What drives the ram pressure stripping?

hints from TIGRESS simulation

Finally.. Submitted in ApJ.. yesterday!

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With *Chang-Goo Kim* (Princeton Univ.) & *Aeree Chung* (Yonsei Univ.)

2022.02.22

How the ISM of different temperatures and densities gets affected by ICM ram pressure

Understanding the underlying physics of momentum transfer in the ICM ram pressure stripping

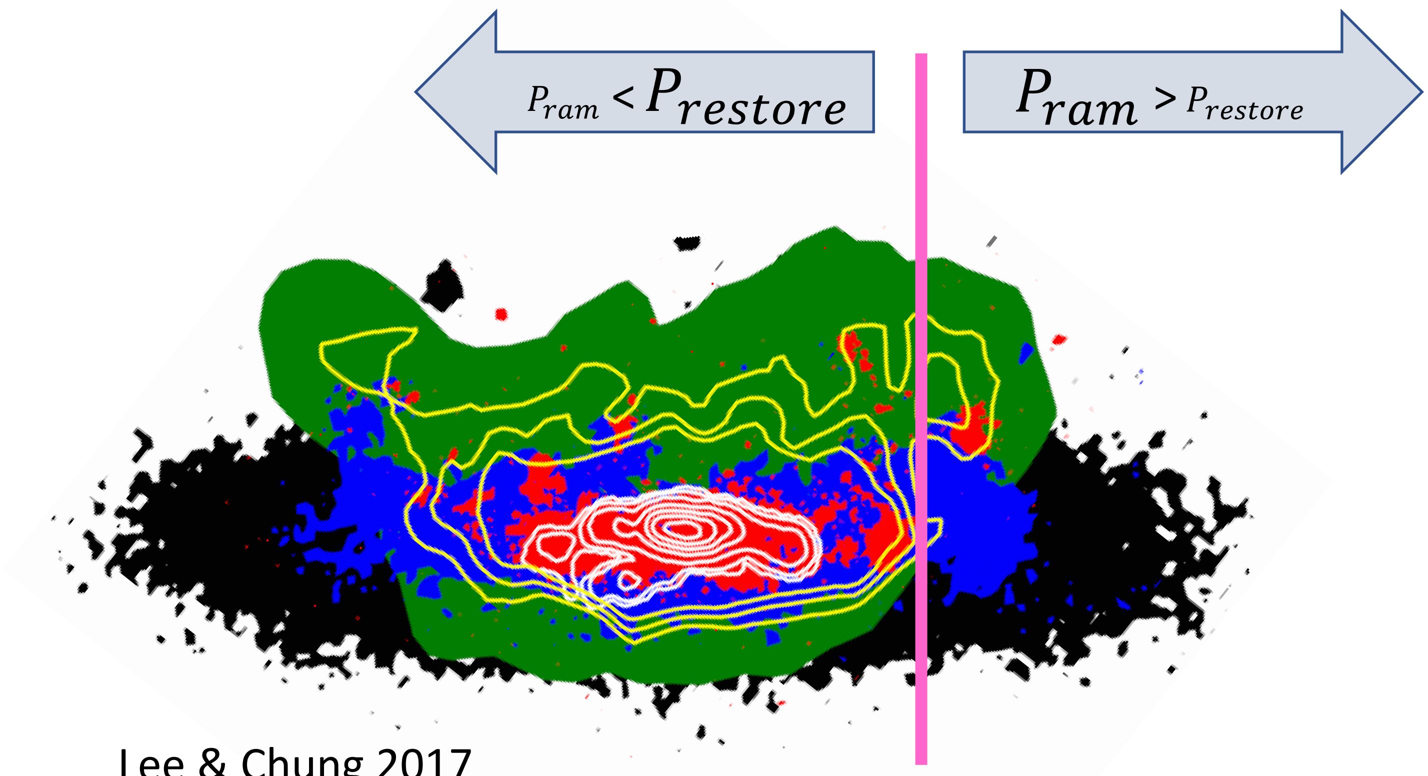
Ram Pressure stripping (RPS)

- Gunn & Gott (1972) :

$\rho_{ICM} v_{rel}^2$ (Ram pressure, P_{ram})

vs.

$\Sigma_{ISM} \frac{d\Phi}{dz}$ (Restoring force, $P_{restore}$)



Lee & Chung 2017

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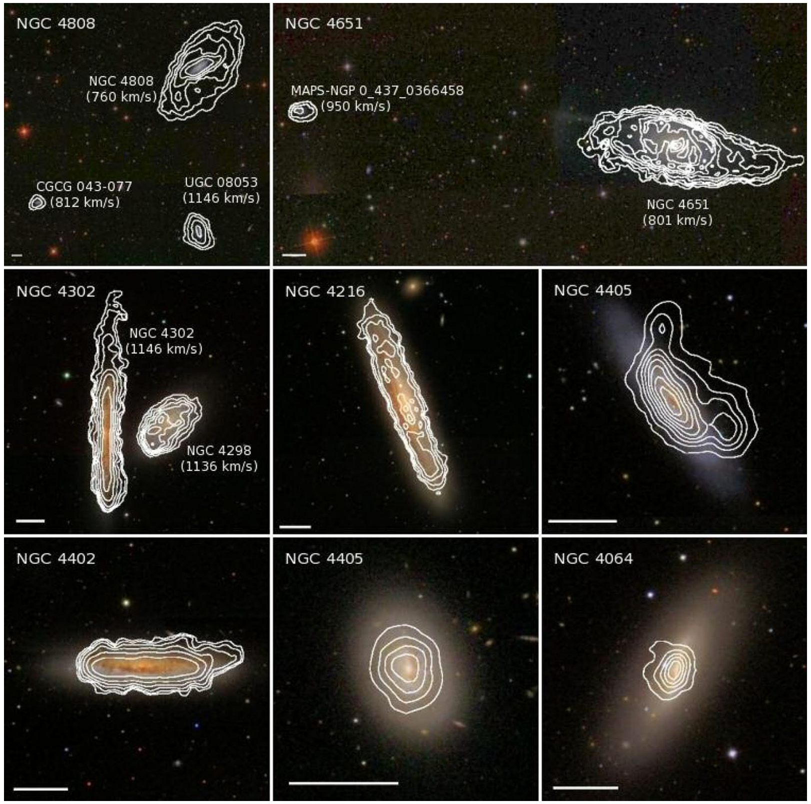
HI of RPS galaxies in Virgo



Chung et al. 09

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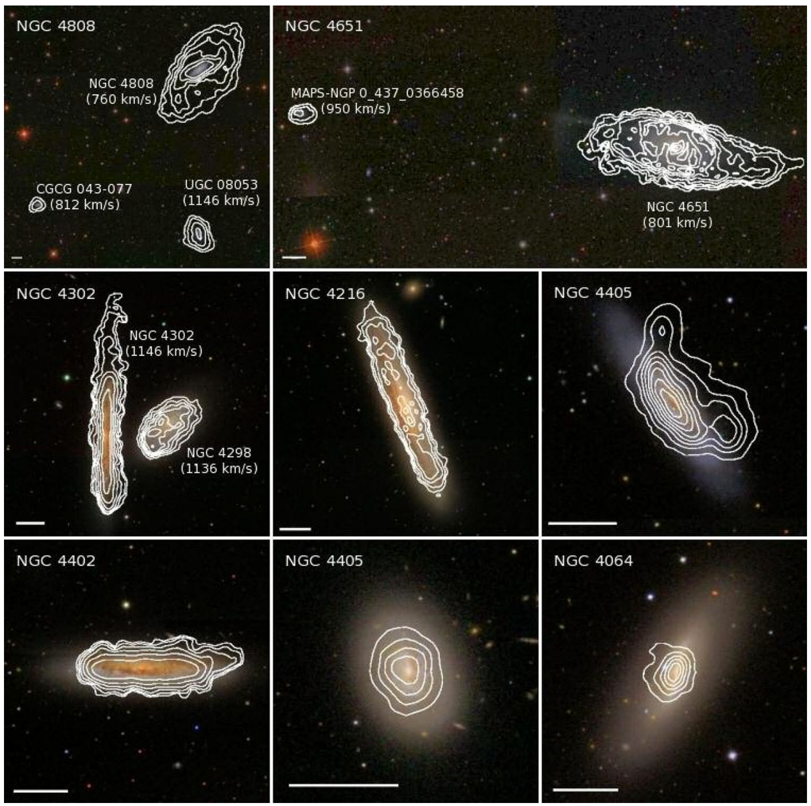
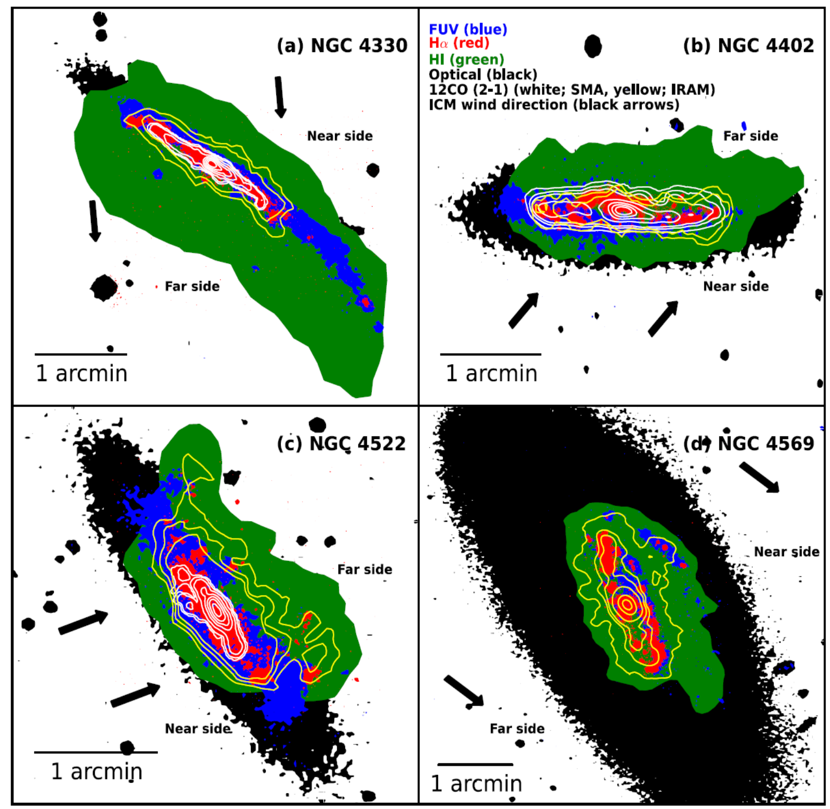


