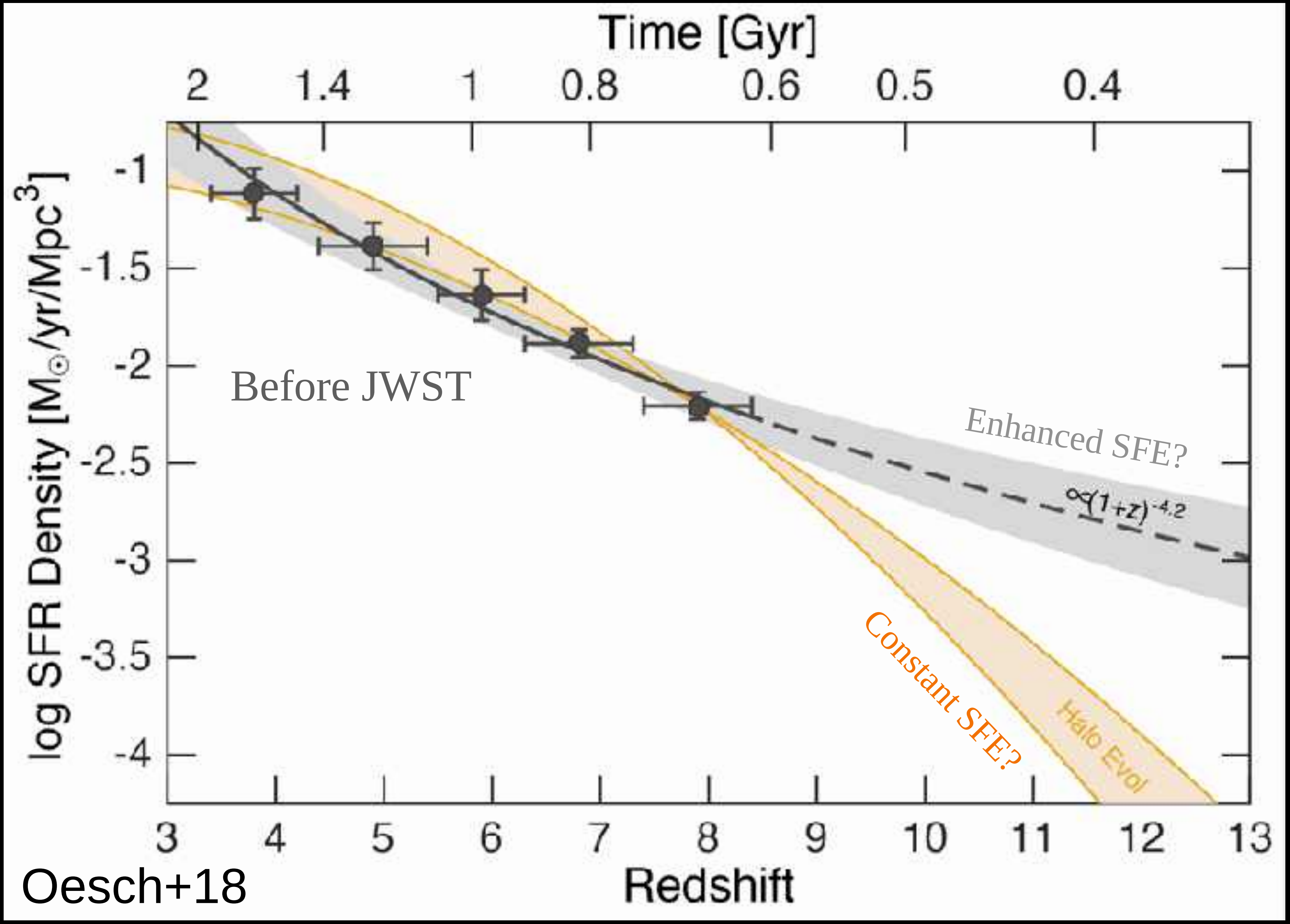
Gas and Dust at early epochs

Seiji Fujimoto
NASA Hubble Fellow
(UT Austin → U. Toronto)

- CITA fellow (theory) — **DL: Nov. 4th**
- Dunlap fellow (observation, instrument) — **DL: Nov. 18th**

Gas and Dust at early epochs

Key Clues to Cosmic Star-formation History (CSFH)



See also talks by Pascal, Stefano, Callum, Ivan, Pratika, Marko, Alice, Andrea, Fengyuan, Alba, Masami, Max

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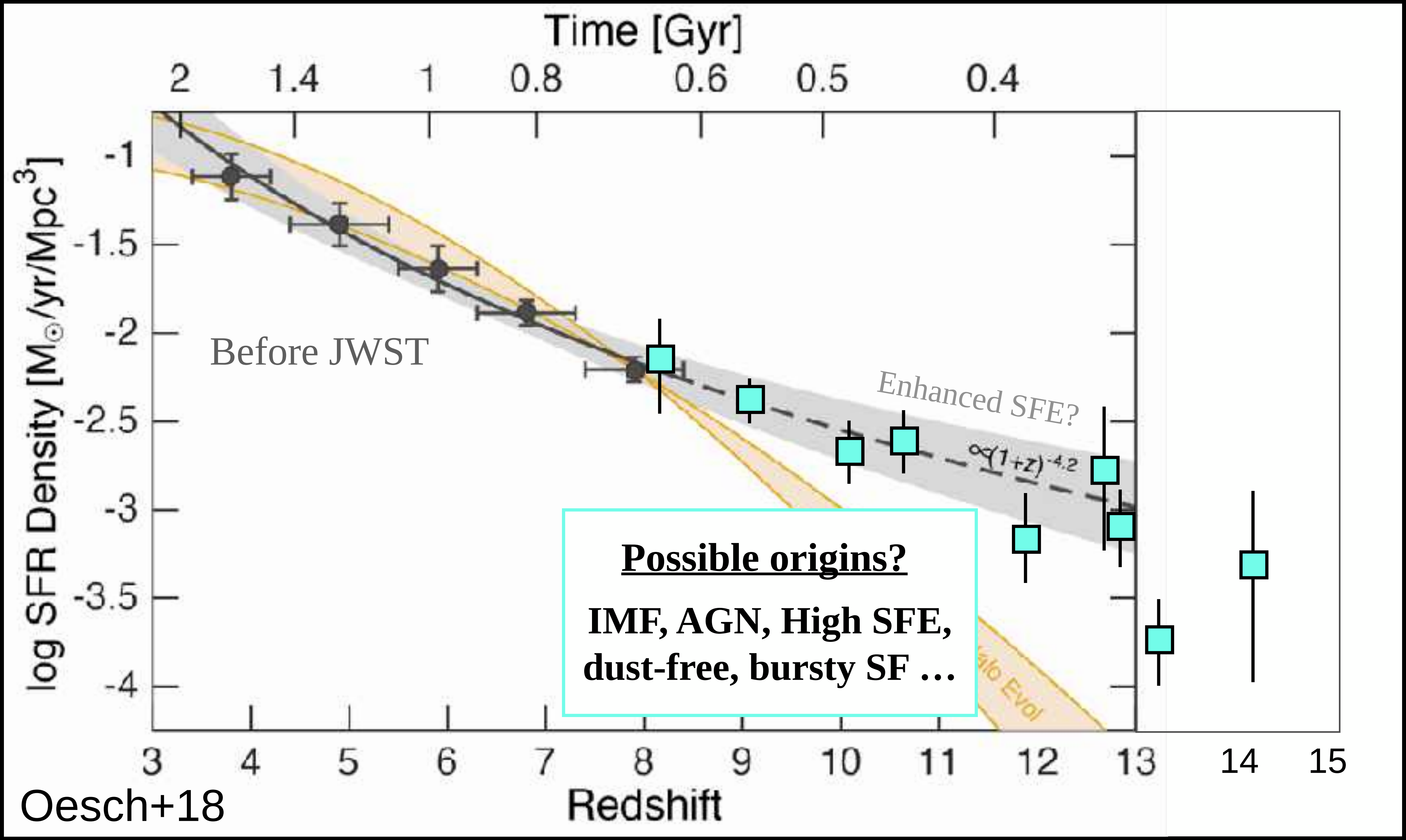

Recent JWST

Compilation from Breakthrough Workshop 2024 Team + Harikane+24b

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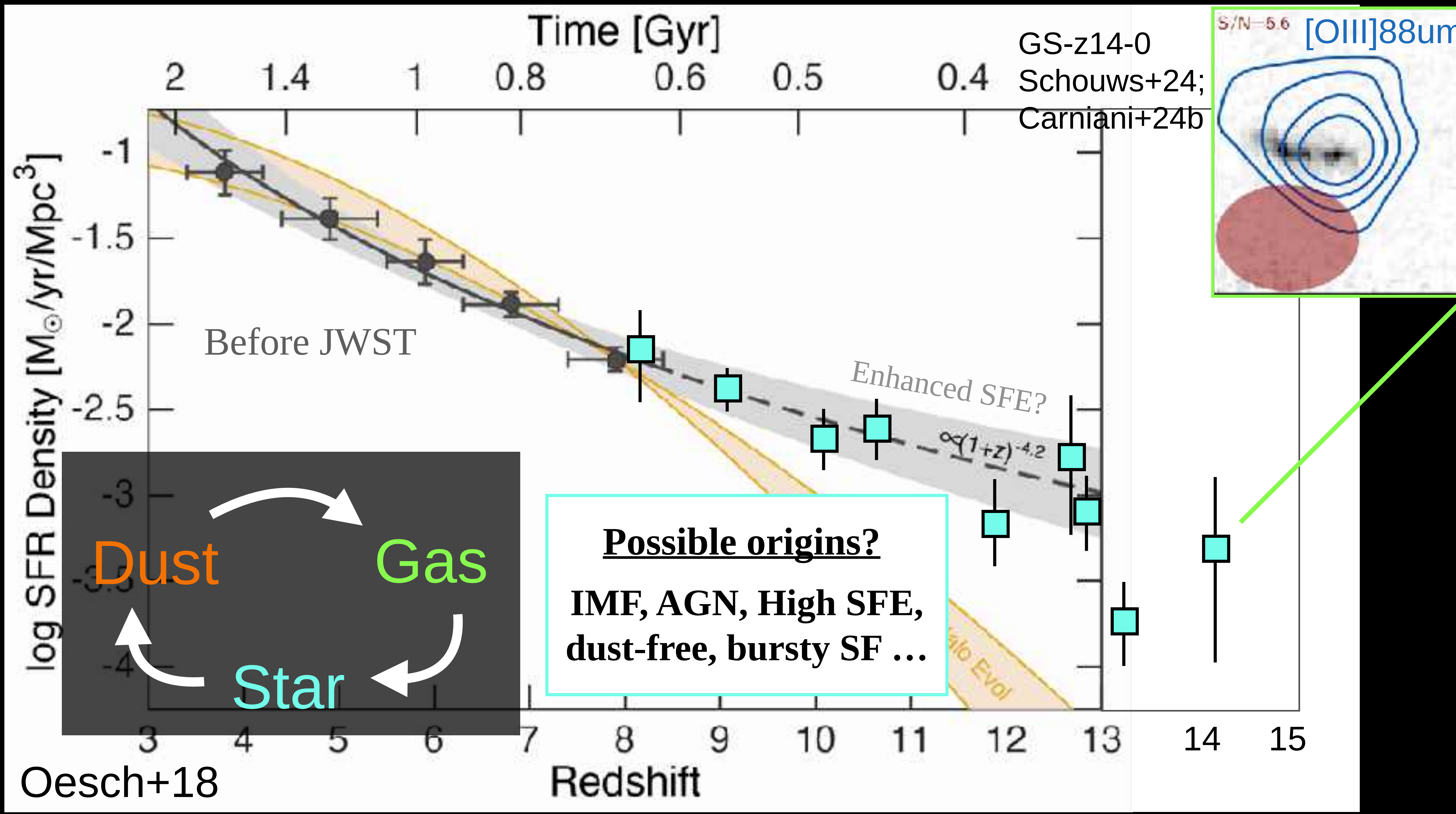

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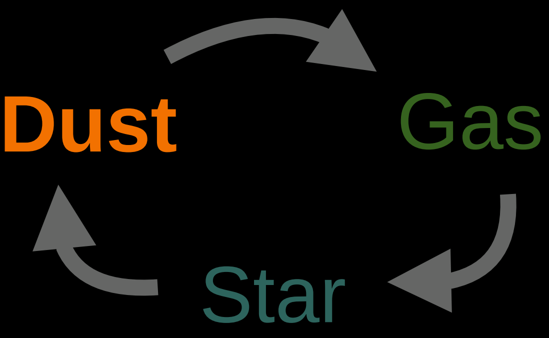
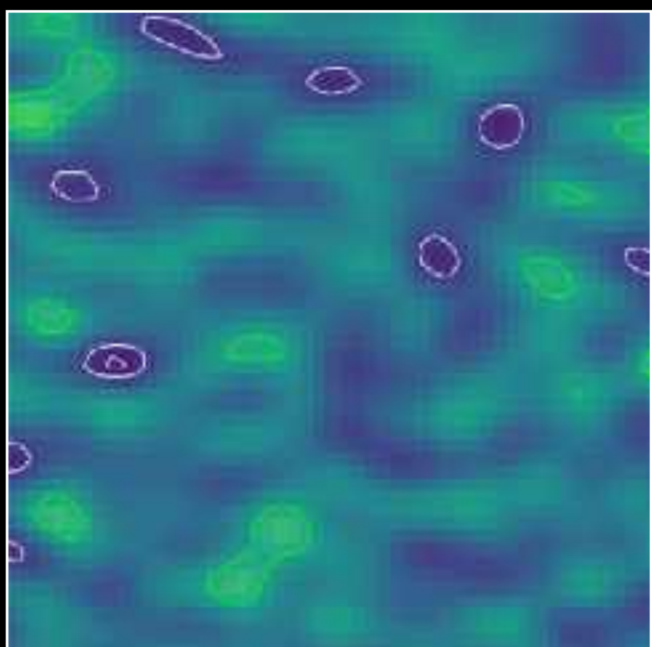
ALMA follow-up for JWST sources at z > 10

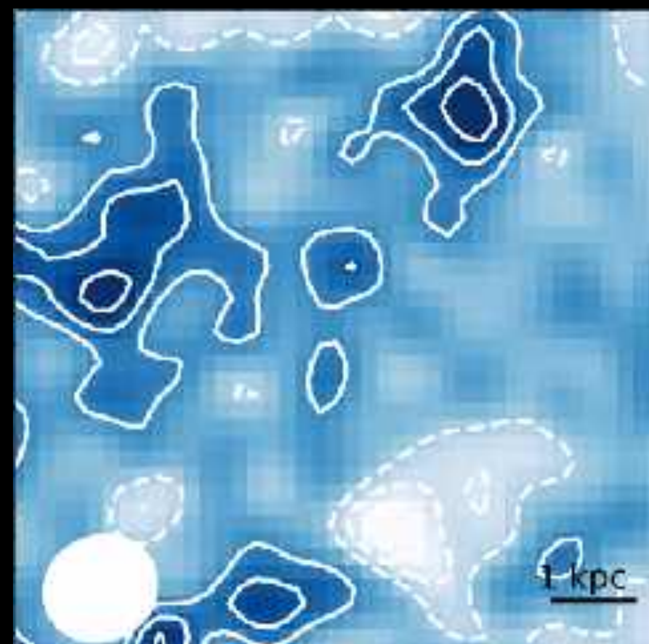


GS-z14-0



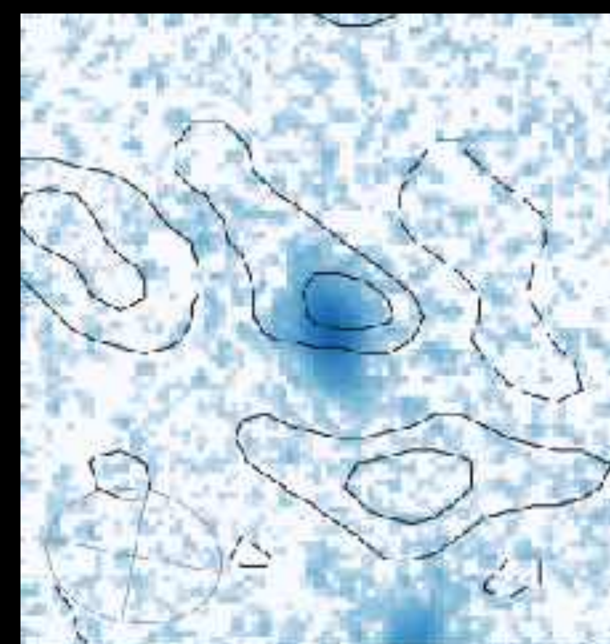
Schouws+24; Carniani+24b

GLz12/GHZ2



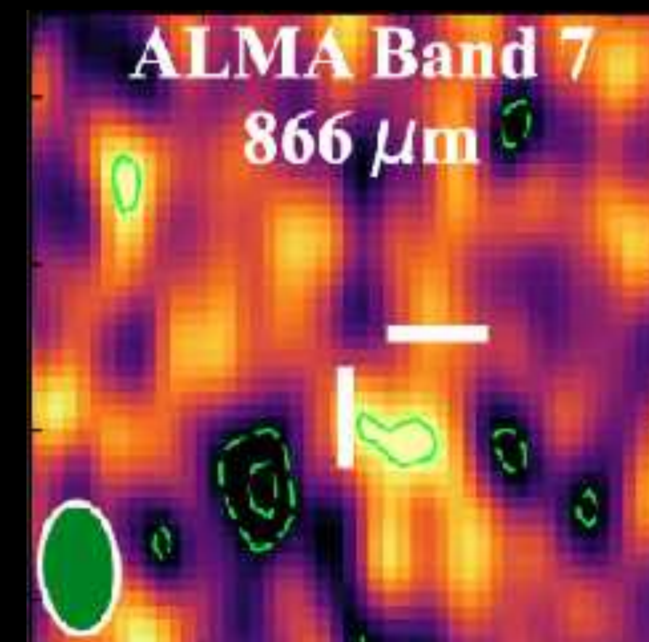
Bakx+23

GLz10/GHZ1



Yoon, Carlli, Fujimoto+23

S5-z17-1

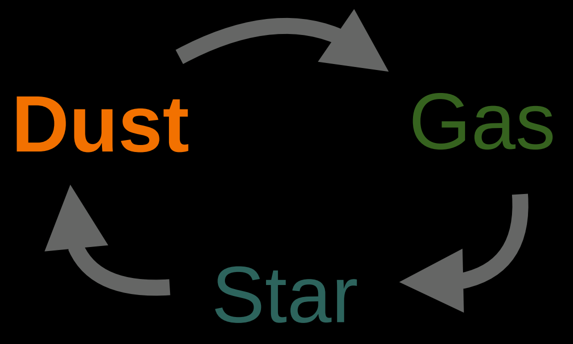


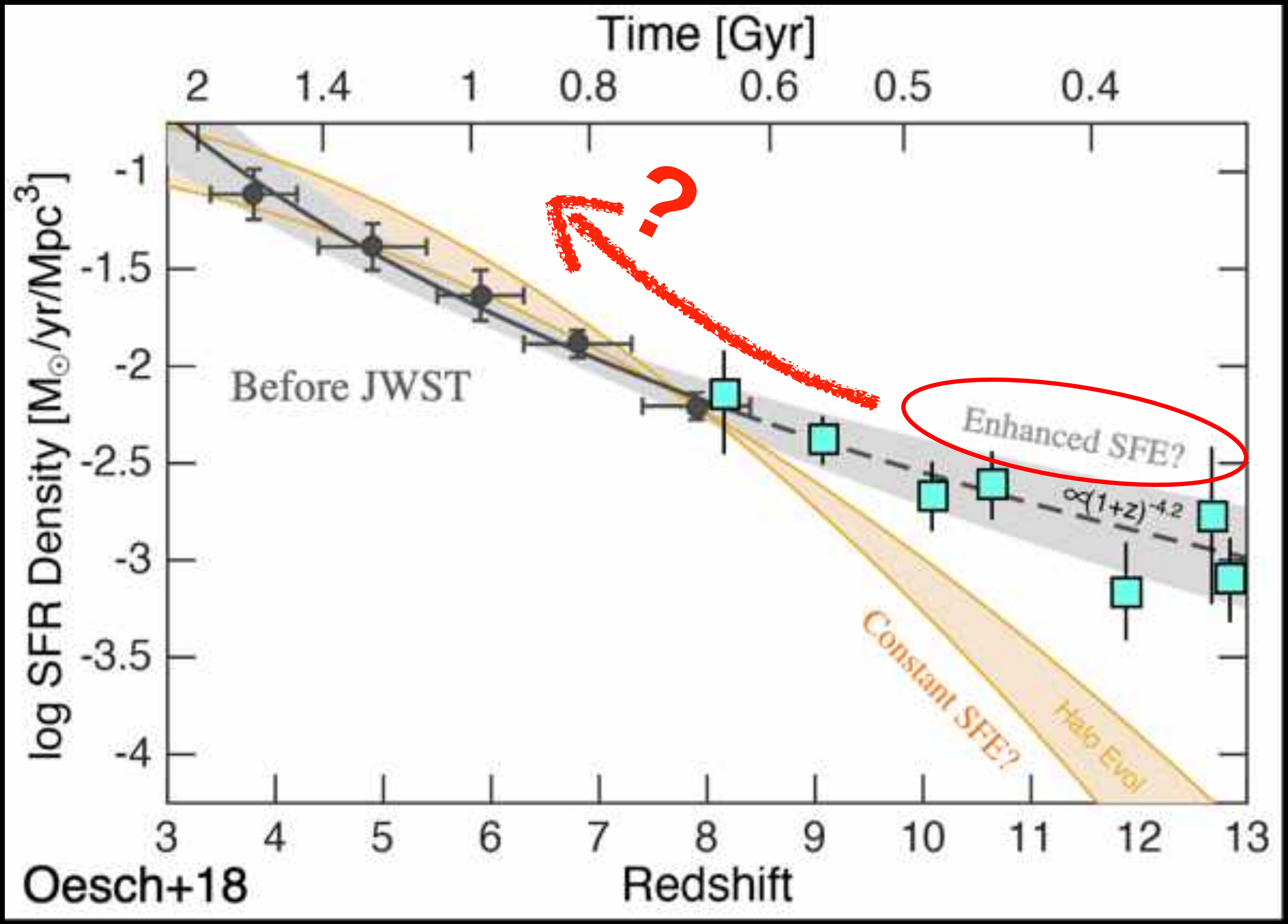
Fujimoto+23

- No robust dust detection so far at z>10
- Dust is ejected by radiative outflow? (e.g., Ziparo+23, Ferrara+23)
- At z > 9-14, CMB temperature (>30-40K) is critical… (e.g., da Cunha+13)

Dust outflow; see also e.g., Fiore+23, +24; Ferrara+24, talks by Stefano

How about z~4-8?





HST-dark / Optical-NIR dark / Dusty galaxies;
see also e.g., Caputi+12, Wang+13, Simpson+15, Stefanon+15, Fujimoto+16, Yamaguchi+19, Wang+19, Williams+19, Franco+20, Zavala+22, Xiao+23, Rodighiero+23, Fujimoto+23b, Barrufet+23,24, Gottumukkala+24, talks by Fengyuan, Andrea, Ivan, Norma, Alba

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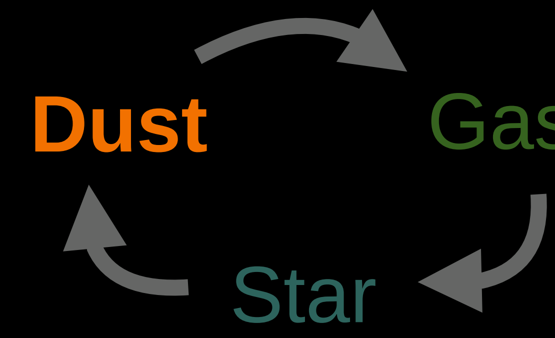
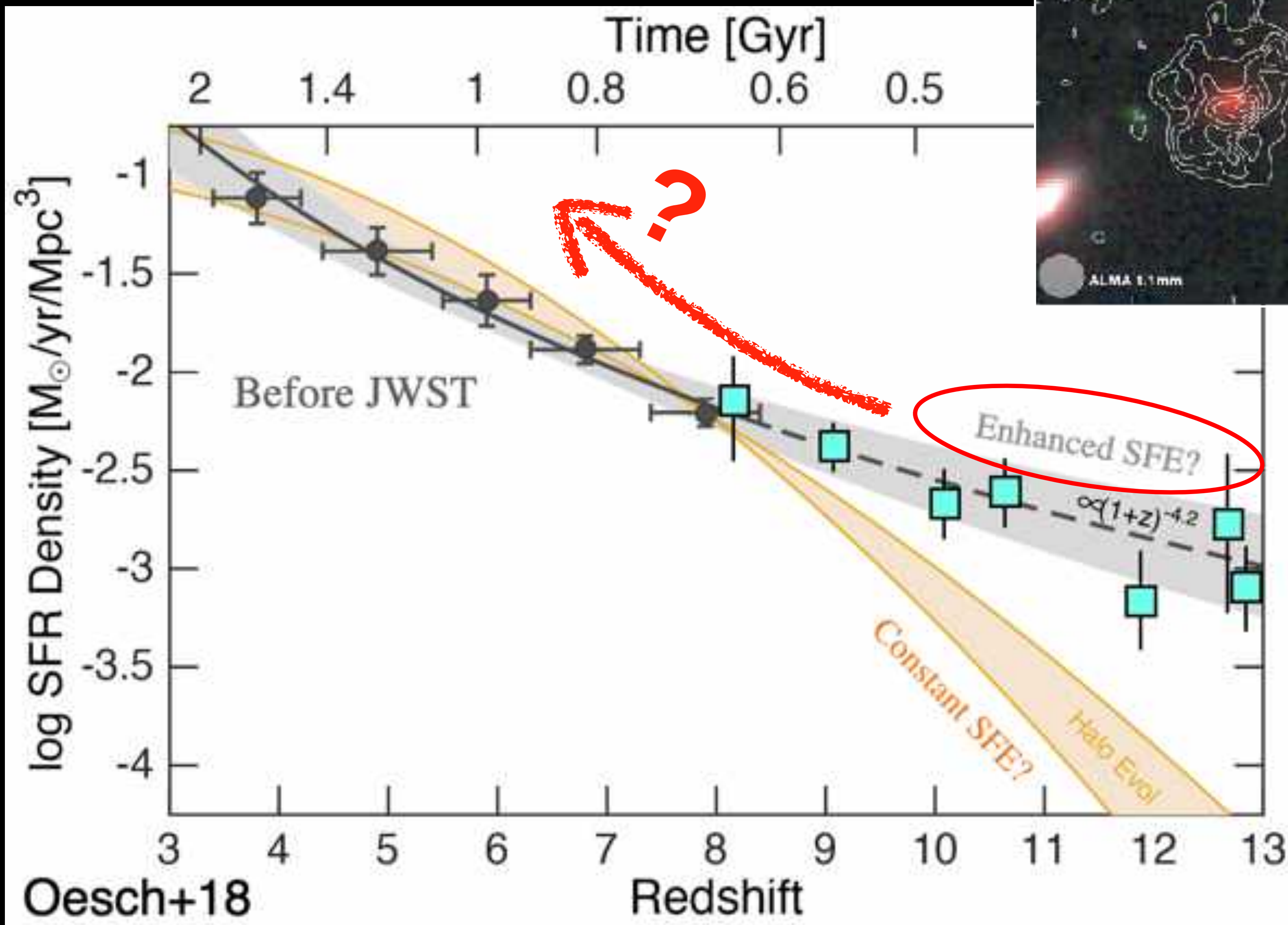
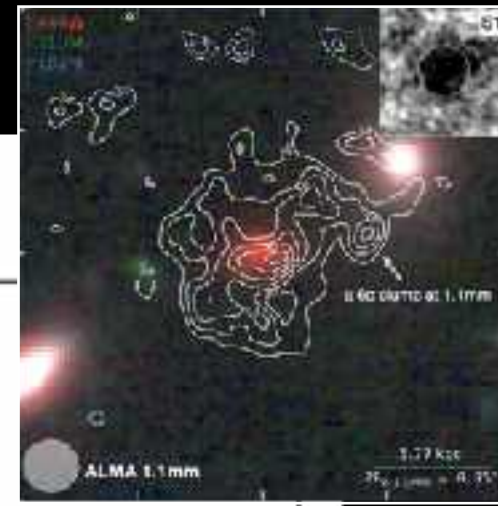
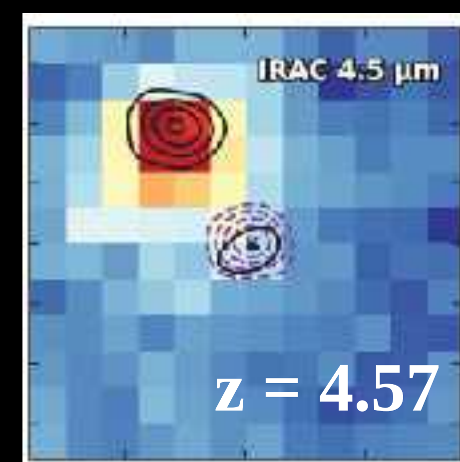




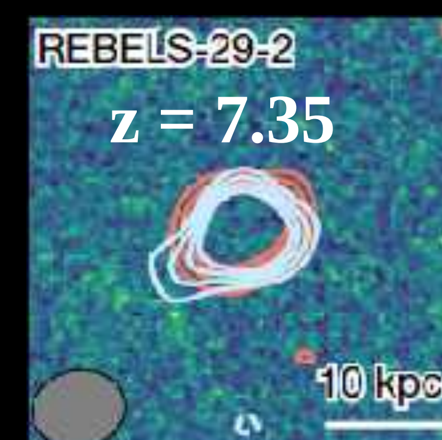


HST-dark, massive galaxy at z = 5.579 (see Mengyuan's talk)

IRAC-dark objects detected by ALMA



Romano, ALPINE+20



Fudamoto, REBELS+21

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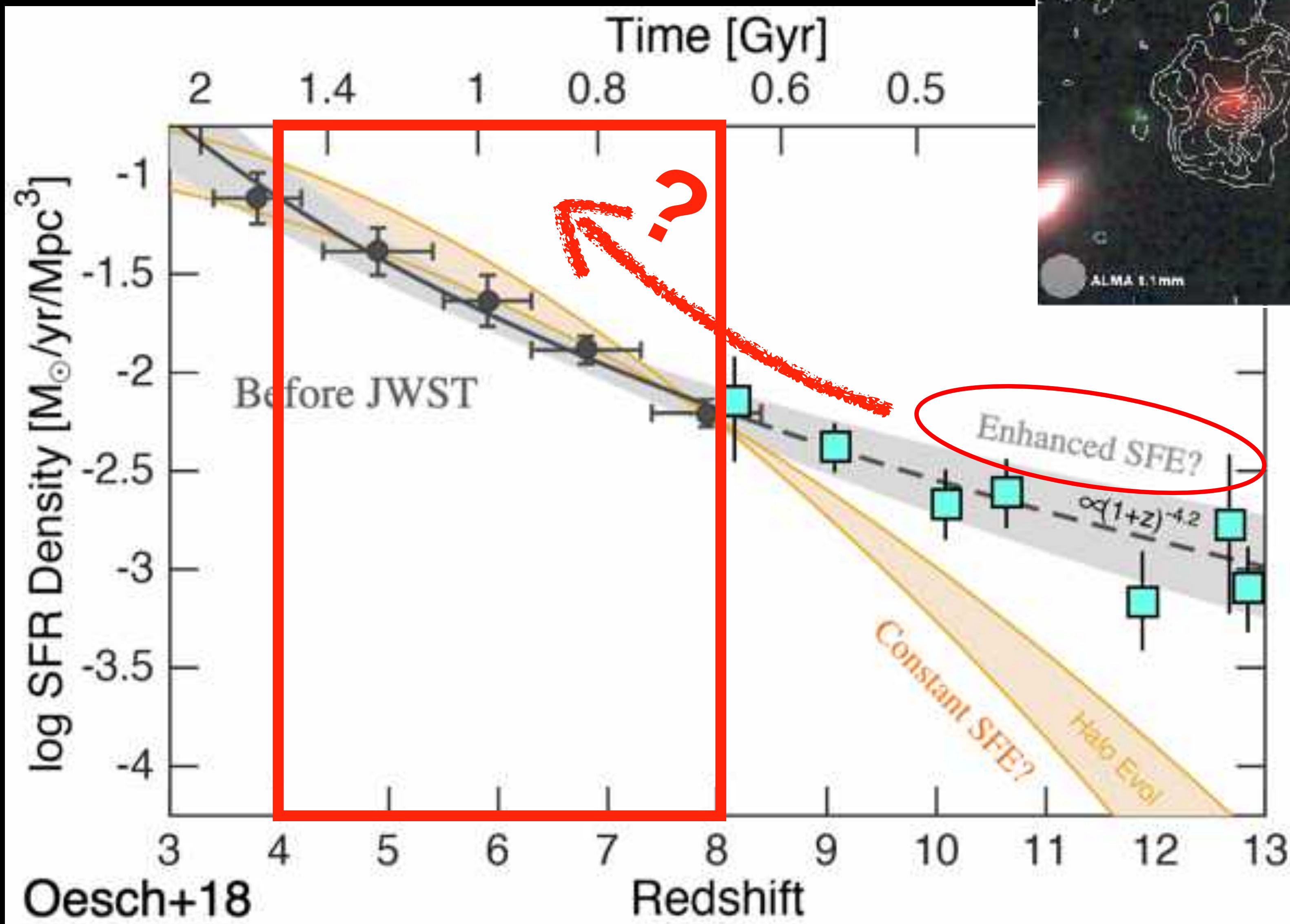
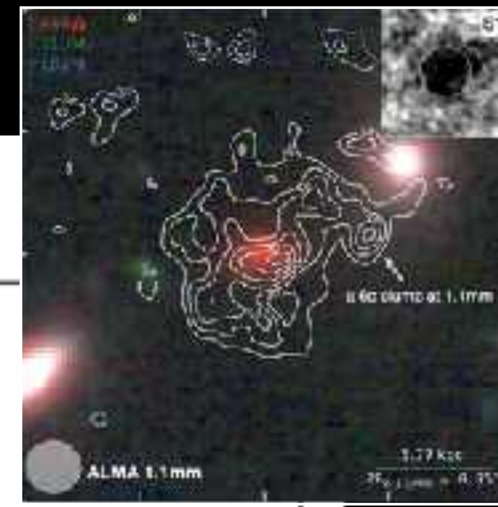
How about z~4-8?

