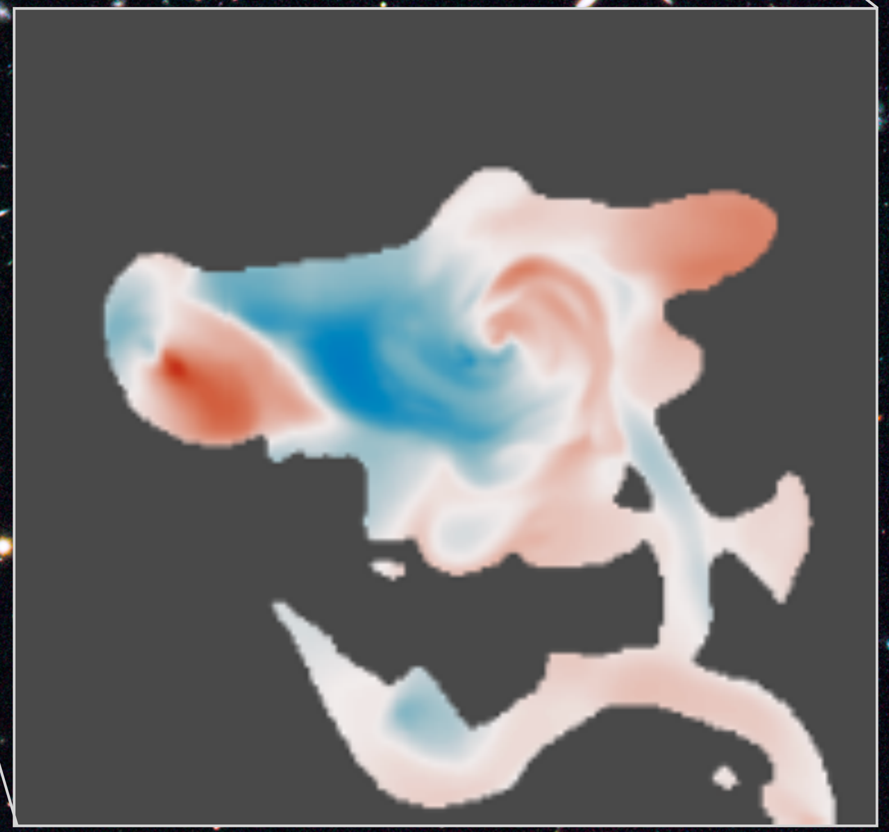
Dynamically Cold Disks in the early Universe: Myth or Reality?

Mahsa Kohandel, *Scuola Normale Superiore, Pisa, Italy*

With: Andrea Pallottini, Andrea Ferrara, Anita Zanella, Francesca Rizzo and Stefano Carniani

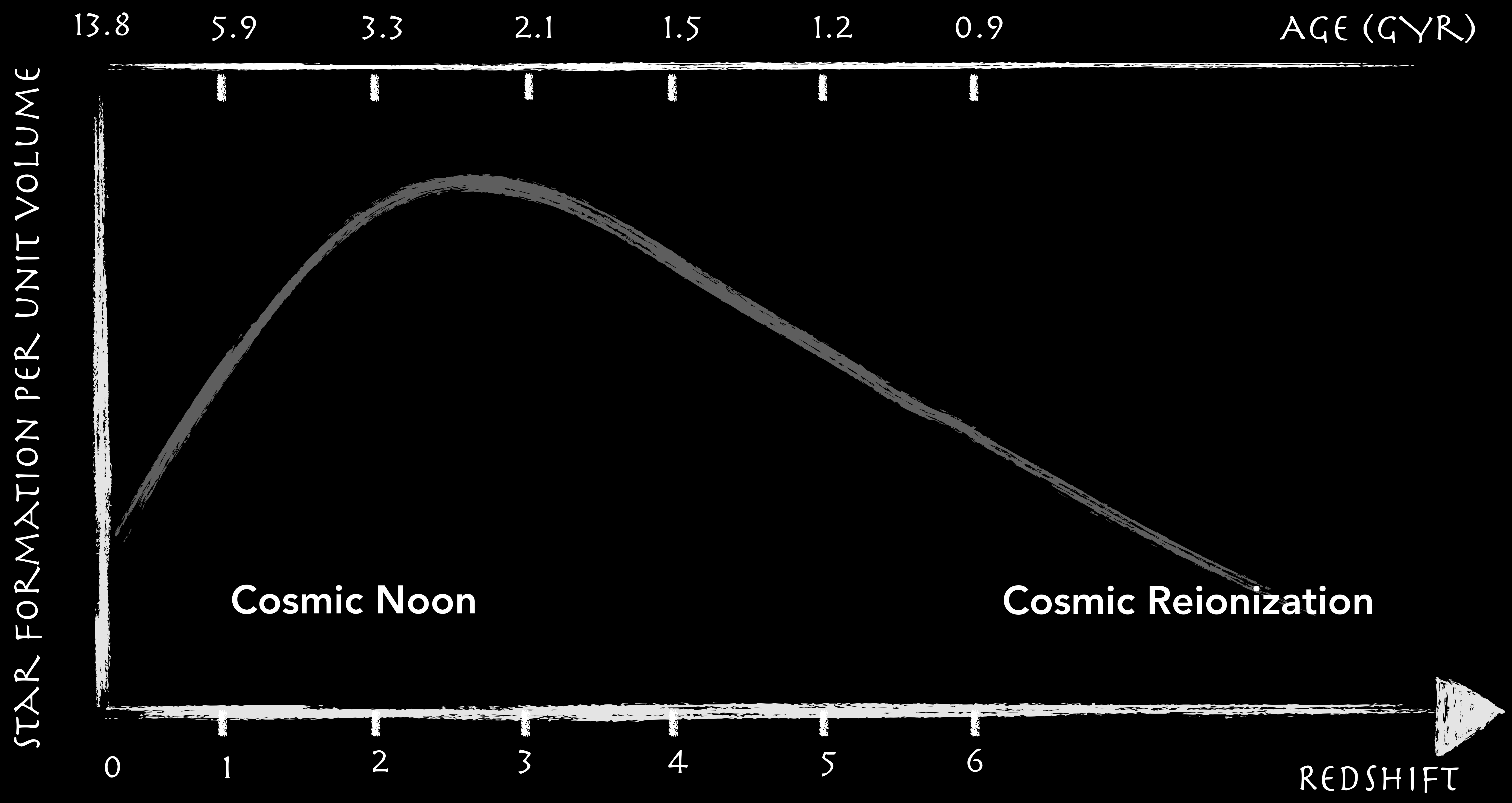


SCUOLA NORMALE SUPERIORE

erc

INTERSTELLAR

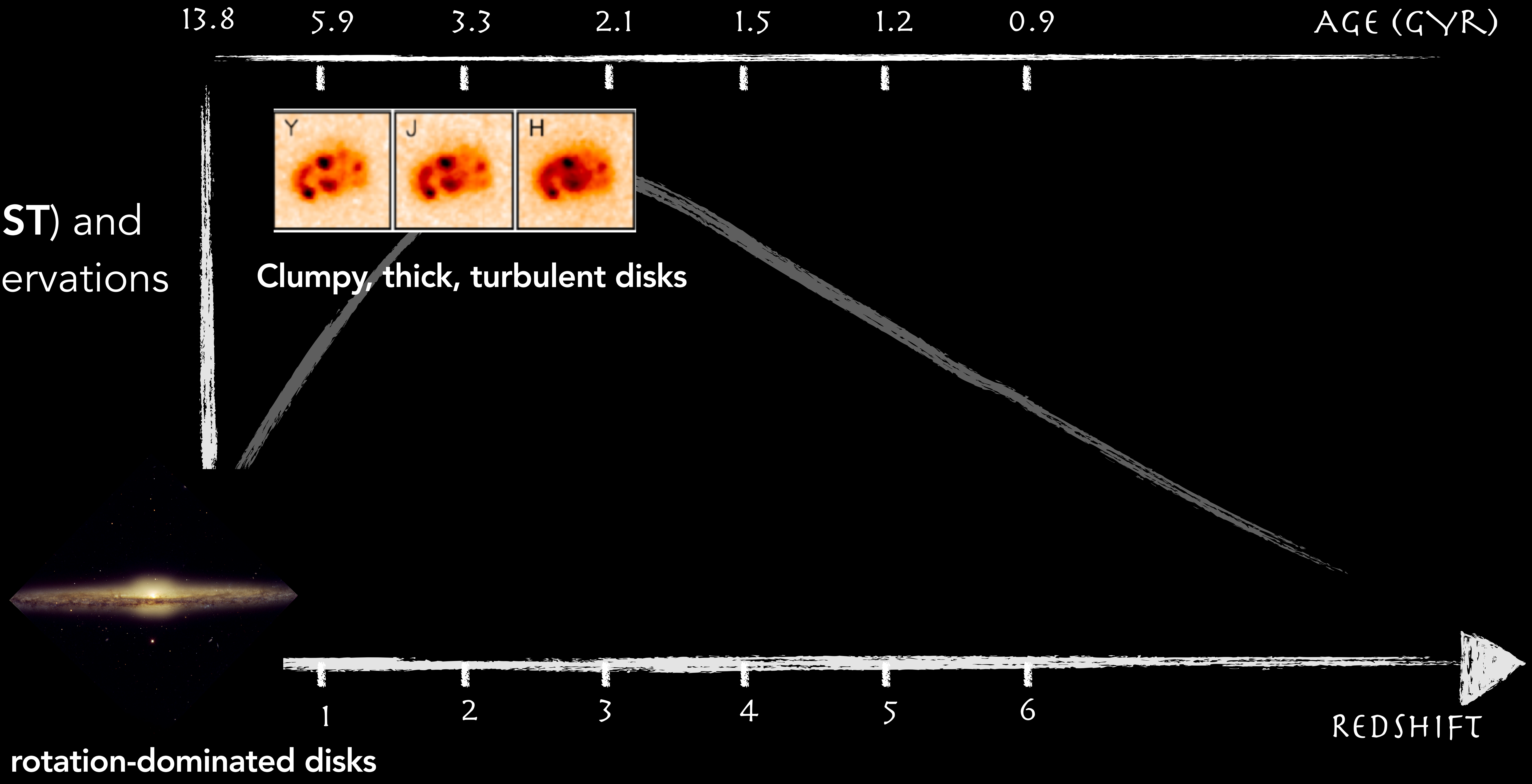
Star formation across Cosmic Time



Madau & Dickinson 2014

SF galaxies across Cosmic Time

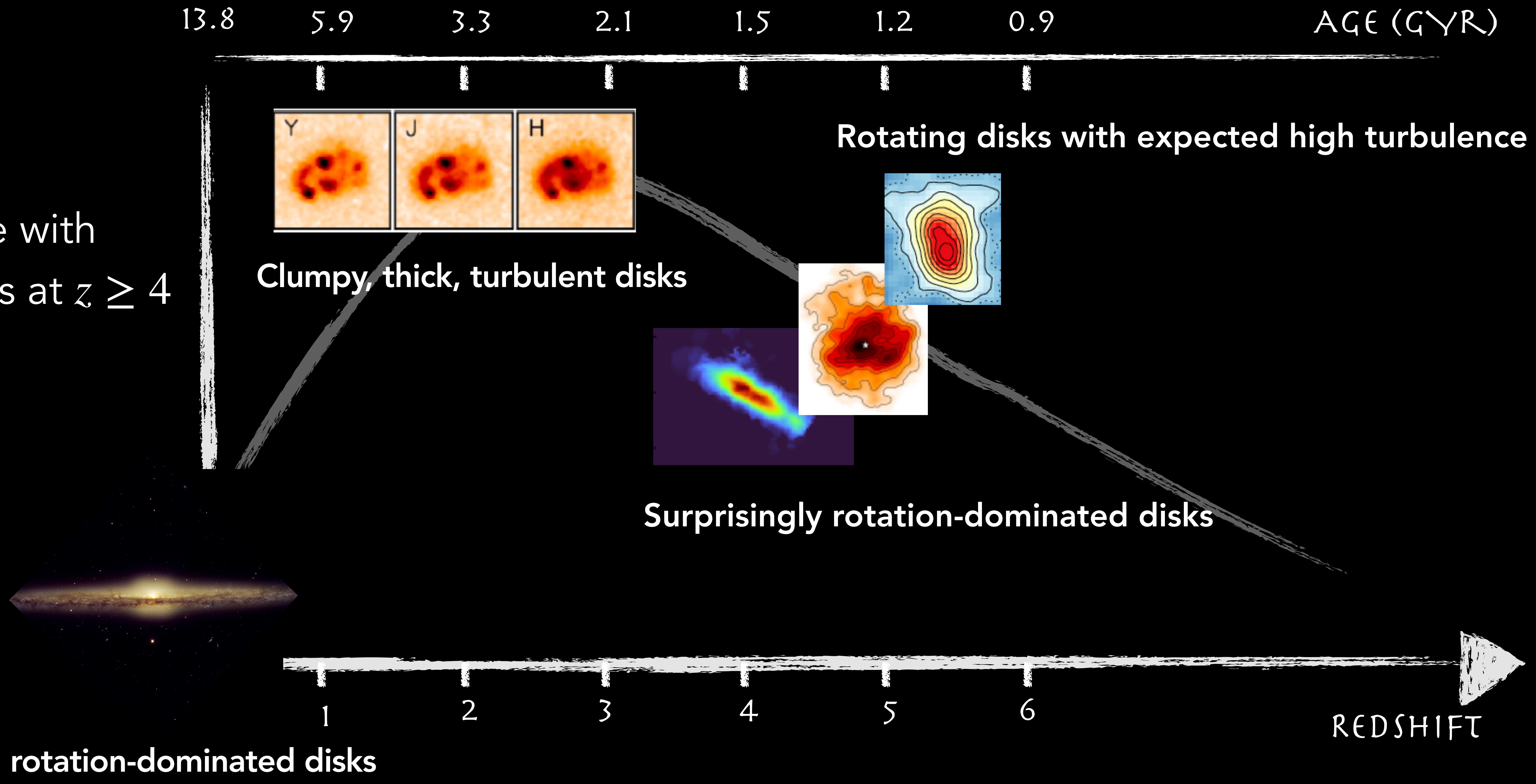
From morphological (e.g., **HST**) and Kinematics (from **IFU/Hα**) observations



e.g., Förster-Schreiber et al. 2006, 2018, Tacconi et al. 2020, Wuyts et al. 2020, Wisnioski et al. 2015, Swinbank et al. 2017, Harrison et al. 2017

