Interacting galaxies on FIRE-2: The connection between enhanced star formation and interstellar gas content

Moreno+2019

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Contents

Abstract

Comprehensive suite of high-resolution (pc-scale), idealized (non-cosmological) galaxy merger simulations (24 runs, stellar mass ratio ~ 2.5:1)

→ Connection between interaction-induced SF and the evolution of ISM

'Galaxy-pair period' between first and second pericentric passage with GIZMO & FIRE-2

ISM classification: hot, warm, cool, cold-dense (in observation hot, ionized, atomic, molecular)

Results

- Enhance SFR of the pair (~30%)
- Elevate cold-dense gas content (~18%)
- Decrease in warm gas (~11%)
- Negligible change in cool gas (~4% increase)
- Substantial increase in hot gas (~400%)
- Cold ultra-dense regime (cold-dense gas > 1000 cm-3) is elevated significantly (~240%), but only account for ~0.15% of the cold-dense gas

1. Introduction

Galaxy mergers and interactions

Observationally …

- Enhance SFR (Ellison+2008, 2013; Patton+2013; Knapen+2015)
- Decrease nuclear metallicities (Kewley+2006; Rupke+2010; Montuori+2010; etc.)
- Drive AGN activity (Ellison+2011; Khabiboulline+2014; etc.)

In idealized binary merger simulations …

- Previous merger simulation suites employ simple model for ISM
  → Treat multi-phase ISM as a single, pressurized fluid (e.g., Springel&Herquist 2003, etc.)
- High resolution simulation resolving GMCs and the structure of the ISM
  → Importance of stellar feedback regulating the ISM structure
- Models that capture the multi-phase structure of the ISM and adopt feedback-regulated SF
  → turbulent pressure, large scale galactic outflow
  but … computationally expensive

The goal of this paper

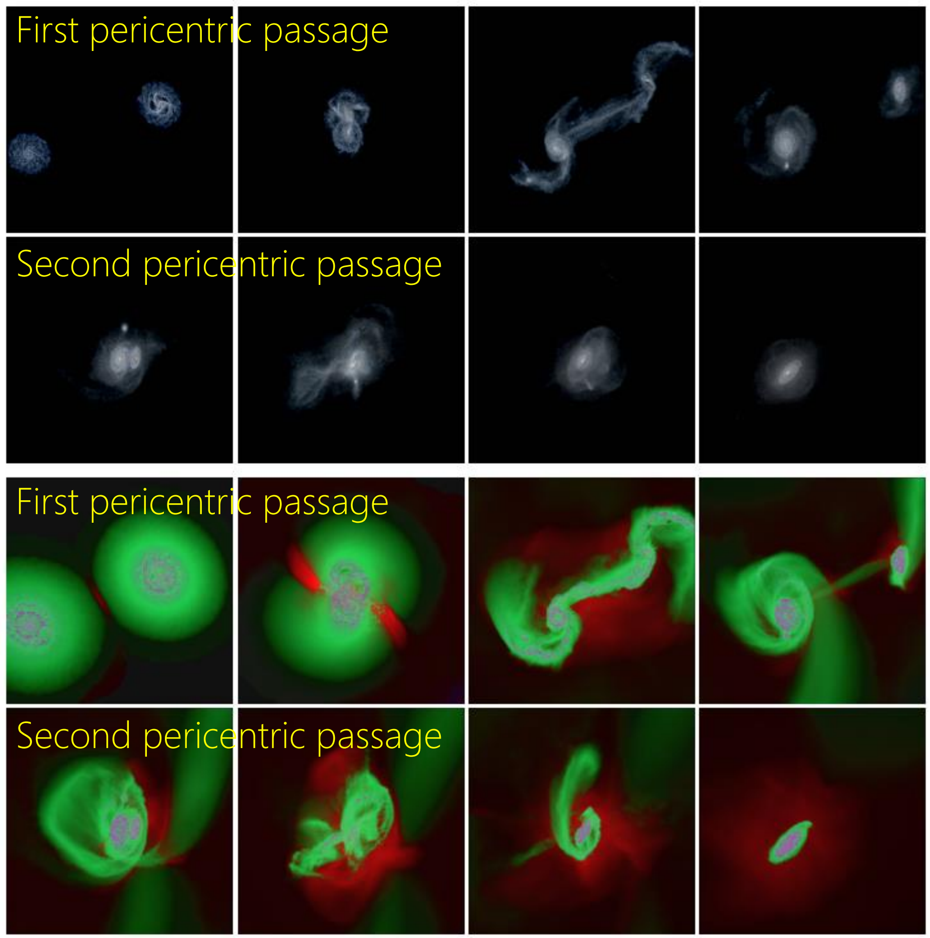
- Investigate the evolution of the ISM in different temperature-density regime during the merger
- Build a comprehensive suite of high-resolution simulations with GIZMO & FIRE-2

1. Introduction

Example of simulation

Fig. 1

Mock *ugr* composite



Disturbed morphology first, ultimately settling down into a disk galaxy with a bulge
Faint shells and streams