Dust → Gas → Star





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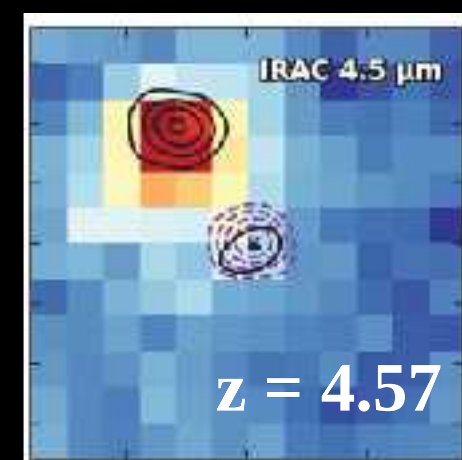

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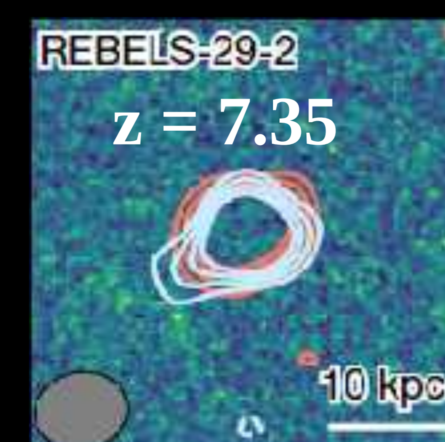
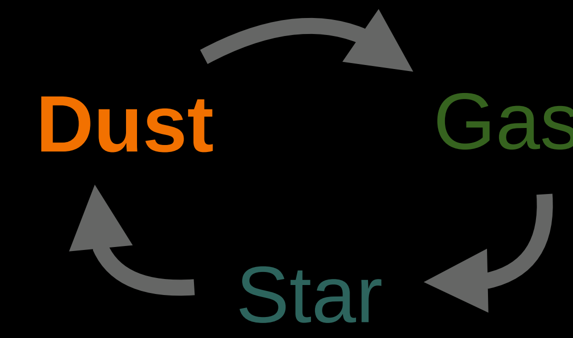


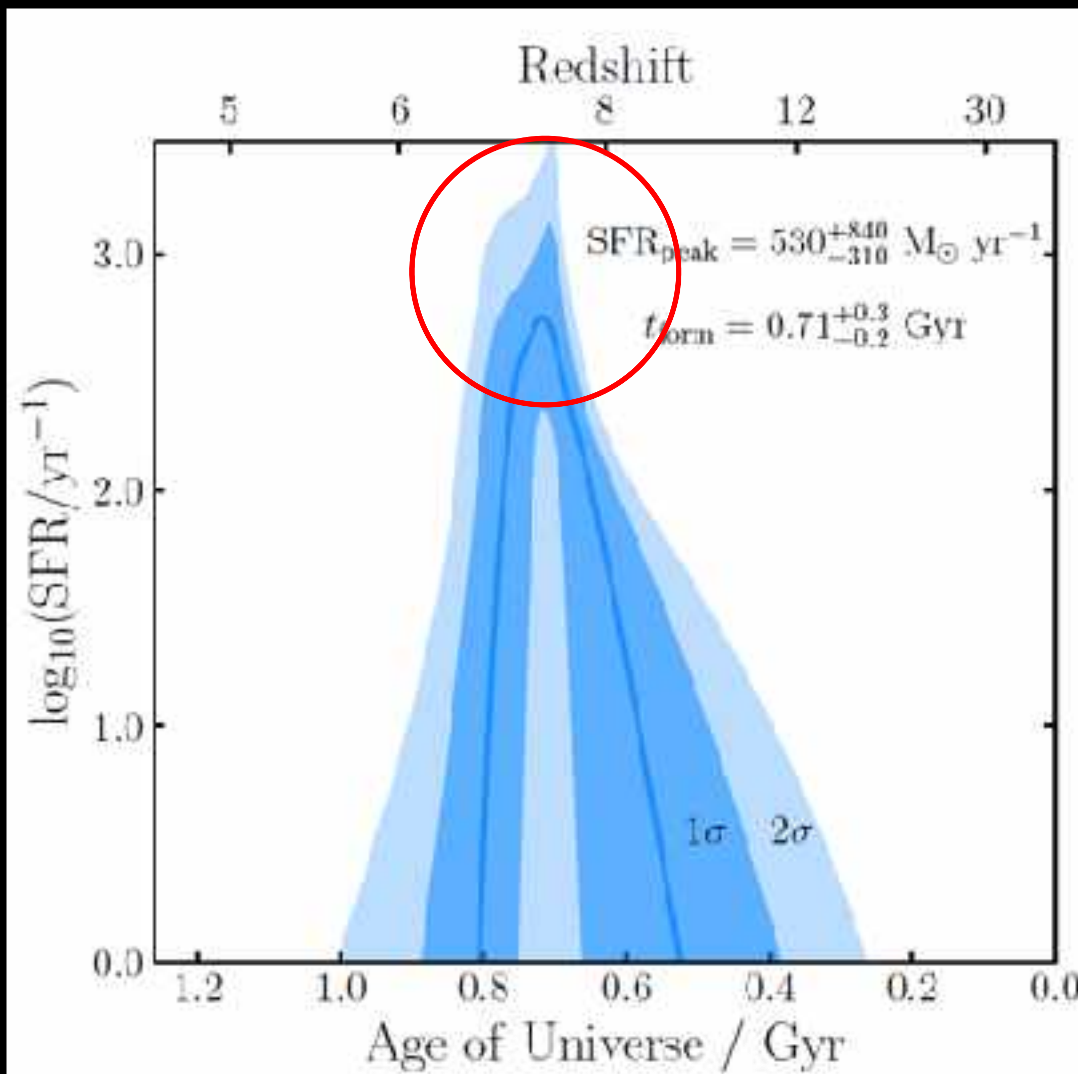
Fudamoto, REBELS+21

Cosmic SFH measurements at z>4 rely on optical/NIR-selected sources…

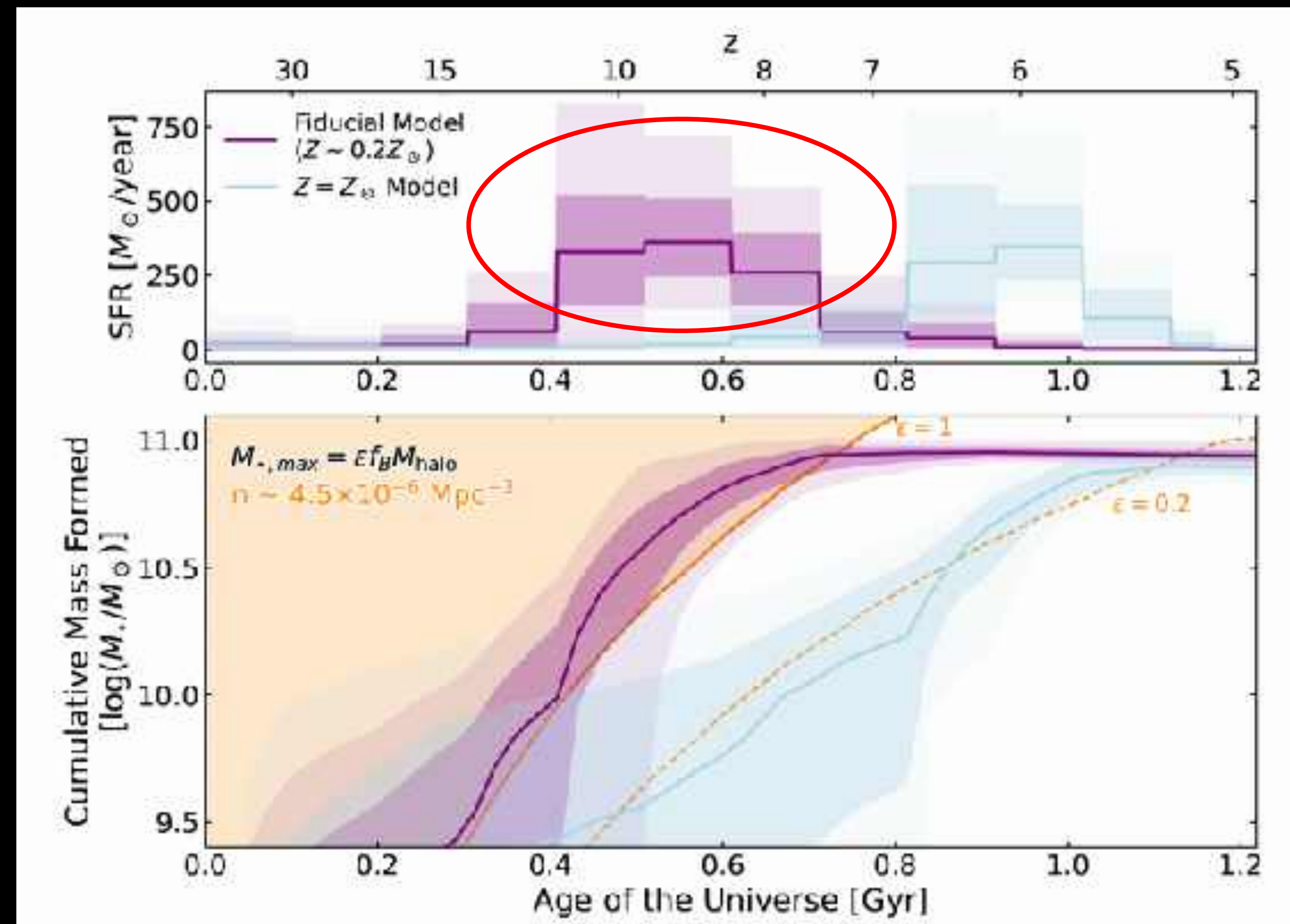
HST-dark / Optical-NIR dark / Dusty galaxies; see also e.g., Caputi+12, Wang+13, Simpson+15, Stefanon+15, Fujimoto+16, Yamaguchi+19, Wang+19, Williams+19, Franco+20, Zavala+22, Xiao+23, Rodighiero+23, Fujimoto+23b, Barrufet+23,24, Gottumukkala+24, talks by Fengyuan, Andrea, Ivan, Norma, Alba

Where are the progenitor of quiescent galaxies at z~4-5?





Carnall+23

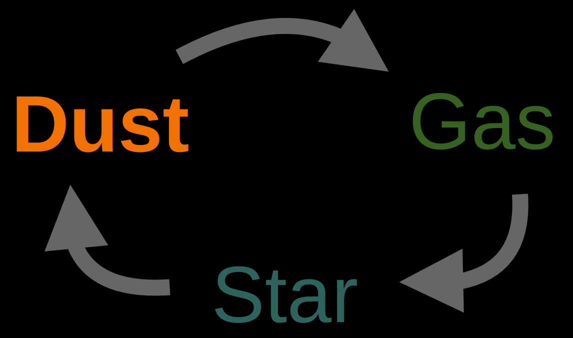


de Graaf+24

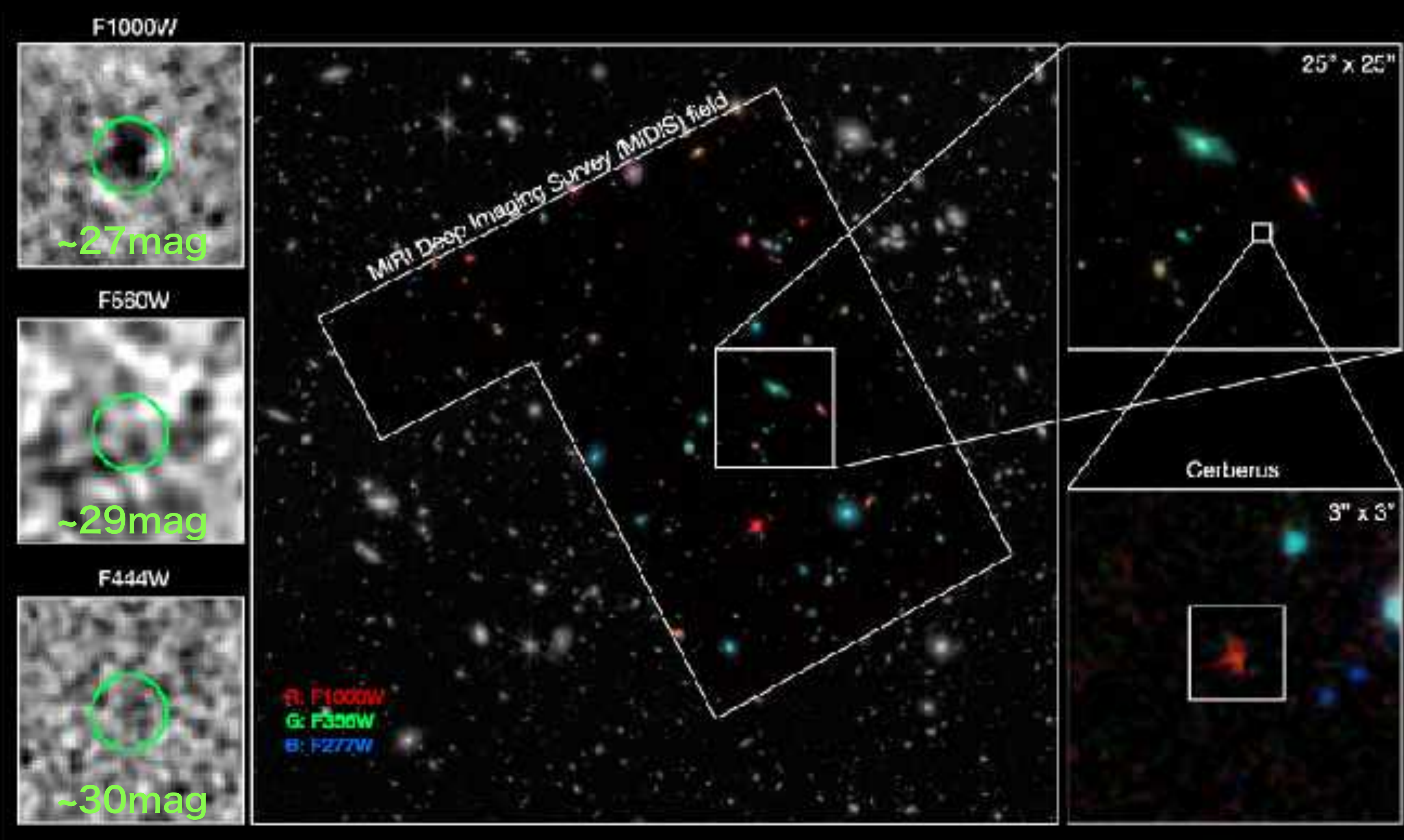
- SFH analysis suggests **SFR ~ 300-500 M◉/yr at z ~ 7-10**
- Why did not JWST observations find them? **Maybe dust obscured?**

High-z quiescent galaxies with JWST; see also e.g., Valentino+23, Antwi-Danso+23, Nanayakkara+24, Wang+24, Kakimoto+24, Looser+24, Chworowsky+24, Weibel+24, talks by Kate, James, Andrea, Adam, Massissilia, Maya, Tobias, Christian

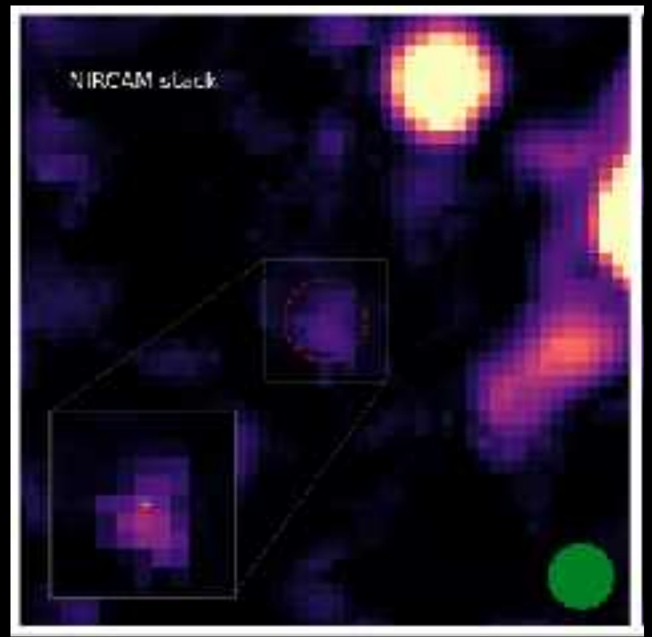
NIRCam-dark galaxies



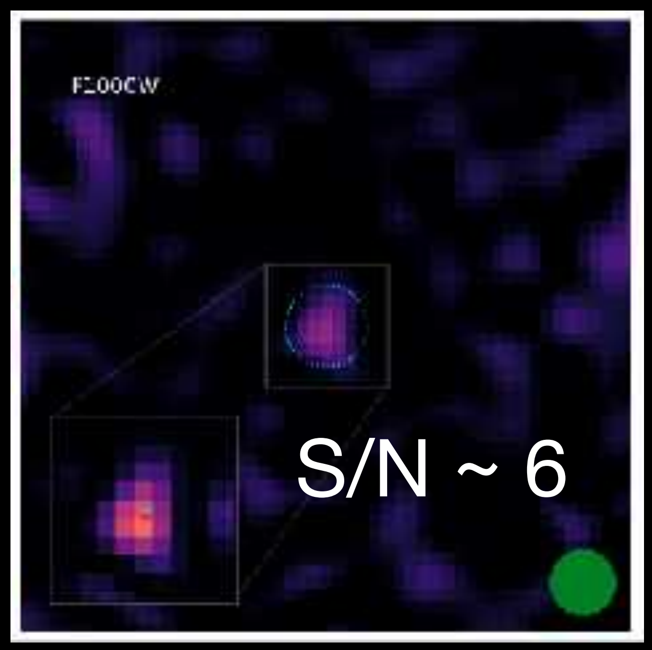
MIRI Deep Imaging Survey (MIDIS) Field **~ 2.3 arcmin²**



NIRCam stack

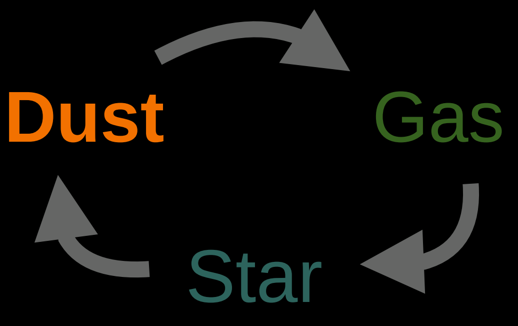


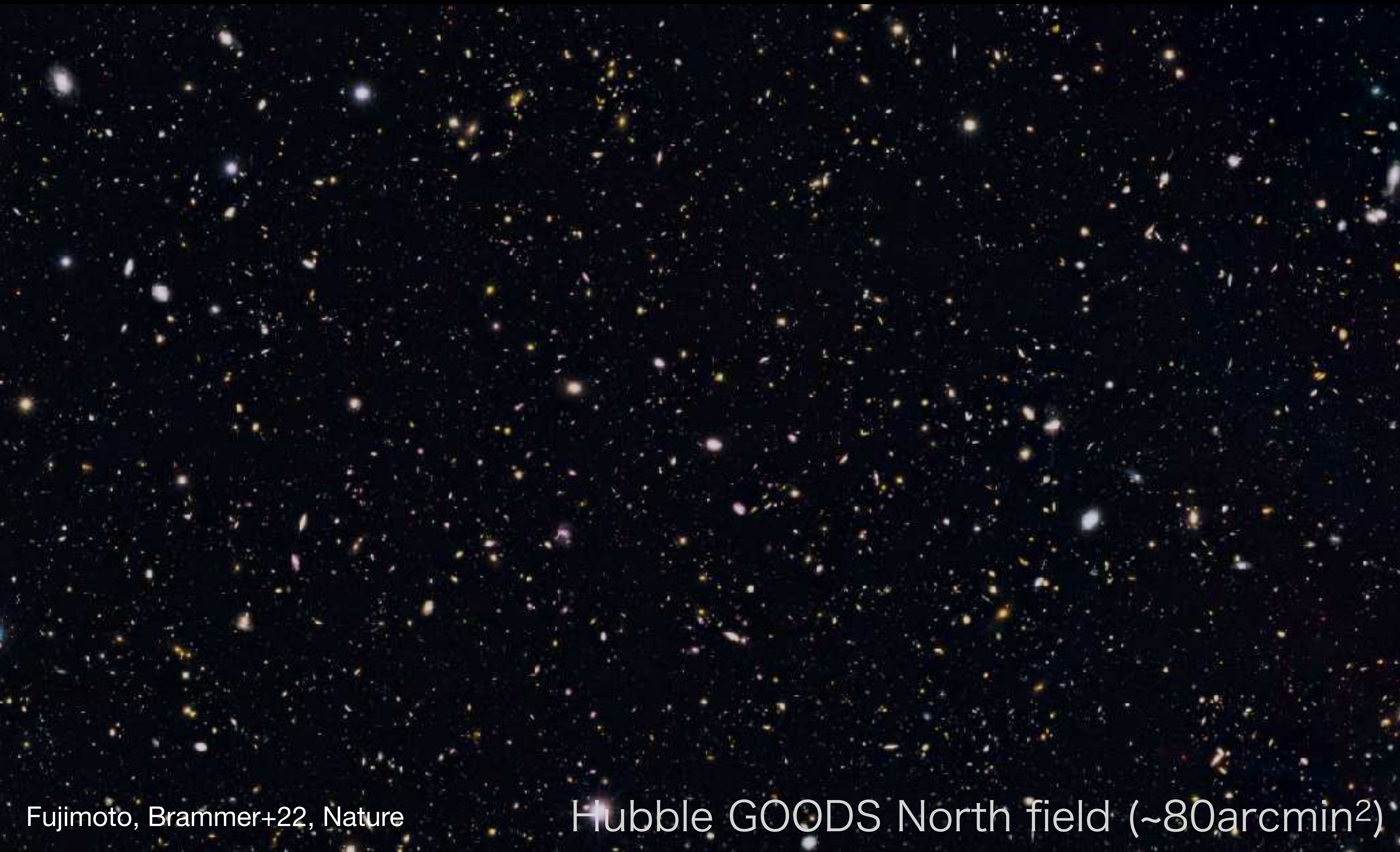
F1000W



- **z~4 low mass dusty galaxy?**
- **z~15 *little red dot* (LRD) ?**

A young, red quasar embedded in dusty starburst host at z=7.2





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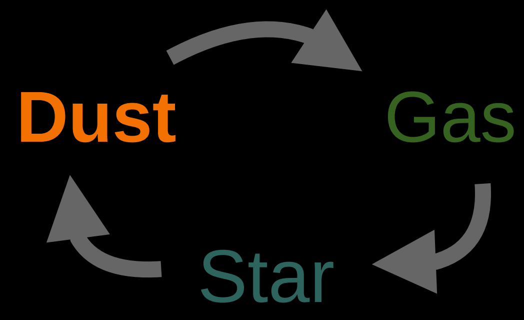

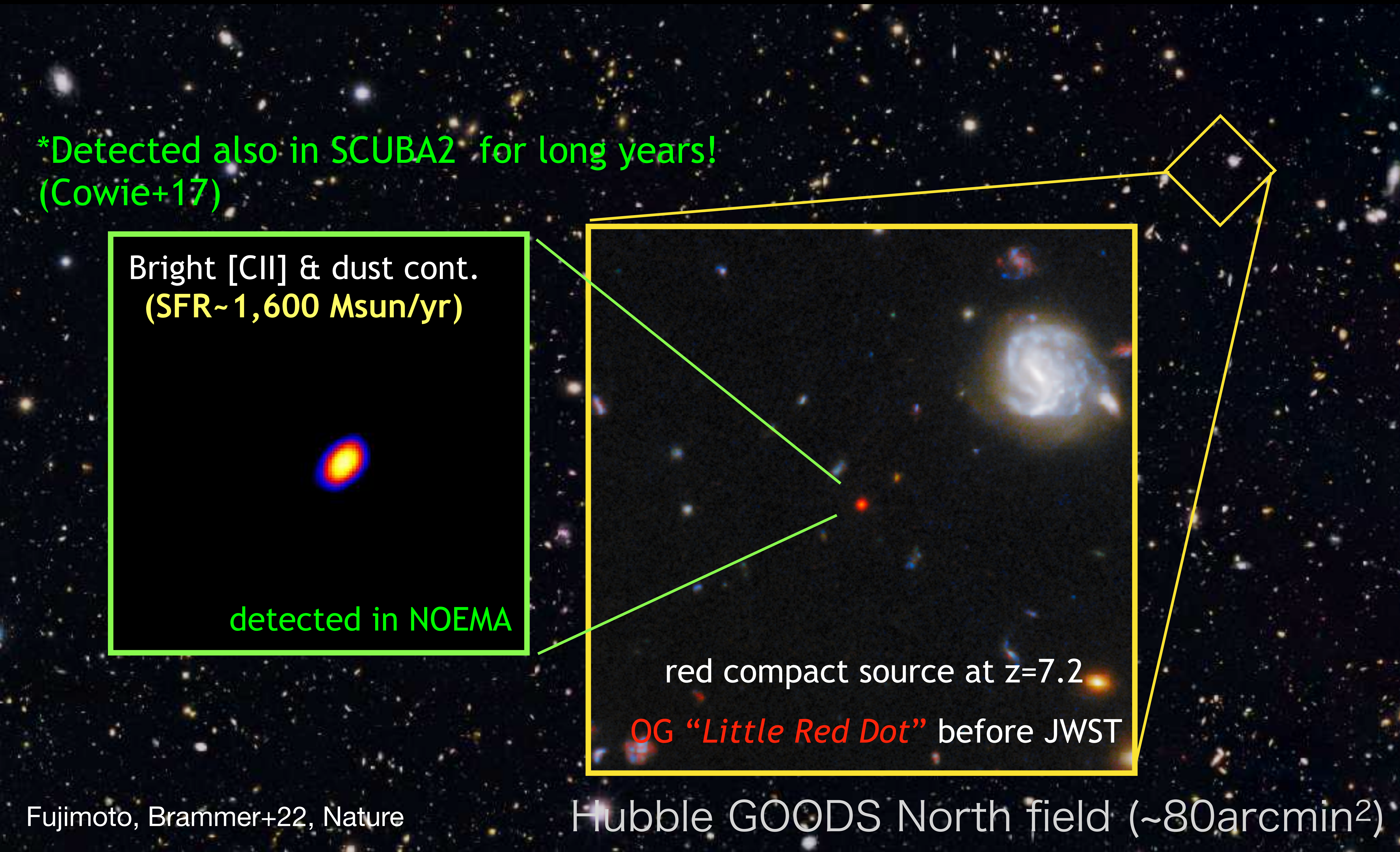

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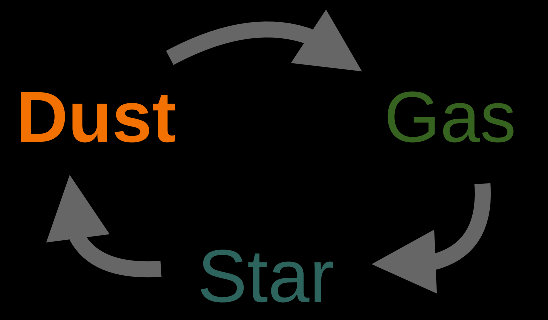

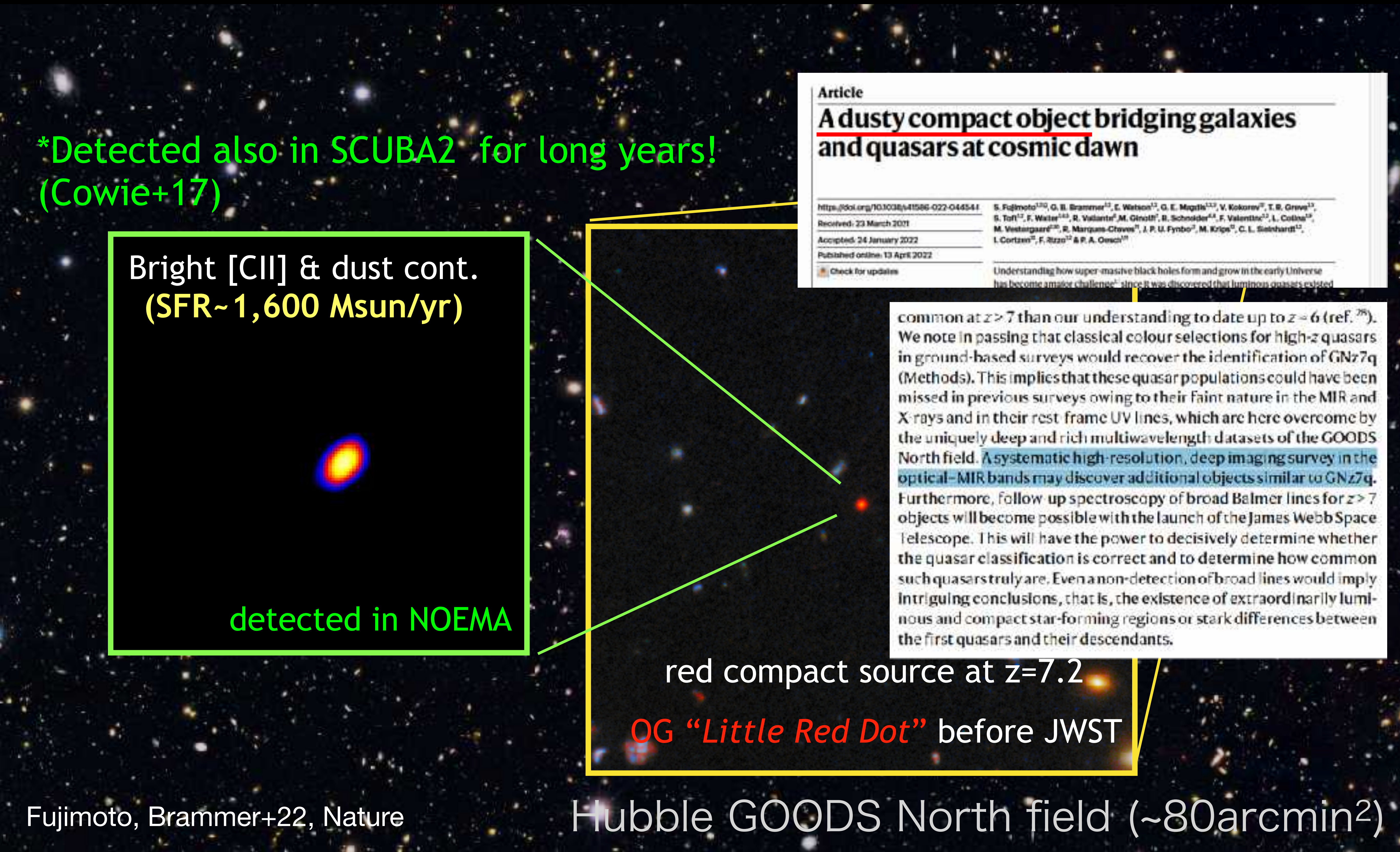

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Dust → Gas → Star

Probing the Host Galaxies of 45 Broad-line Little Red Dots at zspec =4.13-8.50 with ALMA

2024.1.00551.S

Approved

ABSTRACT
We propose the first systematic ALMA census of the [CII] and dust continuum in 45 red-color compact objects, known as Little Red Dots (zspec=4.13-8.50, whose AGN origin has been spectroscopically confirmed by recent JWST observations. Despite their surprising abundance, th physical properties of LRDs' host galaxies remain unknown due to potentially significant dust obscuration. Building upon lessons from recent subm/mm follow-up studies of UV-faint dusty quasars/AGNs, we aim to unveil the hidden star formation and gas content in this new population. Our program will: (1) quantify the fraction of gas-rich, vigorously star-forming hosts, (2) characterize typical star formation rates and gas masses (including through stacking), and (3) provide initial dynamical mass constraints. We have constructed the largest spec-z LRD sample to date, from a dedicated search of literature, public, and internal resources, including the latest JWST surveys. This study will provide the community with the first comprehensive reference ALMA results for a wide variety of LRDs, offering invaluable insights into the rapid SMBH growth and early co-evolution with their host galaxies.

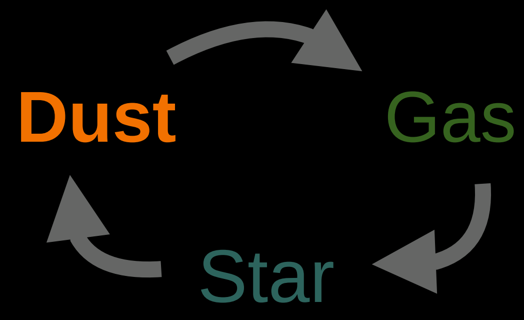
PI: S. Fujimoto
with UNCOVER/ASPIRE/ALT/EIGER teams

SCIENCE CATEGORY:	Cosmology and the High Redshift Universe				
ESTIMATED 12-M TIME:	44.8 h	ESTIMATED 7-M TIME:	0.0 h	ESTIMATED TP TIME:	0.0 h
DUPLICATE OBSERVATION JUSTIFICATION:	Some LRDs in the A2744 field have been observed in a previous wide, shallow mosaic observation. In addition to the different frequency setup optimized for the [CII] line, >2x and >4x better sensitivity are achieved for the continuum and the line, respectively, in this proposed observations.				

Fujimoto, Brammer+22, Nature

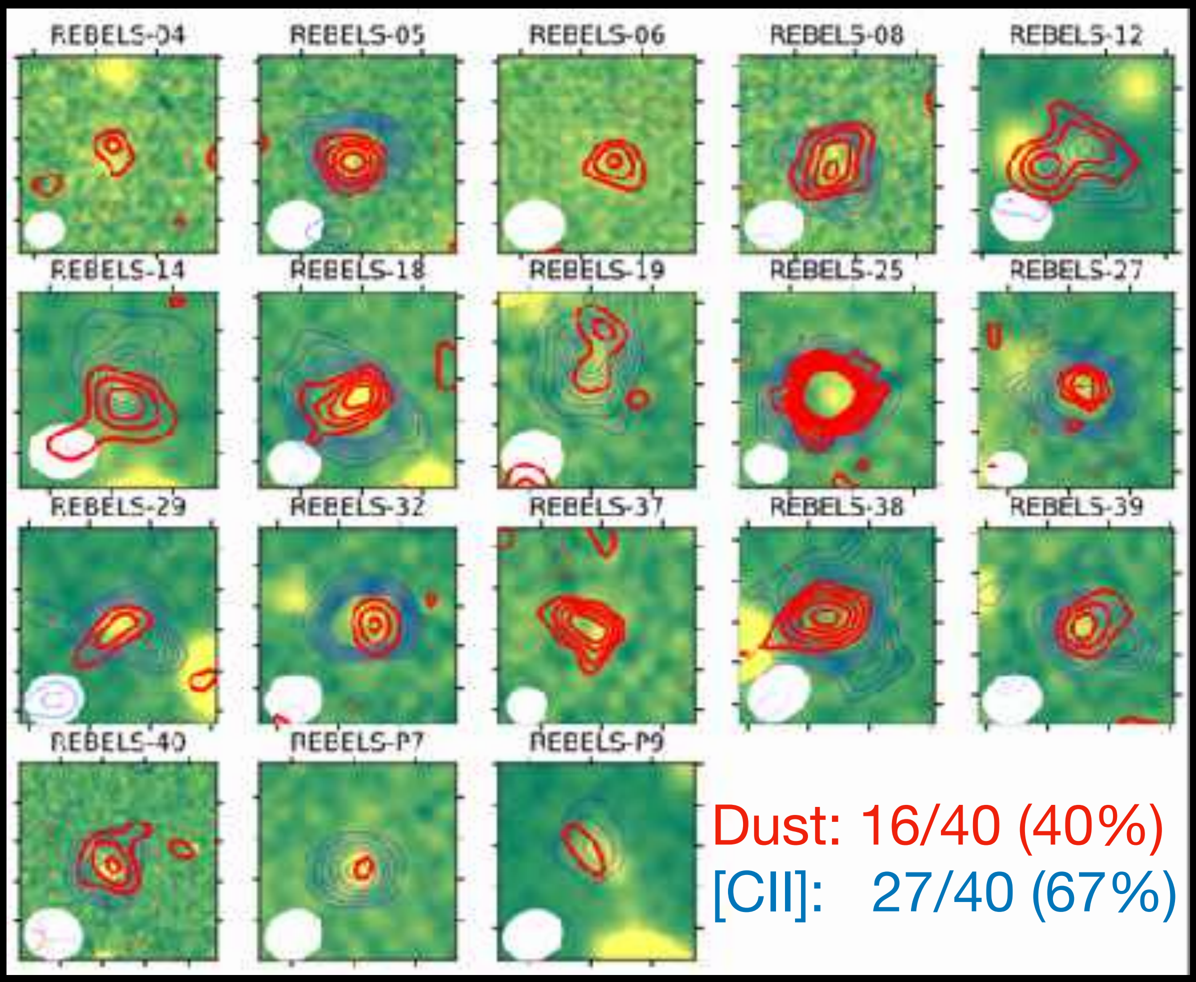
Hubble GOODS North field (~80arcmin^2)

Dust continuum in UV-bright galaxies at z~7

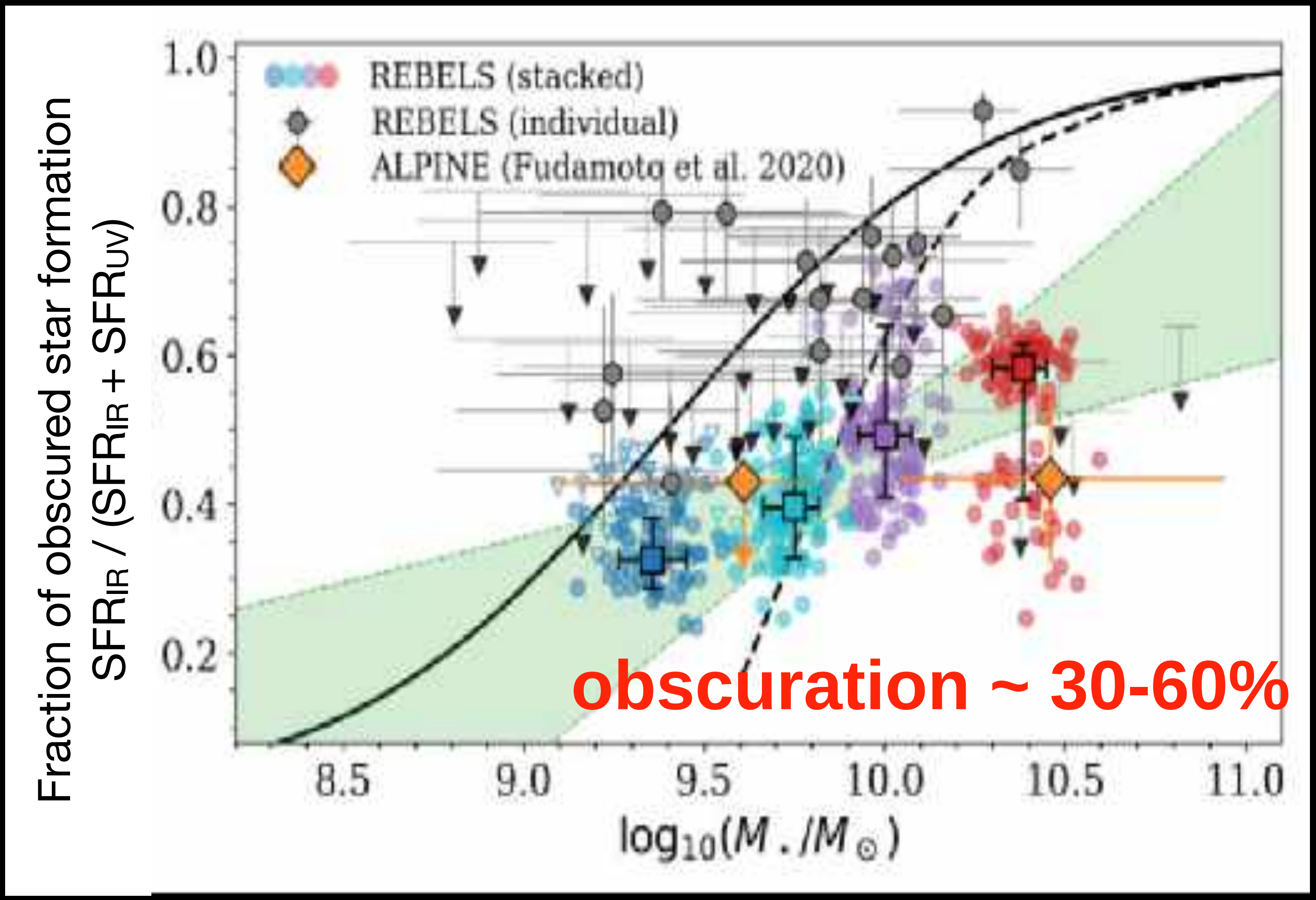


— ALMA REBELS Survey (Bouwens+22) —

Dust & [CII] follow-up for N=40 Muv~[-21:-23] galaxies at z~7



Inami+22

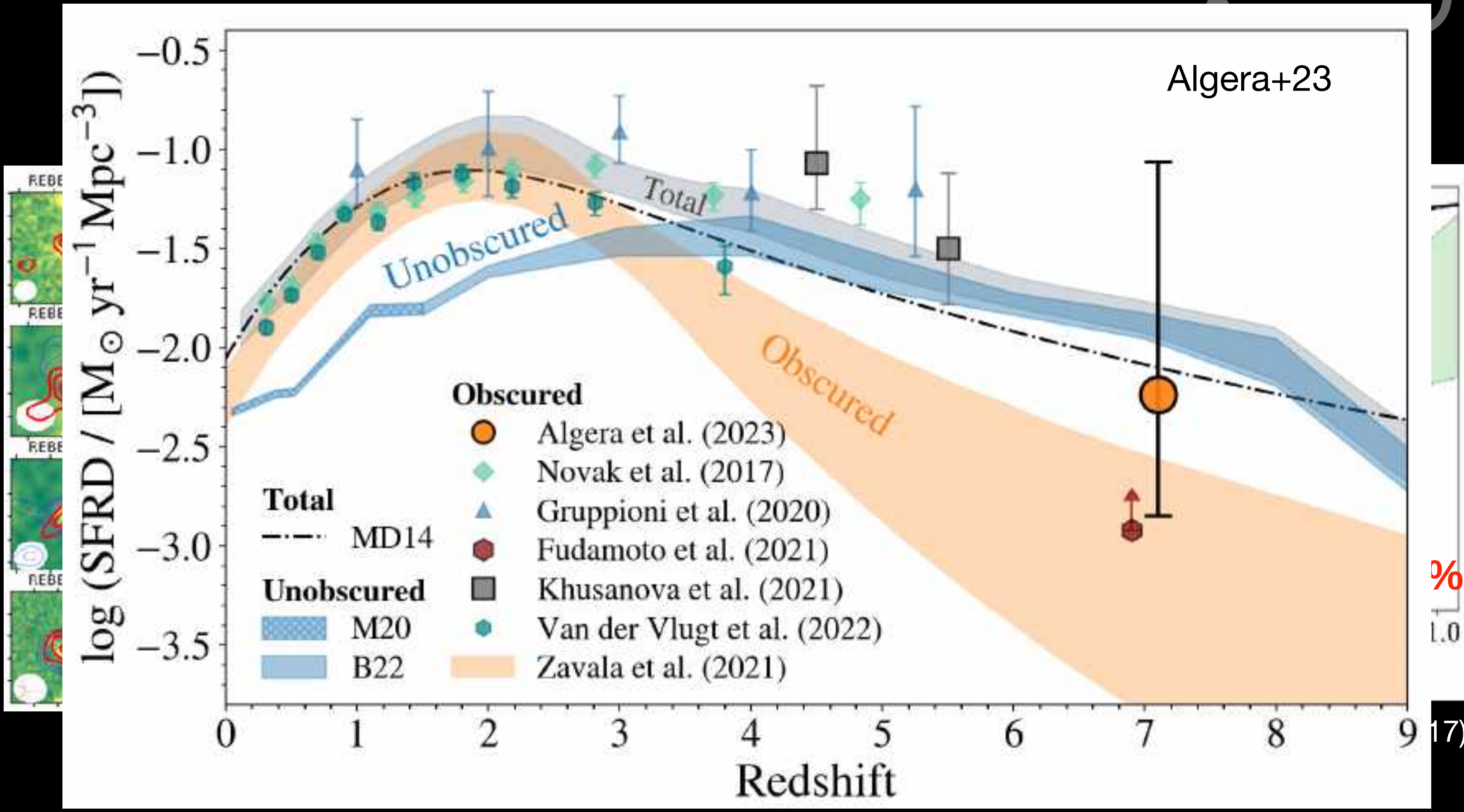


Algera+23 (See also e.g., Whitaker+17)