Chung et al. 09

HI, CO, Ha, FUV of RPS galaxies



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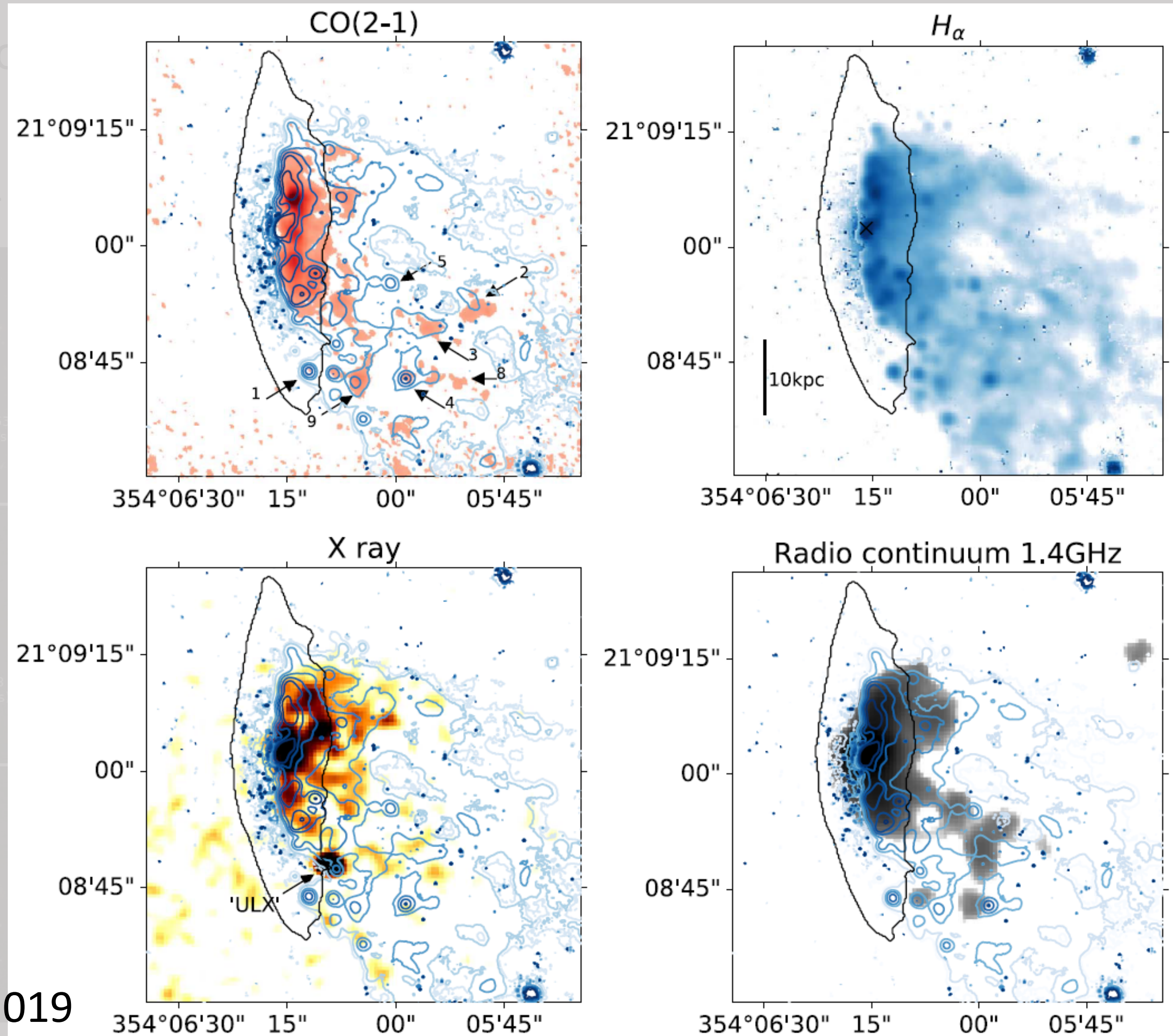

Poggianti et al. 2019

Chung et al. 09

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Ram Pressure stripping (RPS)

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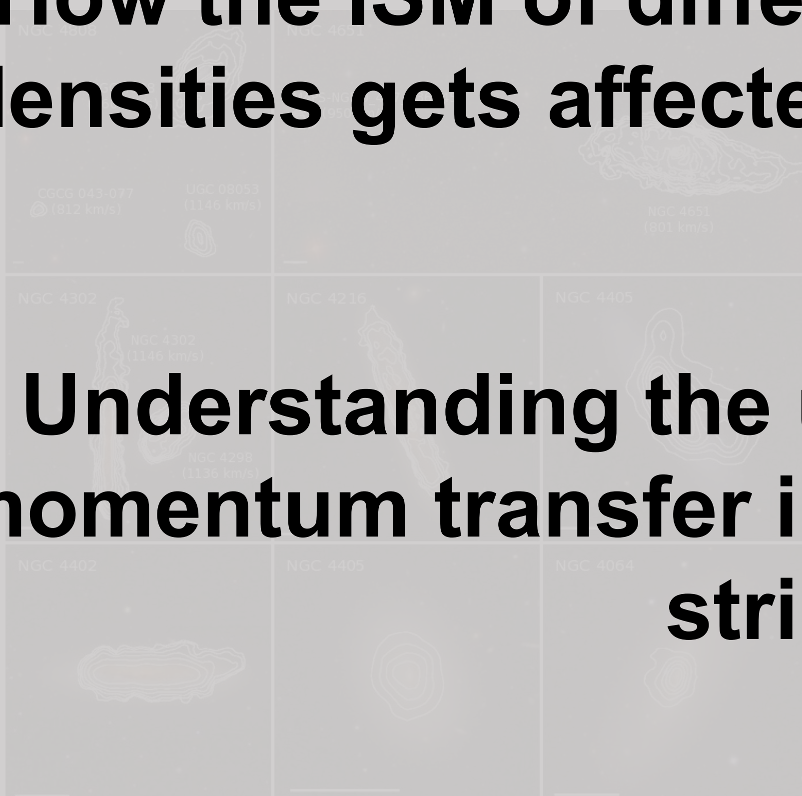
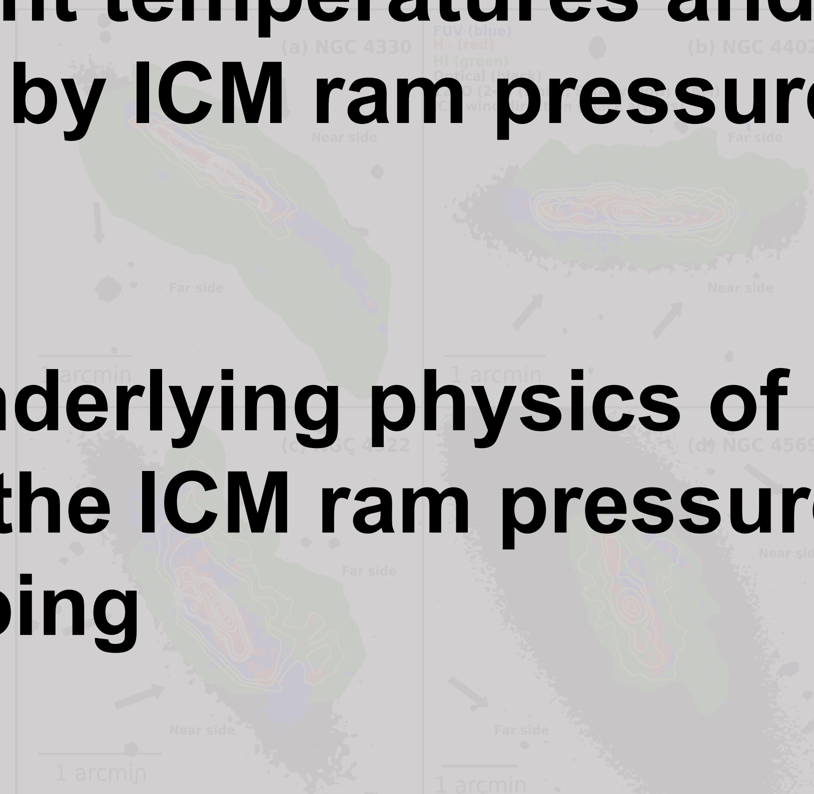
How the ISM of different temperatures and densities gets affected by ICM ram pressure

Understanding the underlying physics of momentum transfer in the ICM ram pressure stripping

