銀河の理論モデルを用いた分子輝線の擬似観測

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ALMA (Atacama Large Millimeter/submillimeter Array)

- Major strength
  - Gas physics
    - Line-spectrum study for each species
      - CO, HCO, NH_3, H_2O, OIII, CII etc…

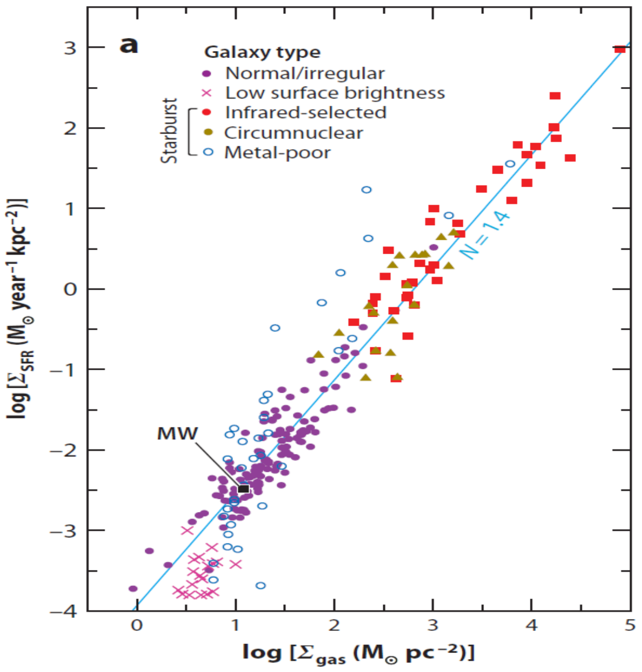
Importance of studying molecular gas (H_2)

- Molecular hydrogen is more directly relevant to star formation than ionized and atomic hydrogen.

HII (ionised) → HI (atomic) → H_2 (molecular) → **Star formation**

- Kennicutt-Schmidt law $\Sigma_{\mathrm{SFR}} \propto \Sigma_{\mathrm{gas}}^{N}$
  - N~1.4 for all neutral hydrogen
  - Most of star-forming gas is molecular.

Star-formation rate density

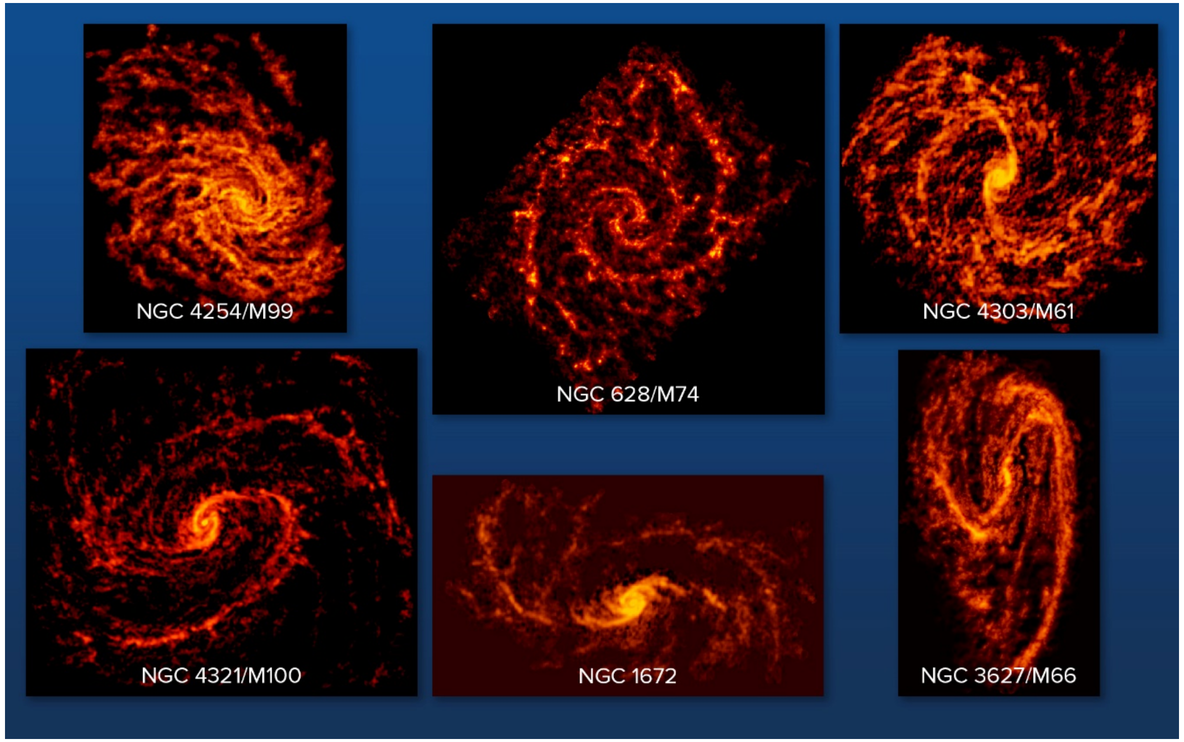


HI + H_2 gas density

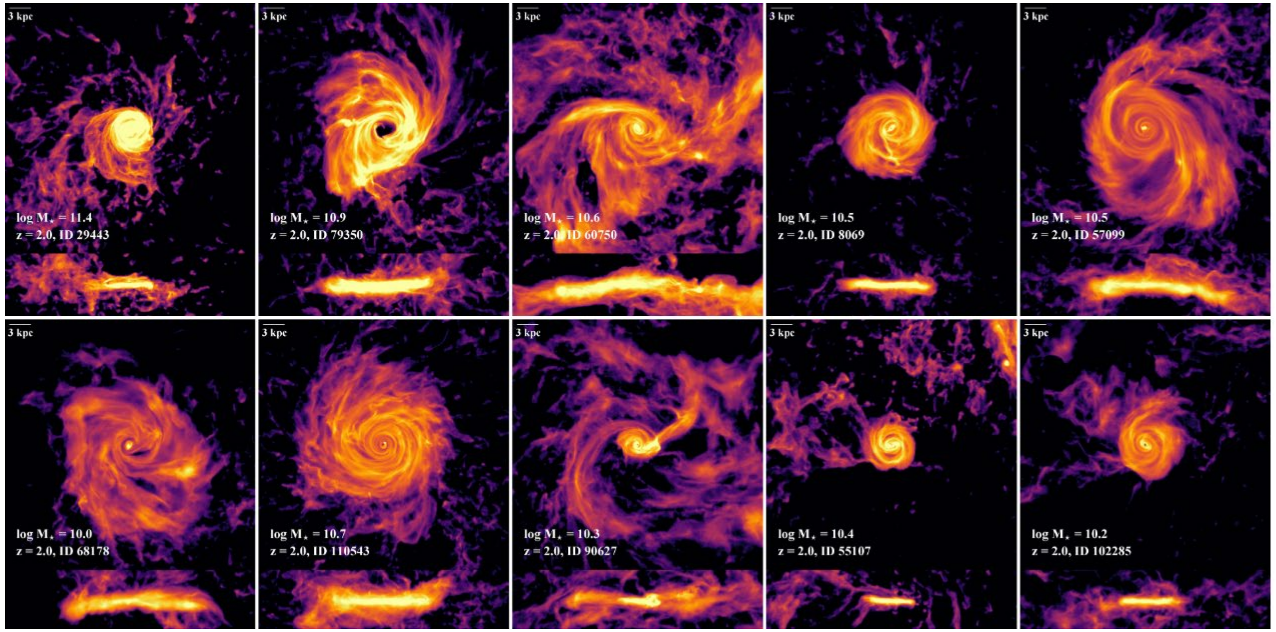
Difficulties in studying molecular gas (H_2)

- It is still difficult to observe and predict amounts of H_2 in galaxies.
  - **Observation:**
    - It is almost hopeless to directly observe H_2 since it little emits electromagnetic waves.
      - CO is used as a proxy of H_2.
        - The conversion factor α_{CO} is, however, determined empirically.
          - Assumed constant or (at best) metallicity-dependent
  - **Theory:**
    - The main channel of H_2 formation is via dust as catalyst.
    - Molecules can be dissociated by UV radiation
      - The formation requires the self-shielding effects.
    - Namely, various physics is involved with H_2 formation/dissociation.
      - UV radiation, dust properties, metallicity, gas pressure etc...

But, still we want to know molecules…



PAHNGS-ALMA survey



Illustris-TNG simulation

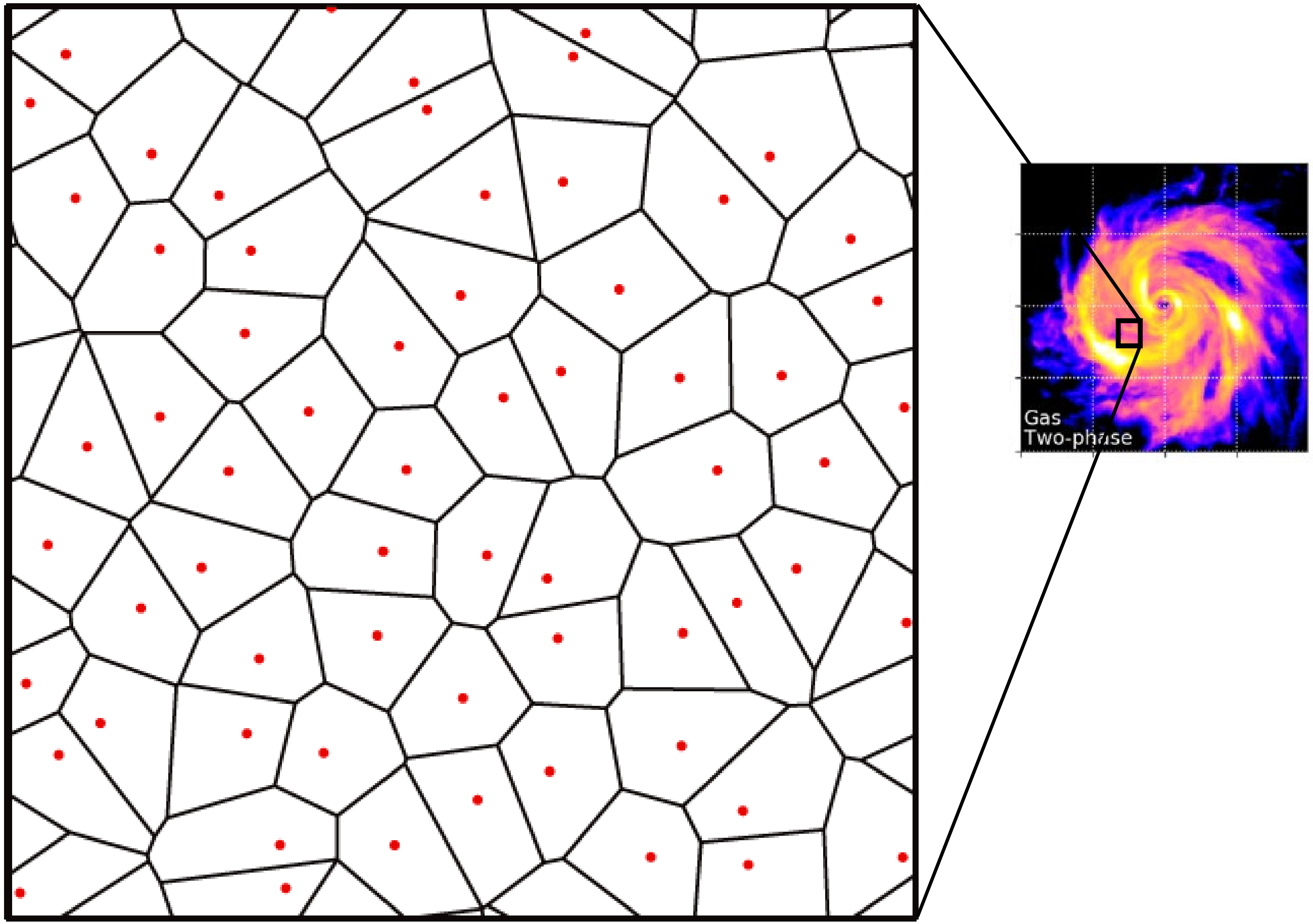
- In nearby galaxies, gas phases vary from nearly all atomic to nearly all molecular.
  - Milky Way: H_2/HI ~ 10 %
  - Arp220 and M51: H_2/HI ~ 100 %,
- How should we interpret the molecular observations?

