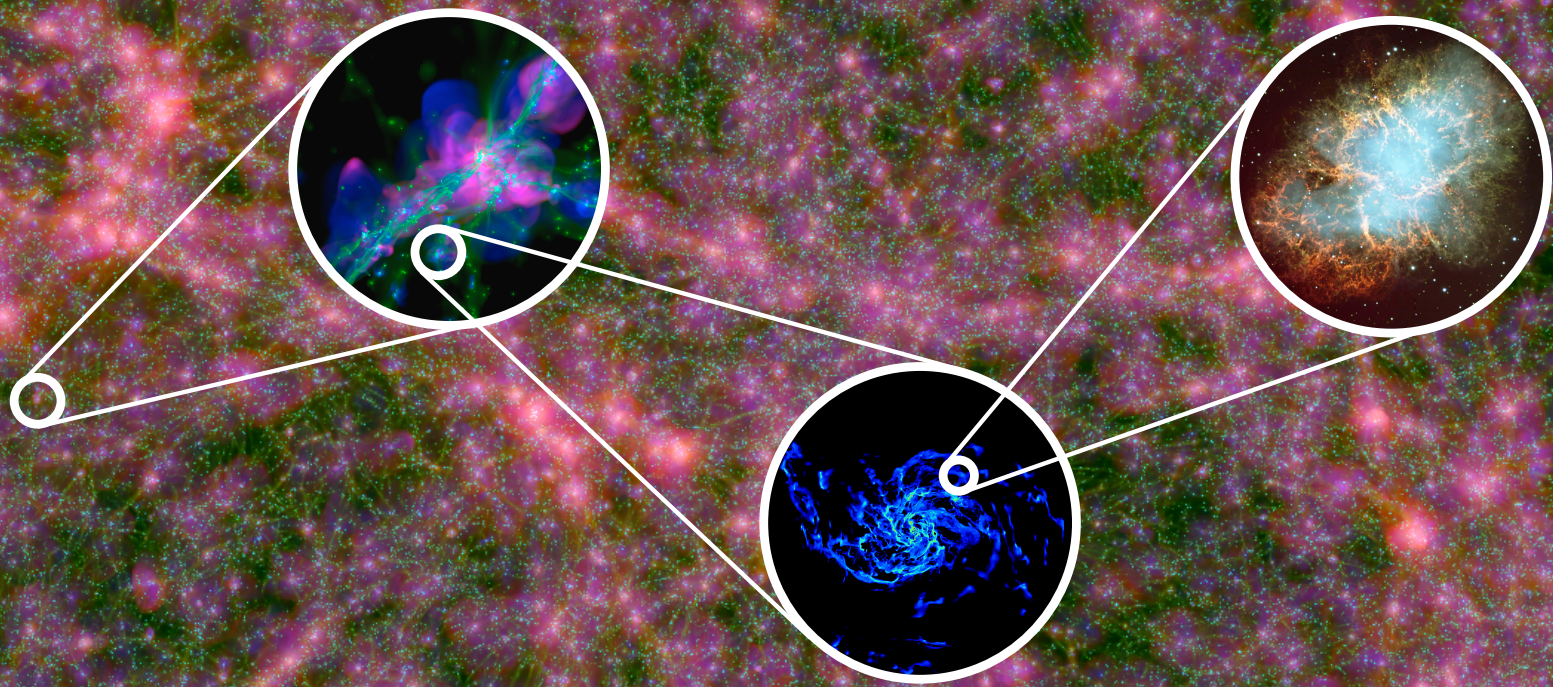
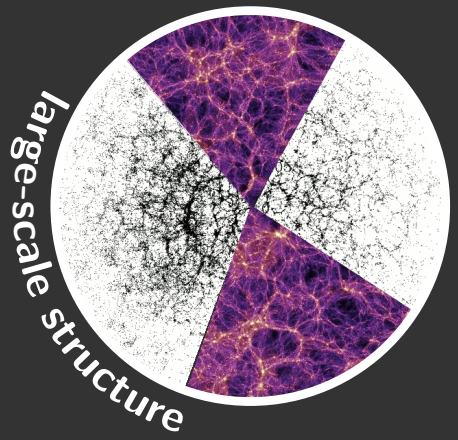
# Galaxy formation and evolution
# Physical models & Theoretical challenges 2°

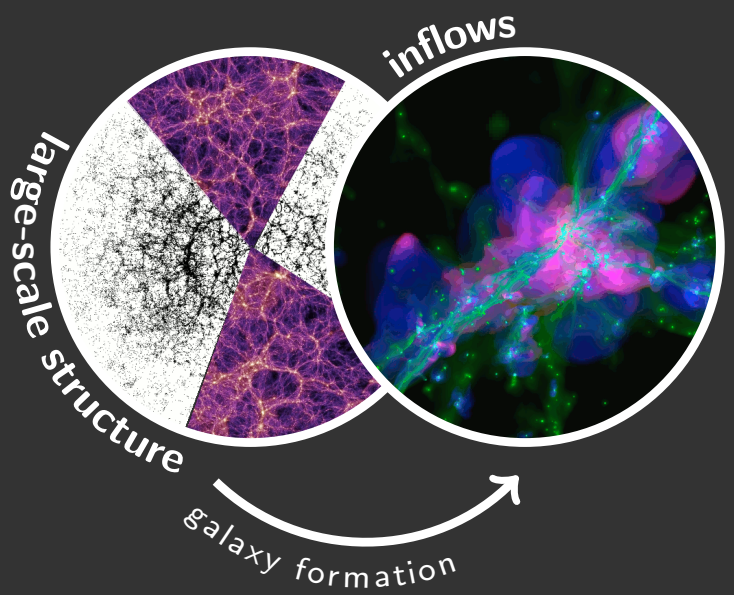


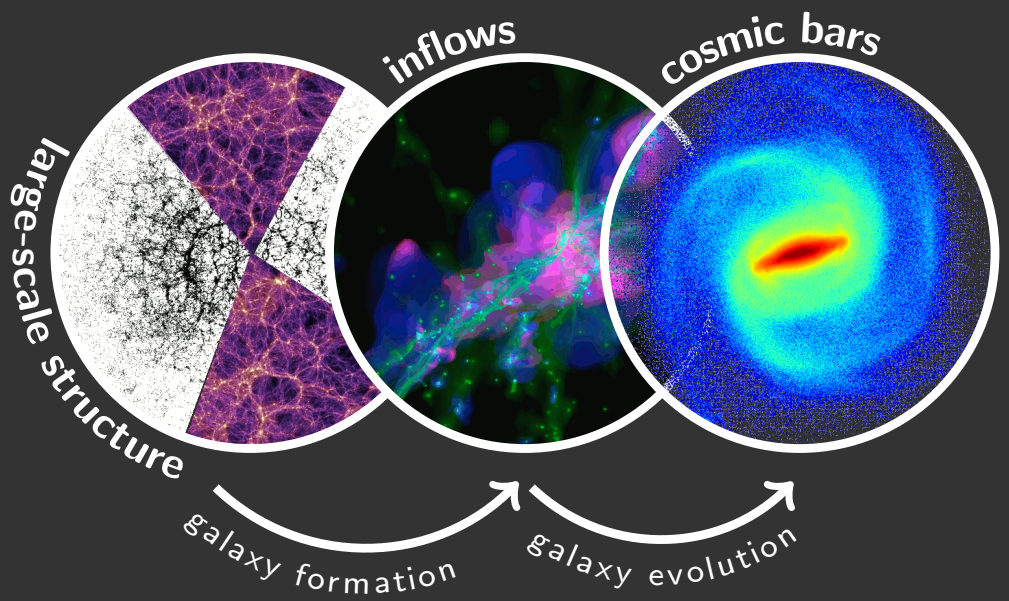
**Katarina Kraljic**

Institute for Astronomy, Edinburgh

July 2019, Petnica


large-scale structure


inflows
large-scale structure
galaxy formation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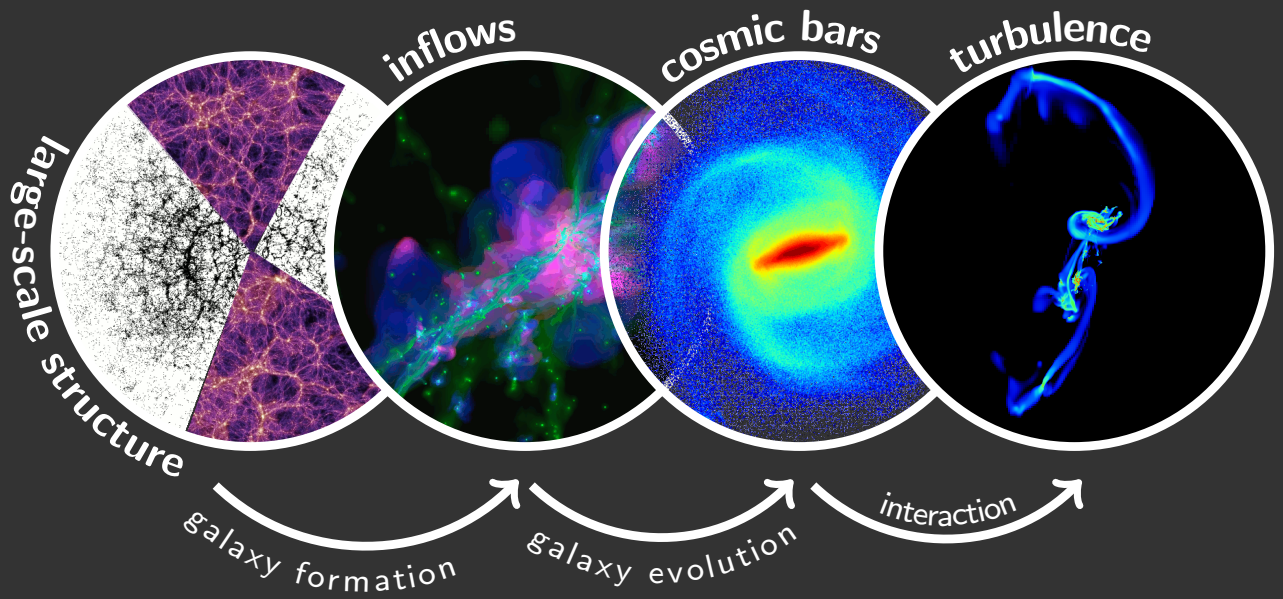
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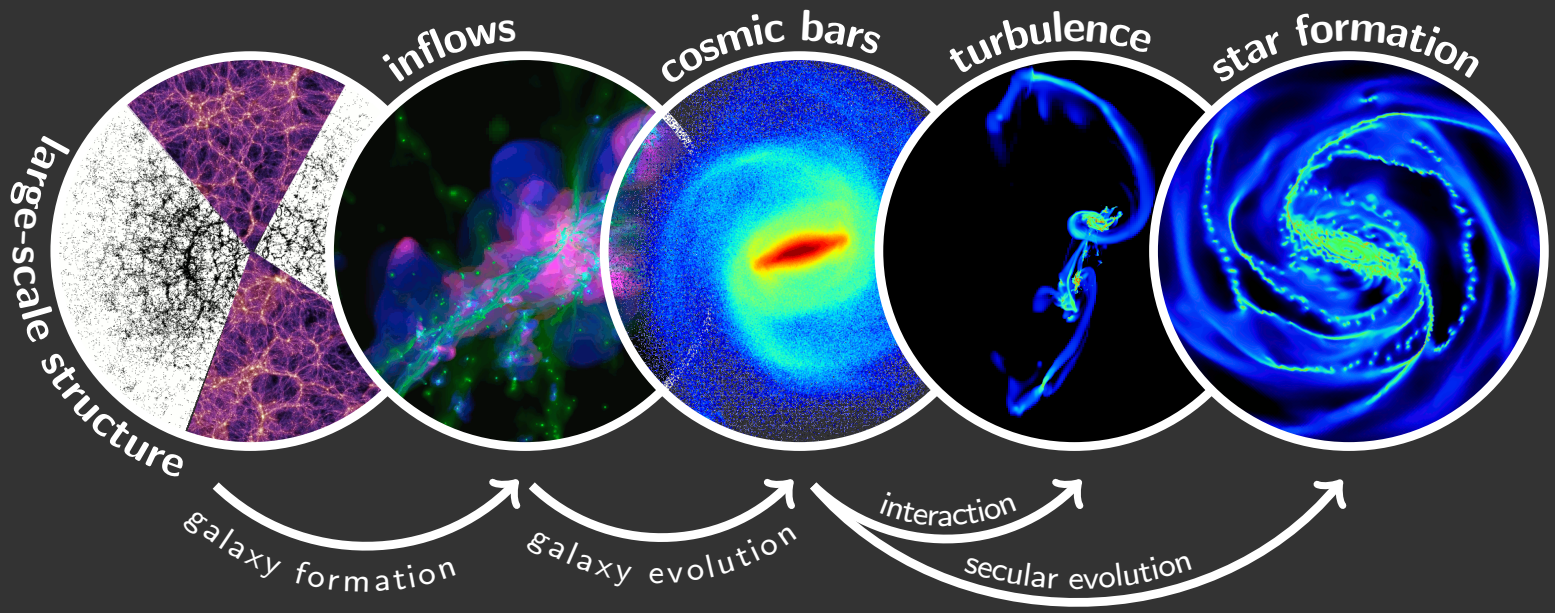
large-scale structure
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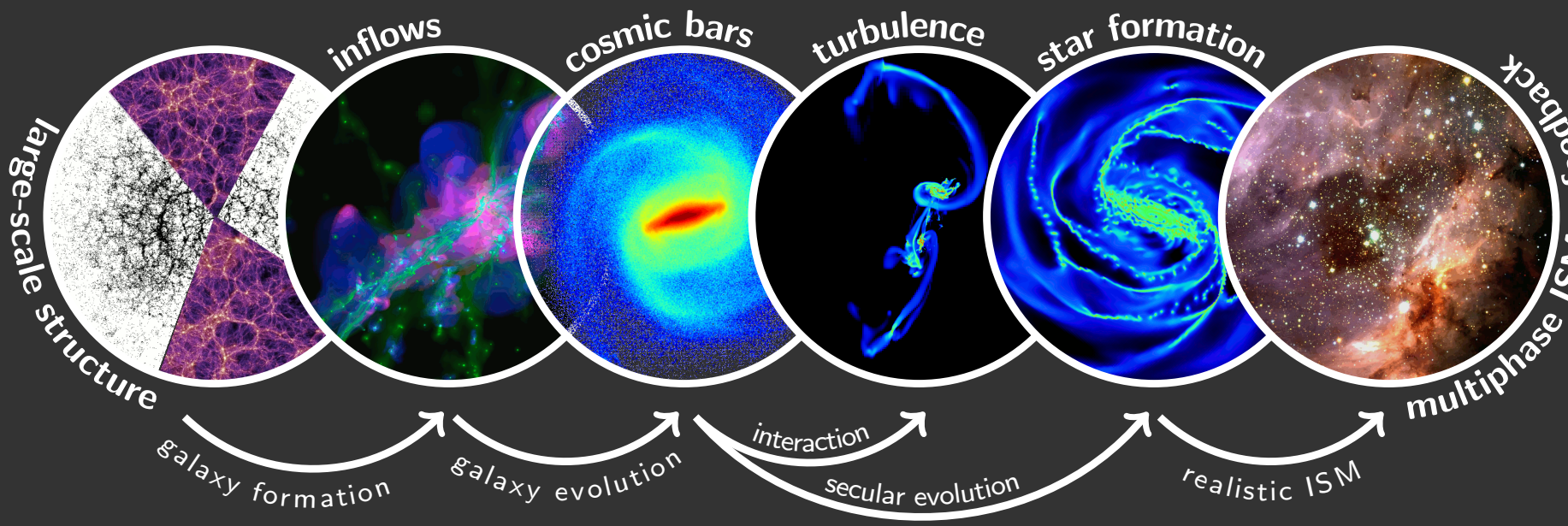
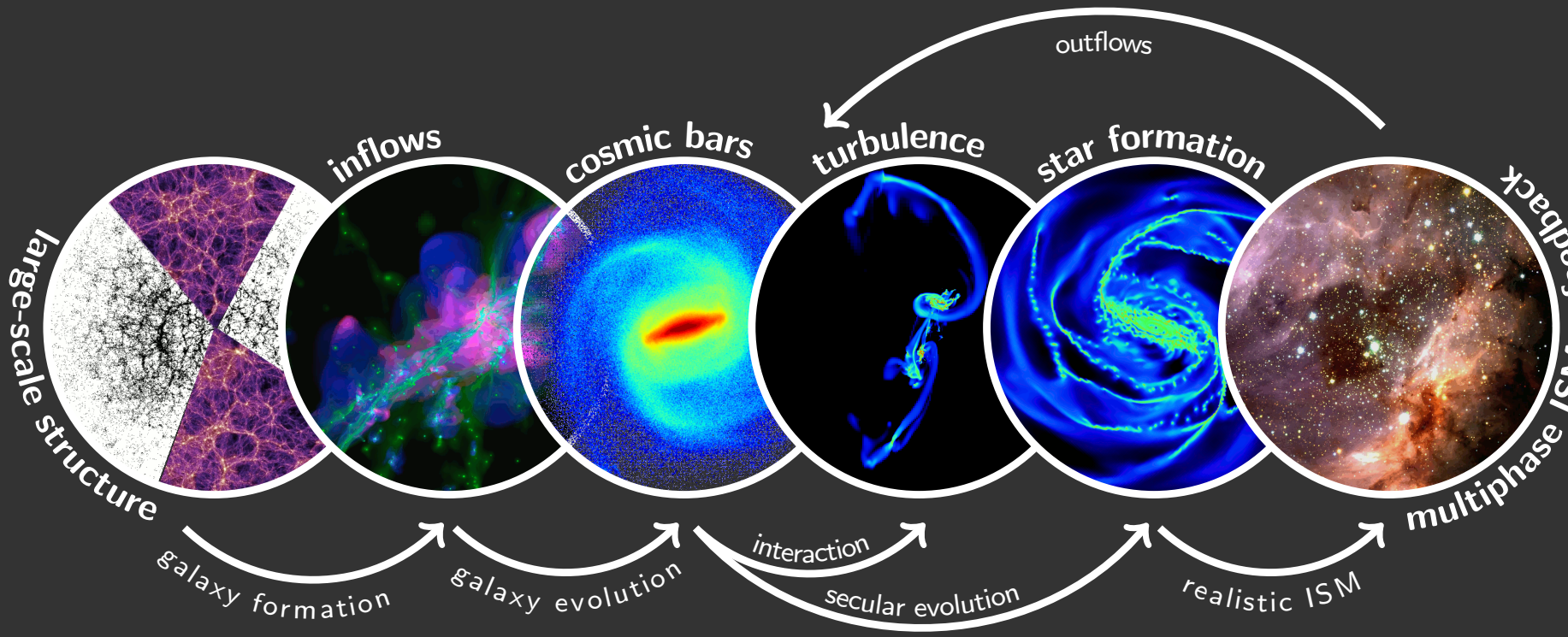
# Ab initio models




outflows
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realistic ISM

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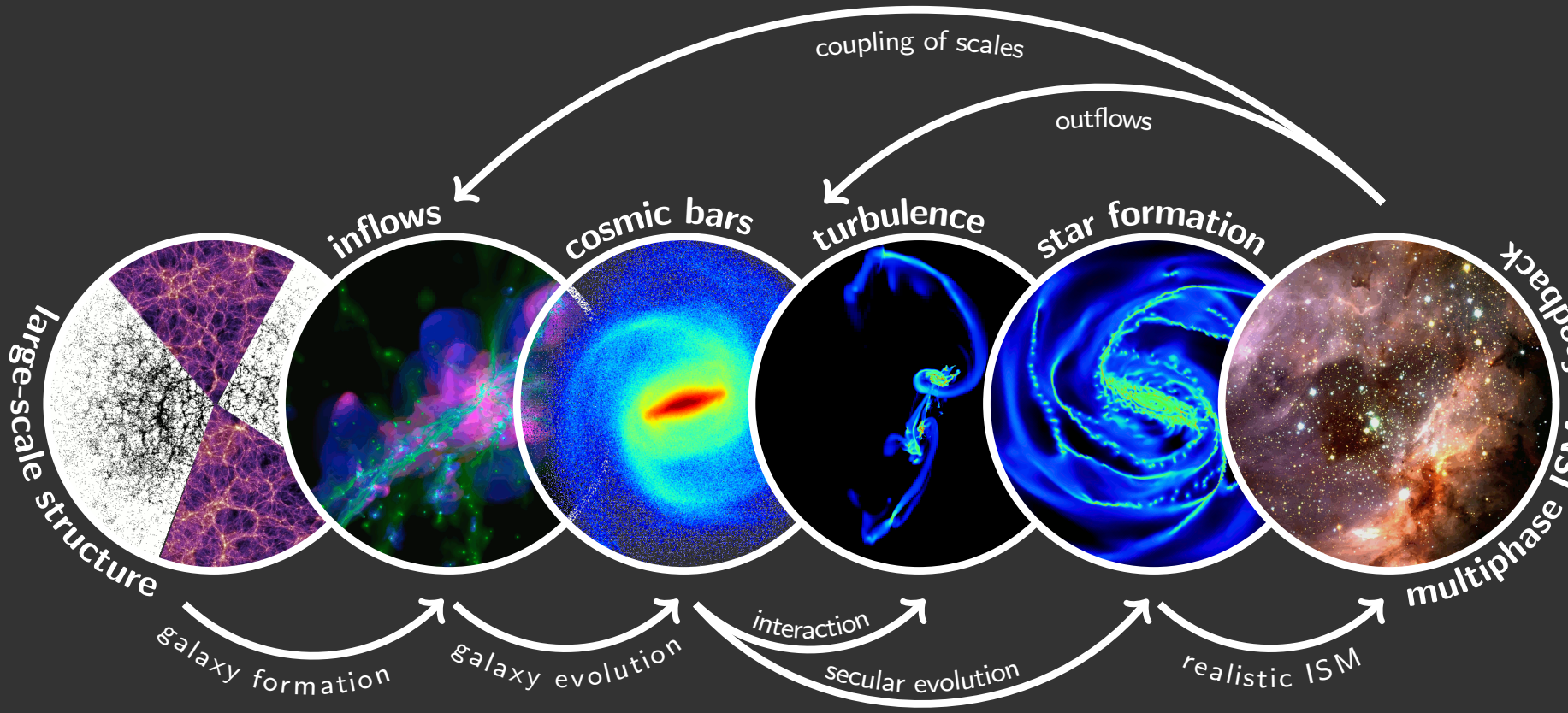

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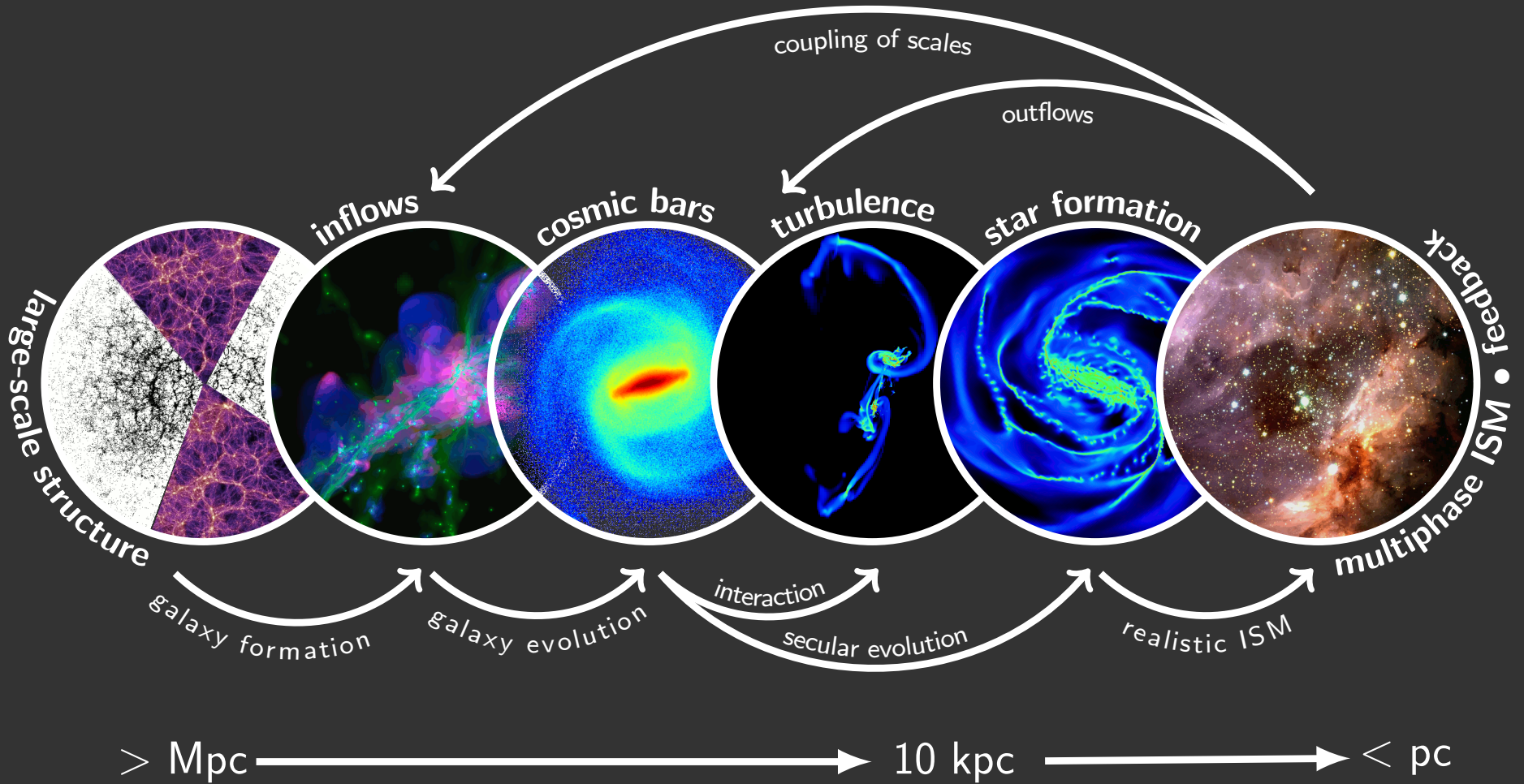

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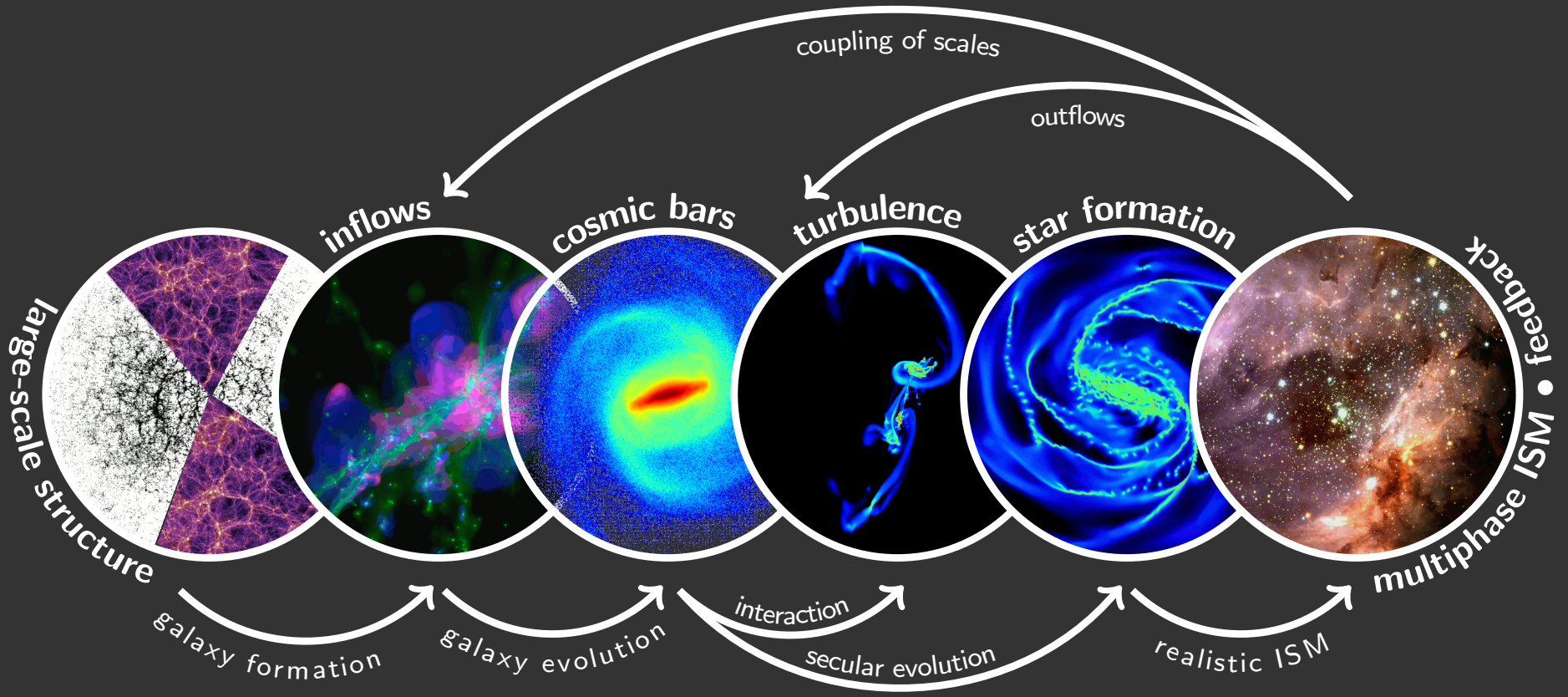


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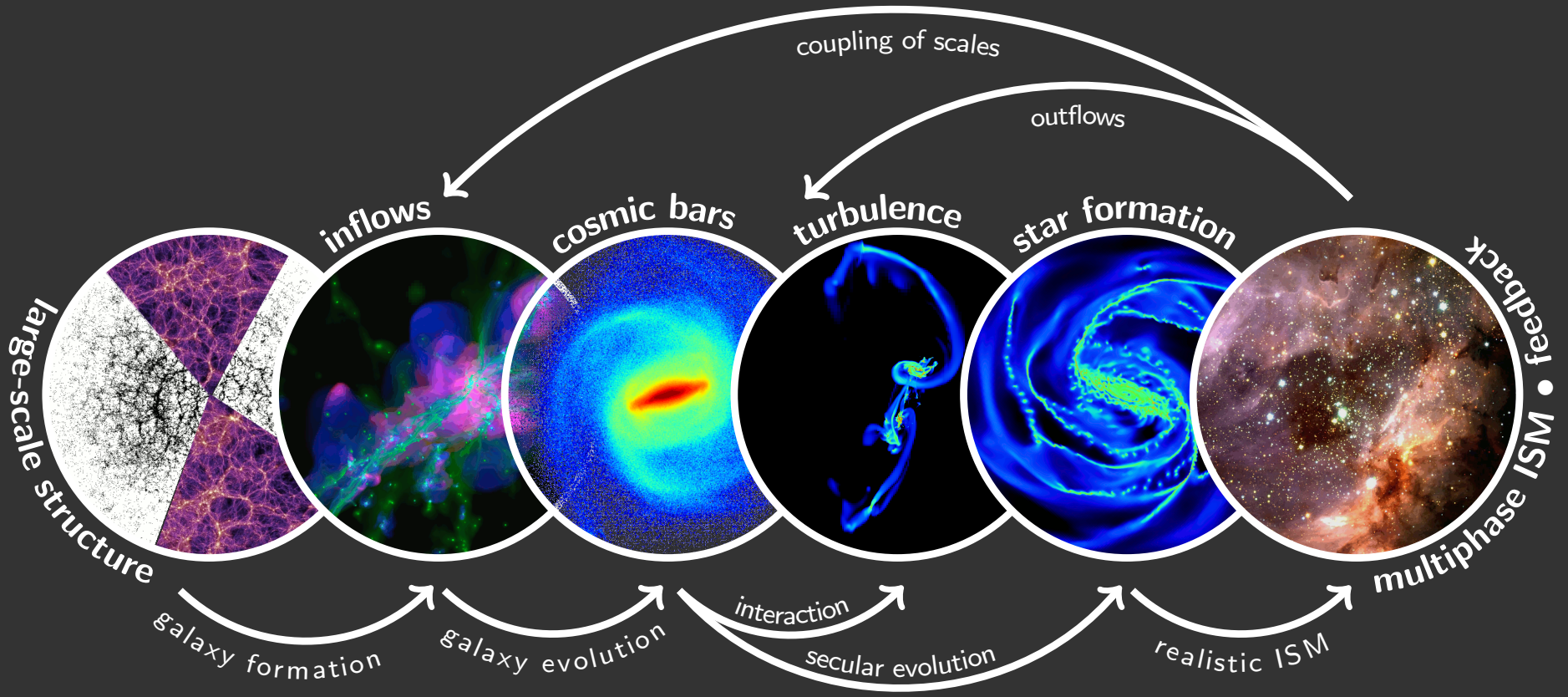
$\sim$ 10 Gyr → Gyr → 10 Myr

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$10^{13}$ $M_\odot$ → $10^{10}$ $M_\odot$ → $M_\odot$

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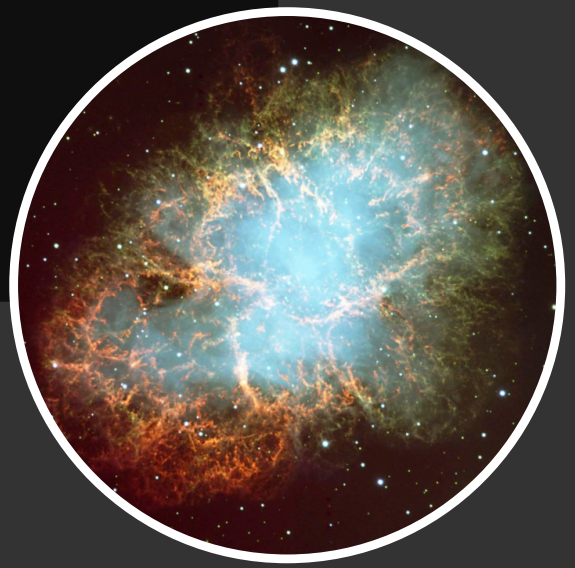
- *evidence*
  - complex space
  - multiple gas phases at different $T$ and $\rho$



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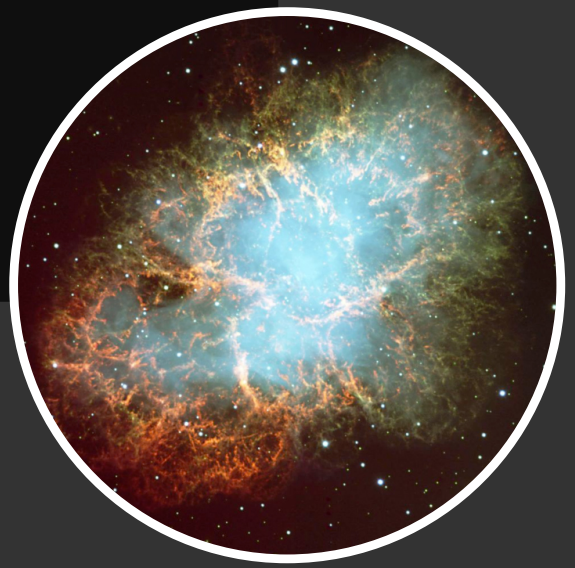
- *solution (?)*
  - smooth over much of the small-scale complexity $\longrightarrow$ use empirical recipes
  - how?



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  - in cold, dense, molecular gas phase
  - inefficient SF $\Longleftrightarrow$ $\sim$ 1% of gas converted into stars per free-fall time
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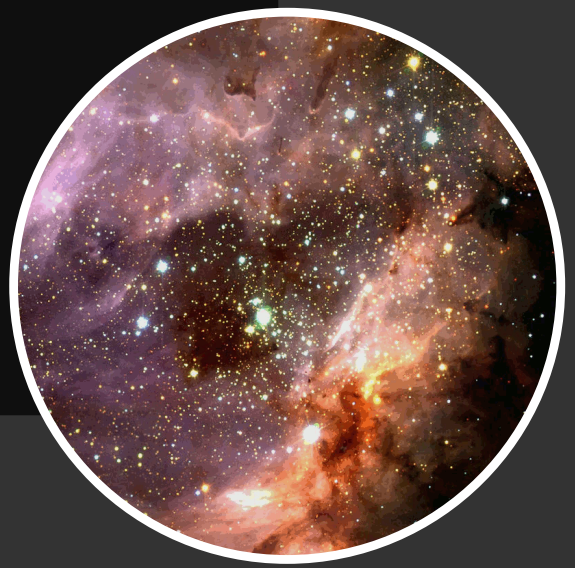

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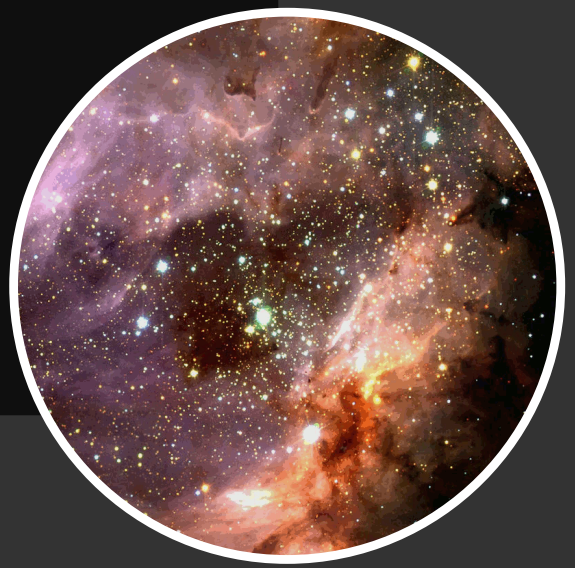

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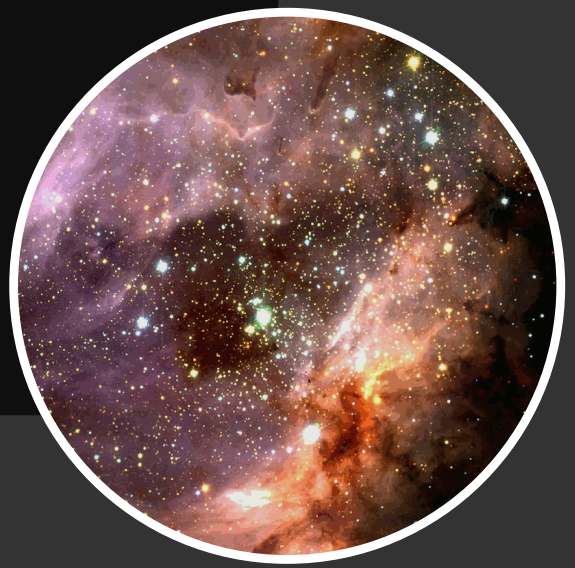

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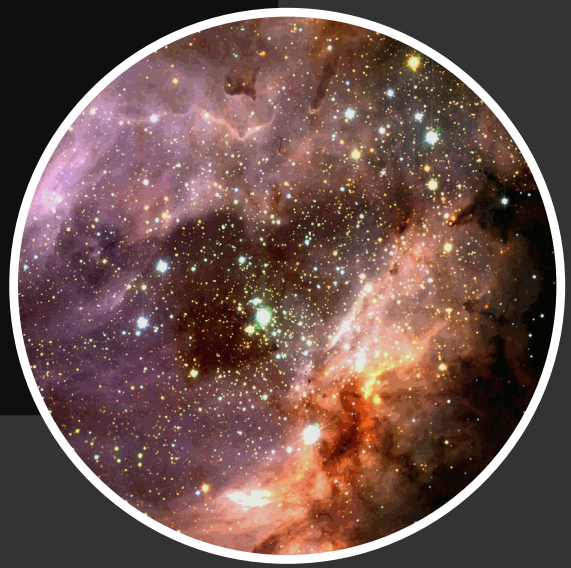
    $\longrightarrow$ empirical relation: $f_{H_2}$ – pressure
    $\longrightarrow$ post-processing



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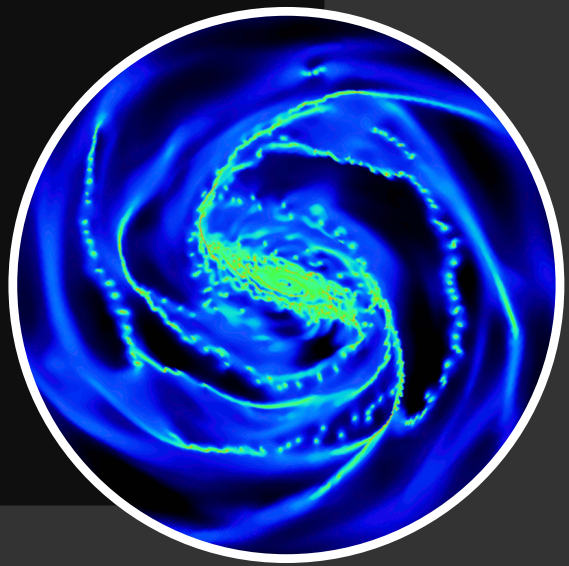

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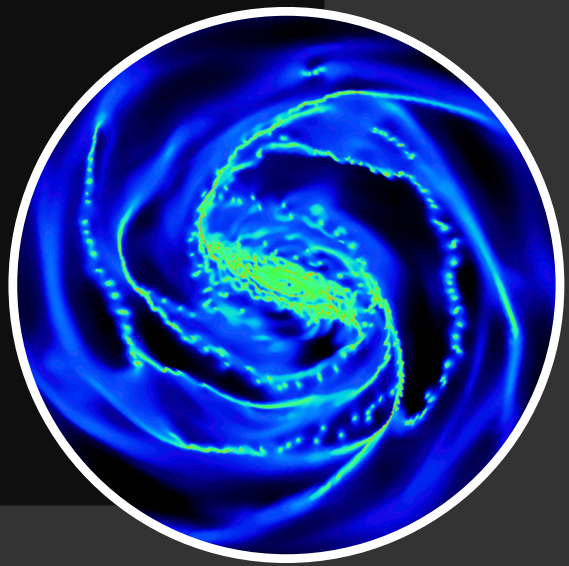

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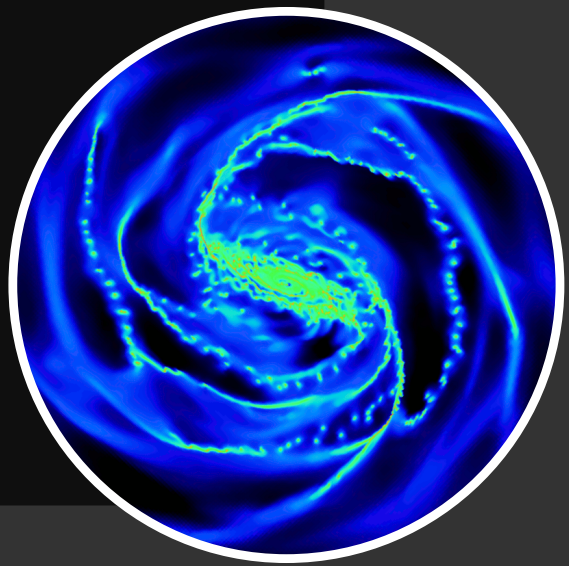

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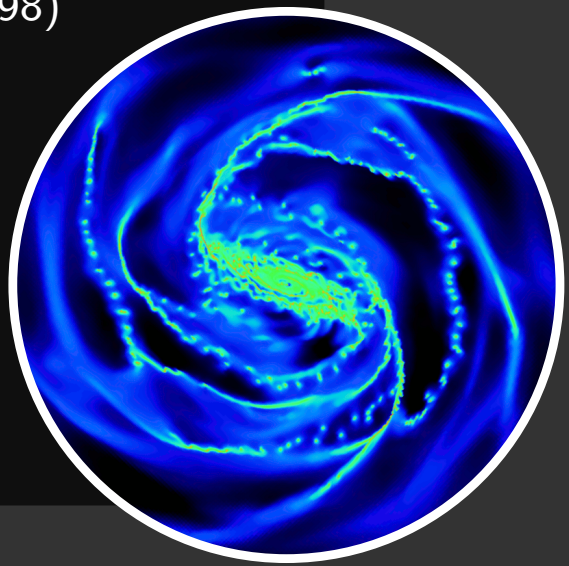
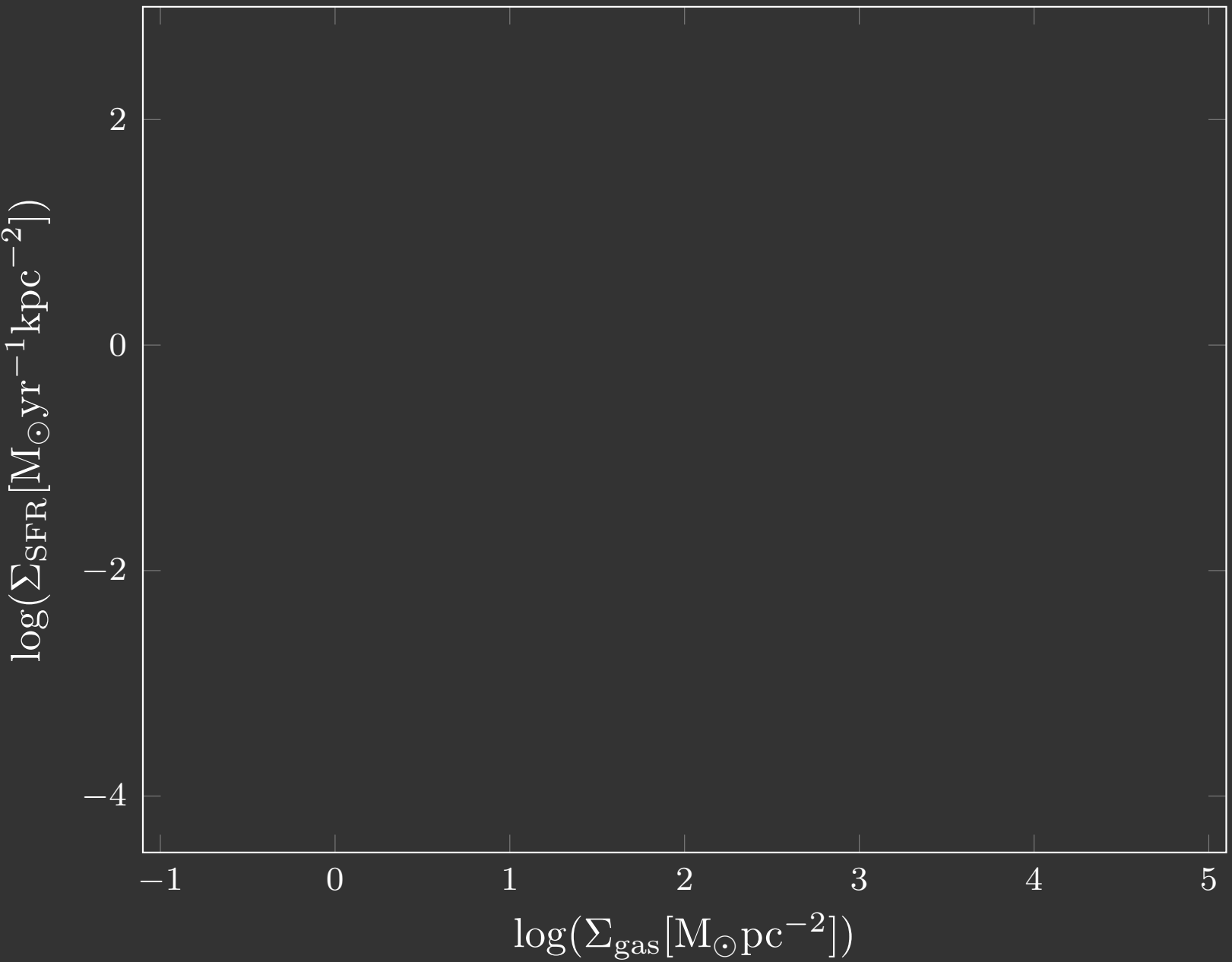
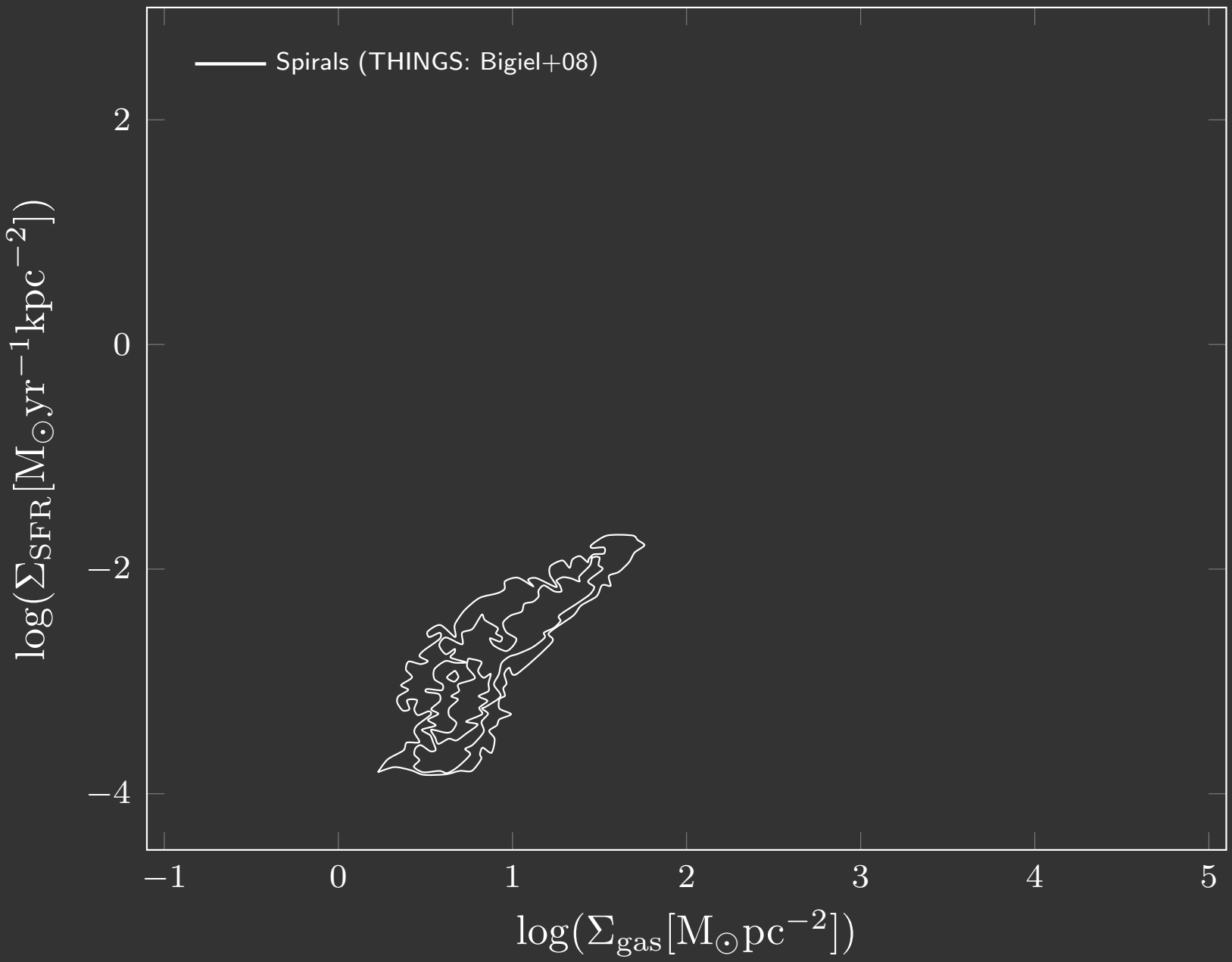
  - $\epsilon \sim 1\% \iff$ Kennicutt-Schmidt relation (Schmidt 1959, Kennicutt 1998)
  - $\rho_0 \sim 0.1$ H/cc in cosmo sims
- problems
  - Kennicutt-Schmidt relation $\sim$ 0.5–1 kpc
  - $\rho_0$ - resolution dependent
- solution?
  - (more) realistic ISM
  - understand better SF






inspired by Daddi et al. 2010


Spirals (THINGS: Bigiel+08)
$\log(\Sigma_{\rm SFR}[{\rm M}_\odot{\rm yr}^{-1}{\rm kpc}^{-2}])$
$\log(\Sigma_{\rm gas}[{\rm M}_\odot{\rm pc}^{-2}])$
2
0
−2
−4
−1
0
1
2
3
4
5
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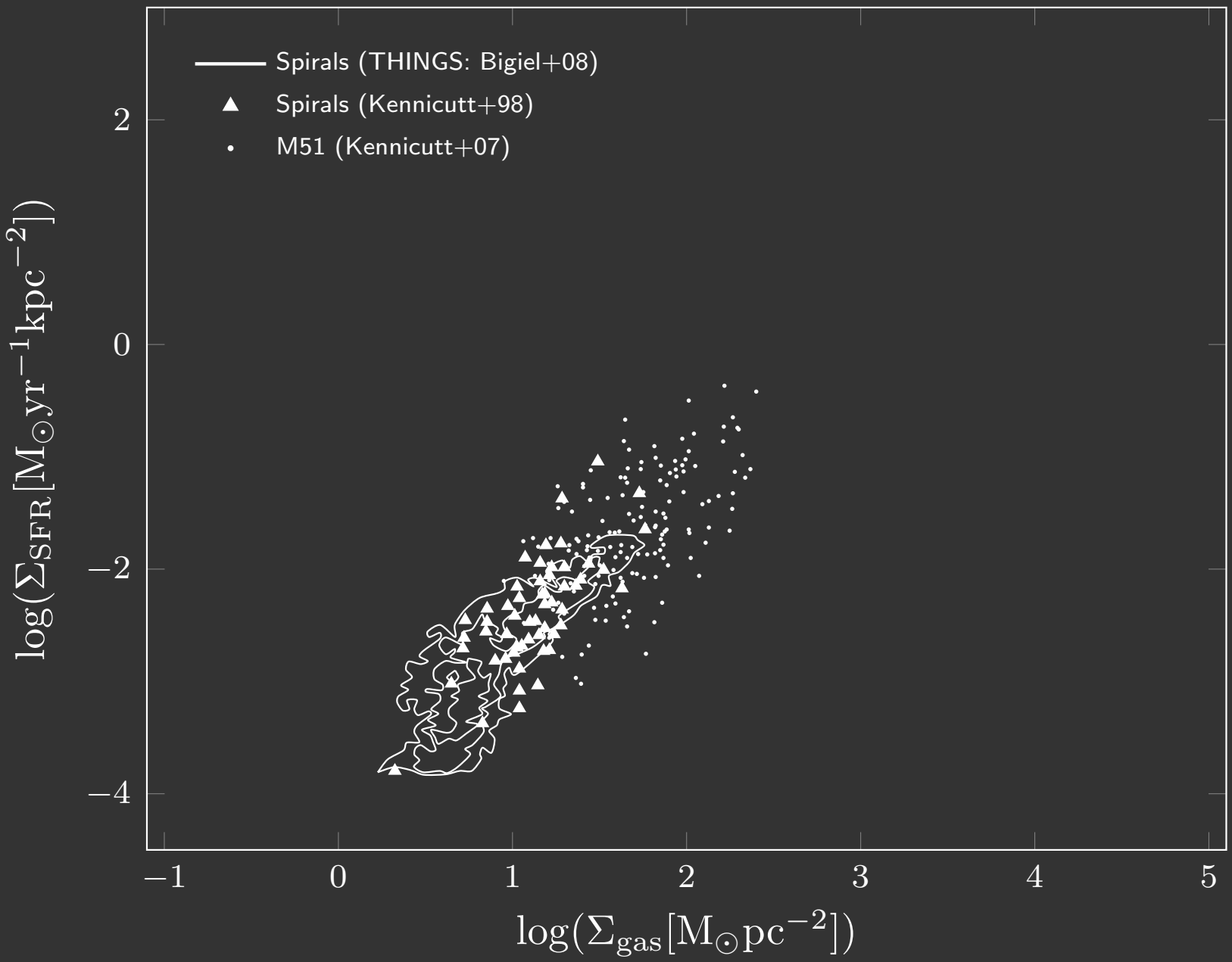
Spirals (THINGS: Bigiel+08)
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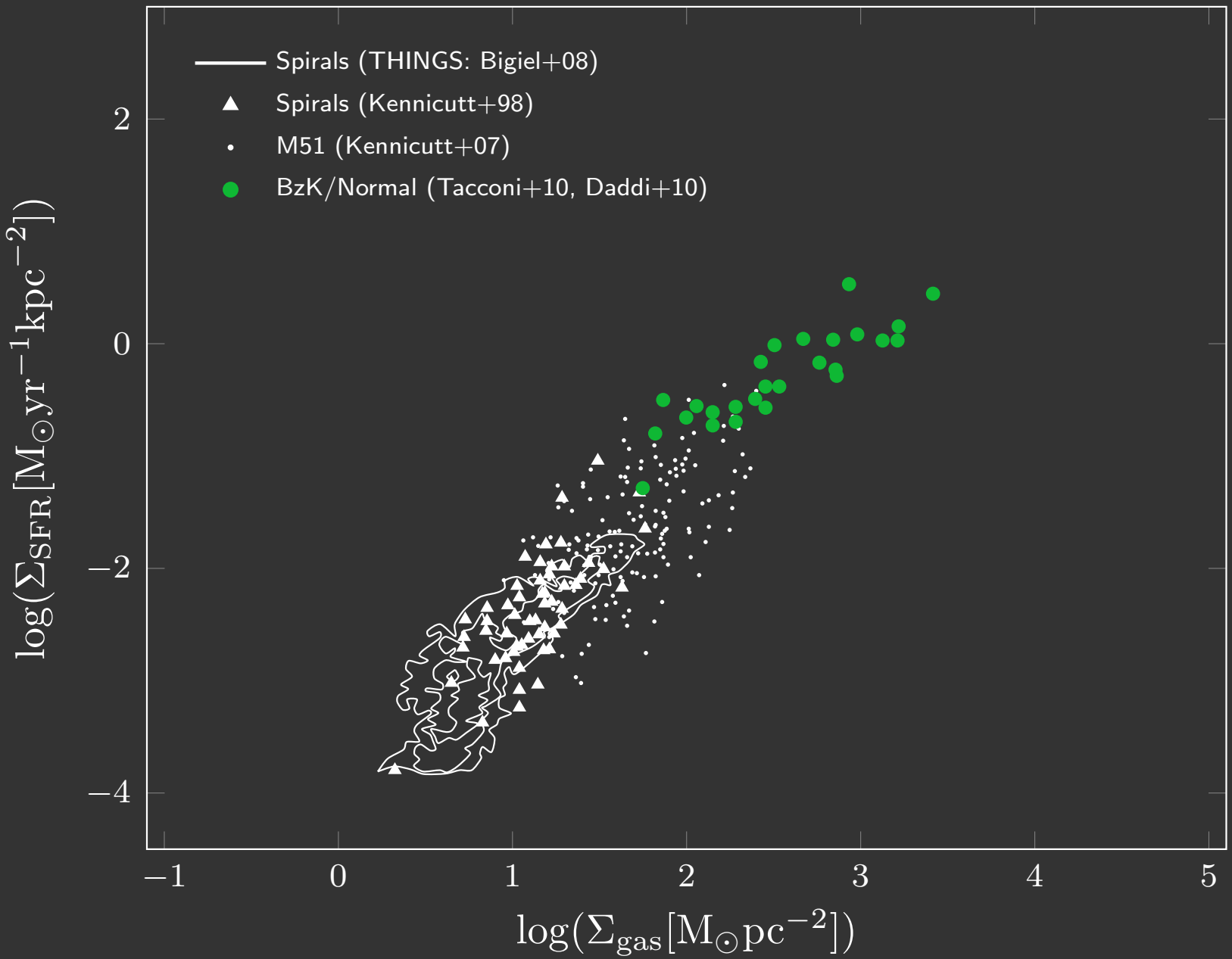


