Starbursts hiding in the main sequence: a pathway toward quenching?

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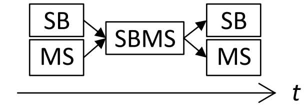
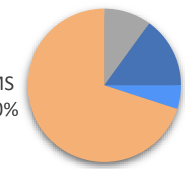
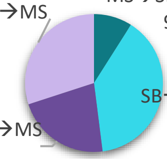
Star-forming galaxies spend most of their lifetimes on the star-forming main sequence, which establishes a tight empirical and statistical relation between stellar mass and star-formation rate. Occasional episodes of rapid star formation can push them temporarily above this sequence, turning them into starbursts. Yet some galaxies display starburst-like traits –rapid, dense, and compact star formation– while still remaining within the scatter of the main sequence. These "starbursts in the main sequence" (SBMSs) reveal the complexity and diversity of star formation modes, making them crucial for understanding how galaxies evolve and transition between different regimes. In this paper, we identify SBMSs in the cosmological simulation NewHorizon and follow their evolution across time to uncover their physical origins and the role of this special regime in shaping galaxy evolution. We explain the existence of SBMSs by a comparatively earlier assembly of their stellar mass, driven in particular by more frequent and repeated mergers as the other galaxies, as well as exceptionnaly productive starburst events triggered by these interactions. As a result, this regime appears preferentially –though not exclusively– in the most massive galaxies. The SBMS behavior is not continuous within individual galaxies but instead arises intermittently as a short-lived (∼ 30 Myr) evolutionary mode. Nevertheless, such SBMS episodes exist throughout cosmic time across the galaxy population, rooted in the inherently stochastic nature of galactic star formation histories. Contrary to common interpretations in the literature, the SBMS phase marks a transition between starburst and more quiescent star formation in only a small fraction of cases (< 25%). Compaction events do raise the star formation rate, but do not reduce the gas depletion time, i.e., the timescale for star formation. We find no evidence linking the SBMS regime to quenching via compaction (i.e., the blue-then-red-nugget pathway). The importance of the SBMS regime and the variety of evolutionary tracks into and out of it challenges attempts to summarize the evolution of star-forming galaxies with a single, universal scenario.





Fraction @ z=3 (from Fig 5d)



SBMS subclass fraction @ z=3

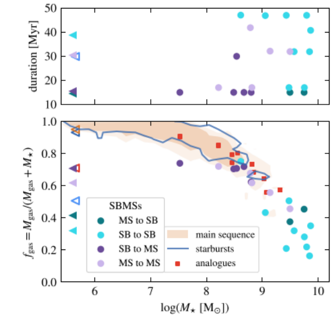


Fig. 11. Duration of the current SBMS episode (*top*) and gas fraction (*bottom*) for the SBMS galaxies detected at $z = 3$, shown as a function of stellar mass. The SBMS galaxies are classified according to their trajectory in the $\tau_{dep} - \Delta SFR_{MS}$ plane before and after the SBMS phase (see text). The triangles to the left of the panels indicate the median value of each group (with all SBMSs in light blue). In the top panel, a small vertical offset has been added to the "SB to SB" and "MS to MS" points to avoid graphical overlap with other points; this offset is not used when computing the medians.

Only 22% of SBMS evolve into MS (and then QGs?).
→ blue-red nugget evolution is **not** the dominant evolutionary path.

Diversity of evolutionary paths of starburst galaxies in M_*-SFR-τ_{dep} space

- Role of starbursts in quenching
  - Classical (simple) scenario: mergers → starburst → gas compaction (observed as blue nuggets) → gas exhaustion → quenching (red nuggets).
- Starburst (SB) and star-forming main sequence (SFMS)
  - Most star-forming galaxies stay on the SFMS.
  - Recent ALMA observations identified MS galaxies with shorter gas depletion time (τ_{dep}).
    → Apparently peculiar (hybrid) population = **Starburst in the MS (SBMS)**
- This work focuses on SBMS using **NEWHORIZON** simulation.
  - Minimum spatial resolution ~ 34 pc, mass resolution ~ $10^6\ M_\odot$
  - Snapshots between z=6 and 0 w/ $\Delta t \sim 10-15\ Myr$
  - SBMS definition (at each z): located in SFMS but with quite short τ_{dep}.
  - Comparison sample "Analogues": similar M_* & SFR but longer τ_{dep}.

