Origin and Evolution of Starburst Galaxies

from the Perspective of Cosmological Simulations

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Feedback In Realistic Environments

FIREbox

University of Zurich[UZH]

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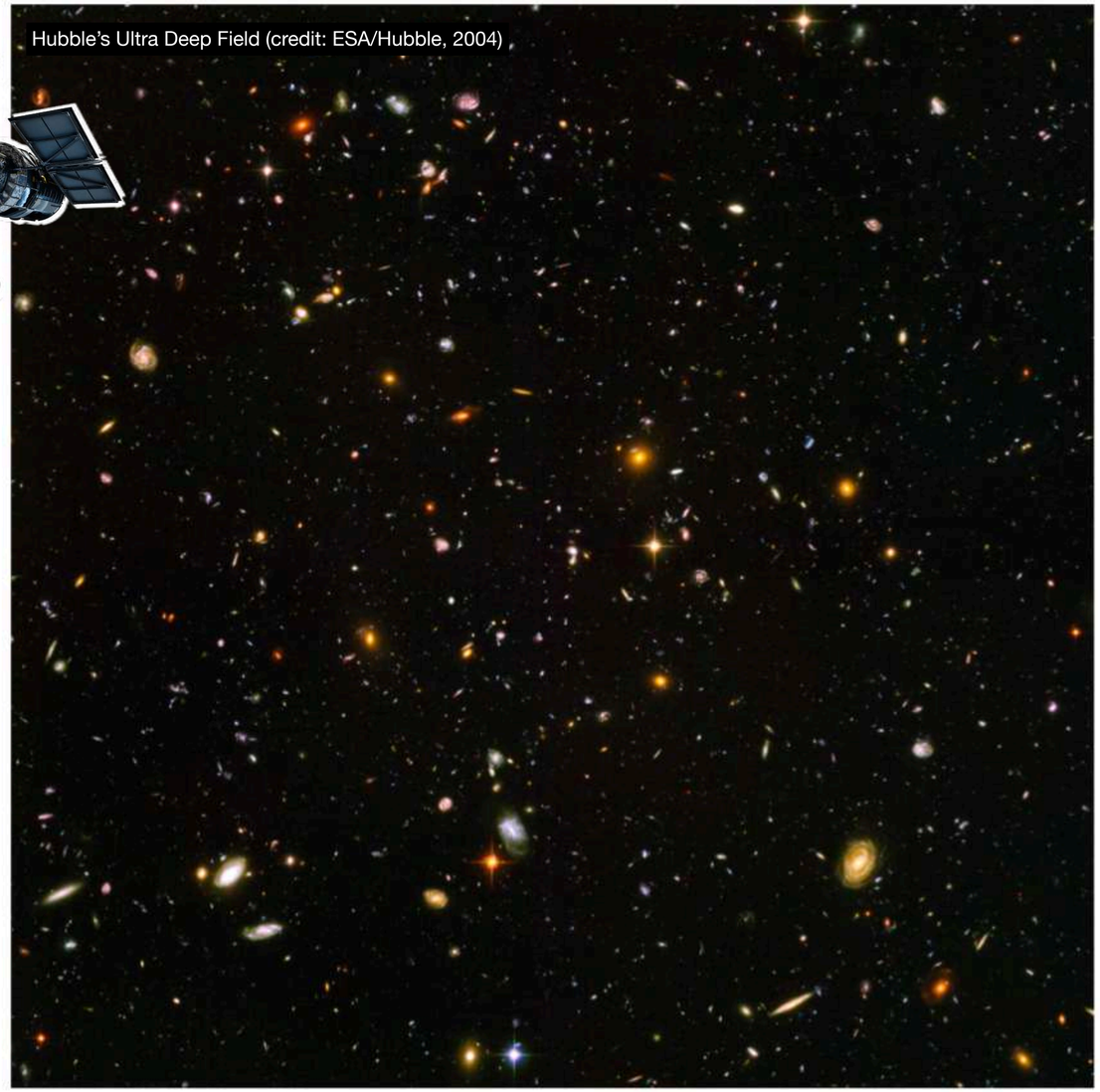
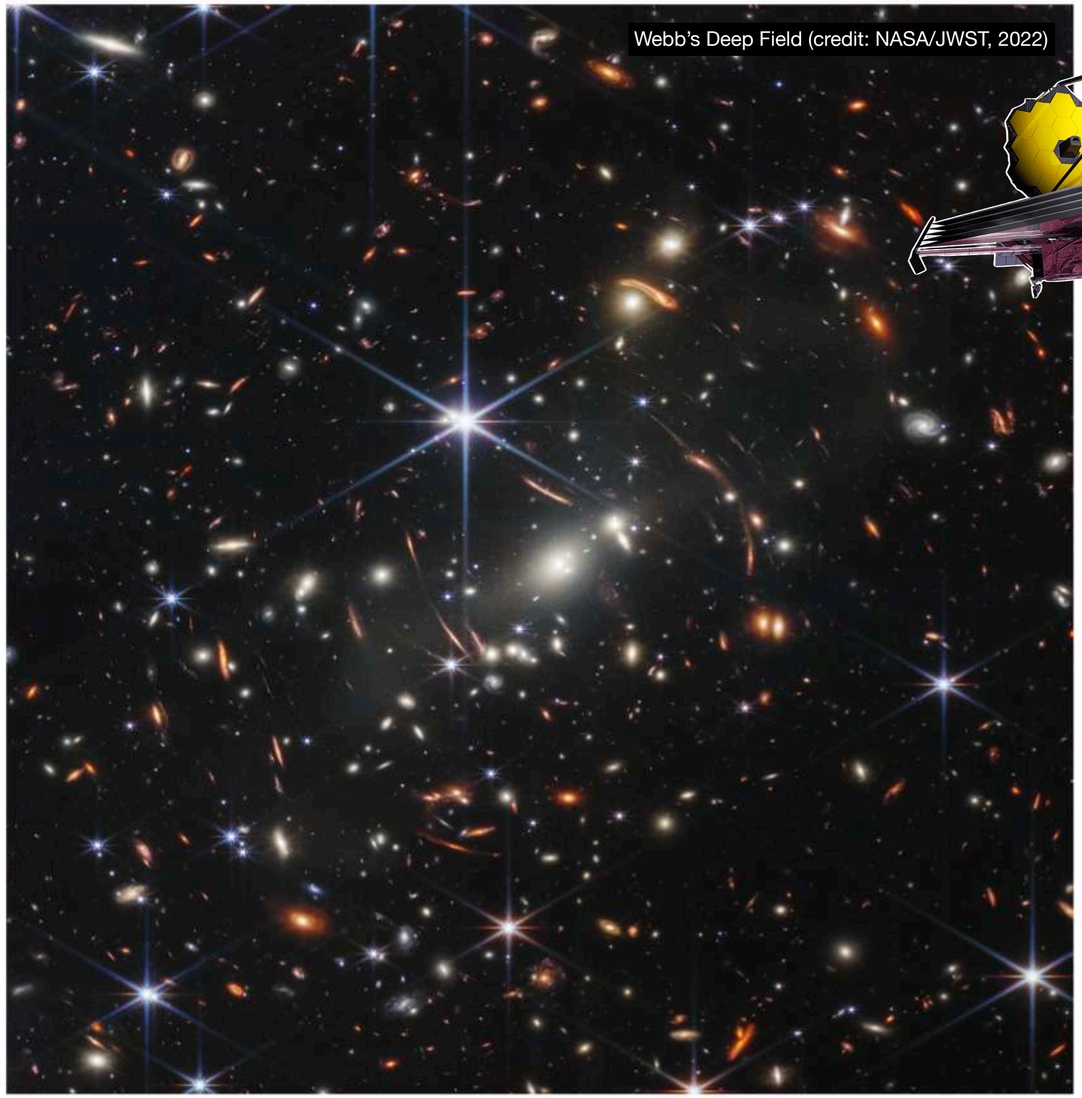
Extragalactic astronomy

A universe in a grain of sand…

A century in the making



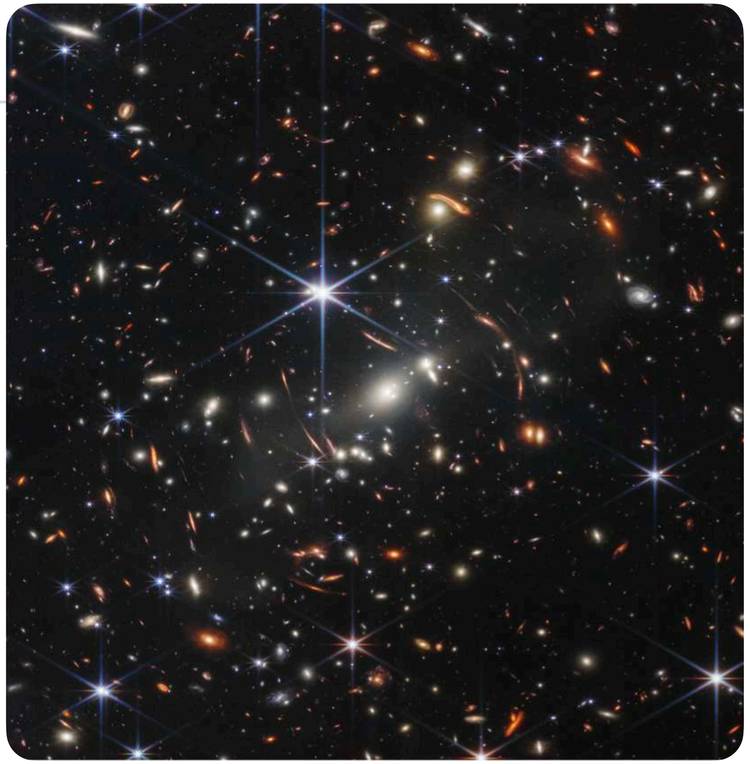
Hubble's Ultra Deep Field (credit: ESA/Hubble, 2004)



Webb's Deep Field (credit: NASA/JWST, 2022)

Galaxies in the Universe

Properties and scaling relations



Diverse galaxy population

⇒ distinct classes of morphologies, structures, colors, star-formation activities

*How can we understand their **formation** and evolution?*

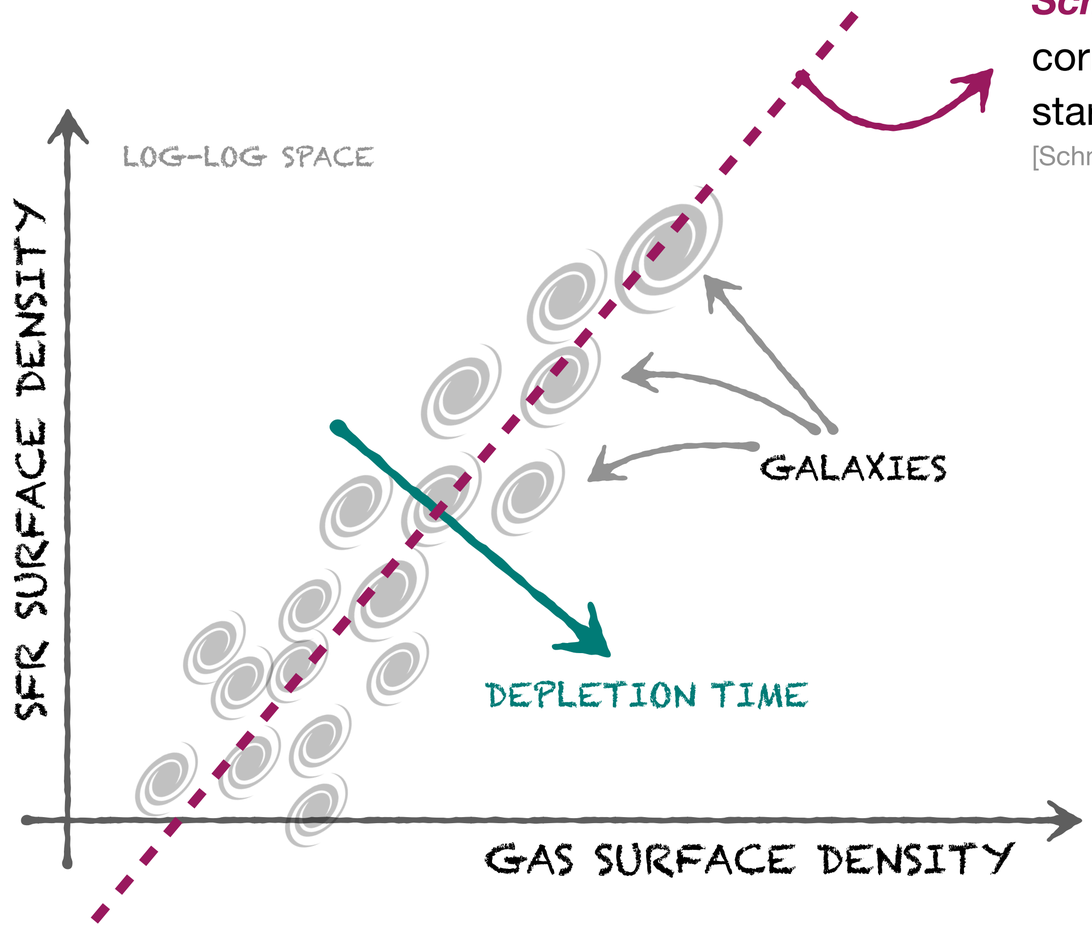
Scaling relations:

tight correlations observed between galaxy properties

(e.g., stellar and gas masses, sizes, black hole masses, kinematics, metallicity)

Galaxies in the Universe

Properties and scaling relations



***Schmidt-Kennicutt* relation**:
correlation between the gas surface density (Σ_{gas}) and star-formation rate surface density (Σ_{SFR}) of galaxies
[Schmidt 1959, 1963; Kennicutt 1998]

⇨ **more gas forms more stars**

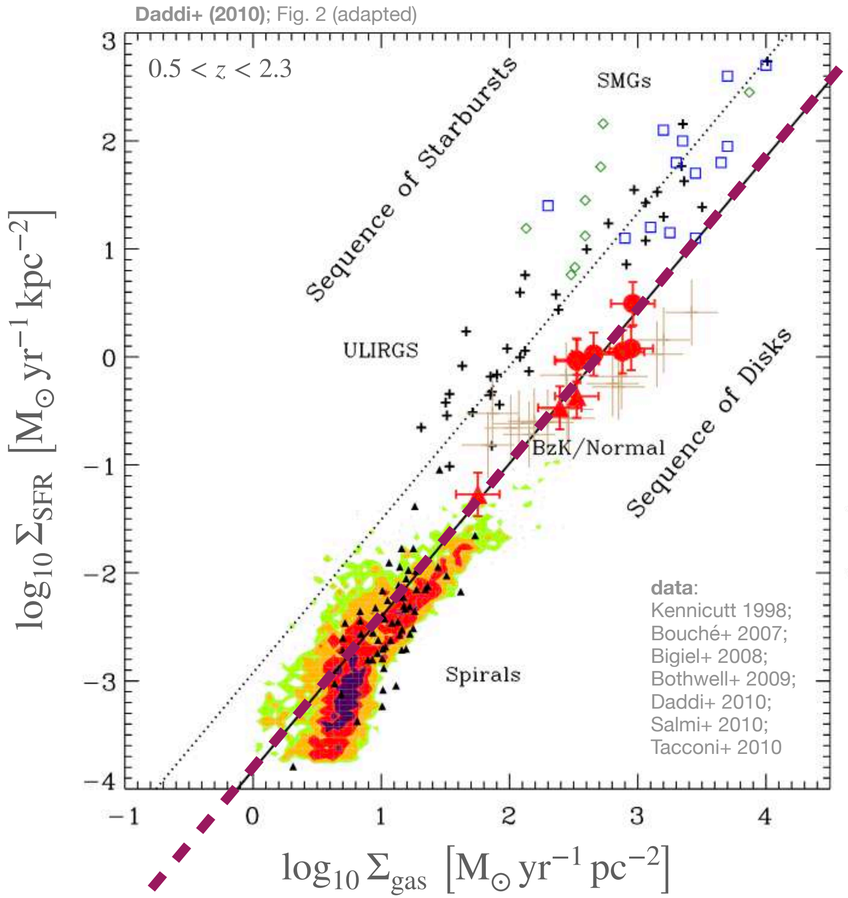
Depletion time: $t_{\mathrm{depl}} = \Sigma_{\mathrm{gas}} / \Sigma_{\mathrm{SFR}}$

Time it takes to turn all the present gas into stars at the current star-formation rate

Galaxies in the Universe

Properties and scaling relations

Daddi+ (2010); Fig. 2 (adapted)