Towards modelling CO line emission

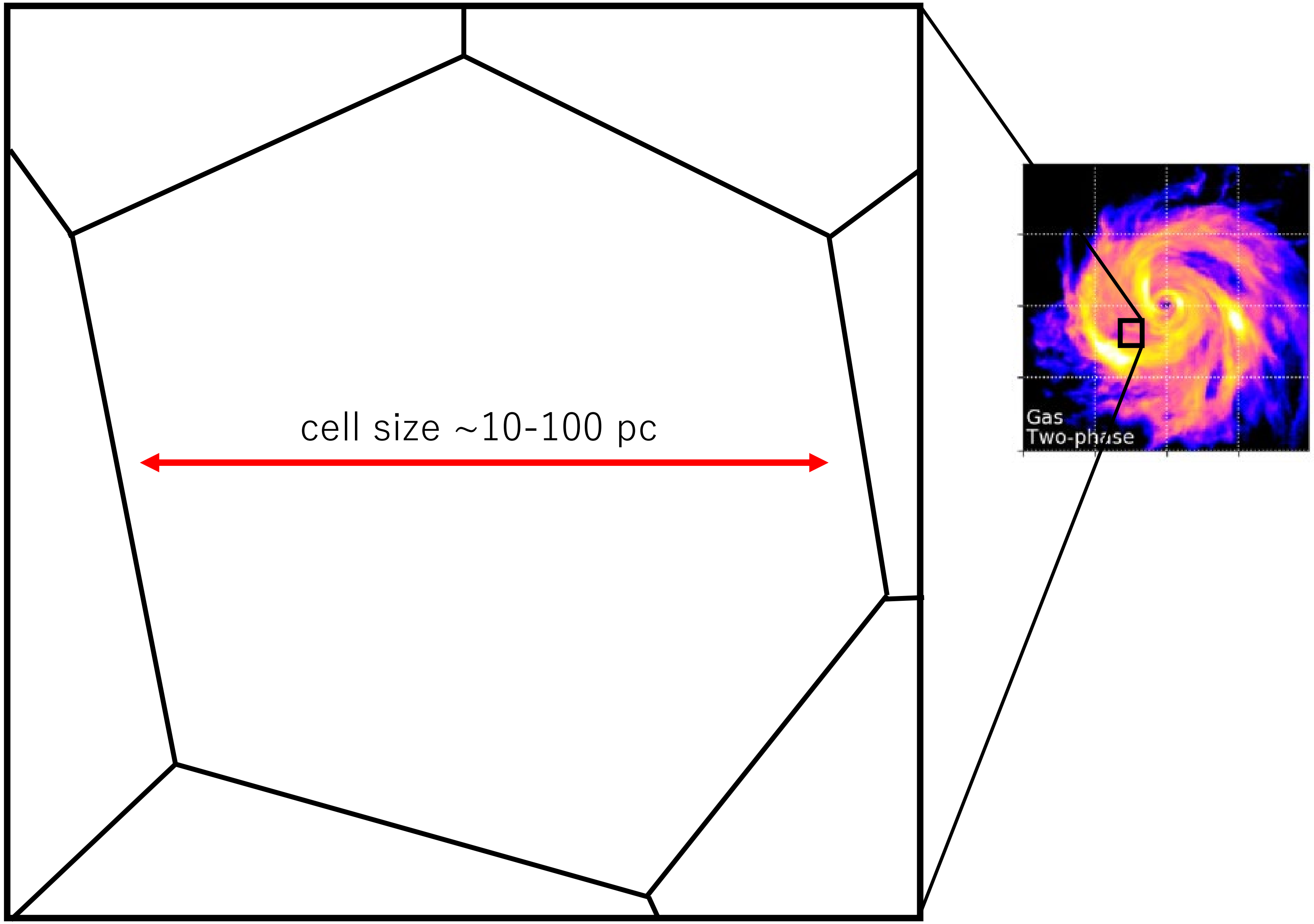
- This study aims to build **a theoretical model for CO emission** from galaxies
  - By combining
    - **Cosmological simulation (post-process)**
    - **Cloud model**
    - **Radiation transfer computation**

  - In this talk…
    - Mock observations for kinematic analysis with a CO line.
    - Discuss potential bias in the dynamical analysis

Post-process modelling for molecules



Post-process modelling for molecules



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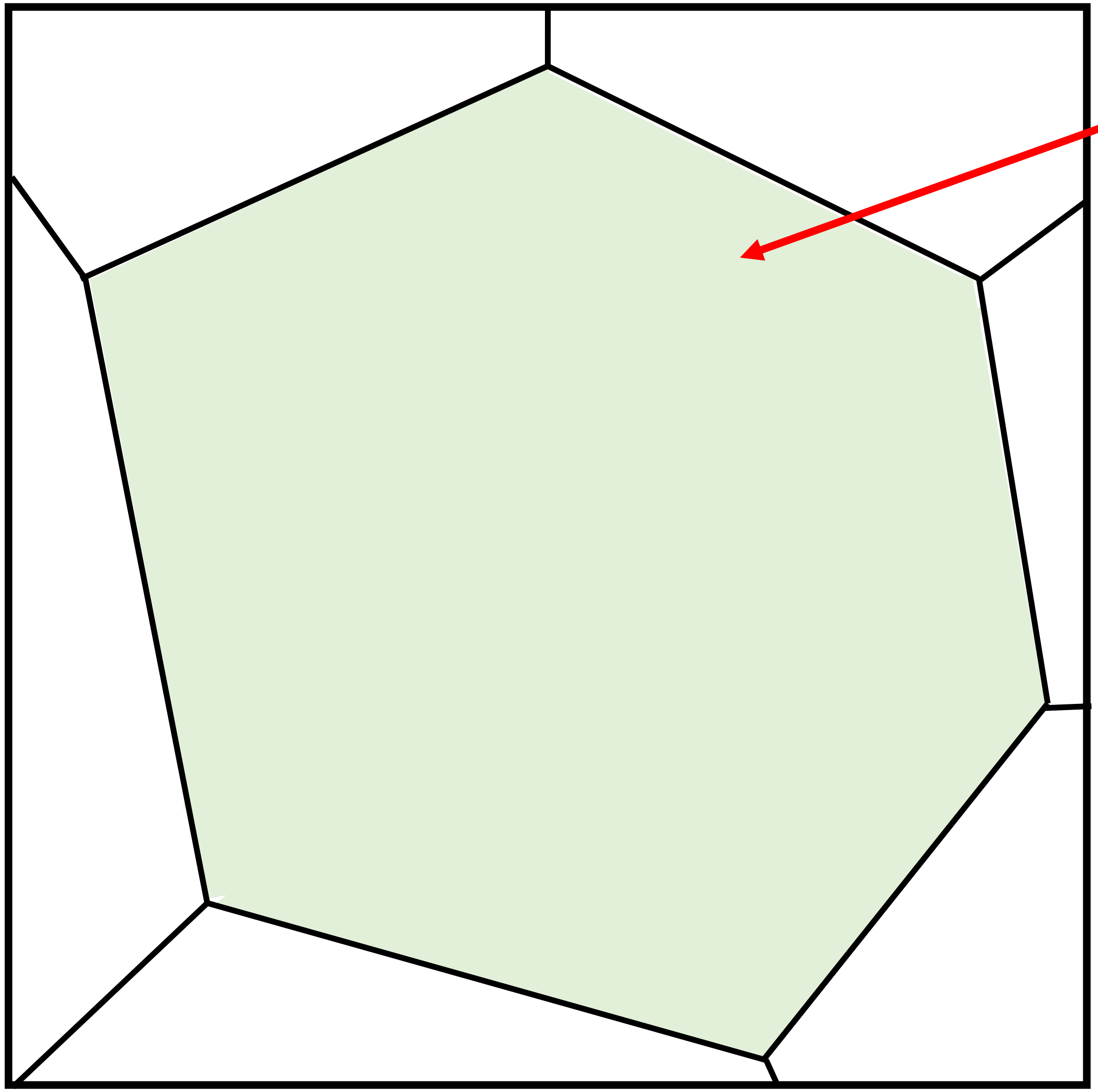
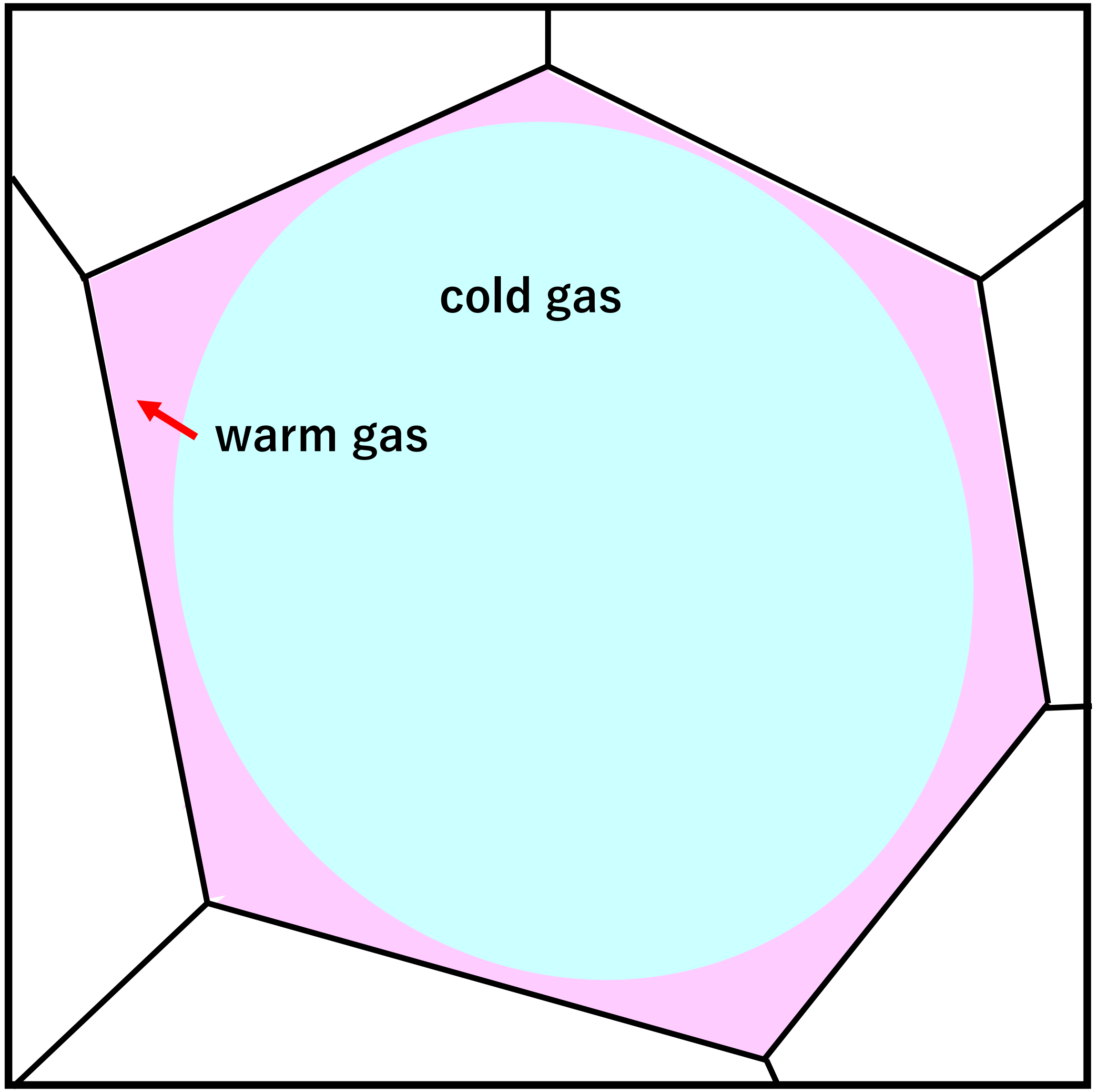