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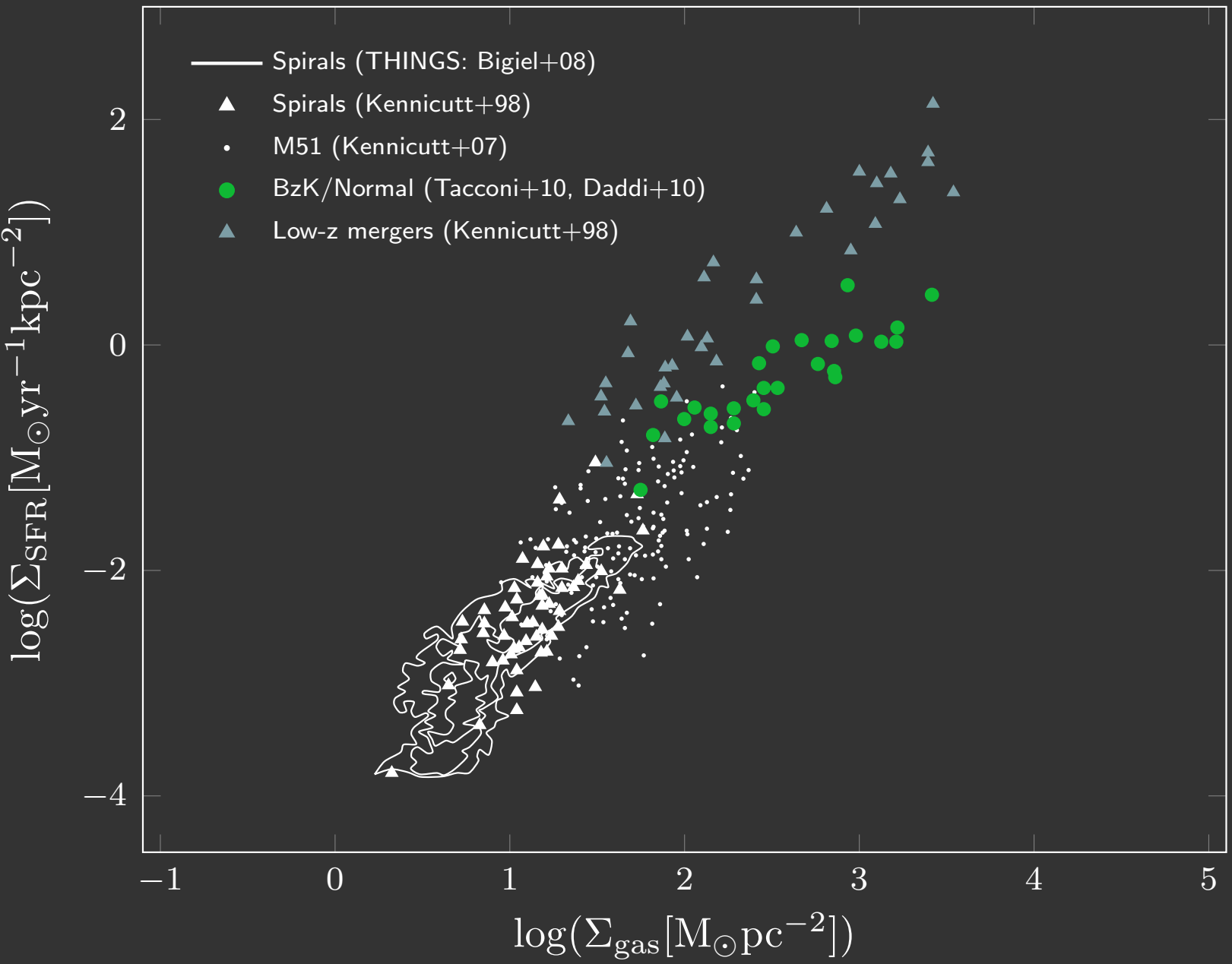
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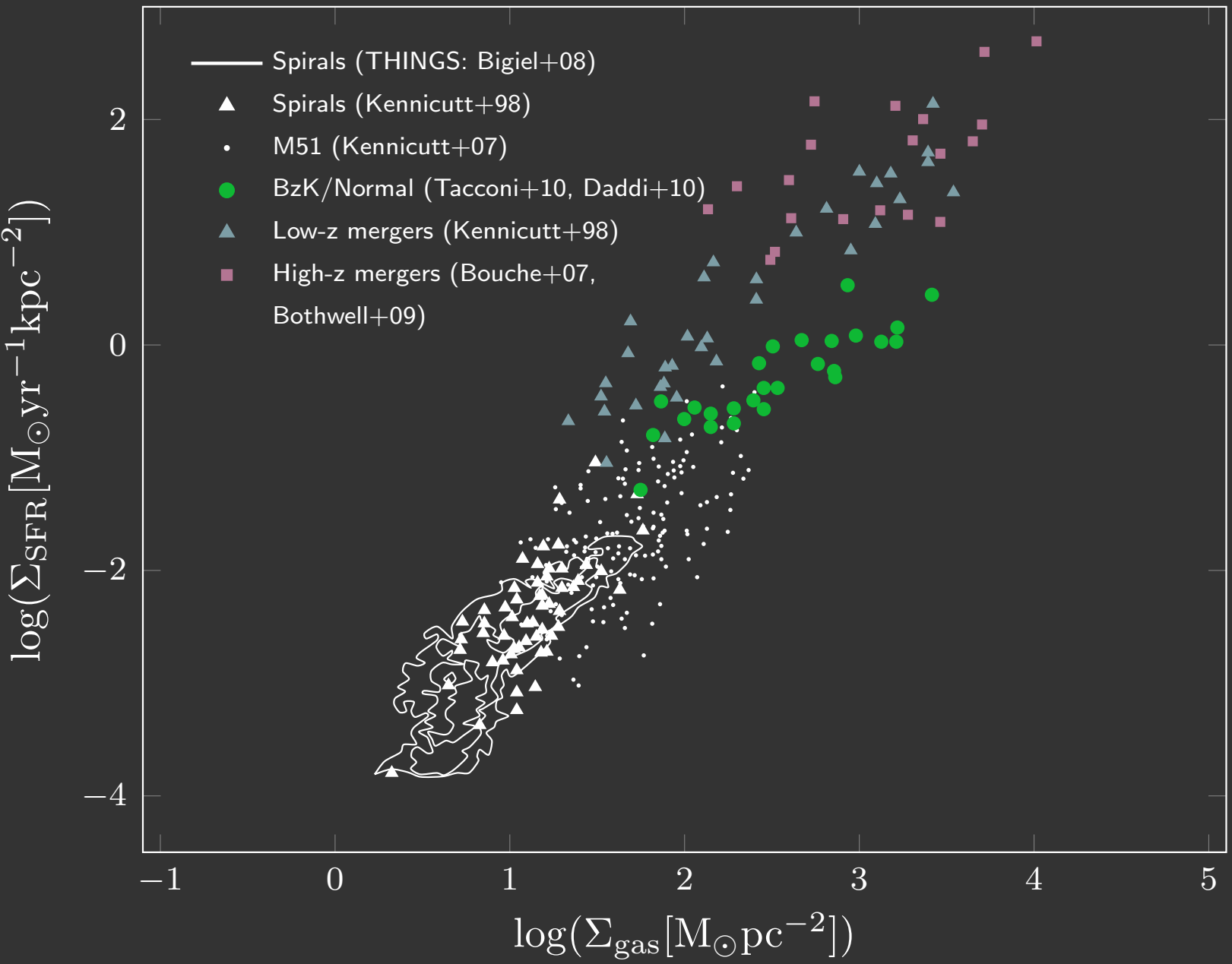
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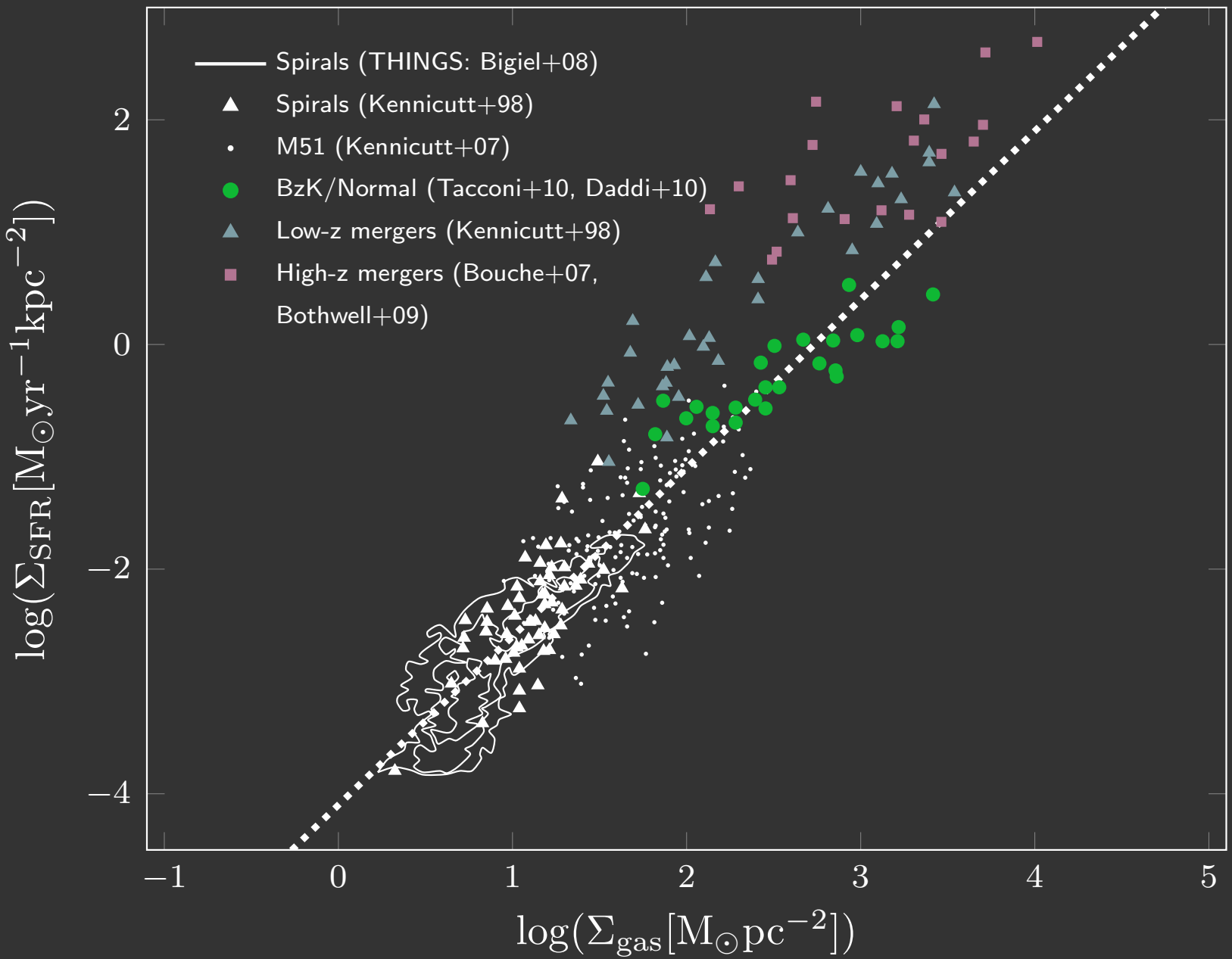
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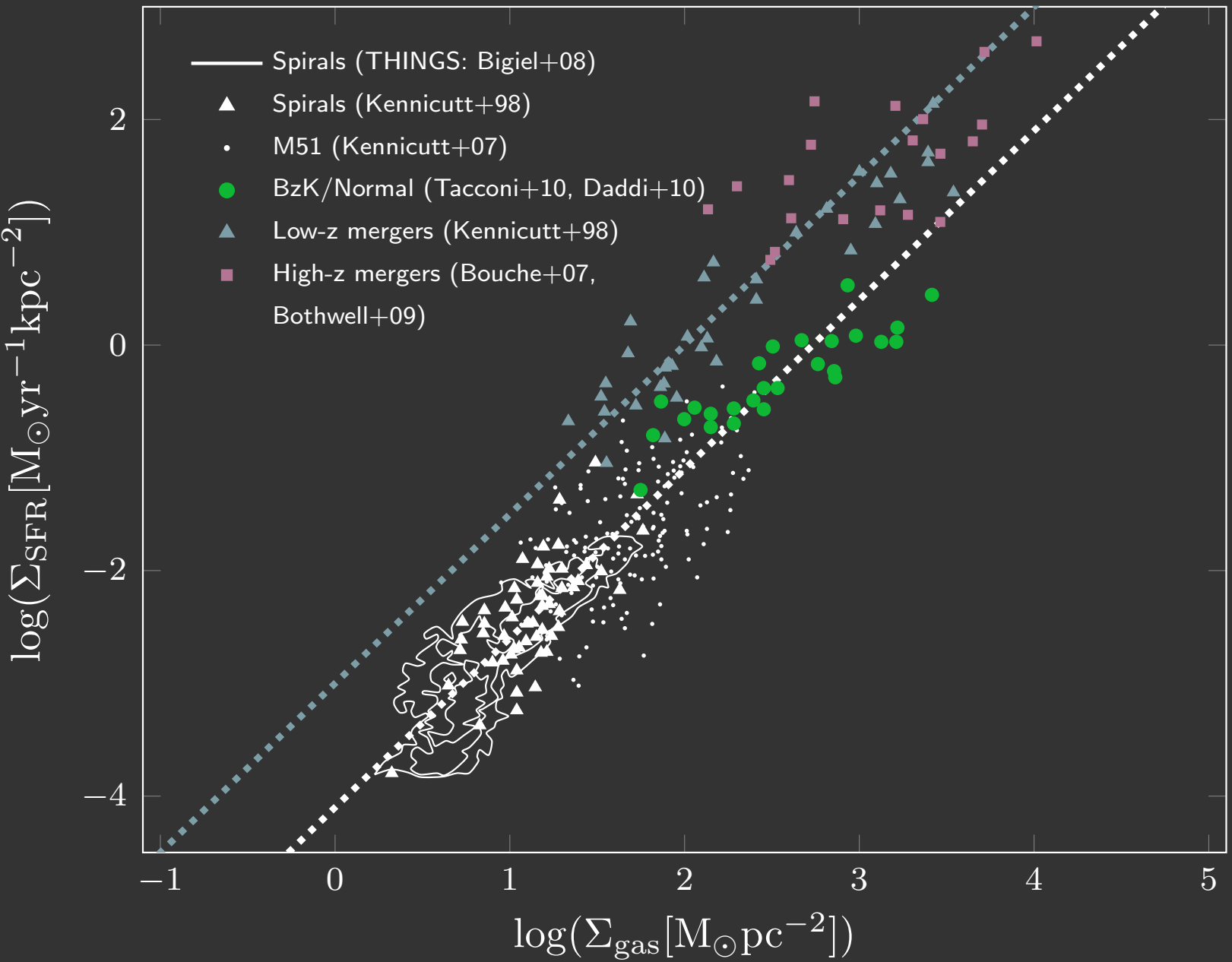
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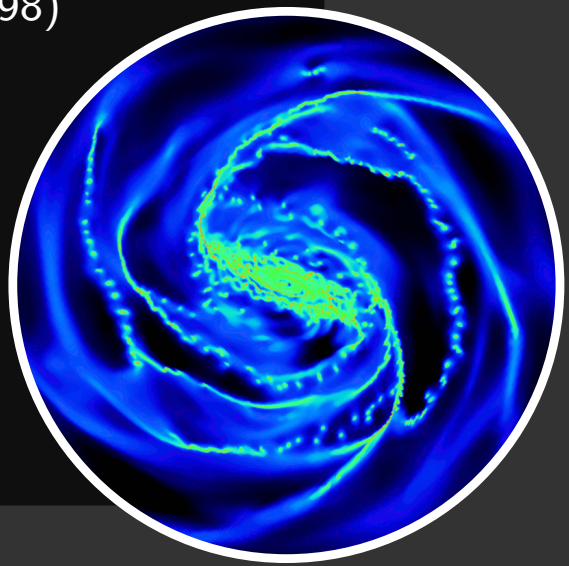

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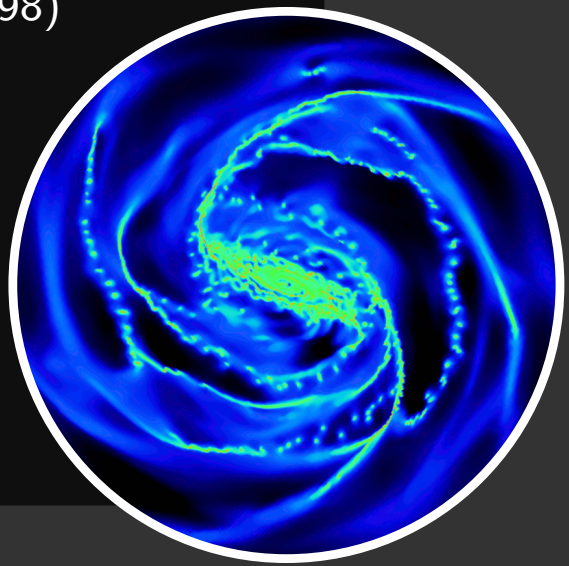

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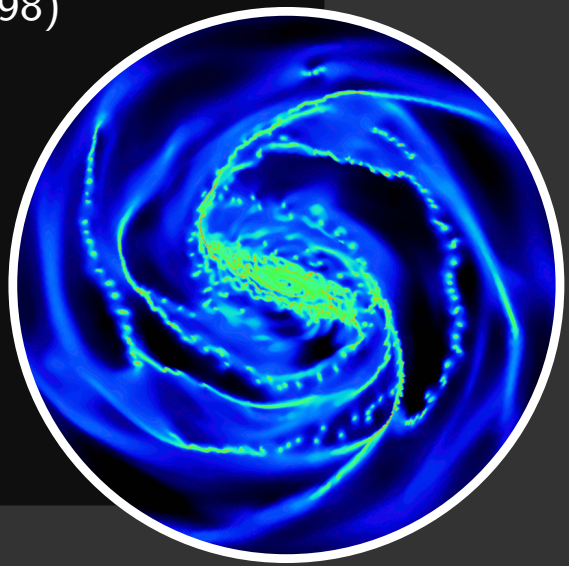

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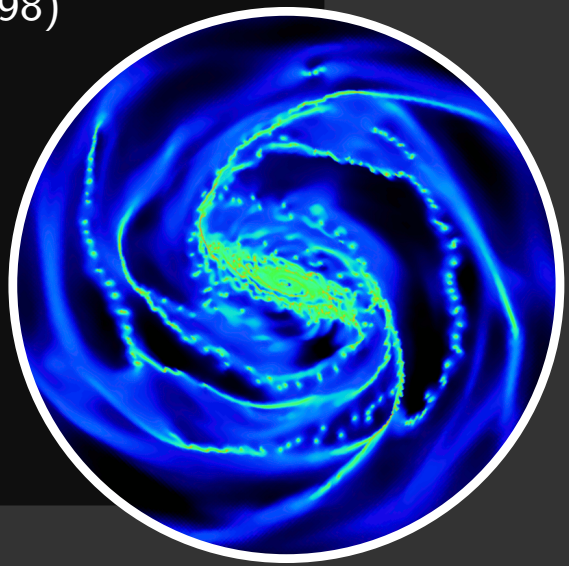

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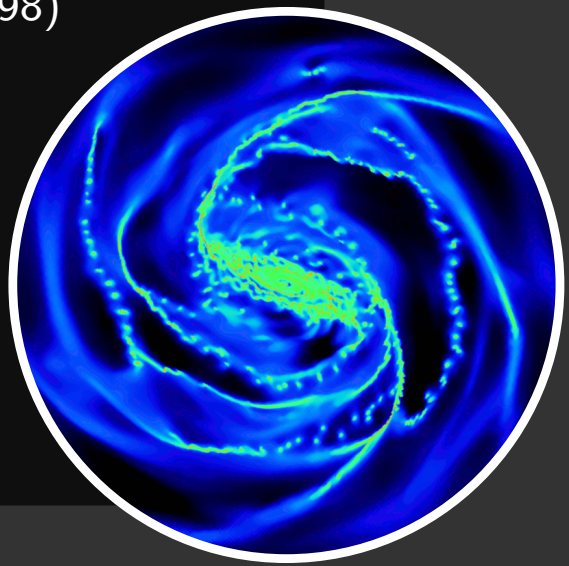

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# Ab initio models

## Sub-grid model

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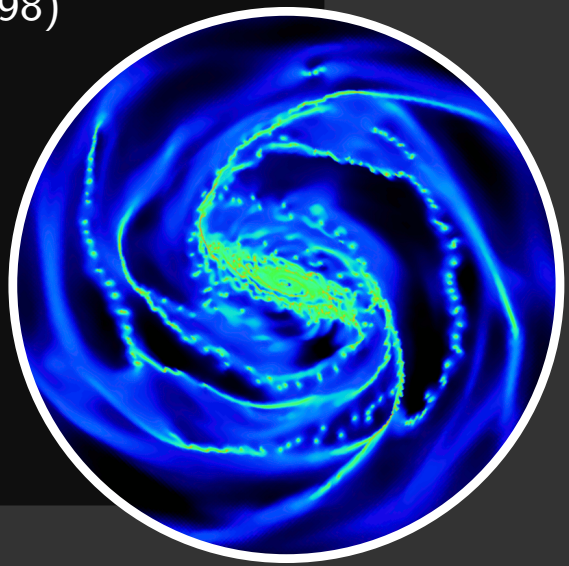

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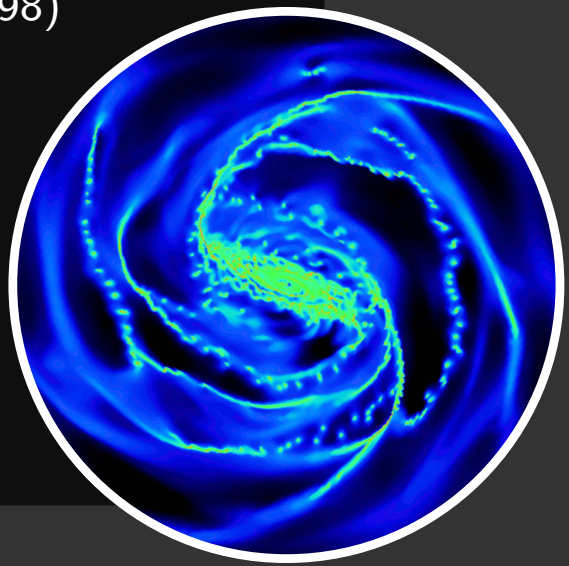

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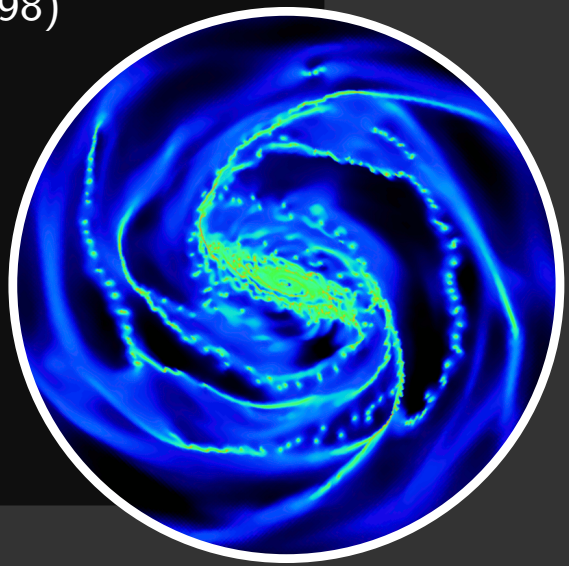

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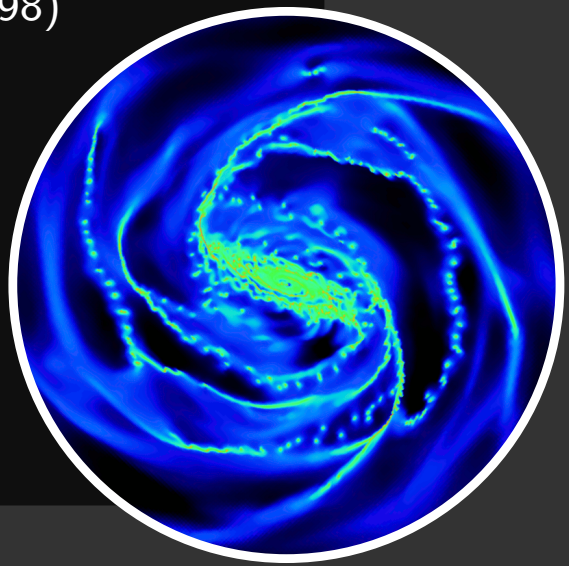

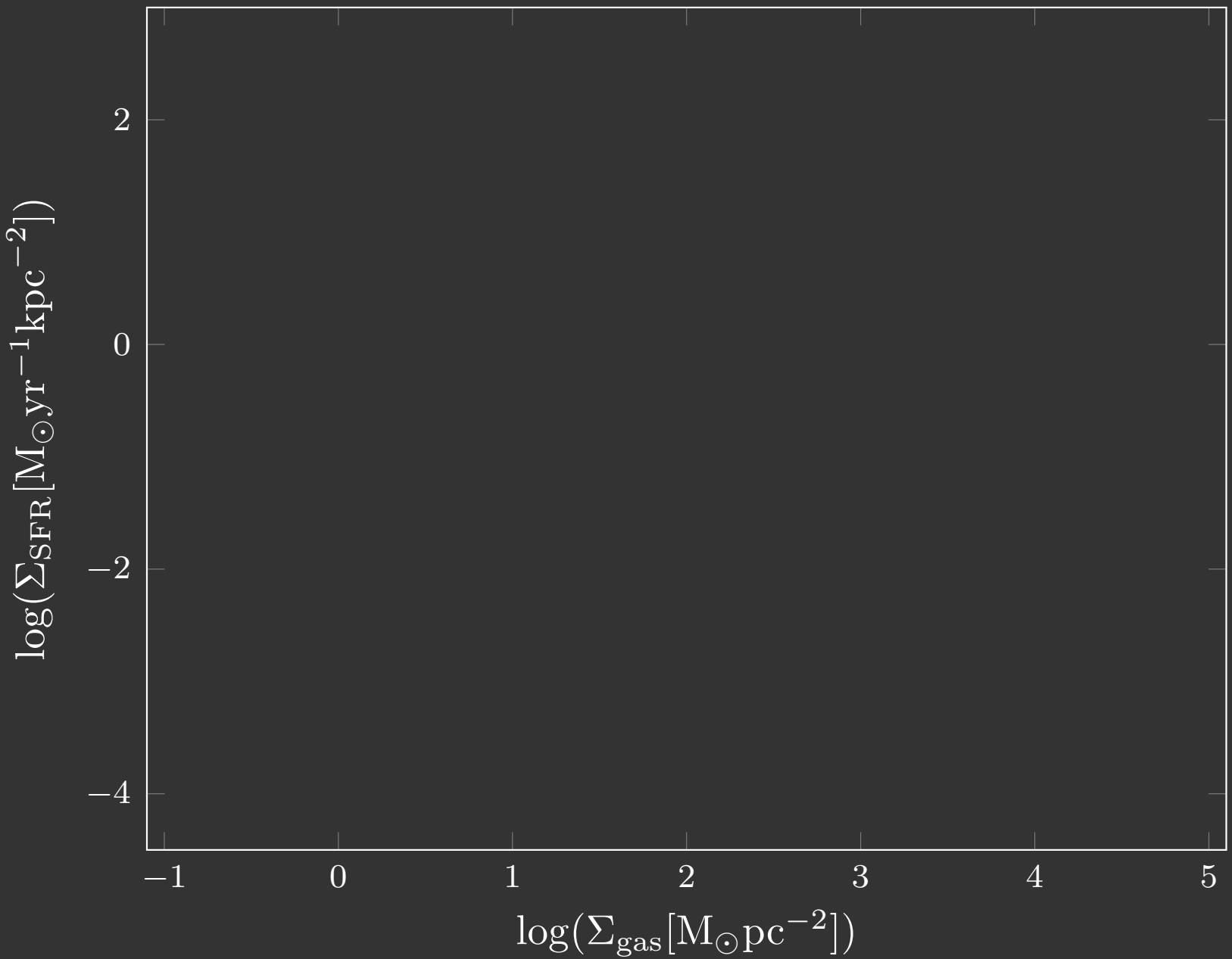


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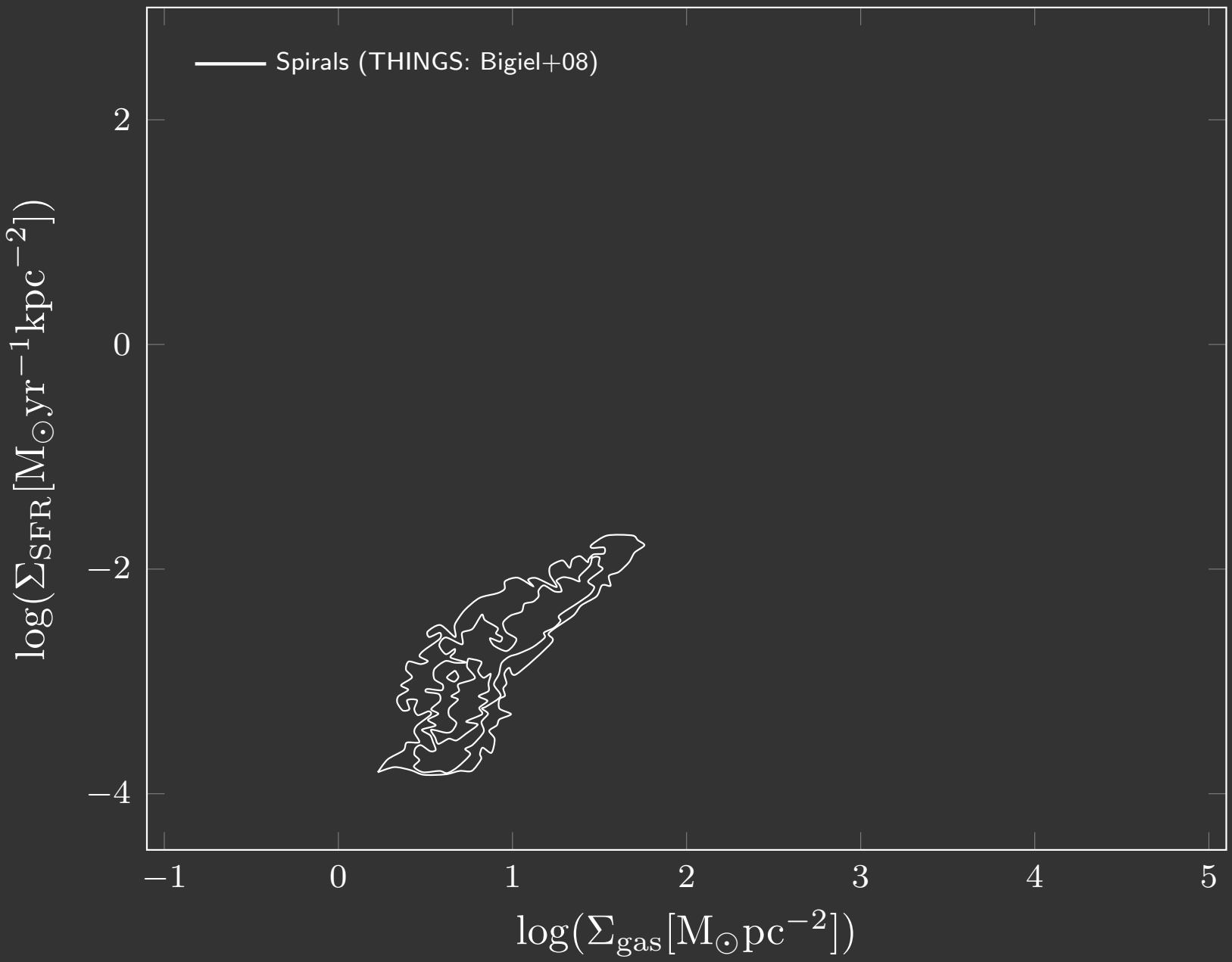
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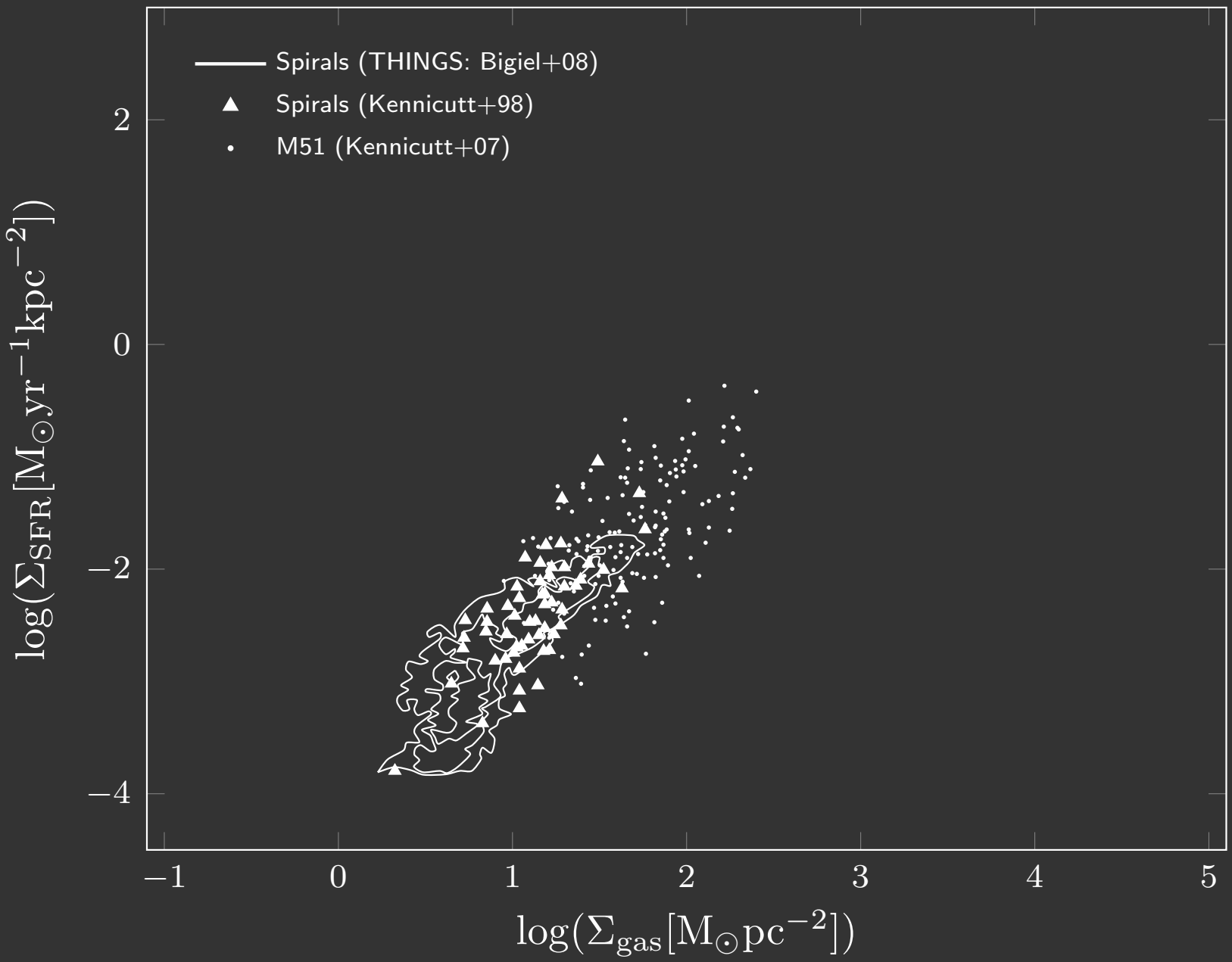
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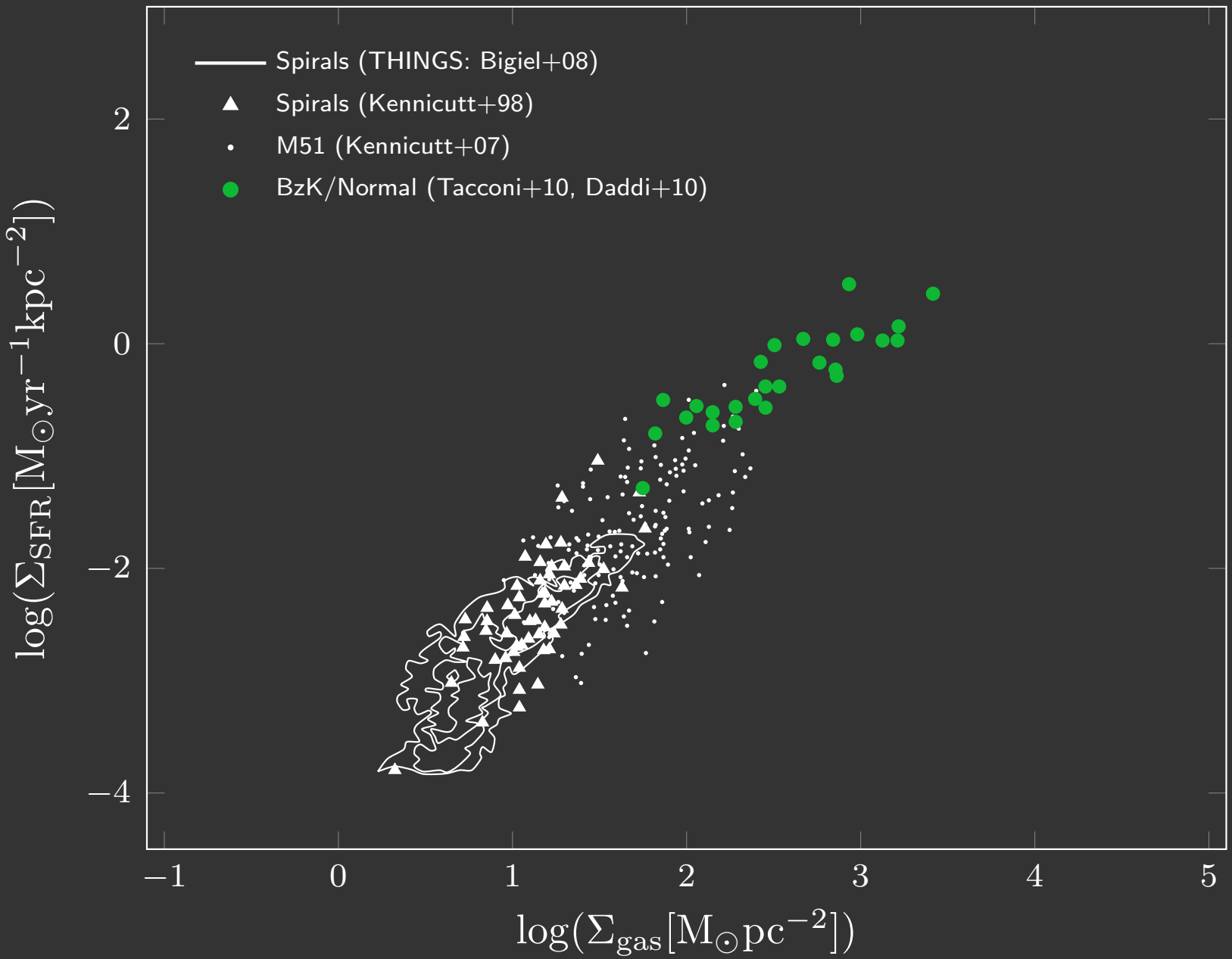


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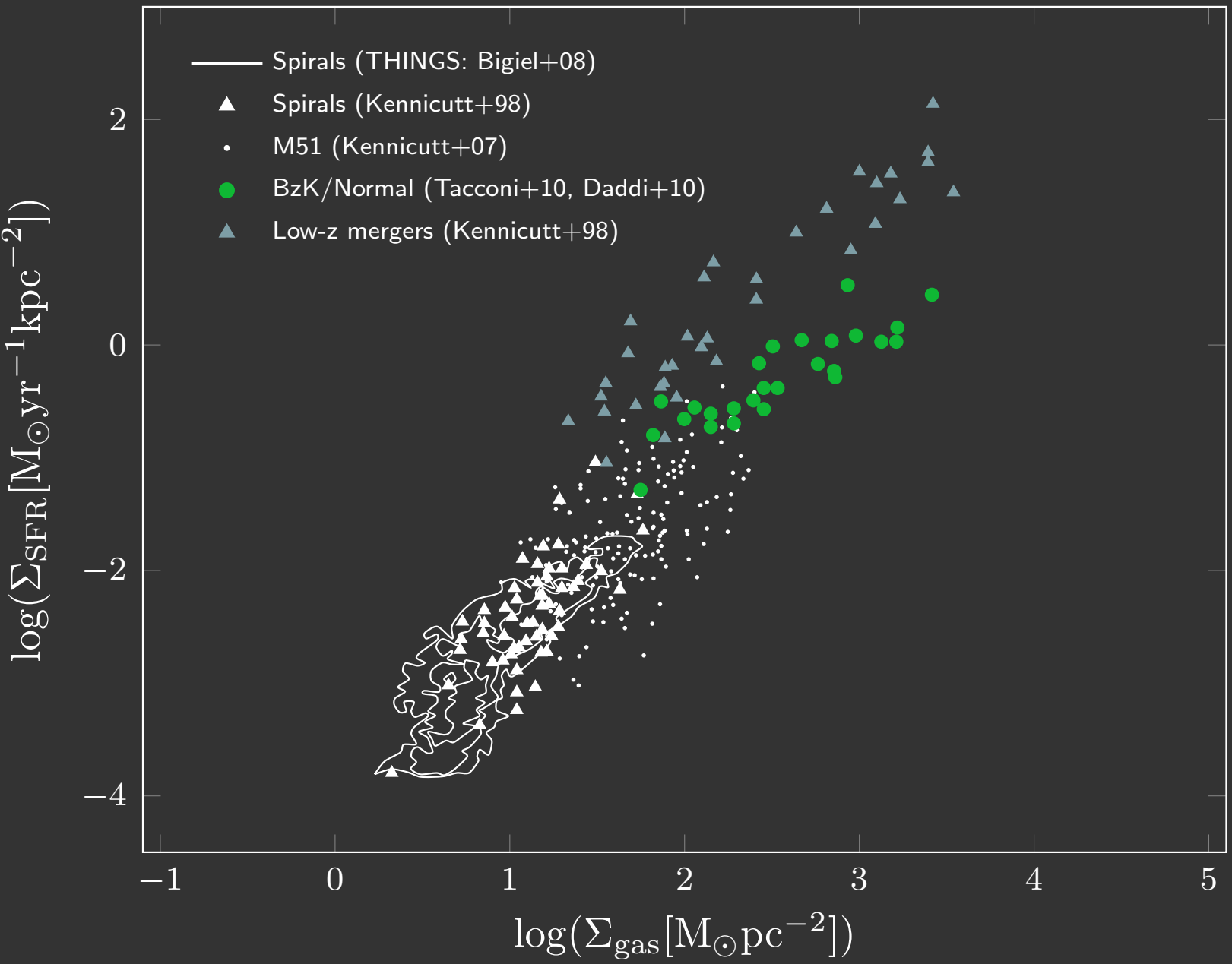
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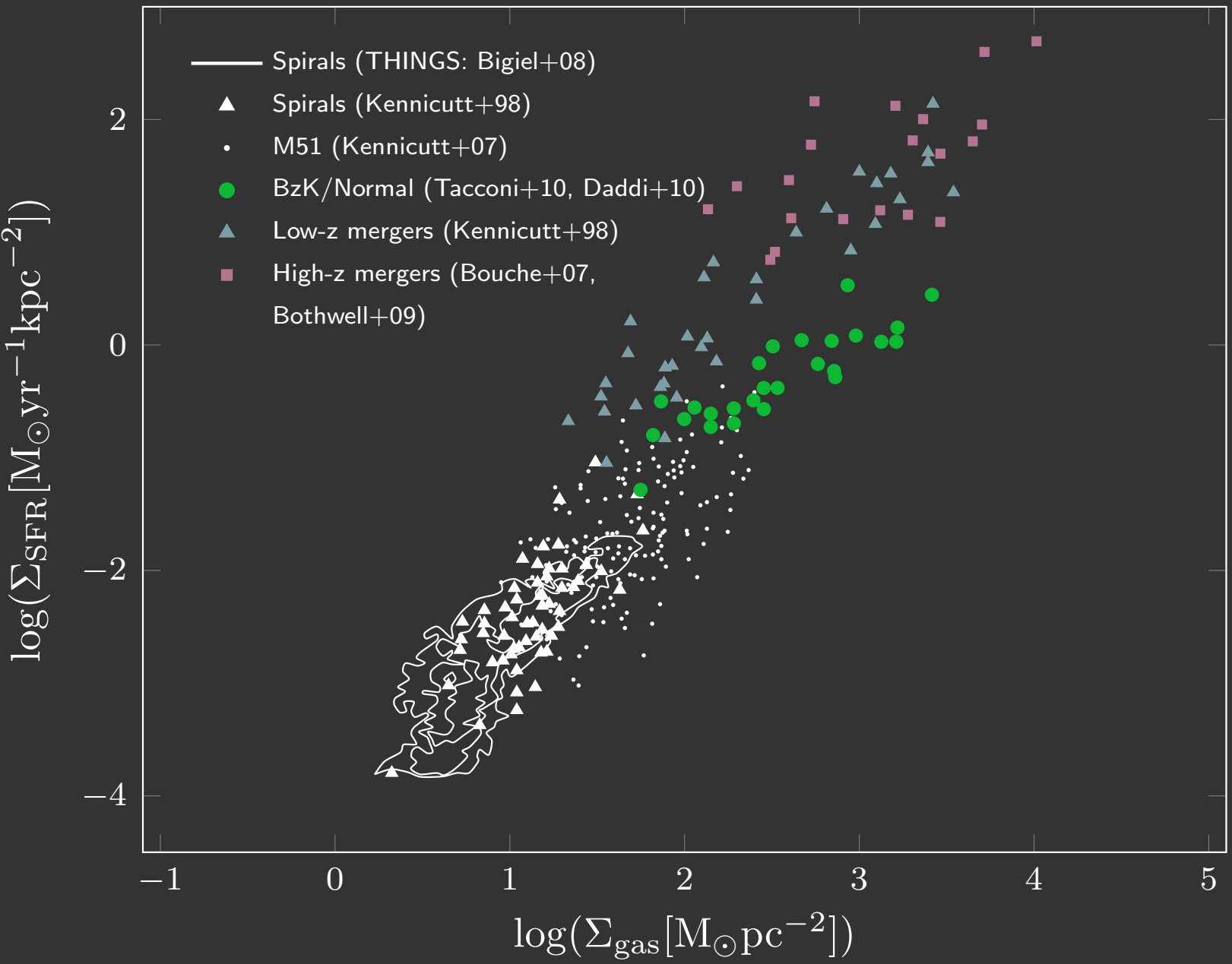
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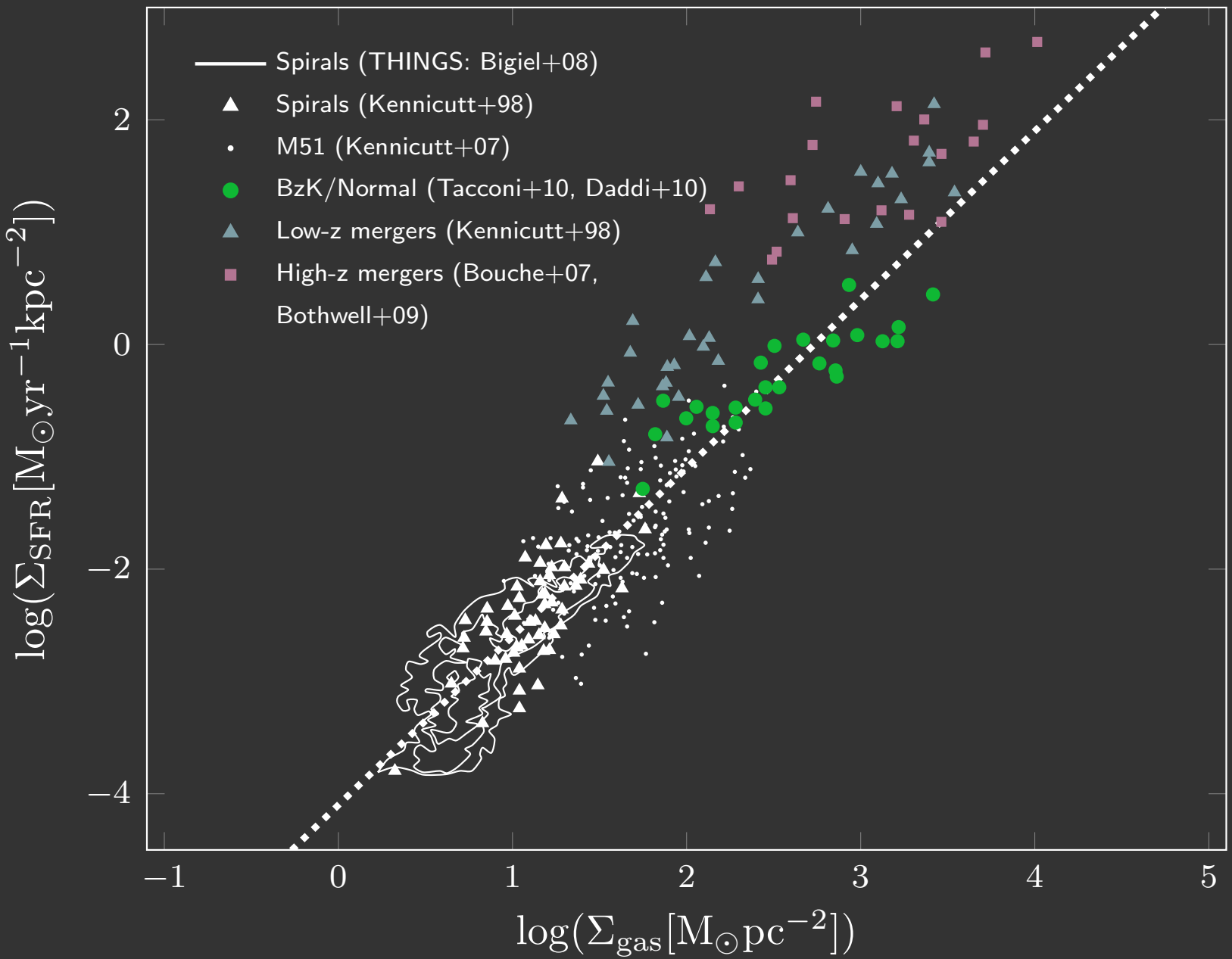
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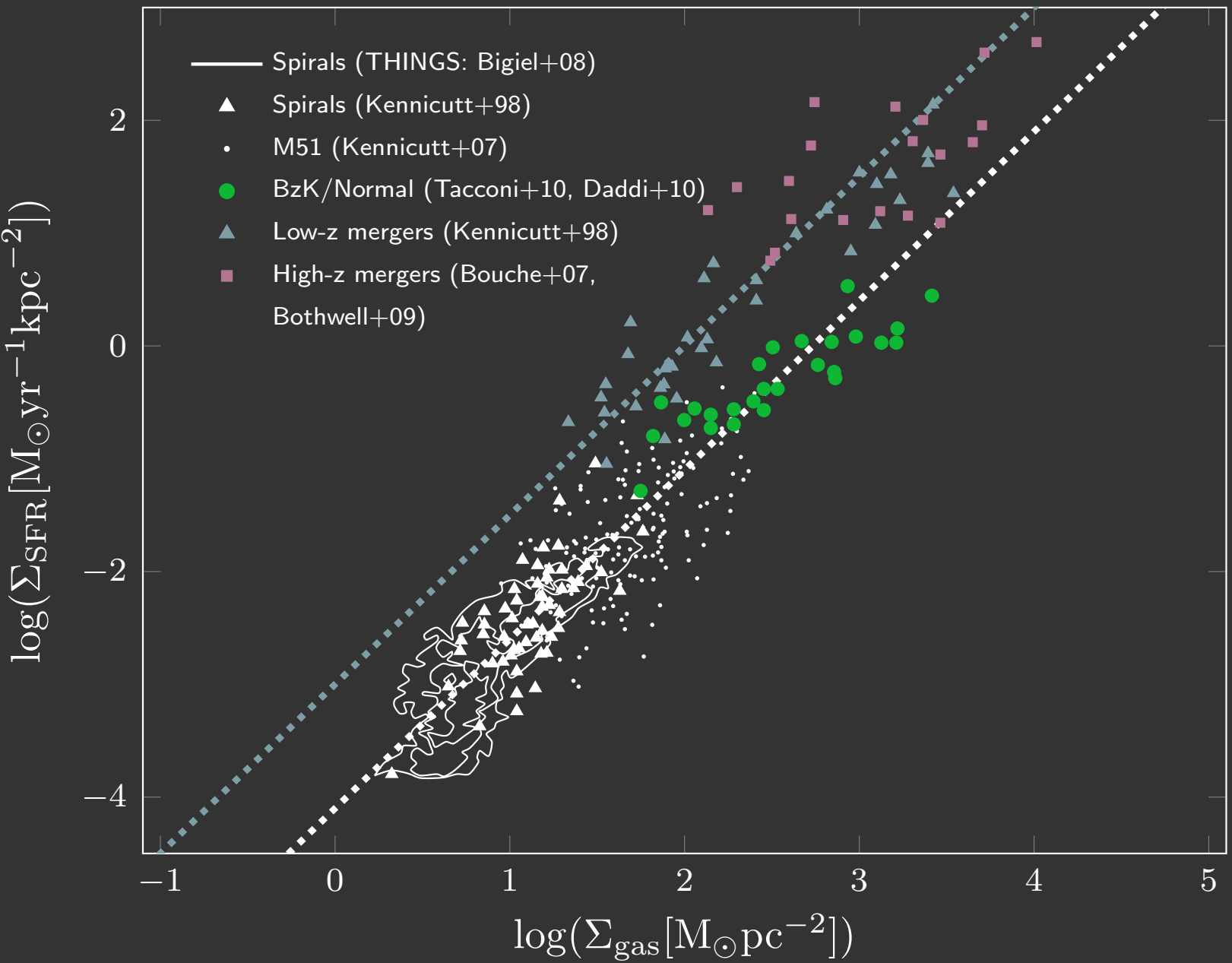
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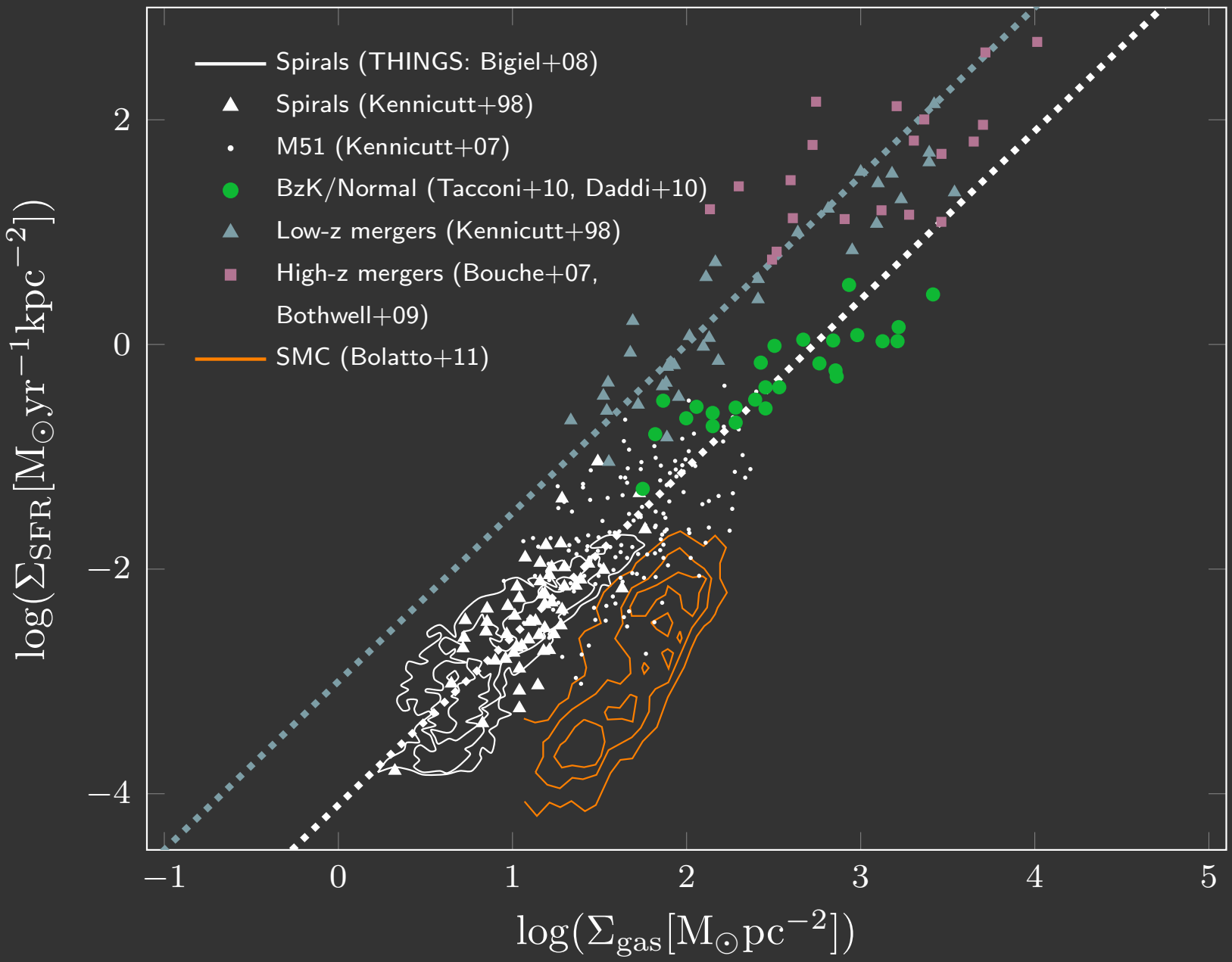
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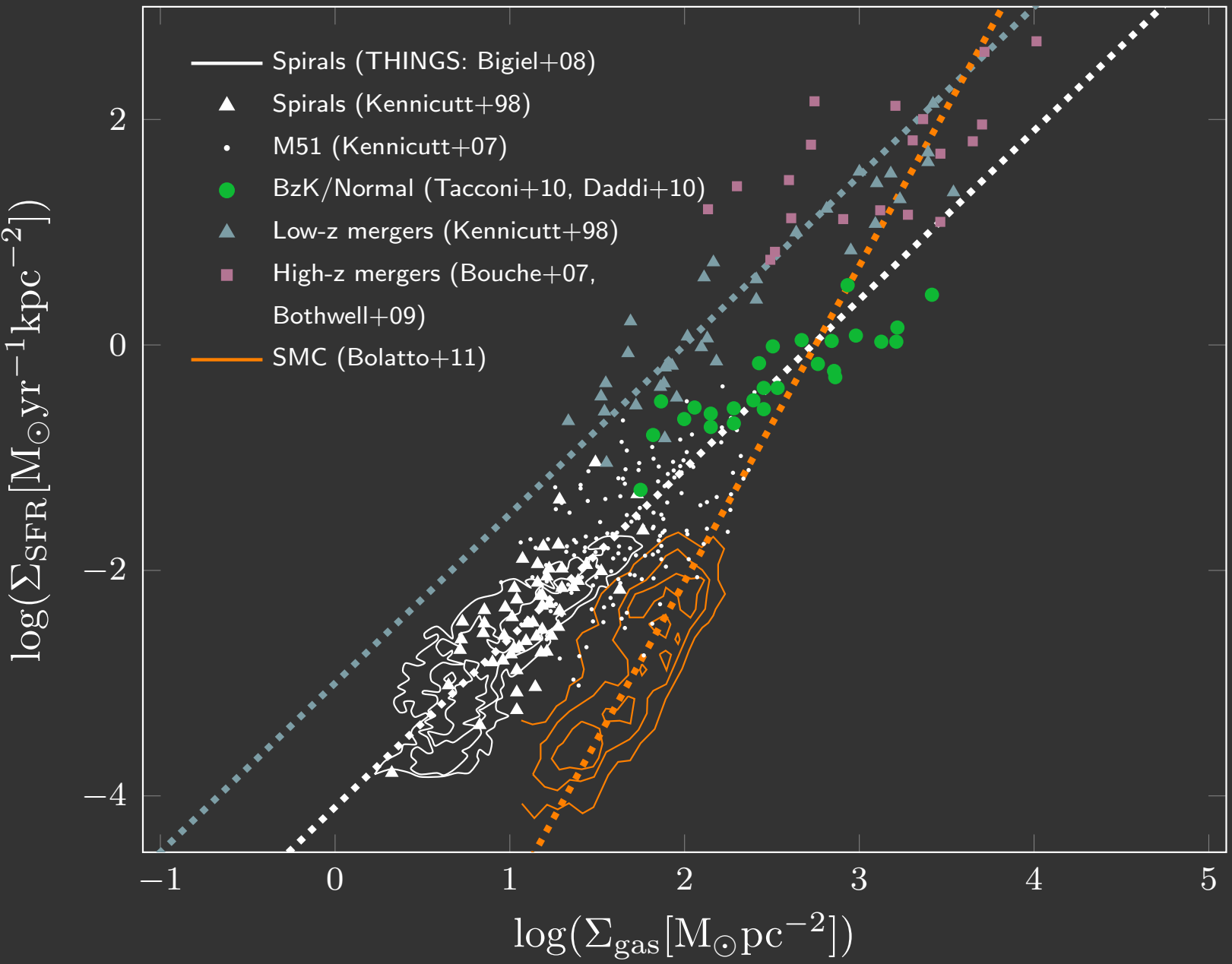
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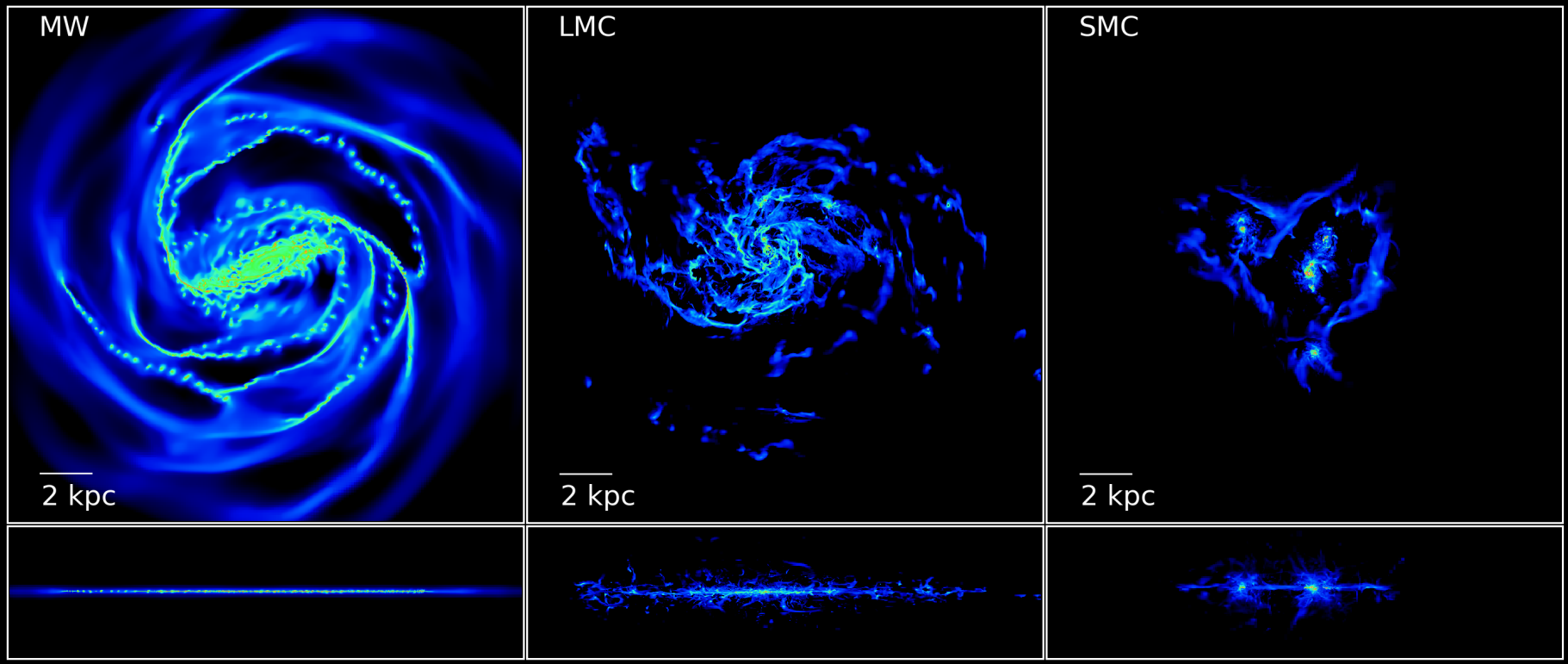

