Evolution of massive galaxy disks across cosmic time

Francesca Rizzo
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Credit: NASA/ESA

Evolution of galaxy disks across human (~30 years) time

Morphology of galaxies

1996 — 2009 (WFC3/HST)

"None of the z ~ 2 galaxies appear to be normal Hubble-sequence galaxies". Papovich et al. 2005

see also Abraham et al. 1996, Giovalisco et al. 1996, Daddi et al. 2004, Conselice et al. 2005

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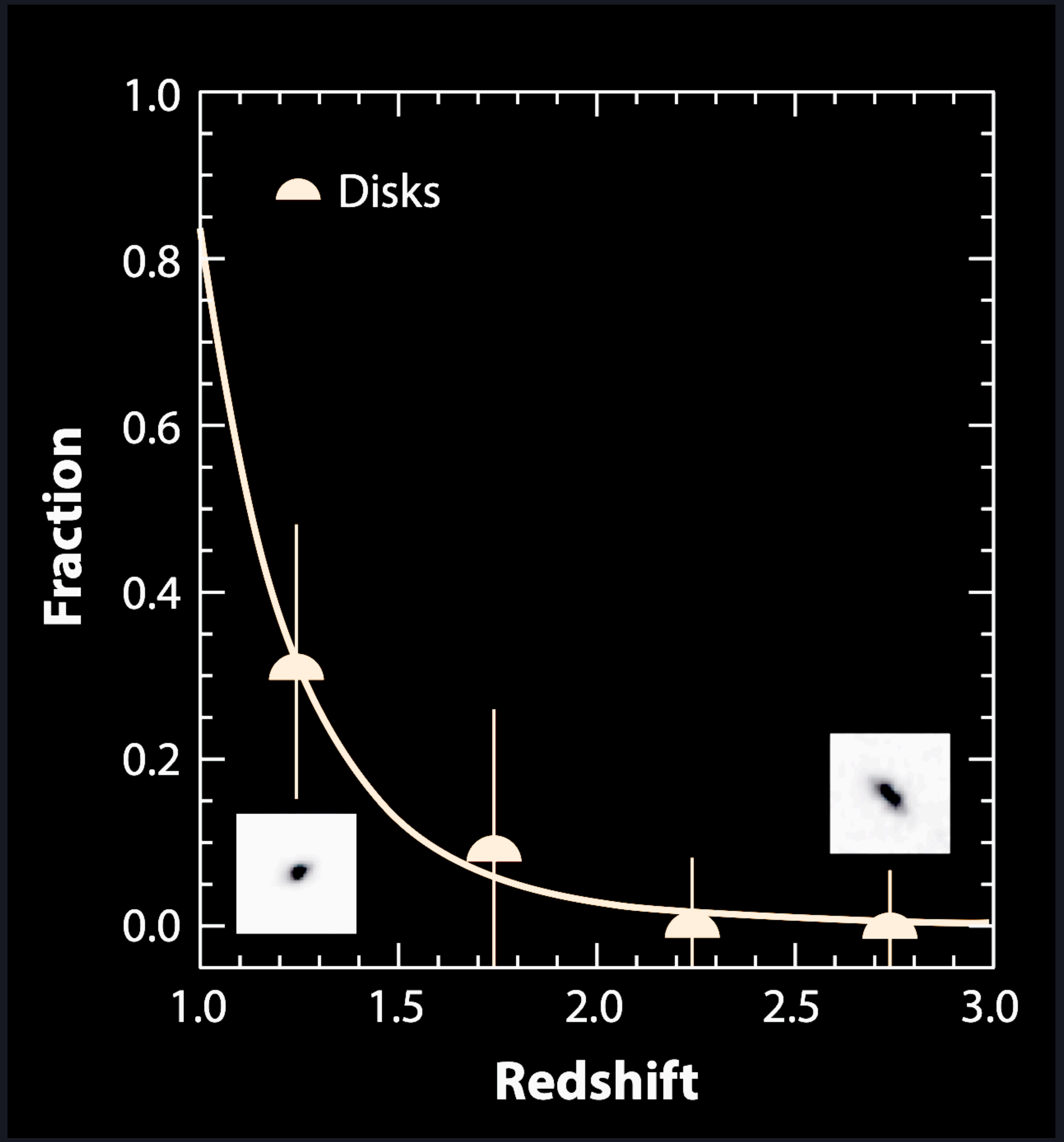
2009 — 2021 (JWST launch)

Small fraction of disks at z > 1 (~10 - 15%)

e.g., Cameron et al. 2011, Conselice et al. 2011, Mortlock et al. 2013



Conselice et al. 2014

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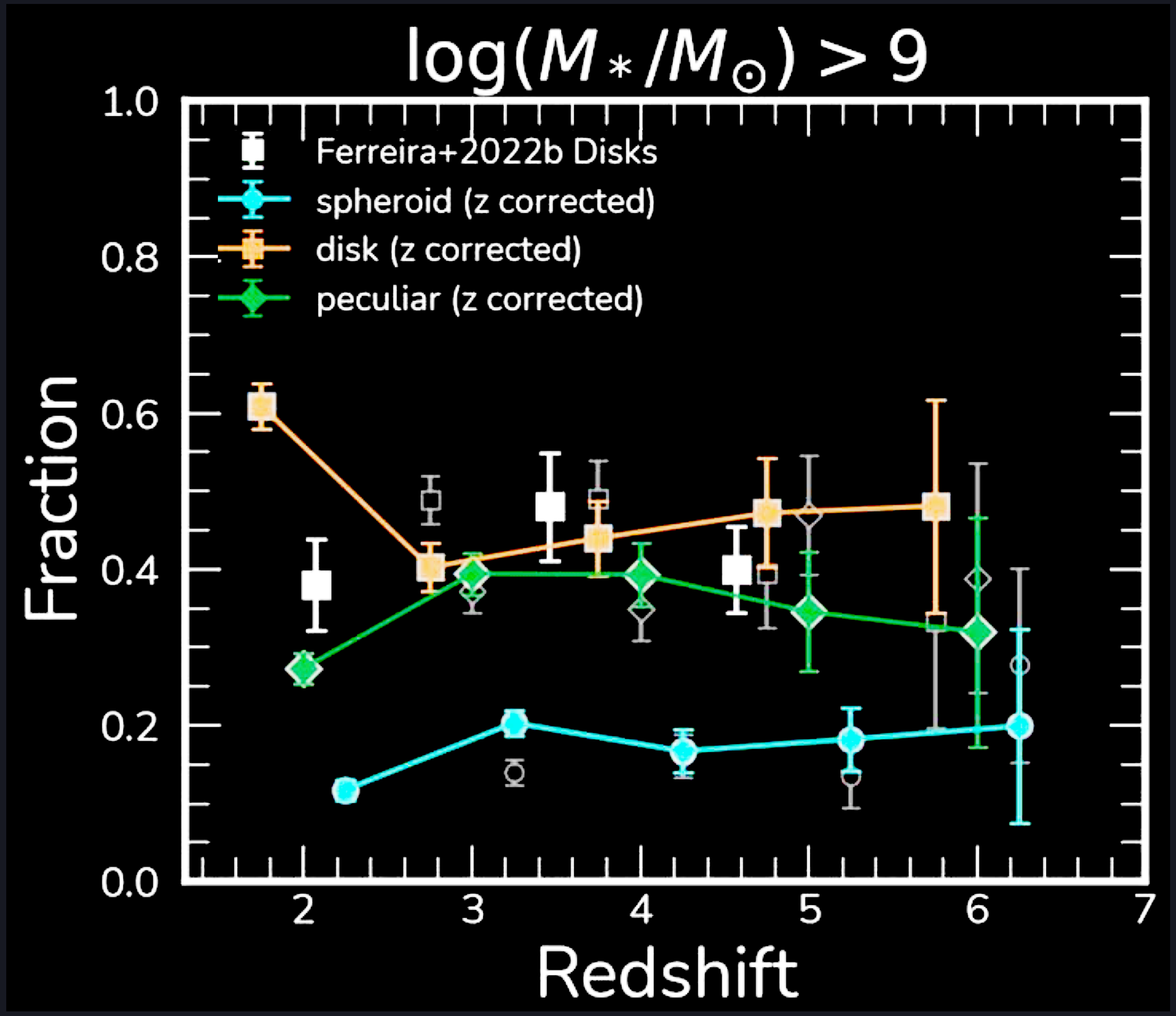
2021 — today

"Contribution to the total stellar mass is dominated by disk galaxies at z < 4”. Ferreira et al. 2023

See also Lee et al. 2024, Kolesnikov et al. 2025 , Westcott et al. 2025



Ferreira et al. 2023

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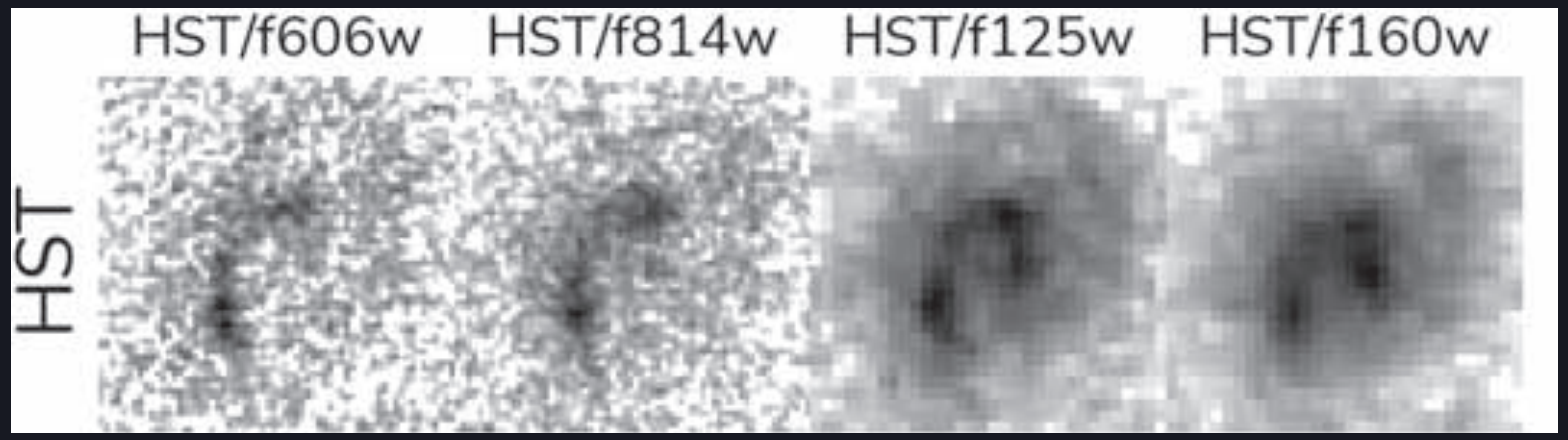
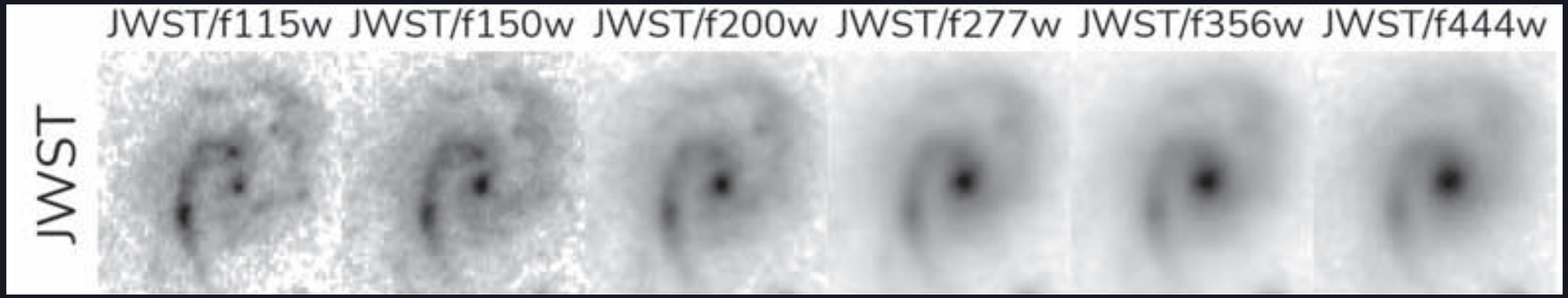
From irregular/interacting…



To a spiral galaxy

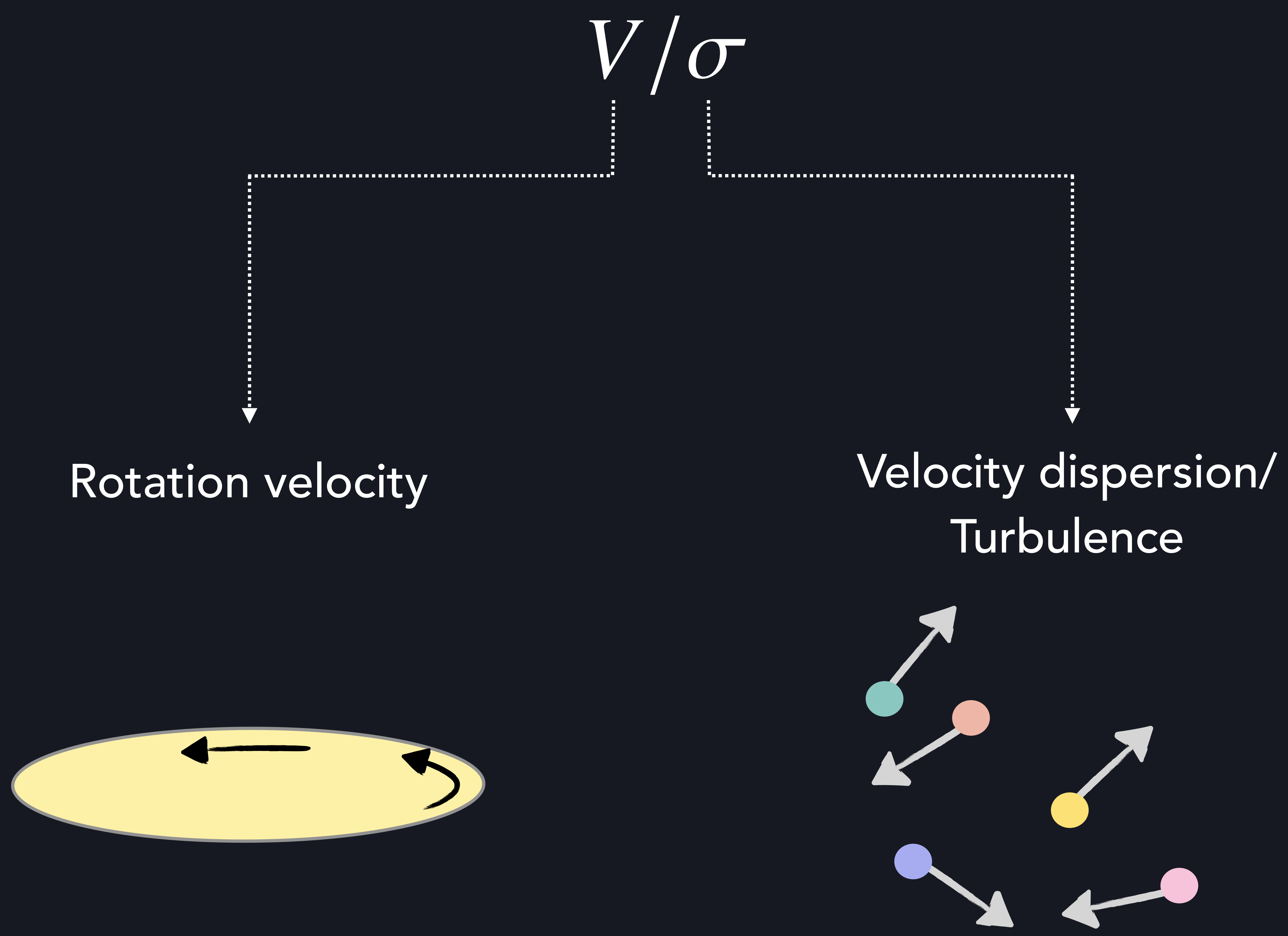


Ferreira et al. 2023

Evolution of galaxy disks across human (~30 years) time

Kinematics of galaxies

Redshift evolution of σ and V/σ



Evolution of galaxy disks across human (~30 years) time

Kinematics of galaxies

2006 — 2019 (IFS surveys, Hα)

At z ~ 2: 50% of disks.

