Investigating ram pressure stripping via

TIGRESS simulation
&
JVLA polarization observation

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Ram Pressure stripping (RPS)

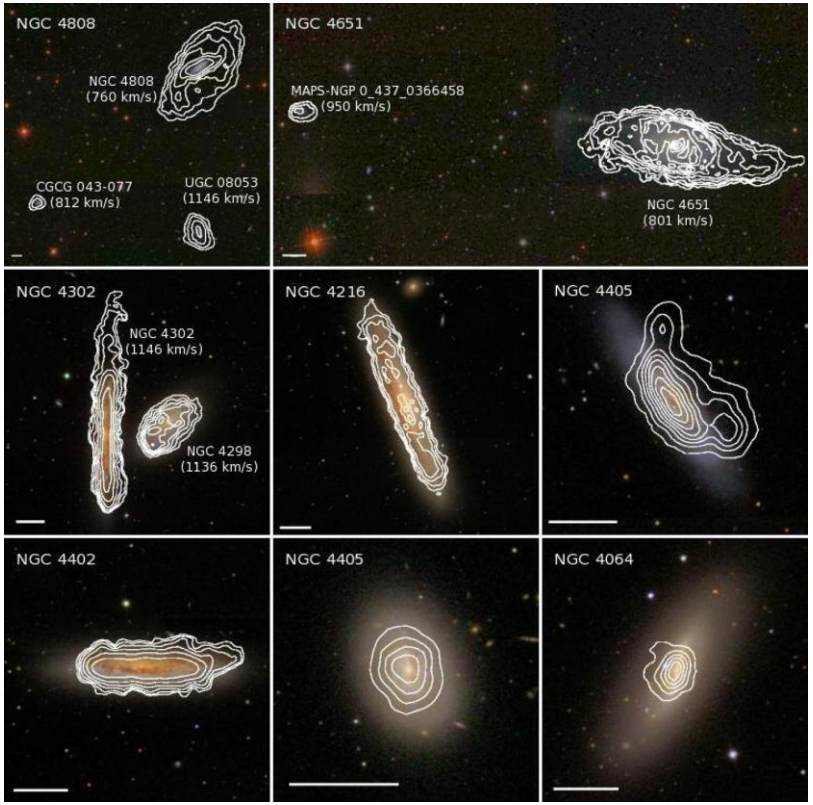
Chung+ 09

- ISM is disturbed by the intracluster medium (ICM) without stellar disturbance

- Gunn & Gott (1972) :

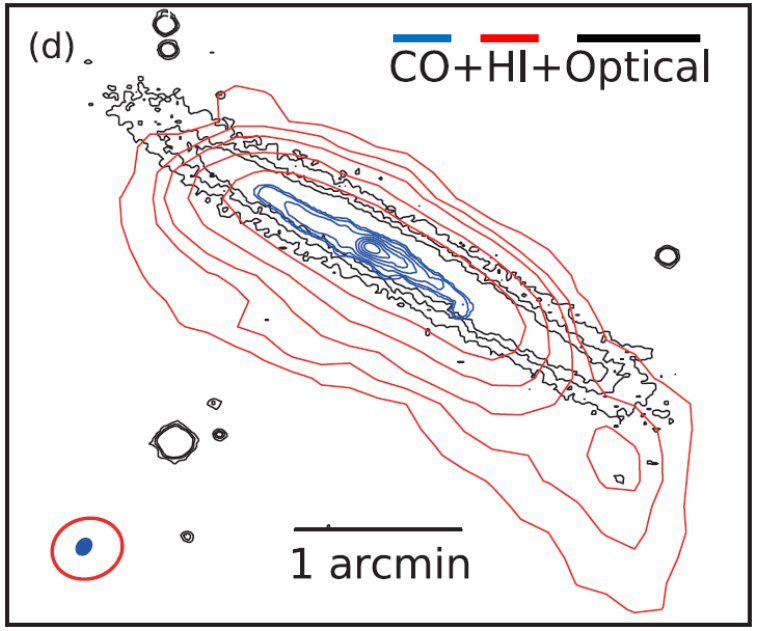
$$\rho_{ICM} v_{rel}^2 \text{ (Ram pressure)}$$
vs.
$$\Sigma_{ISM} \frac{d\Phi}{dz} \text{ (Restoring force)}$$

- HI observations have shown various RPS samples (e.g., Chung et al. 2009)

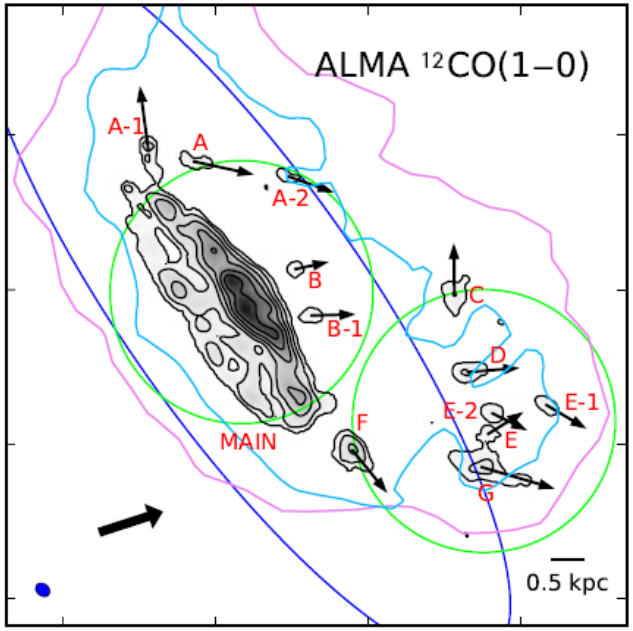


Molecular gas observation for RPS galaxies

- Conflicting results of molecular gas deficiency of RPS galaxies (Kenney & Young 1989; Boselli et al. 2014)
- Morphological similarity between HI and CO (Lee et al. 2017)
- Existence of extraplanar molecular gas (Lee & Chung 2018)

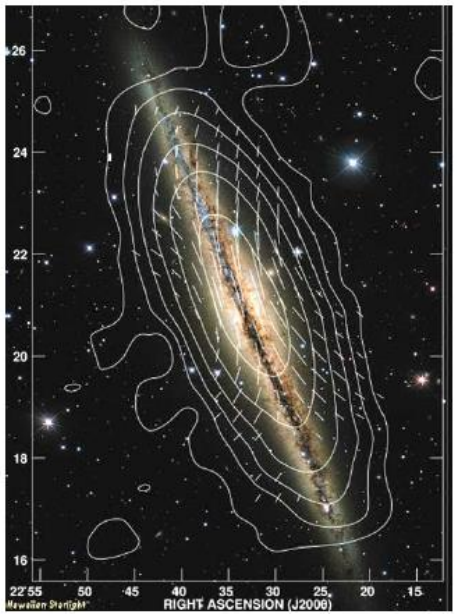


Lee et al. 2017



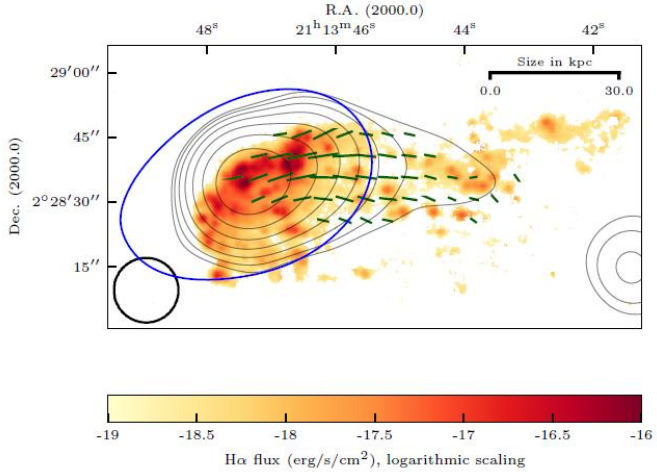
Lee & Chung 2018

Polarized radio continuum observation for RPS galaxies

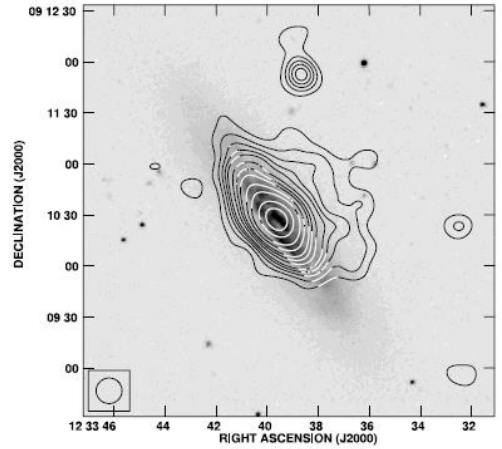


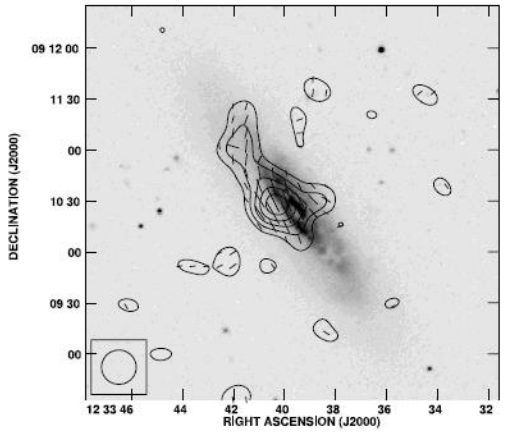
NGC 891,
Krause (2009)

Edge-on galaxy

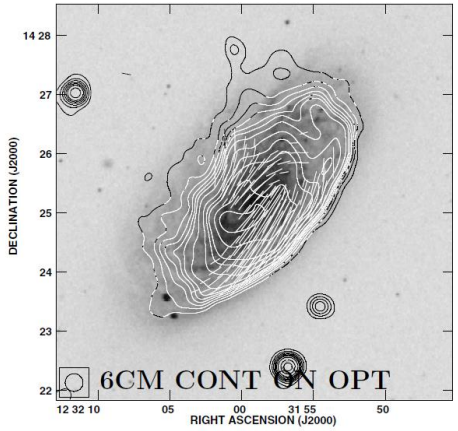


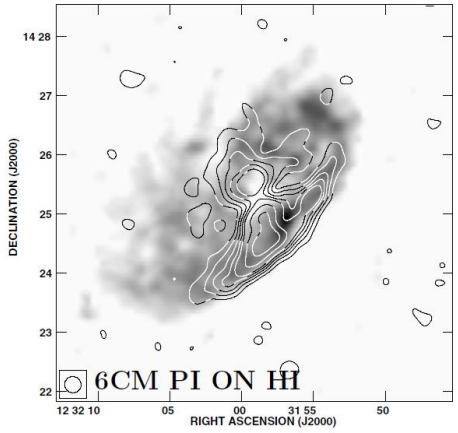
Müller et al. (2020), GASP JO206





Vollmer et al. (2004)





Vollmer et al. (2010)

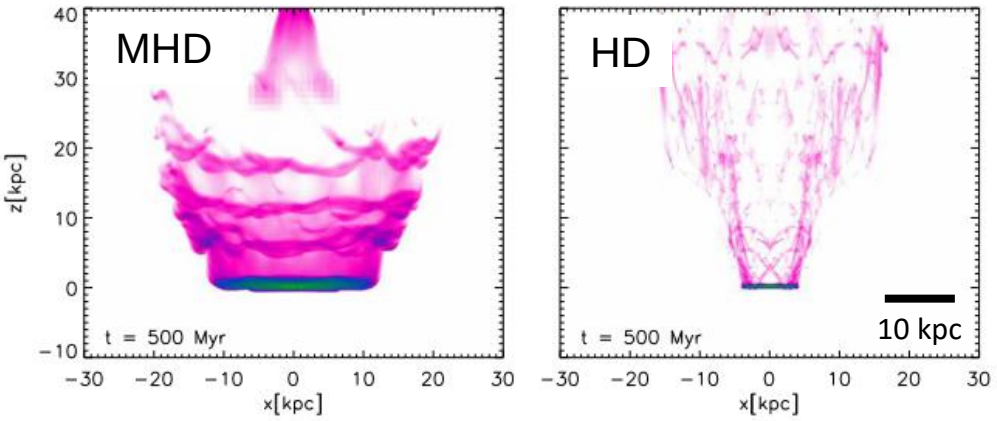
Disturbed total radio continuum & partially compressed (or appeared) polarized continuum and aligned magnetic field

Is it possible to remove the molecular gas from the disk?

