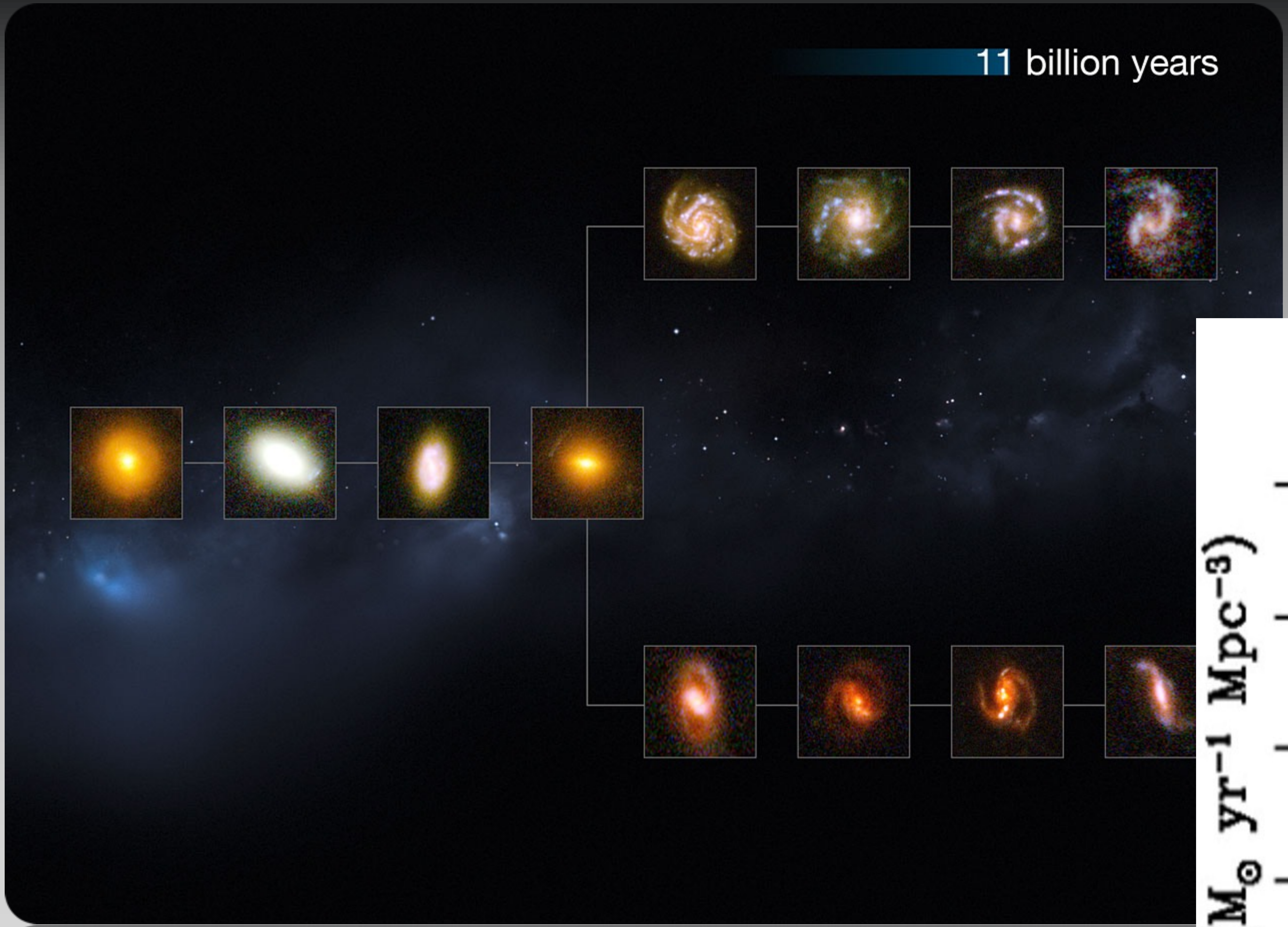
Star formation and molecular gas at cosmic noon with ALMA Band 2

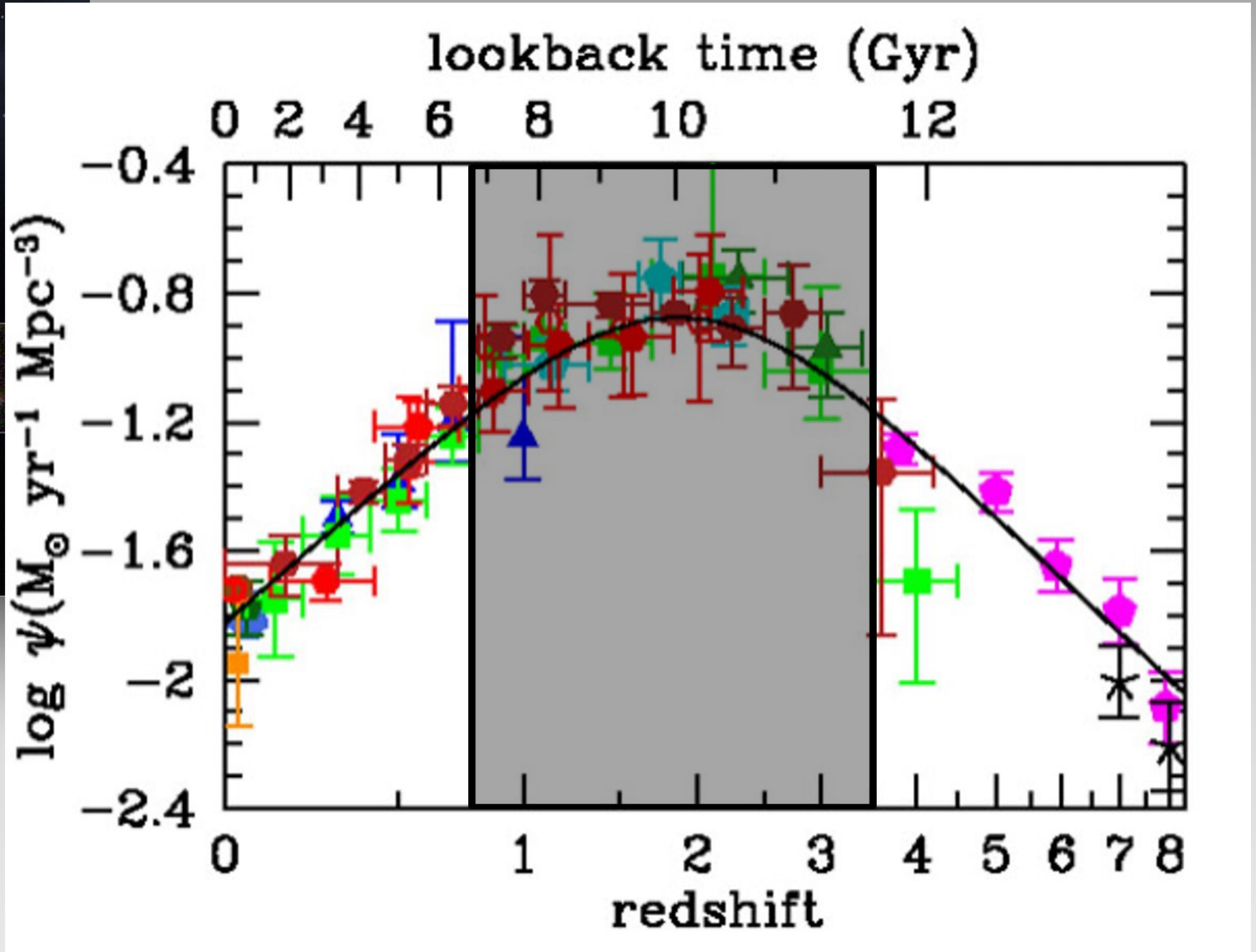
Annagrazia **Puglisi** (she/her)