Tidal tails and a bridge are more evident in gas

Multi-phase ISM
Magenta: T<1000 K
Green: T~10^3-10^4 K
Red: T>10^6 K

2. Methods

2.1 FIRE-2: The 'Feedback In Realistic Environments' Physics Model (Version 2)

Radiative heating/cooling

- 11 species (free-free, photo-ionization/recombination, Compton, photoelectric, dust-collisional, cosmic ray, molecular, metal- line and fine-structure processes)
- UV background (Faucher-Ginguere+2009)
- Locally-driven photo-heating
- Self-shielding

Star formation

- Self-gravitating, self-shielded gas denser than $1000 cm^{-3}$

Stellar feedback

- SNe (Ia & II) and stellar mass loss (OB and AGB)
  - momentum flux from radiation field, energy momentum, mass & metal injection

SSP model for each star particles

- STARBURST99 with Kroupa IMF

Not include AGN feedback ← Not well understood yet

Not include hot gas at the start of the simulation ← Lack of observational constraints

2. Methods

2.2 Suite of Galaxy Merger Simulations

Similar to previous simulation by authors (e.g. Moreno+2015), but …

- Fewer runs (24 vs 75)
- Substantially higher resolution
- New physical model

2.2.1 Isolated Galaxies

Setting up progenitor galaxies

- Mo+ 19989 (procedure in Springel+2005)
- For bulges and DM halos, Hernquist 1990
- Scaling of stellar mass and DM halo mass (Moster+2013)
- Bulge-to-total mass ratio (SDSS result; Mendel+2014)
- Gass mass following Saintonge+2016
- Gas disk length ~10 kpc (diameter ~ 25kpc), in line with observation by Broeils&Rhee 1997
- Set initial gas condition to 10^5K with solar metallicity

Table 1: Simulation Specifications

Property	Value
Mass resolution (dark matter)	$1.9 \times 10^5\ M_\odot$
Mass resolution (gas)	$1.4 \times 10^4\ M_\odot$
Mass resolution (stars)	$8.4 \times 10^3\ M_\odot$
Highest gas density	$5.8 \times 10^5\ \mathrm{cm}^{-3}$
Highest spatial gas resolution	1.1 pc
Gravitational softening (collisionless)	0.01 kpc
Gravitational softening (gas)	0.001 kpc

Table 2: Properties of progenitor galaxies

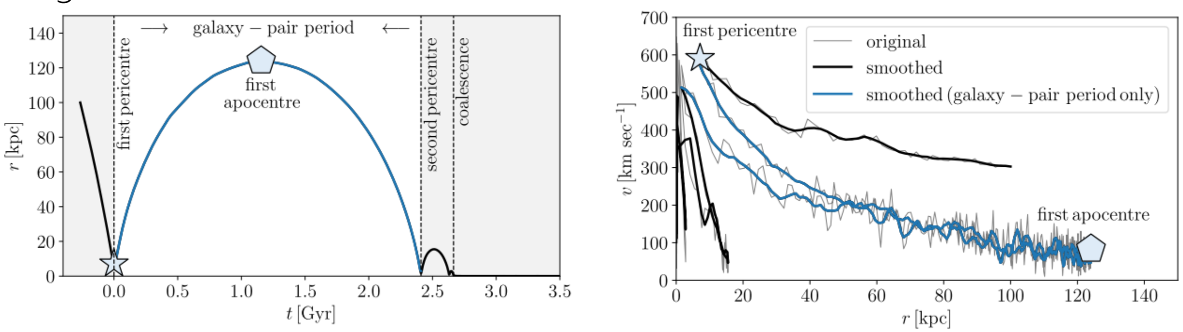
Property	Primary	Secondary
M_{halo}	$7.5 \times 10^{11} M_\odot$	$3.5 \times 10^{11} M_\odot$
M_{stellar}	$3.0 \times 10^{10} M_\odot$	$1.2 \times 10^{10} M_\odot$
M_{bulge}	$2.5 \times 10^{9} M_\odot$	$7.0 \times 10^{8} M_\odot$
M_{gas}	$8.0 \times 10^{9} M_\odot$	$7.0 \times 10^{9} M_\odot$
λ_{halo}	0.05	0.05
R_{disk}	2.85 kpc	1.91 kpc
$h_{\mathrm{disk\,(bulge)}}/R_{\mathrm{disk}}$	0.14 (0.13)	0.2 (0.136)

2. Methods

2.2.2 The Fiducial Run

Nearly prograde orbit with small impact parameter (~ 7kpc) and highly eccentric orbit

Fig. 2



Note:
Make t=0 at first pericenter

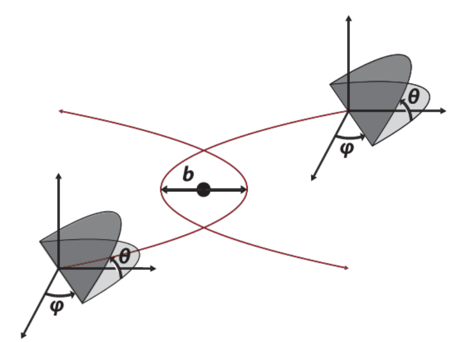
2.2.3 Galaxy Merger Simulations

- Effects by variations in orbital merging configuration
- 24 galaxy merger simulations split into 3 groups
  - Prograde
  - Polar
  - Retrograde