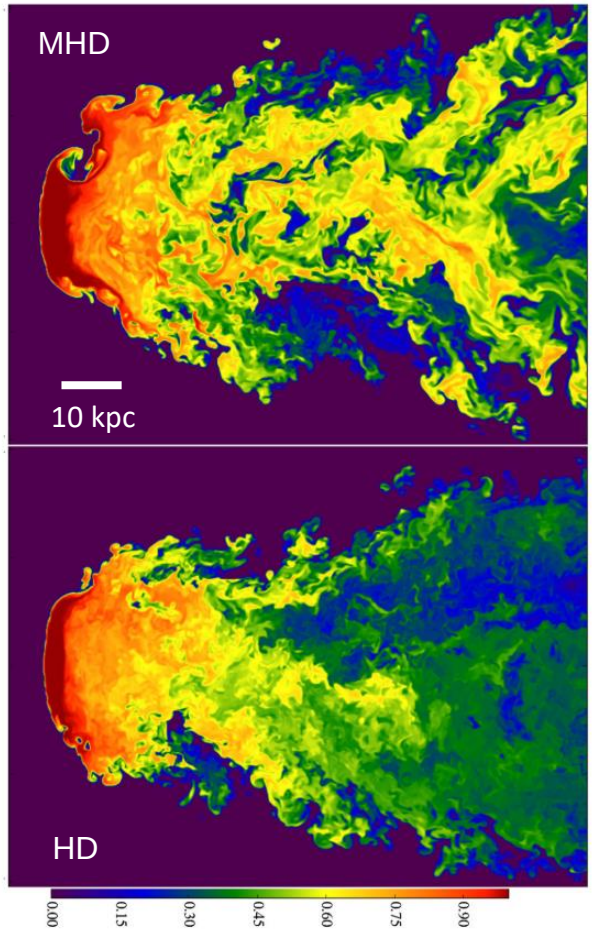
How different phases of ISM react to the ram pressure?

What is a role of magnetic field in RPS?
&
How magnetic field reacts and looks like?

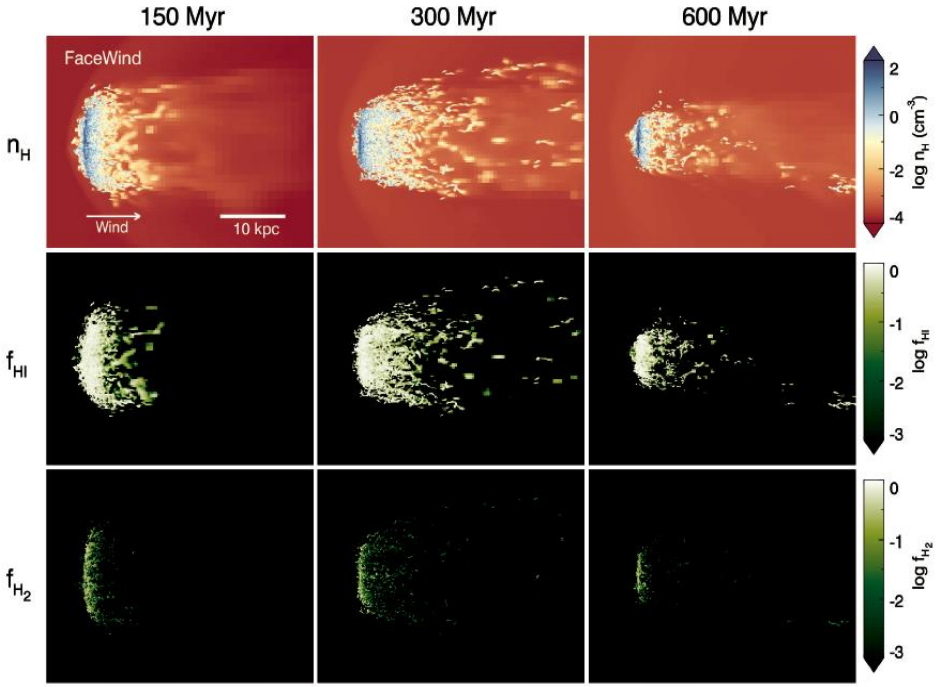
Various RPS simulations in galaxy scale



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



Tonnesen & Stone (2014) : 159 pc resolution



Lee et al. (2020) : 18 pc resolution

- Galactic scale studies in simulations
- Usually focus on role of
  - the inclination (Roediger & Brüggen 2006)
  - the magnetic field (Ruszkowski, Brüggen & Shin 2014; Tonnesen & Stone 2014)
  - Or the morphology of gas disk and tail
- Insufficient resolution
  - Difficult to classify ISM into various phases
  - Difficult to reproduce realistic star formation & SN feedback and magnetic field simultaneously.

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 ($T < 2 \text{ x } 10^4 K$)

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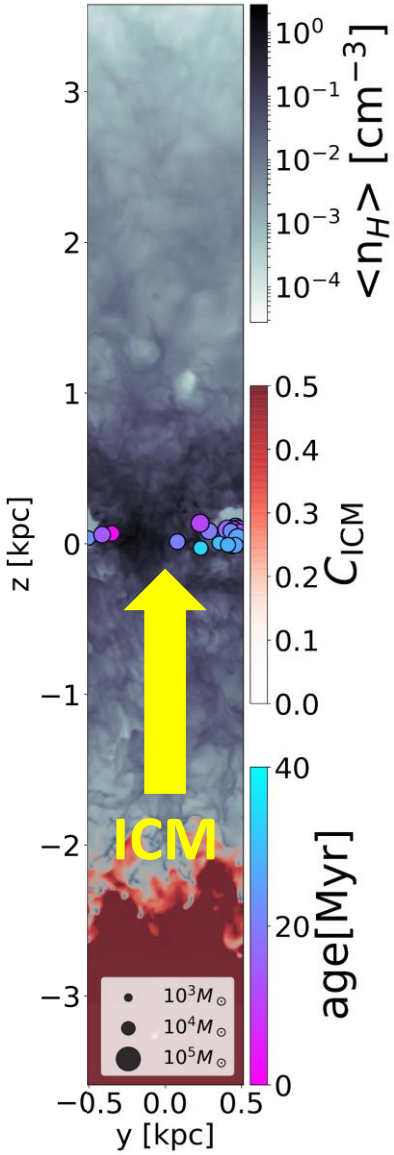
- 1 kpc x 1 kpc x 7 kpc periodic box / 4 & 8 pc resolution
- ~ 250 Myr duration
- Constant & Continuous ICM from –z (face-on interaction)

ICM wind parameters, ICM wind parameters are comparable with Virgo galaxy NGC 4522's environment (Kenney, van Gorkom & Vollmer 2004)

	P1	P3(h)	P7(h)	P14
$\mathbf{n_{ICM}\ [cm^{-3}]}$	0.5×10^{-4}	1×10^{-4}	2×10^{-4}	2×10^{-4}
$\mathbf{v_{ICM}\ [km/s]}$	1000	1414	1414	2000
$\mathbf{P_{ram}\ /\ k_b\ [Kcm^{-3}]}$	0.94×10^{4}	3.6×10^{4}	7.2×10^{4}	14×10^{4}
Ratio[1)]	0.18	0.69	1.4	2.7

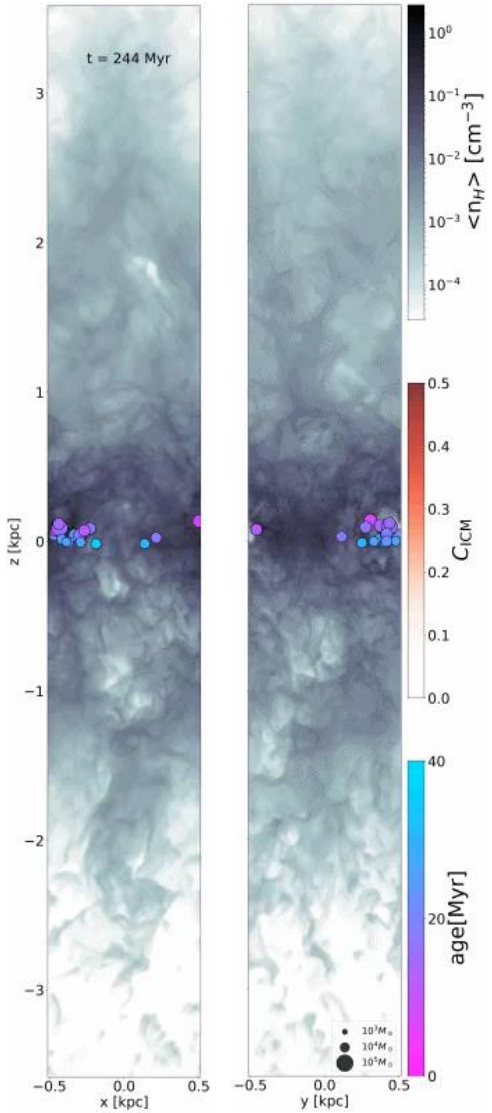
1) $P_{ram}\ /\ W_{ISM}$



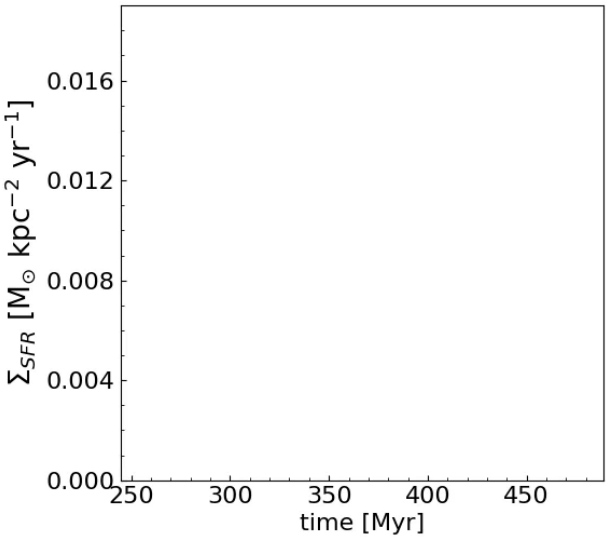
Movie_link:
https://www.dropbox.com/sh/orsbnd57ly9iwfs/AAAo0TQxmwSPXZVKnjwepCjYa?dl=0

Weak ICM wind (P3h, 4pc)

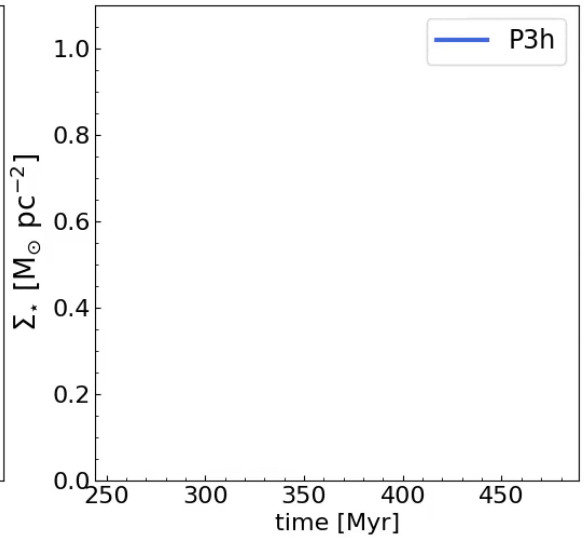
x proj. **y proj.**



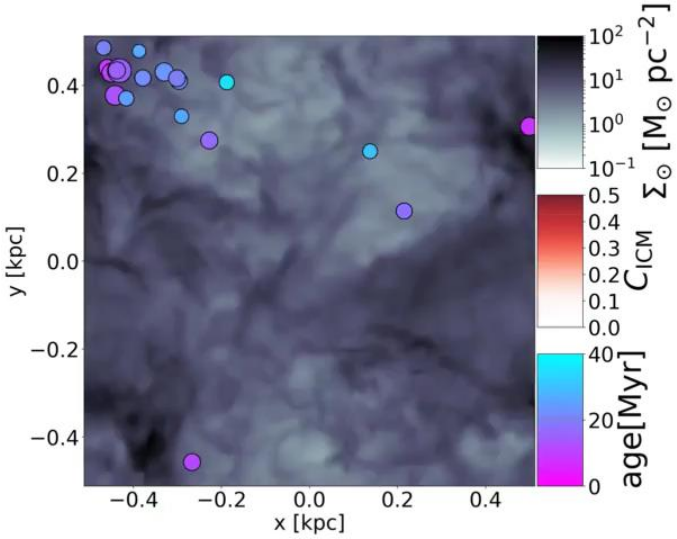
Σ_{SFR} vs. time



Σ_{star} vs. time



z proj.