University of Southampton

Bologna, 24/02/2026



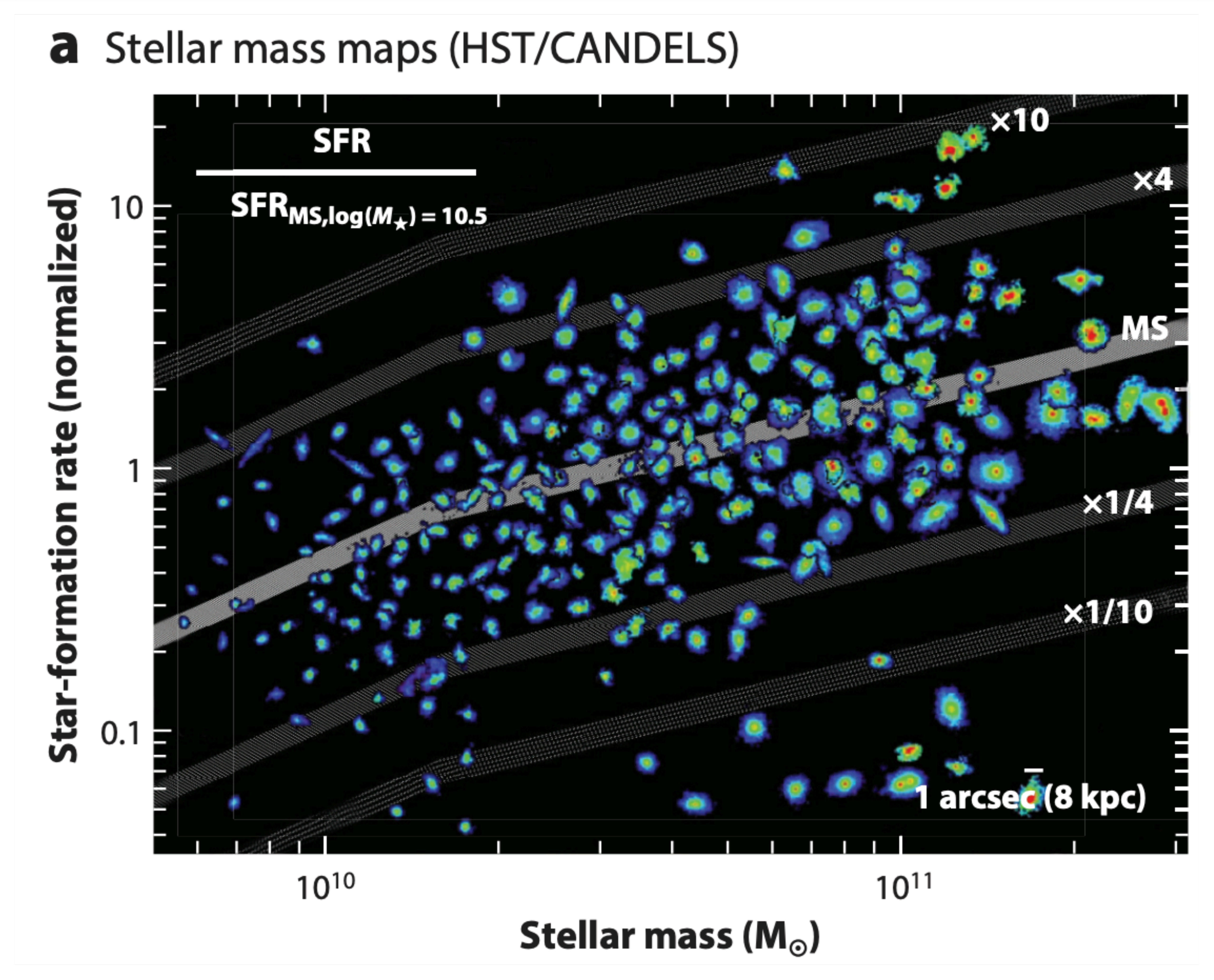
Credits: NASA, ESA, M. Kornmesser



Madau & Dickinson, 2014

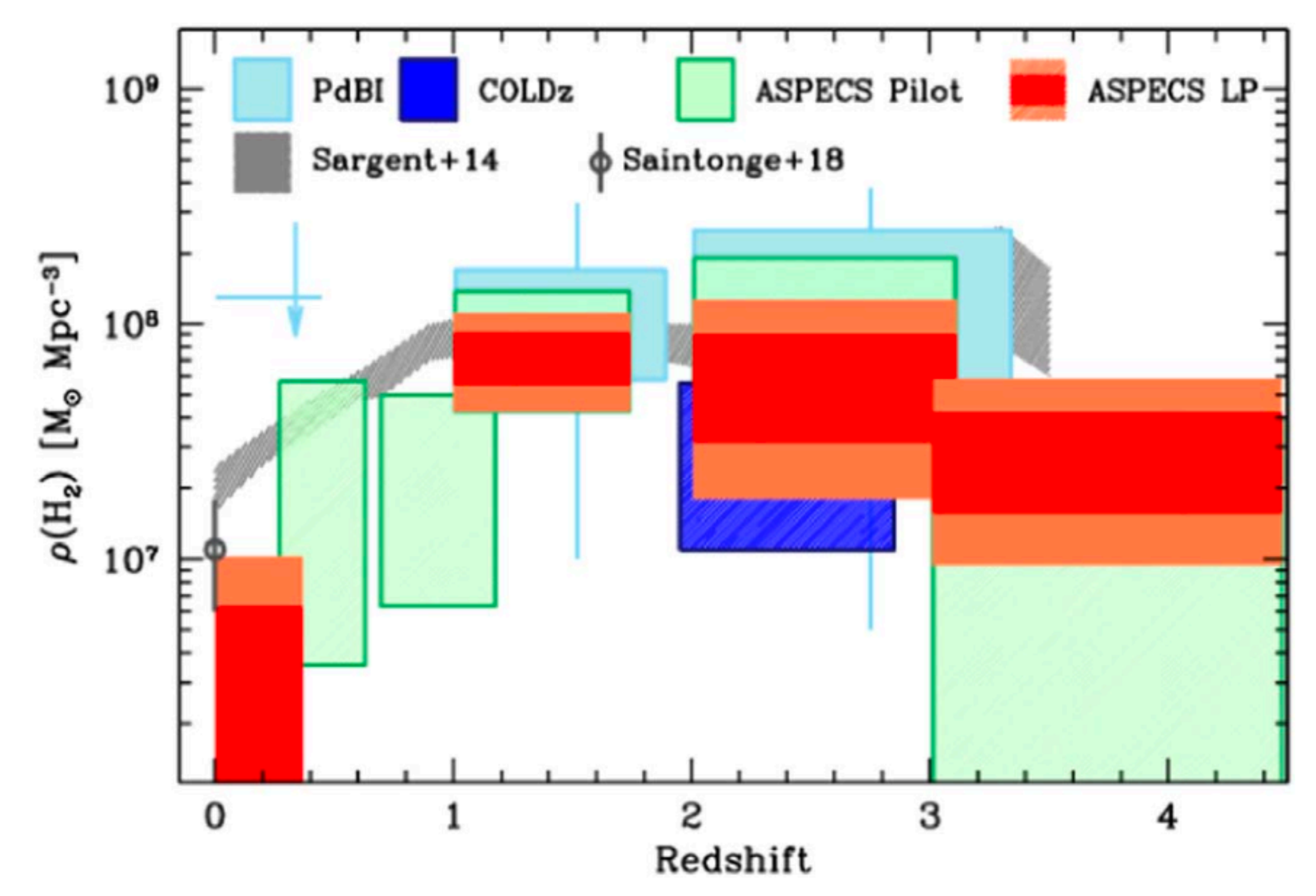
Star-Forming Galaxies at cosmic noon

- **Most star formation** occurs in large rotating discs within the main sequence, with prominence of bulges increasing with stellar mass
- Few starbursts (**~2-10%**) with SFR >> SFR_{MS} and predominantly irregular morphologies
- Optical/near-infrared properties of SFGs suggest **smooth growth** of galaxies regulated by a balance between **accretion and feedback**.



Forster-Schreiber and Wuyts, ARAA, 2020

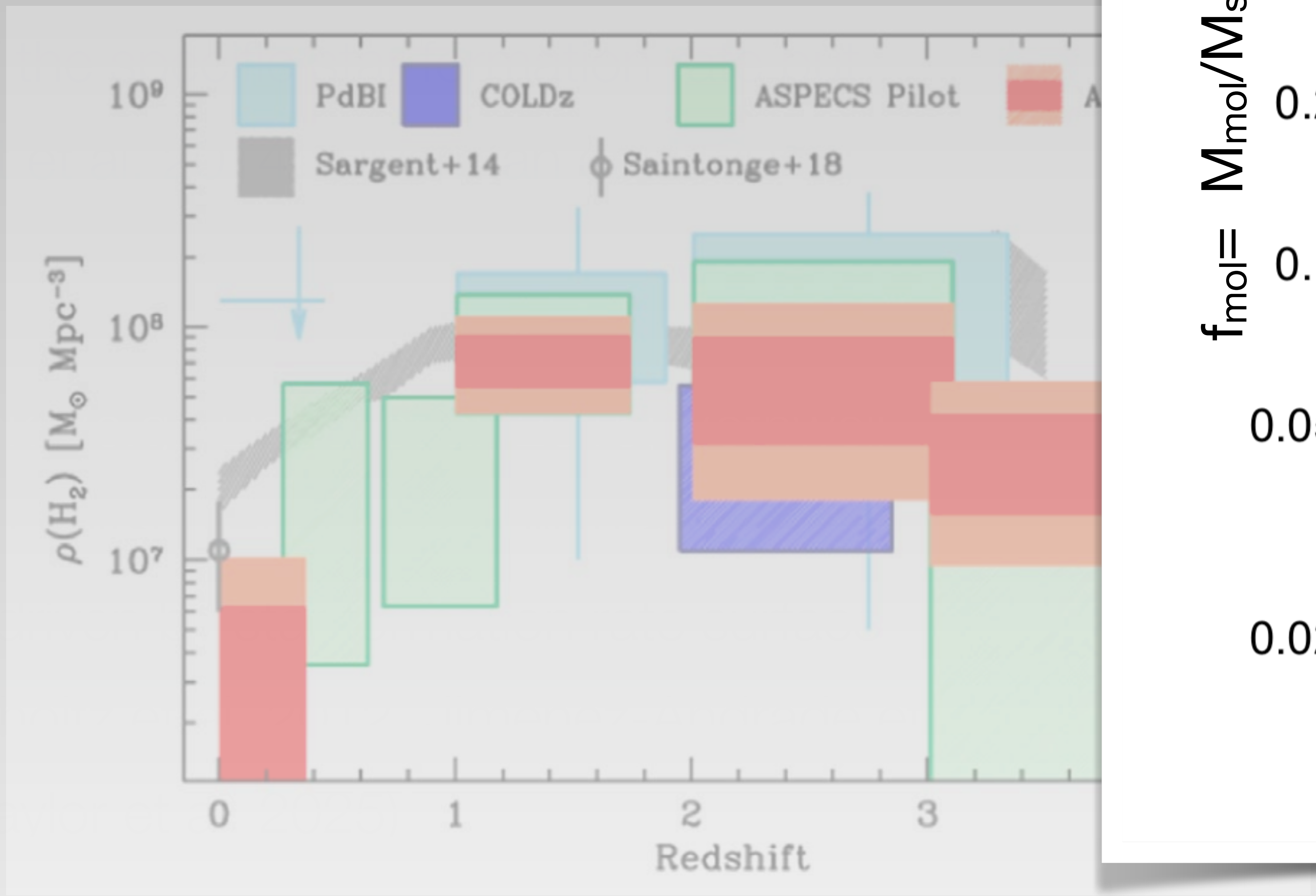
Molecular gas properties of cosmic noon SFGs

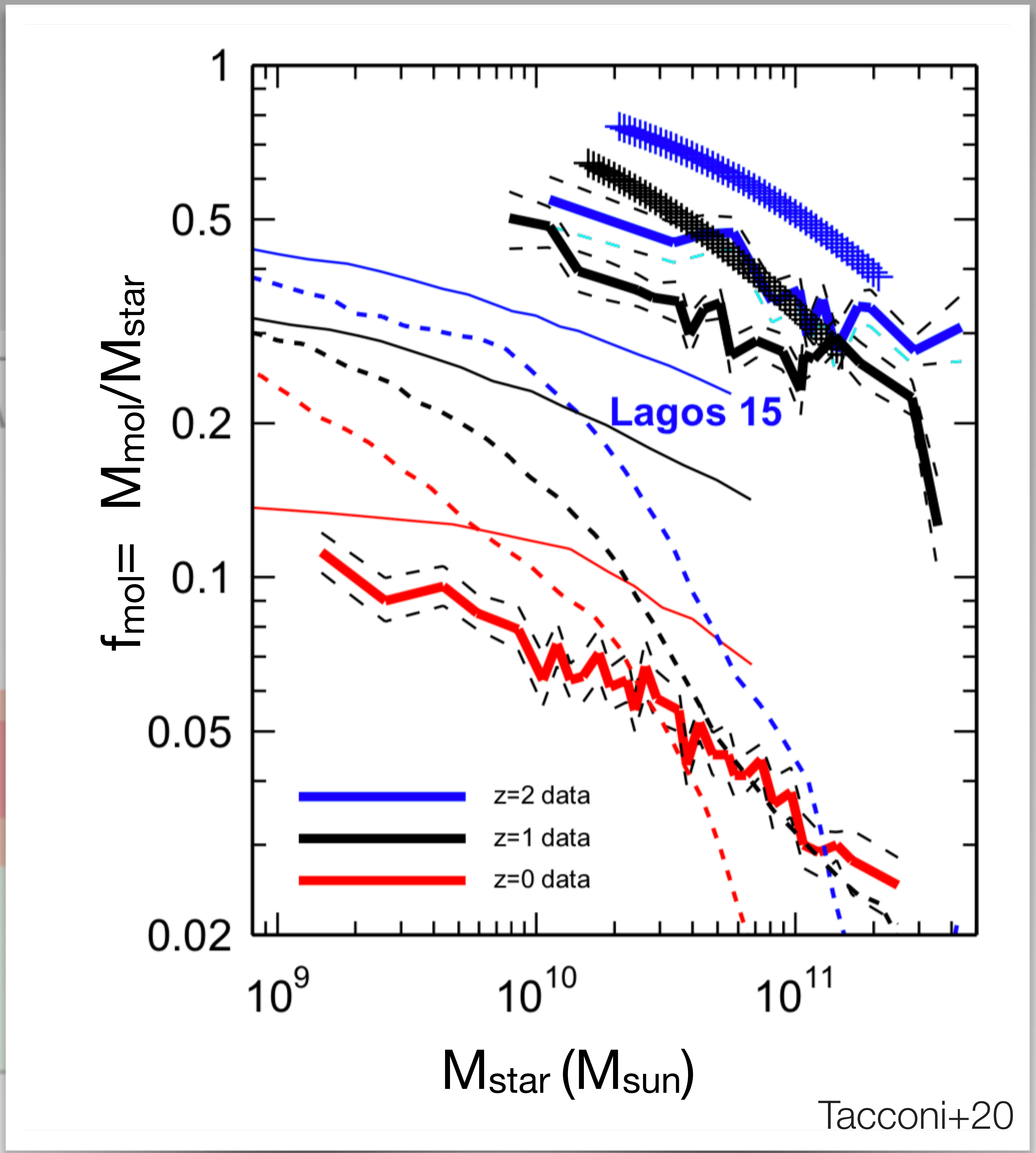


Decarli+19

Molecular gas properties of cosmic noon SFGs

- Strong evolution in **cosmic molecular gas density** and **high gas fractions** (~50%, e.g. Tacconi et al. 2020; Decarli et al. 2019)