SF galaxies across Cosmic Time

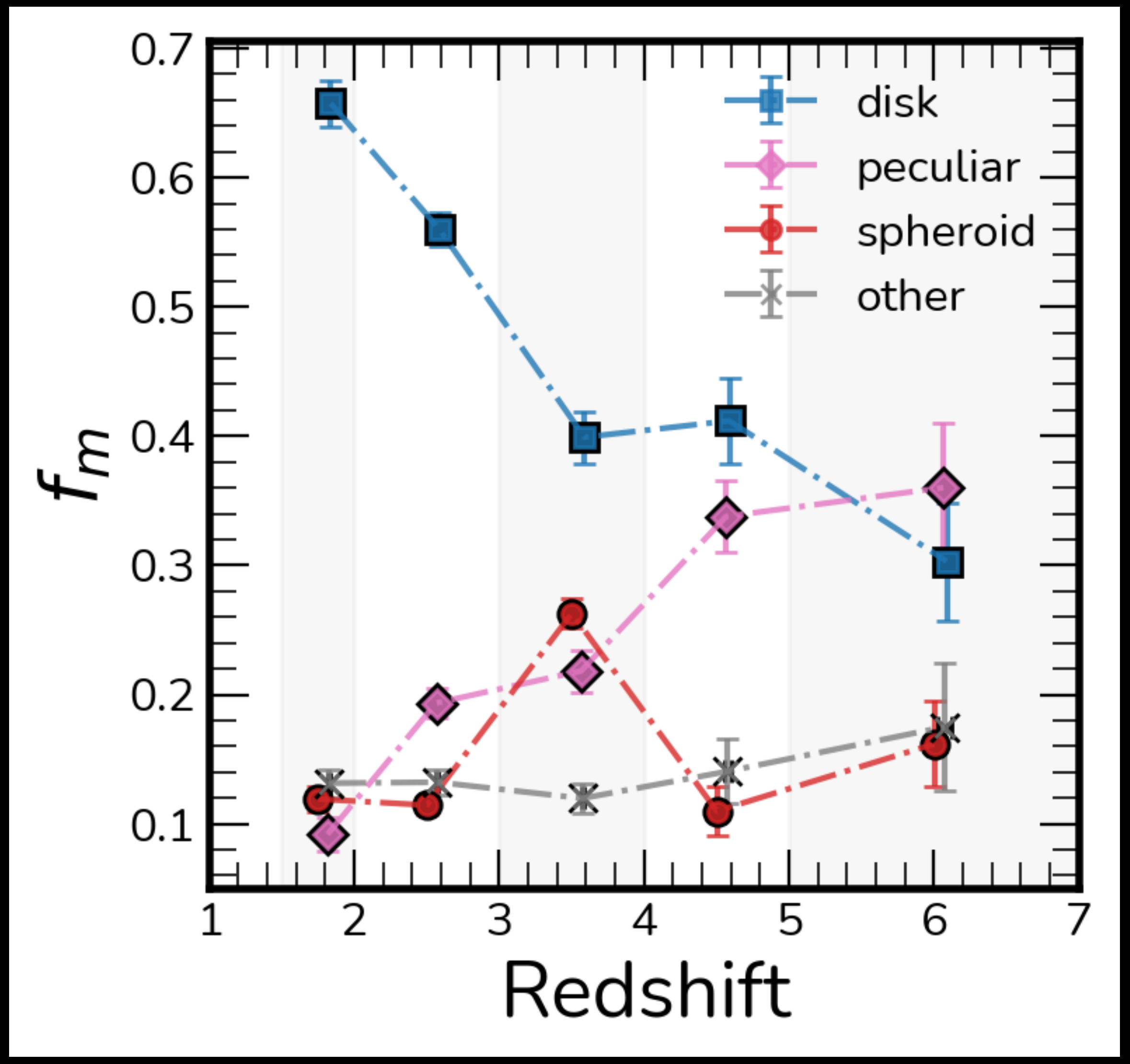
ALMA complicated the picture with contradictory kinematics results at $z \geq 4$



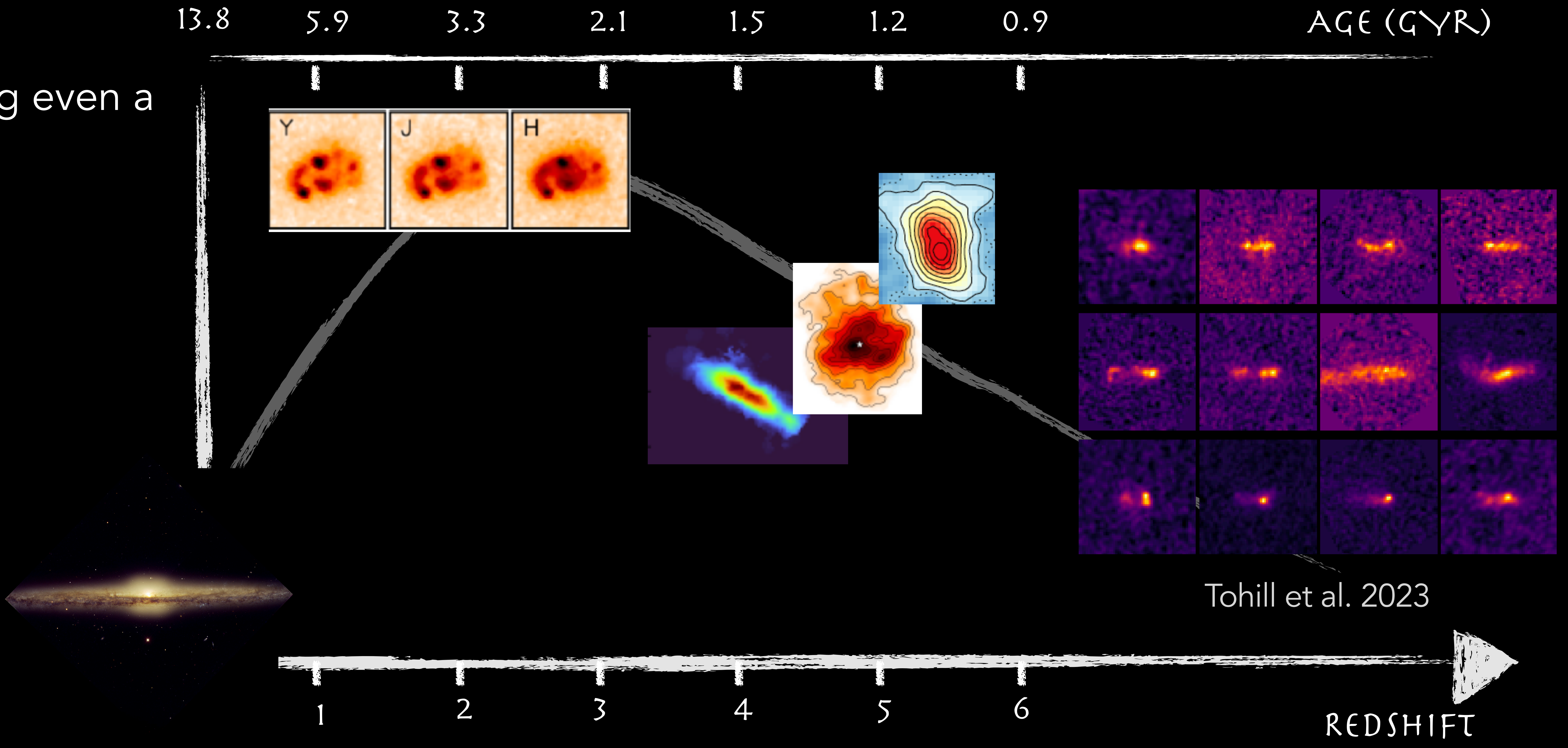
e.g., Tsukui et al. 2021, Jones et al. 2021, Rizzo et al. 2021, Herrera-Camus et al. 2022, Lelli et al. 2021, Fraternali et al. 2021, Roman-Oliveira et al. 2023, Pope et al. 2023, Parlanti et al. 2023

More disks in the Early Universe

JWST is not helping by revealing even a higher fraction of disks**.**



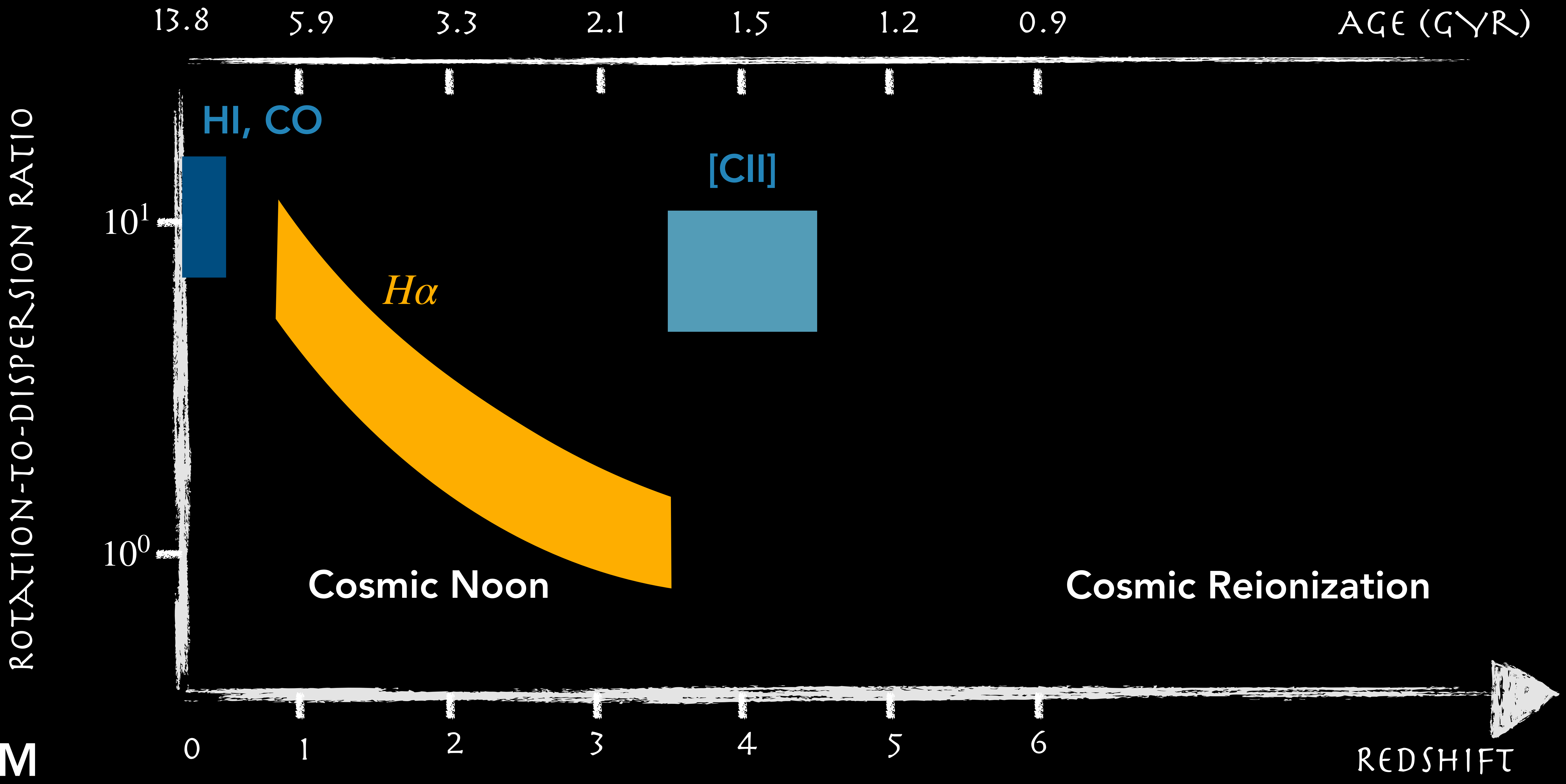
Ferreira et al. 2023



Tohill et al. 2023

See also Fudamoto et al. 2022; Jacobs et al. 2022; Wu et al 2022; Huertas-Company et al. 2023, Robertson et al. 2023