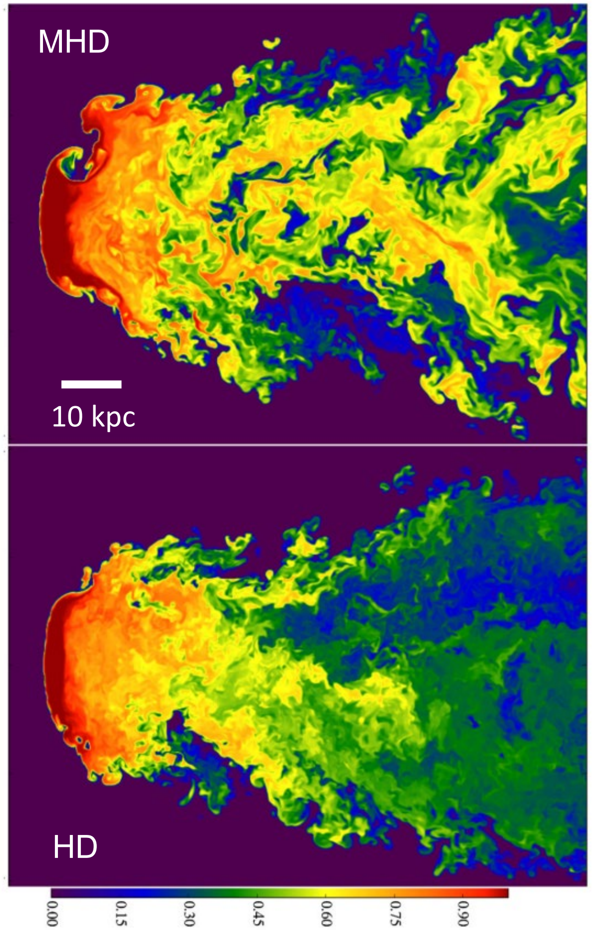


Chung + 09

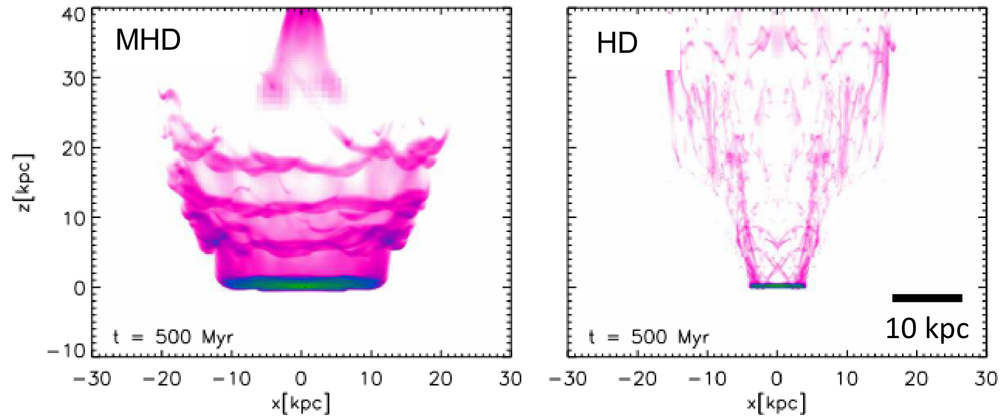


Lee & Chung 2017

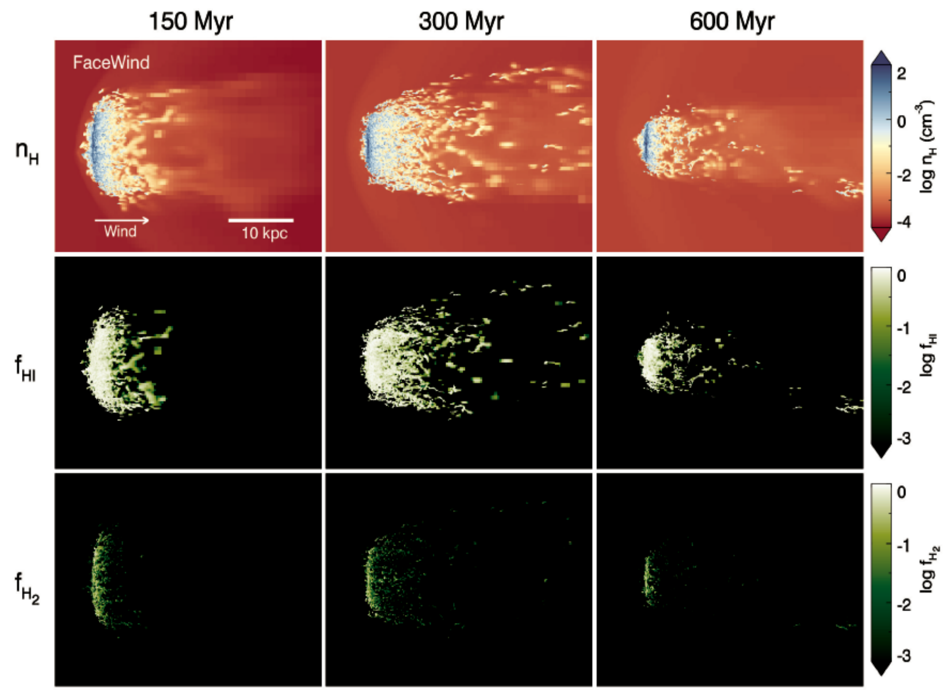
Various RPS simulations in galactic scale



Tonnesen & Stone (2014) : 159 pc resolution



Ramos-Martinez et al. (2018) : 59 pc resolution



Lee et al. (2020) : 18 pc resolution

Three-phase ISM in Galaxies Resolving Evolution with Star formation and Supernova feedback

Kim & Ostriker (2017), ApJ, 846, 133

TIGRESS Physics

a) **MHD** simulation : Based on the Athena (Stone et al. 2008)

b) FUV radiation and **SN rates by population synthesis**

c) Hot ISM ($T > 10^6 K$) created by SN shocks (**resolved Sedov-Taylor phase**)

d) SN in clusters + OB runaways (realistic space-time correlation of SNe for multi-phase ISM)

e) External gravity by old stars & dark matter (Kuijken & Gilmore 1989)

f) Star formation using self-gravity and sink particles (= star clusters) (Gong & Ostriker 2013)

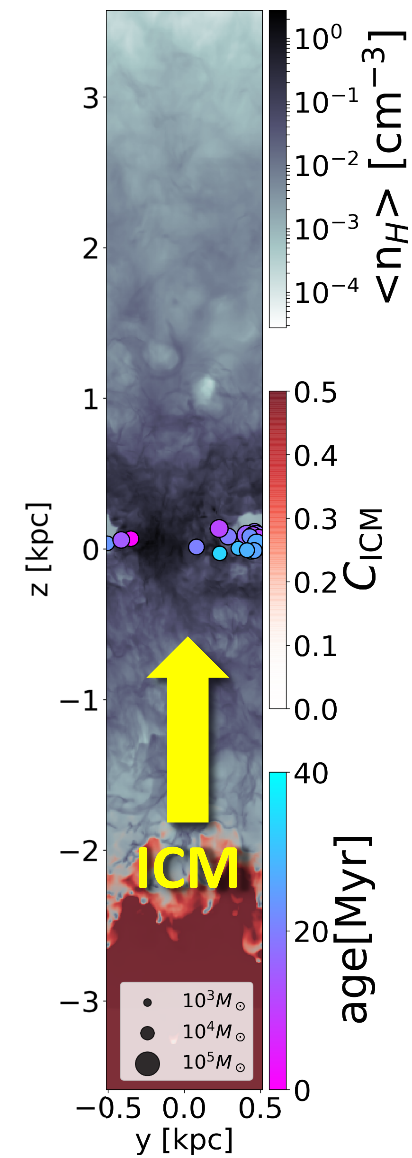
g) Optically thin cooling ($10K < T < 10^9 K$) (Koyama & Inutsuka 2002; Sutherland & Dopita 1993)

h) Photoelectric heating in the warm/cold ISM ($T < 2 \text{ x } 10^4 K$)

- 4 pc (and 8 pc) uniform resolution & ~ 250 Myr duration
- ICM conditions refer to NGC 4522's environment

Table 1. ICM Model Parameters

Model	$n_{\rm ICM}$	$v_{\rm ICM}$	$P_{\rm ICM}/k_{\rm B}$	$P_{\rm ICM}/\mathcal{W}_{\rm GG}$	Δx
	(10^{-4} cm^{-3})	(10^3 km s^{-1})	(10^4 cm^{-3} K)		(pc)
(1)	(2)	(3)	(4)	(5)	(6)
ICM-P1	0.5	1	0.94	0.18	8
ICM-P3(h)	1	1.4	3.6	0.69	8(4)
ICM-P7(h)	2	1.4	7.2	1.4	8(4)
ICM-P14	2	2	14	2.7	8



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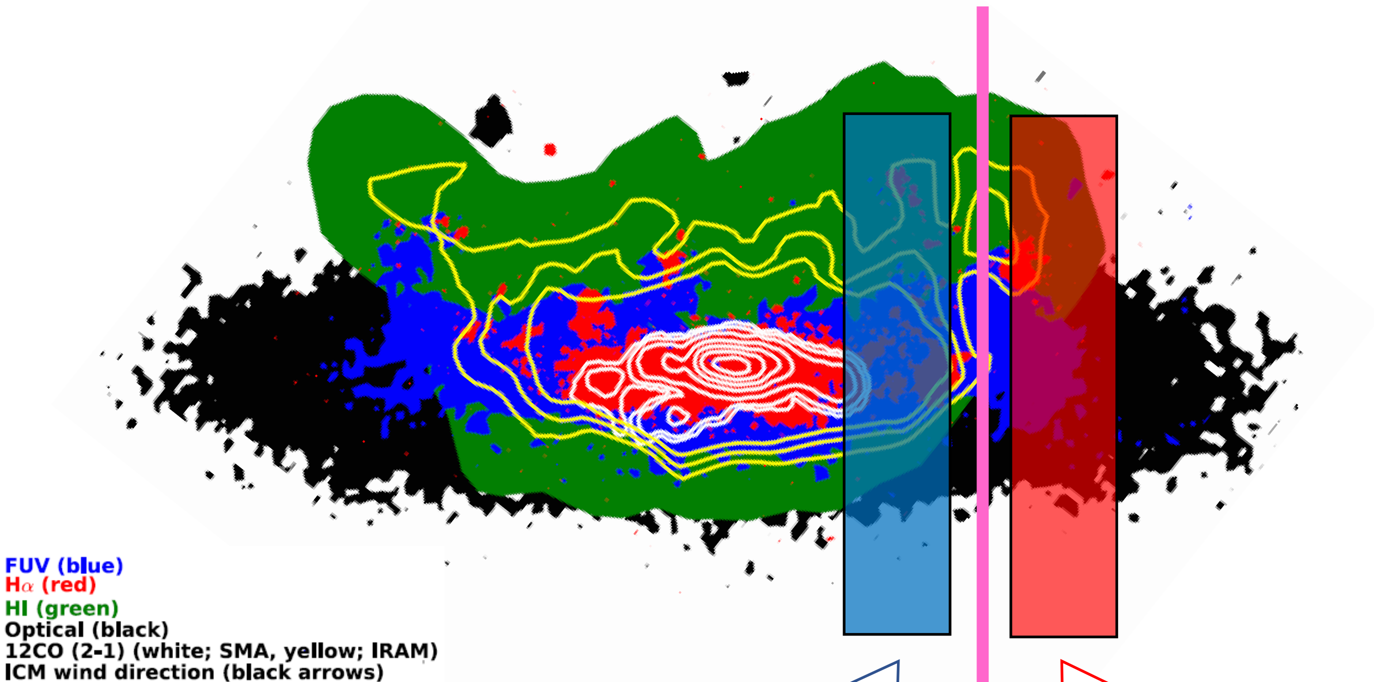
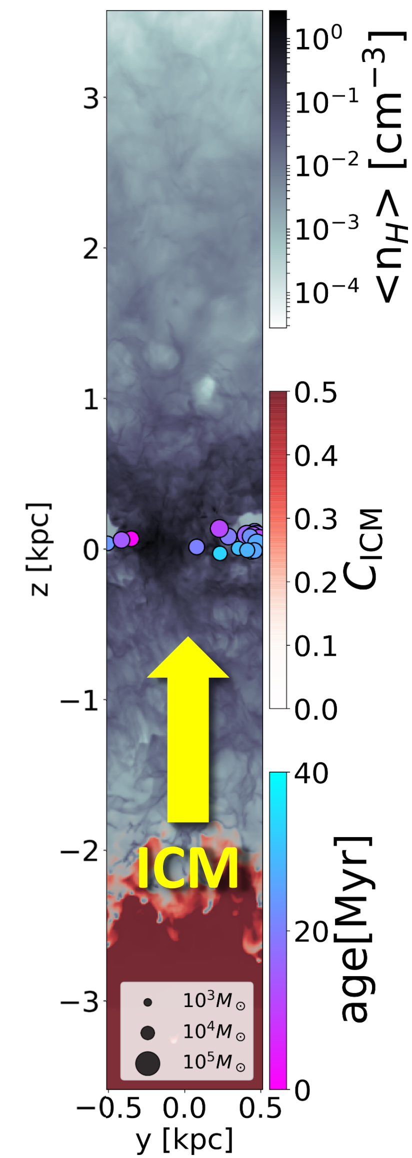