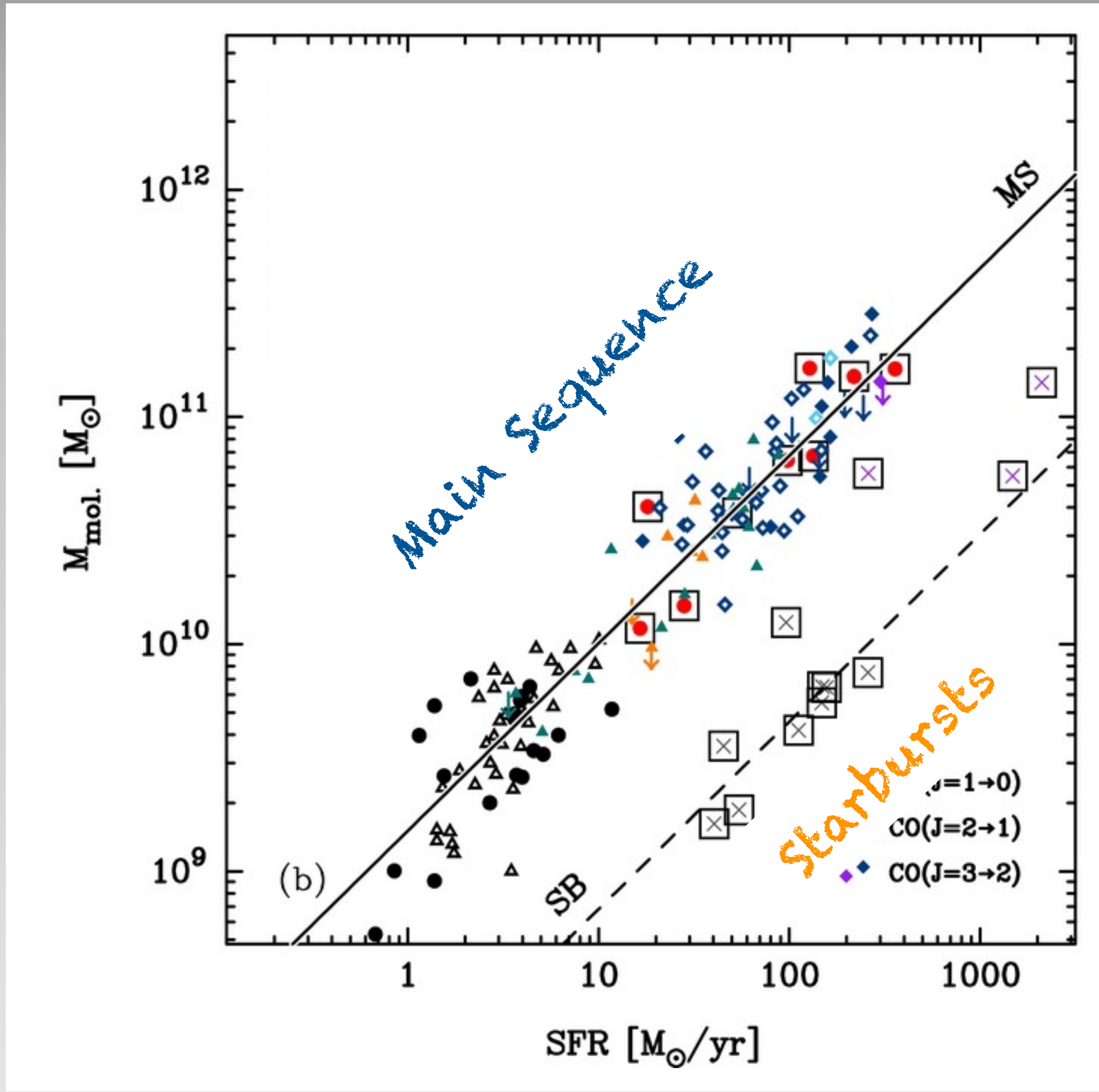




Molecular gas properties of cosmic noon SFGs

- Strong evolution in **cosmic molecular gas density** and **high gas fractions** (~50%, e.g. Tacconi et al. 2020; Decarli et al. 2019)

- Mild evolution of **star formation efficiency** (SFE = SFR / M_{gas}), with gradual increase as a function of the specific star formation rate but with **large scatter** (e.g., Sargent et al. 2014; Silverman et al. 2018; Valentino et al. 2020).



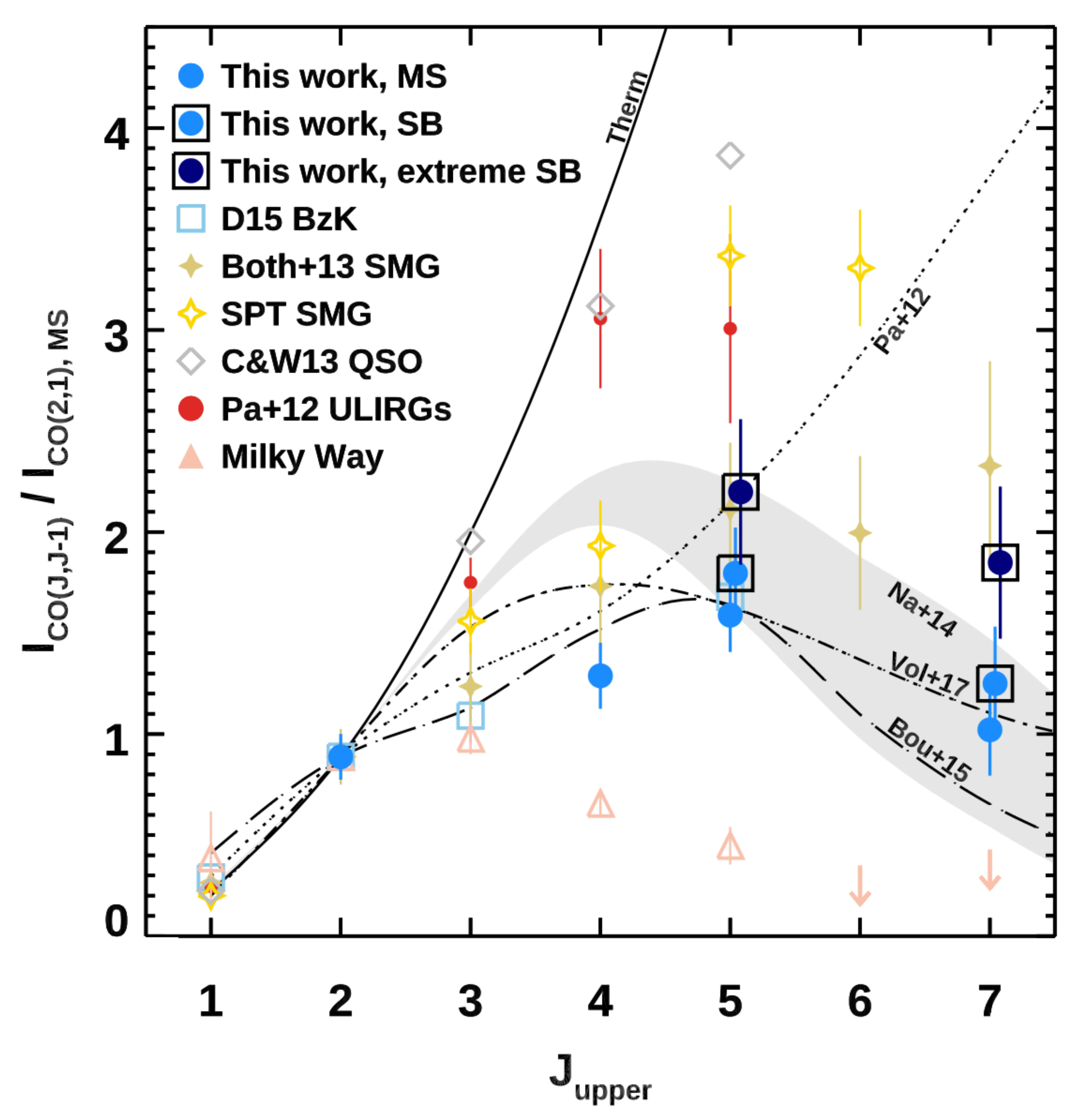
Sargent+14

Molecular gas properties of cosmic noon SFGs

- Strong evolution in **cosmic molecular gas density** and **high gas fractions** (~50%, e.g. Tacconi et al. 2020; Decarli et al. 2019)

- Mild evolution of **star formation efficiency** (SFE = SFR / M_{gas}), with gradual increase as a function of the specific star formation rate but with **large scatter** (e.g., Sargent et al. 2014; Silverman et al. 2018; Valentino et al. 2020).

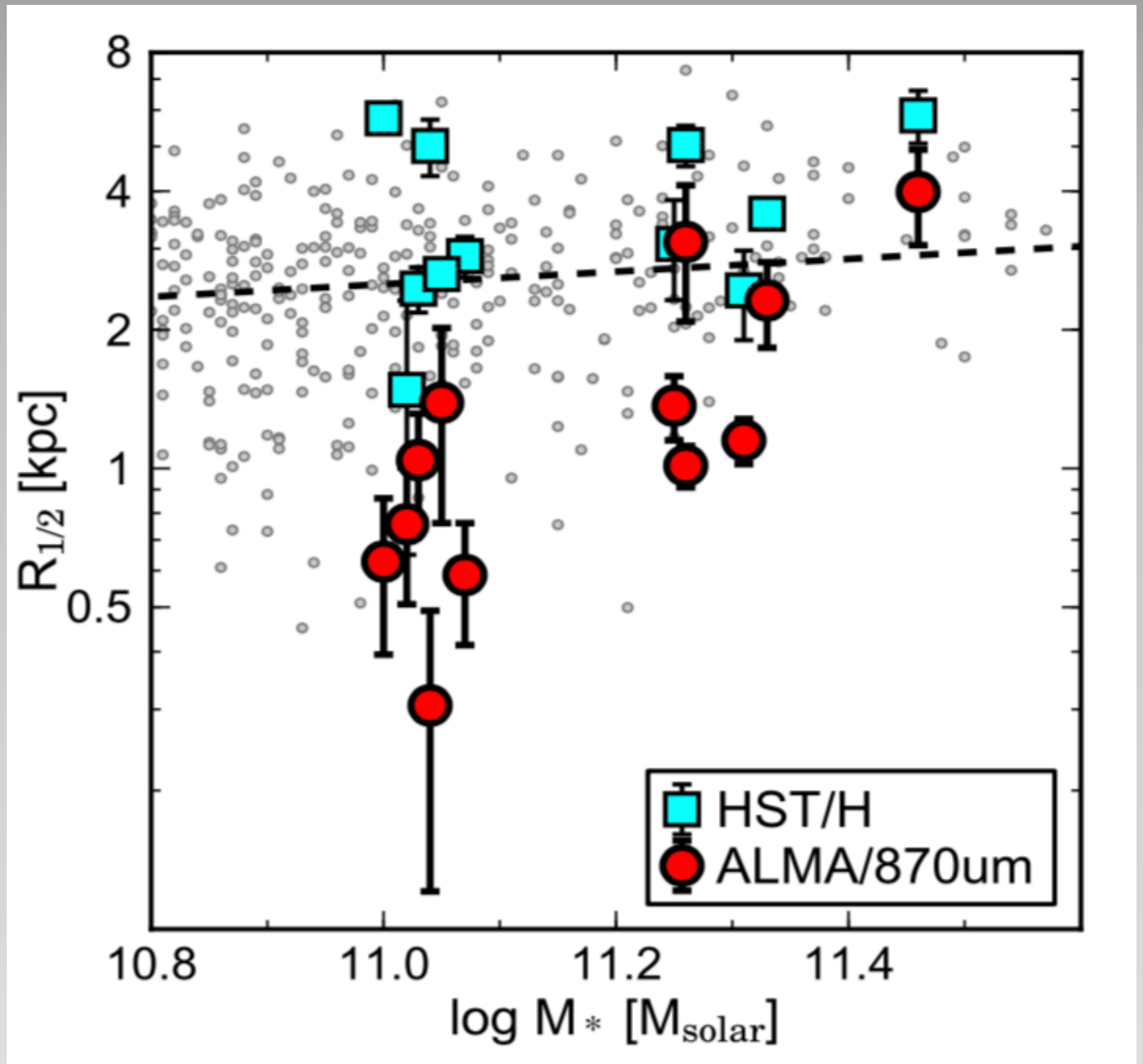
- **Higher excitation** than local disks (e.g., Daddi et al. 2015; Bothwell et al. 2013; Boogaard et al. 2020; Klitsch et al. 2022) with a wide **variety of conditions** primarily driven by star formation rate surface density (e.g., Narayanan & Krumholtz et al. 2012, Jimenez-Andrade et al. 2019; Valentino et al. 2020, Taylor et al. 2025)



Valentino+20

Molecular gas sizes of cosmic noon SFGs

- Dust **continuum** seems **more compact** than rest-optical emission in SMGs (e.g., Ikarashi et al. 2015; Fujimoto et al. 2017; Gullberg et al. 2019) and at the massive end of the MS (Elbaz et al. 2018; Franco et al. 2020; Gomez-Gujiarro et al. 2022); but unclear how this extrapolates to lower masses (e.g. Lindroos et al. 2016).