Evolution of galaxy disks across human (~30 years) time

Kinematics of galaxies

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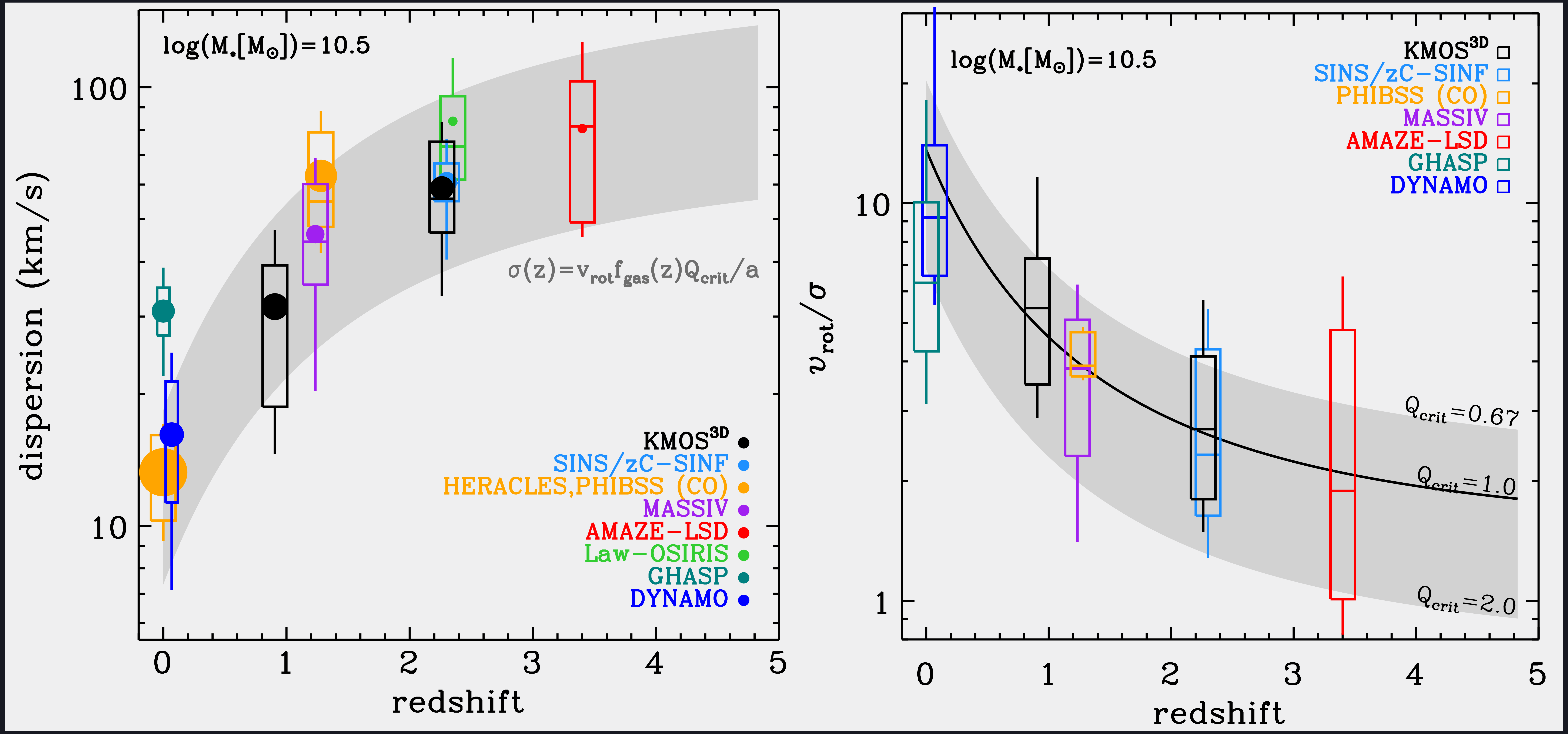
At z ~ 2: 50% of disks, but galaxies more turbulent and less rotationally supported than galaxies at z ~ 0.



Wisnioski et al. 2015

See also Förster-Schreiber et al. 2006, 2009; Epinat et al. 2009; Stott et al. 2016; Turner et al. 2017; Johnson et al. 2018

Evolution of galaxy disks across human (~30 years) time

Kinematics of galaxies

2006 — 2019 (IFS surveys, Hα)

At z ~ 2: 50% of disks, but galaxies more turbulent and less rotationally supported than galaxies at z ~ 0.

Evolution due to gravitational instabilities driven by gas accretion, mergers.

Bulge formation

Star formation regulation

Turbulence within the ISM

Bar formation

Disk evolution

Metallicity gradient

Evolution of galaxy disks across human (~30 years) time

Kinematics of galaxies

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❖ Warm and cold gas: same σ.
σ from Hα traces turbulence

Warm gas (ionised): T ~ 10^4 K
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Cold gas (atomic, molecular): T < 10^4 K
HI, CO, [CII]

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❖ Disks are marginally stable (Q ~ 1)

$$Q = \frac{\kappa\sigma}{\pi G \Sigma_{\rm gas}}$$

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Not a good disk instability diagnostic!!!
see Romeo et al. 2010, 2014, 2018

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$$Q = \frac{\kappa\sigma}{\pi G \Sigma_{\rm gas}} \;\not\longrightarrow\; Q_{\rm approx} = \frac{\sqrt{2}\sigma}{V f_{\rm gas}}$$

$$\sigma(z) = \frac{V f_{\rm gas}(z)}{\sqrt{2}}$$

Cecilia Bacchini's talk!

Evolution of galaxy disks across human (~30 years) time

Kinematics of galaxies

2006 — 2019 (IFS surveys, Hα)

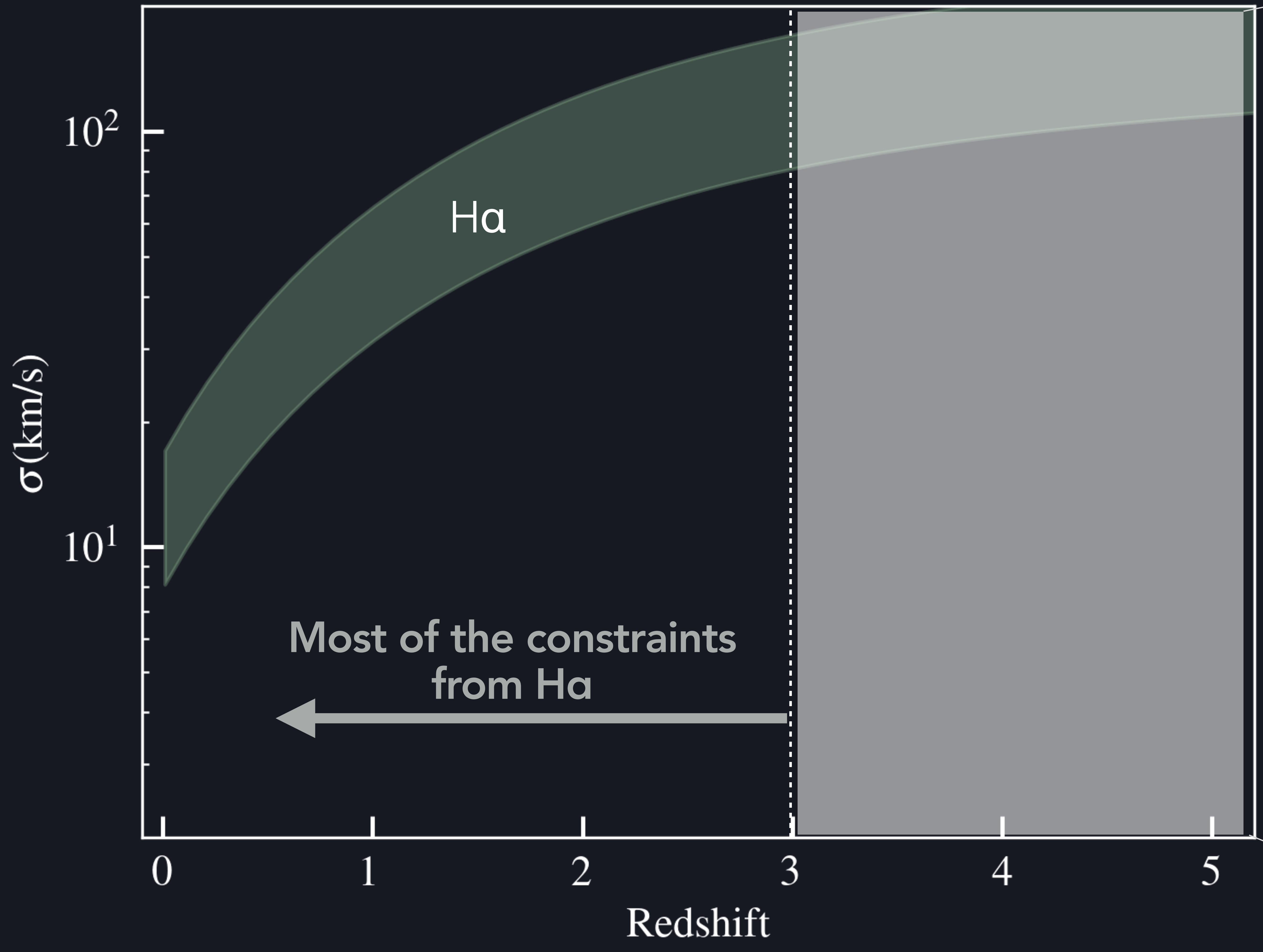
At z ~ 2, galaxies more turbulent and less rotationally supported than galaxies at z ~ 0.

2020 — today (ALMA, cold gas)

....

ALMA: a revolution in the study of high-z galaxy dynamics

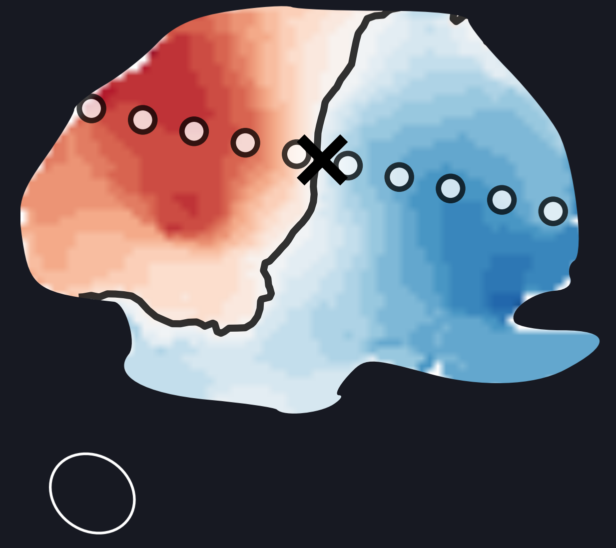
High angular resolution observations of galaxies at z > 4 with [CII]



Lensed (6 galaxies)

Rizzo et al. 2020
Rizzo et al. 2021

Non-Lensed (10 galaxies)



Roman-Oliveira et al. 2023

Neeleman et al. 2020, Lelli et al. 2021,
Tsukui et al. 2021, Pope et al. 2023, Rowlands et al. 2024

e.g., Wisnioski et al 2015, 2018; Johnson et al. 2018; Krumholz et al. 2018; Pillepich et al. 2019; Genzel et al. 2023

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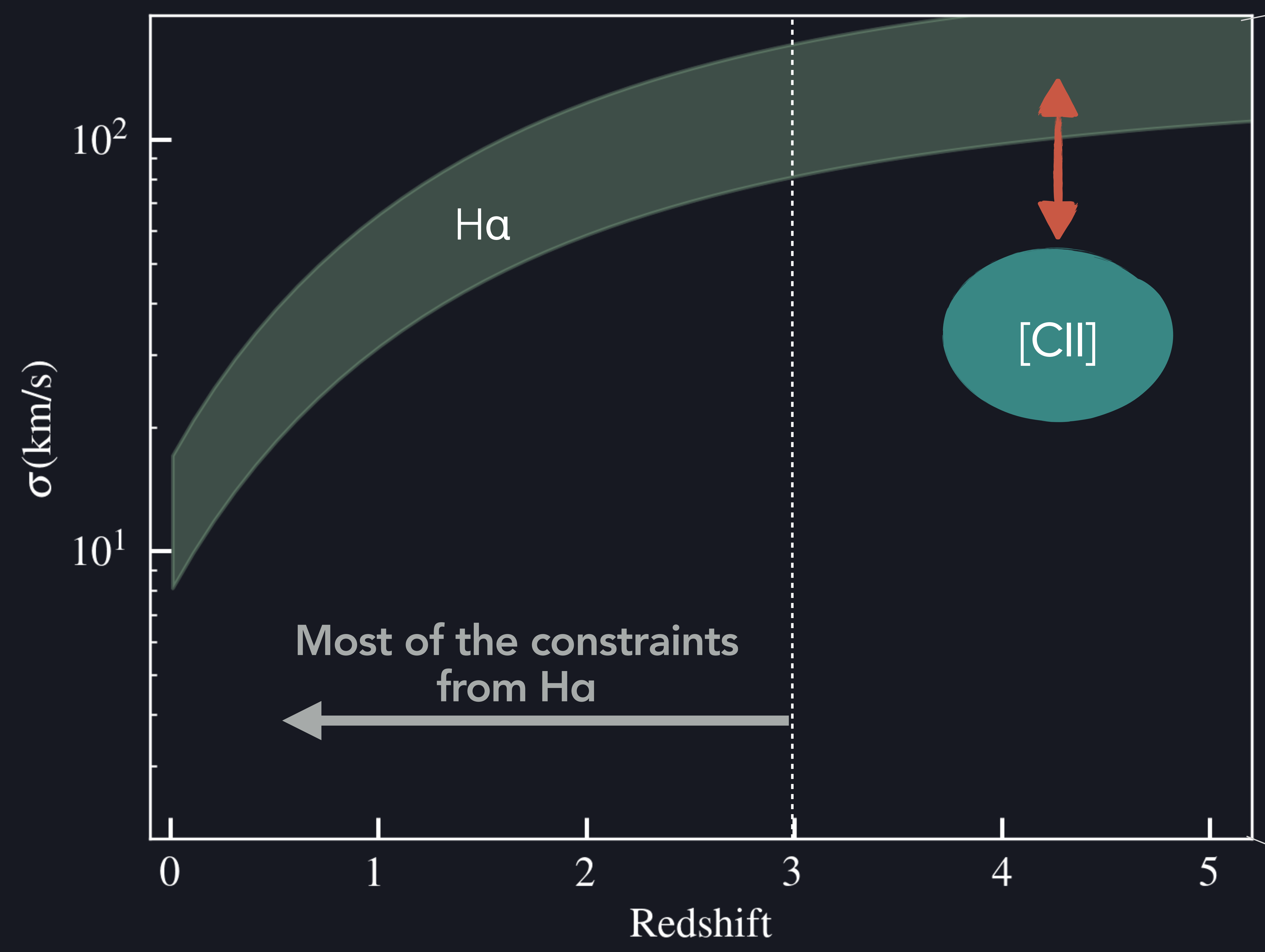