	Prograde ("e")	Polar ("f")	Retrograde ("k")
Primary			
ϕ_1	60°	60°	-30°
θ_1	30°	60°	-109°
Secondary			
ϕ_2	45°	0°	-30°
θ_2	-30°	150°	71°

Table 3

Fig. 1 of Moreno+2015



2. Methods

2.2.3 Cont'd

Don't fine-tune the orbital parameters

→ Certain properties at first pericentric passage (Bottom of Fig. 3)

→ Drop 3 orbit with merging times > 5Gyr

24 mergers
= (3orientations
x 3 first-pericentric separations
x 3 relative velocities at first pericentric passage)
– (3 mergers with merging time > 5Gyr)

Fig. 3

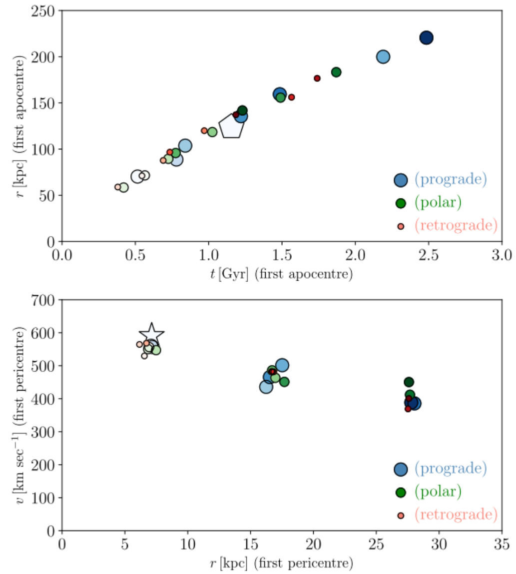
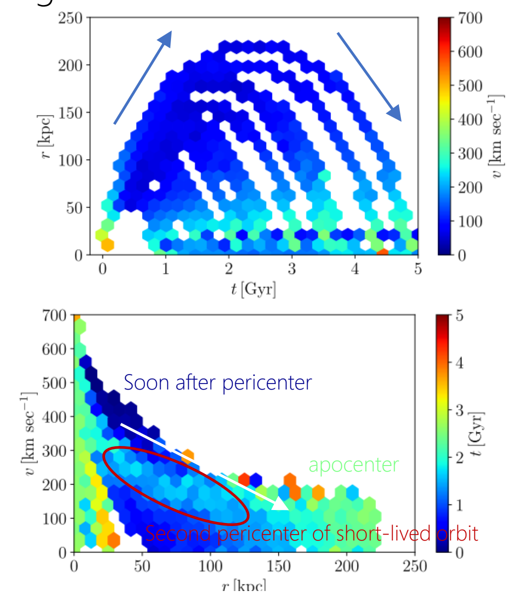


Fig. 4



Range of separations and merging timescales

- Separation as high as 300kpc ~ Observation
- At large separations, galaxies slow down → Spend long time

2. Methods

2.3 ISM Temperature-Density Regimes

Four regime

- Hot: A result of feedback heating ⇔ Hot gas in observation
- Warm: Dominated by warm-ionized gas (bright band above 8000K) ⇔Ionized gas
- Cool, Cold-dense: Diffuse valley, Clouds. Mixture of atomic and molecular gas
  ⇔ atomic & molecular gas

Not employ sophisticated models of ionized, atomic and molecular gas

→ Currently refining (Orr+2018, Lakhlani+in prep)

