理論モデルを用いた分子輝線の面分光疑似観測：力学解析へのバイアス

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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…
  - 2D-spectrum study
    - Dynamical analysis

Importance of studying molecular gas (H_2)

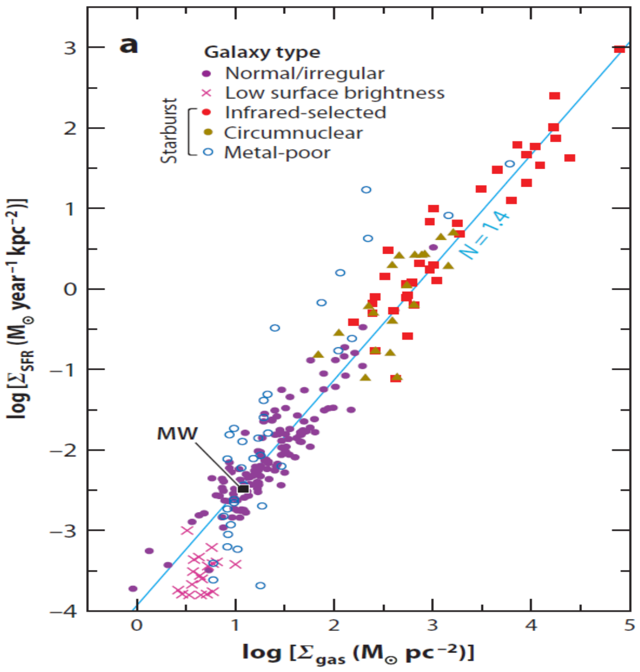
- Molecular hydrogen is more directly relevant to star formation than ionized and atomic hydrogen.

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.

Kennicutt & Evans (2012)

Star-formation rate density

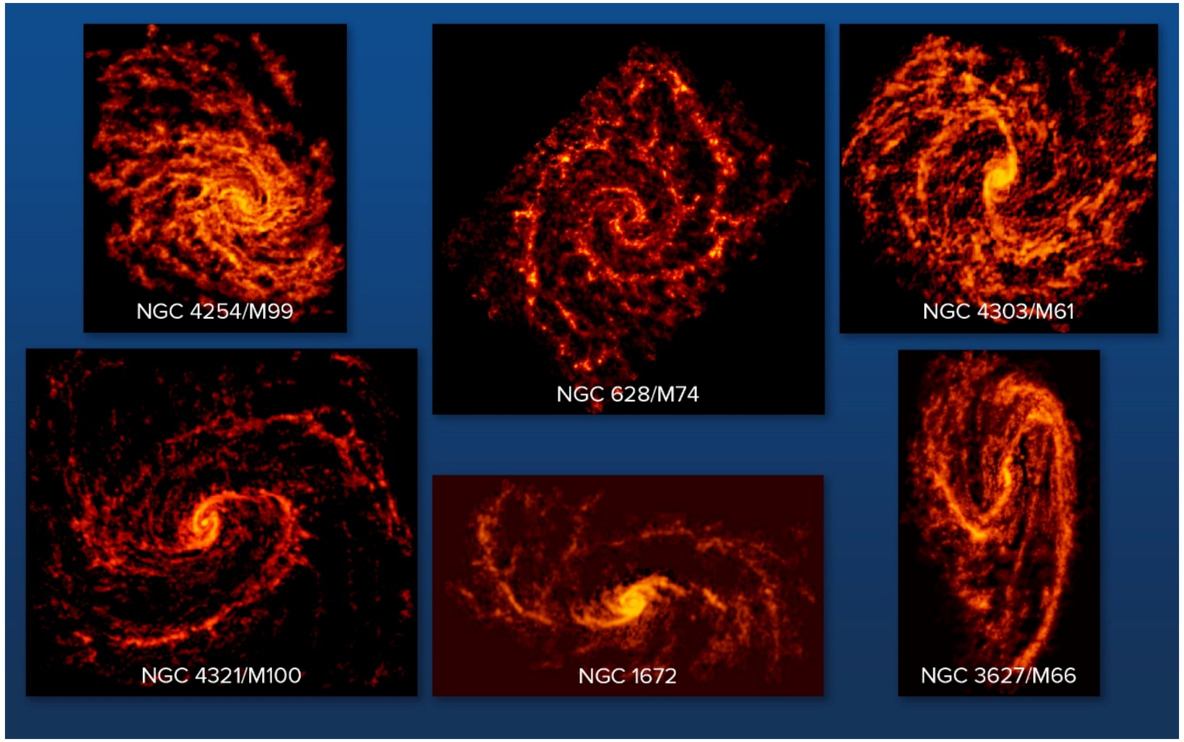


HI + H_2 gas density

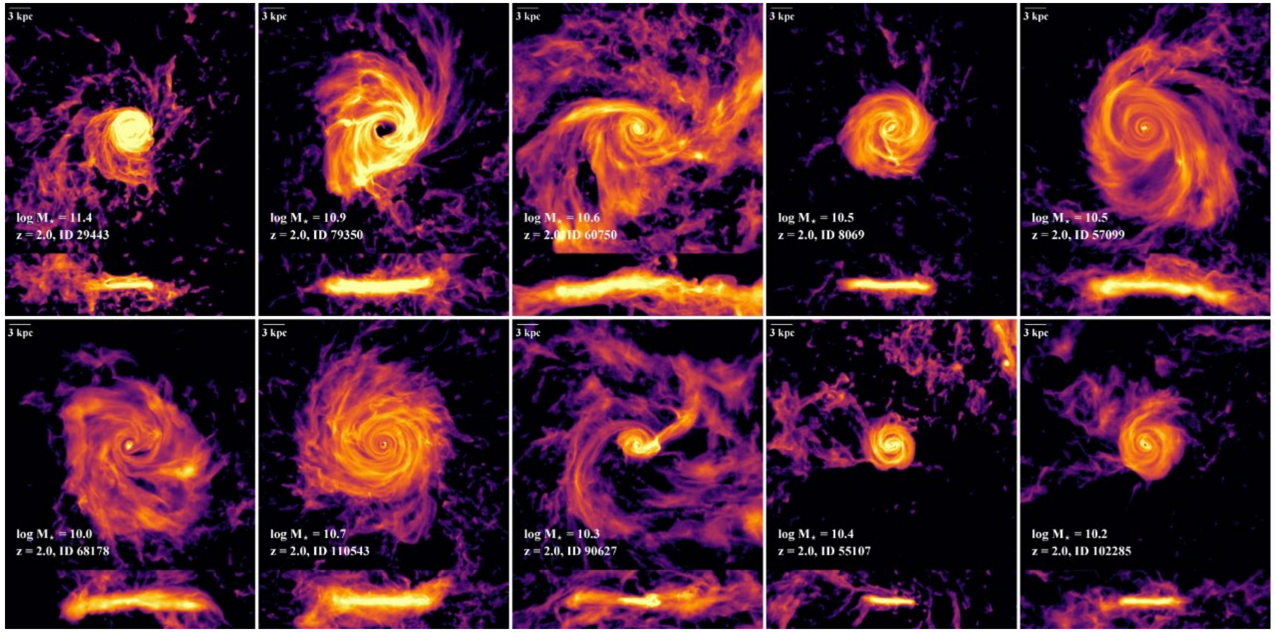
Difficulties in studying molecular gas (H_2)

- 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

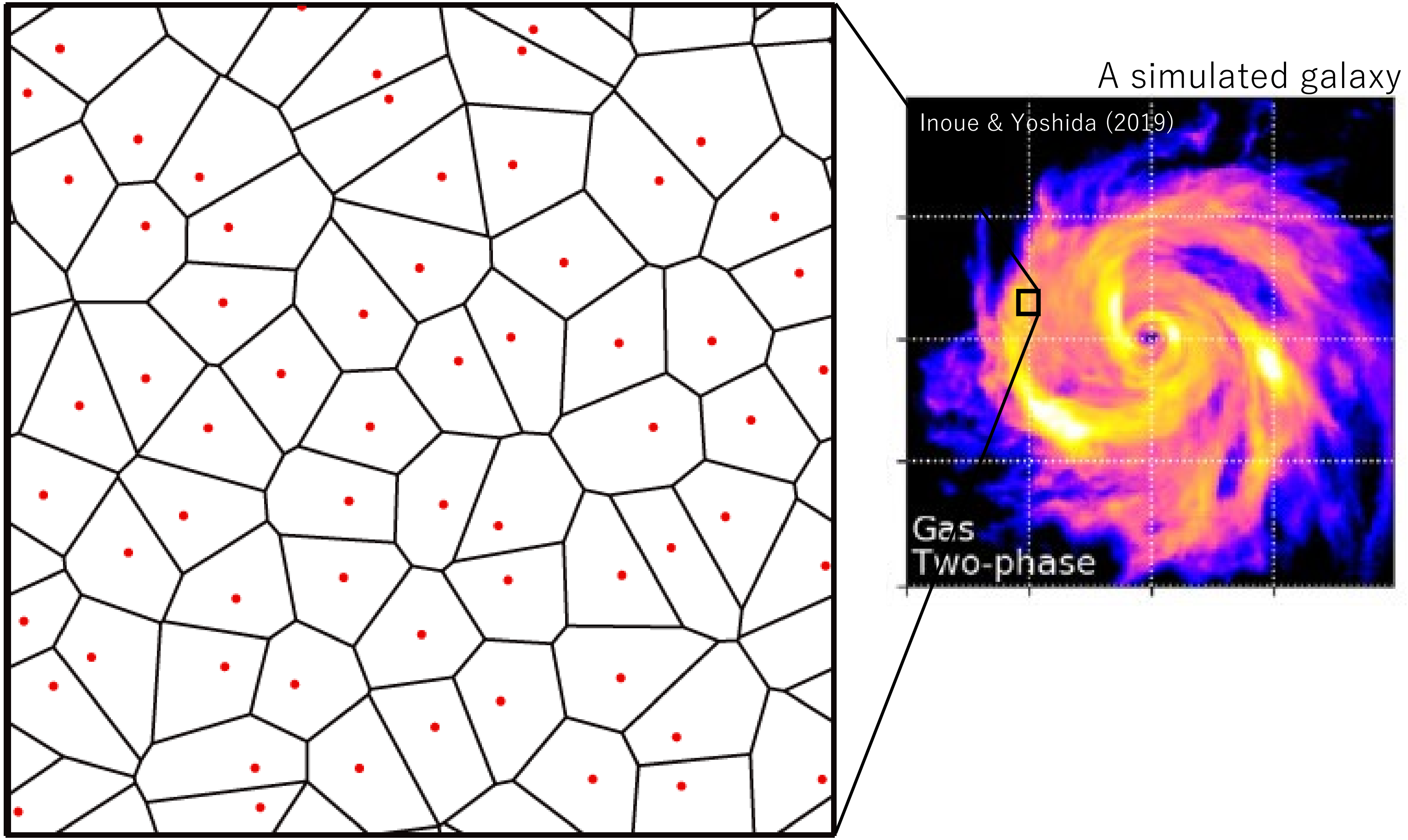
- How should we interpret the molecular observations?

  ➡ mock observations for molecules by utilizing simulations.

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-processing model for molecules



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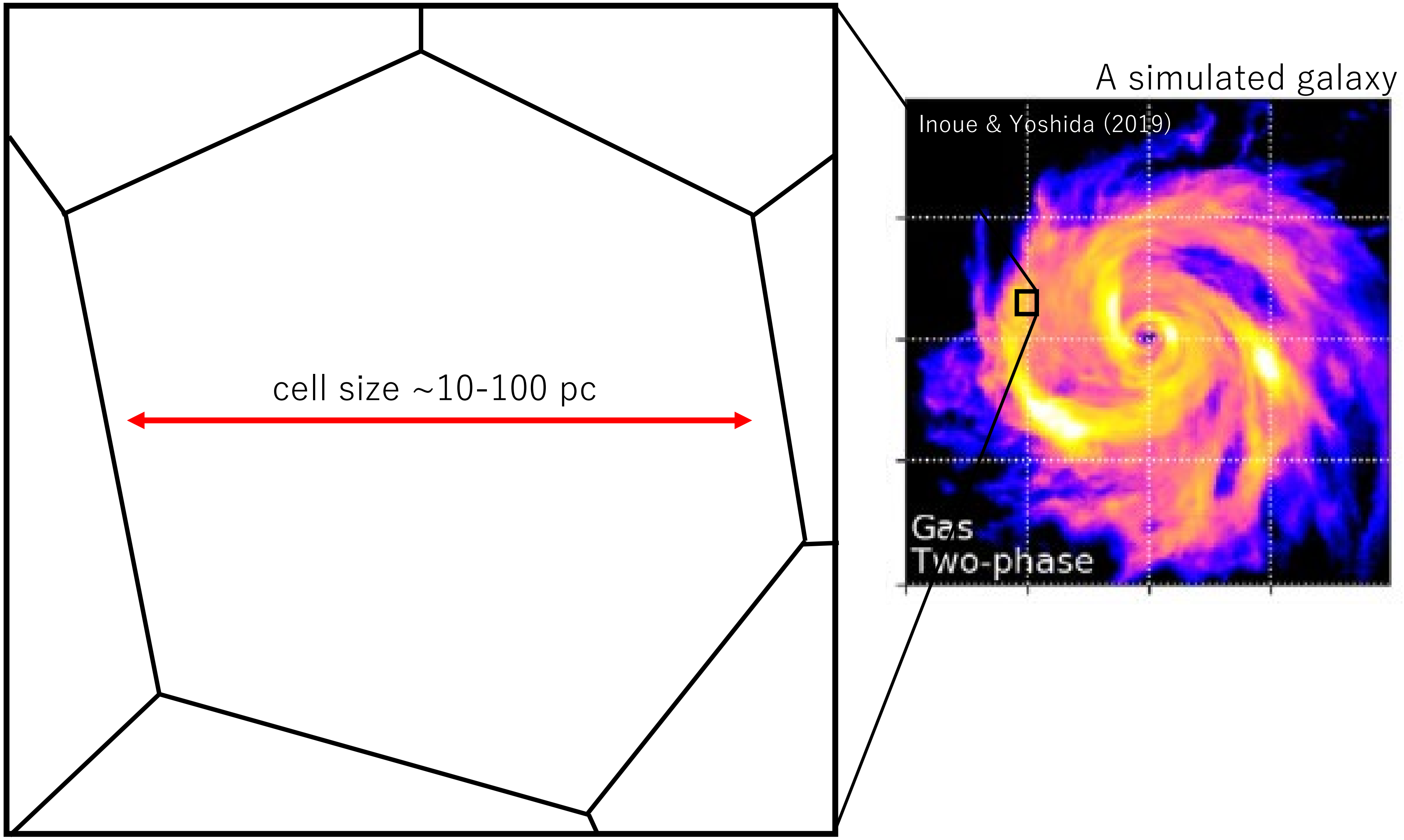