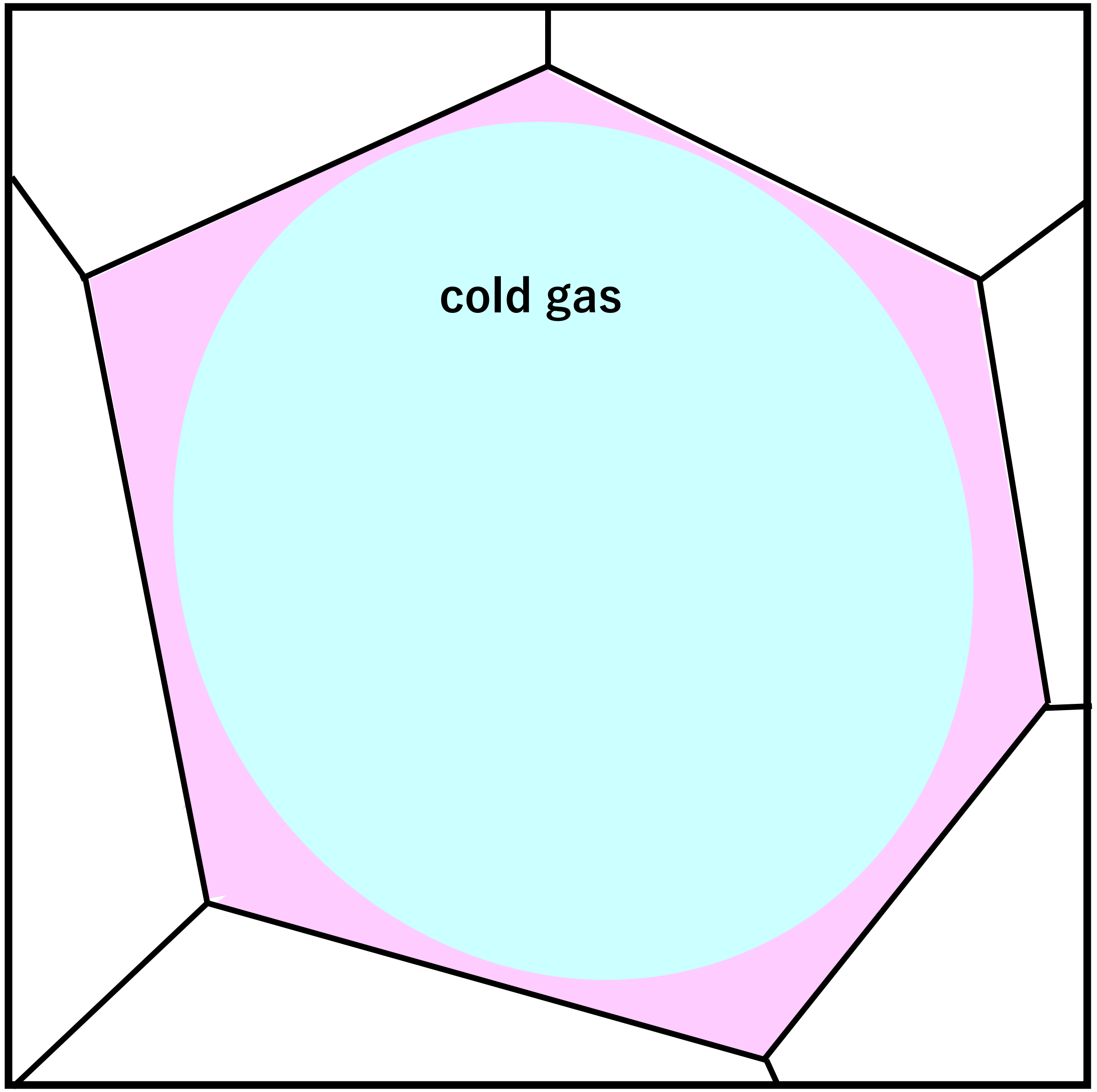
- Directory from simulation,
  - $\rho_{cell}, P_{cell}, M_{cell}, Z_{cell}$

Post-process modelling for molecules



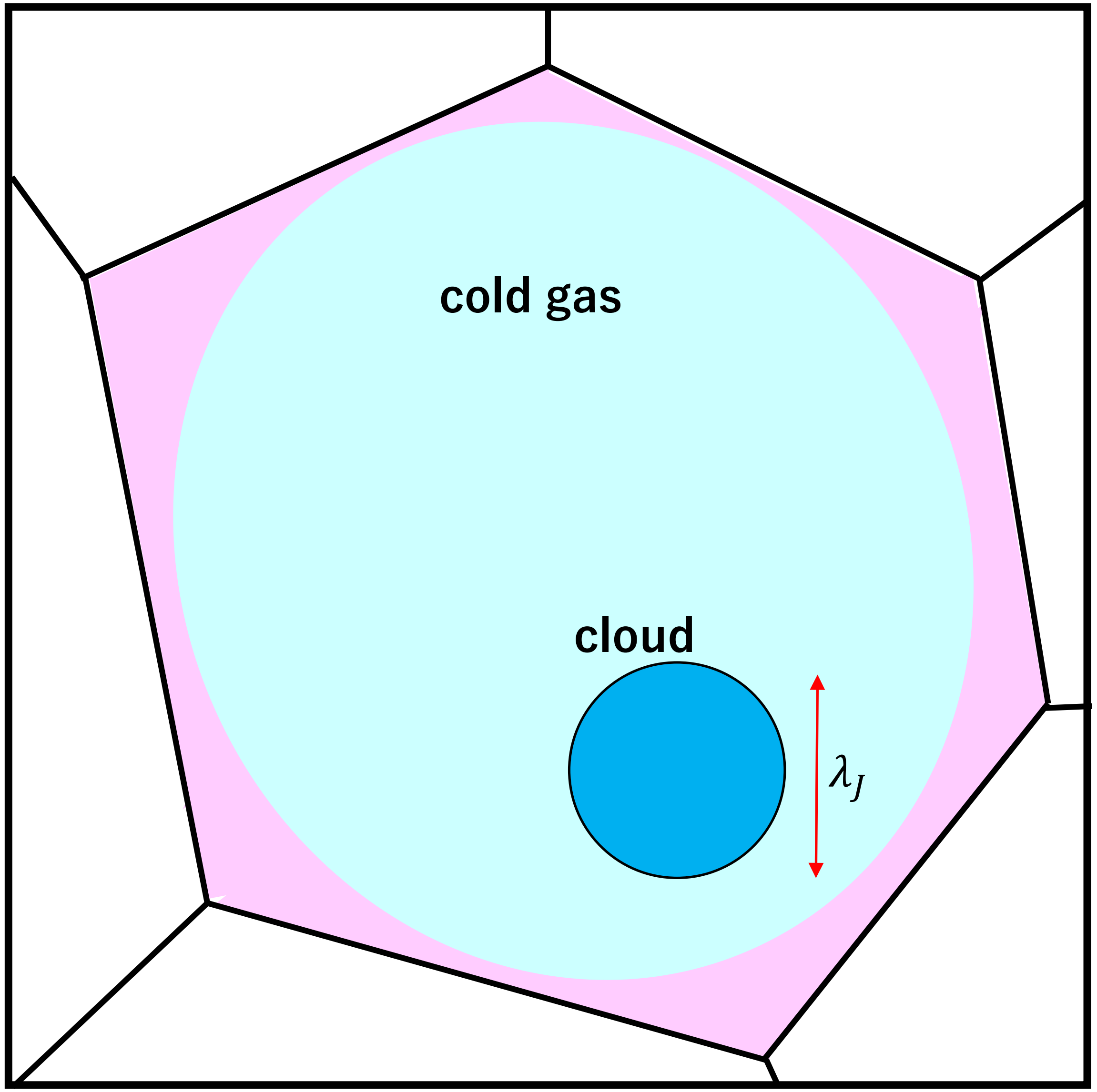
- Directory from simulation,
  - $\rho_{cell}, P_{cell}, M_{cell}, Z_{cell}$
- Consider two-phase ISM model
  - cold/worm neutral media in a cell
  - Parameters
    - **Cold-mass fraction**: $f_m \equiv \frac{M_{cold}}{M_{cell}} \sim 0.9$
      - Springel & Hernquist (2003)
    - **Density contrast**: $\phi \equiv \frac{\rho_{cold}}{\rho_{warm}} \sim 100$
      - Pres.-equilibrium (e.g. Wolfire et al. 1995)
  - Cold-volume fraction: $f_V \equiv \frac{V_{cold}}{V_{cell}} = \frac{x_m}{(1-x_m)\phi + x_m}$

Post-process modelling for molecules



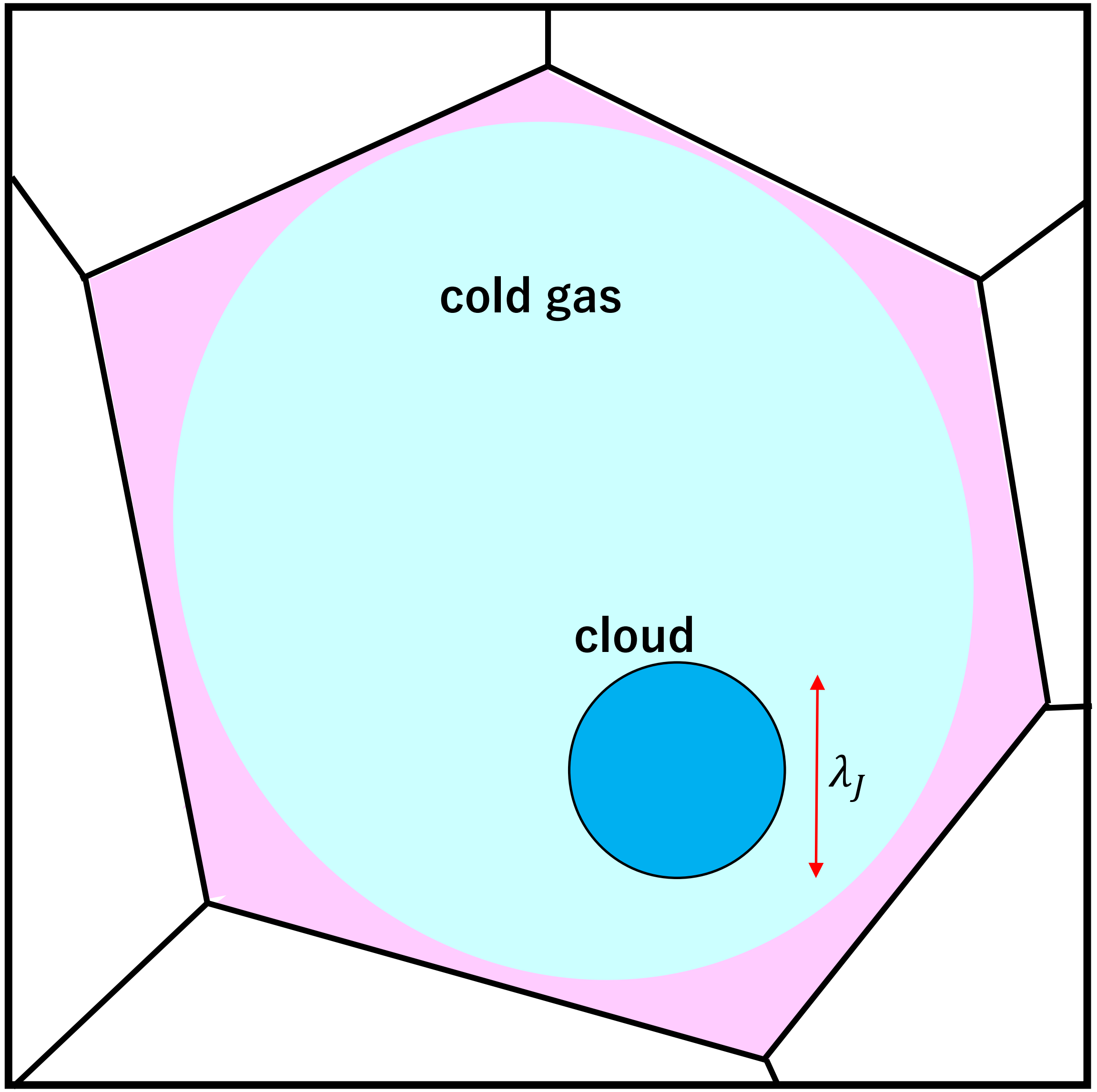
- Directory from simulation,
  - $\rho_{cell}, P_{cell}, M_{cell}, Z_{cell}$
- The cold gas has
  - $\rho_{cold}, P_{cell}, M_{cold}, Z_{cell}$
  - Jeans length $\lambda_J \equiv \sqrt{\frac{P_{cell}}{G\rho_{cold}}}$

Post-process modelling for molecules



- Directory from simulation,
  - ρ_{cell}, P_{cell}, M_{cell}, Z_{cell}
- The cold gas has
  - ρ_{cold}, P_{cell}, M_{cold}, Z_{cell}
  - Jeans length $\lambda_J \equiv \sqrt{\frac{P_{cell}}{G\rho_{cold}}}$
- Typical cloud size
  - $R_{cloud} = \lambda_J/2.$
  - $\Sigma_{cloud} = \rho_{cold}\lambda_J$
  - Dust abundance: $D_{cloud} = D_{MW}\frac{Z_{cell}}{Z_{MW}}$
  - ISRF: $I_{cloud} = I_{MW}\frac{SFR_{tot}}{SFR_{MW}}$