***Schmidt-Kennicutt* relation**:
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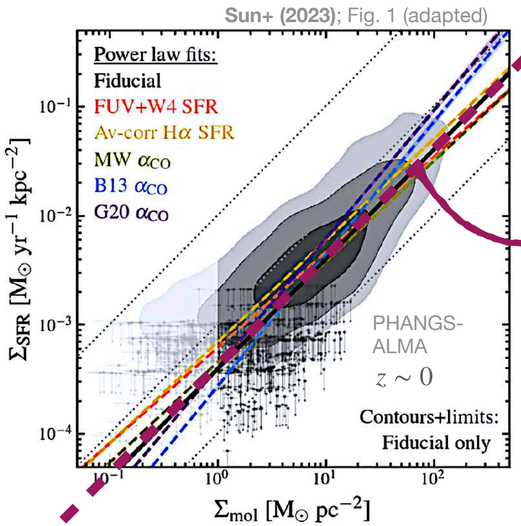
Sun+ (2023); Fig. 1 (adapted)



Molecular gas surface density ($\Sigma_{\rm mol}$) results in a ∼ **linear relation**

⇨ more **molecular** gas forms more stars

Even tighter, linear correlation considering high-density gas

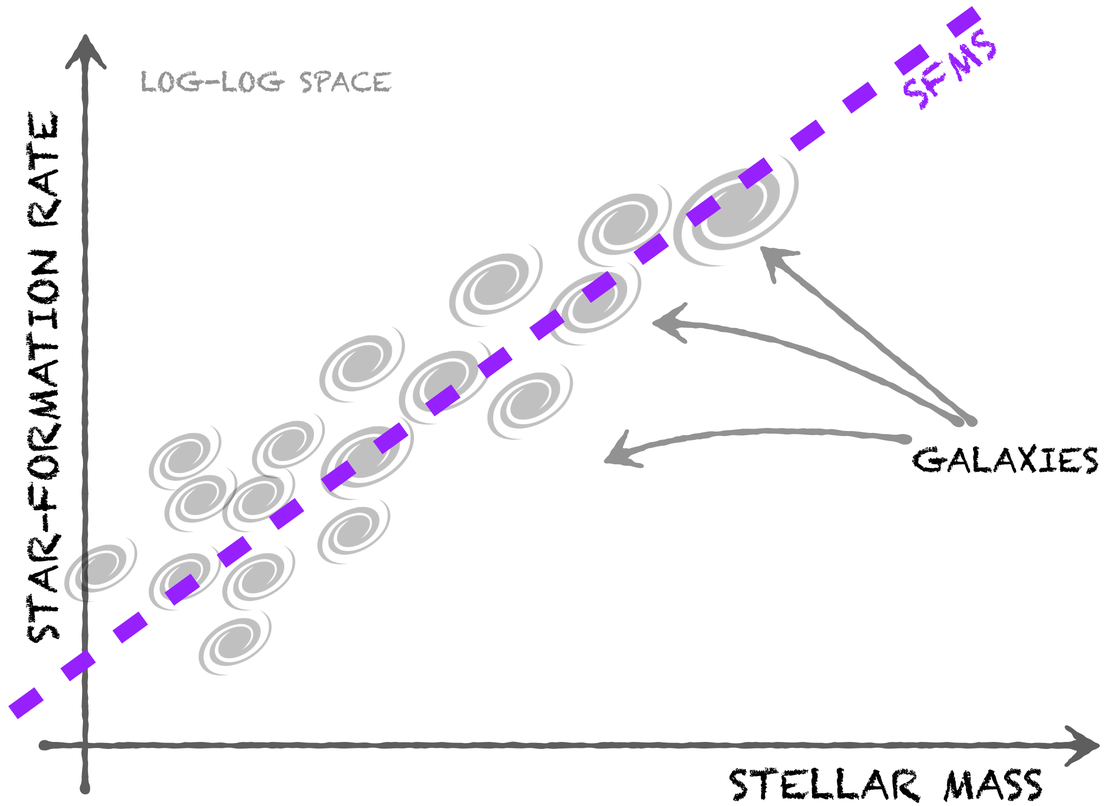
⇨ more **dense**, **molecular** gas forms more stars

Galaxies in the Universe

Properties and scaling relations

Star-forming main sequence (SFMS):
tight correlation between the stellar mass ($M_\star$)
and star-formation rate (SFR) of galaxies

⇨ the **more stars** a galaxy has,
the **more stars** it **forms**



Schmidt - Kennicutt — *Gas sequence*

$$\mathrm{SFR} \sim \mathrm{gas} \sim \mathrm{star}$$

Galaxies in the Universe

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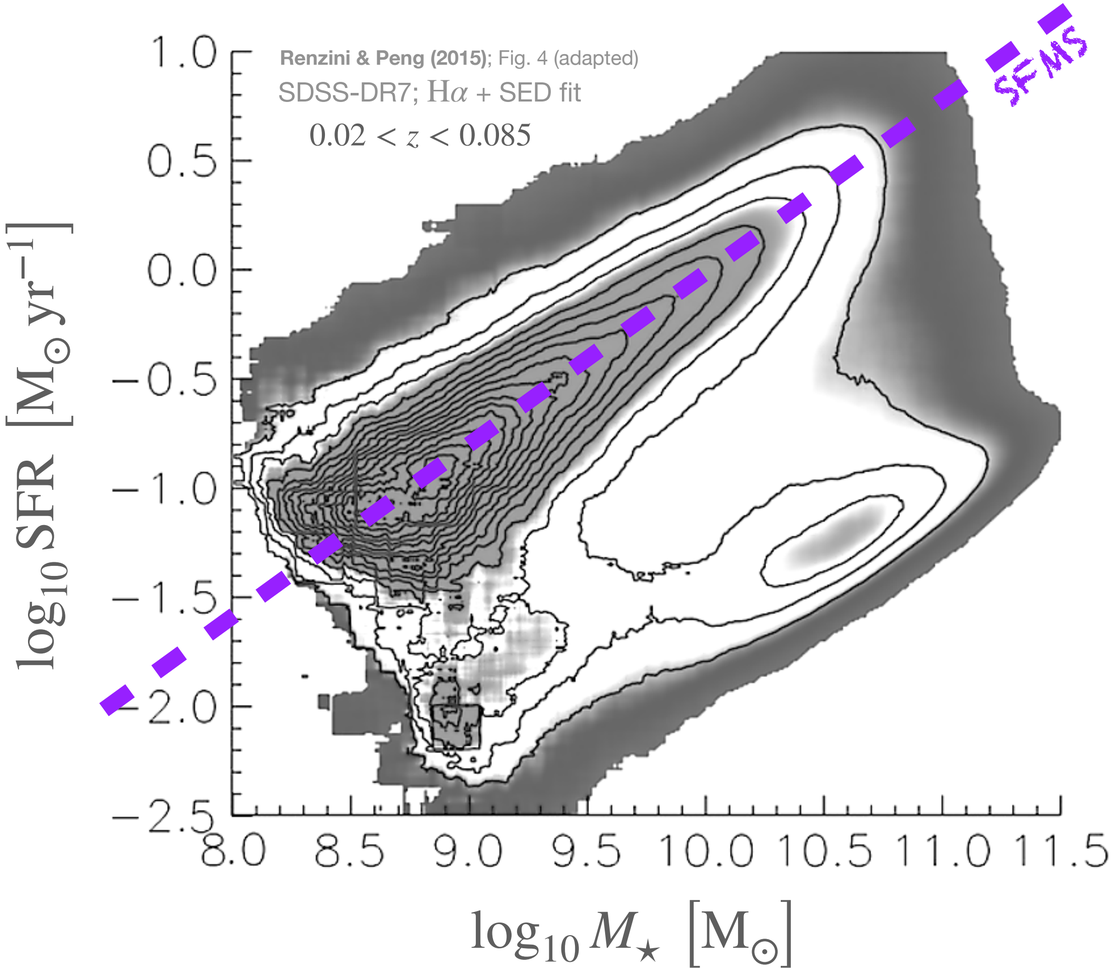
Observed both at low and high redshift
[e.g., Brinchmann+ 2004; Daddi+ 2007; Salim+ 2007]

Normalisation increases with redshift, as gas fractions are higher at earlier epochs, while its ***slope*** and scatter only mildly change with redshift and stellar mass
[e.g., Daddi+ 2010; Leslie+ 2020; Noeske+ 2007; Whitaker+ 2012; Speagle+ 2014; Schreiber+ 2015]



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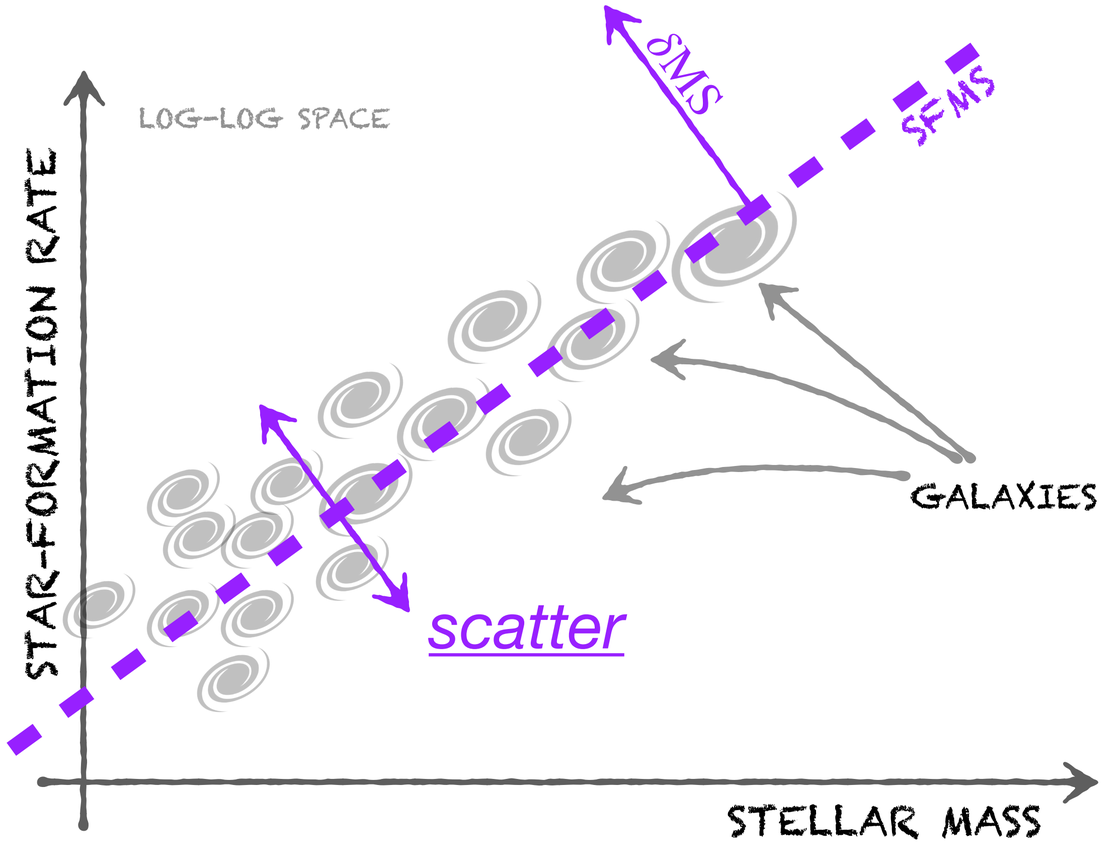
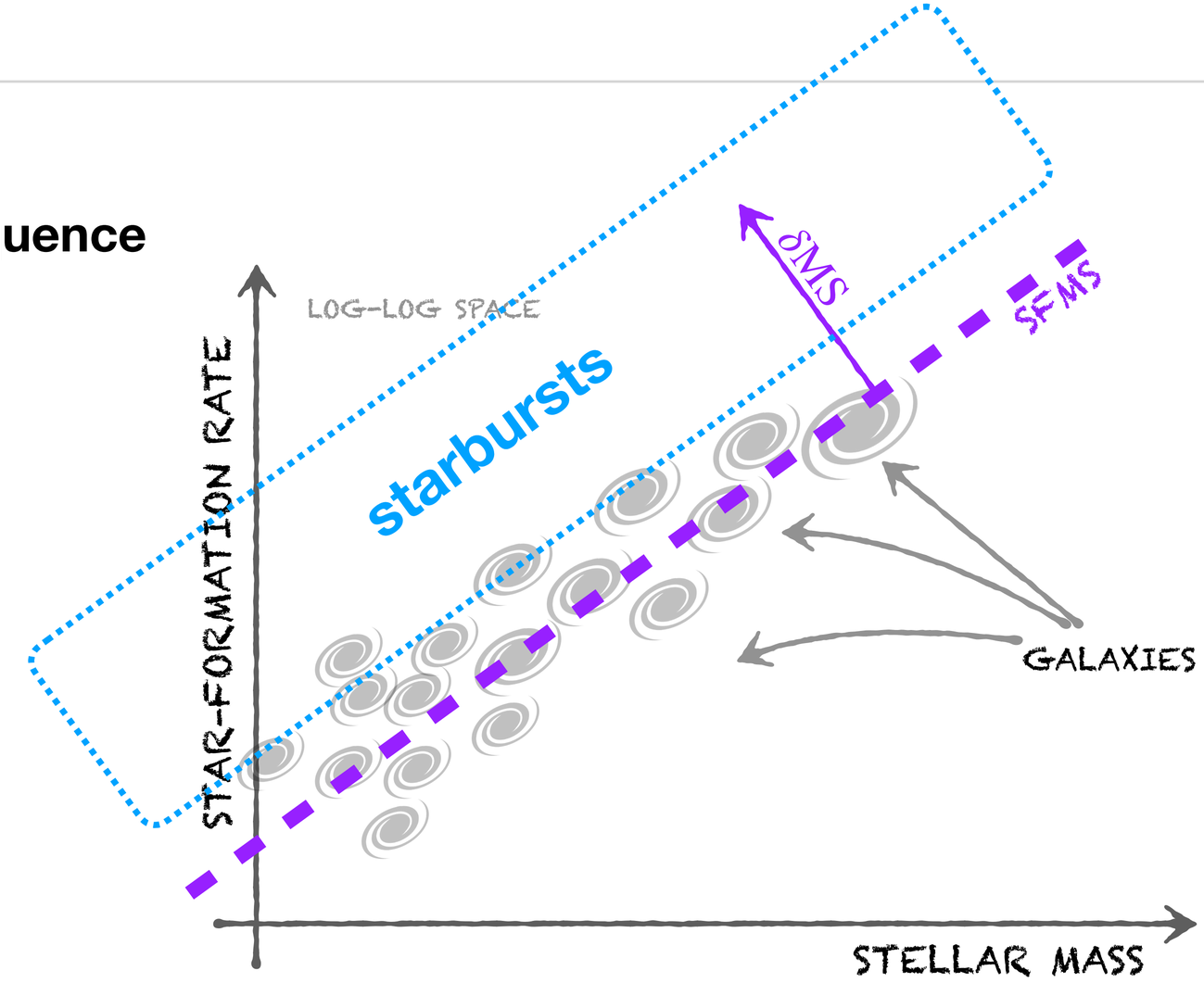


What causes galaxies to scatter around the main sequence?
[see also, e.g., Tacchella+ 2016a]