Tadaki+17

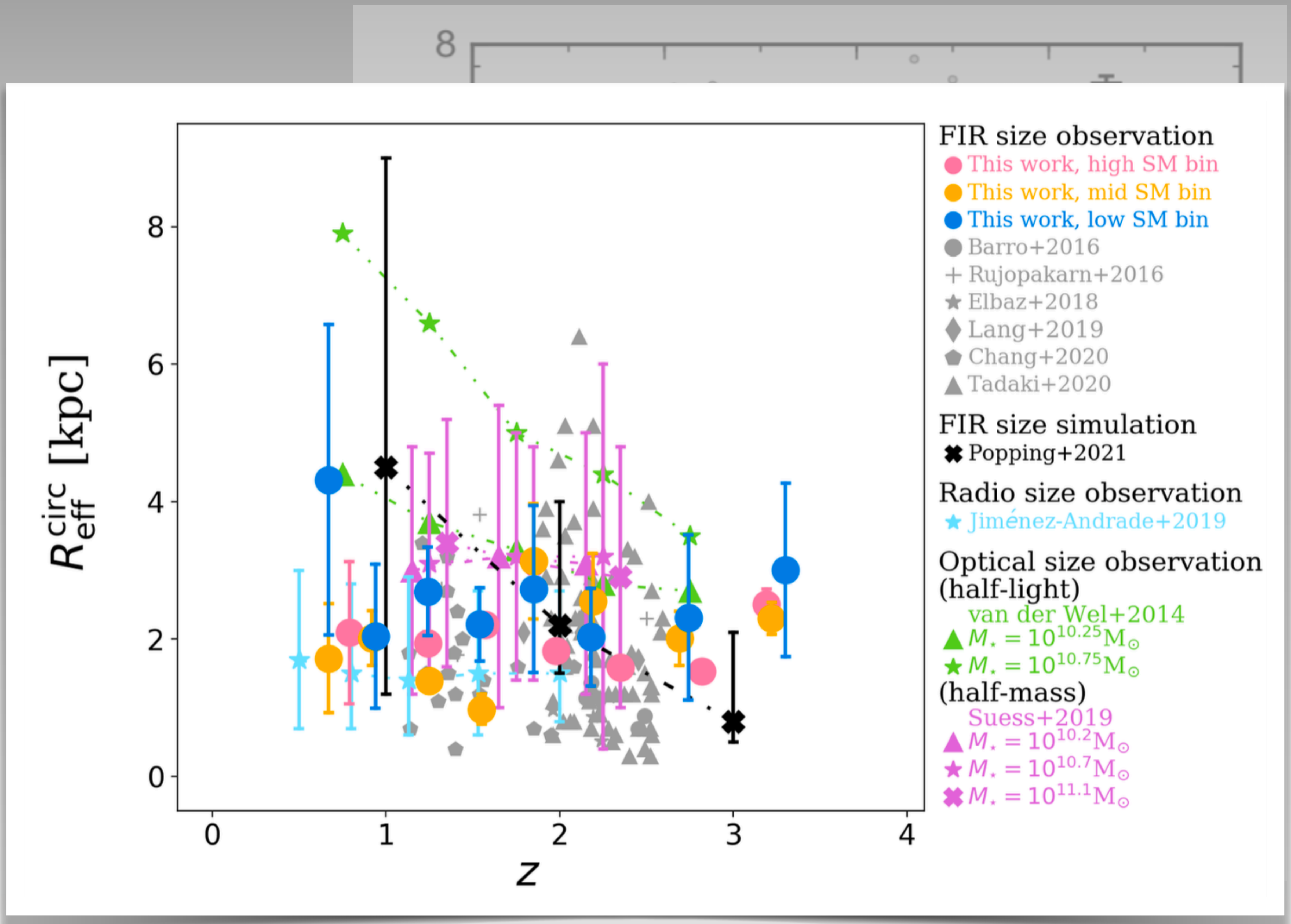
- No significant evolution of FIR sizes with redshift or stellar mass (A³COSMOS; Wang et al. 2022).

- Wide range of sizes also in CO, with more than 50% of MS galaxies at $M_* \sim 10^{11}$ $M_\odot$ appearing compact (Puglisi et al. 2019; Ikeda et al. 2022; Tadaki et al. 2023).

Molecular gas sizes of cosmic noon SFGs

- Dust **continuum** seems **more compact** than rest-optical emission in SMGs (e.g., Ikarashi et al. 2015; Fujimoto et al. 2017; Gullberg et al. 2019) and at the massive end of the MS (Elbaz et al. 2018; Franco et al. 2020; Gomez-Gujiarro et al. 2022); but unclear how this extrapolates to lower masses (e.g. Lindroos et al. 2016).

- **No significant evolution** of FIR sizes with redshift or stellar mass (A^{3}COSMOS, Wang et al. 2022).



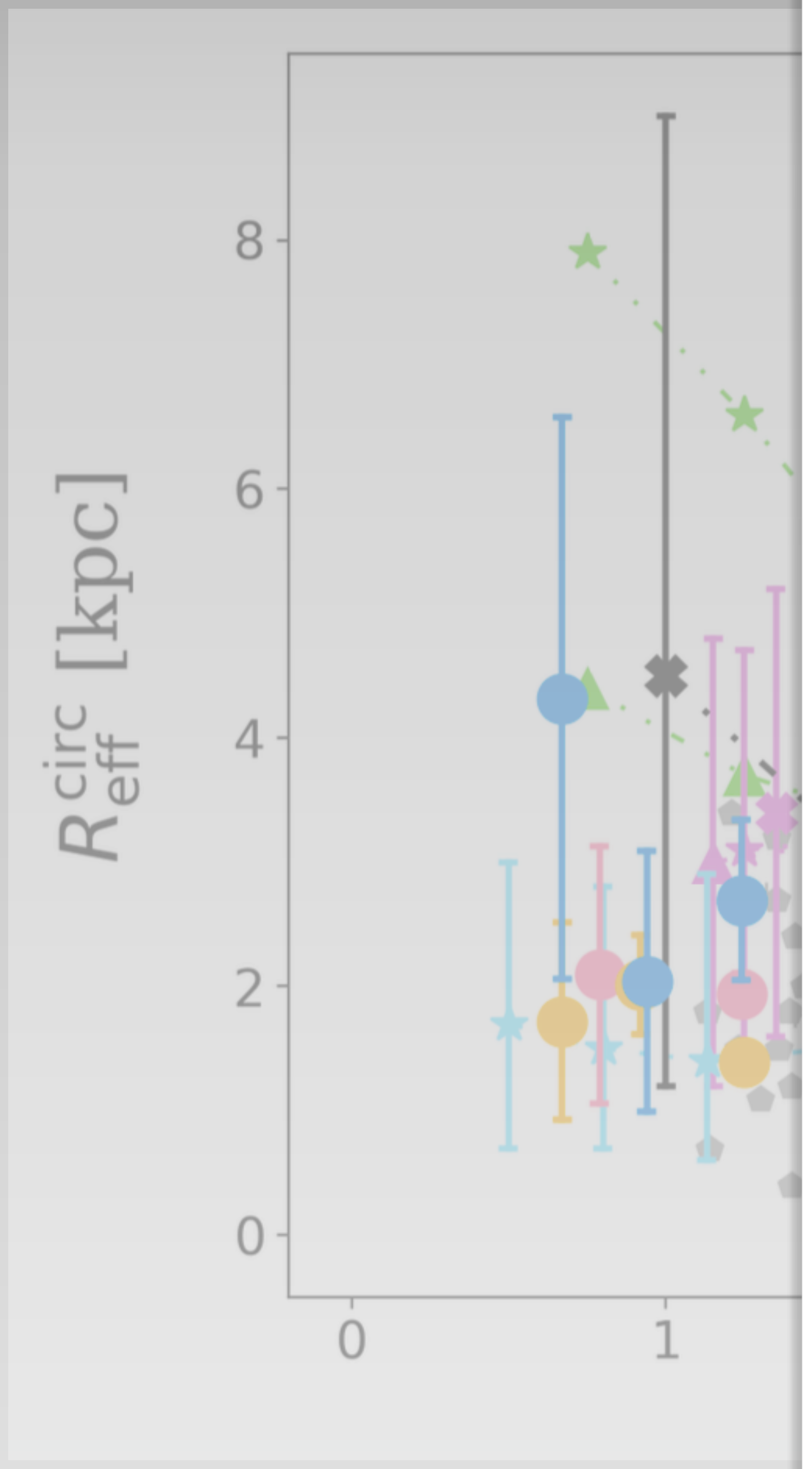
Wang+22

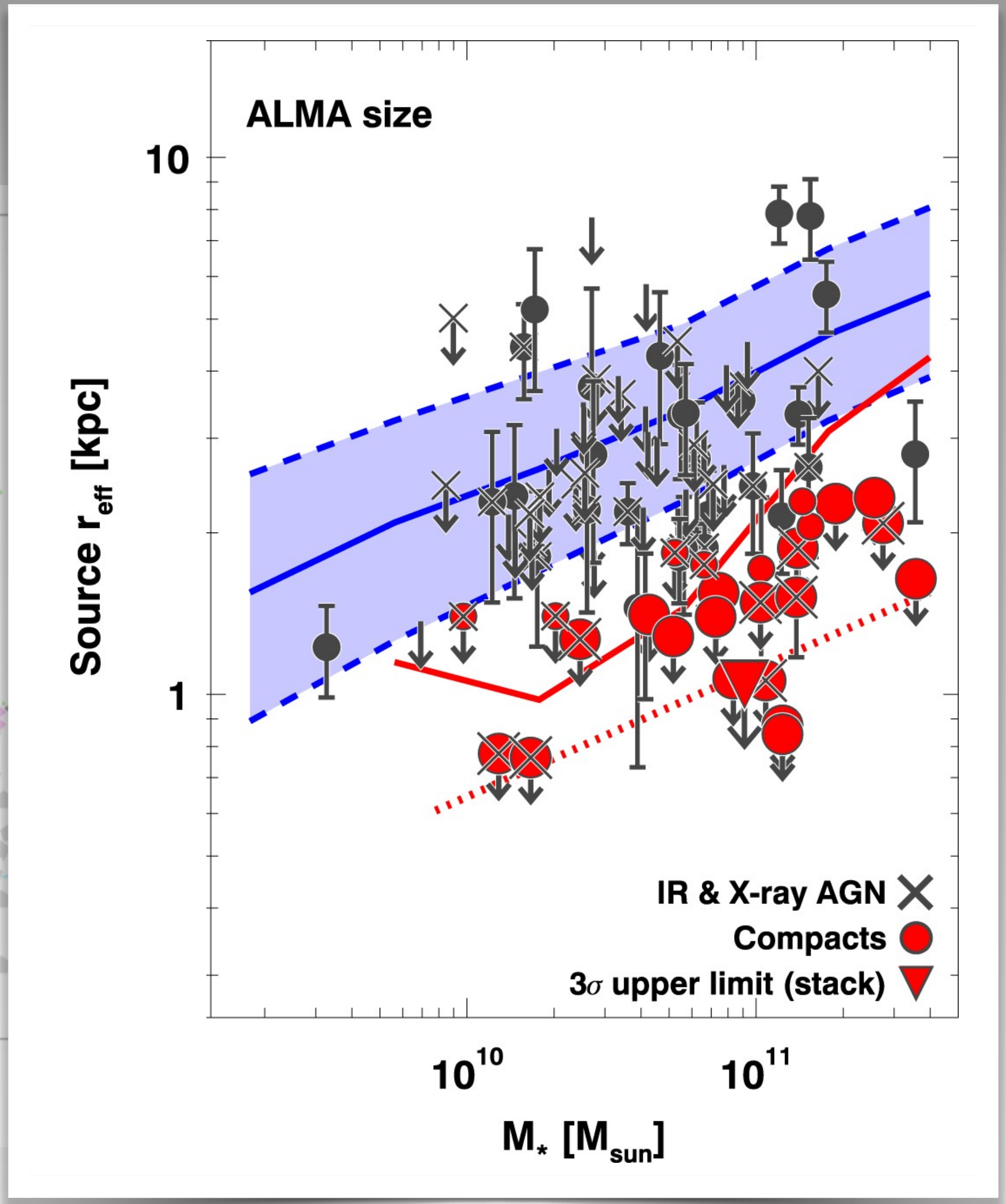
Molecular gas sizes of cosmic noon SFGs

- Dust **continuum** seems **more compact** than rest-optical emission in SMGs (e.g., Ikarashi et al. 2015; Fujimoto et al. 2017; Gullberg et al. 2019) and at the massive end of the MS (Elbaz et al. 2018; Franco et al. 2020; Gomez-Gujiarro et al. 2022); but unclear how this extrapolates to lower masses (e.g. Lindroos et al. 2016).

- **No significant evolution** of FIR sizes with redshift or stellar mass (A^{3}COSMOS, Wang et al. 2022).