Gray : ISM density
Red : ICM
Circle : New star clusters (< 40 Myr)

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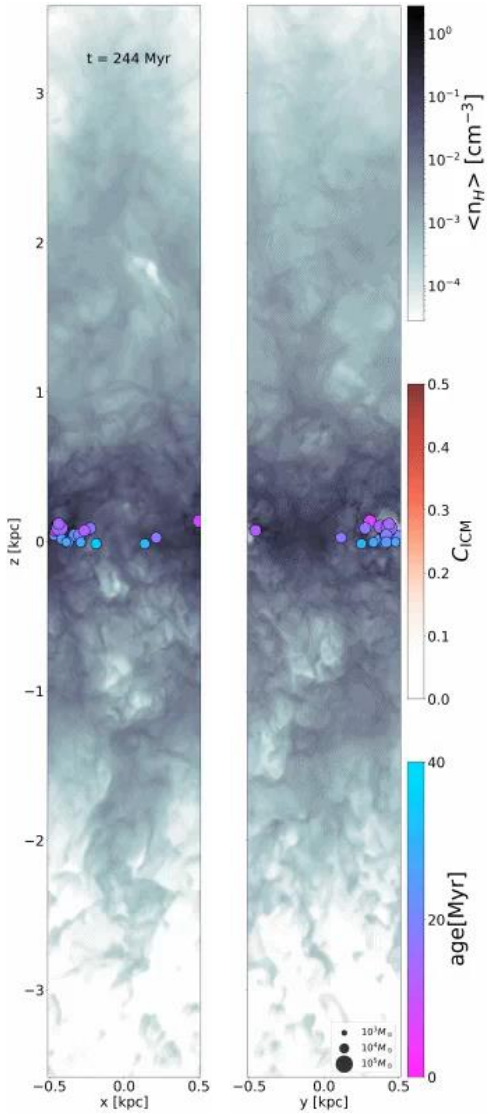
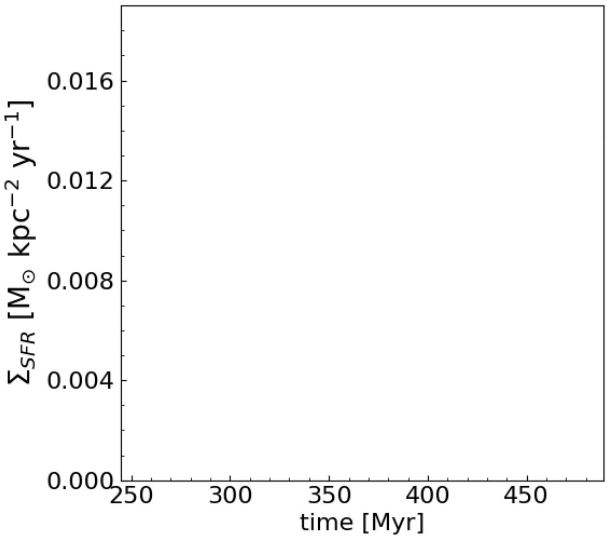
Movie_link:
https://www.dropbox.com/sh/nez02aduwpml1e5/AADrNuHQoGPRjPrjNs5obcgfa?dl=0

Strong ICM wind (P7h, 4pc)

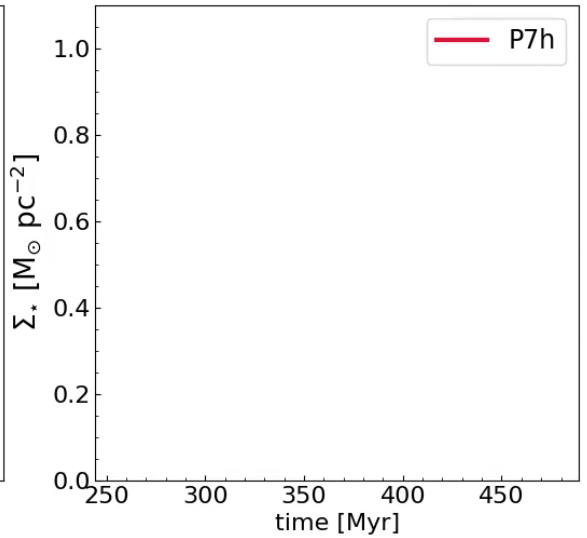
x proj. **y proj.**



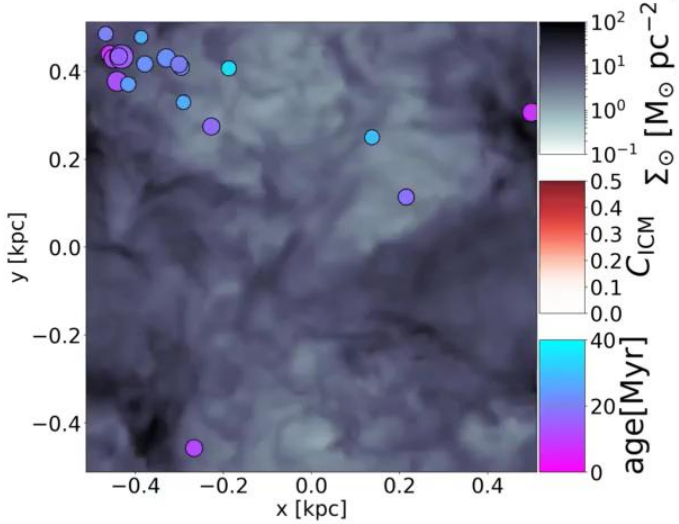
Σ_{SFR} vs. time



Σ_{star} vs. time



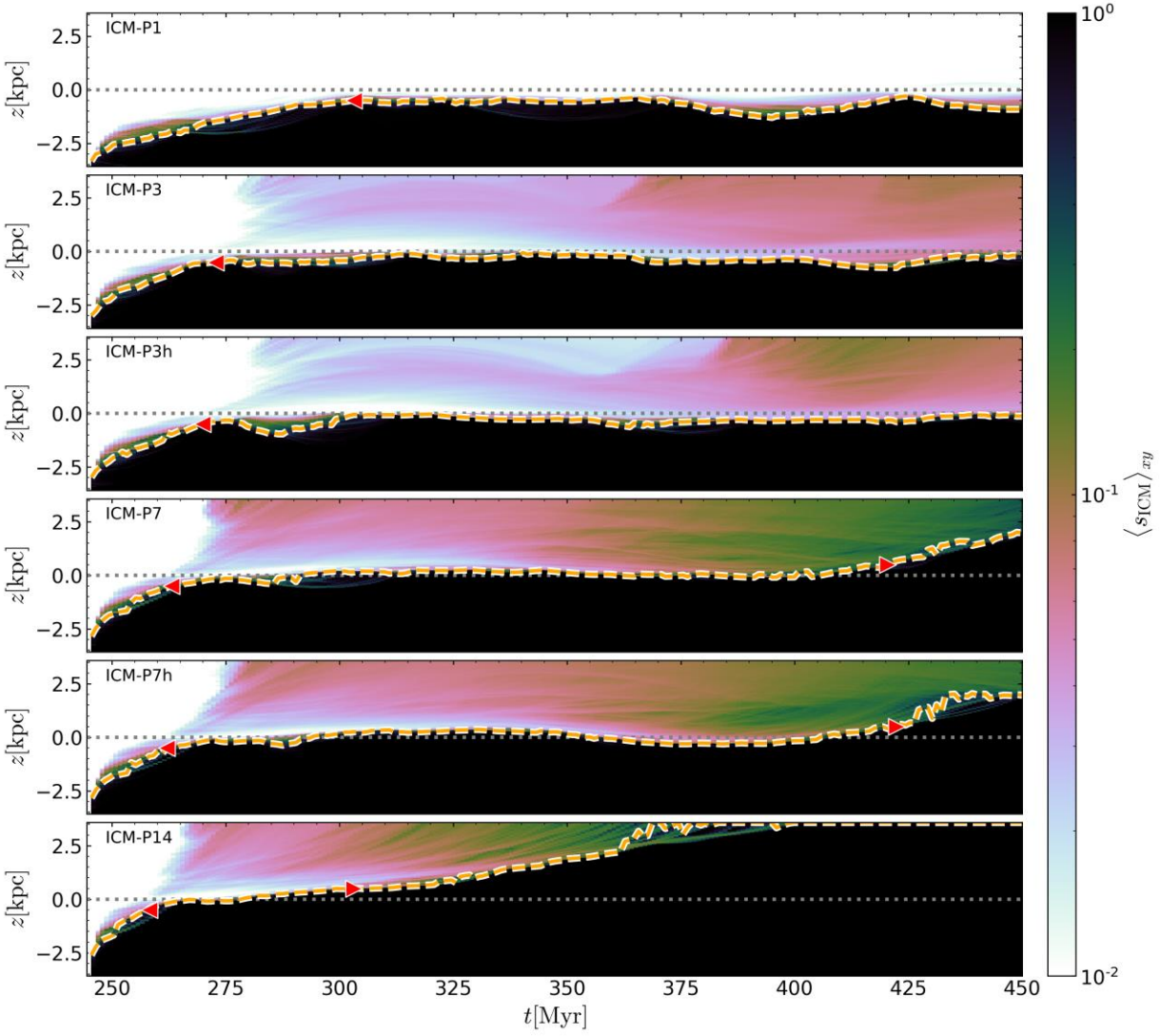
z proj.