Starburst galaxies

An introduction

Outliers above the star-forming **main sequence**



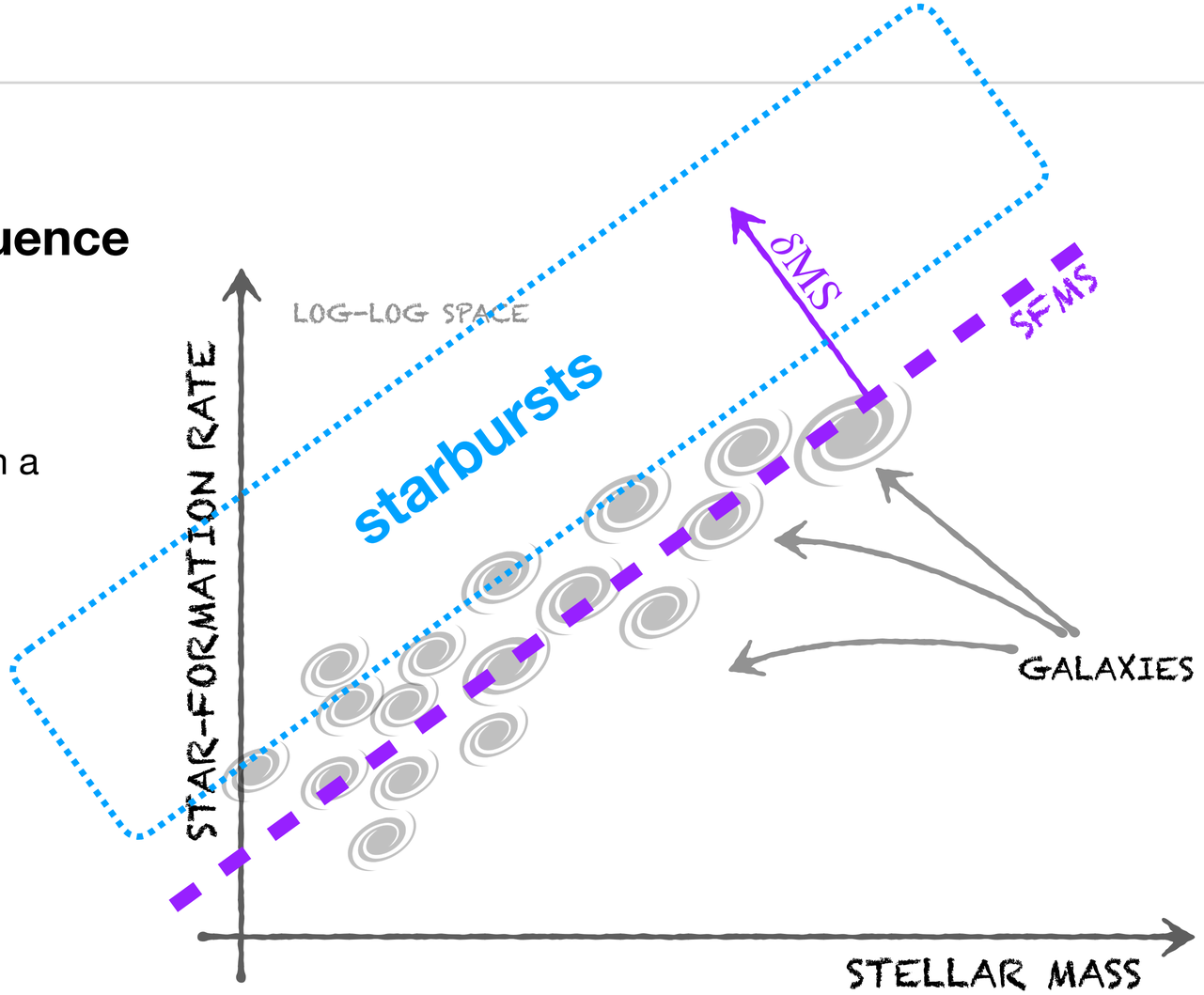
Starburst galaxies

An introduction

Outliers above the star-forming **main sequence**

1-5% of all star-forming galaxies at $z = 0 - 1$
[e.g., Bergvall+ 2016; Bisigello+ 2018; Rinaldi+ 2022]

With their intense star formation activity, SB galaxies form a large fraction of their stellar mass in up to **a few 100 Myr**
[e.g., Cenci+ 2024a]



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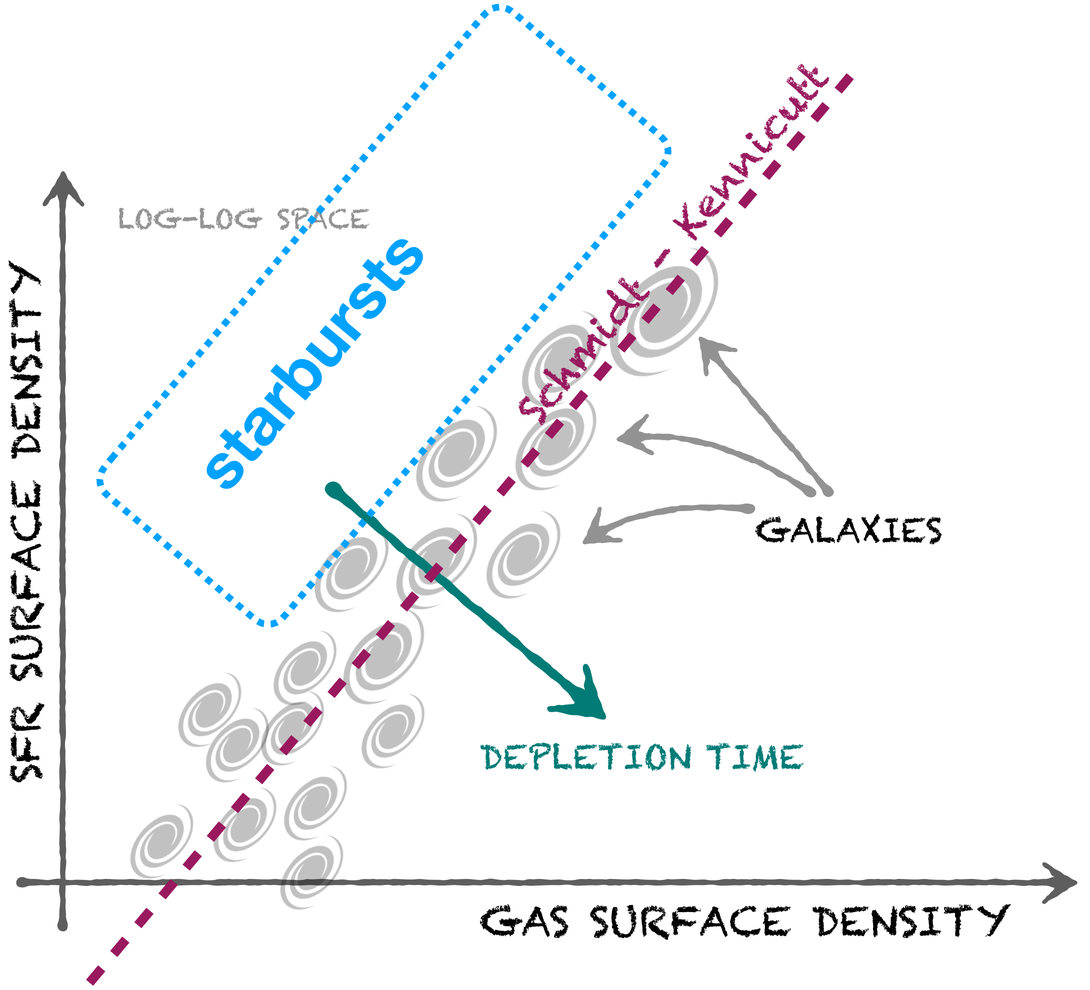
Separate sequence in the **Schmidt-Kennicutt** plane, with larger $\Sigma_{\rm SFR}$ at fixed $\Sigma_{\rm gas}$ (i.e., shorter $t_{\rm depl}$)
[e.g., Daddi+ 2010; Genzel+ 2010; Kennicutt & Evans 2012; Kennicutt & De Los Reyes 2021]



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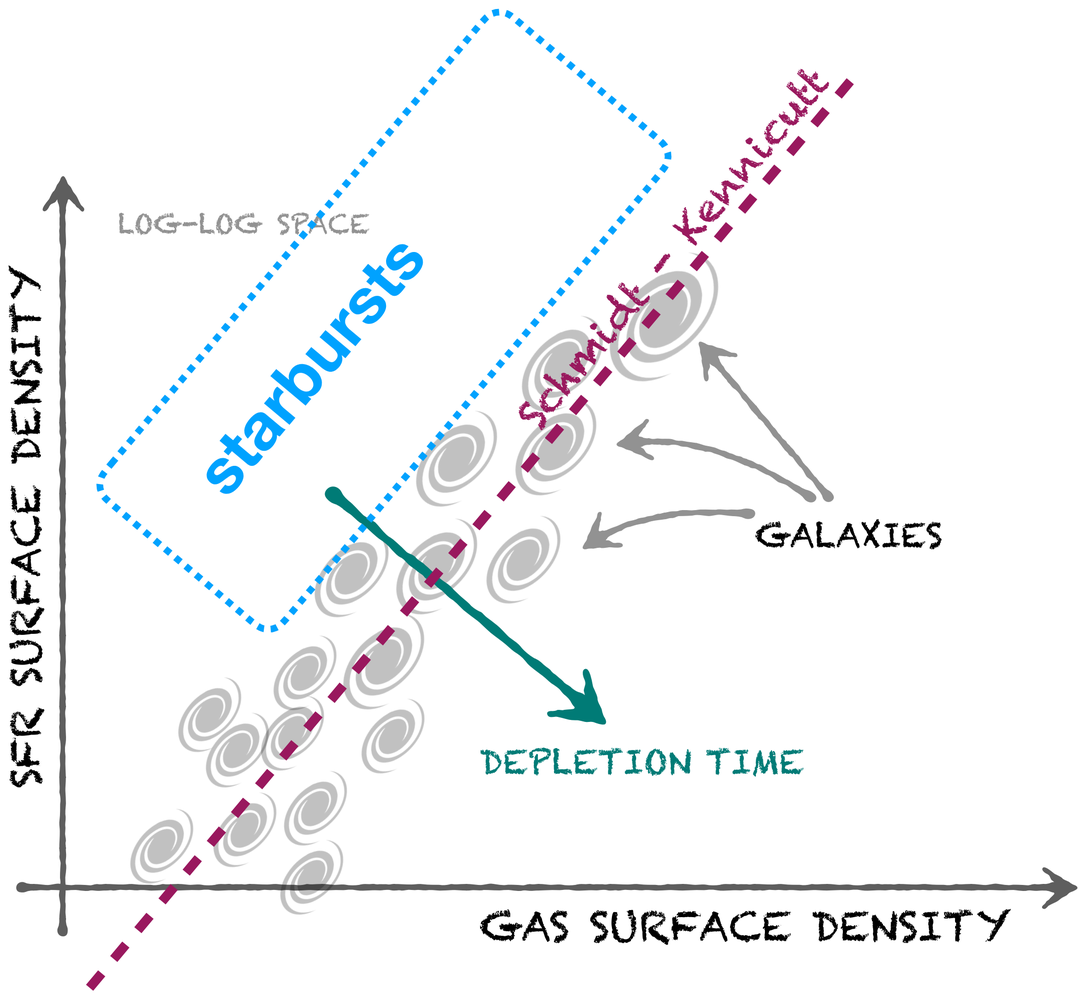

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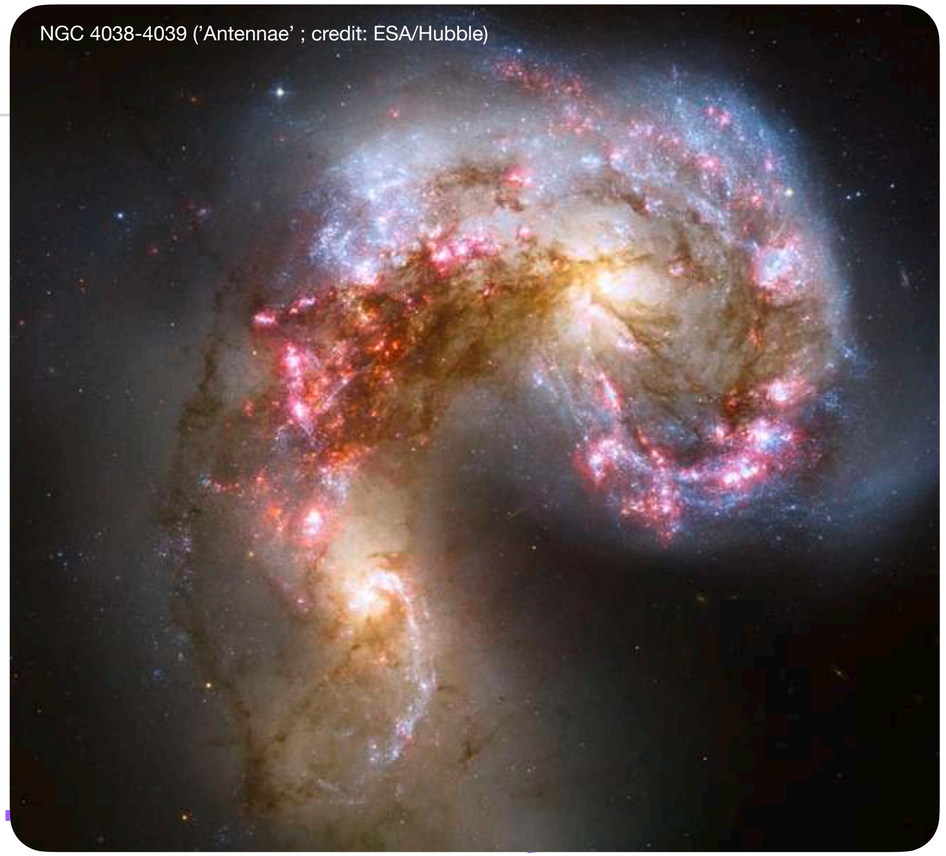
NGC 4038-4039 ('Antennae' ; credit: ESA/Hubble)

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What is causing SBs?

- **Larger** molecular gas **reservoir**
  [e.g., Combes+1994; Casasola+2004; Scoville+2016, 2017; Tacconi+2018]
- **Increased efficiency** in converting gas into stars
  [e.g., Sofue+1993; Solomon & Sage 1988; Sargent+2014; Michiyama+2016; Silverman+2015, 2018; Feldmann 2020]
- Caused by **interactions**
  [e.g., Genzel+2010; Ellison+2013; Renaud+2014; Hopkins+2018; Moreno+2019; Renaud+2019; Pan+2018; Segovia Otero+2022]
- **Not** caused by **mergers**
  [e.g., Di Matteo+2008, 2009; 2009; Sparre & Springel 2016; Violino+2018; Wilkinson+2018]

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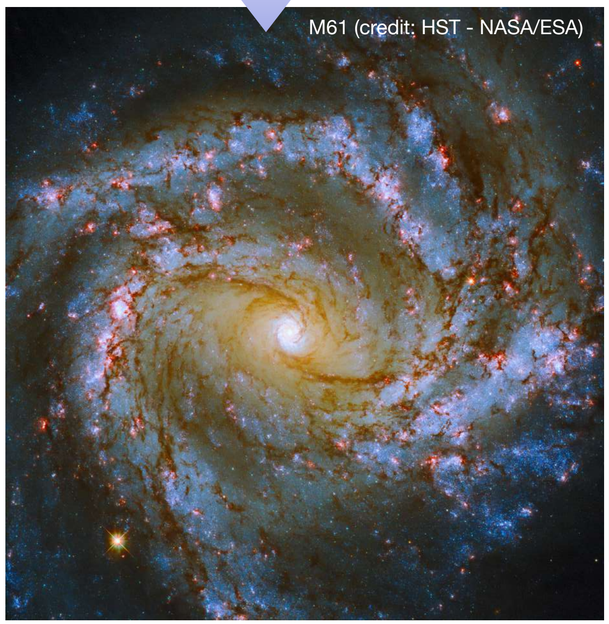
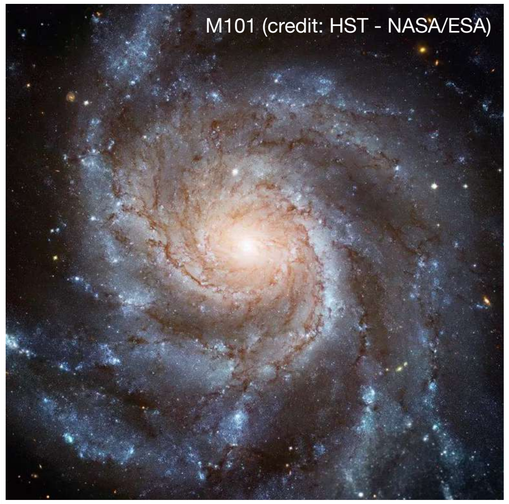
Numerical Methods