Fig. 5

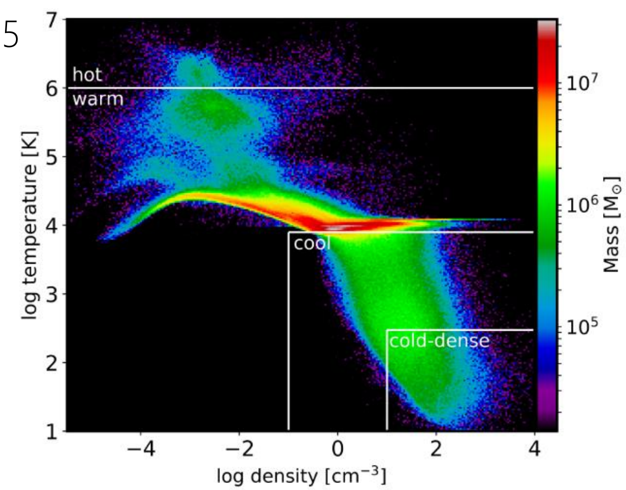


Table 4

ISM regimes	Temperature-density demarcations
warm	$(T < 10^6\,\mathrm{K}, n < 0.1\,\mathrm{cm}^{-3})$
	& $(8000\,\mathrm{K} < T < 10^6\,\mathrm{K}, n > 0.1\,\mathrm{cm}^{-3})$
cool	$(T < 8000\,\mathrm{K}, 0.1\,\mathrm{cm}^{-3} < n < 10\,\mathrm{cm}^{-3})$
	& $(300\,\mathrm{K} < T < 8000\,\mathrm{K}, n < 0.1\,\mathrm{cm}^{-3})$
cold-dense	$(T < 300\,\mathrm{K}, n > 10\,\mathrm{cm}^{-3})$
hot	$(T > 10^6\,\mathrm{K})$
cold moderately-dense	$(T < 300\,\mathrm{K}, 10 < n < 1000\,\mathrm{cm}^{-3})$
cold ultra-dense	$(T < 300\,\mathrm{K}, n > 1000\,\mathrm{cm}^{-3})$

2. Methods

2.4 Caveats and Limitations

- Without employing full radiative transfer calculation coupled with chemical network solvers
- Lack of feedback from SMBH accretion
- Not include hot gas atmospheres at the start of simulation (effect of hot gas cooling)
- Lack of cosmological context

Some solutions for above disadvantage (especially for environmental factors)

- Avoid long-lived galaxy-galaxy interactions
    - Effect of gas accretion from cosmic web and third galaxies
- Comparing merging systems against isolated 'control' galaxies
  → Reduce the effects caused by other environmental factors

3. Results

3.1 Fiducial Run: Star Formation

Comparison with 'control' isolated counter part

SFR enhancement:

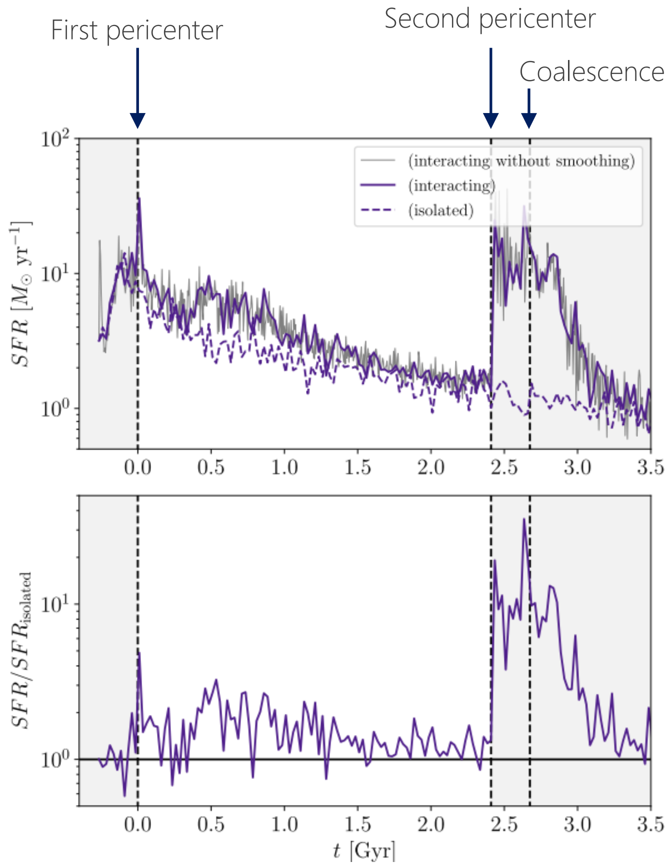
$$\frac{\text{(SFR in the interacting galxies)}}{\text{(Sum of the SFR in the two isolated galaxies)}}$$

Note: calculate for the entire galaxy-pair system

Interaction elevate SFR in galaxies

- Sudden spike at the first pericentric passage
- Prolonged period of enhancement (by factors of ~2-3) between t=0 – 1.3 Gyr
- Sudden rise at second pericentric passage
    - Half of the runs exhibit
    - Depending on internal properties of the colliding galaxies and the geometry of collision

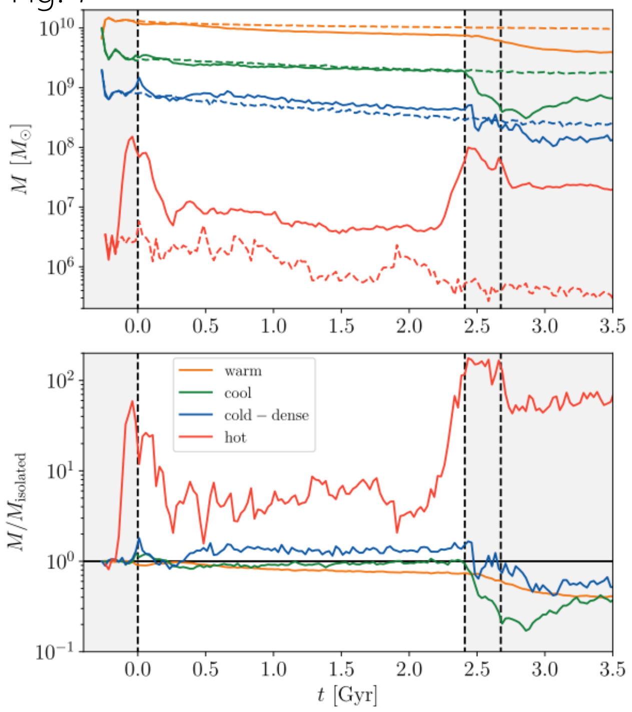
Fig. 6



3. Results

3.2 Fiducial Run: The Structure of the ISM

Fig. 7



Warm gas

- Most of gas is in this regime
- Gradually depleted in both isolated and interacting
- Depletion is magnified by interactions