REBELS obscured SFRD results; see also e.g., Bowler+21, Schouws+22, Fudamoto+21, Barrufet+23, talks by **Mauro**

Dust continuum in UV-bright galaxies at z~7

Dust
Gas



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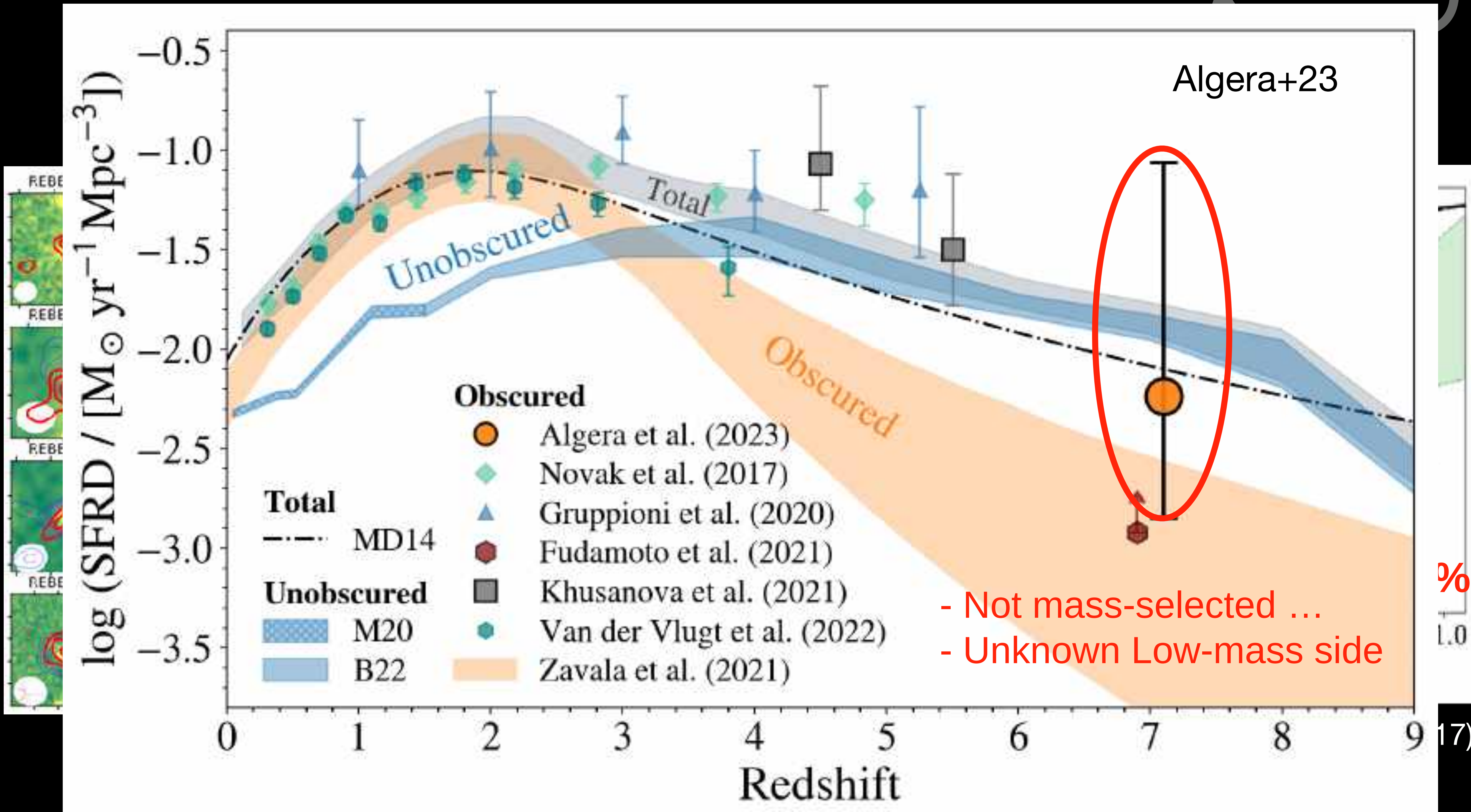
Dust → Gas

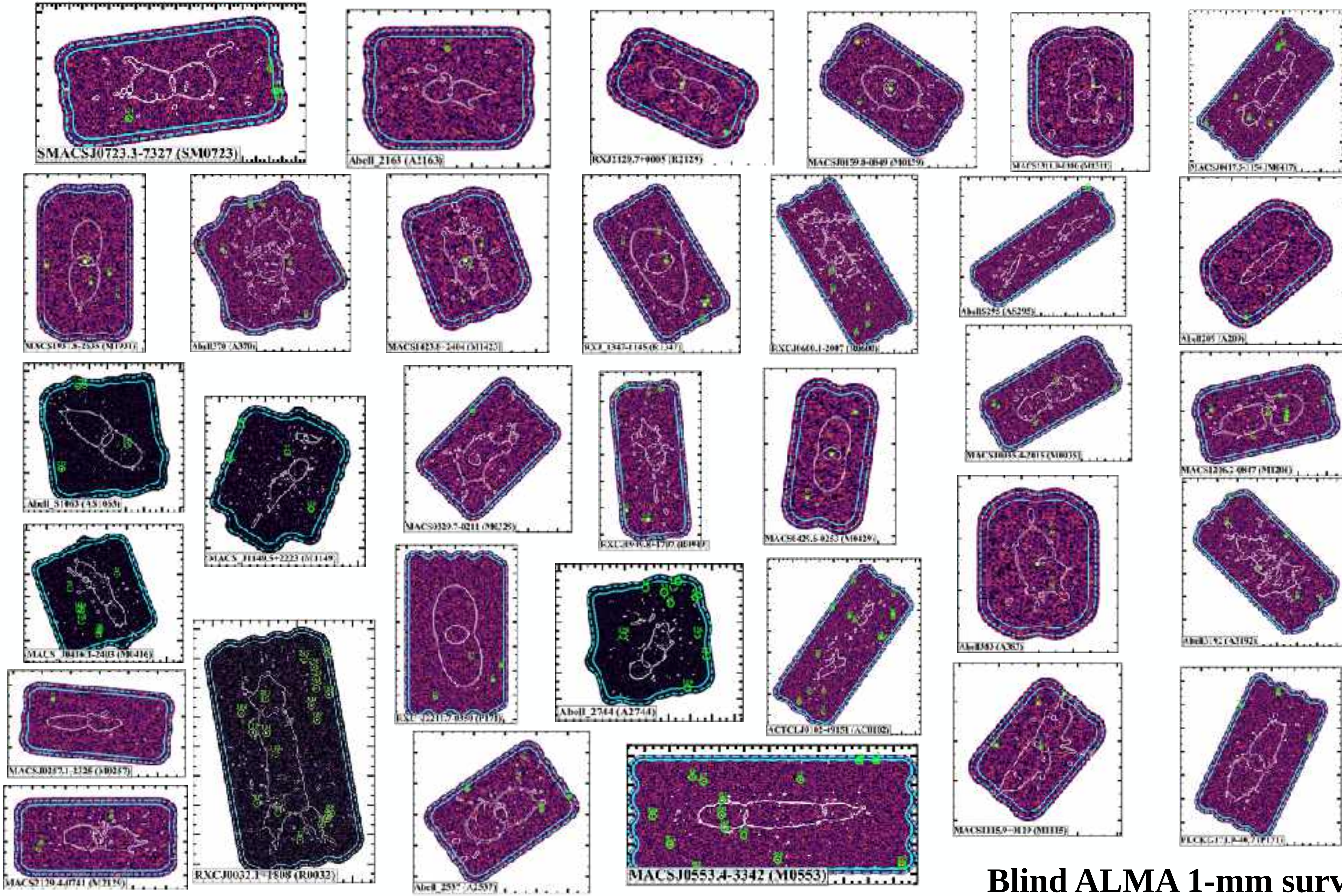


HST/NIRCam-dark? Abundant faint AGN hosts? UV-selected galaxies?

Wide x Deep x Blind Survey for IR sources is required

REBELS obscured SFRD results; see also e.g., Bowler+21, Schouws+22, Fudamoto+21, Barrufet+23, talks by **Mauro**

ALMA Lensing Cluster Survey (ALCS)



Blind ALMA 1-mm survey for 33 massive lensing clusters

Kohno+23, Fujimoto+23b, ApJS in press

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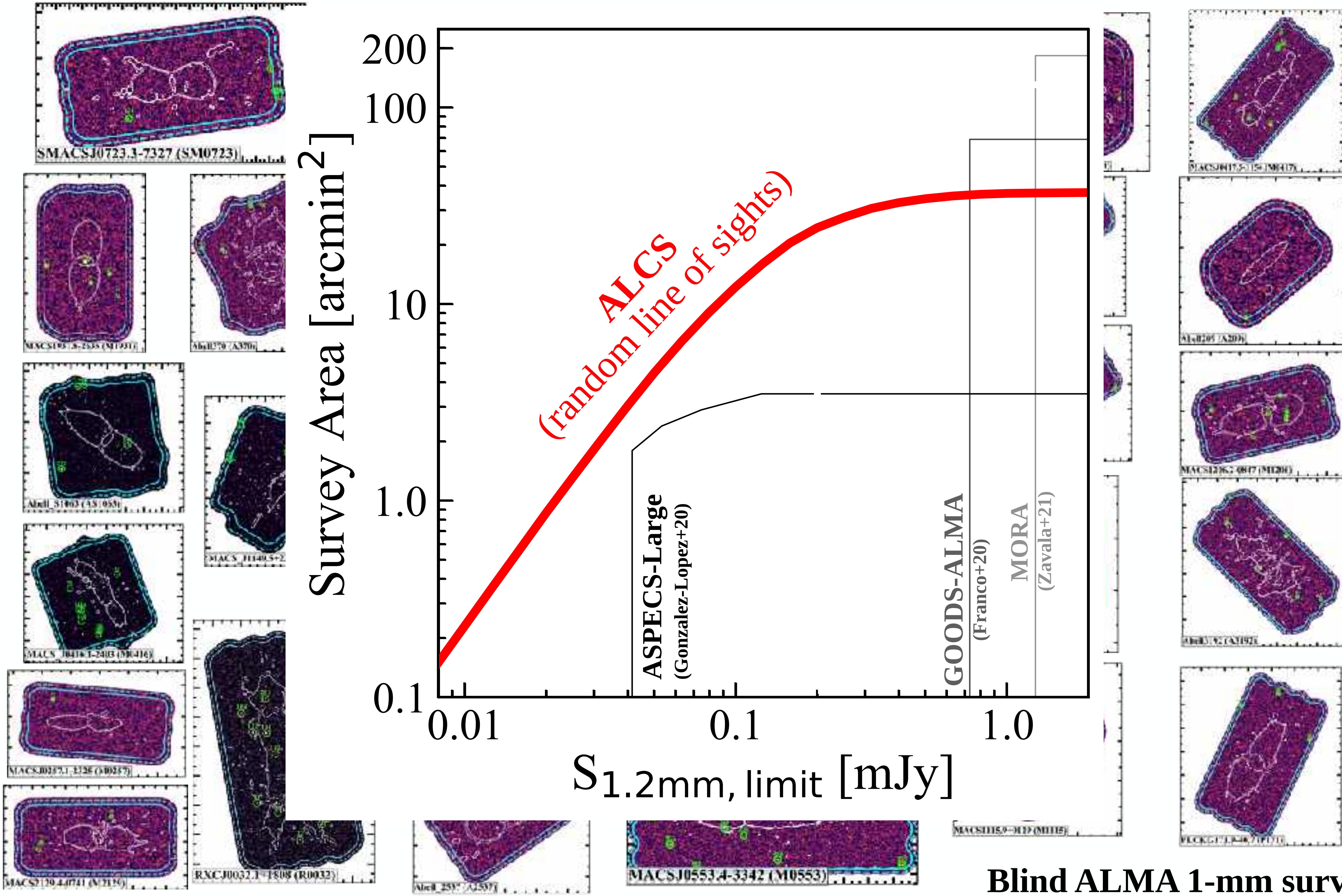

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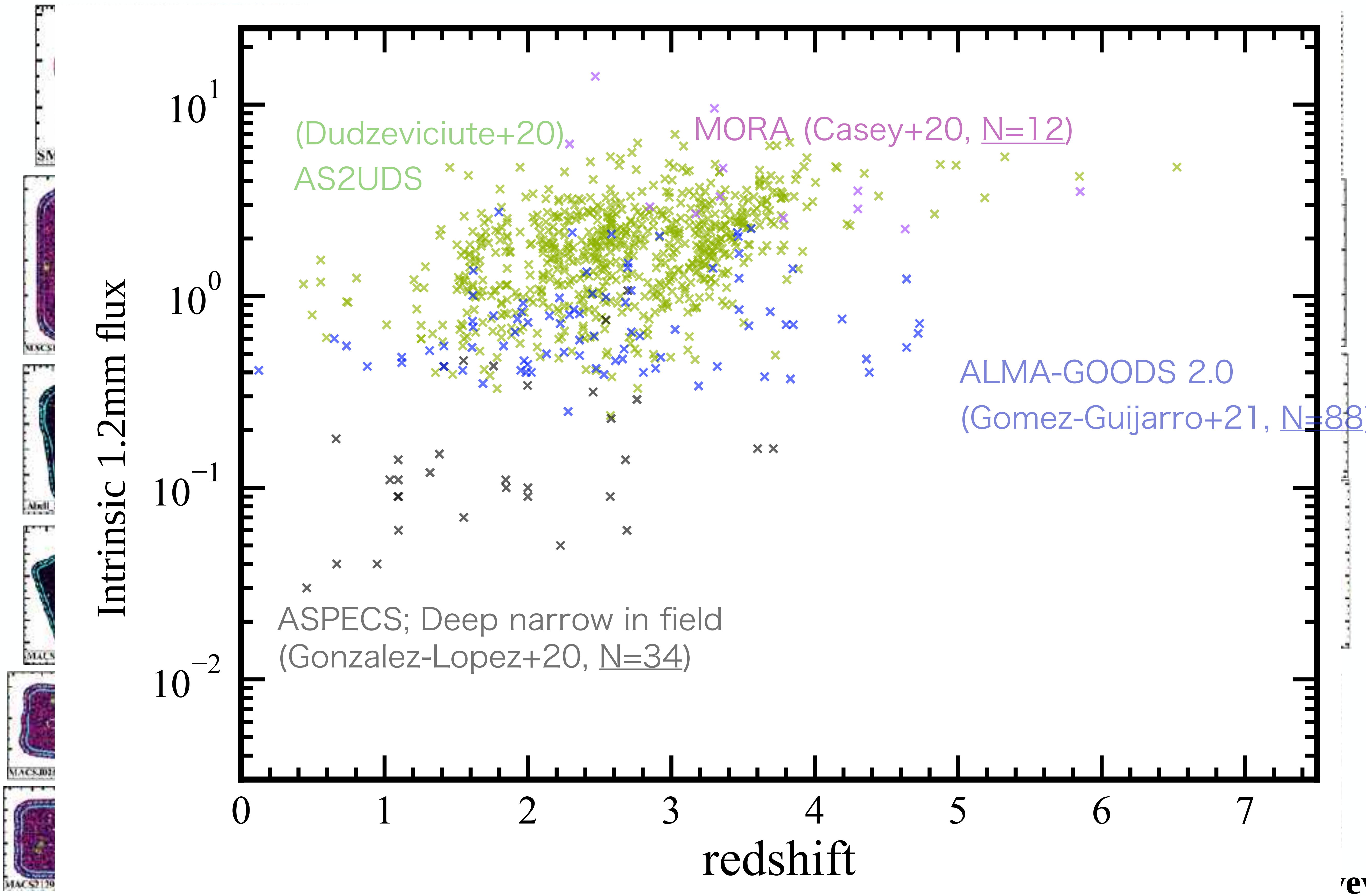

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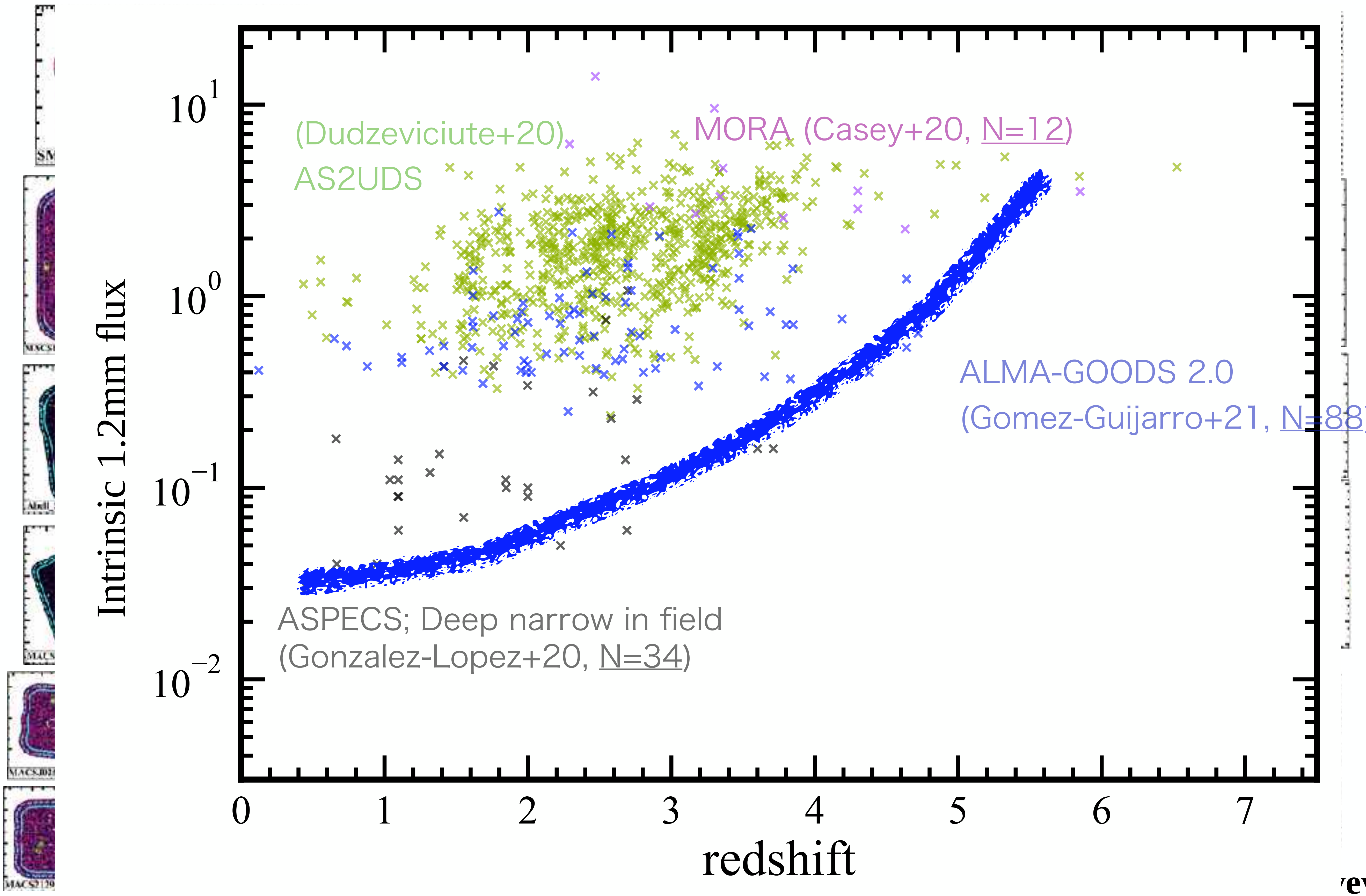

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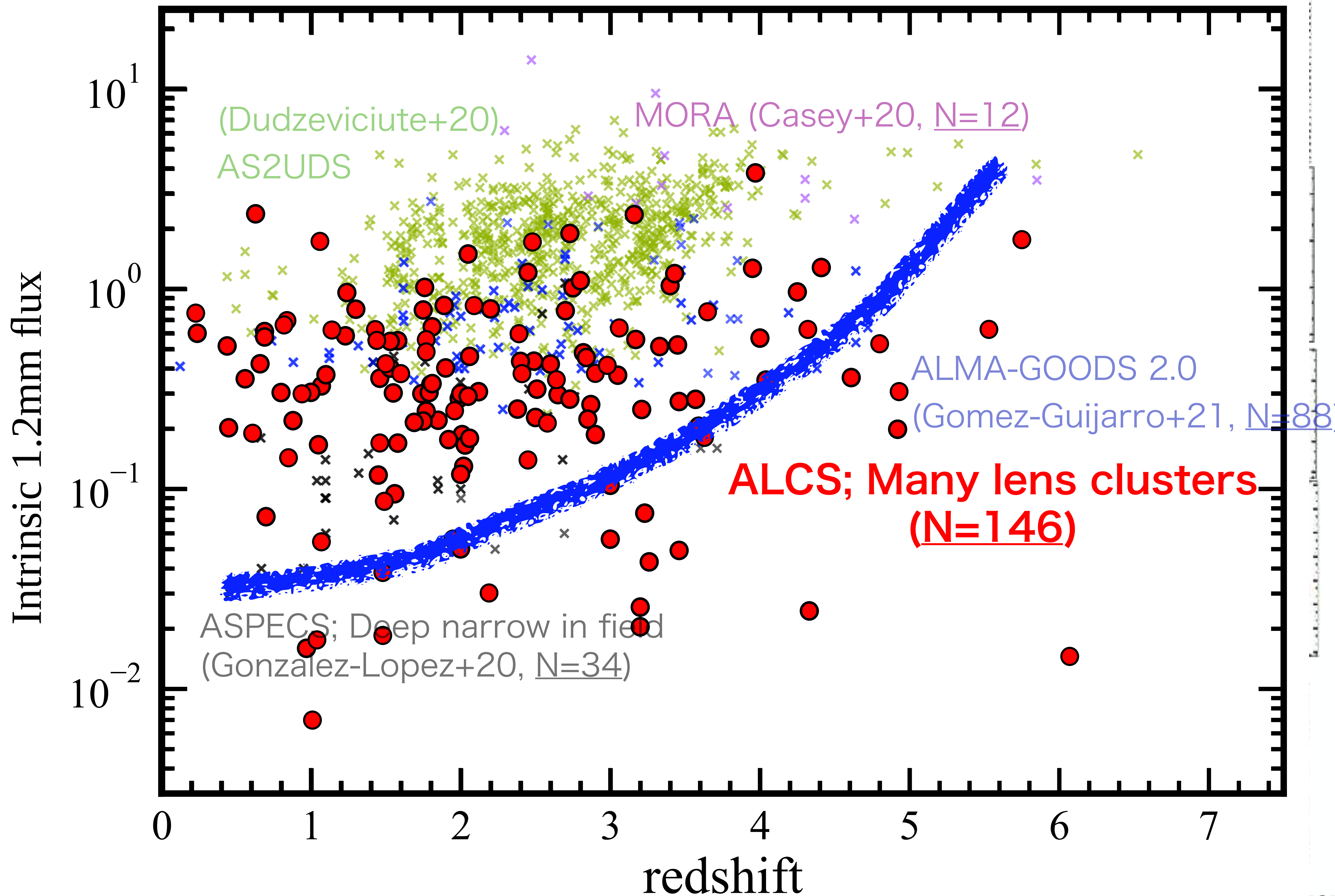

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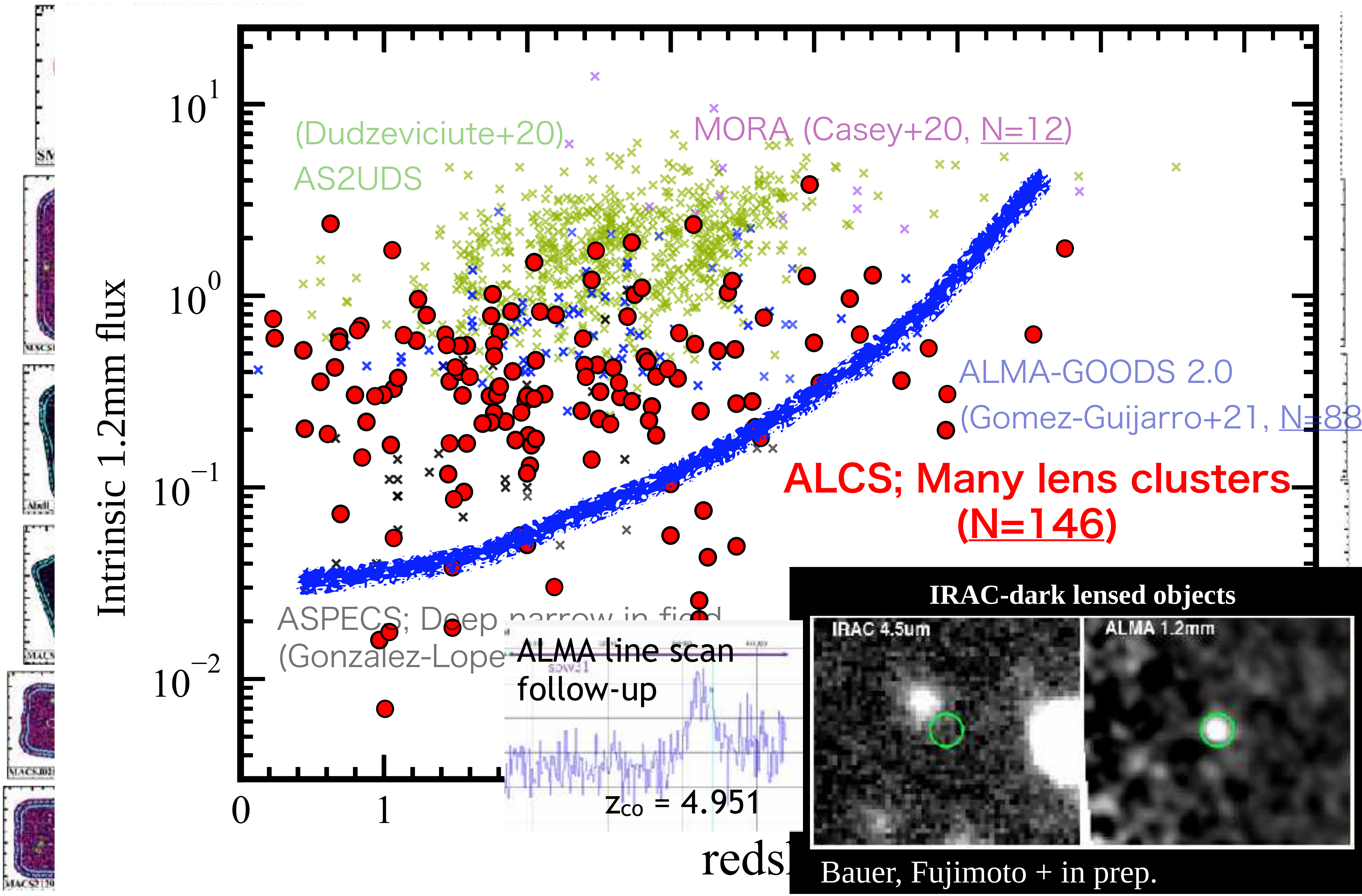

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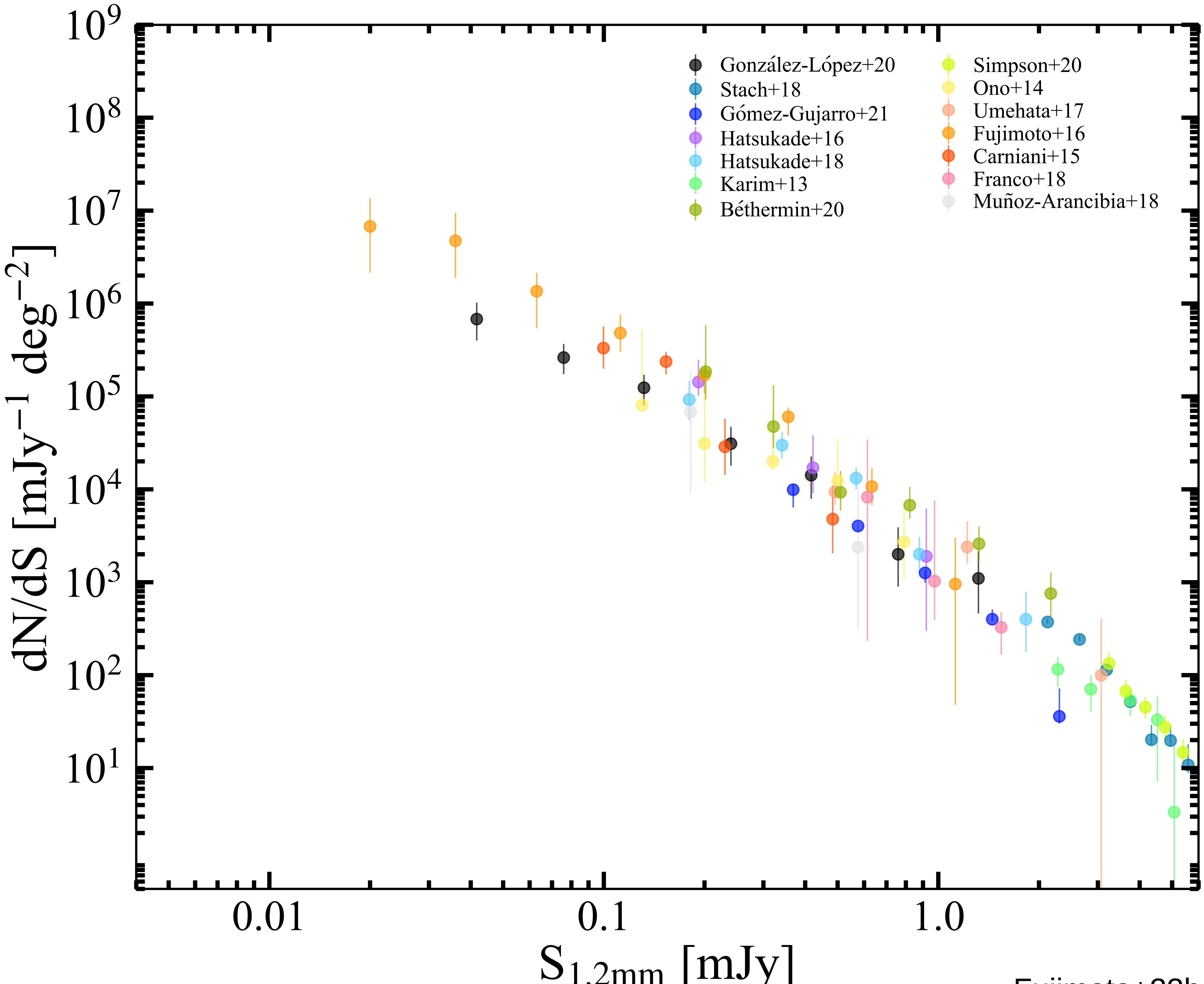
for 33 massive lensing clusters

Number counts at 1.2mm



Fujimoto+23b, ApJS in press

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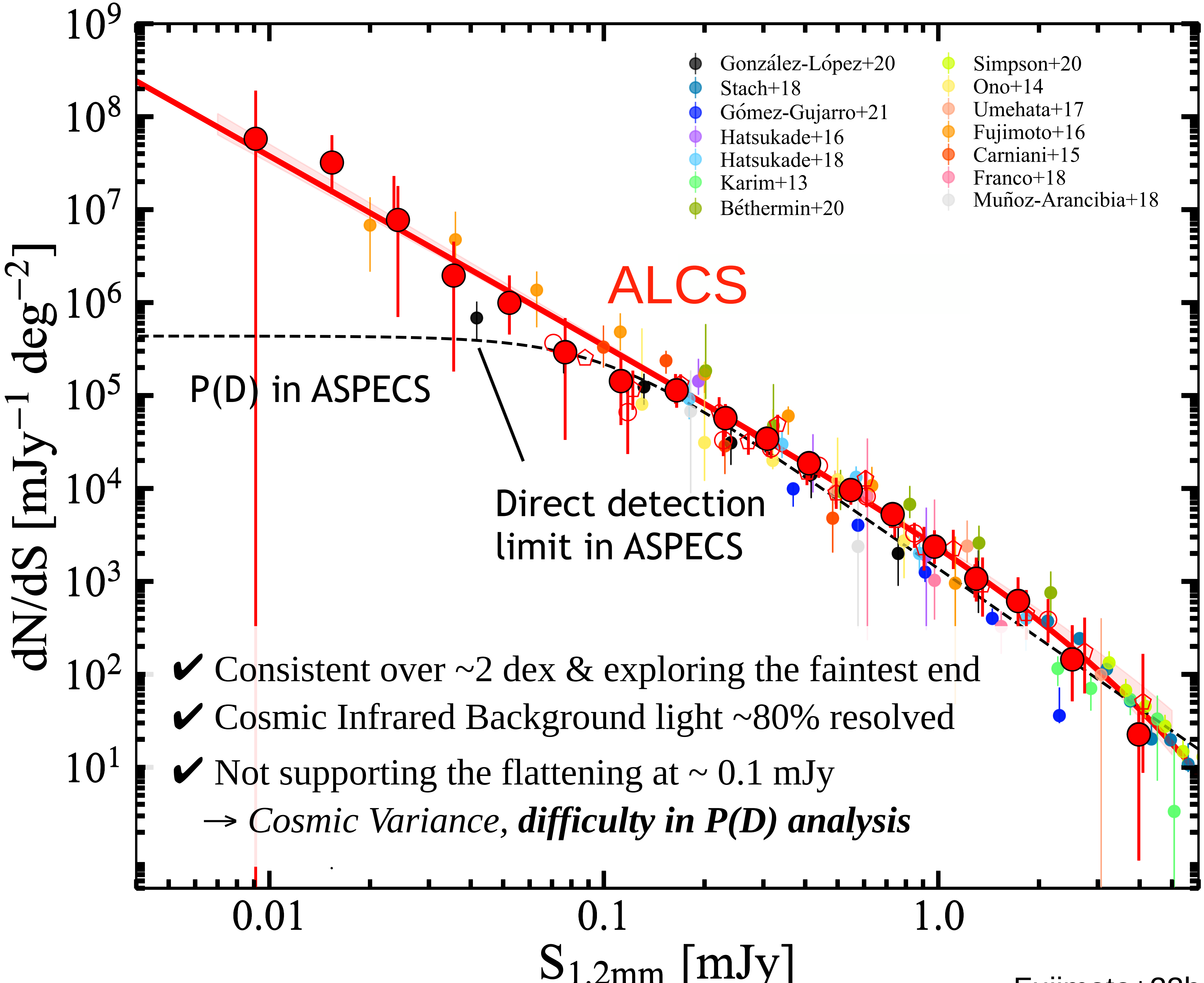
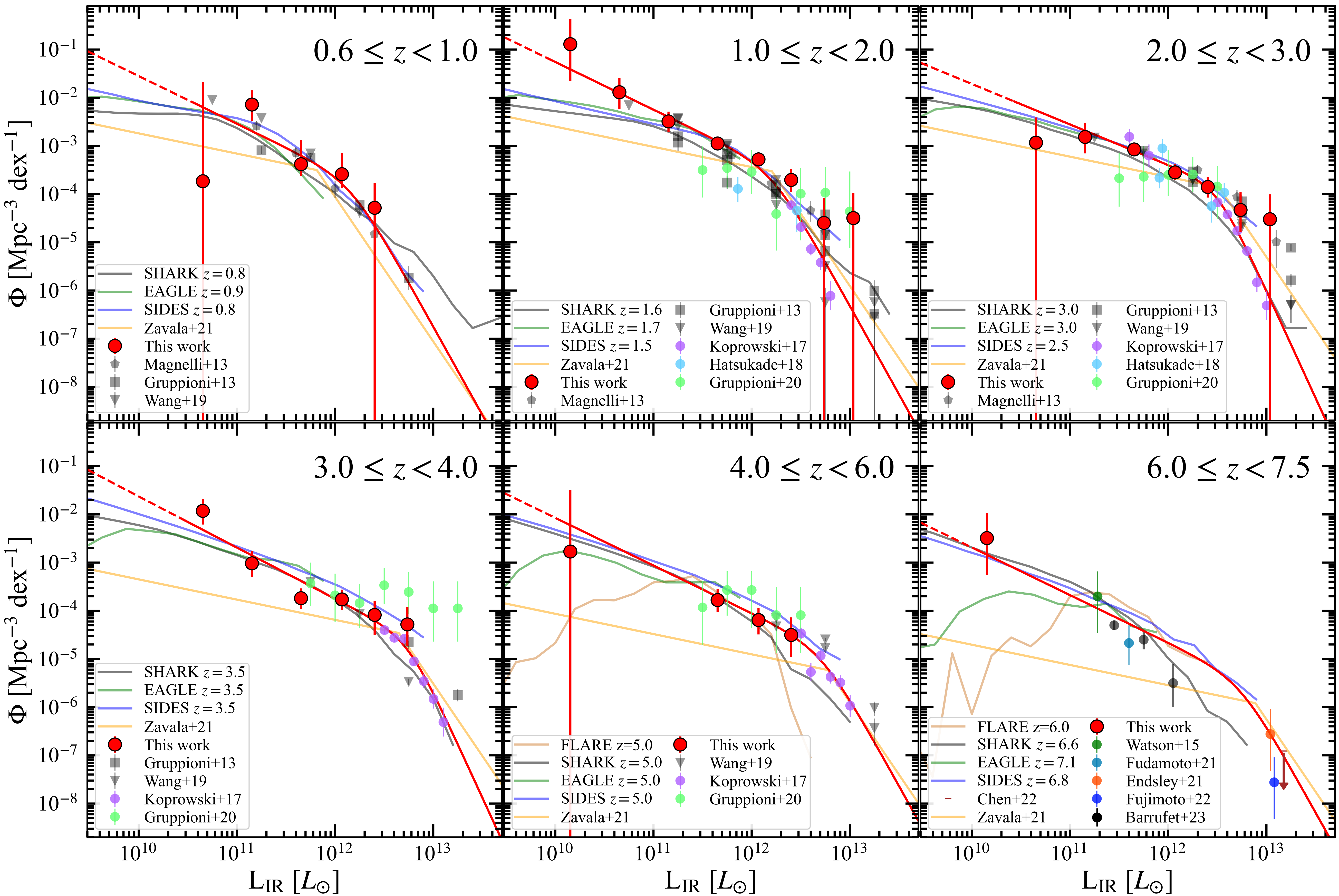