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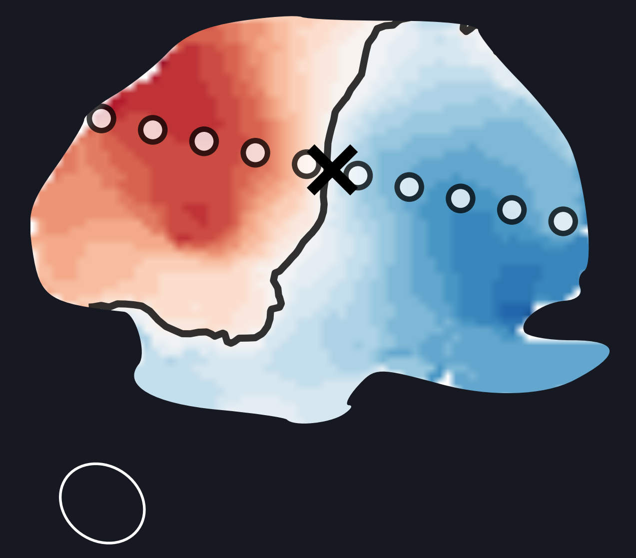

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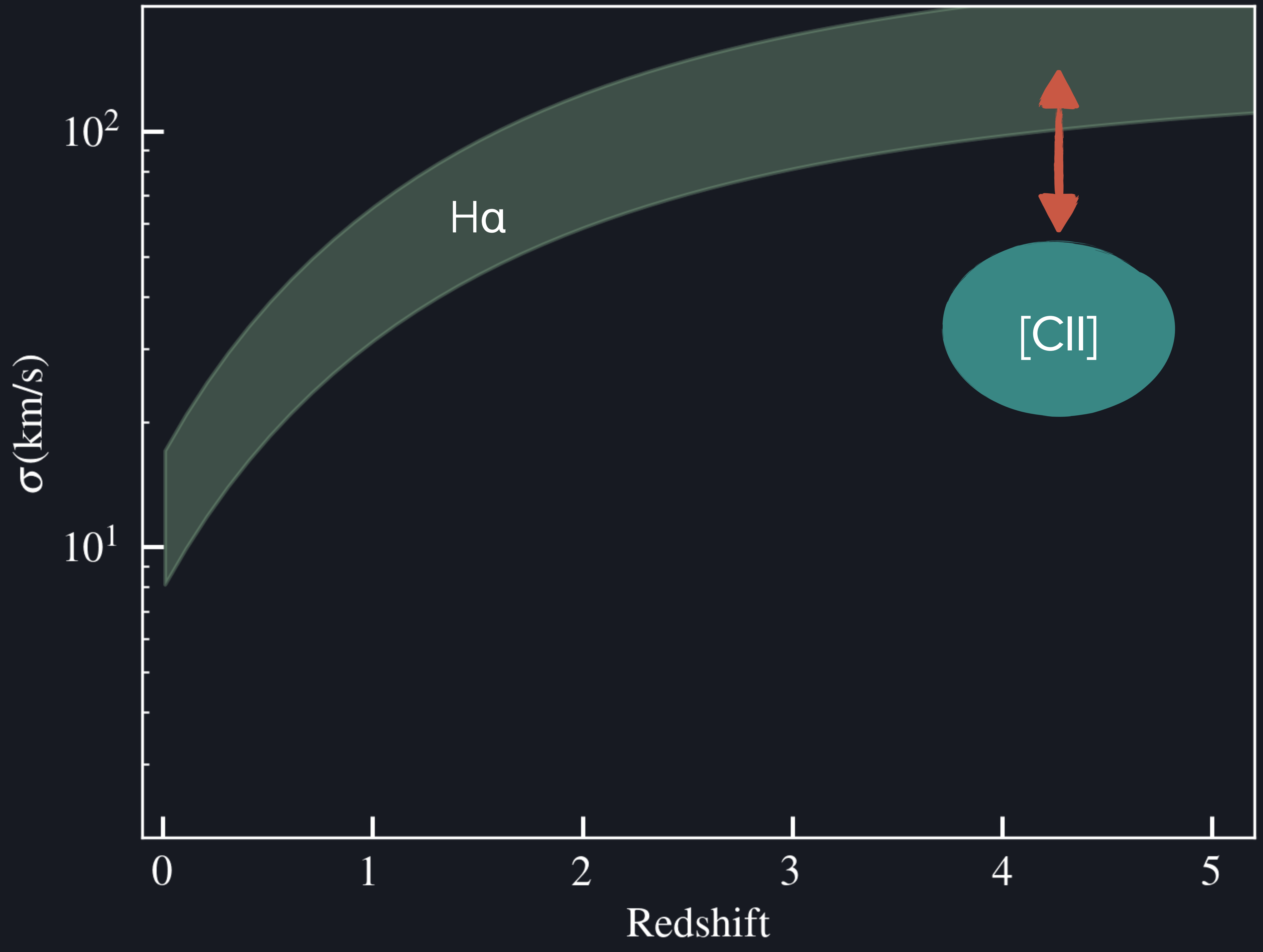
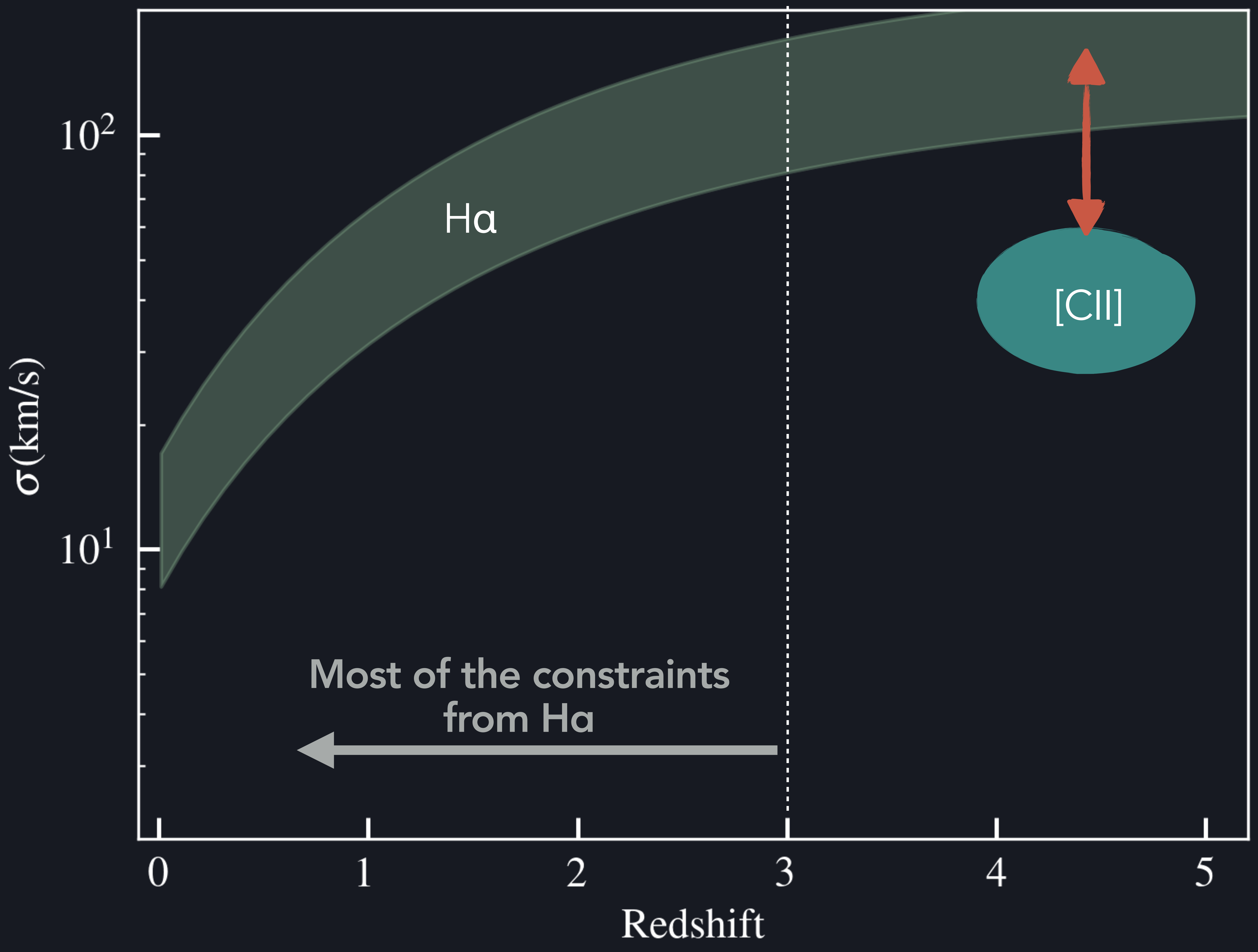


❖ Why surprising?

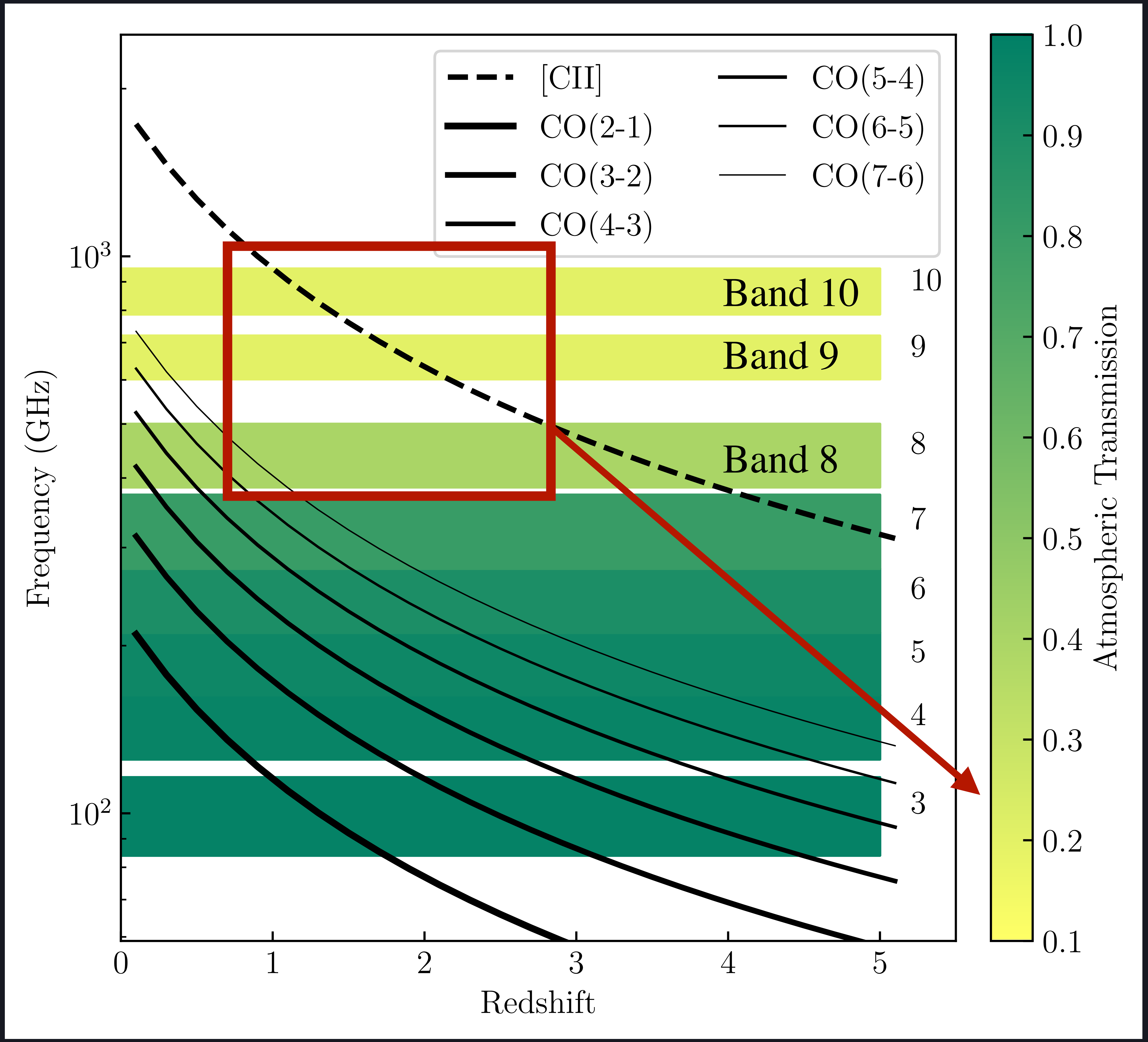
- Most of the galaxies with [CII] observations: SFR: 300 - 1000 $M_\odot$/yr. Disks: expected to be transient!
- σ ~ 35 km/s (close to the spectral resolution)
- V/σ ~ 10. Expected: < 2



Why is there a difference?