Cool gas

- Depleted in both isolated and interacting
- In the interacting, a brief boost, followed by a drop and long-term steady recovery

Cold-dense gas

- Depletion over long timescales
- A brief and sudden spike followed by a mild and brief suppression. Soon after, replenished

Hot gas

- At both pericentric passage and coalescence, hot gas increase dramatically ← shock heating
- Excess appears before the actual pericentric passage ← outer regions
- Excess of hot gas is maintained during pair-period and doubles t~1.3-1.9 Gyr

3. Results

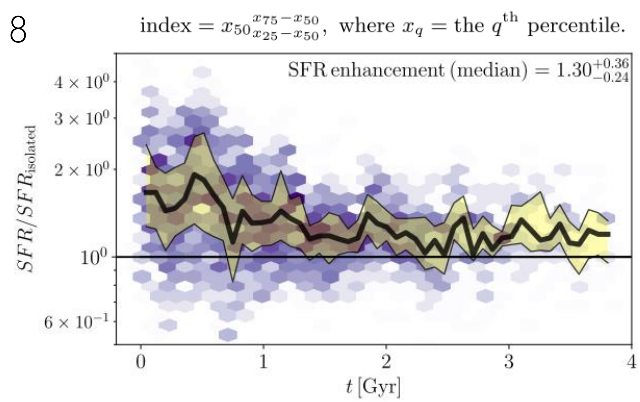
3.3 Merger Suite: Star Formation

SFR enhancement only for galaxy-pair period

- Enhance across merger suite
- Level of enhancement and the scatter diminished with time

Note: Combine several mergers with different time duration

Fig. 8



3.3 Merger Suite: The structure of the ISM

Warm gas

- Suppressed (Intensity and duration varies from merger to merger)

Cool gas

- Suppression followed by a slow and steady recovery
- Mild excess t > 1Gyr

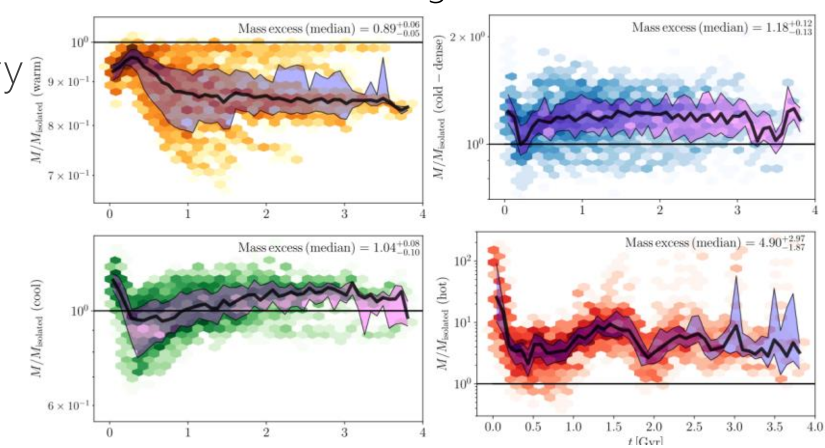
Cold-dense gas

- Excess at all time with brief dip at first

Hot gas

- Highest levels of enhancement, especially at first pericentric passage

Fig. 9



3. Results

3.5 Merger Suite: Star Formation and its Connection to the ISM

Correlation between SFR enhancement and gas mass enhancement

- No correlation with warm and hot gas
- Weak anti-correlation with cool gas
- Weak correlation with cold-dense gas