Fujimoto+23b, ApJS in press

Infrared LFs at z ~ 1 - 8



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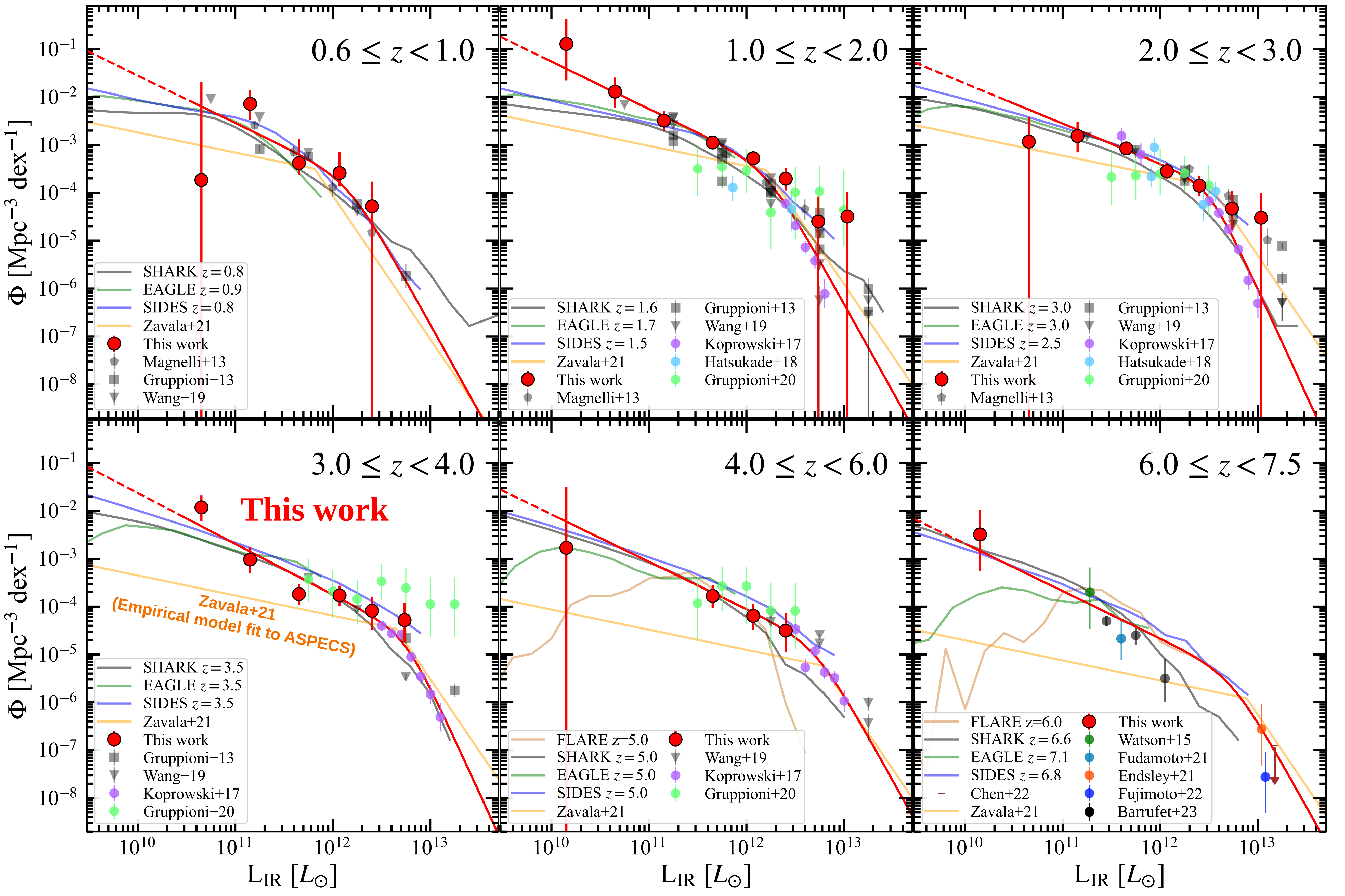
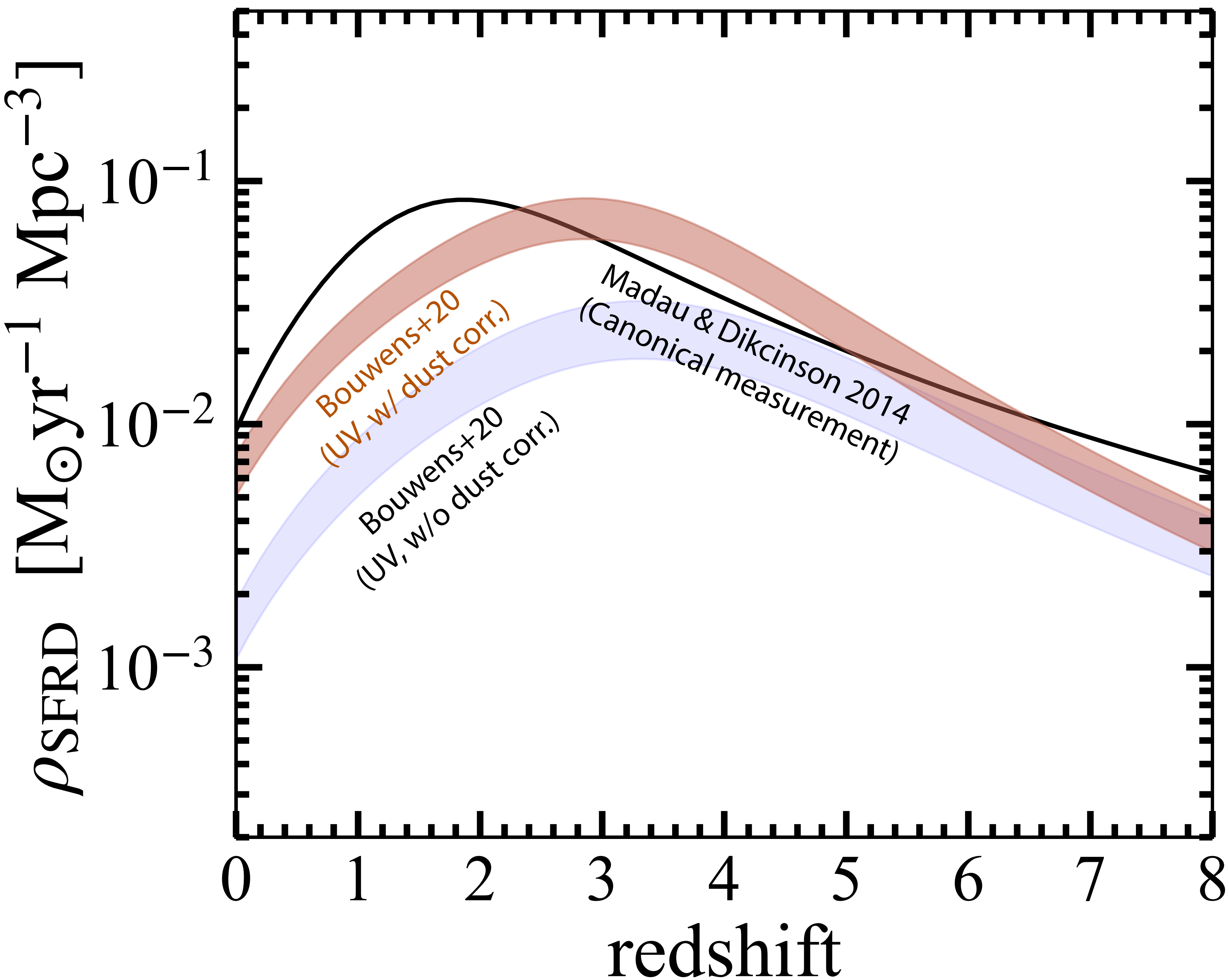


Fujimoto+23b, ApJS in press

UV+IR LFs = Total CSFH at z~1-8



Fujimoto+23b, ApJS in press

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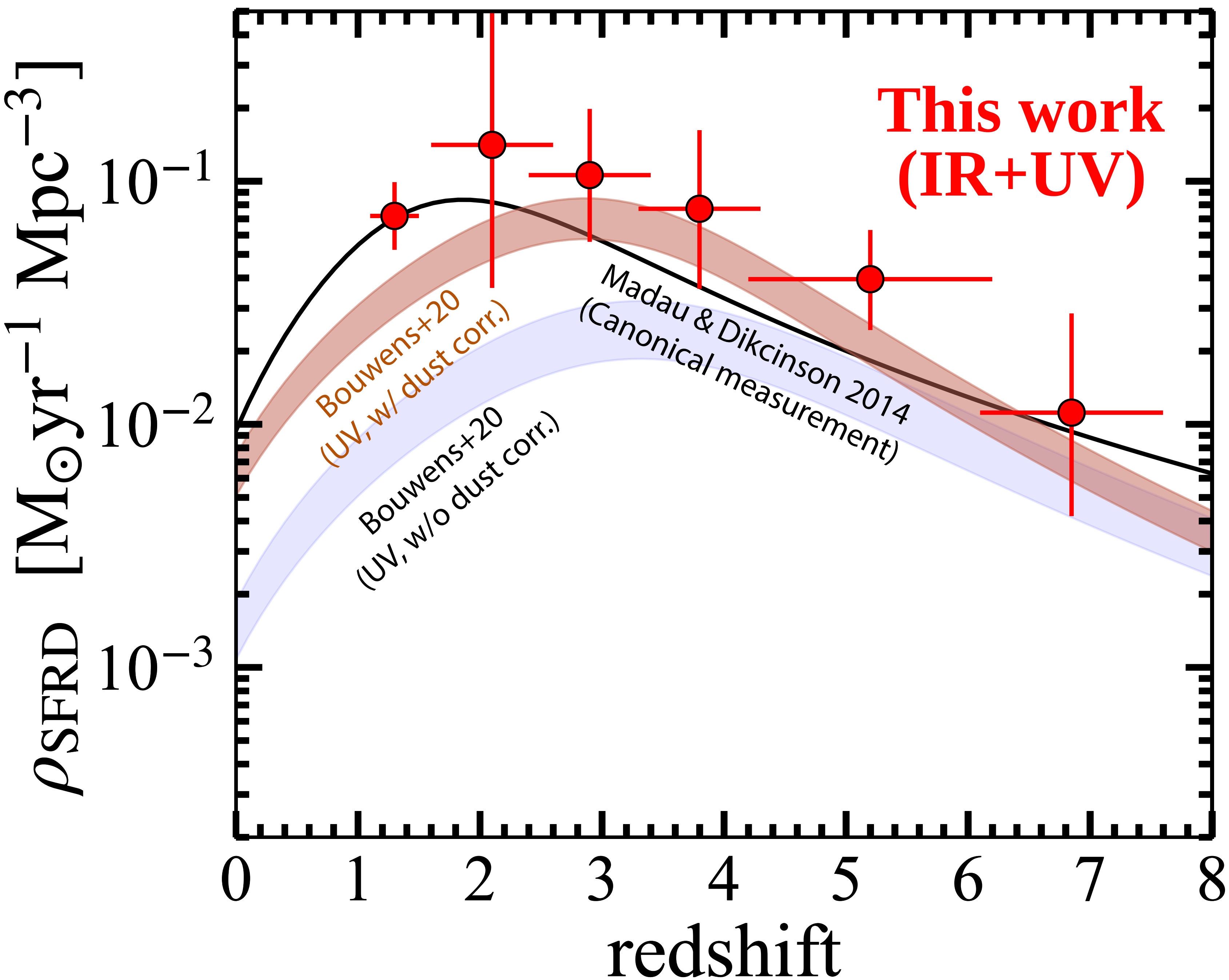

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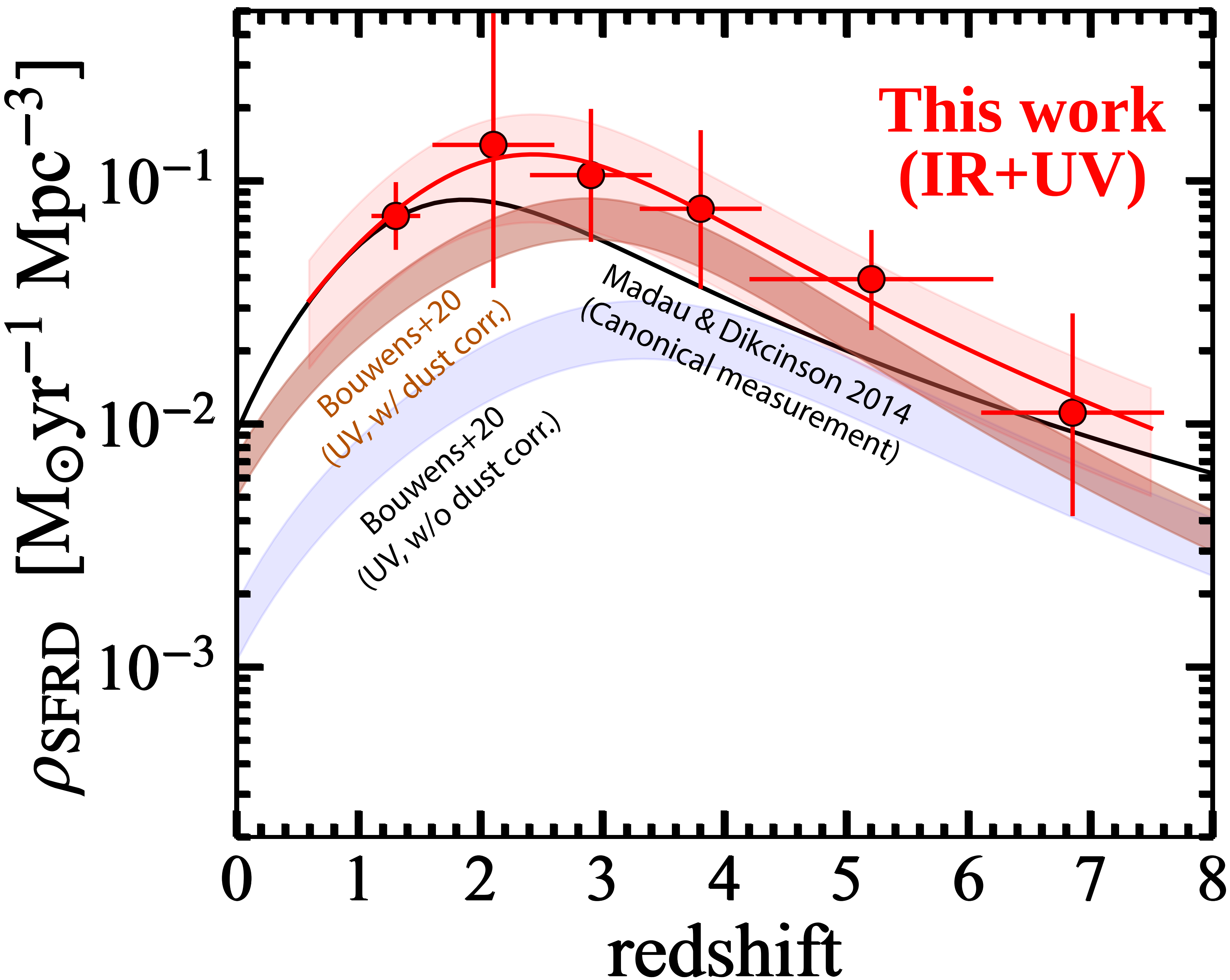
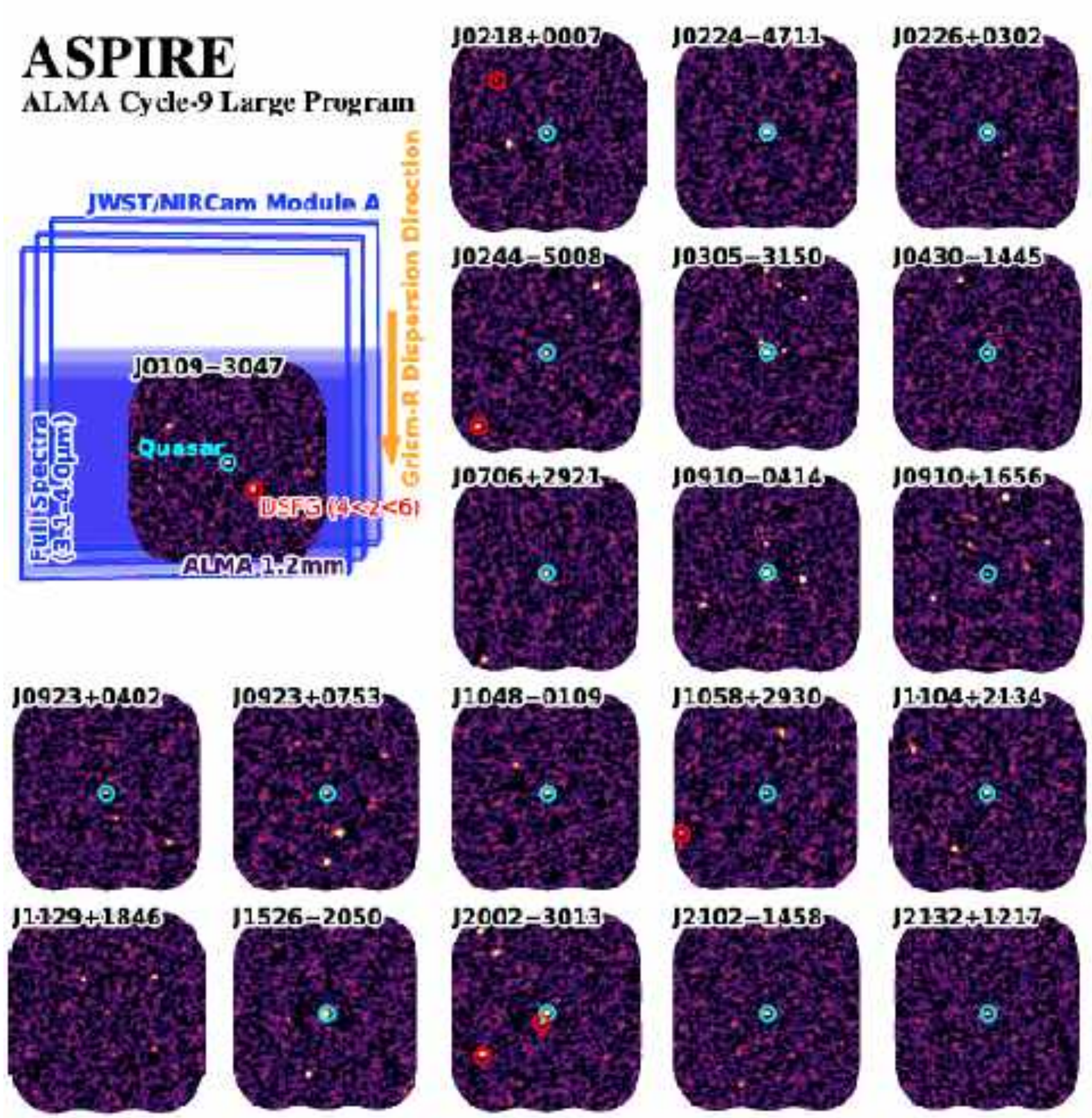


- 160 ± 60% of previous measurements at z>4.
  Potential contributions (~60%) from NIR-dark objects at z > 4.

Fujimoto+23b, ApJS in press

ASPIRE x ALMA

z=4-6 UVLF spectroscopically constrained by serendipitous ALMA sources

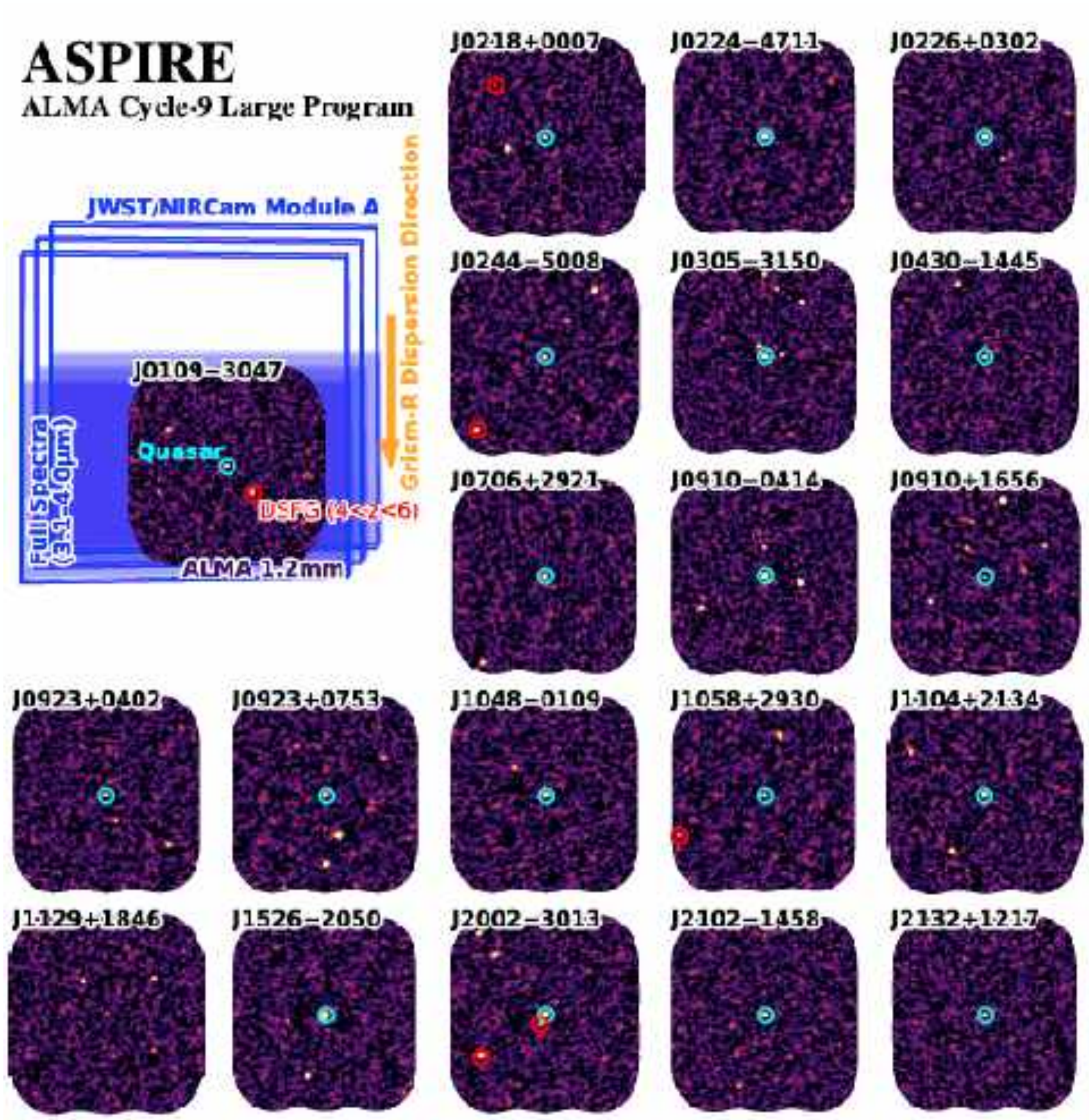


ASPIRE: NIRCam grism survey for z~6 quasars
ALMA: 1-mm mosaic around these quasar fields

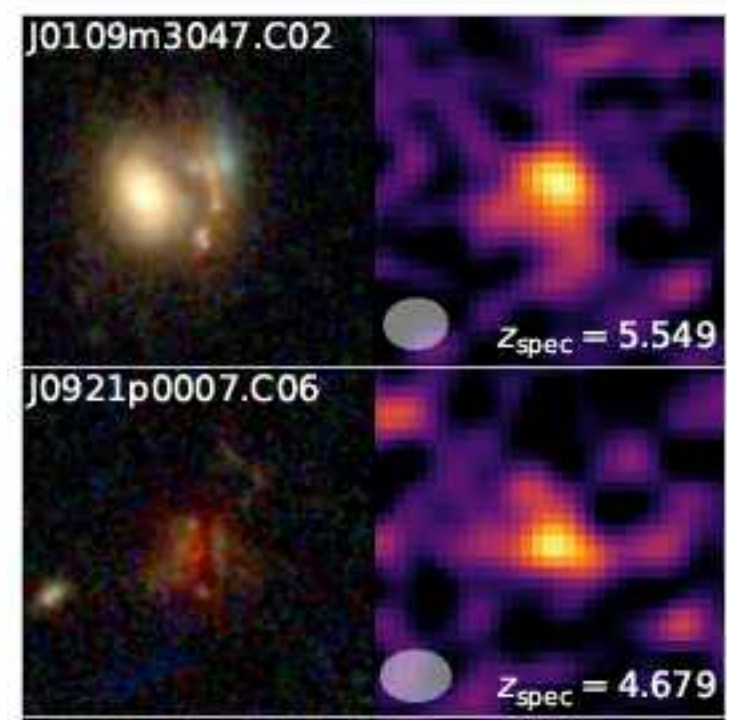
Sun, ASPIRE team+24, submitted

ASPIRE x ALMA

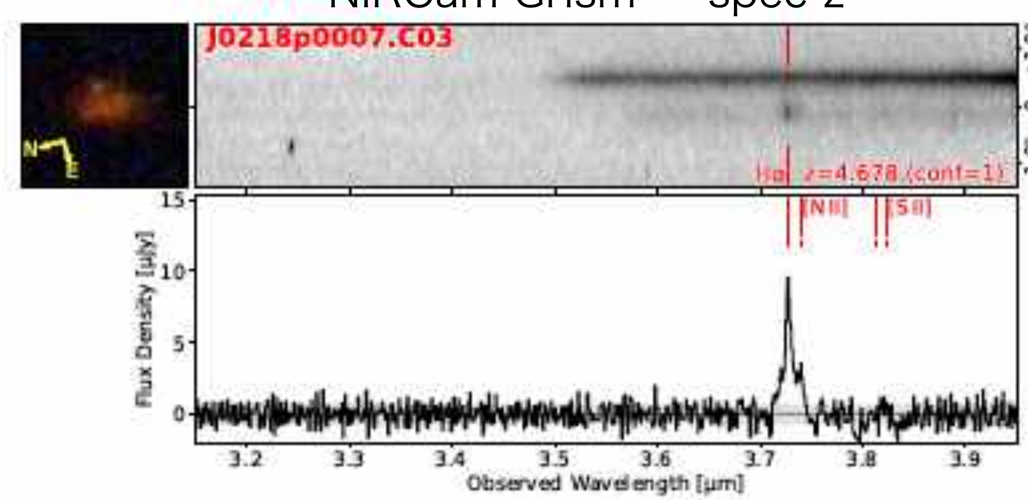
z=4-6 UVLF spectroscopically constrained by serendipitous ALMA sources



NIRCam ALMA



NIRCam Grism → spec-z

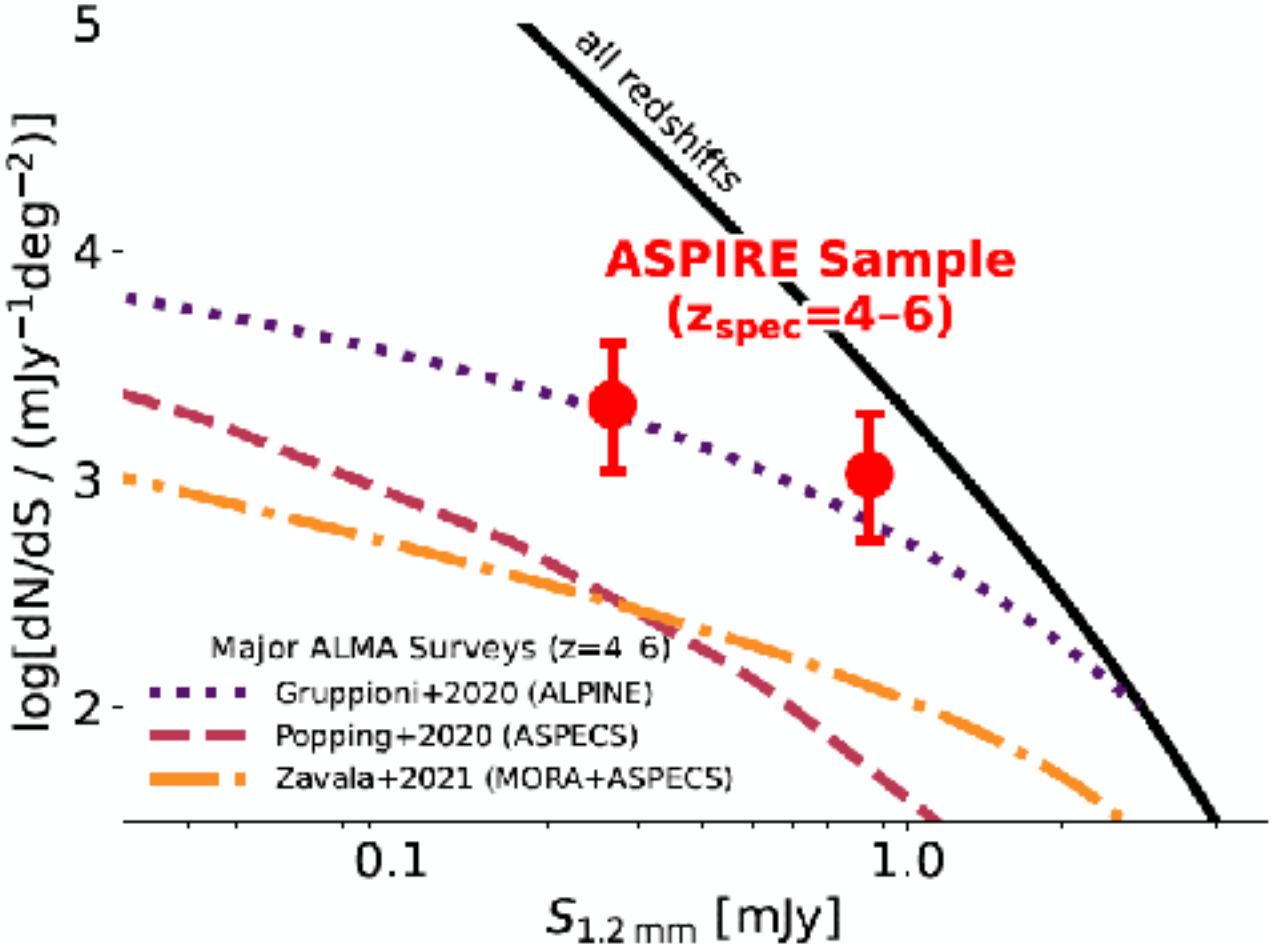


ASPIRE: NIRCam grism survey for z~6 quasars
ALMA: 1-mm mosaic around these quasar fields

Sun, ASPIRE team+24, submitted

ASPIRE x ALMA

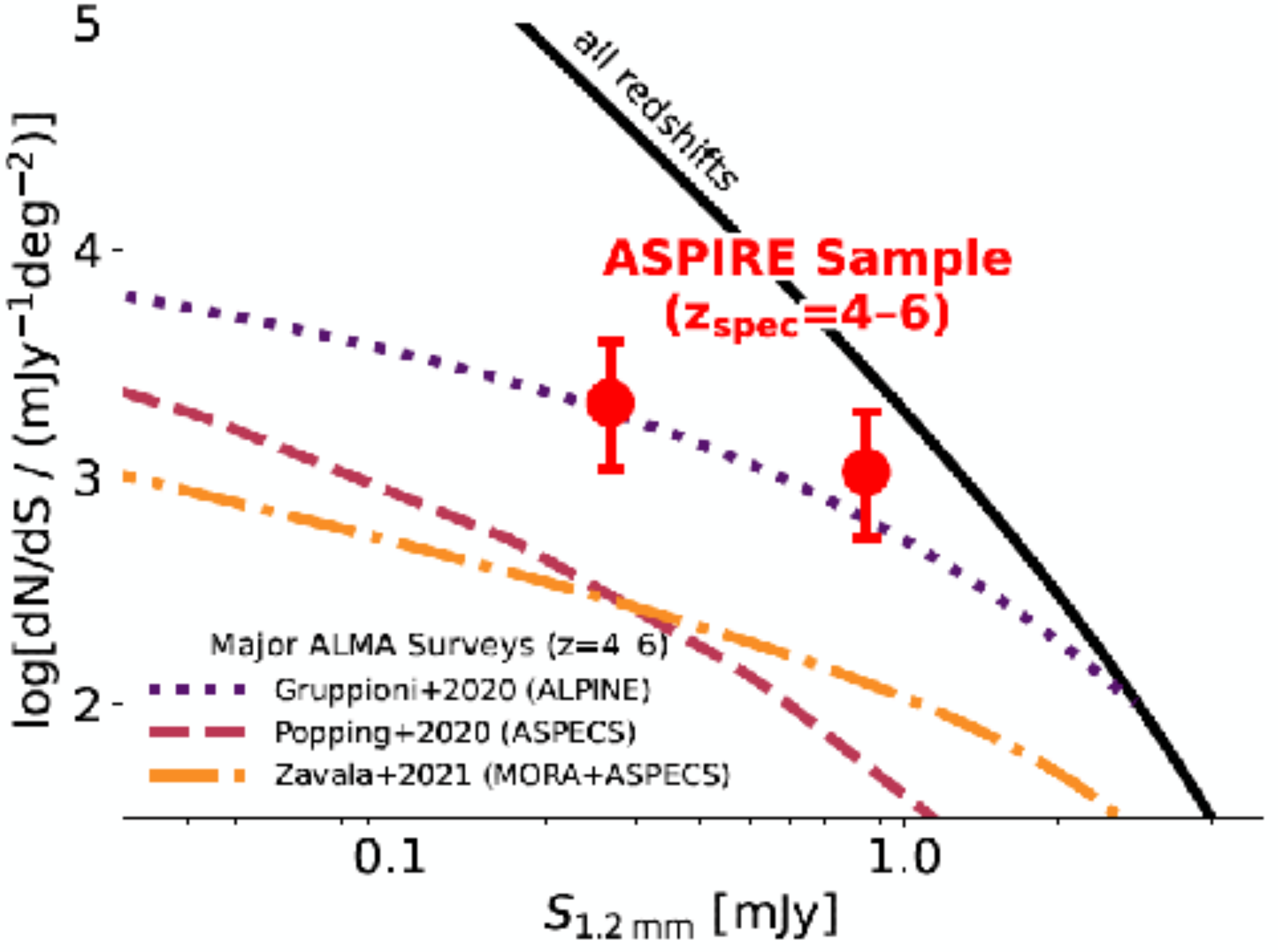
z=4-6 UVLF spectroscopically constrained by serendipitous ALMA sources