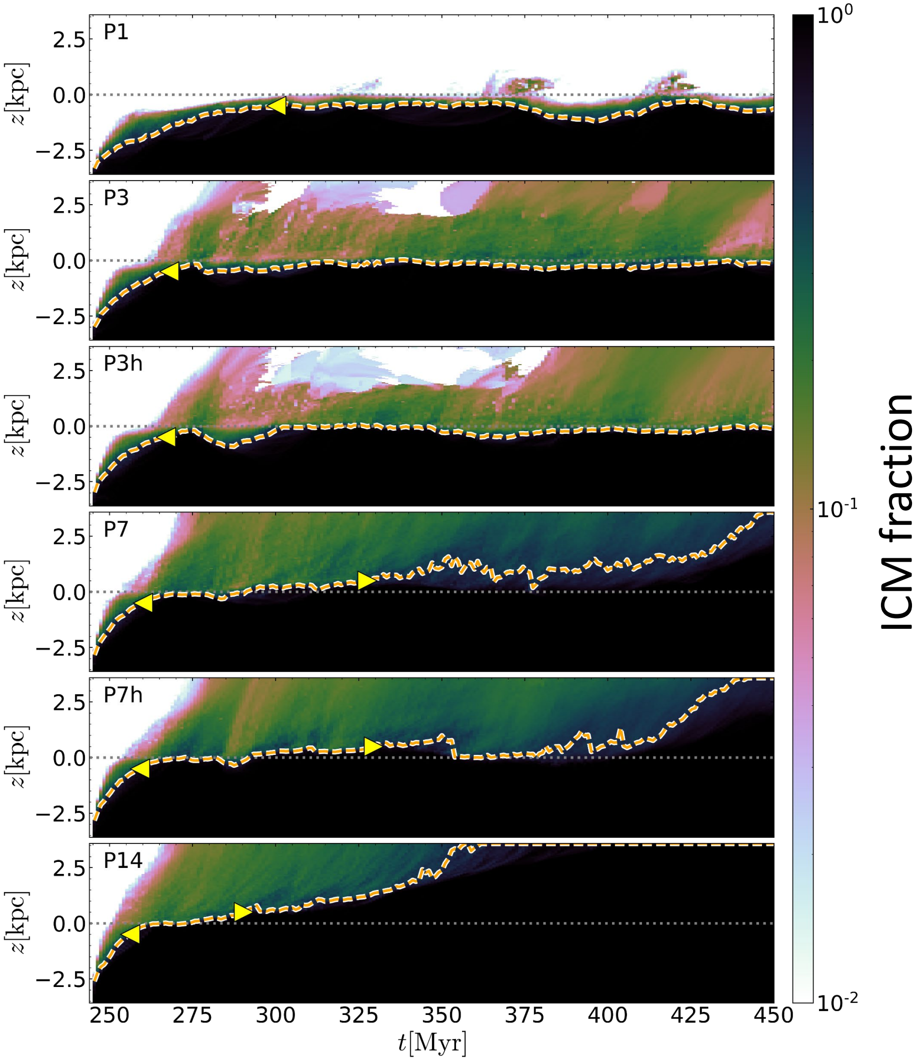
NGC4522; Lee et al. 2017

P1, P3(h)
Relatively Weak ICM
$P_{ram} < P_{restore}$

P7(h), P14
Relatively Strong ICM
$P_{ram} > P_{restore}$



Overall Evolution



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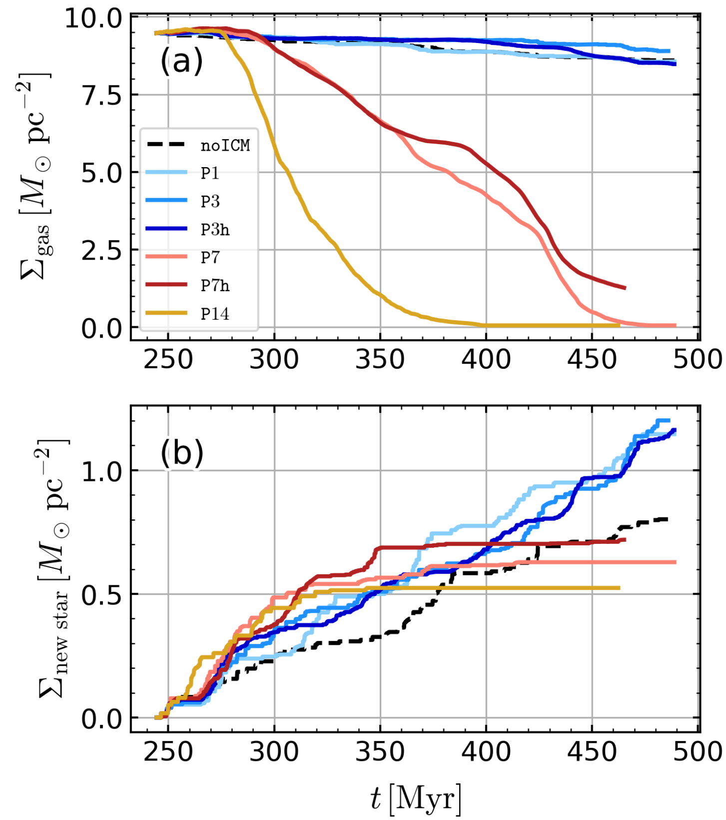
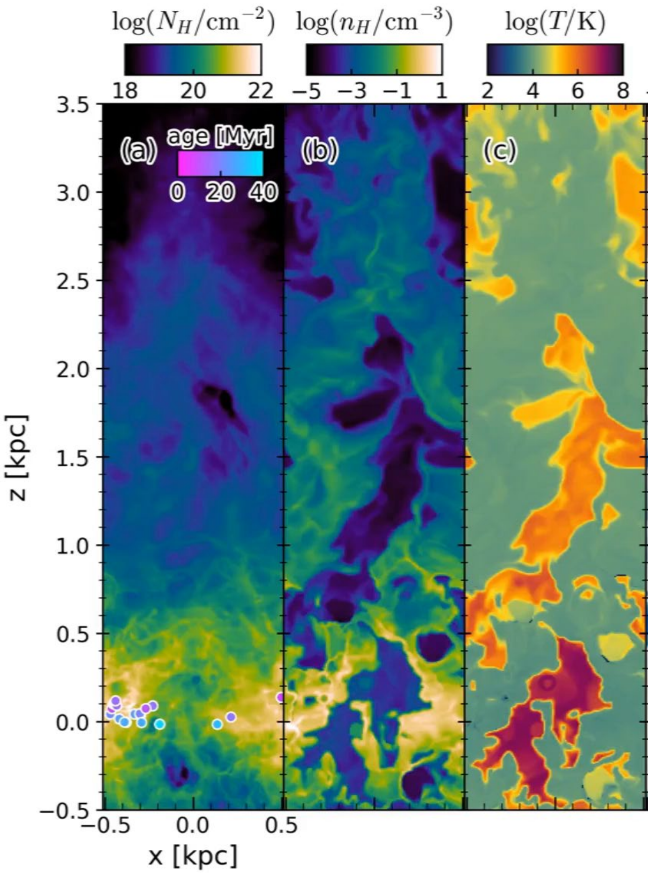
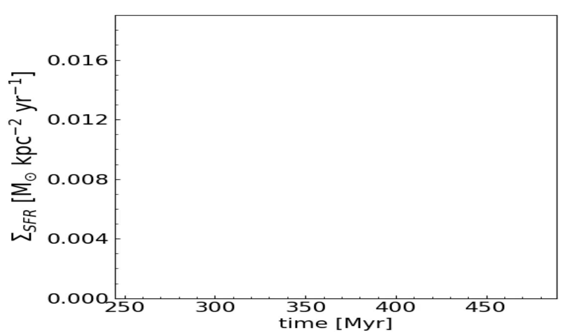


Weak ICM wind (P3h, 4pc) | Strong ICM wind (P7h, 4pc)

Column Density; Density; Temperature



- Deformed but maintained ISM disk
- ICM penetration through low density channel of ISM disk



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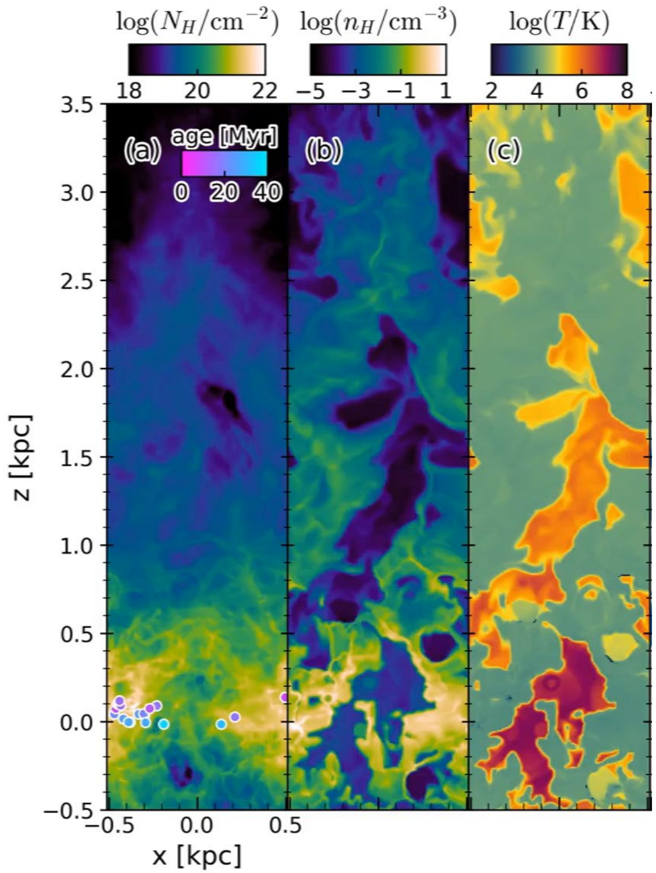

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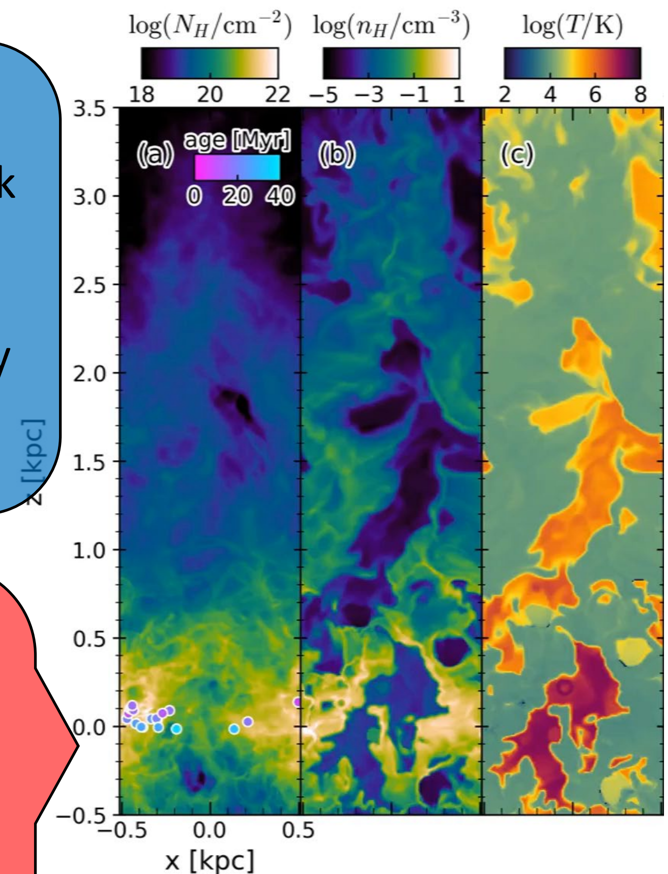
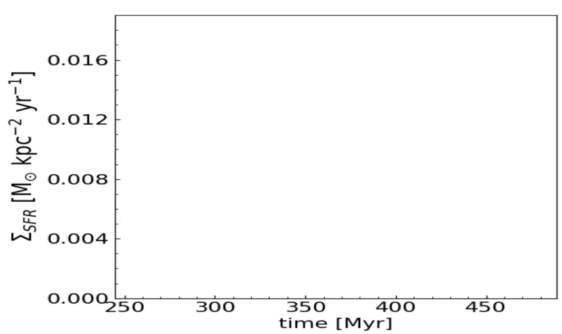
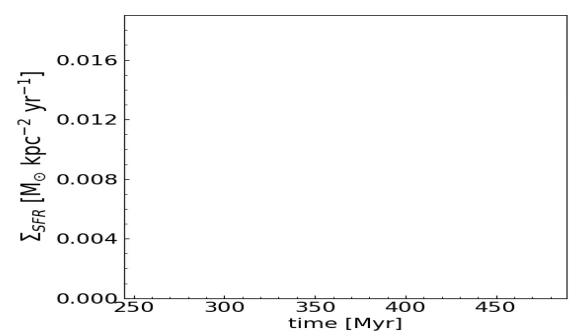