Other SBMS characteristics:

- SBMS **exists commonly** (~5%) across all redshifts (0—6). → possibly a universal population.
- SBMS has experienced more (x 1.5 at z~3) **major mergers** than others **in the past**.
  - Consistently, SBMS tends to be massive (>1e9) and shows lower f_{gas} due to large M_*.
- SBMS is more **compact** in both stellar distribution and SF region than others. → possibly due to frequent mergers and/or angular momentum loss.
  - Such **compaction** enhances SFR, while τ_{dep} does not change significantly (possibly because gas inflow increases M_{gas})
- SBMS has shorter τ_{dep} than MS (by definition), while 1.4 times longer than SB (Fig.3).
  → possibly due to feedback (redistribution of gas; "**dilation**").
- SBMS stage is short-lived (~30 Myr) → impossible to exhaust gas during this stage.

Possible pathways to become SBMS:

Key features:
1. Massive
2. Low f_{gas}
3. Short τ_{dep}

	Process	Dense regions	Field
1	Mass assembly	Frequent major mergers	Steady long-term growth
2	Gas consumption (f_{gas} decreases)	Intense SF	Less gas inflow
3	Stay on MS	Short τ_{dep} required to keep SF.	
4	Triggering SBMS	Additional merger	Internal stochastic fluctuation in SF

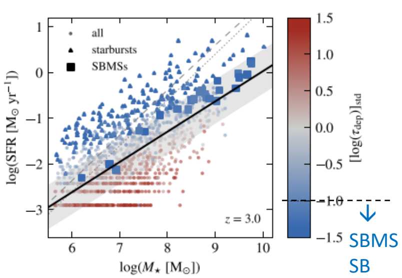


Fig. 2. Distribution of galaxies in the stellar mass–SFR plane at $z = 3$ (for illustration). The color indicates the standardized depletion time (i.e., the difference from the median value of the entire population, divided by the robust standard deviation; see Equation 1). The solid line represents the best least absolute deviation fit, and the shaded area indicates ±1 times the mean absolute deviation from this relation, defining the main sequence of the simulation at this redshift. For comparison, the dotted and dashed lines show the empirical main sequence relations from fits of observed galaxy populations in Schreiber et al. (2015, their Eq. 9) and Popesso et al. (2023, their Eq. 14), respectively (see Dubois

Comparison of (median) properties at z=3 snapshot:

- M_* : SB < MS < AN ~ SBMS
- SFR : MS < AN ~ SBMS < SB
- τ_{dep} : SB < SBMS < AN < MS
- f_{gas} : SBMS < AN < SB < MS (Fig.11)

$$\tau_{dep} = M_{gas} / SFR$$
$$f_{gas} = M_{gas} / (M_{gas} + M_*)$$

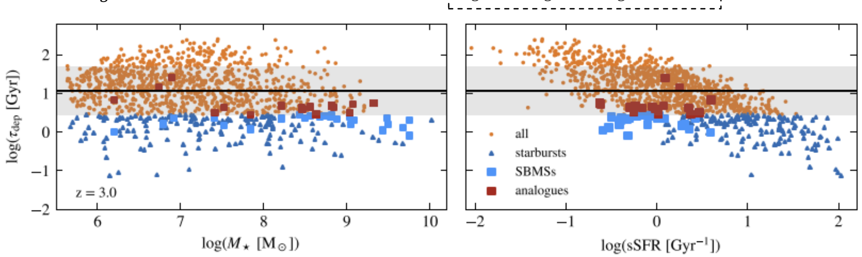


Fig. 3. Depletion times of the total gas of star-forming galaxies as a function of stellar mass (left) and sSFR (right), shown here at $z = 3$. The

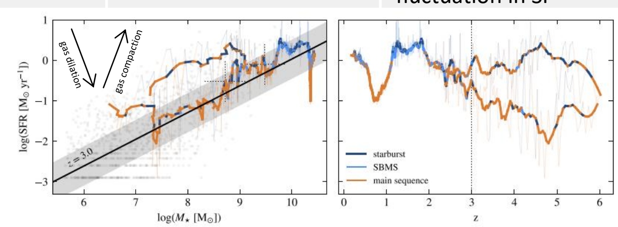


Fig. A.1. *Left panel:* Evolution of two examples of SBMS galaxies identified as such at $z = 3$ in the stellar mass-SFR plane. The positions of the galaxies at $z = 3$ are indicated by the large plus signs. *Right panel:* Evolution of the SFR as function of redshift of the same galaxies. The curves are color-coded by the category of the galaxy: SBMS in light blue, off-main sequence starburst in dark blue, and main sequence in orange. The curves have been smoothed by a Savitzky-Golay algorithm to improve readability, with the original measurements shown by the semi-transparent lines. Black dots represent the entire population of star forming galaxies at $z = 3$, with the main sequence shown with the solid line and shaded area. We remind the reader that the position of the main sequence changes with redshift: these elements in black can be used to guide the eye only at $z = 3$.