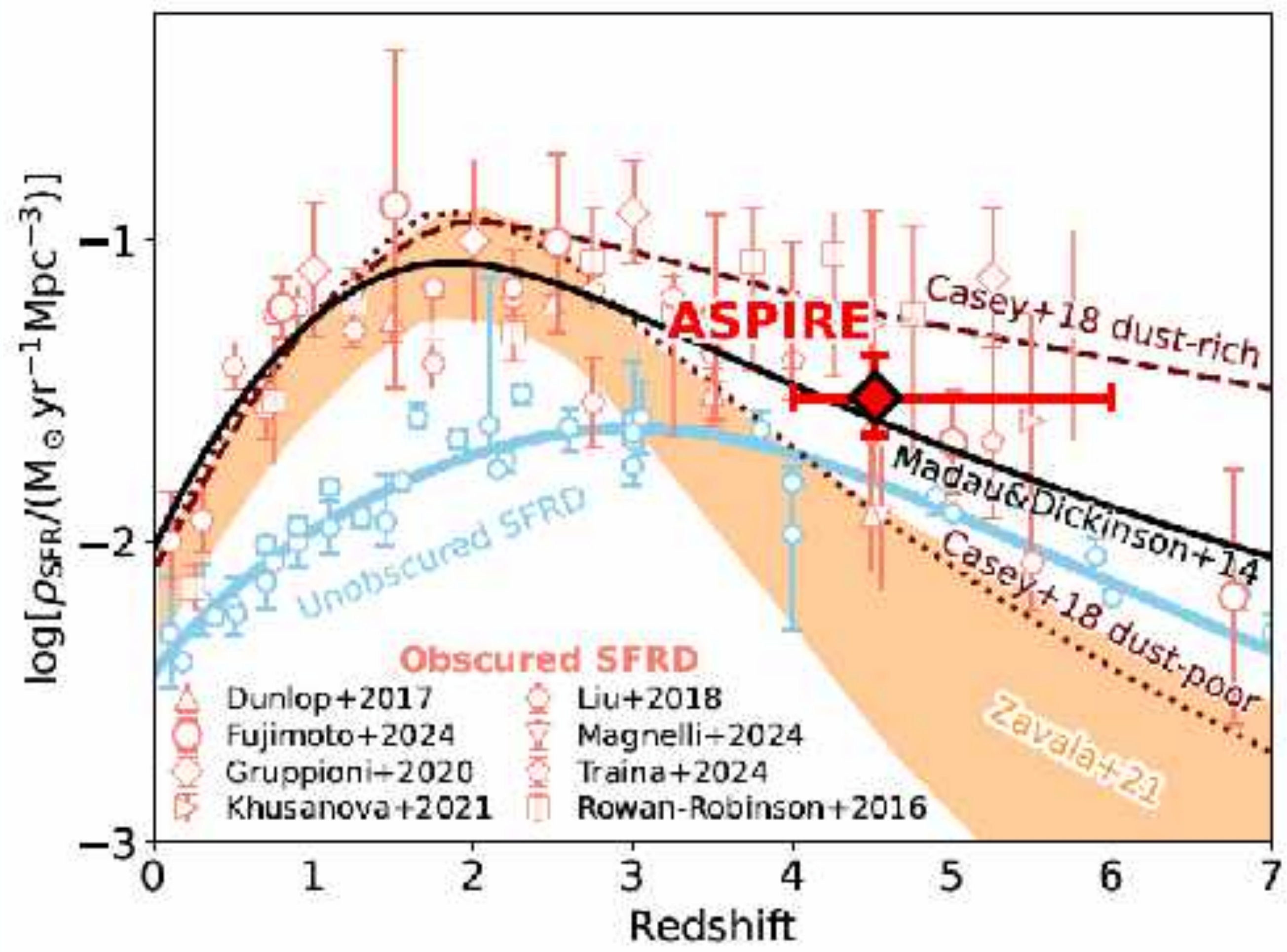


Sun, ASPIRE team+24, submitted

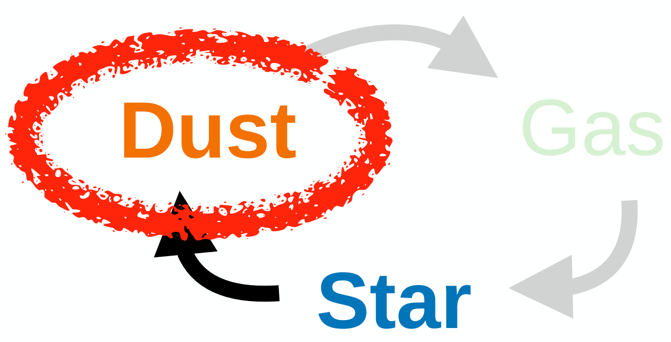
ASPIRE x ALMA

z=4-6 UVLF spectroscopically constrained by serendipitous ALMA sources



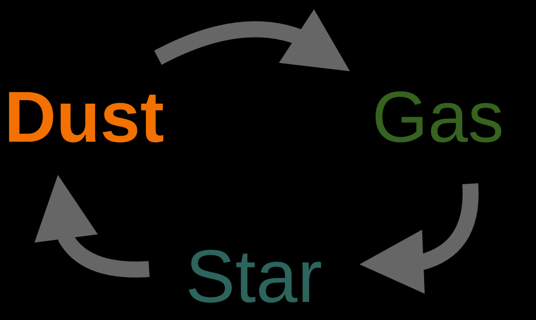


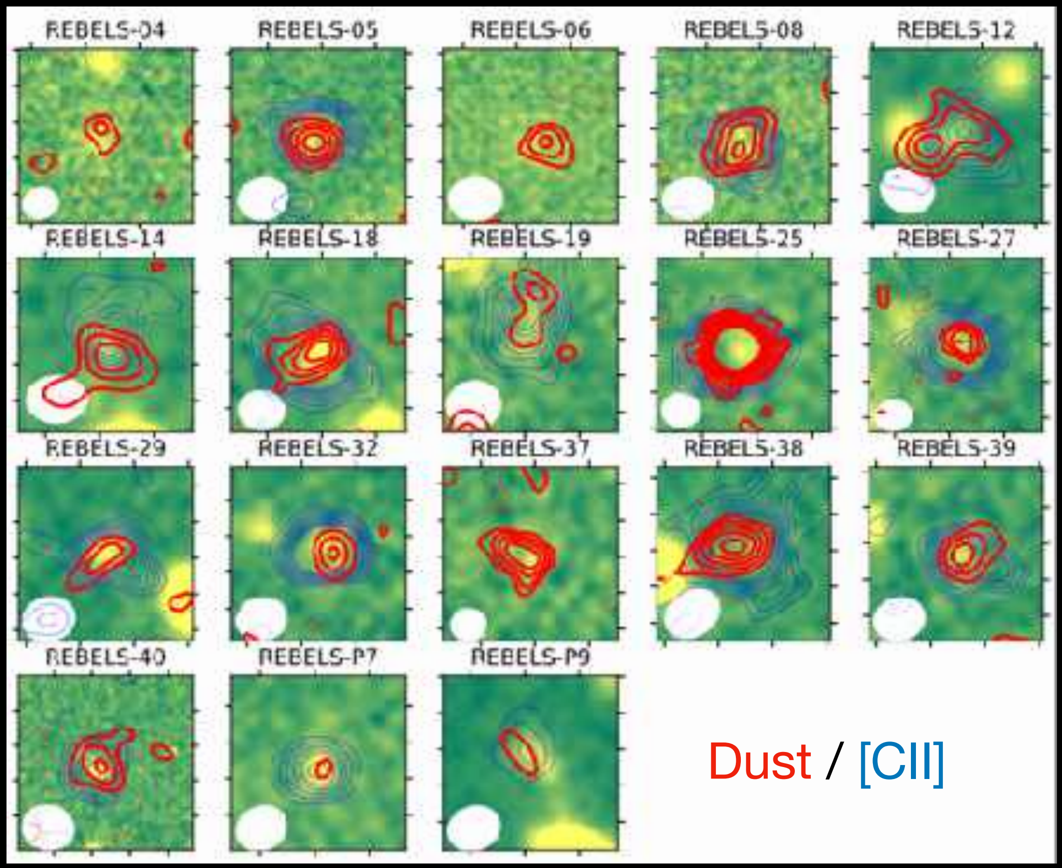
Potential excess from previous optical-NIR based measurements spectroscopically confirmed at z=4-6, consistent with ALCS



Sun, ASPIRE team+24, submitted

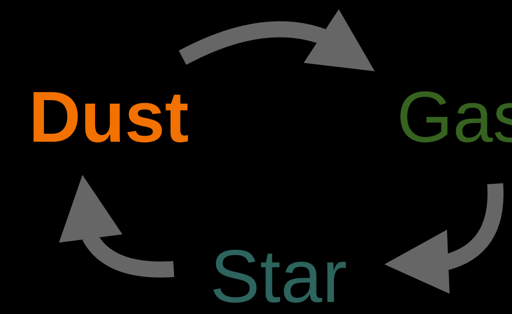
REBELS-25: Massive dust reservoir at z=7.31

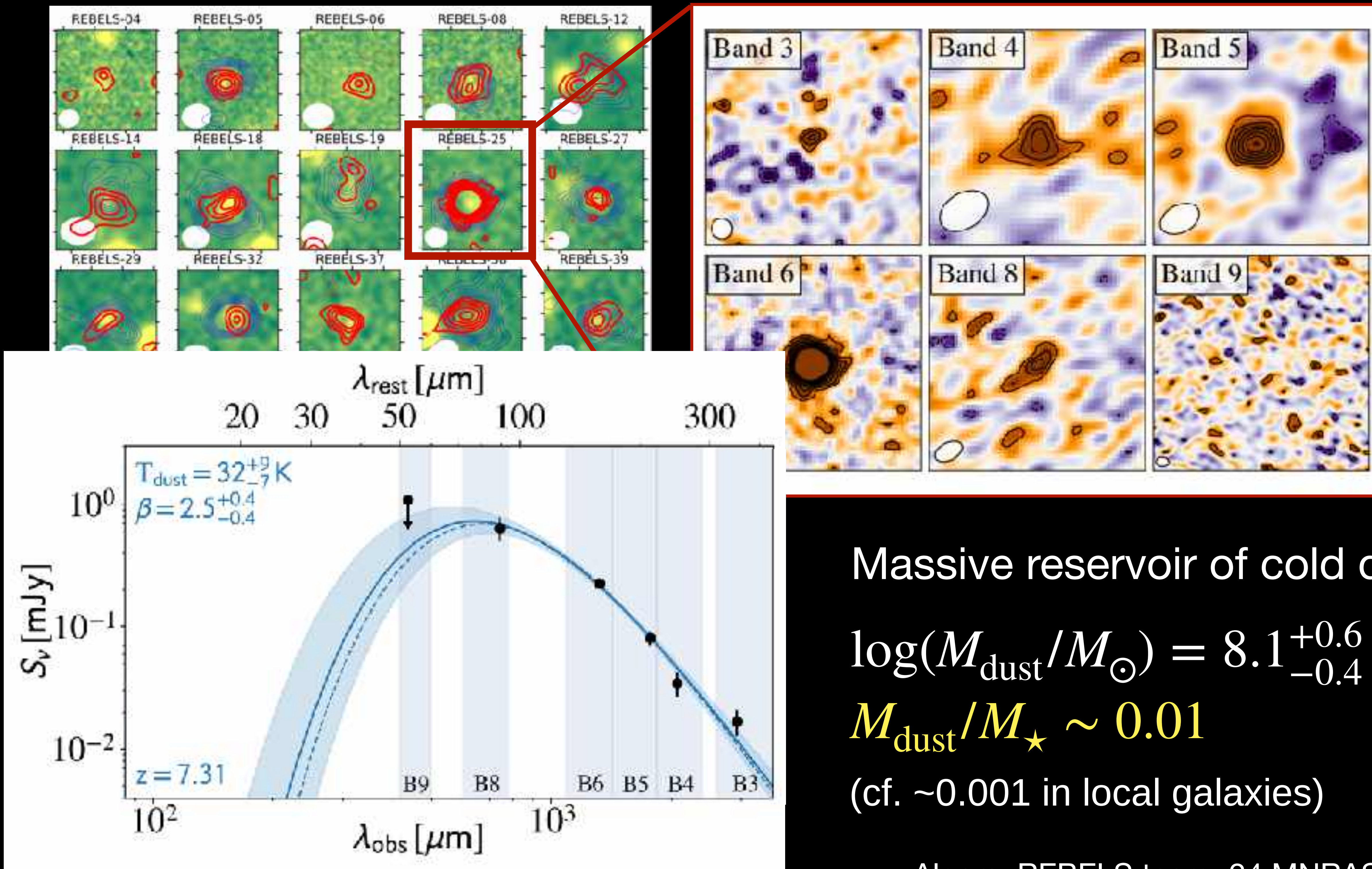




Algera, REBELS team+24,MNRAS, 533, 3

REBELS-25: Massive dust reservoir at z=7.31





Massive reservoir of cold dust:

$$\log(M_{dust}/M_\odot) = 8.1^{+0.6}_{-0.4}$$

$$M_{dust}/M_\star \sim 0.01$$

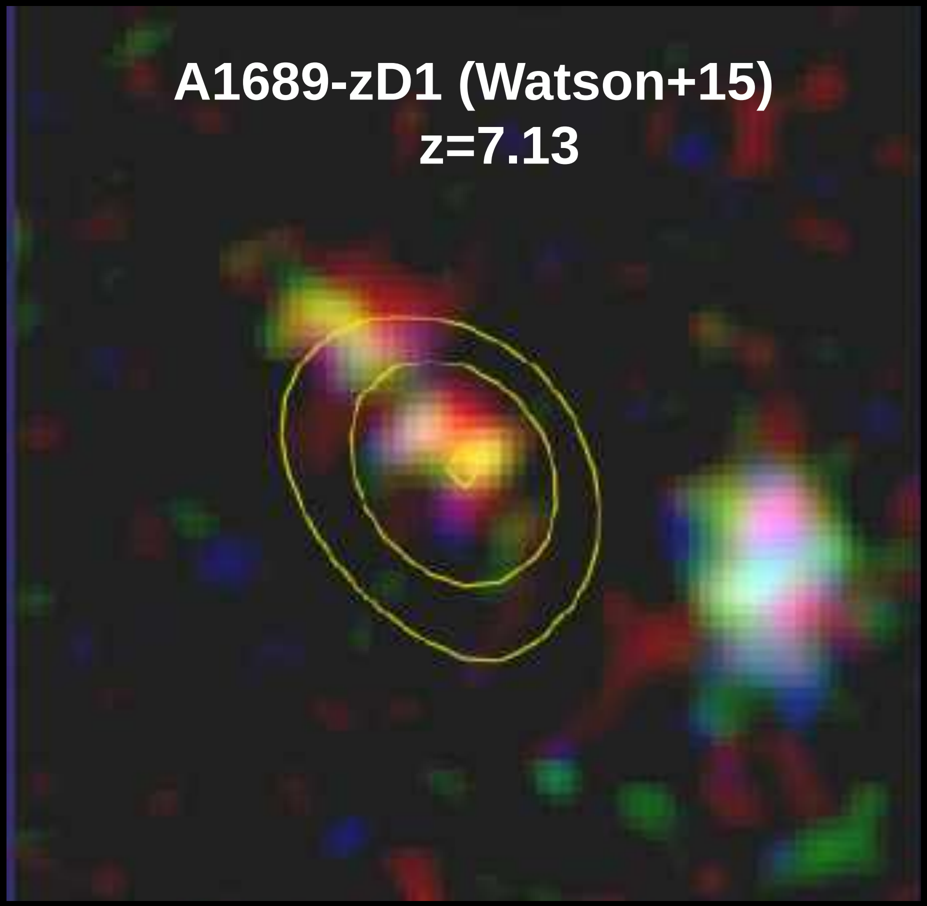
(cf. ~0.001 in local galaxies)

Algera, REBELS team+24,MNRAS, 533, 3

ALMA Multi-Band FIR SED results; see also e.g., Harikane+20, Wistok+22, Valentino+24, Ikki+24, Villanueva+24

A high $M_{dust}/M_\star$ also in a sub-L* galaxy at z=7

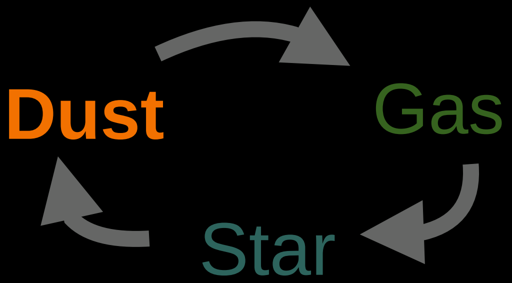
Dust Gas Star

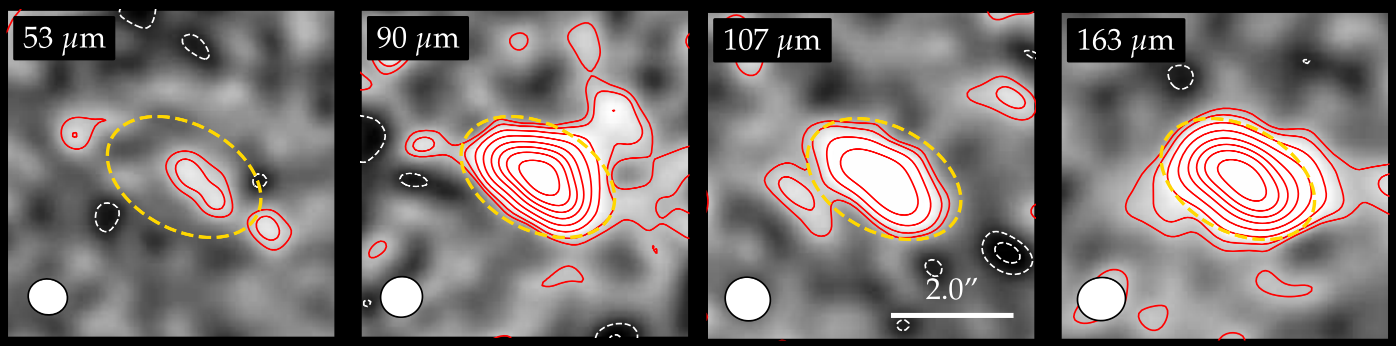


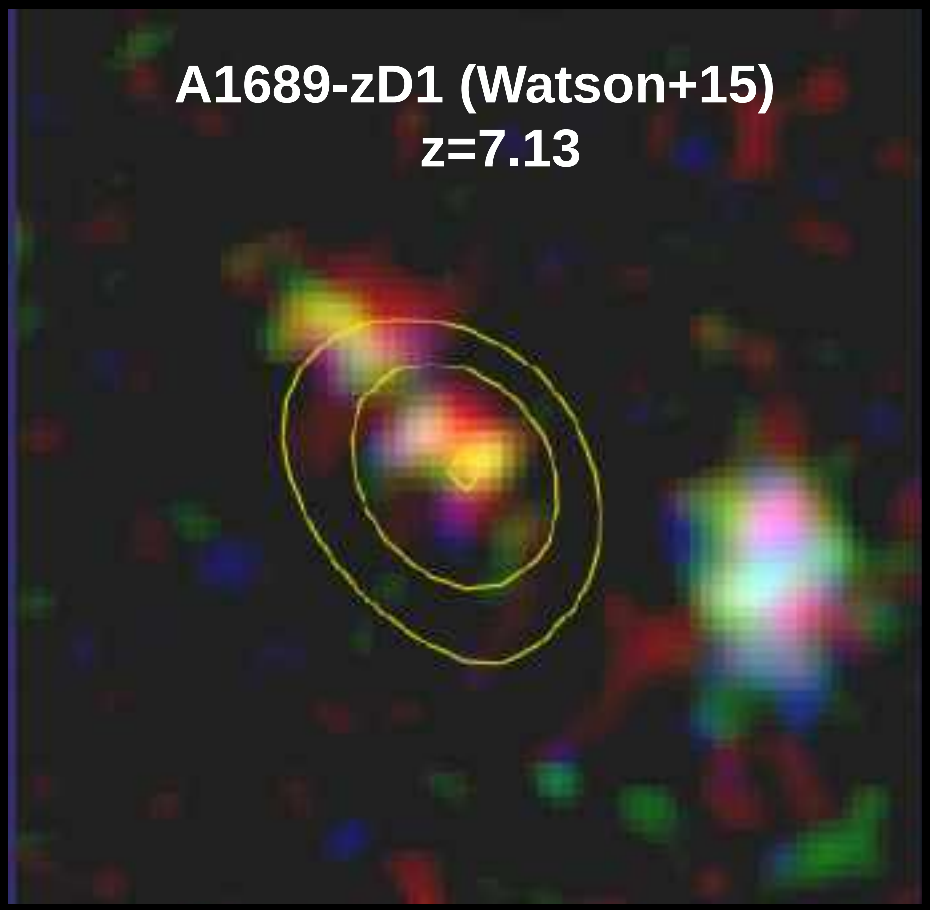
(spatially integrated)

A1689-zD1 results; see also Watson+15, Knudsen+18, Bakx+21, Wong+22, and **Carmen's talk**

A high $M_{dust}/M_\star$ also in a sub-L* galaxy at z=7







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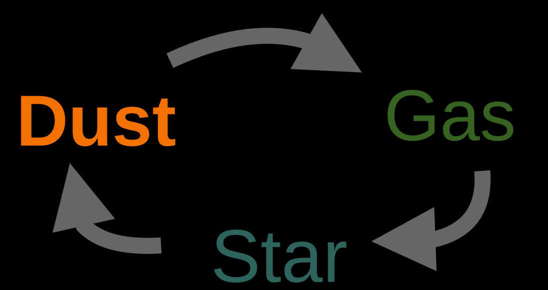

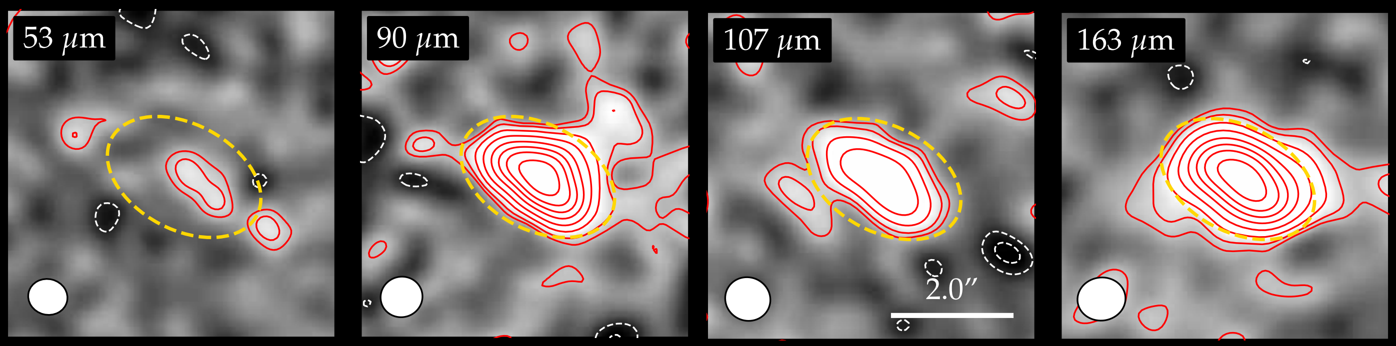

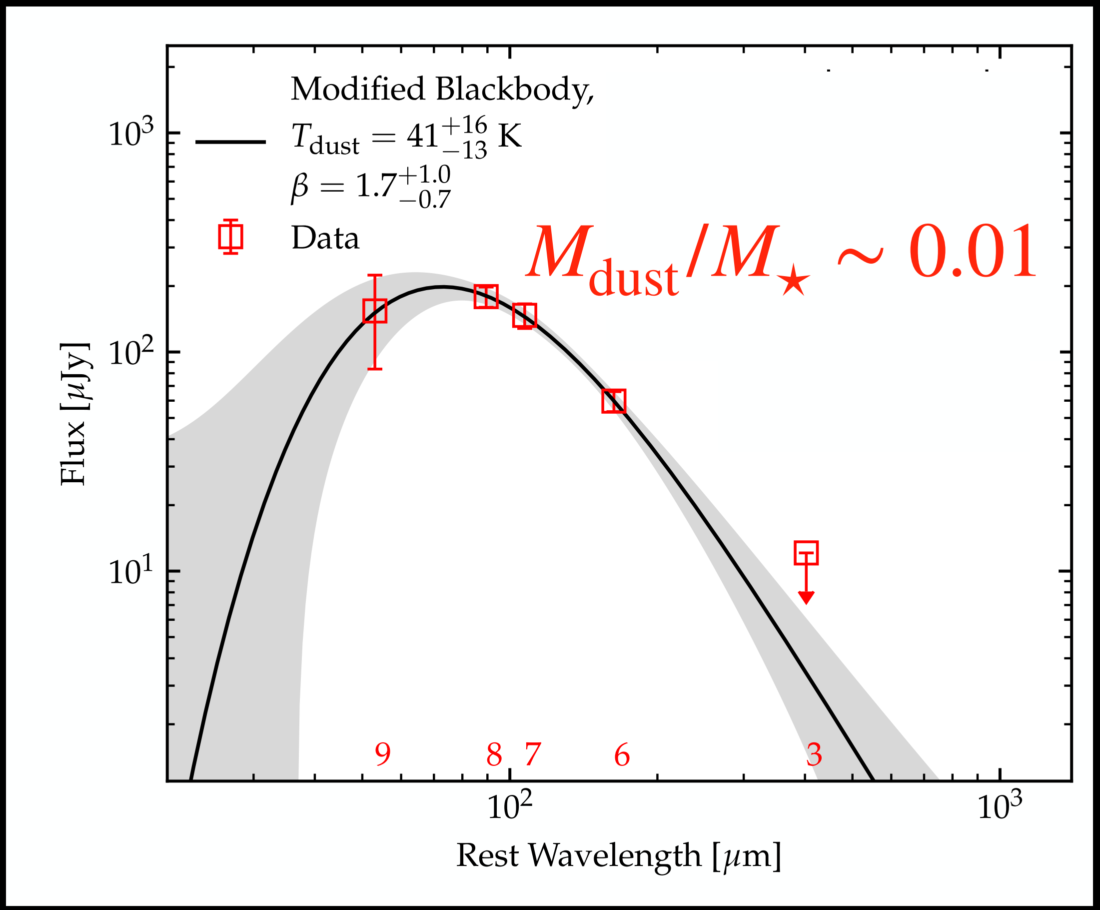

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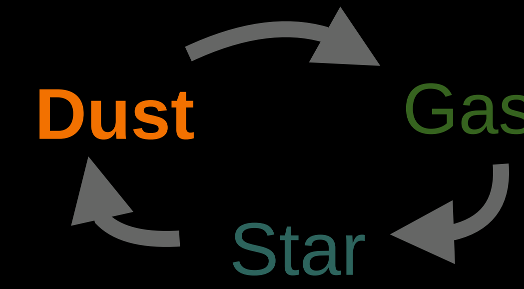
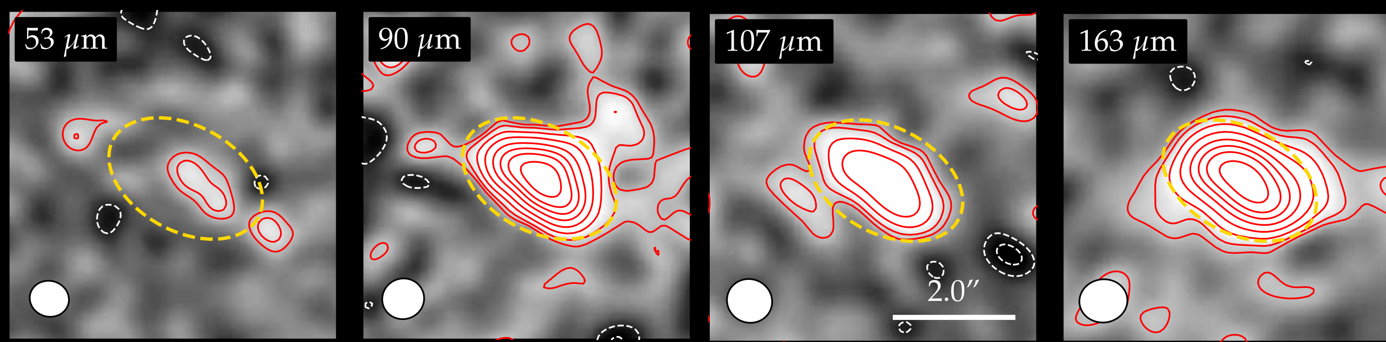
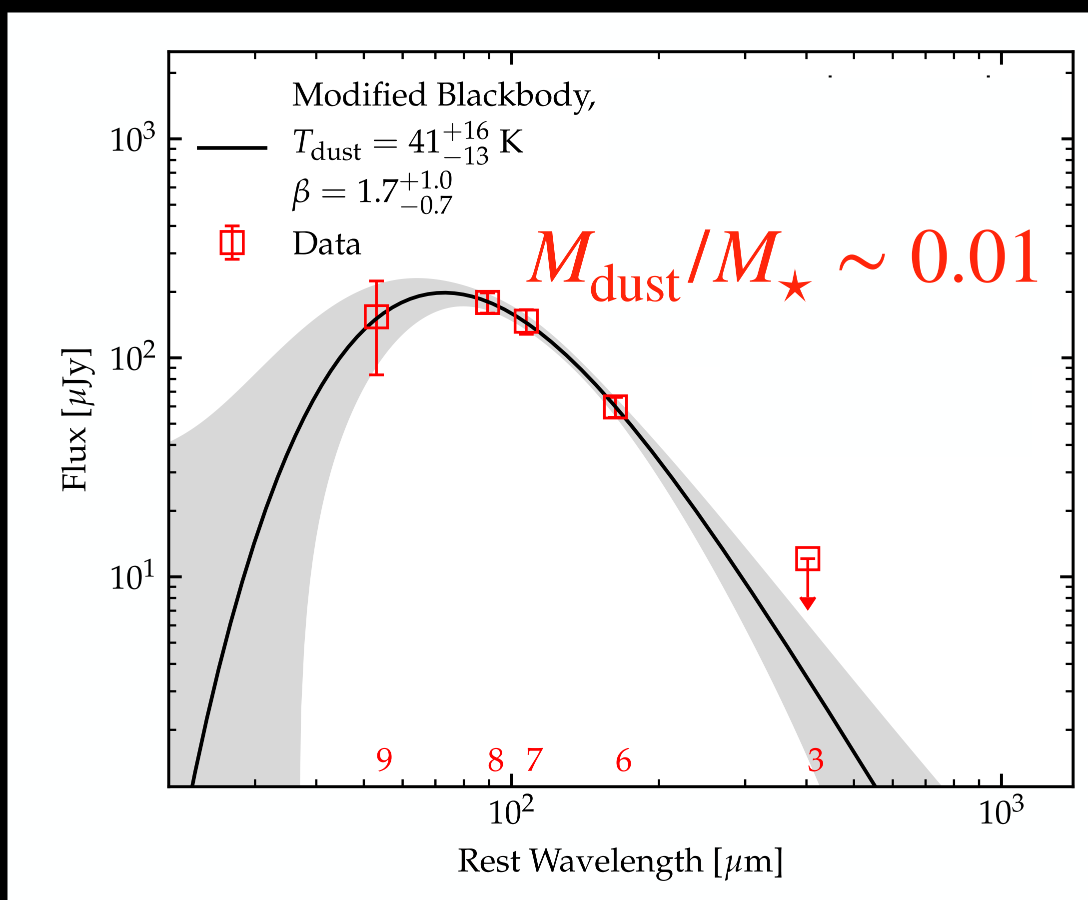
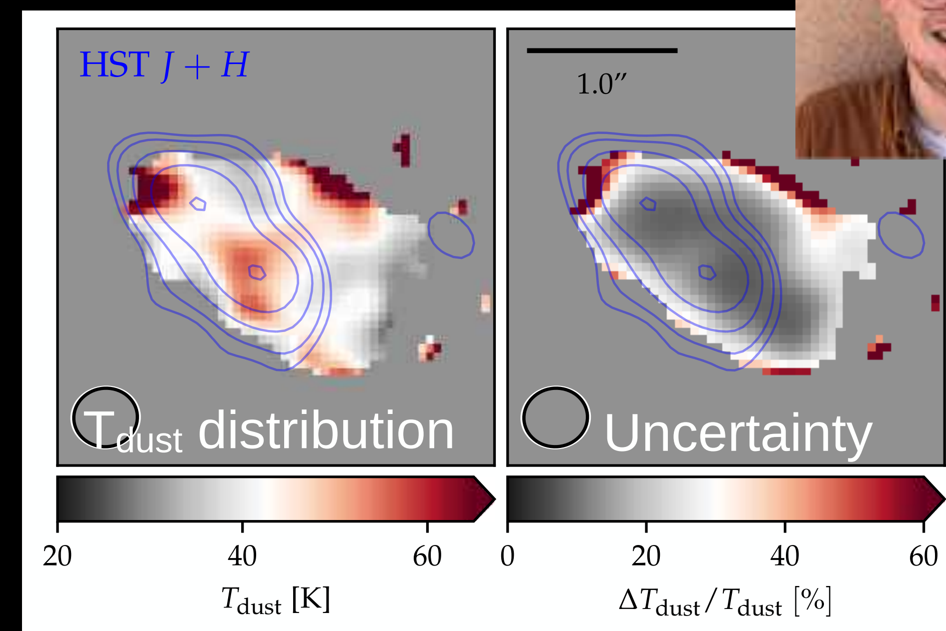
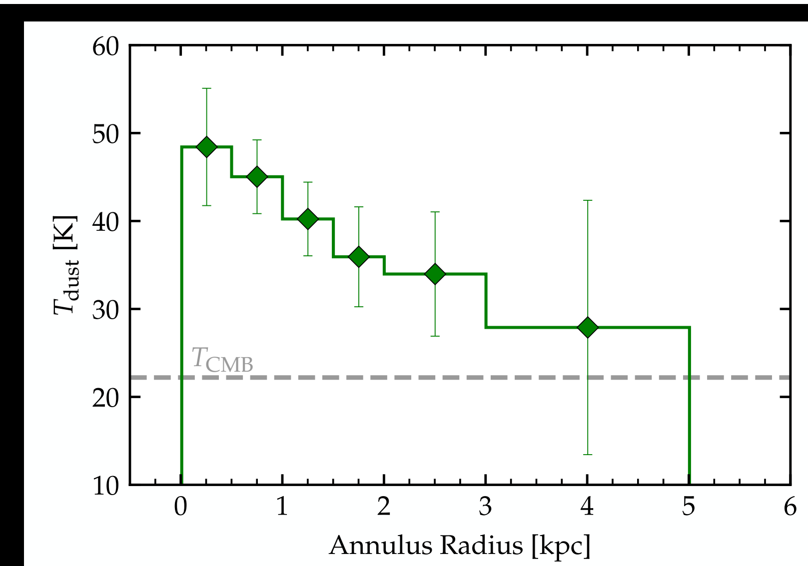






Akins, Fujimoto, Watson+22



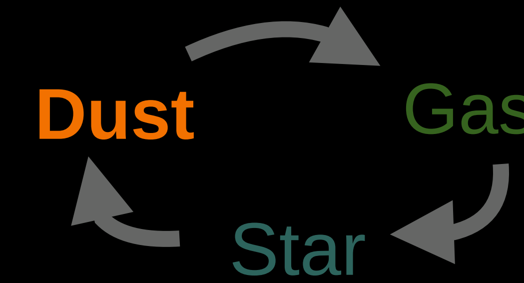


- M_{dust} estimate even increases by ~60%, considering low T_{dust} component
- T_{dust} is close to T_{CMB} at outskirt → **A large portion of M_{dust} might be missed**

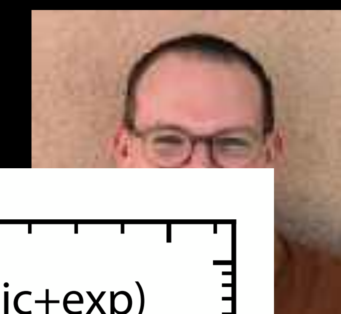
(spatially integrated)

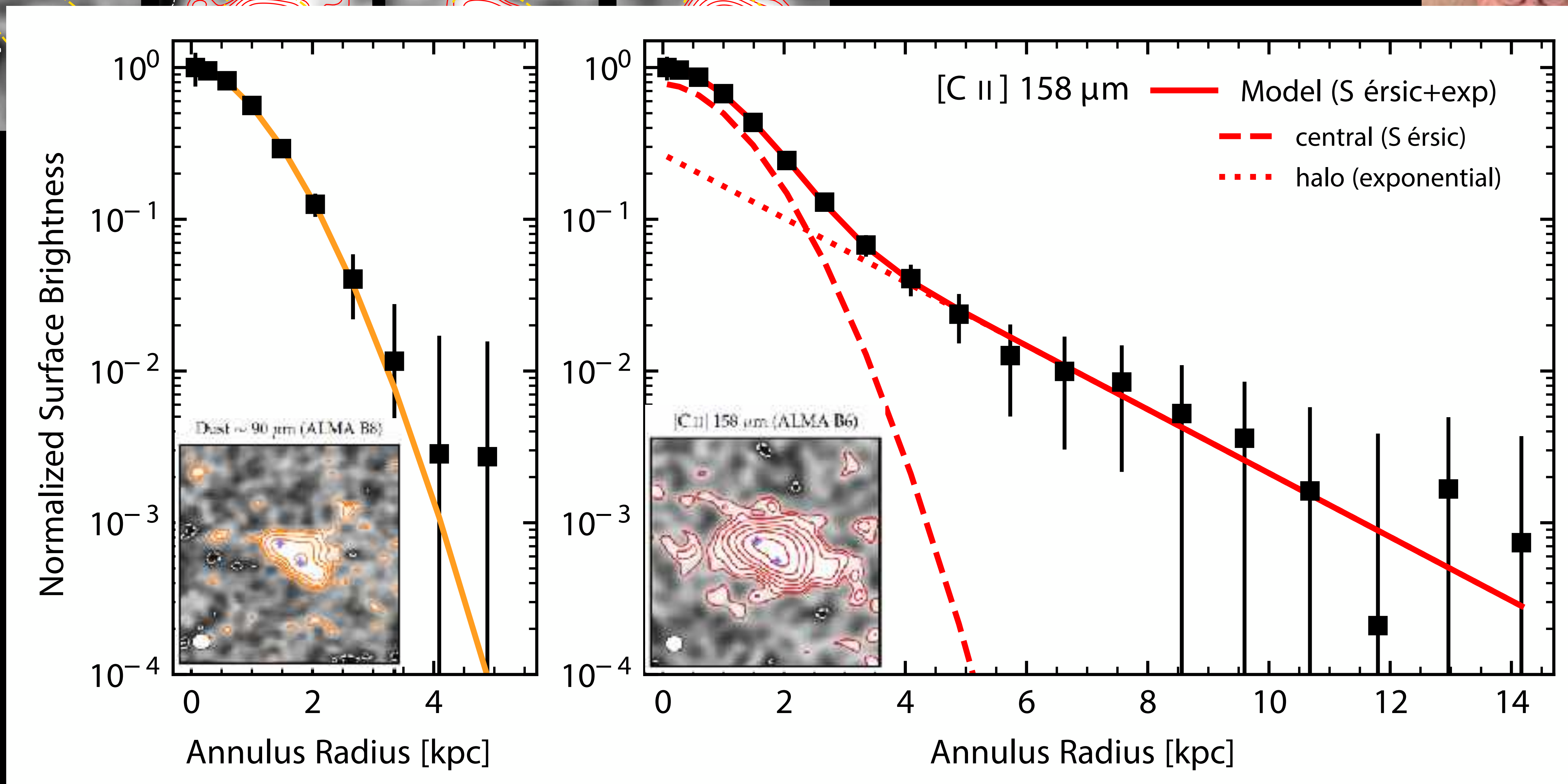
A1689-zD1 results; see also Watson+15, Knudsen+18, Bakx+21, Wong+22, and **Carmen's talk**