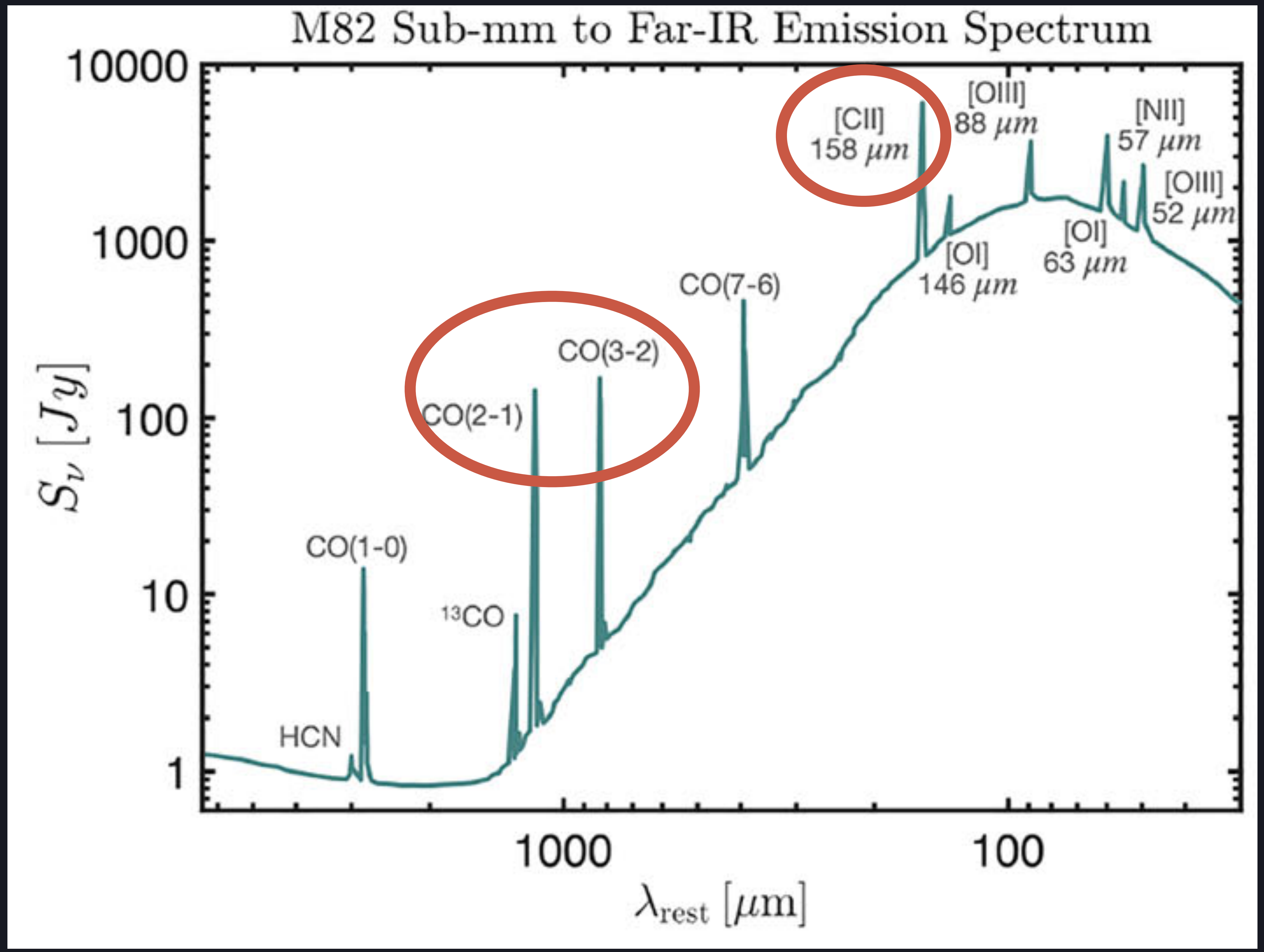
Galaxy population?
Gas tracers?

Cold gas kinematics at z = 0.5 - 3



Cold gas kinematics at z = 0.5 - 3

CO observations at z = 0.5 - 3 more challenging than [CII] observations at z > 4!



Bernal et al. 2022

ALPAKA

Archival Large program to Advance the Kinematic Analysis

Selection criteria from the ALMA Archive:

CO or [CI] observations of galaxies at z = 0.5 - 4

Angular resolution: < 0.4″

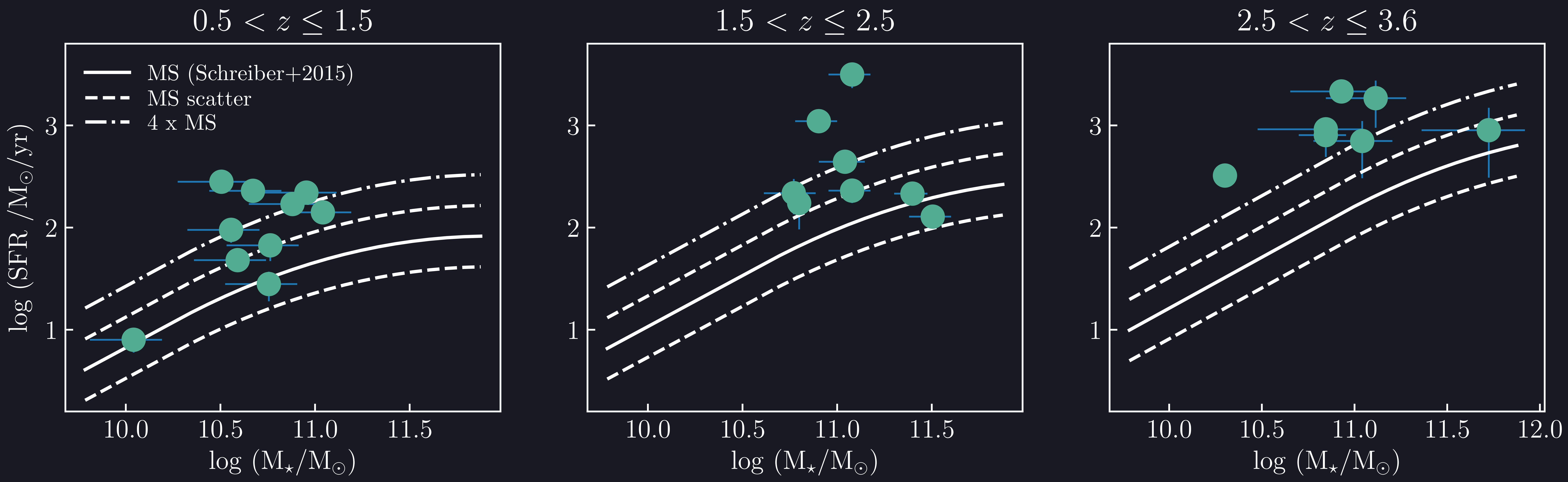
Spectral resolution: < 40 km/s

Signal-to-noise ratio > 10

28 star-forming galaxies

ALPAKA Sample

- UV-selected and sub-mm galaxies in well-characterized fields (e.g., COSMOS, GOOD-S)
- 60%: in overdense regions (clusters, protoclusters, groups)
- 50%: main sequence galaxies



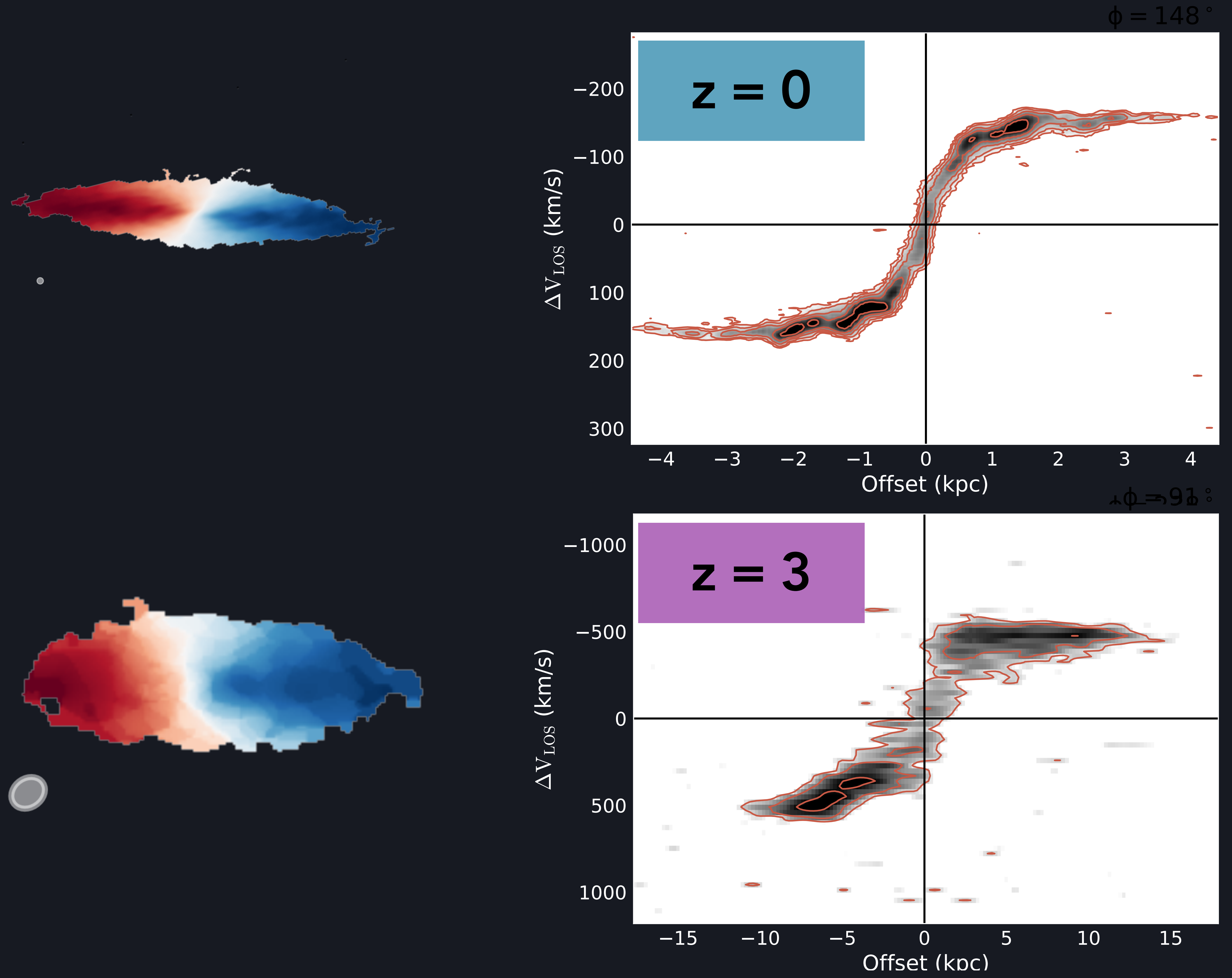
Rizzo et al., 2023

A L P A K A Kinematic classification

Beyond the classical classification based on the velocity gradient

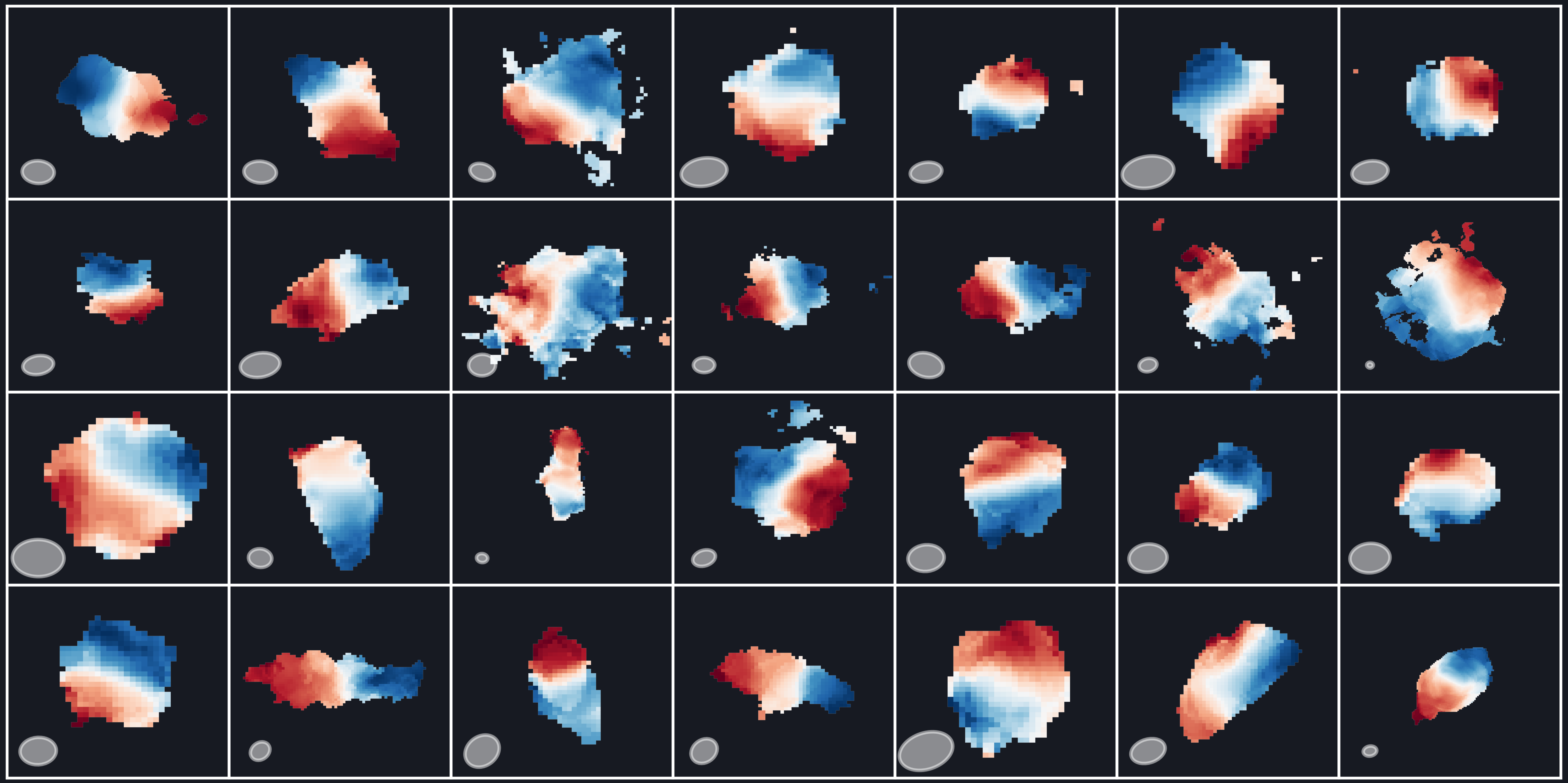
Identification of galaxy disks based on analysis of the cubes and the position-velocity diagram

PVsplit (see Rizzo et al. 2022)



Rizzo et al., 2023

ALPAKA Kinematic analysis



Disks: 19/28 ············ ^{3D}BAROLO to derive V and σ. Beam-smearing correction