- Deformed disk but soon destroyed
- ICM penetration also
- ISM is not stripped at once
- Gas tail via mixing and hot gas cooling



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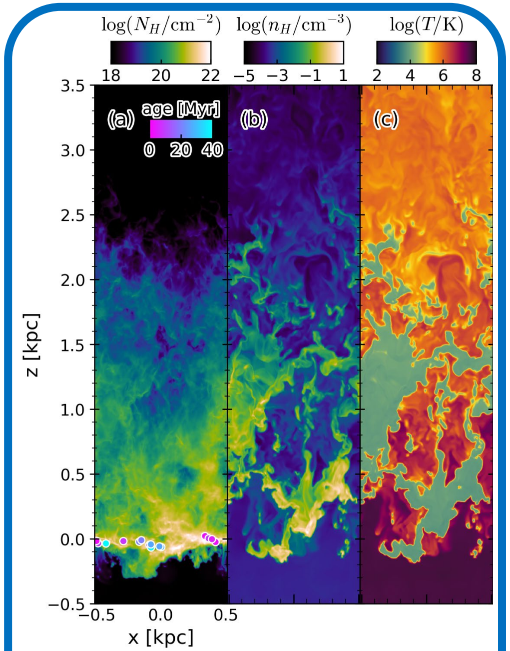
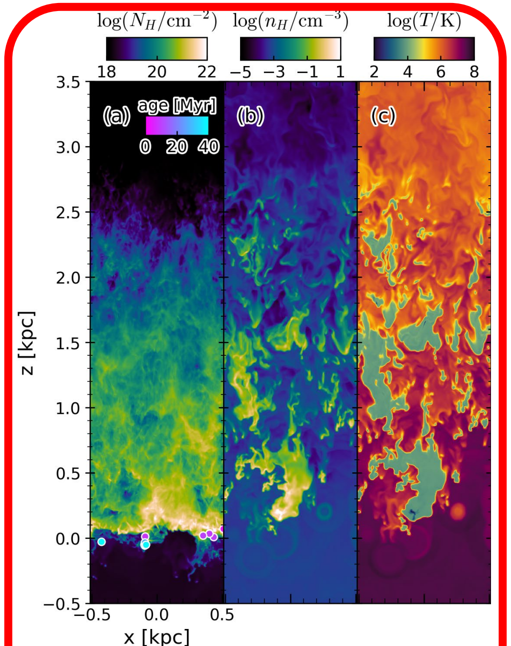
Simulation Snapshots

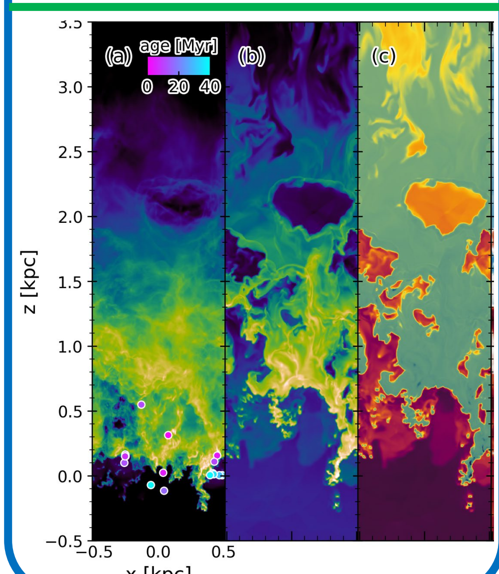
Column Density; Density; Temperature

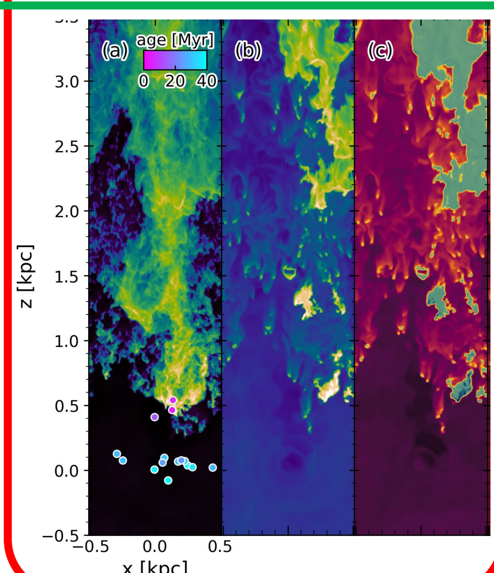




t = 270 Myr

- Deformed disk in both models
- ICM penetration
- Cool gas (< 2e4 K) is a bit more shredded in the strong model





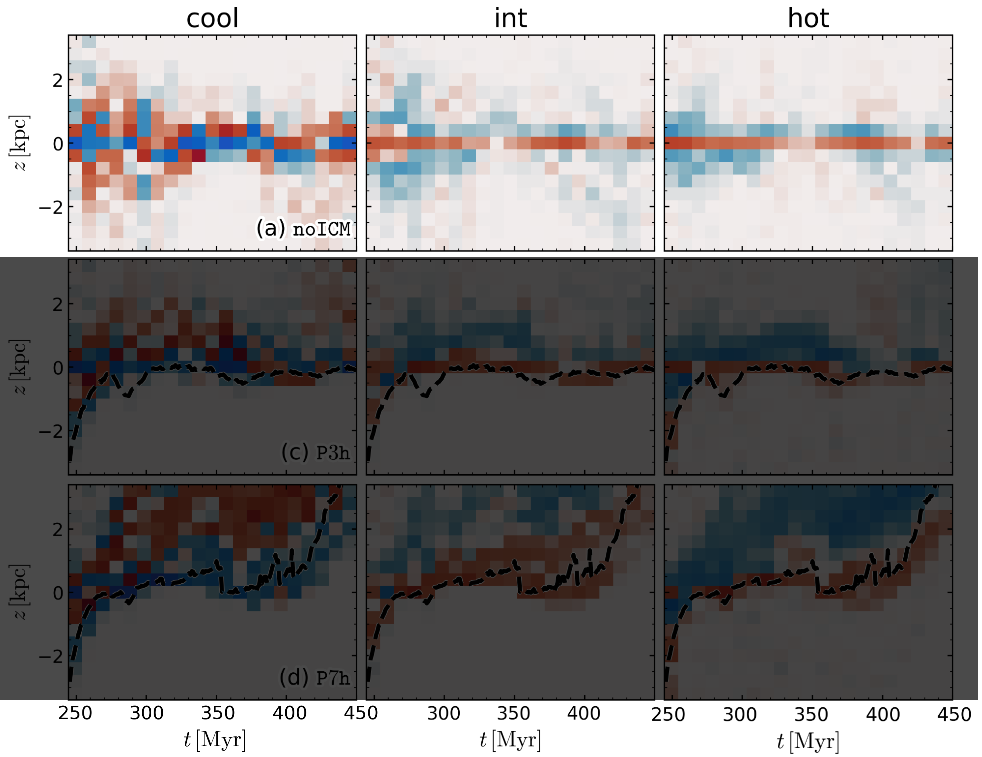
t = 340 Myr

- Disk -> maintained in the weak model
  -> destroyed in the strong model
- Vertically extended structures in strong model
- ISM is not stripped at once

Net gain of mass (left) and momentum (right)

Cool gas: < 2e4 K; Int. gas: 2e4~5e5 K Hot gas: > 5e5 K   Red: net gain; Blue: net loss

Mass evolution   Momentum evolution



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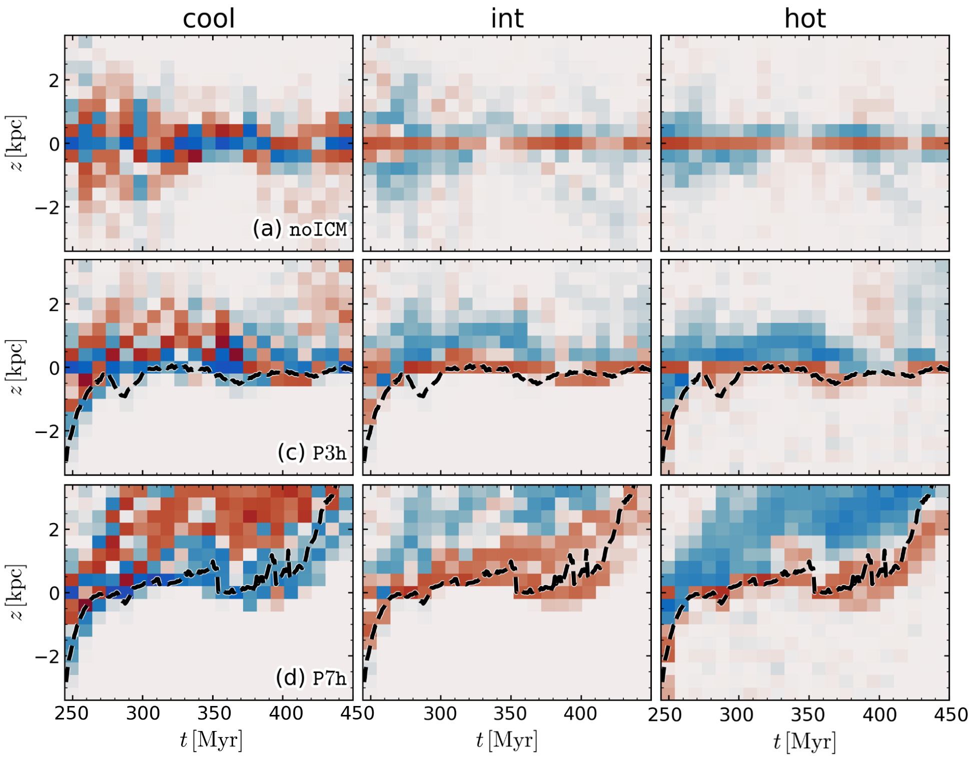

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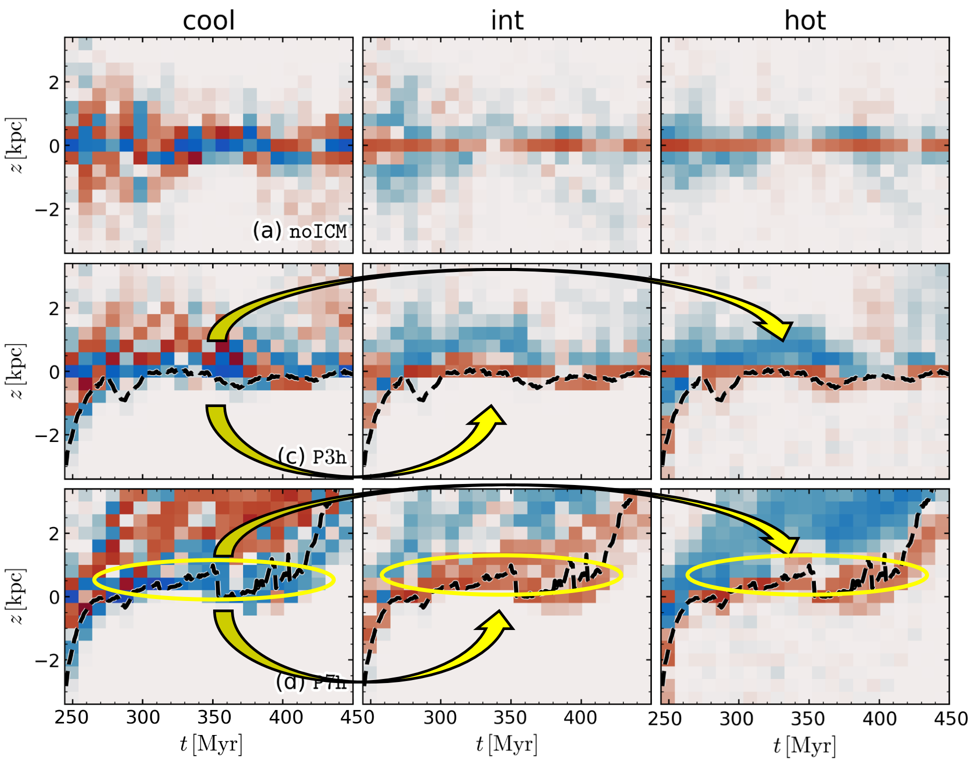