A high $M_{dust}/M_\star$ also in a sub-L* galaxy at z=7



Akins, Fujimoto, Watson+22





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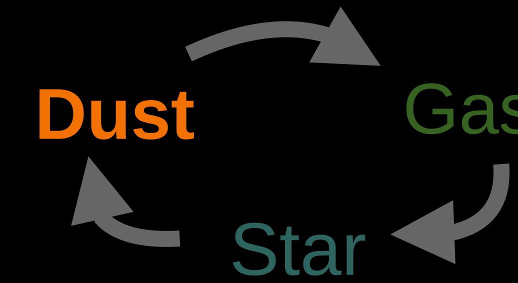
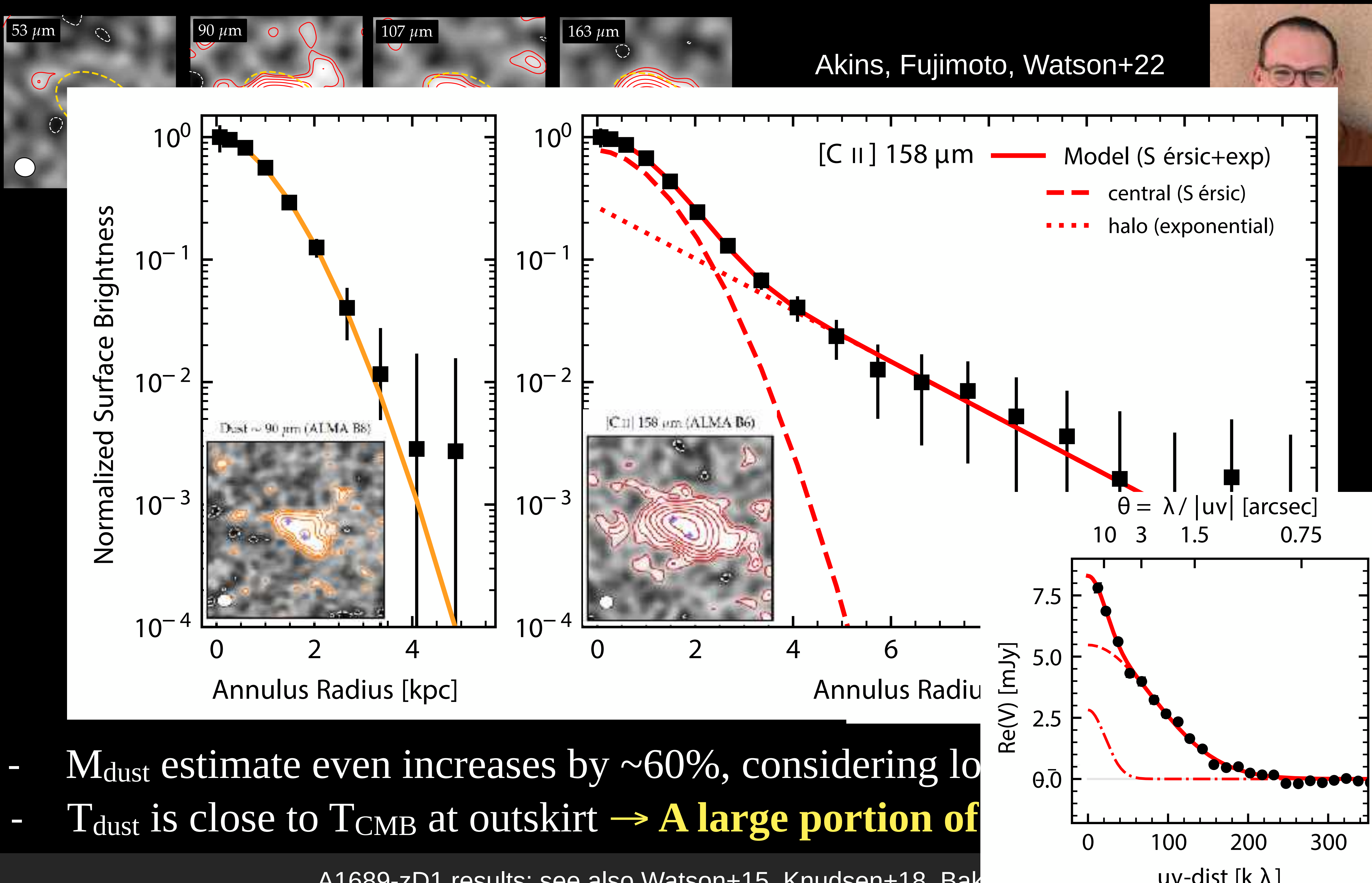


Akins, Fujimoto, Watson+22



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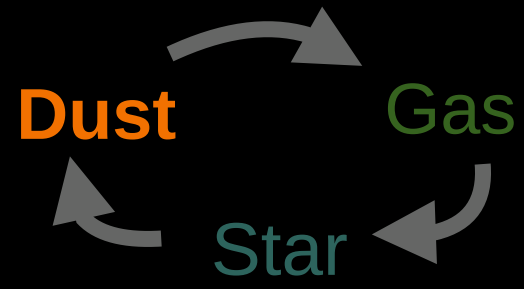
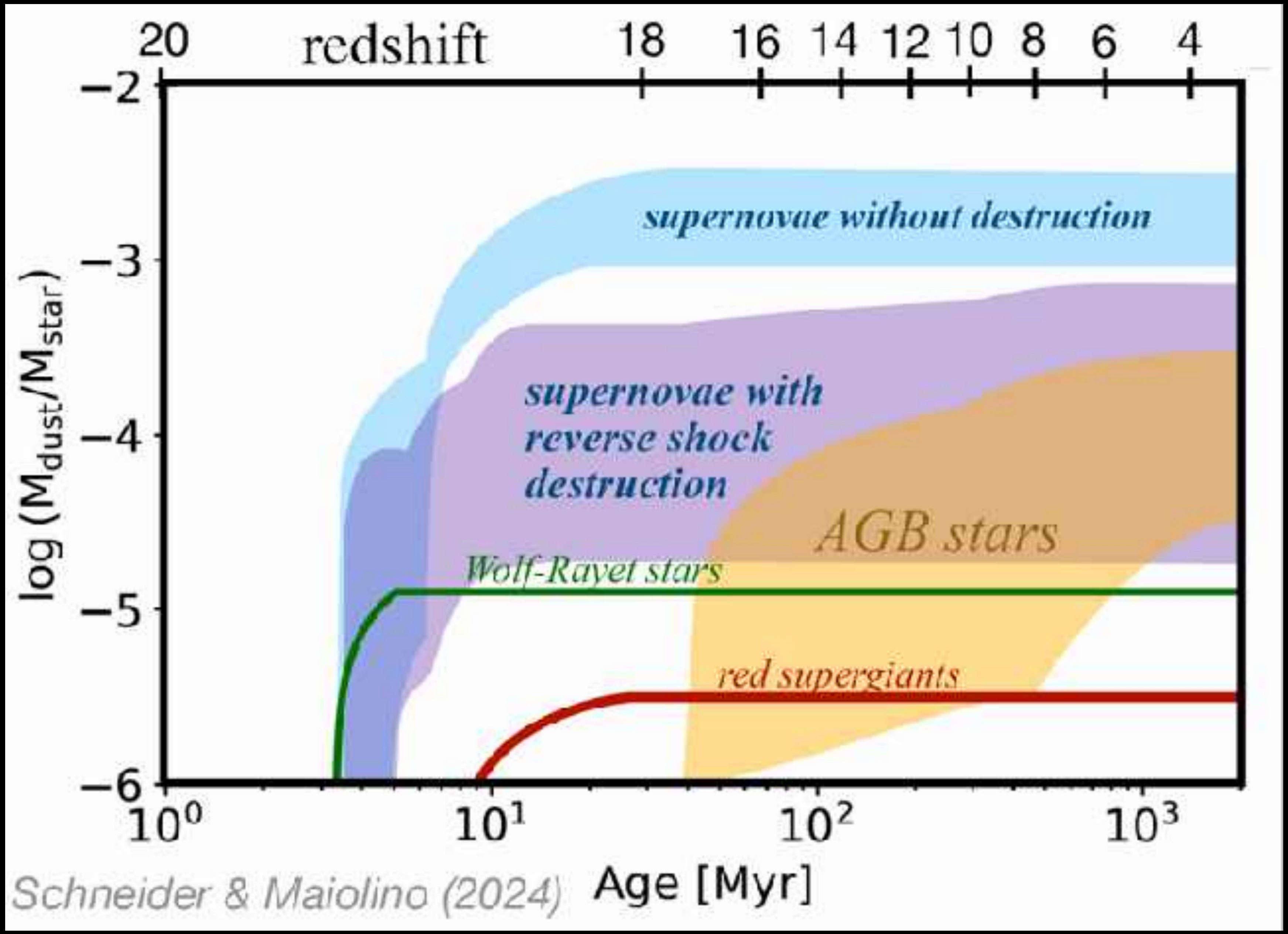
A1689-zD1 results; see also Watson+15, Knudsen+18, Bak

Efficient Dust growth (+ SN ejection) is required





High-z dust production & growth theory; see also e.g., Asada+13, Schneider+14, Mancini+15, Slavin+20, Graziani+20, Choban+22, Di Cesara+23

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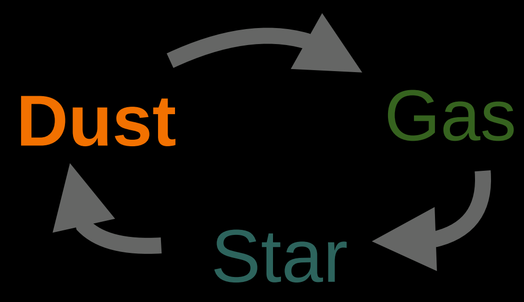
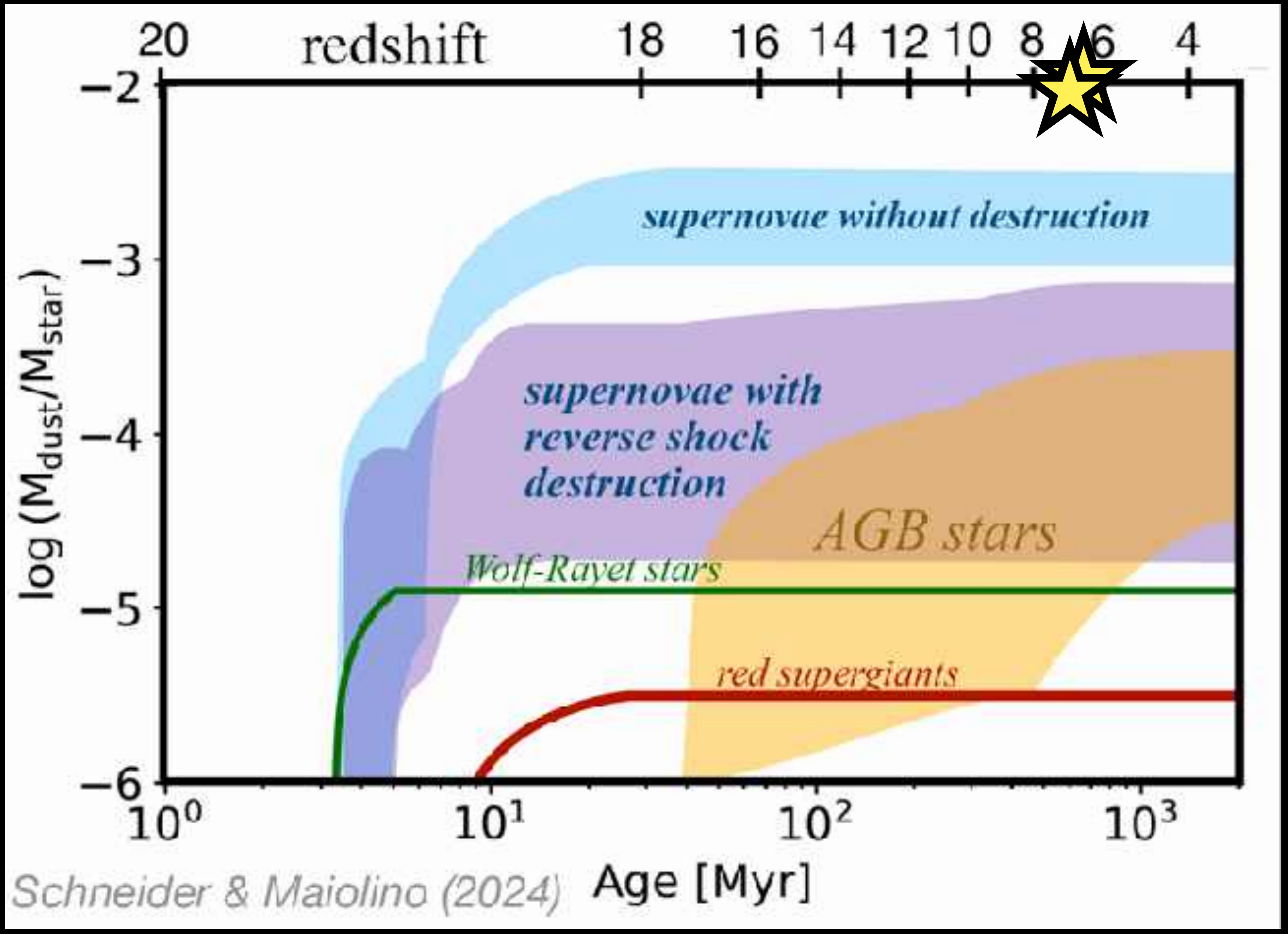


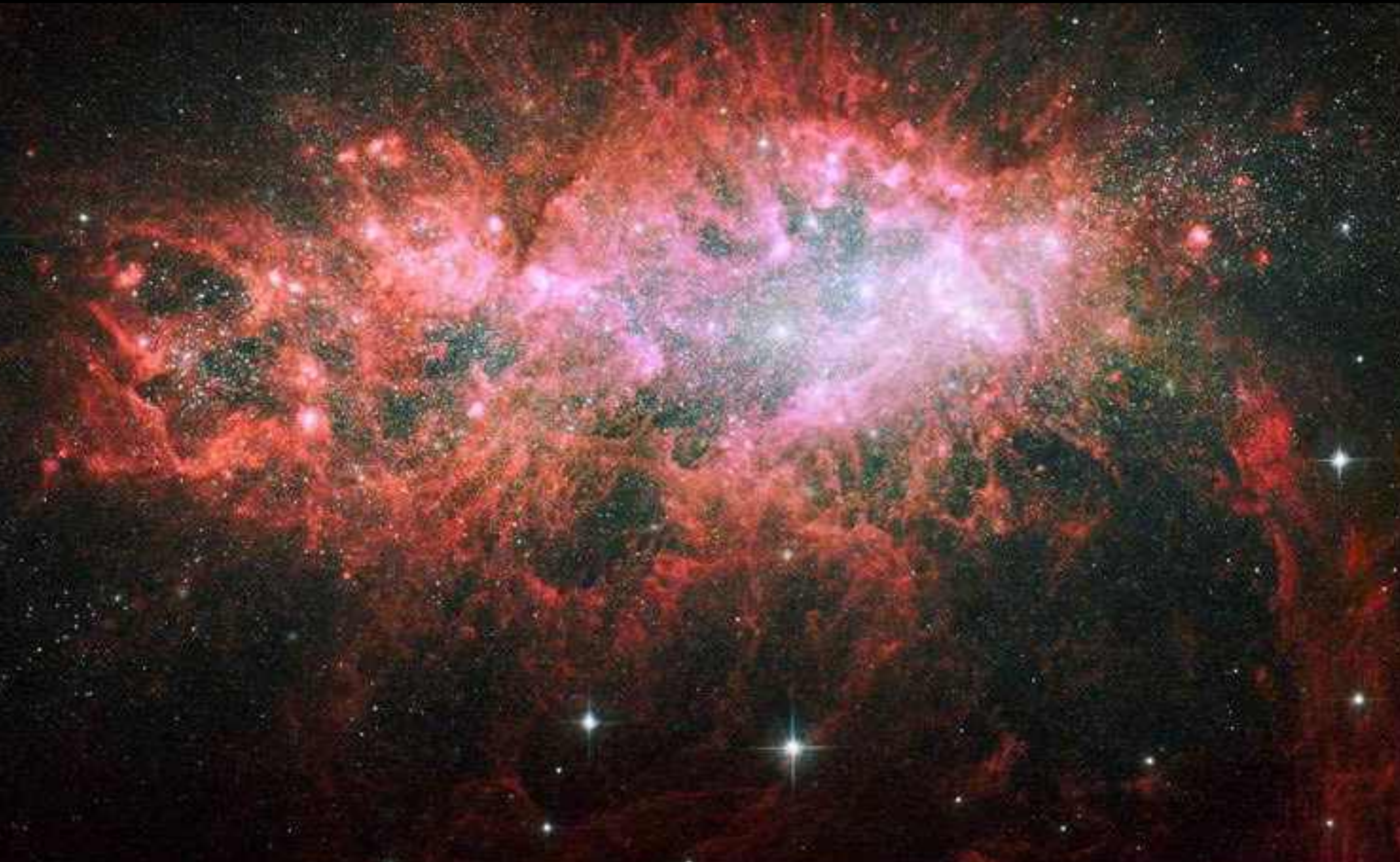


Efficient Dust growth (+ SN ejection)

→ Detailed ISM characterizations is important **(Cold dense ISM gas?)**

High-z dust production & growth theory; see also e.g., Asada+13, Schneider+14, Mancini+15, Slavin+20, Graziani+20, Choban+22, Di Cesara+23

How to dive into detailed ISM physics in early galaxies?



How to dive into detailed ISM physics in early galaxies?

Difficulty in <u>sensitivity</u> and <u>spatial resolution</u> ….

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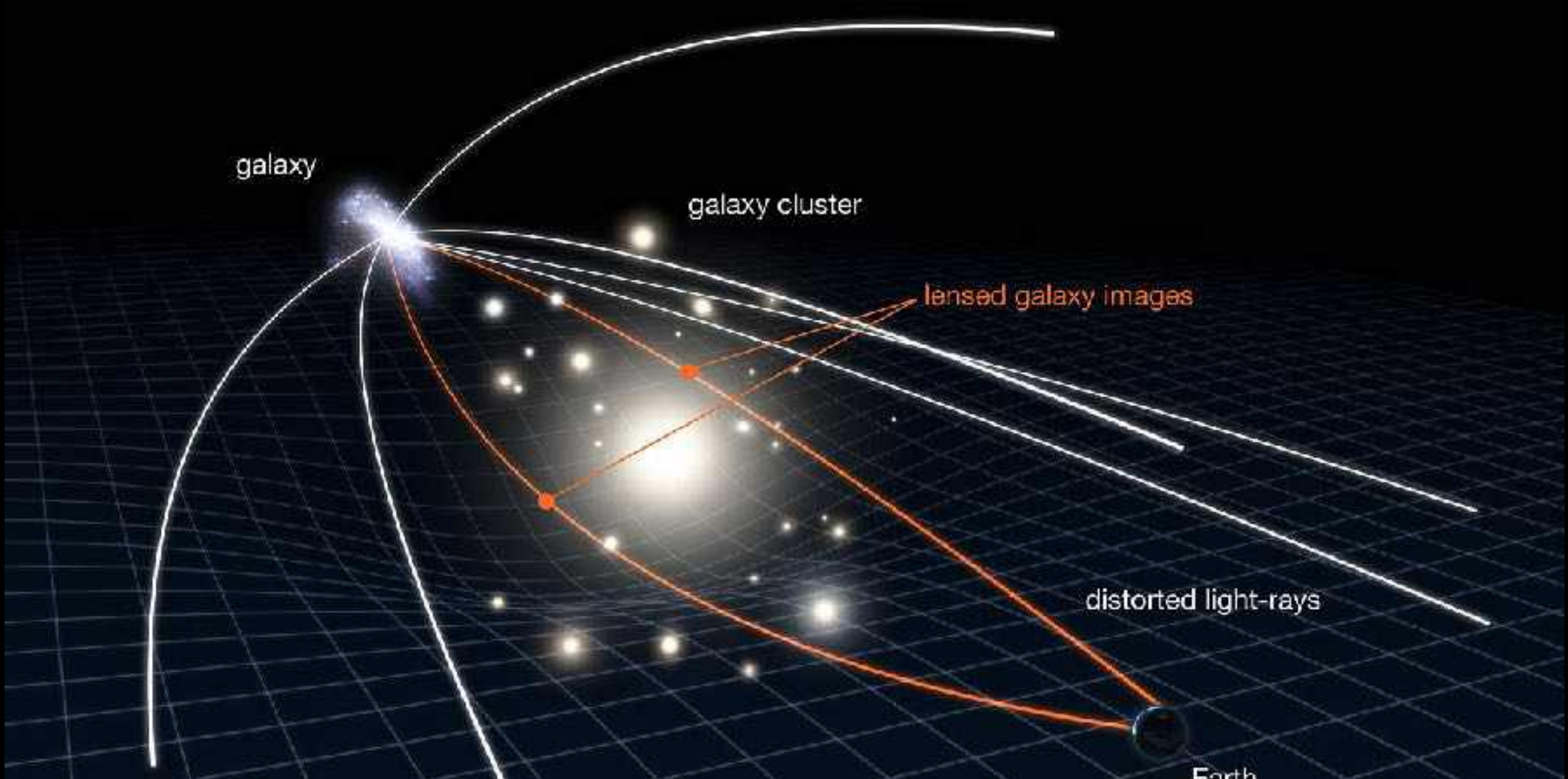

Difficulty in sensitivity and spatial resolution ….

Overcome by making use of the gravitational lensing

Approved programs scheduled in 2022–2024 for

Telescope	Instrument/band	PI	Time (hrs)	Scope	Observation
JWST cy1	NIRSpec IFU, NIRCam	S. Fujimoto	13,2	Key optical emission lines & UV-optical continuum	late 2022 ~ early 2023
JWST cy2	NIRCam	S. Fujimoto	5,0	Mapping Hα	early 2024
ALMA cy8	Band6, 5	S. Fujimoto	16,3	Deep [CII]158um & [OI]146um follow-up	late 2022
ALMA cy8	Band7, 8	S. Fujimoto	19,2	Detecting [OIII] & [NII]122um, 205um	late 2022
ALMA cy8	Band 3	F. Valentino	19,4	Detecting CO(7-6), [CI](2-1), 3-mm continuum	late 2021
ALMA cy9	Band 6	S. Fujimoto	26,5	High-resolution (~0.”05) deep [CII] follow-up	July~Sep 2023
ALMA cy9	Band7, 8	S. Fujimoto	24,5	Detecting [OIII] & [NII]122um, 205um (resub)	partially taken in early 2023
ALMA cy10	Band 6	S. Fujimoto	16,4	Low resolution (~1.”5) deep [CII] follow-up	early 2024
VLT S22A	MUSE	S. Fujimoto	8,9	Detecting Lya	complete in early 2023
Keck S22B	MOSFIRE	Y. Ono	1 night	Detecting rest-UV lines	bad weather
JVLA S20A, S21A	Band Ku	S. Fujimoto	23,2	Detecting CO(1-0)	complete in early 2022

Approved programs scheduled in 2022–2024 for a single lensed galaxy at z = 6

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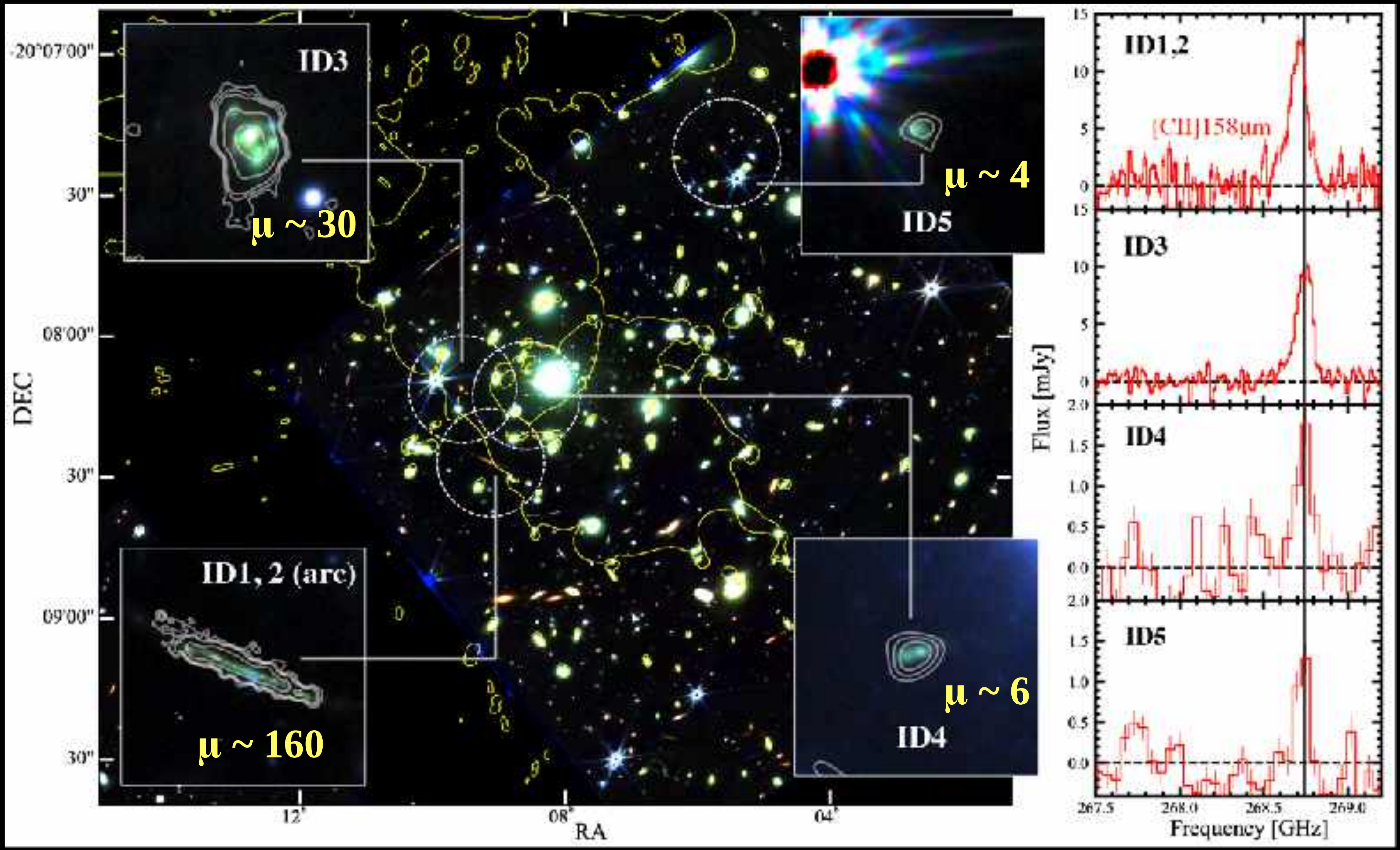
~160hrs

Target: A sub-L* main-sequence galaxy at z=6.07



- **Multiple images** spectroscopically confirmed at = 6.07 with [CII]158um (→ secure μ!)
- **Brightest** ([CII]~20mJy, F160W~23.5mag) so far known at zspec > 6 in the observed-frame, but still intrinsically **a low-mass main-sequence galaxy (M_{star} ~ 10^9 M_{sun}, ~local dwarf)**

Fujimoto+24, submitted

See also Salmon+18, Laporte+21, Fujimoto+21

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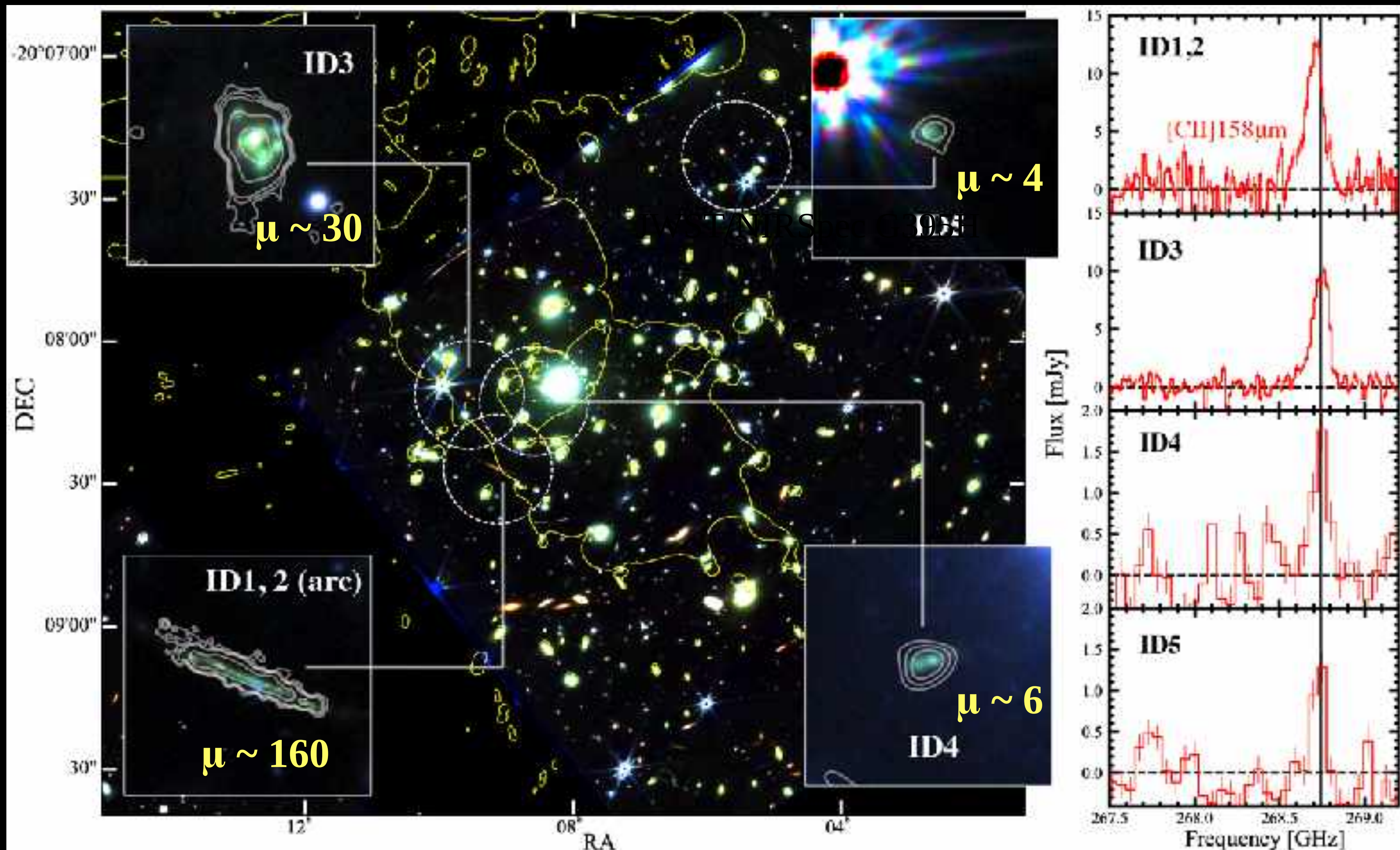

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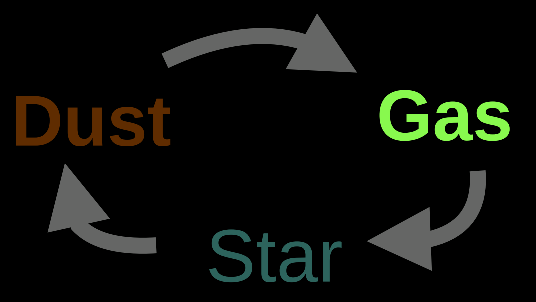
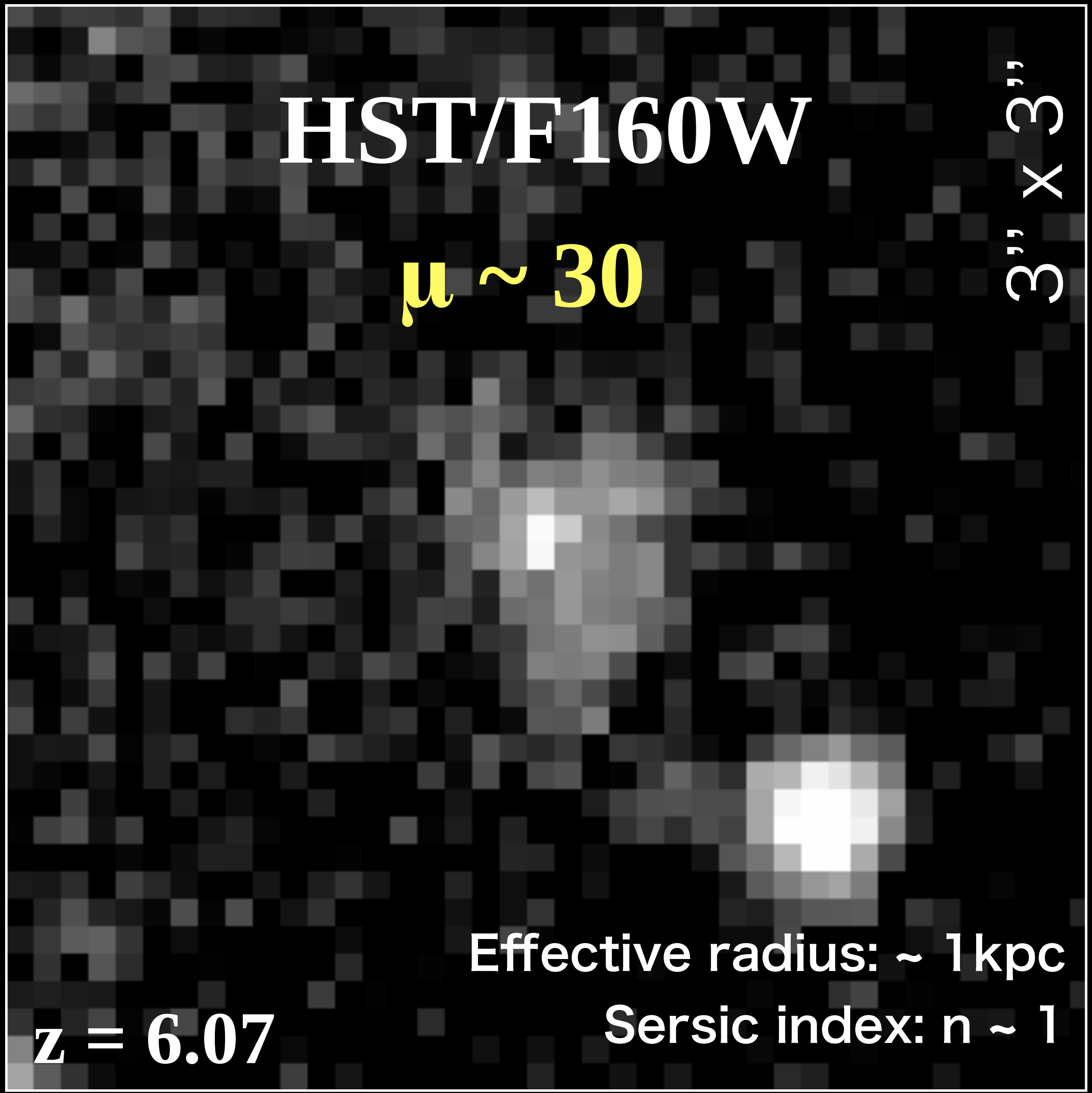
Deepest Dive into the Early Galaxy





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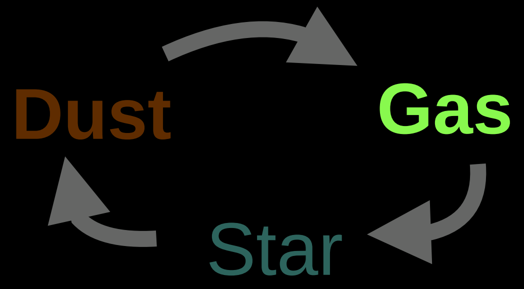