- Wide range of sizes also in CO, with more than 50% of MS galaxies at $M_* \sim 10^{11}$ $M_\odot$ appearing compact (Puglisi et al. 2019; Ikeda et al. 2022; Tadaki et al. 2023).

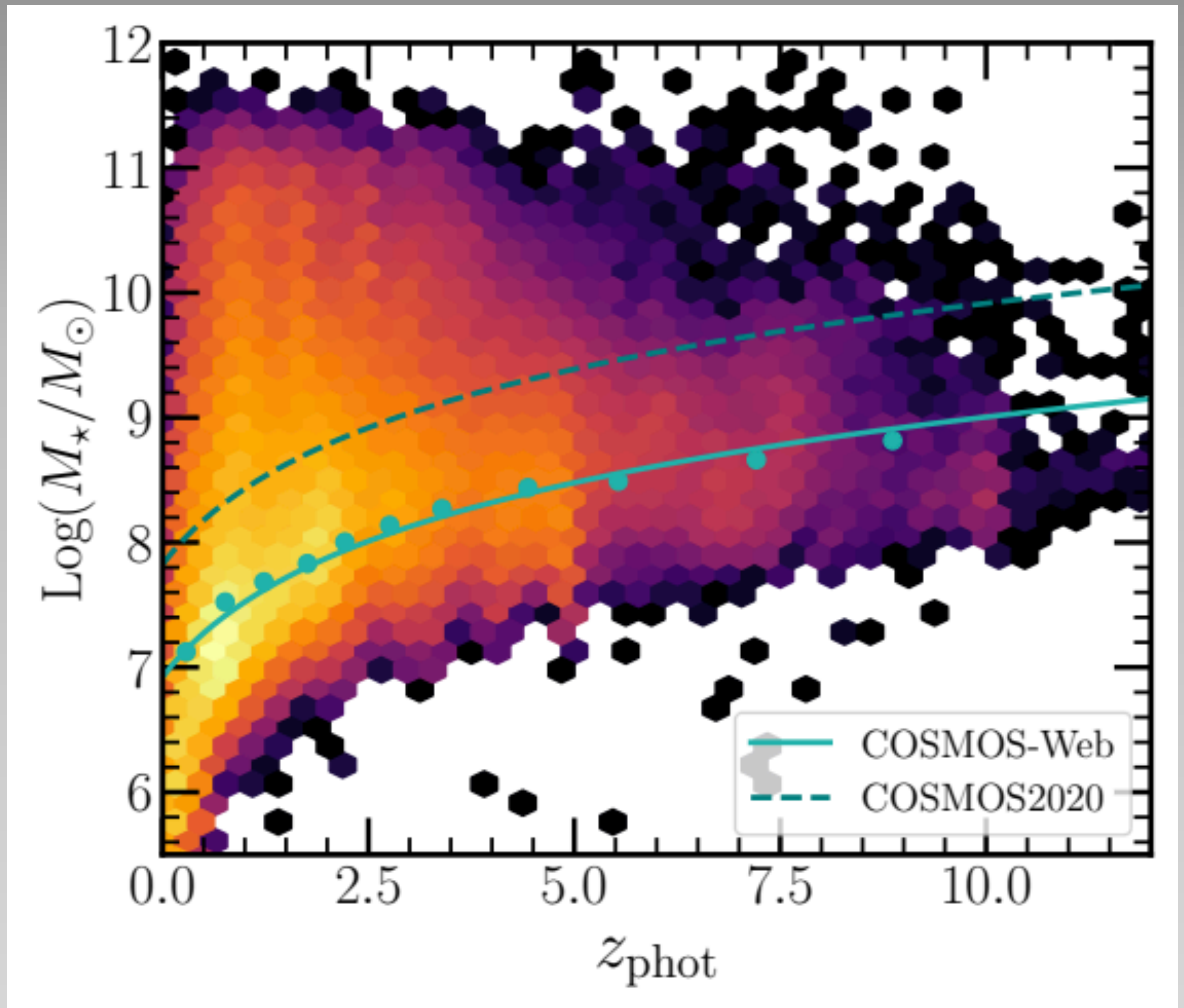




Puglisi+19

Pushing mass complete samples to lower stellar masses

- JWST deep and wide surveys now reach typical main-sequence galaxies at z~1–3 down to 10^8-10^9 $M_\odot$, i.e. **10x lower mass-complete limits** pre-JWST (e.g., Navarro-Carrera et al. 2024; Shuntov et al. 2025);

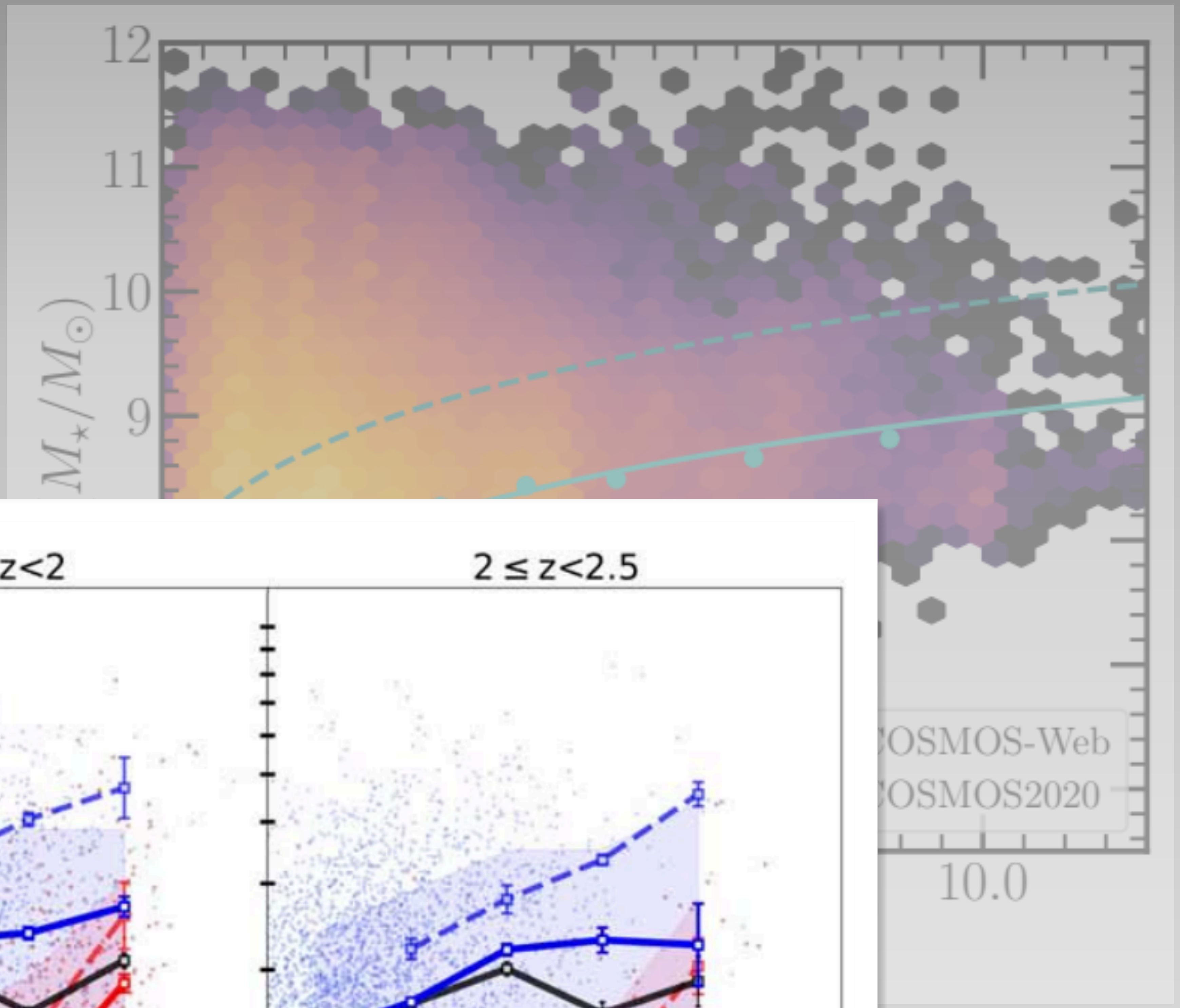


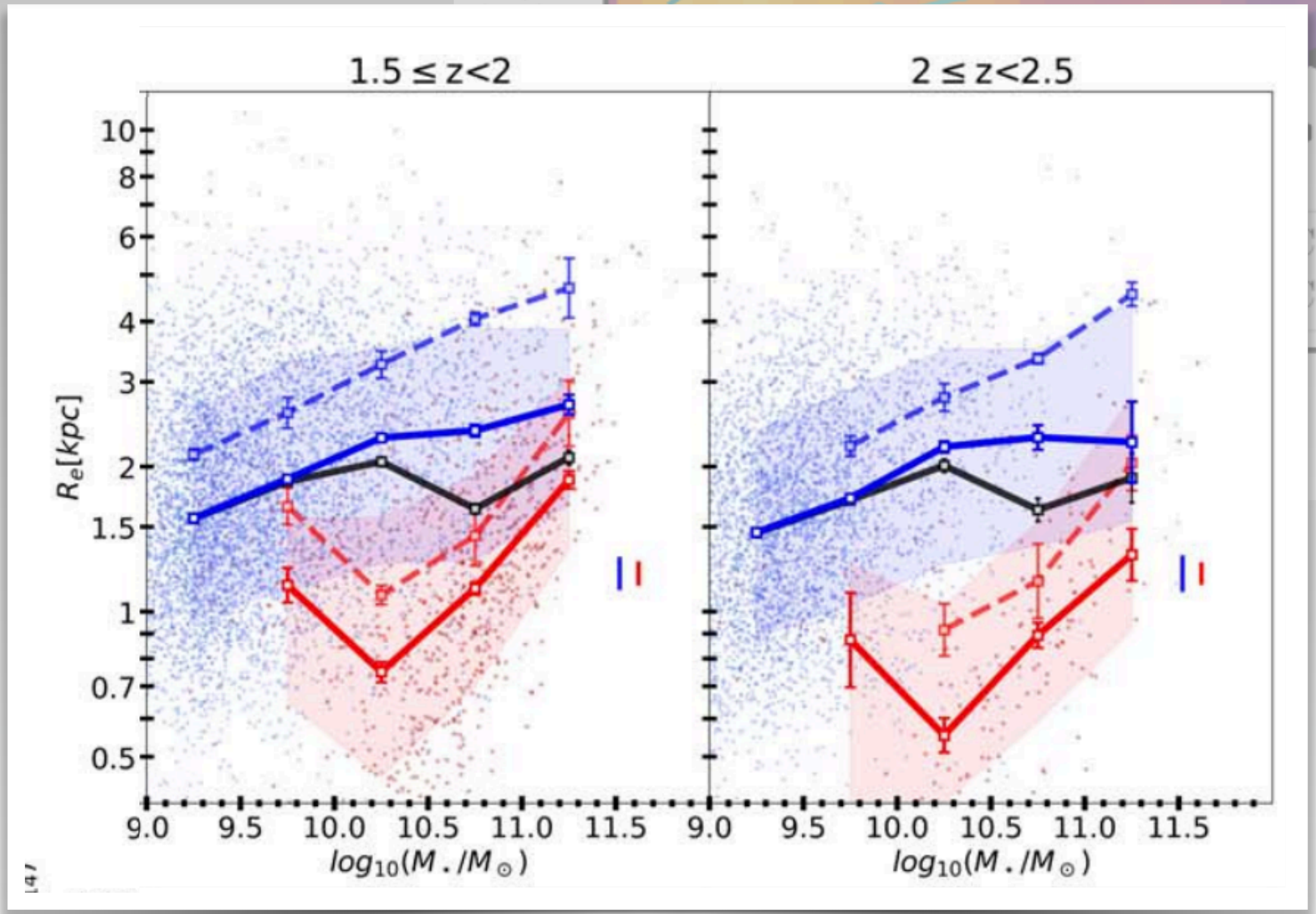
Shuntov+25

Pushing mass complete samples to lower stellar masses

- JWST deep and wide surveys now reach typical main-sequence galaxies at z~1–3 down to 10^8-10^9 $M_\odot$, i.e. **10x lower mass-complete limits** pre-JWST (e.g., Navarro-Carrera et al. 2024; Shuntov et al. 2025);

- Large, homogeneous samples with well-measured **stellar masses, SFRs, and structural parameters** down to **10^9 $M_\odot$** (e.g. Martorano et al. 2024; Hamadouche et al. 2025; Genin et al. 2025)