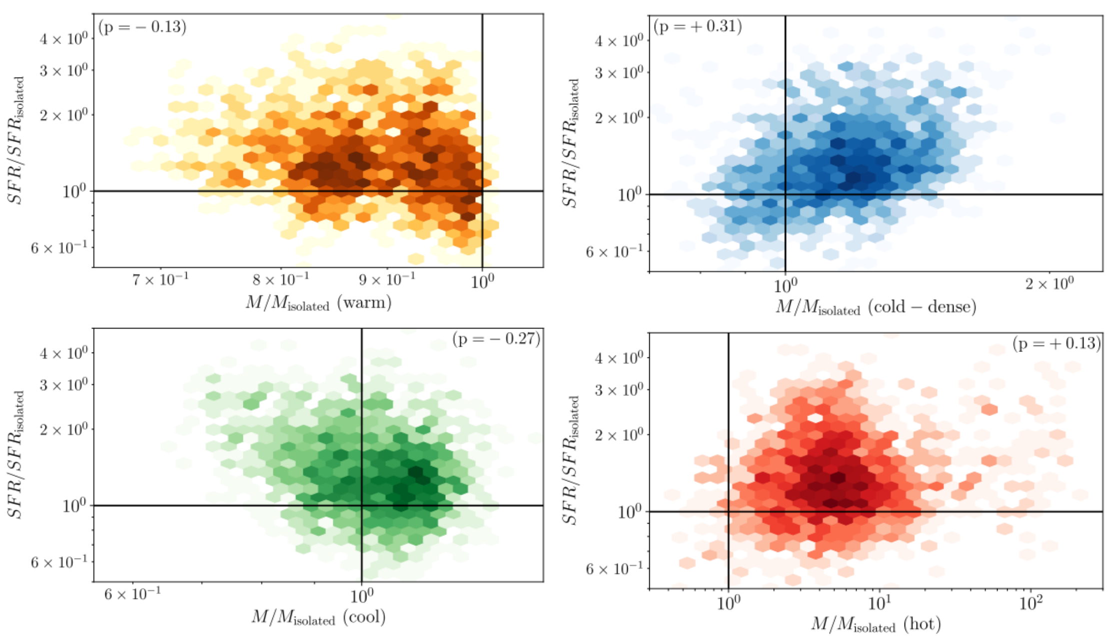
Note: Bimodality of the warm gas

- High mass enhancement peak: Retrograde mergers
- Low mass enhancement peak: Prograde and polar mergers

→ spin-orbit orientation governs the effectiveness of warm gas depletion

(Detail study in a future paper)

Fig. 10



3. Results

3.6 Inter-Regime Transition Rate

How the various gas regime feed and drain one another on the fiducial case

Mass transition rates (Between regime α and regime β)

$$\frac{\mathrm{d}M_\alpha(t)}{\mathrm{d}t} = \sum_{\beta\neq\alpha} \mathcal{R}_{\alpha\leftrightarrow\beta}(t), \qquad \mathcal{R}_{\alpha\leftrightarrow\beta}(t) = R_{\alpha\to\beta}(t) - R_{\beta\to\alpha}(t), \qquad R_{\alpha\to\beta}(t) = \frac{\mathrm{d}M(t)}{\mathrm{d}t}\Big|_{\alpha\to\beta}$$

Employing particle IDs and tracing the state of it

Few comment for all the results

- In the figures from next slide, they only display *net* transition $R_{\alpha\leftrightarrow\beta}$, not $R_{\alpha\to\beta}$
- Simulation show that inter-regime transition tend to favor a preferred direction
- The main effect caused by encounters is the amplification of net transition rates: "Interacting vs Isolated"

3. Results

3.6 Cont'd

Warm gas (Fig. 11)

- "Gain by cold-dense gas → warm gas"
  vs "Loss by warm gas → cool gas"
  → Overall slow depletion of warm gas
- Deviation by halting (reversing) the loss of warm gas possibly due to intense stellar feedback (e.g. t~0.3 Gyr)

Cool gas (Fig 12)

- "Gain by warm gas → cool gas"
  vs "Loss by cool gas → cold-dense gas"
  → Overall slow depletion of cool gas
- Deviation by …
  - High influx from warm gas (e.g. t=0 Gyr)
  - Halting (reversing) transformation from warm gas

Fig. 11

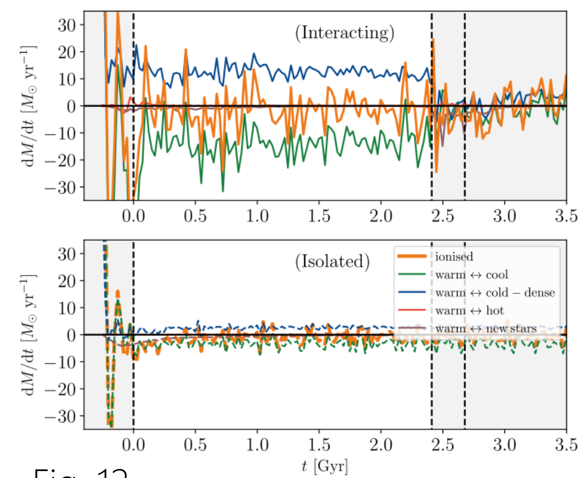
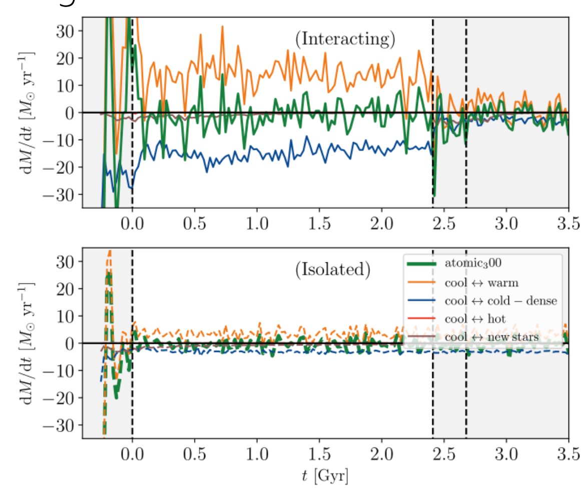