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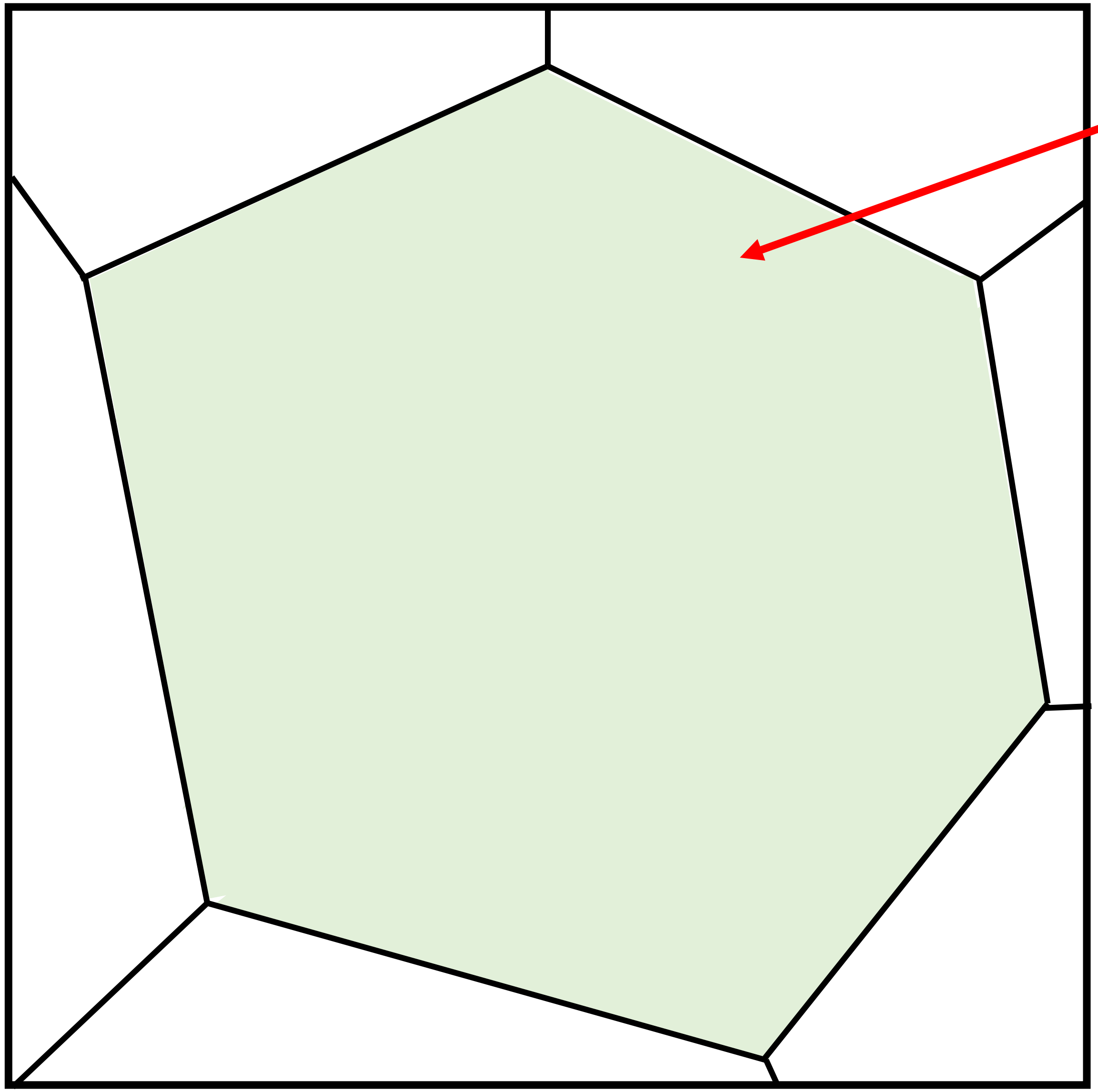
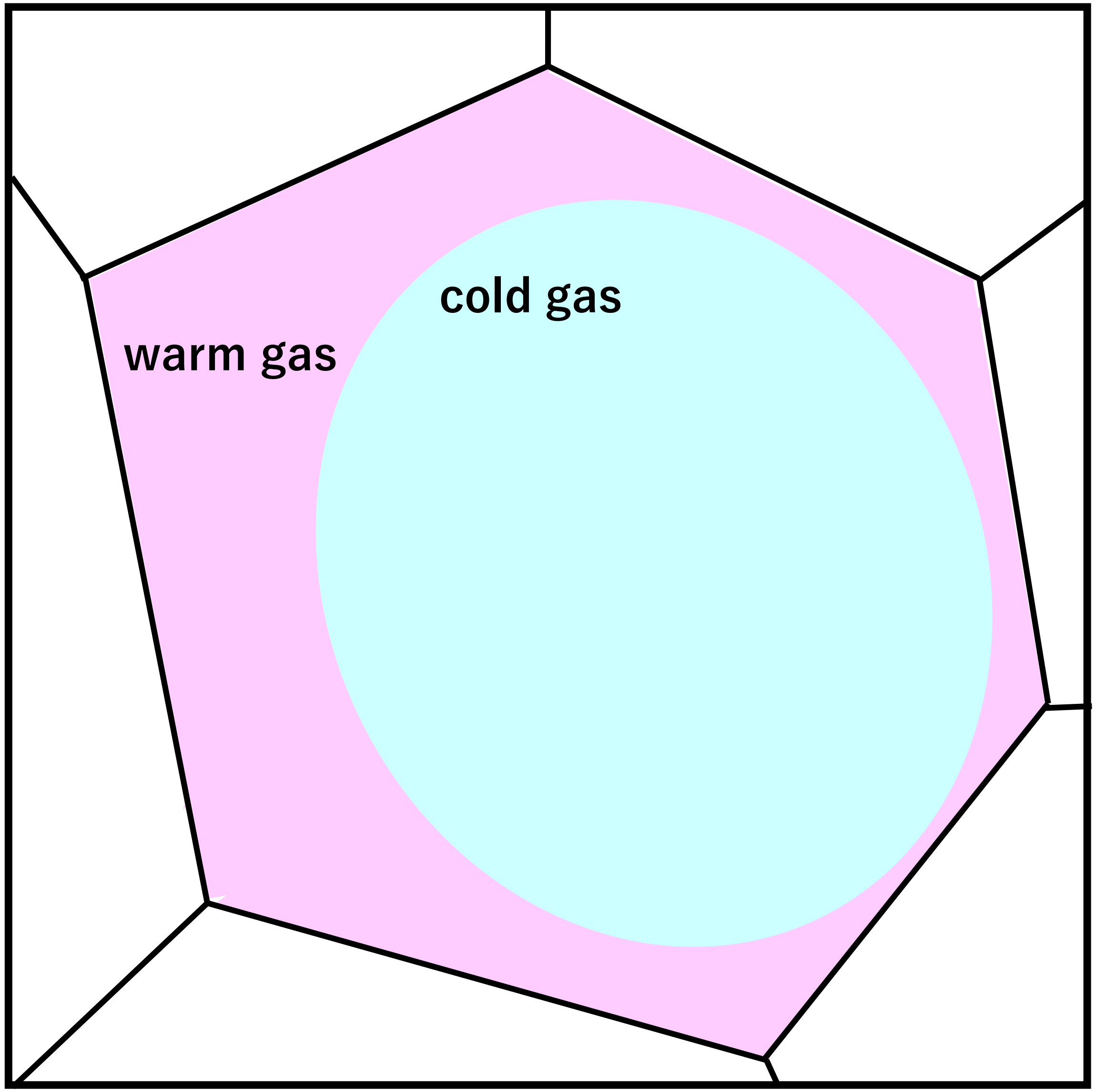
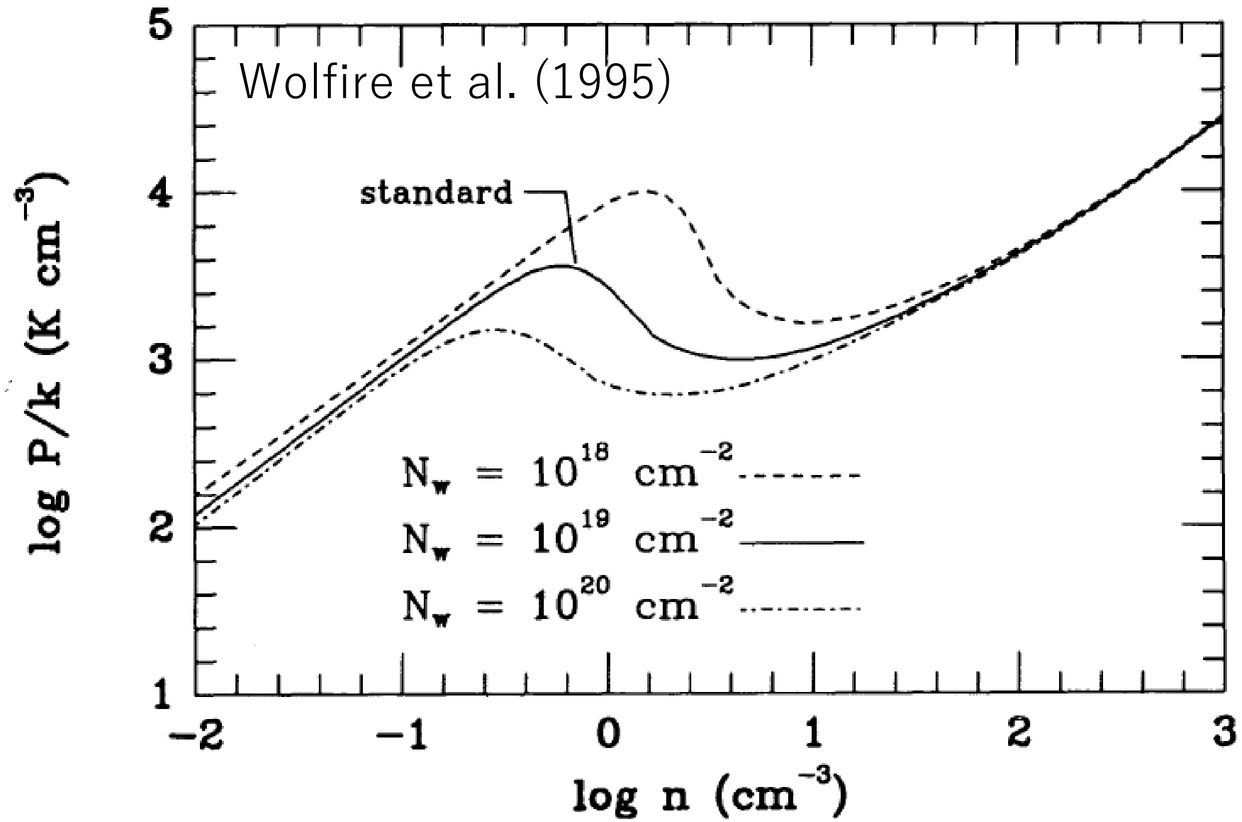


- Directory from simulation,
  - $\rho_{cell}, P_{cell}, M_{cell}, Z_{cell}$
- Exclude diffuse gas
  - $n_H < 0.1$ cm^{-3} (SF criterion in simulation)