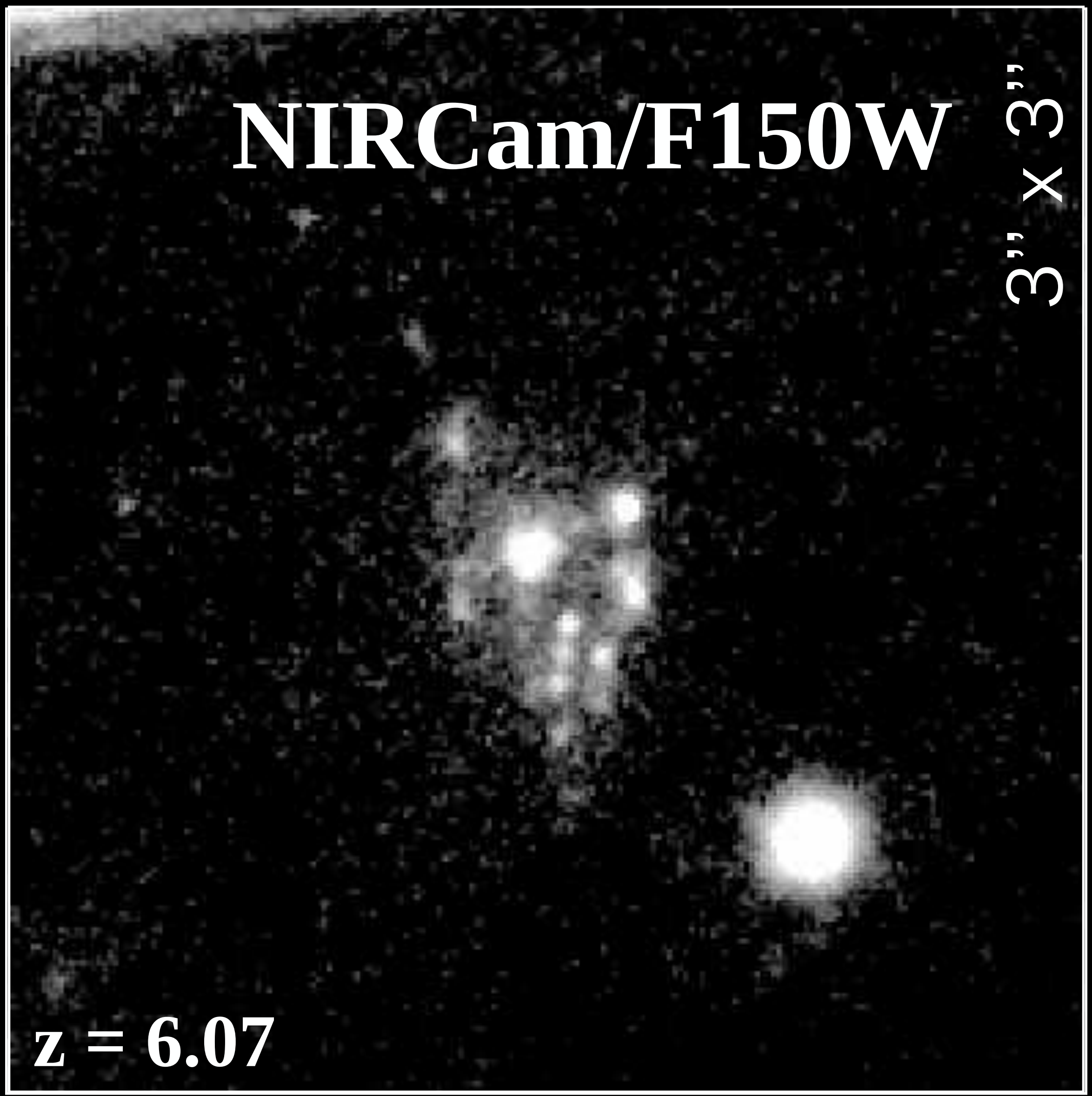

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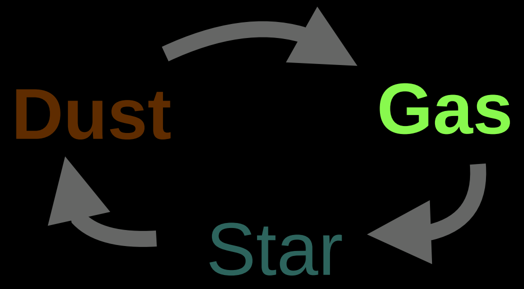
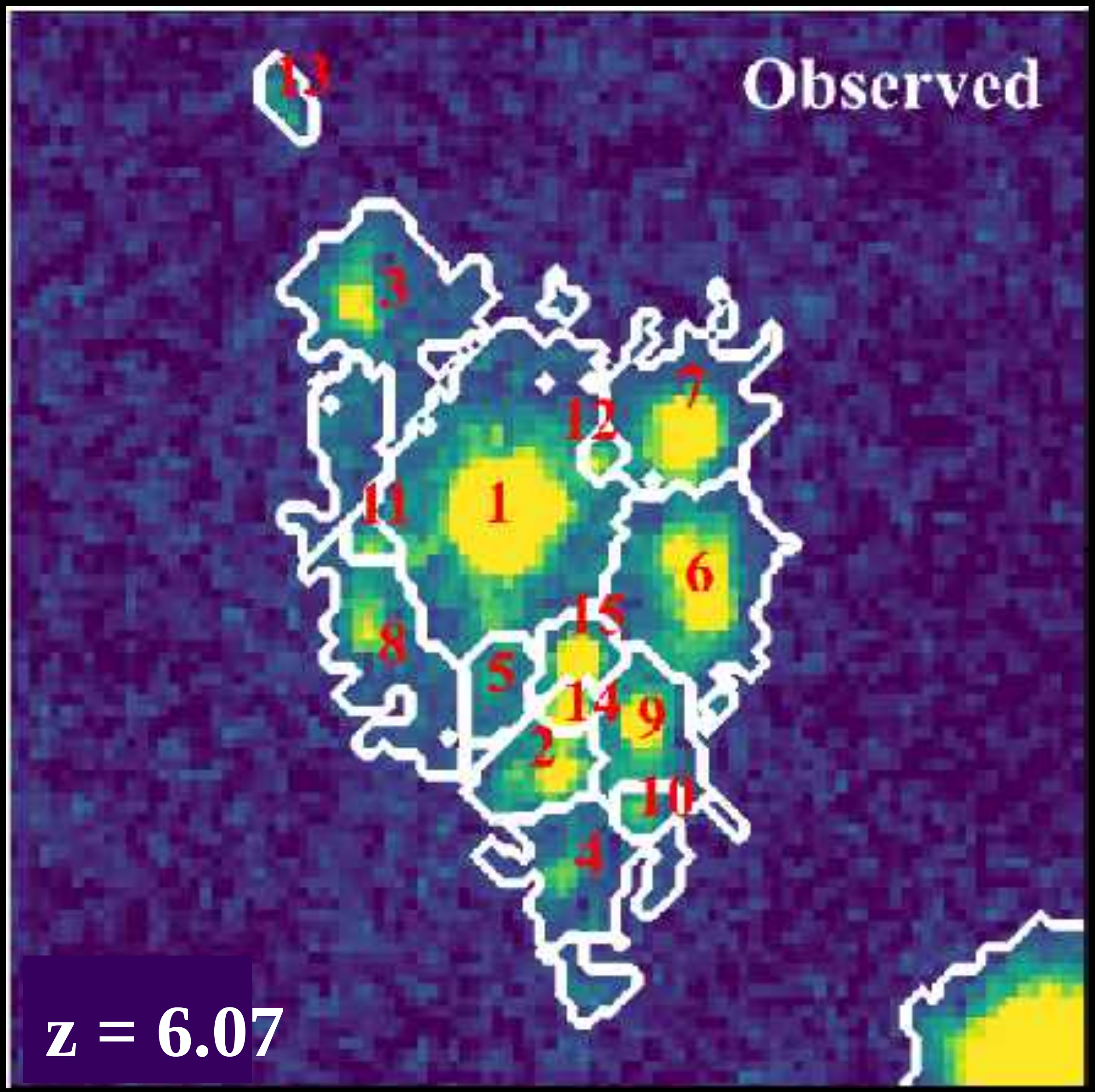
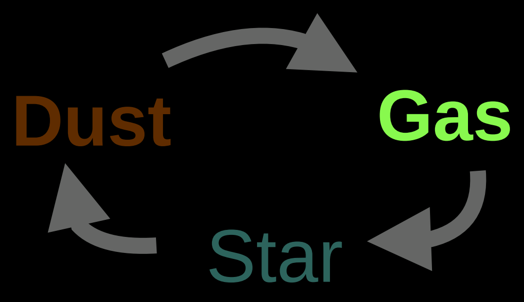


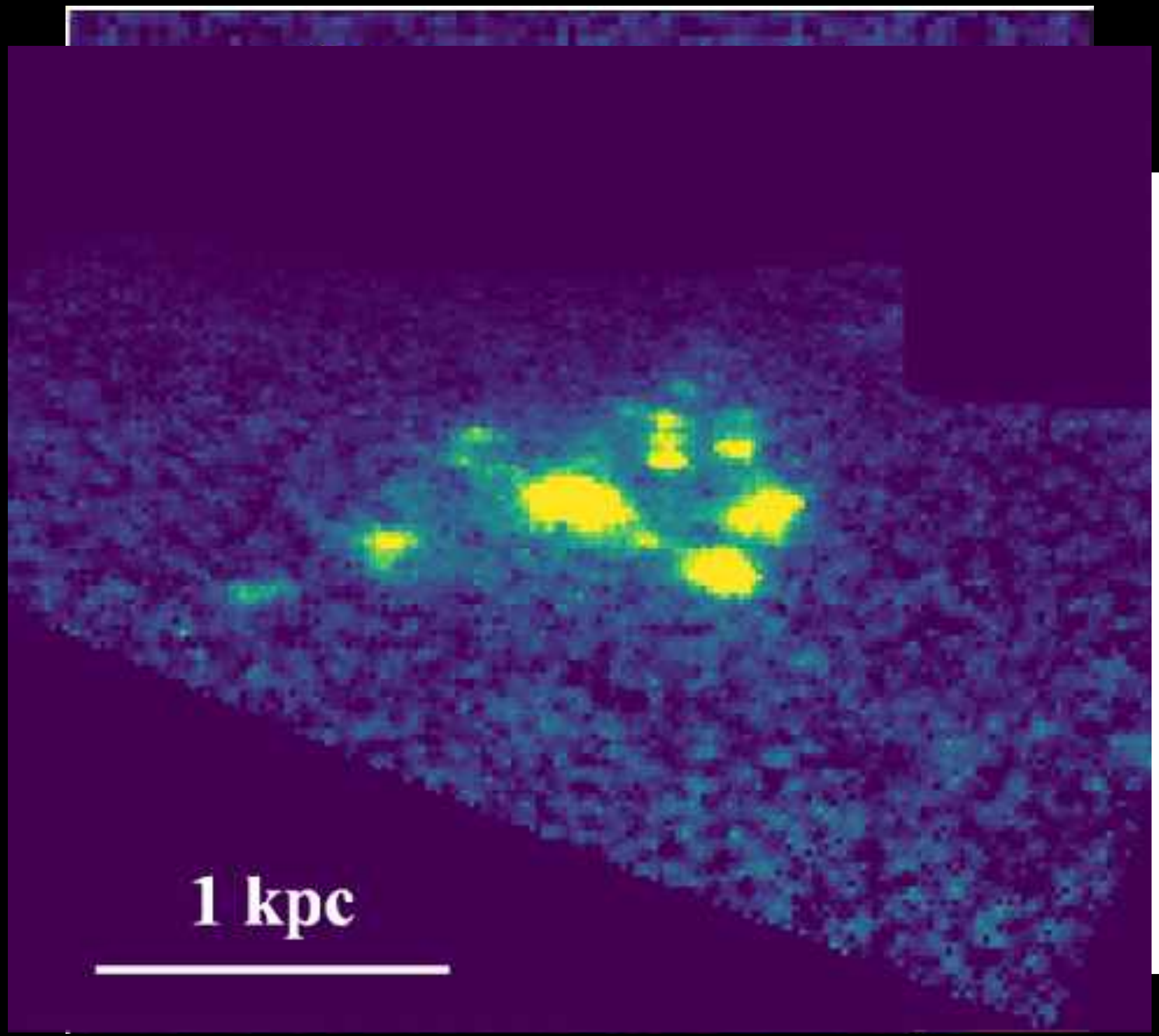


- **A single disk galaxy resolved into**
  ~ 15 individual small (Re ~10-60pc, after lens corr.) clumps

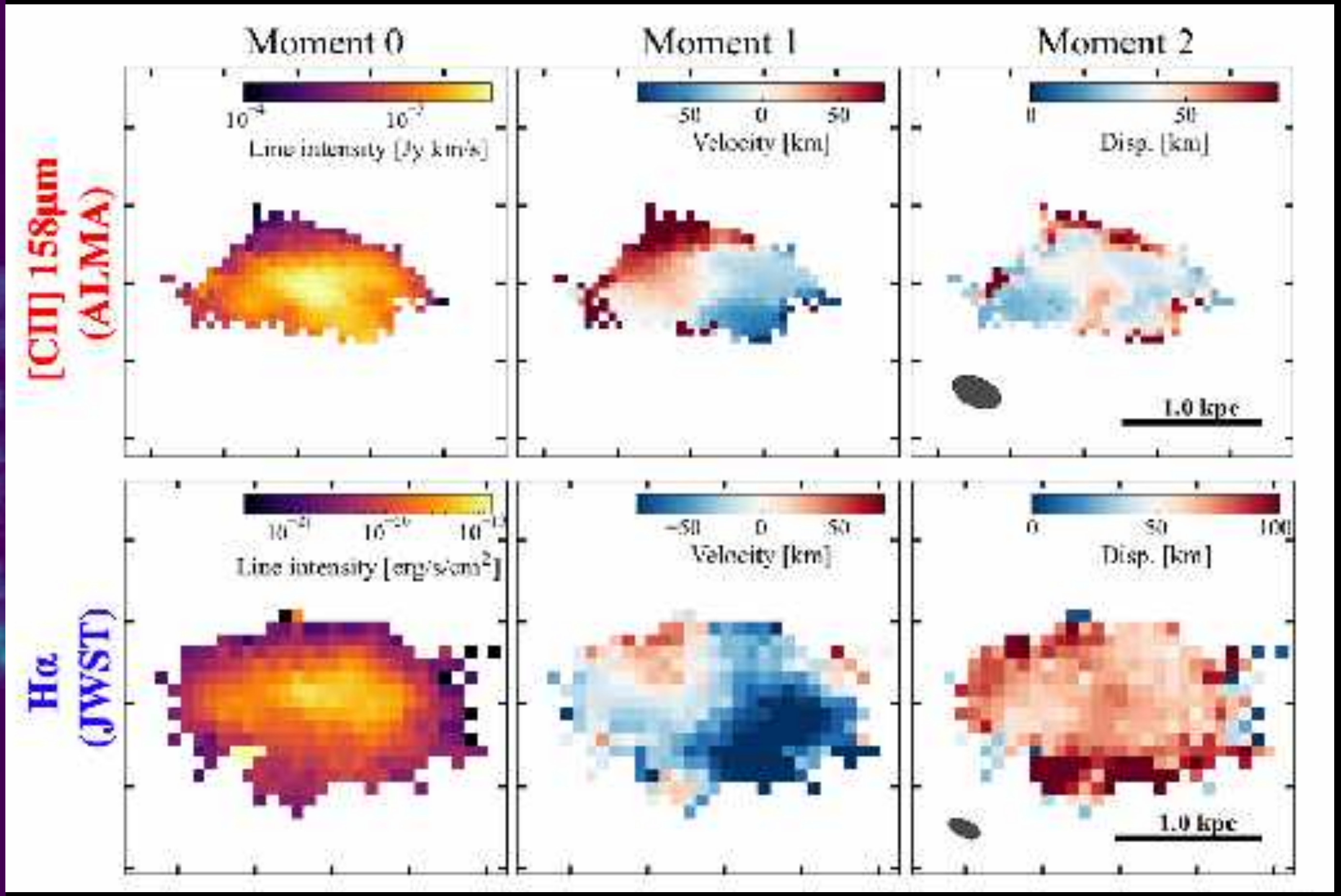
Fujimoto+24, submitted

Deepest Dive into the Early Galaxy



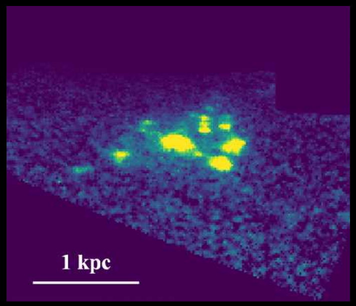


IFU (in the source plane)



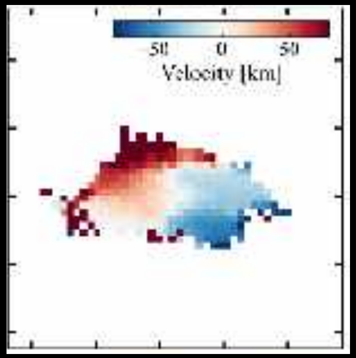
- **A single disk galaxy resolved into**
  ~ 15 individual small (Re ~10-60pc, after lens corr.) clumps

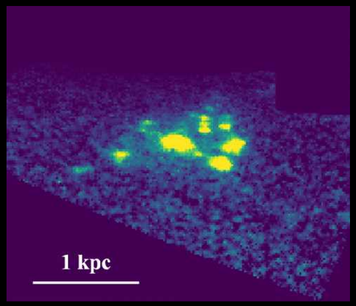
- **Embedded in a smooth (σ~20km/s) rotating disk**



Numerous clumps + Rotating disk

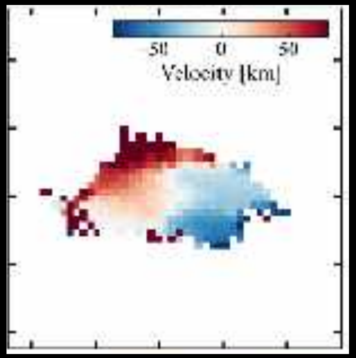
= Challenging to current models

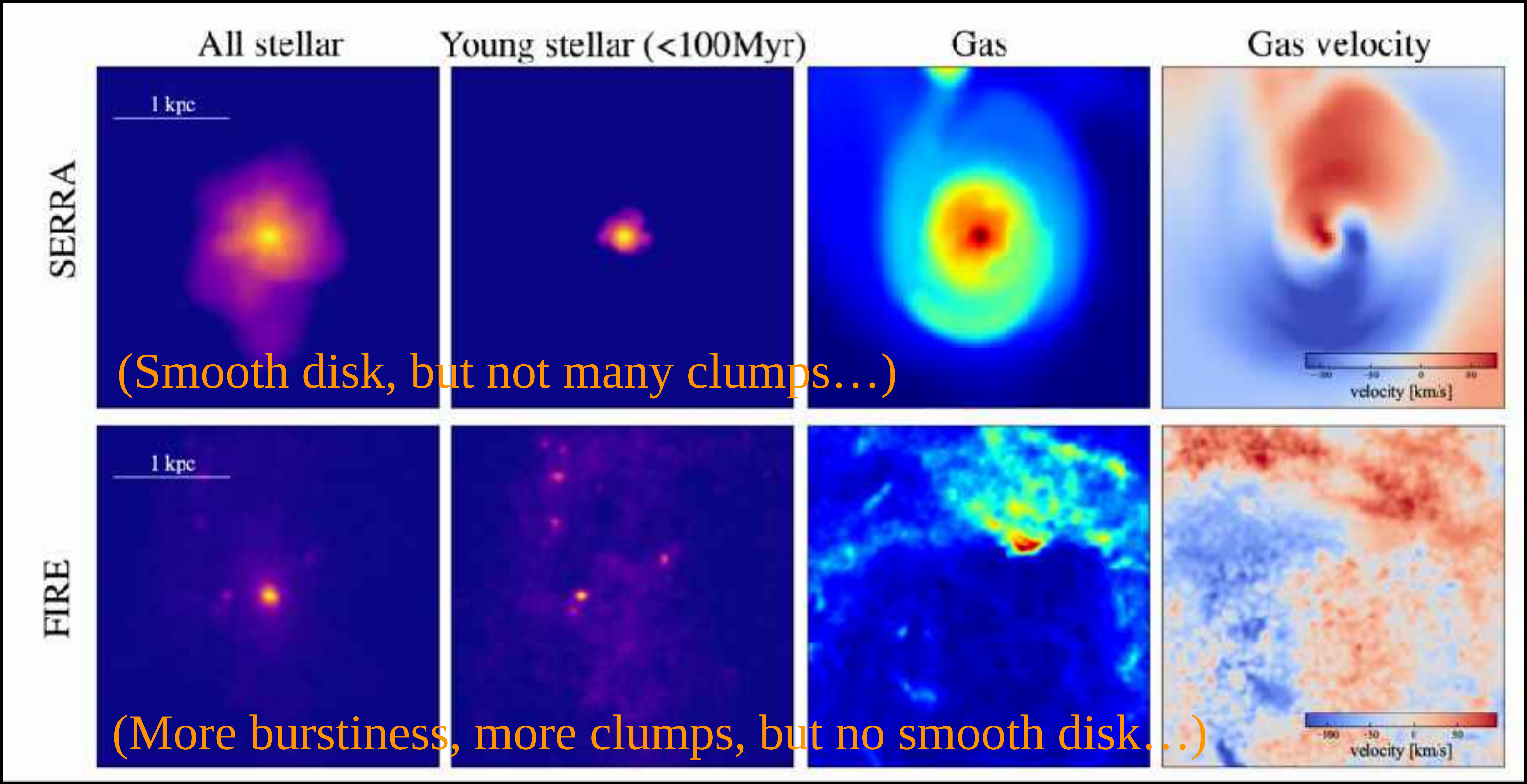




Numerous clumps + Rotating disk

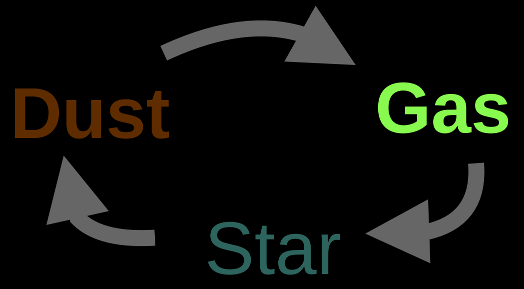
= Challenging to current models



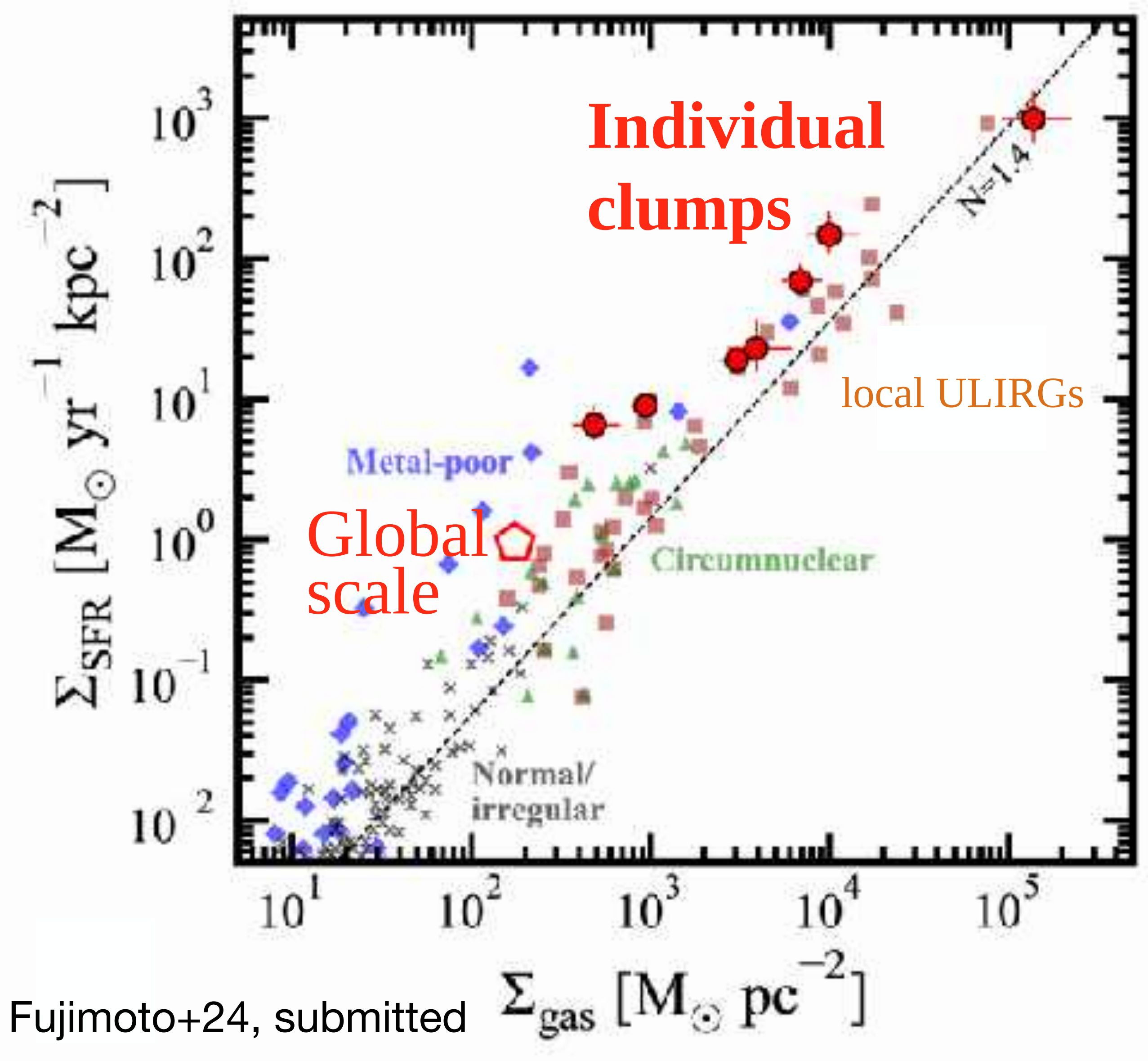


Frequent bursty star-formation ⇔ Smooth rotating disk = Weak feedback?

Weak feedback in Early Galaxies?



($L_{[CII]} \rightarrow M_{gas}$; Cross-checked with M_{dyn}, $\delta_{GDR}(Z)$)



Fujimoto+24, submitted

Observational implication for high ϵ_* at high-z with JWST; see also e.g., Casey+23, Xiao+23, Chworowsky+24, Marques-Chaves+24, de Graaf+24, Dessauges-Zavadsky+24, Turner+24

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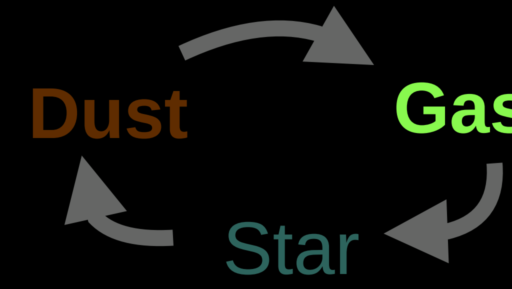

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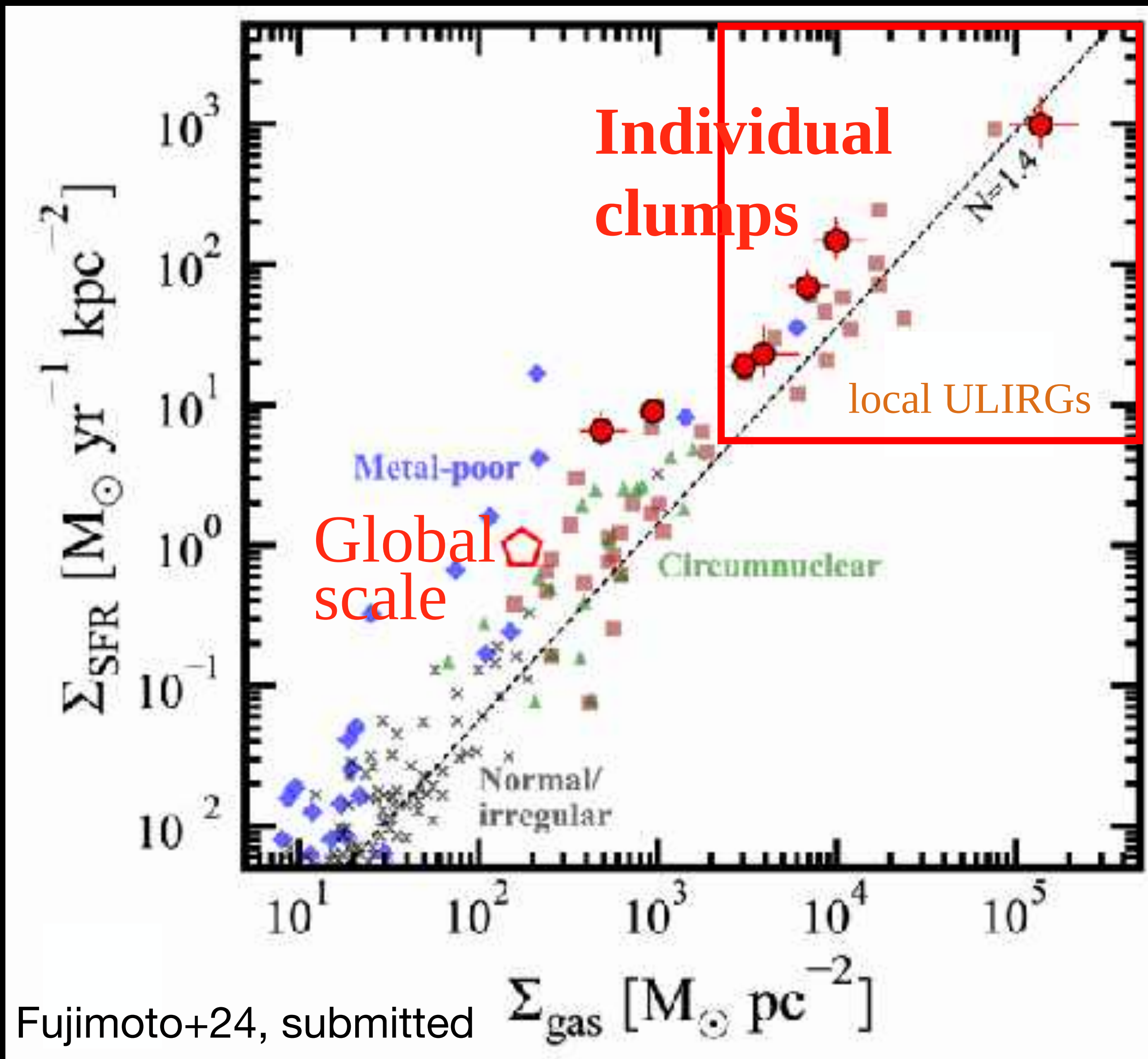

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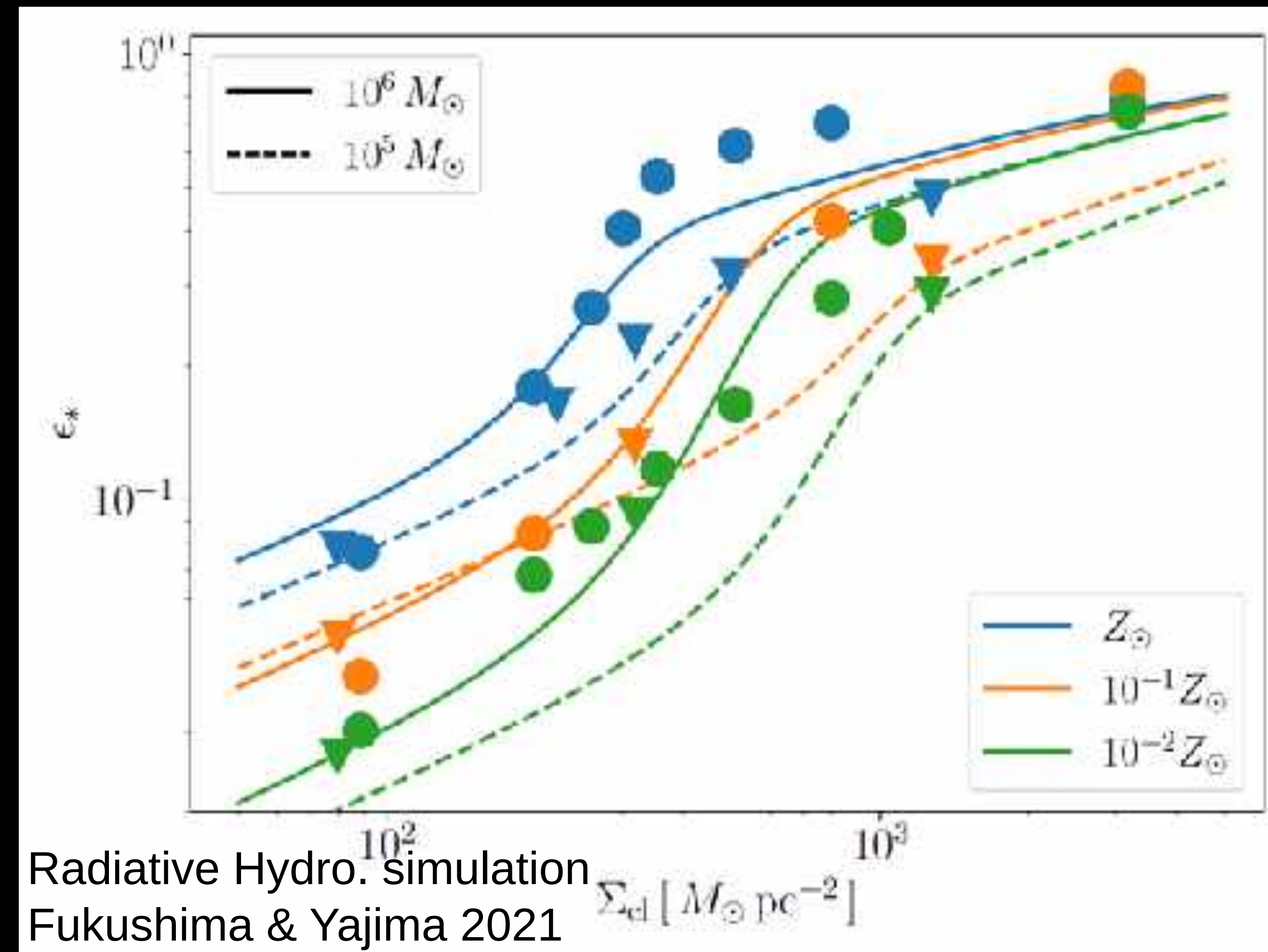

Radiative Hydro. simulation
Fukushima & Yajima 2021

See also feedback-free burst model
(> 3,000 M◉/pc²; Dekel+23; Li+24)

$\varepsilon_* \equiv M_{star} / (f_{baryon} M_{halo})$: Integrated over the lifetime of the system

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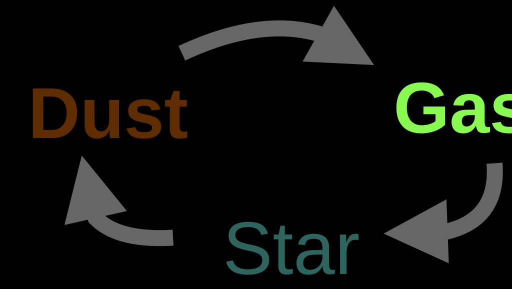

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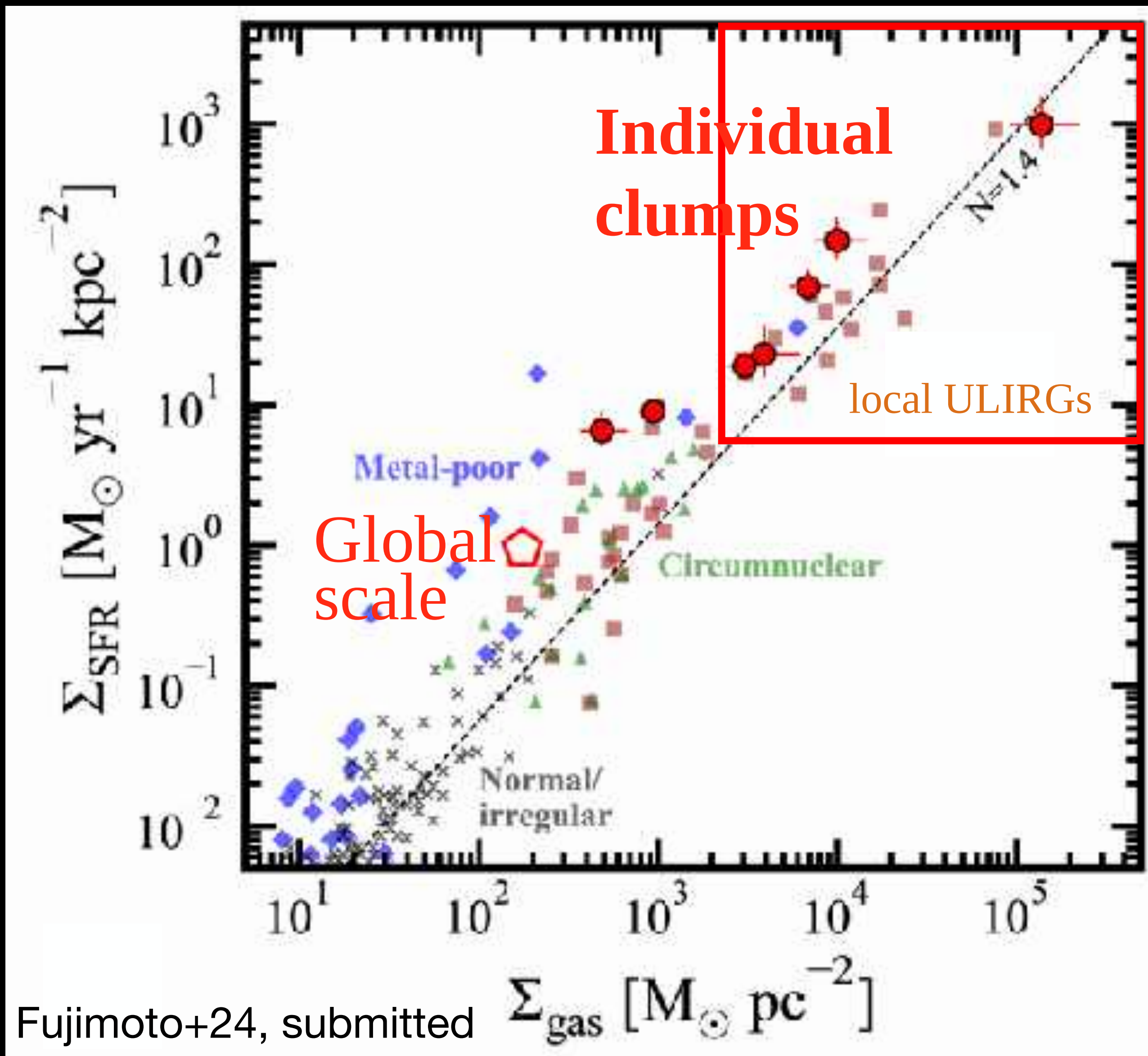