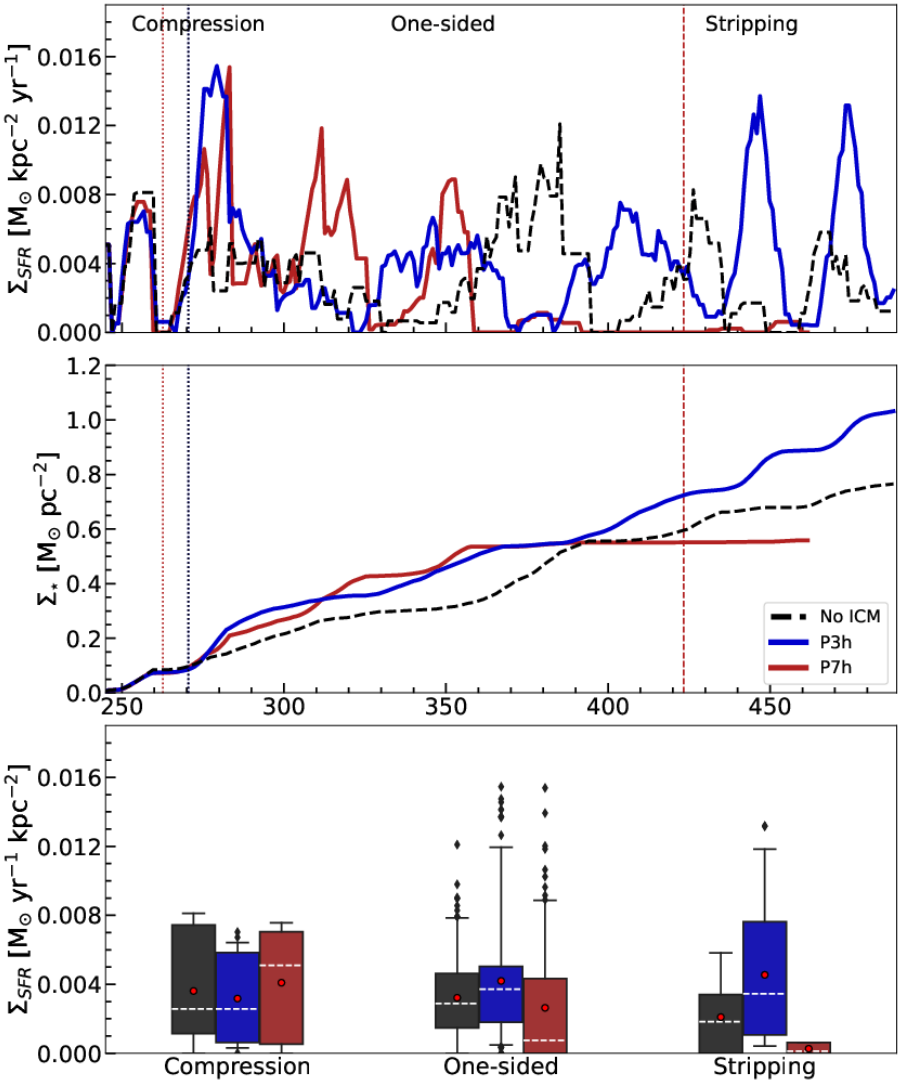
Gray : ISM density
Red : ICM
Circle : New star clusters (< 40 Myr)

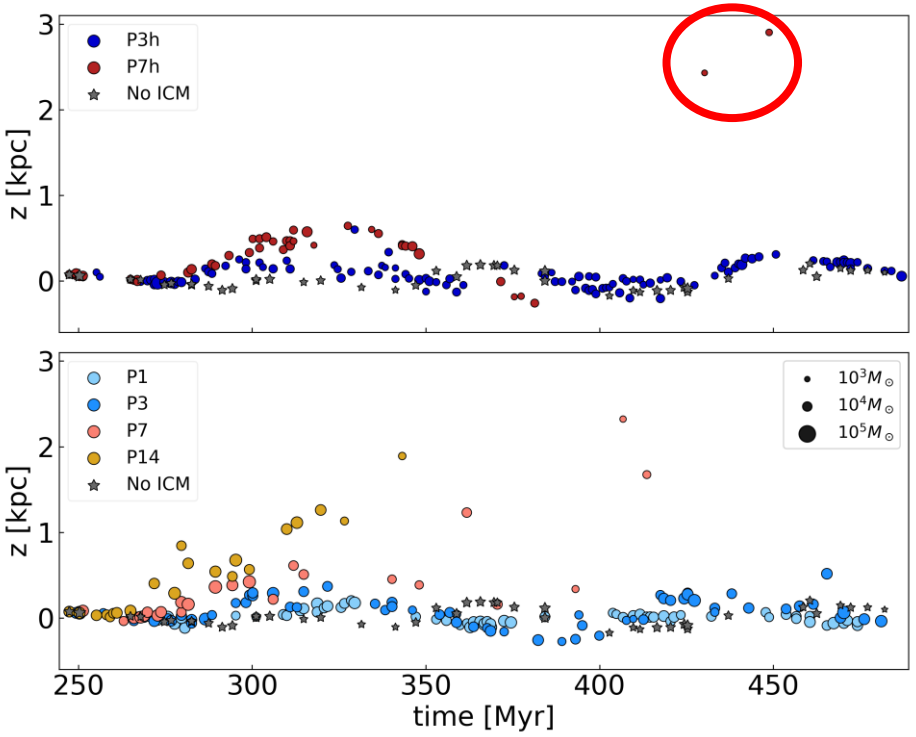
Horizontally averaged ICM fraction – for dividing the stage of each simulation

Compression (Until s=0.5 reaches -0.5 kpc) / One-sided disk (Until s=0.5 reaches +0.5 kpc) / Active Stripping



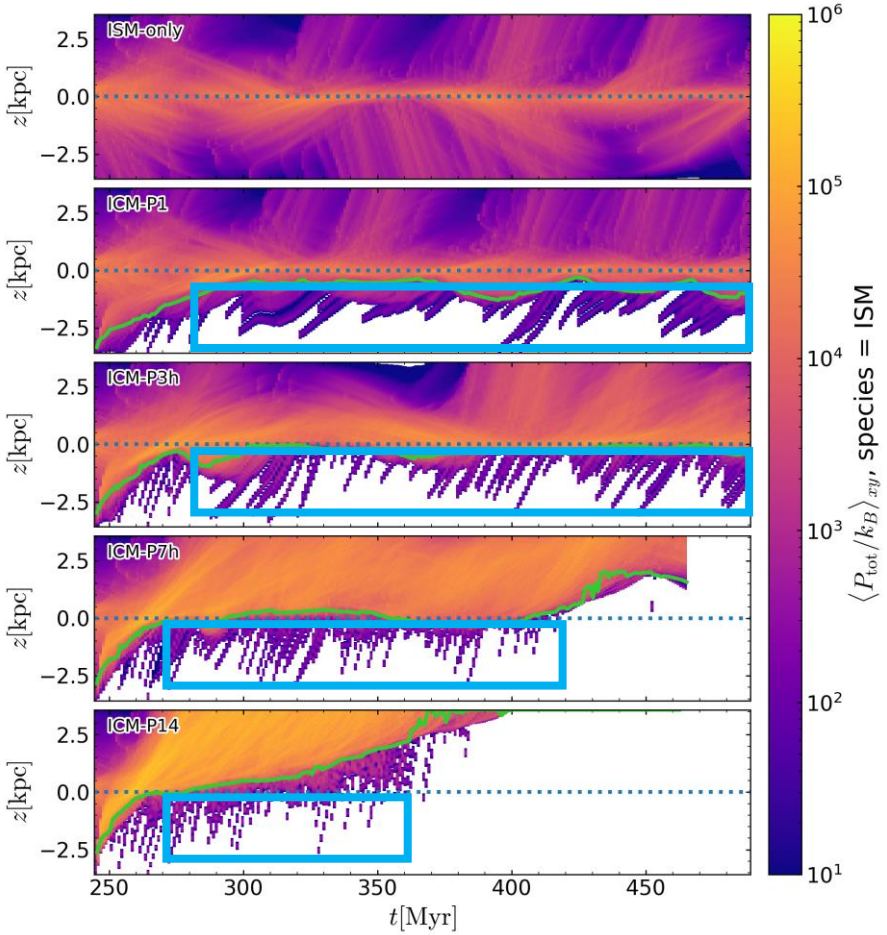
Star formation rate & location



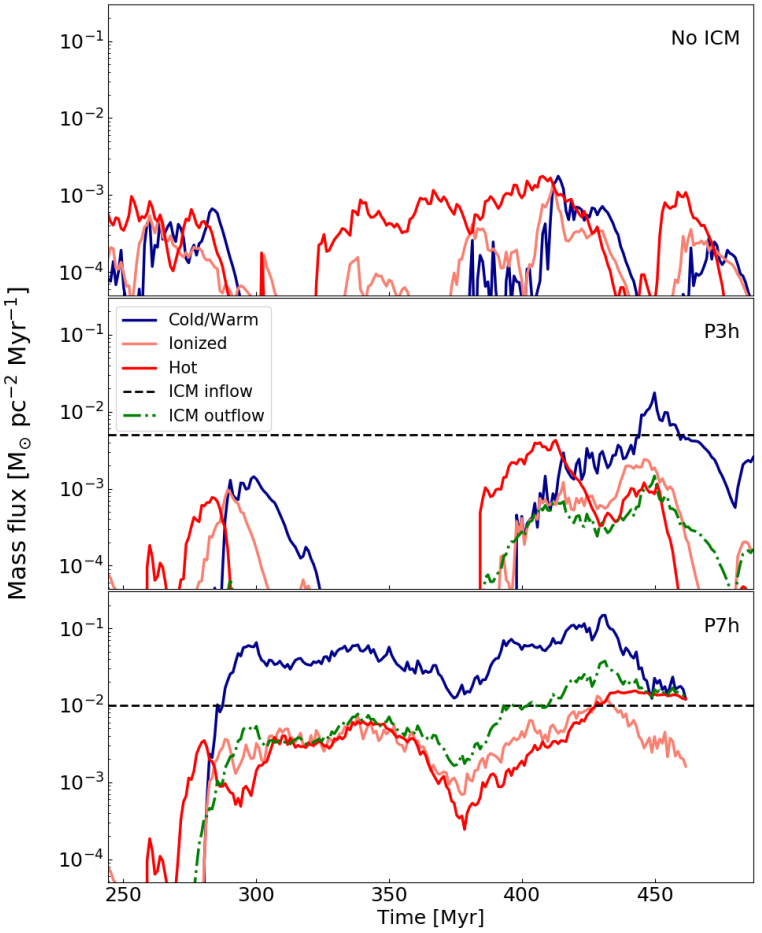


- Star formation is enhanced 2-4 times instantaneously and 30-50 % in 250 Myr
- Star formation is quenched in 100 Myr at the midplane
- Extraplanar star formations occur above 2 kpc height