Galaxy kinematics through various emission lines



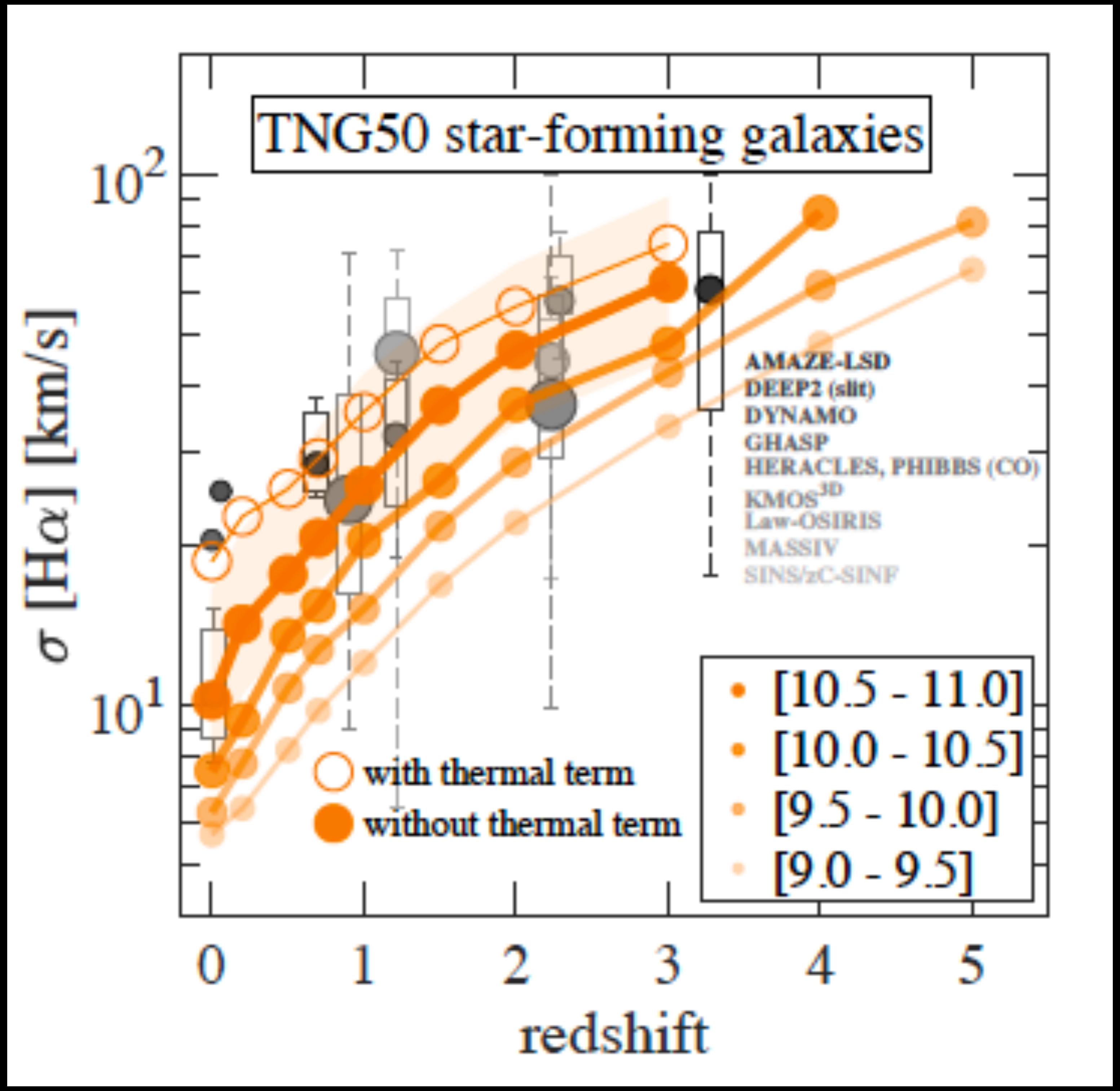
Tracing various phases of the ISM

Hα: 10^4 K

[CII]: ~10^2 K

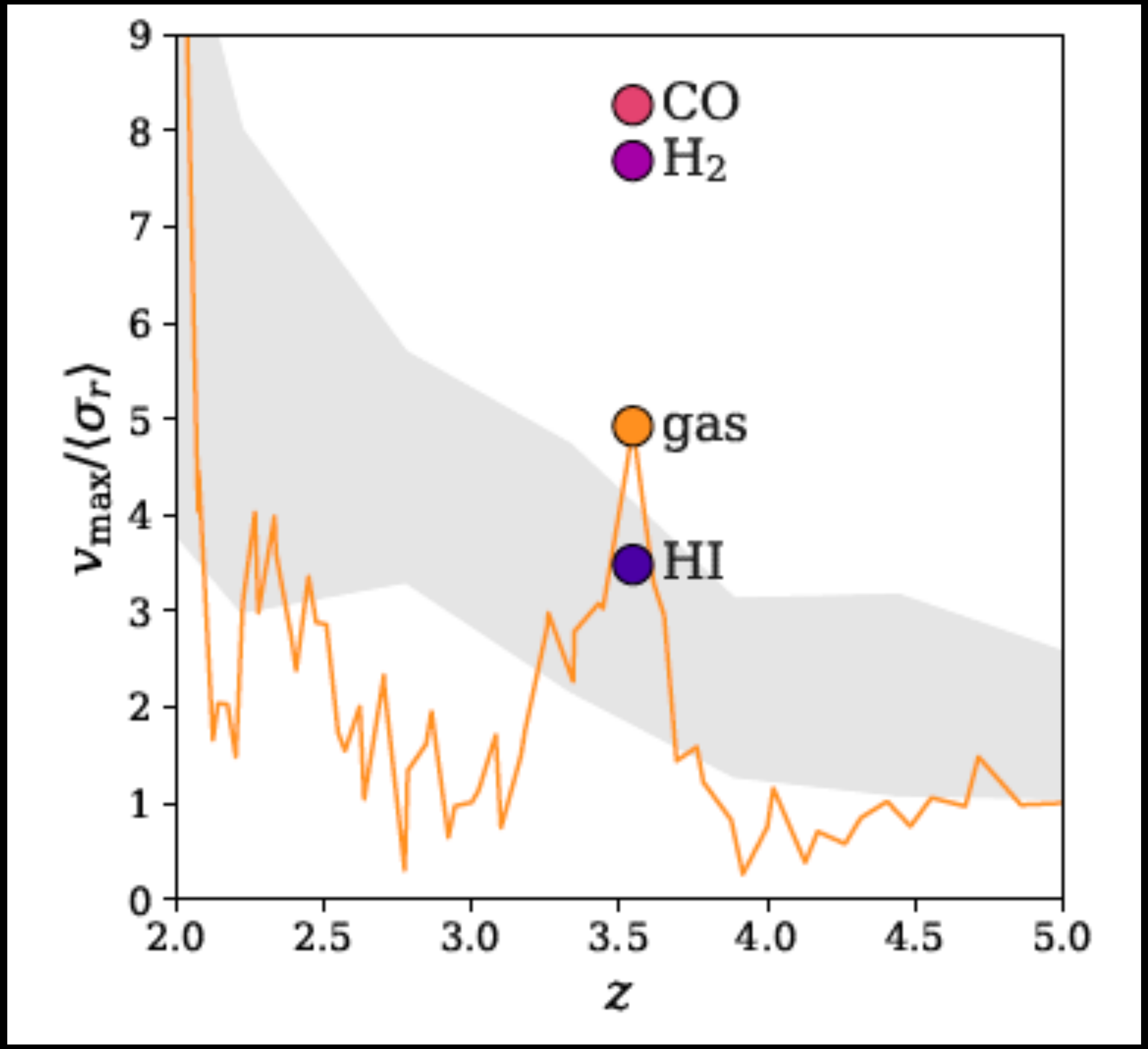
CO < 10^2 K

Standard theoretical scenario



Pillepich et al. 2019

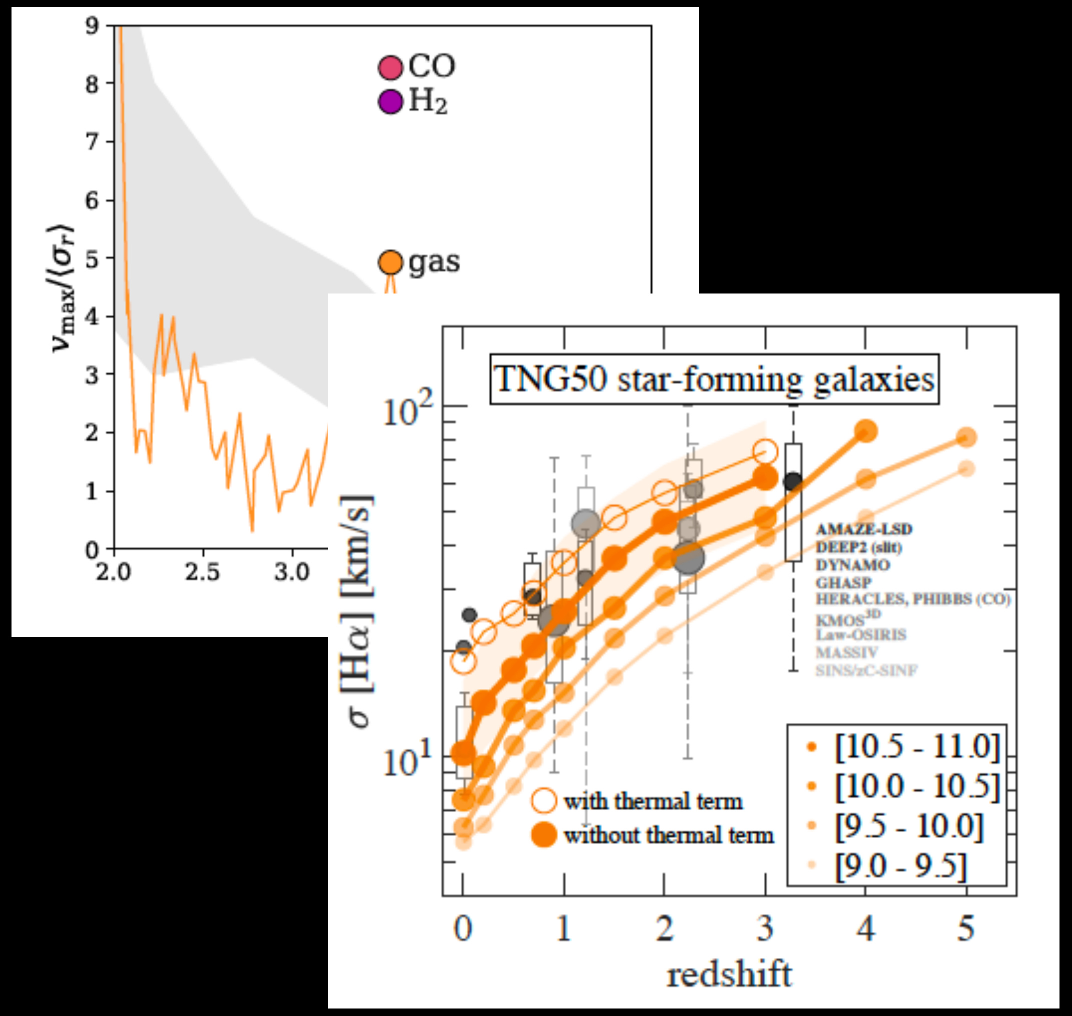
$z \geq 4$ galaxies are predicted to be Irregular, clumpy and turbulent and rotation-dominated disk structures are transient.

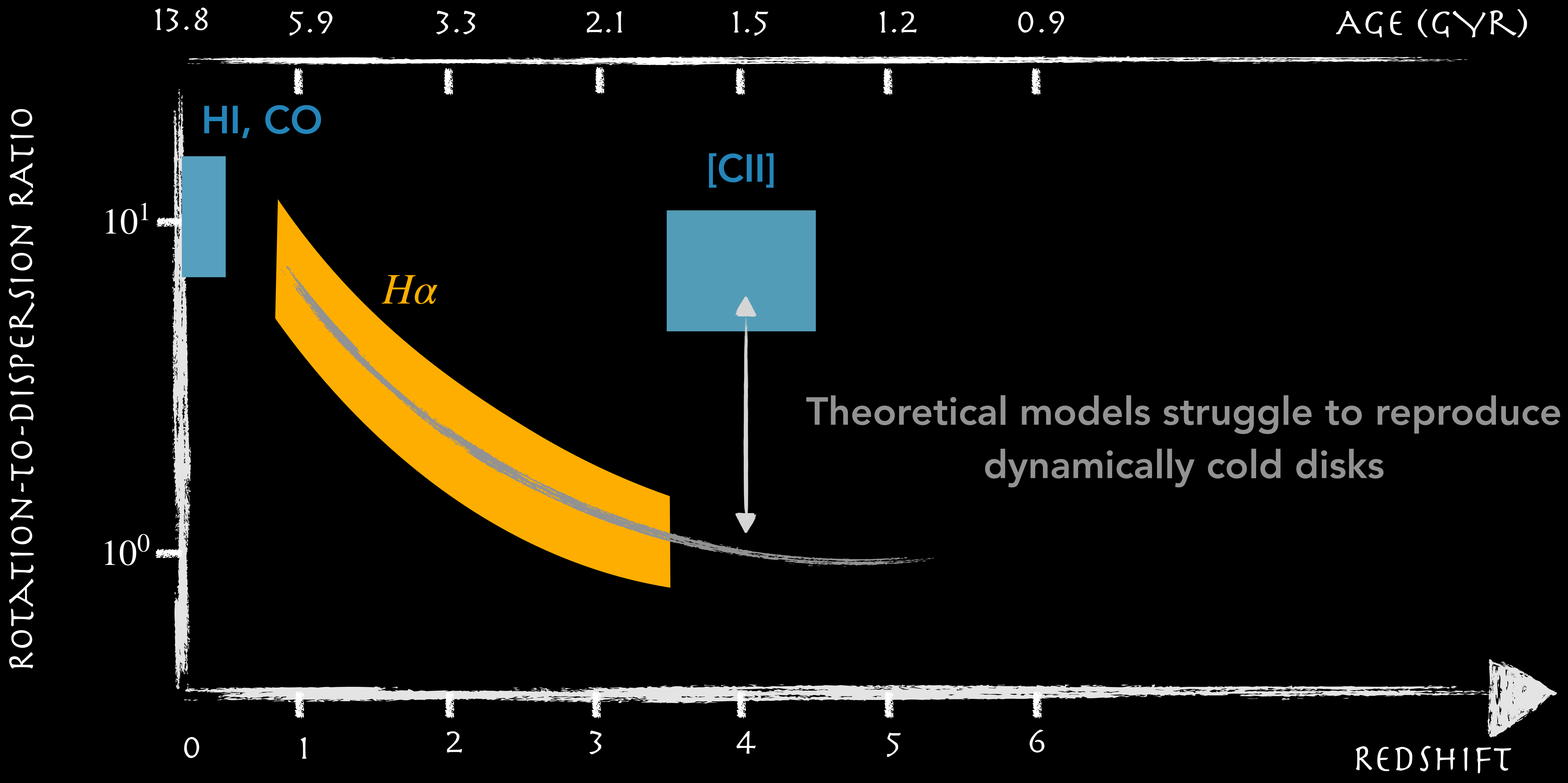


Kretschmer et al. 2021

But also: Dekel et al. 2014; Zolotov et al. 2015; Bird et al. 2013, 2021; Dekel et al. 2021; Yu et al. 2021

Tension between theory and observations





Q1) Do zoom-in cosmological simulations with a more complex chemistry and emission line modelling reproduce dynamically cold disks?

Q2) Can we reconcile the tension between theory and observations by employing different kinematic tracers?

SERRA: A suite of zoom-in early galaxies

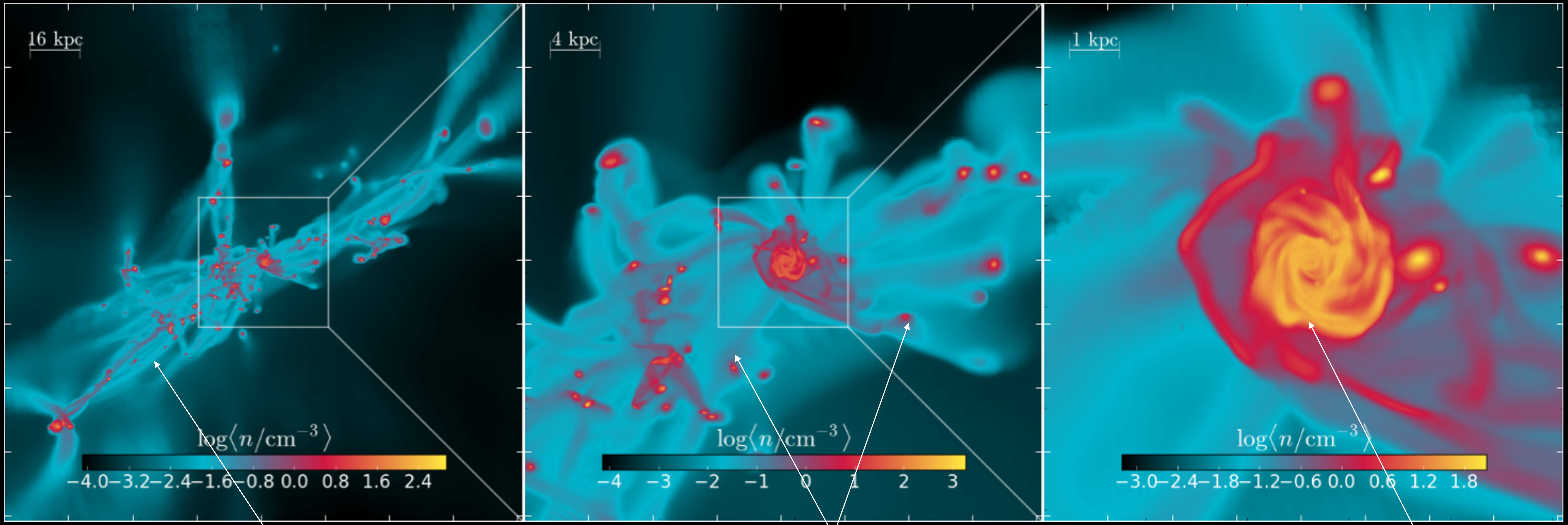
SERRA properties summary:

- Redshift range: $15 < z < 4$
- Stellar masses: $10^6 - 5 \times 10^{10}\, M_\odot$
- IR Luminosities: $10^7 - 5 \times 10^{11}\, L_\odot$
- UV mag: $-21 < M_{UV} < -15$
- [CII] luminosities: $10^6 - 10^{10}\, L_\odot$

From cosmological to molecular cloud scales

- Non-equilibrium chemical networks to form molecular hydrogen and turn it into stars
- Radiation field tracked on the fly to account for ionization and photodissociation effects