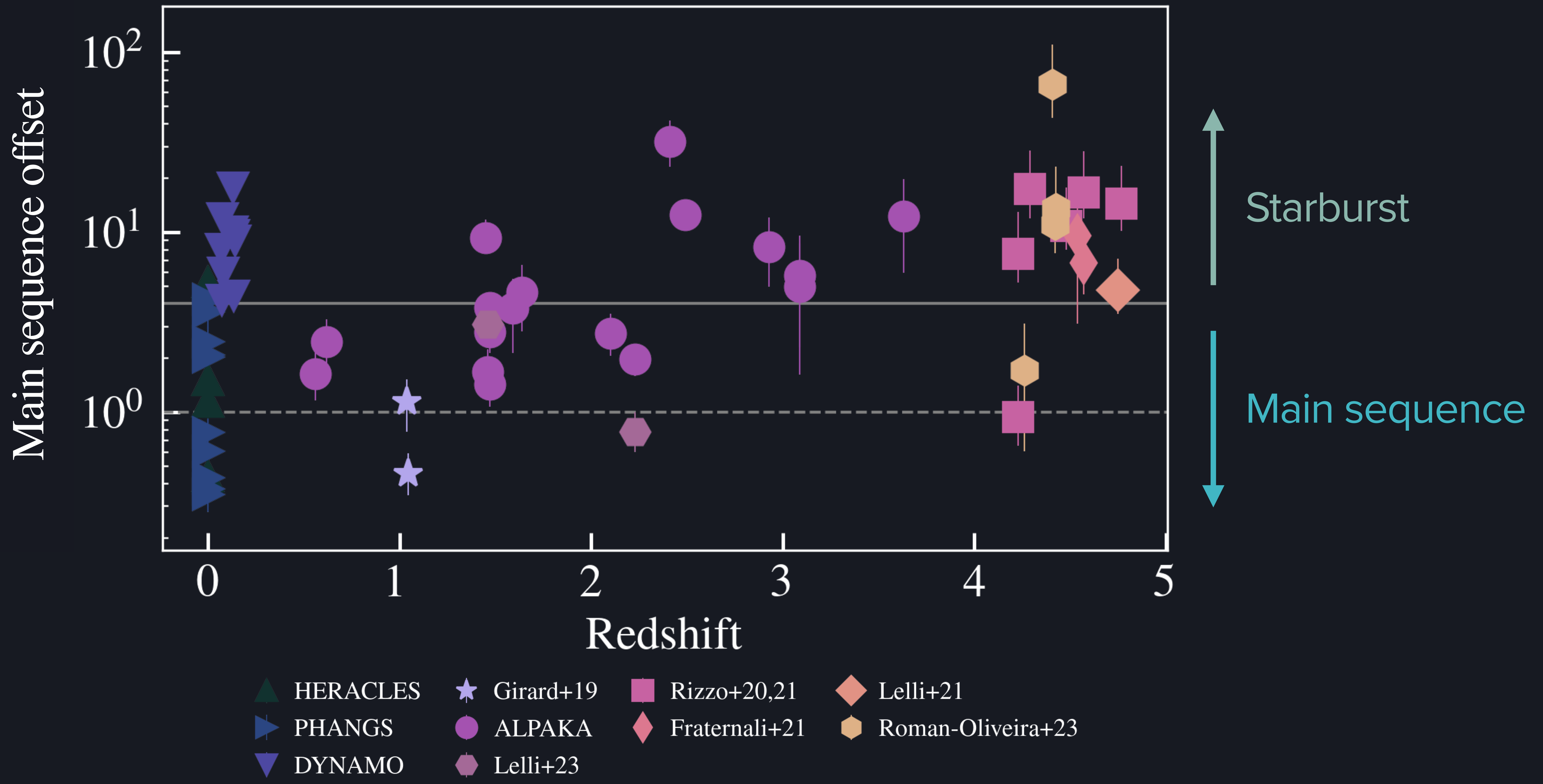
Mergers: 2/28

Uncertain: 7/28

Rizzo et al., 2023

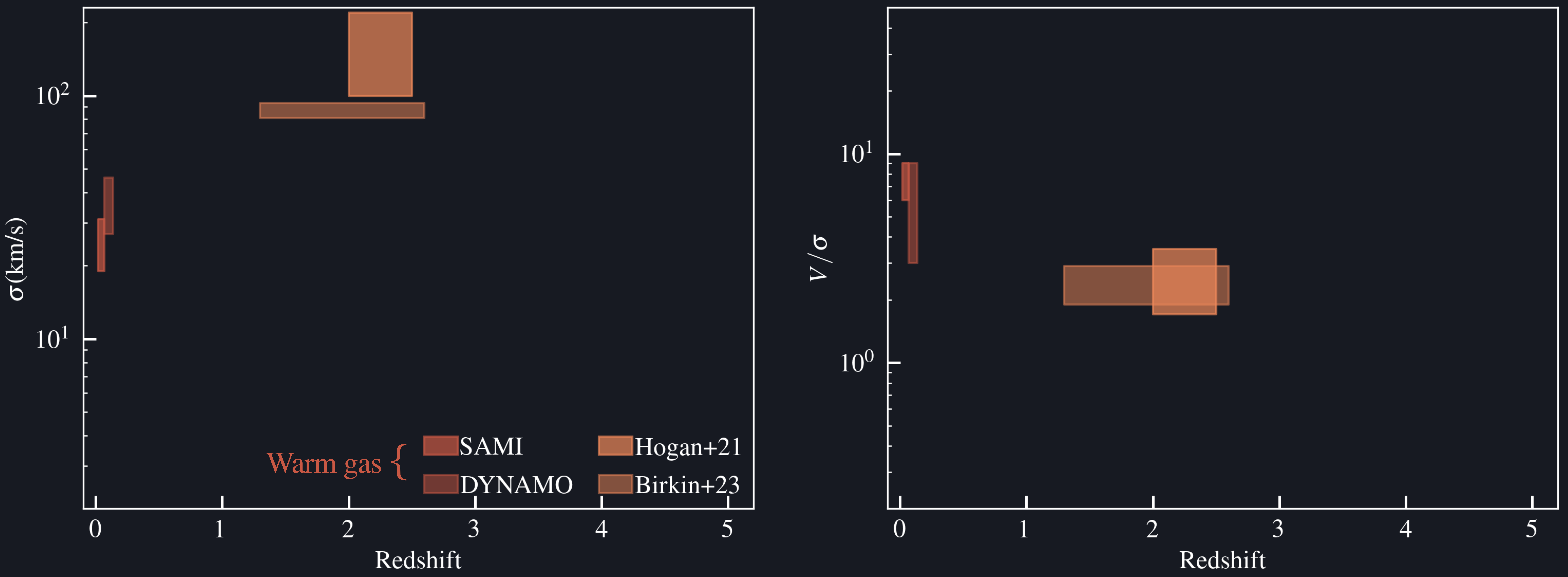
ALPAKA +

57 galaxies in total: same stellar mass range and MS offset of ALPAKA disks



Rizzo et al., 2024

Cold vs warm gas (same galaxy populations)



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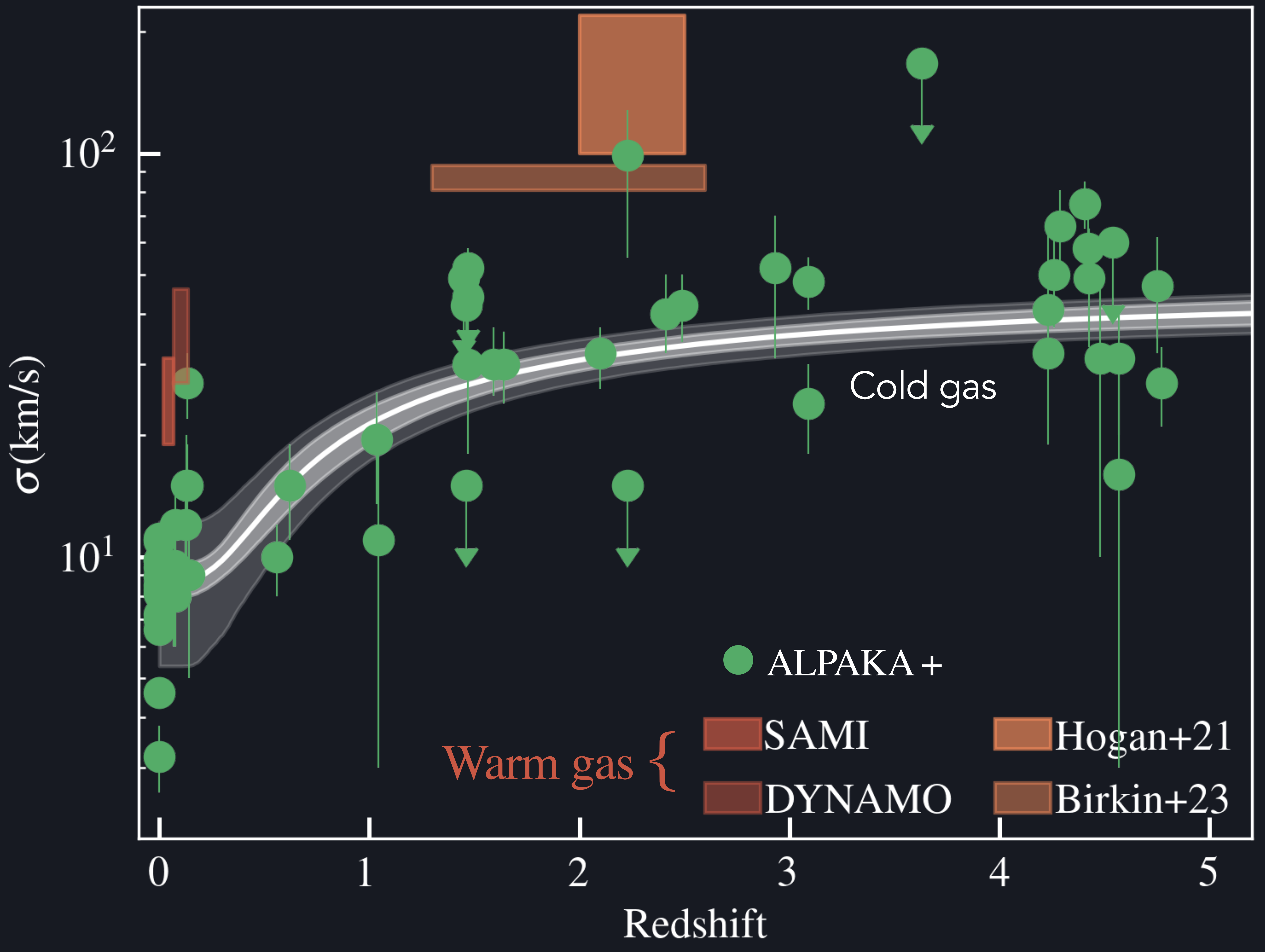
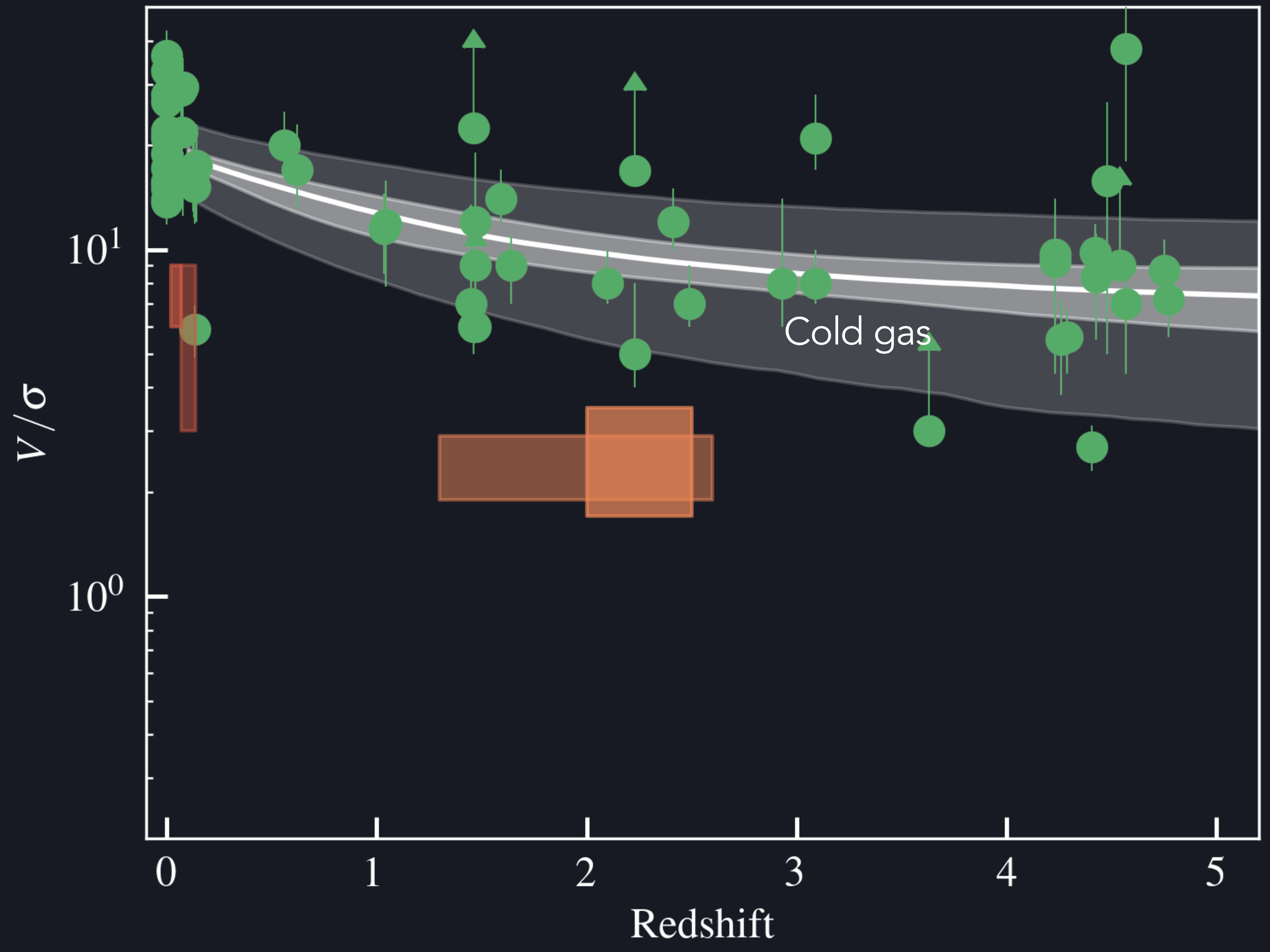
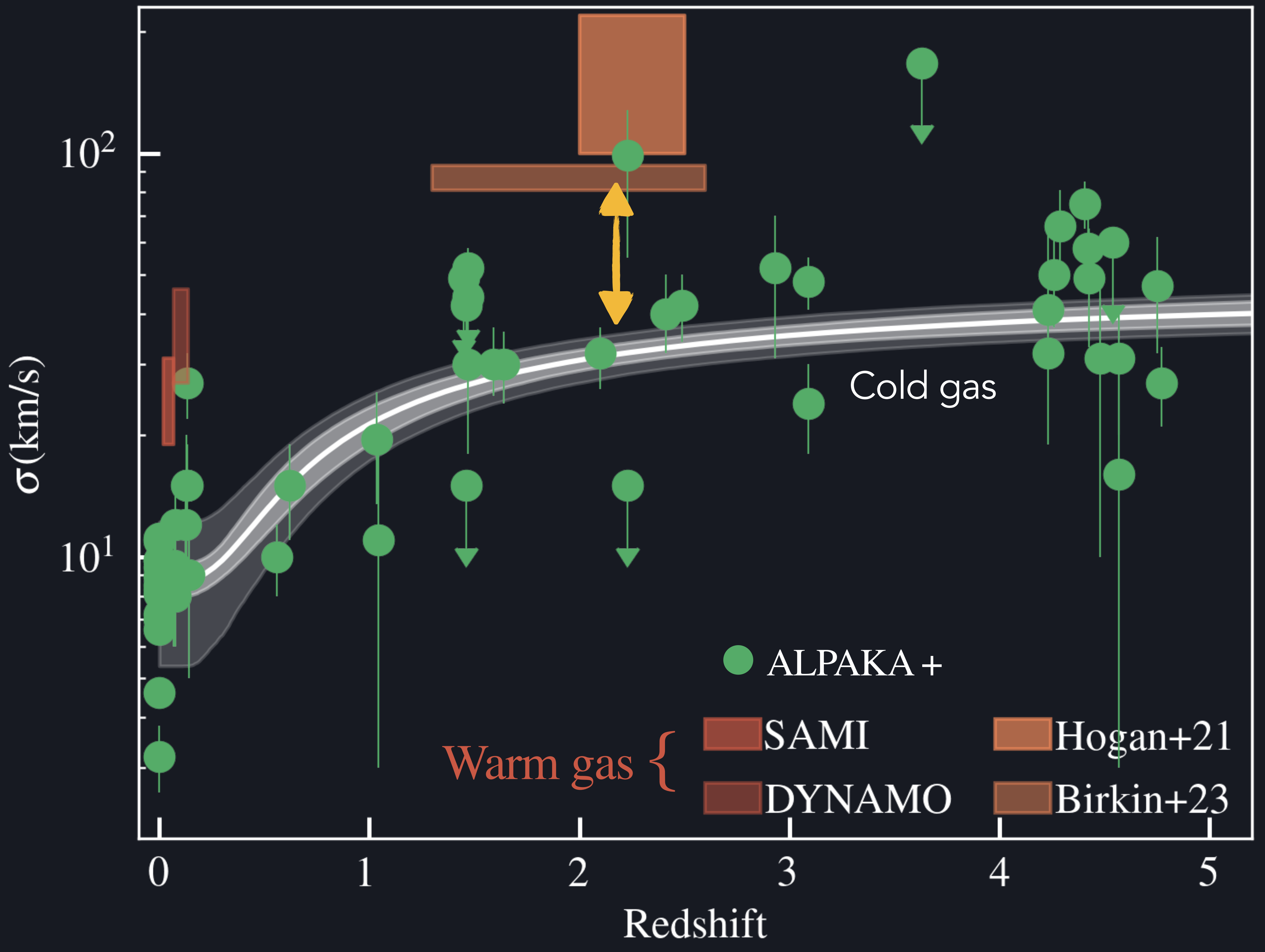