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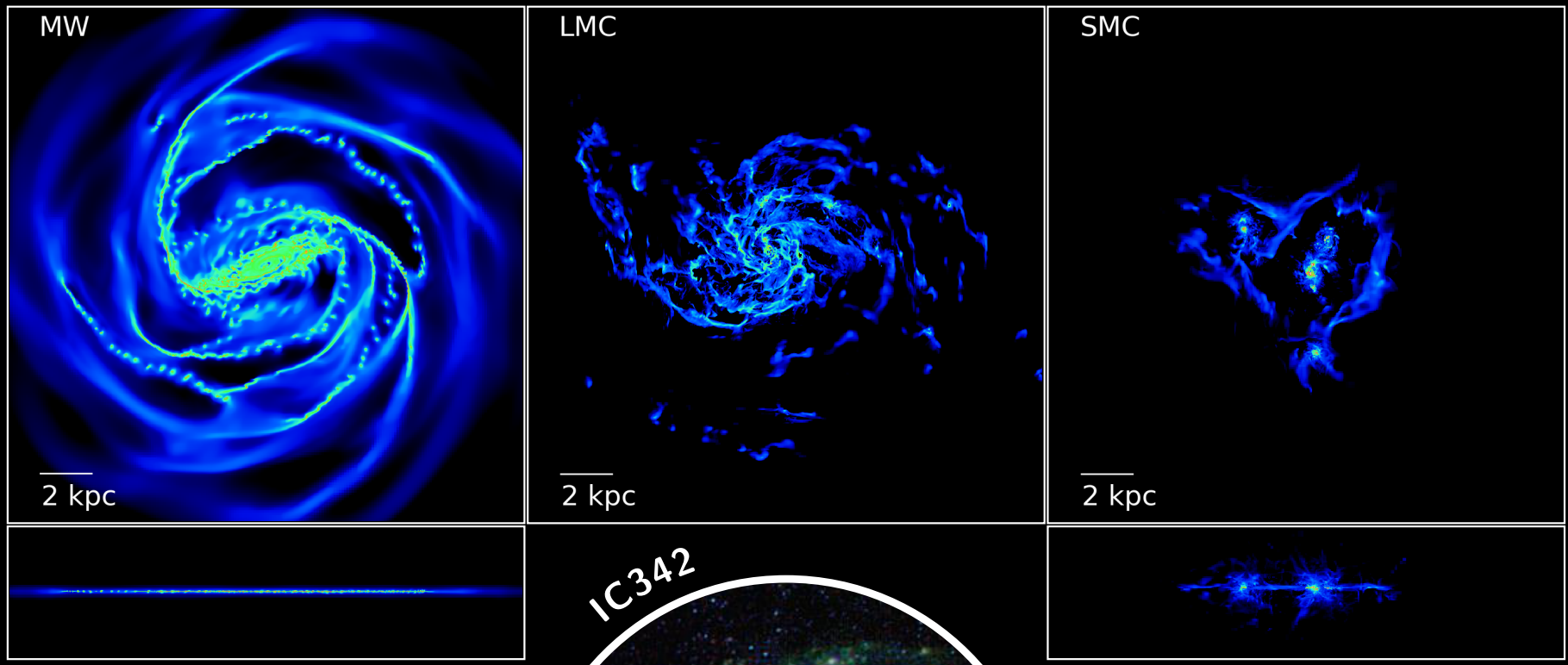

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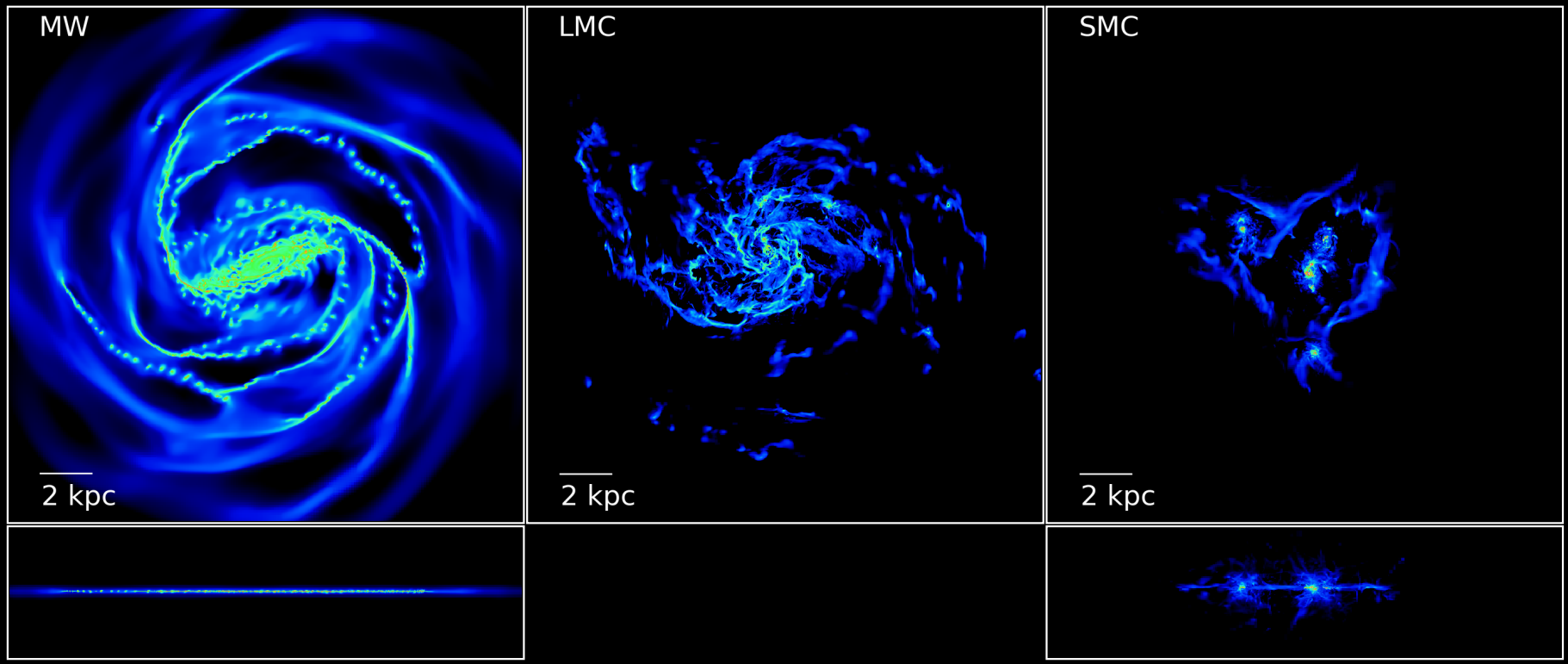

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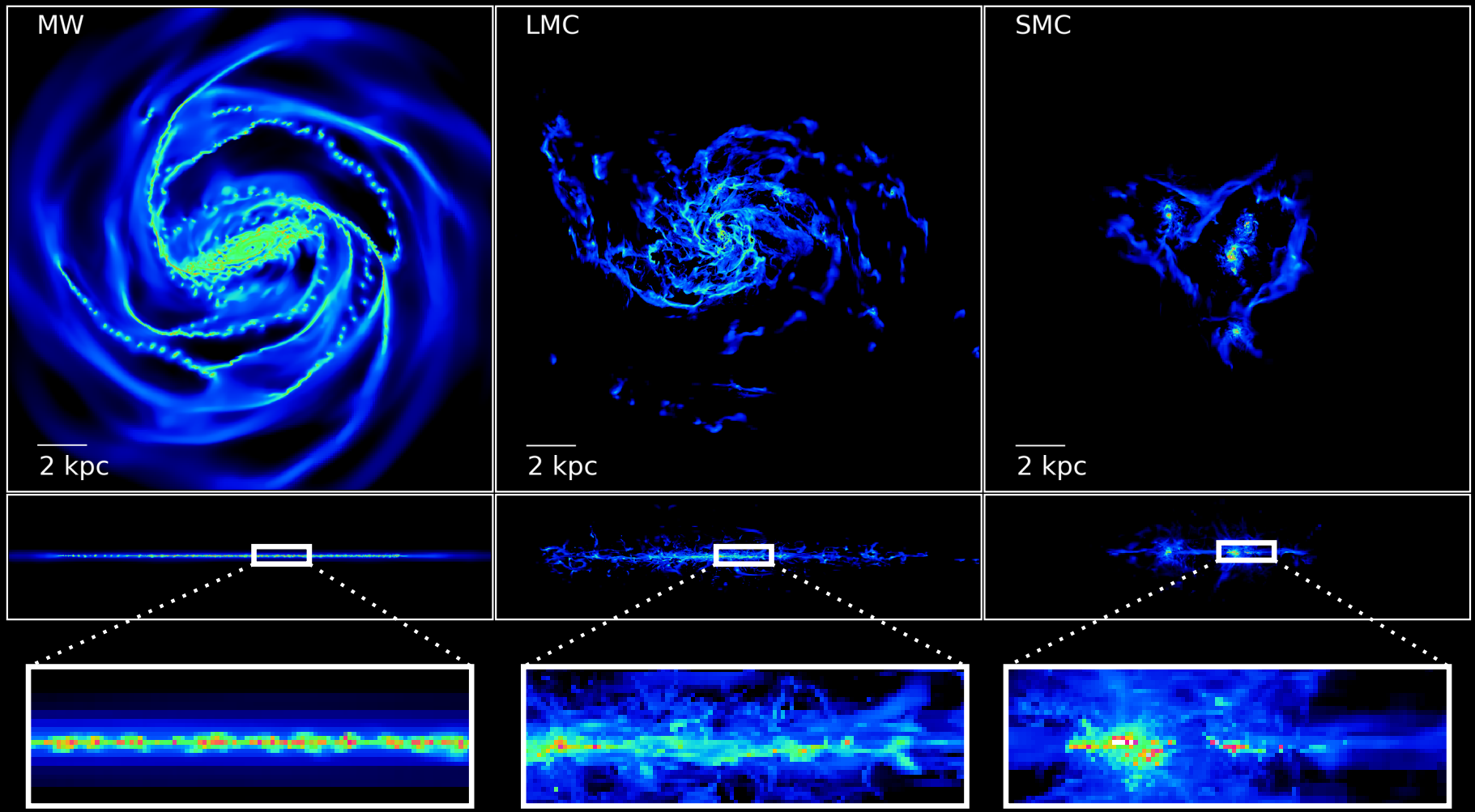

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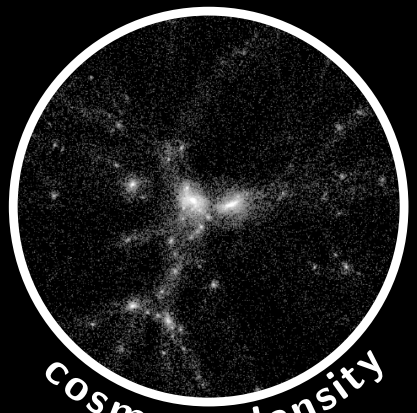


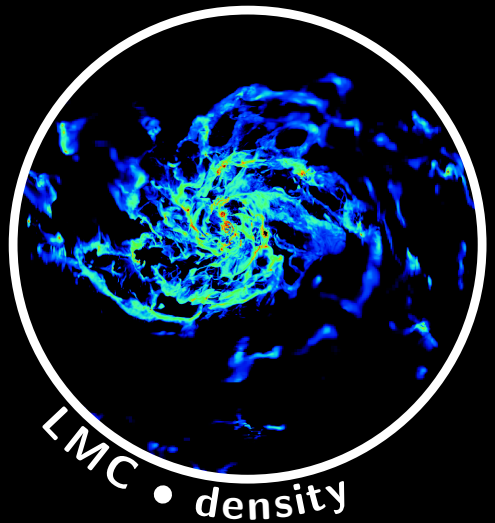

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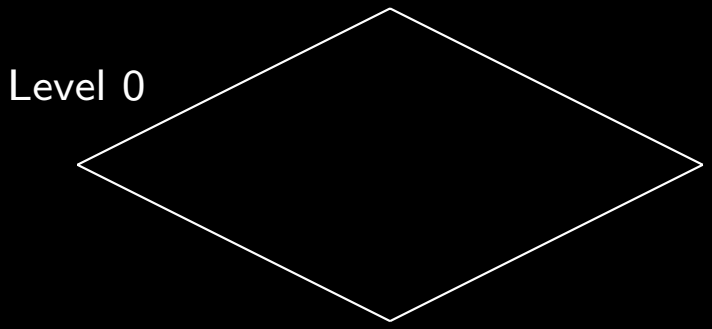


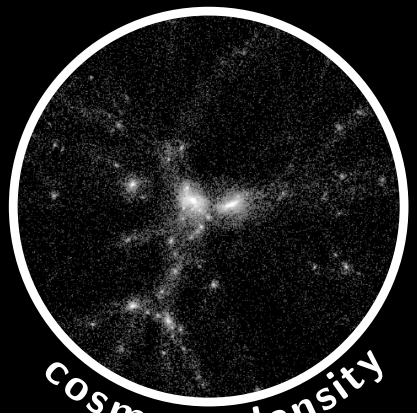


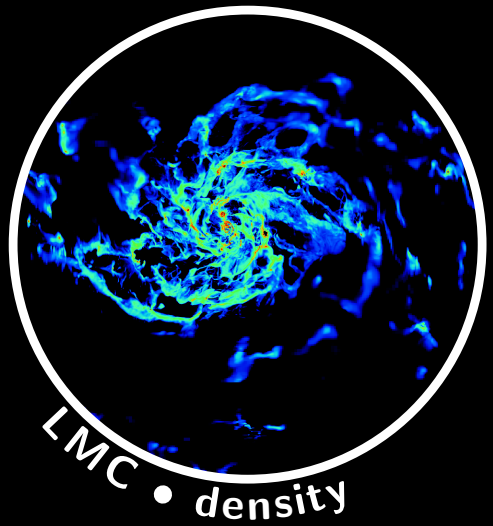

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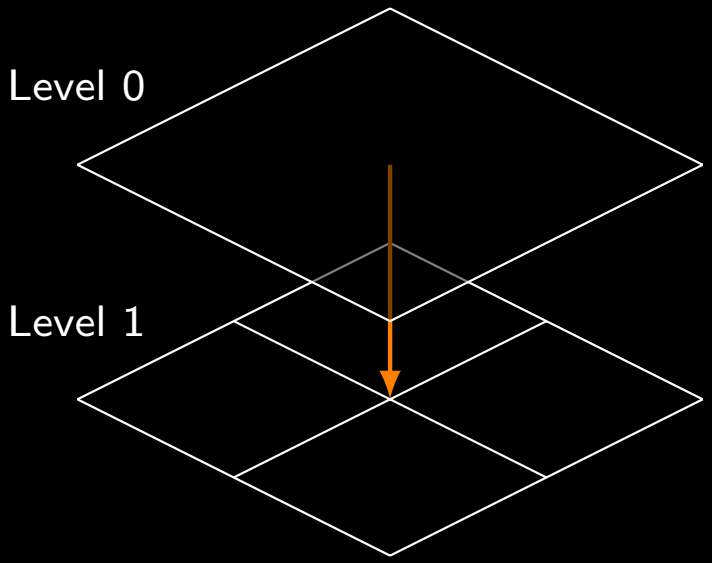


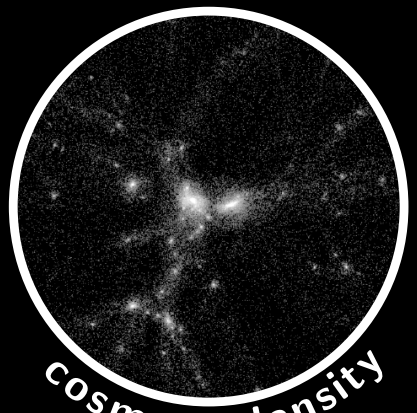


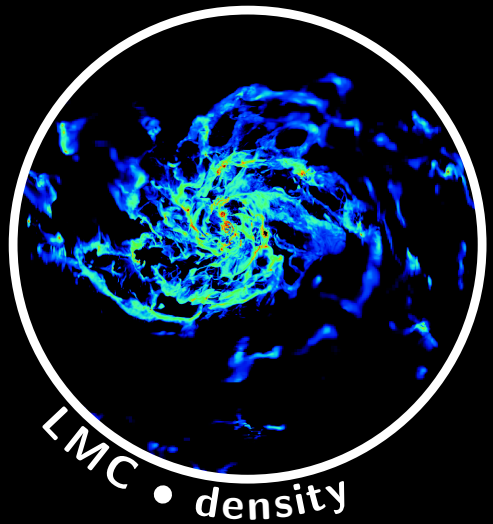

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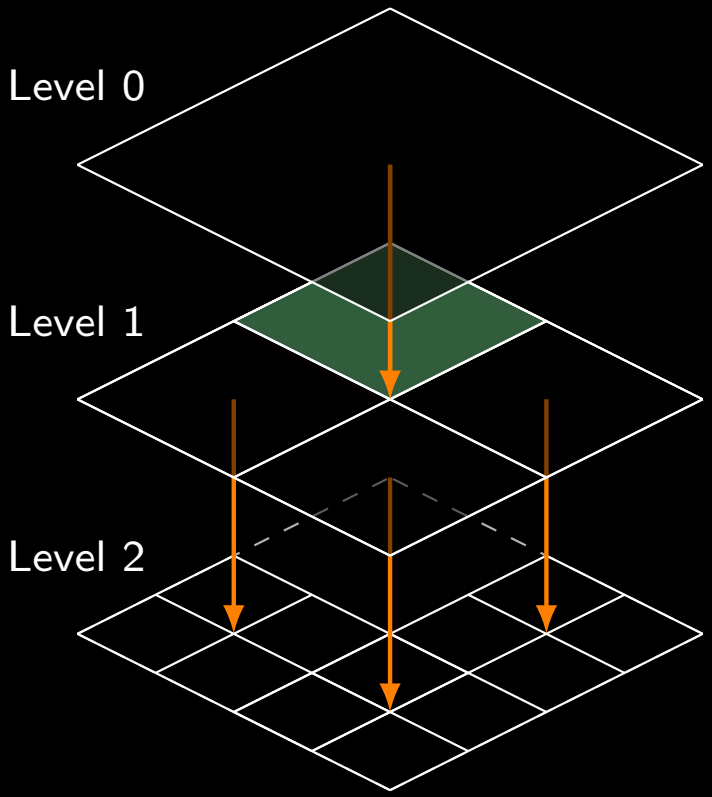


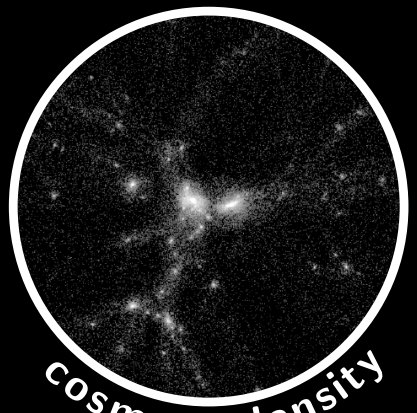


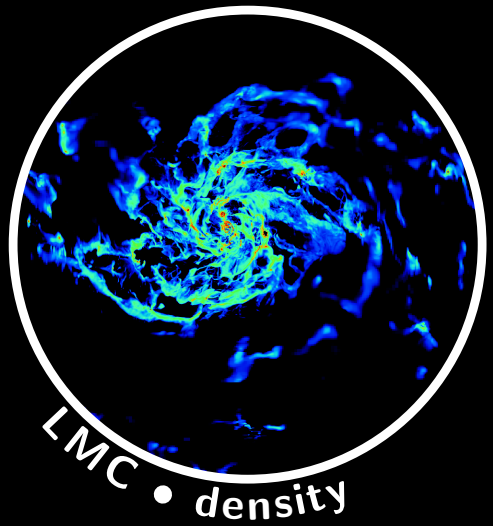

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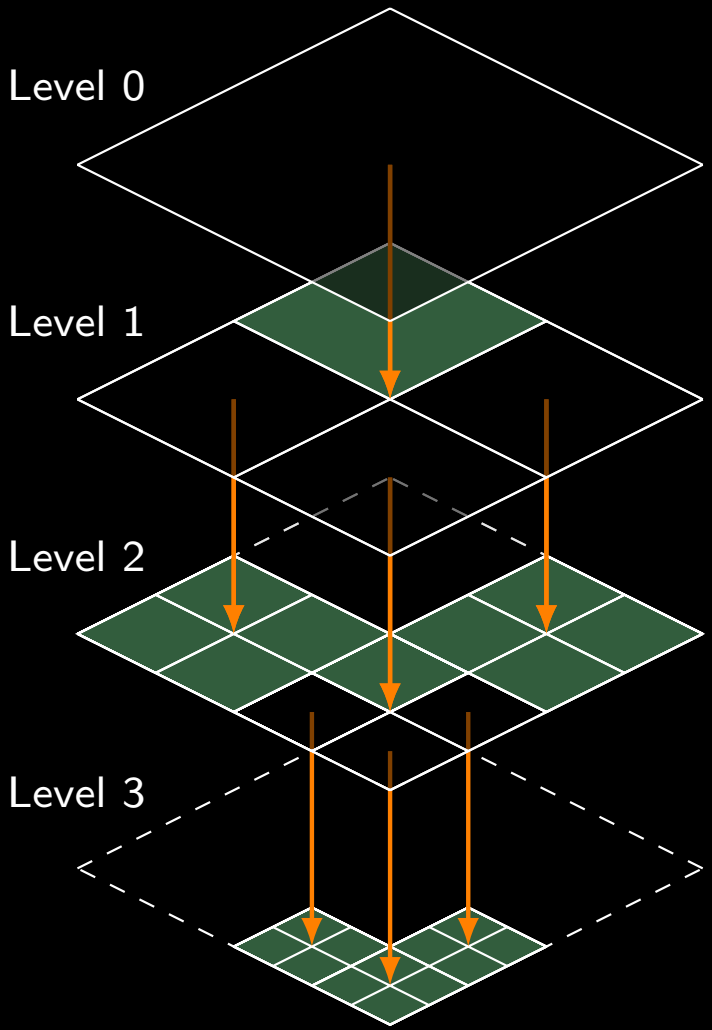


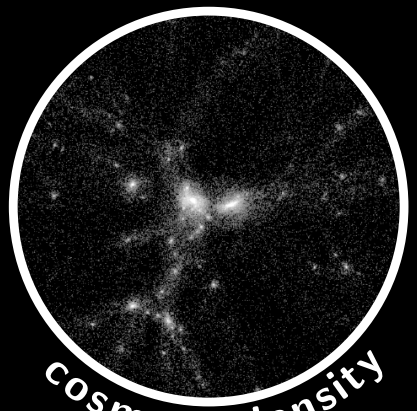


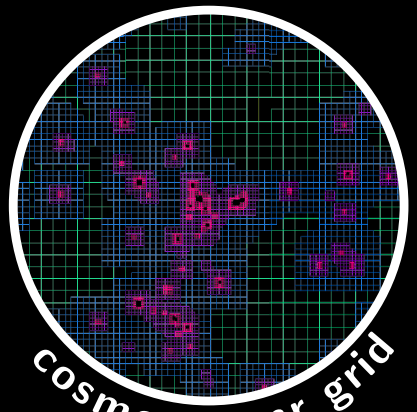


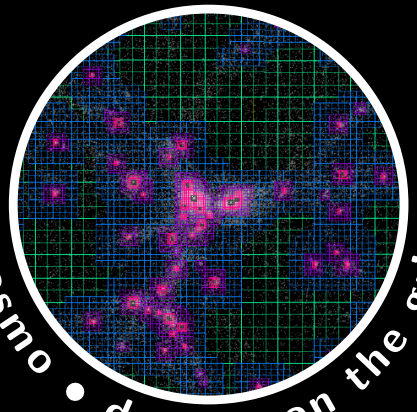


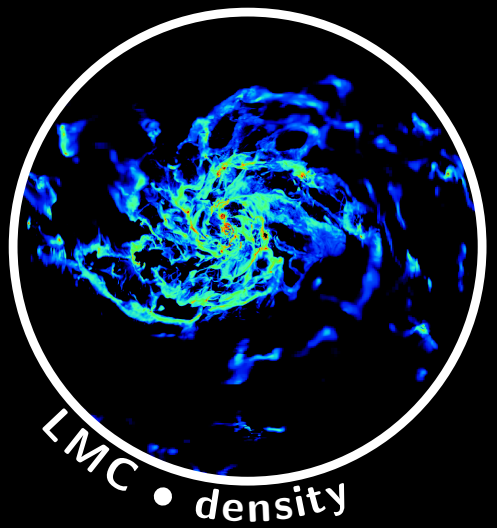


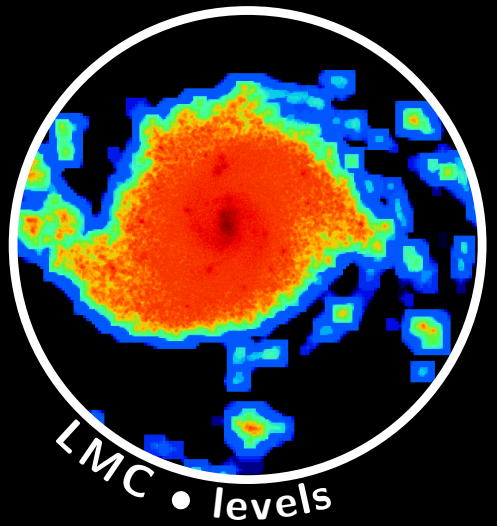

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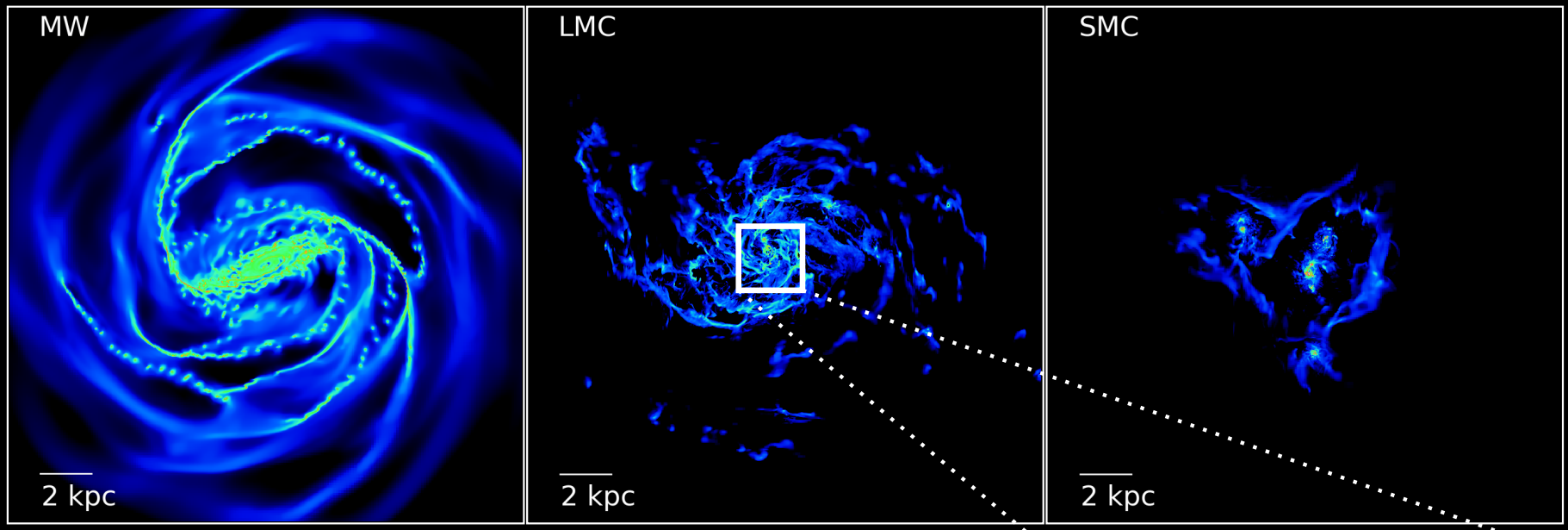
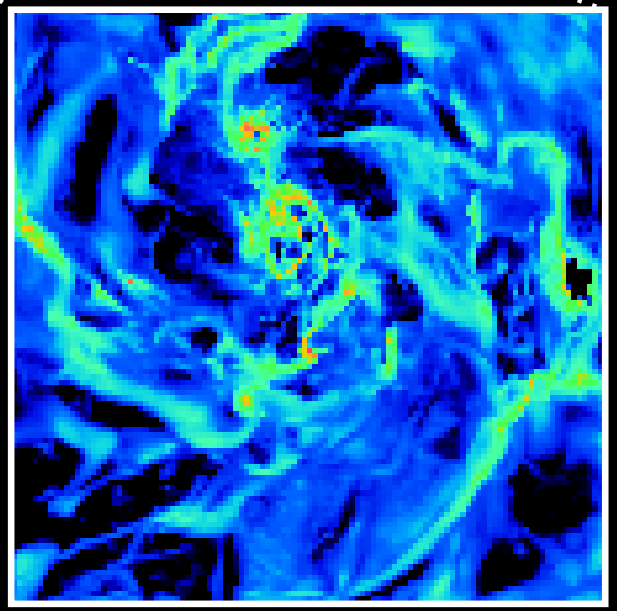



## Simulations

- AMR code RAMSES (Teyssier 2002)
- heating/cooling vs EoS
- local star formation: Schmidt relation (n=1.5, $\epsilon$=3%)
- stellar feedback



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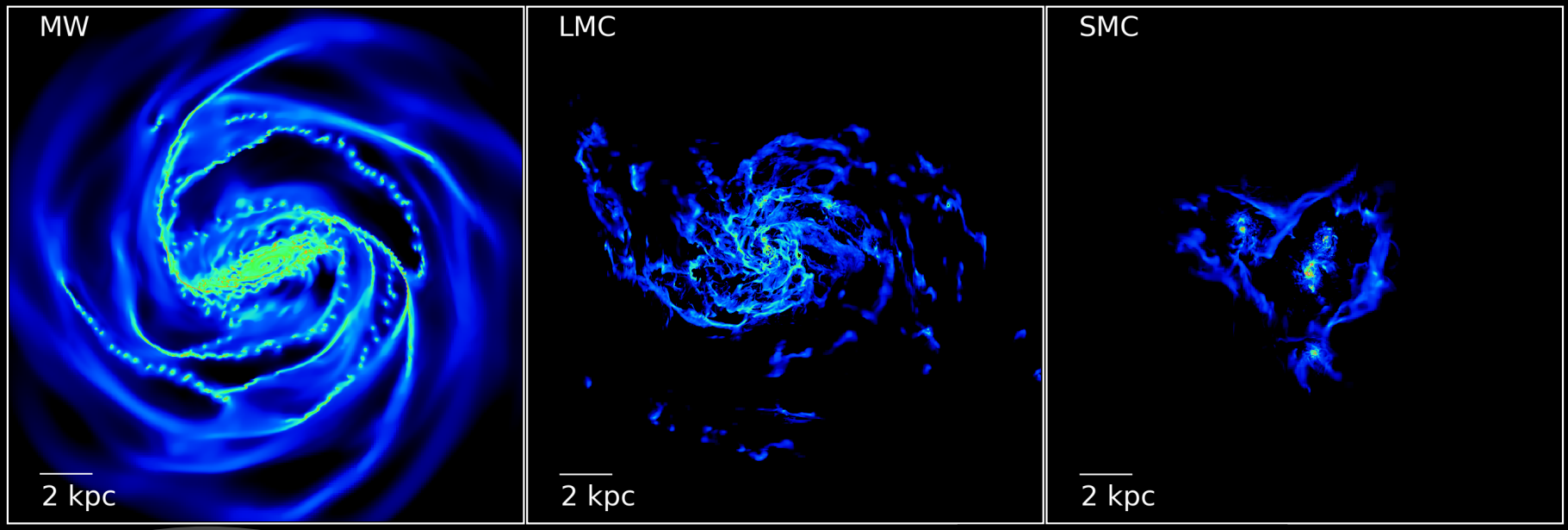



**Renaud et al. 2014**

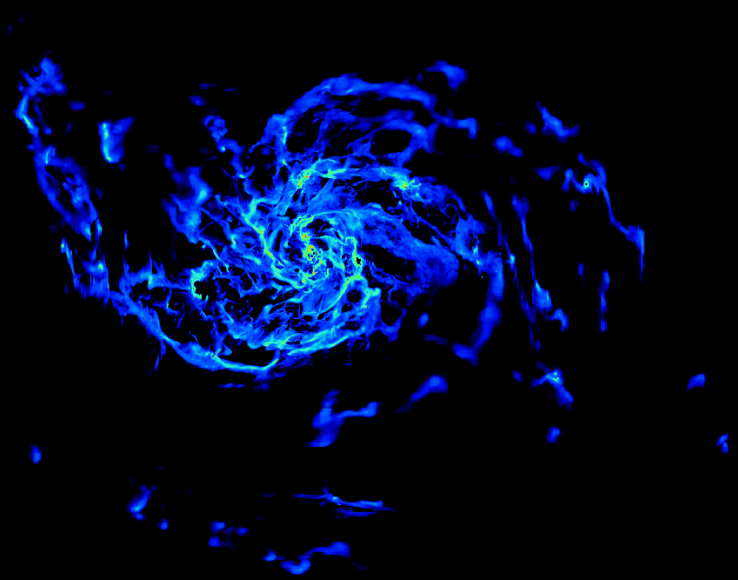
- box length: 100 kpc
- resolution: 0.05 pc
- EoS: pseudo-cooling
- SNe, photo-ionization, radiative pressure

**Kraljic et al. 2014**

- box length: 25 kpc 30 kpc
- resolution: 1 pc 1.5 pc
- metallicity: $Z=Z_\odot$ $Z=\{0.1,1,1/3\}Z_\odot$
  EoS: pseudo-cooling, self-shielding
- SNe (Dubois et al. 2008)

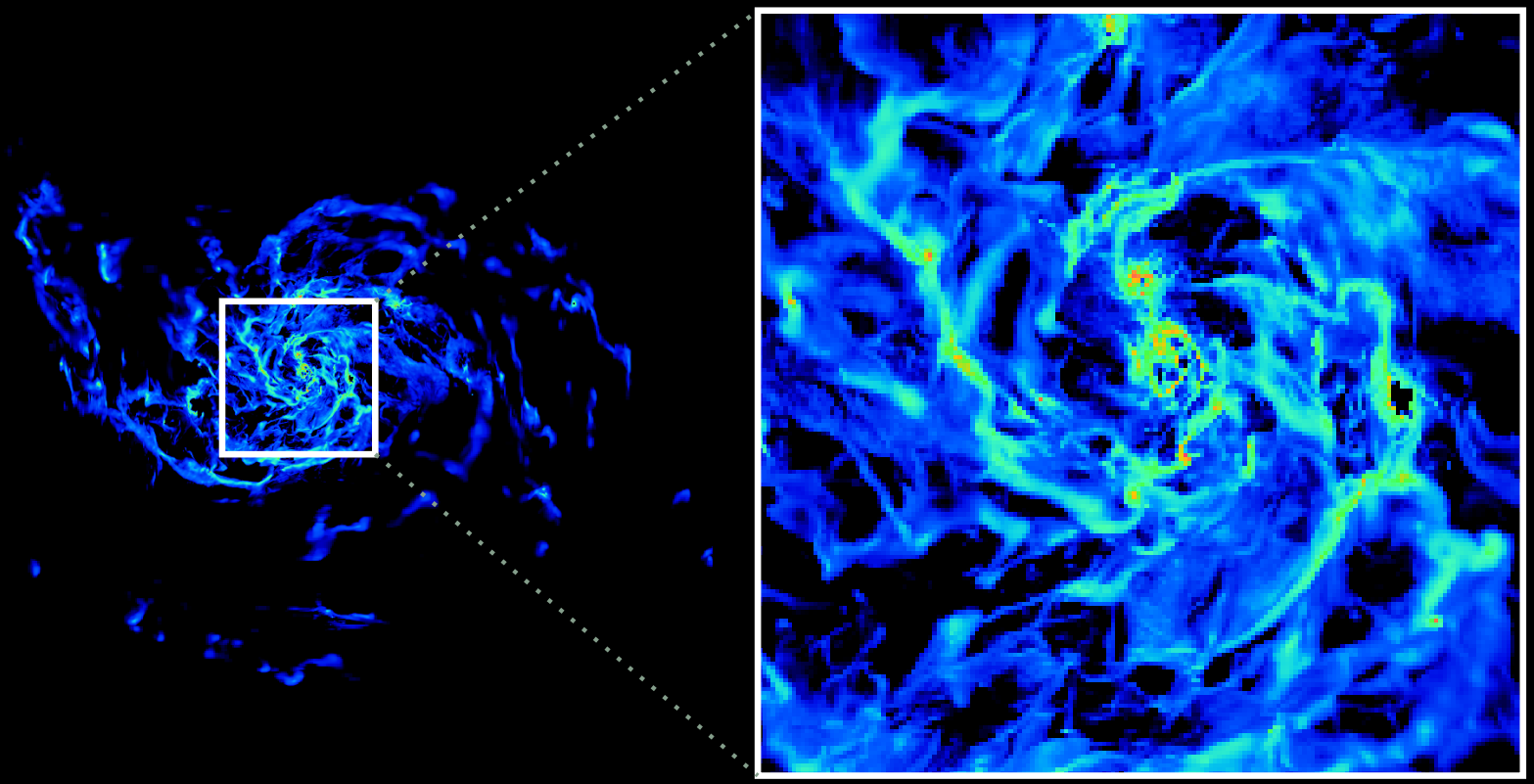
# Ab initio models





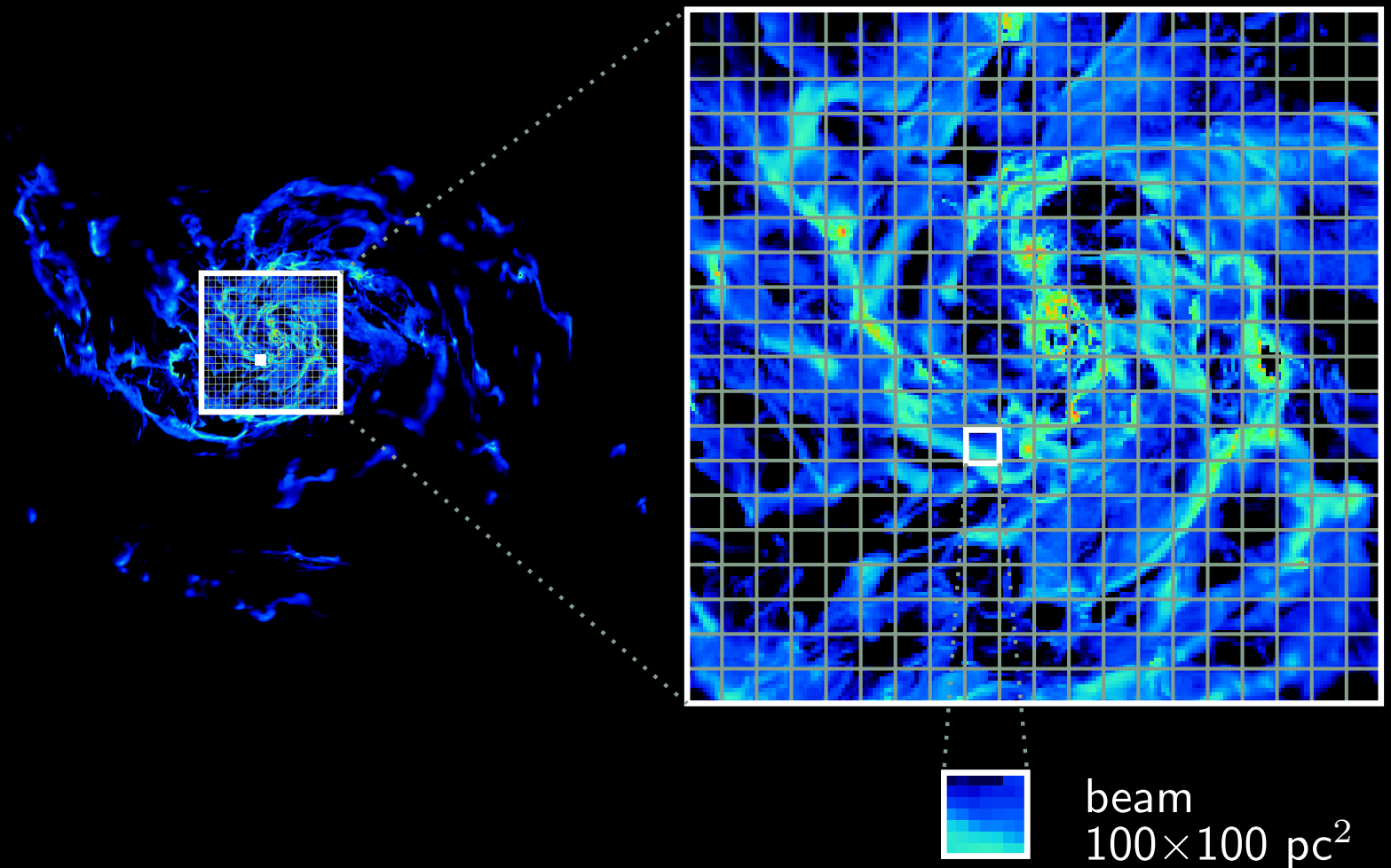
# Ab initio models

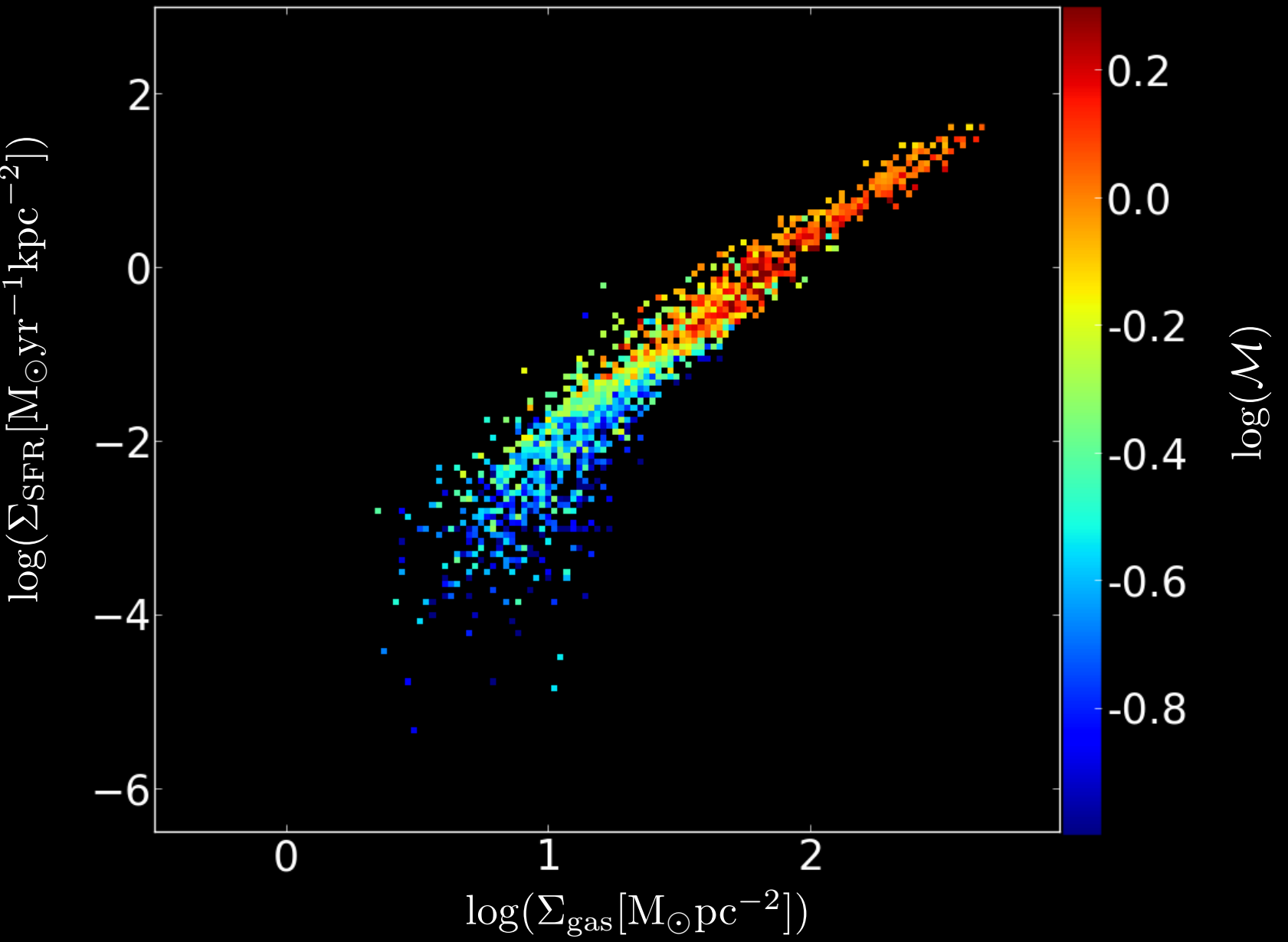


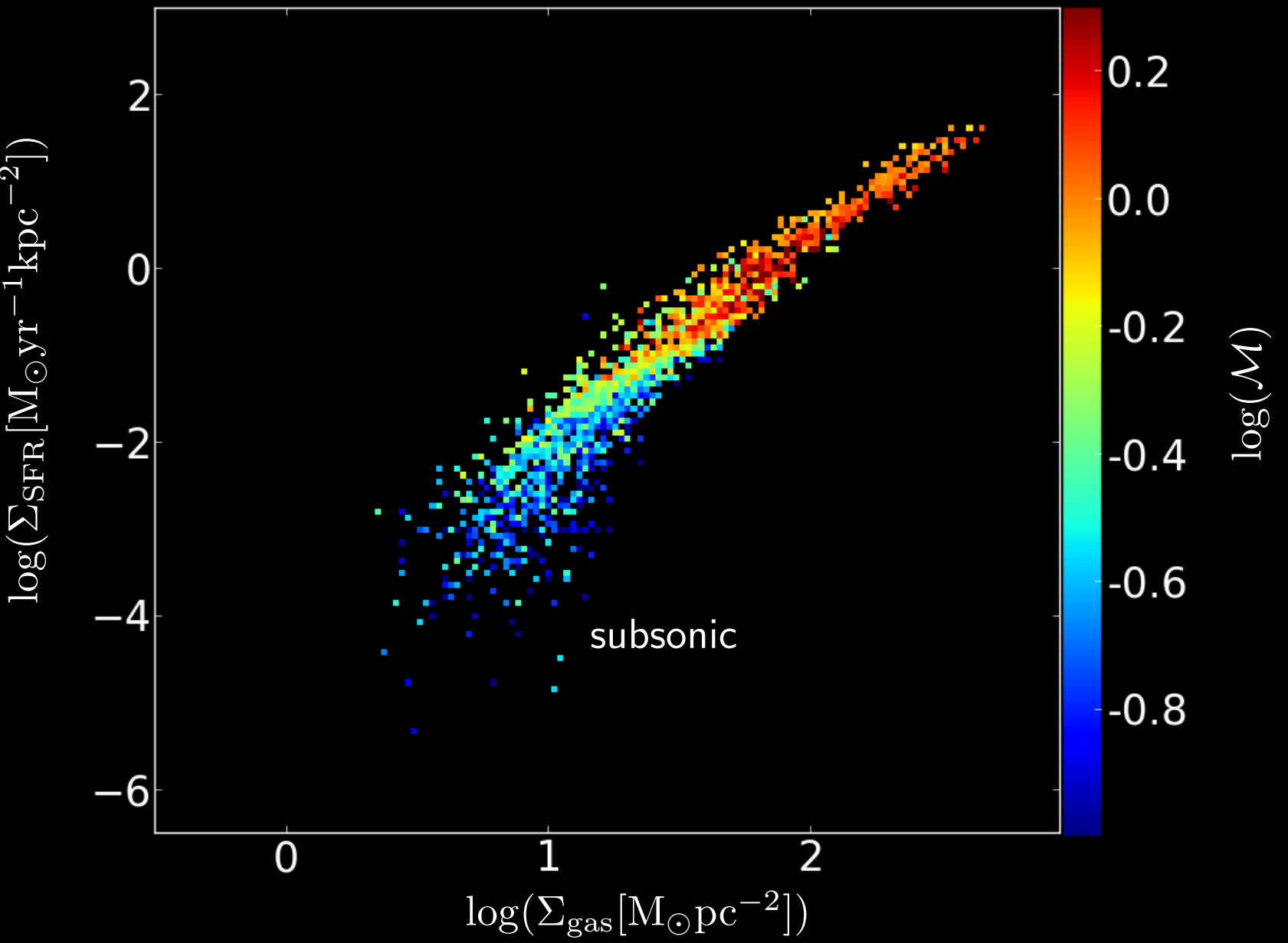


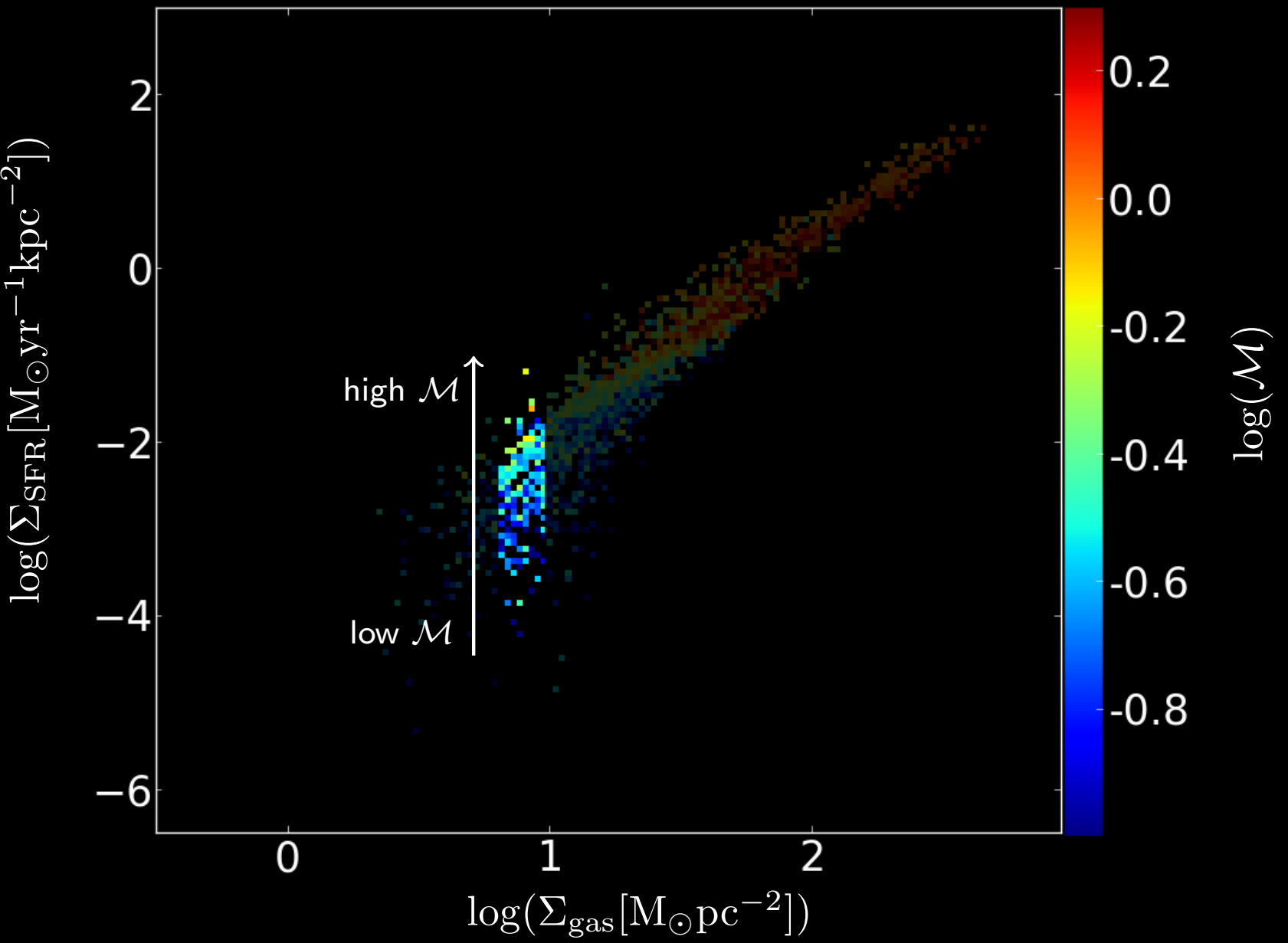
# Ab initio models

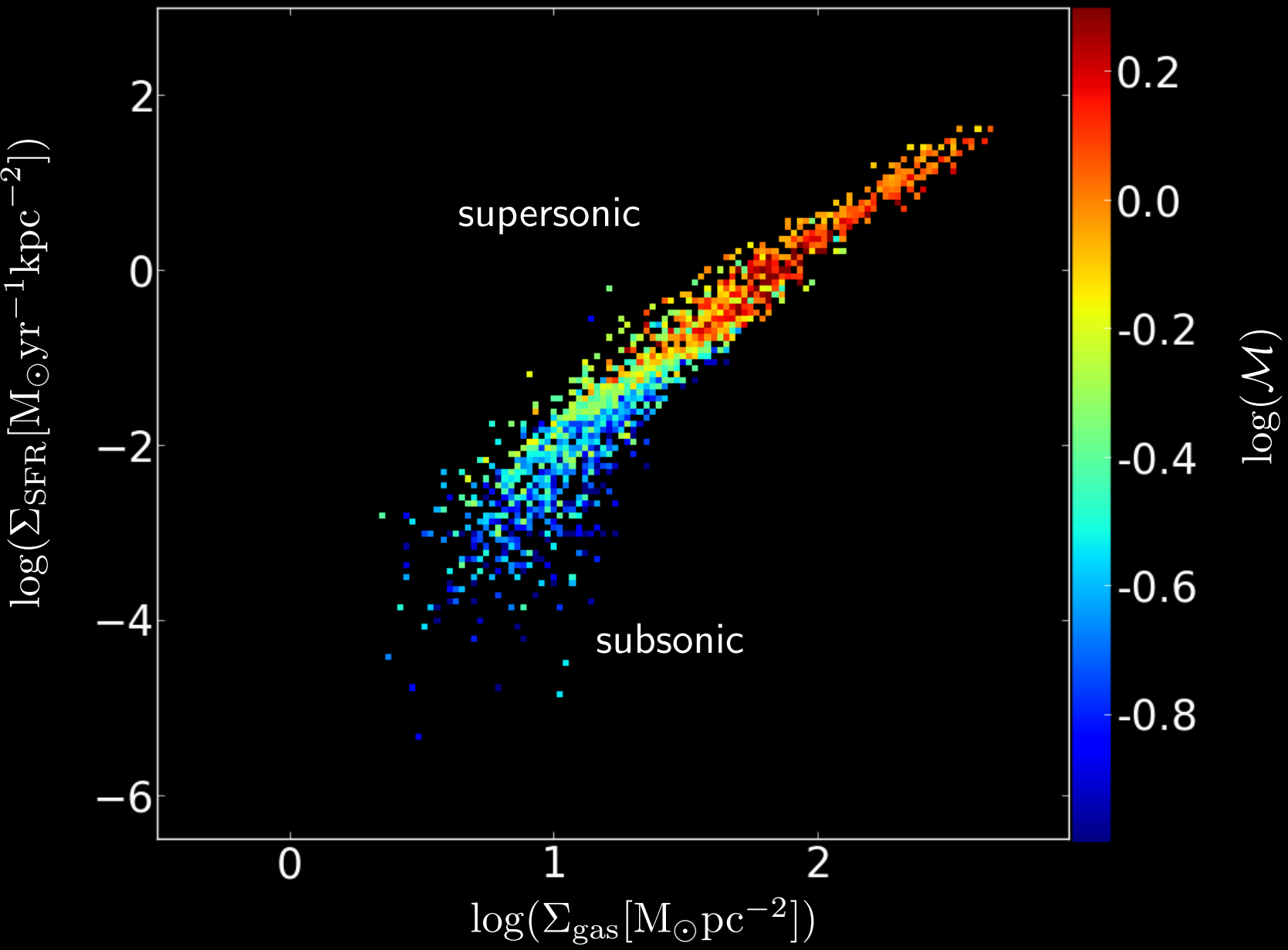


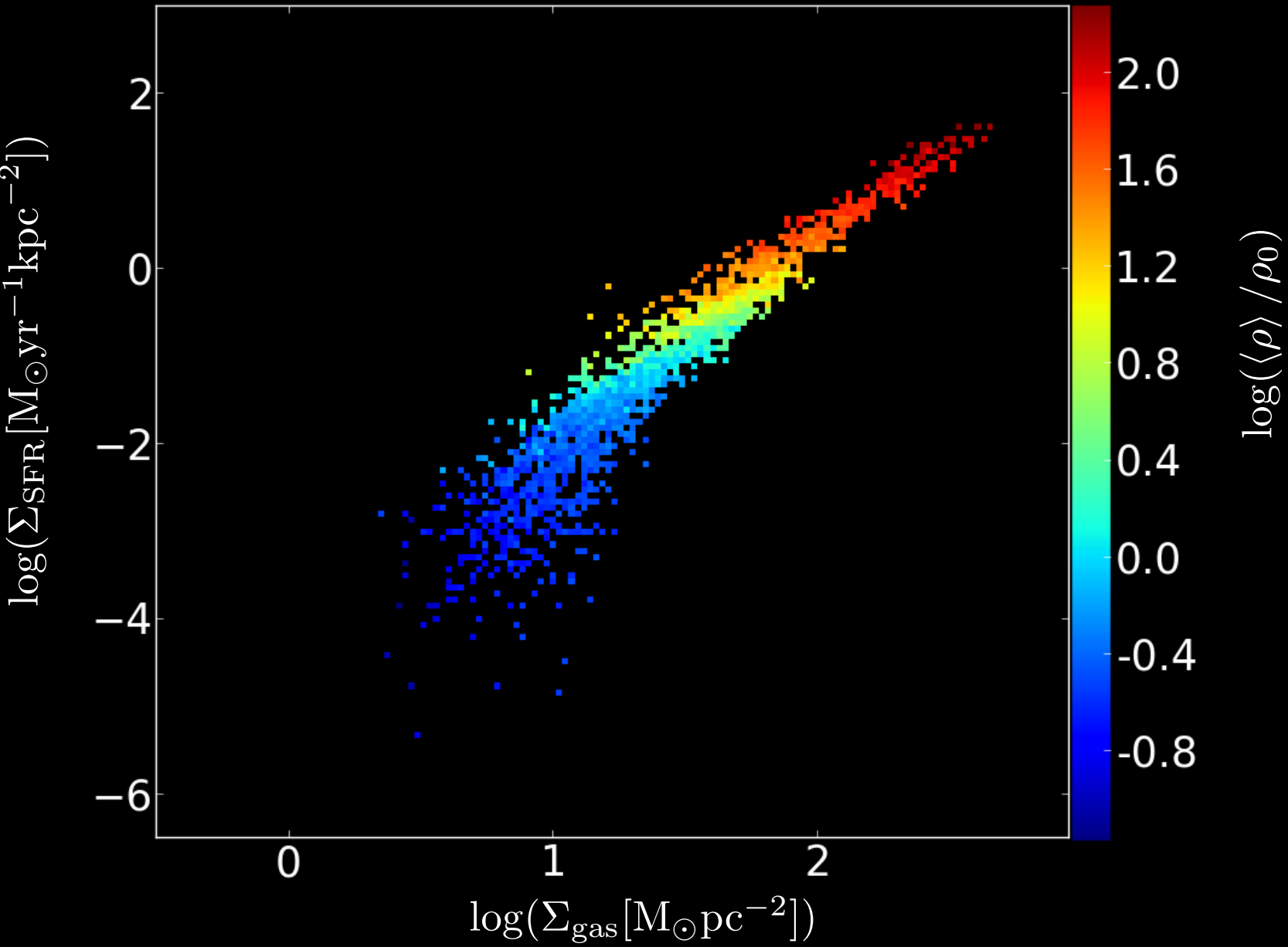


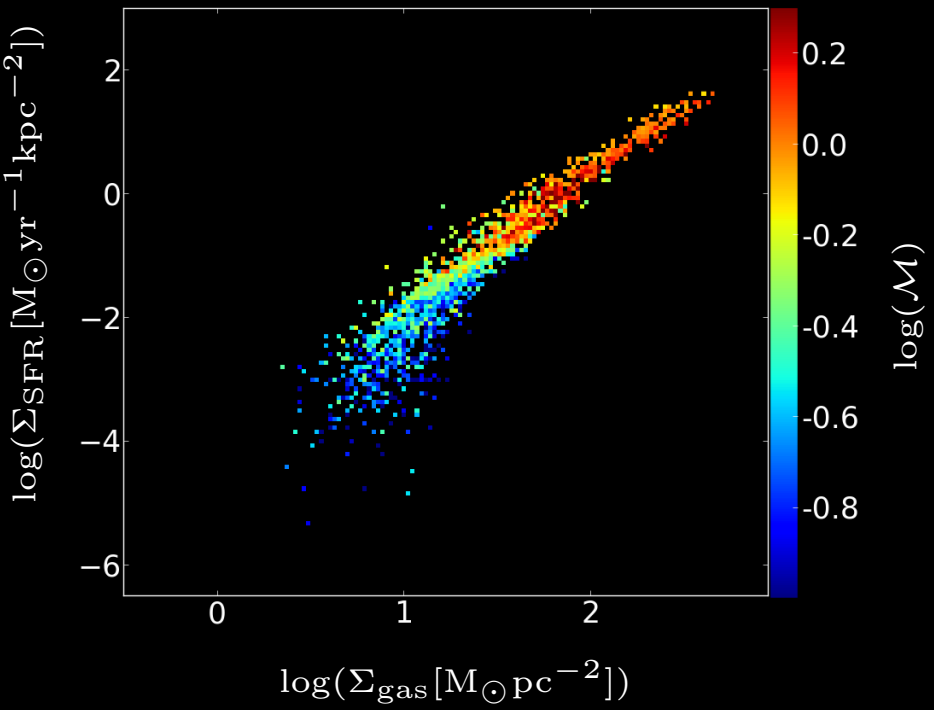

2
0
−2
−4
−6
0
1
2
$\log(\Sigma_{\rm SFR}[{\rm M}_\odot{\rm yr}^{-1}{\rm kpc}^{-2}])$
$\log(\Sigma_{\rm gas}[{\rm M}_\odot{\rm pc}^{-2}])$
0.2
0.0
-0.2
-0.4
-0.6
-0.8
$\log(\mathcal{M})$