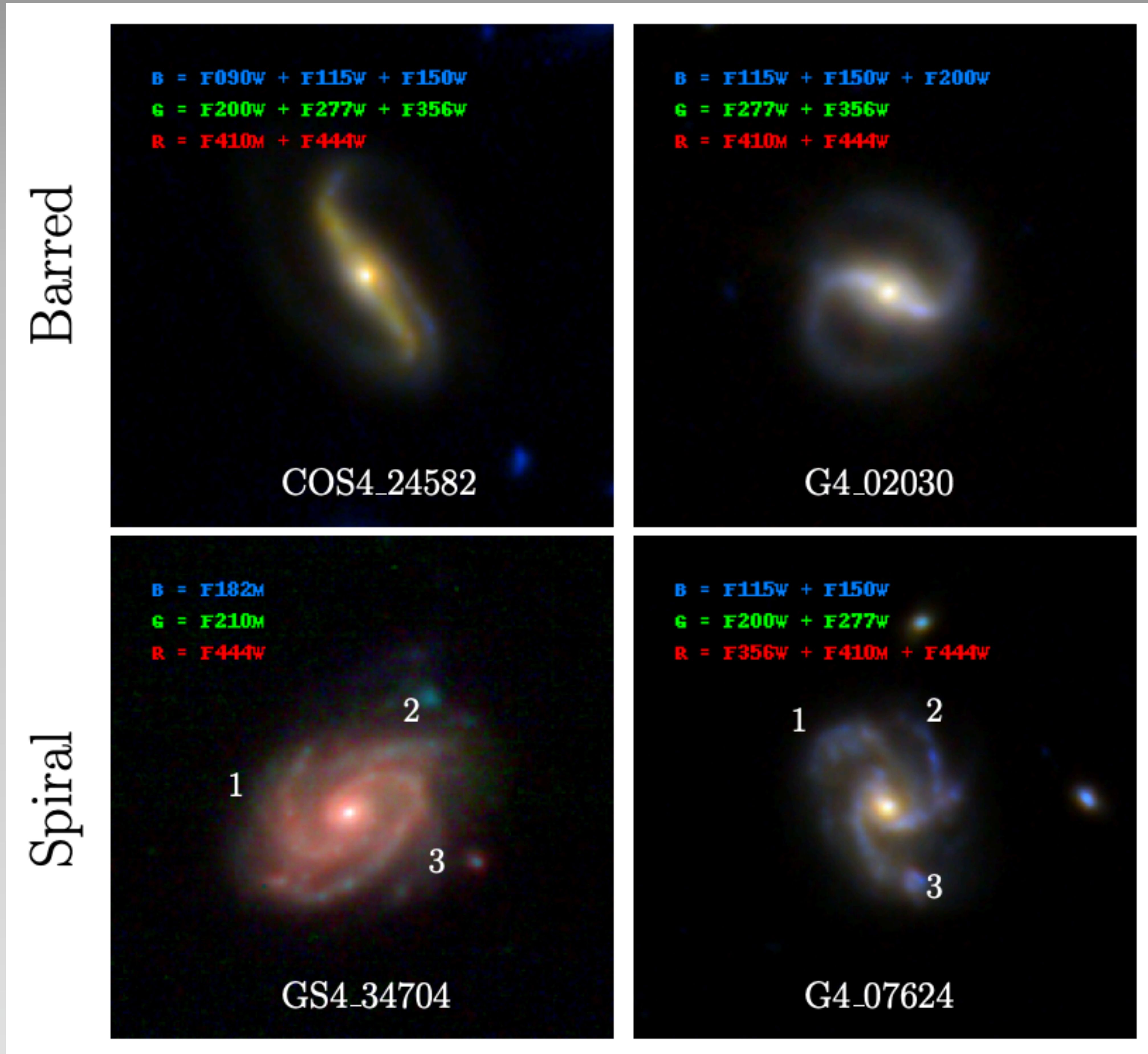




Martorano+24

Unveiling complexity across the main sequence

- Disks dominate (≳80%) but with a **wide variety of internal sub-structures** across the main sequence (e.g., Espejo-Salcedo et al. 2025)
- Bars and spiral arms **often dynamically "mature"** already at z ~ 1 (e.g., Kalita et al. 2025).
- ALMA-selected **dusty star-forming galaxies** share this structural complexity: mostly **disk-like** and some **minor interactions**, with only a minority in late-stage major mergers (e.g., Gillman et al. 2024; Chan et al. 2025) and many **sub-structures** (Puglisi et al., in prep).



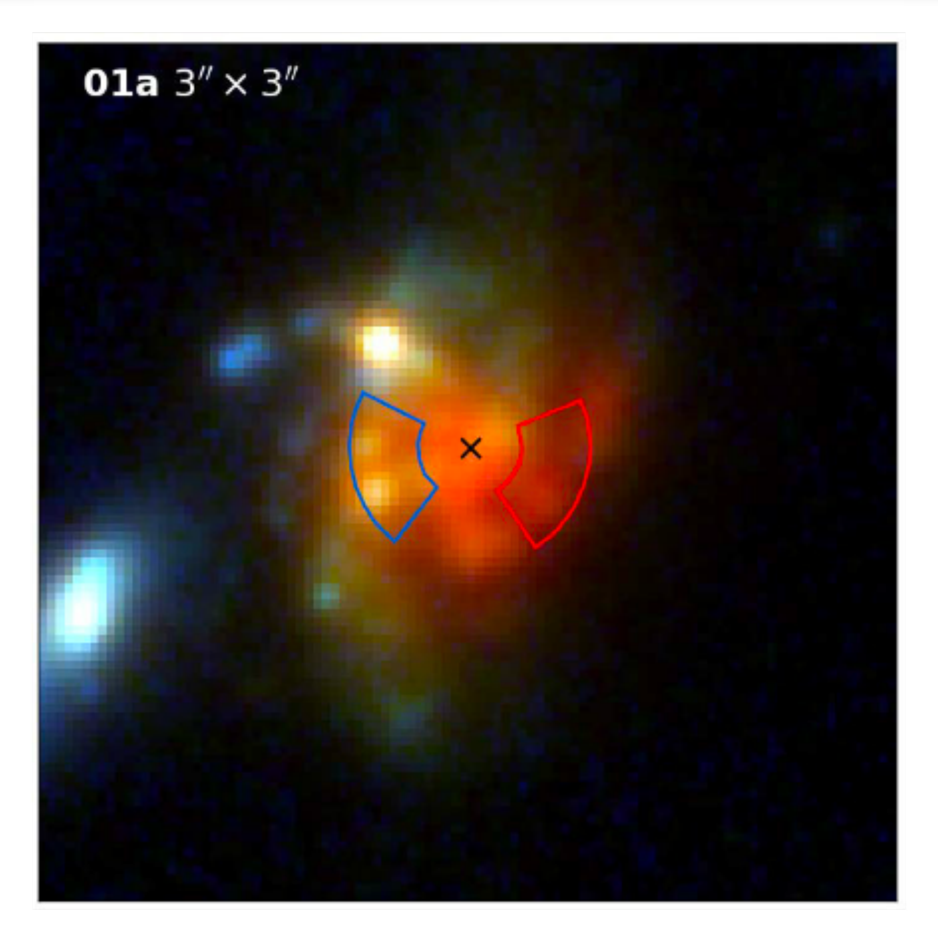
Espejo Salcedo et al. 2025

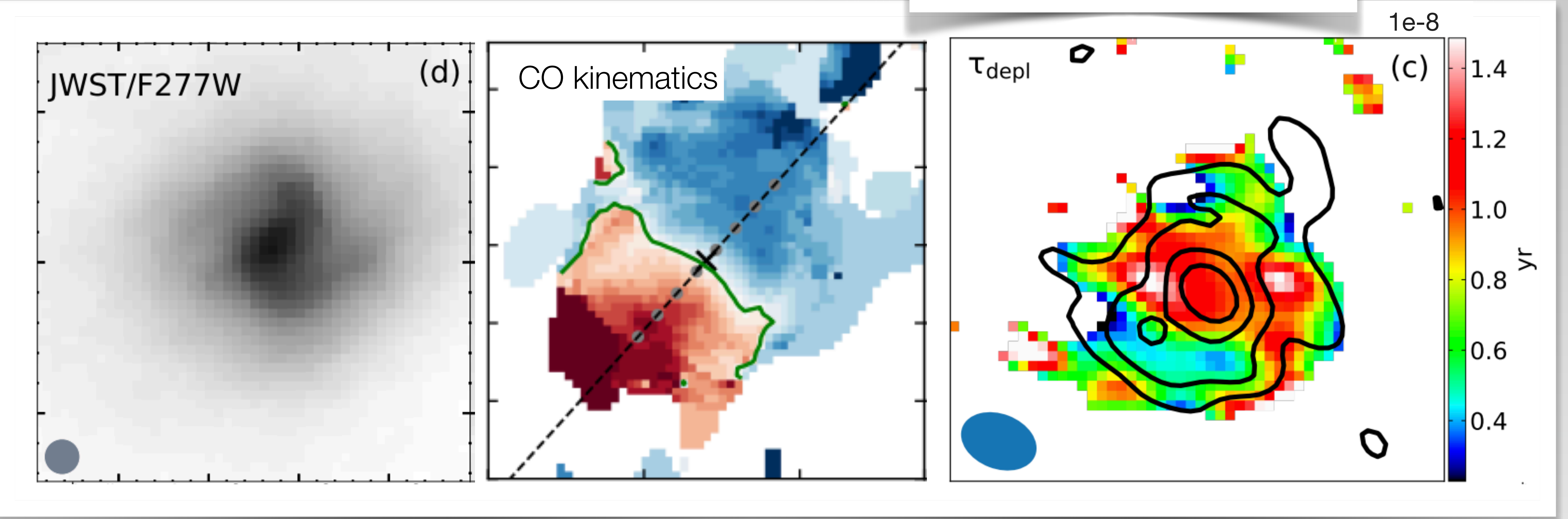
A holistic approach to understanding the physics of star formation

- Dust and stars display **complex distributions** on sub-kpc scales (e.g., Polletta et al. 2024; Le Bail et al. 2024);

- CO shows **rotation-dominated kinematics**, yet **starburst-like** molecular gas **conditions** with high gas fractions and very short depletion times (e.g., Liu et al. 2024).

Polletta et al. 2024





Liu et al. 2024

Current open questions in the ALMA+JWST era

What are the cold-gas properties of typical star-forming discs?

How does cold gas/dust trace the stellar morphologies JWST is revealing?