Pressure of ISM



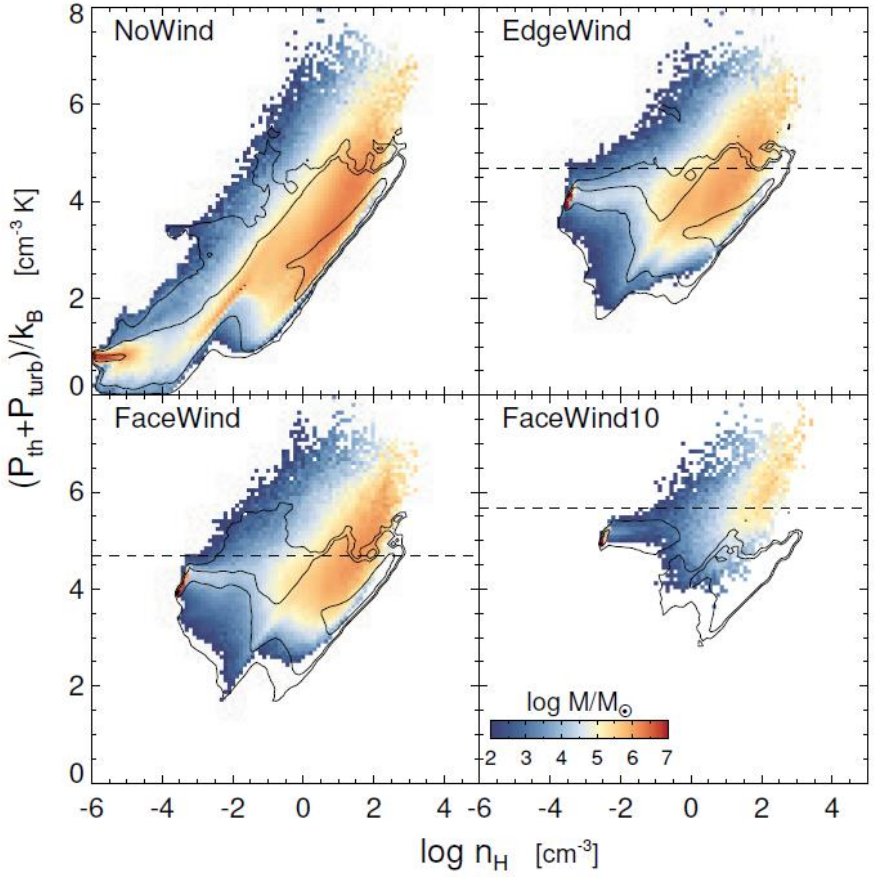
Mass outflow rate

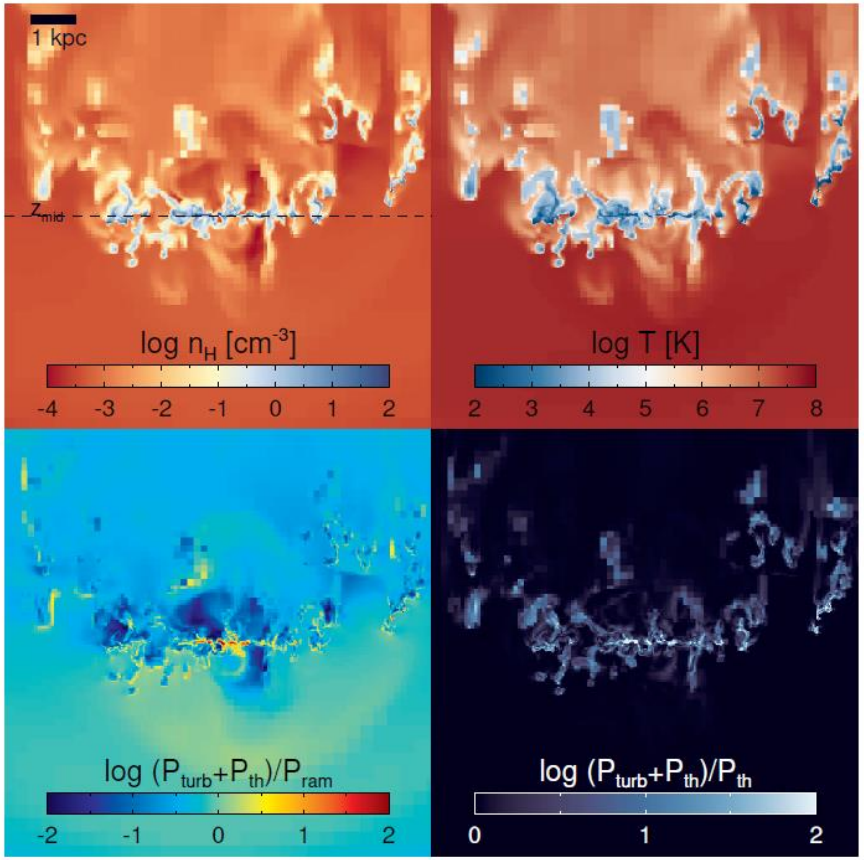


Origin:
Vertical oscillation of the ISM disk +SN feedback

Components of pressure / Phase Diagram

Lee et al. (2020)

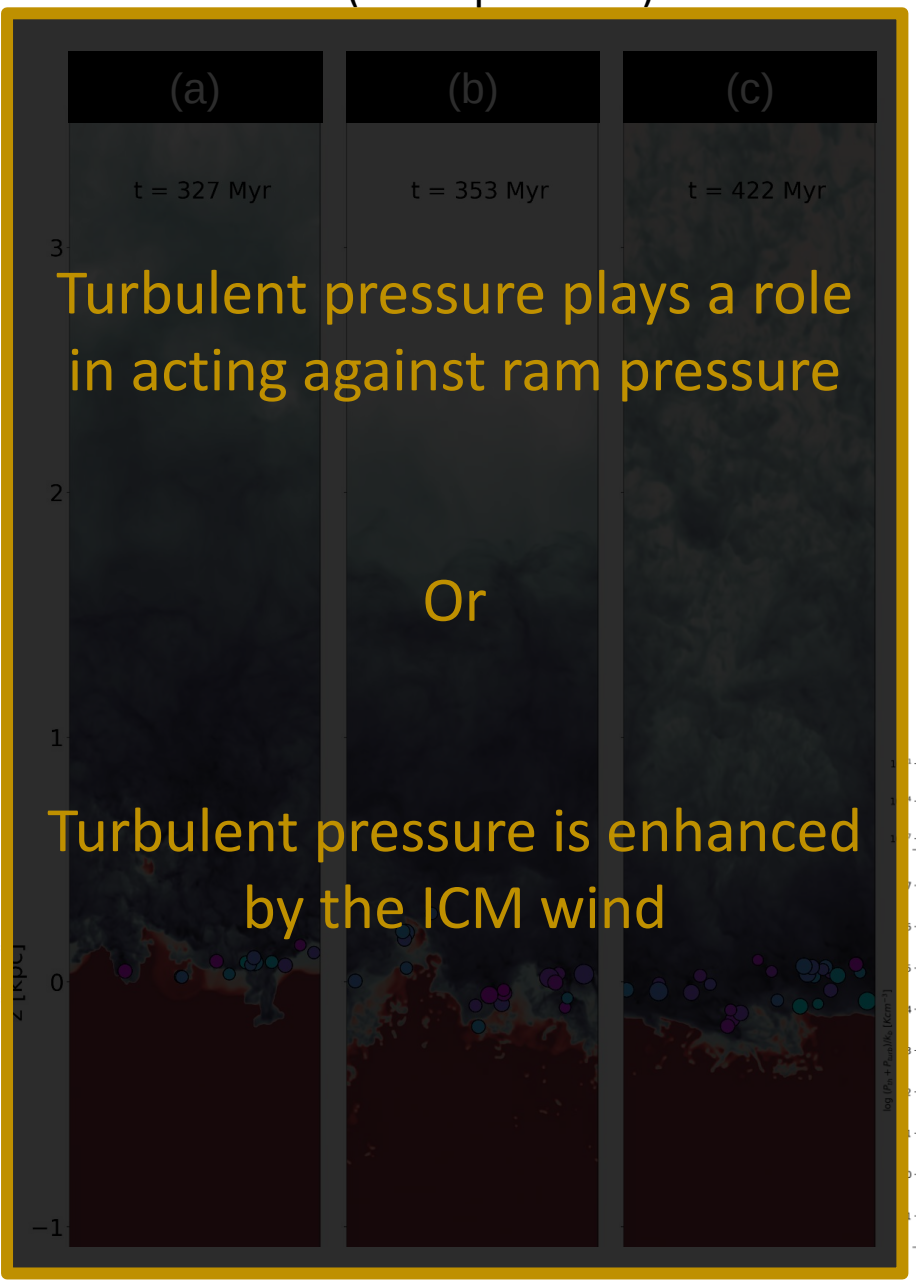


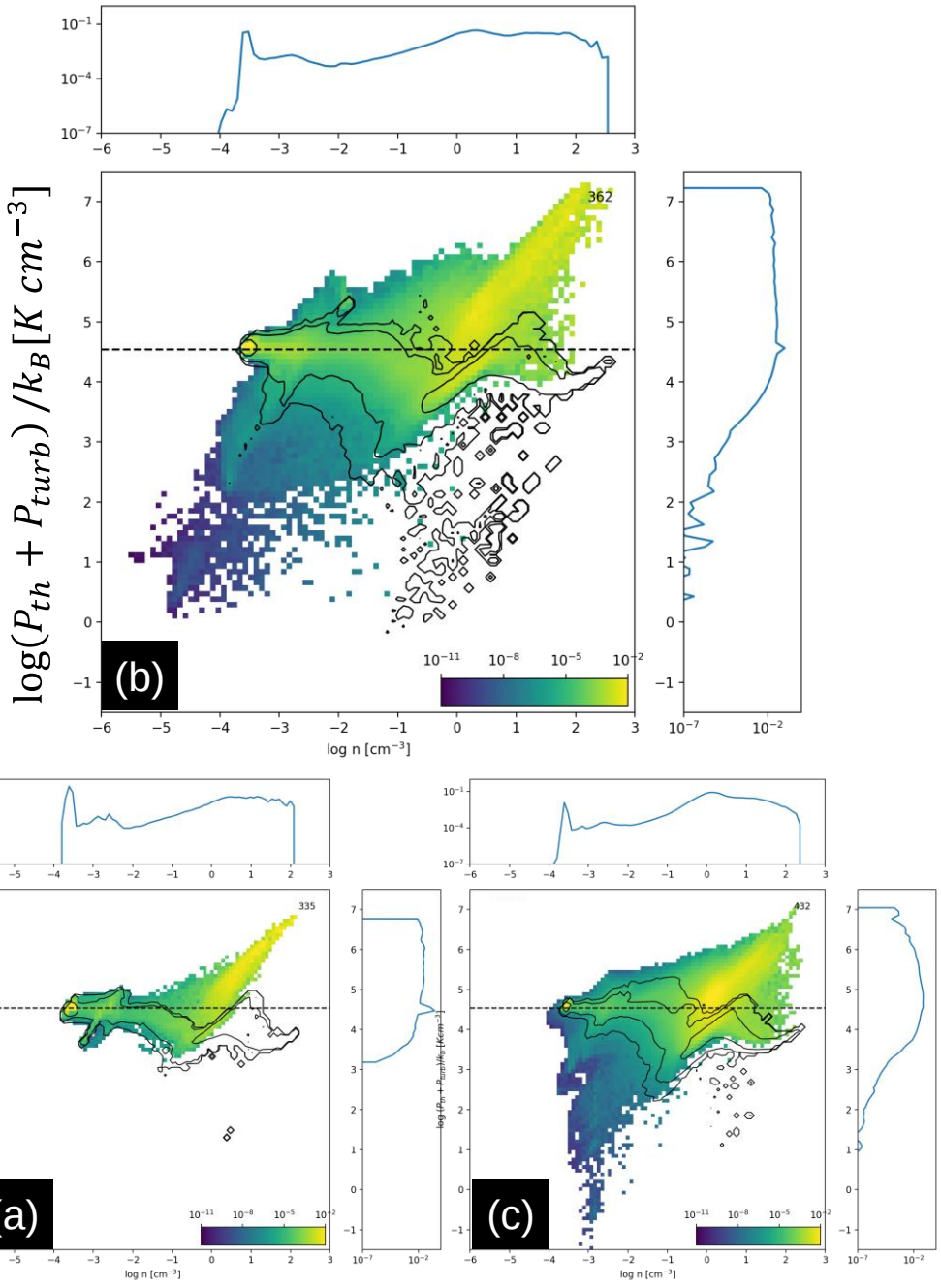


Turbulent pressure seems to have a role to act against ram pressure at the front side of the ISM-ICM interaction

Topic 1: TIGRESS simulation

P3h (weak pressure)





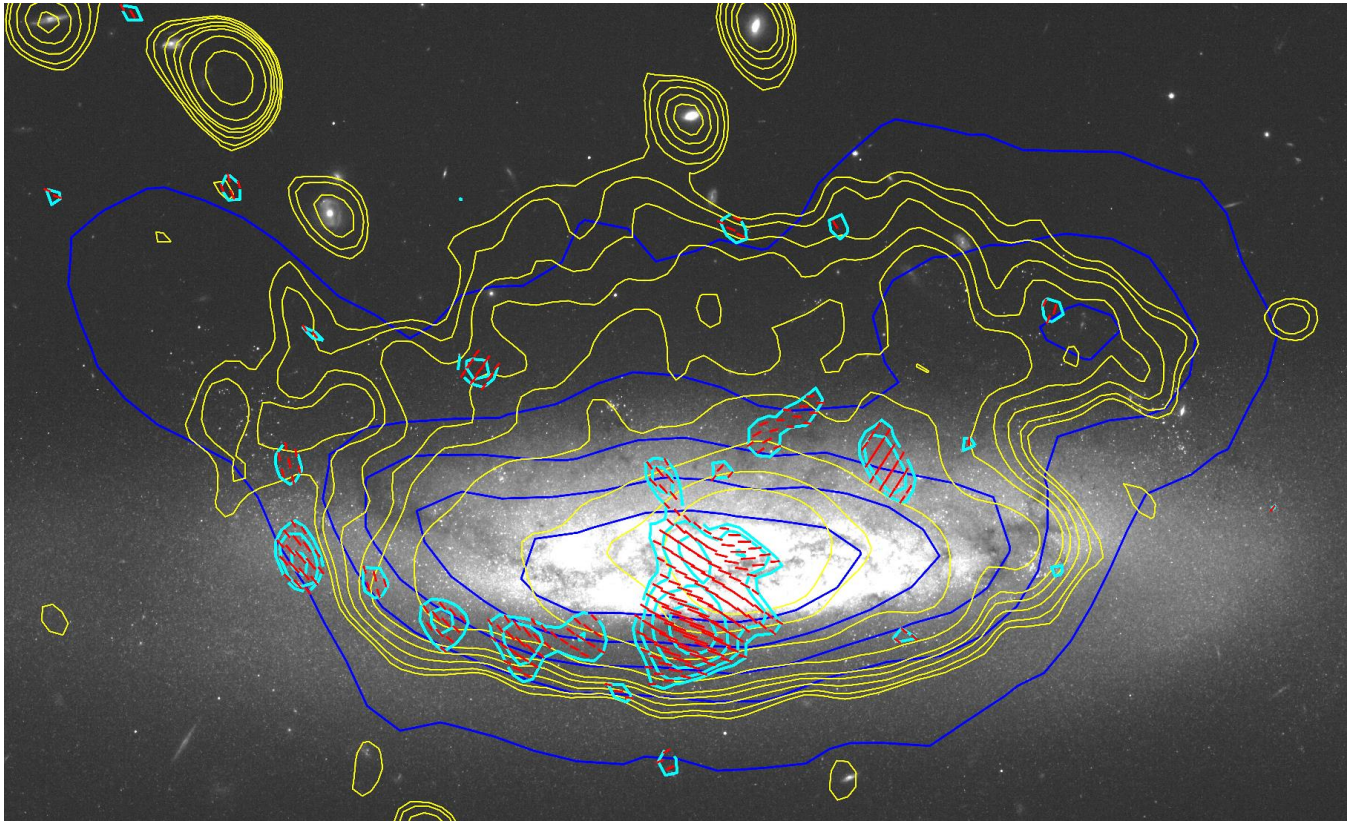
Limitation of previous polarized continuum observations