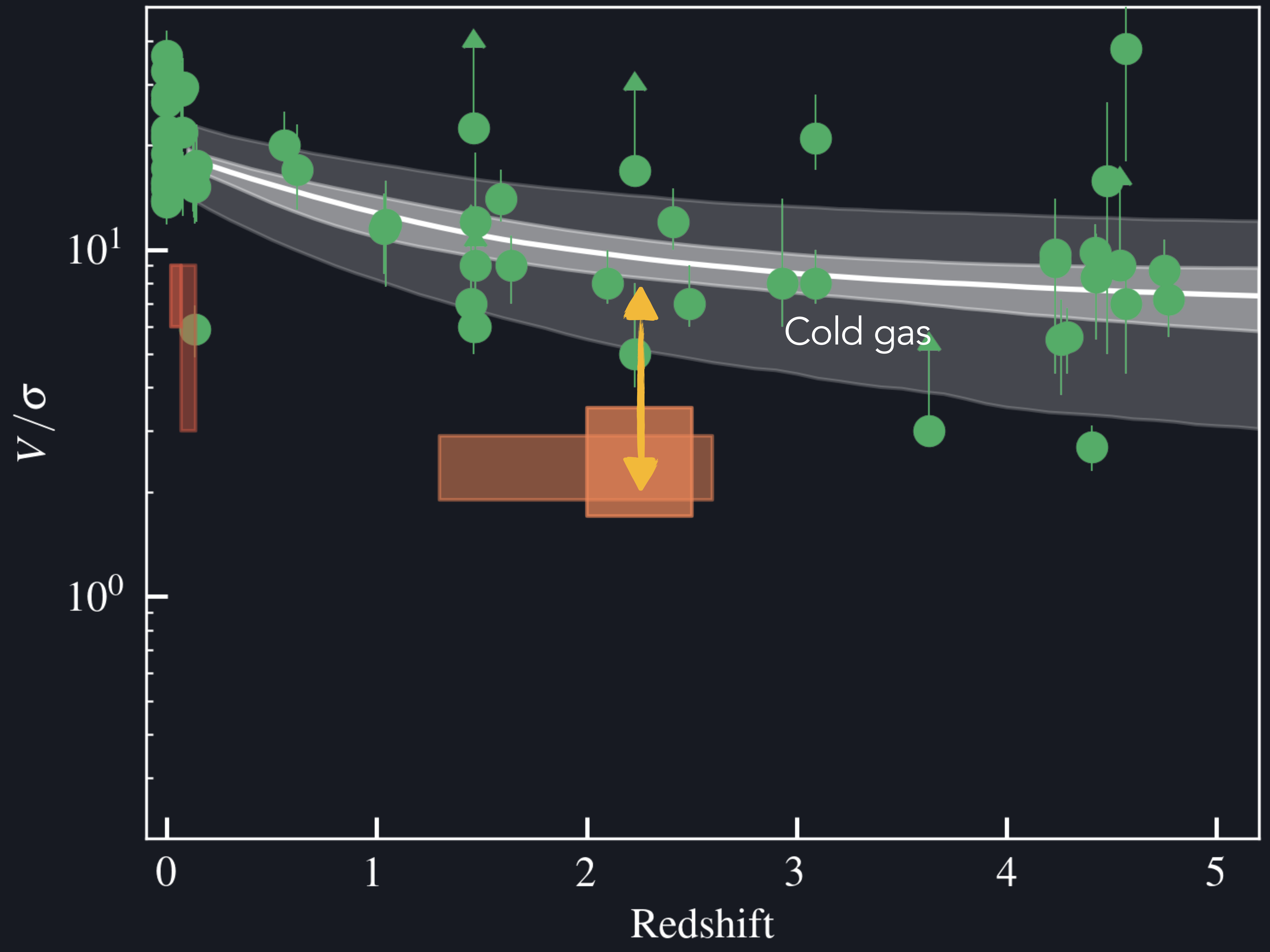


Rizzo et al., 2024

Cold vs warm gas (same galaxy populations)

Factor of 3 difference between warm and cold gas





Rizzo et al., 2024

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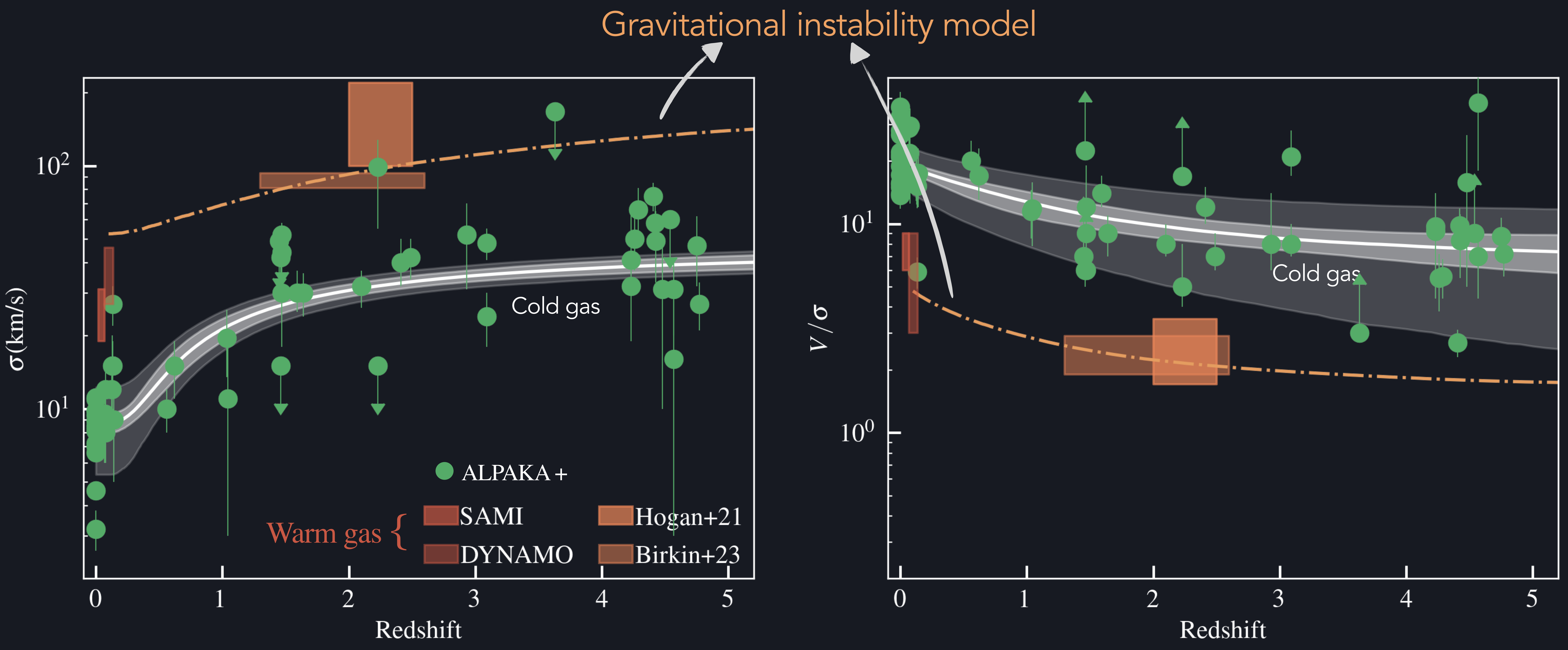

Rizzo et al., 2024

Why is there a difference between cold and warm gas kinematics?

1. σ from Hα overestimated: spectral (and angular) resolution of Hα observations worse than ALMA

2. σ from Hα: contamination from non-circular motions (e.g., see results from zoom-in simulations)

Kohandel et al., 2024, including FR

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+

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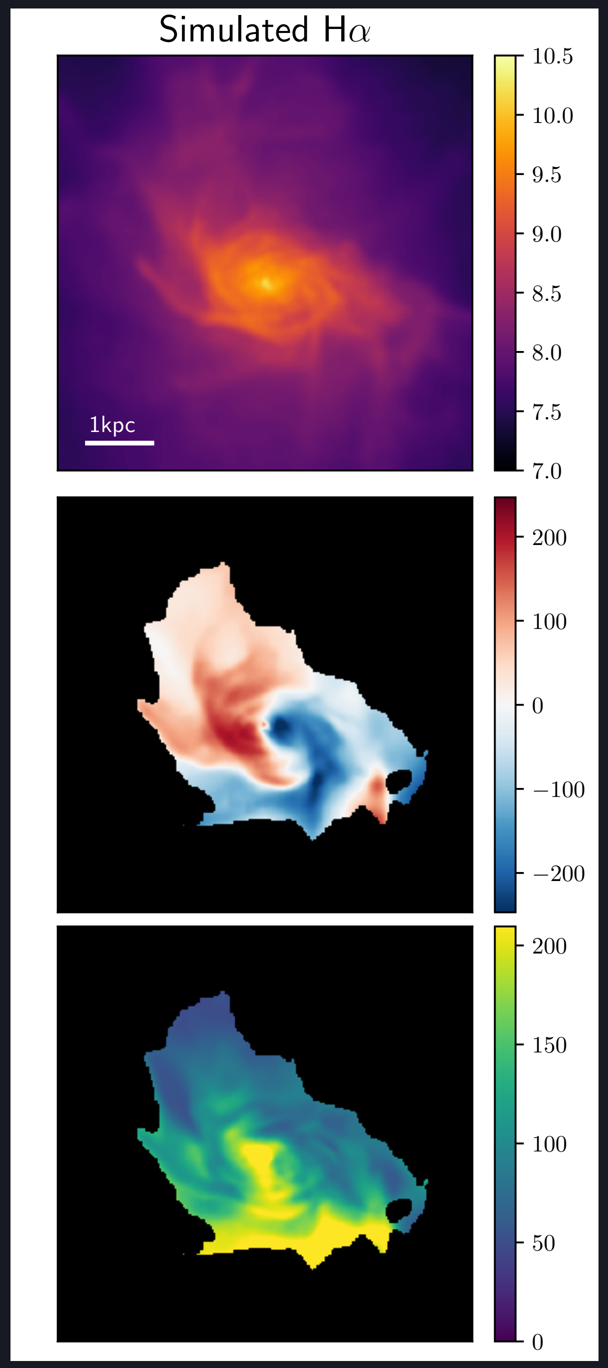
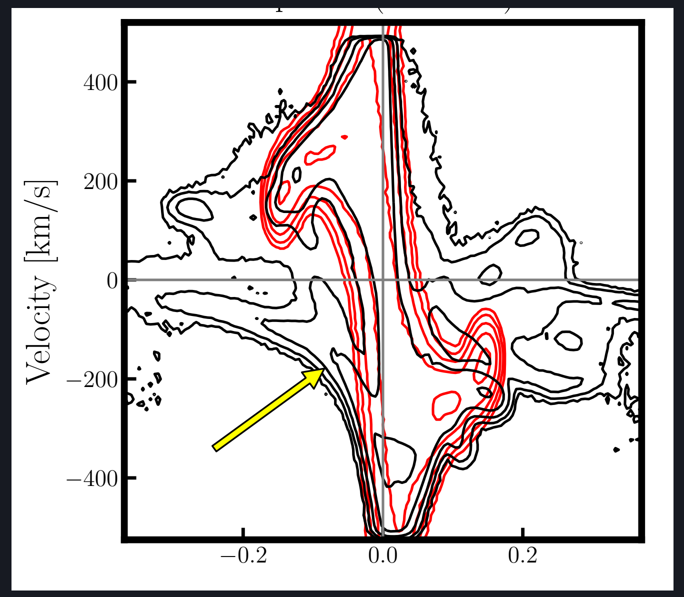
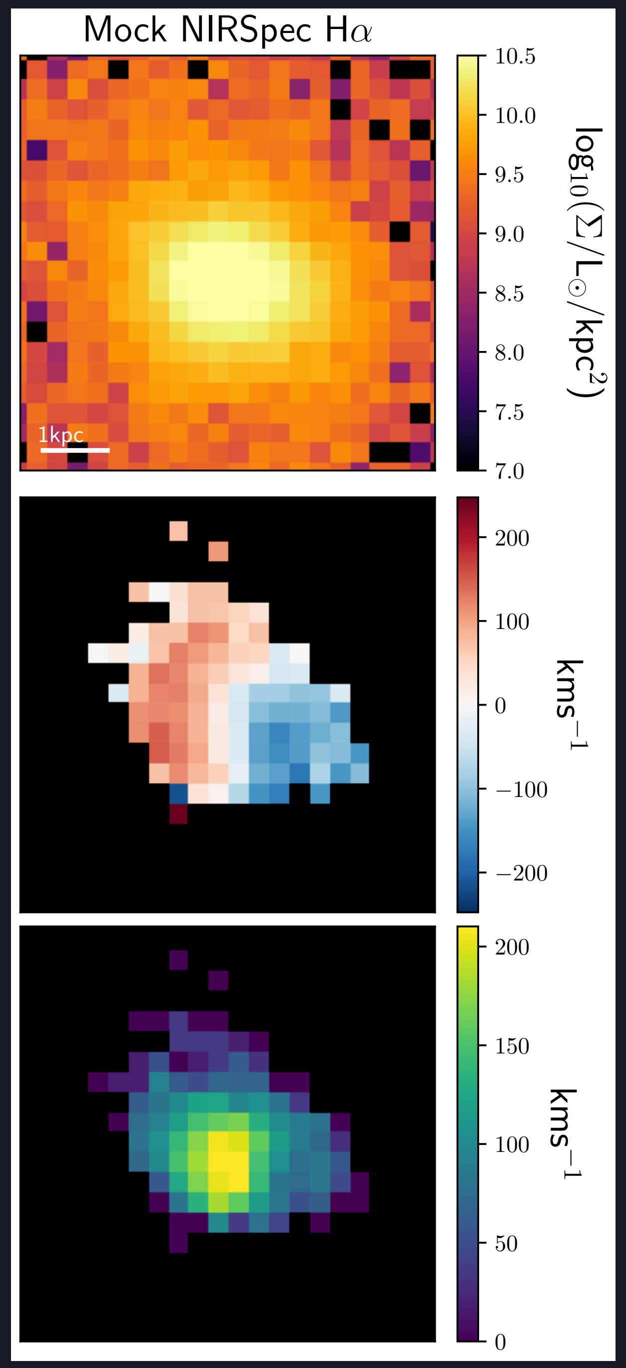
Simulation