Fig. 12



3. Results

3.6 Cont'd

Cold-dense gas (Fig. 13)

- "Gain by cool gas → cold-dense gas"
  vs "Loss by cold-dense gas → warm gas"
  vs "Consumption by cold-dense gas → stars"
  → Overall slow depletion of cold-dense gas
- Deviation by a high net influx from both cool and warm gas (e.g. t~0, 0.4 Gyr)

Hot gas (Fig 14)

- Hot gas "follows" warm gas
- Exception at t~0.4 Gyr:
  Time derivative of hot gas recover to zero following net conversion from cold-dense and cool gas
  ← Enhanced star formation ?
- Note: Hot gas budget is significantly smaller than others

Fig. 13

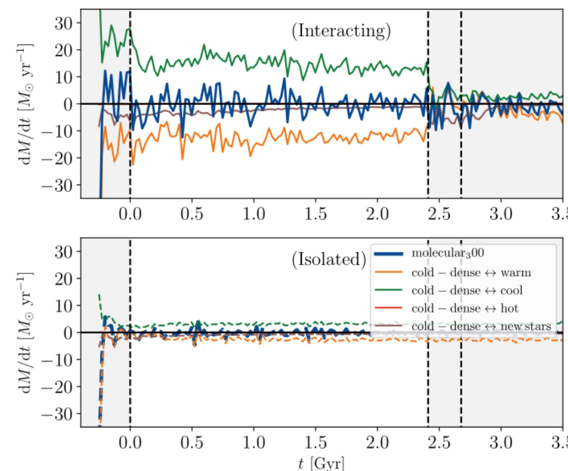
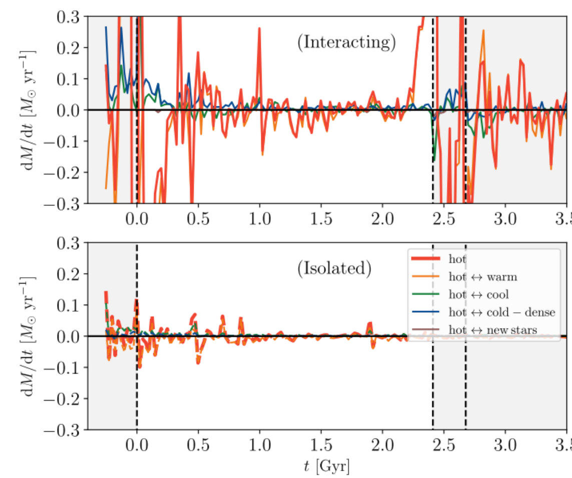


Fig. 14



4. Disucussion

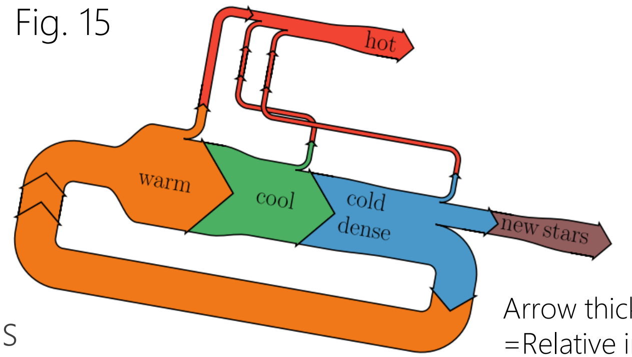
4.1 An Emerging Picture

The role of interactions

- Amplifying warm gas depletion
- Amplifying cool gas depletion, especially early
- Enhancing cold-dense gas reservoir

← Accelerate, halt, or reverse the direction of transitions

Fig. 15



Arrow thickness
=Relative importance
(Not strict)

4.2 Cold Ultra-Dense Gas

Cold moderately-dense gas: n = 10 – 1000 cm^{-3}

Cold ultra-dense gas: n >1000 cm^{-3}
(Sometimes close to resolution limit)