Pallottini+17a,b,+19

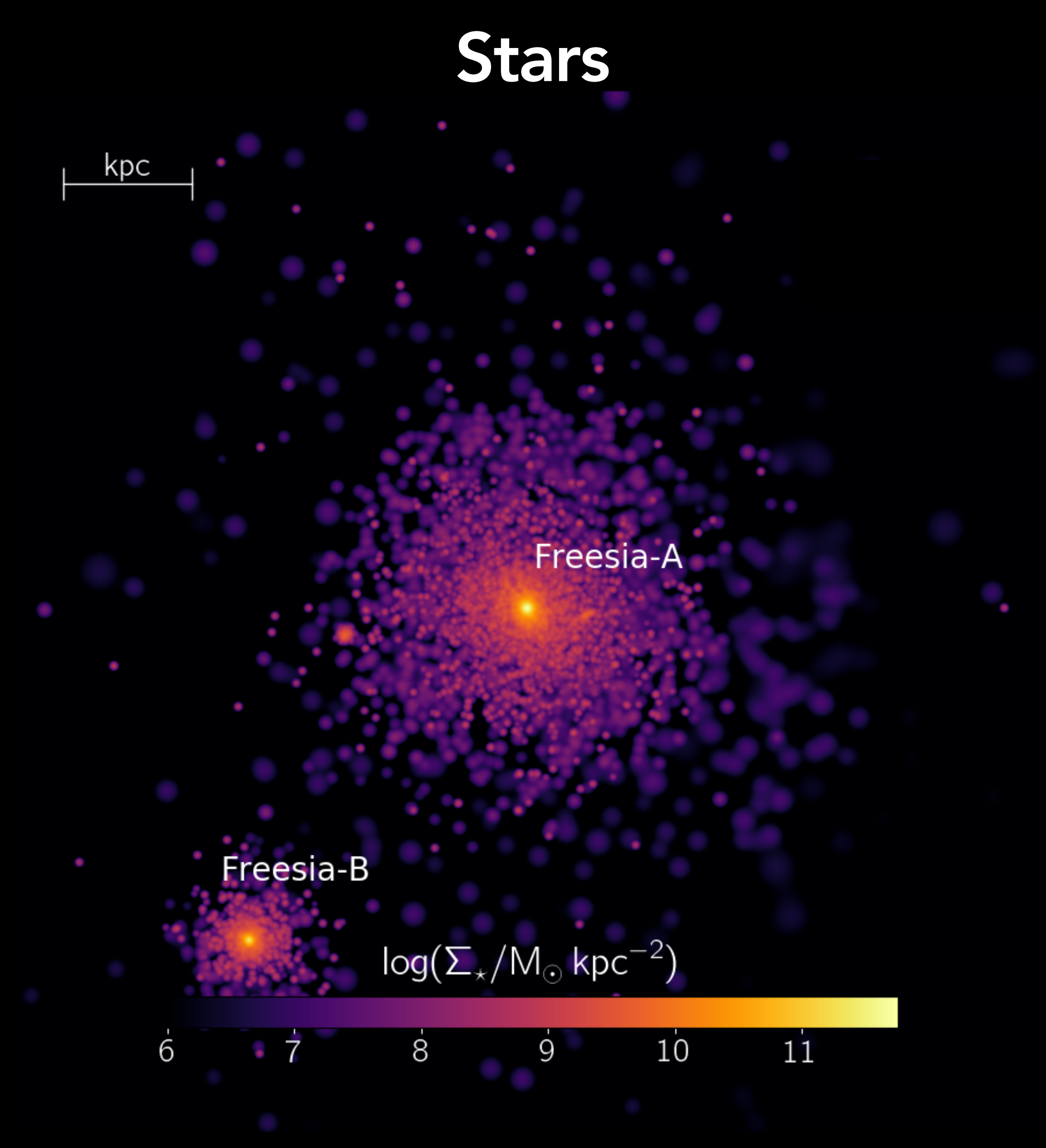


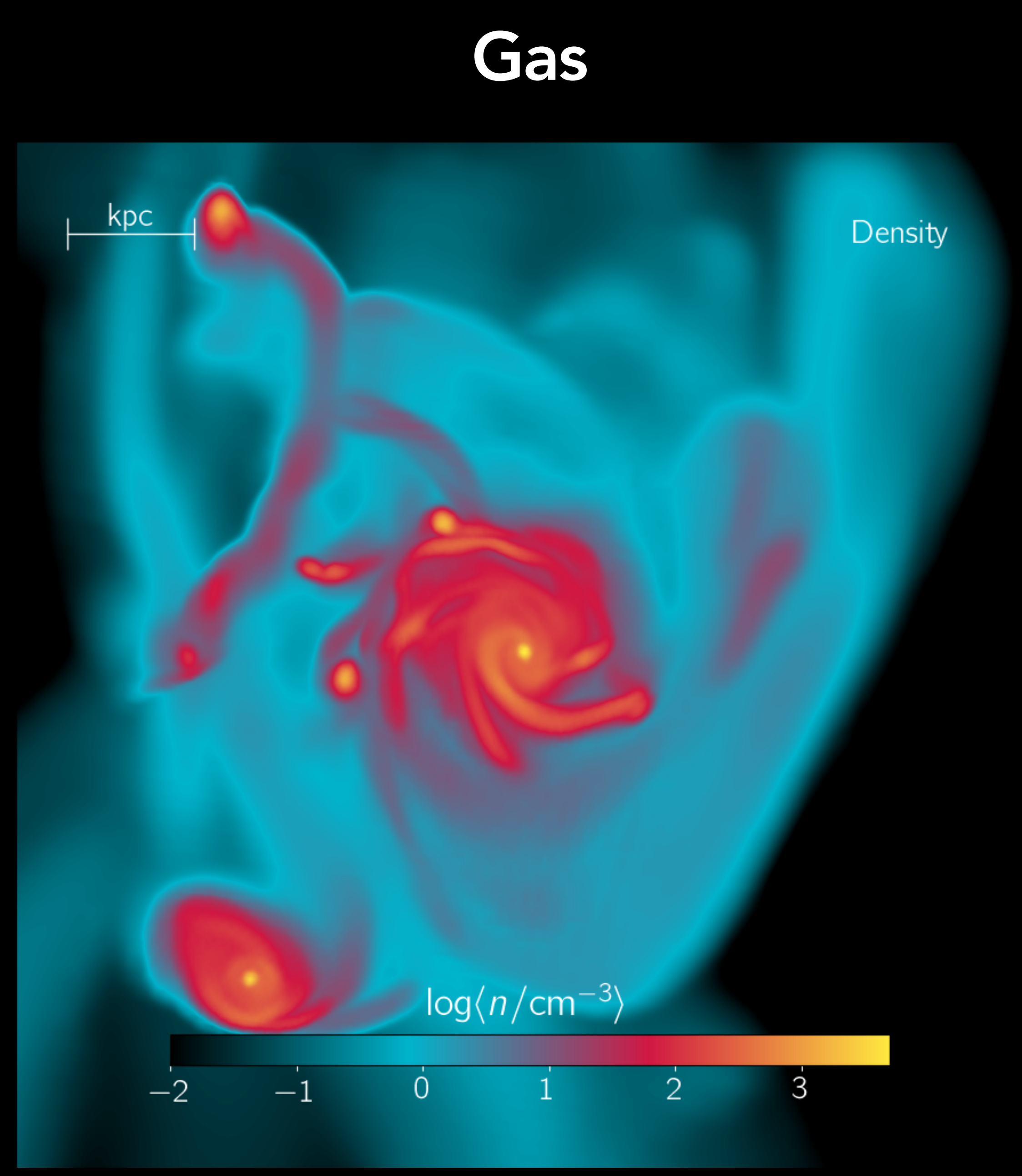
Accreting filaments | Merging clumps/satellites | Molecular/stellar disk

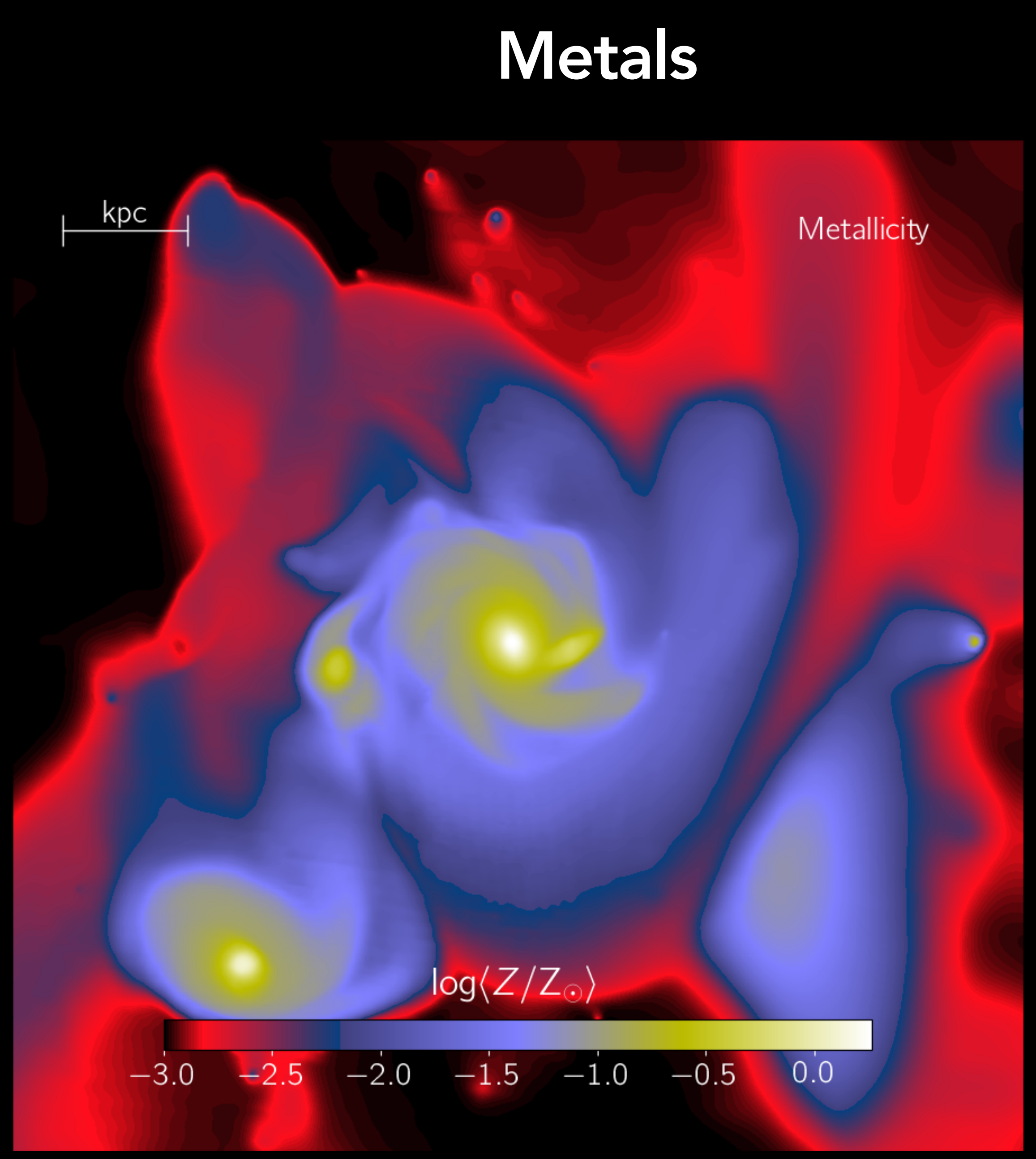
Resolution	
Gas mass	$M_g = 10^4\, M_\odot$
AMR	$\sim 80 - 0.1$ cKpc/h
At $z \simeq 6$	$\Delta x \simeq 30$ pc