Post-process modelling for molecules

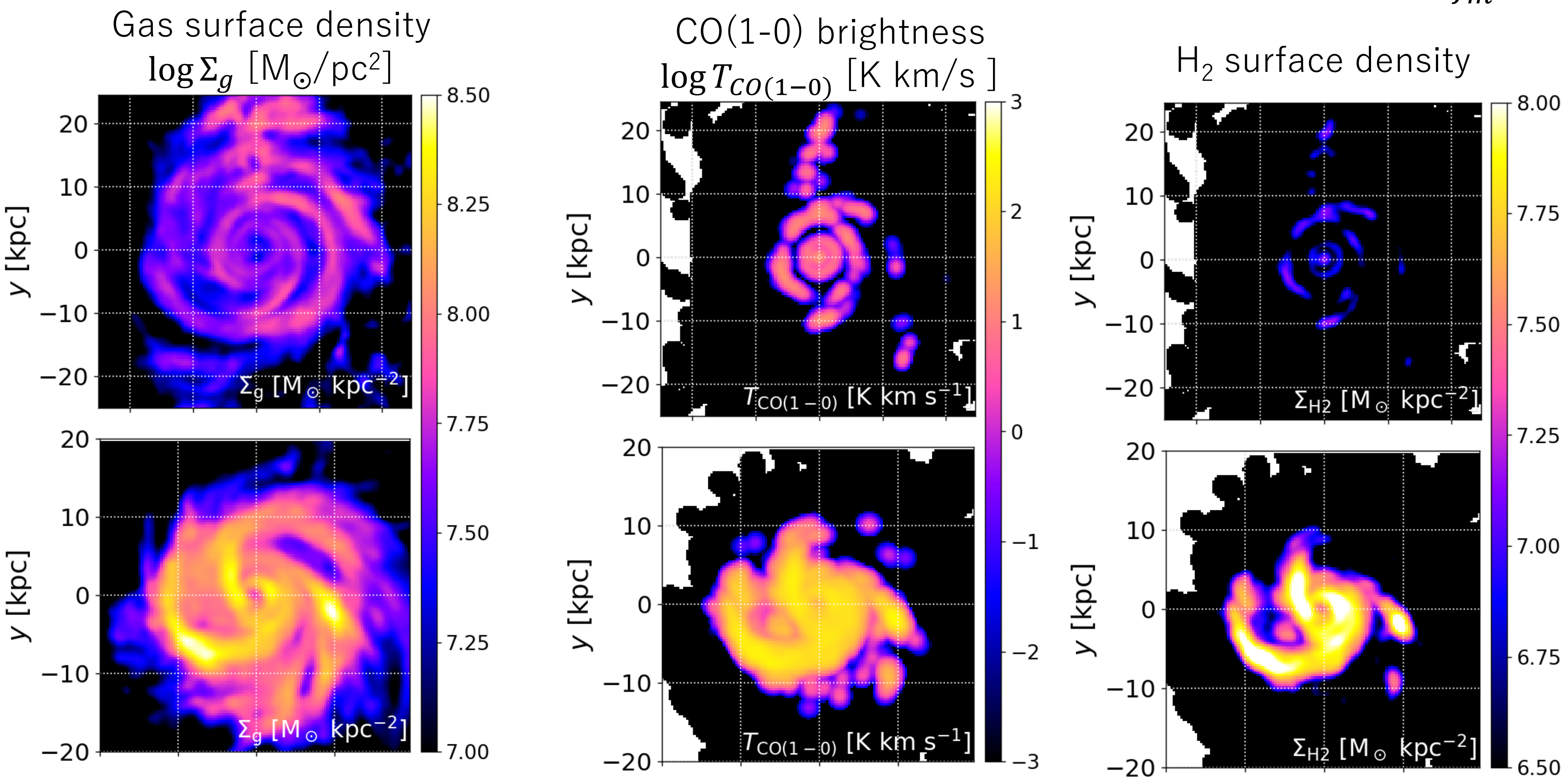


- Input these parameters into an RT code
  - DESPOTIC (Krumholz 2014)
  - which returns molecular emissions and abundances for a cloud.

- Cumulate the cloud emissions and obtain the total value of the cell.
  - The number of clouds in a cell
    - $N_{cloud} = \frac{V_{cold}}{V_{cloud}}$

Applying to simulations

Density contrast: $\phi = 100$
Cold mass frac.: $f_m = 0.9$



Top: z=1.5, $M_s = 1.7 \times 10^{11}$ M$_\odot$
Bottom: z=1.0, $M_s = 1.8 \times 10^{11}$ M$_\odot$

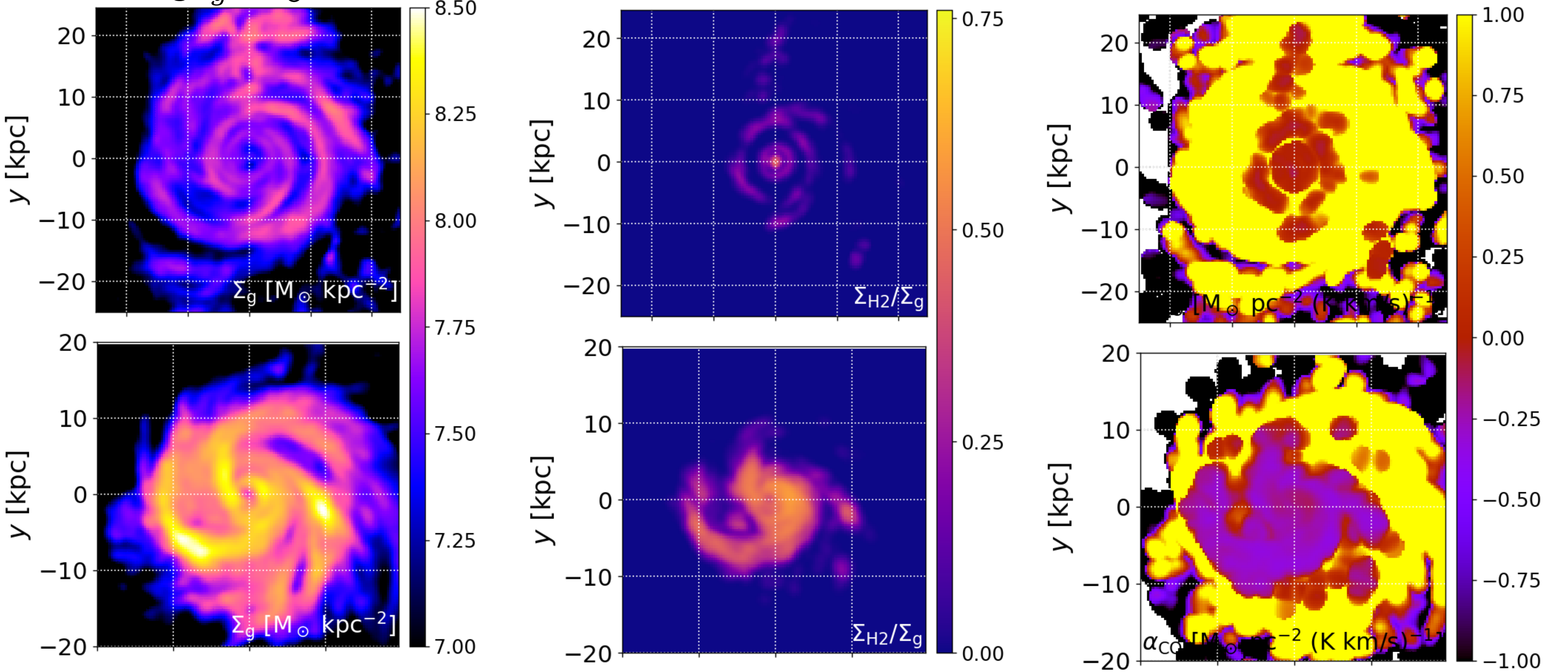
Applying to simulations

Density contrast: $\phi = 100$
Cold mass frac.: $f_m = 0.9$

Gas surface density $\log \Sigma_g$ [M$_\odot$/pc^2]

H_2 density fraction

$\log \alpha_{CO}$ [M$_\odot$/(K km/s pc^2)]



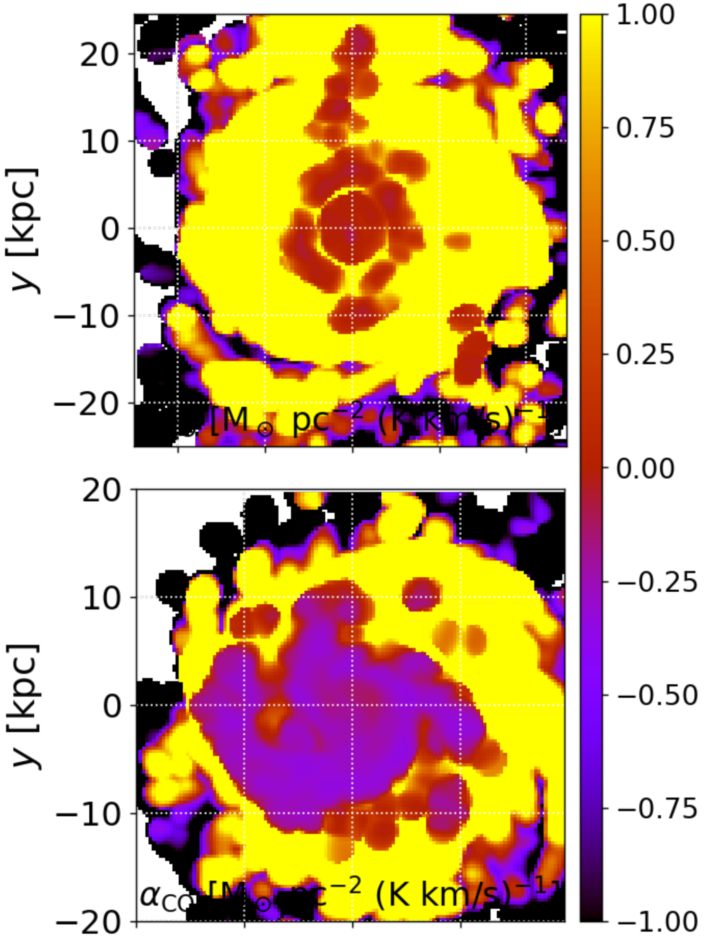
Top: z=1.5, $M_s = 1.7 \times 10^{11}$ M$_\odot$
Bottom: z=1.0, $M_s = 1.8 \times 10^{11}$ M$_\odot$

Applying to simulations

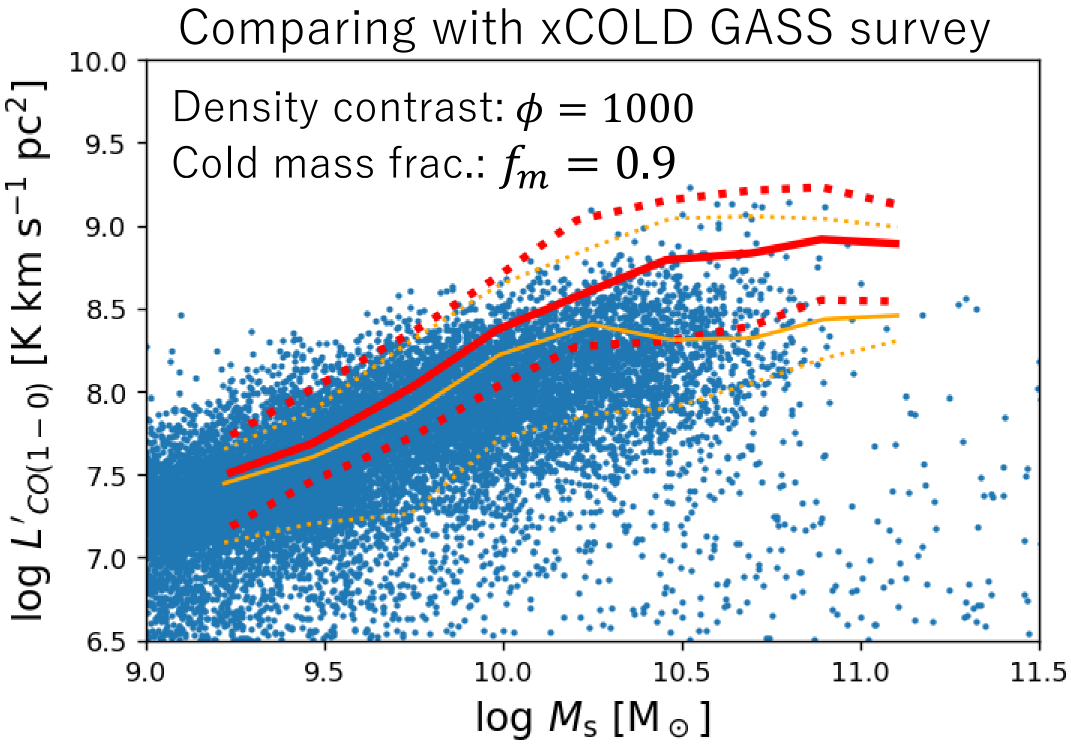
Density contrast: $\phi = 100$
Cold mass frac.: $f_m = 0.9$