1. Cool to hot transition: due to the cool ISM shredding at ICM-ISM interface

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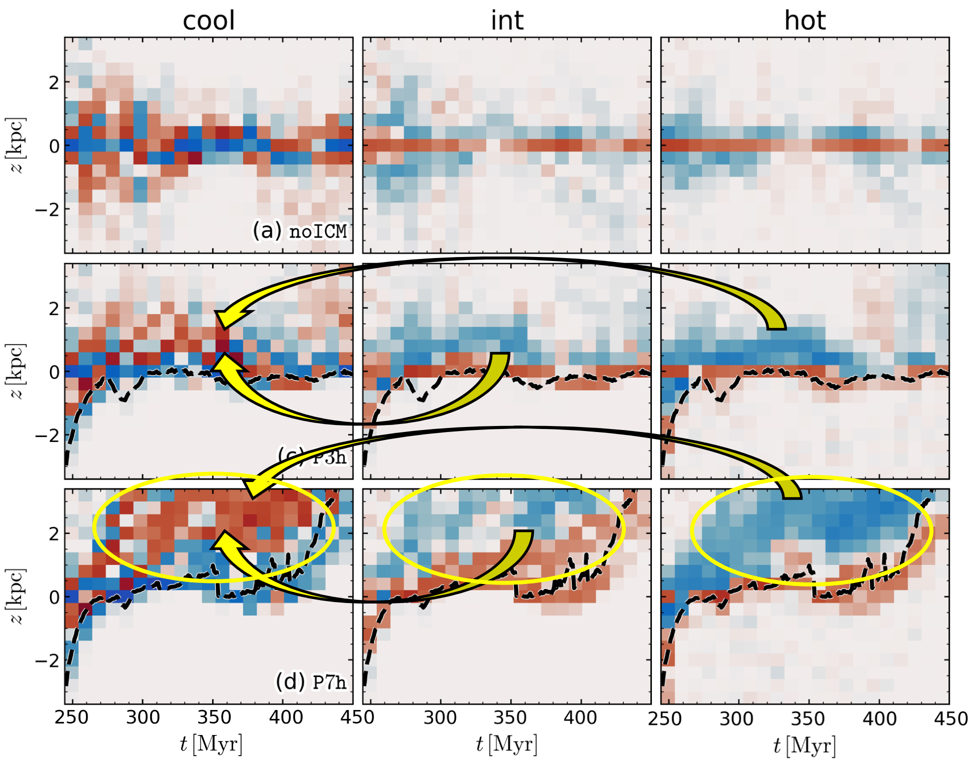

1. Cool to hot transition: due to the cool ISM shredding at ICM-ISM interface

2. Hot to cool transition: hot gas cooling and mixing between hot and cool gas

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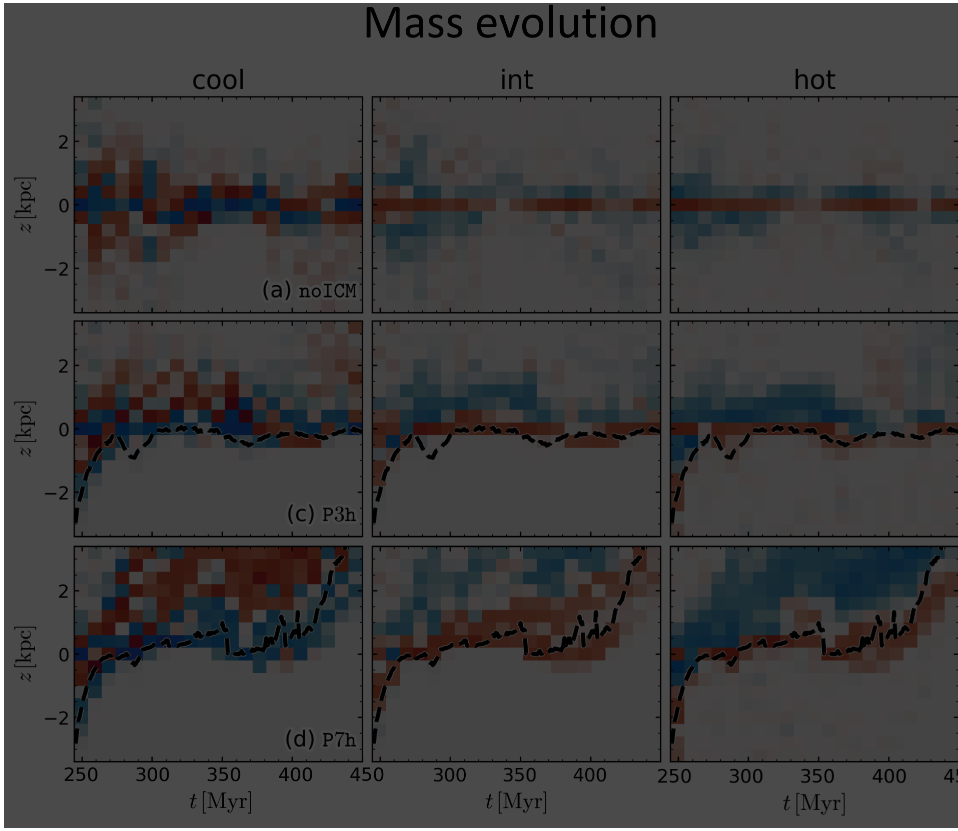

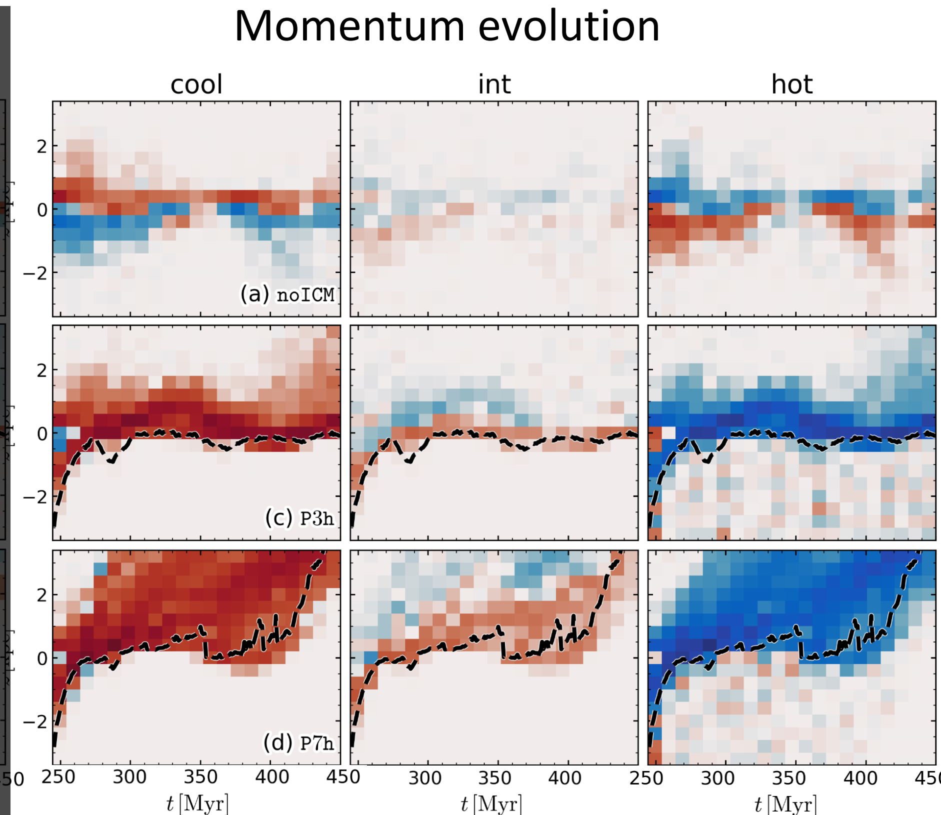

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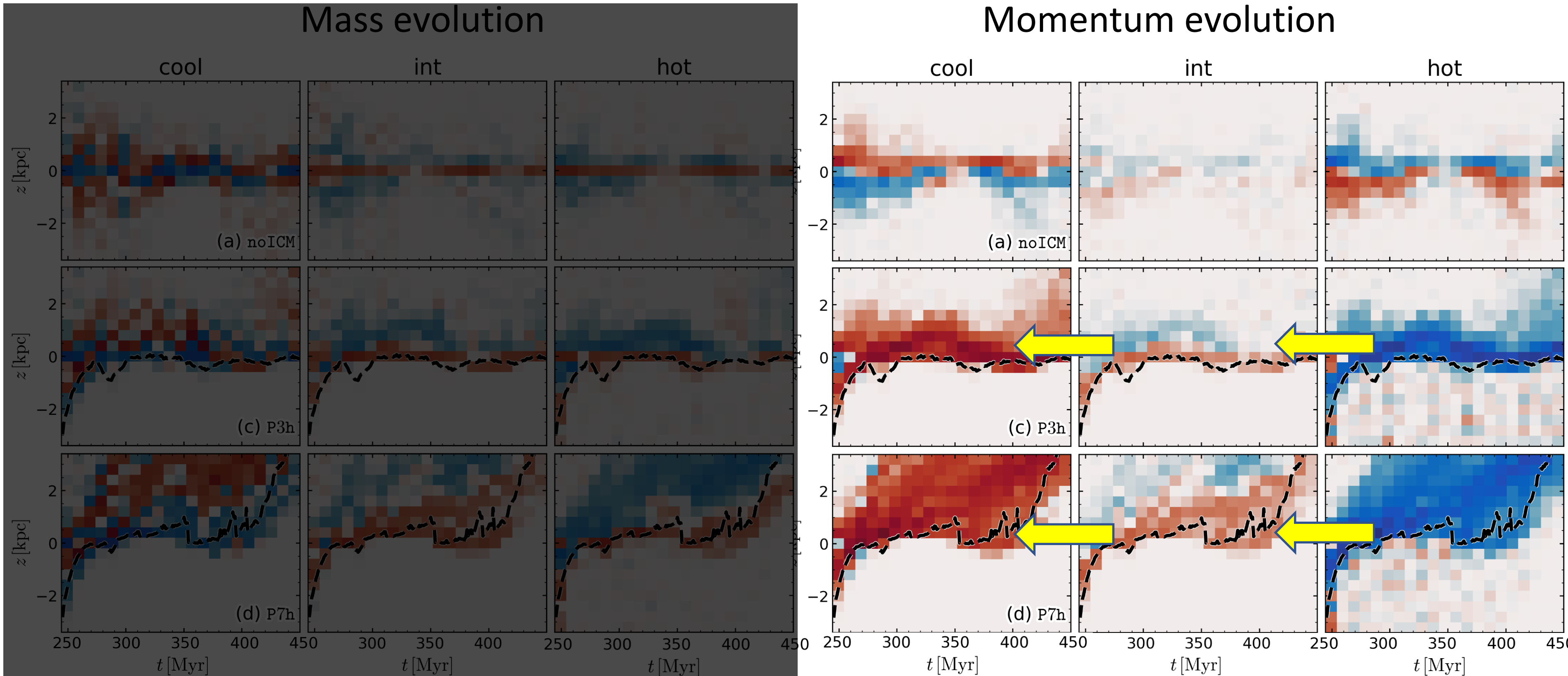