Pallottini et al. 2022

Portrait of a SERRA galaxy at z=8

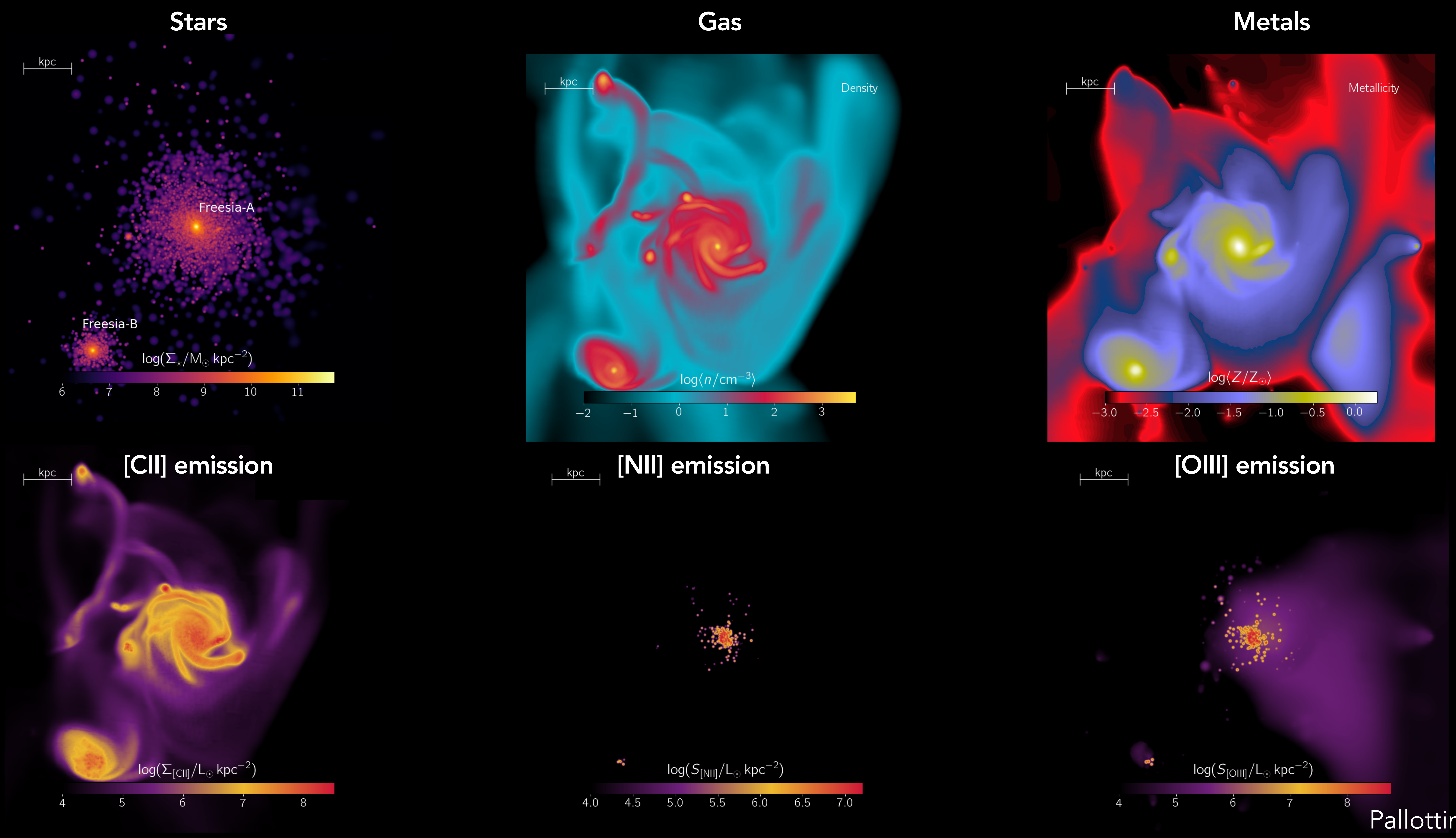






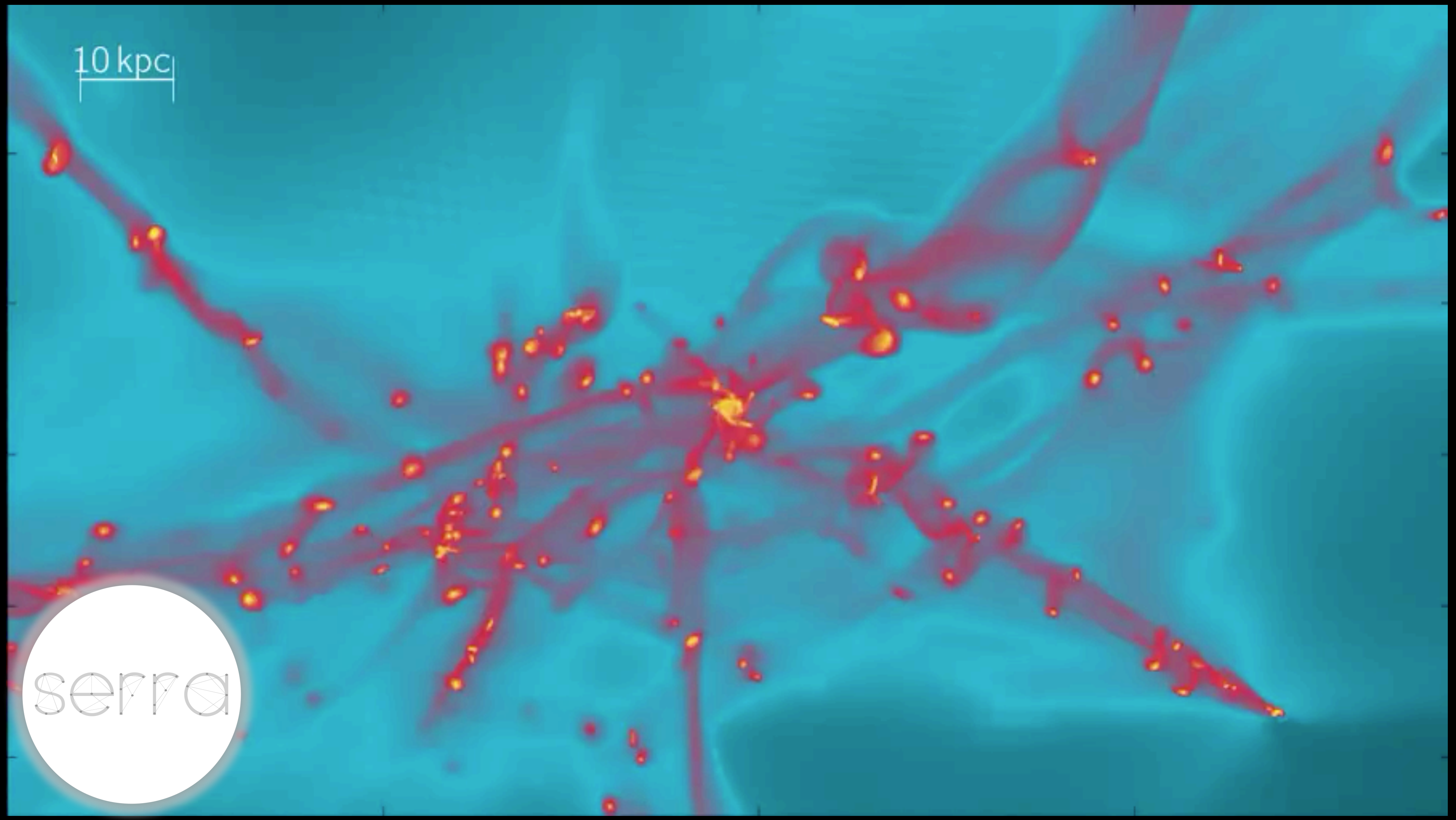
Pallottini et al. 2019

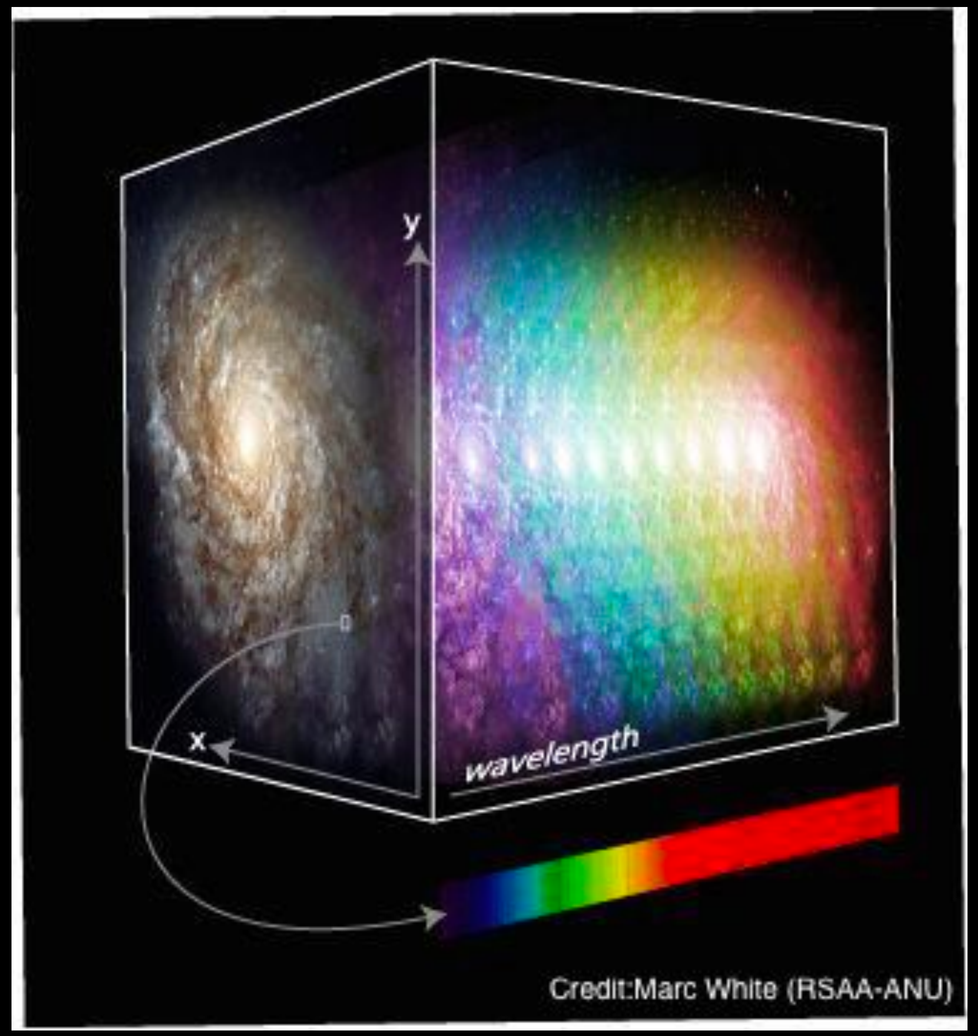
Portrait of a SERRA galaxy at z=8



Pallottini et al. 2019

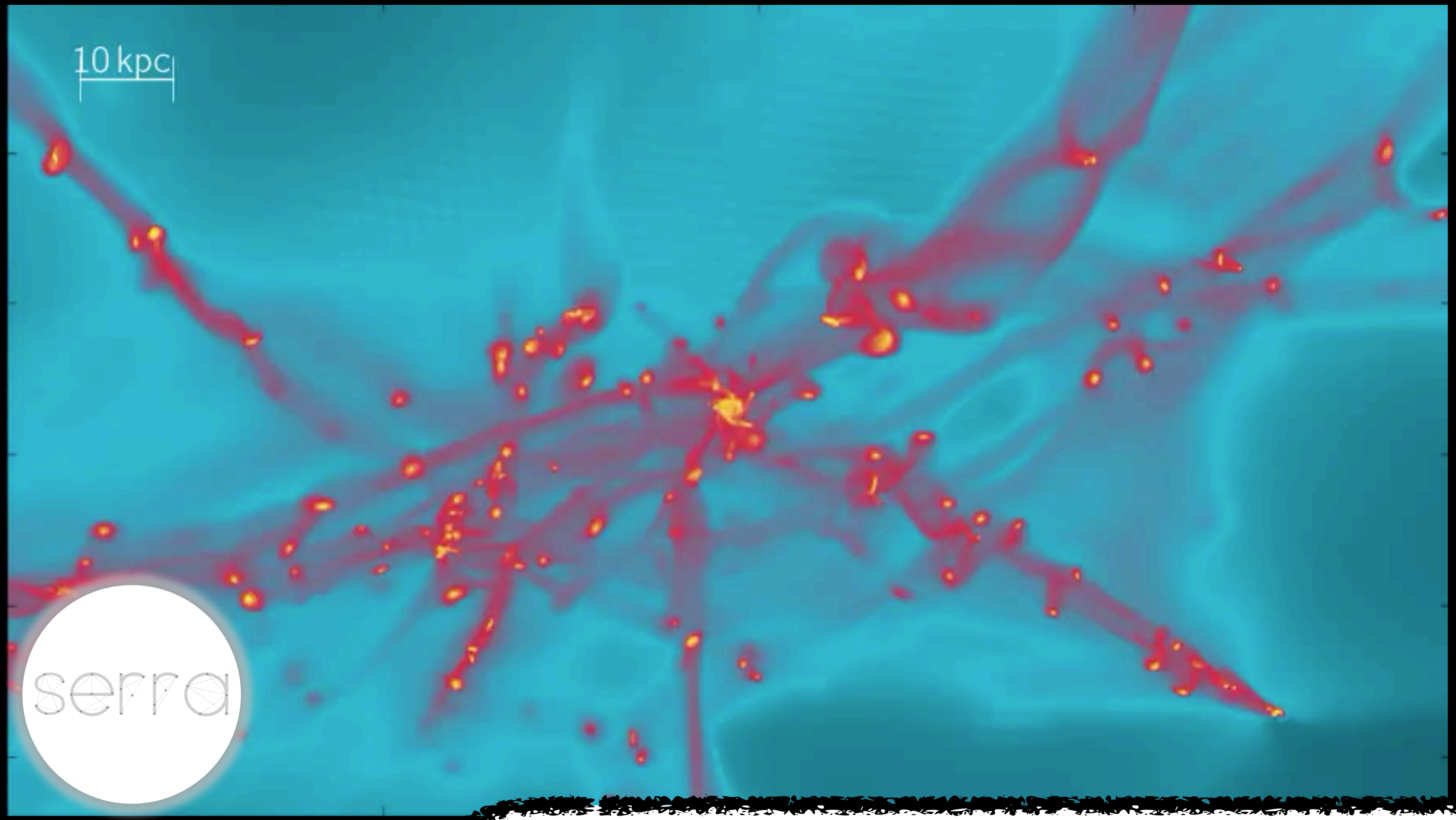
Bridging simulations and IFU-like observations

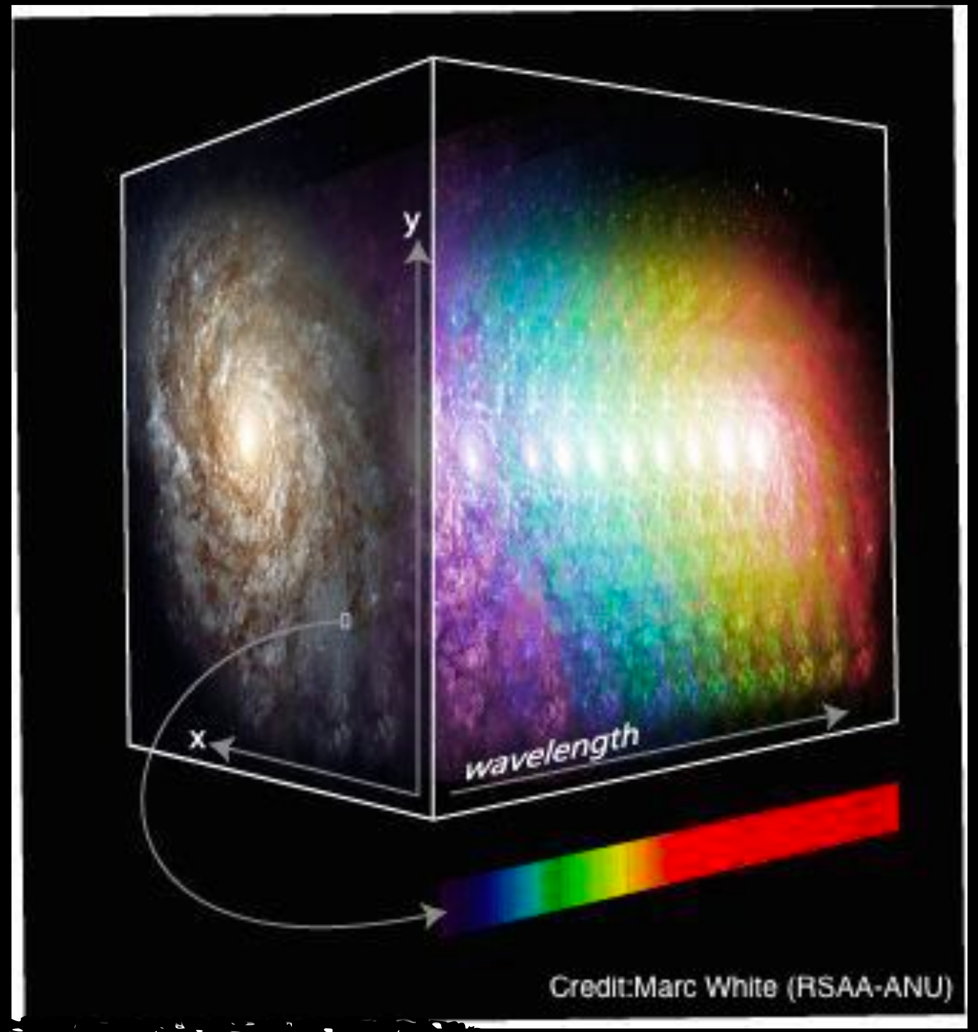




Kohandel et al. 2020, 2023a, 2023b

Bridging simulations and IFU-like observations





[CII] $158\,\mu$m: **Cold, molecular/neutral gas tracer** ($T \sim 100\,$K)