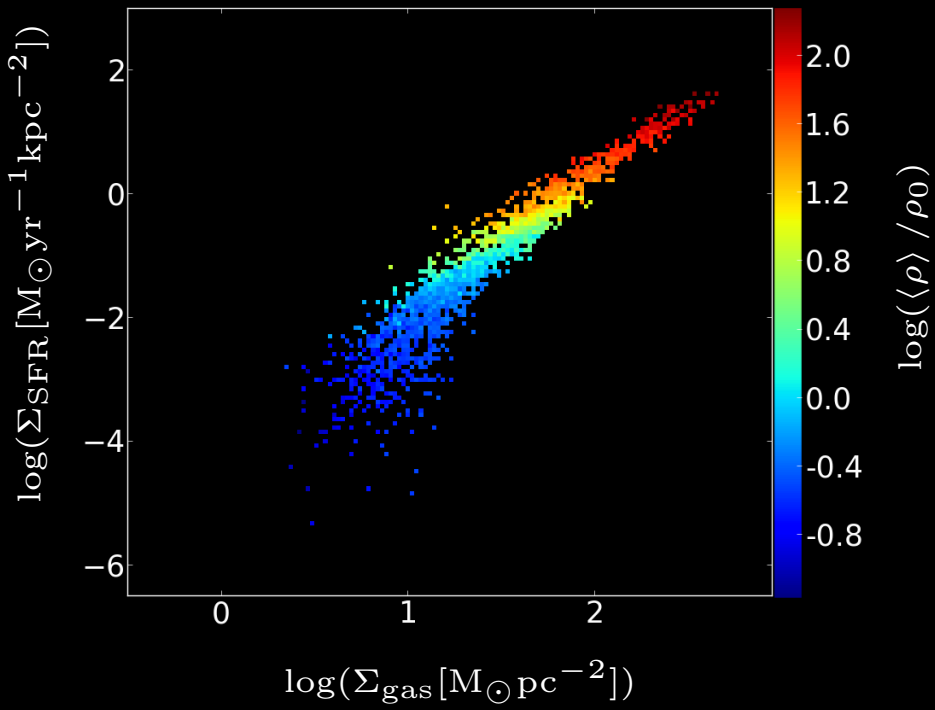

2
0
−2
−4
−6
0
1
2
0.2
0.0
-0.2
-0.4
-0.6
-0.8
subsonic
$\log(\Sigma_{\rm SFR}[{\rm M}_\odot{\rm yr}^{-1}{\rm kpc}^{-2}])$
$\log(\Sigma_{\rm gas}[{\rm M}_\odot{\rm pc}^{-2}])$
$\log(\mathcal{M})$


high $\mathcal{M}$
low $\mathcal{M}$
$\log(\Sigma_{\rm SFR}[{\rm M}_\odot{\rm yr}^{-1}{\rm kpc}^{-2}])$
$\log(\Sigma_{\rm gas}[{\rm M}_\odot{\rm pc}^{-2}])$
$\log(\mathcal{M})$
2
0
−2
−4
−6
0
1
2
0.2
0.0
-0.2
-0.4
-0.6
-0.8


supersonic
subsonic
2
0
−2
−4
−6
0
1
2
0.2
0.0
-0.2
-0.4
-0.6
-0.8
$\log(\Sigma_{\rm SFR}[{\rm M}_\odot{\rm yr}^{-1}{\rm kpc}^{-2}])$
$\log(\Sigma_{\rm gas}[{\rm M}_\odot{\rm pc}^{-2}])$
$\log(\mathcal{M})$

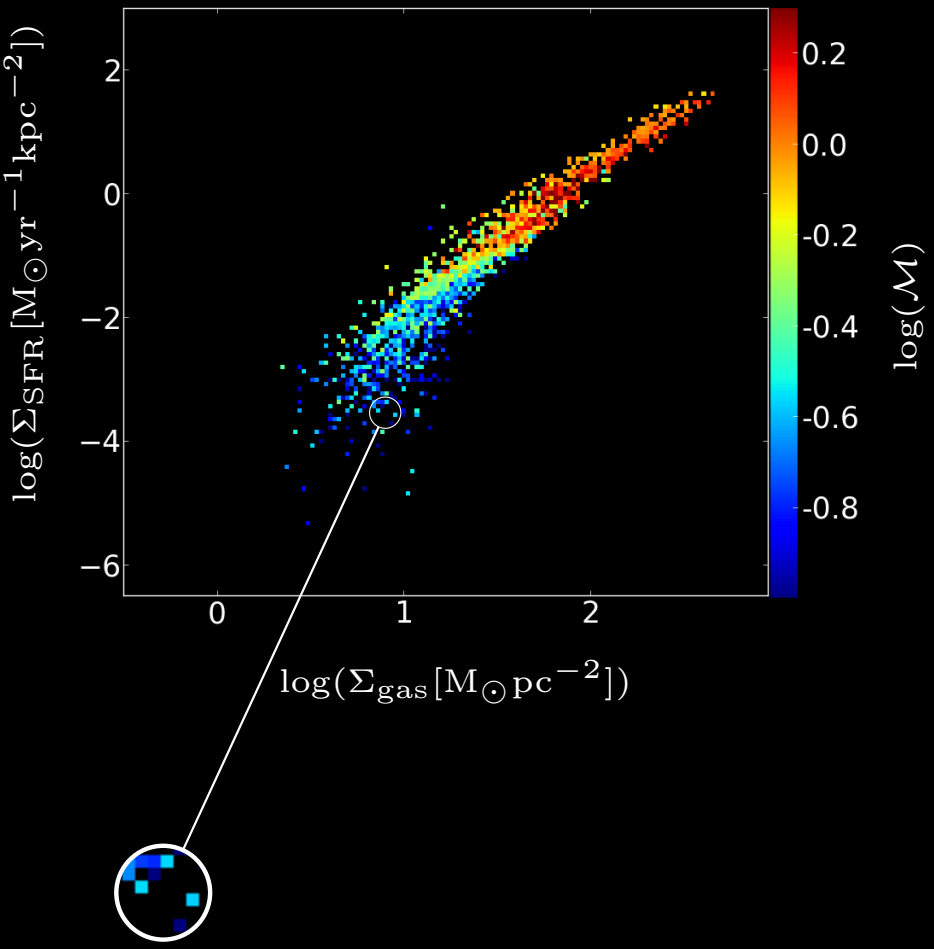

2
0
−2
−4
−6
0
1
2
$\log(\Sigma_{\rm SFR}[{\rm M}_\odot{\rm yr}^{-1}{\rm kpc}^{-2}])$
$\log(\Sigma_{\rm gas}[{\rm M}_\odot{\rm pc}^{-2}])$
2.0
1.6
1.2
0.8
0.4
0.0
-0.4
-0.8
$\log(\langle\rho\rangle/\rho_0)$

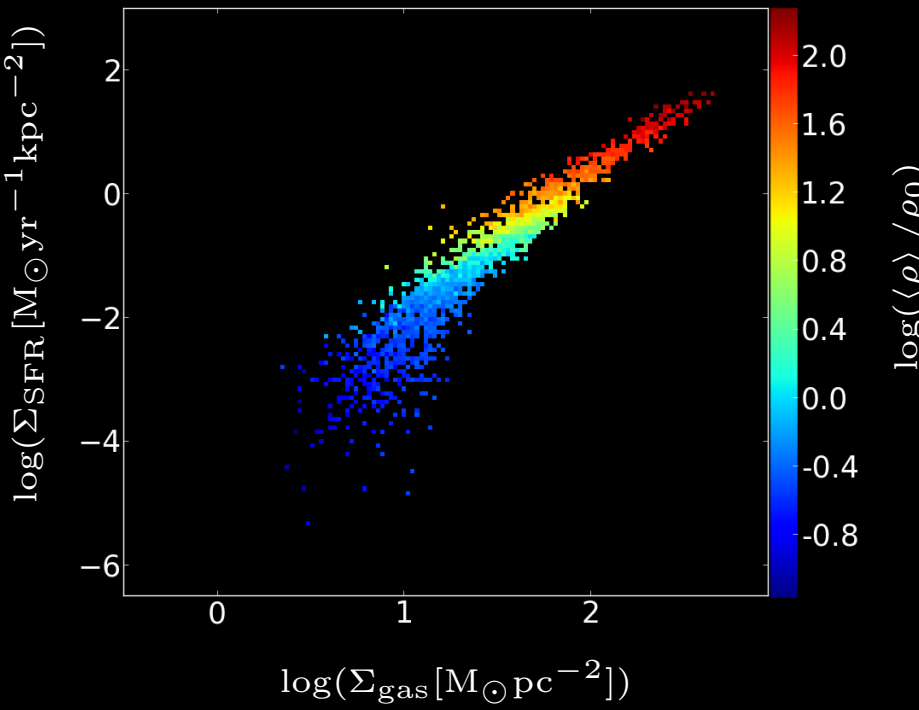

$\log(\Sigma_{\rm SFR}\,[{\rm M}_\odot{\rm yr}^{-1}{\rm kpc}^{-2}])$
$\log(\Sigma_{\rm gas}\,[{\rm M}_\odot{\rm pc}^{-2}])$
$\log(\mathcal{M})$
2
0
−2
−4
−6
0
1
2
0.2
0.0
-0.2
-0.4
-0.6
-0.8


$\log(\Sigma_{\rm SFR}\,[{\rm M}_\odot{\rm yr}^{-1}{\rm kpc}^{-2}])$
$\log(\Sigma_{\rm gas}\,[{\rm M}_\odot{\rm pc}^{-2}])$
$\log(\langle\rho\rangle\ /\ \rho_0)$
2
0
−2
−4
−6
0
1
2
2.0
1.6
1.2
0.8
0.4
0.0
-0.4
-0.8

# Ab initio models

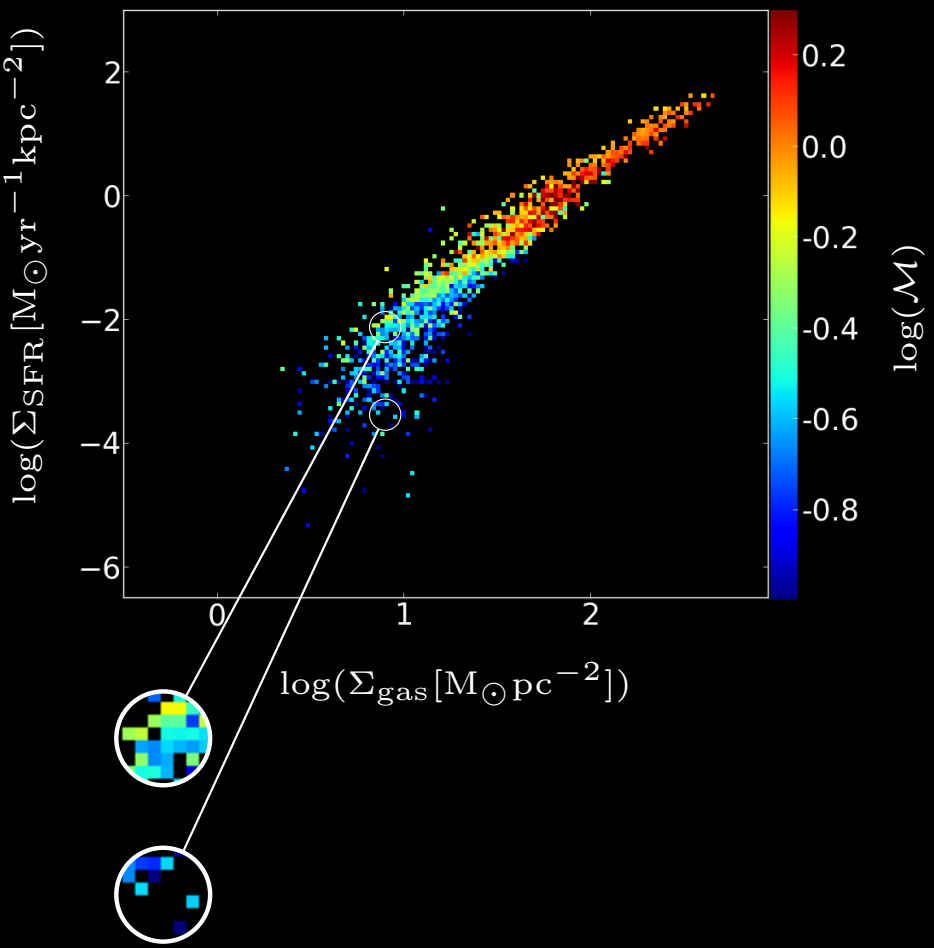


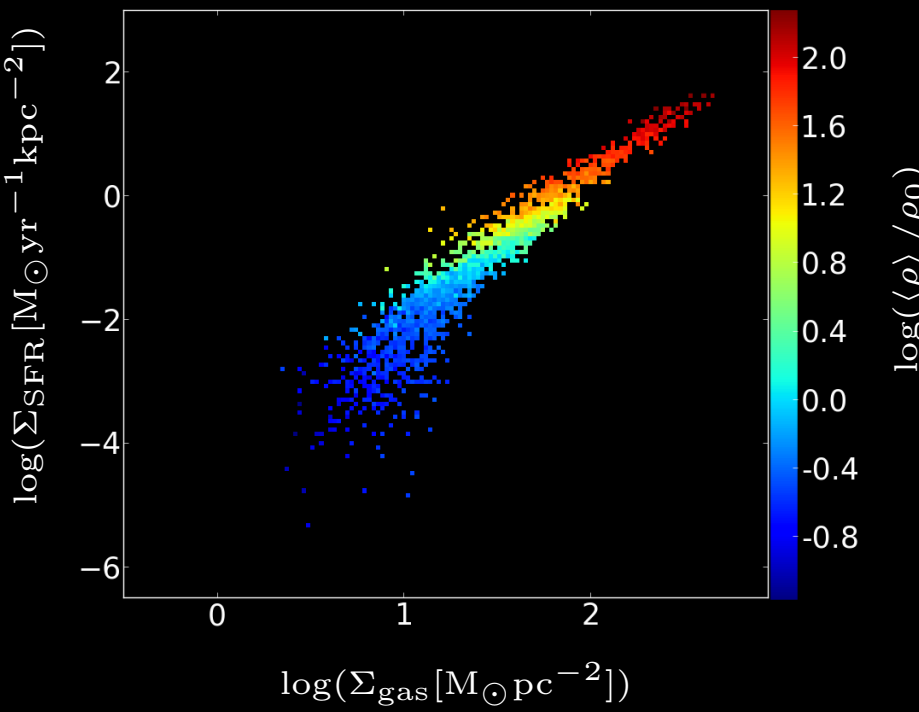


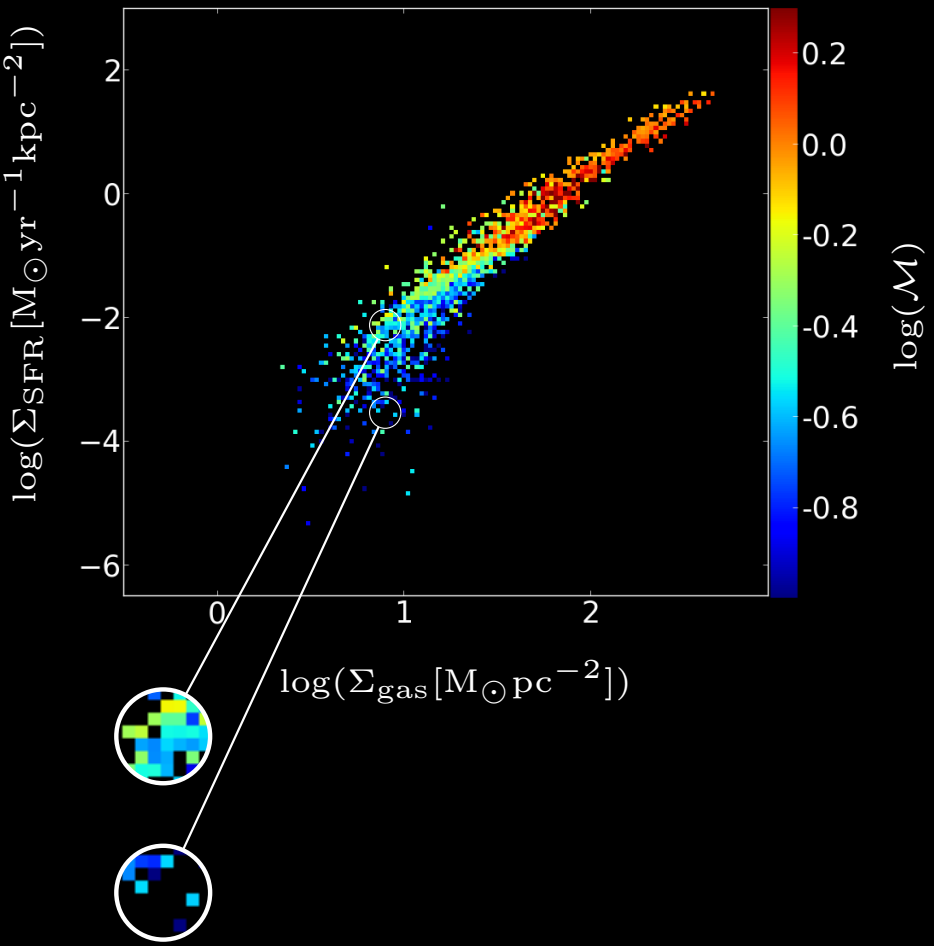



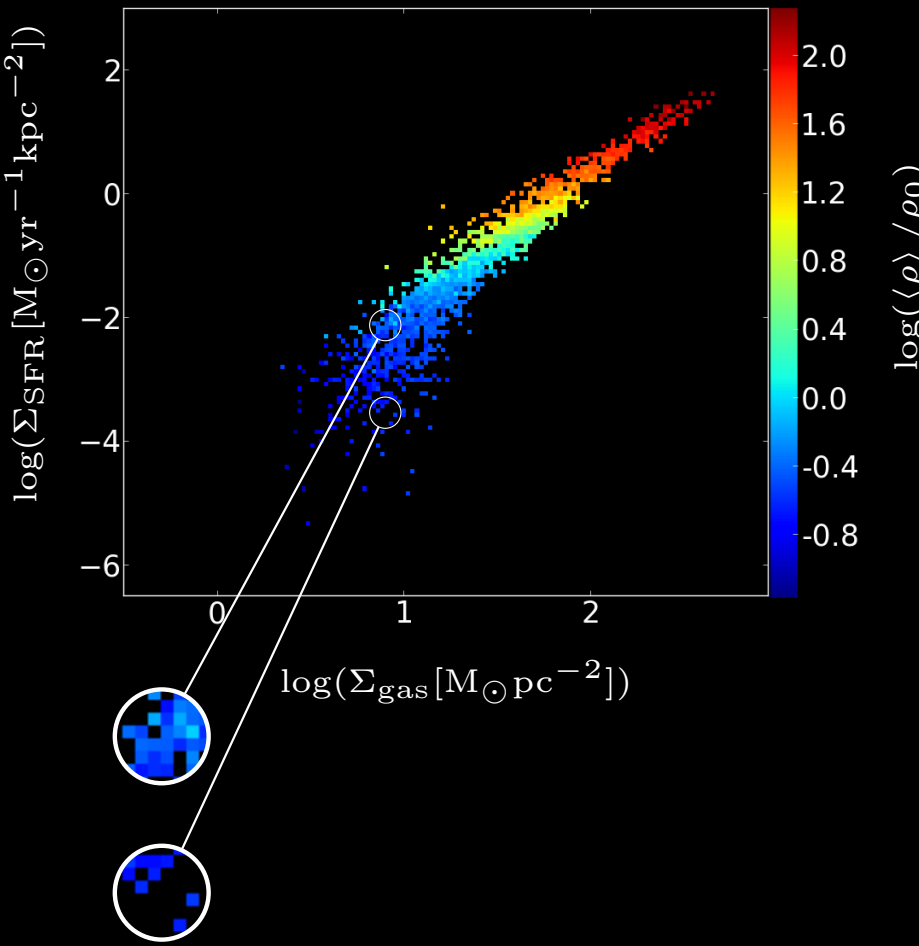
# Ab initio models

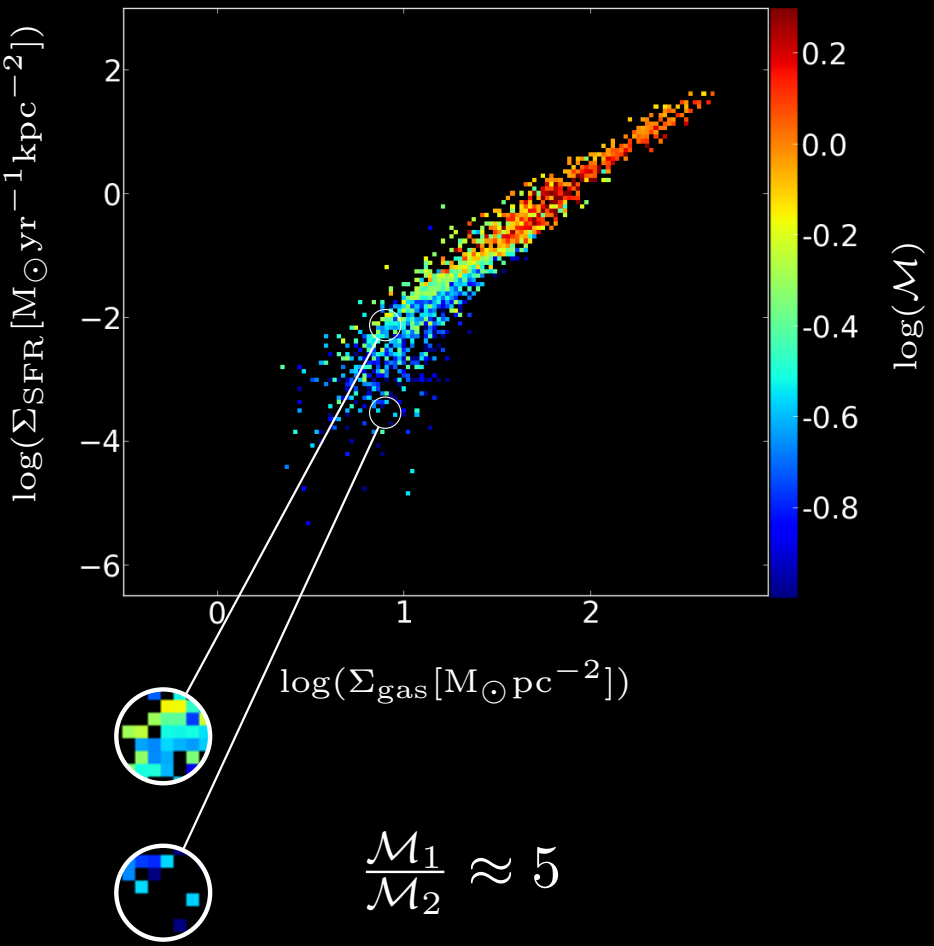




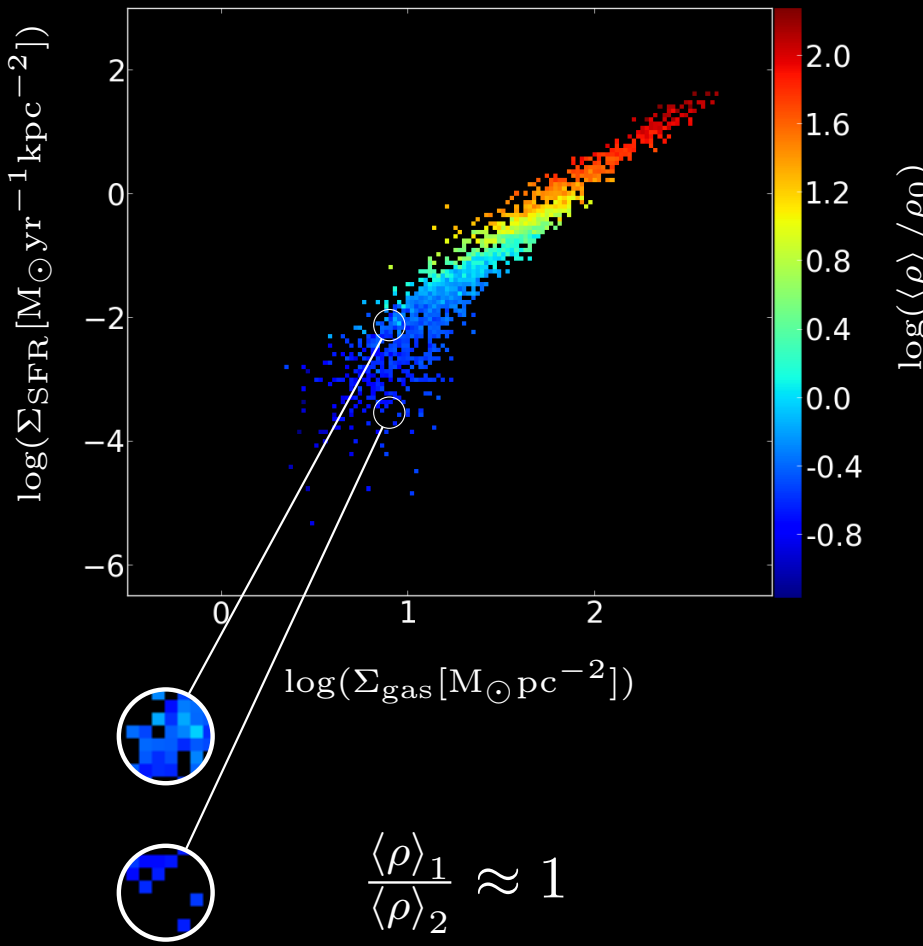




$\log(\Sigma_{\rm SFR}\,[{\rm M}_\odot{\rm yr}^{-1}{\rm kpc}^{-2}])$
$\log(\Sigma_{\rm gas}\,[{\rm M}_\odot{\rm pc}^{-2}])$
$\log(\mathcal{M})$
2
0
−2
−4
−6
0
1
2
0.2
0.0
-0.2
-0.4
-0.6
-0.8

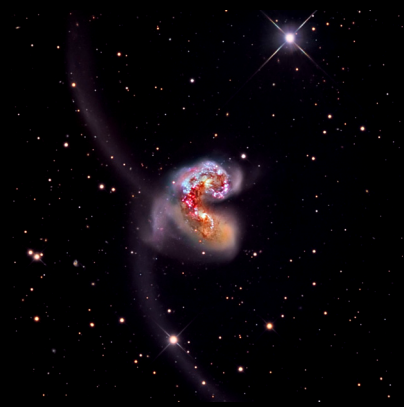

$\log(\Sigma_{\rm SFR}\,[{\rm M}_\odot{\rm yr}^{-1}{\rm kpc}^{-2}])$
$\log(\Sigma_{\rm gas}\,[{\rm M}_\odot{\rm pc}^{-2}])$
$\log(\langle\rho\rangle\,/\,\rho_0)$
2
0
−2
−4
−6
0
1
2
2.0
1.6
1.2
0.8
0.4
0.0
-0.4
-0.8

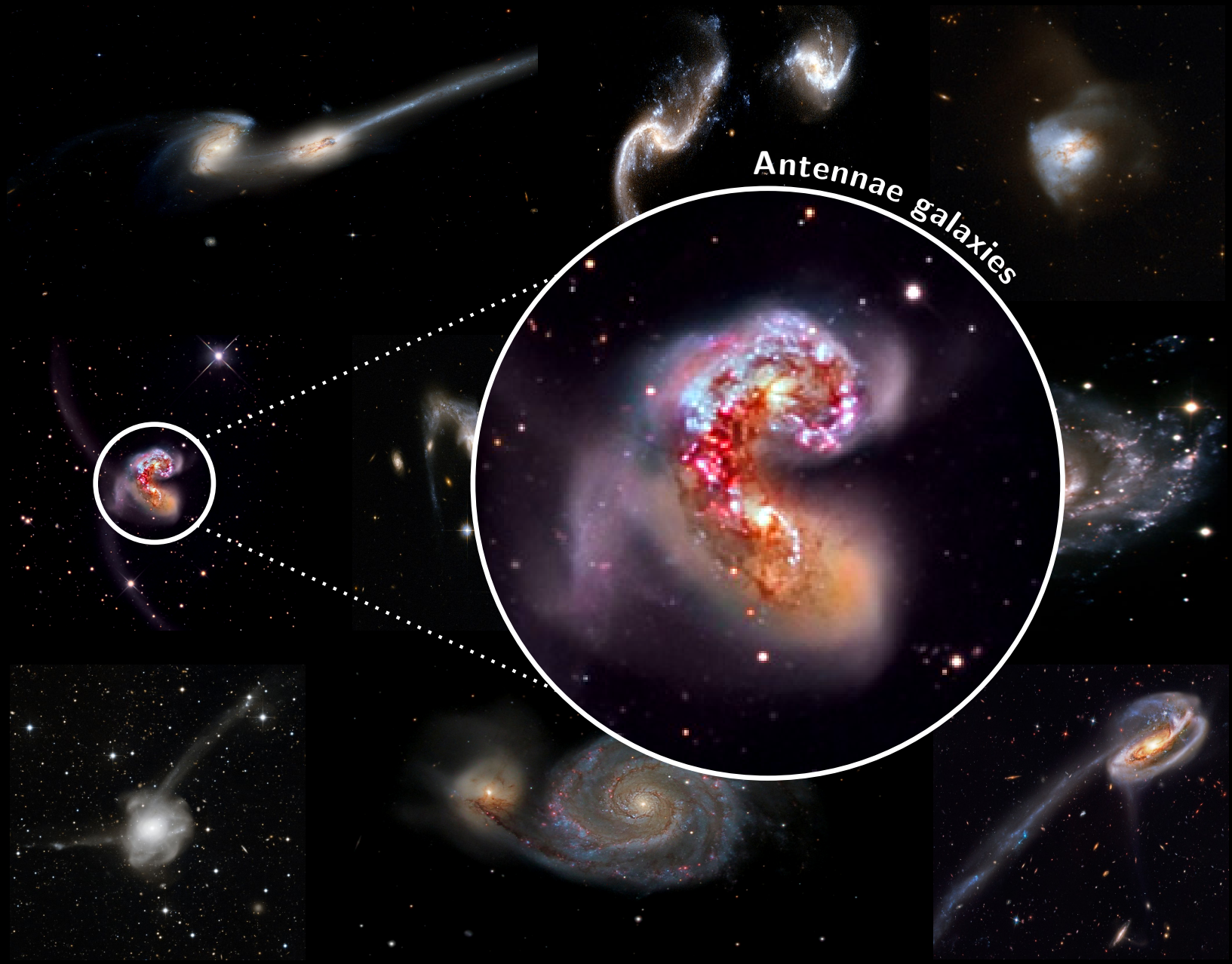


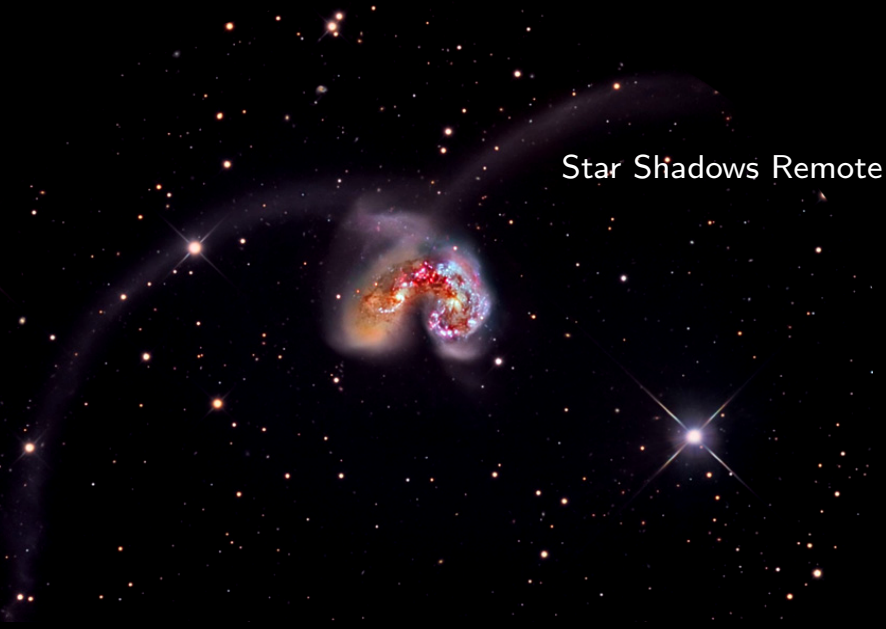

$$\frac{\mathcal{M}_1}{\mathcal{M}_2} \approx 5$$

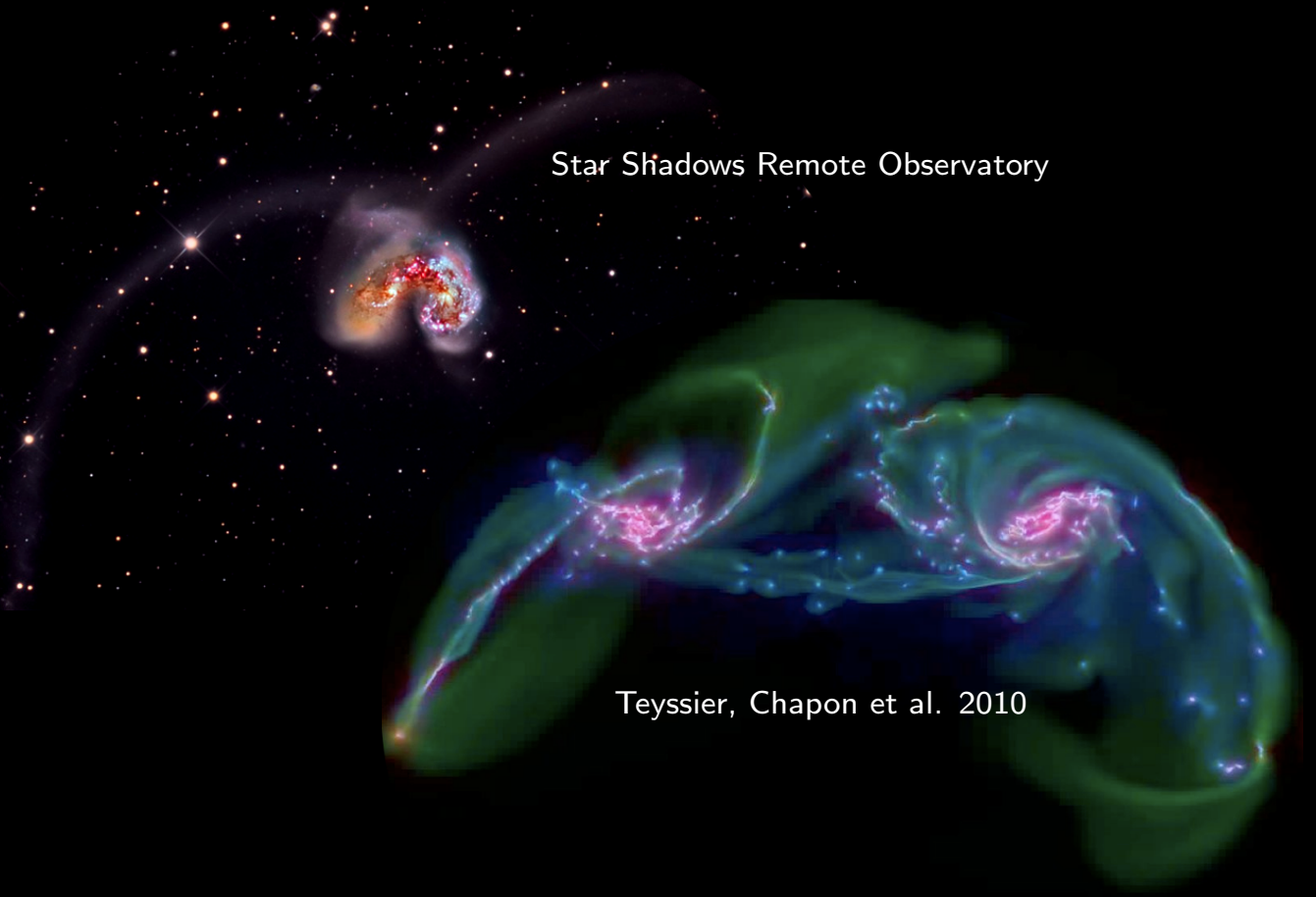



$$\frac{\langle\rho\rangle_1}{\langle\rho\rangle_2} \approx 1$$



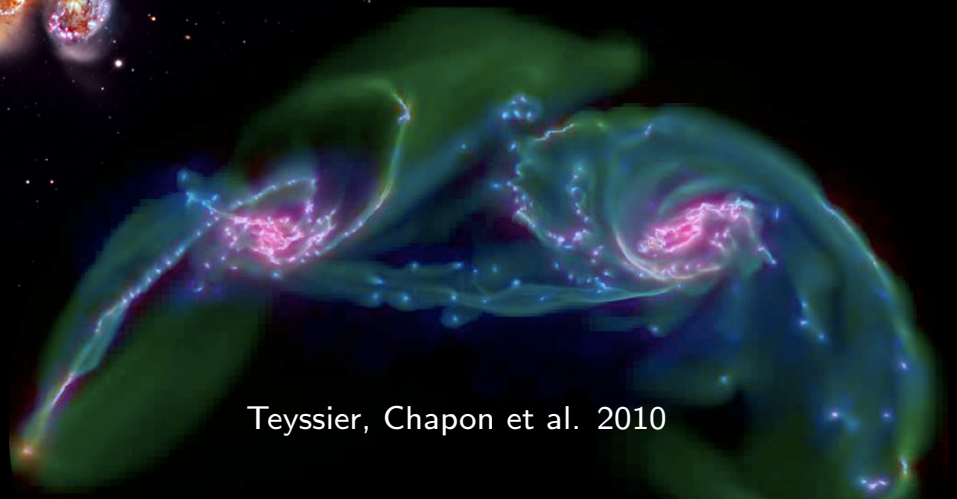

Antennae galaxies


Star Shadows Remote Observatory


Star Shadows Remote Observatory
Teyssier, Chapon et al. 2010

# Ab initio models

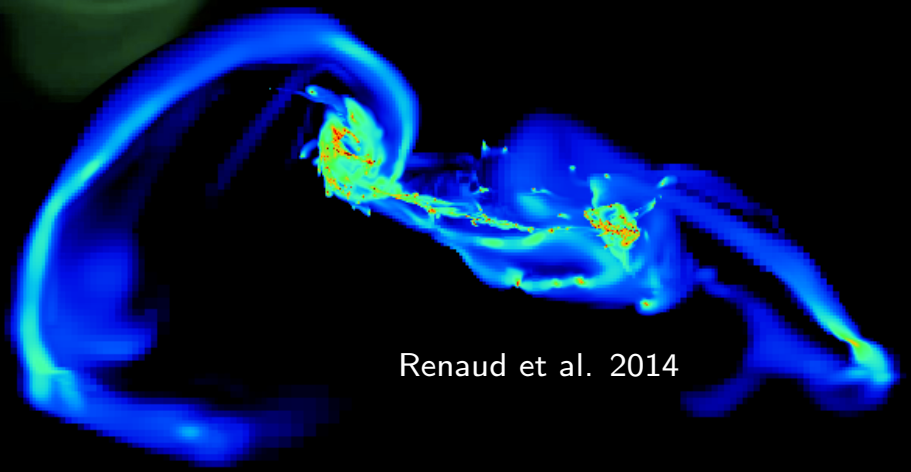
Star Shadows Remote Observatory



Teyssier, Chapon et al. 2010

**Renaud et al. 2014**

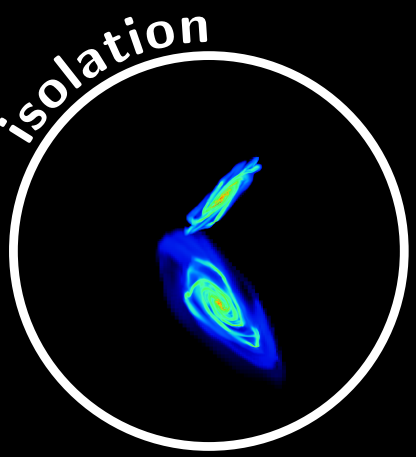
- resolution: 1.5 pc
- multiphase ISM
- feedback
- converged SFR