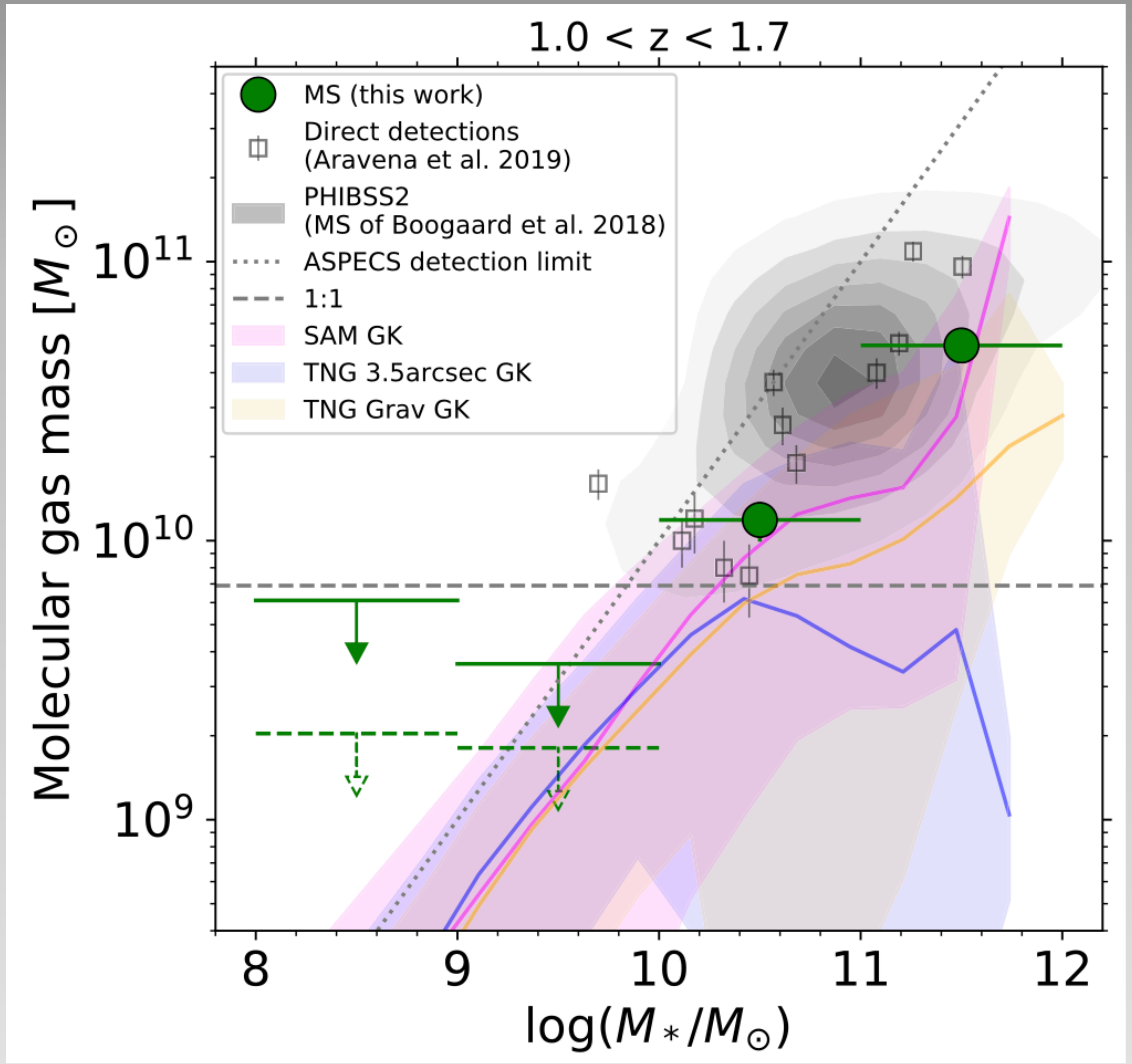
What processes regulate gas transport and star formation?

Where are we at: cold gas below the massive end of the main sequence

- Gas fractions/depletion times **broadly consistent** with scaling relations extrapolation, especially when folding in observables-to-gas systematics;

- Even deep surveys only provide a **handful** of **detections** around the Schechter-mass ($M_* \sim 10^{10.5}$ $M_\odot$ at z~1-2, e.g., Aravena et al. 2019 for CO; Popping et al. 2023 for continuum);

- Constraining the molecular gas content of more typical galaxies requires **stacking** even at ASPECS depth or large archival ALMA coverage in A^{3}COSMOS, and often **heterogeneous mid-to-high J CO/continuum mixes**.

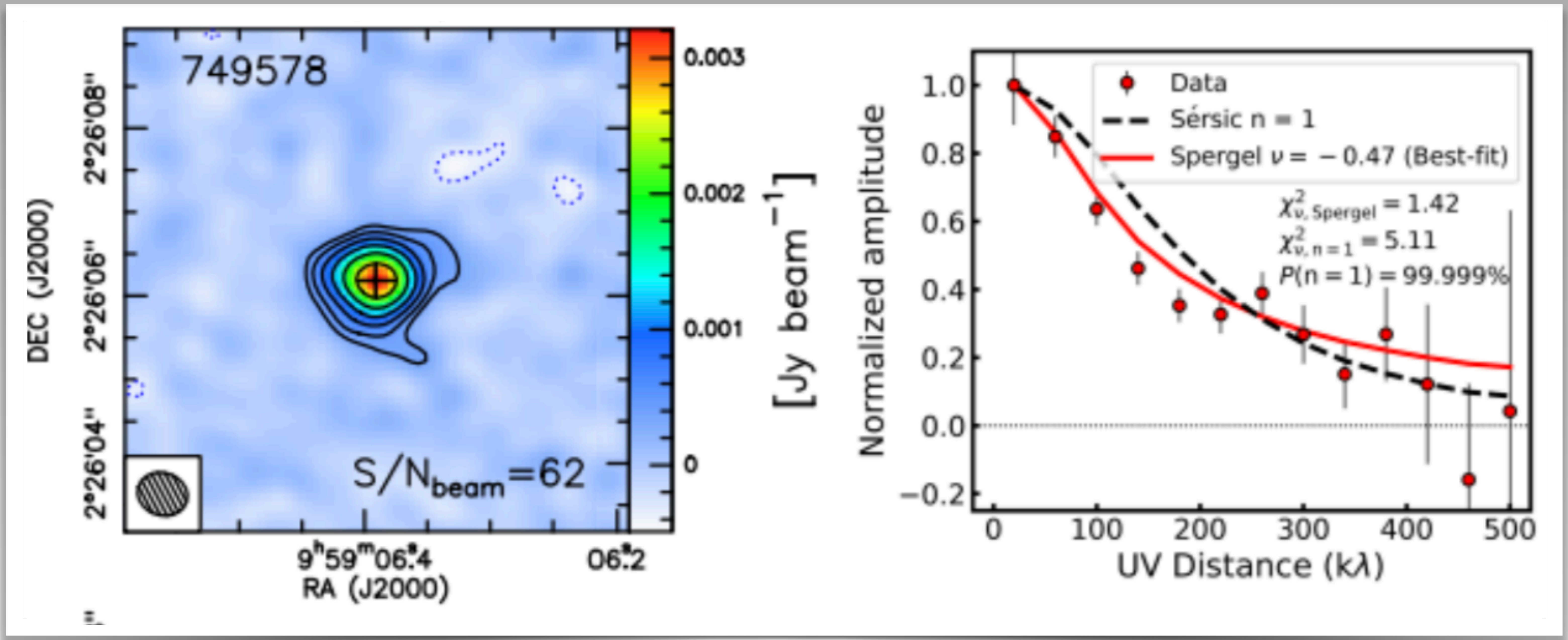


Inami et al. 2020

Where are we at: cold gas/dust morphologies

- Analysis of ALMA visibilities for sub-mm bright galaxies reveal **triaxial spheroids** suggestive of in-situ bulge formation;
- Measuring robust sub-mm structure requires **SNR $\gtrsim$ 20** in the visibilities and **resolution $\lesssim$ 0.2”** (Tan et al. 2024);
- Robust morphological analyses are currently limited to **only the brightest SMGs** at z $\gtrsim$ 2.

Tan+25, *Nature*

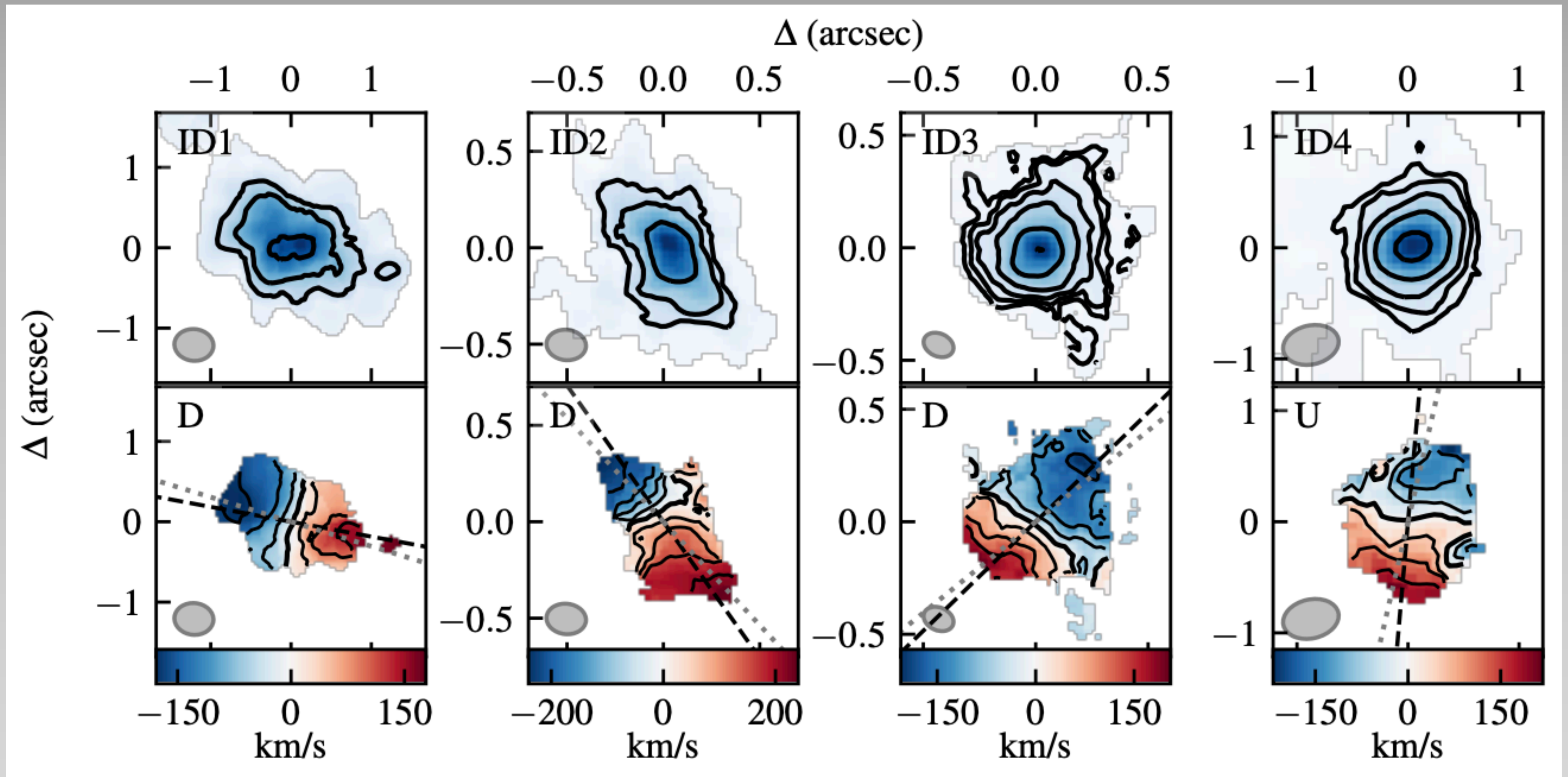


Where are we at: gas transport and SF regulation

- Overall **ordered rotating cold-gas discs** from main-sequence galaxies (e.g. Molina 2019; Rizzo et al. 2023) to the most extreme dusty starbursts (Amvrosiadis et al. 2025);

- Still very **limited samples** and **complex selection functions** (massive and/or starbursts, often in overdensities and with heterogeneous z_{spec} coverage from archival efforts like ALPAKA);

- **Heterogeneous mid-to-high-J** CO coverage.