- Insufficient resolution due to sensitivity (~20 arcsec ≈ 1.6 kpc at Virgo distance)
  - ➢ Hard to see a detailed structure of the magnetic field
  - ➢ Difficult to compare with other wavelength data, such as Ha and CO

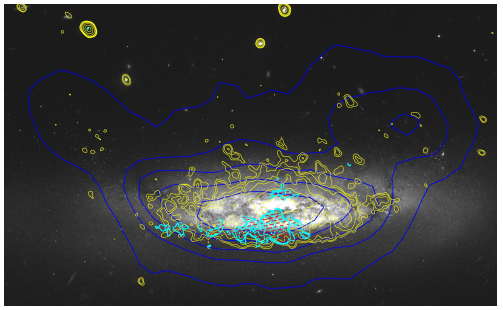
Proposed ~ 7 hours JVLA observation for NGC 4522 in S-band (10 cm) and X-band (3 cm)

- Proposal was accepted (JVLA 20A-310; PI: W. Choi) and observation was conducted in last April
- This observation has 2.5 (S-band, 7 arcsec) and 7 (X-band, 2.5 arcsec) times better resolution than previous works

S-band (10 cm)



X-band (3 cm)

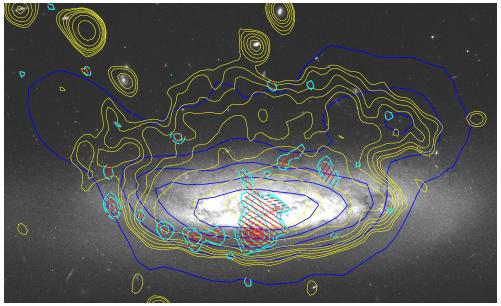


Total continuum emission (**yellow**) and polarized emission (**cyan**) with the magnetic field (**red vectors**) and HI (**blue**, Chung et al. 2009) on HST F814W image.

- Measuring strength and direction of magnetic field, rotation measure, and spectral index

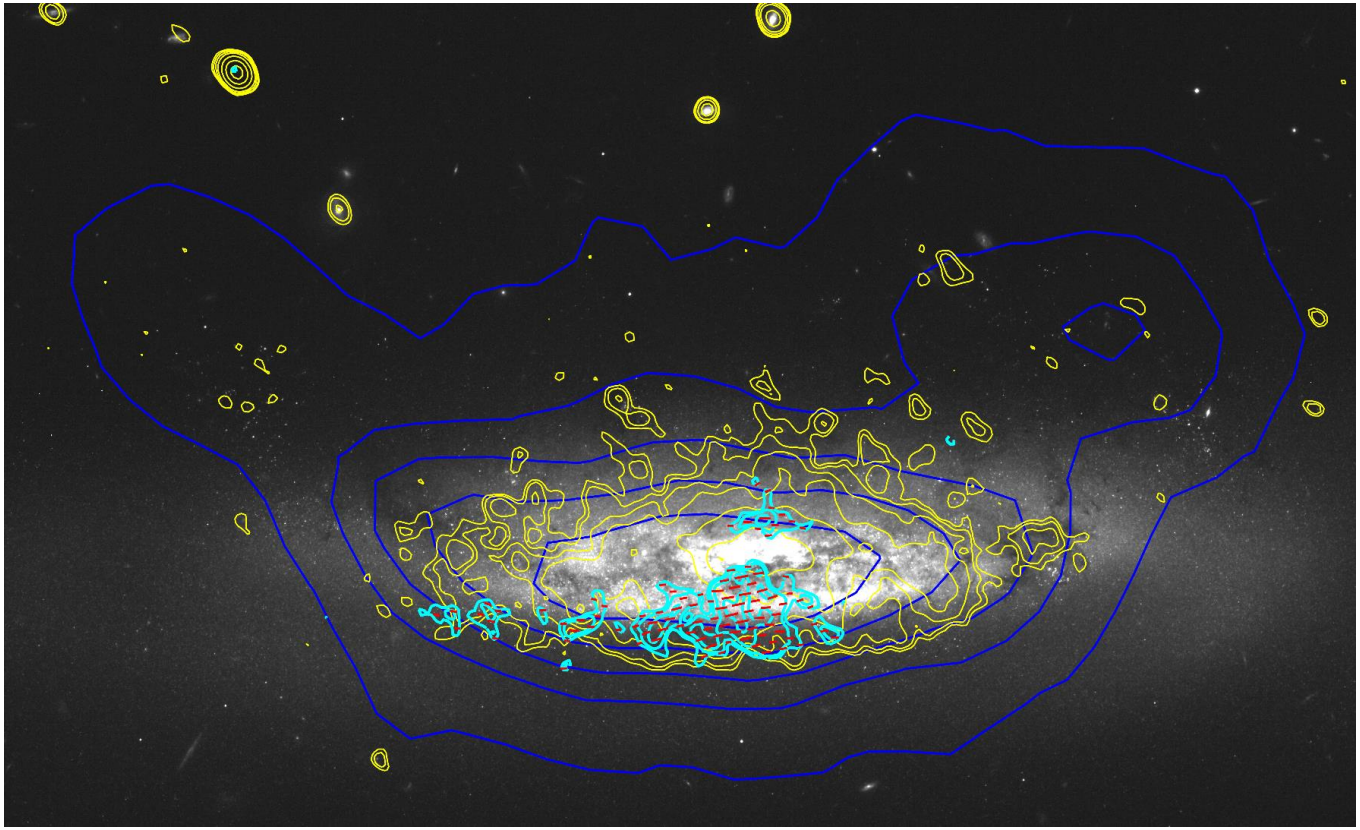
Topic 2: Polarization observation

S-band (10 cm)



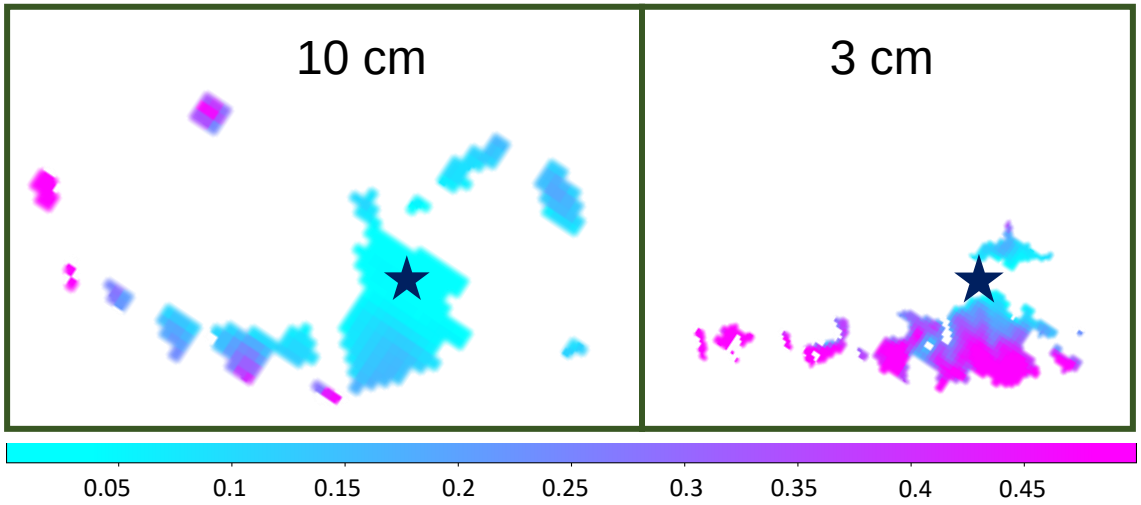
Total continuum emission (**yellow**) and polarized emission (**cyan**) with the magnetic field (**red vectors**) and HI (**blue**, Chung et al. 2009) on HST F814W image.

X-band (3 cm)



- Measuring strength and direction of magnetic field, rotation measure, and spectral index

Degree of polarization



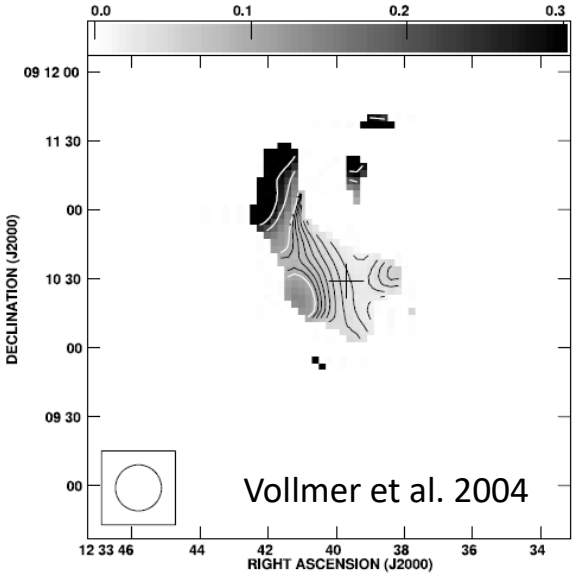
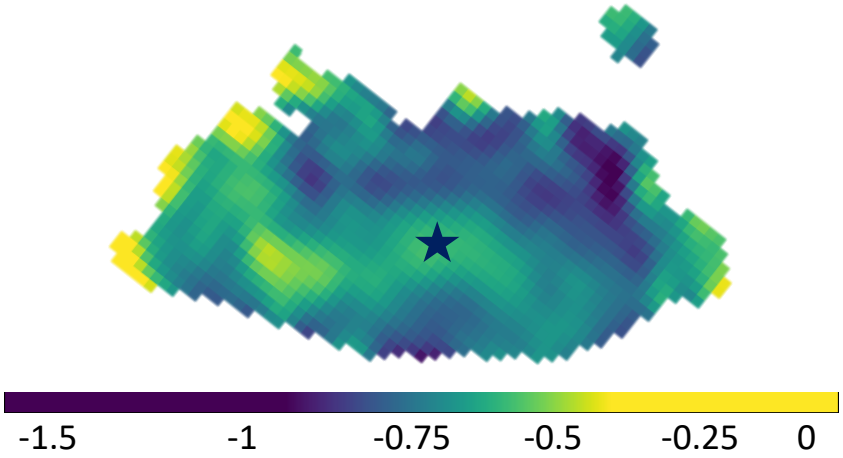


FIG. 5.—Degree of polarization at 6 cm. The gray scale ranges from 0 to 0.3. The contour levels are 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 20, and 30 × 0.01. The beam of the total and polarized emission (20″ × 20″) is shown in the bottom left corner. The galaxy center is marked by a cross.