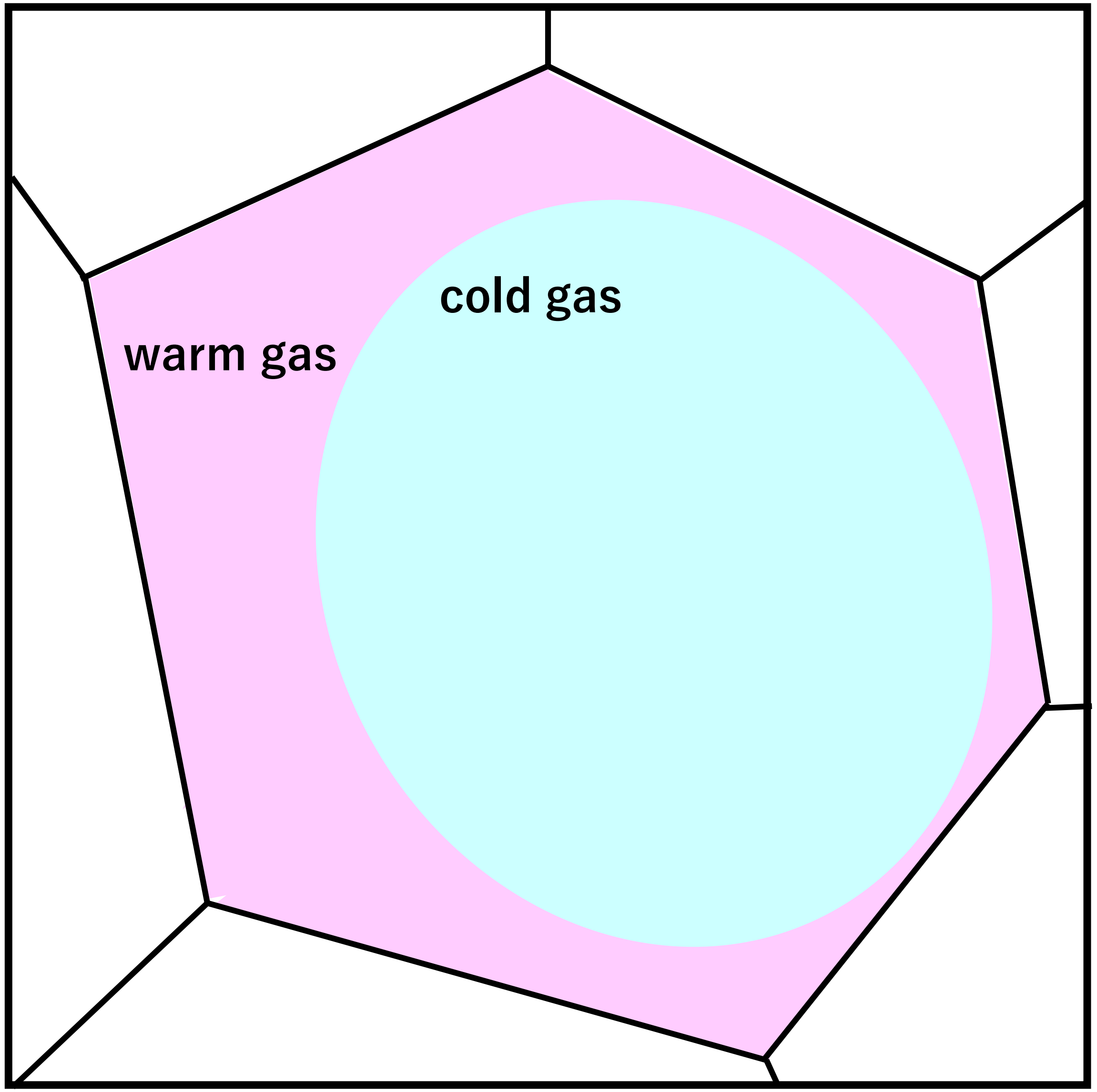
Post-processing model for molecules



- Directory from simulation,
  - $\rho_{cell}, P_{cell}, M_{cell}, Z_{cell}$
- Consider a two-phase ISM model
  - cold/warm neutral media in a cell



Post-processing model for molecules



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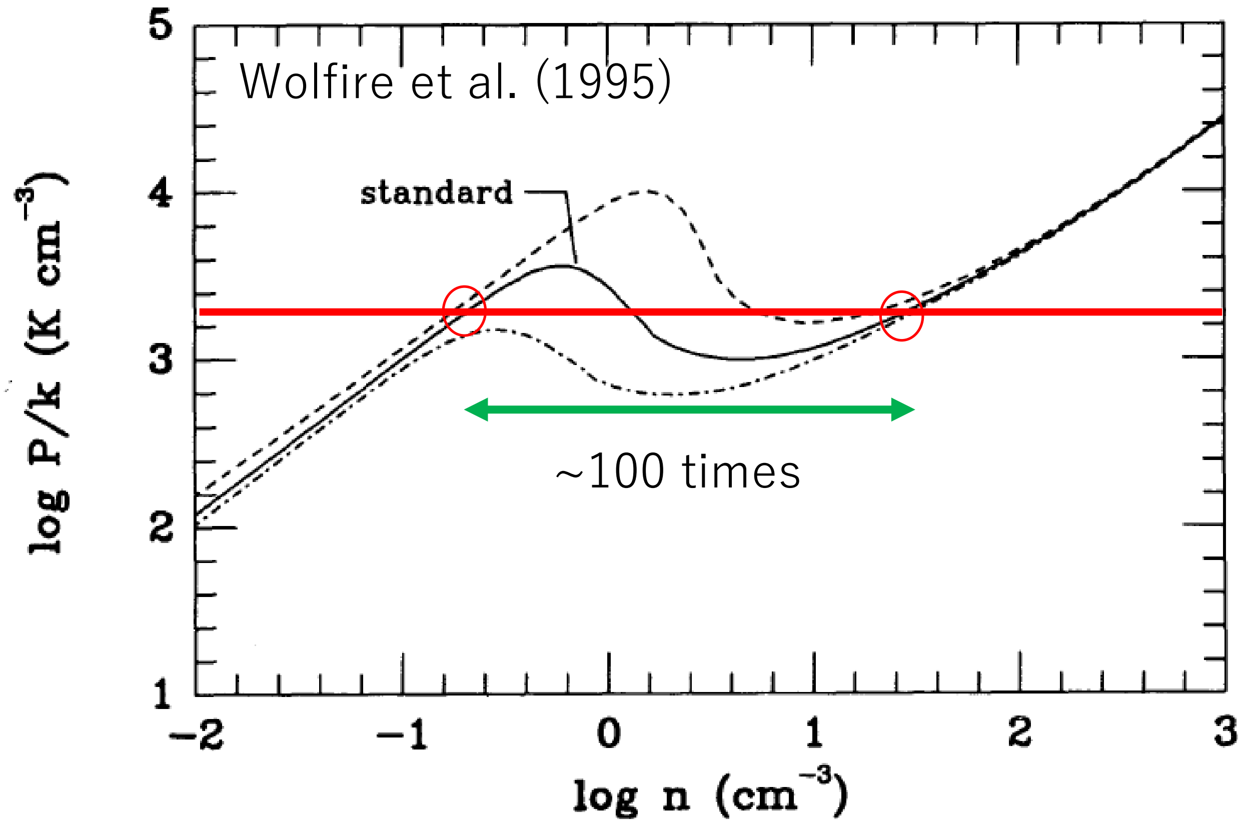

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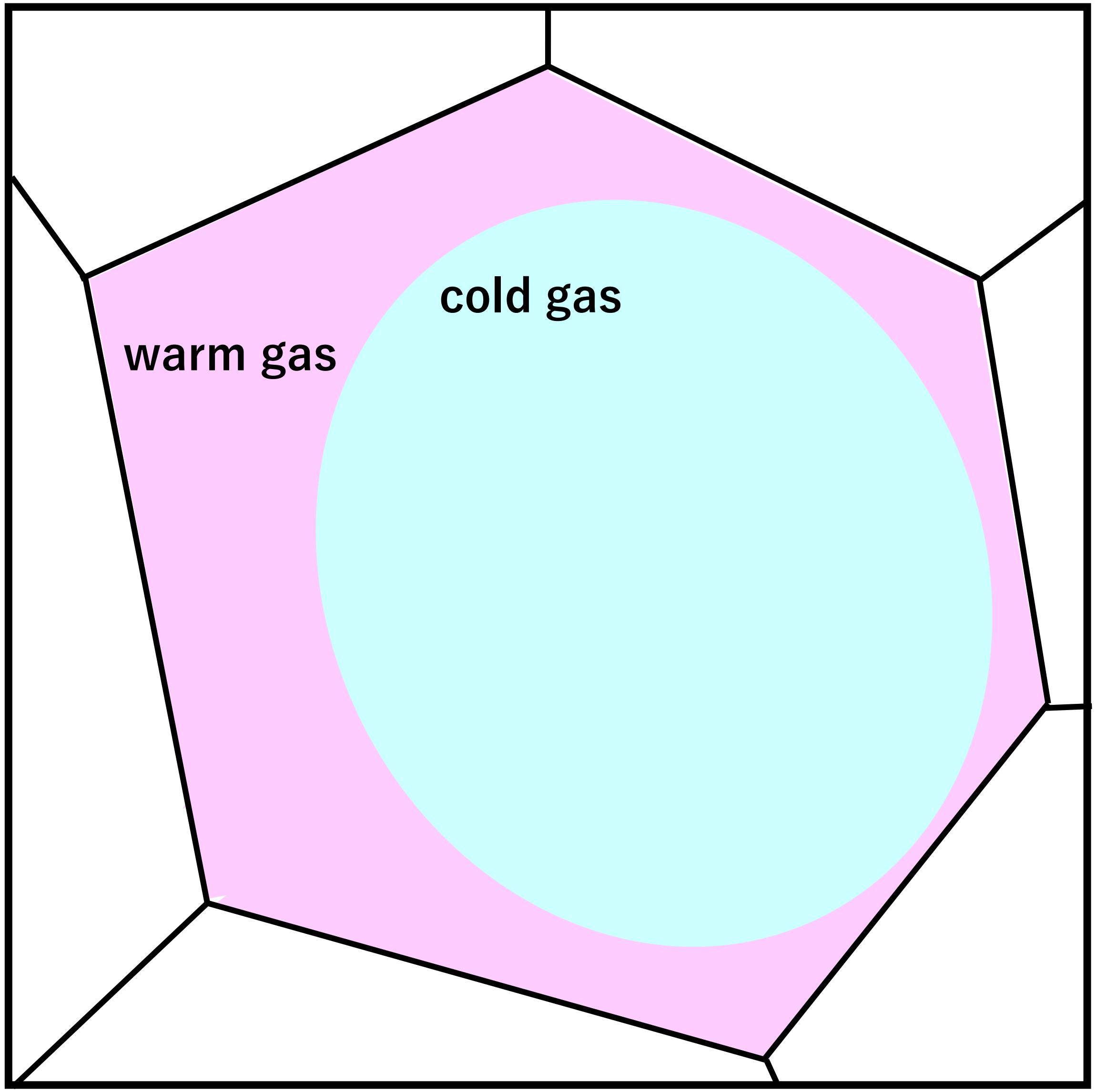
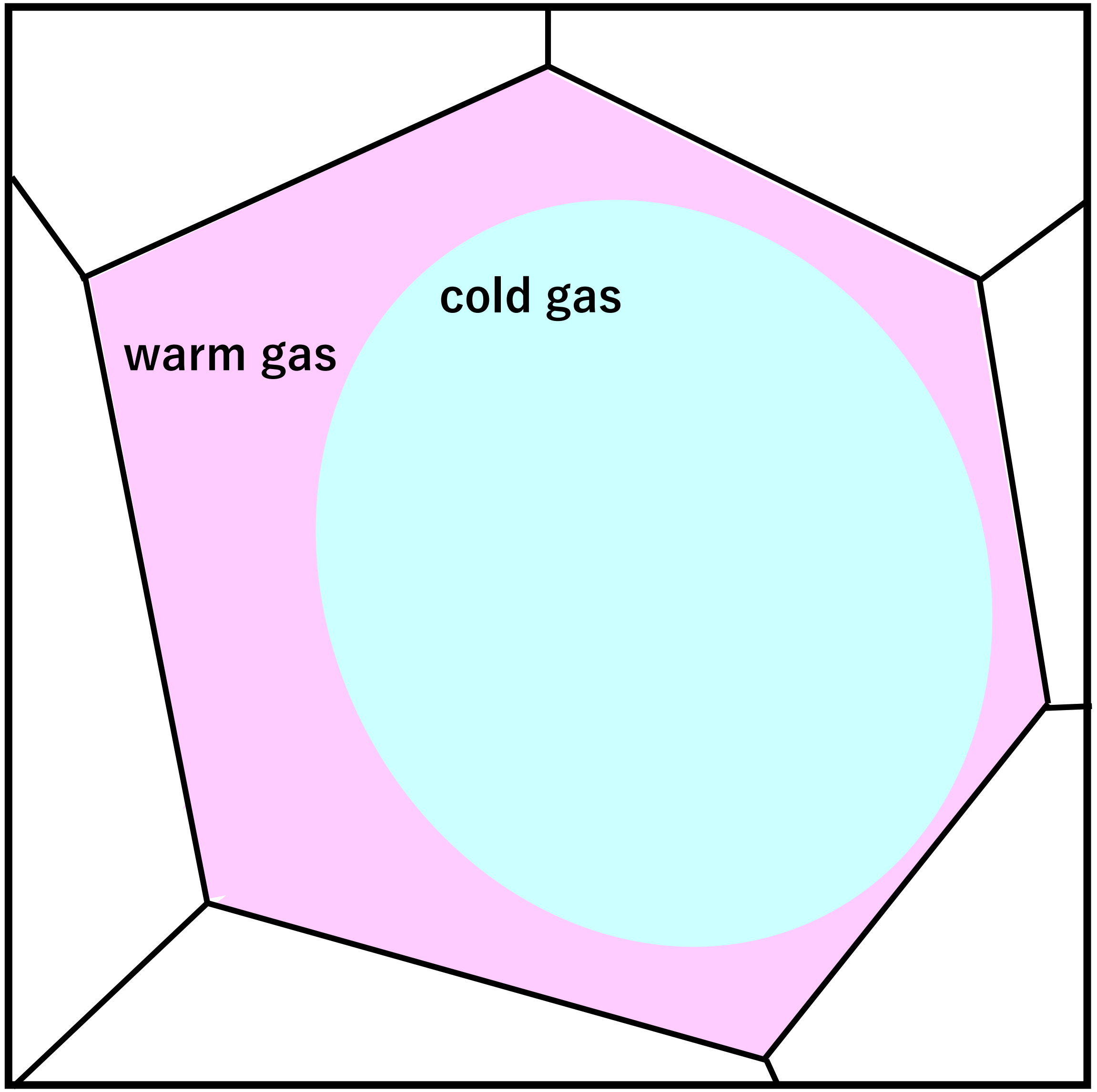