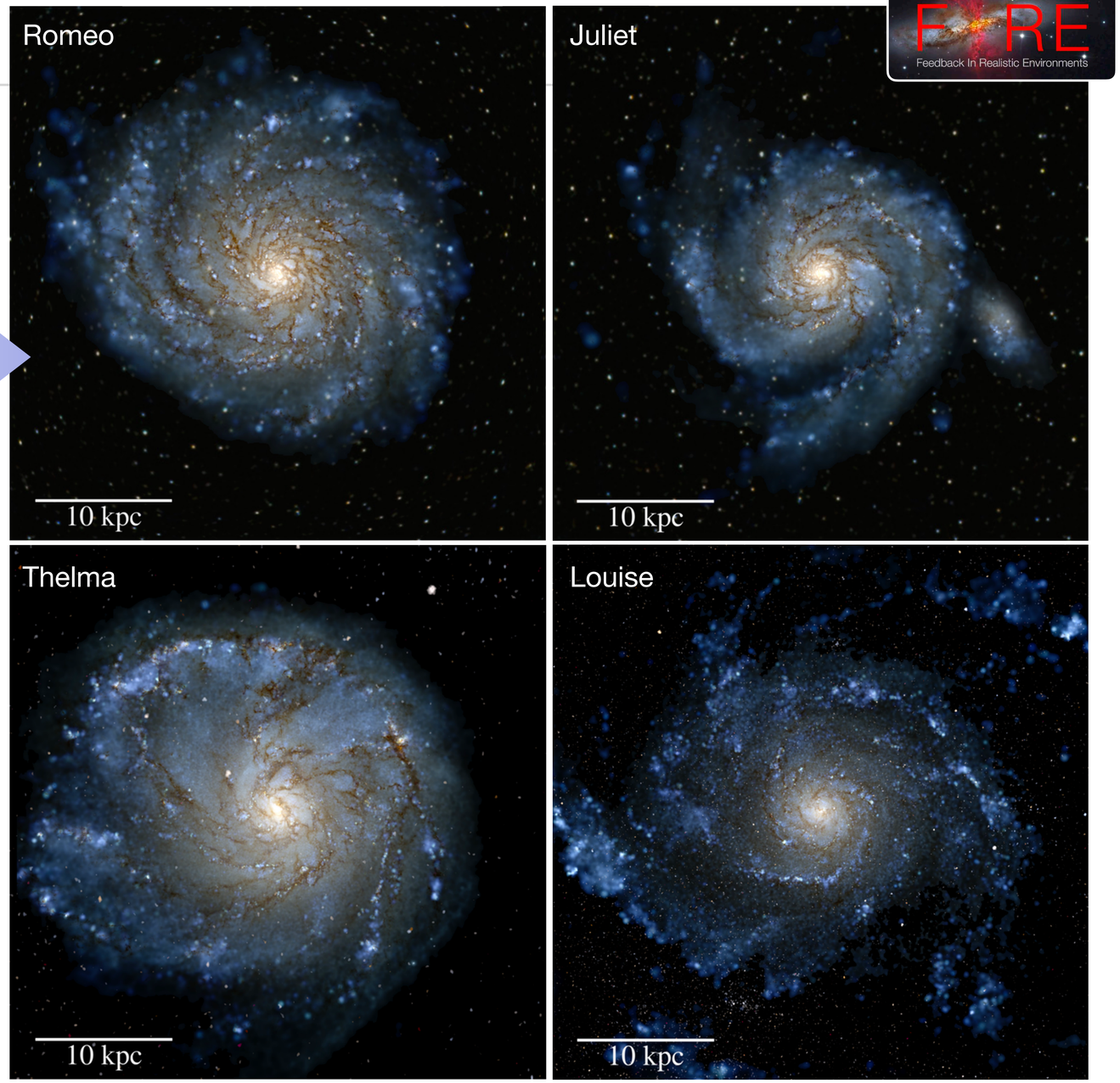
Cosmological hydrodynamical simulations

SIMULATED

REAL







Mock HST images of $z = 0$ FIRE simulated galaxies. Credit: **Phil Hopkins, 2015**
[http://www.tapir.caltech.edu/~phopkins/Site/animations/gallery-of-simulated-galaxi/]

Numerical Methods

Cosmological hydrodynamical simulations

Studying **starburst galaxies** **in simulations**:

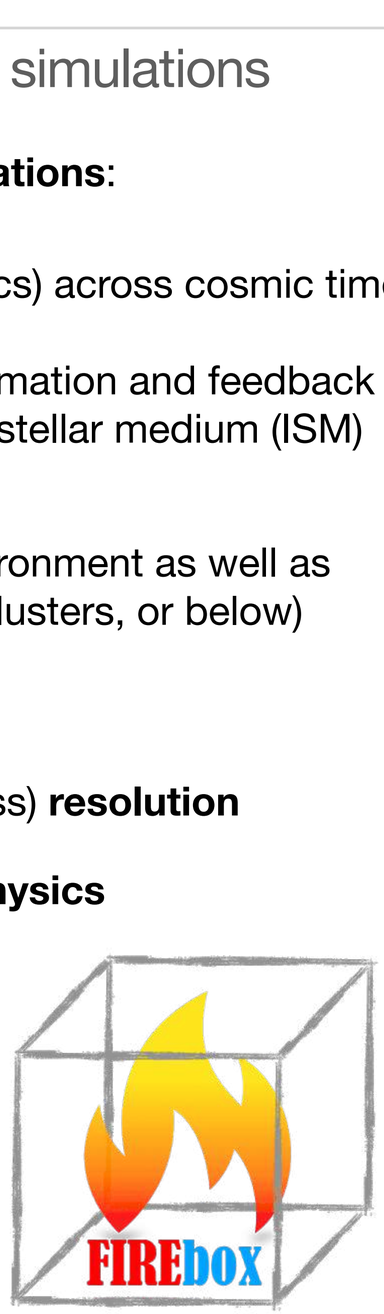
- galaxy interactions
- large galaxy sample (for statistics) across cosmic time
- wide range of galaxy masses
- realistic prescription for star formation and feedback
- accurate modelling of the inter-stellar medium (ISM)

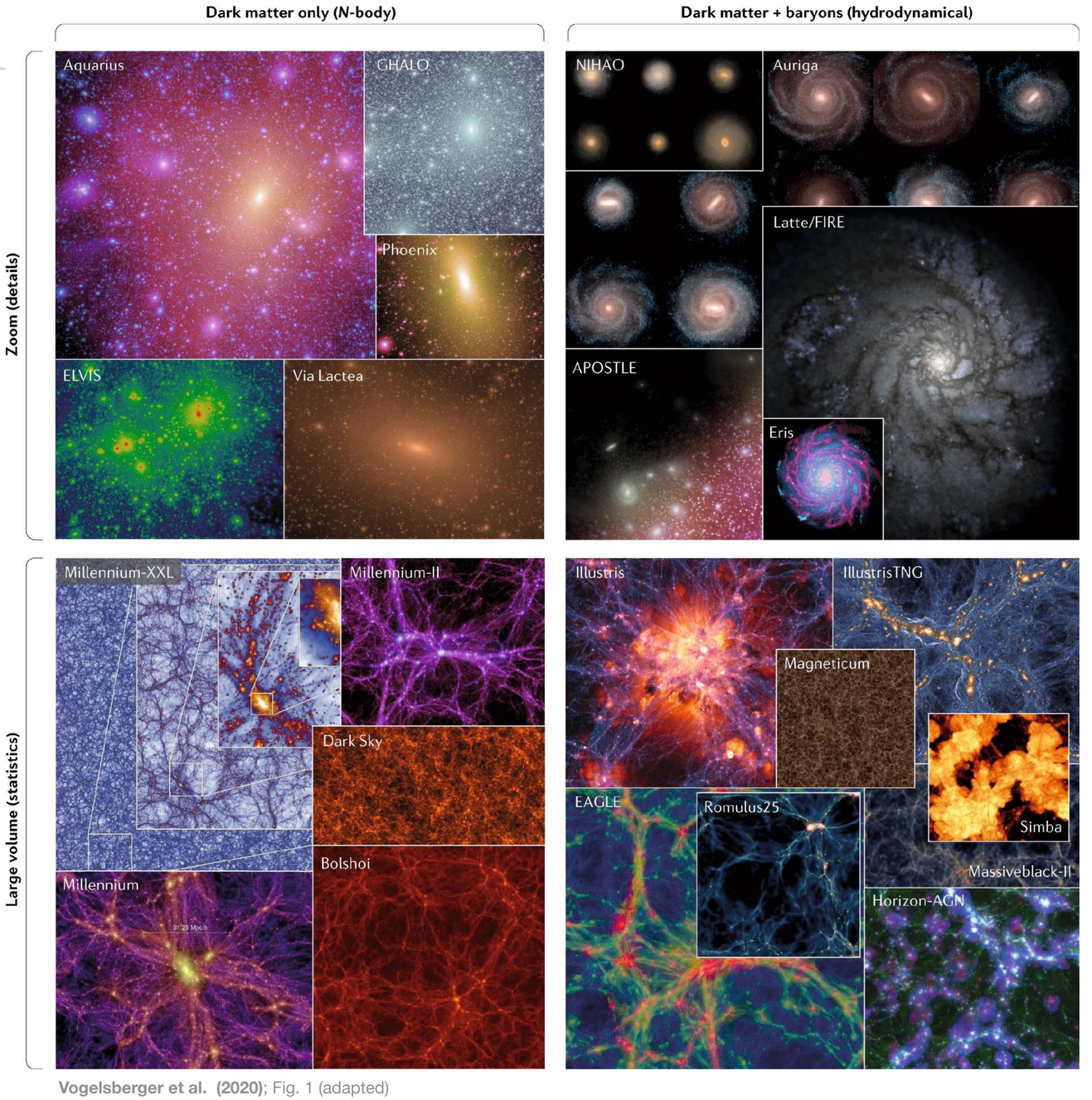
Need to model a cosmological environment as well as processes on small scales (stellar clusters, or below)

⇨ **large** simulation **box**

⇨ **high** (spatial and mass) **resolution**

⇨ accurate **sub-grid physics**





Vogelsberger et al. (2020); Fig. 1 (adapted)

Numerical Methods

FIREbox and the FIRE-2 model

FIREbox

[Feldmann, …, EC, et al., 2023, MNRAS]

Cubic (non-zoom) **cosmological volume**, **high-resolution** simulation with periodic boundary conditions.

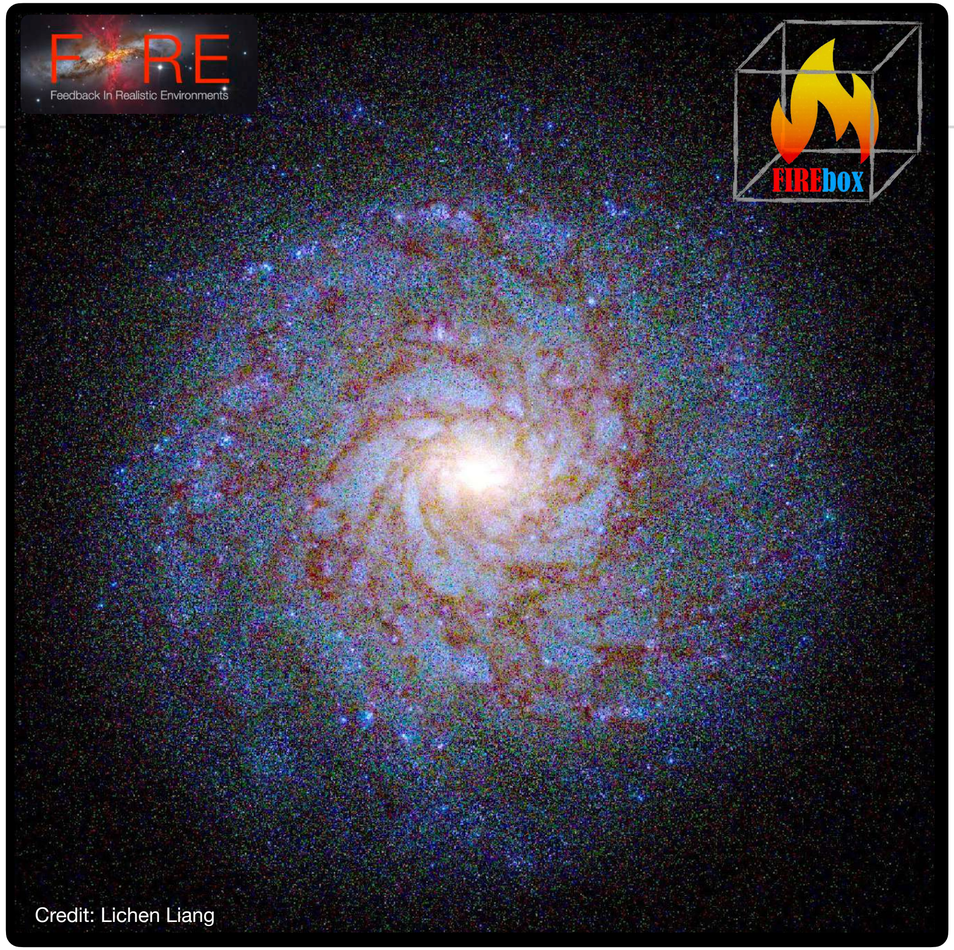
$$V = (22\ \mathrm{cMpc})^3$$

$$m_\mathrm{b} = 6.26 \times 10^4\ \mathrm{M}_\odot$$
$$\varepsilon_\mathrm{gas,min} = 1.5\ \mathrm{pc}$$
$$\epsilon_\star = 12\ \mathrm{pc}$$

Part of the **FIRE** project [Hopkins+2014, 2018], with **FIRE-2 physics** model, accounting for gas cooling and heating, star formation, and stellar feedback (*AGN feedback is not included*).

Star-formation prescription:
dense, Jeans-unstable, self-shielded, gas with **100% efficiency per free-fall time**

$$\rho_\mathrm{SFR} = \rho_{\mathrm{H}_2} / t_\mathrm{ff}$$
$$n_\mathrm{H,\,SF} = 300\ \mathrm{cm}^{-3}$$



Origin and evolution of starburst galaxies in cosmological simulations

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   Starburst driven by central gas compaction
   [Cenci et al., 2024a, MNRAS]

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   Starburst-induced gas-star kinematic misalignment
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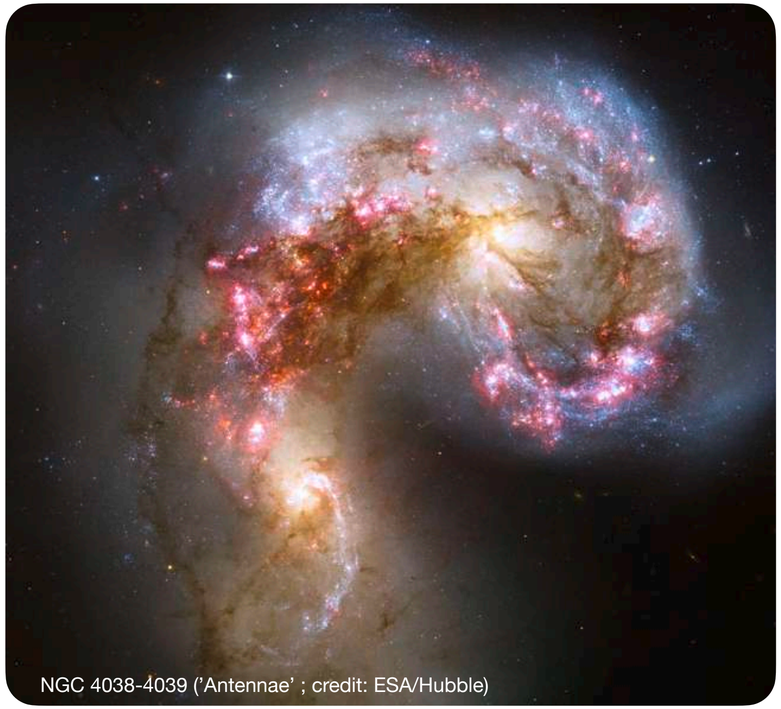


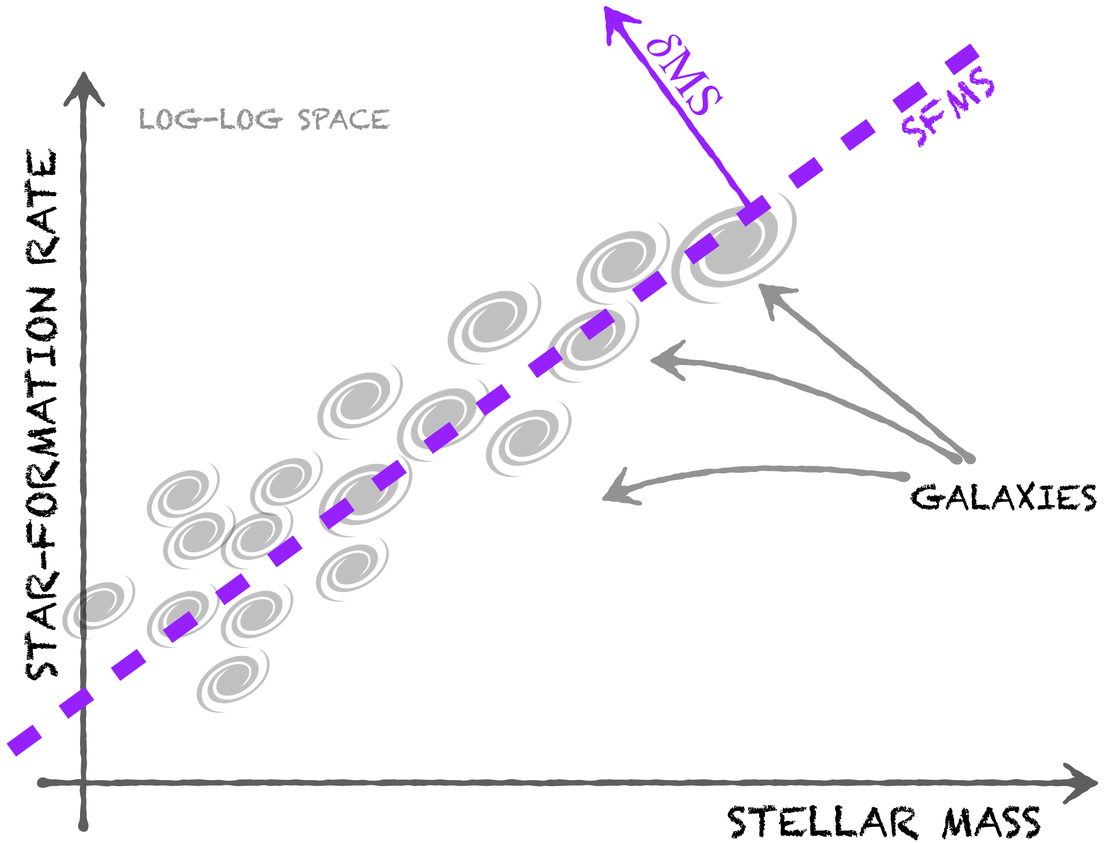
NGC 4038-4039 ('Antennae' ; credit: ESA/Hubble)