Position-velocity
Major axis



JWST/IFU mock



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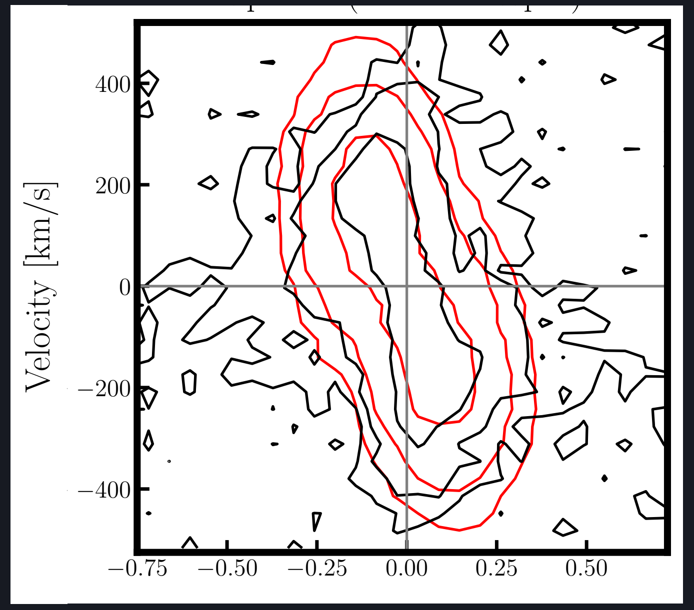

Measured $\sigma_{H\alpha}$: 2 x intrinsic $\sigma_{H\alpha}$

Measured $\sigma_{H\alpha}$: 5 x intrinsic σ_{CII}

Phillips, Rizzo et al. submitted to MNRAS

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2. σ from Hα: contamination from non-circular motions (e.g., see results from zoom-in simulations)
3. Intrinsic difference (e.g., z =0 galaxies)

Evolution of galaxy disks across human (~30 years) time

Kinematics of galaxies

2006 — 2019 (IFS surveys, Hα)

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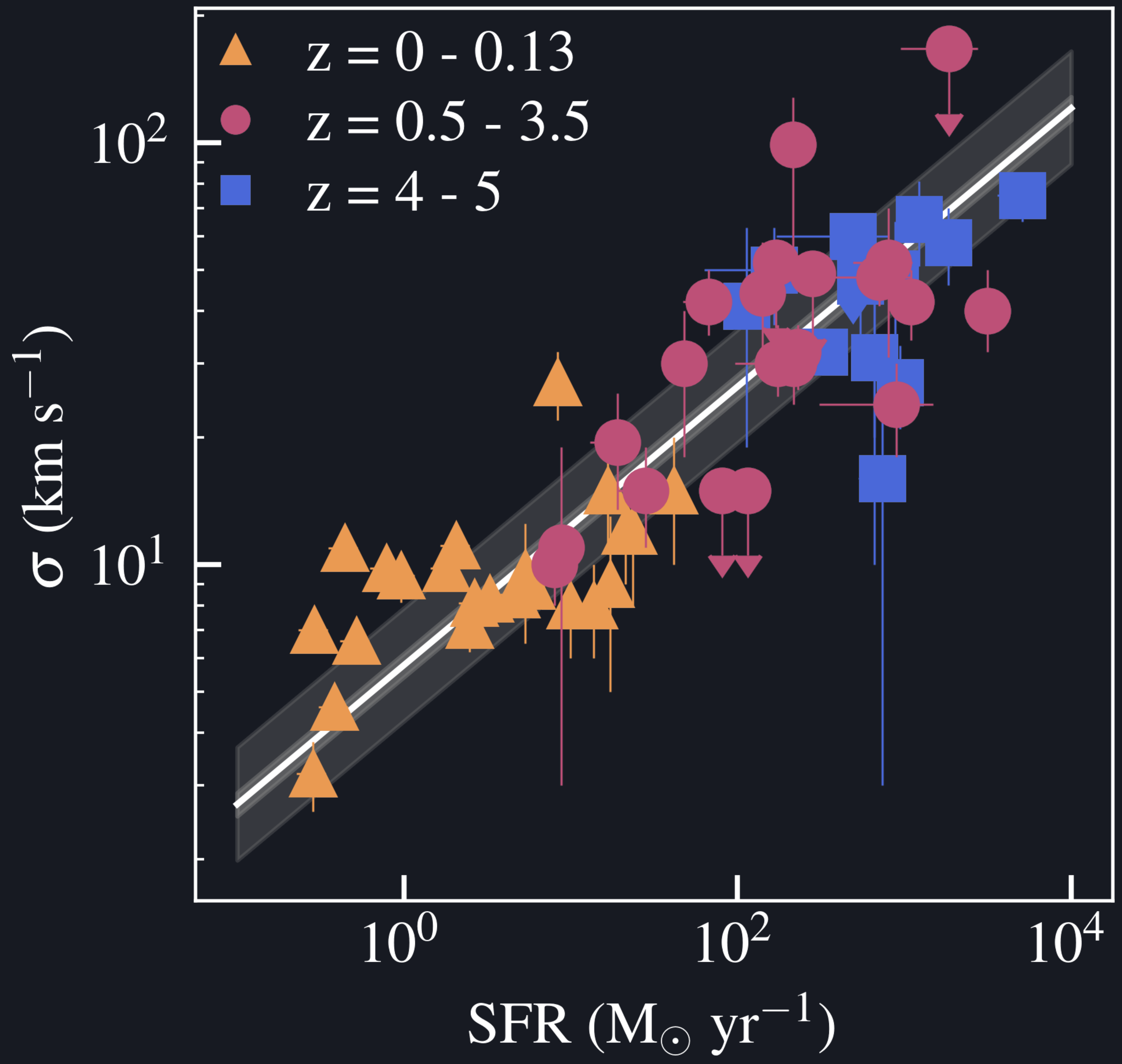
$$\sigma(z) = \frac{V f_{gas}(z)}{\sqrt{2}}$$

The impact of stellar feedback on the ISM



Rizzo et al., 2024

Injection of turbulence from supernova (SN) explosions is sufficient to explain the (global) values of turbulence.

Evolution of galaxy disks across human (~30 years) time

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Take-home message

Kinematics of galaxies

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2020 — today (ALMA, cold)

Massive star-forming disks at z > 1: dynamically cold (V/σ ~ 10).

Do we need to rethink our assumptions about how galaxy disks assemble and evolve in the early universe?

Take-home message

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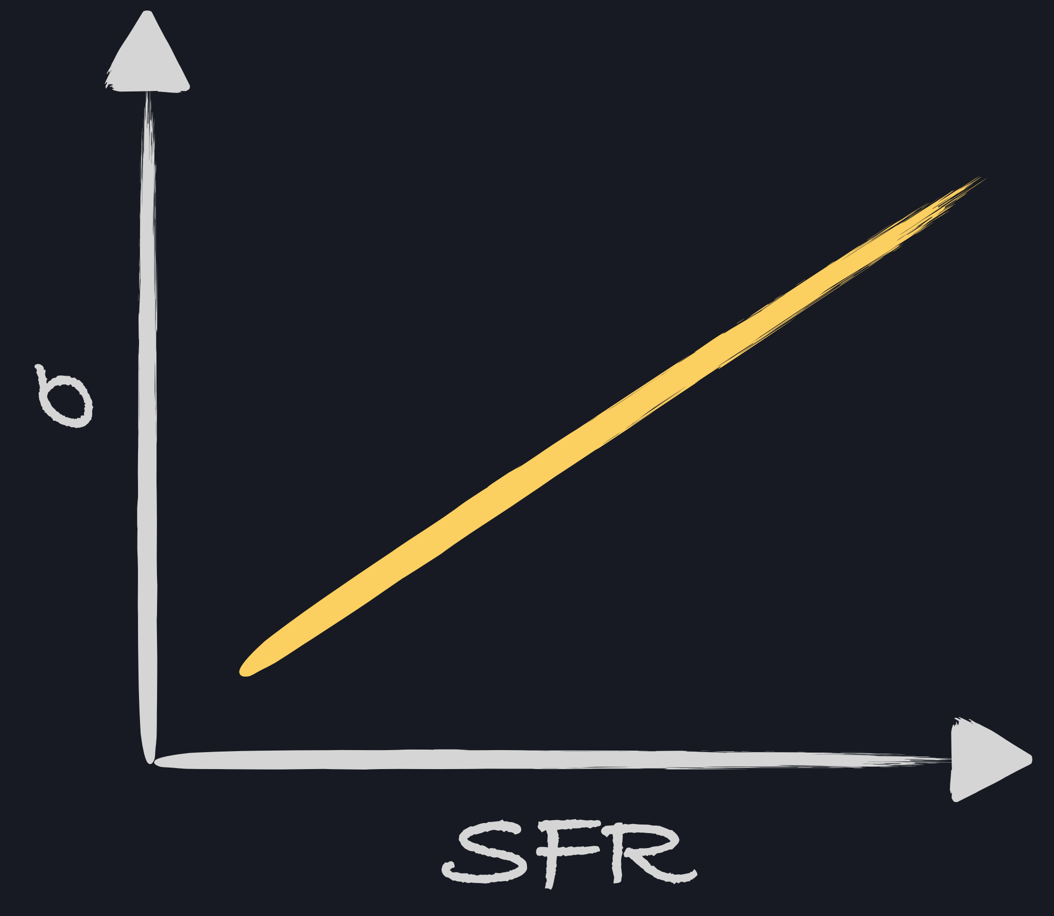
Warm gas kinematics: biased metrics

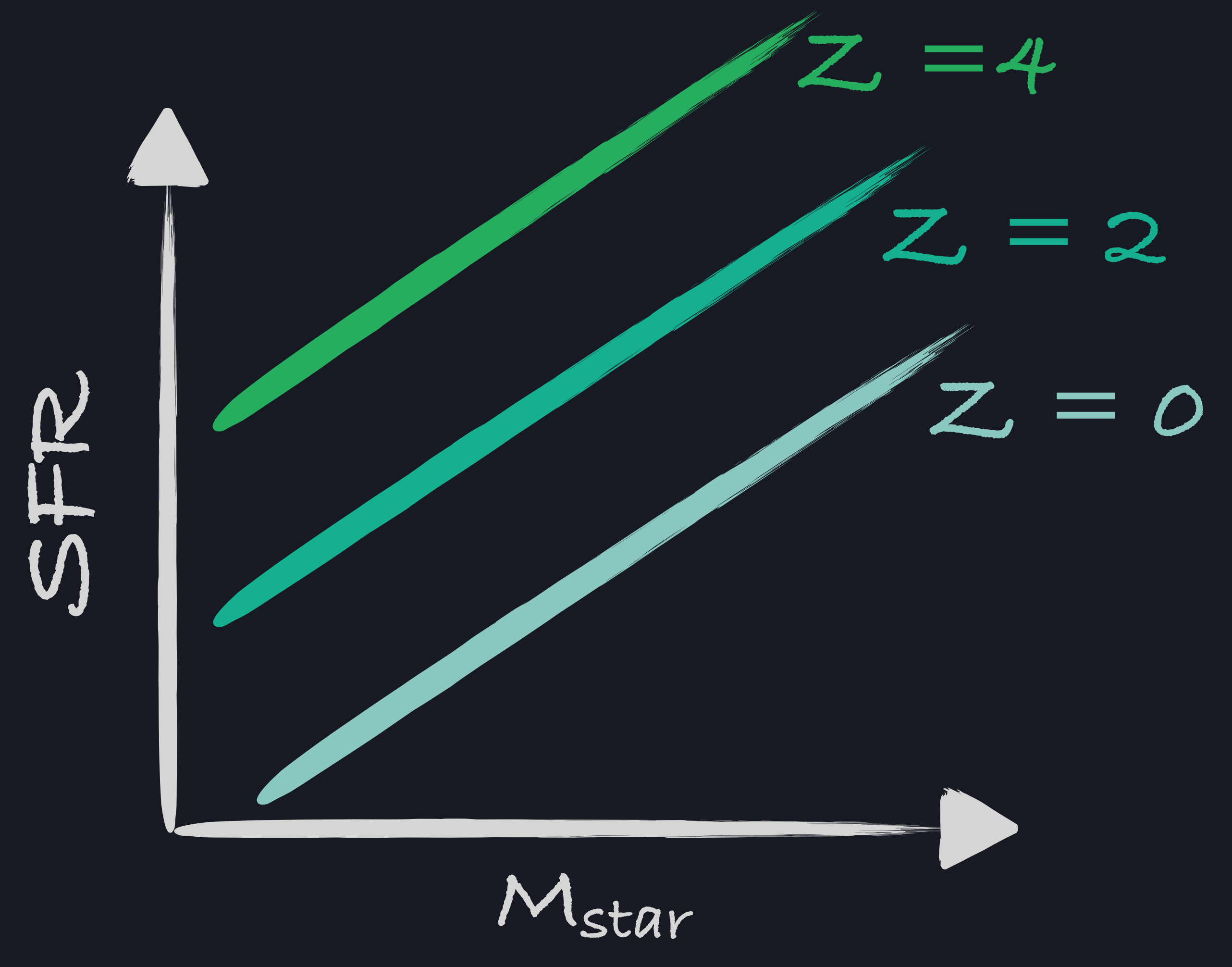
Cold gas kinematics needed to understand the evolution of galaxy disks