- Directory from simulation,
  - $\rho_{cell}, P_{cell}, M_{cell}, Z_{cell}$
- Consider a two-phase ISM model
  - cold/warm neutral media in a cell

- **Density contrast**: $\phi \equiv \frac{\rho_{cold}}{\rho_{warm}} = 100$
  - Pres.-equilibrium (e.g. Wolfire et al. 1995)
- **Cold-mass fraction**: $f_m \equiv \frac{M_{cold}}{M_{cell}} \sim 0.8 - 1$
  - Springel & Hernquist (2003)

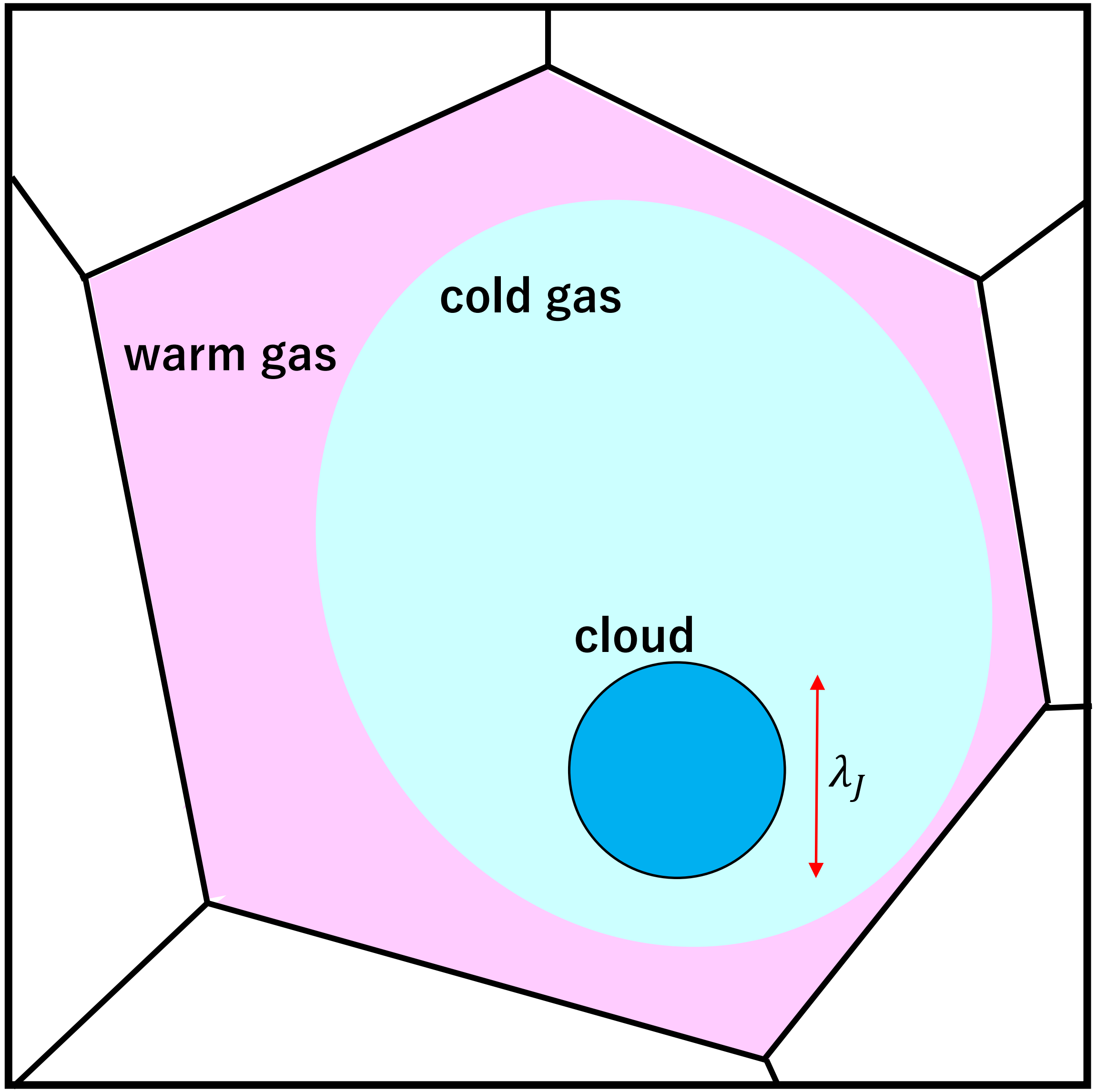
- Cold-volume fraction: $f_V \equiv \frac{V_{cold}}{V_{cell}} = \frac{f_m}{(1-f_m)\phi + f_m}$

Post-processing model for molecules



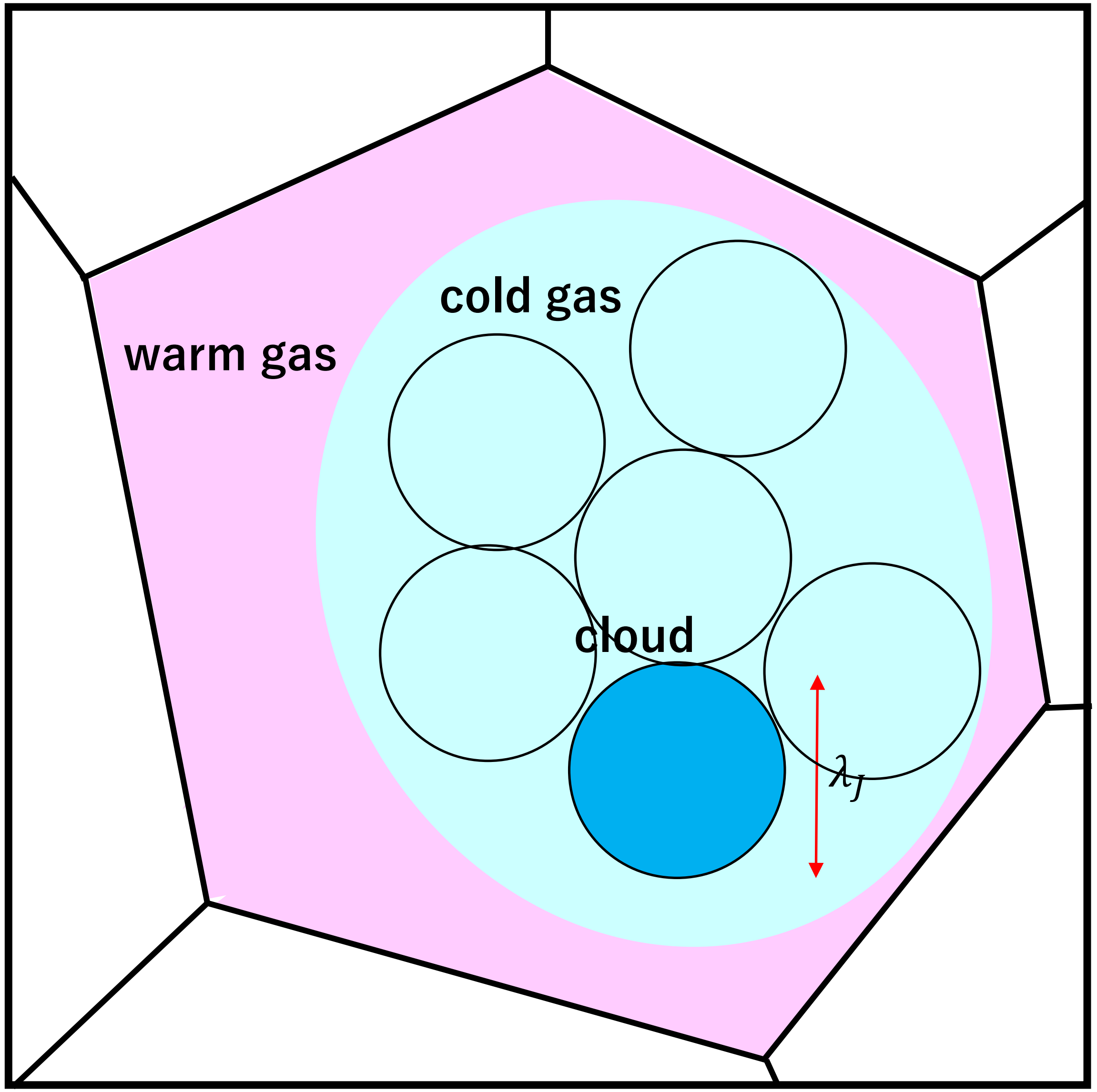
- Directory from simulation,
  - $\rho_{cell}, P_{cell}, M_{cell}, Z_{cell}$
- The cold gas has
  - $\rho_{cold}, P_{cell}, M_{cold}, Z_{cell}$
  - Jeans length $\lambda_J \equiv \sqrt{\frac{P_{cell}}{G\rho_{cold}}}$

Post-processing model 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: $D_{cloud} = D_{MW}\frac{Z_{cell}}{Z_{MW}}$
  - Radiation field: $I_{cloud} \sim 0$
    - **"well-shielded approximation"**

Post-processing model for molecules



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

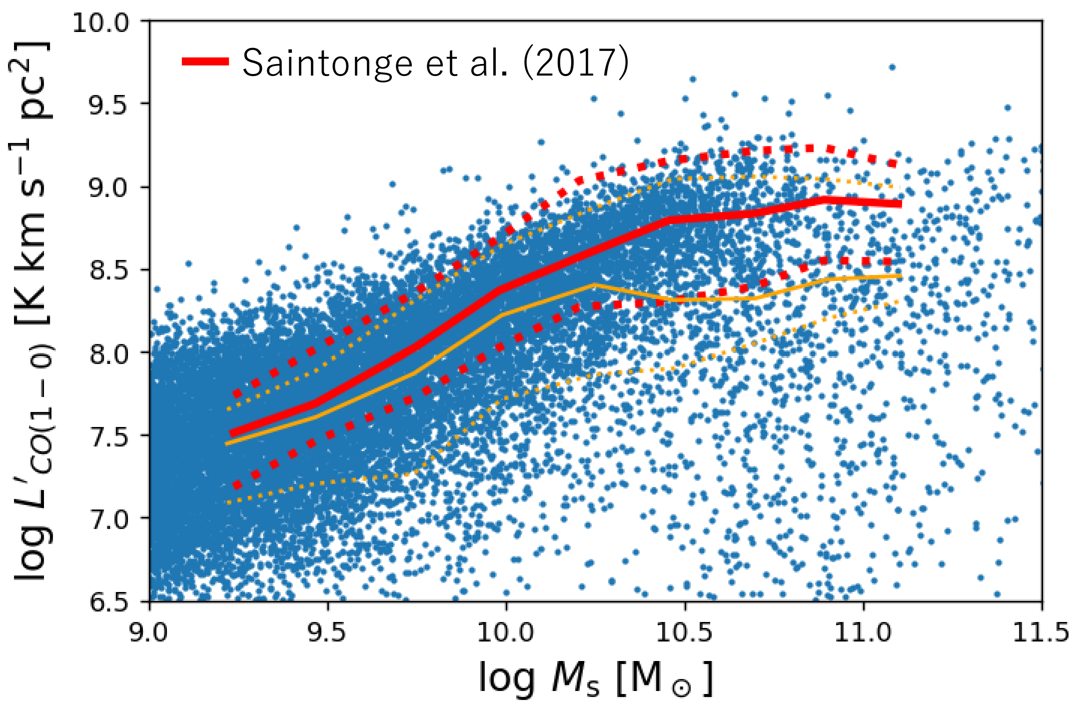
- Cumulate the cloud emissions and obtain the total value of the cell.
  - The number of clouds in a cell
    - $N_{cloud} = \frac{V_{cold}}{V_{cloud}}$
      - Implying the optically-thin approx.

- Cumulate the gas cells within every single galaxy.