Starbursts Driven by Central Gas Compaction

Starburst and control samples

- ***FIREbox galaxies*** : $M_\star \geq 10^8\,\mathrm{M}_\odot\,,\, z = 0 - 1$

- ***SFMS*** *in FIREbox* :
  $\lg \mathrm{sSFR}_{\mathrm{SFMS}} = A\,(1+z)^{\alpha}\,\lg M_\star + B\,(1+z)^{\beta}$



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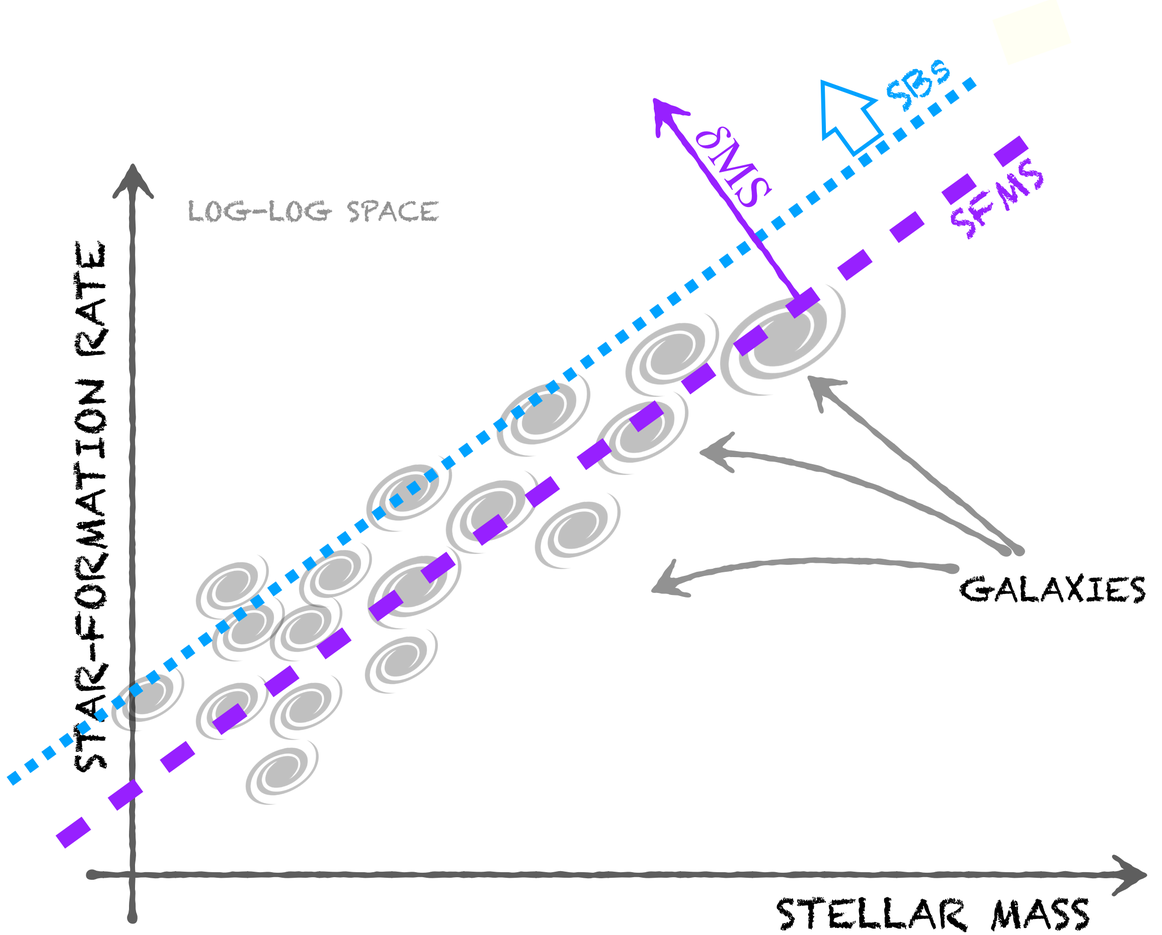

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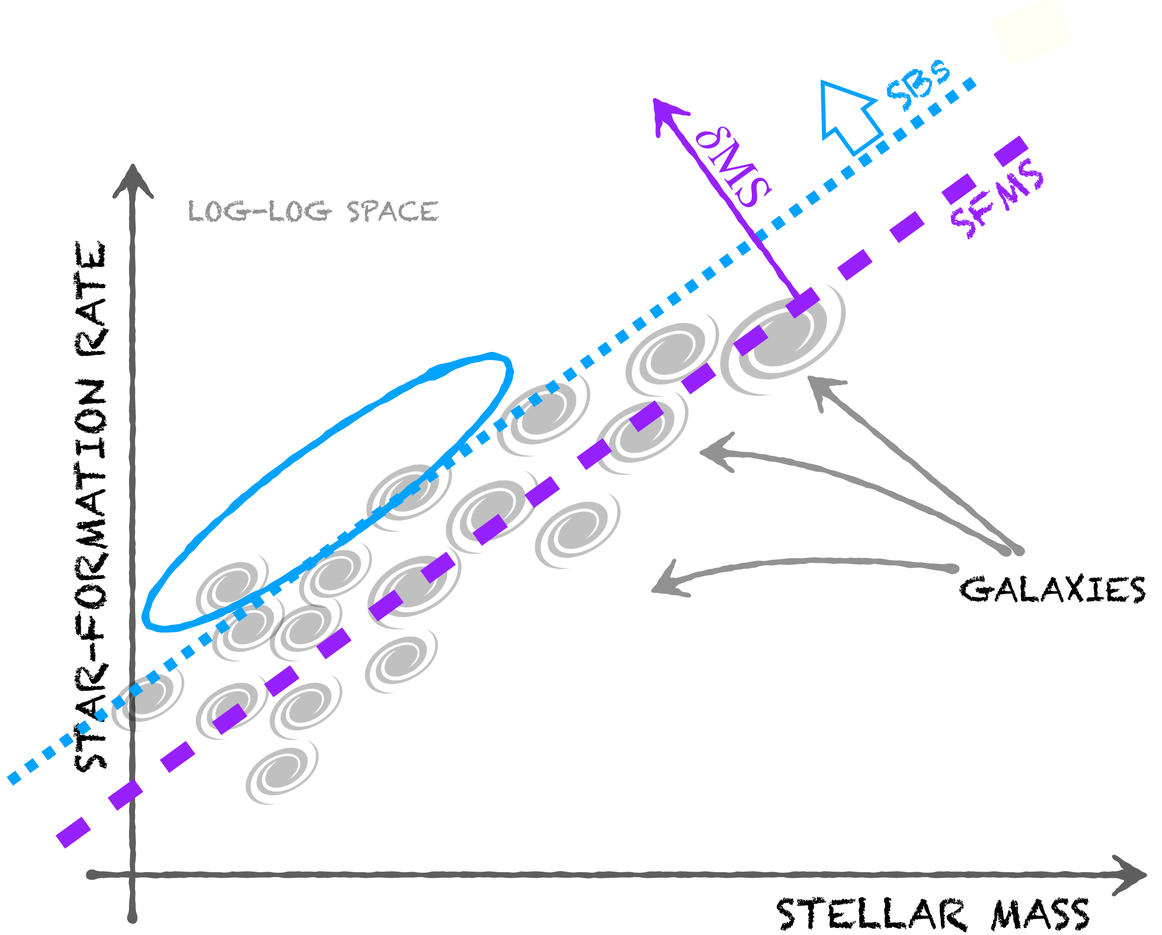
  $\mathrm{SFR} \times 4$ above the SFMS ($\delta\mathrm{MS} \geq 0.6\,\mathrm{dex}$)



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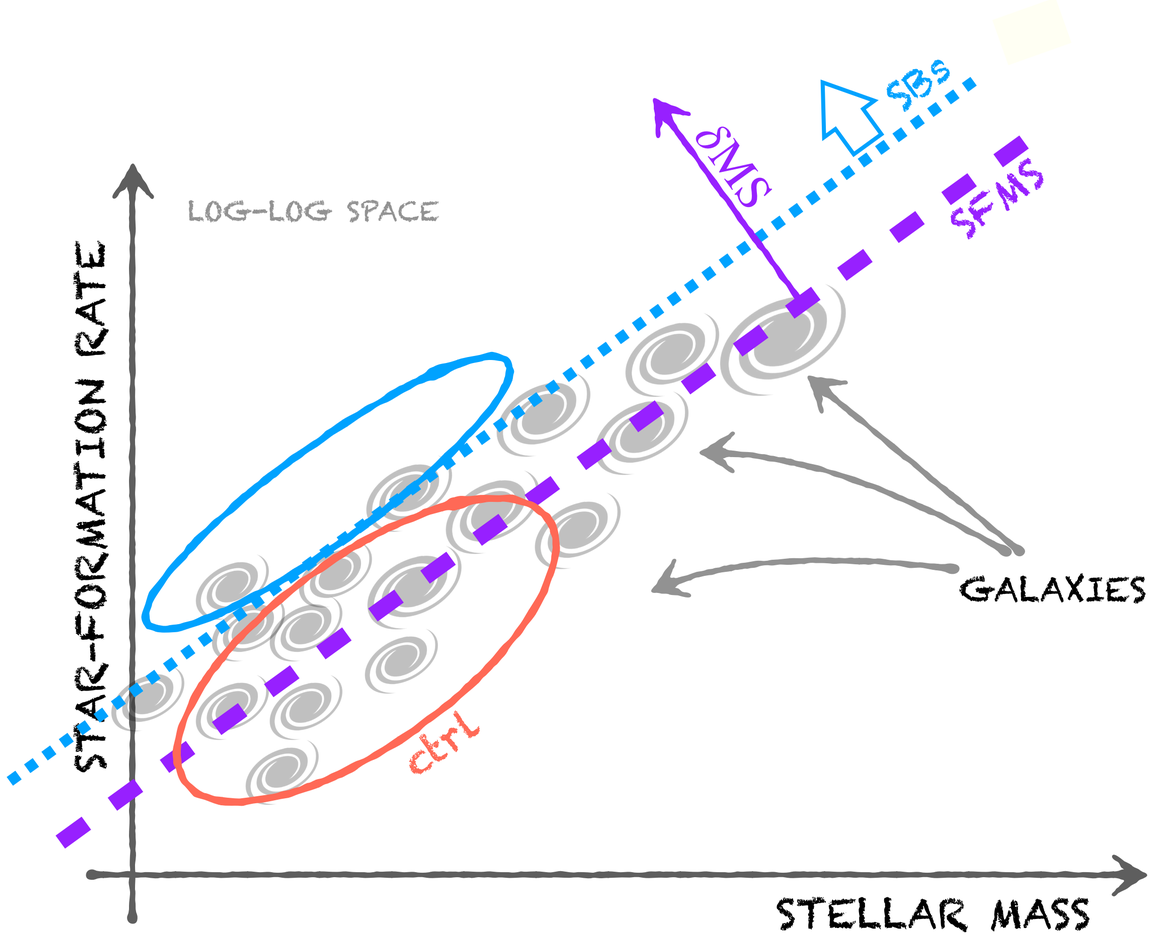
- ***Starburst*** *(SB) sample* :
  $\mathrm{SFR} \times 4$ above the SFMS ($\delta\mathrm{MS} \geq 0.6\,\mathrm{dex}$)
- ***Control*** *(ctrl) sample* :
  Mass- and redshift-matched of non-SB galaxies

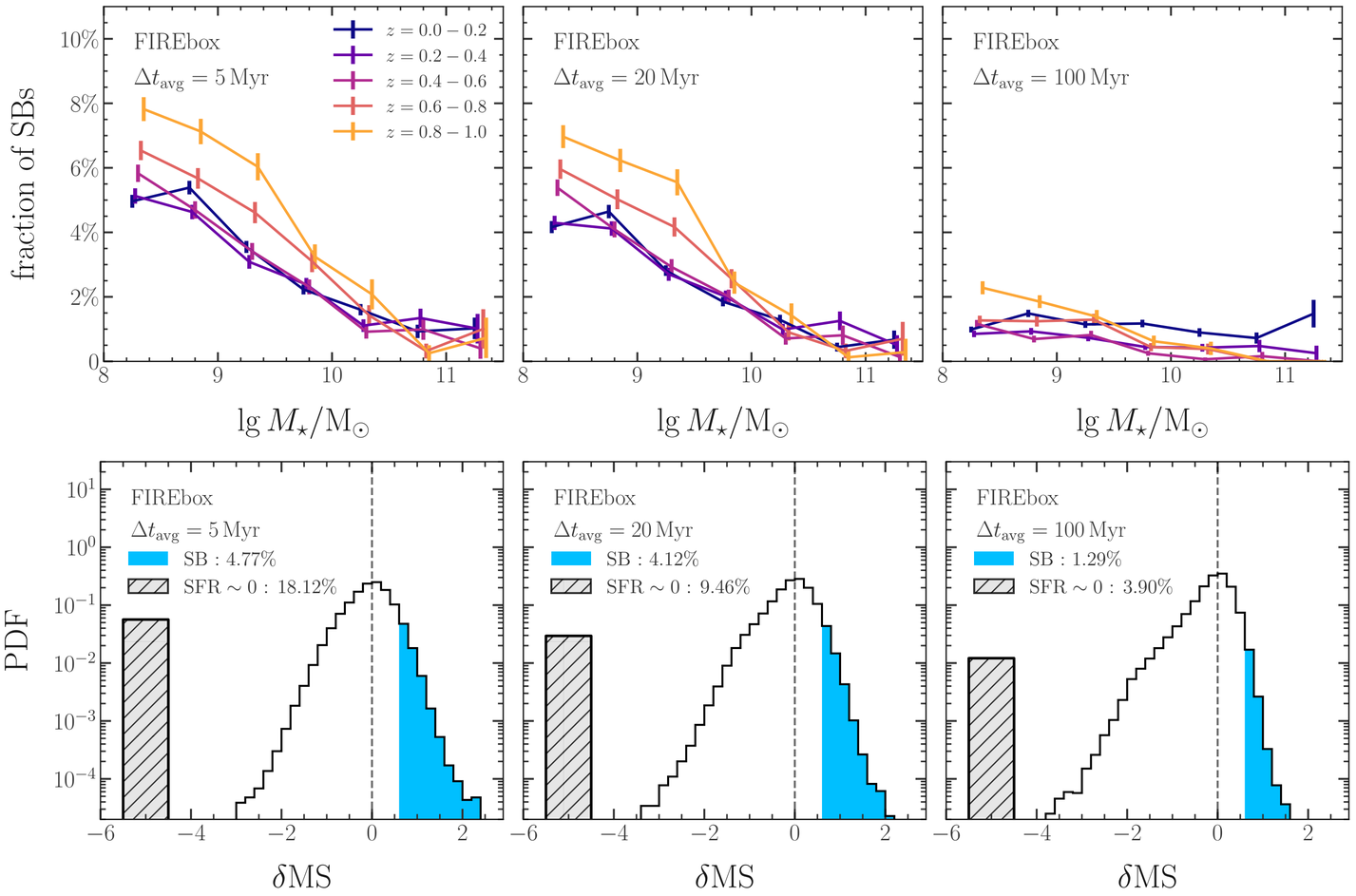


Starbursts Driven by Central Gas Compaction

Starburst fraction

- The SB fraction increases with increasing z and with decreasing $M_\star$

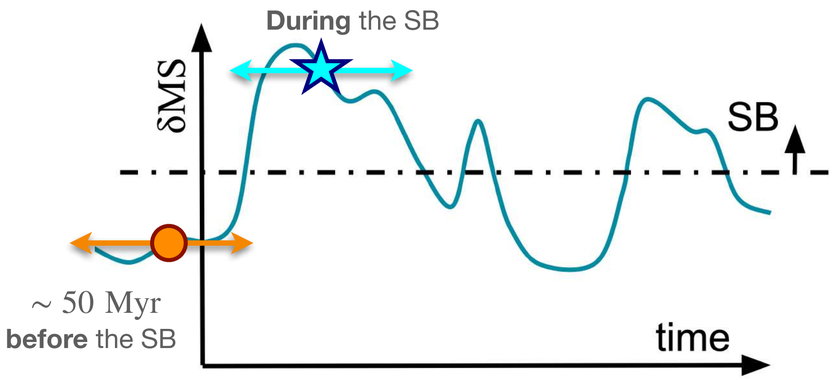
- For $\Delta t_{\rm avg} = 5, 20, 100$ Myr, SB galaxies make up $\sim 5, 4, 1\,\%$ of star-forming galaxies, respectively