1. Cool to hot transition: due to the cool ISM shredding at ICM-ISM interface

2. Hot to cool transition: hot gas cooling and mixing between hot and cool gas

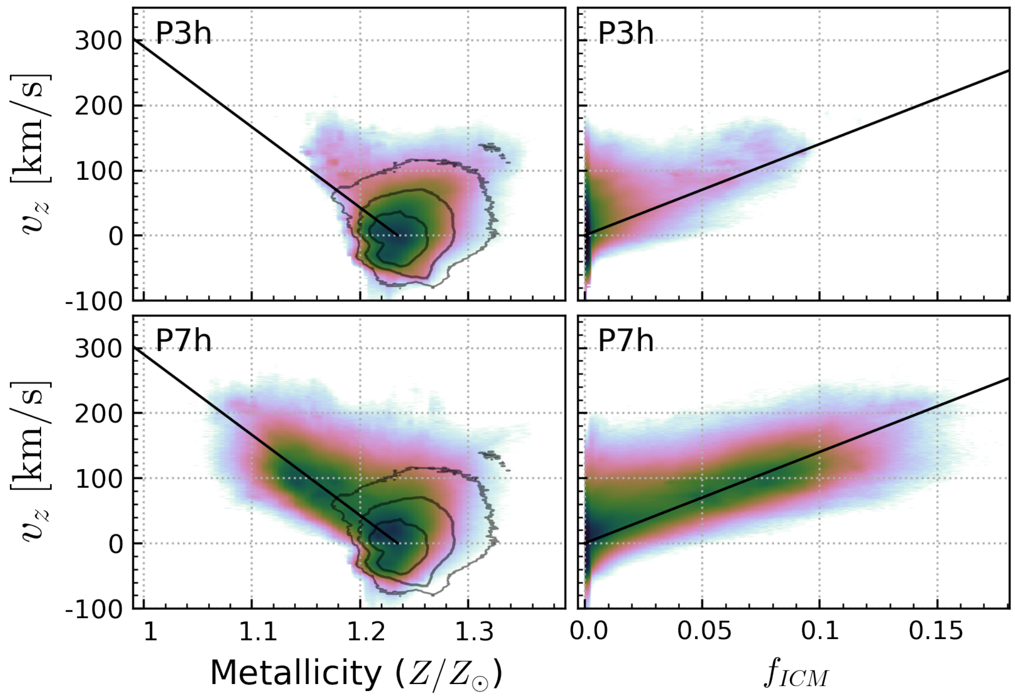
3. Momentum: Always transfer from hot to cool

<u>-> Momentum is transferred via mixing in wide spatial ranges -> RPS</u>

Other hints for mixing-driven momentum transfer

Only cool gas : < 2e4 K (~HI gas)

t = 260 ~ 280 Myr



- Correlation between the ICM fraction and the vertical velocity of cool gas (Schneider et al. 2020; Tonnesen & Bryan 2021)

If mixing dominates momentum transfer,

$$v_{\mathrm{z}}^{\mathrm{cool}} = v_{\mathrm{in}} f_{\mathrm{ICM}}^{\mathrm{cool}}$$

: More ICM -> Higher velocity & Lower metallicity

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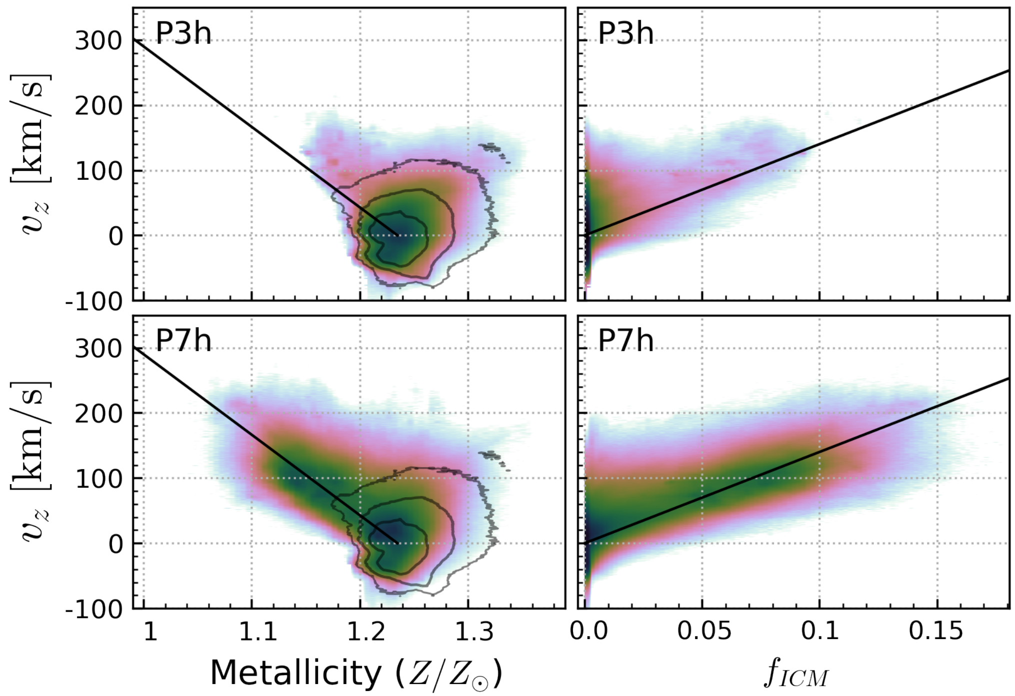

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- Our results support the mixing-driven momentum transfer
- ICM fraction in the cool gas is non-negligible

Mixing driven momentum transfer plays an important role in the ram pressure stripping

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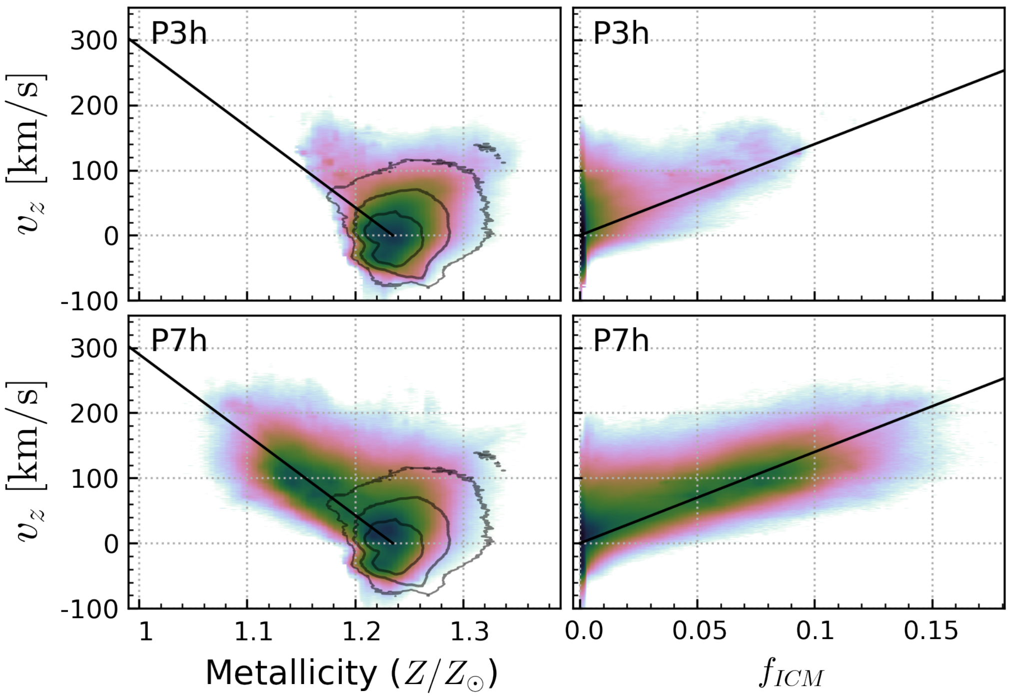