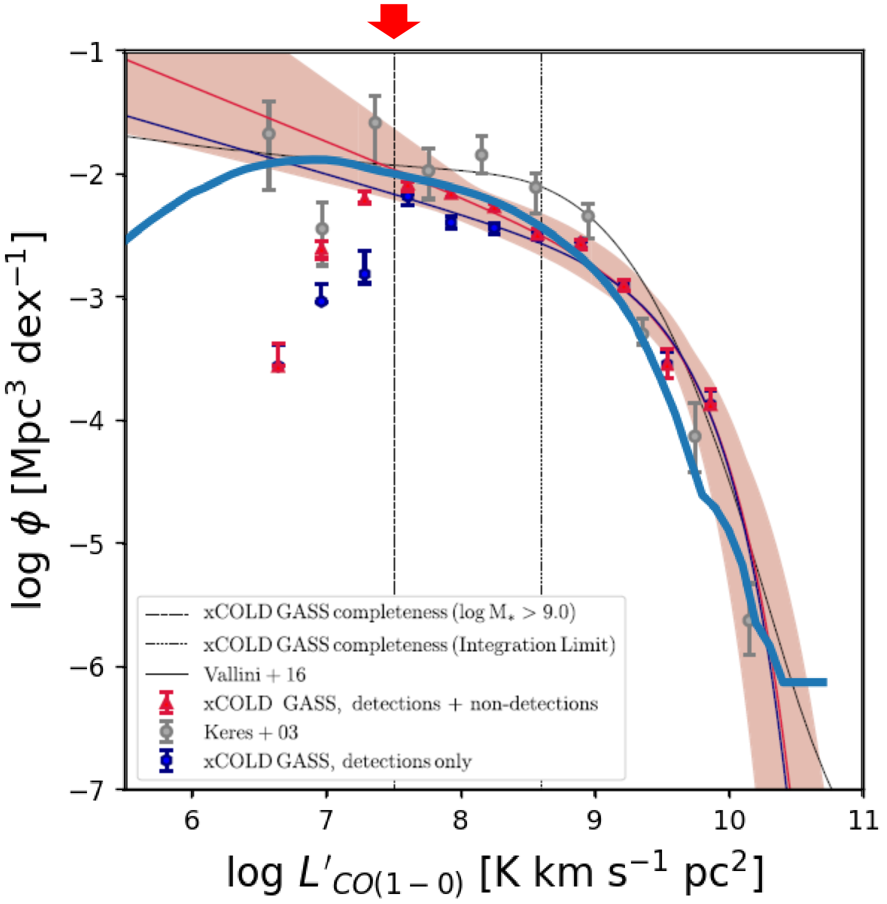
Applying to Illustris-TNG (z=0, TNG100-1)

- Comparing with xCOLD GASS survey (Saintonge et al. 2017)

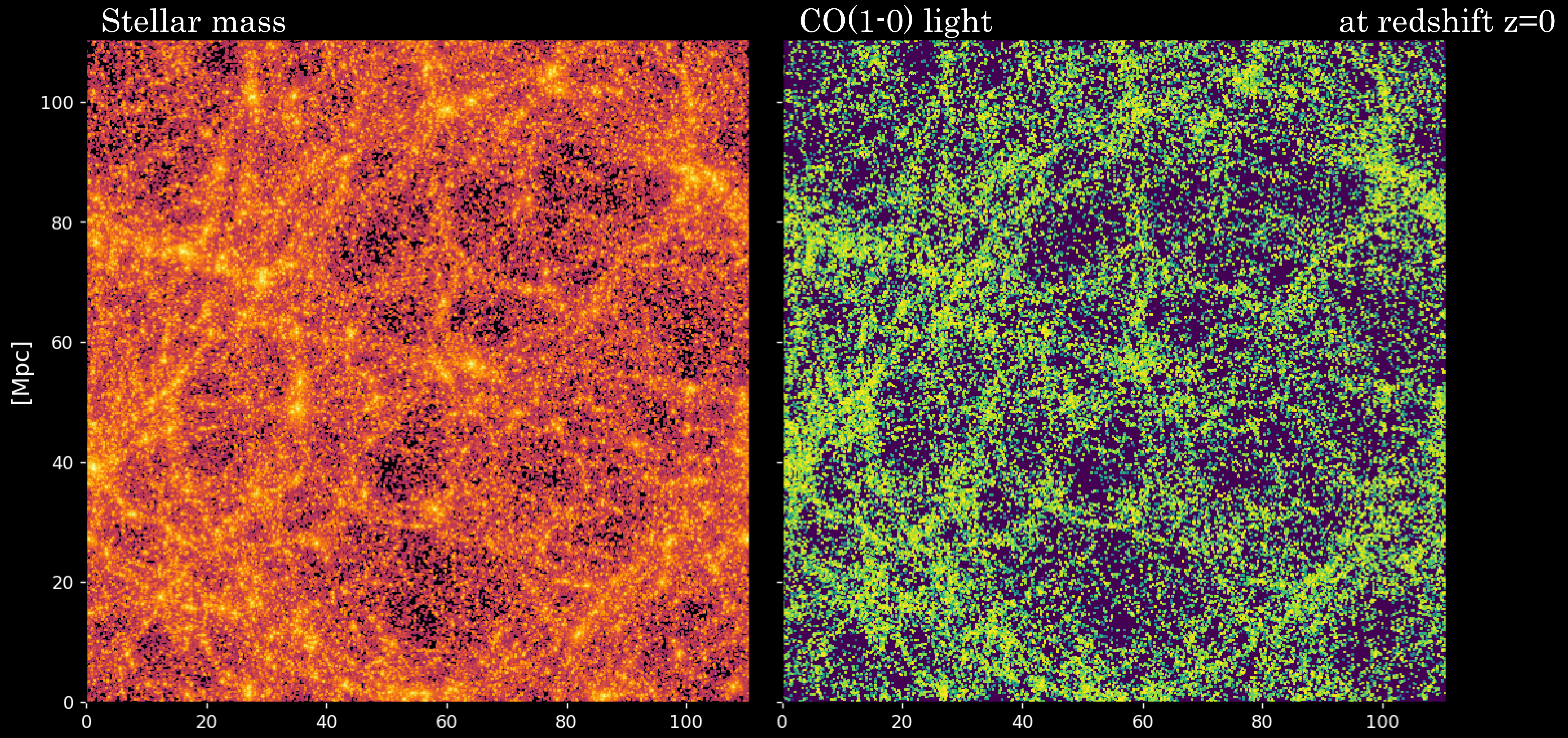
Density contrast: $\phi = 100$
Radiation field: $I_{cloud} \sim 0$