Renaud et al. 2014

# Ab initio models

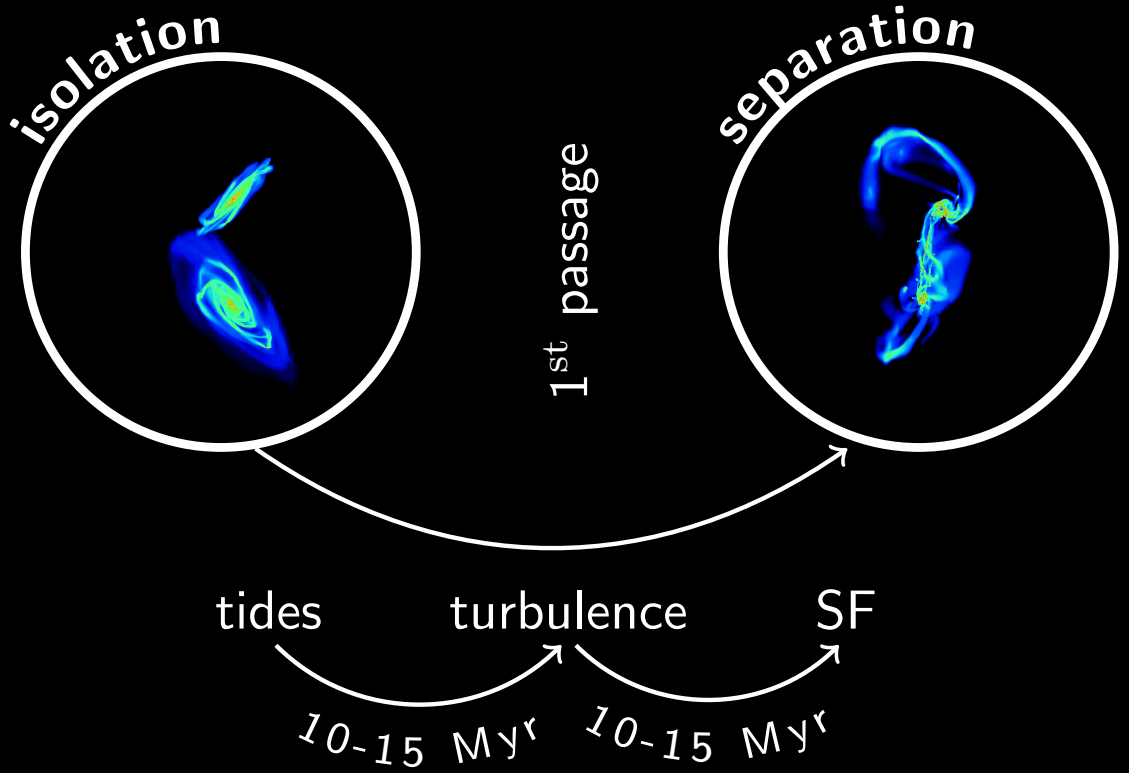


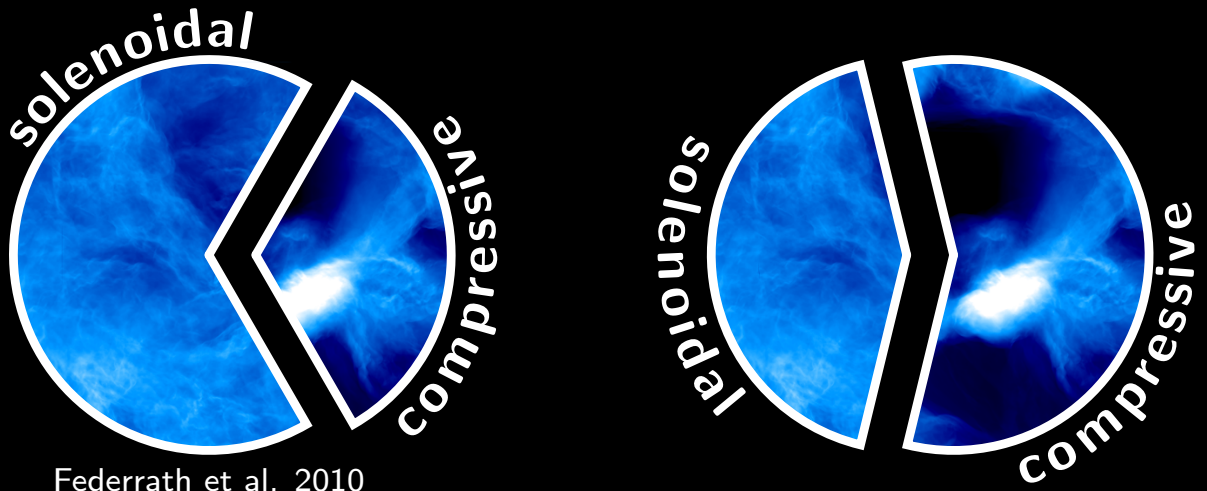


Federrath et al. 2010

# Ab initio models



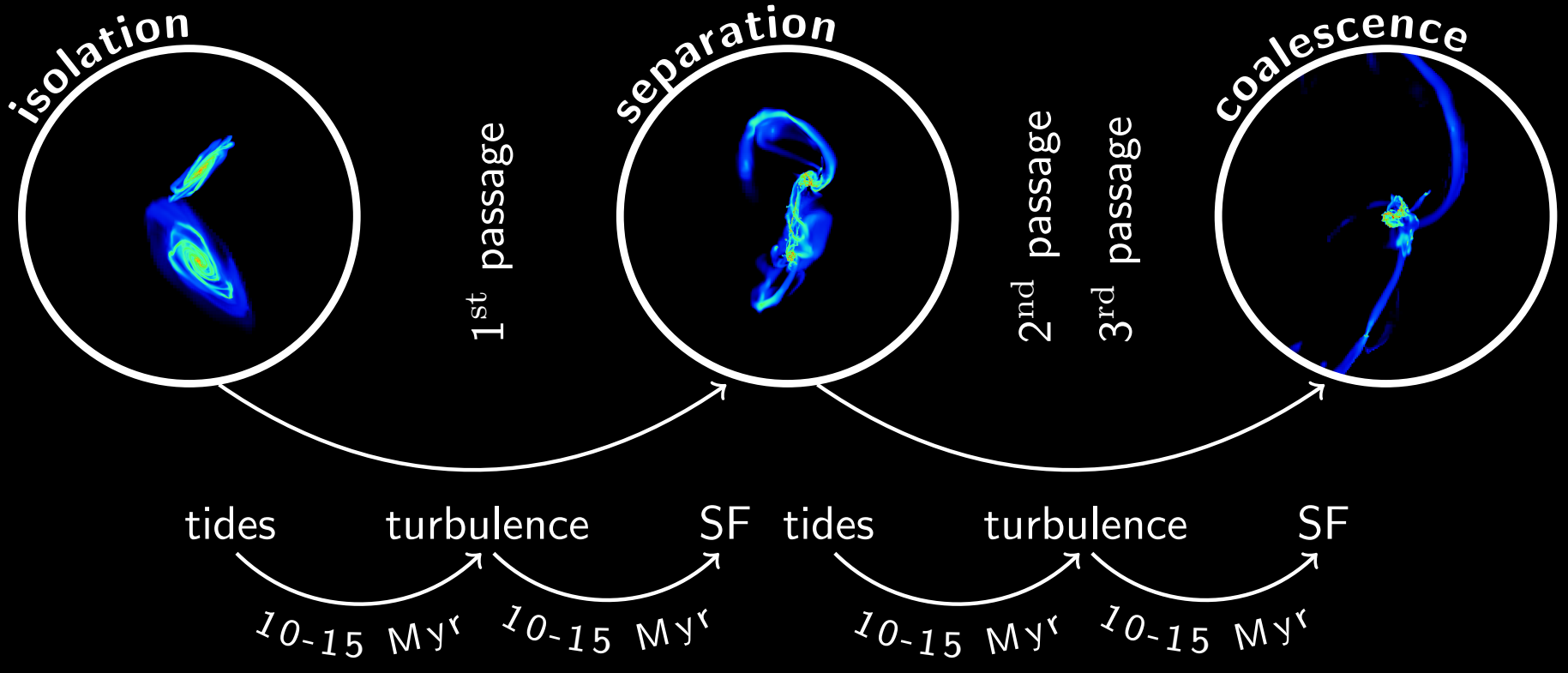


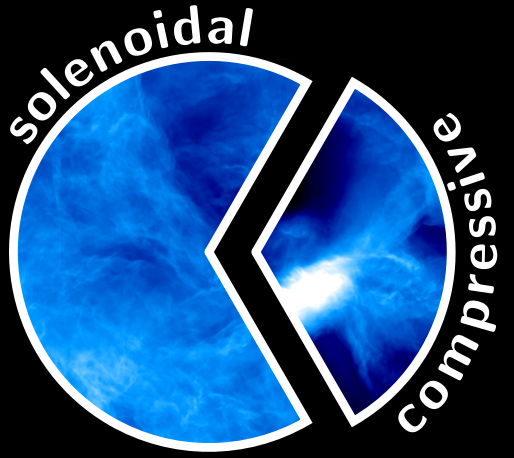



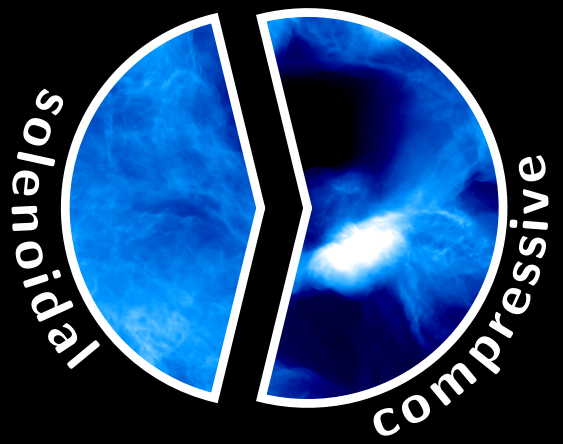

Federrath et al. 2010

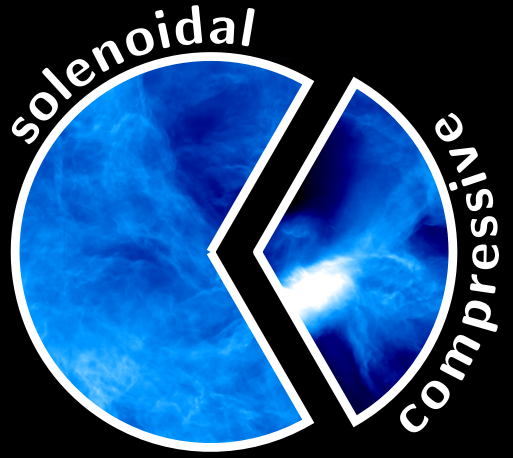
# Ab initio models



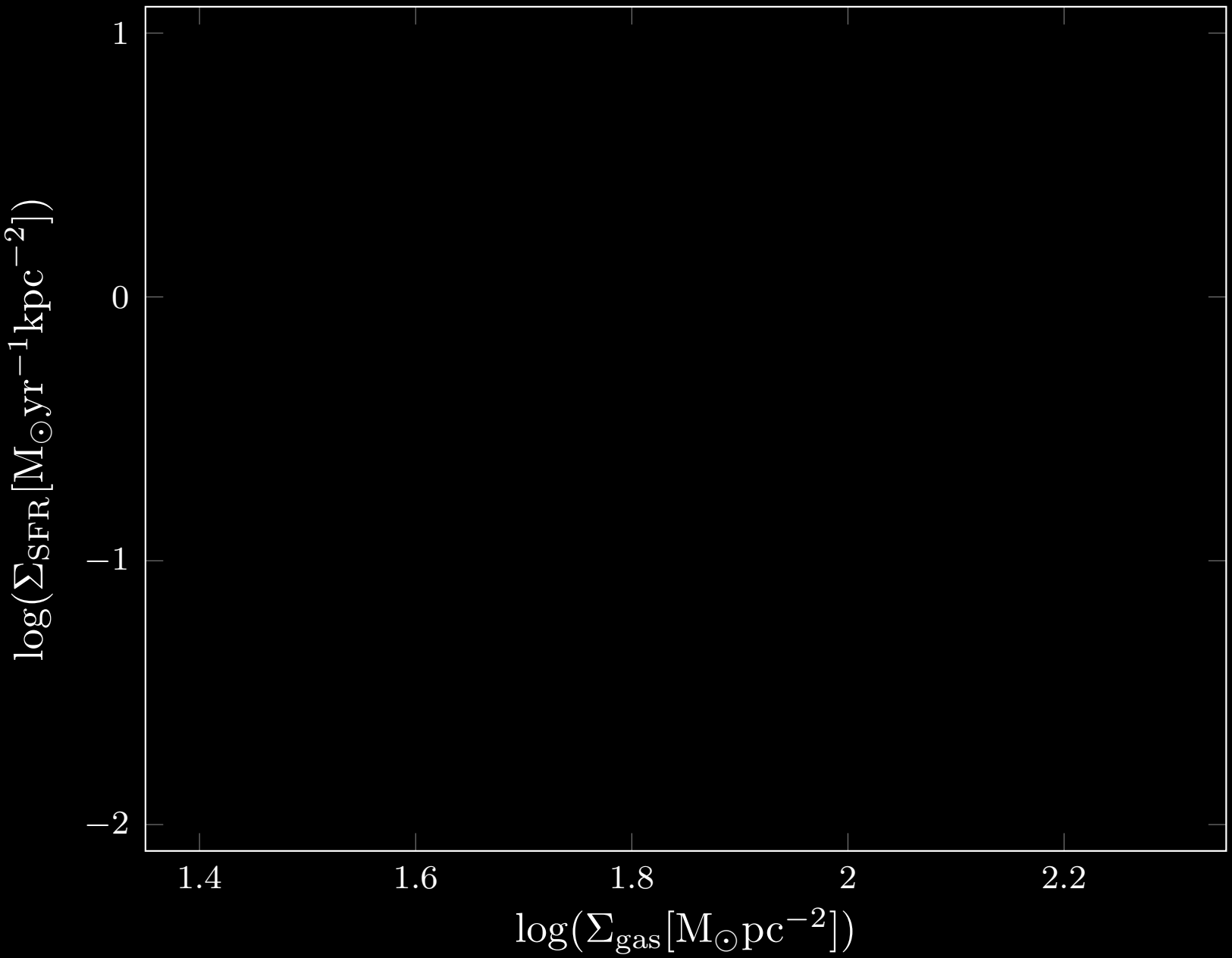


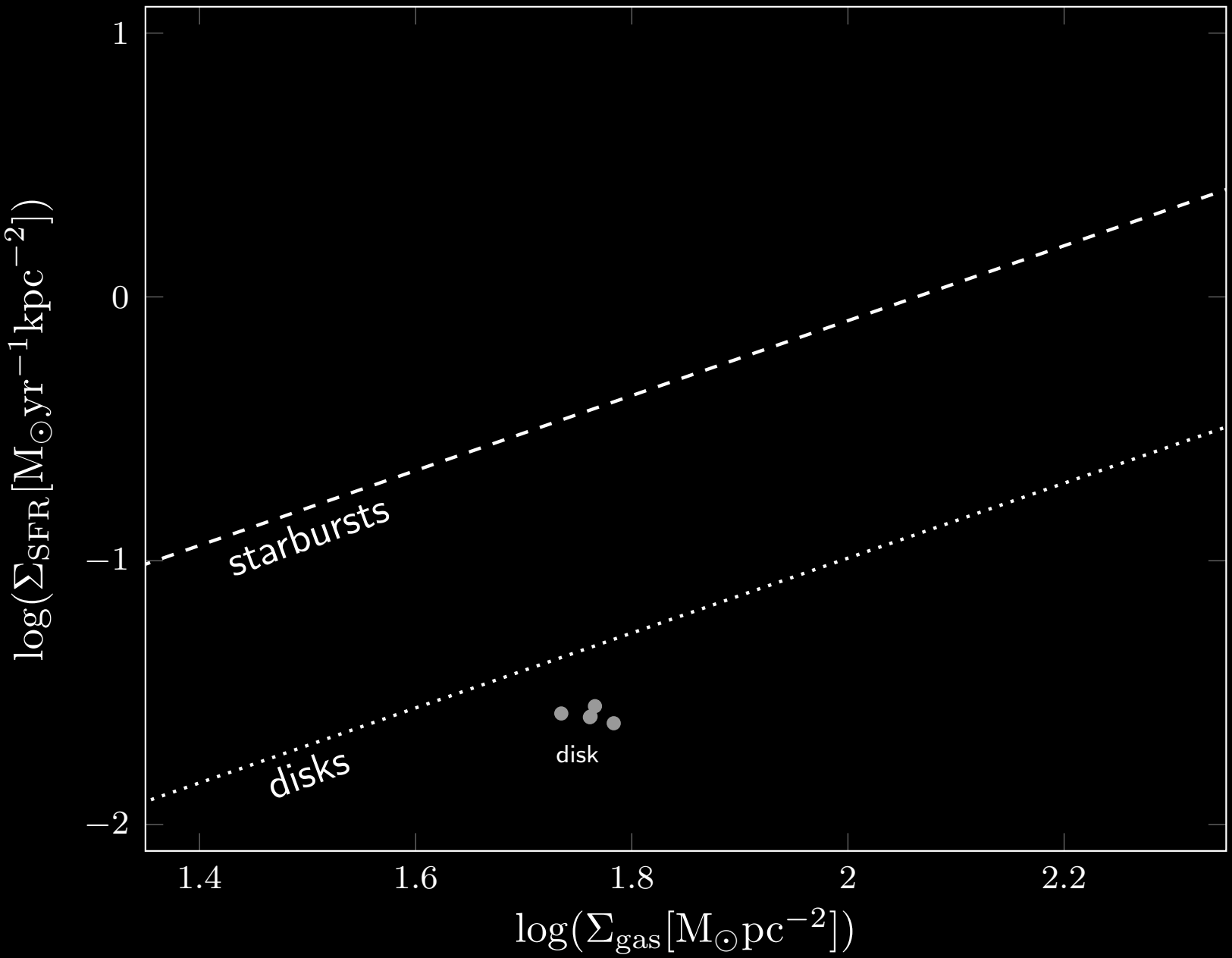



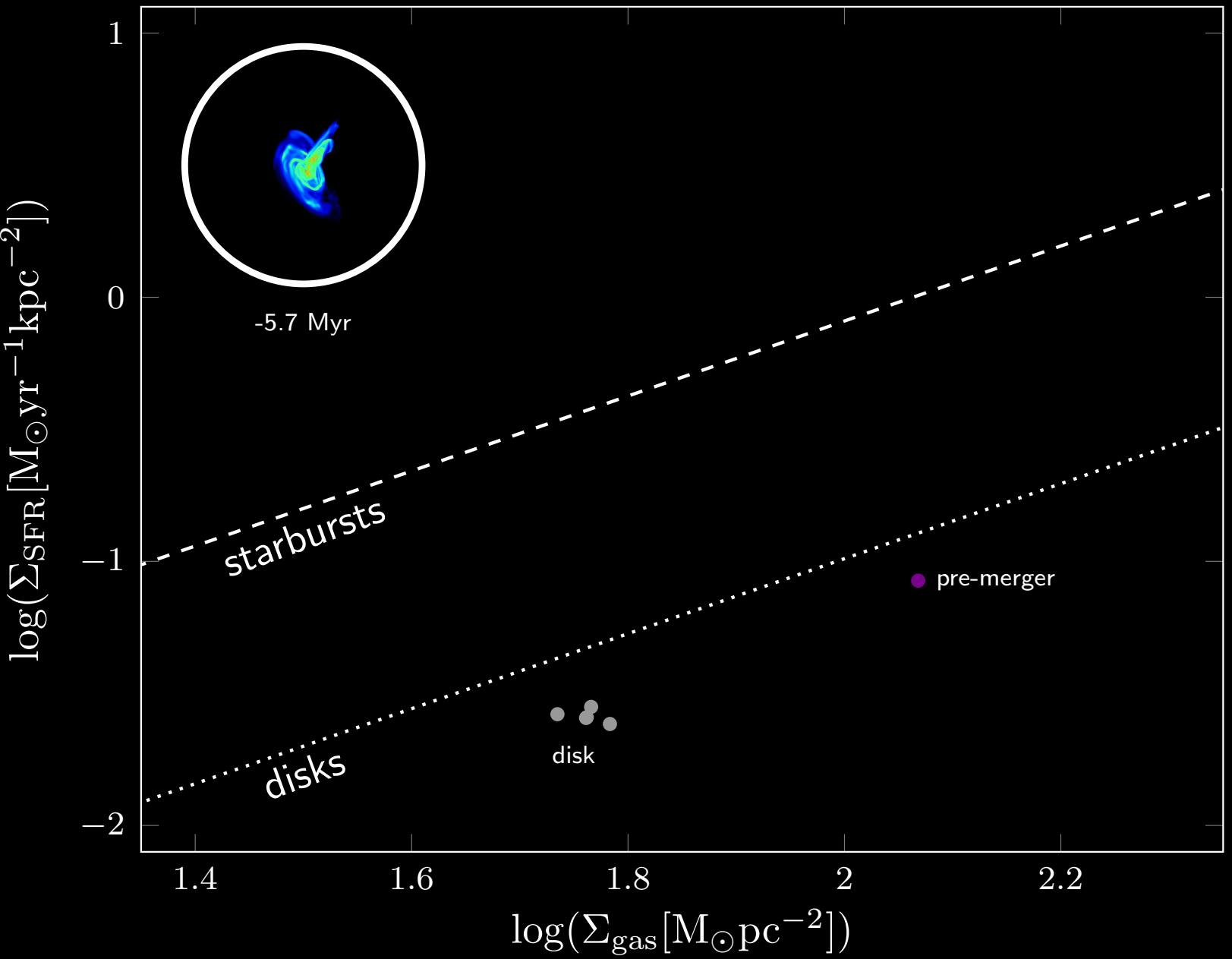



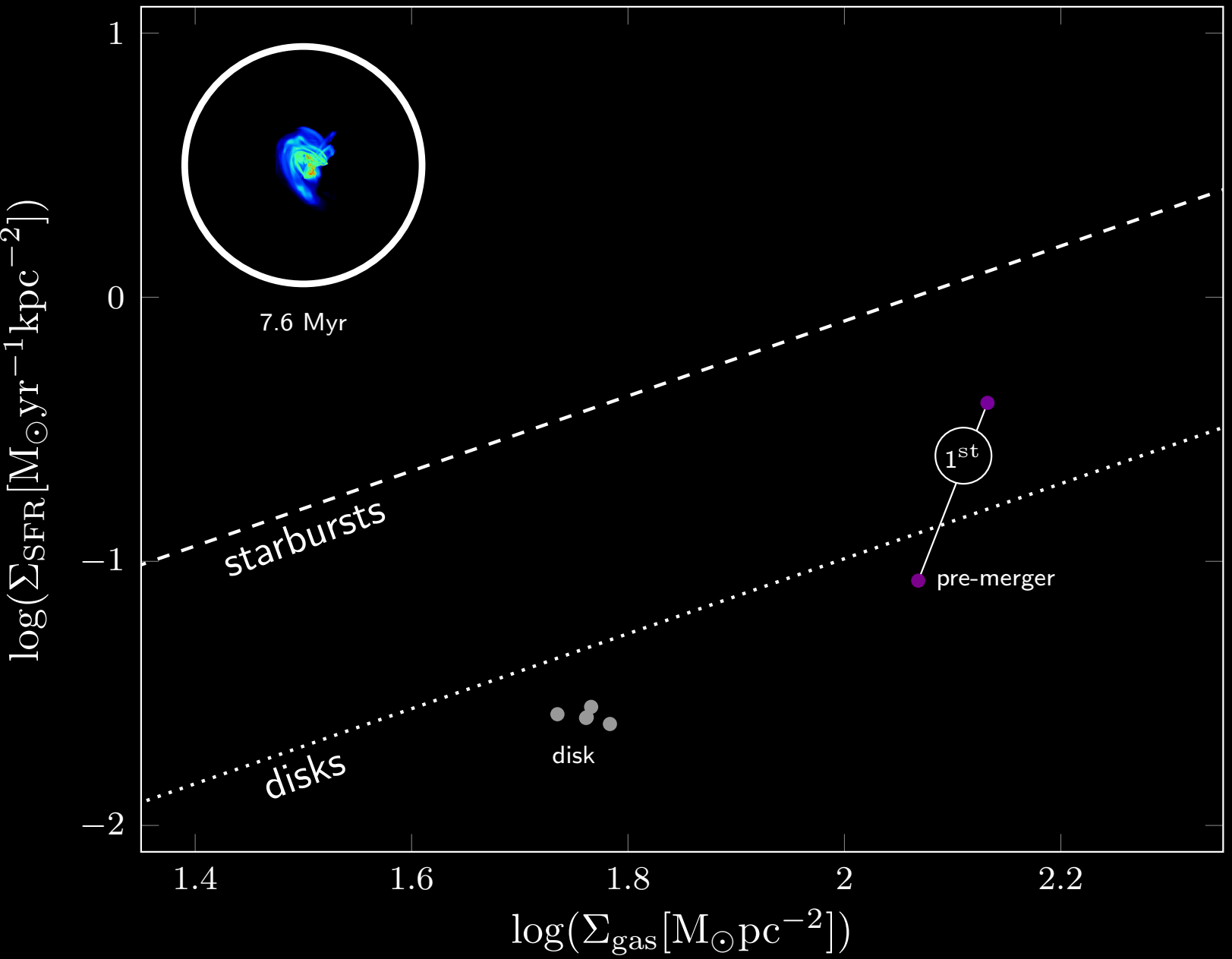



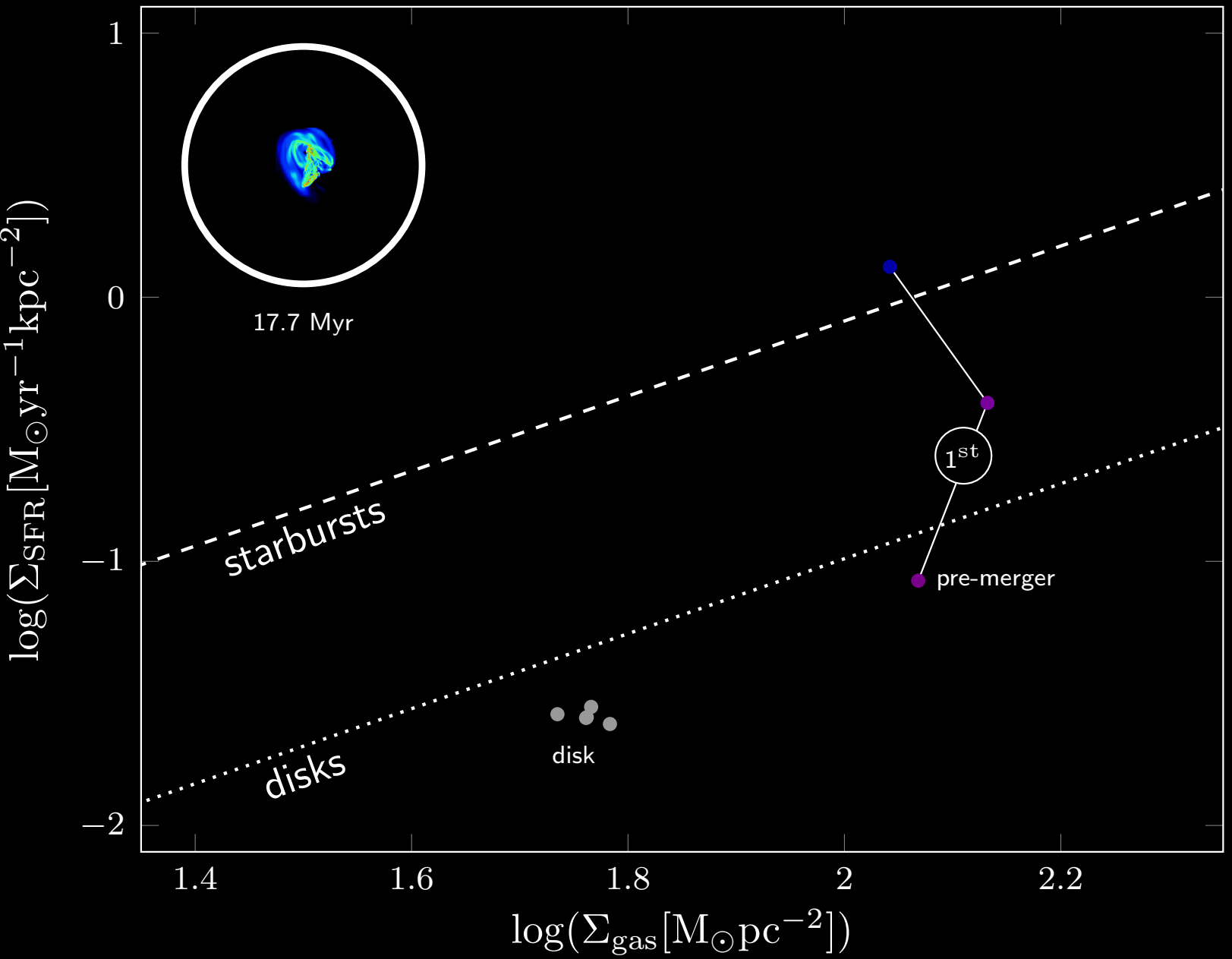

Federrath et al. 2010

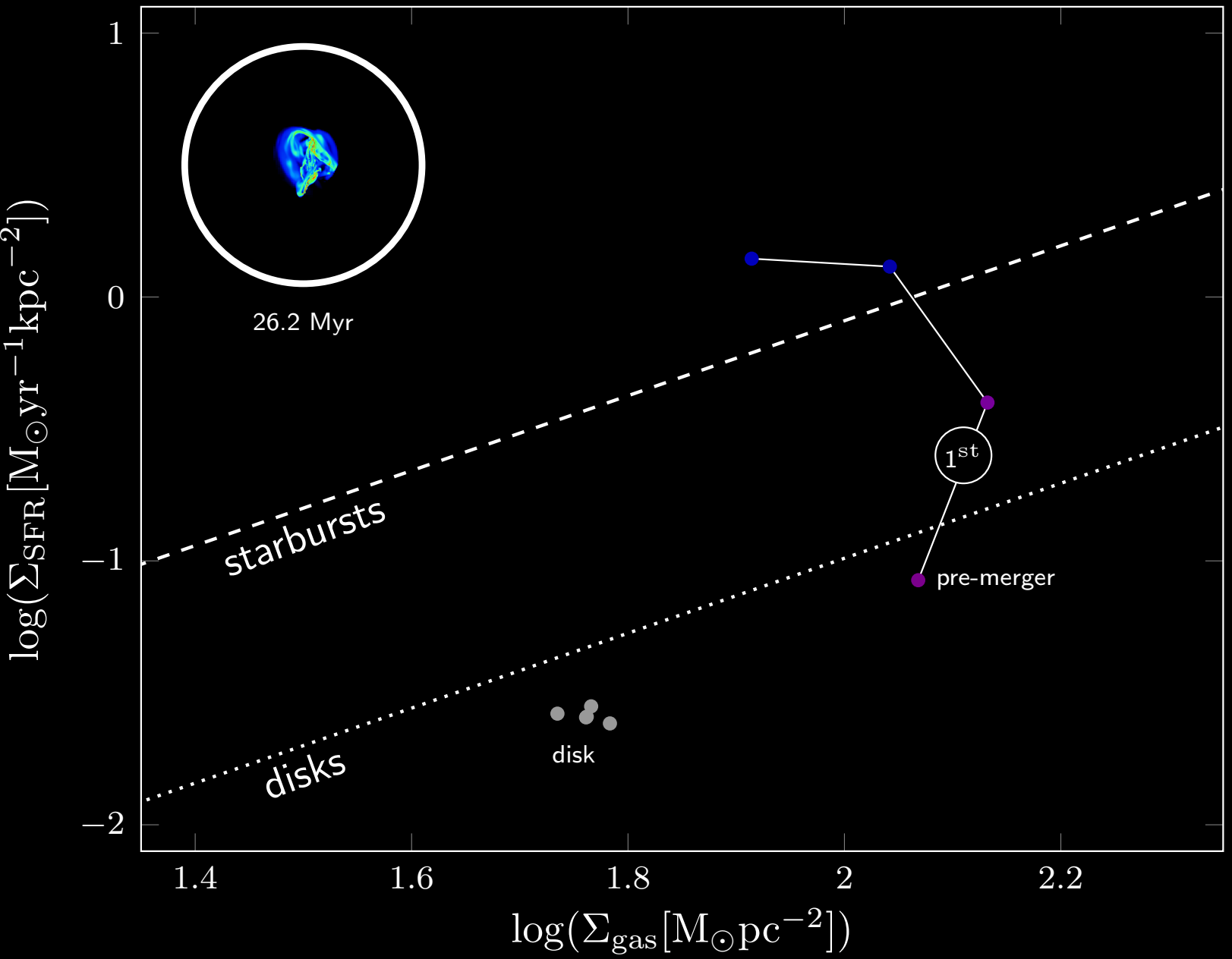

1
0
−1
−2
1.4
1.6
1.8
2
2.2
$\log(\Sigma_{\rm SFR}[{\rm M}_\odot{\rm yr}^{-1}{\rm kpc}^{-2}])$
$\log(\Sigma_{\rm gas}[{\rm M}_\odot{\rm pc}^{-2}])$

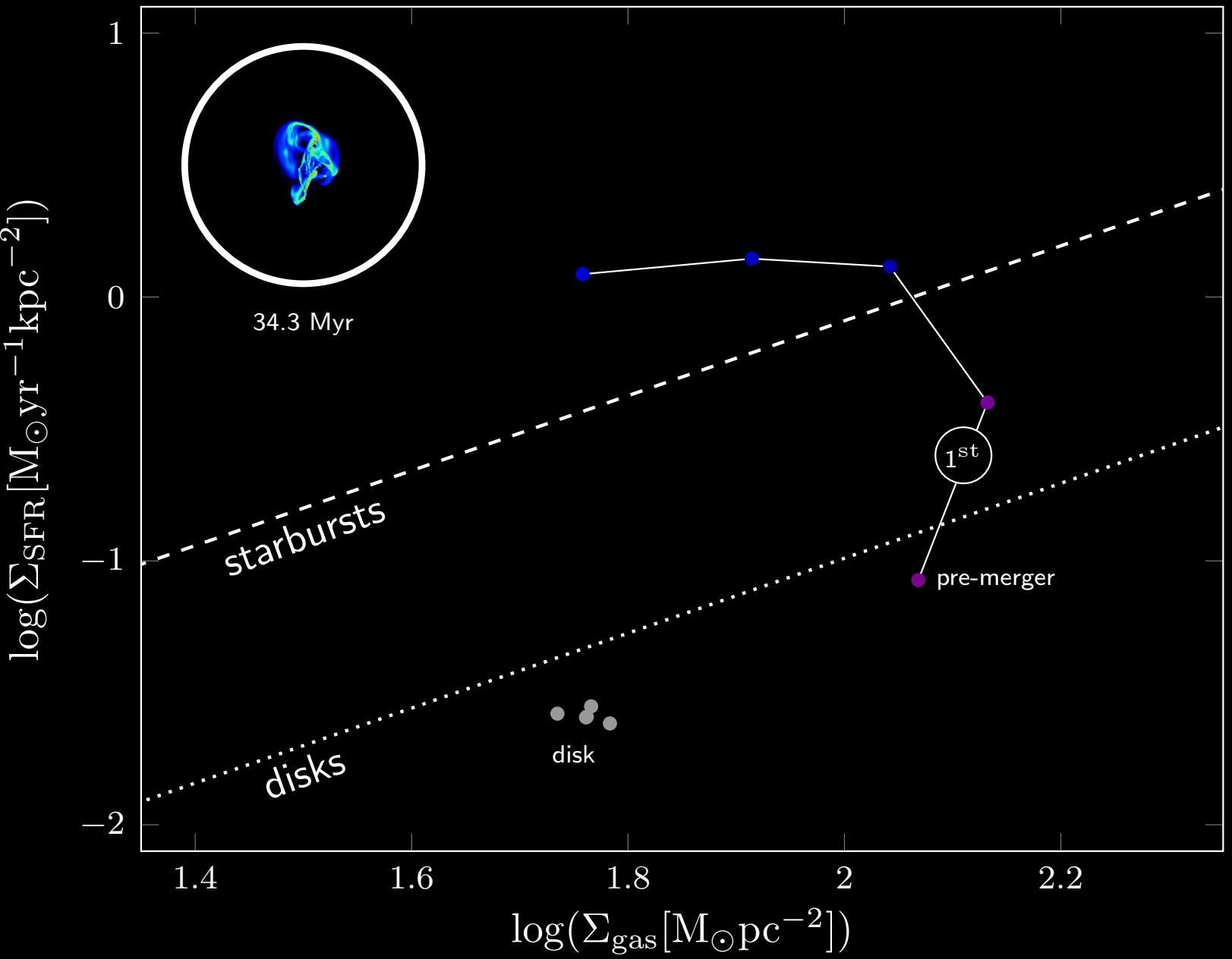

1
0
−1
−2
1.4
1.6
1.8
2
2.2
$\log(\Sigma_{\rm SFR}\,[{\rm M}_\odot{\rm yr}^{-1}{\rm kpc}^{-2}])$
$\log(\Sigma_{\rm gas}\,[{\rm M}_\odot{\rm pc}^{-2}])$
starbursts
disks
disk

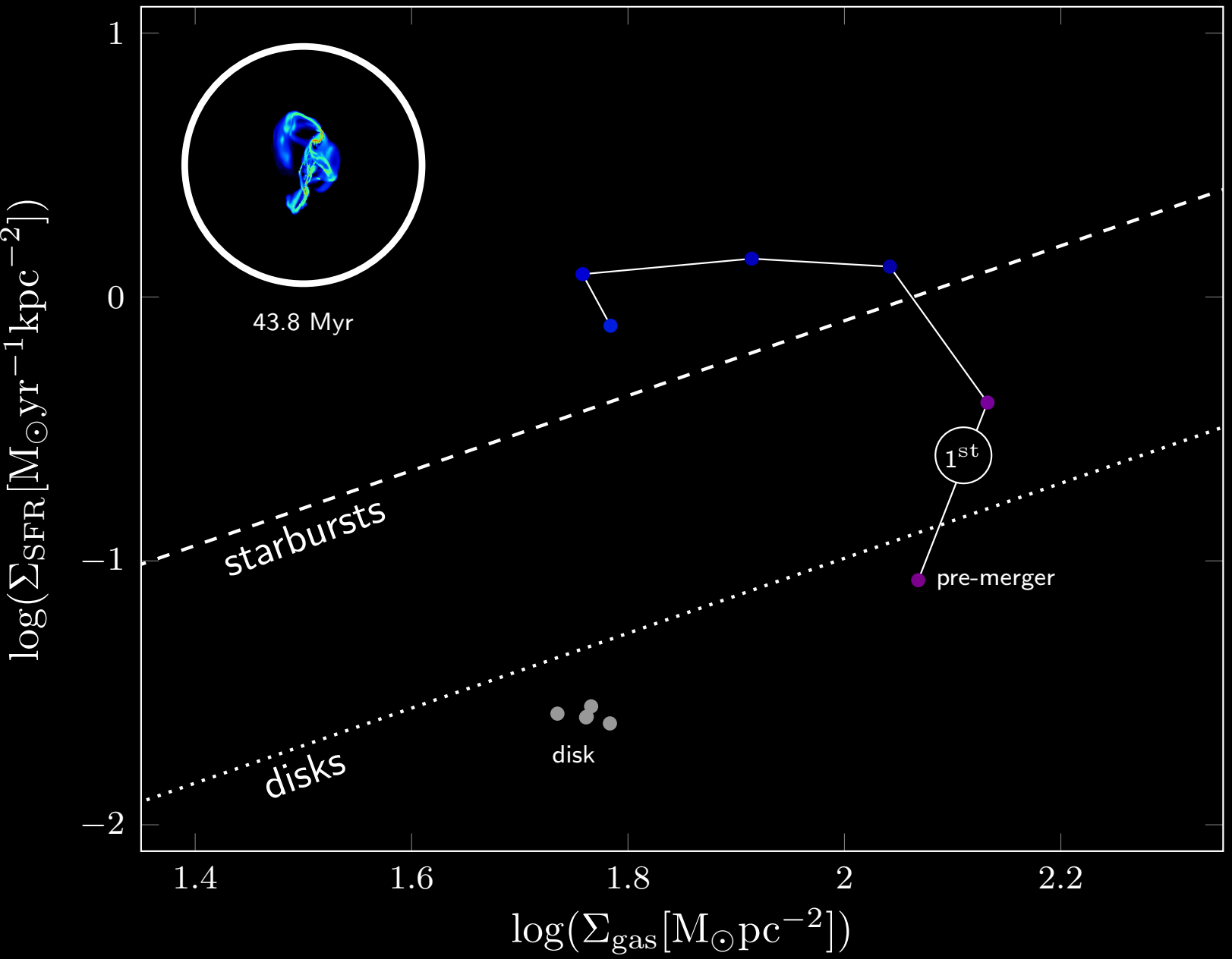

1
0
−1
−2
1.4
1.6
1.8
2
2.2
$\log(\Sigma_{\rm SFR}\,[{\rm M}_\odot{\rm yr}^{-1}{\rm kpc}^{-2}])$
$\log(\Sigma_{\rm gas}\,[{\rm M}_\odot{\rm pc}^{-2}])$
-5.7 Myr
starbursts
disks
pre-merger
disk

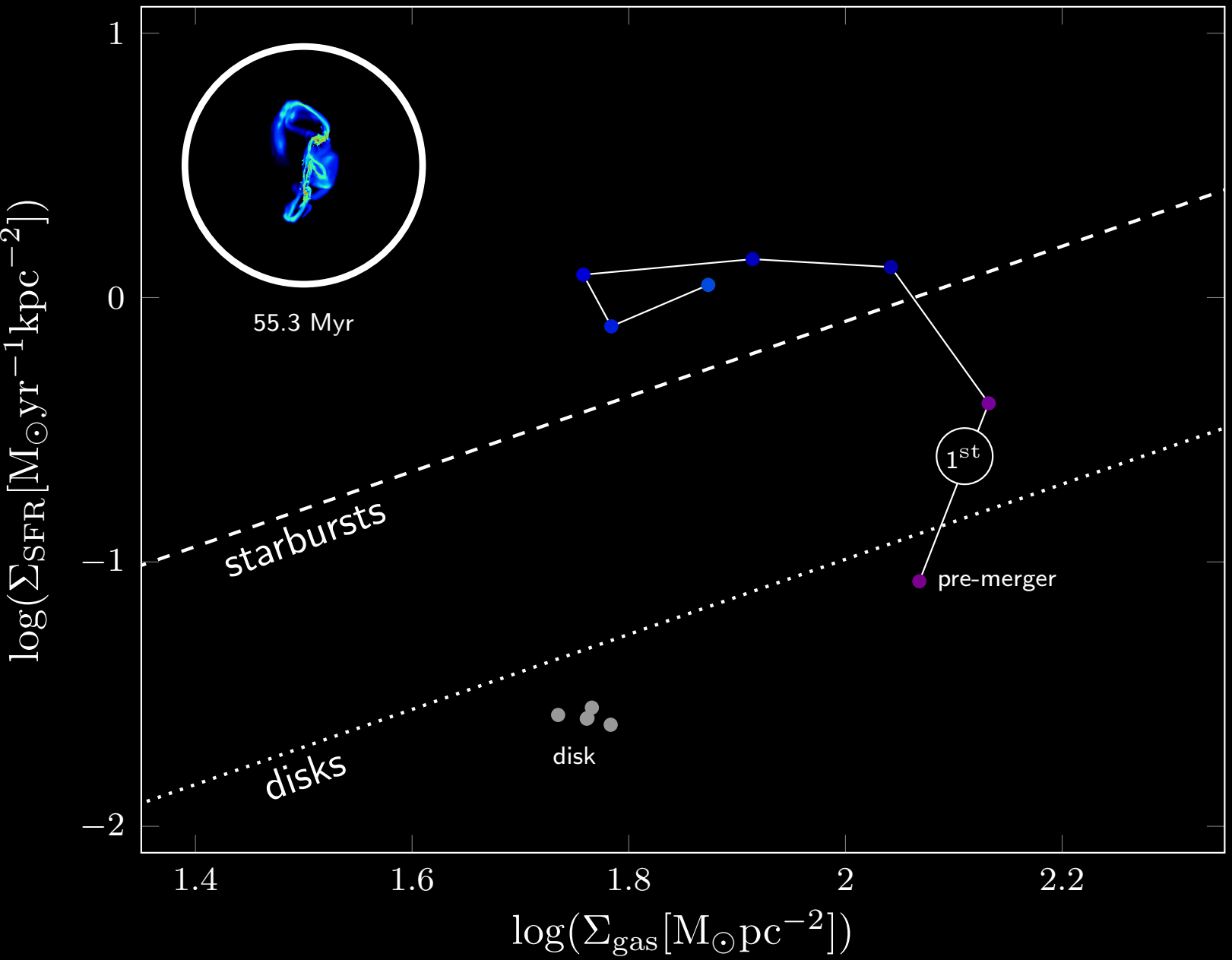

1
0
−1
−2
1.4
1.6
1.8
2
2.2
$\log(\Sigma_{\rm SFR}\,[{\rm M}_\odot{\rm yr}^{-1}{\rm kpc}^{-2}])$
$\log(\Sigma_{\rm gas}\,[{\rm M}_\odot{\rm pc}^{-2}])$
7.6 Myr
starbursts
disks
disk
1st
pre-merger

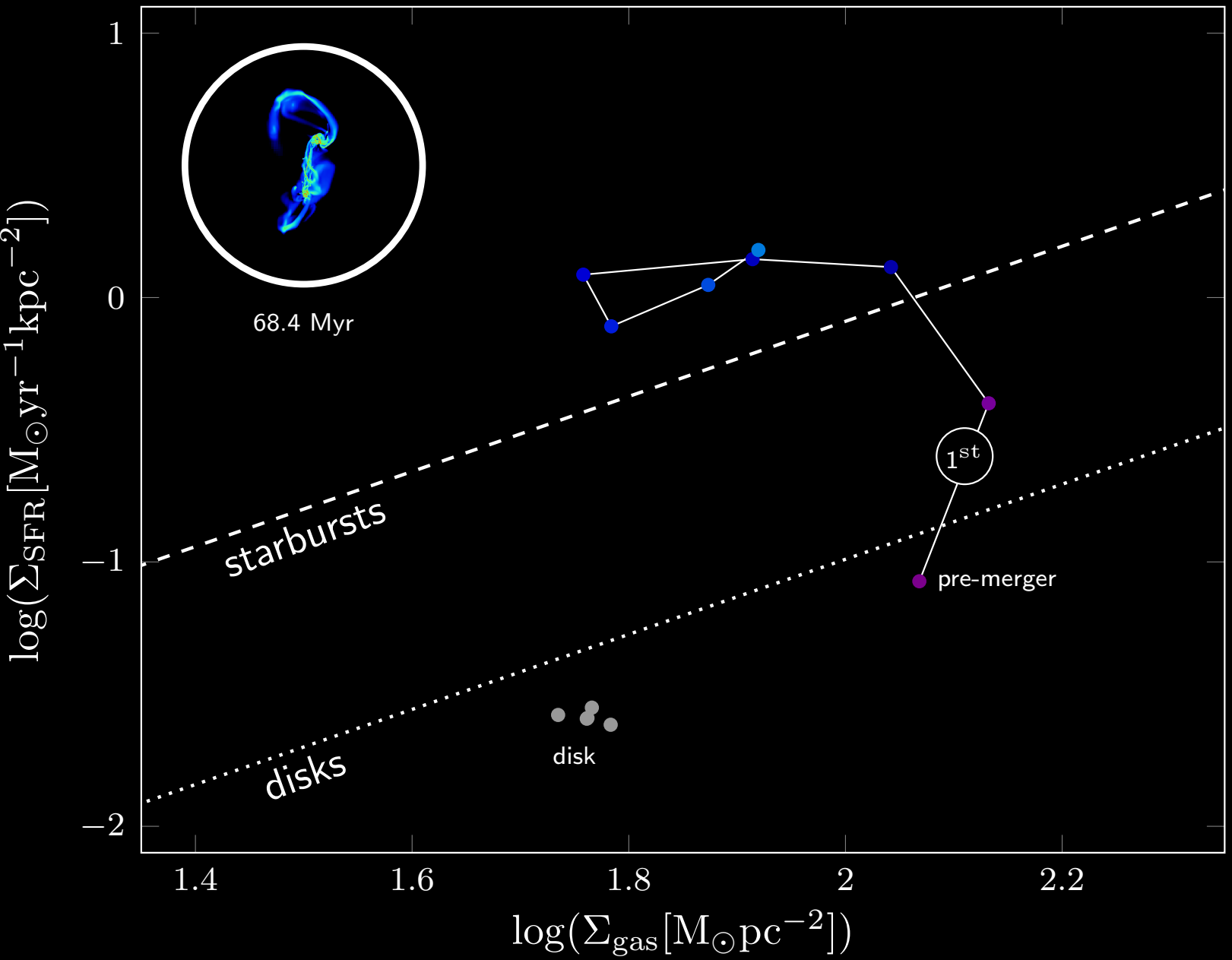

17.7 Myr
starbursts
disks
1st
pre-merger
disk
1
0
−1
−2
1.4
1.6
1.8
2
2.2
log(Σgas [M⊙pc−2])
log(ΣSFR [M⊙yr−1kpc−2])

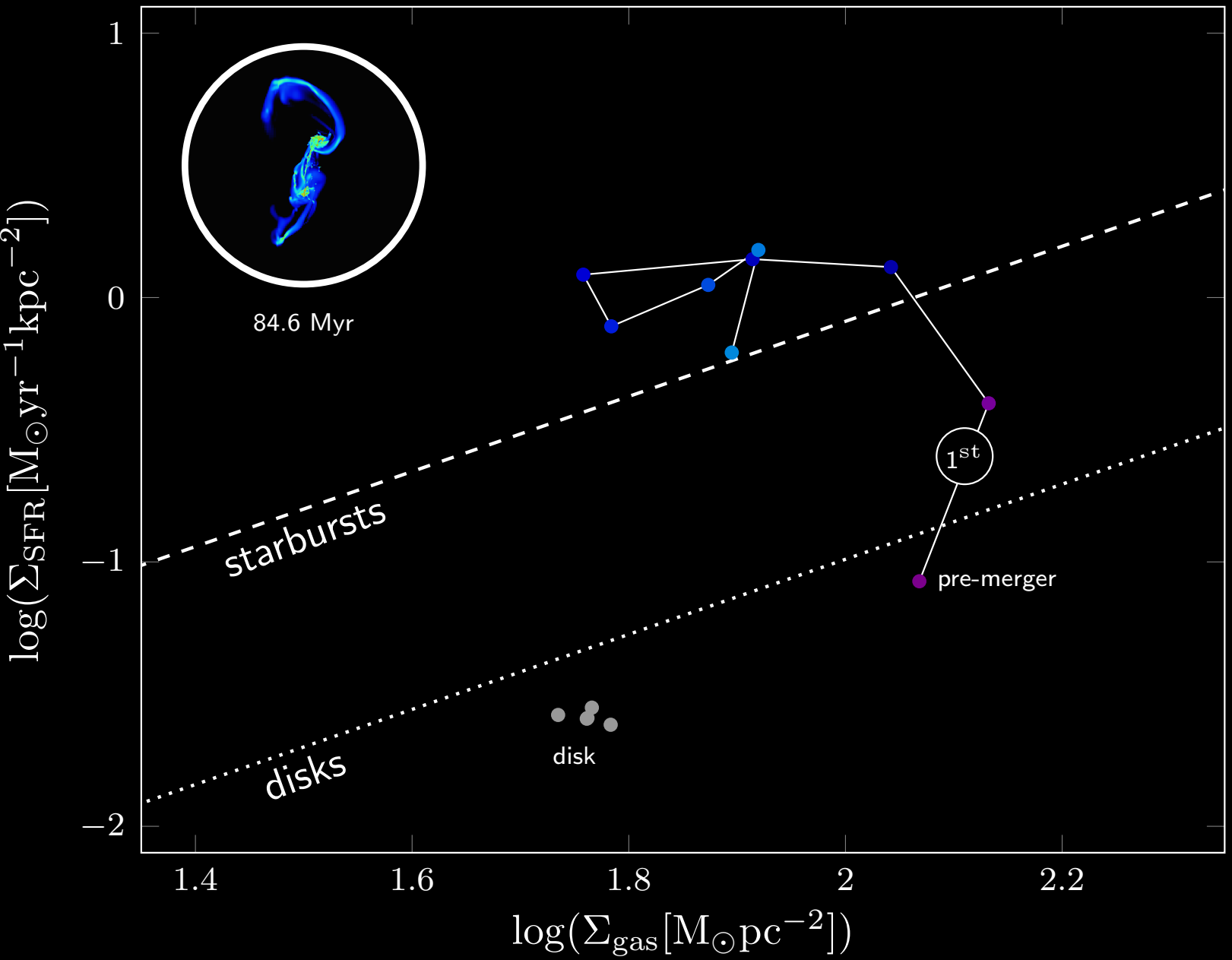

1
0
−1
−2
1.4
1.6
1.8
2
2.2
$\log(\Sigma_{\rm SFR}\,[{\rm M}_\odot{\rm yr}^{-1}{\rm kpc}^{-2}])$
$\log(\Sigma_{\rm gas}\,[{\rm M}_\odot{\rm pc}^{-2}])$
26.2 Myr
starbursts
disks
disk
1st
pre-merger

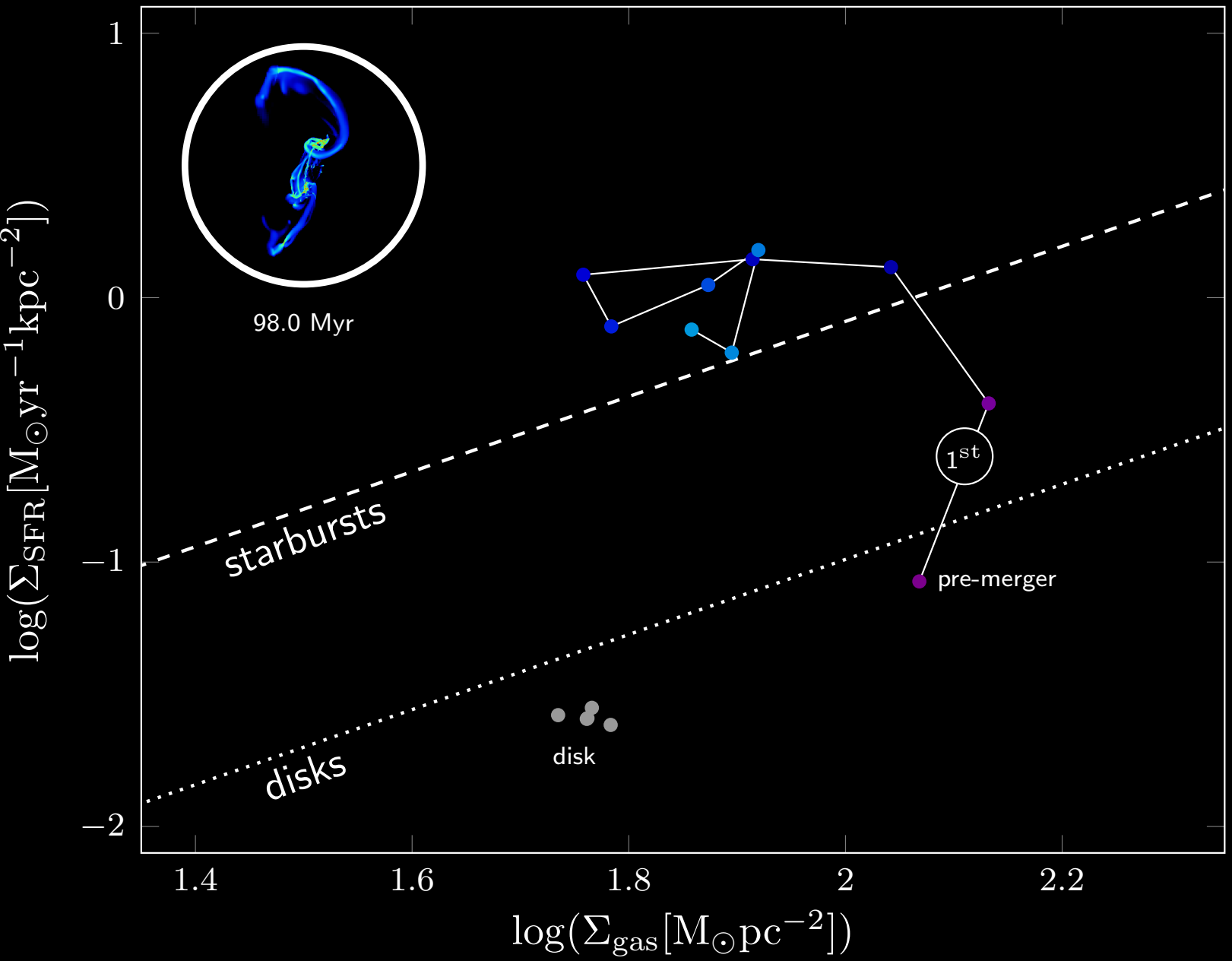

34.3 Myr
starbursts
disks
1st
pre-merger
disk
1
0
−1
−2
1.4
1.6
1.8
2
2.2
log(Σgas [M⊙pc−2])
log(ΣSFR [M⊙yr−1kpc−2])

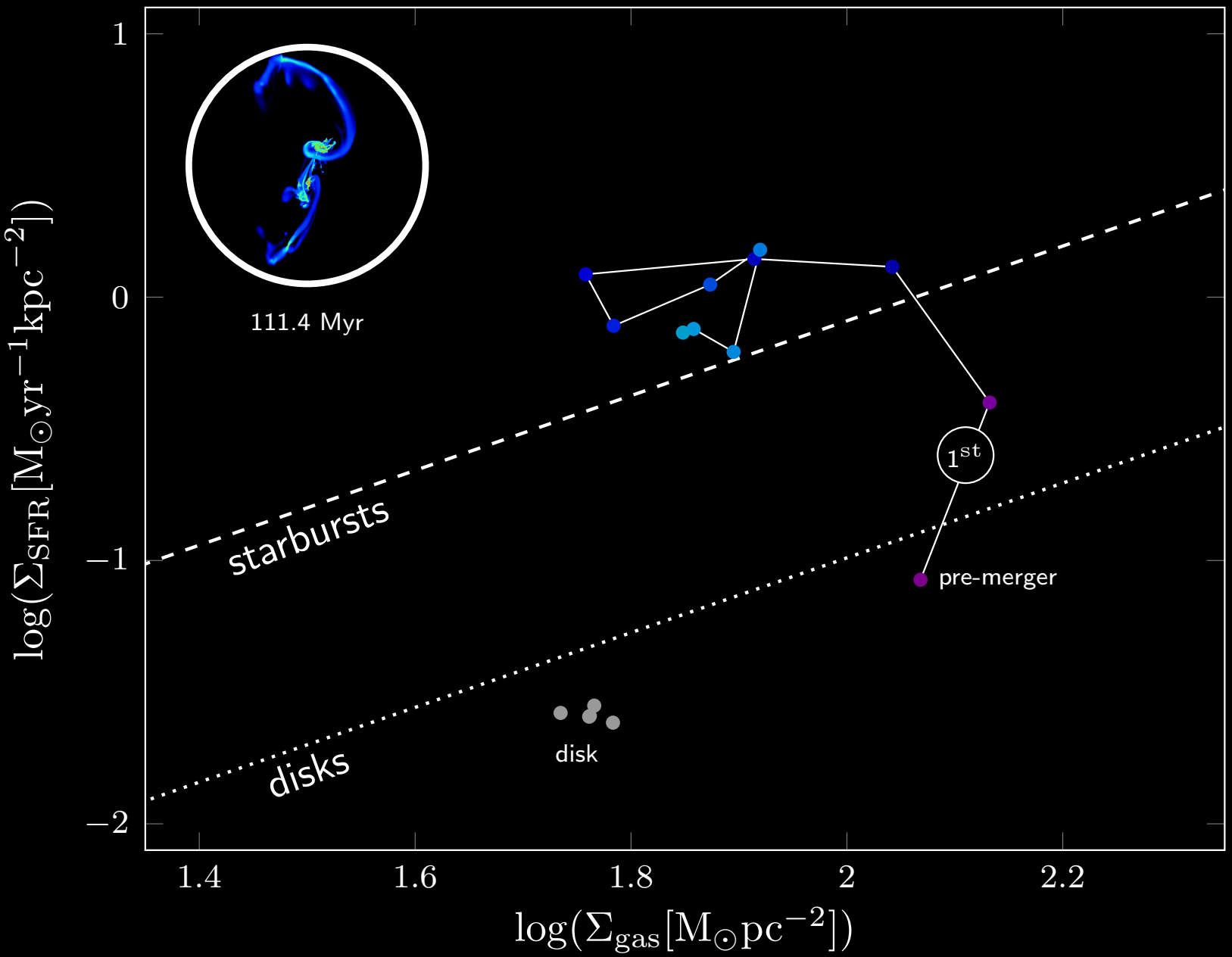

1
0
−1
−2
1.4
1.6
1.8
2
2.2
$\log(\Sigma_{\rm SFR}\,[{\rm M}_\odot{\rm yr}^{-1}{\rm kpc}^{-2}])$
$\log(\Sigma_{\rm gas}\,[{\rm M}_\odot{\rm pc}^{-2}])$
43.8 Myr
starbursts
disks
disk
1st
pre-merger

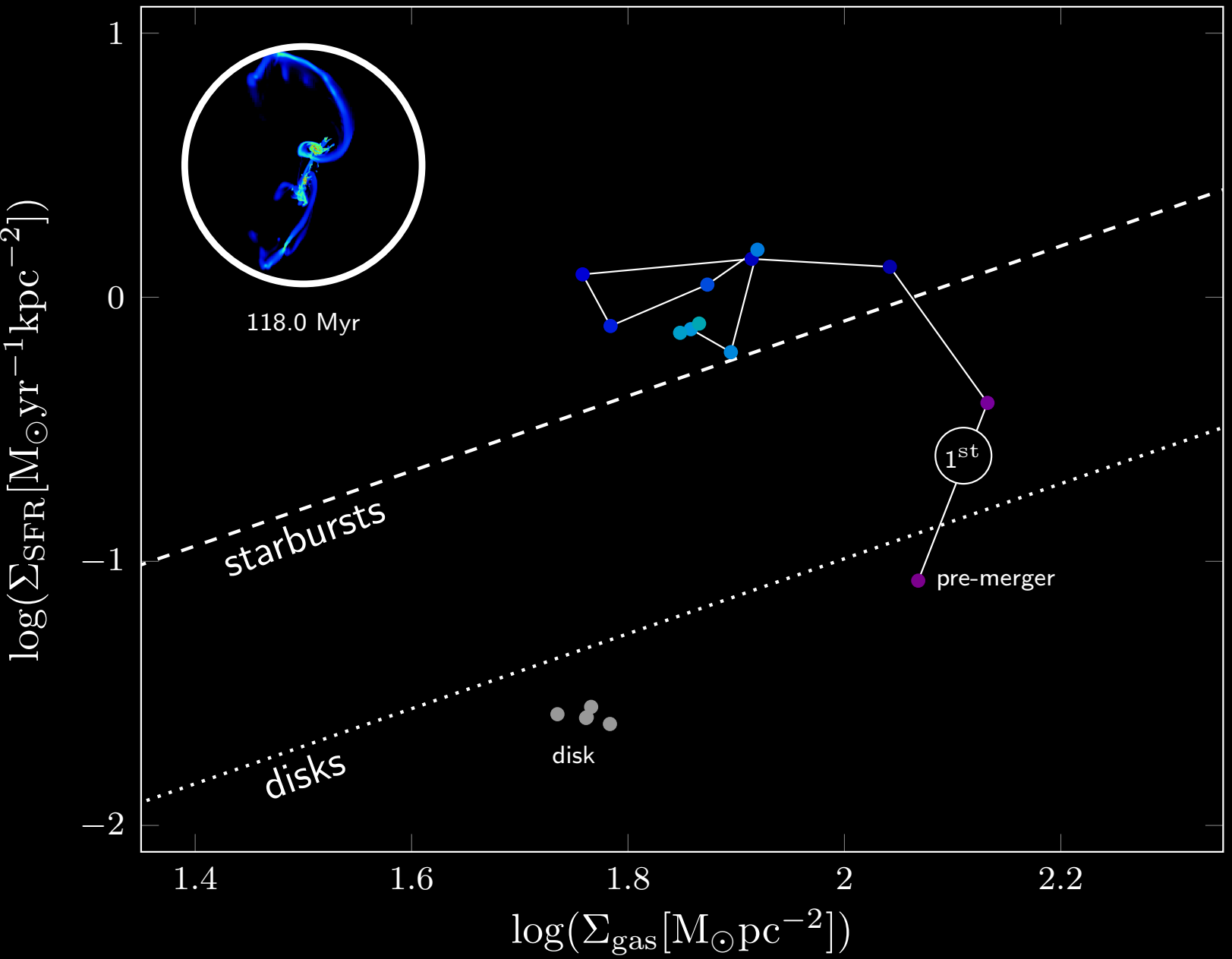

55.3 Myr
starbursts
disks
1st
pre-merger
disk
1
0
−1
−2
1.4
1.6
1.8
2
2.2
log(Σgas [M⊙pc−2])
log(ΣSFR [M⊙yr−1kpc−2])

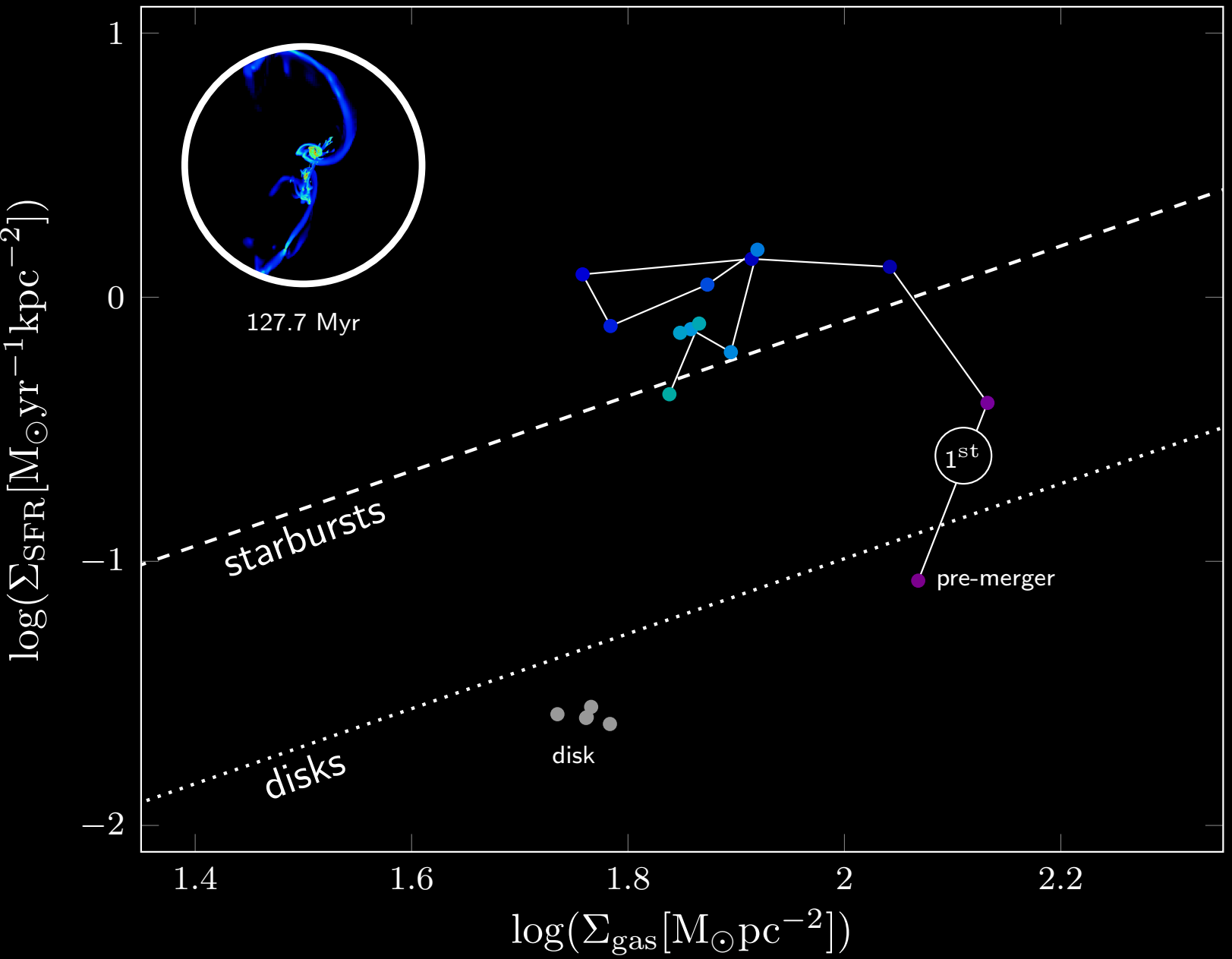

1
0
−1
−2
1.4
1.6
1.8
2
2.2
$\log(\Sigma_{\rm SFR}\,[{\rm M}_\odot{\rm yr}^{-1}{\rm kpc}^{-2}])$
$\log(\Sigma_{\rm gas}\,[{\rm M}_\odot{\rm pc}^{-2}])$
68.4 Myr
starbursts
disks
disk
1st
pre-merger