Stellar feedback: crucial role in driving the turbulence

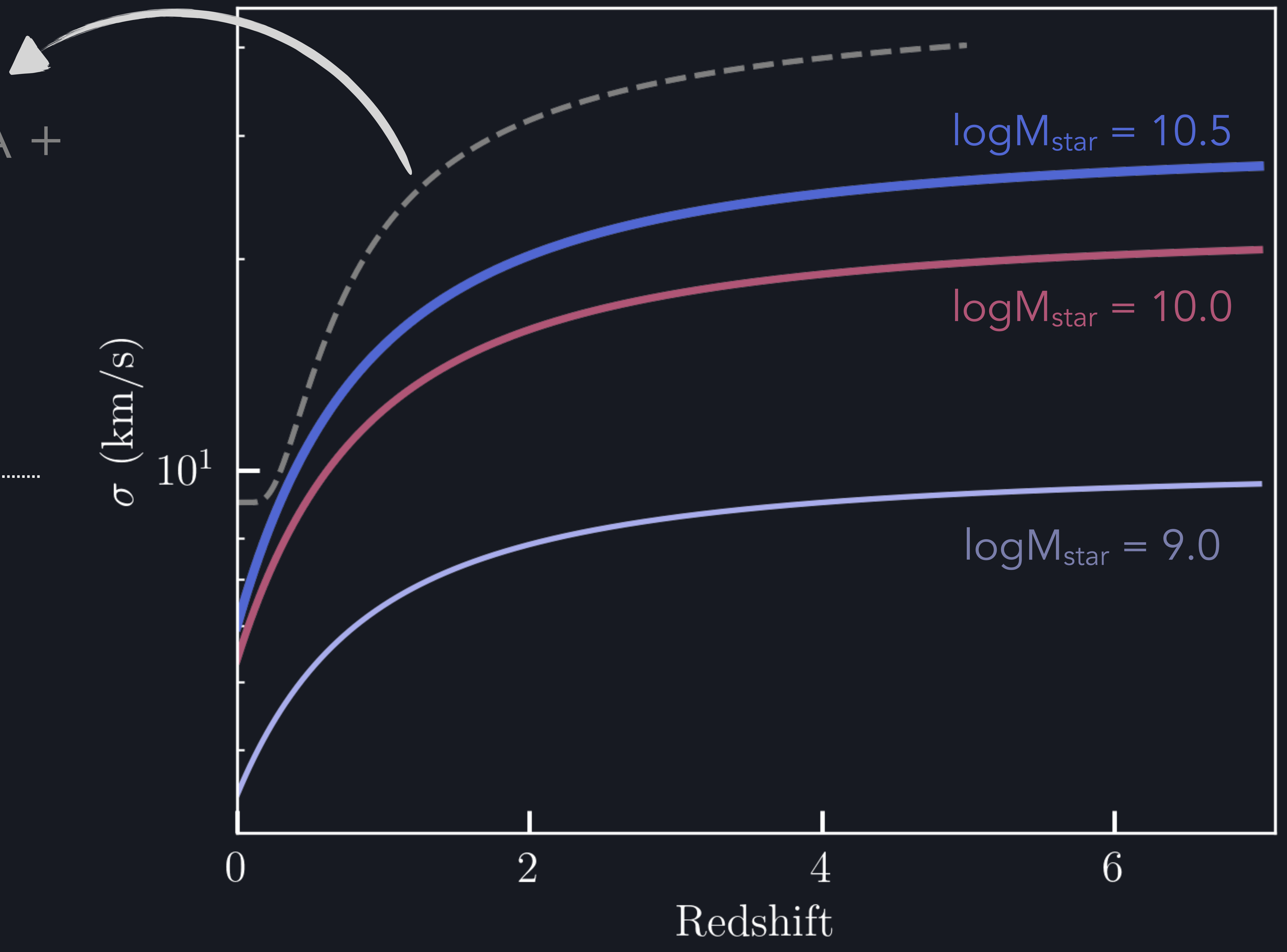
Future prospects

What about main-sequence galaxies?





ALPAKA +



Rizzo et al., 2024

Studying typical star-forming galaxies at z = 1 – 2.5

Cycle 11 ALMA Large Program: 230 hours for ~1 kpc resolution CO(3-2) + dust continuum (Band 7)

Massive, main-sequence galaxies (> 10^{10} $M_\odot$)

PIs: Rizzo, Kaasinen, Aravena, Neeleman

Key objectives:

Dynamical properties of typical massive disks

Star-formation regulation and local gravitational instability (gas surface brightness, gas thickness, etc.)

Scaling relations (e.g., specific angular momentum vs Mass)

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"Coming astronomical facilities such as Atacama Large Millimeter/submillimeter Array (ALMA) will be able to resolve the scaling properties of galactic turbulence up to very high redshifts. Such data [..] will reveal the interplay between gravitational instability and turbulence".

A. Romeo et al. 2010

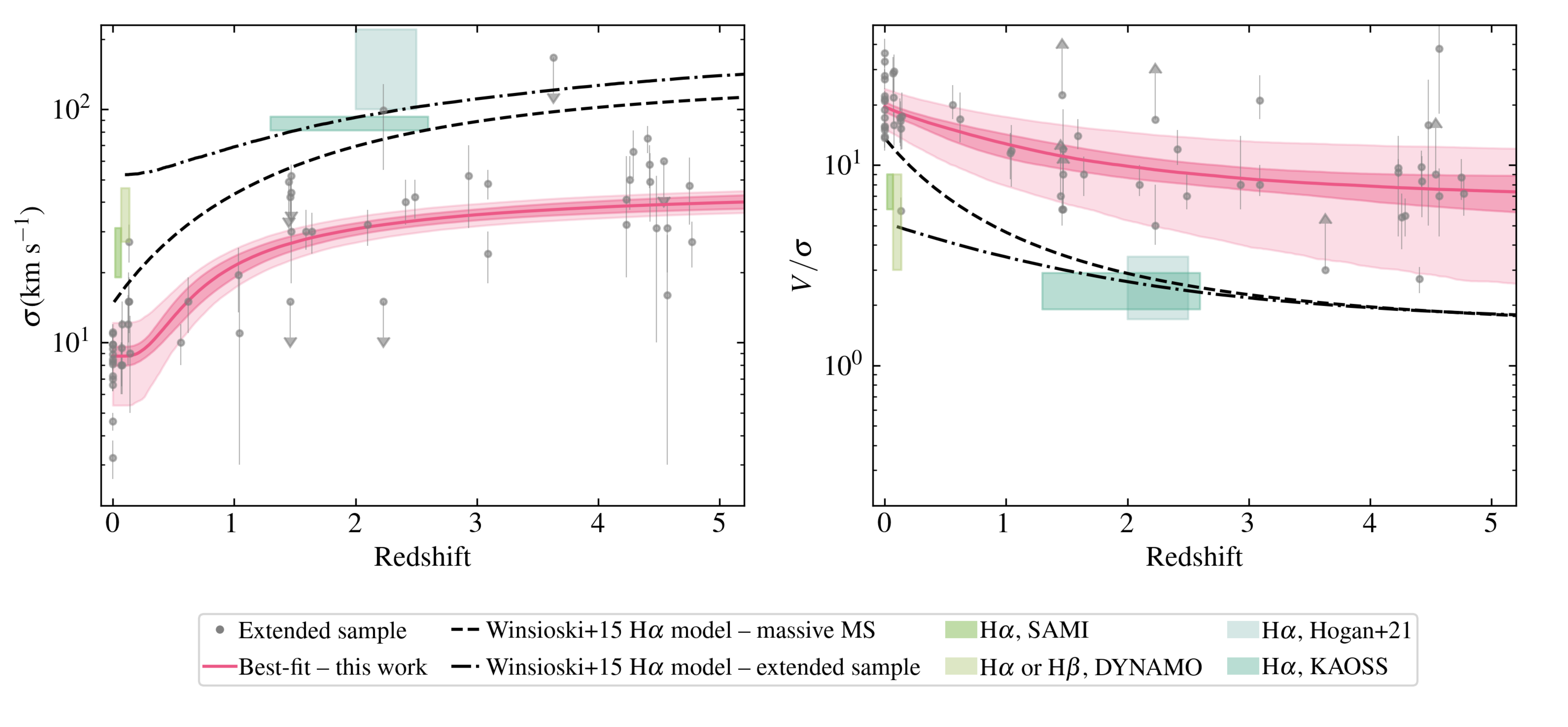
Future prospects

Short-term: CONDOR, cold gas kinematics in massive main-sequence galaxies

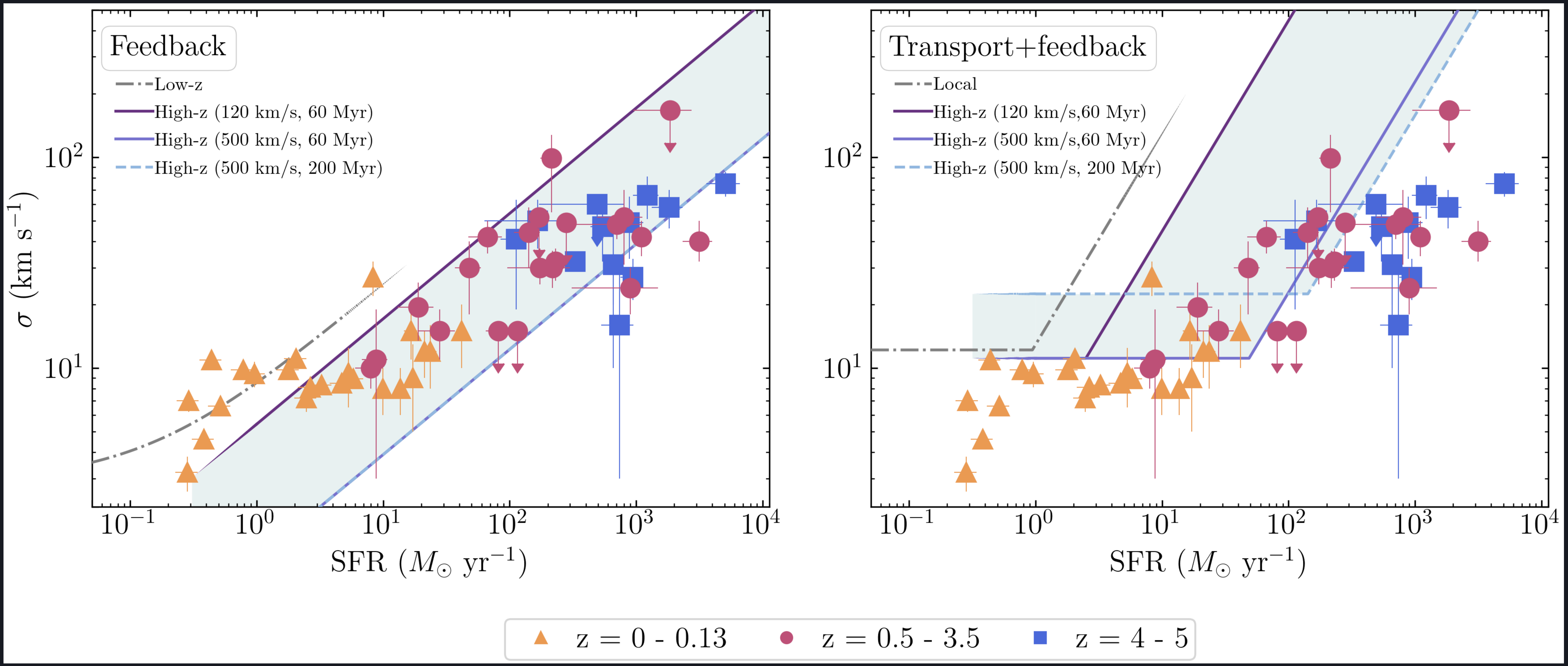
Long-term: major upgrade of mm-facilities needed for exploring new parameter spaces:

- ❖ “Normal” star-forming galaxies at $z > 4$
- ❖ Low-mass galaxies (Milky-Way progenitors) at $z > 1$

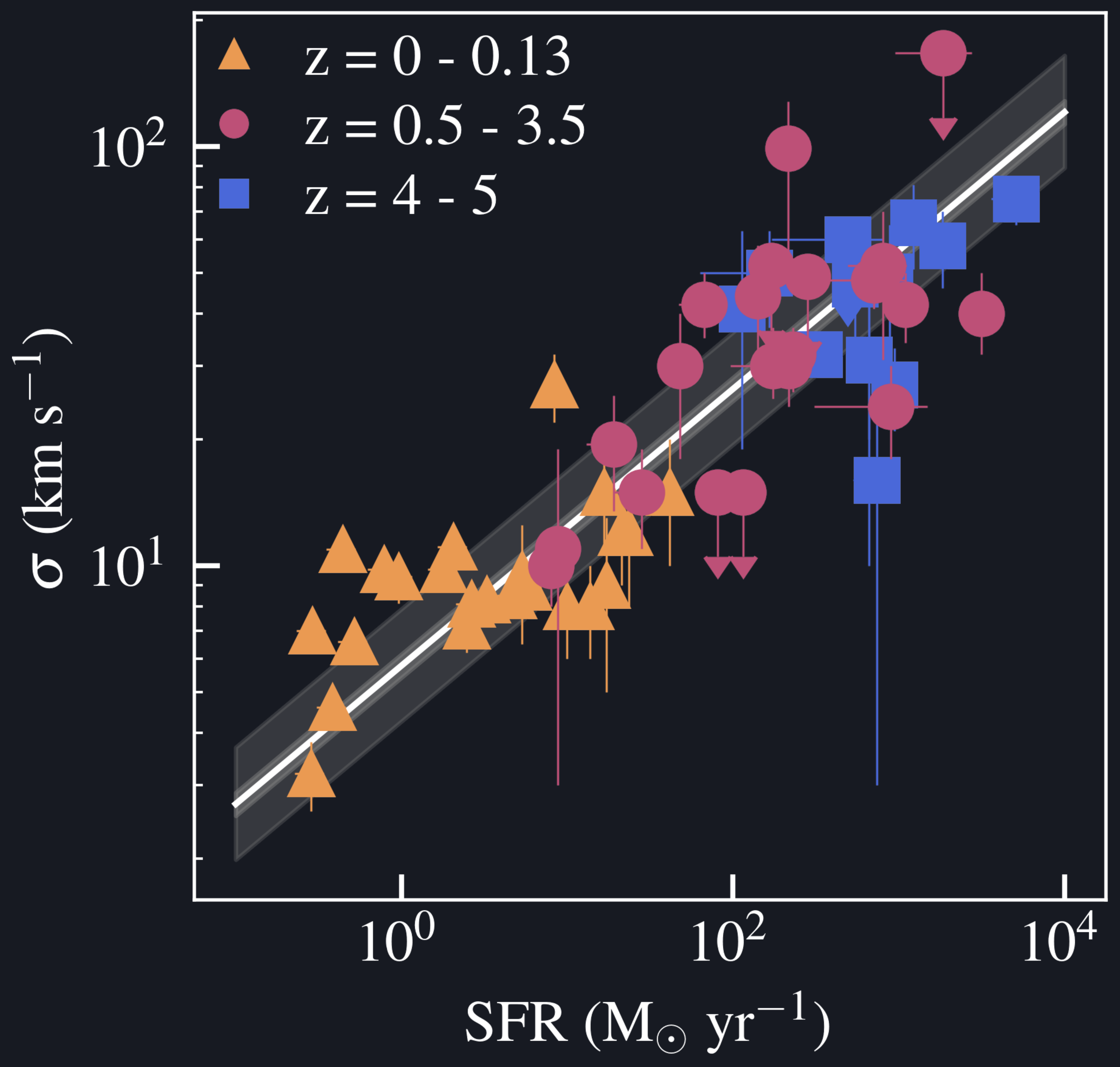
Warm vs cold gas kinematics



What is driving the turbulence?



The impact of stellar feedback on the ISM



Rizzo et al., 2024

Injection of turbulence from supernova (SN) explosions

$$E_{\rm kin} = \frac{3}{2} M_{\rm gas} \sigma^2$$

$$E_{\rm SF} = \epsilon_{\rm SN}\, {\rm SFR}\, \eta_{\rm SN}\, E_{\rm SN} \frac{2h}{\sigma}$$

$$\sigma \propto {\rm SFR}^{1/3}$$

$$\sigma = {\rm SFR}^{1/3} \left(\frac{4\, \epsilon_{\rm SN}\, \eta_{\rm SN}\, E_{\rm SN}\, h}{3\, M_{\rm gas}} \right)^{1/3}$$