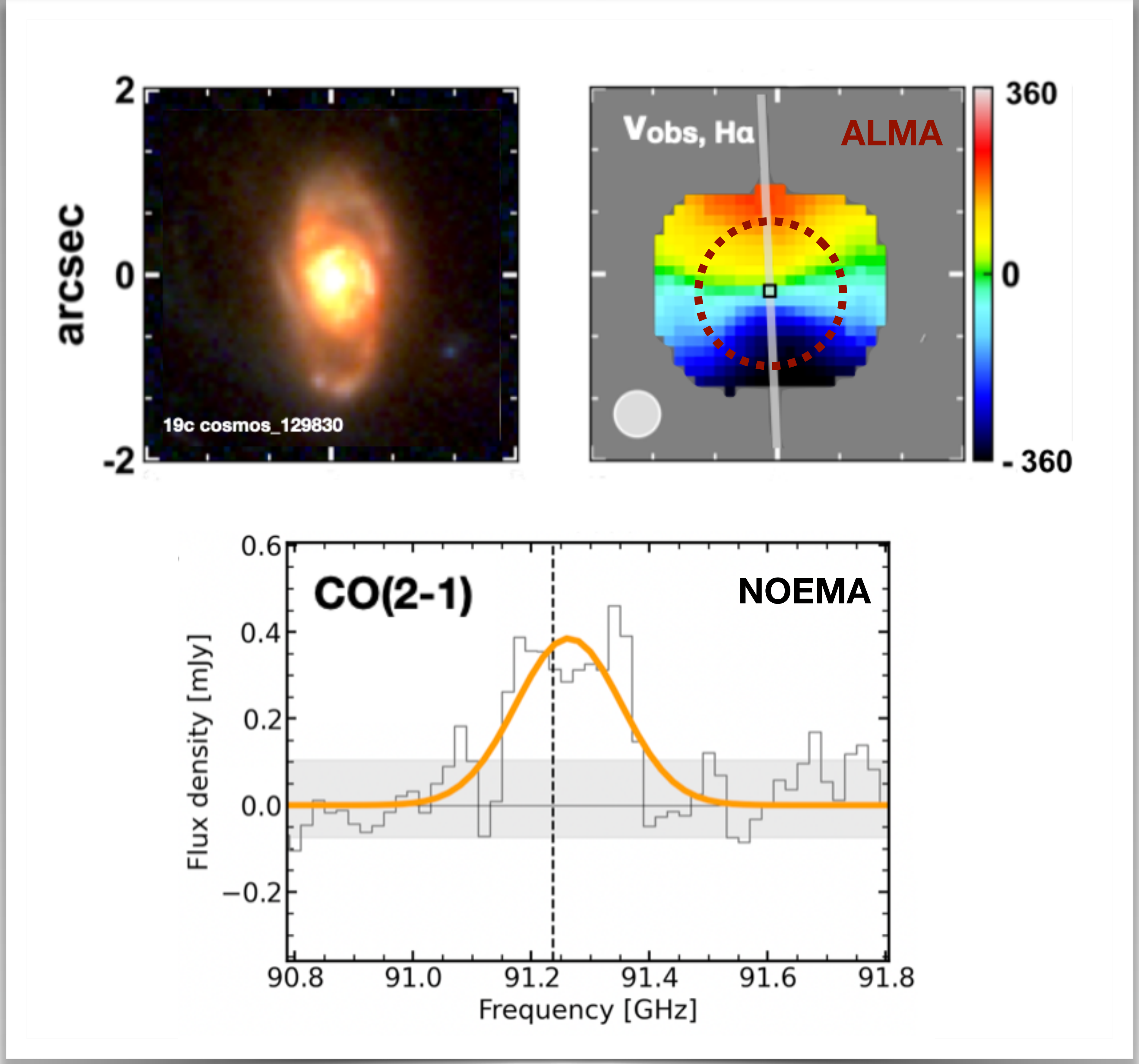


Rizzo+23

Resolving gas in typical SFGs with current ALMA capabilities

- Forward modelling of Simba predictions suggests that for typical z~1–3 star-forming galaxies, CO low-J becomes **too faint to detect** at ~kpc resolution beyond the inner few kpcs in reasonable times (Anirudh et al. 2025);

- Indeed CO low-J and dust are very expensive and require combining multiple configurations: **e.g. 5h NOEMA + 15 h ALMA** for Hα-selected discs at M* ≥ $10^{10.5}$ to map total (3”) and disc-scale (0.5”) kinematics.

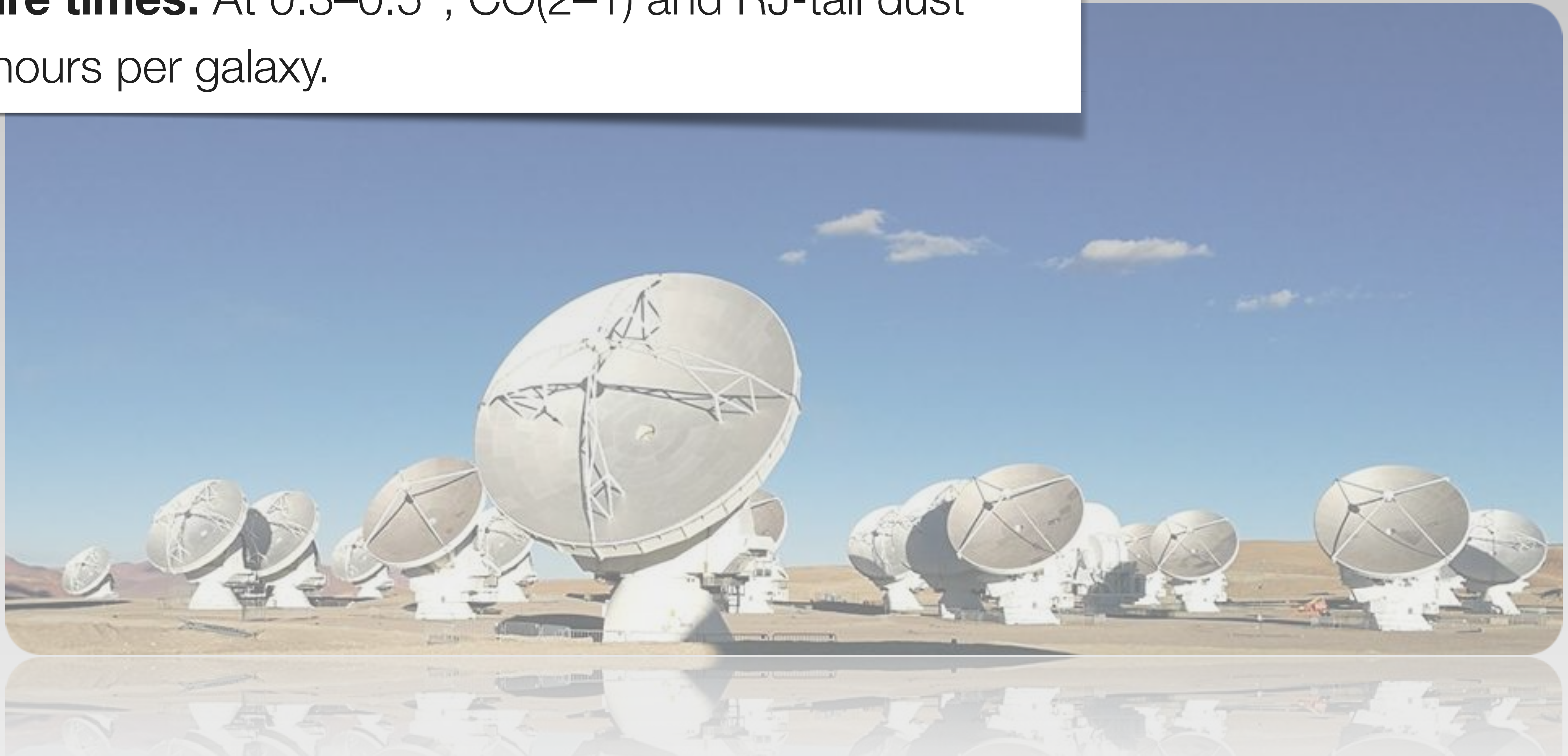


ALMA Band 2 & Wideband Sensitivity Upgrade

- **Frequency range 67–116 GHz:**
  - CO(1–0) up to z~0.7, CO(2–1) at z~1-2.4, plus Rayleigh–Jeans dust continuum at z~1–3.
- **Survey speed / sensitivity:**
  - ~3× faster continuum mapping and ~2–3× faster spectral-line mapping, plus lower receiver noise.

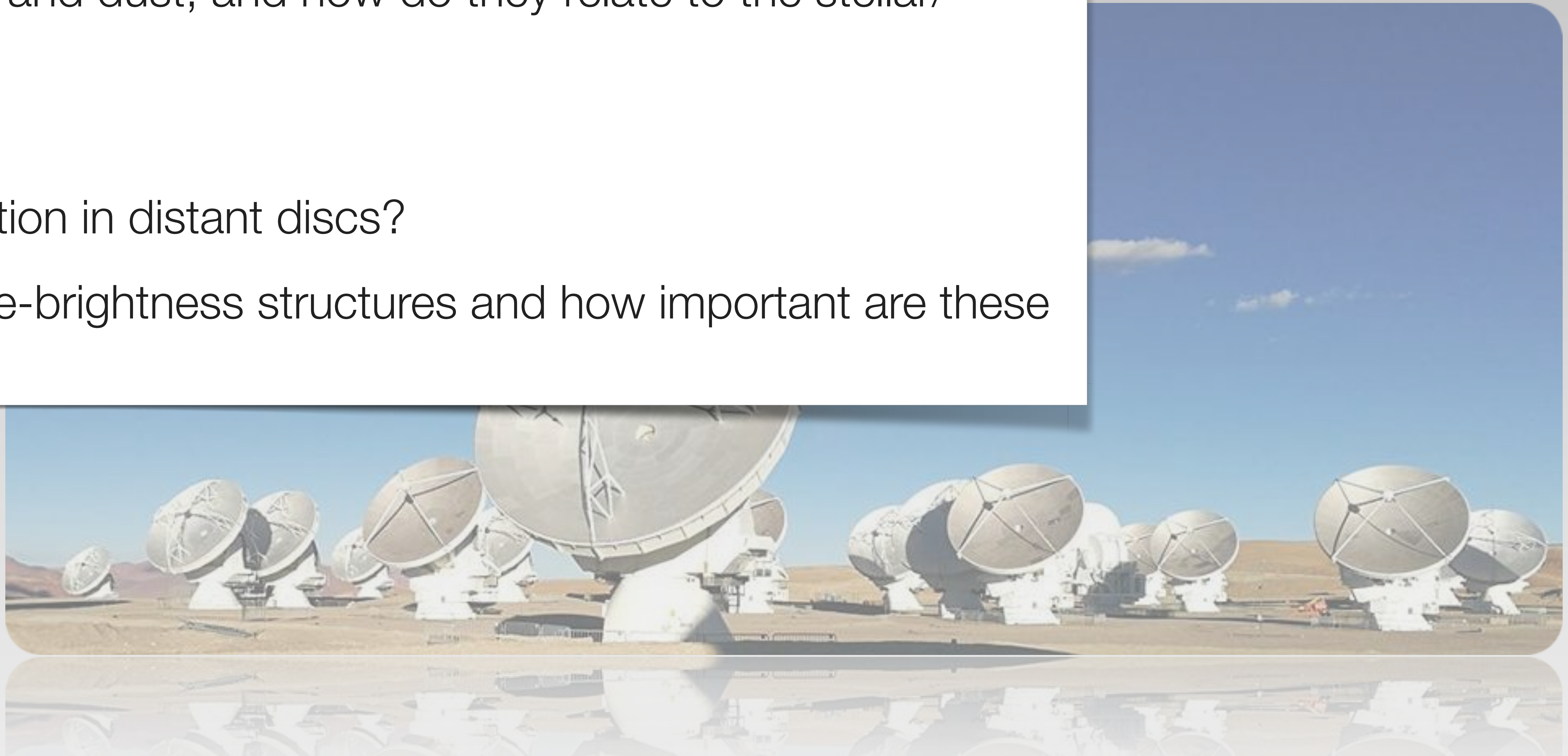
ALMA Band 2 & Wideband Sensitivity Upgrade

- **CO(2–1) as total gas tracer over an extended z range:** cleaner handle on total H_2 than multi-J CO/dust mixes, and minimal excitation corrections dependences;
- **RJ-tail continuum "for free":** dust with better sensitivity towards low-surface-brightness regions;
- **Access to more typical galaxies:** increase statistics below the massive end of the main-sequence;
- **Resolve discs in (a bit more) realistic exposure times:** At 0.3–0.5″, CO(2–1) and RJ-tail dust maps for main-sequence discs feasible with~10 hours per galaxy.



Key questions for Band 2 (and beyond) for cosmic noon science

- **Gas content**
  - How do molecular gas fractions and depletion times behave in star-forming galaxies below the very massive end of the main sequence?
- **Structure of the cold ISM**
  - How common are nuclear sub-mm compact phases across the main sequence?
  - What are the morphologies of molecular gas and dust, and how do they relate to the stellar/JWST structures?
- **Star formation regulation**
  - What regulates gas transport and star formation in distant discs?
  - How much gas mass is stored in low–surface-brightness structures and how important are these reservoirs for the baryon cycle?



Summary

- **ALMA** has revealed a **rich diversity** of **cold ISM properties** in massive main-sequence galaxies at cosmic noon: high gas fractions, elevated and diverse excitation, and compact dust/molecular components compared to the stars. However, detailed **constraints** are still **largely limited to small, biased samples** at the massive/bright end, while more typical galaxies and cold-gas morphologies remain poorly characterised.

- **JWST** has now opened up a **larger parameter space** in stellar mass and shows that star-forming galaxies at these epochs display **mature and diverse sub-structures** across a broad range of stellar masses. This underscores the need for spatially resolved **maps of cold gas and dust** to connect **structures and ISM physics**, and to push cold-gas studies to **more typical systems**.

- The **Band 2 wideband sensitivity upgrade** will allow us to bridge these gaps and address key open questions on gas content and depletion times around the Schechter mass, structural properties, and the mechanisms that **transport and redistribute gas** and **regulate star formation across disks at cosmic noon.**