ALMA

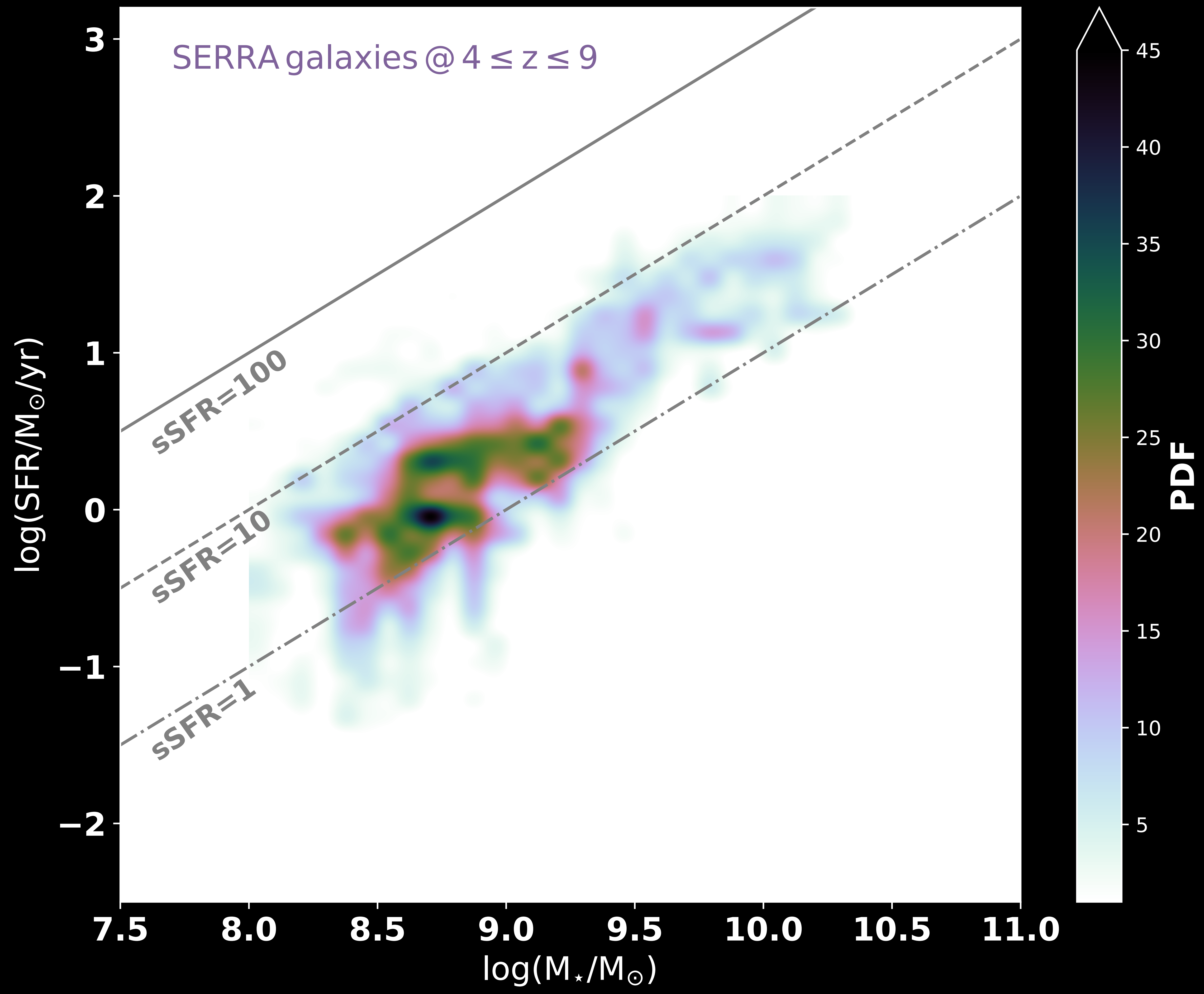
WEBB SPACE TELESCOPE

Hα 6562Å : **Hot ionised gas tracer** ($T > 10^4\,$K)

Kohandel et al. 2023b

arXiv:2311.05832

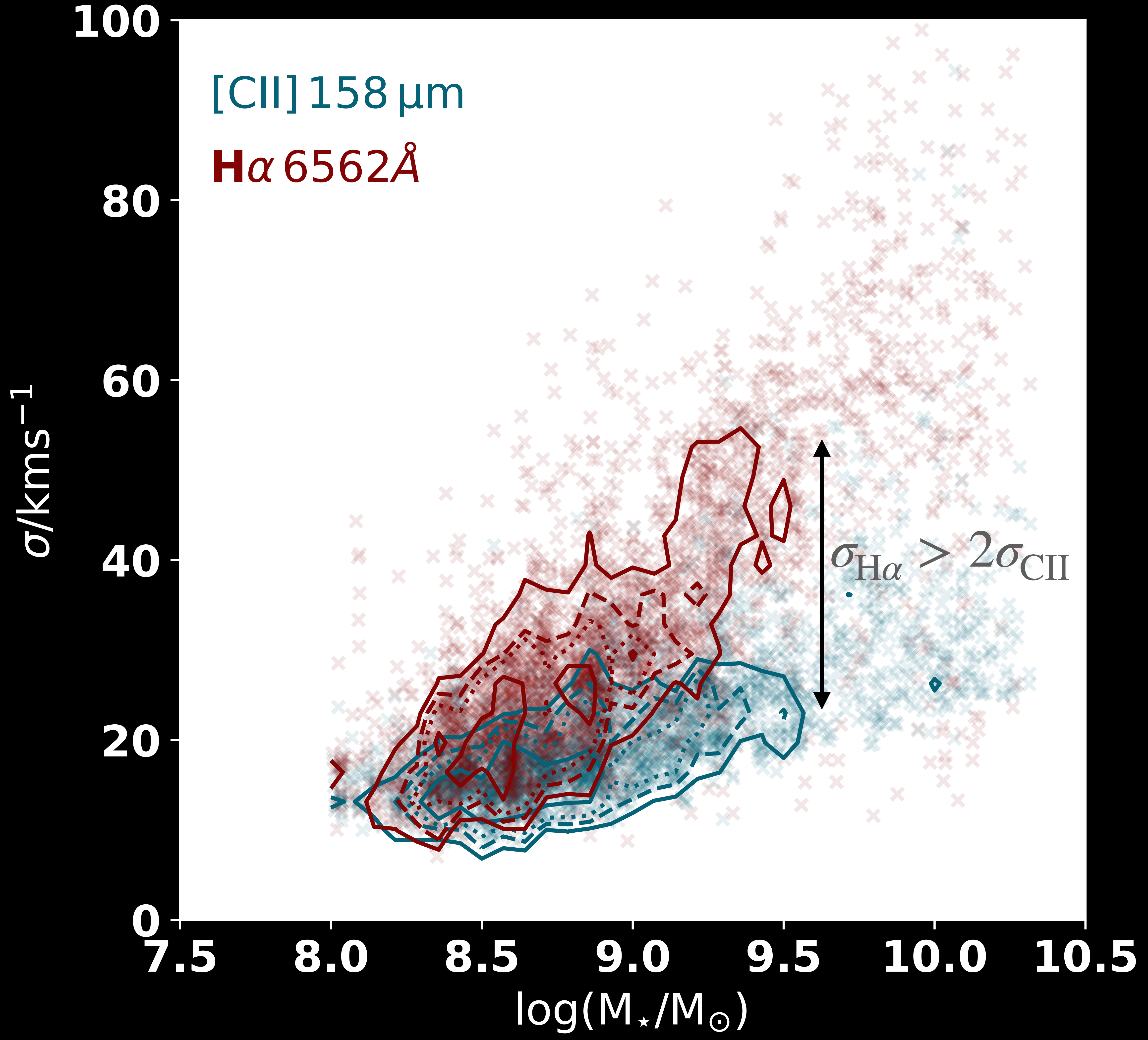
A sample of $\sim 3\mathrm{K}$ SERRA galaxies