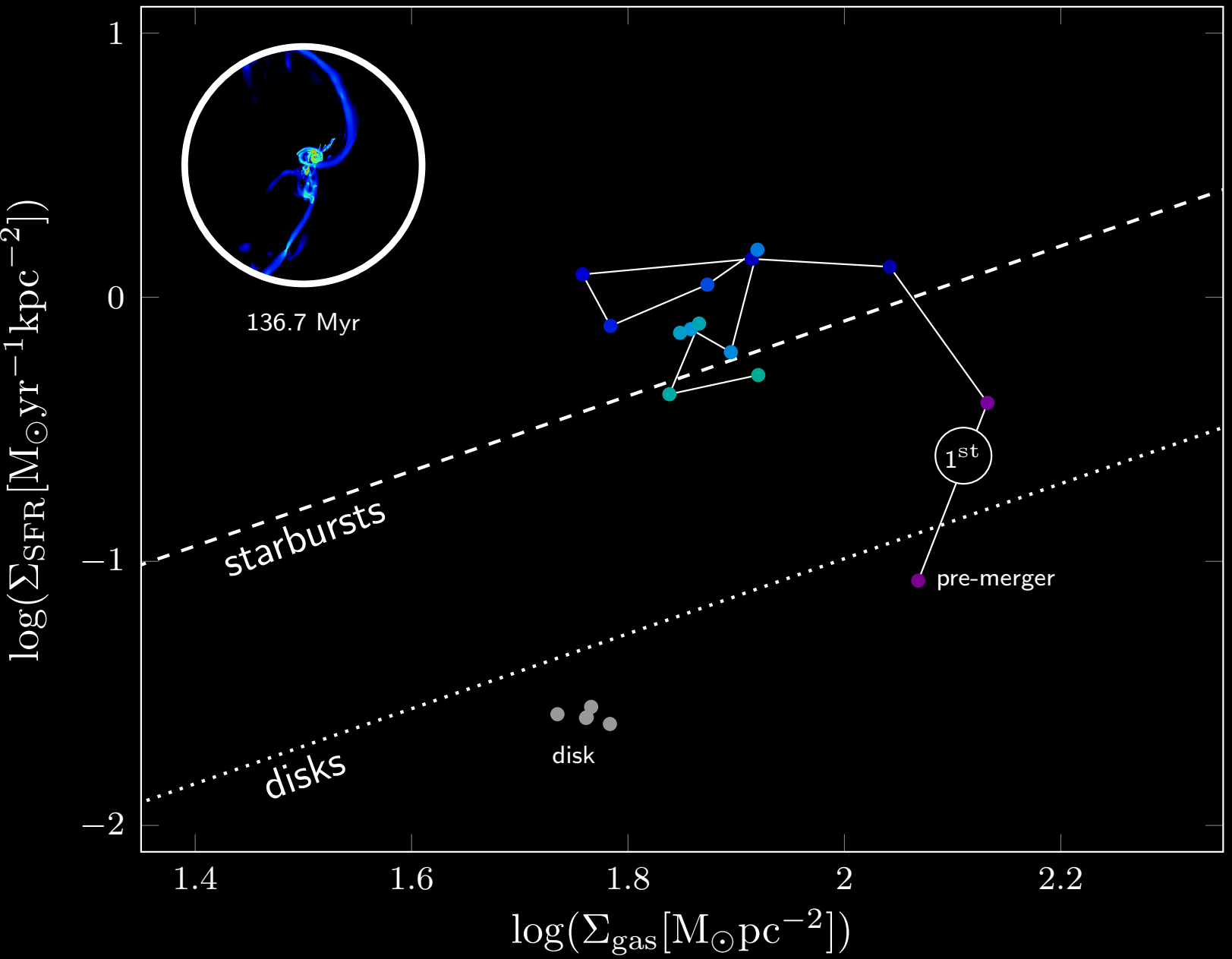

84.6 Myr
starbursts
disks
disk
1st
pre-merger
1
0
−1
−2
1.4
1.6
1.8
2
2.2
log(Σgas [M⊙pc−2])
log(ΣSFR [M⊙yr−1kpc−2])

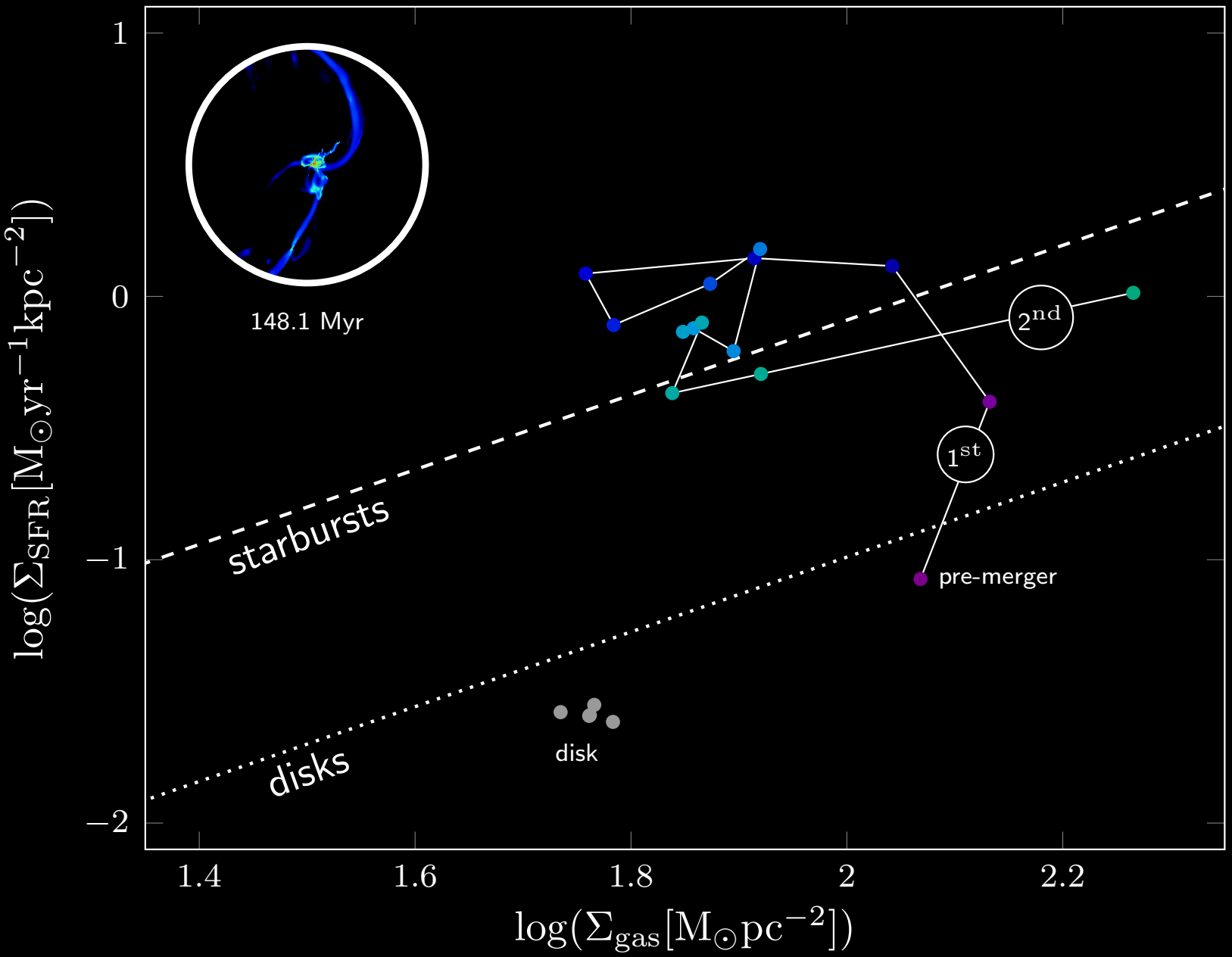

98.0 Myr
starbursts
disks
disk
1st
pre-merger
1
0
−1
−2
1.4
1.6
1.8
2
2.2
log(Σgas [M⊙pc−2])
log(ΣSFR [M⊙yr−1kpc−2])

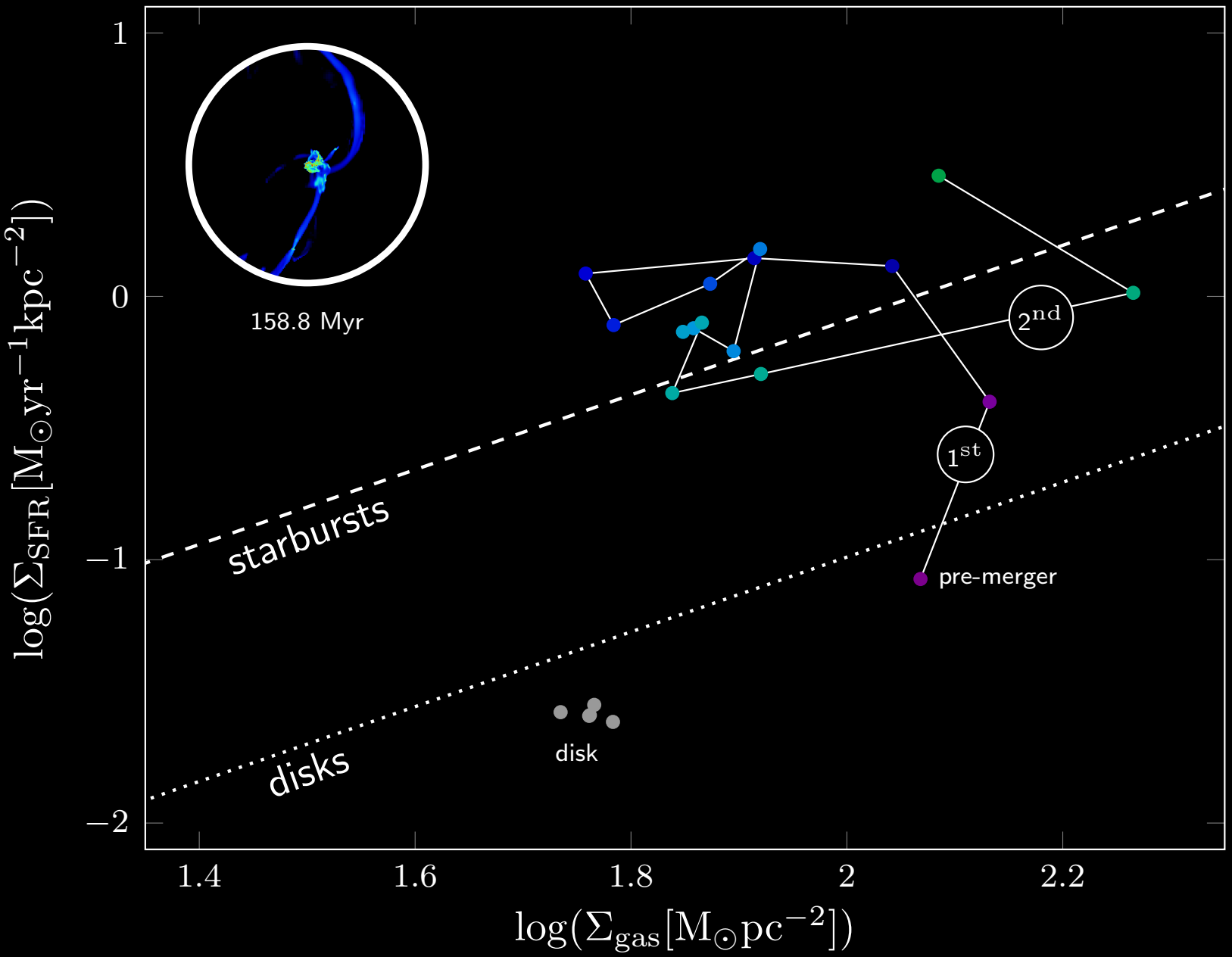

111.4 Myr
starbursts
disks
1st
pre-merger
disk
1
0
−1
−2
1.4
1.6
1.8
2
2.2
log(Σgas [M⊙ pc−2])
log(ΣSFR [M⊙ yr−1 kpc−2])

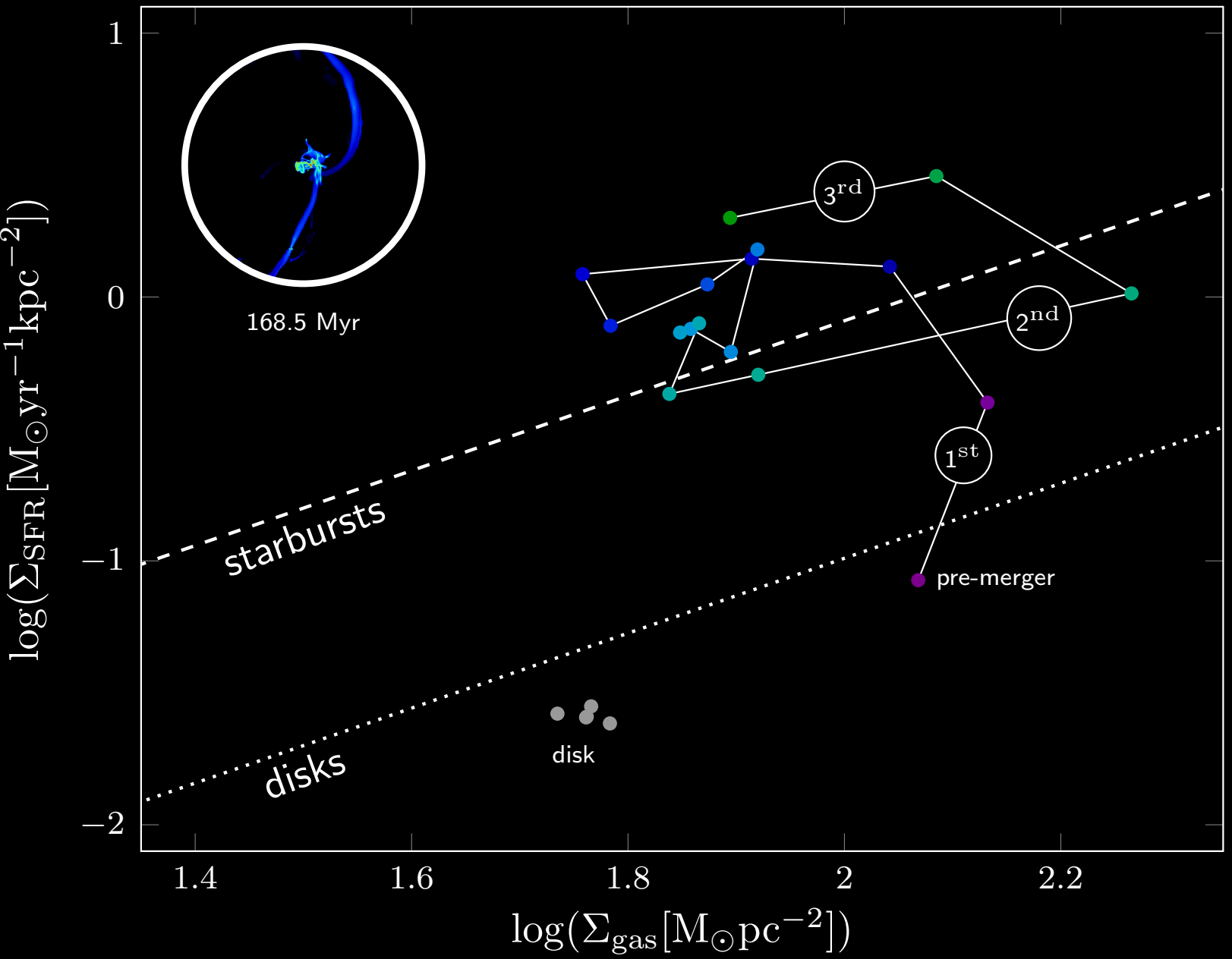

118.0 Myr
starbursts
disks
1st
pre-merger
disk
1
0
−1
−2
1.4
1.6
1.8
2
2.2
log(Σgas [M⊙ pc−2])
log(ΣSFR [M⊙ yr−1 kpc−2])

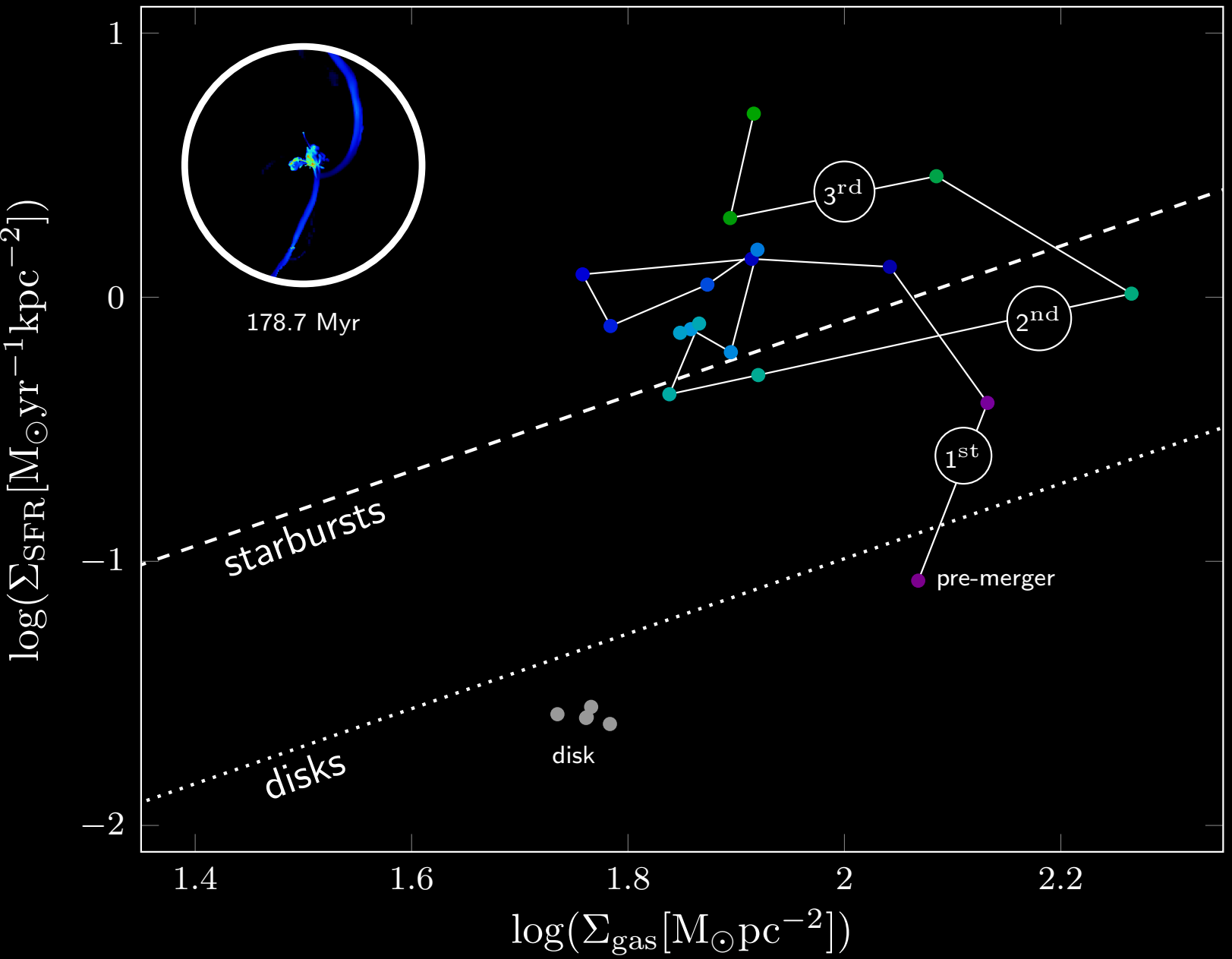

1
0
−1
−2
1.4
1.6
1.8
2
2.2
$\log(\Sigma_{\rm SFR}\,[{\rm M}_\odot{\rm yr}^{-1}{\rm kpc}^{-2}])$
$\log(\Sigma_{\rm gas}\,[{\rm M}_\odot{\rm pc}^{-2}])$
127.7 Myr
starbursts
disks
disk
1st
pre-merger

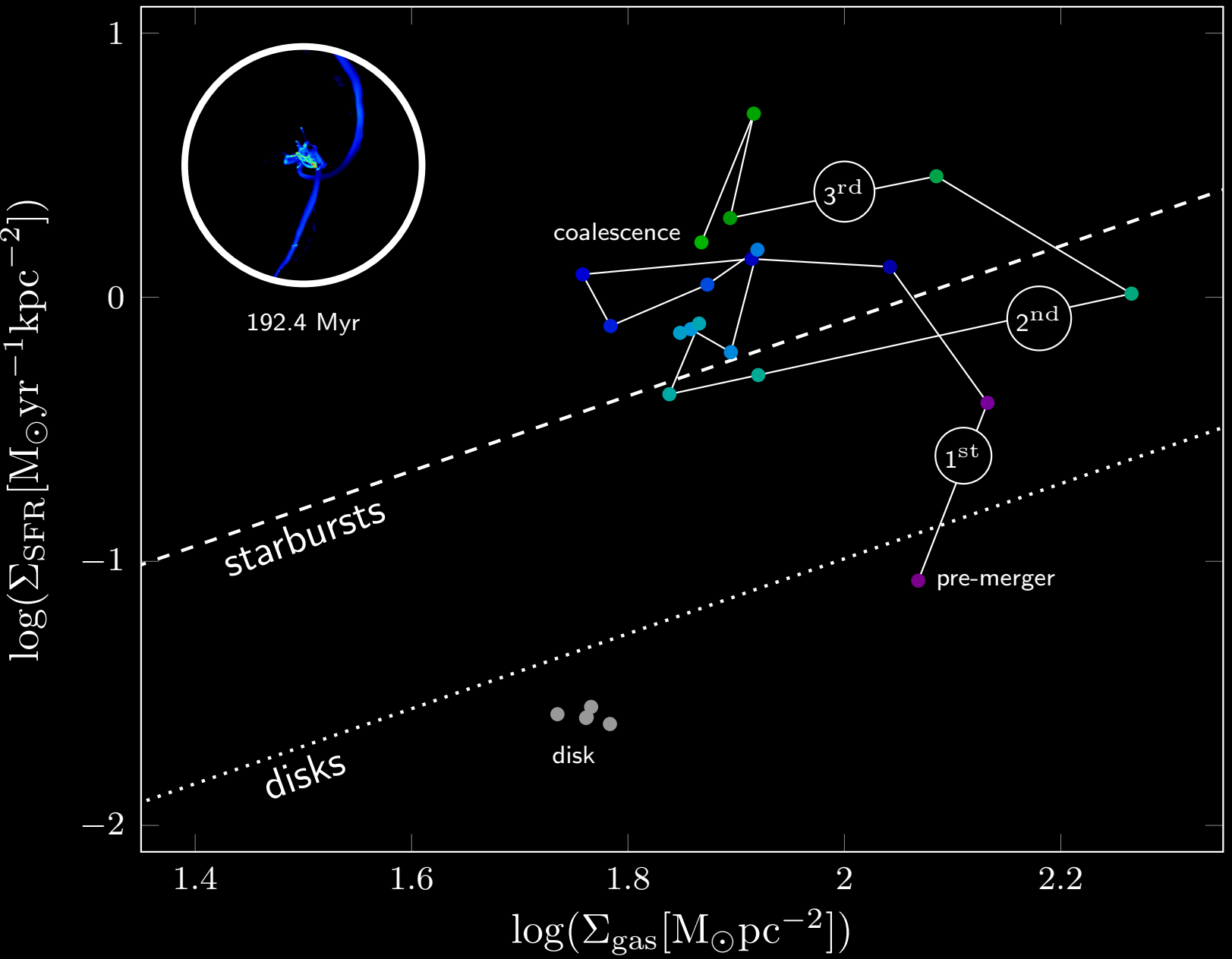

136.7 Myr
starbursts
disks
disk
1st
pre-merger
1
0
−1
−2
1.4
1.6
1.8
2
2.2
log(Σgas [M⊙ pc−2])
log(ΣSFR [M⊙ yr−1 kpc−2])

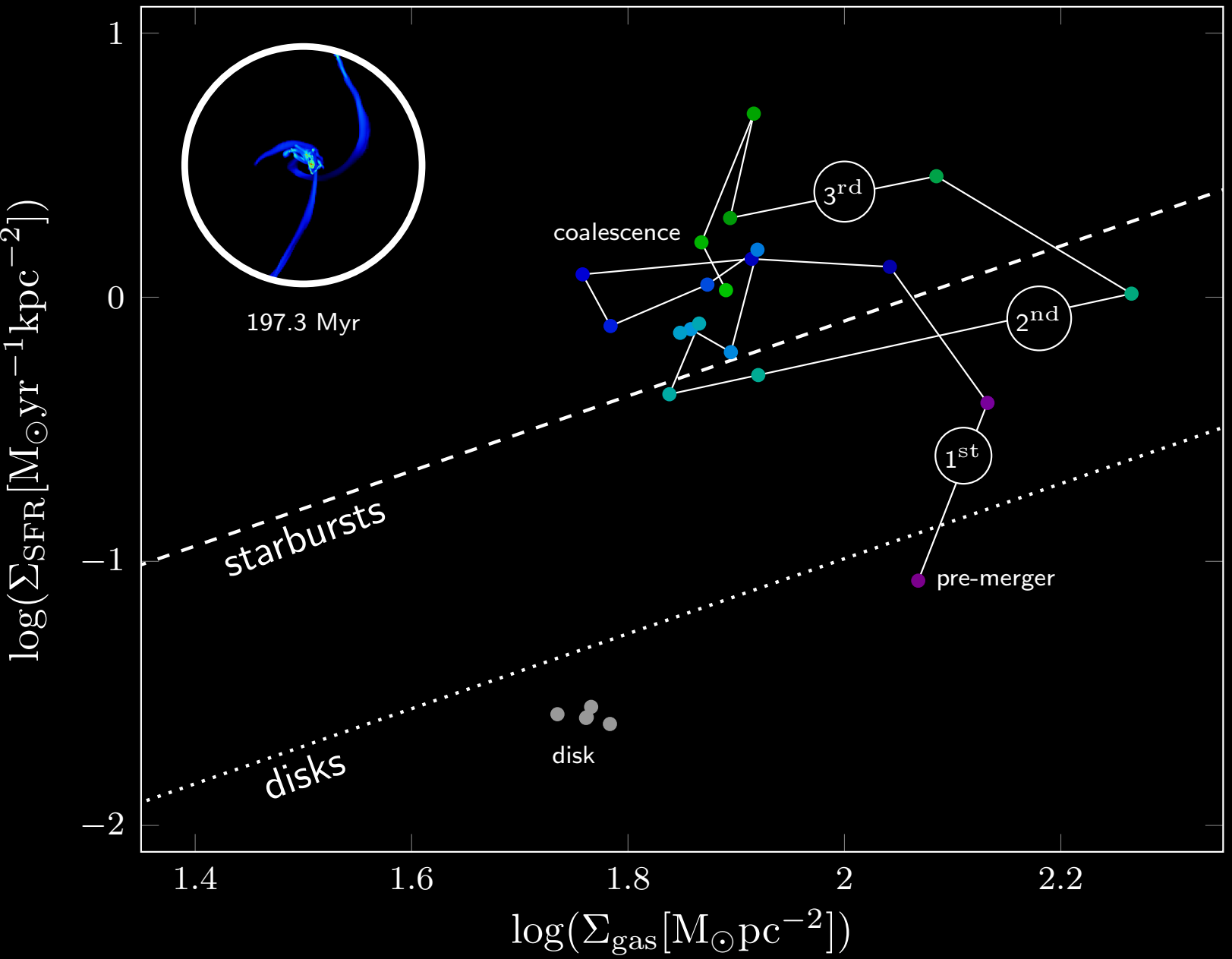

148.1 Myr
2nd
1st
pre-merger
starbursts
disks
disk
1
0
−1
−2
1.4
1.6
1.8
2
2.2
log(Σgas [M⊙ pc−2])
log(ΣSFR [M⊙ yr−1 kpc−2])

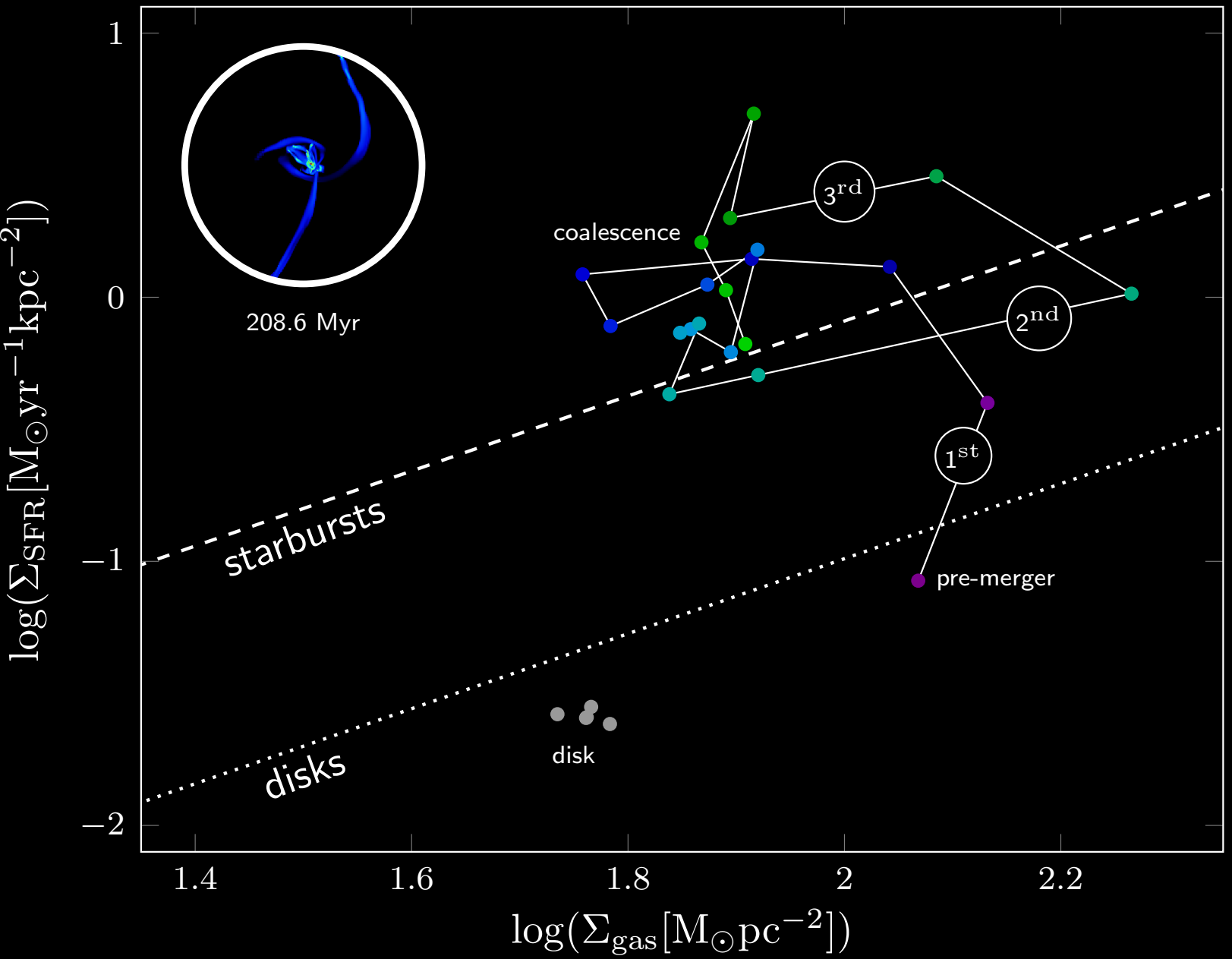

158.8 Myr
2nd
1st
pre-merger
starbursts
disks
disk
1
0
−1
−2
1.4
1.6
1.8
2
2.2
log(Σgas [M⊙ pc−2])
log(ΣSFR [M⊙ yr−1 kpc−2])

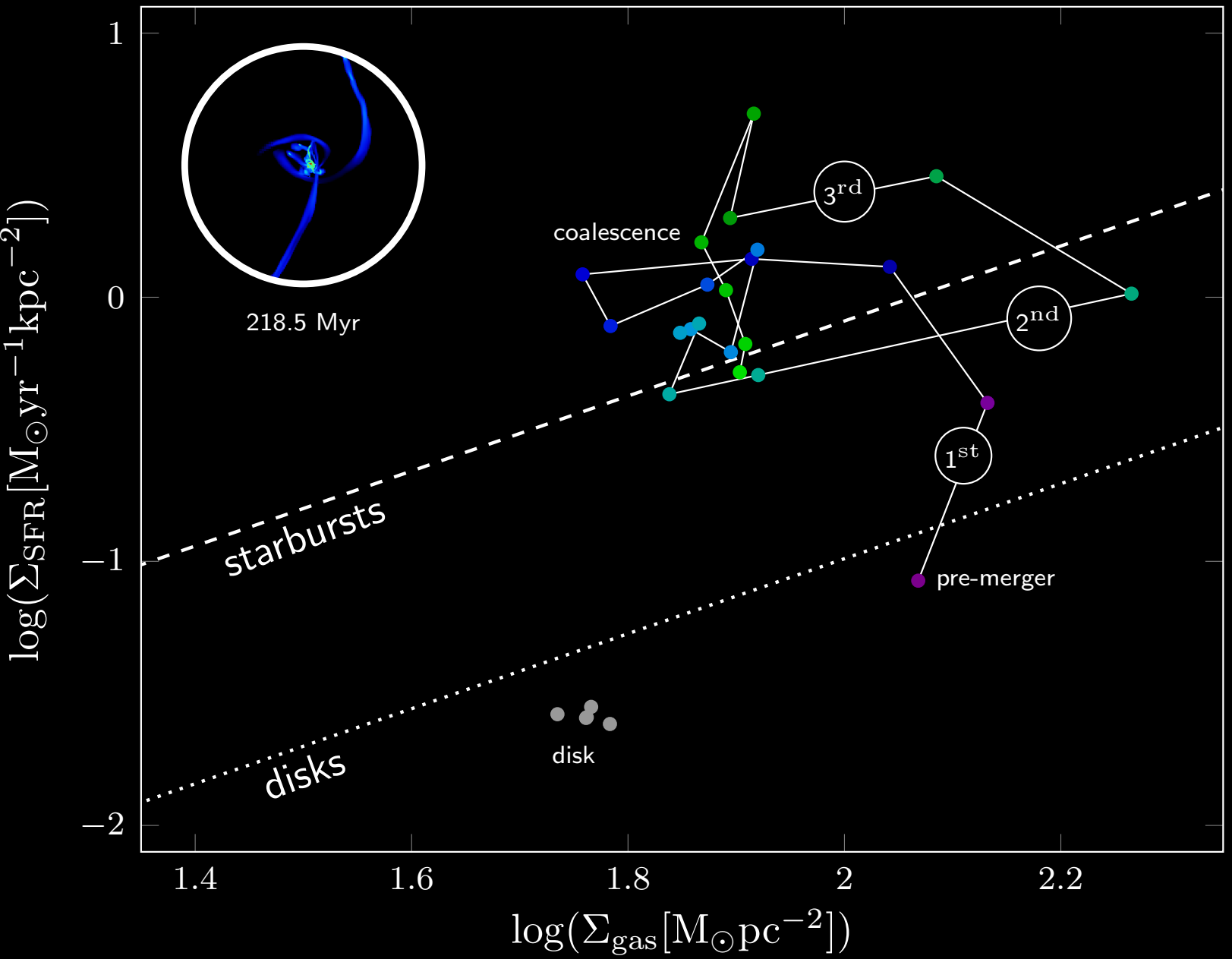

168.5 Myr
3rd
2nd
1st
pre-merger
starbursts
disks
disk
1
0
−1
−2
1.4
1.6
1.8
2
2.2
log(Σgas [M⊙ pc−2])
log(ΣSFR [M⊙ yr−1 kpc−2])

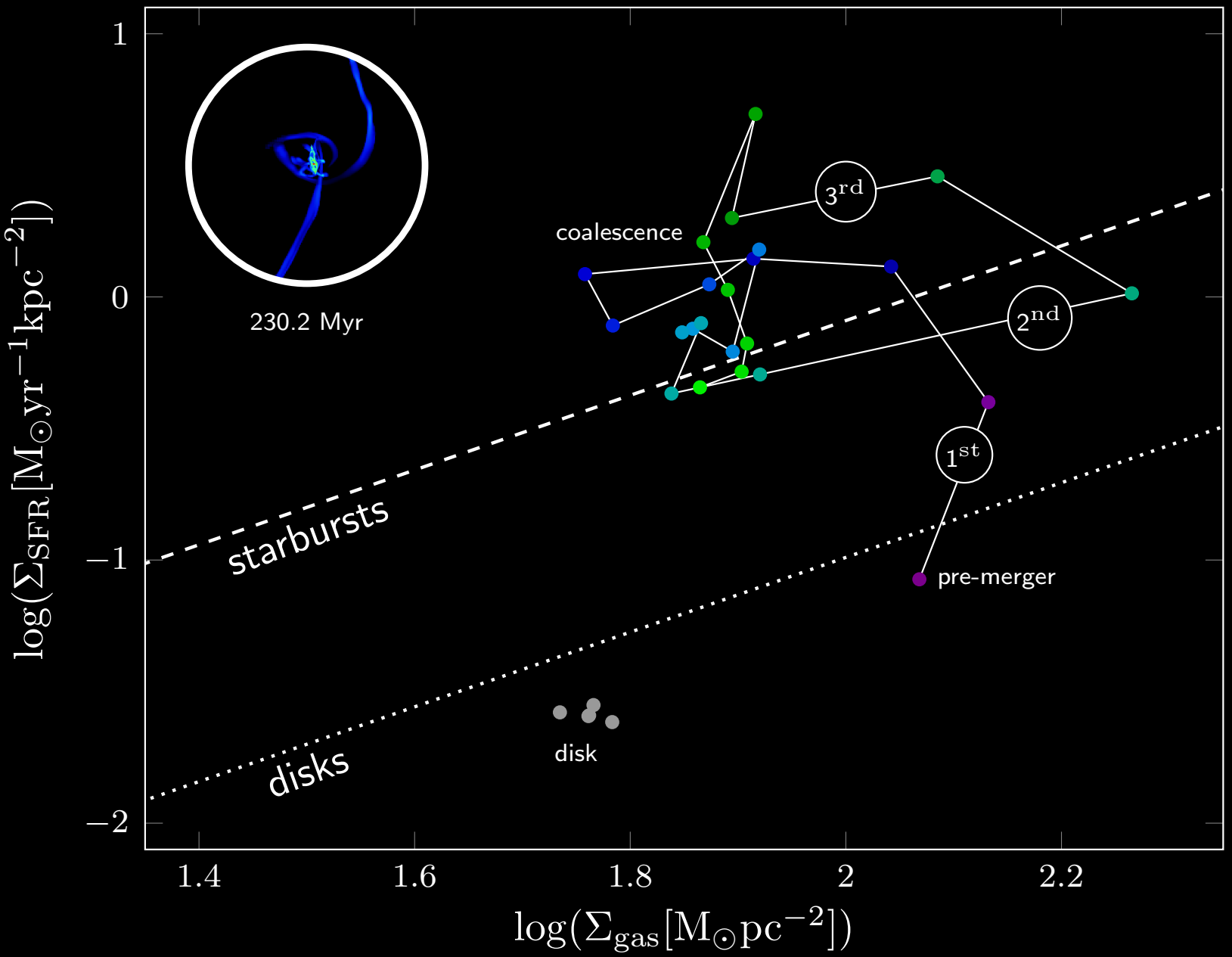

178.7 Myr
3rd
2nd
1st
pre-merger
starbursts
disks
disk
1
0
−1
−2
1.4
1.6
1.8
2
2.2
log(Σgas [M⊙ pc−2])
log(ΣSFR [M⊙ yr−1 kpc−2])

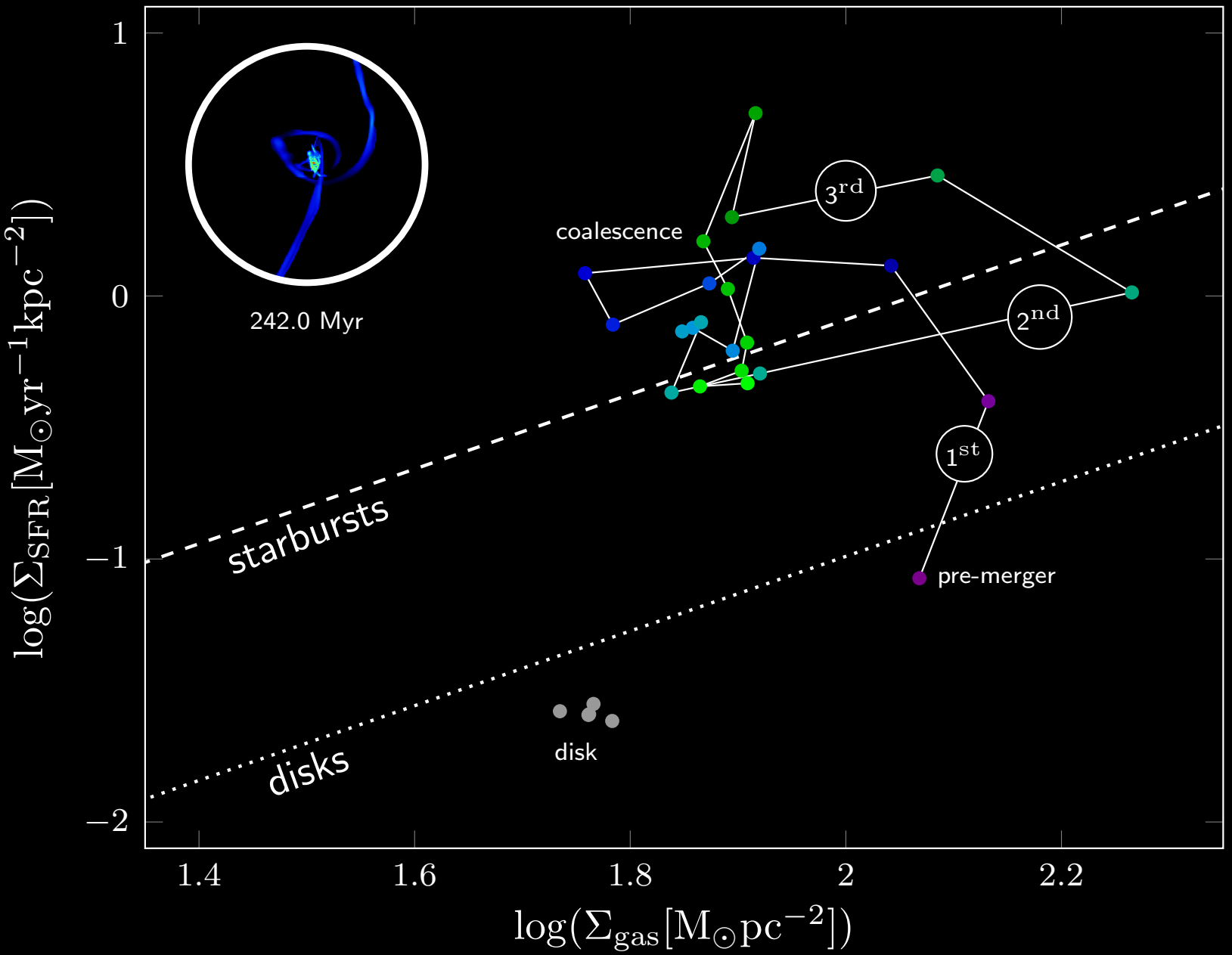

192.4 Myr
coalescence
3rd
2nd
1st
pre-merger
starbursts
disks
disk
1
0
−1
−2
1.4
1.6
1.8
2
2.2
log(Σgas [M⊙ pc−2])
log(ΣSFR [M⊙ yr−1 kpc−2])

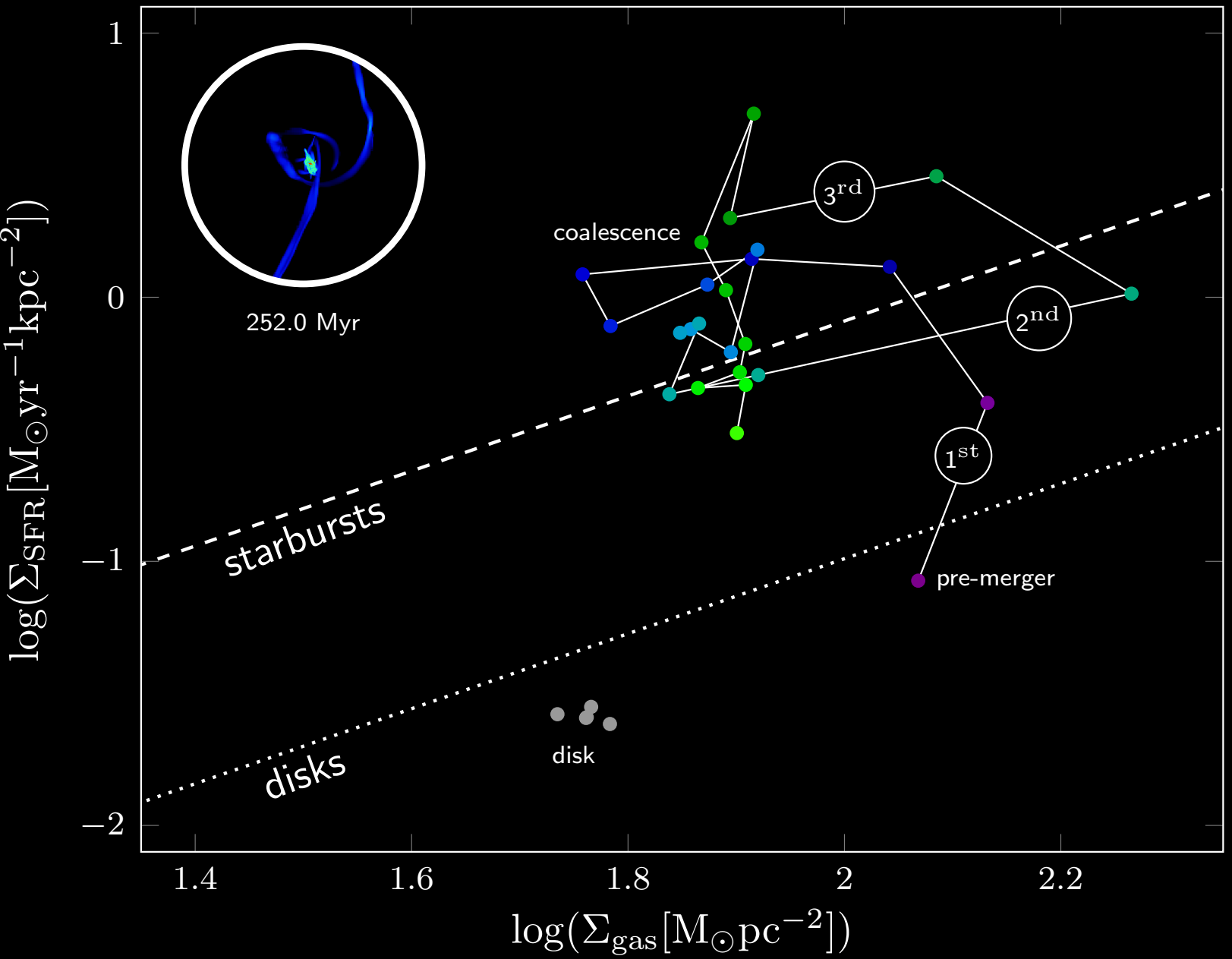

197.3 Myr
coalescence
3rd
2nd
1st
pre-merger
starbursts
disks
disk
1
0
−1
−2
1.4
1.6
1.8
2
2.2
log(Σgas [M⊙ pc−2])
log(ΣSFR [M⊙ yr−1 kpc−2])

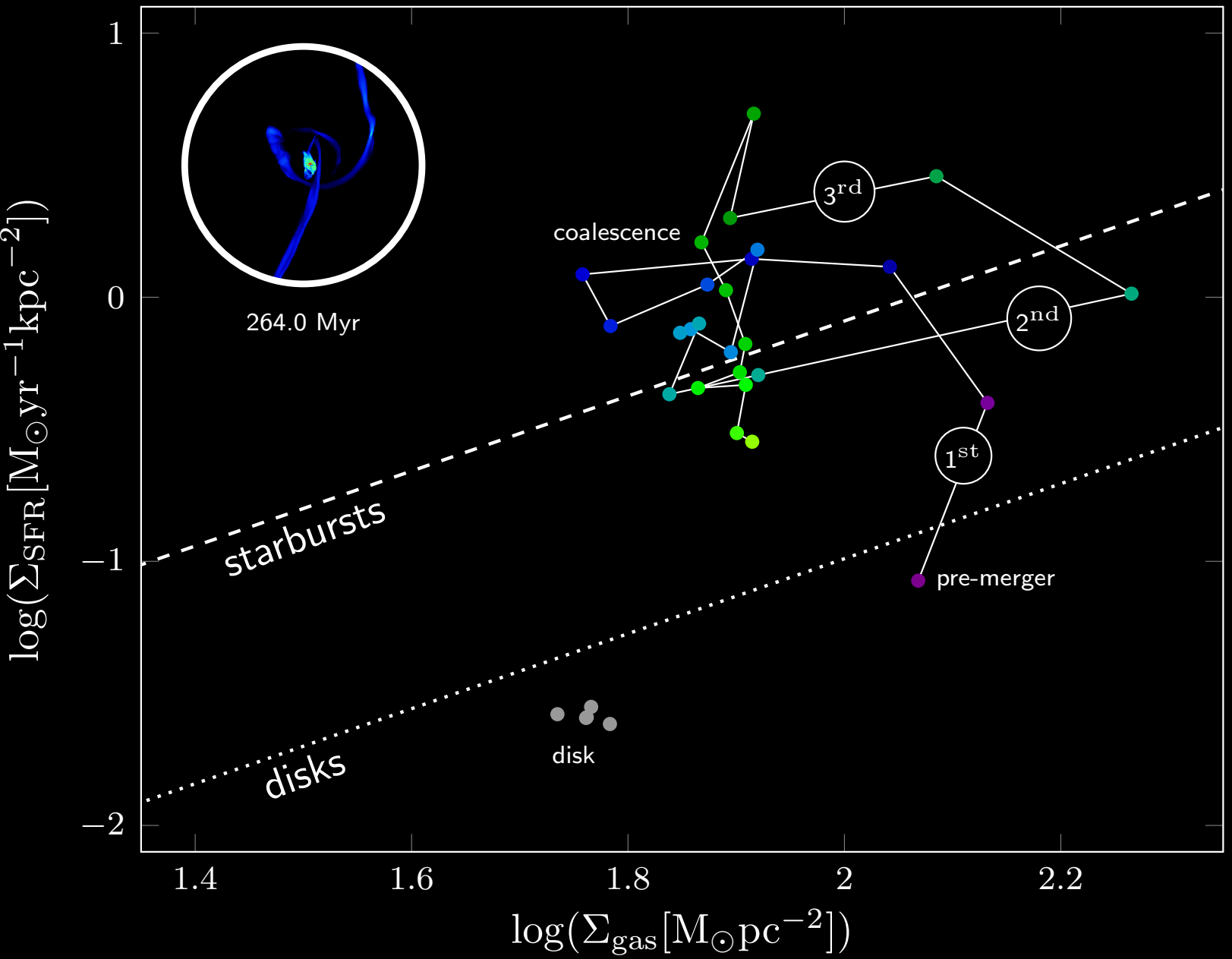

208.6 Myr
coalescence
3rd
2nd
1st
pre-merger
starbursts
disks
disk
1
0
−1
−2
1.4
1.6
1.8
2
2.2
log(Σgas [M⊙ pc−2])
log(ΣSFR [M⊙ yr−1 kpc−2])

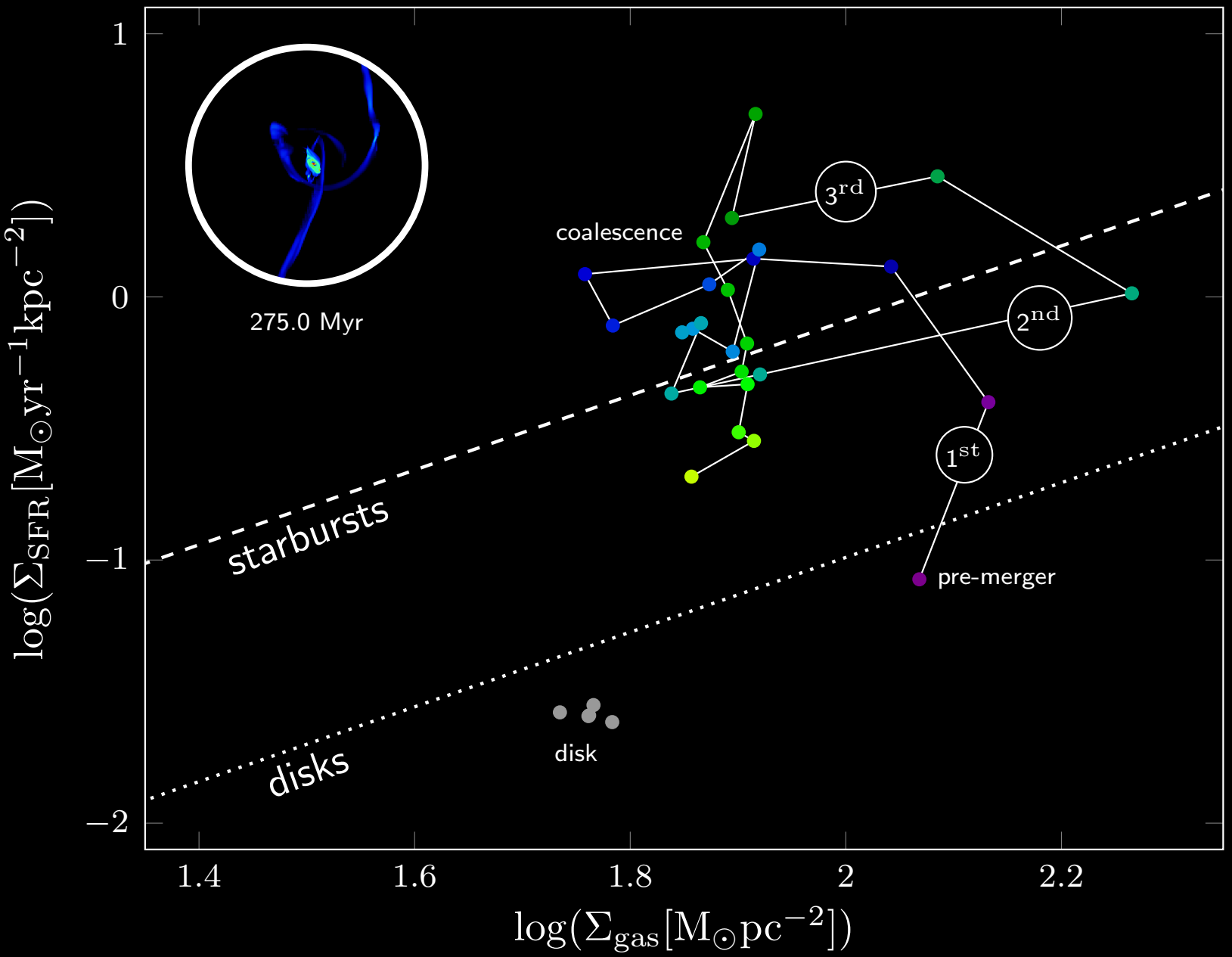

1
0
−1
−2
1.4
1.6
1.8
2
2.2
$\log(\Sigma_{\rm SFR}\,[{\rm M}_\odot{\rm yr}^{-1}{\rm kpc}^{-2}])$
$\log(\Sigma_{\rm gas}\,[{\rm M}_\odot{\rm pc}^{-2}])$
218.5 Myr
coalescence
3rd
2nd
1st
pre-merger
starbursts
disks
disk

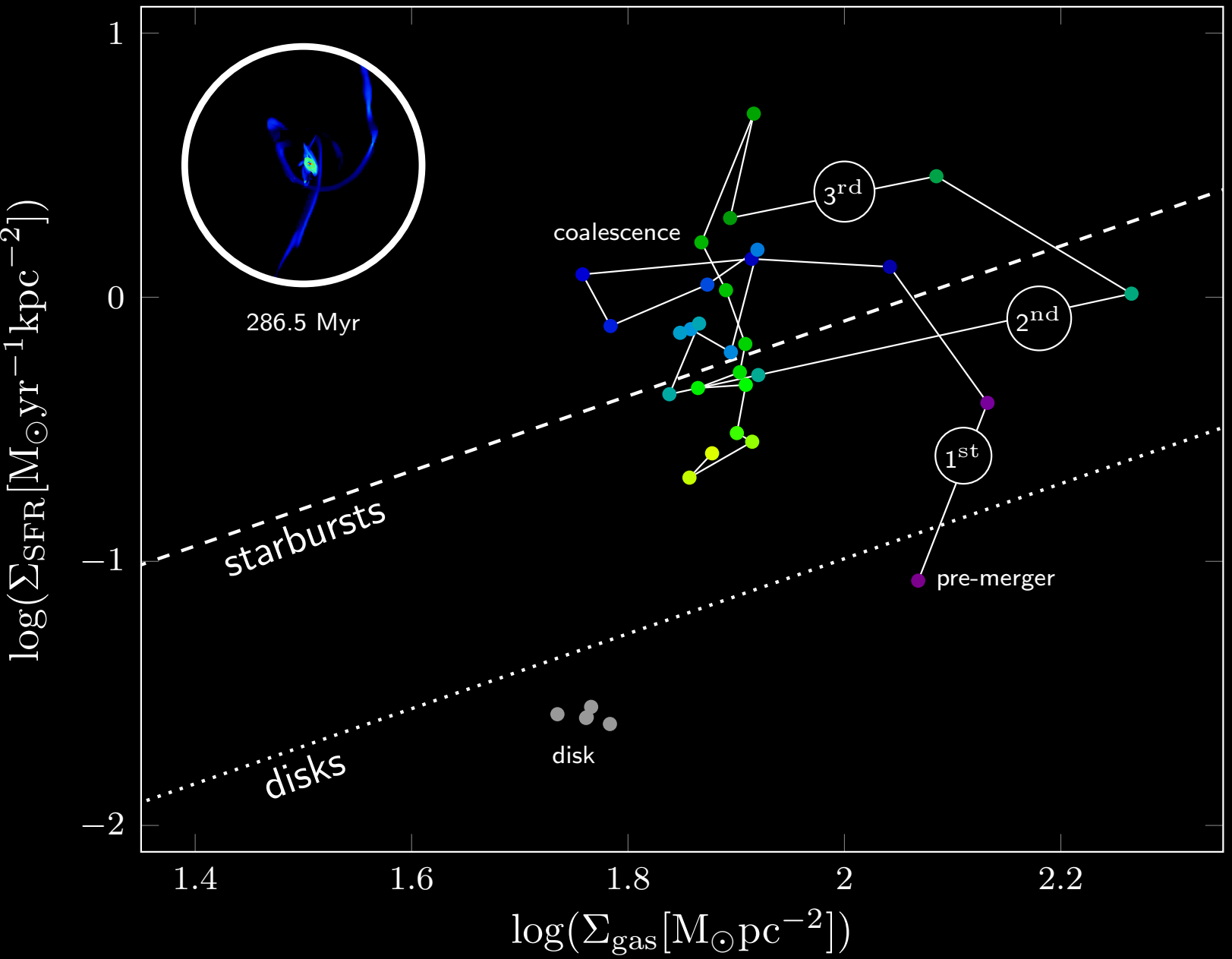

1
0
−1
−2
1.4
1.6
1.8
2
2.2
$\log(\Sigma_{\rm SFR}\,[{\rm M}_\odot{\rm yr}^{-1}{\rm kpc}^{-2}])$
$\log(\Sigma_{\rm gas}\,[{\rm M}_\odot{\rm pc}^{-2}])$
230.2 Myr
coalescence
3rd
2nd
1st
pre-merger
starbursts
disks
disk

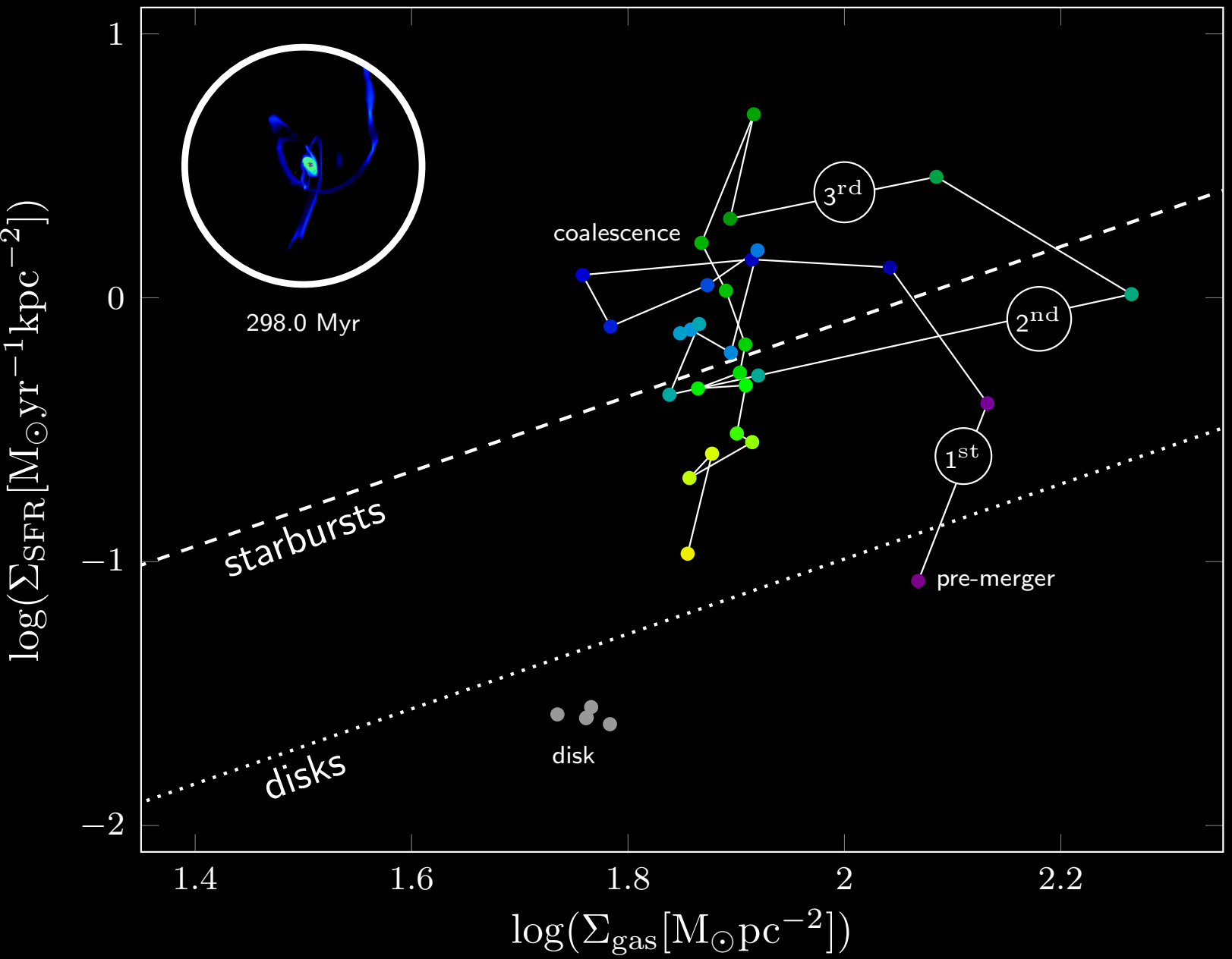

242.0 Myr
coalescence
3rd
2nd
1st
pre-merger
starbursts
disks
disk
1
0
−1
−2
1.4
1.6
1.8
2
2.2
log(Σgas [M⊙ pc−2])
log(ΣSFR [M⊙ yr−1 kpc−2])

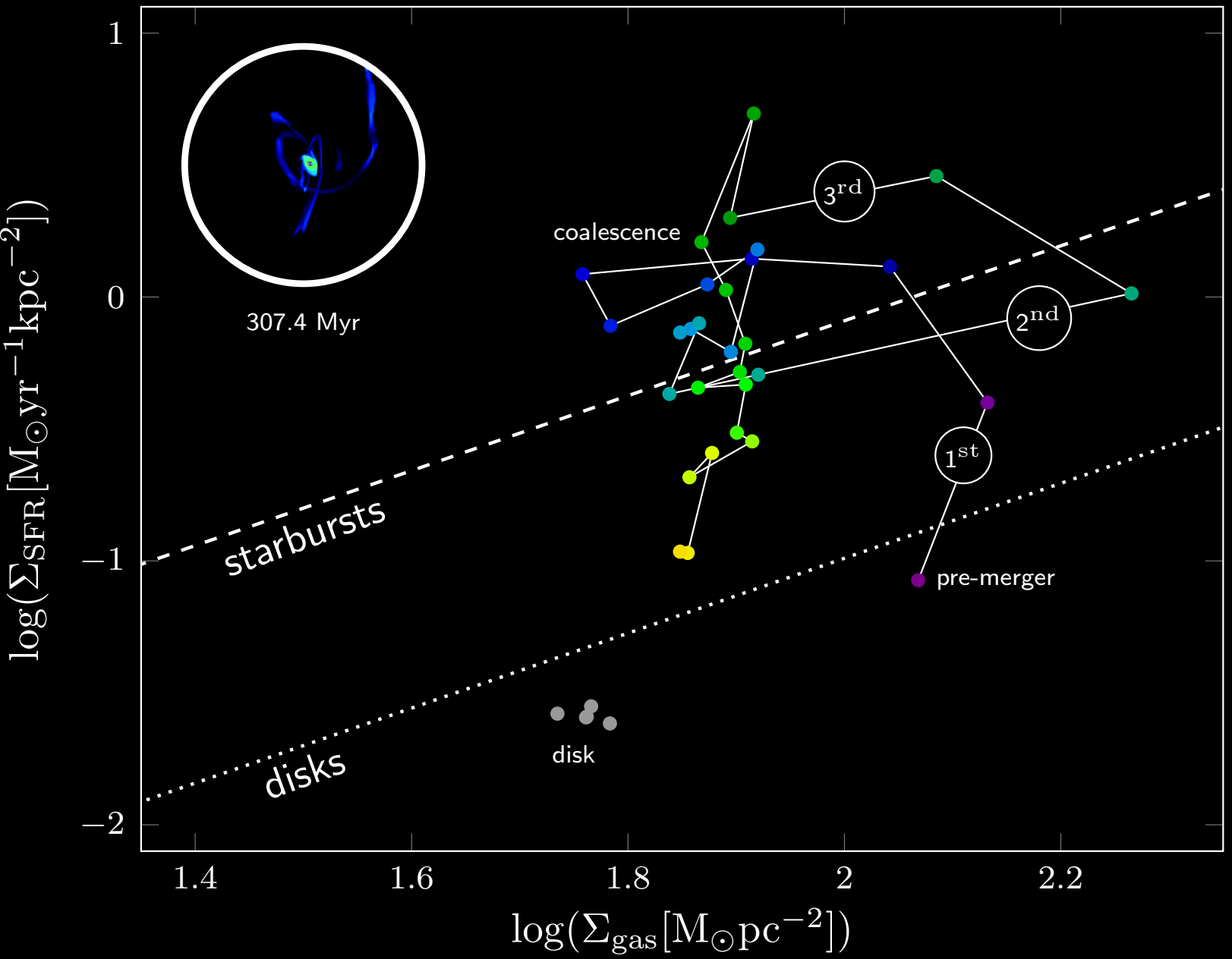

252.0 Myr
coalescence
3rd
2nd
1st
pre-merger
starbursts
disks
disk
1
0
−1
−2
1.4
1.6
1.8
2
2.2
log(Σgas [M⊙ pc−2])
log(ΣSFR [M⊙ yr−1 kpc−2])