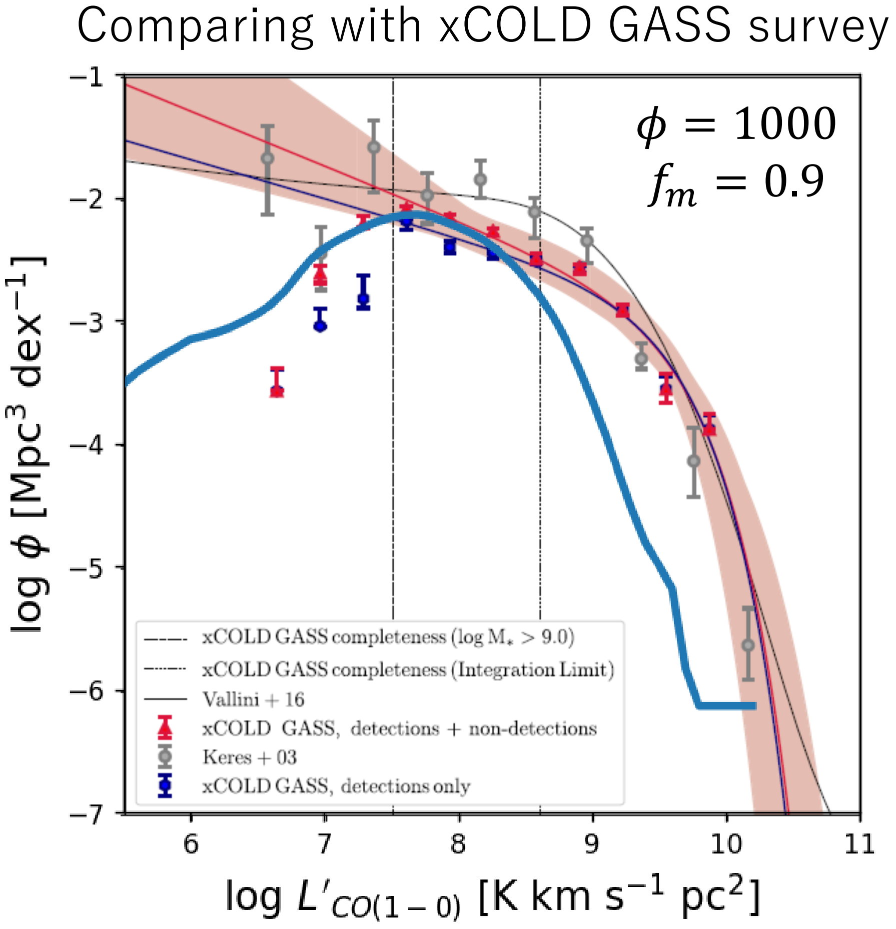
- In the Milky Way inner disc
  - $\alpha_{CO} = 4.3$ M$_\odot$/(K km/s pc^2)
- In local star-forming galaxies
  - $\alpha_{CO} = 3.6$ M$_\odot$/(K km/s pc^2)
- In high-z star-forming galaxies
  - $\alpha_{CO} = 2$ M$_\odot$/(K km/s pc^2)
- In ULIRG
  - $\alpha_{CO} = 0.8$ M$_\odot$/(K km/s pc^2)

$\log \alpha_{CO}$ [M$_\odot$/(K km/s pc^2)]



Applying to Illustris-TNG (z=0)





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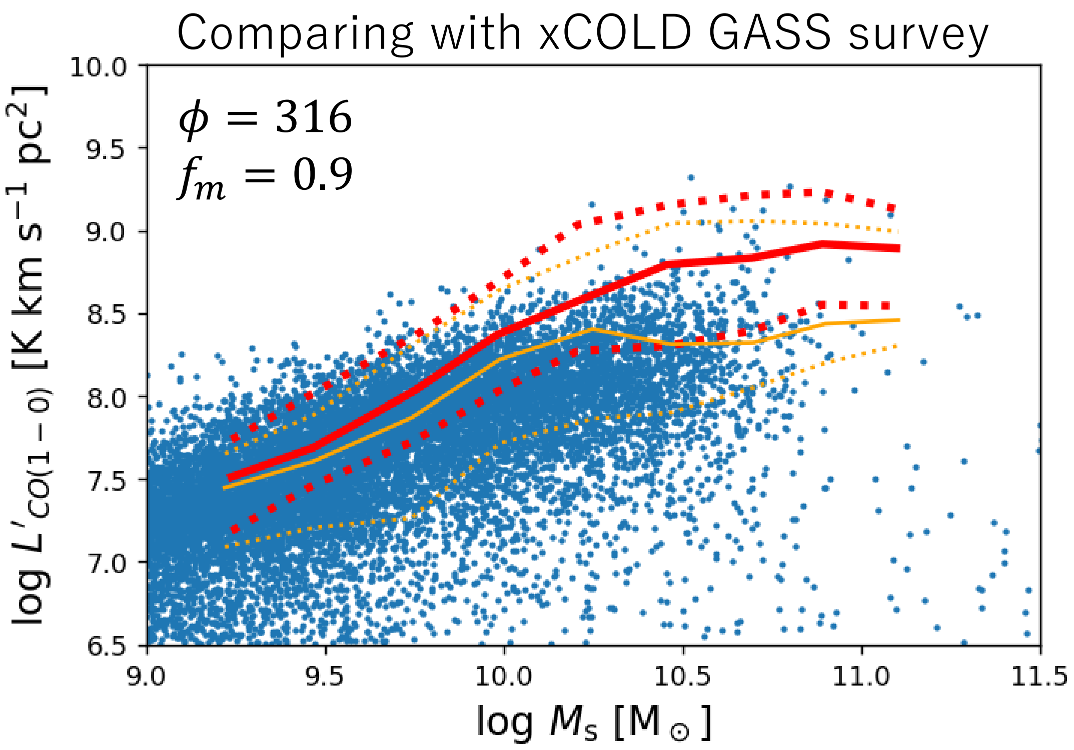
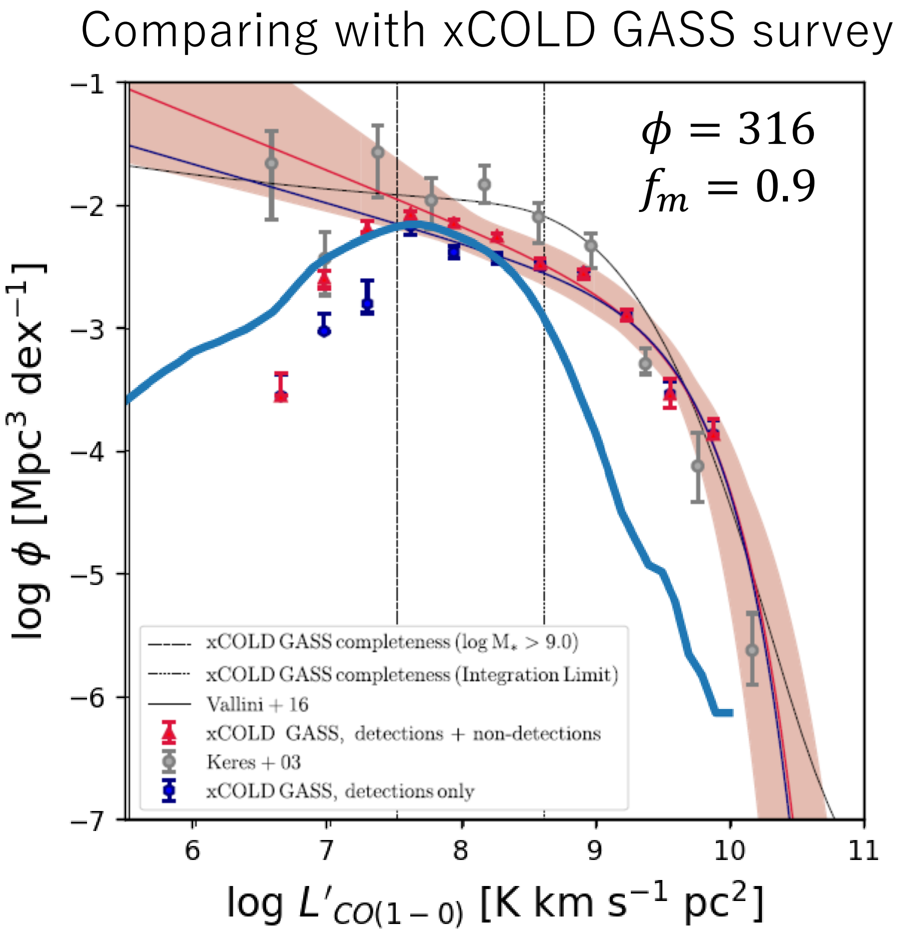
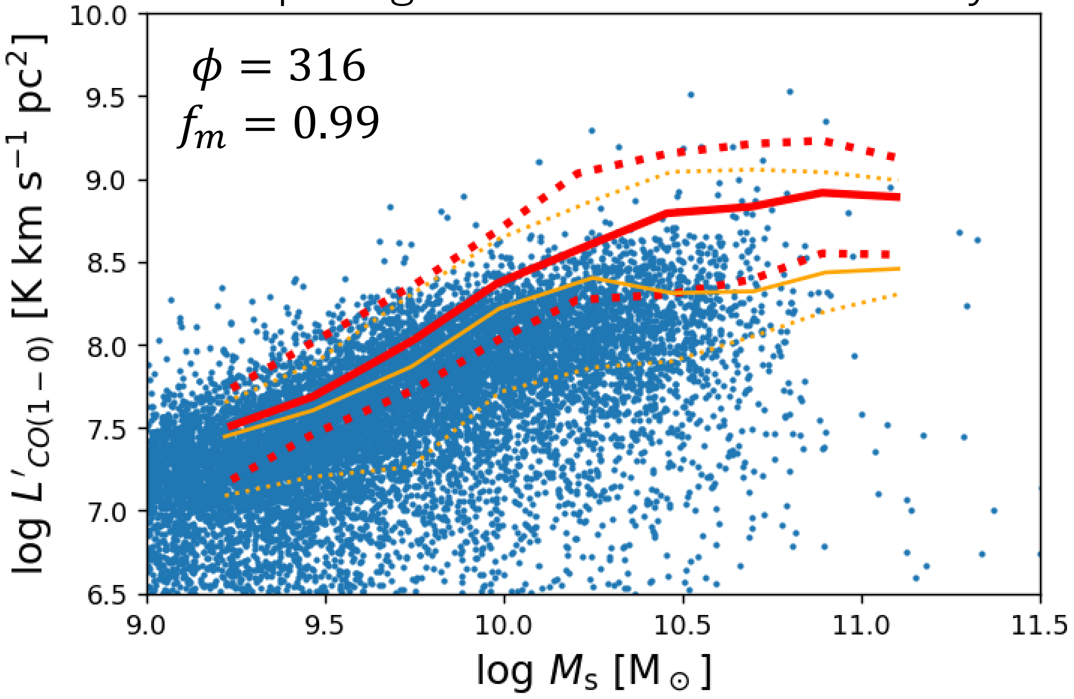