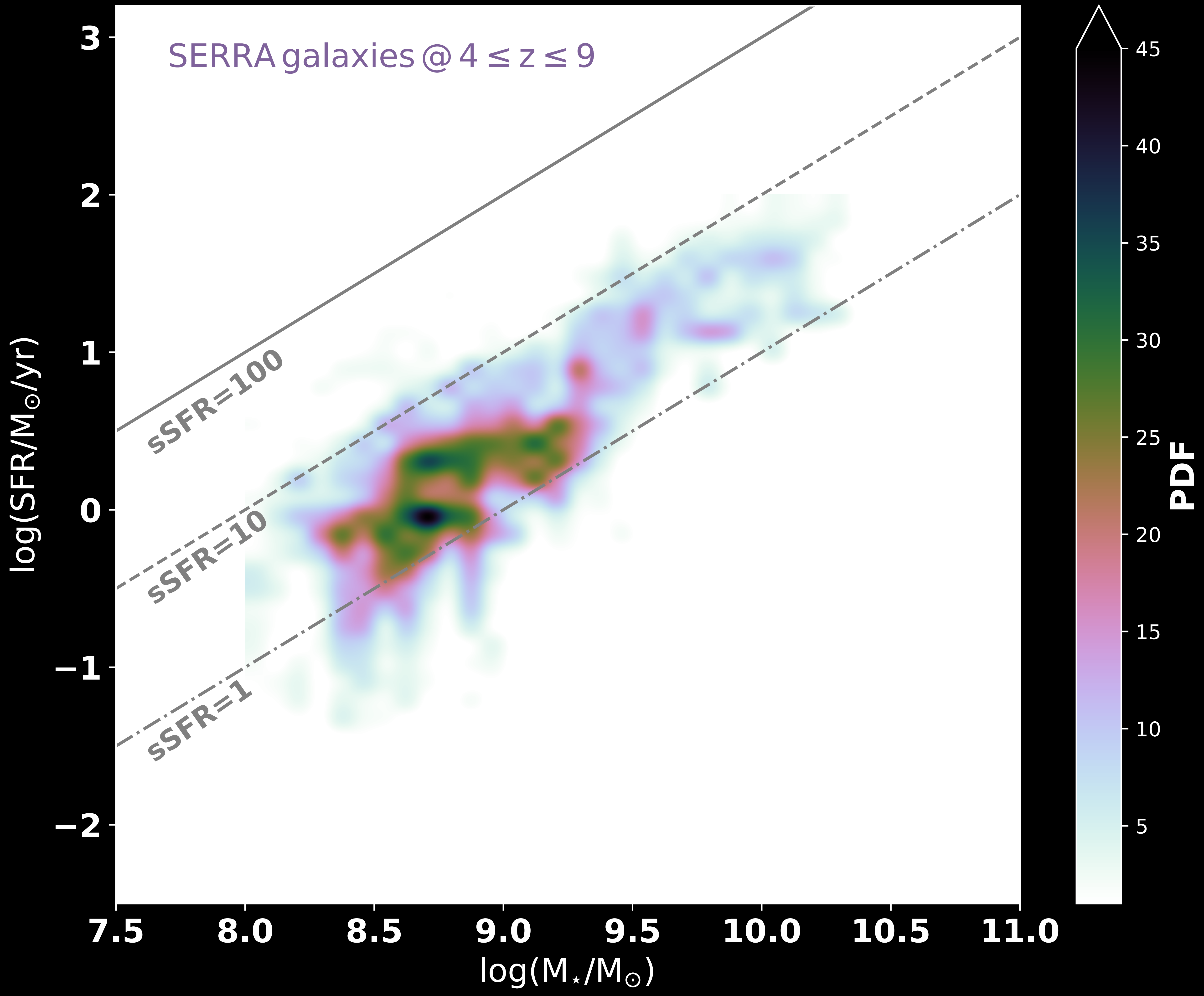


Kohandel et al. 2023b

arXiv:2311.05832

$M_\star - \sigma$ relation in SERRA galaxies



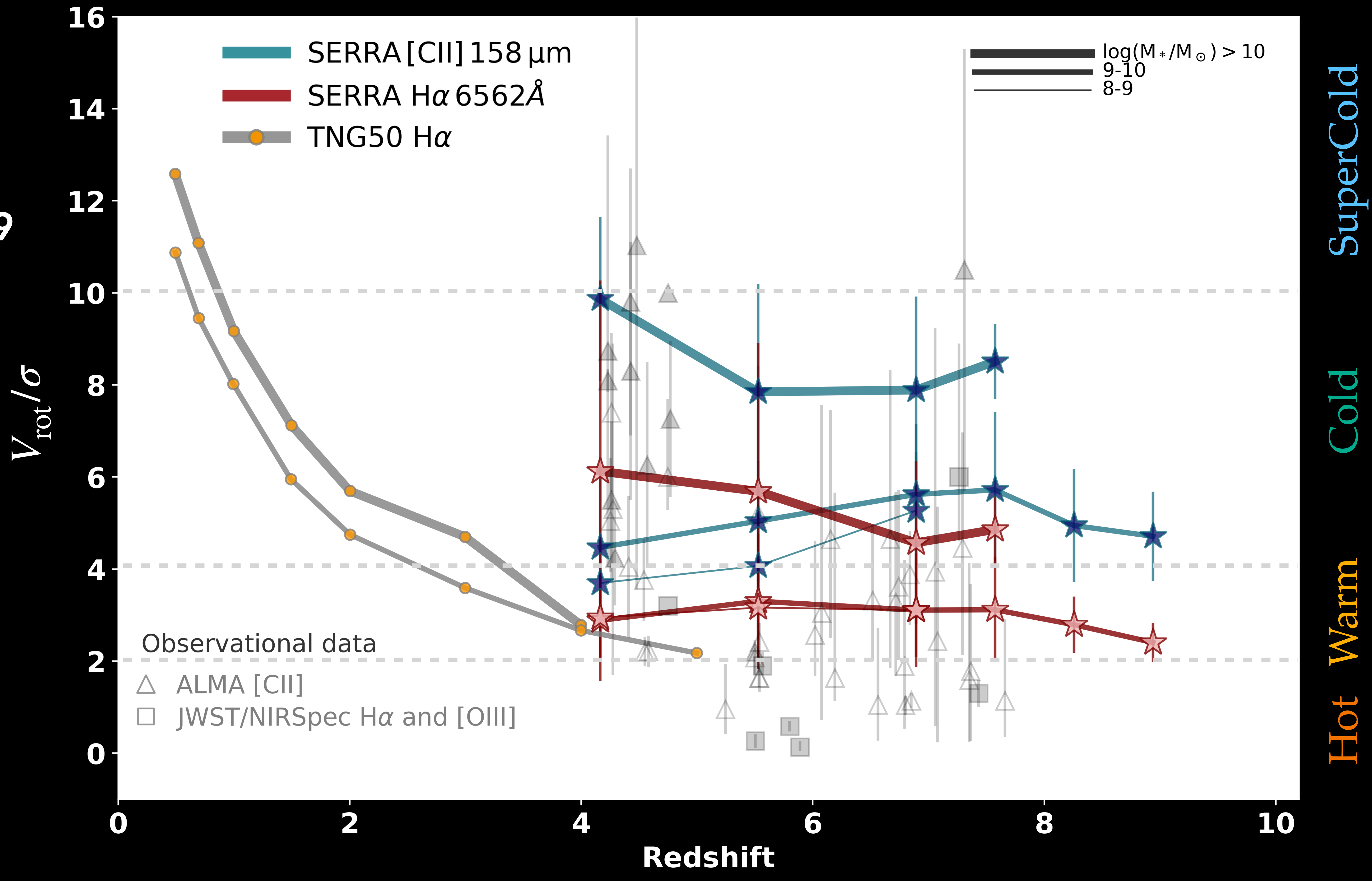


Kohandel et al. 2023b

arXiv:2311.05832

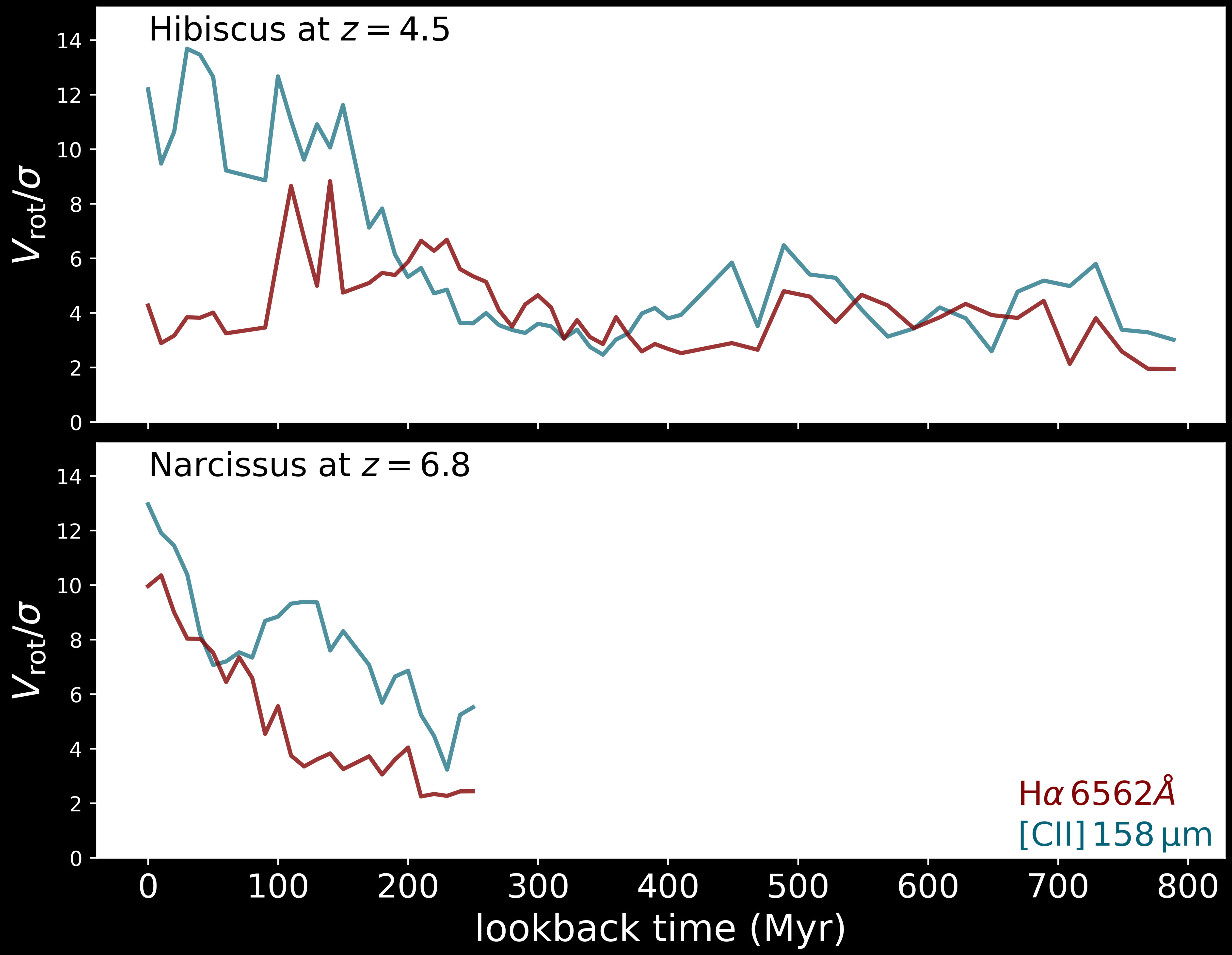
Dynamically cold disks do exist in SERRA

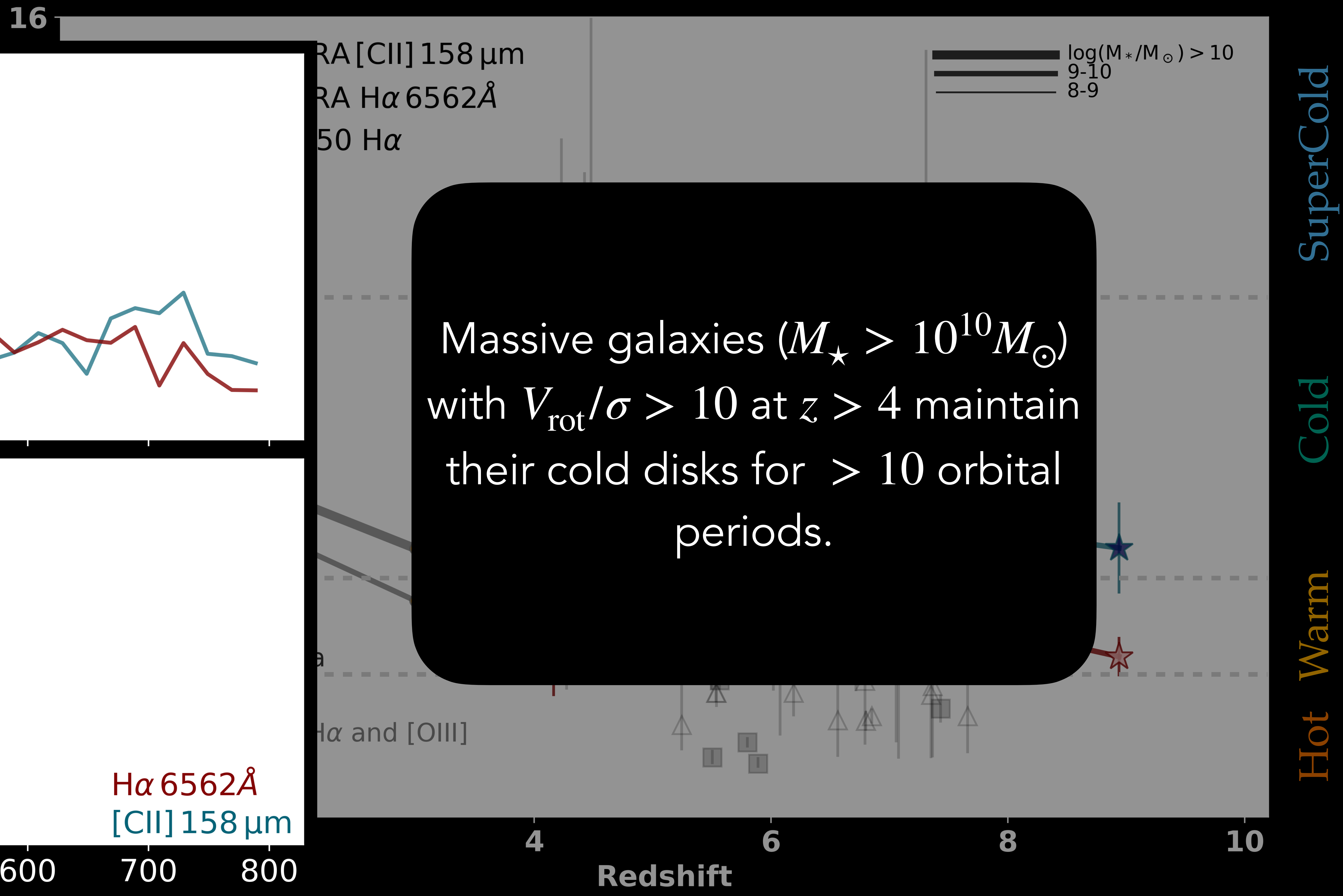
No significant evolution of V/σ at z = 4 - 9



Kohandel et al. 2023b
arXiv:2311.05832

And they are not transient





Massive galaxies ($M_\star > 10^{10} M_\odot$) with $V_{rot}/\sigma > 10$ at $z > 4$ maintain their cold disks for > 10 orbital periods.

Kohandel et al. 2023b
arXiv:2311.05832

High-z dynamically cold disks: ~~Myth~~ or Reality?

Q1) Do zoom-in cosmological simulations with a more complex chemistry and emission line modelling reproduce dynamically cold disks?

A1) Yes! One needs to model detailed ISM physics and multi-wavelength kinematic observables from simulations

See also: Vadim Semenov, Aniket Bhagwat and Floor van Donkelaar presentations

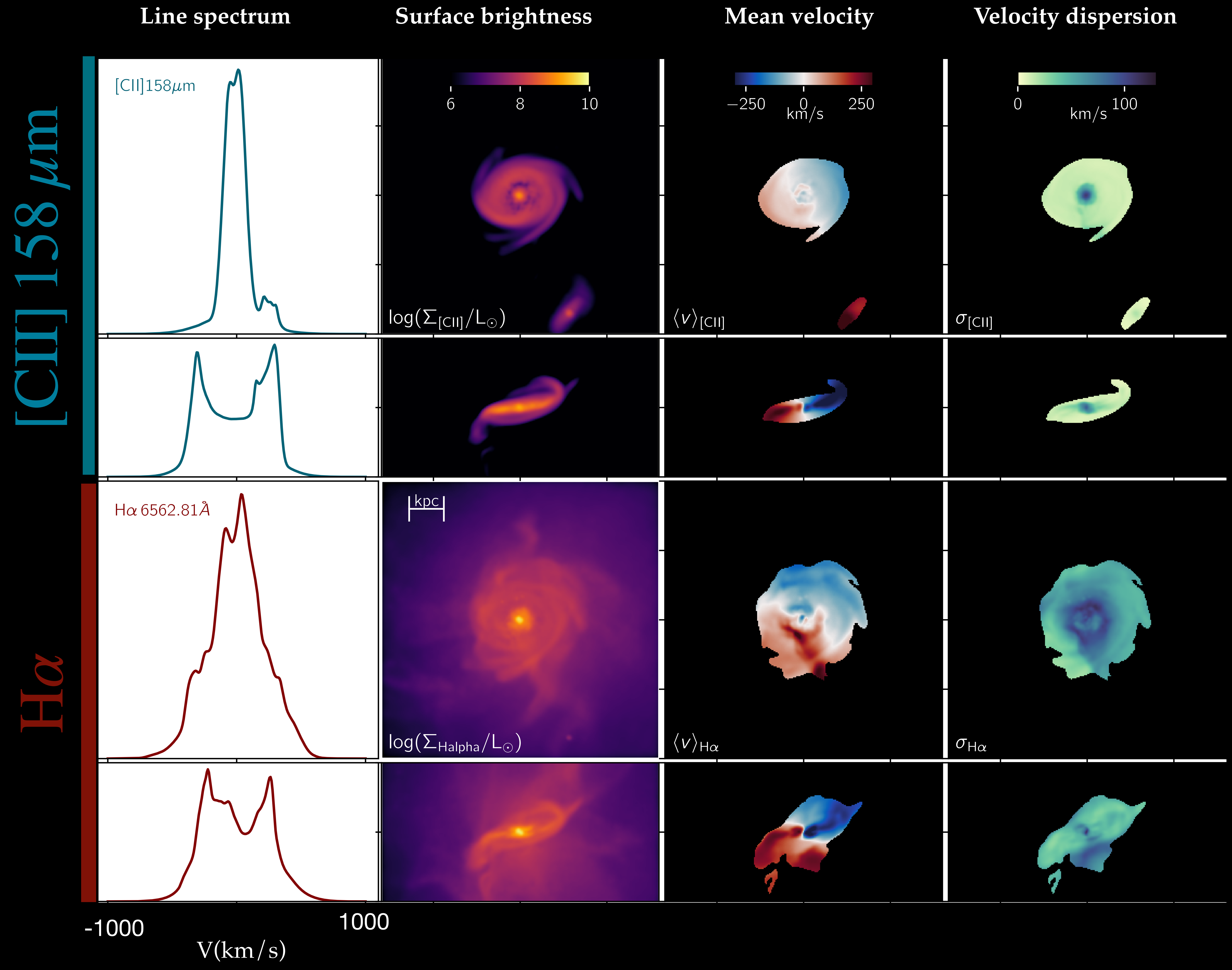
High-z dynamically cold disks: ~~Myth~~ or Reality?

Q1) Do zoom-in cosmological simulations with a more complex chemistry and emission line modelling reproduce dynamically cold disks?

A1) Yes! One needs to model detailed ISM physics and multi-wavelength kinematic observables from simulations

Q2) Can we reconcile the tension between theory and observations by employing different kinematic tracers?