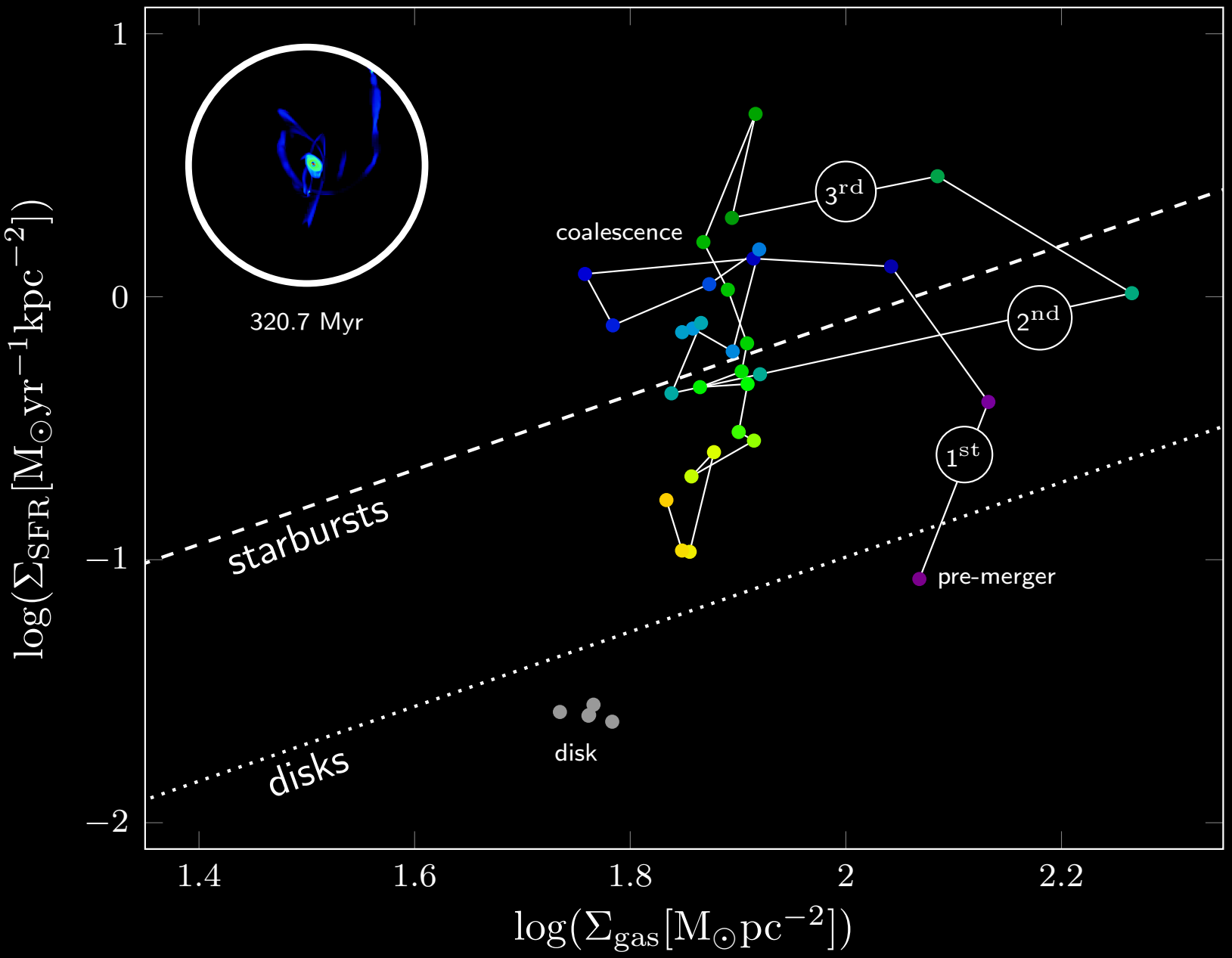

264.0 Myr
coalescence
3rd
2nd
1st
pre-merger
starbursts
disks
disk
1
0
−1
−2
1.4
1.6
1.8
2
2.2
log(Σgas [M⊙ pc−2])
log(ΣSFR [M⊙ yr−1 kpc−2])

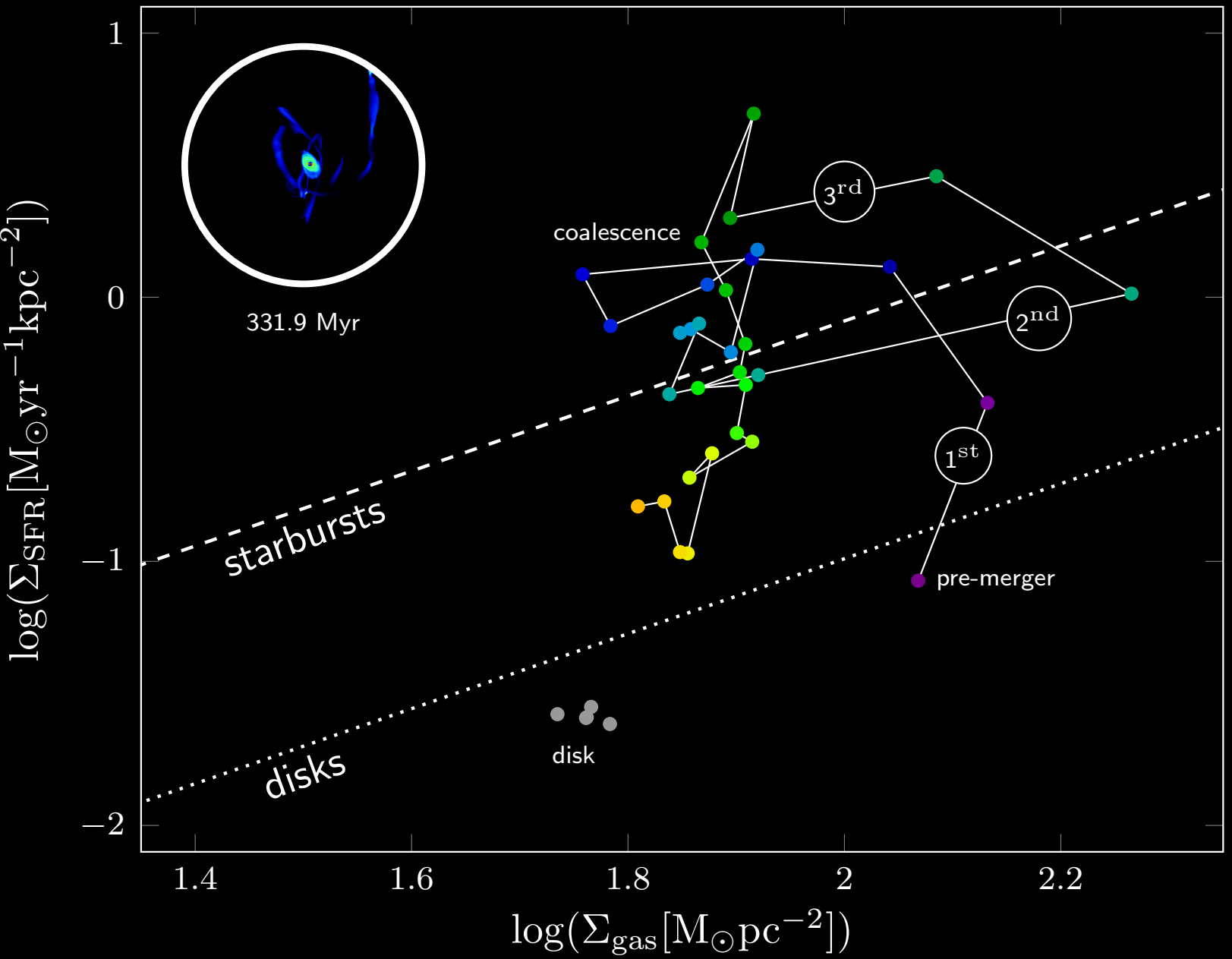

275.0 Myr
coalescence
3rd
2nd
1st
pre-merger
starbursts
disks
disk
1
0
−1
−2
1.4
1.6
1.8
2
2.2
log(Σgas [M⊙ pc−2])
log(ΣSFR [M⊙ yr−1 kpc−2])

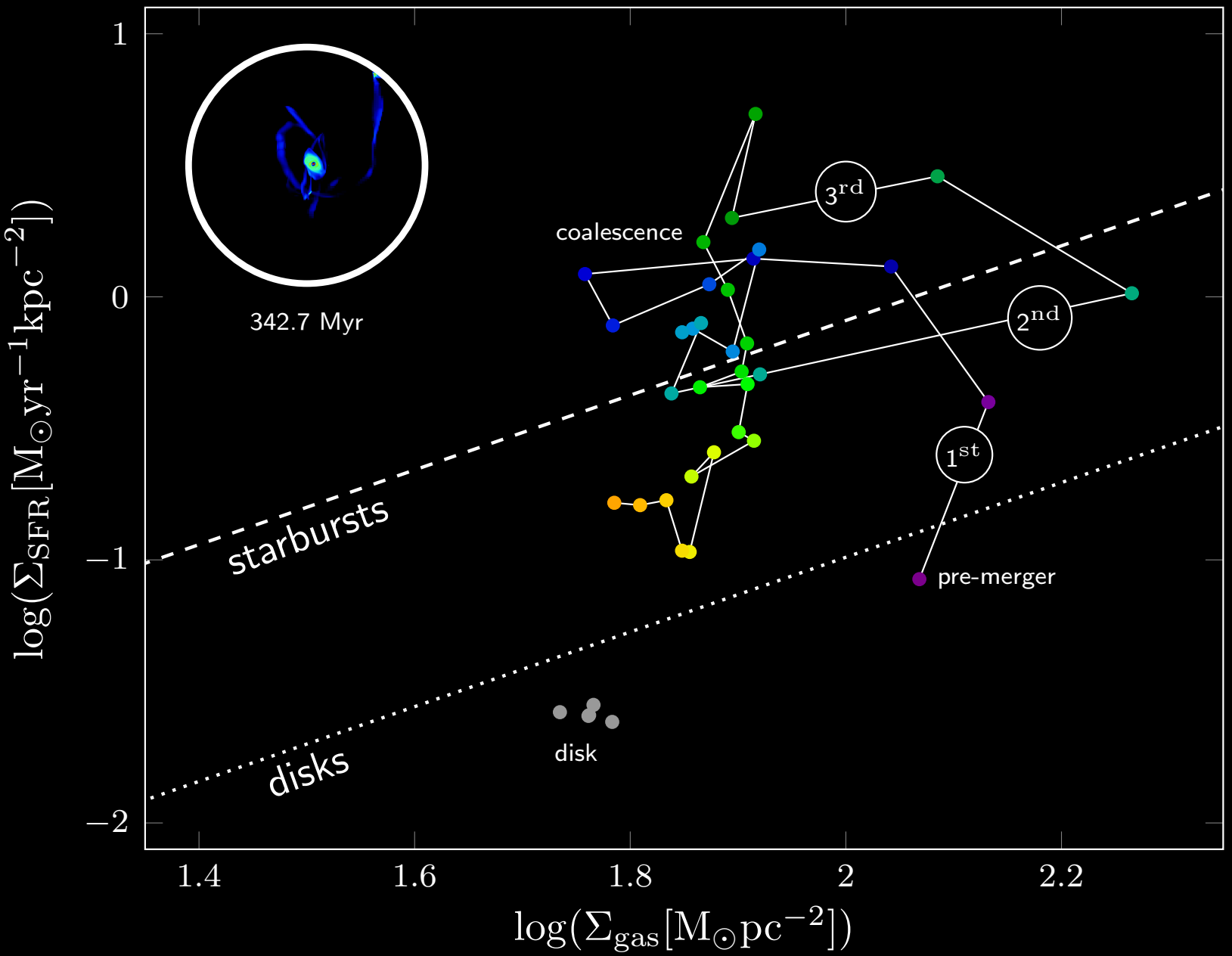

286.5 Myr
coalescence
3rd
2nd
1st
pre-merger
starbursts
disks
disk
1
0
−1
−2
1.4
1.6
1.8
2
2.2
log(Σgas [M⊙ pc−2])
log(ΣSFR [M⊙ yr−1 kpc−2])

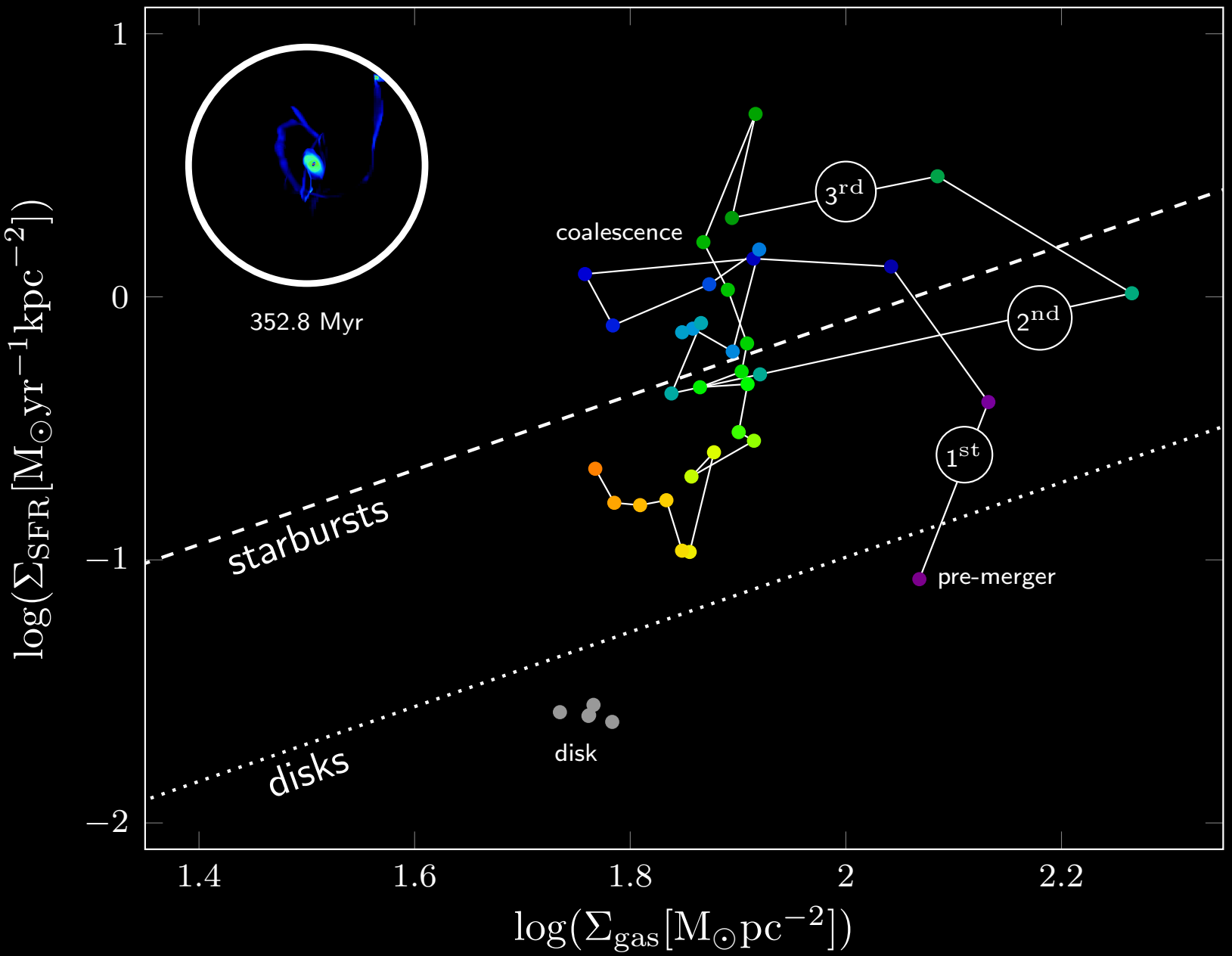

298.0 Myr
coalescence
3rd
2nd
1st
pre-merger
starbursts
disks
disk
1
0
−1
−2
1.4
1.6
1.8
2
2.2
log(Σgas [M⊙ pc−2])
log(ΣSFR [M⊙ yr−1 kpc−2])

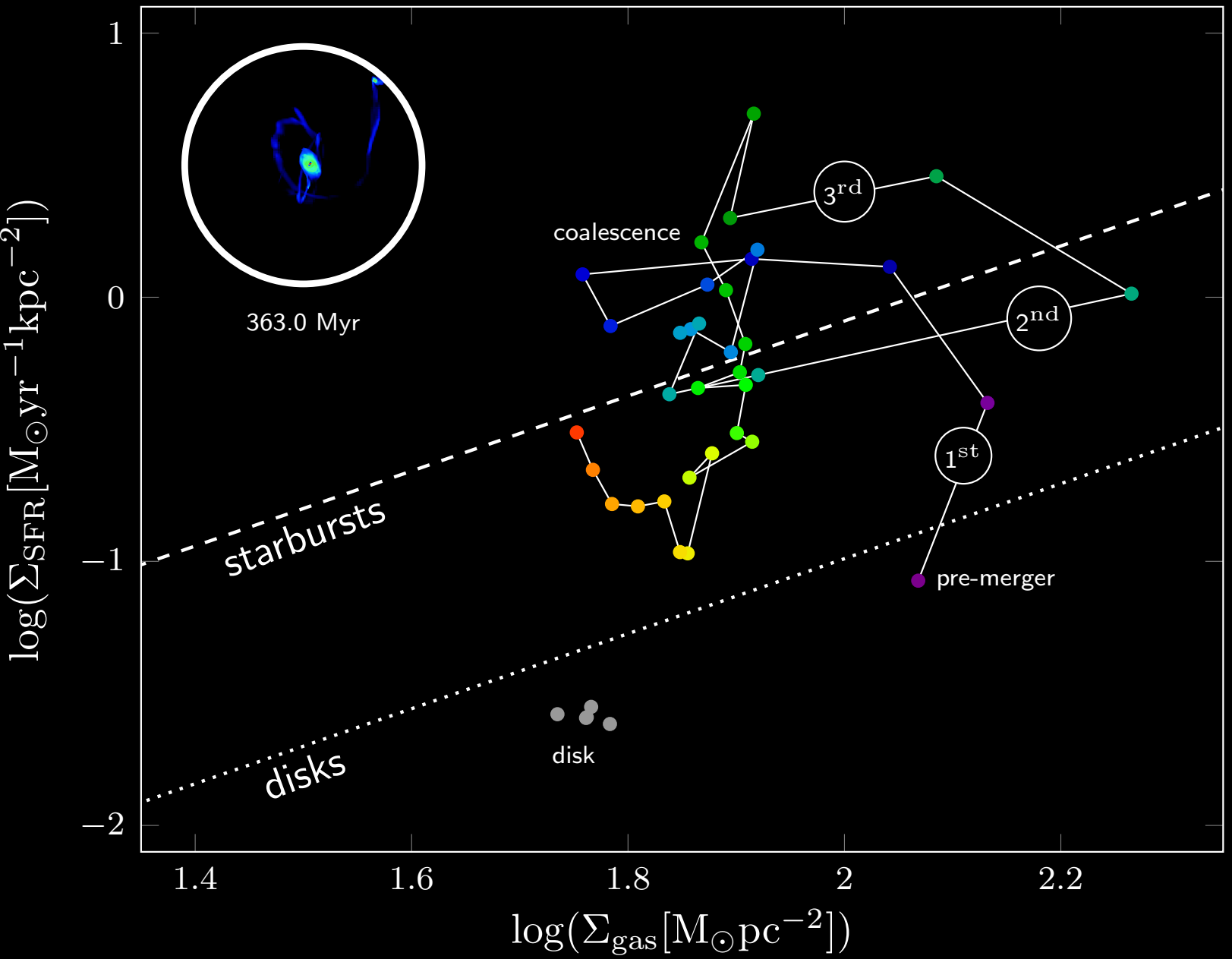

307.4 Myr
coalescence
3rd
2nd
1st
pre-merger
starbursts
disks
disk
1
0
−1
−2
1.4
1.6
1.8
2
2.2
log(Σgas [M⊙ pc−2])
log(ΣSFR [M⊙ yr−1 kpc−2])

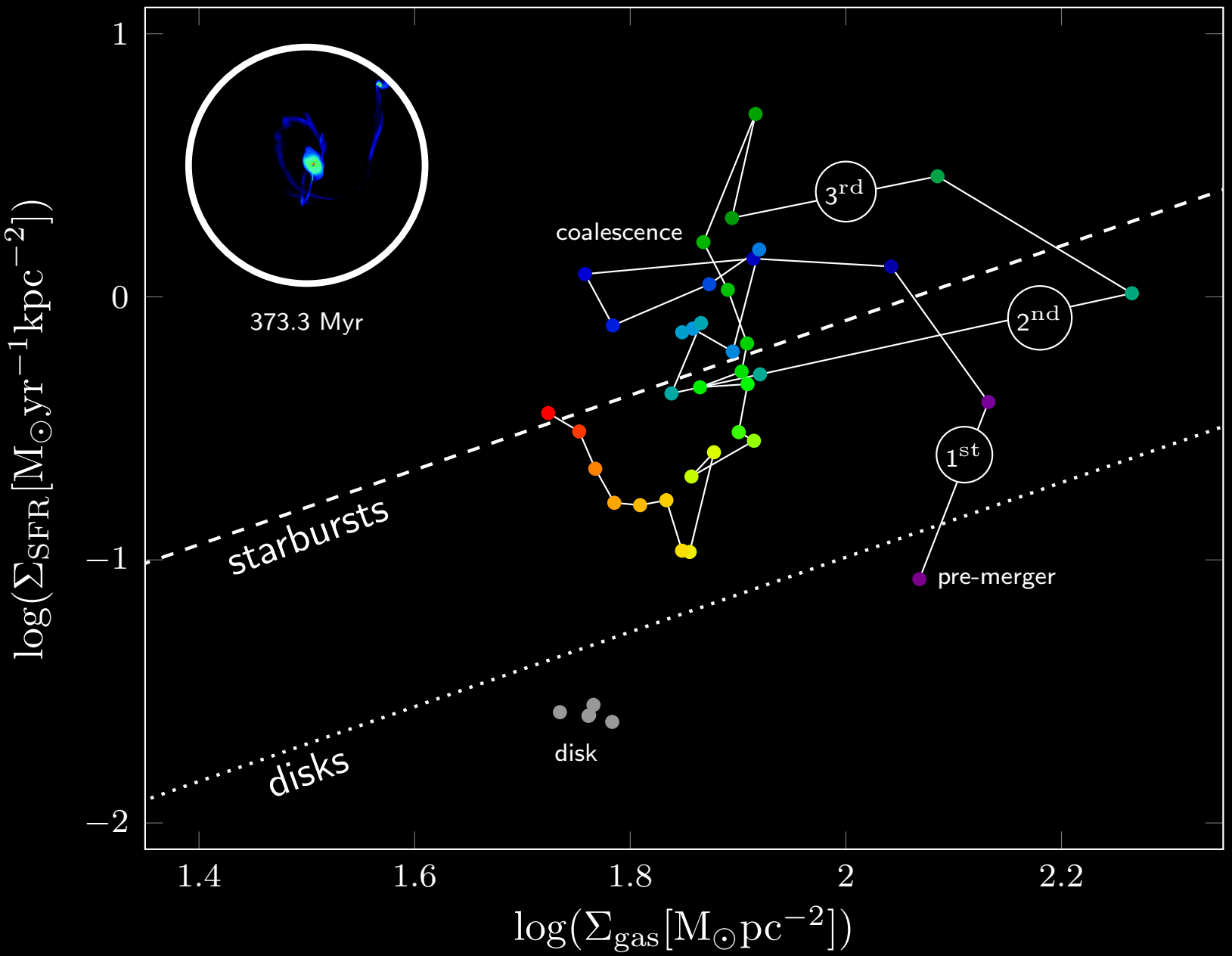

320.7 Myr
coalescence
3rd
2nd
1st
pre-merger
starbursts
disks
disk
1
0
−1
−2
1.4
1.6
1.8
2
2.2
log(Σgas [M⊙ pc−2])
log(ΣSFR [M⊙ yr−1 kpc−2])

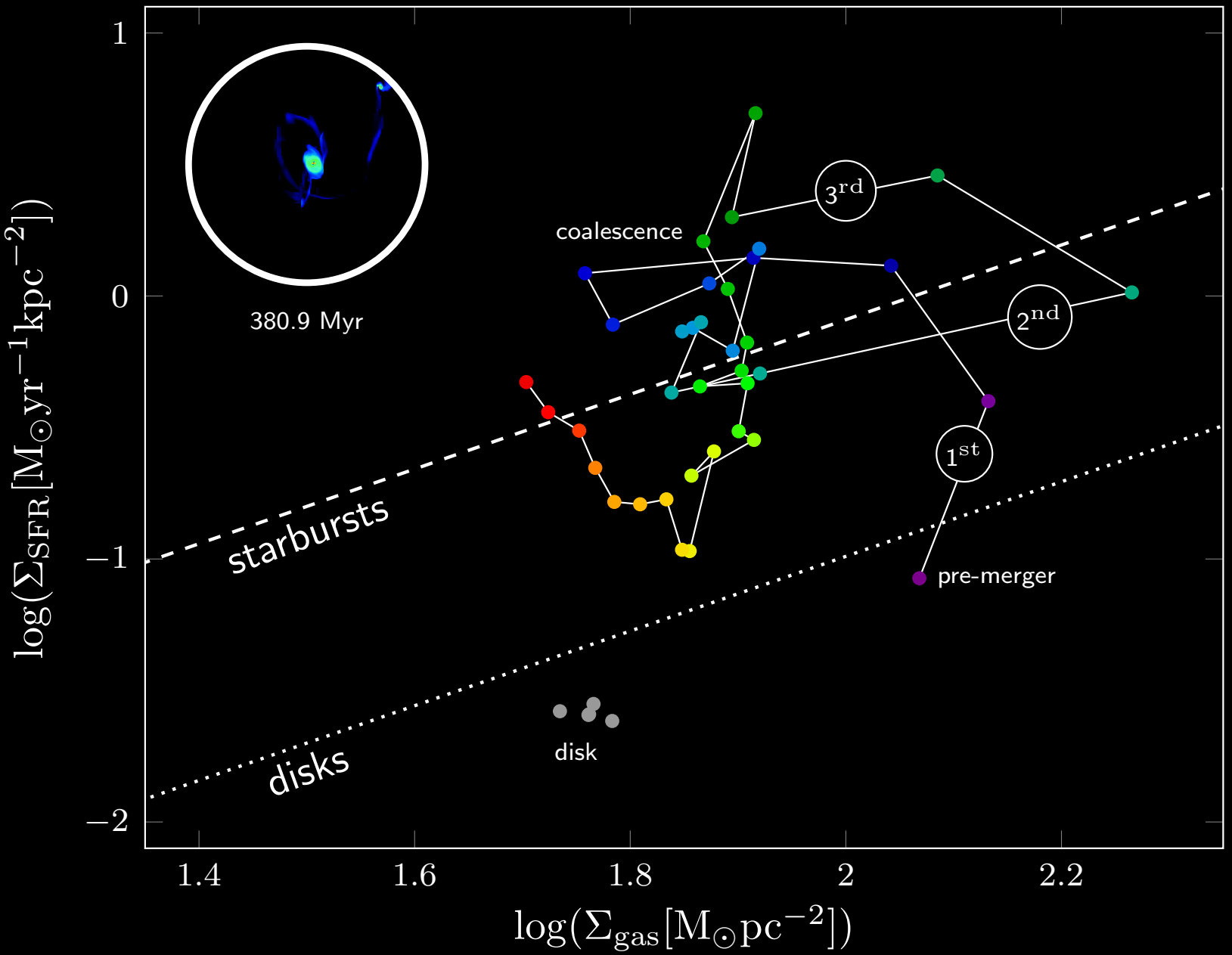

331.9 Myr
coalescence
3rd
2nd
1st
pre-merger
starbursts
disks
disk
1
0
−1
−2
1.4
1.6
1.8
2
2.2
log(Σgas [M⊙ pc−2])
log(ΣSFR [M⊙ yr−1 kpc−2])

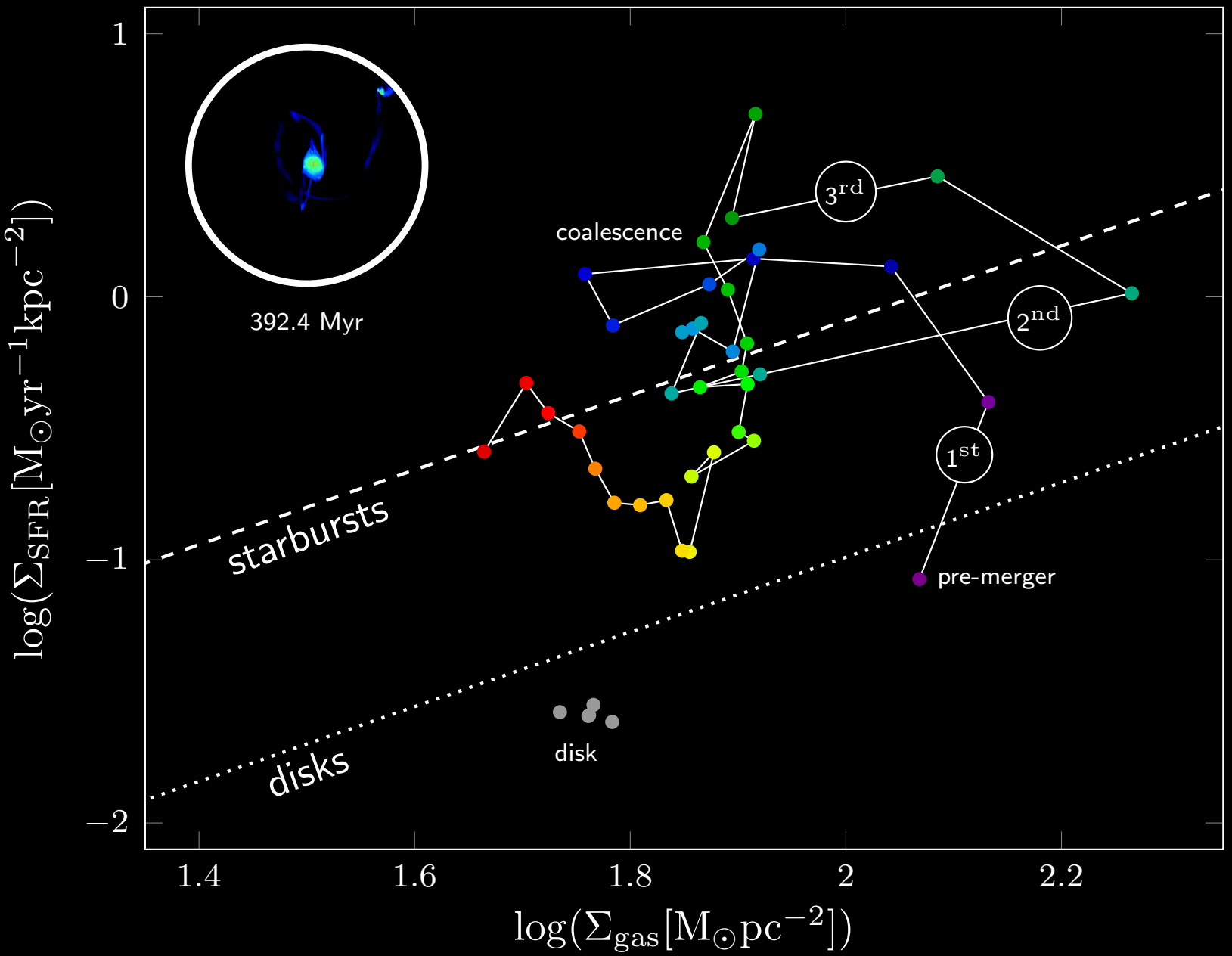

342.7 Myr
coalescence
3rd
2nd
1st
pre-merger
starbursts
disks
disk
1
0
−1
−2
1.4
1.6
1.8
2
2.2
log(Σgas [M⊙ pc−2])
log(ΣSFR [M⊙ yr−1 kpc−2])

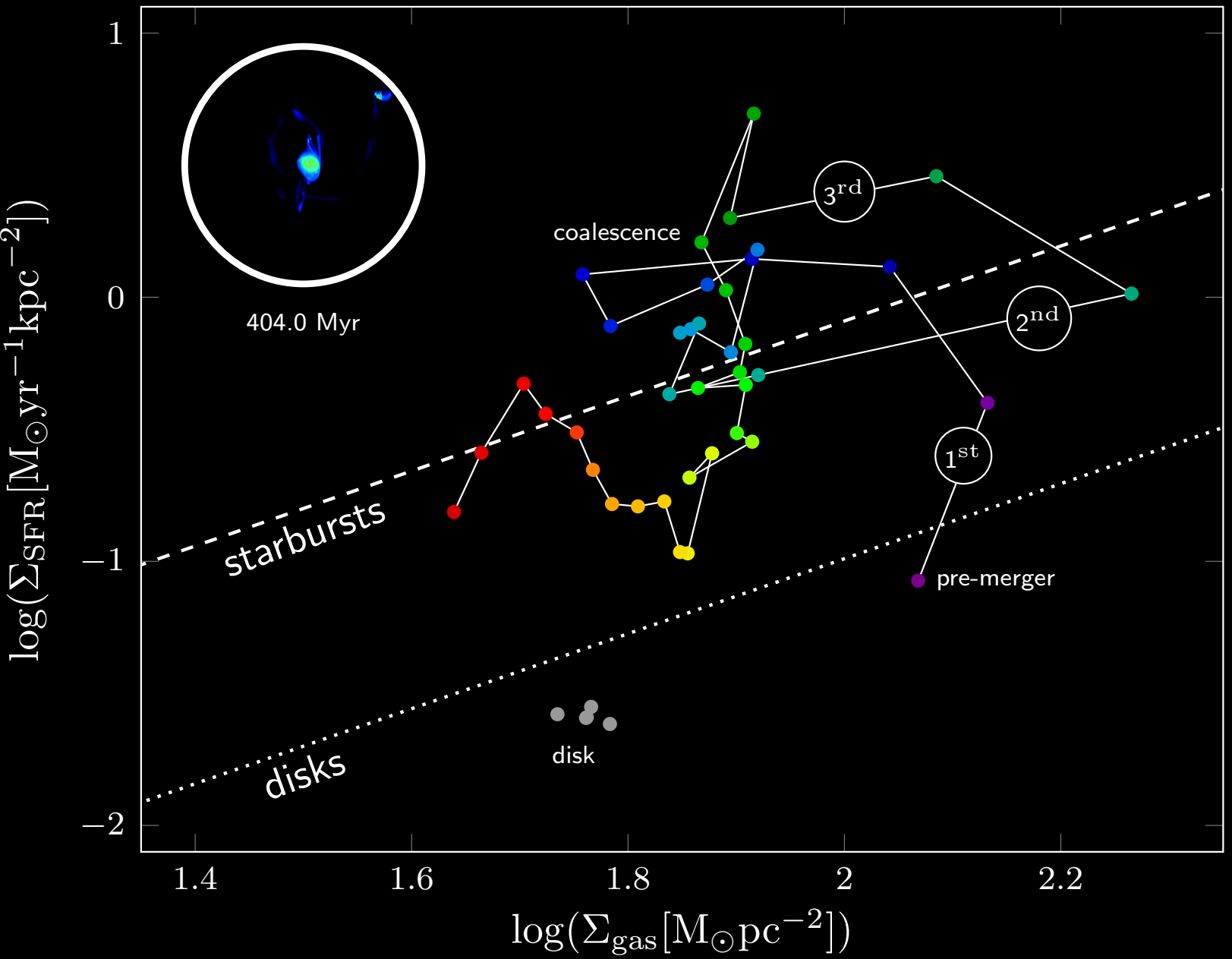

352.8 Myr
coalescence
3rd
2nd
1st
pre-merger
starbursts
disks
disk
1
0
−1
−2
1.4
1.6
1.8
2
2.2
log(Σgas [M⊙ pc−2])
log(ΣSFR [M⊙ yr−1 kpc−2])

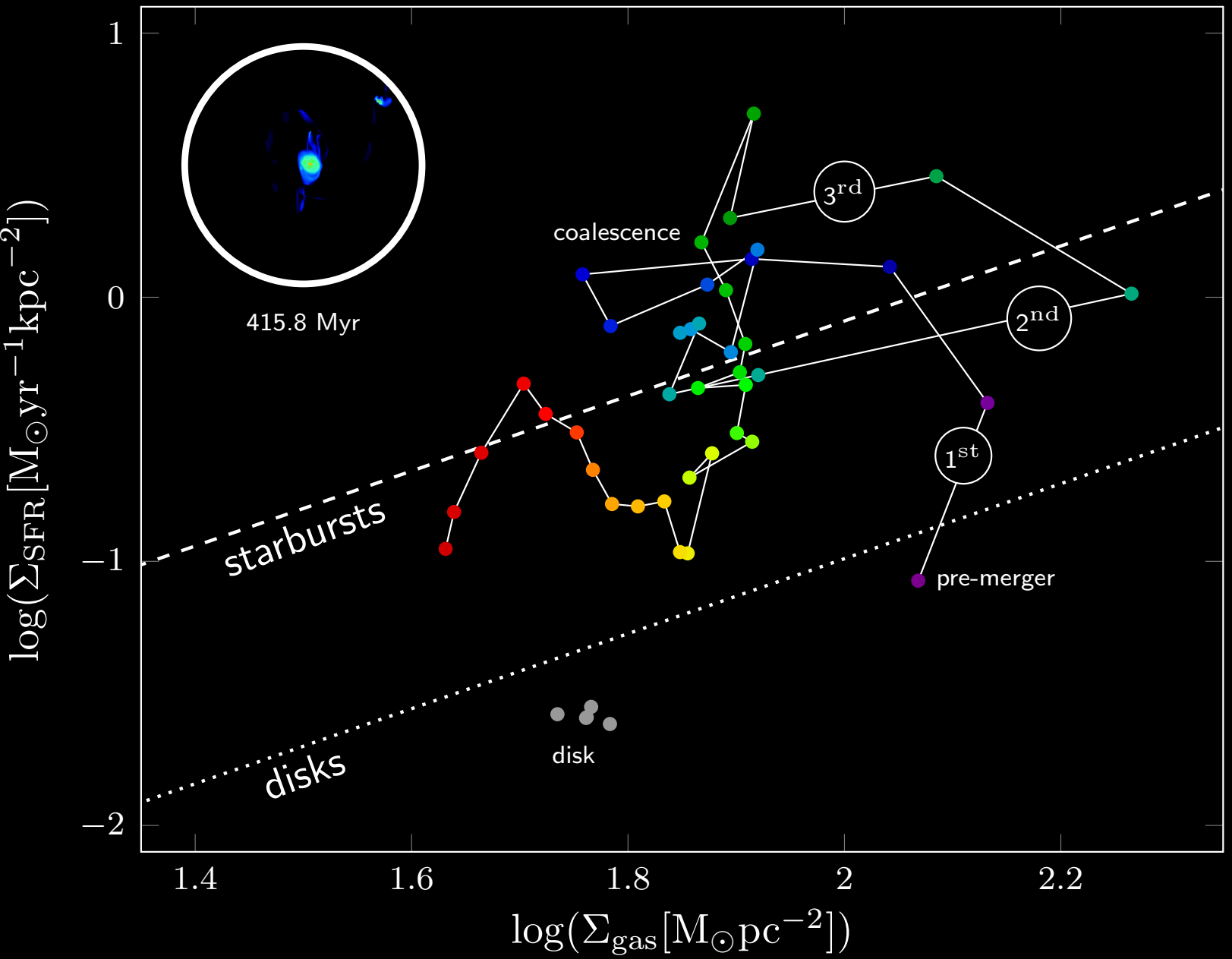

363.0 Myr
coalescence
3rd
2nd
1st
pre-merger
starbursts
disks
disk
1
0
−1
−2
1.4
1.6
1.8
2
2.2
log(Σgas [M⊙ pc−2])
log(ΣSFR [M⊙ yr−1 kpc−2])

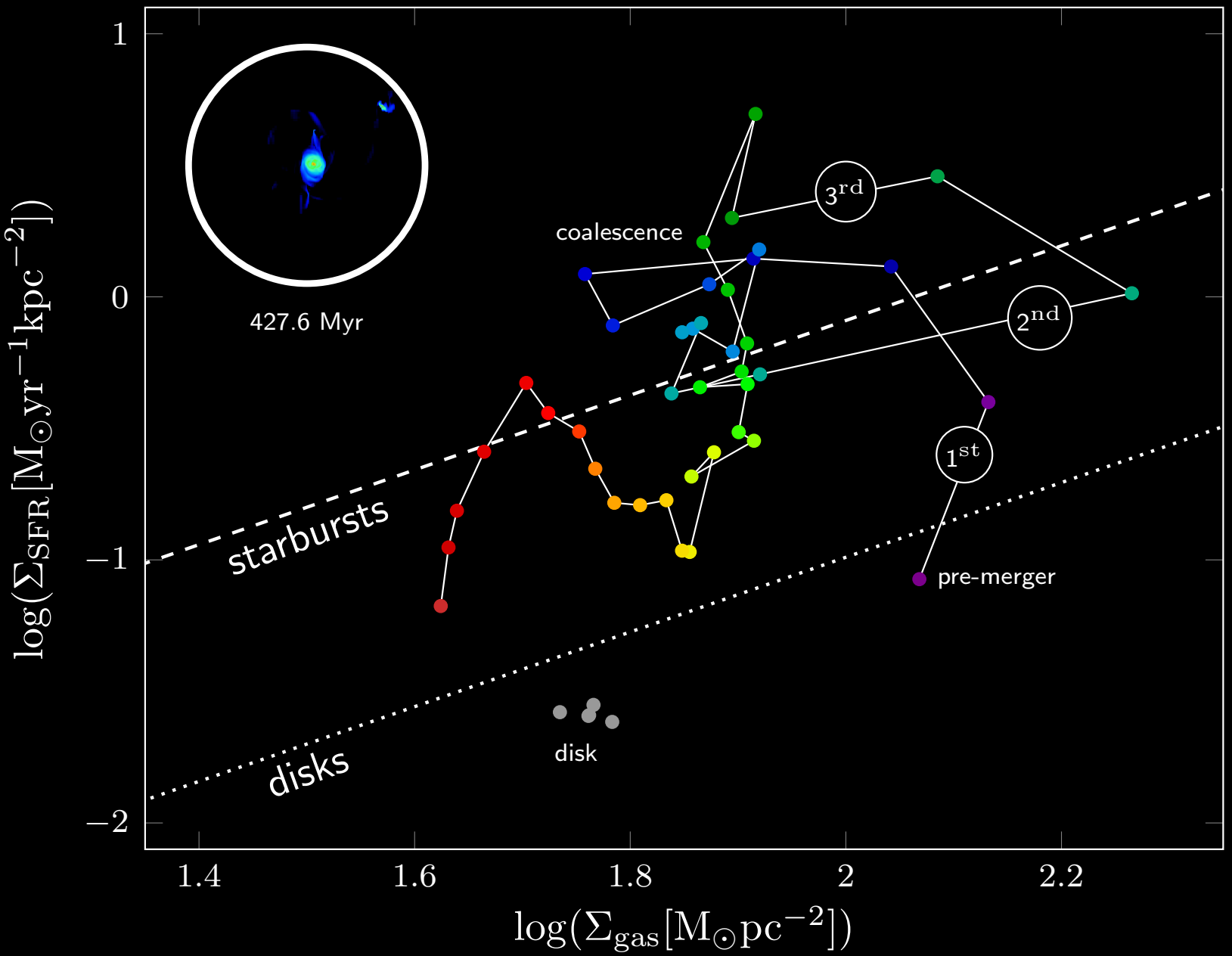

373.3 Myr
coalescence
3rd
2nd
1st
pre-merger
starbursts
disks
disk
1
0
−1
−2
1.4
1.6
1.8
2
2.2
log(Σgas [M⊙ pc−2])
log(ΣSFR [M⊙ yr−1 kpc−2])

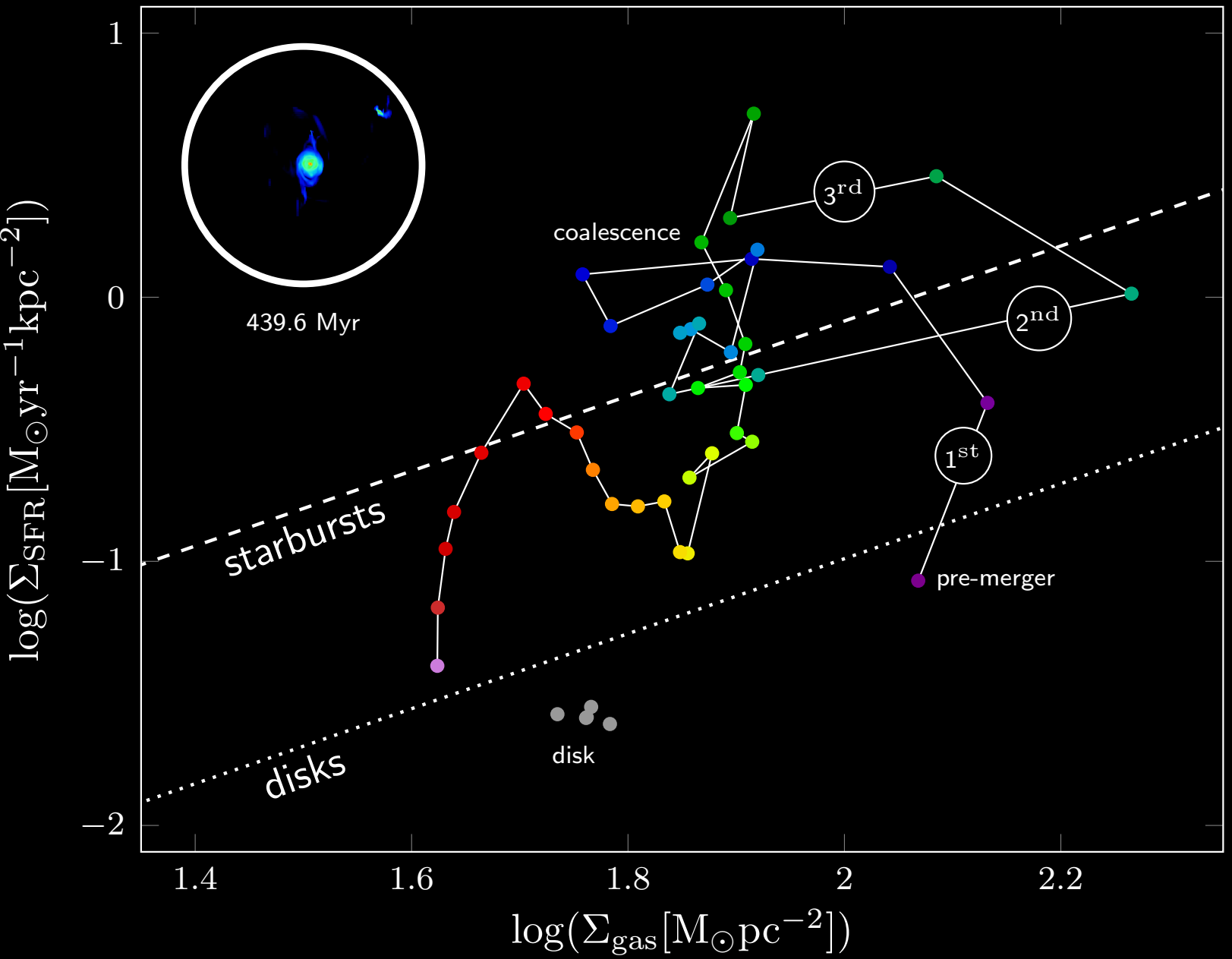

380.9 Myr
coalescence
3rd
2nd
1st
pre-merger
starbursts
disks
disk
1
0
−1
−2
1.4
1.6
1.8
2
2.2
log(Σgas [M⊙ pc−2])
log(ΣSFR [M⊙ yr−1 kpc−2])

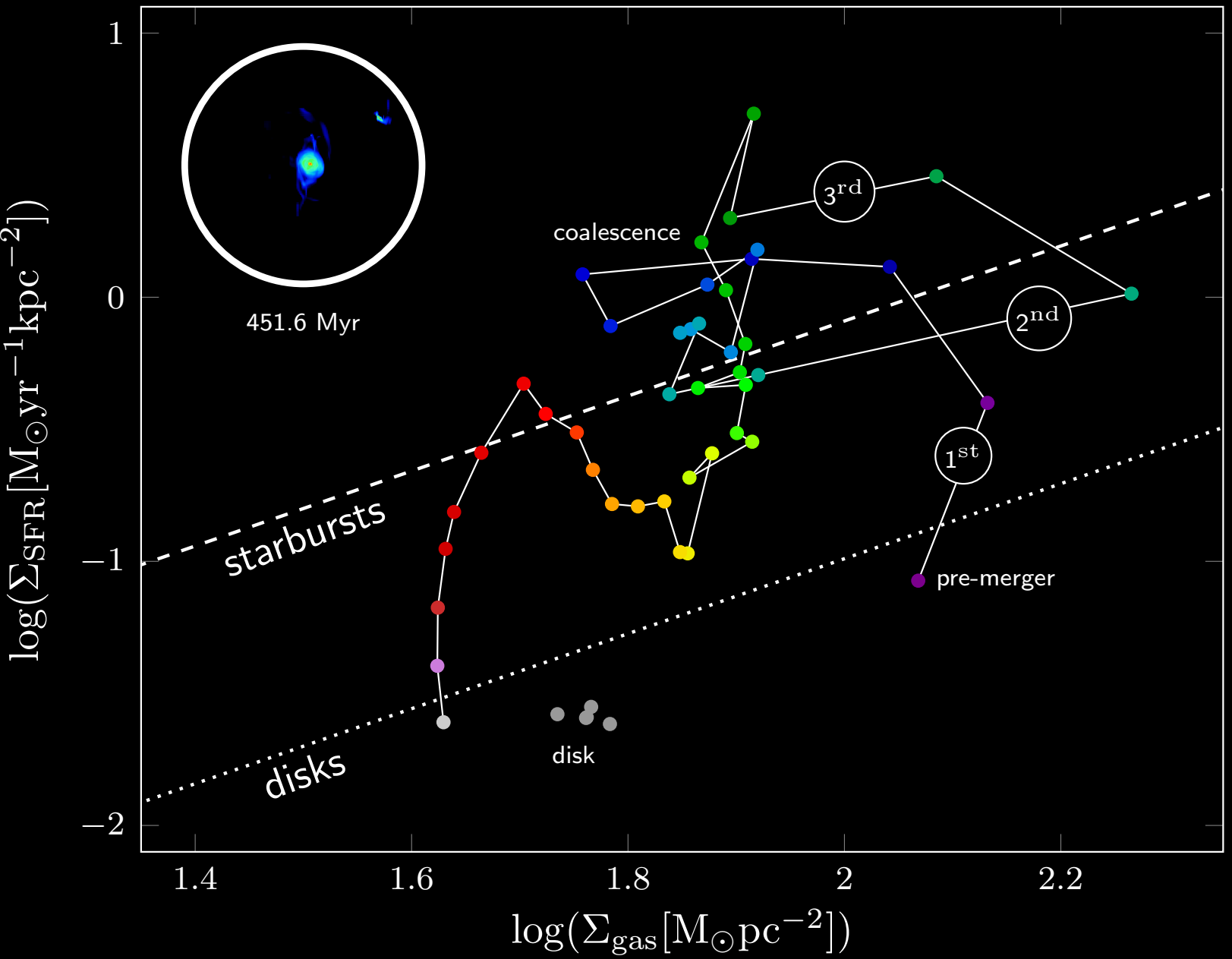

392.4 Myr
coalescence
3rd
2nd
1st
pre-merger
starbursts
disks
disk
1
0
−1
−2
1.4
1.6
1.8
2
2.2
log(Σgas [M⊙ pc−2])
log(ΣSFR [M⊙ yr−1 kpc−2])

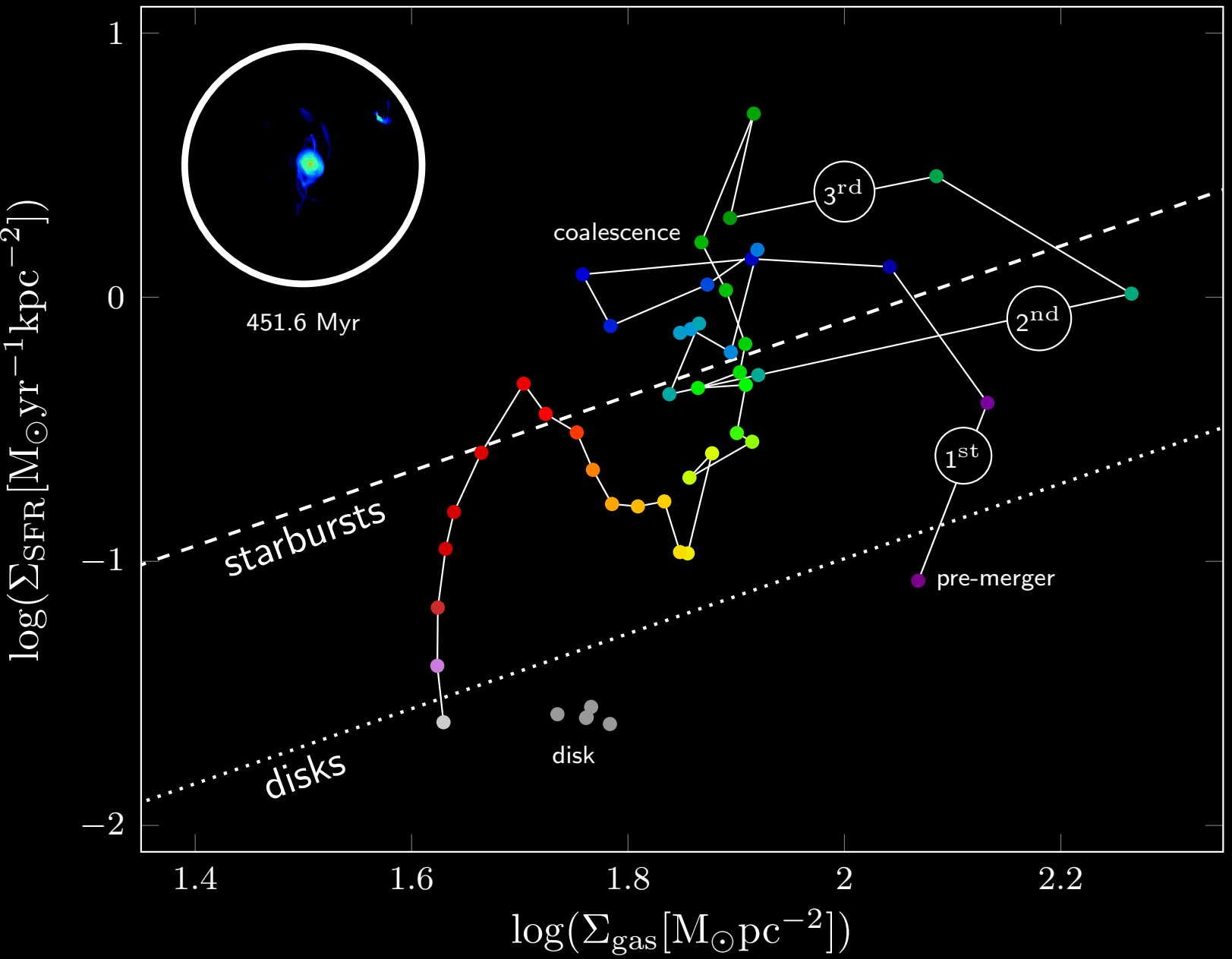

404.0 Myr
coalescence
3rd
2nd
1st
starbursts
disks
pre-merger
disk
1
0
−1
−2
1.4
1.6
1.8
2
2.2
log(Σgas [M⊙ pc−2])
log(ΣSFR [M⊙ yr−1 kpc−2])

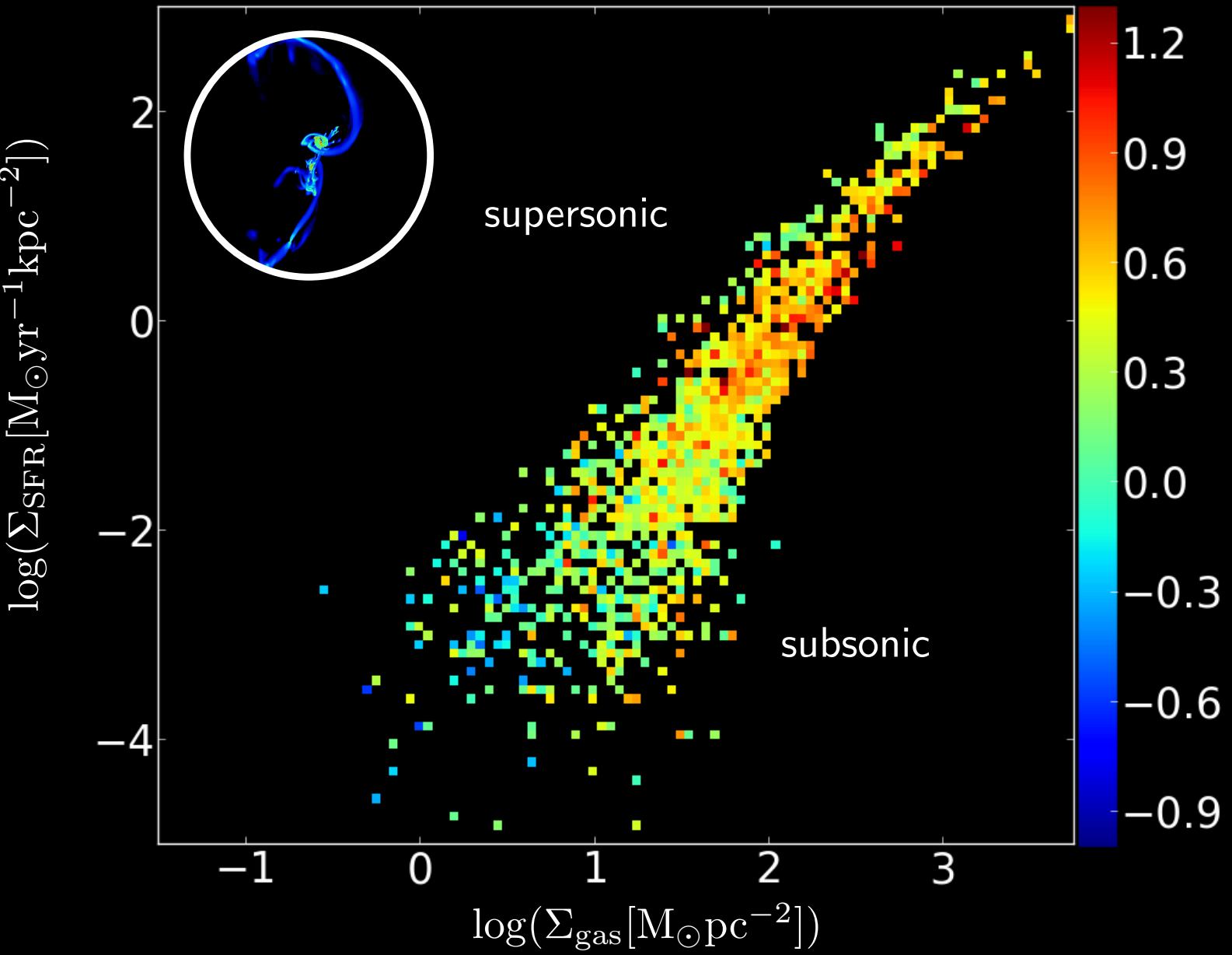

415.8 Myr
coalescence
3rd
2nd
1st
pre-merger
starbursts
disks
disk
1
0
−1
−2
1.4
1.6
1.8
2
2.2
log(Σgas [M⊙ pc−2])
log(ΣSFR [M⊙ yr−1 kpc−2])