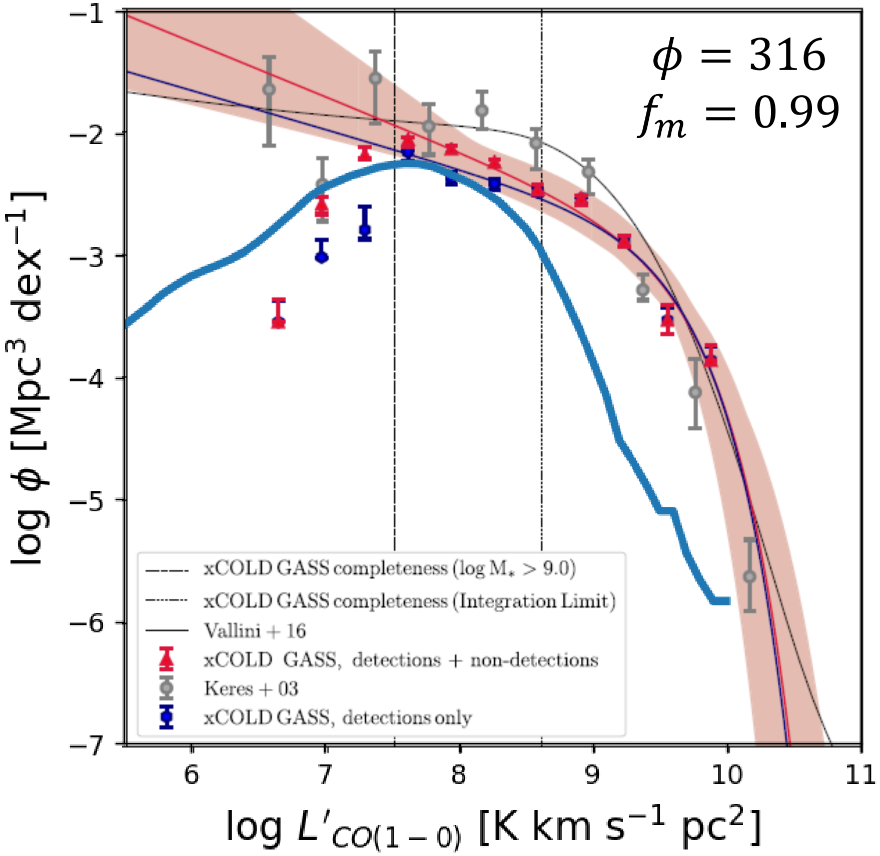


Applying to Illustris-TNG (z=0)

Comparing with xCOLD GASS survey



Comparing with xCOLD GASS survey



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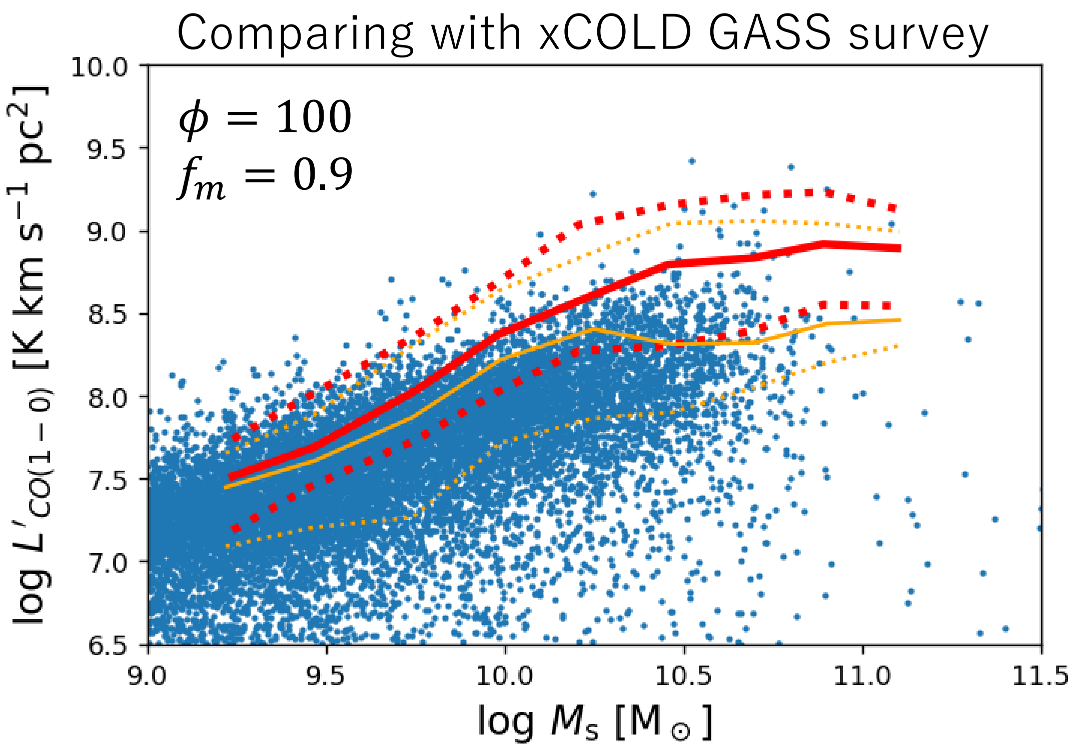

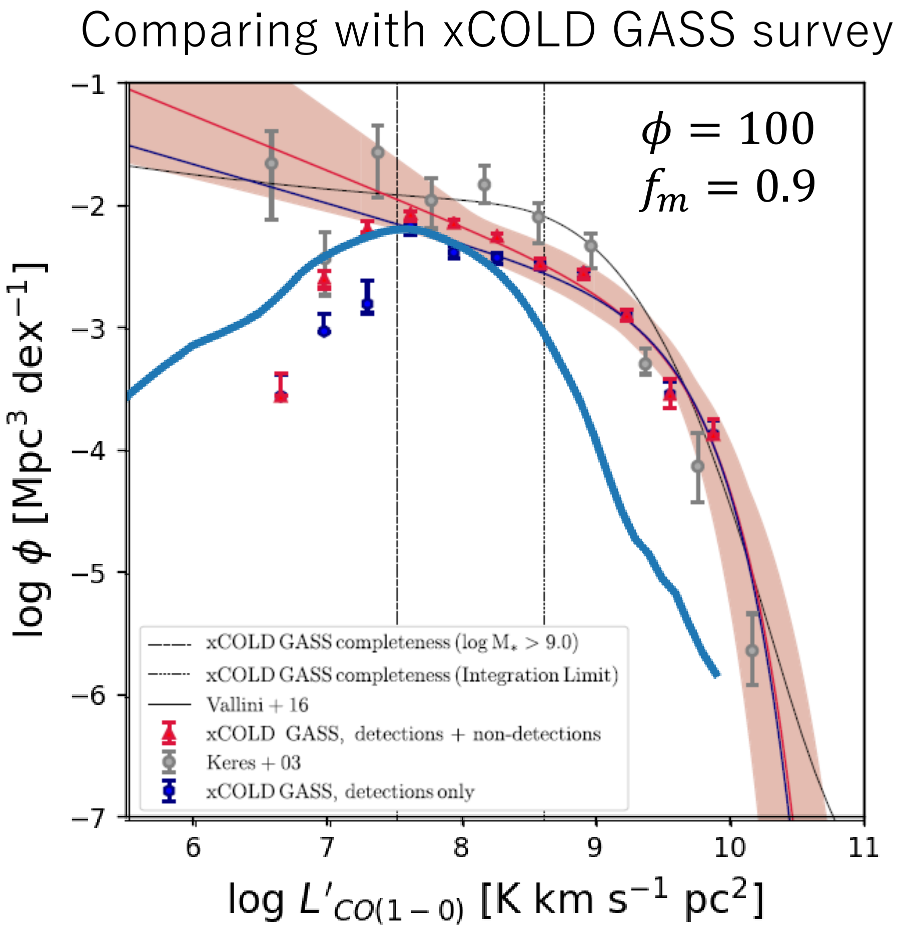

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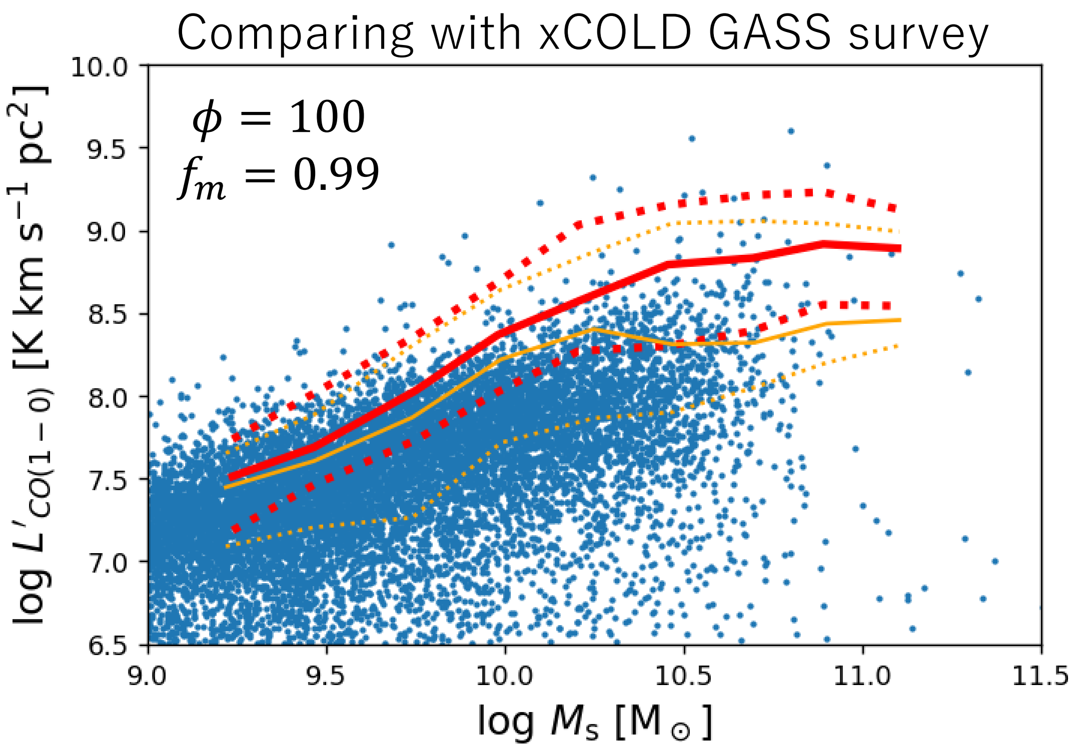
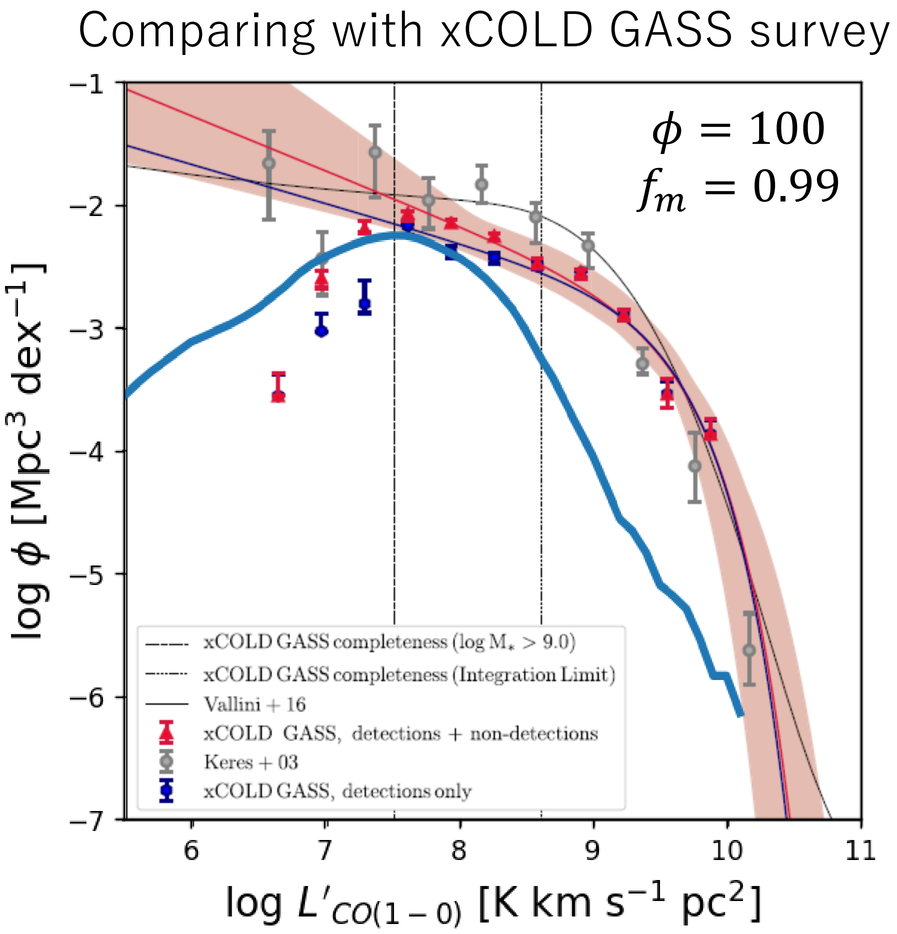
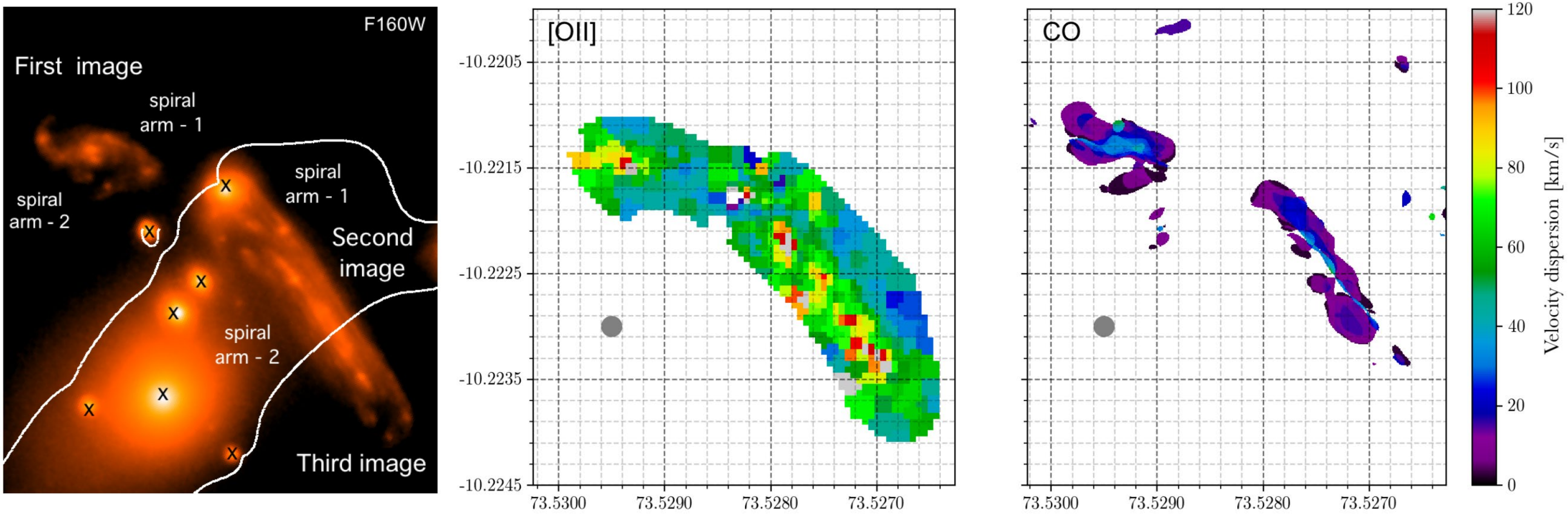