Multi-wavelength kinematics of Hibiscus at z=4.5

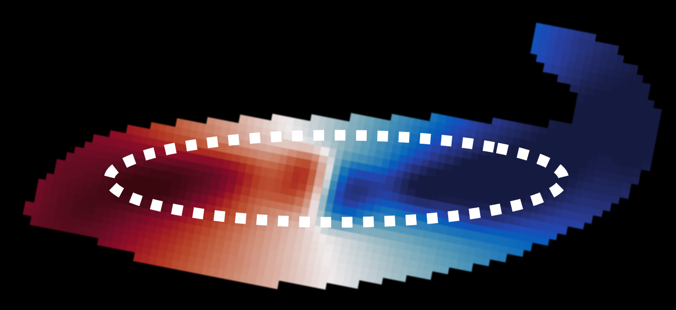


Kohandel et al. 2023b

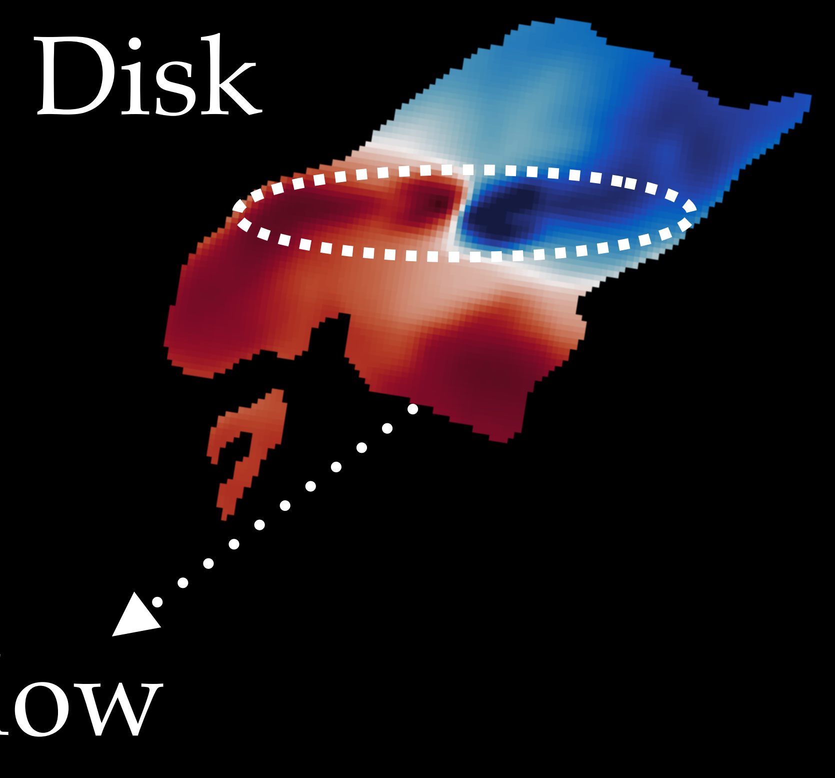
arXiv:2311.05832

Outflows complicate Hα kinematics …

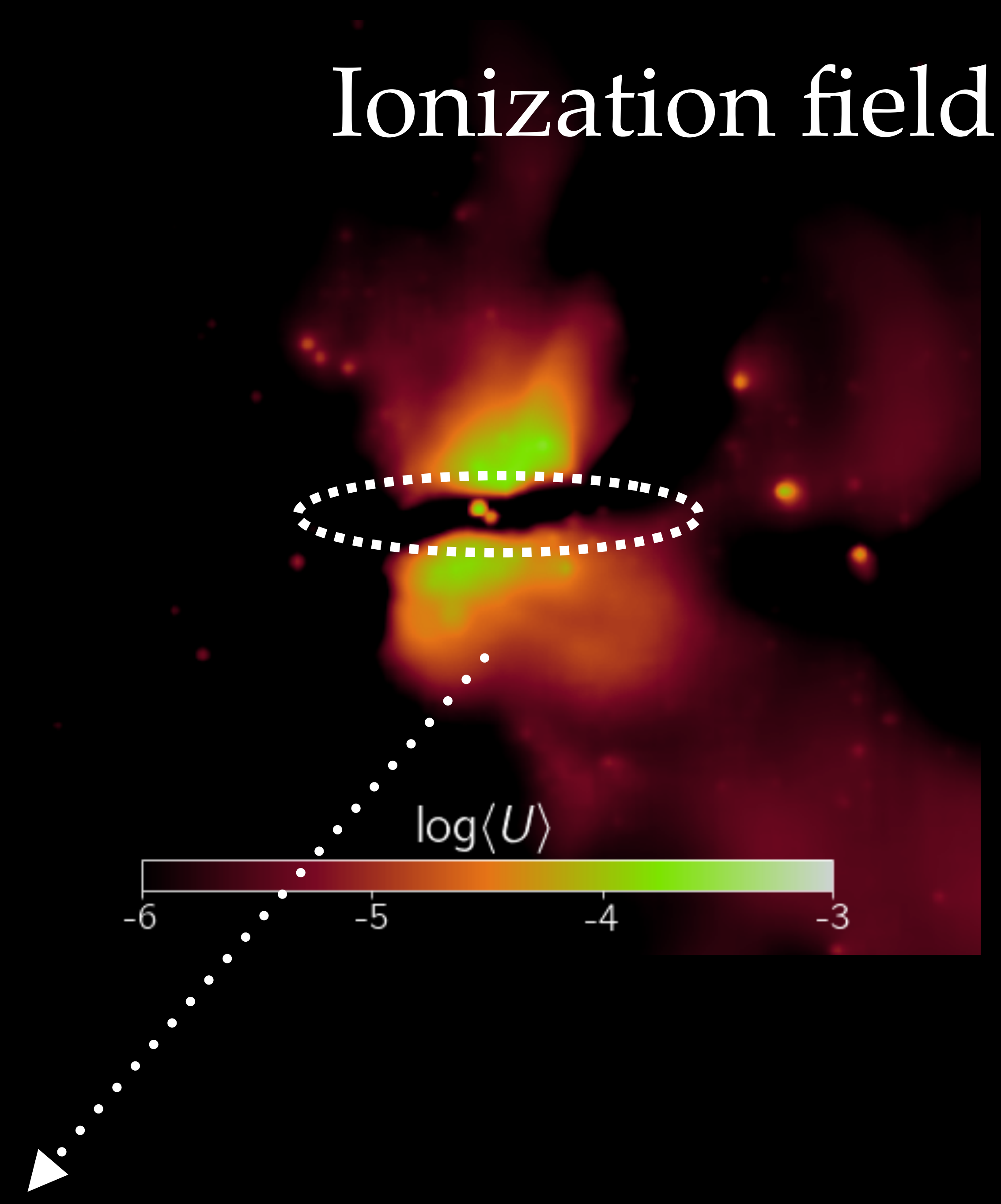
[CII] velocity map



Hα velocity map



Ionization field



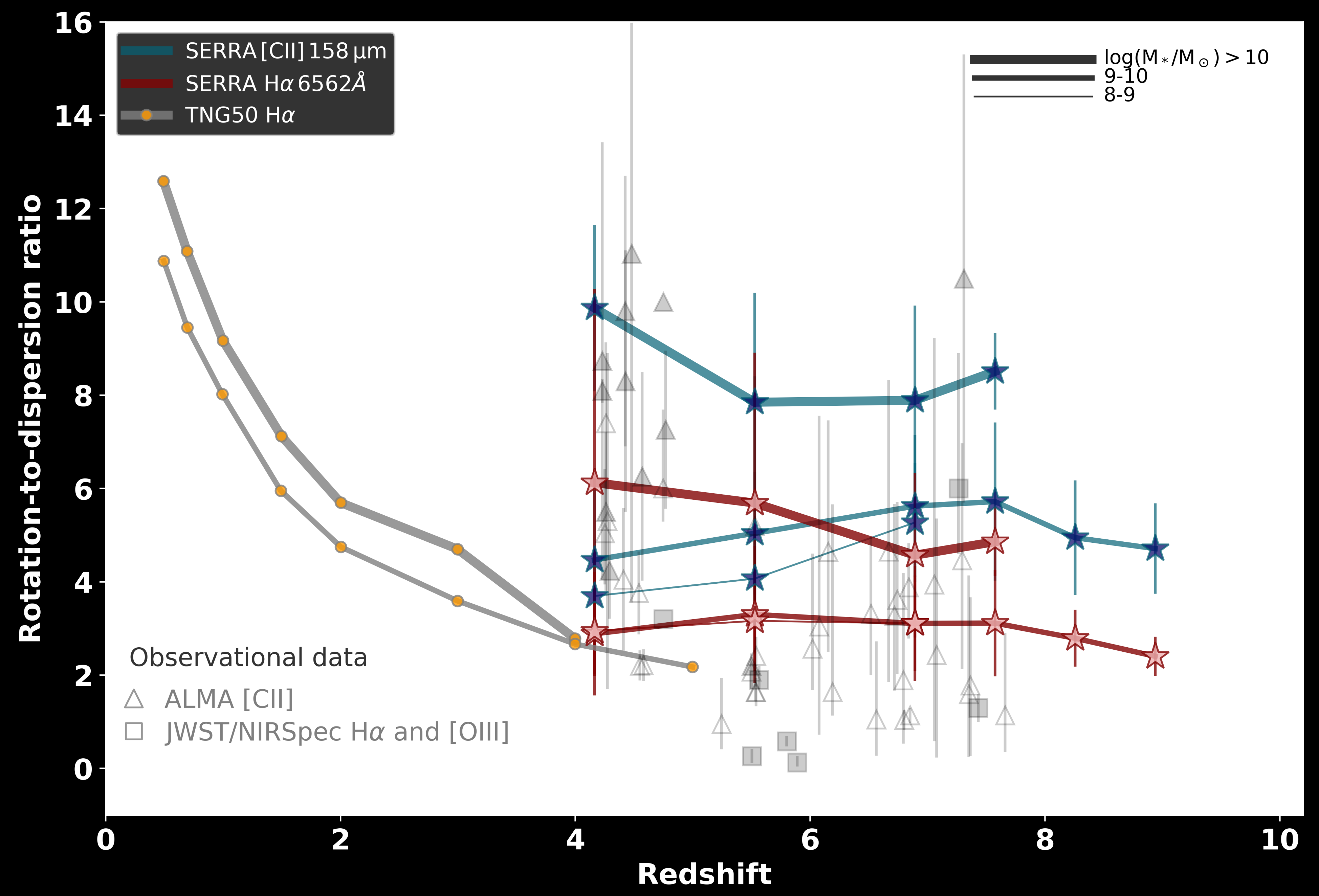
Photoionized regions outside the disk that are part of an expanding, cooling outflow

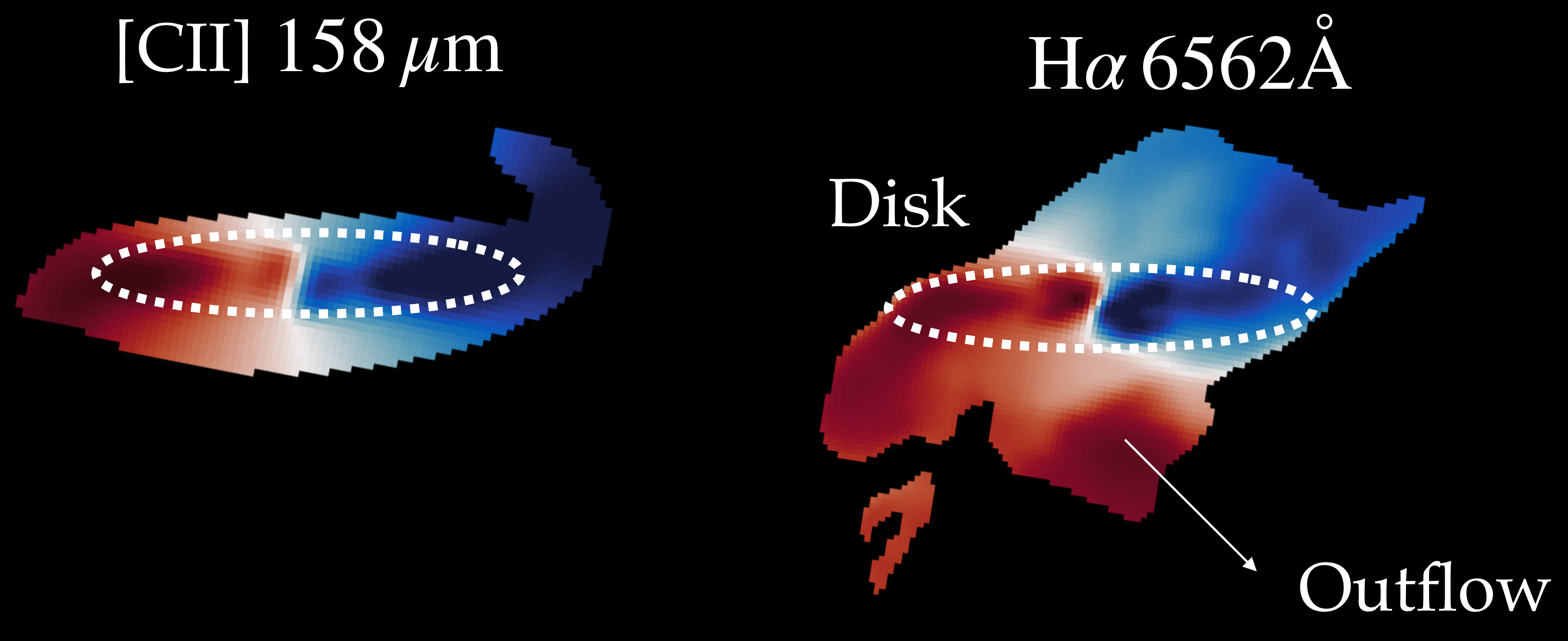
See also Ejdetjärn et al. 2024
arXiv:2401.04160

Kohandel et al. 2023b
arXiv:2311.05832

Takeaways

When equipped with comprehensive ISM physics and multi-wavelength treatments, zoom-in cosmological simulations reveal galaxies that efficiently form and sustain their dynamically cold disks as early as the EoR.





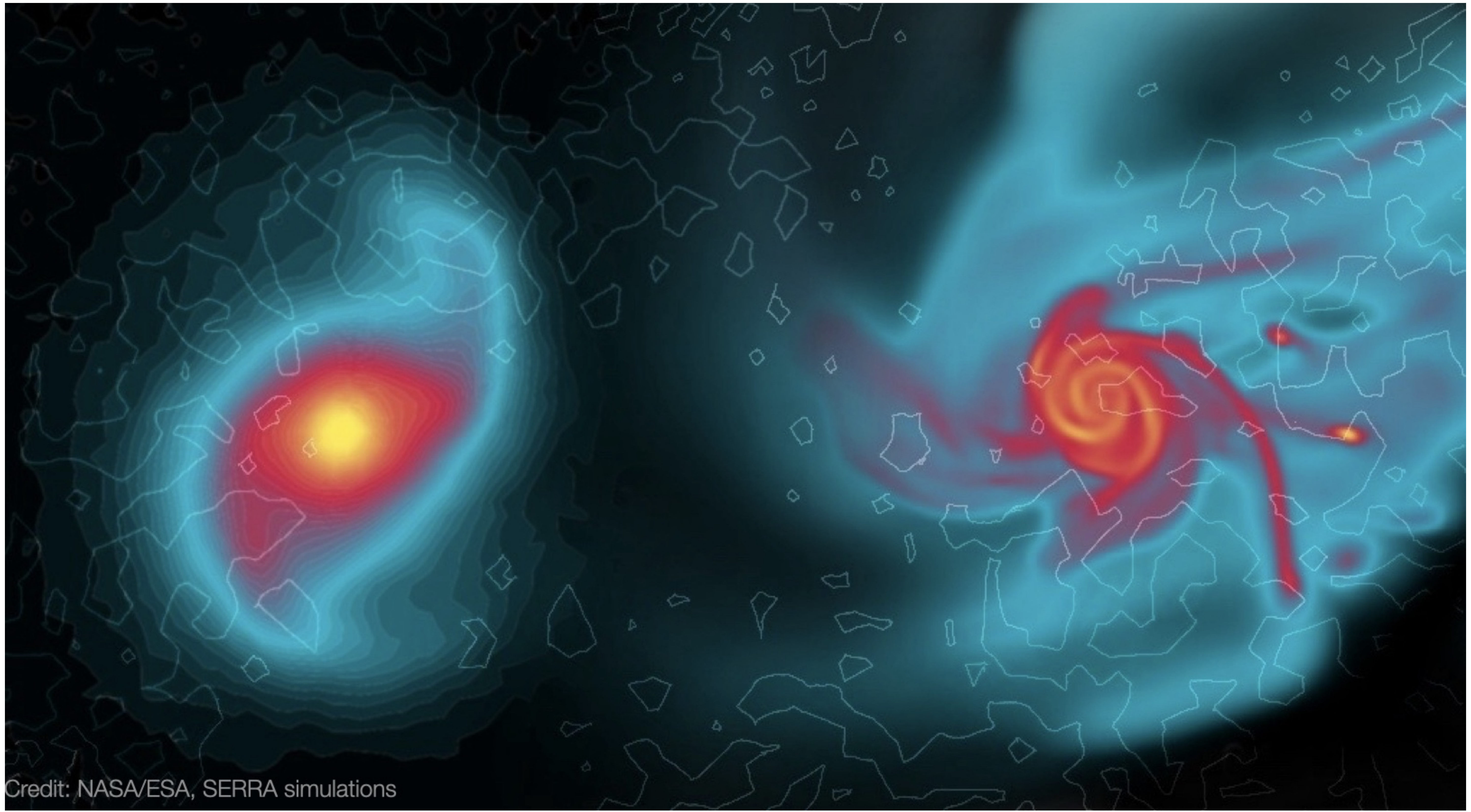
Galaxy kinematics is sensitive to the tracer used. [CII] effectively maps the thin, gaseous disk of galaxies, whereas Hα also has contributions from extraplanar gas, such as outflows. Thus, using it as a kinematic tracer necessitates careful consideration and treatment.

More work is needed to bridge simulations and observations

Special Session SS8

2 July 2024

Zoom-in views of galaxy disks across Cosmic Time:
Bridging simulations and observations



eas 2024 Padova

Deadline: March 4