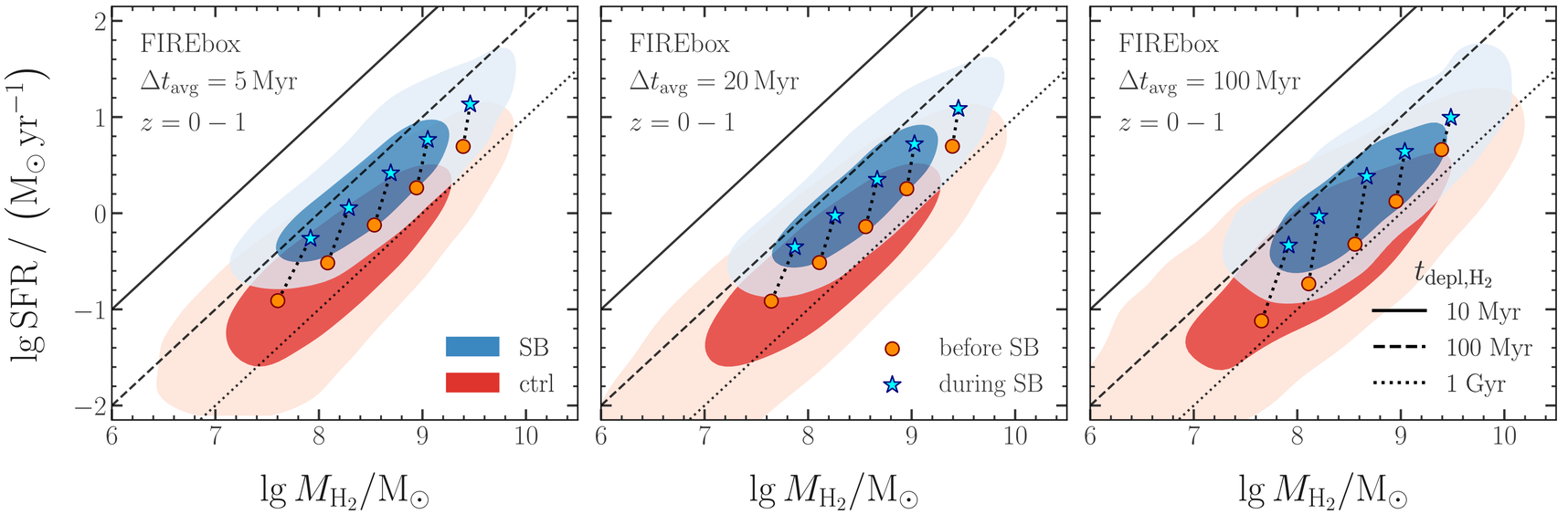


Starbursts Driven by Central Gas Compaction

More gas or more efficient star-formation?

- On average, **SB** galaxies have **shorter** molecular gas **depletion times** ($t_{\mathrm{depl,\,H_2}} \sim 200$ Myr) and **larger molecular gas** than control galaxies.
- Both M_{H_2} and $t_{\mathrm{depl,\,H_2}}$ change in the ~ 50 Myr prior to the SB, with a more significant change in $t_{\mathrm{depl,\,H_2}}$

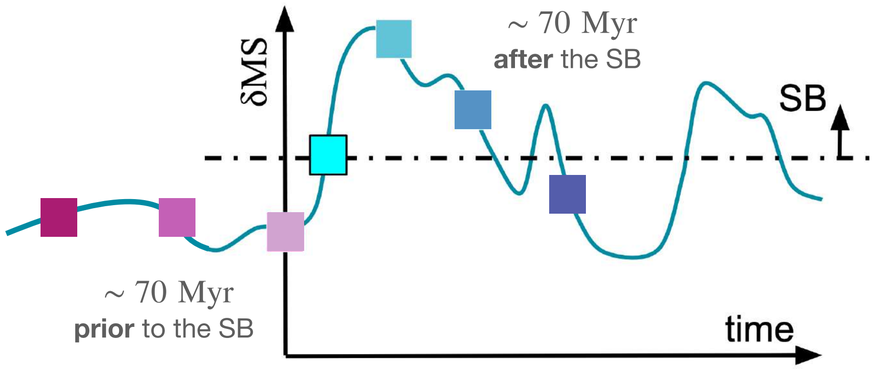


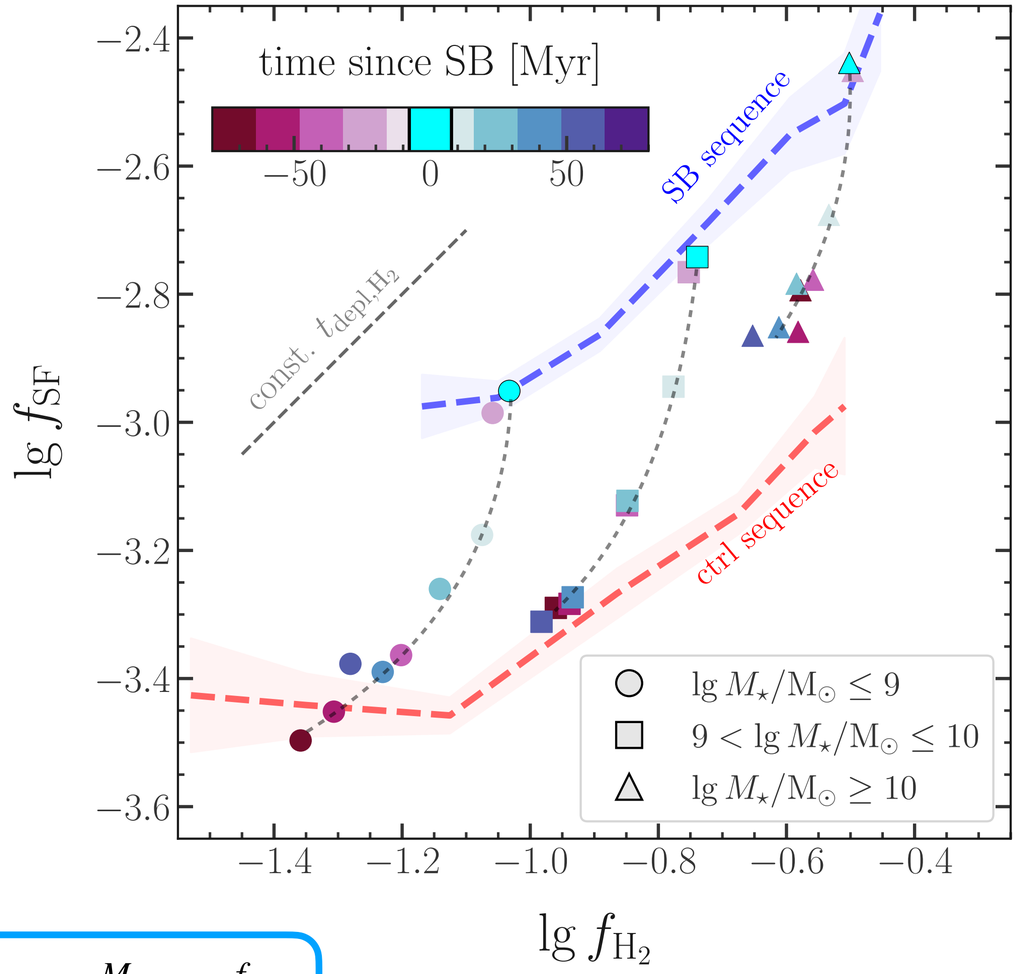


Starbursts Driven by Central Gas Compaction

How do galaxies become SBs?

- Evolution from **control** to **SB sequence** by increasing **both** $f_{\rm SF}$ and f_{H_2} in the ~ 70 Myr **prior to the SB**
- The $f_{\rm SF}$ increases more than f_{H_2}, resulting in **shorter depletion times**
- **Reversed path** in the ~ 70 Myr **after** the SB





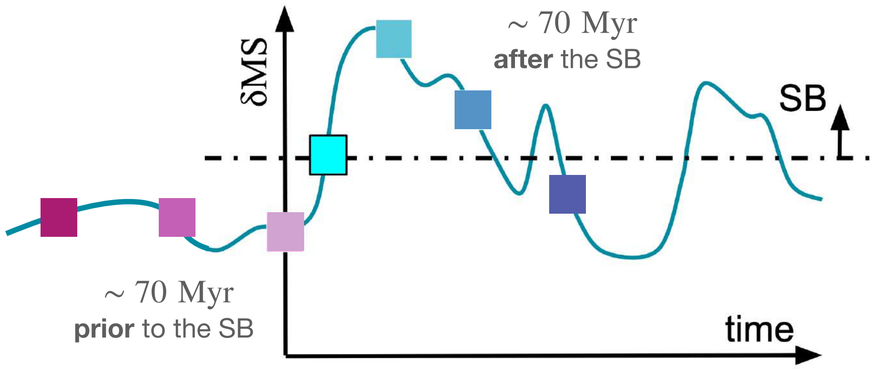
$$t_{\rm depl,\,H_2} \equiv \frac{M_{H_2}}{\rm SFR} \sim \frac{f_{H_2}}{f_{\rm SF}}$$

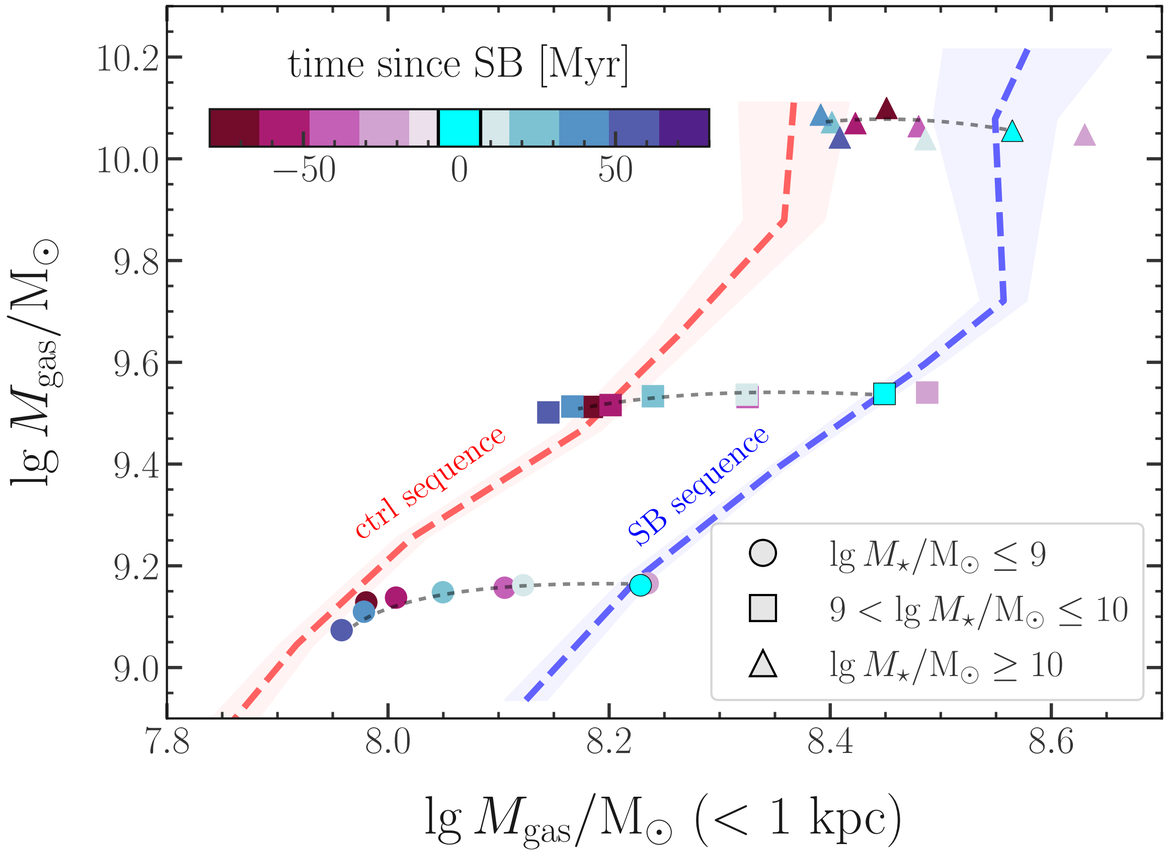
$f_{\rm SF}$: fraction of high-density, star-forming gas
f_{H_2} : fraction of molecular gas

Starbursts Driven by Central Gas Compaction

How do galaxies become SBs?

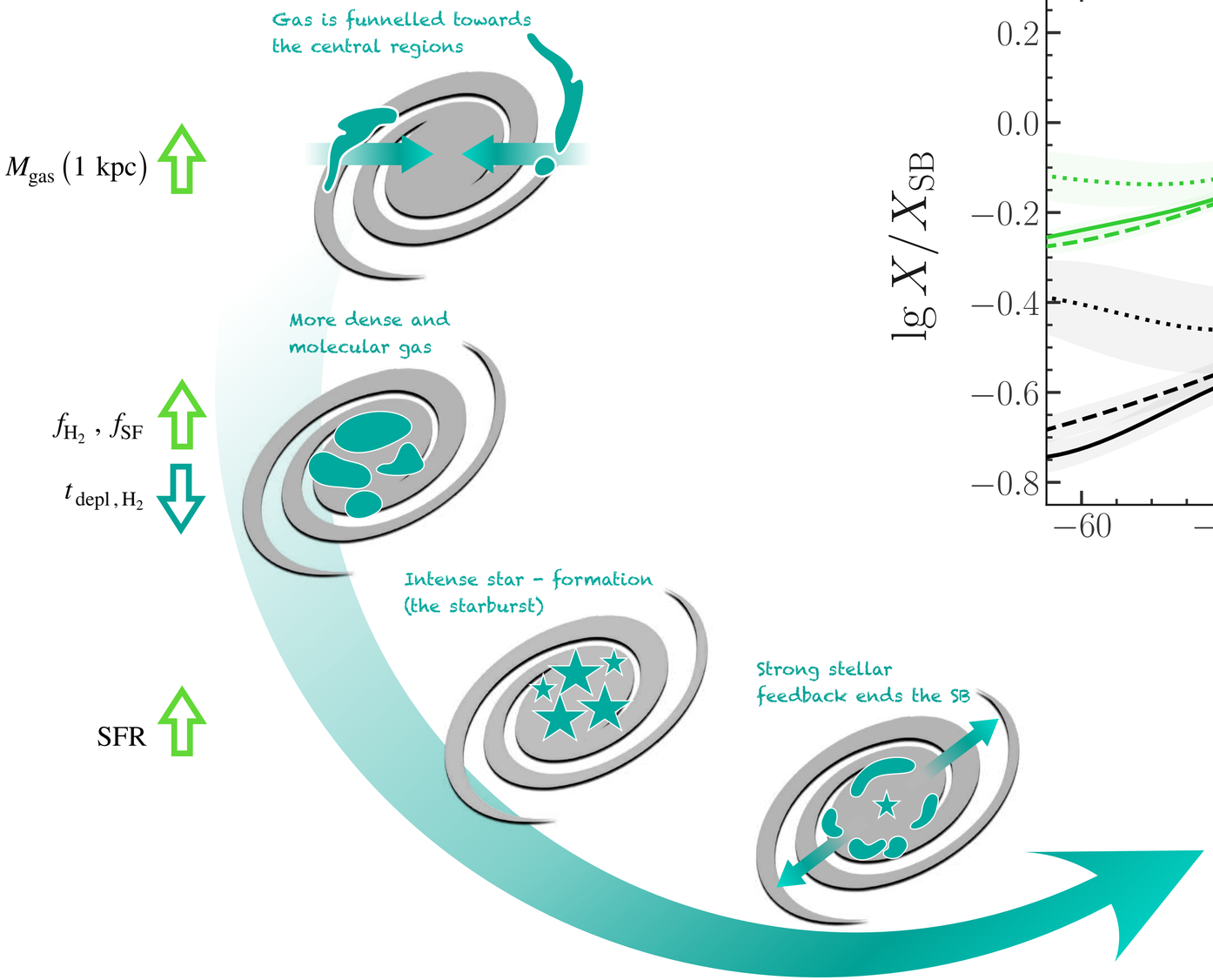
- Evolution from **control** to **SB sequence** by increasing the **central mass** at constant $M_{\rm gas}$ in the ~ 70 Myr **prior to the SB**
- **Reversed path** in the ~ 70 Myr **after** the SB