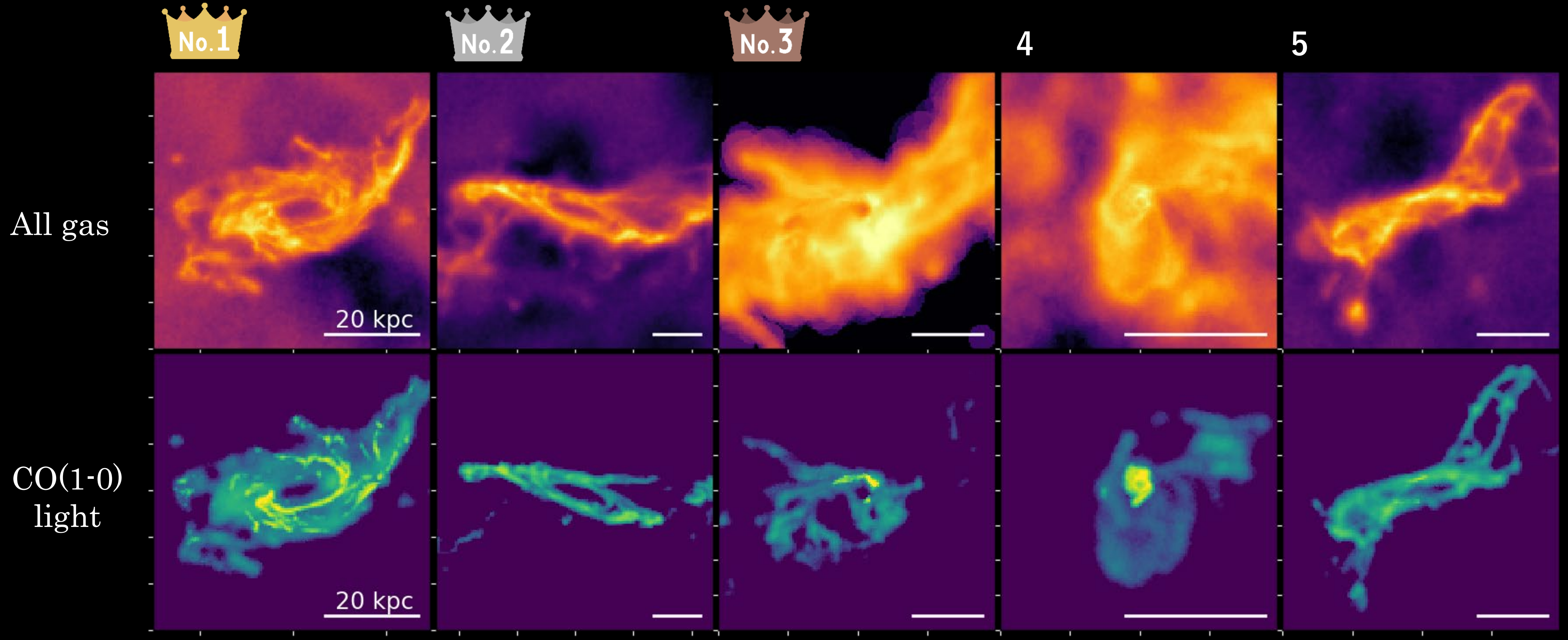
Completeness limit



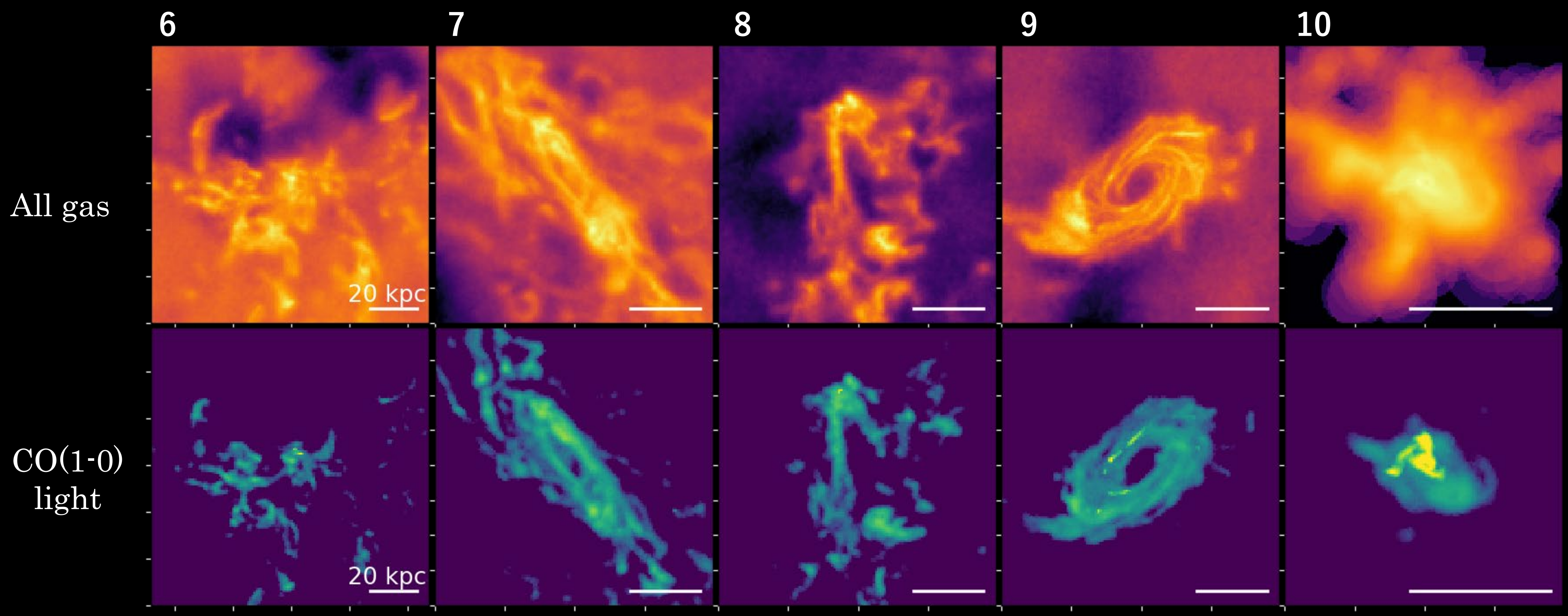
The CO-Universe



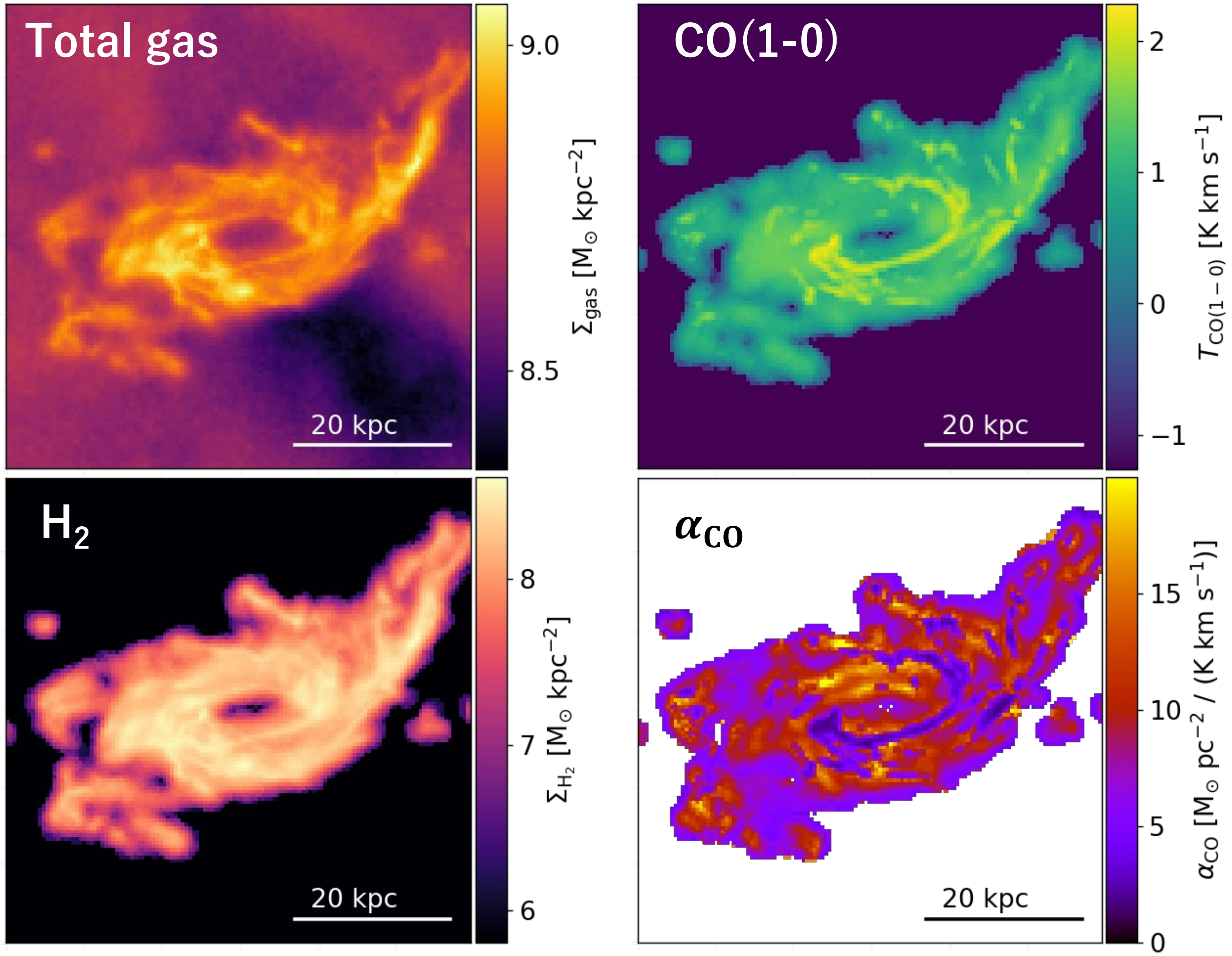
The top 10 CO-brightest galaxies



The top 10 CO-brightest galaxies



Applying to Illustris-TNG (z=0, TNG100-1)



In the Milky Way inner disc

- $\alpha_{CO} = 4.3$ $M_\odot$/(K km/s pc^2)

In local main-sequence galaxies

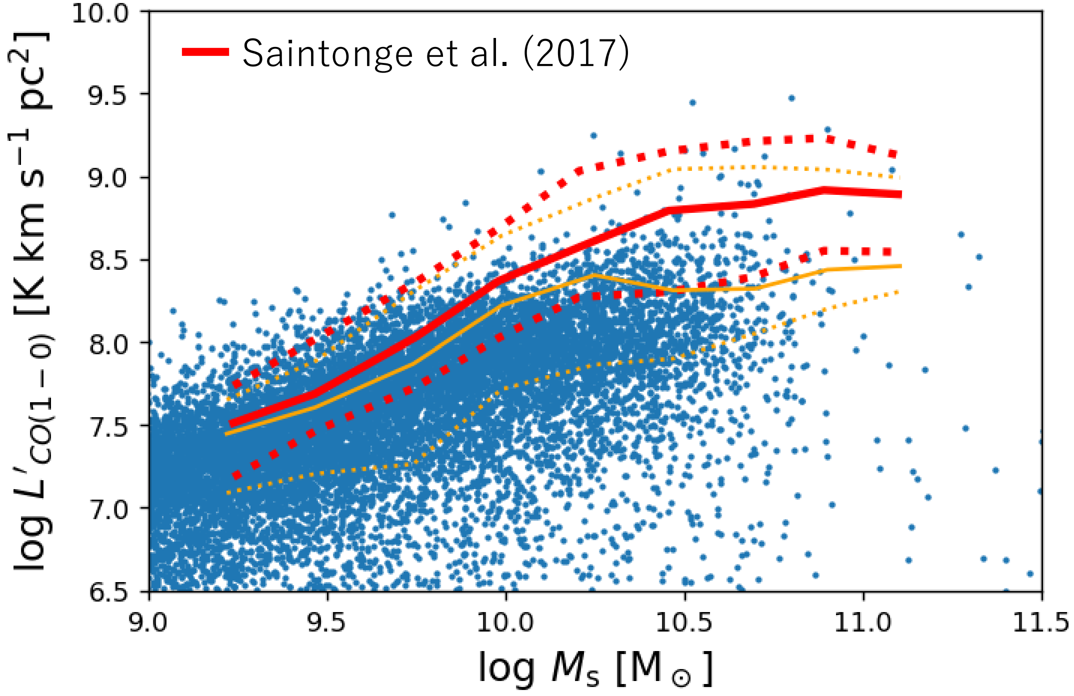
- $\alpha_{CO} = 3.6$ $M_\odot$/(K km/s pc^2)

Dependence on the radiation fields

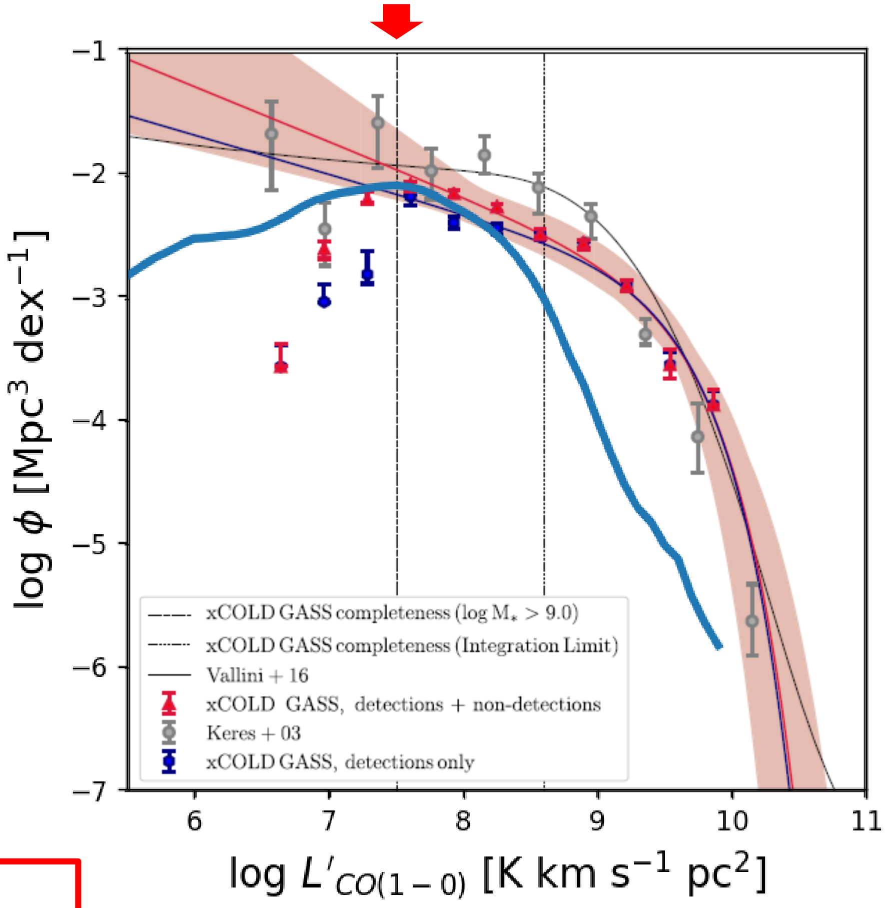
- Is the “well-shielded” approximation correct?

Density contrast: $\phi = 100$

Radiation field: $I_{cloud} = I_{MW} \frac{SFR_{tot}}{SFR_{MW}}$



Completeness limit



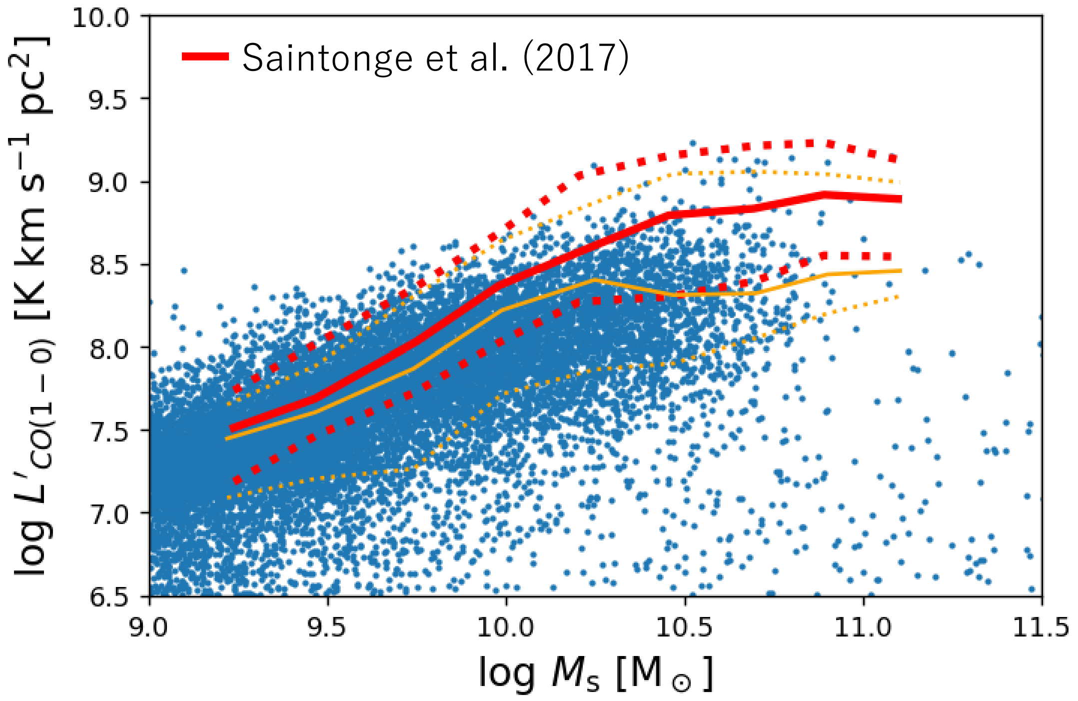
Radiation in massive galaxies needs to be well shielded.

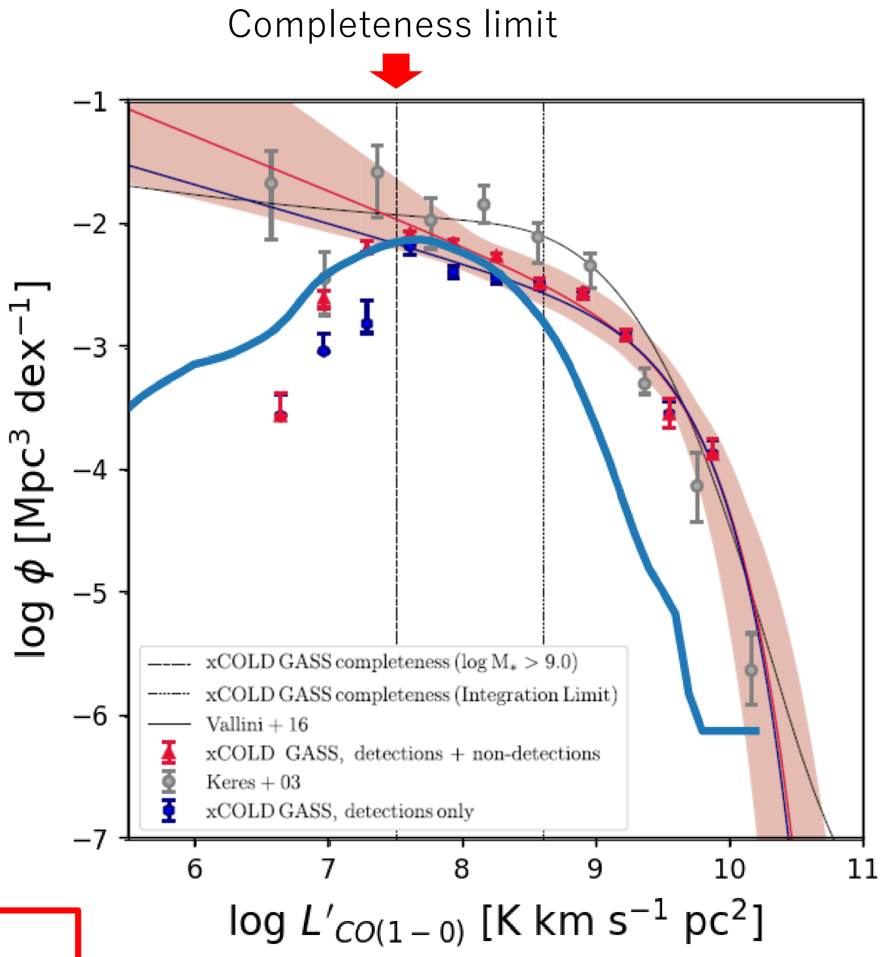
Dependence on the radiation fields

- Is the “well-shielded” approximation correct?