Kinematic analysis

- 2D-spectrum is so powerful for kinematic analysis.
  - But, beware of potential biases.

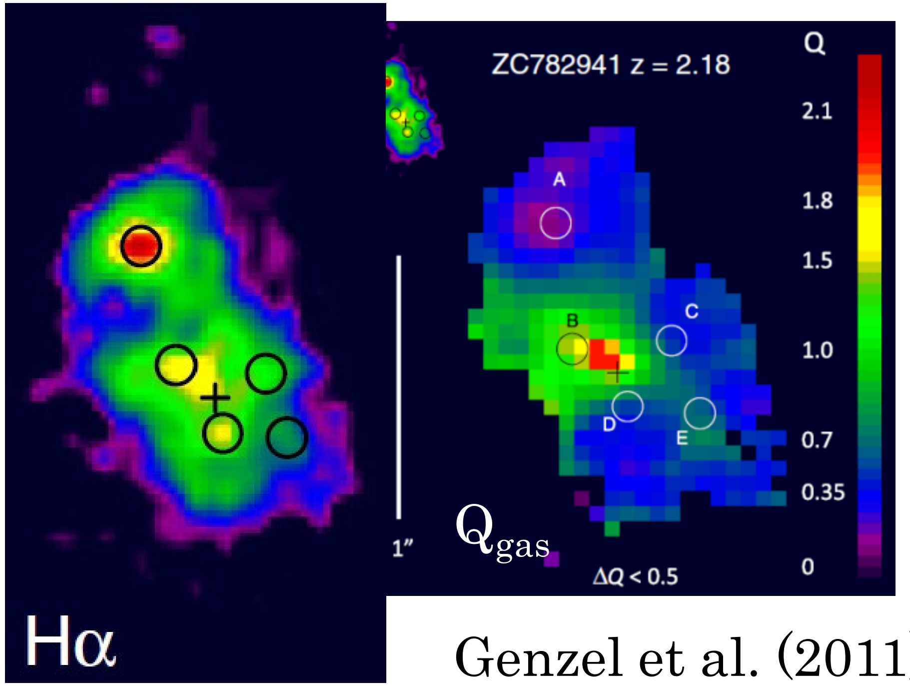
Girard et al. (2019)
A521: strong-lensed galaxy @ z=1

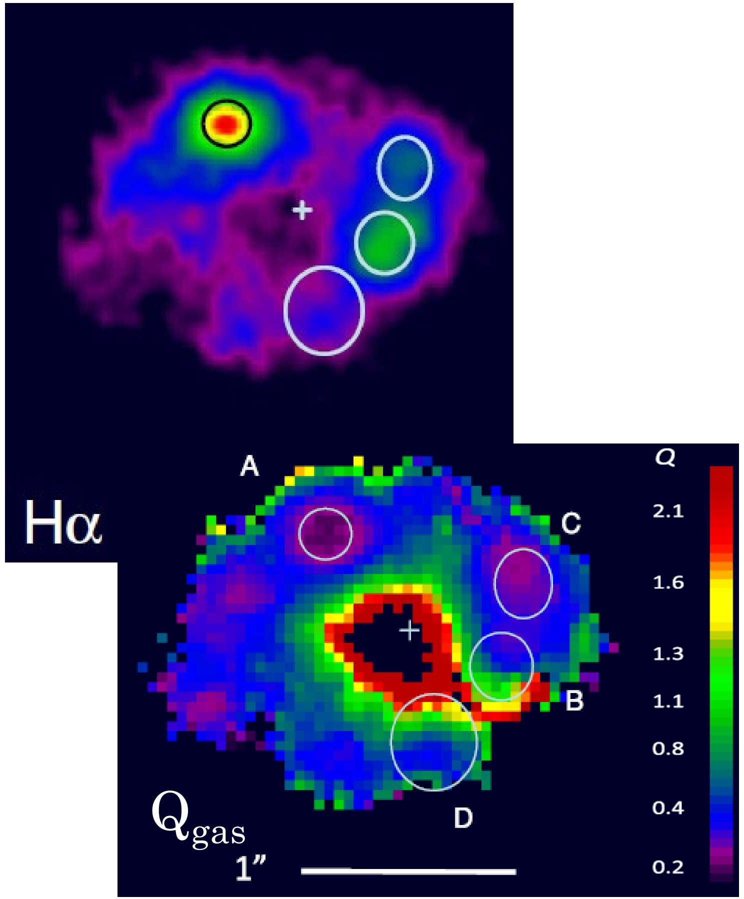


Can dynamically unstable galaxies really exist?

Toomre instability criterion: $Q \equiv \dfrac{\sigma\kappa}{\pi G \Sigma} < 1$

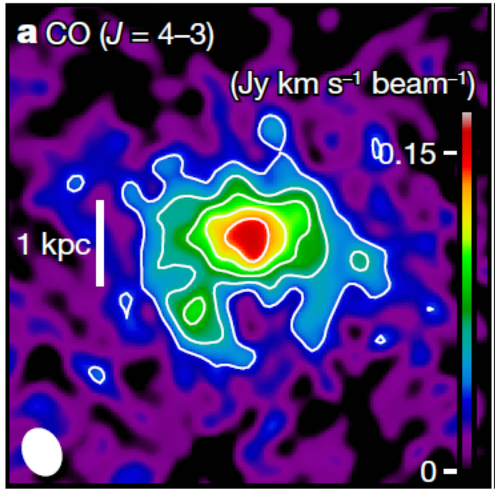
- Velocity dispersion in the Toomre analysis may be biased.

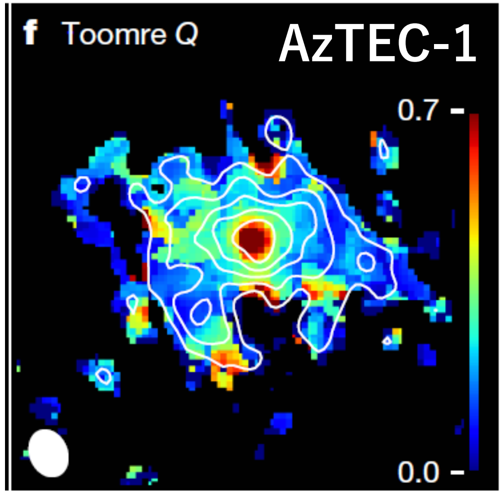




Genzel et al. (2011)

Tadaki et al. (2018)





Can dynamically unstable galaxies really exist?

- What is “dynamical instability”?
  - **It is a state where the system cannot hold on the current state.**

It can never last long!!

How do you measure velocity dispersions?

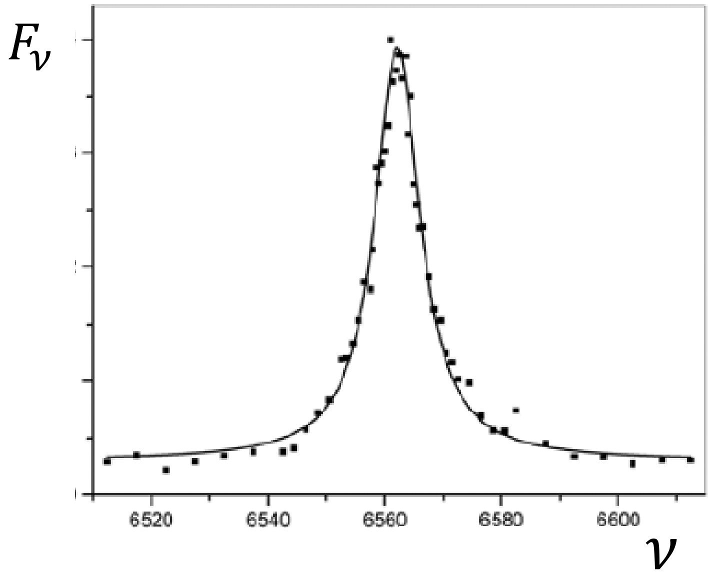
- Difference in measurement (definition) of velocity dispersion.
  - **In theory: mass-weighted**

$$\sigma_{\rm the}^2 = \frac{\sum (v_i - \overline{v})^2 m_i}{\sum m_i}.$$

  - **In observation: flux-weighted**

$$\sigma_{\rm obs}^2 = \frac{\int (v_\nu - \overline{v})^2 F_\nu d\nu}{\int F_\nu d\nu}.$$