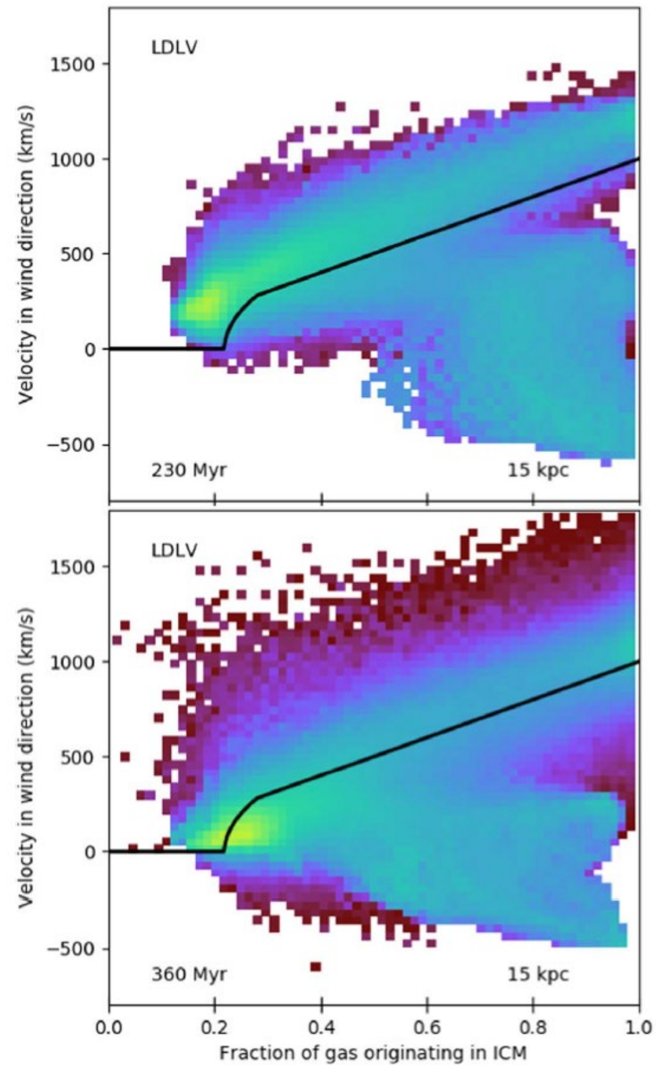

Tonnesen & Bryan 2021

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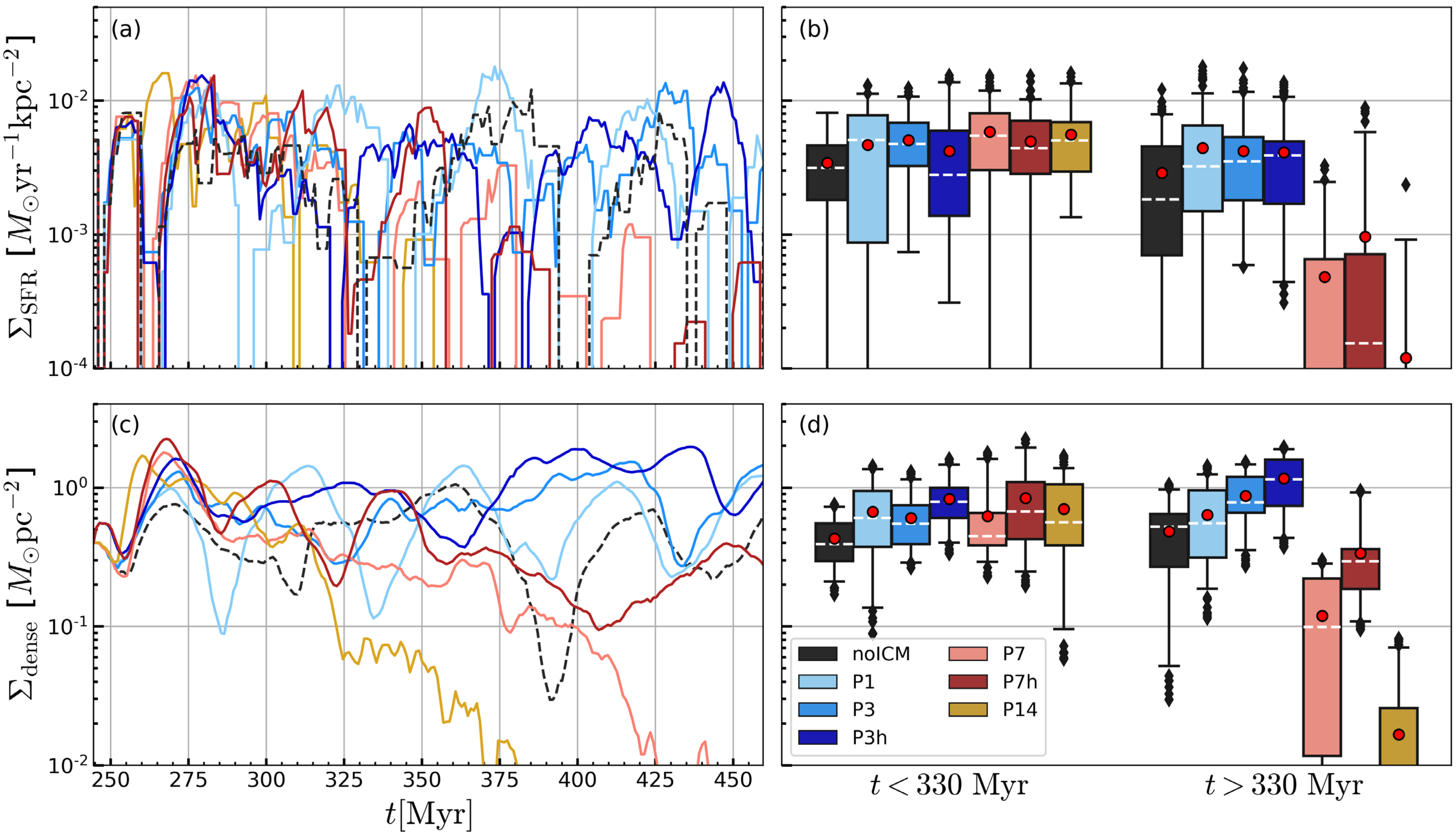
<u>Mixing driven momentum transfer plays an important role in the ram pressure stripping</u>

Star formation rate & dense gas



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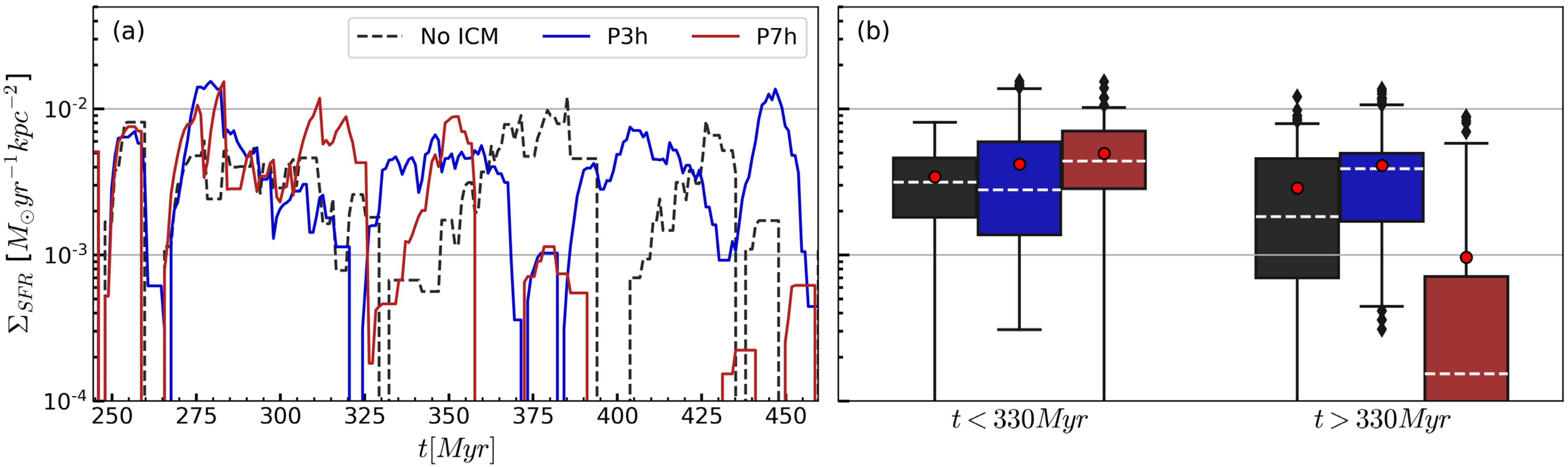
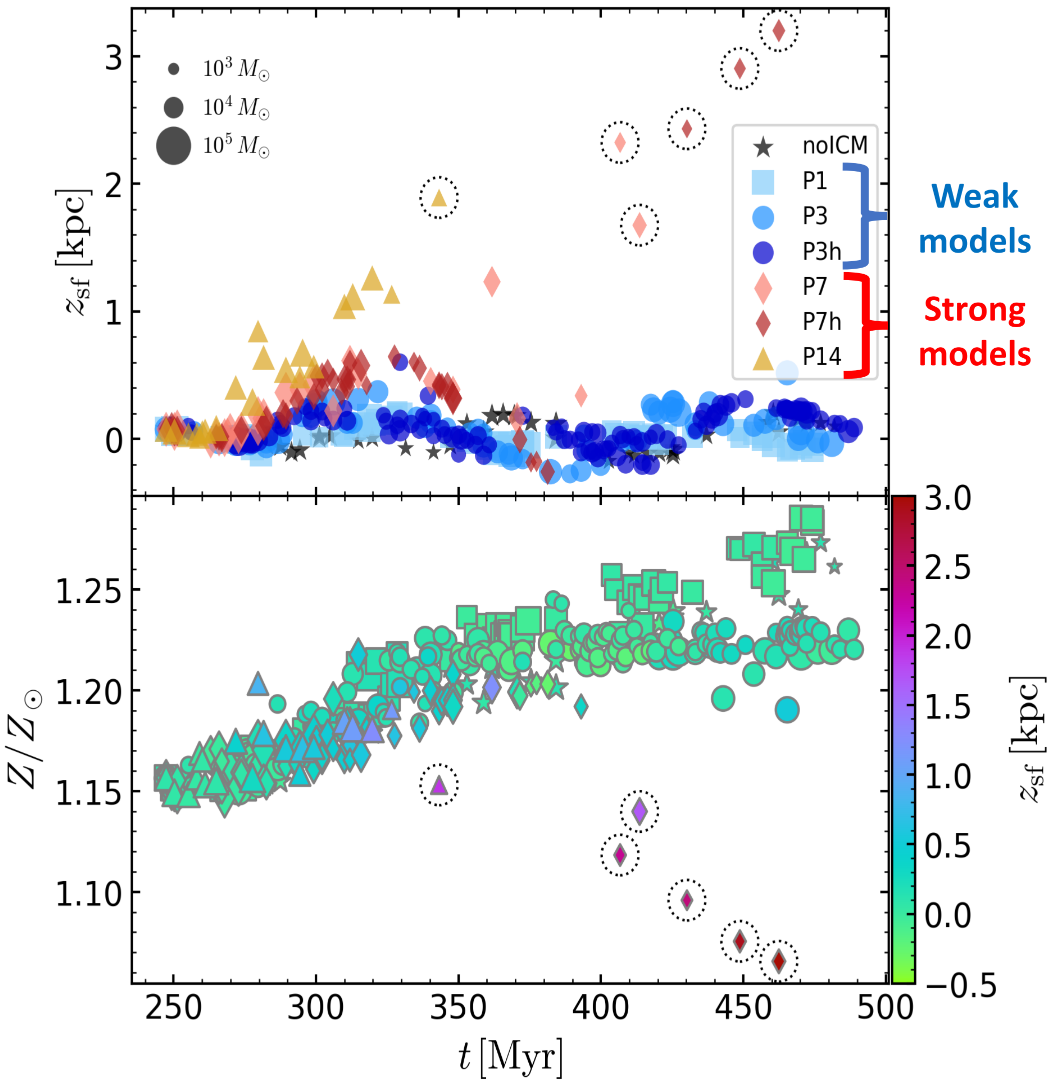


- Enhanced 2-4 times instantaneously and 30-50 % on average
- Weak model: Enhanced star formation is maintained
- Strong model : Star formation is quenched in 100 Myr
- This is qualitatively consistent result with previous simulations (e.g., Kronberger et al. 2008; Steinhauser et al. 2012, 2016; Sparre et al. 2020; Lee et al. 2020) and observations (SFR enhancement of 0.2-0.3 dex; Vulcani et al. 2018; Roberts & Parker 2020)

Extraplanar star formation



- Extraplanar star formation are found up to 3 kpc height
- Metallicity of these star clusters is 0.03 – 0.16 dex lower compared to the midplane star clusters

-> Mixed ISM forms the stars at the extraplanar space (within 3 kpc)

-> Farther extraplanar ISM contains more ICM

Take home message

- We use the local model TIGRESS simulation (4 pc resolution) to study the ram pressure stripping

Q) How the ISM of different temperatures and densities gets affected by ICM ram pressure

A) Cool-to-hot transition at the interface and hot-to-cool transition at the rear-side are found

Q) Understanding the underlying physics of momentum transfer in the ICM ram pressure stripping

A) Mixing driven momentum transfer plays a dominant role in the RPS

- SFR enhancement : 30 – 50% on average (all models)
- Star formation quenching timescale : ~ 100 Myr (strong models)

- Extraplanar star formations are found up to 3 kpc height
- Extraplanar stars have relatively low metallicities