M_{gas}/M_{star} \sim 5$$

and the SF efficiency per free fall time is

$$\varepsilon_{ff} \sim 0.1$$

for the whole galaxies

→ 10x higher efficiency than SF locally



E&E 2017 ApJ 851:L44

… Endless applications of the Common Theme “Extreme Star Formation”

Massive Optically Dark Galaxies Unveiled by JWST Challenge Galaxy Formation Models

M. Xiao[1]✉, P. A. Oesch[1,2], D. Elbaz[3], L. Bing[4], E. Nelson[5], A. Weibel[1], R. P. Naidu[6], E. Daddi[3], R. J. Bouwens[7], J. Matthee[8], S. Wuyts[9], J. Chisholm[10], G. Brammer[2], M. Dickinson[11], B. Magnelli[3], L. Leroy[3], P. van Dokkum[12], D. Schaerer[1], T. Herard-Demanche[7], L. Barrufet[1], R. M. Endsley[10], Y. Fudamoto[13,14], C. Gómez-Guijarro[3], R. Gottumukkala[1], G. D. Illingworth[15], I. Labbe[16], D. Magee[15], D. Marchesini[17], M. Maseda[18], Y. Qin[19,20], N. Reddy[21], A. Shapley[22], I. Shivaei[23], M. Shuntov[2], M. Stefanon[24,25], K. Whitaker[26,2], J. S. B. Wyithe[19,20].

MNRAS **523,** 3201–3218 (2023)
Advance Access publication 2023 May 25

https://doi.org/10.1093/mnras/stad1557

→

Efficient formation of massive galaxies at cosmic dawn by feedback-free starbursts

Avishai Dekel,[1,2]★ Kartick C. Sarkar,[1,3] Yuval Birnboim,[1] Nir Mandelker[1] and Zhaozhou Li[1]

[1]*Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel*
[2]*SCIPP, University of California, Santa Cruz, CA 95064, USA*
[3]*Department of Astronomy, Tel Aviv University, Tel Aviv 6195001, Israel*

Summary:

What we know about local SF can be **scaled** to understand SF in the early universe.

What **differs** at high z is:

Higher sSFRs

… which mean higher gas/star ratios, higher Σ_{gas}, higher Σ_{SFR}, higher P, higher $M_{cluster}$

All of this is observed at high z and it follows as a **single block of inter-related properties** by scaling local observations.

This scaling also means:

… more unstable disks, more galaxy irregularity, bigger clumps and thicker disks, larger torques and faster secular evolution

→ Scaling tells us what to expect and how to evaluate our observations.



This research has been funded by grants PID2022-136598NB-C31, C32, and C33

The wokshop has been funded by grant PID2019-107408GB-C41

all grants are funded by MCIN/AEI/10.13039/501100011033 and by "ERDF A way of making Europe"