Density contrast: $\phi = 1000$

Radiation field: $I_{cloud} = I_{MW} \frac{SFR_{tot}}{SFR_{MW}}$





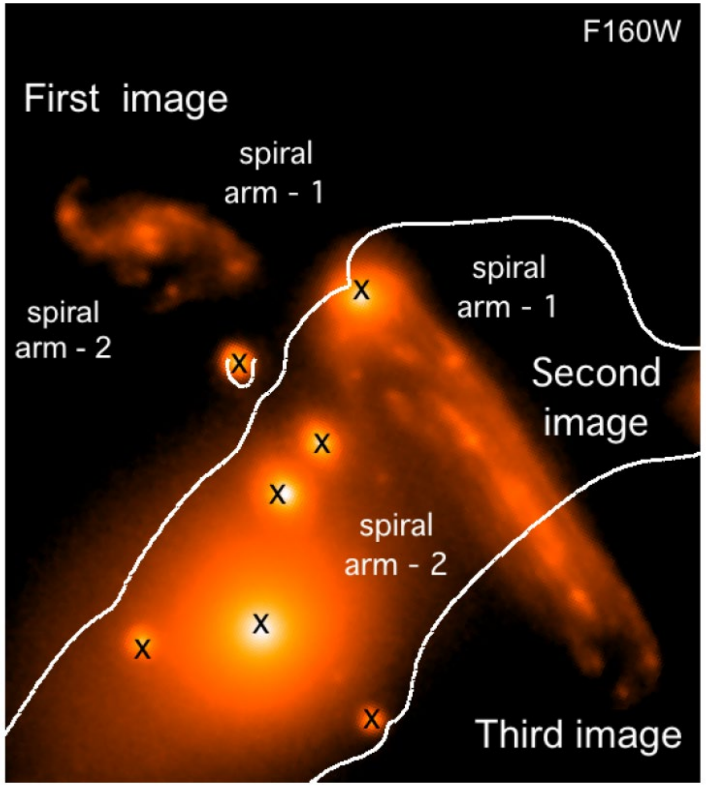
Radiation in massive galaxies needs to be well shielded.

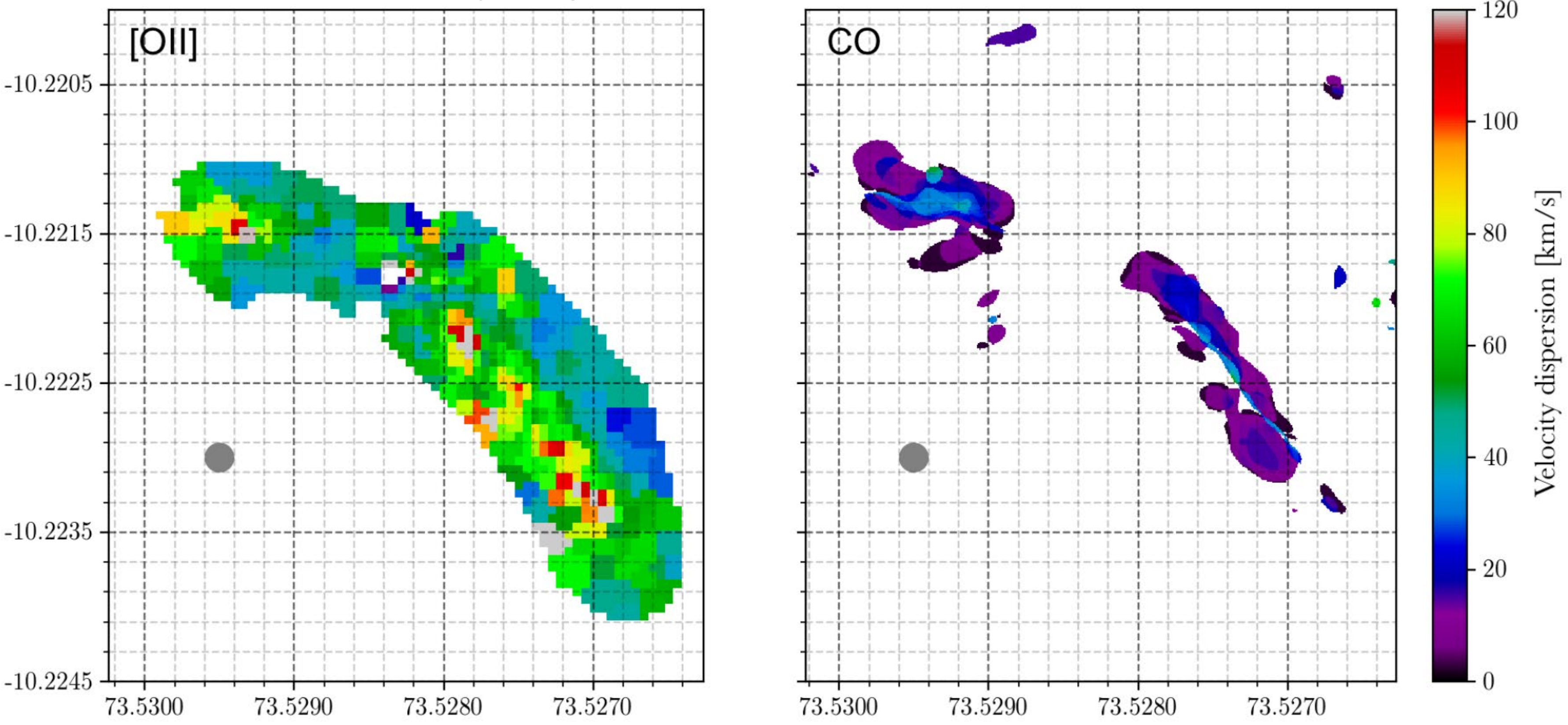
Kinematic analysis

Kinematic analysis

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

Velocity dispersions measured with different lines



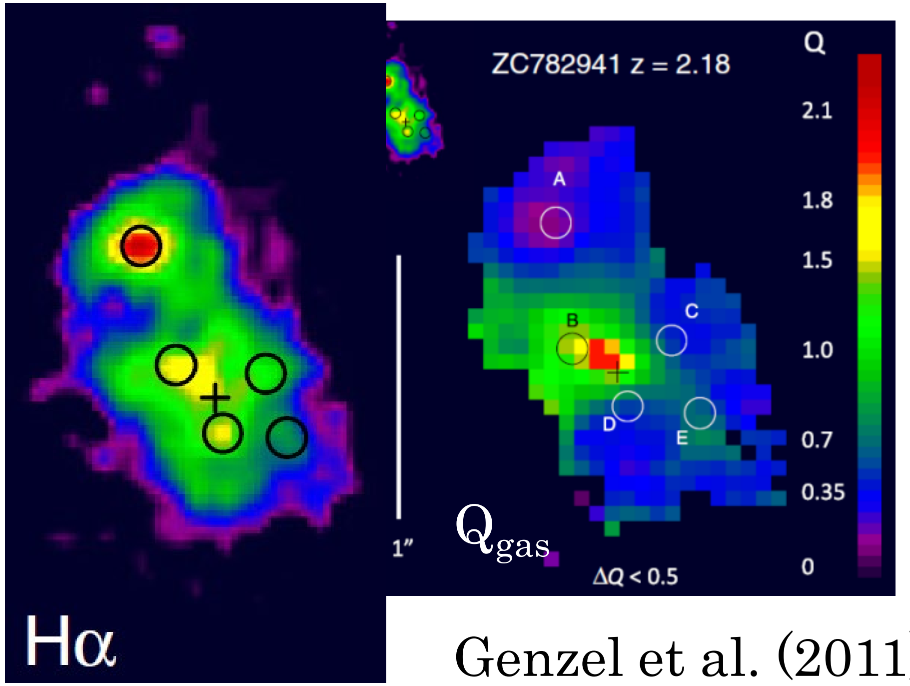


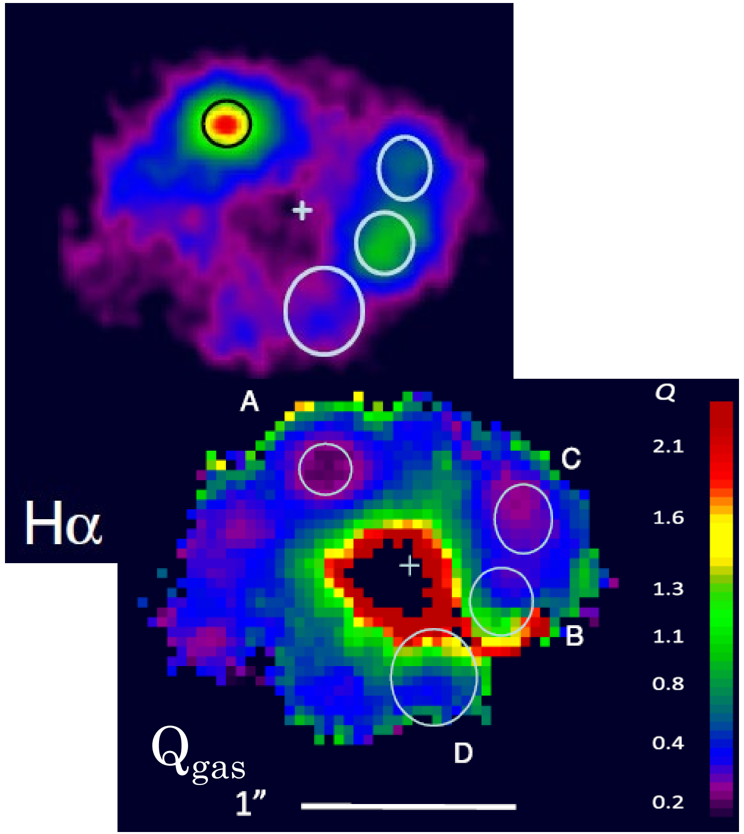
Girard et al. (2019)
A521: strong-lensed galaxy @ z=1

Can dynamically unstable galaxies really exist?

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

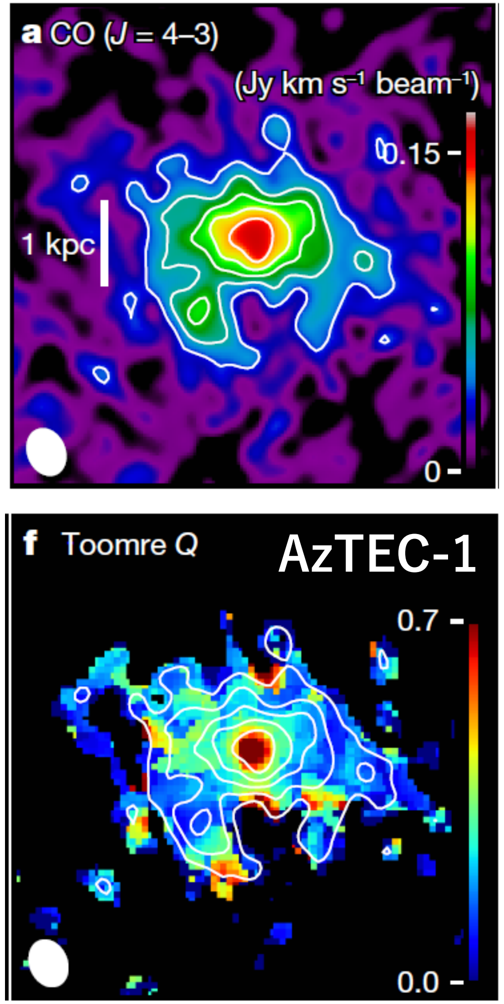
- Discs with $Q < 1$ are considered to be **dynamically unstable**.
  - Due to their self-gravity





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!!

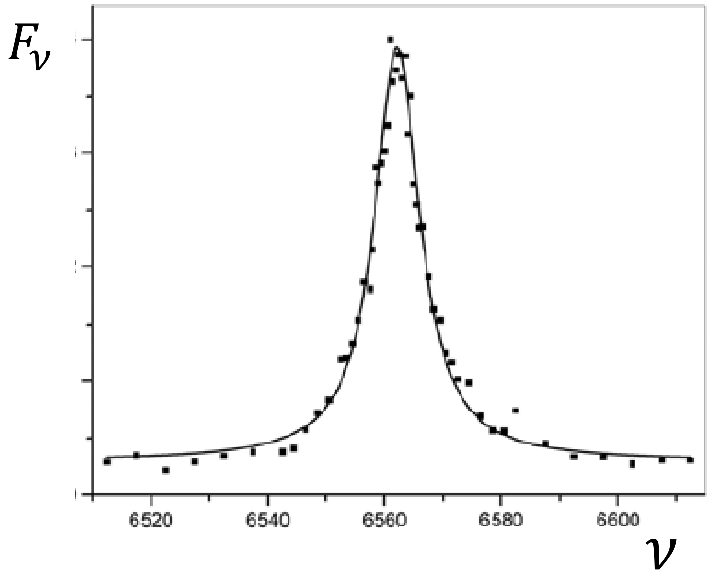
How do you measure velocity dispersions?