- Degree of polarization: how many radio continuums are originated from aligned magnetic field (I_{pol}/I_{total})
- The degree of polarization increases from the center to the bottom (ICM wind interface) and the left edge (extraplanar HI region) part in both observations.
- Overall degree of polarization is much higher in 3 cm continuum.

Spectral index map between 3 cm and 10 cm



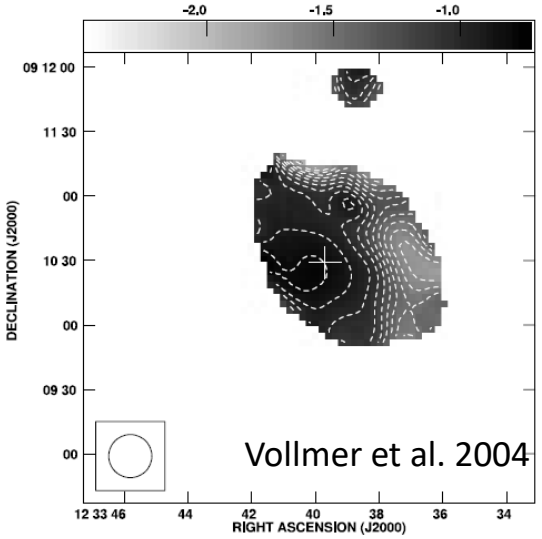
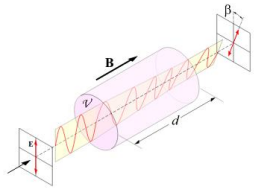


FIG. 10.—Spectral index map between 20 cm (Kenney et al. 2004) and our 6 cm data. The contours range from −2.3 to −0.7 in steps of 0.1. The galaxy center is marked by a cross.

- Spectral index ($S_\nu \propto \nu^\alpha$): generally α is -0.7 ~ -1.0. close to 0 (flat spectrum) indicates that there are sources of fresh electrons. Less than -1 (steep spectrum) indicates that synchrotron emission has been aging.

- The overall spectral index near the galaxy center shows -0.7 while the outer parts show a much flatter spectral index, except the upper right region.

- This map is generally well-matched with the previous result (Vollmer et al. 2004), but local variations are detected because of the higher resolution of our observation.

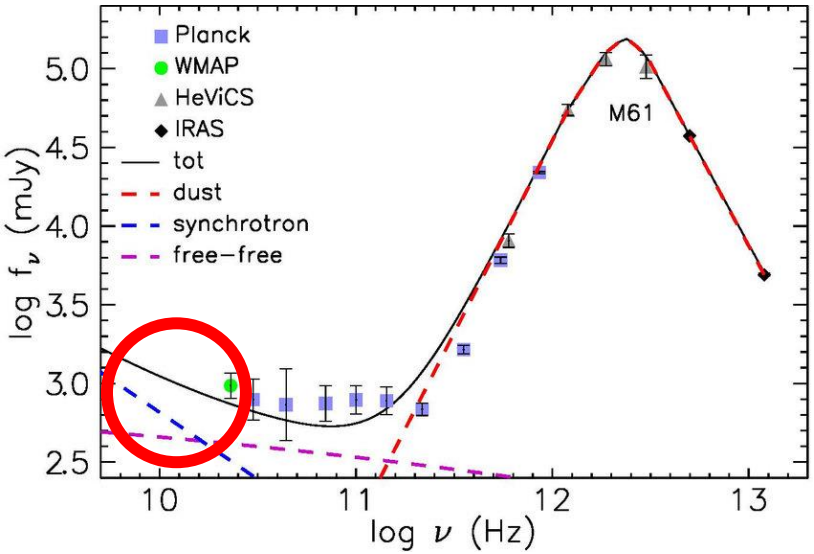


- Rotation Measure & Faraday depolarization

$$\Delta\phi \propto \lambda^2 \int n_e B_{||}(x)\mathrm{d}x$$

where n_e is the electron density, $B_{||}$ is the component of the magnetic field which is parallel to the direction in which the wave is travelling, and x is the distance along the line of propagation. This is known as **Faraday rotation**, or the **Faraday effect**. The integral is known as the **rotation measure**.