    - F_ν: flux density of line emission

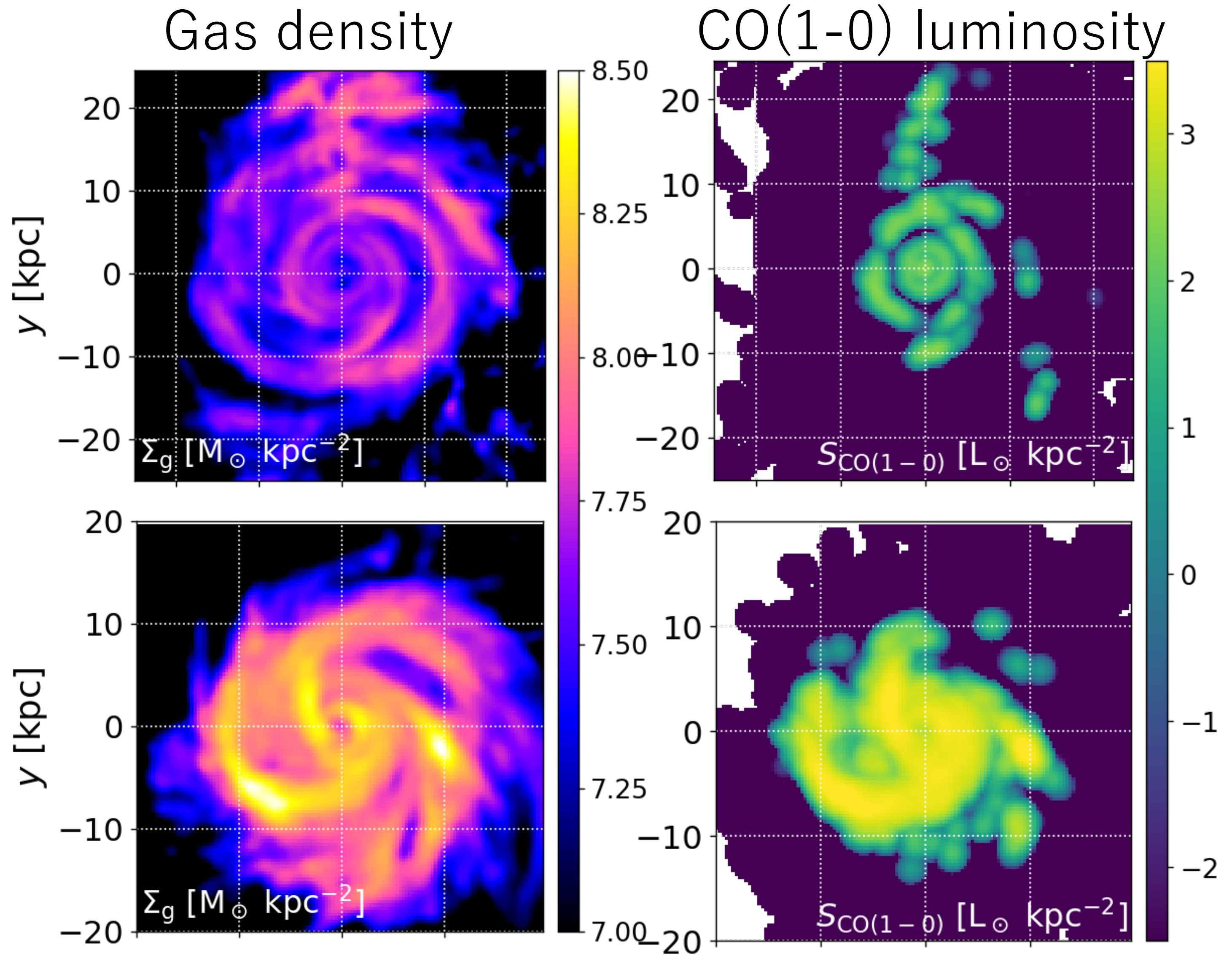


e.g. in the case of H α line,

$$L_{H\alpha} \propto SFR \propto \frac{m_{H_2}}{\tau_{SF}} \propto m_{H_2}\sqrt{\rho_{H_2}}, \quad \text{where} \quad \tau_{\rm SF} \sim \frac{1}{\sqrt{G\rho_{\rm H_2}}}.$$

Can dynamically unstable galaxies really exist?

- Mock CO(1-0) observations.



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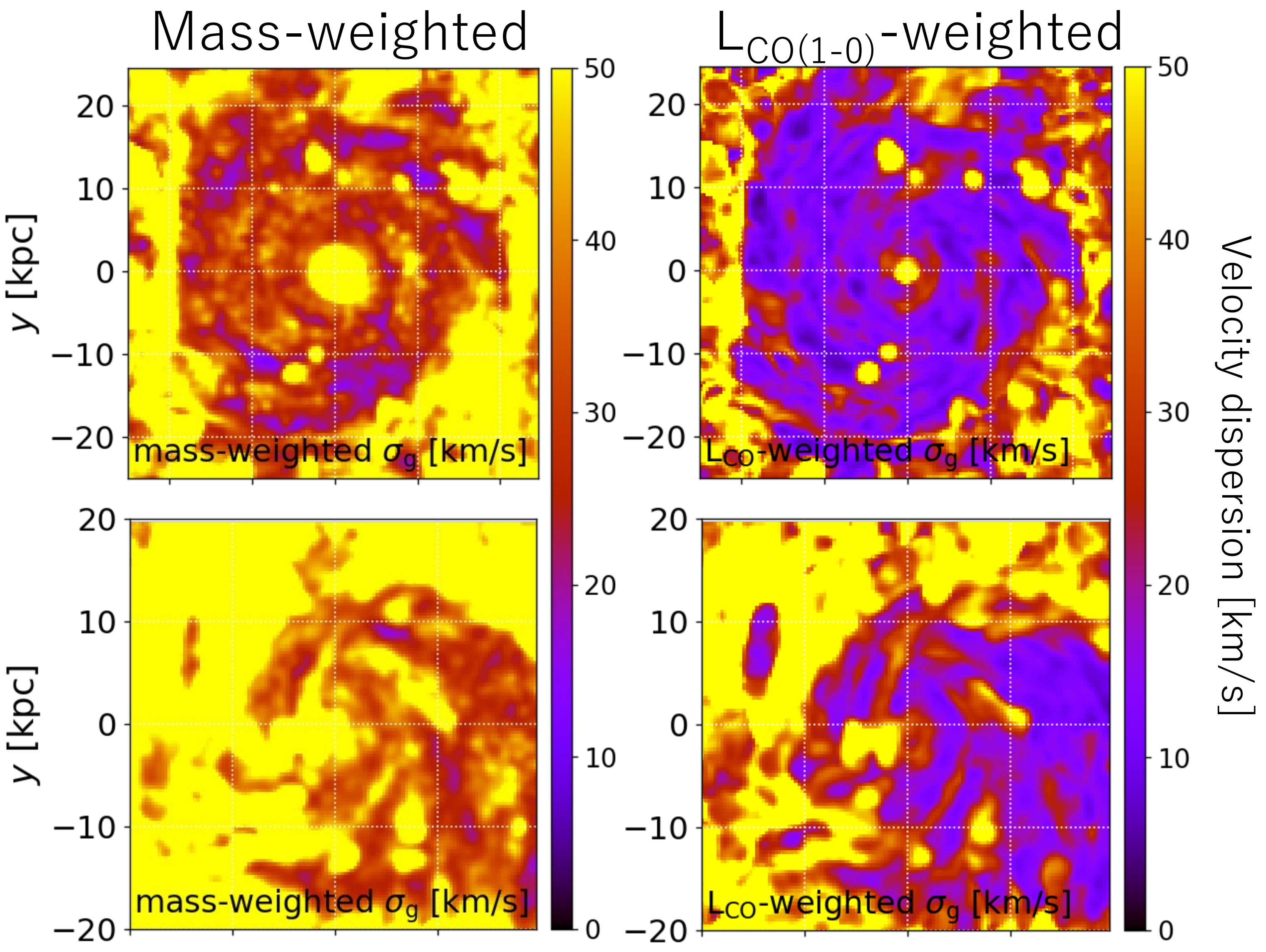

Can dynamically unstable galaxies really exist?

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$$Q \equiv \frac{\sigma \kappa}{\pi G \Sigma}$$

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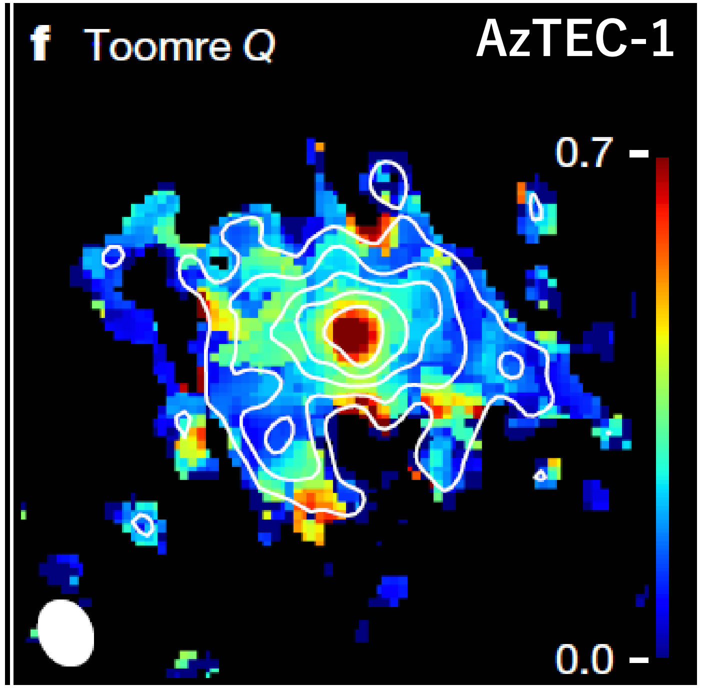

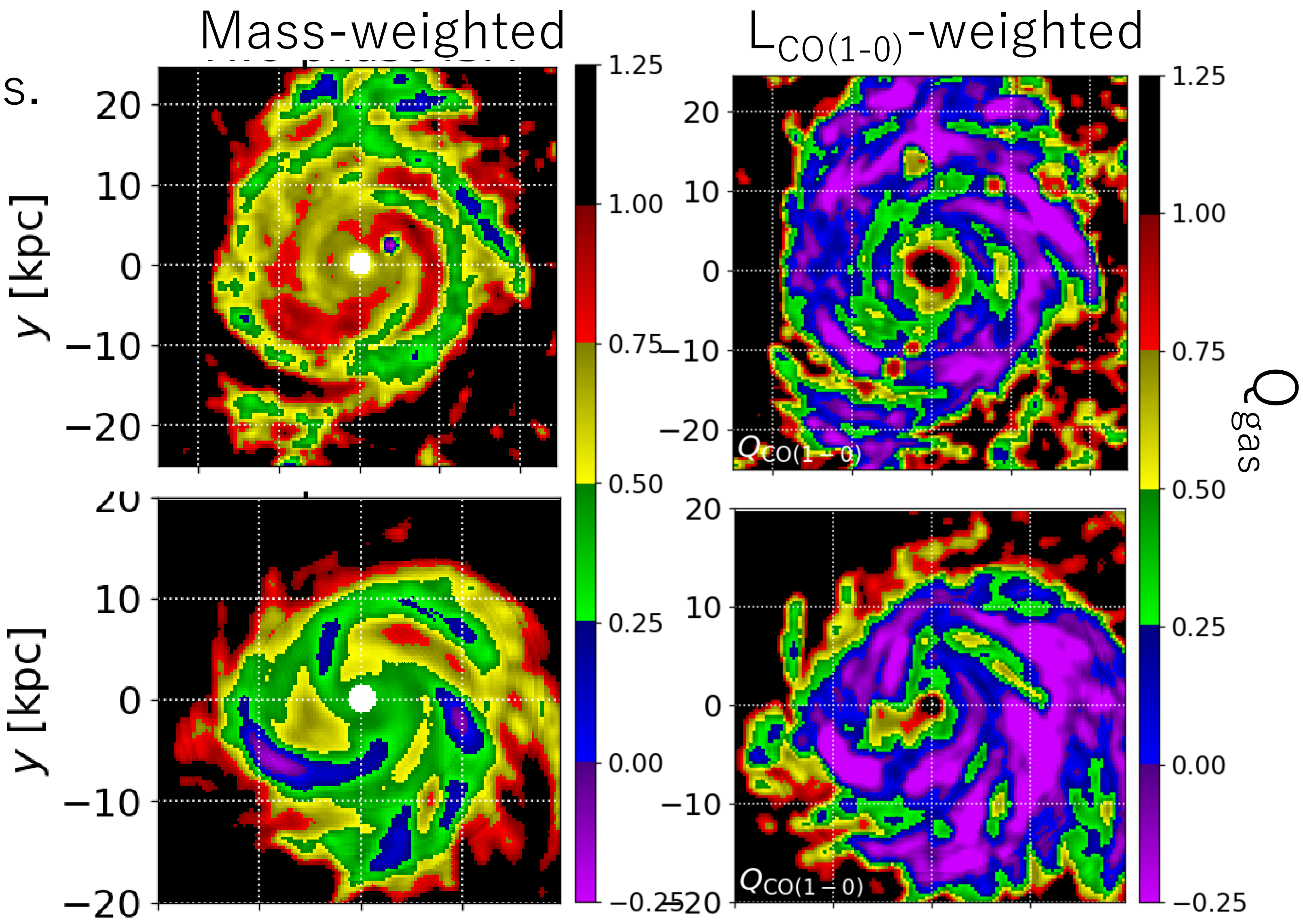

Summary

- I am developing a new model for molecular line emissions.
  - Still (very) preliminary.
  - Have a difficulty in reproducing high-mass CO-bright galaxies.

- Kinematic analysis based on line spectra can be biased
  - depending on which line you are looking at.
    - Different molecule has different reaction density.
    - Not necessarily mass-weighted

  - The low values of $Q<1$ in high-z discs may be attributed to this bias.