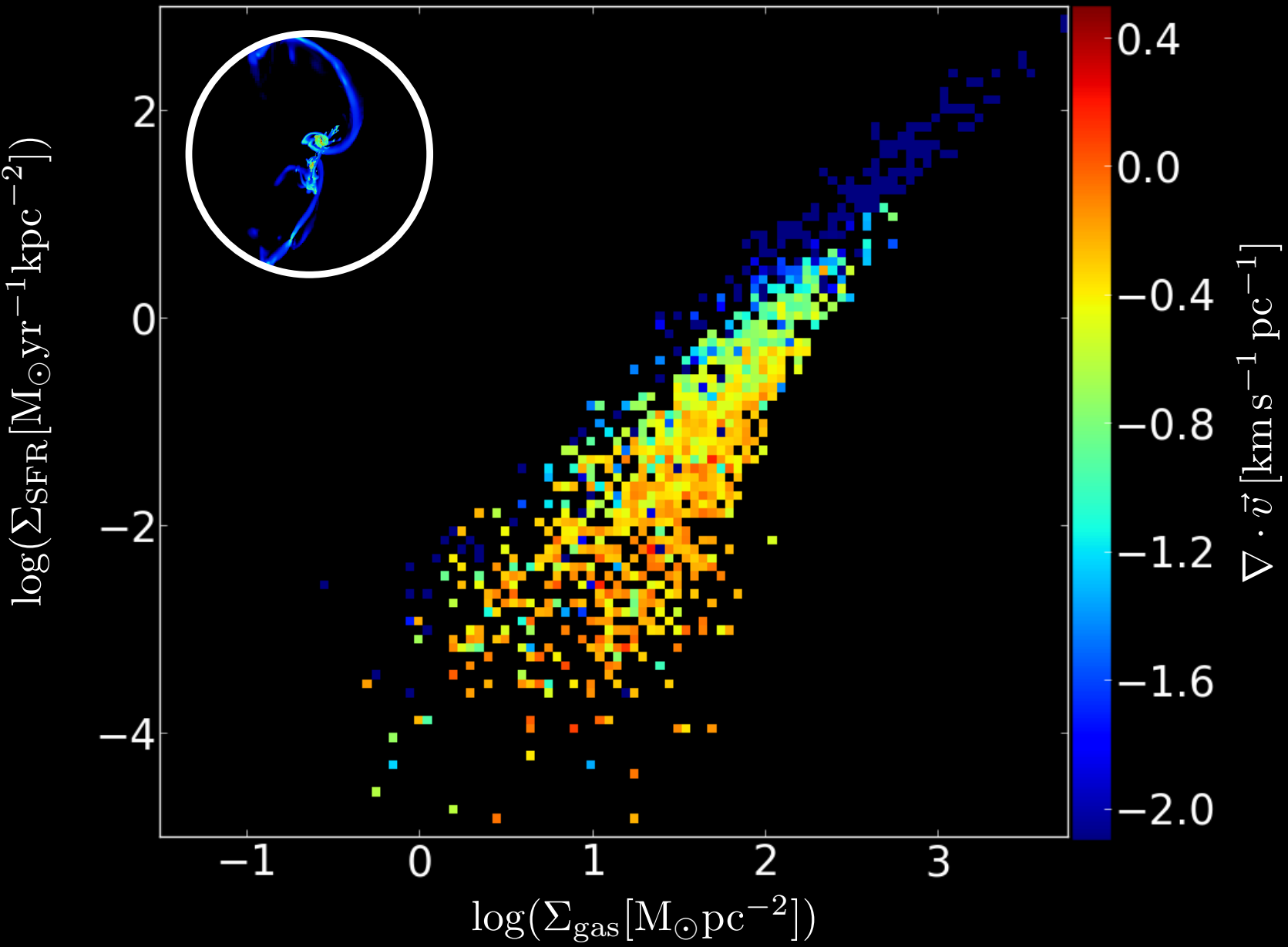

427.6 Myr
coalescence
3rd
2nd
1st
pre-merger
starbursts
disks
disk
1
0
−1
−2
1.4
1.6
1.8
2
2.2
log(Σgas [M⊙ pc−2])
log(ΣSFR [M⊙ yr−1 kpc−2])


439.6 Myr
coalescence
3rd
2nd
1st
pre-merger
starbursts
disks
disk
1
0
−1
−2
1.4
1.6
1.8
2
2.2
log(Σgas [M⊙ pc−2])
log(ΣSFR [M⊙ yr−1 kpc−2])


451.6 Myr
coalescence
3rd
2nd
1st
pre-merger
starbursts
disks
disk
1
0
−1
−2
1.4
1.6
1.8
2
2.2
log(Σgas [M⊙ pc−2])
log(ΣSFR [M⊙ yr−1 kpc−2])


451.6 Myr
coalescence
3rd
2nd
1st
pre-merger
starbursts
disks
disk
1
0
−1
−2
1.4
1.6
1.8
2
2.2
log(Σgas [M⊙ pc−2])
log(ΣSFR [M⊙ yr−1 kpc−2])


supersonic
subsonic
$\log(\Sigma_{\rm SFR}[{\rm M}_\odot{\rm yr}^{-1}{\rm kpc}^{-2}])$
$\log(\Sigma_{\rm gas}[{\rm M}_\odot{\rm pc}^{-2}])$
$\log(\mathcal{M})$
2
0
−2
−4
−1
0
1
2
3
1.2
0.9
0.6
0.3
0.0
−0.3
−0.6
−0.9


2
0
−2
−4
−1
0
1
2
3
$\log(\Sigma_{\rm SFR}[{\rm M}_\odot{\rm yr}^{-1}{\rm kpc}^{-2}])$
$\log(\Sigma_{\rm gas}[{\rm M}_\odot{\rm pc}^{-2}])$
0.4
0.0
−0.4
−0.8
−1.2
−1.6
−2.0
$\nabla\cdot\vec{v}\,[{\rm km\,s}^{-1}\,{\rm pc}^{-1}]$

Surface: $$V = hS = \int_0^\infty \frac{Mf(x)}{\rho}\,dx = \frac{M}{\overline{\rho}}\int_0^\infty \frac{f(x)}{x}\,dx$$

Surface: $$V = hS = \int_0^\infty \frac{Mf(x)}{\rho}\,dx = \frac{M}{\overline{\rho}}\int_0^\infty \frac{f(x)}{x}\,dx$$

SFR: $$\Sigma_{\mathrm{SFR}} = \frac{M_{\mathrm{SFR}}}{S} = \frac{1}{S}\int_0^\infty \frac{Mf(x)}{\rho}\rho_{\mathrm{SFR}}(x)\,dx$$

Surface: $$V = hS = \int_0^\infty \frac{Mf(x)}{\rho}\,dx = \frac{M}{\overline{\rho}}\int_0^\infty \frac{f(x)}{x}\,dx$$

SFR: $$\Sigma_{\mathrm{SFR}} = \frac{M_{\mathrm{SFR}}}{S} = \frac{1}{S}\int_0^\infty \frac{Mf(x)}{\rho}\rho_{\mathrm{SFR}}(x)\,dx$$

$$\Rightarrow$$

General $\Sigma_{\mathrm{SFR}}$: $$\Sigma_{\mathrm{SFR}} = h\frac{\int_0^\infty f(x)x^{-1}\rho_{\mathrm{SFR}}(x)\,dx}{\int_0^\infty f(x)x^{-1}\,dx}$$

Surface: $$V = hS = \int_0^\infty \frac{Mf(x)}{\rho}\,dx = \frac{M}{\overline{\rho}}\int_0^\infty \frac{f(x)}{x}\,dx$$

SFR: $$\Sigma_{\rm SFR} = \frac{M_{\rm SFR}}{S} = \frac{1}{S}\int_0^\infty \frac{Mf(x)}{\rho}\rho_{\rm SFR}(x)\,dx$$

$$\Rightarrow$$

General $\Sigma_{\rm SFR}$: $$\Sigma_{\rm SFR} = h\frac{\int_0^\infty f(x)x^{-1}\rho_{\rm SFR}(x)\,dx}{\int_0^\infty f(x)x^{-1}\,dx}$$

2 ingredients: $f(x)$ - how gas is distributed

Surface: $$V = hS = \int_0^\infty \frac{Mf(x)}{\rho}\,dx = \frac{M}{\bar{\rho}}\int_0^\infty \frac{f(x)}{x}\,dx$$

SFR: $$\Sigma_{\rm SFR} = \frac{M_{\rm SFR}}{S} = \frac{1}{S}\int_0^\infty \frac{Mf(x)}{\rho}\rho_{\rm SFR}(x)\,dx$$

$$\Rightarrow$$

General $\Sigma_{\rm SFR}$: $$\Sigma_{\rm SFR} = h\frac{\int_0^\infty f(x)x^{-1}\rho_{\rm SFR}(x)\,dx}{\int_0^\infty f(x)x^{-1}\,dx}$$

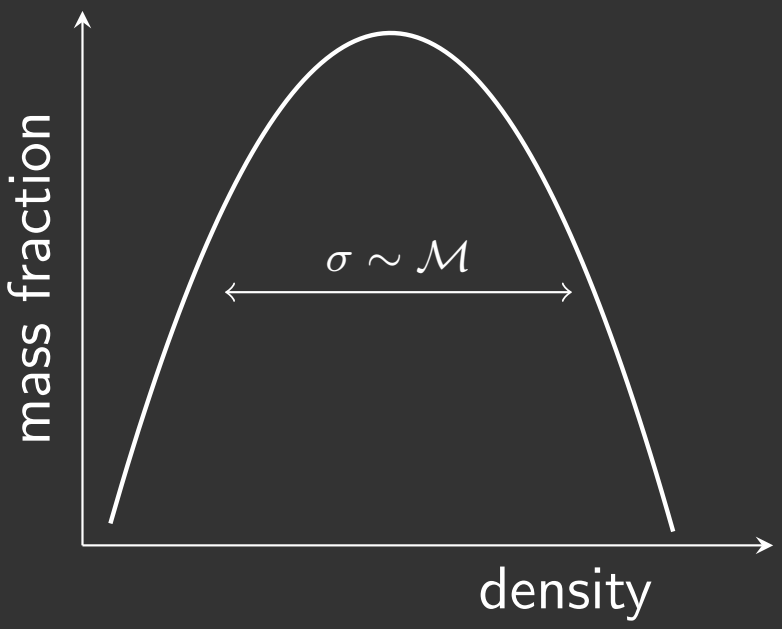
2 ingredients:

$f(x)$ - how gas is distributed

$\rho_{\rm SFR}(x)$ - how gas is converted into stars

**PDF**

- turbulence
- log-normal density distribution




$$f_\sigma(x) = \frac{1}{x\sqrt{2\sigma^2\pi}} \exp\left[-\frac{\left(\ln(x) - \frac{\sigma^2}{2}\right)^2}{2\sigma^2}\right]$$

$\sigma^2 = \ln(1 + b^2\mathcal{M}^2)$

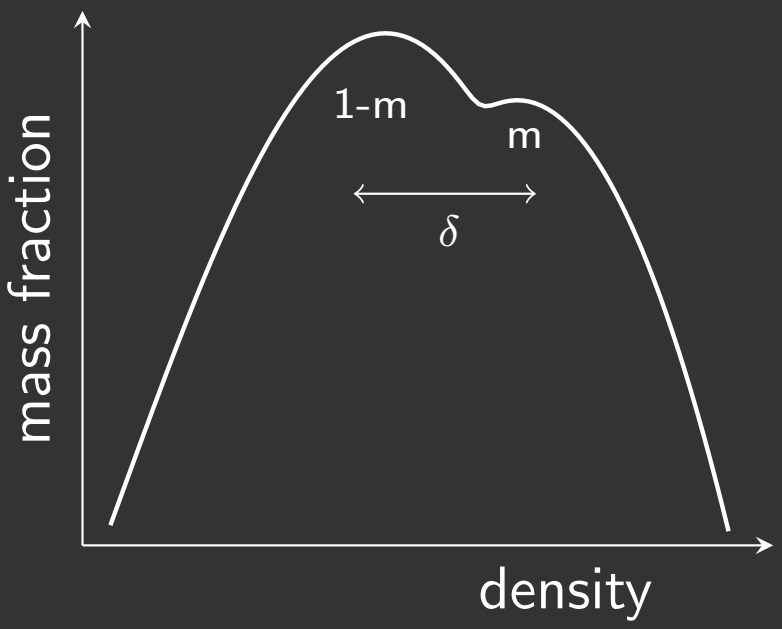
$\mathcal{M} = v_{\rm rms}/c_s$

$b$ – nature of the turbulence

Vazquez-Semadeni (1994)
Nordlund & Padoan (1999)
Wada & Norman (2001) ...

**PDF**

- turbulence
- log-normal density distribution




$$f_\sigma(x) = \frac{1}{x\sqrt{2\sigma^2\pi}} \exp\left[-\frac{\left(\ln(x) - \frac{\sigma^2}{2}\right)^2}{2\sigma^2}\right]$$

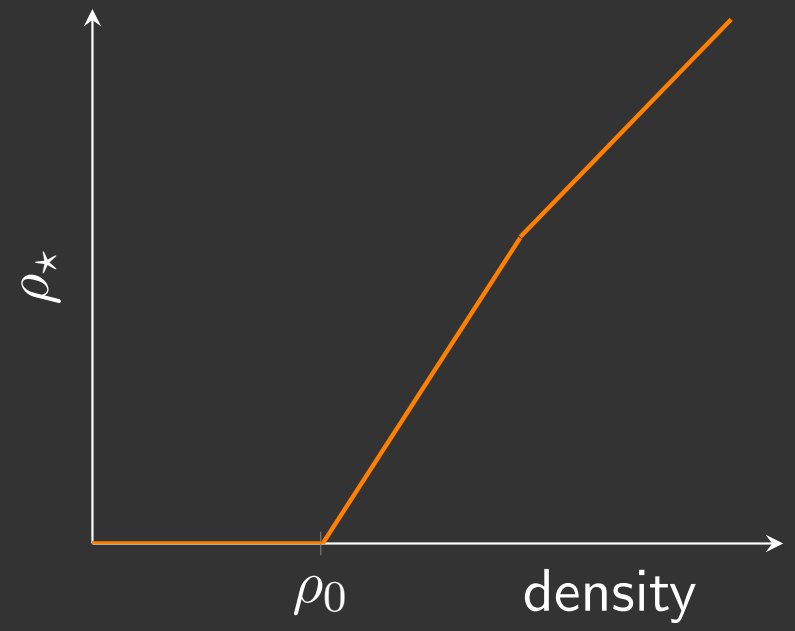
$$f(x) = (1-m) f_{\sigma_1}(x) + m f_{\sigma_2}(x/\exp\delta)$$

Teyssier et al. (2010)
Bournaud et al. (2011)
García-Burillo et al. (2012)
Renaud et al. (2014) ...

**SFR**

- Schmidt relation:
  $\rho_\star = \epsilon \frac{\rho_{\rm gas}}{t_{\rm ff}} \propto {\rho_{\rm gas}}^{3/2}$

$$\rho_\star = \begin{cases} 0 & \text{if} \rho \leq \rho_0 \\ \epsilon \sqrt{\frac{32G}{3\pi}} \rho^{3/2} & \text{else} \end{cases}$$



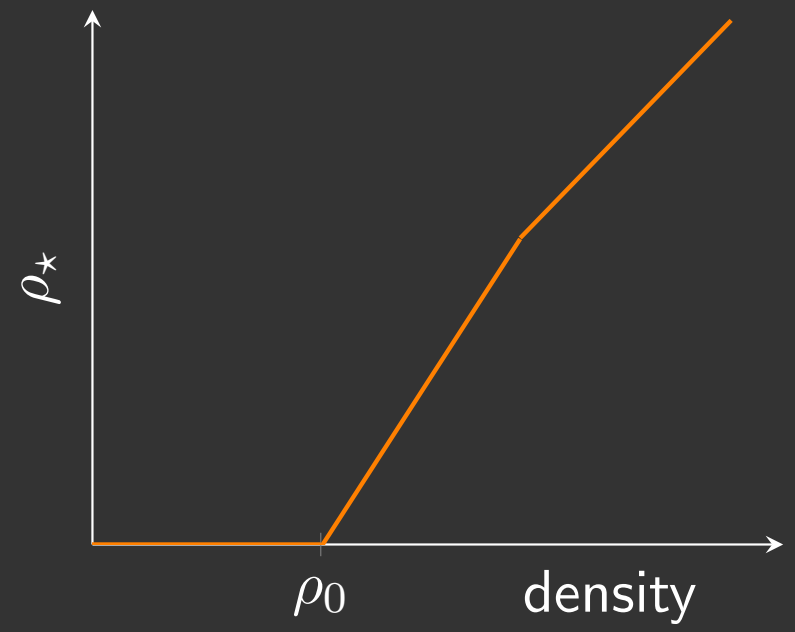

Elmegreen (2002)
Renaud, Kraljic & Bournaud (2012)

**SFR**

- Schmidt relation:
  $\rho_\star = \epsilon \frac{\rho_{\rm gas}}{t_{\rm ff}} \propto {\rho_{\rm gas}}^{3/2}$
- regulation

$$\rho_\star = \begin{cases} 0 & \text{if} \rho \leq \rho_0 \\ \epsilon \sqrt{\frac{32G}{3\pi}} \rho^{3/2} & \text{else} \end{cases}$$

$$\rho_\star = \begin{cases} 0 & \text{if} \rho \leq \rho_0 \\ \min\left( \epsilon \sqrt{\frac{32G}{3\pi}} \rho^{3/2}, \frac{\epsilon_s}{t_s} \rho \right) & \text{else} \end{cases}$$




Elmegreen (2002)
Renaud, Kraljic & Bournaud (2012)

normal w/o feedback:

$$\Sigma_{\mathrm{SFR}} = \epsilon \sqrt{\frac{8G}{3\pi}} \frac{\exp(\frac{3\sigma^2}{8})}{\sqrt{h}} \Sigma_{\mathrm{gas}}{}^{3/2} \operatorname{erfc}\left( \frac{\ln(\frac{\rho_0 h}{\Sigma_{\mathrm{gas}}}) - \sigma^2}{\sigma\sqrt{2}} \right)$$

normal w/o feedback:

$$\Sigma_{\mathrm{SFR}} = \epsilon \sqrt{\frac{8G}{3\pi}} \frac{\exp(\frac{3\sigma^2}{8})}{\sqrt{h}} {\Sigma_{\mathrm{gas}}}^{3/2} \operatorname{erfc}\left( \frac{\ln(\frac{\rho_0 h}{\Sigma_{\mathrm{gas}}}) - \sigma^2}{\sigma\sqrt{2}} \right)$$

normal w/o feedback:

$$\Sigma_{\mathrm{SFR}} = \epsilon \sqrt{\frac{8G}{3\pi}} \frac{\exp(\frac{3\sigma^2}{8})}{\sqrt{h}} {\Sigma_{\mathrm{gas}}}^{3/2} \operatorname{erfc}\left( \frac{\ln(\frac{\rho_0 h}{\Sigma_{\mathrm{gas}}}) - \sigma^2}{\sigma\sqrt{2}} \right)$$

normal w/o feedback:

$$\Sigma_{\rm SFR} = \epsilon\sqrt{\frac{8G}{3\pi}}\frac{\exp(\frac{3\sigma^2}{8})}{\sqrt{h}}{\Sigma_{\rm gas}}^{3/2}\,\mathrm{erfc}\left(\frac{\ln(\frac{\rho_0 h}{\Sigma_{\rm gas}})-\sigma^2}{\sigma\sqrt{2}}\right)$$

mergers w/o feedback:

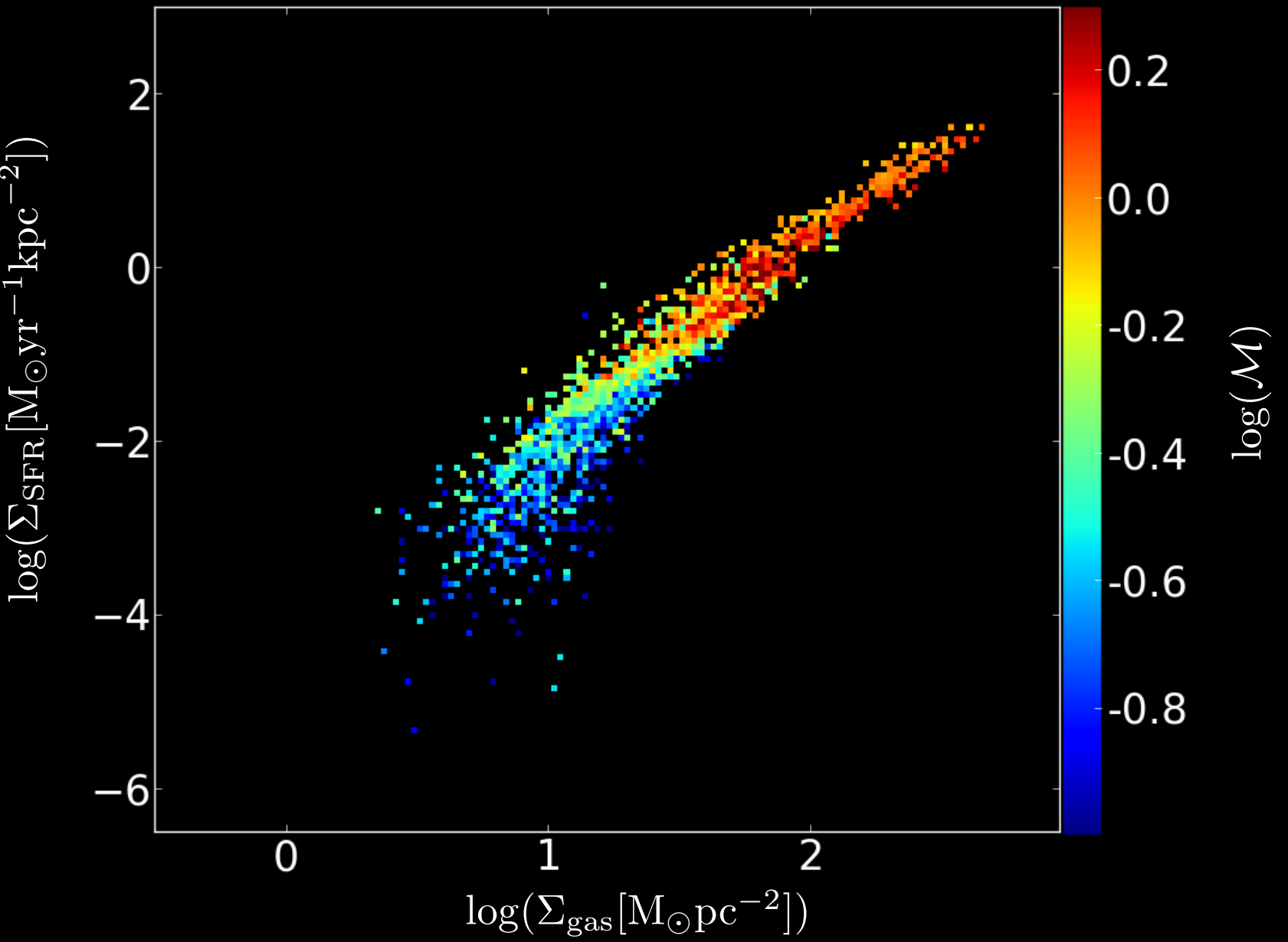
$$\Sigma_{\rm SFR} = \epsilon\sqrt{\frac{8G}{3\pi}}\frac{\Sigma_{\rm gas}^{3/2}}{\sqrt{h}}\left[(1-m)\exp\left(\frac{3}{8}\sigma_1^2\right)\mathrm{erfc}\left(\frac{\ln\left(\frac{\rho_0 h}{\Sigma_{\rm gas}}\right)-\sigma_1^2}{\sqrt{2}\sigma_1}\right)\right.$$
$$\left. + \; m\exp\left(\frac{3}{8}\sigma_2^2\right)\exp\left(\frac{3}{2}\delta\right)\mathrm{erfc}\left(\frac{\ln\left(\frac{\rho_0 h}{\Sigma_{\rm gas}}\right)-\sigma_2^2-\delta}{\sqrt{2}\sigma_2}\right)\right]$$

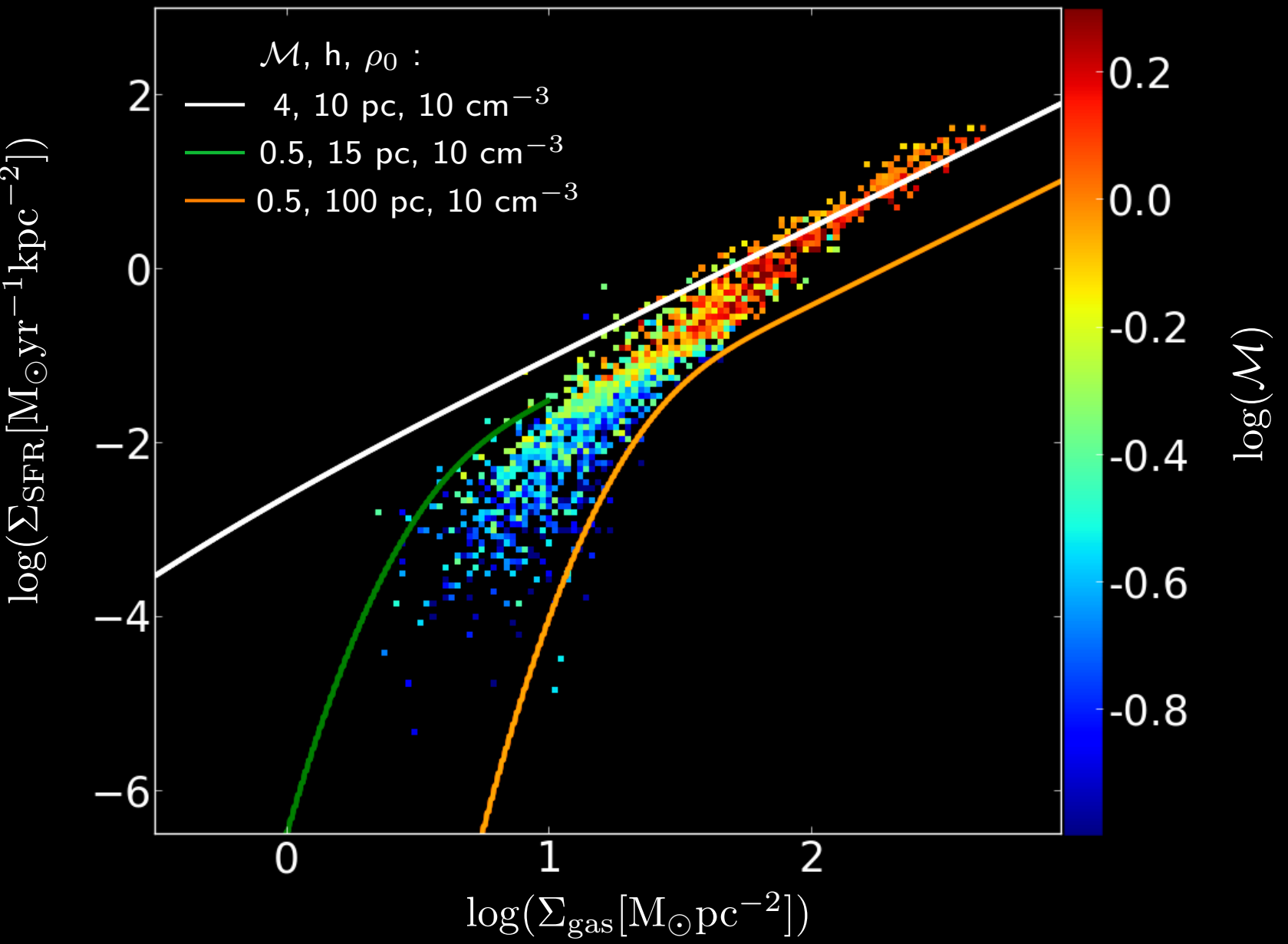
normal with feedback:

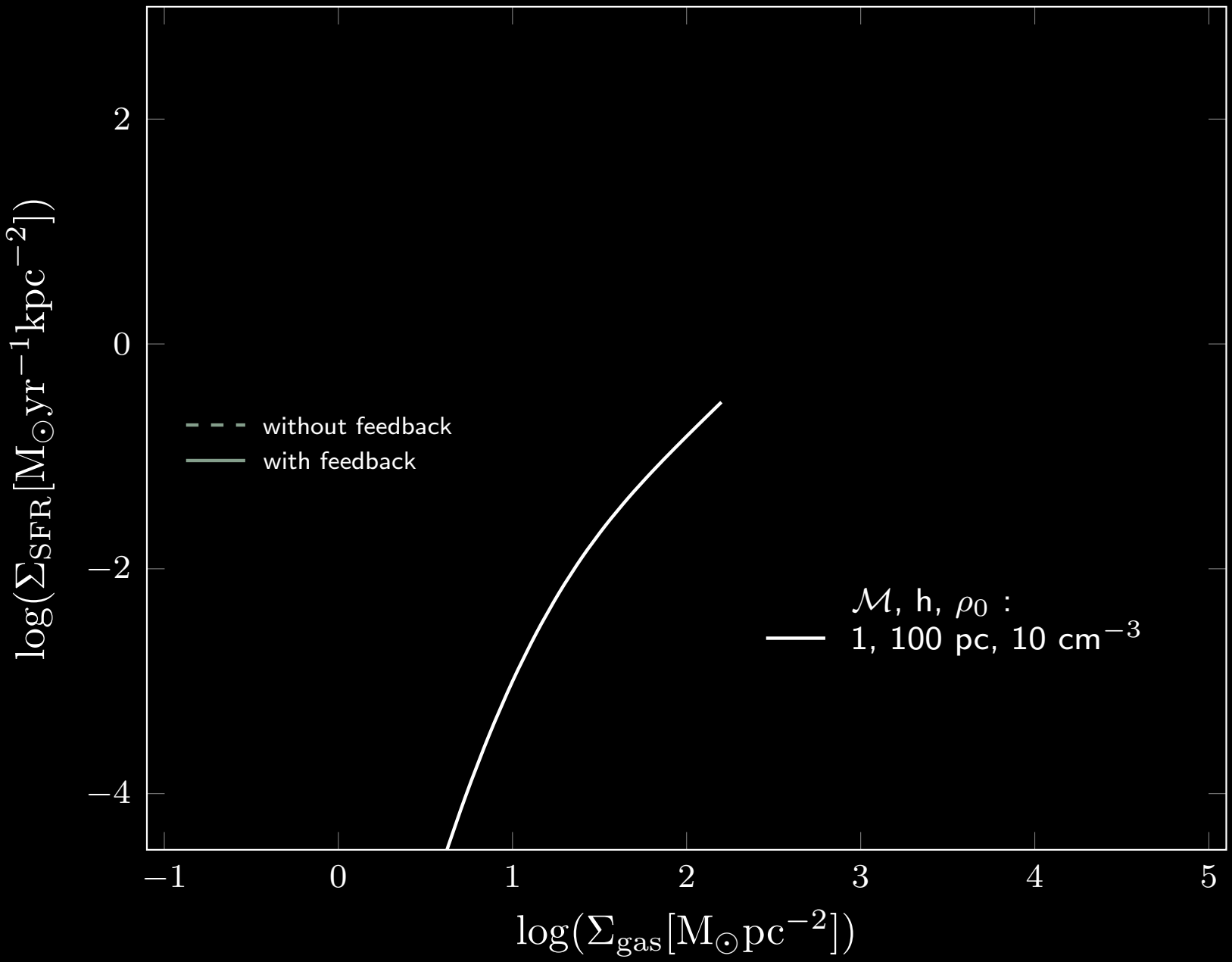
$$\begin{aligned}\Sigma_{\mathrm{SFR}} =& \epsilon\sqrt{\frac{8G}{3\pi}}\frac{\exp\left(\frac{3}{8}\sigma^2\right)}{\sqrt{h}}\Sigma_{\mathrm{gas}}^{3/2}\left[\mathrm{erfc}\left(\frac{\ln\left(\frac{\rho_0 h}{\Sigma_{\mathrm{gas}}}\right)-\sigma^2}{\sqrt{2}\sigma}\right)\right.\\ &\left.-\ \mathrm{erfc}\left(\frac{\ln\left(\frac{\epsilon_s^2 3\pi h}{\mathrm{t}_s^2 32G\epsilon^2\Sigma_{\mathrm{gas}}}\right)-\sigma^2}{\sqrt{2}\sigma}\right)\right]\\ &+\frac{\epsilon_s}{2\mathrm{t}_s}\Sigma_{\mathrm{gas}}\,\mathrm{erfc}\left(\frac{\ln\left(\frac{\epsilon_s^2 3\pi h}{\mathrm{t}_s^2 32G\epsilon^2\Sigma_{\mathrm{gas}}}\right)-\frac{\sigma^2}{2}}{\sqrt{2}\sigma}\right)\end{aligned}$$

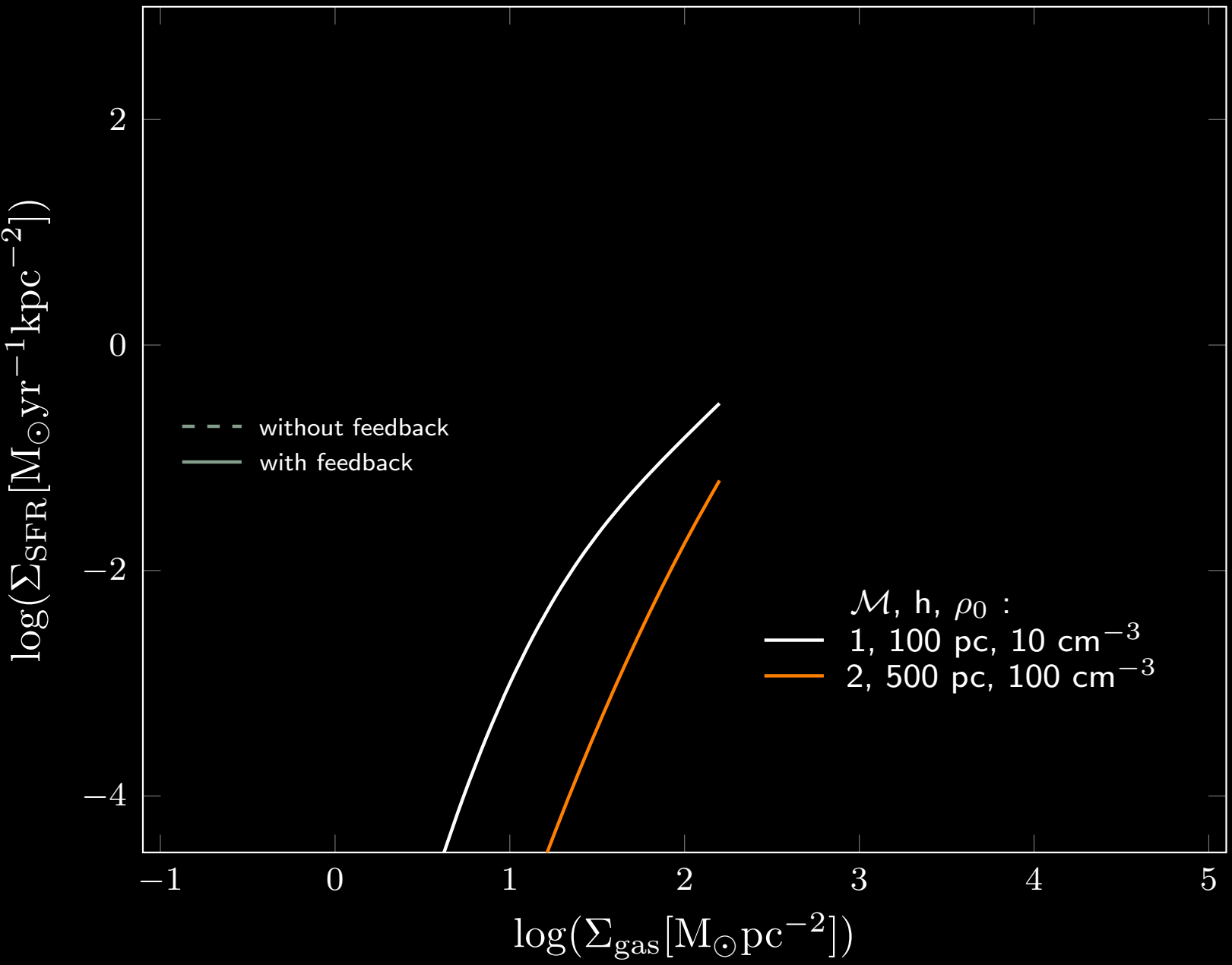
merger with feedback:

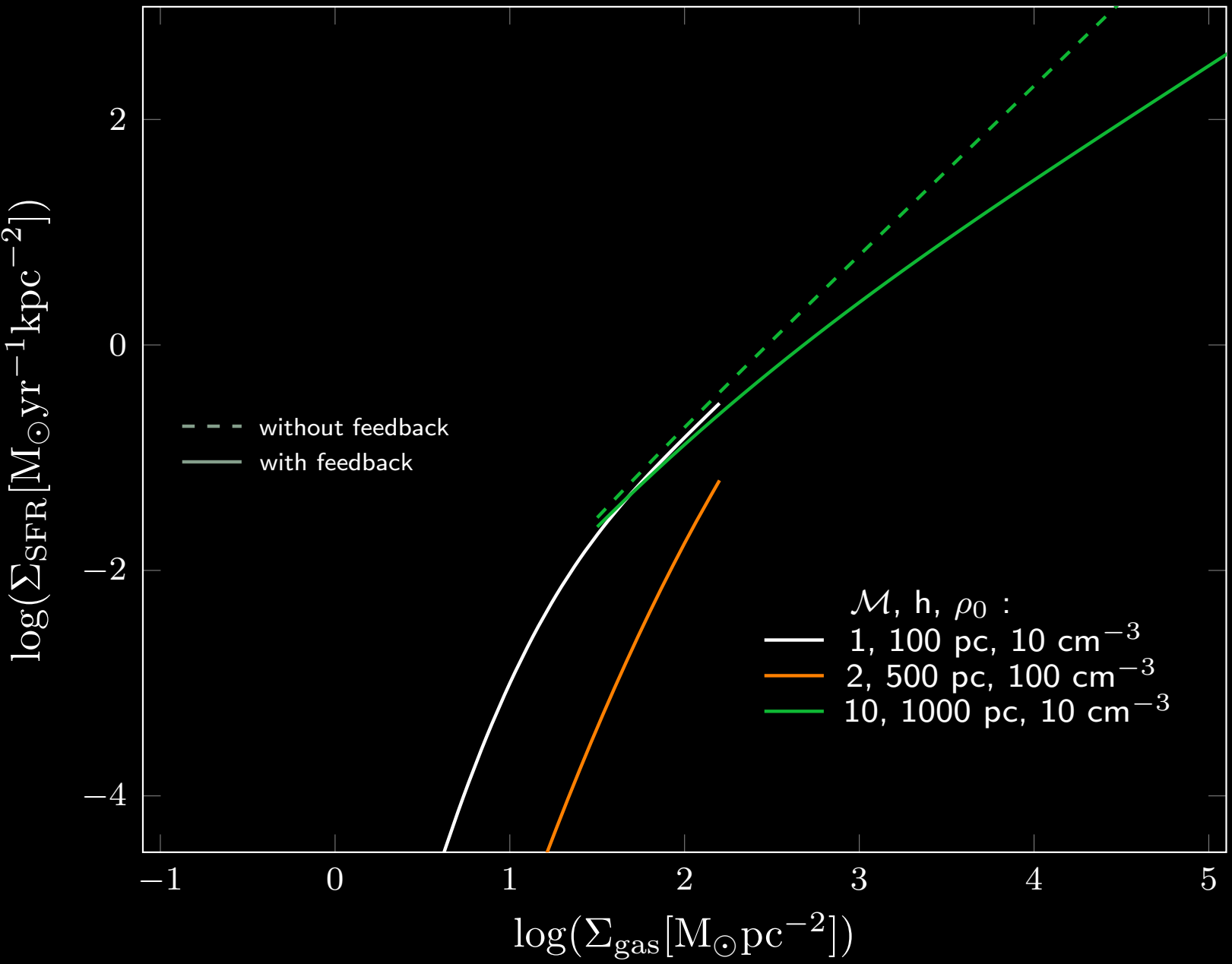
$$\begin{aligned}
\Sigma_{\mathrm{SFR}} = & \epsilon\sqrt{\frac{8G}{3\pi}}\frac{\Sigma_{\mathrm{gas}}^{3/2}}{\sqrt{h}}(1-m)\exp\left(\frac{3}{8}\sigma_1^2\right)\left[\mathrm{erfc}\left(\frac{\ln\left(\frac{\rho_0 h}{\Sigma_{\mathrm{gas}}}\right)-\sigma_1^2}{\sqrt{2}\sigma_1}\right)\right. \\
& \left. -\ \mathrm{erfc}\left(\frac{\ln\left(\frac{\epsilon_s^2 3\pi h}{\mathrm{t}_s^2 32G\epsilon^2\Sigma_{\mathrm{gas}}}\right)-\sigma_1^2}{\sqrt{2}\sigma_1}\right)\right] \\
& + (1-m)\Sigma_{\mathrm{gas}}\frac{\epsilon_s}{2t_s}\,\mathrm{erfc}\left(\frac{\ln\left(\frac{\epsilon_s^2 3\pi h}{\mathrm{t}_s^2 32G\epsilon^2\Sigma_{\mathrm{gas}}}\right)-\frac{\sigma_1^2}{2}}{\sqrt{2}\sigma_1}\right) \\
& + \epsilon\sqrt{\frac{8G}{3\pi}}\frac{\Sigma_{\mathrm{gas}}^{3/2}}{\sqrt{h}}m\exp\left(\frac{3}{2}\delta\right)\exp\left(\frac{3}{8}\sigma_2^2\right)\left[\mathrm{erfc}\left(\frac{\ln\left(\frac{\rho_0 h}{\Sigma_{\mathrm{gas}}}\right)-\sigma_2^2-\delta}{\sqrt{2}\sigma_2}\right)\right. \\
& \left. -\ \mathrm{erfc}\left(\frac{\ln\left(\frac{\epsilon_s^2 3\pi h}{\mathrm{t}_s^2 32G\epsilon^2\Sigma_{\mathrm{gas}}}\right)-\sigma_2^2-\delta}{\sqrt{2}\sigma_2}\right)\right] \\
& + m\Sigma_{\mathrm{gas}}\frac{\epsilon_s}{2t_s}\exp\delta\,\mathrm{erfc}\left(\frac{\ln\left(\frac{\epsilon_s^2 3\pi h}{\mathrm{t}_s^2 32G\epsilon^2\Sigma_{\mathrm{gas}}}\right)-\frac{\sigma_2^2}{2}-\delta}{\sqrt{2}\sigma_2}\right)
\end{aligned}$$

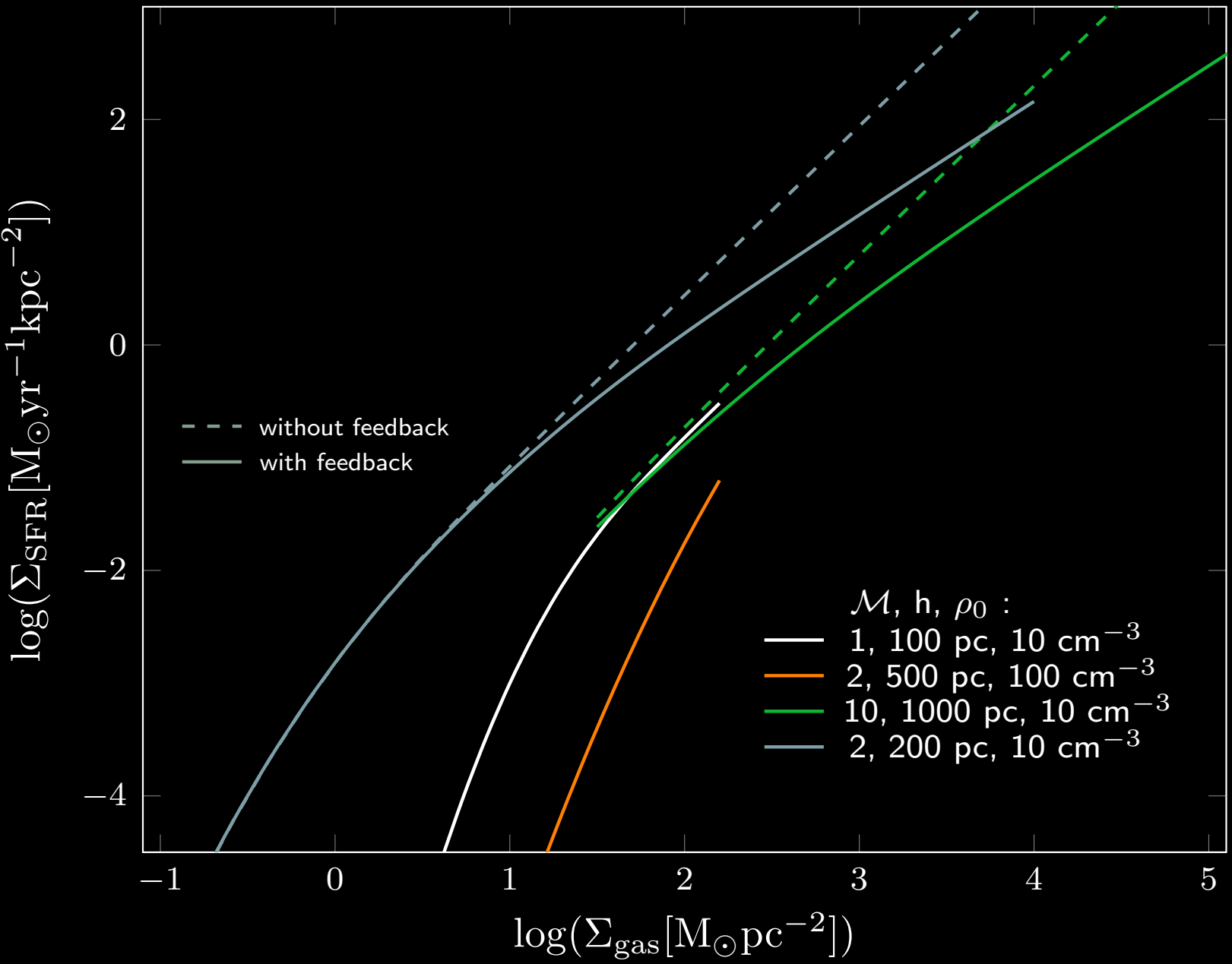

2
0
−2
−4
−6
0
1
2
$\log(\Sigma_{\rm SFR}[{\rm M}_\odot{\rm yr}^{-1}{\rm kpc}^{-2}])$
$\log(\Sigma_{\rm gas}[{\rm M}_\odot{\rm pc}^{-2}])$
0.2
0.0
-0.2
-0.4
-0.6
-0.8
$\log(\mathcal{M})$

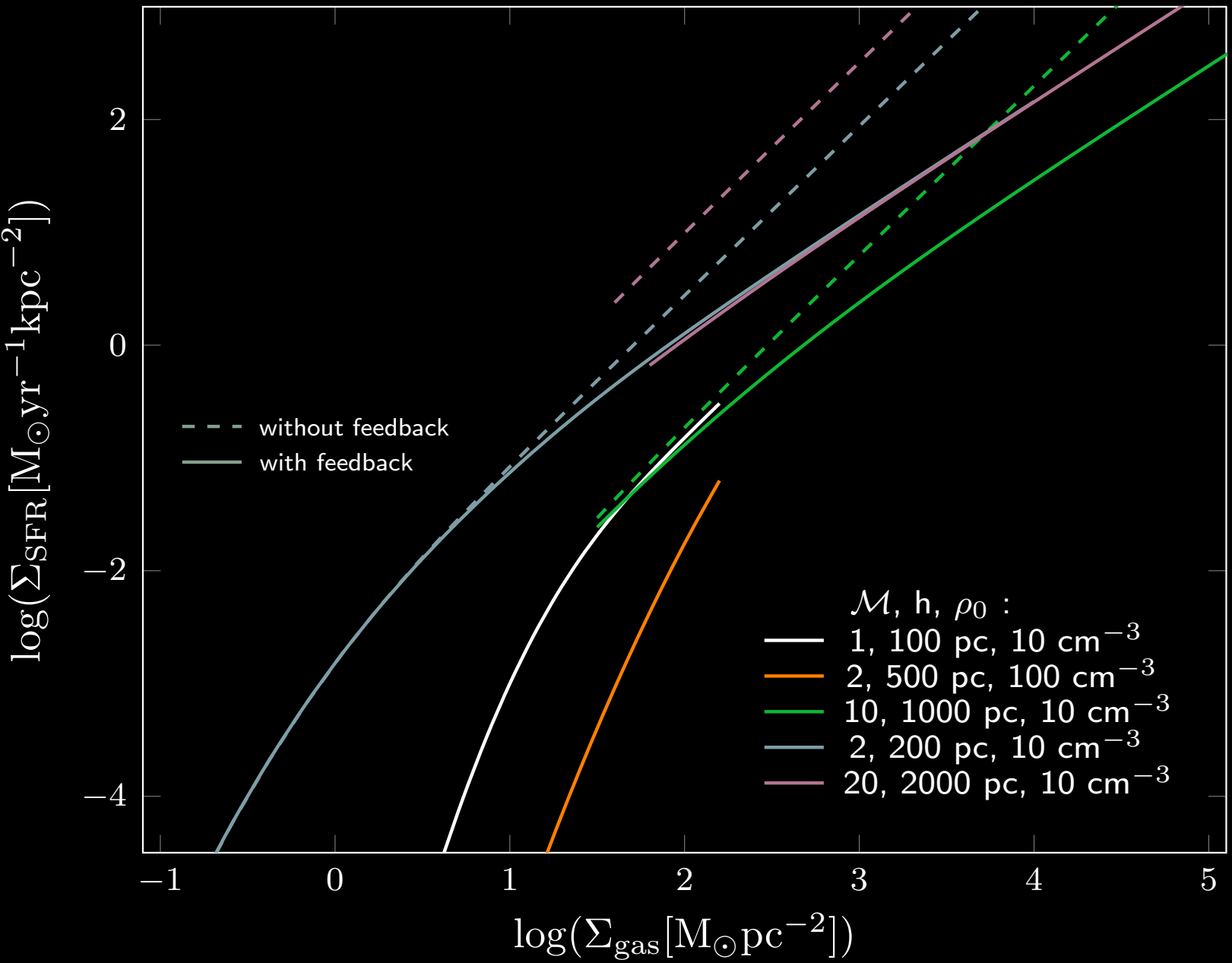

$\mathcal{M}$, h, $\rho_0$ :
4, 10 pc, 10 cm$^{-3}$
0.5, 15 pc, 10 cm$^{-3}$
0.5, 100 pc, 10 cm$^{-3}$
$\log(\Sigma_{\rm SFR}[{\rm M}_\odot{\rm yr}^{-1}{\rm kpc}^{-2}])$
$\log(\Sigma_{\rm gas}[{\rm M}_\odot{\rm pc}^{-2}])$
$\log(\mathcal{M})$
2
0
−2
−4
−6
0
1
2
0.2
0.0
-0.2
-0.4
-0.6
-0.8

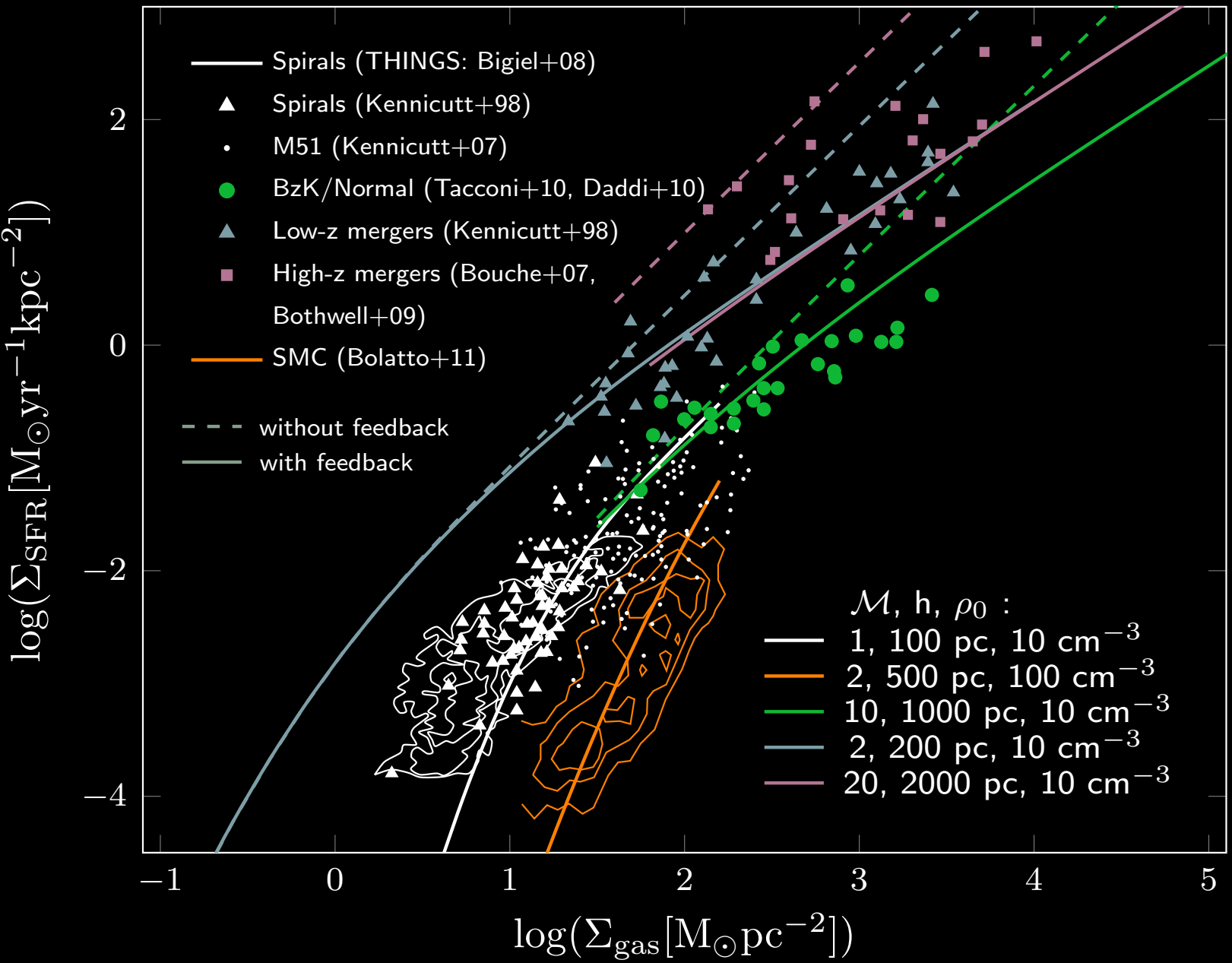

2
0
−2
−4
−1
0
1
2
3
4
5
$\log(\Sigma_{\rm SFR}[{\rm M}_\odot{\rm yr}^{-1}{\rm kpc}^{-2}])$
$\log(\Sigma_{\rm gas}[{\rm M}_\odot{\rm pc}^{-2}])$
without feedback
with feedback
$\mathcal{M}$, h, $\rho_0$ :
1, 100 pc, 10 cm$^{-3}$


2
0
−2
−4
−1
0
1
2
3
4
5
$\log(\Sigma_{\rm SFR}[{\rm M}_\odot{\rm yr}^{-1}{\rm kpc}^{-2}])$
$\log(\Sigma_{\rm gas}[{\rm M}_\odot{\rm pc}^{-2}])$
without feedback
with feedback
$\mathcal{M}$, h, $\rho_0$ :
1, 100 pc, 10 cm$^{-3}$
2, 500 pc, 100 cm$^{-3}$


without feedback
with feedback
$\mathcal{M}$, h, $\rho_0$ :
1, 100 pc, 10 cm$^{-3}$
2, 500 pc, 100 cm$^{-3}$
10, 1000 pc, 10 cm$^{-3}$
$\log(\Sigma_{\rm SFR}[{\rm M}_\odot{\rm yr}^{-1}{\rm kpc}^{-2}])$
$\log(\Sigma_{\rm gas}[{\rm M}_\odot{\rm pc}^{-2}])$
2
0
−2
−4
−1
0
1
2
3
4
5


without feedback
with feedback
$\mathcal{M}$, h, $\rho_0$ :
1, 100 pc, 10 cm$^{-3}$
2, 500 pc, 100 cm$^{-3}$
10, 1000 pc, 10 cm$^{-3}$
2, 200 pc, 10 cm$^{-3}$
$\log(\Sigma_{\rm SFR}[{\rm M}_\odot{\rm yr}^{-1}{\rm kpc}^{-2}])$
$\log(\Sigma_{\rm gas}[{\rm M}_\odot{\rm pc}^{-2}])$
2
0
−2
−4
−1
0
1
2
3
4
5


without feedback
with feedback
$\mathcal{M}$, h, $\rho_0$ :
1, 100 pc, 10 cm$^{-3}$
2, 500 pc, 100 cm$^{-3}$
10, 1000 pc, 10 cm$^{-3}$
2, 200 pc, 10 cm$^{-3}$
20, 2000 pc, 10 cm$^{-3}$
$\log(\Sigma_{\rm SFR}[{\rm M}_\odot{\rm yr}^{-1}{\rm kpc}^{-2}])$
$\log(\Sigma_{\rm gas}[{\rm M}_\odot{\rm pc}^{-2}])$
2
0
−2
−4
−1
0
1
2
3
4
5


Spirals (THINGS: Bigiel+08)
Spirals (Kennicutt+98)
M51 (Kennicutt+07)
BzK/Normal (Tacconi+10, Daddi+10)
Low-z mergers (Kennicutt+98)
High-z mergers (Bouche+07, Bothwell+09)
SMC (Bolatto+11)
without feedback
with feedback
$\mathcal{M}$, h, $\rho_0$ :
1, 100 pc, 10 cm$^{-3}$
2, 500 pc, 100 cm$^{-3}$
10, 1000 pc, 10 cm$^{-3}$
2, 200 pc, 10 cm$^{-3}$
20, 2000 pc, 10 cm$^{-3}$
$\log(\Sigma_{\rm SFR}[{\rm M}_\odot{\rm yr}^{-1}{\rm kpc}^{-2}])$
$\log(\Sigma_{\rm gas}[{\rm M}_\odot{\rm pc}^{-2}])$
2
0
−2
−4
−1
0
1
2
3
4
5

## Problems

- number of physical processes we know are important, but remain unsolved (feedback)

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- which physical processes regulate the multi-phase structure of the ISM?

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- which physical processes regulate the multi-phase structure of the ISM?
- what is the main driver of galactic outflows?

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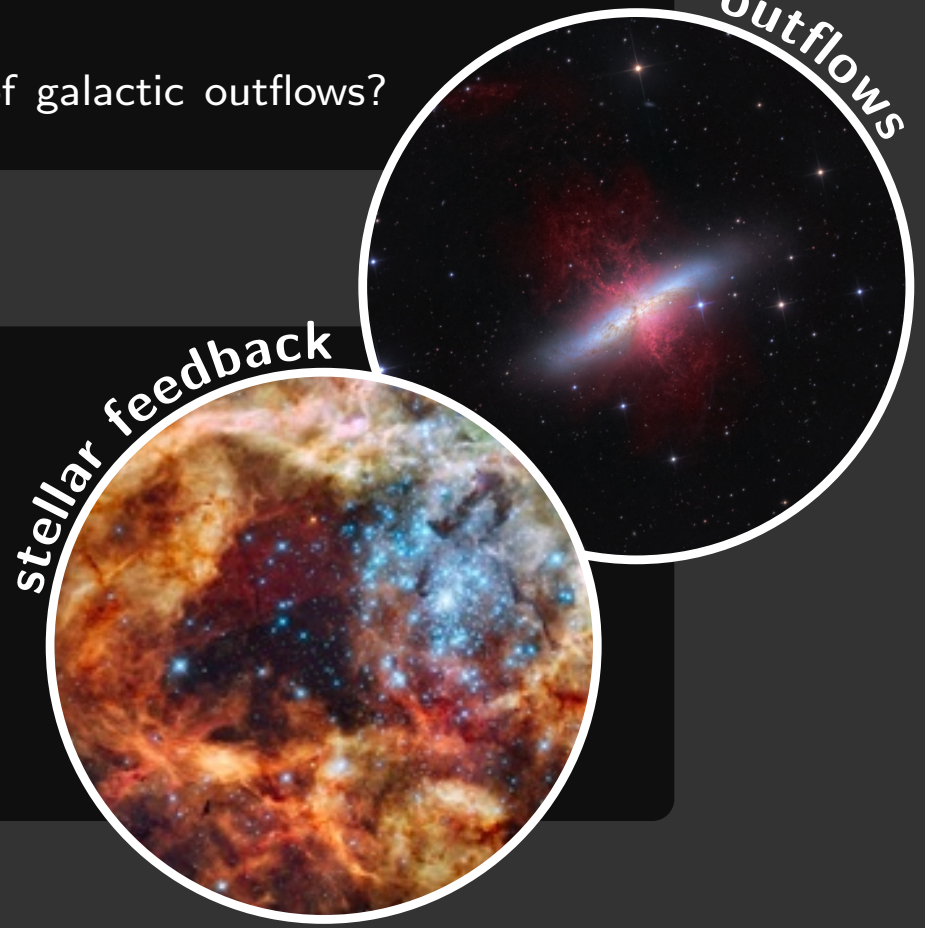
- which physical processes regulate the multi-phase structure of the ISM?
- what is the main driver of galactic outflows?

## Important processes

- core-collapse explosions
- stellar winds
- radiation
- AGN feedback
- magnetic fields
- cosmic rays ...