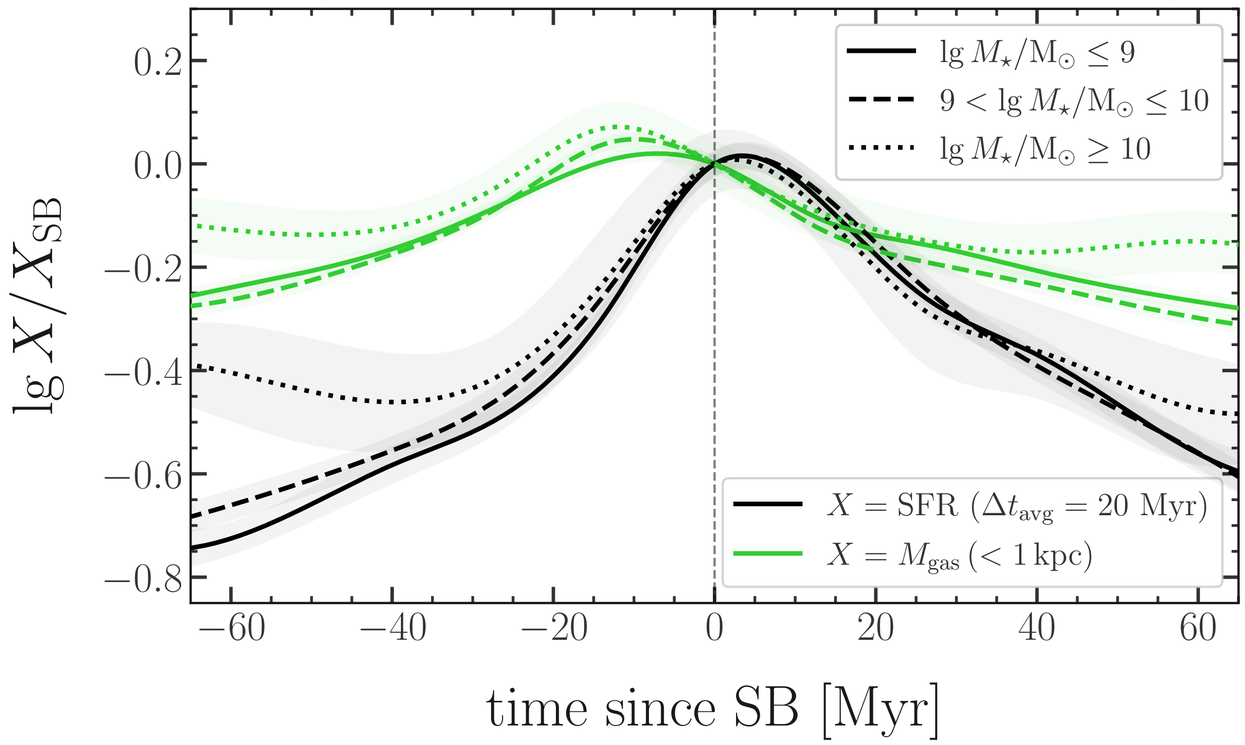


Starbursts Driven by Central Gas Compaction

How do galaxies become SBs?



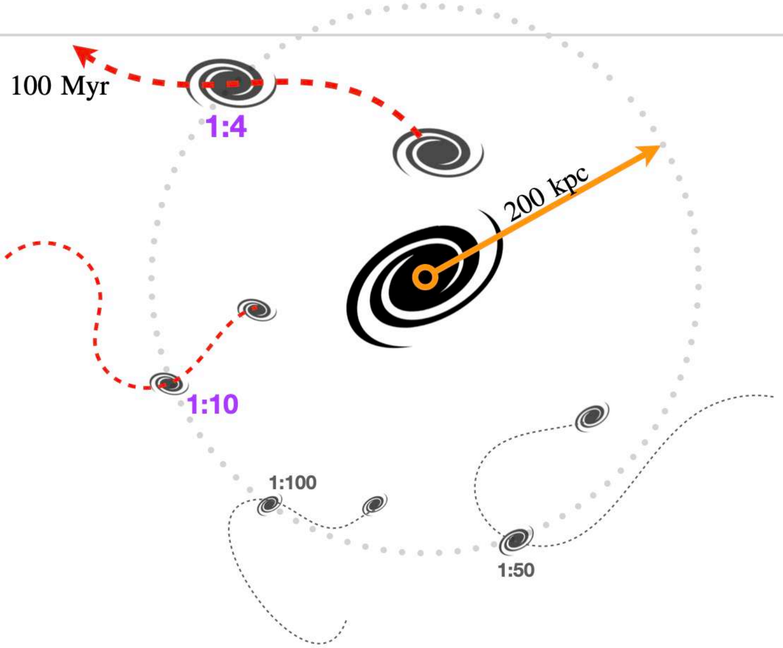
[see also, e.g., Dekel&Burkert 2014; Danovich+ 2015; Zolotov+ 2015; Tacchella+ 2016a; Lapiner+ 2023]



Central gas compaction *drives the increase in the dense (and molecular) gas fraction*

Starbursts Driven by Central Gas Compaction

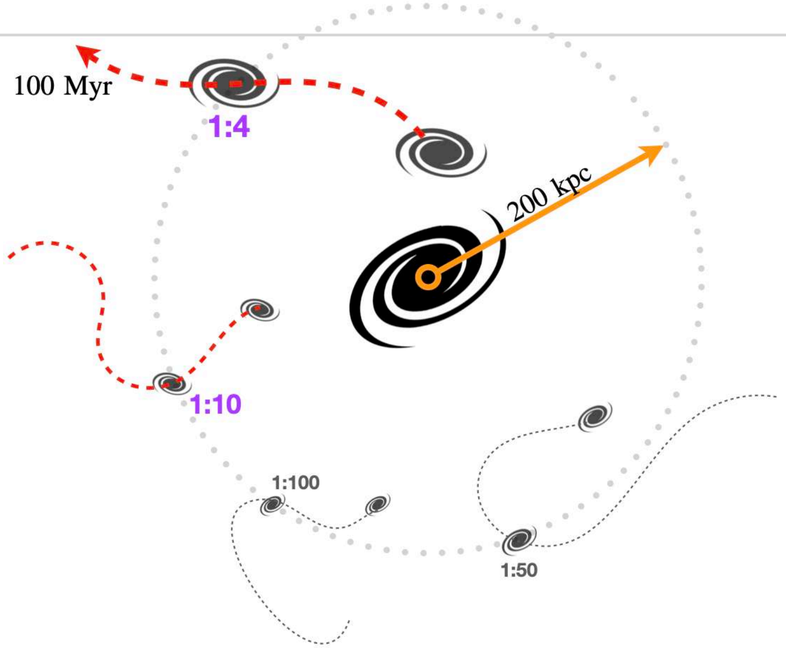
What is the role of galaxy interactions?

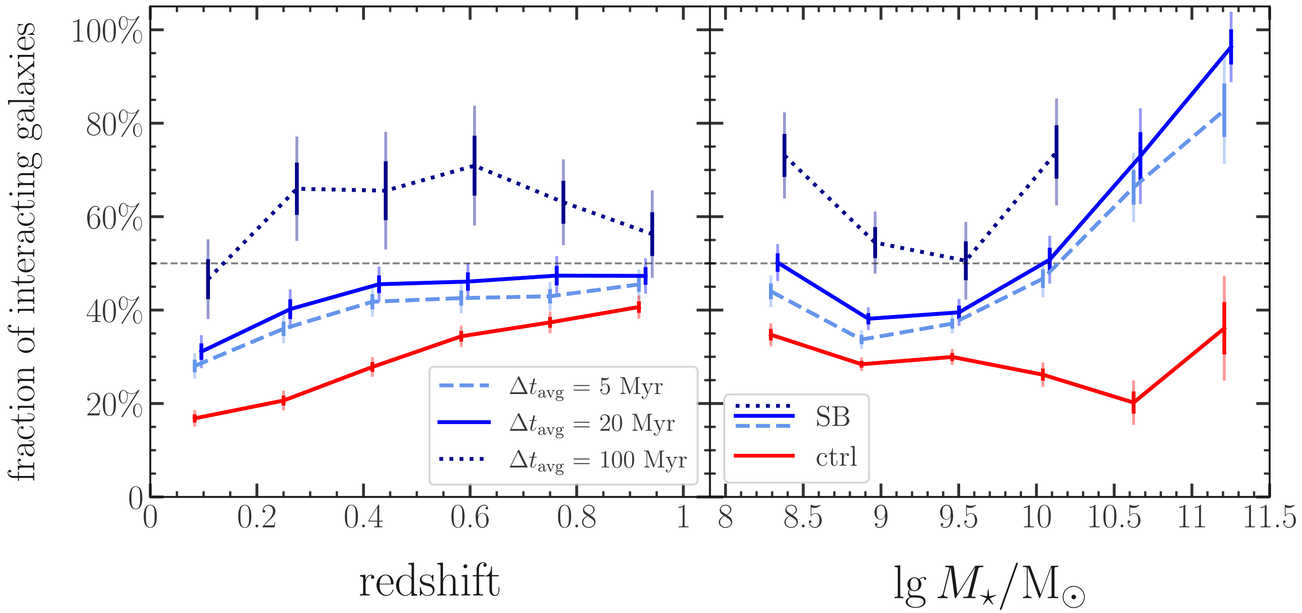


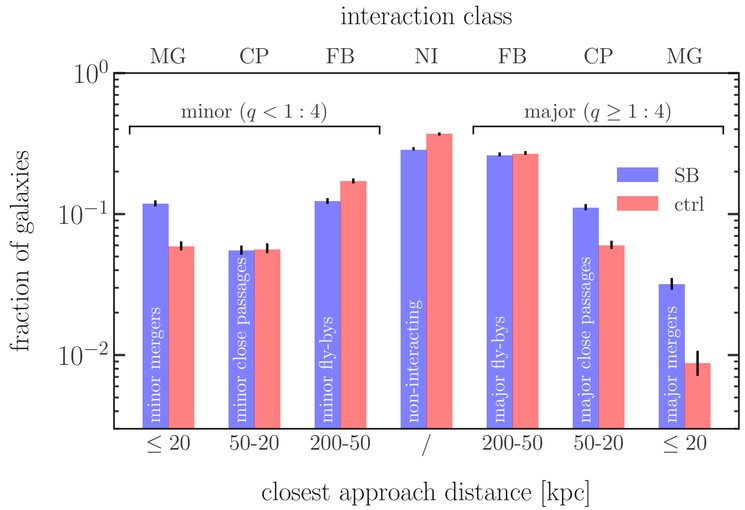
Starbursts Driven by Central Gas Compaction

What is the role of galaxy interactions?

- Main SBs driver **at high masses** and increasing importance at low redshifts
- Preferentially selected by longer $\Delta t_{\rm avg}$
- Significant fraction of **non-interacting** SBs, especially at low masses
- **Major mergers** result in the **largest difference** between the fractions of interacting SB and control galaxies

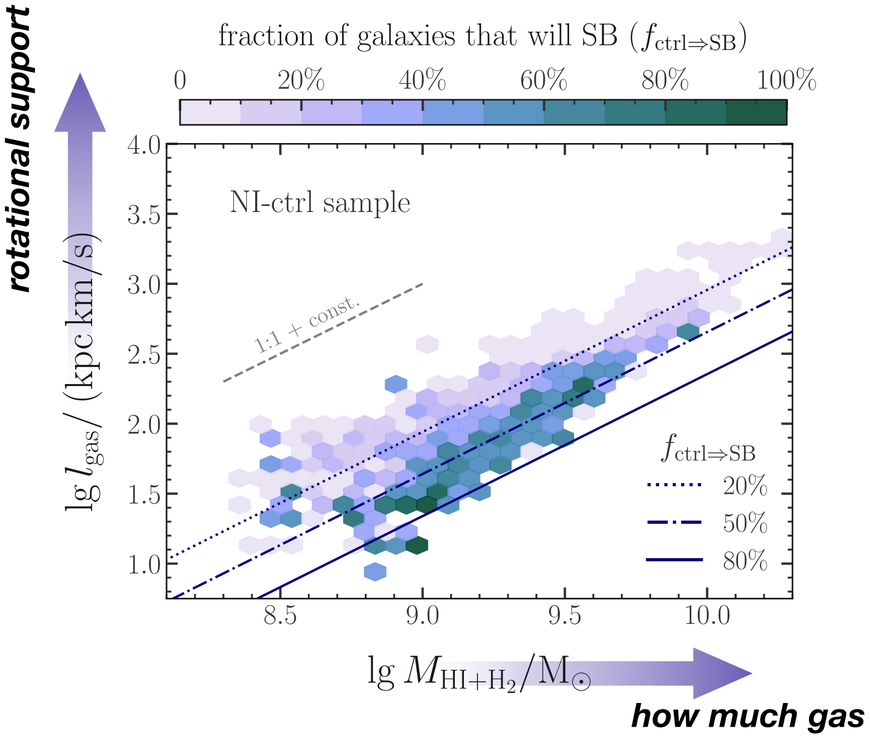






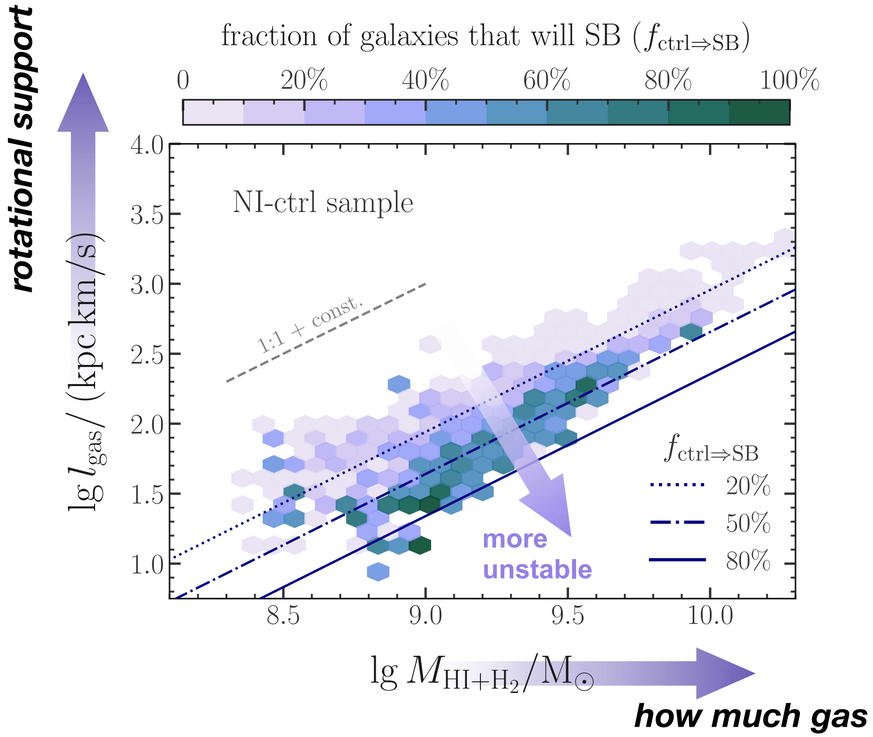
Starbursts Driven by Central Gas Compaction