- Thermal emission

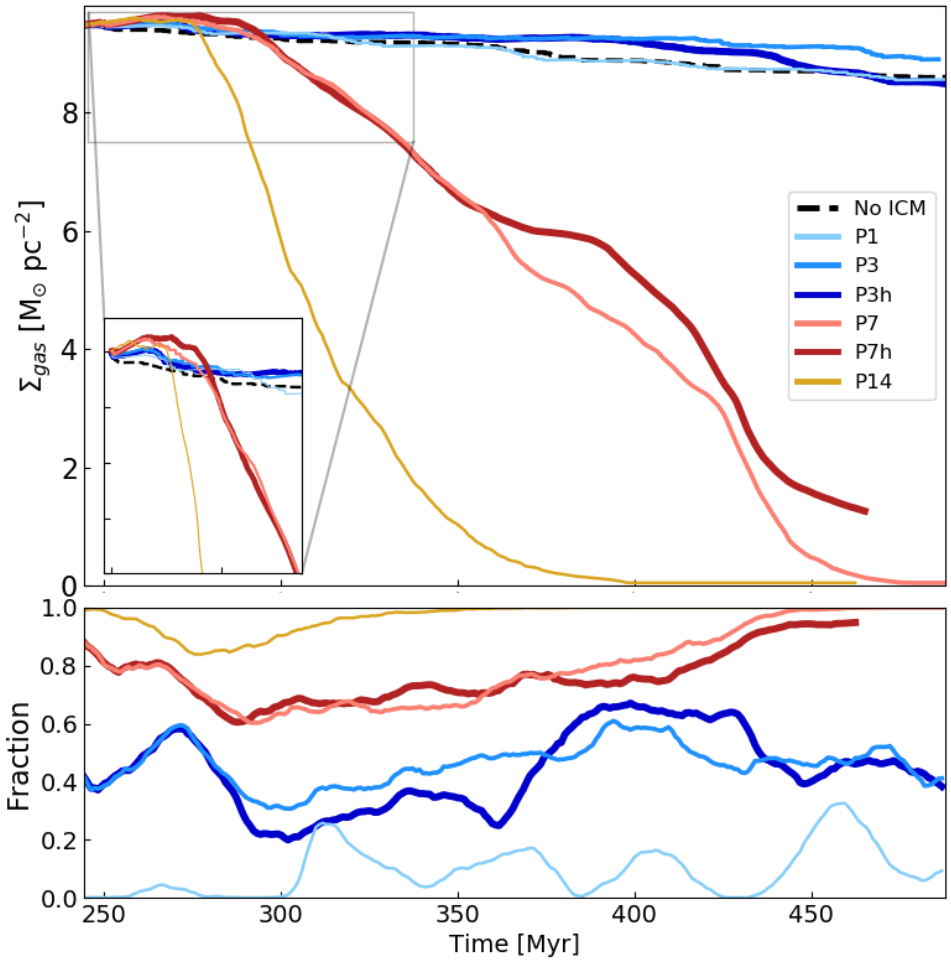


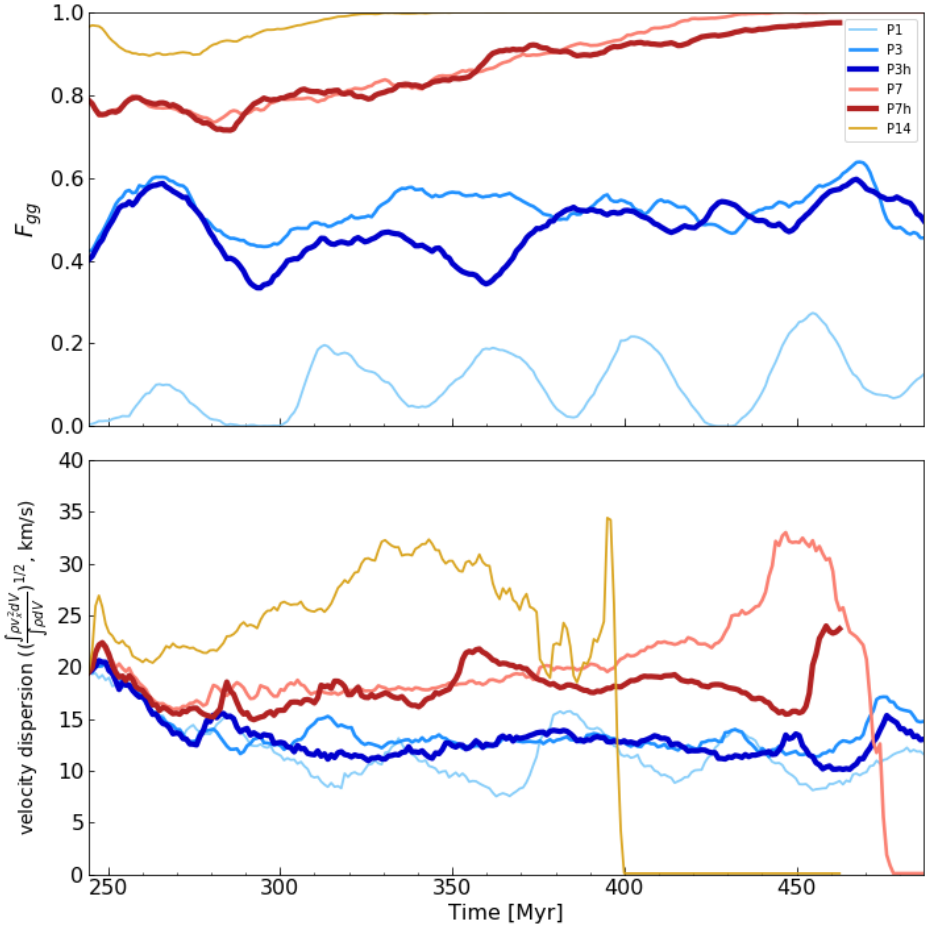
- Inclination, etc

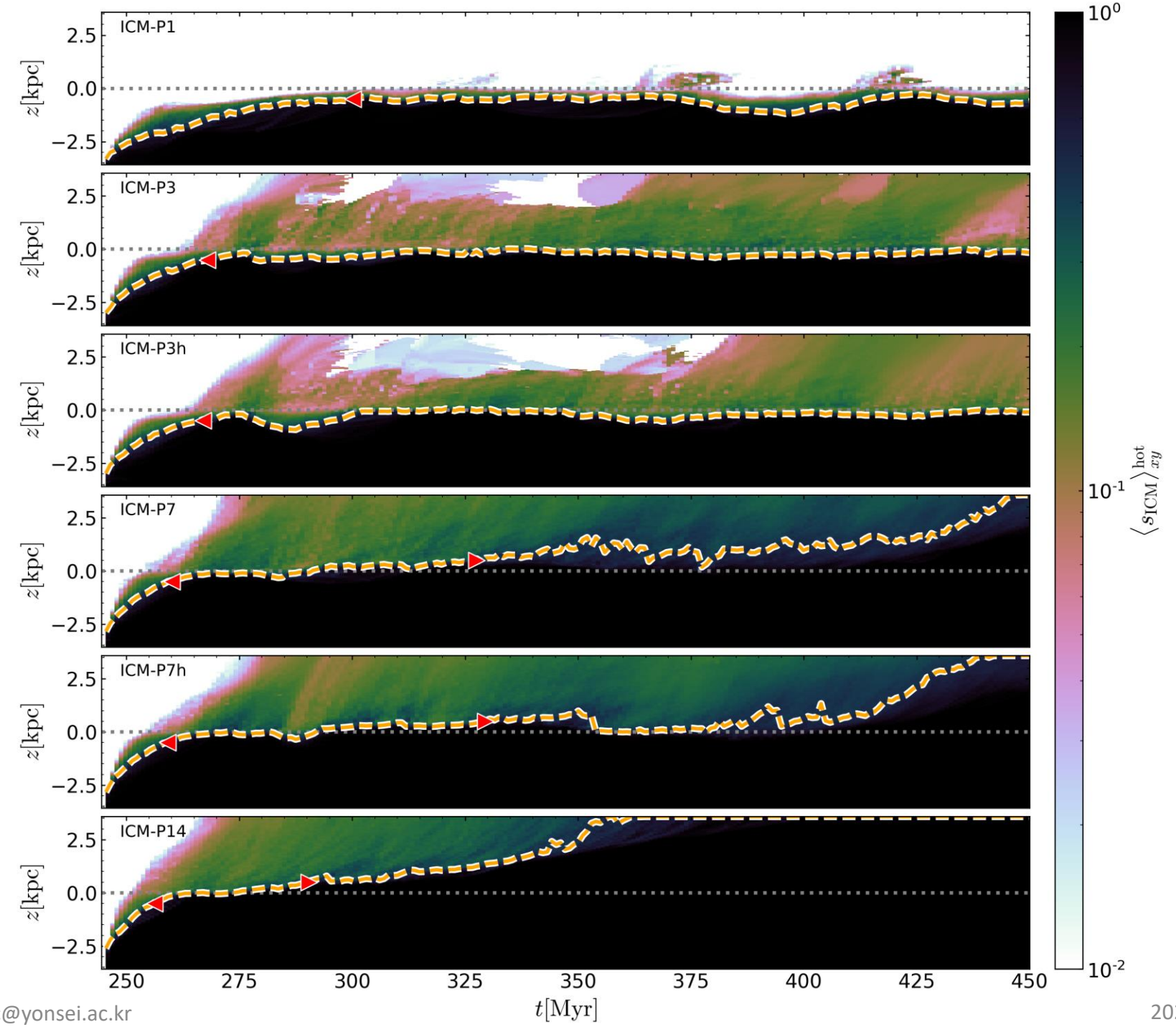
Summary

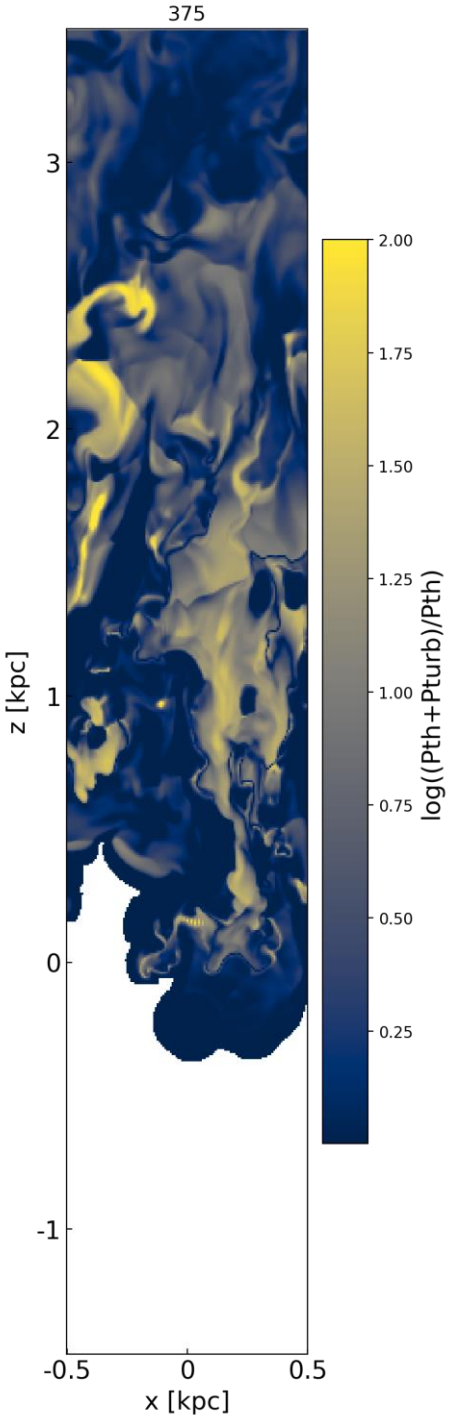
- Simple G&G description is working even though the ISM is multiphase & magnetized
- Ram pressure stripping seems to have a multiple stage and the ISM is not stripped uniformly (Strong ram pressure eventually blows away the ISM within 150 Myr)
- Both weak and strong ram pressure affect the star formation at midplane but to a different degree.
- Star formation can be enhanced with both strong and weak ram pressure at the early compression stage, but enhancement does not last long.
- Weak ram pressure can enhance the star formation continuously (at least 200 Myr)
- Star formation can occur at extraplanar region (2-3 kpc height from the disk)
- Polarized radio continuum emission shows clear evidence of RPS, but it should be analyzed deeply and carefully
- Magnetic field information from polarized emission will be analyzed thoroughly

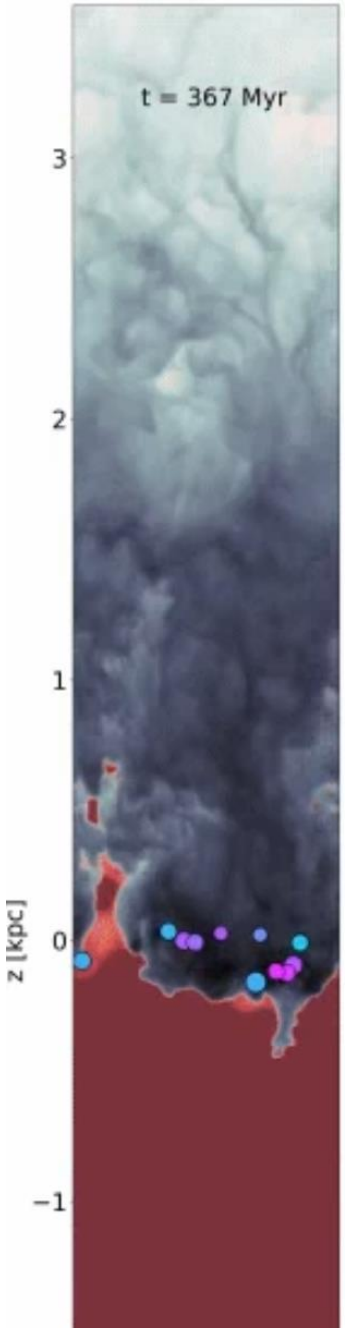
감사합니다


Σ_{gas} [$M_\odot$ pc^{-2}]
No ICM
P1
P3
P3h
P7
P7h
P14
Fraction
Time [Myr]


F_{gg}
P1
P3
P3h
P7
P7h
P14
velocity dispersion ($(\frac{\int \rho v_z^2 dV}{\int \rho dV})^{1/2}$, km/s)
Time [Myr]


ICM-P1
ICM-P3
ICM-P3h
ICM-P7
ICM-P7h
ICM-P14
z[kpc]
2.5
0.0
−2.5
250
275
300
325
350
375
400
425
450
t[Myr]
10^0
10^{-1}
10^{-2}
$\langle s_{\rm ICM} \rangle_{xy}^{\rm hot}$


375
3
2
1
0
-1
z [kpc]
-0.5
0
0.5
x [kpc]
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
log((Pth+Pturb)/Pth)


t = 367 Myr
3
2
1
0
−1
z [kpc]

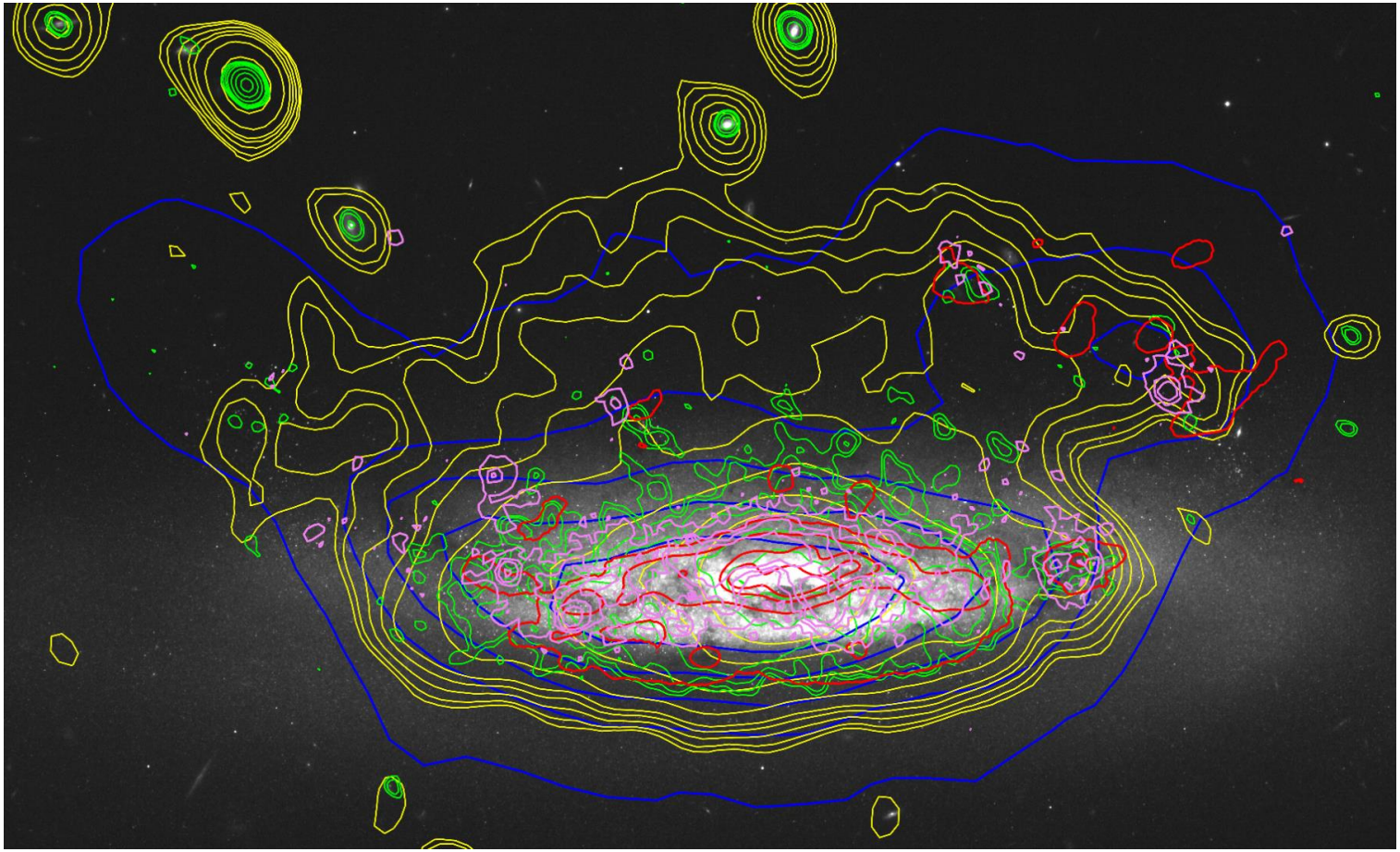
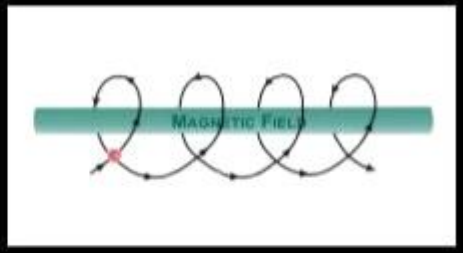


Figure 5. Overlay of multi-wavelength data S-band: Yellow; X-band: Green; Optical: Background; HI: Blue; 12CO(1-0): Red; Hα: Violet). As described above, the overall distribution of 3 cm and 10 cm continuum well follow the HI distribution. There is a detached emission at the right edge of the disk (region A) where CO, Ha, and 3 cm emission coincide. Region B also shows all three emissions coincidentally, even though it locates far from the disk. Whereas, region C does not show a clear 3 cm emission while others exist. This might indicate that although regions B and C located at a similar distance from the disk, they have been experienced environmental effects differently or the time since stripped differs between them.

Radio continuum components

Nonthermal (synchrotron) emission



- from the SNRs and diffuse ionized gas
- strongly polarized
- with a power law spectrum
- study of magnetic field: strength and orientation
- cosmic ray electrons and their distribution

Thermal (free-free) emission

- from HII regions and diffuse ionized gas
- not polarized
- flat spectrum