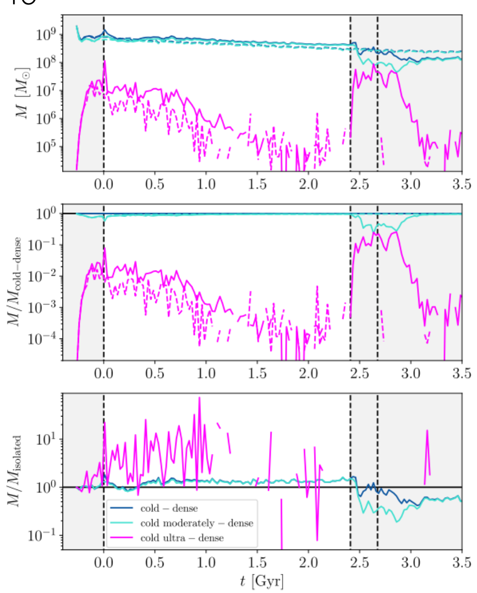
Fraction in the cold-dense gas

- Cold ultra-dense gas: at most a few %

Interaction-induced mass excesses

- Cold-dense, Cold moderately-dense: x ~1-2
- Cold ultra-dense –dense: x ~10

Fig. 16



4. Disucussion

4.2 Cont'd

For the cold ultra-dense gas across entire simulations

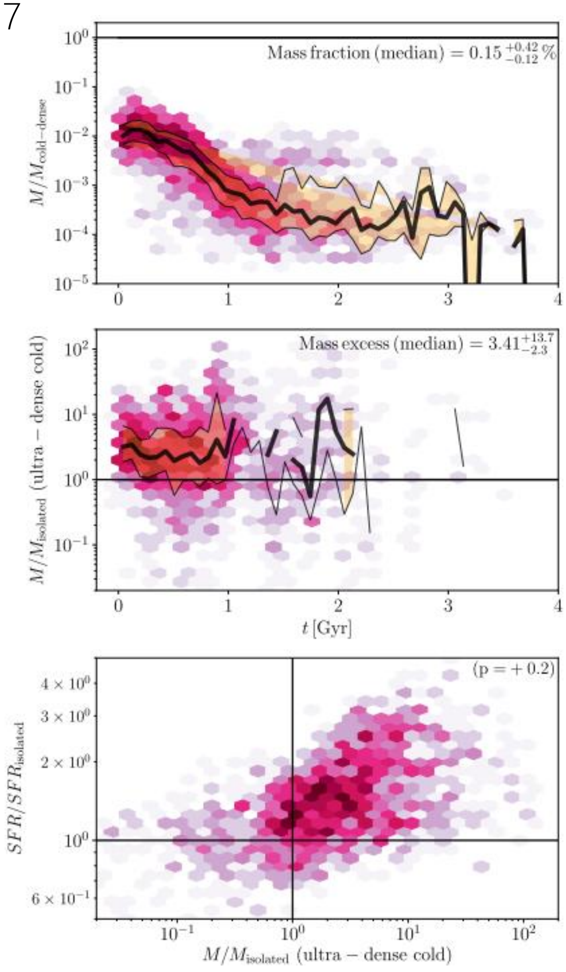
- Only ~0.15% of cold-dense gas on average
- Interaction enhance cold ultra-dense gas
  by factor of ~3.41 on average
- Only mild correlation with SFR enhancement
  ← Exploring the high-density tail of the gas density function
  due to the resolution of the simulation

4.3 Connection to Observations

Cool gas: median ~ 4% increase (Fig 9)

- HI is the standard tracer
- Conflicting indications from observations
    - No difference in merging and control (e.g. Zuo+2018)
    - Enhanced gas fraction (e.g. Ellison+2018)
- Observational challenges
    - Single dish telescopes: large beams → Source blending
    - Interferometers: Cannot do statistical studies

Fig. 17



4. Disucussion

4.3 Cont'd

Cold-dense gas: median ~18% increase

Molecular gas with CO emissions (e.g. Braine&Combes 1993, Combes+1994, etc.)

- Enhancement of CO luminosity
- Correlation of CO luminosities and FIR luminosities

→ "Enhancement in molecular gas ⇒ Enhancement of SF" in interacting system

Caveat for comparison between simulation and observation

- α_{CO} in observation
- Radiative-transfer calculations on the simulation-side

Cold-dense gas enhancement vs SFR enhancement

Cold-dense gas reservoir remains even when SFR enhancement diminish
→ Cold-dense gas content is not exhausted after elevation of SF

Cold ultra-dense gas: ~0.15% of the cold gas

- $L_{CO(3-2)}/L_{CO(1-0)}$ and $L_{HCN}/L_{CO(1-0)}$ have potential to constrain

4. Discussion

4.3 Cont'd

Hot gas: median ~ 400%

Very few observations

- Henriksen & Cousineau 1999:
  At fixed B-band luminosity, X-ray luminosity in spiral-spiral pair is enhanced
- Casasola+2004:
  X-ray luminosities from diffuse gas is higher in interacting system
- Smith+2018:
  For galaxies with SFR > $1M_{\odot}$/yr, L_X(gas)/SFR is not correlated with SFR or interacting stage

4.4 Connection to Other Simulations

- Di Matteo+2008: Modest SFR enhancement in simulated low-redshift major merger
- Cox+2008: Amplitude of the SFR enhancement at coalescence decrease sharply
  with increasing mass ratio.
  Even for equal-mass, SFR increase in pre-coalescence < factor of a few
- Fensch+2017: Mergers are less efficient at high redshift owing to its higher gas fraction
- Teyssier+2010: Sufficiently high resolution (12pc, $4\times10^4M_{\odot}$)
  - Enhanced fragmentation into cold clouds → SFR enhancement
  - Gas density PDF shift to higher densities in the interactions