You too can become a starburst



Starbursts Driven by Central Gas Compaction

You too can become a starburst

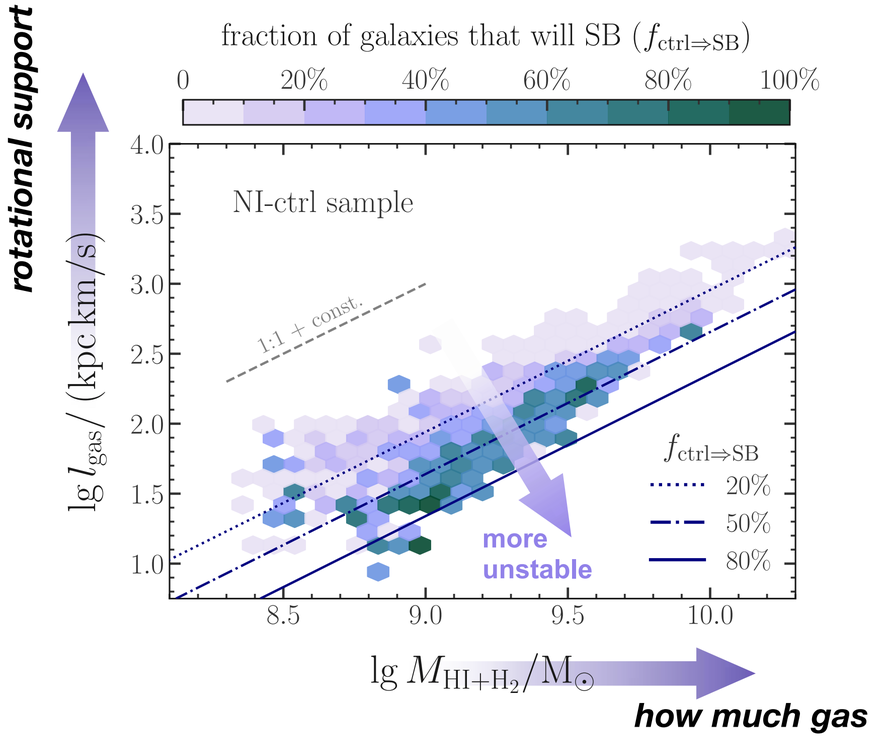


$$\Phi_{\rm gas} \sim \frac{l_{\rm gas}\sigma_{\rm gas}}{M_{\rm gas}}$$

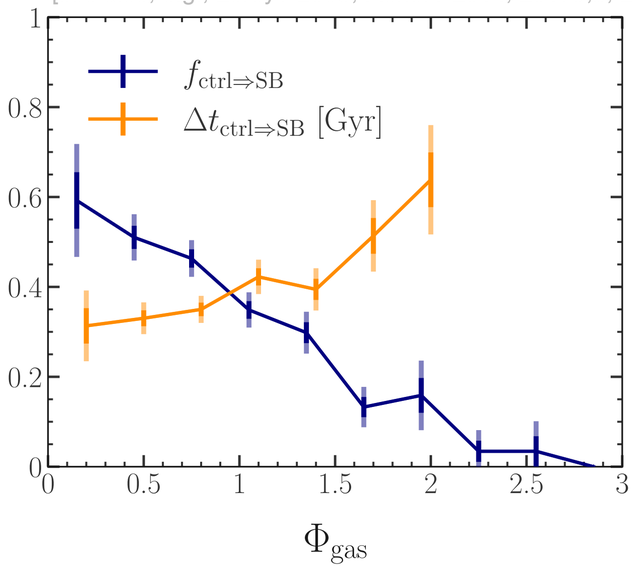
(Toomre-like) **instability parameter** for gas

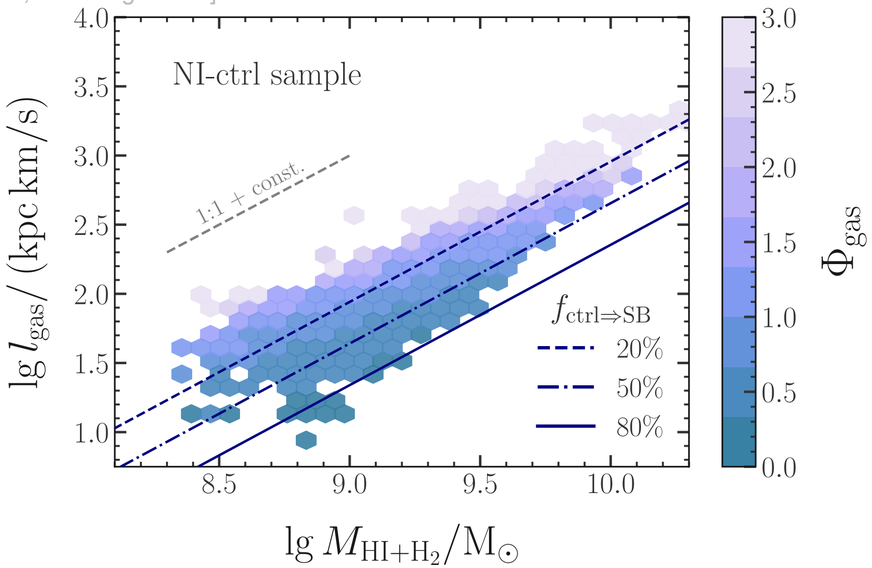
Starbursts Driven by Central Gas Compaction

You too can become a starburst



[see also, e.g., Leroy+ 2008; Fisher+ 2014, 2017a,b, 2022; Puschnig+ 2023]





$$\Phi_{\rm gas} \sim \frac{l_{\rm gas}\sigma_{\rm gas}}{M_{\rm gas}}$$

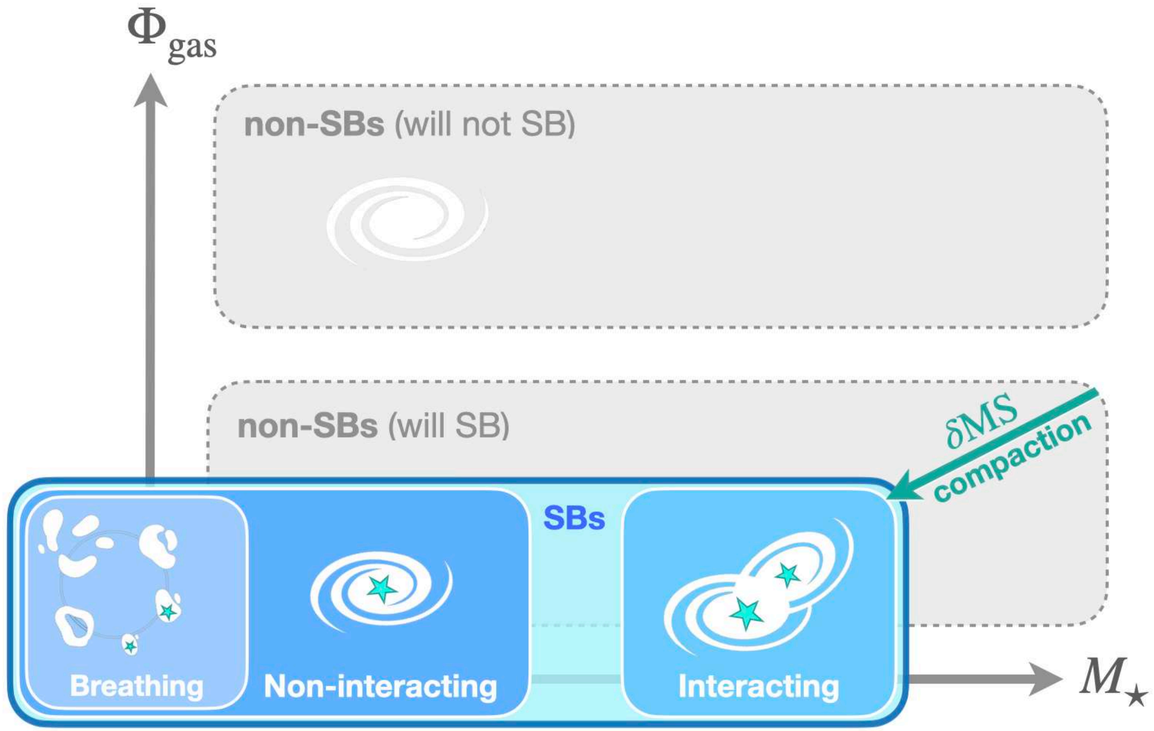
(Toomre-like) **instability parameter** for gas

- Unstable non-interacting control galaxies will **more likely** become a SB
- The more unstable, the **sooner** the SB

Starbursts Driven by Central Gas Compaction

Summary

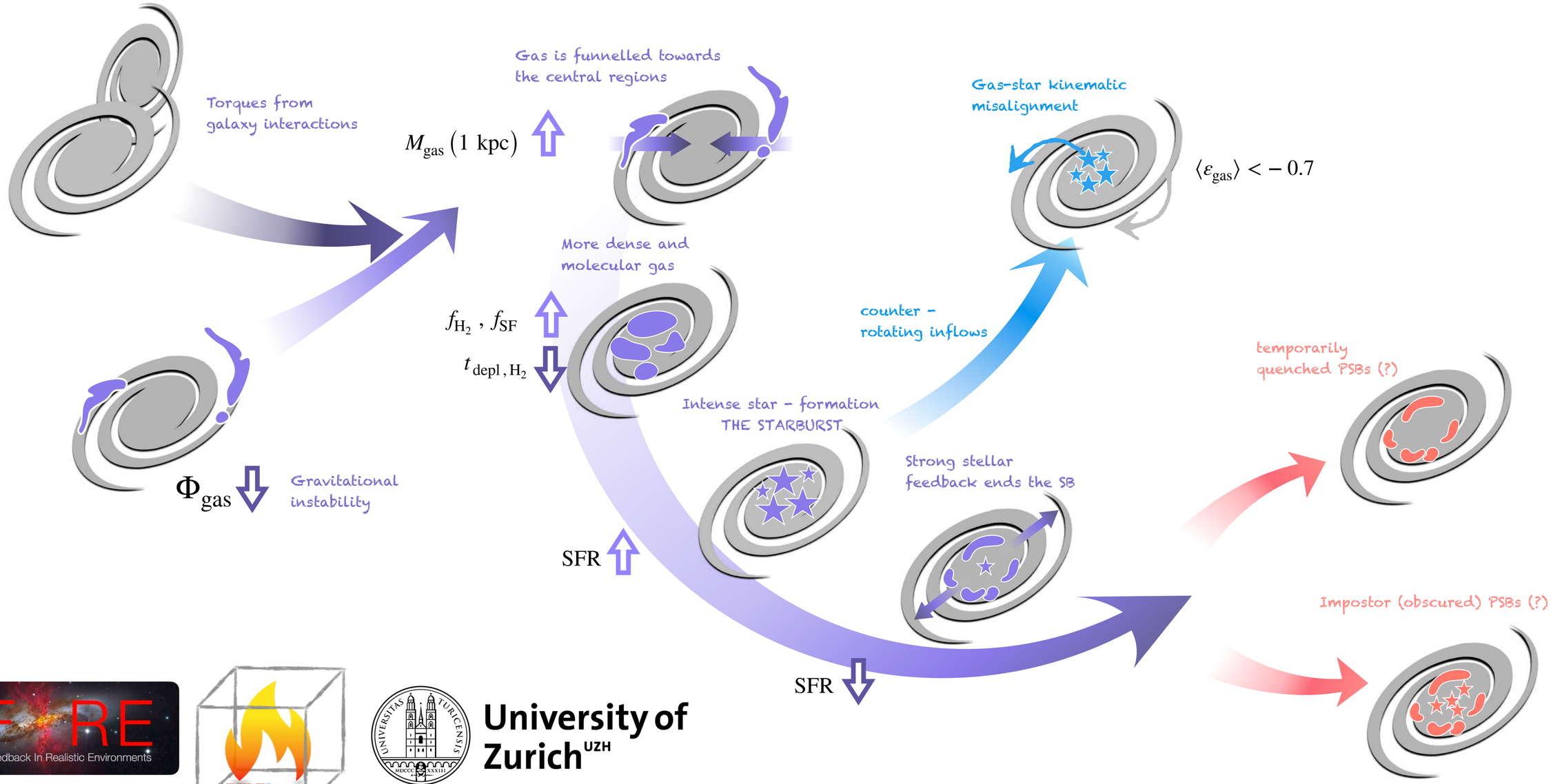
- SBs result from **globally unstable** gas reservoirs experiencing a **compaction event**
- The **more** gravitationally **unstable** the gas reservoir is, the **sooner** the SB happens
- Prior to the SB, the **fraction of high-density and molecular gas increase** together with the gas mass in the central regions, at **fixed total gas mass**
- SBs have **shorter depletion times**, larger molecular gas masses, and similar total gas masses to non-SB control galaxies
- **Interactions** can be associated with SBs, but they are dominant only **in massive galaxies**



Origin and evolution of starburst galaxies in cosmological simulations

Summary

That's all folks!



FIRE Feedback In Realistic Environments

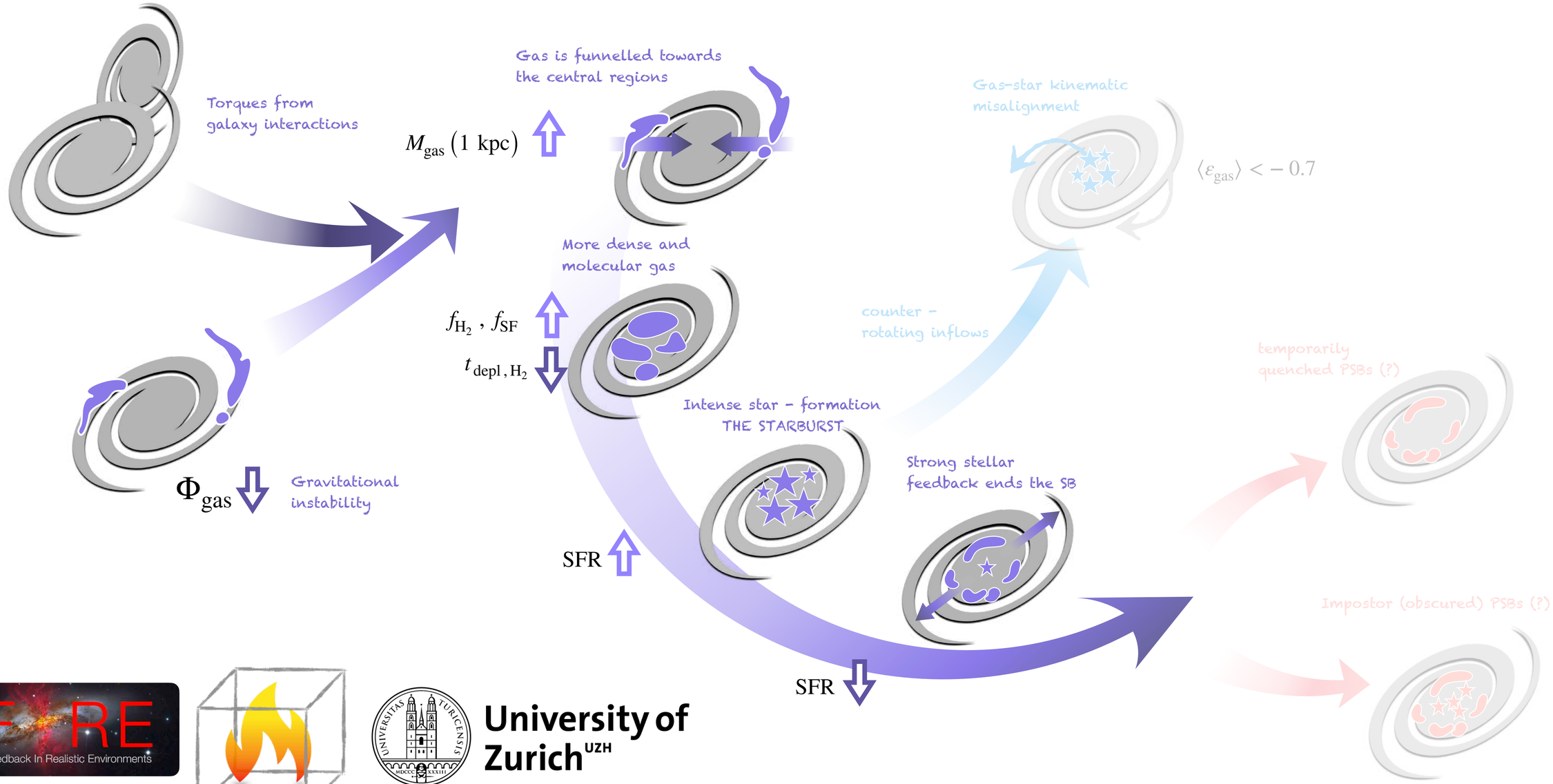
FIREbox

University of Zurich[UZH]

Origin and evolution of starburst galaxies in cosmological simulations

Summary

That's all folks!



Feedback In Realistic Environments

FIREbox

University of Zurich[UZH]