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

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

  - **In observation: flux-weighted**

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



    - F_ν: flux density of line emission

e.g. in the case of H α line,

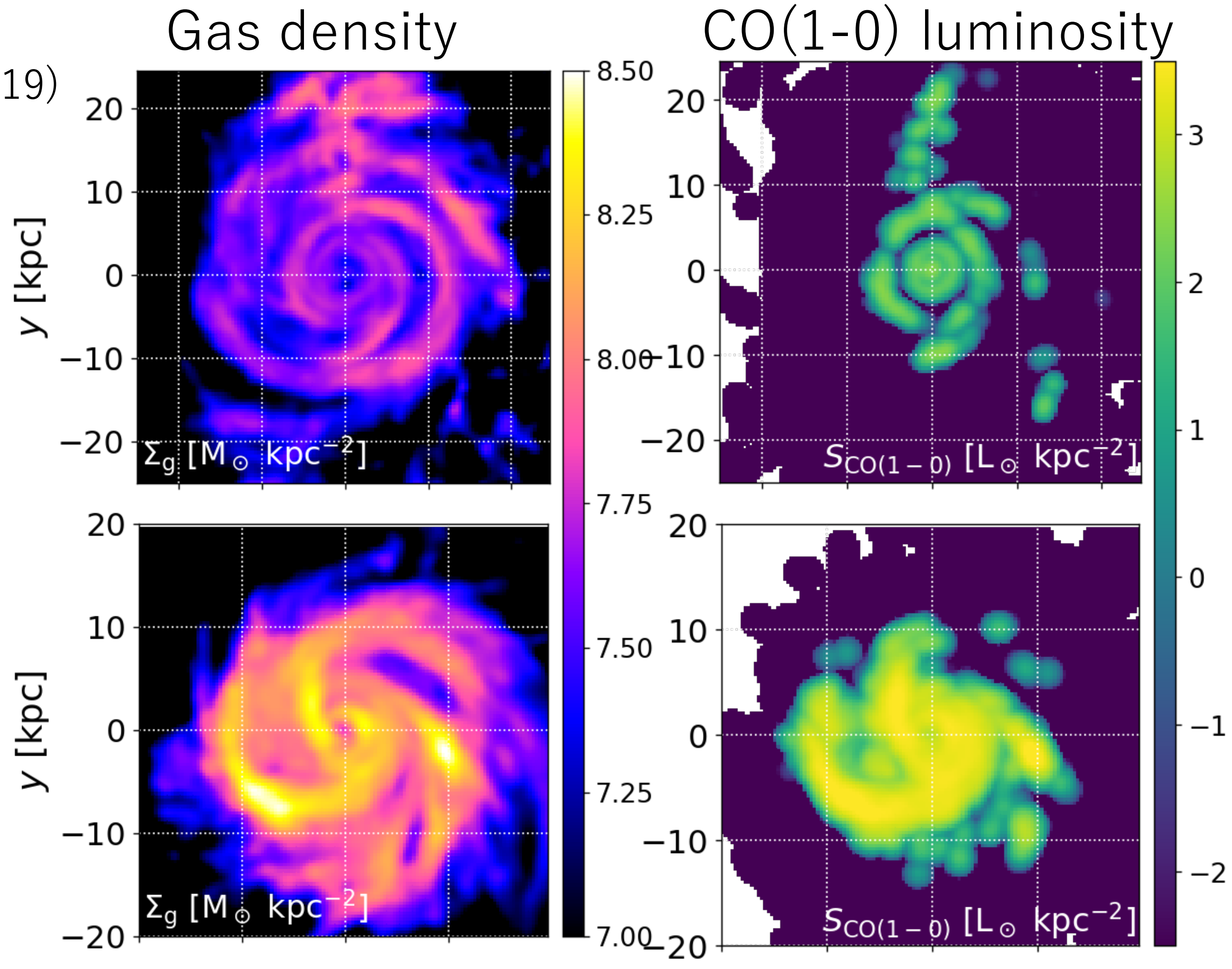
$$L_{H\alpha} \propto SFR \propto \frac{m_{H_2}}{\tau_{SF}} \propto m_{H_2}\sqrt{\rho_{H_2}}, \quad \text{where} \quad \tau_{\rm SF} \sim \frac{1}{\sqrt{G\rho_{\rm H_2}}}.$$

Mock CO(1-0) observations for dynamical analysis

- Simulations from Inoue & Yoshida (2019)

z=1.5
Ms=1.7×10¹¹ M$_\odot$

z=1.0
Ms=1.8×10¹¹ M$_\odot$

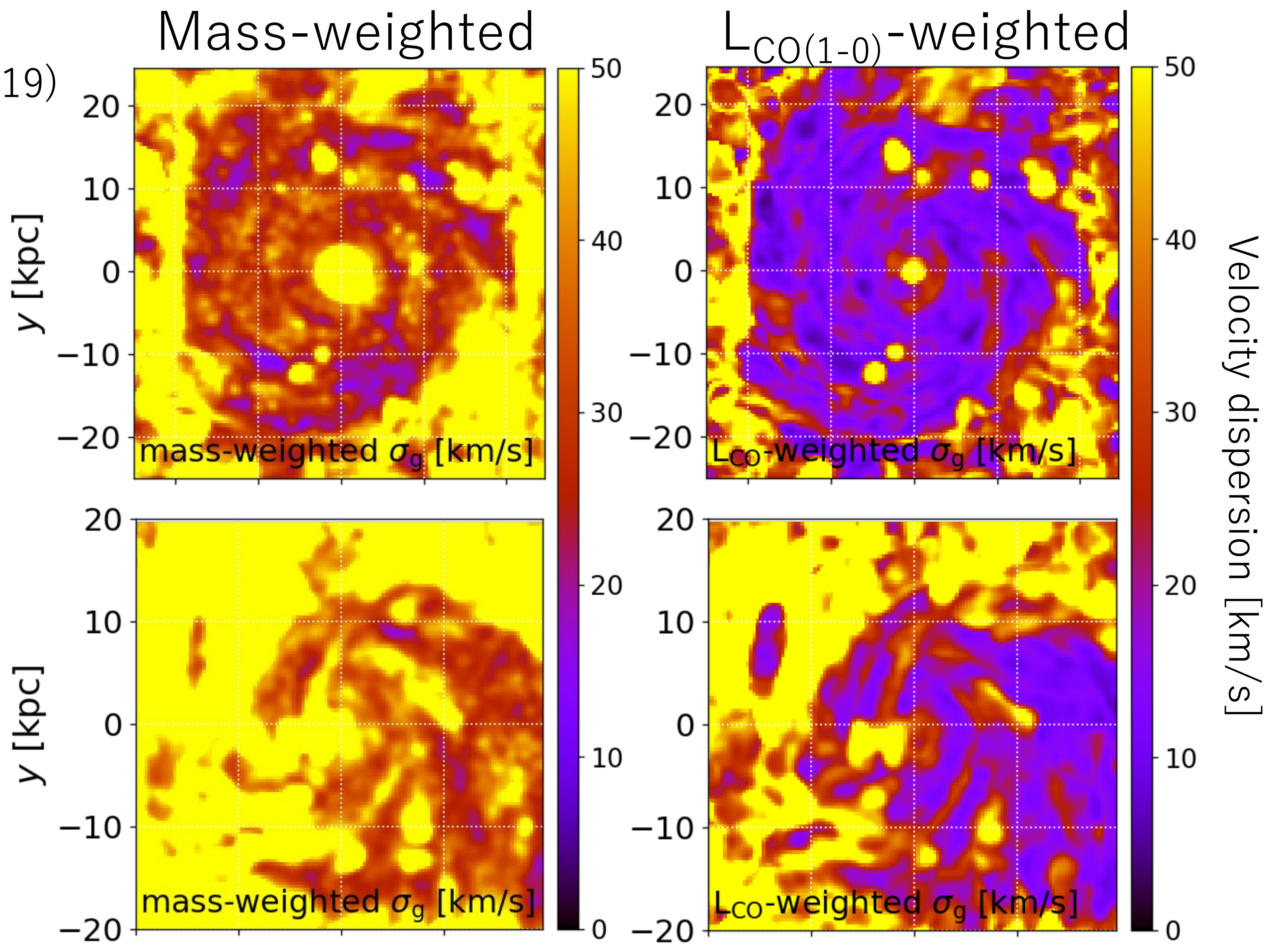


Mock CO(1-0) observations for dynamical analysis

- Simulations from Inoue & Yoshida (2019)

z=1.5
Ms=1.7×10^11 M⊙

z=1.0
Ms=1.8×10^11 M⊙

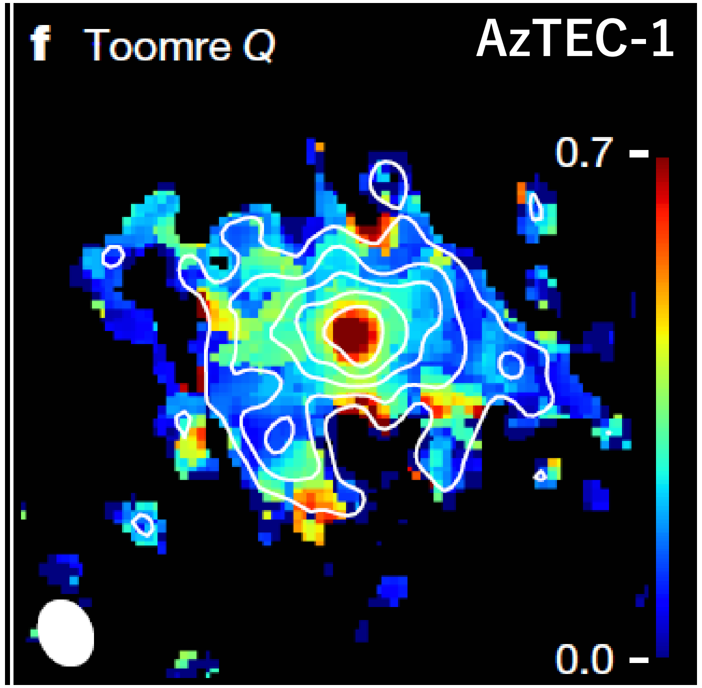


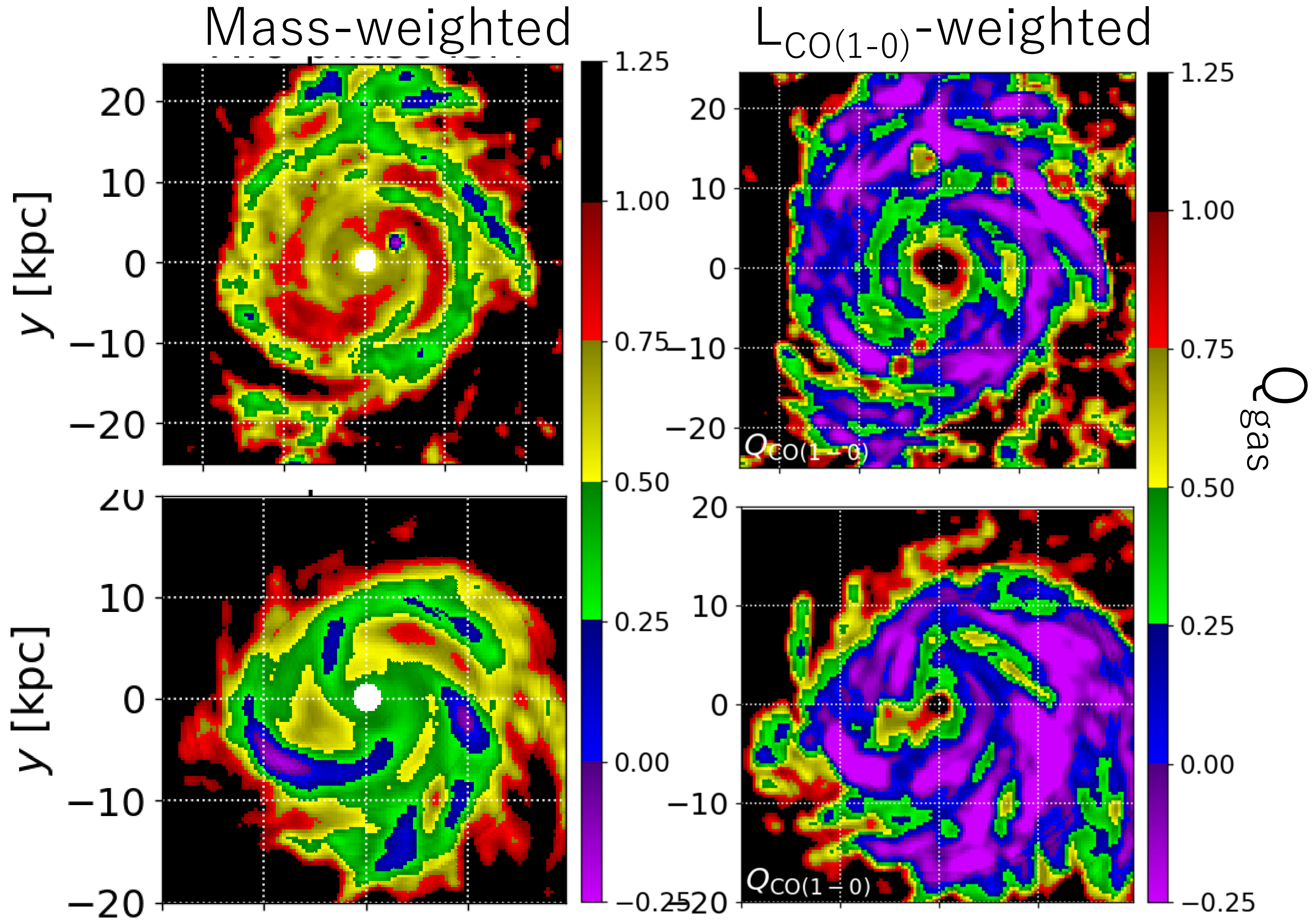
Mock CO(1-0) observations for dynamical analysis

- Replacing only σ in Q.

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

Tadaki et al. (2018)





Summary

- I am developing a new model for molecular line emissions.
  - Designed to be independent from resolutions of simulations.
  - In good agreement with the observations at $z=0$.
    - Needs to assume all gas clouds to be well shielded.

- Kinematic analysis based on line spectra can be biased
  - depending on which line you are looking at.
  - Observed VD can be biased because it is flux-weighted.
  - The low values of $Q<1$ in high-z discs may be attributed to this bias.