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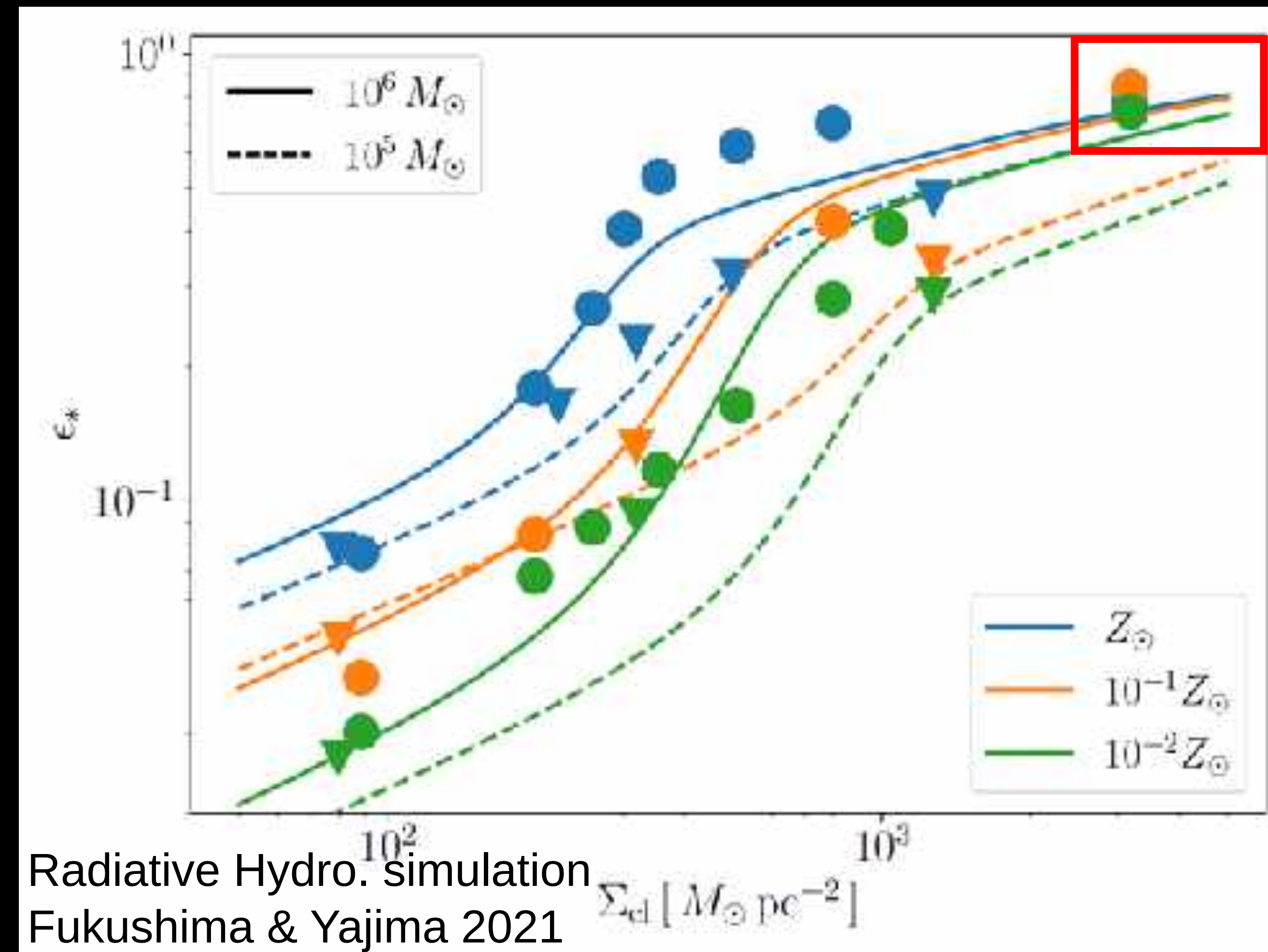

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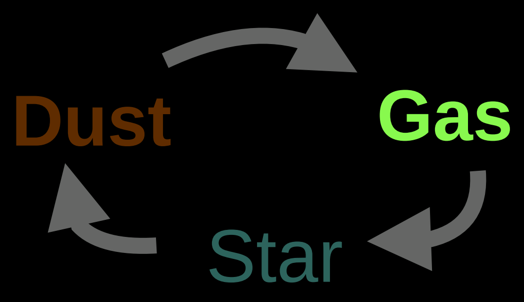
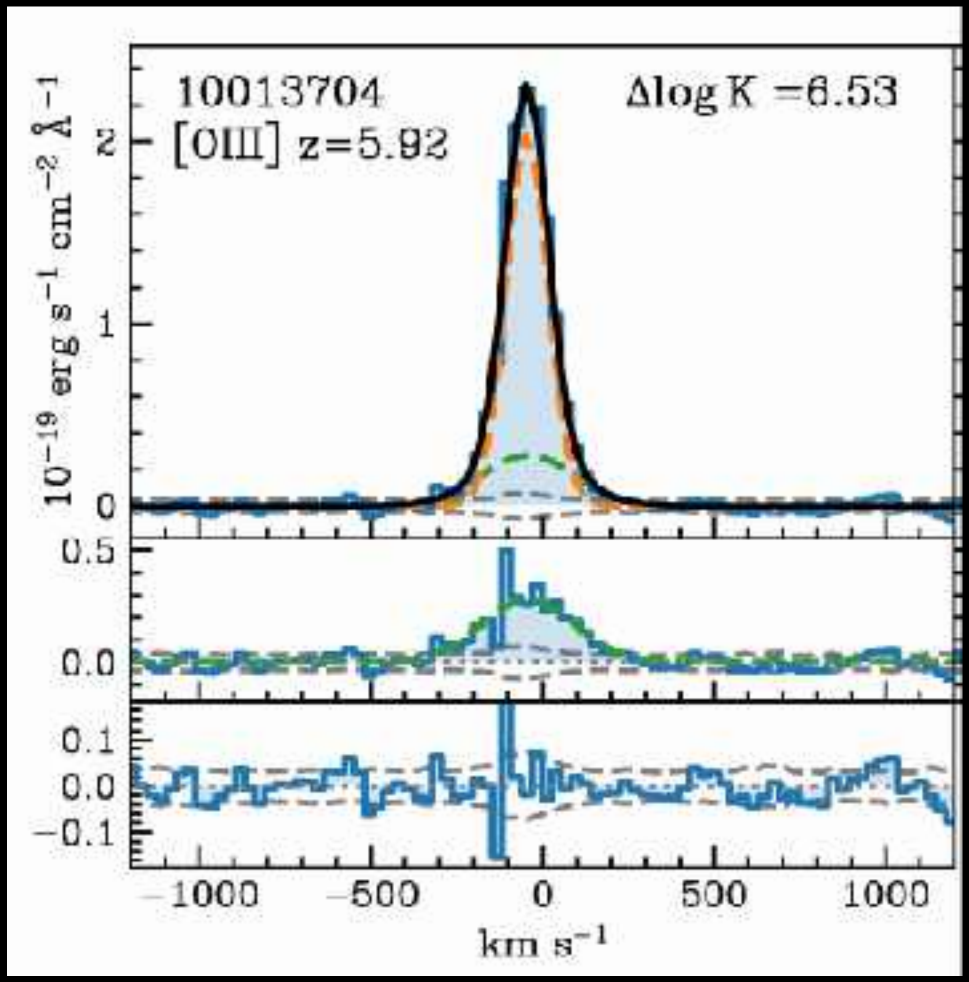
$\varepsilon_* \equiv M_{star} / (f_{baryon} M_{halo})$: Integrated over the lifetime of the system

Very high gas density (~comparable to local ULIRGs) observed,
well aligned with weak feedback ~ high star-formation efficiency of $\varepsilon_* > 0.6 - 0.8$
(cf. $\varepsilon_* < 0.1$ in local galaxies)

Observational implication for high ε_* at high-z with JWST; see also e.g., Casey+23, Xiao+23, Chworowsky+24, Marques-Chaves+24, de Graaf+24, Dessauges-Zavadsky+24, Turner+24

Presence of outflow does not contradict weak feedback





Carniani+24

High-z outflow with JWST; see also e.g., Zhang+24, Venturi+24, Zhu+24, Parlanti+24, Xu+24, talks by Carniani, Giacomo

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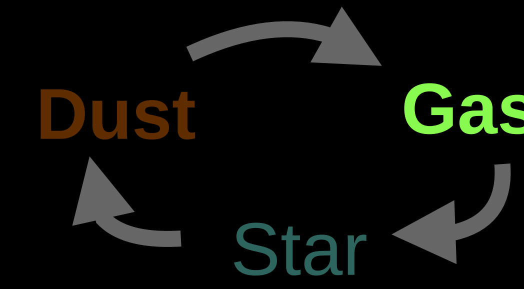

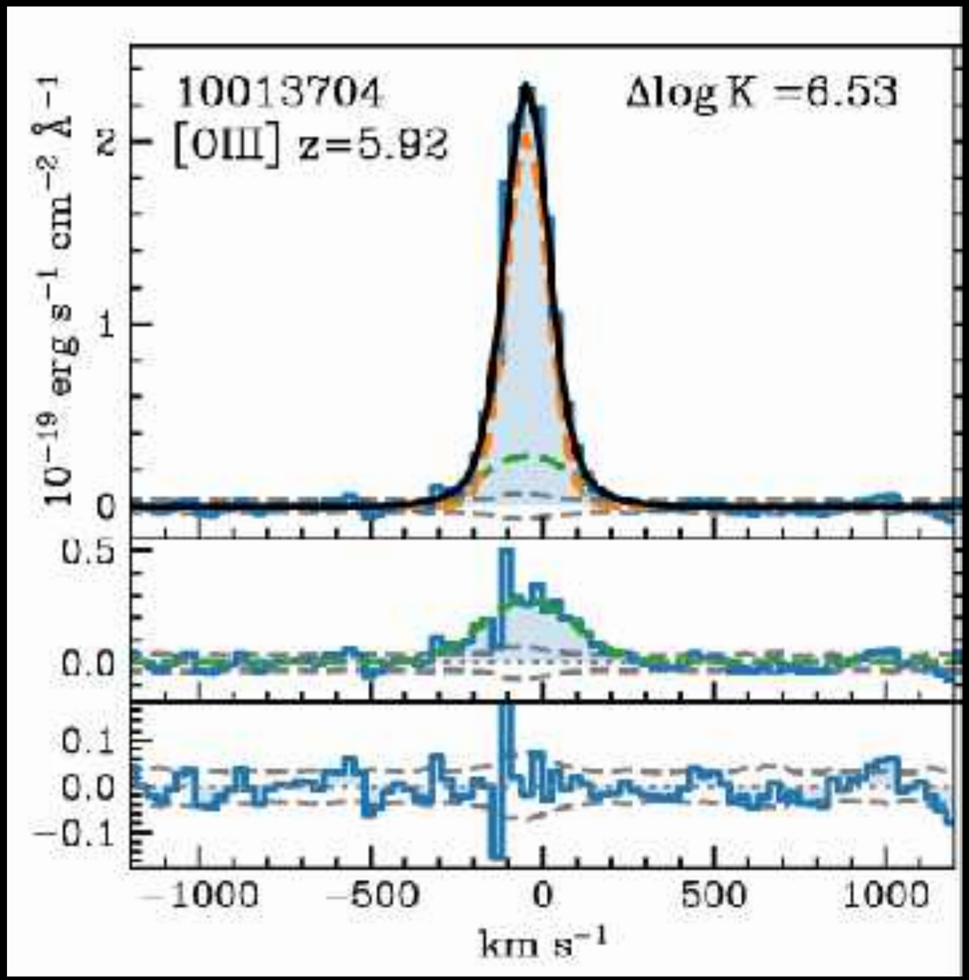

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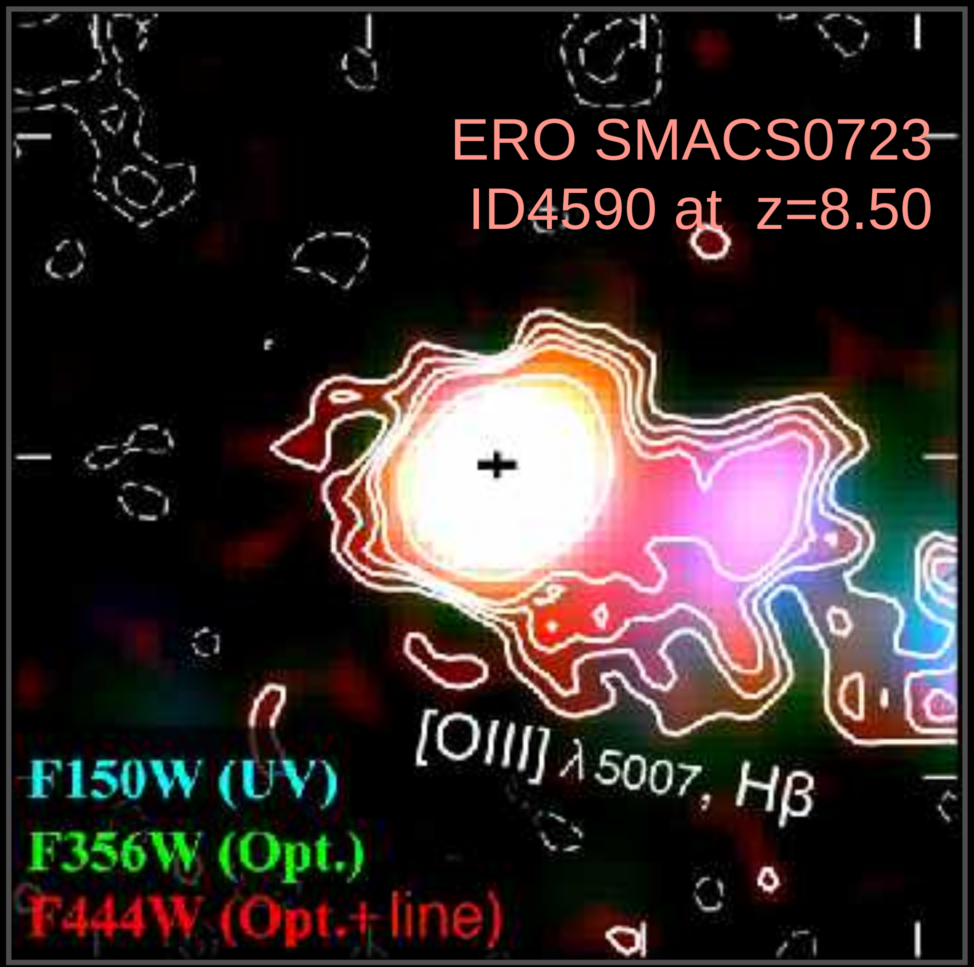

Fujimoto+22c

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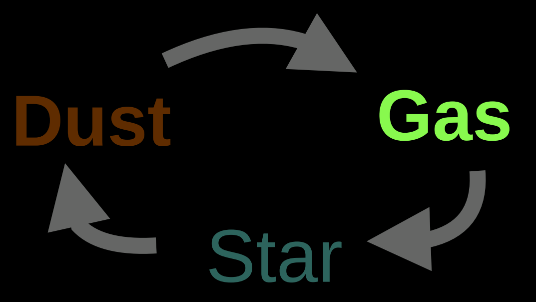

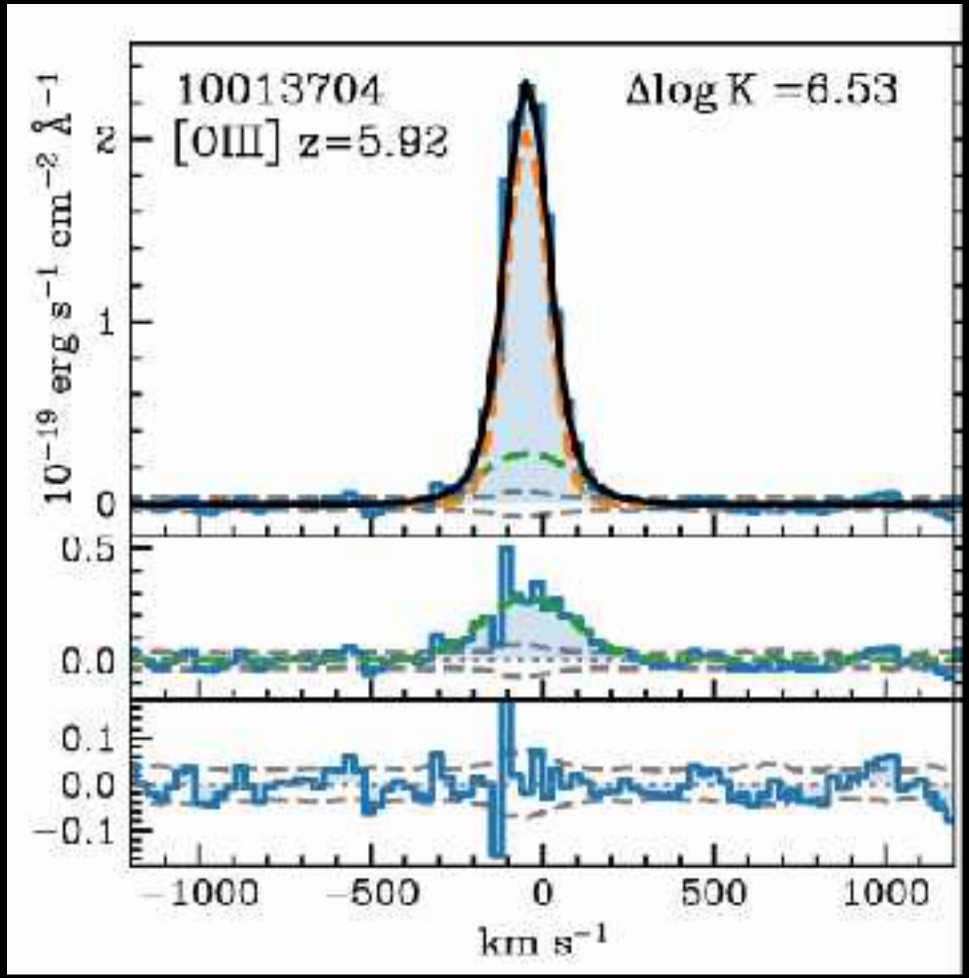

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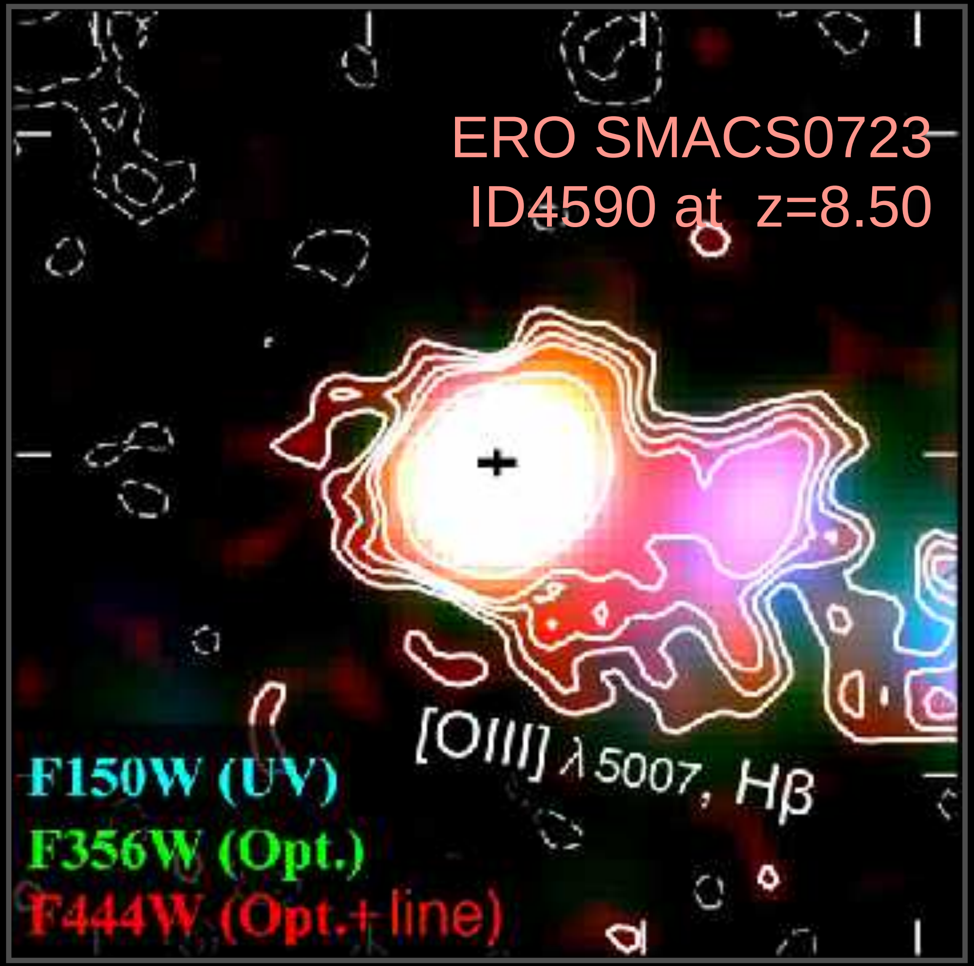
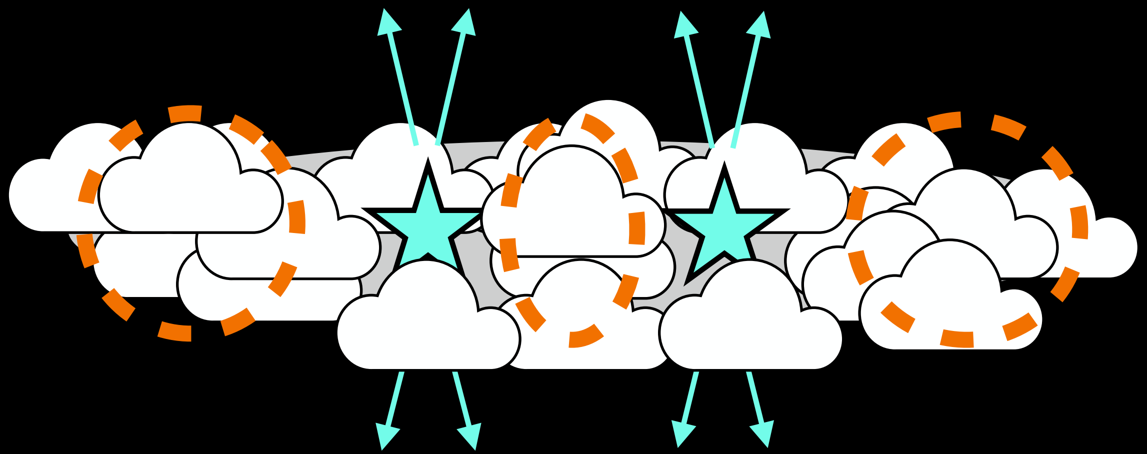


Fujimoto+22c

Outflow does exist in early galaxies

but High gas density maintains High SFE



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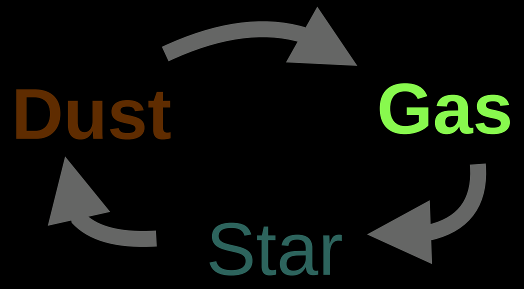
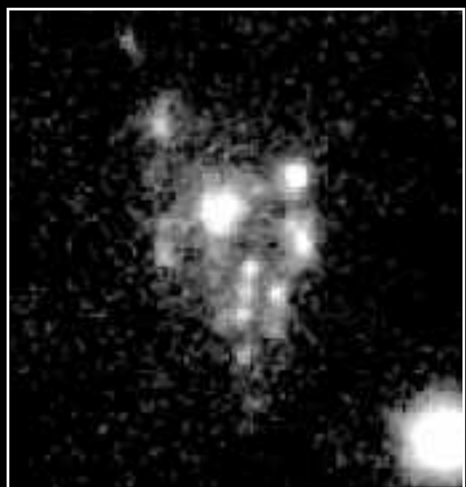
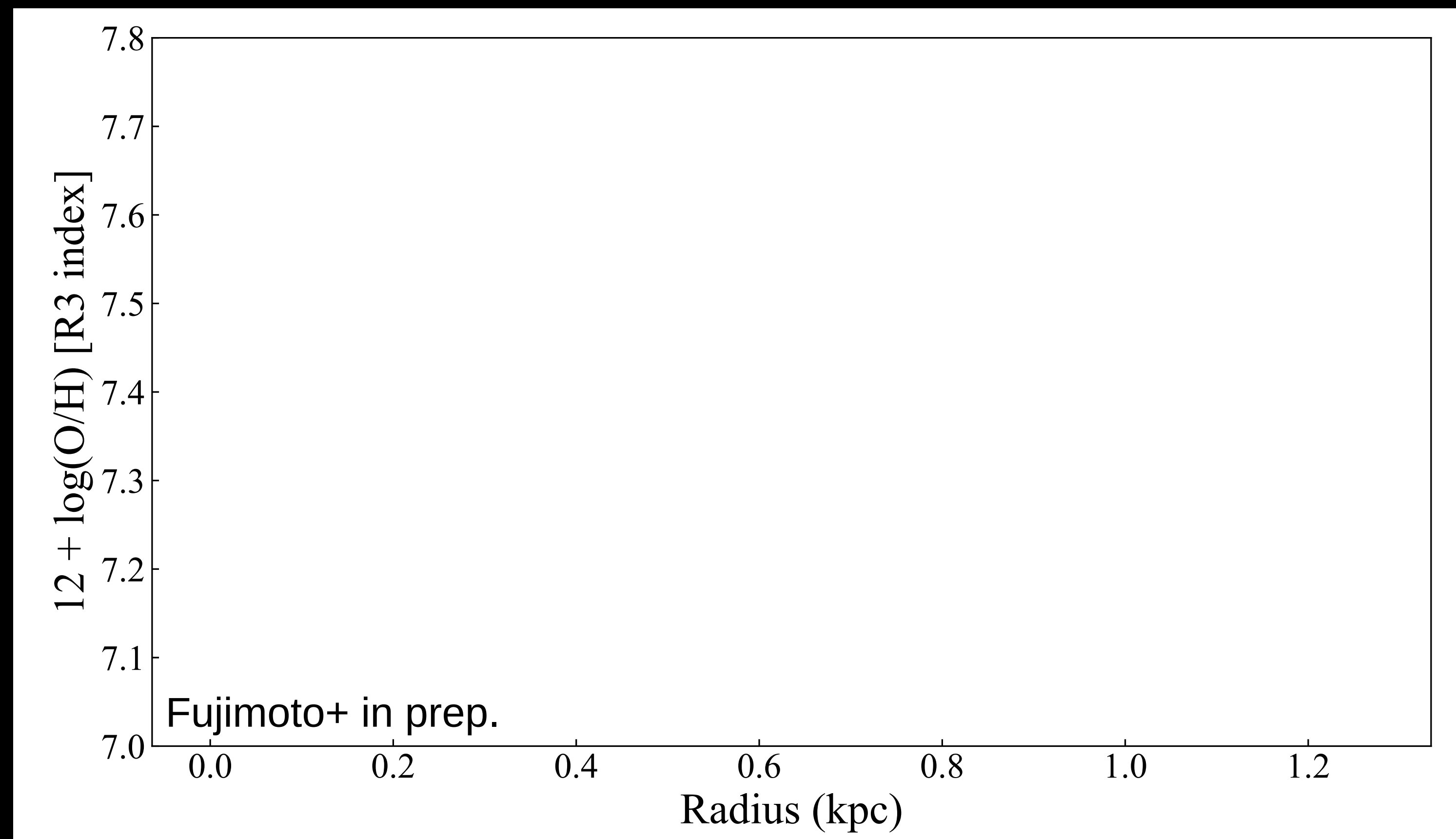
Metallicity gradient:
Probe for the feedback effect







Metallicity gradient measurements with JWST; see also e.g., Wang+22, Venturi+24, Ju+24

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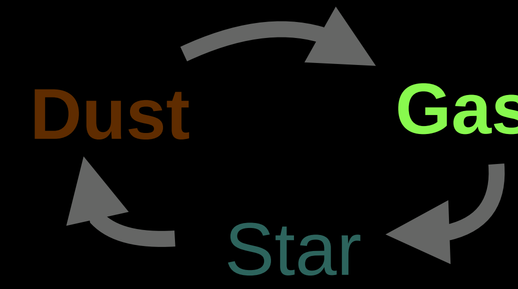
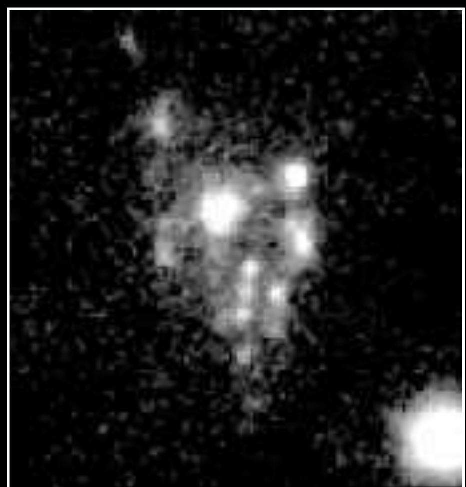
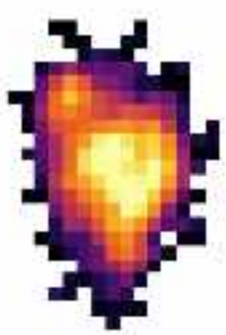
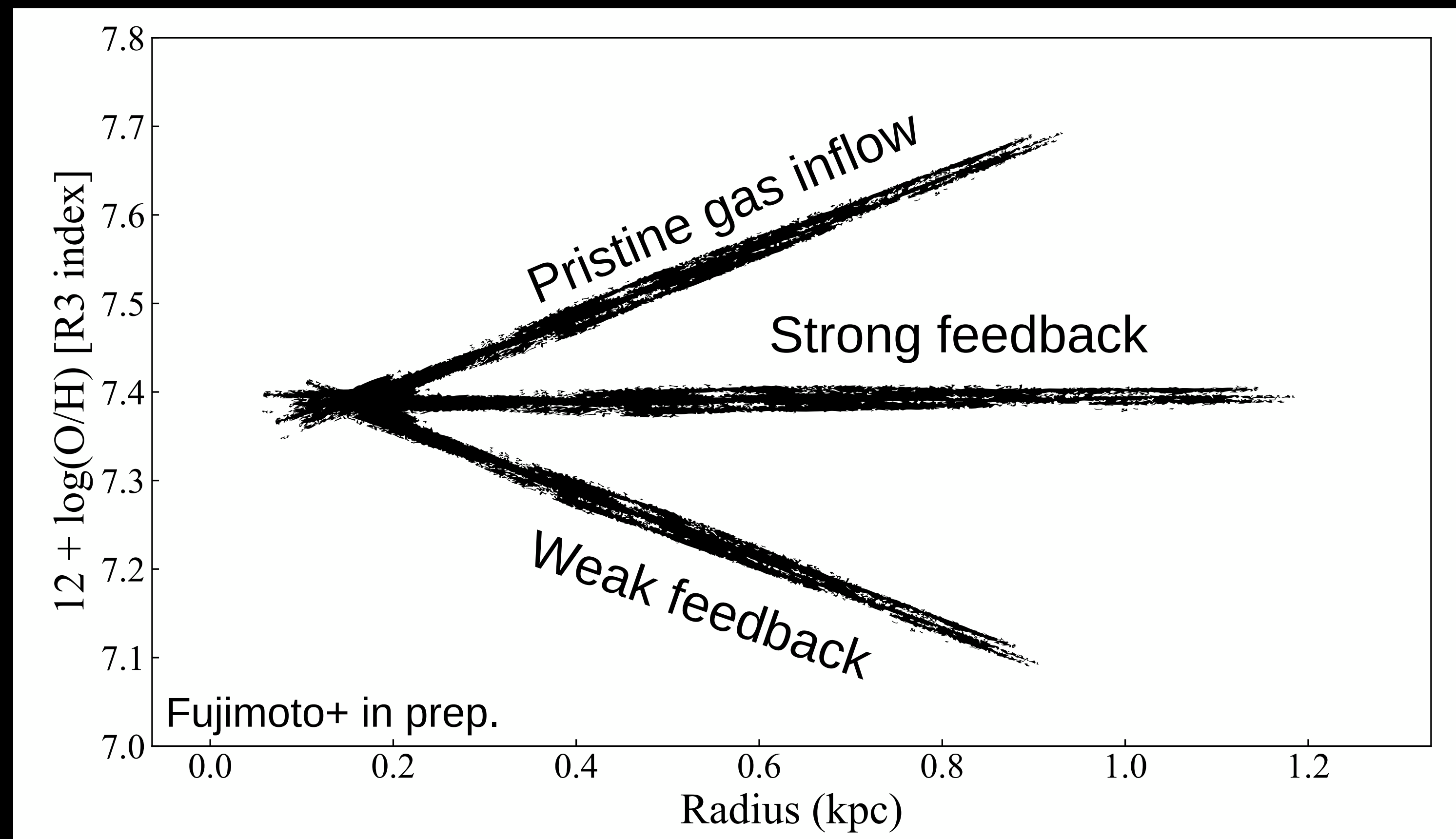




[OIII] 5008



Hβ



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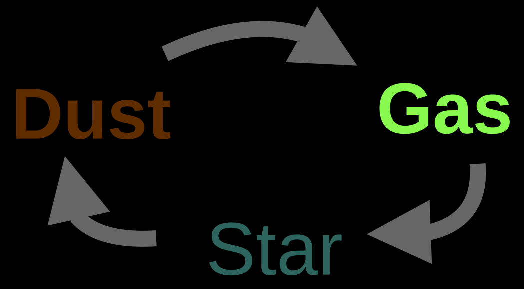
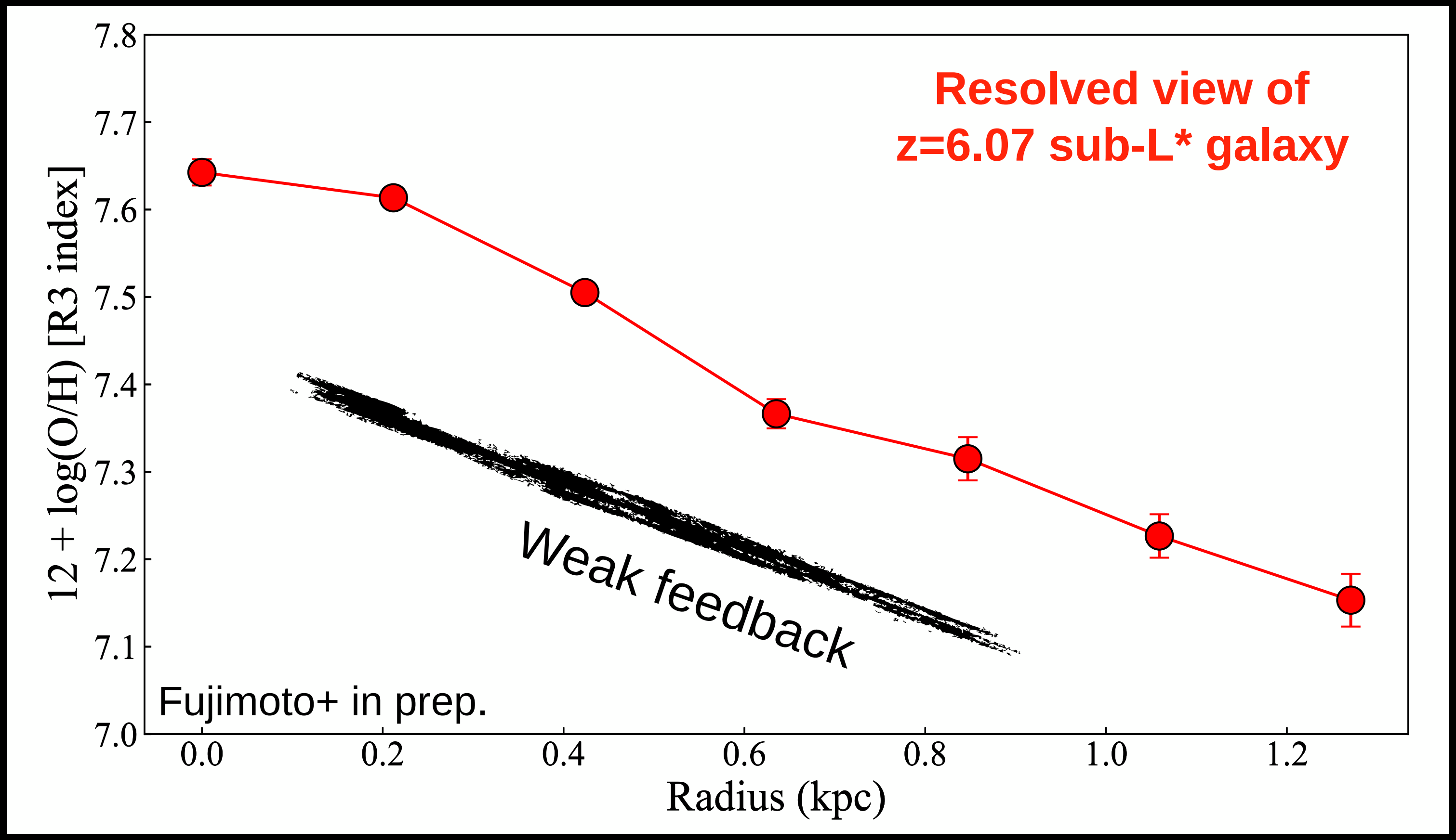




Weak feedback is independently confirmed by the negative metallicity gradient

Metallicity gradient measurements with JWST; see also e.g., Wang+22, Venturi+24, Ju+24

Summary

Gas and dust at early epochs

Summary

Gas and dust at early epochs

**High abundance of
bright galaxies at $z>10$?**

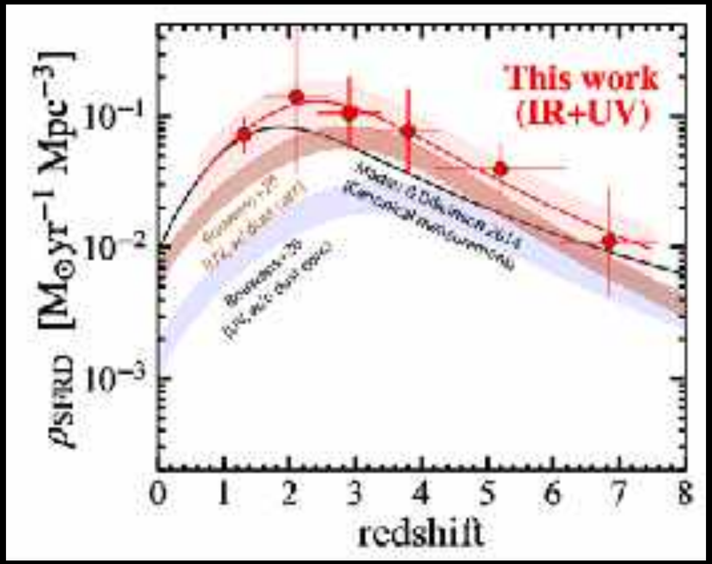
Summary

Gas and dust at early epochs

High abundance of bright galaxies at z>10?

Star

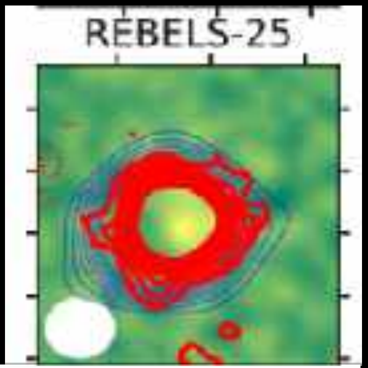
Dust

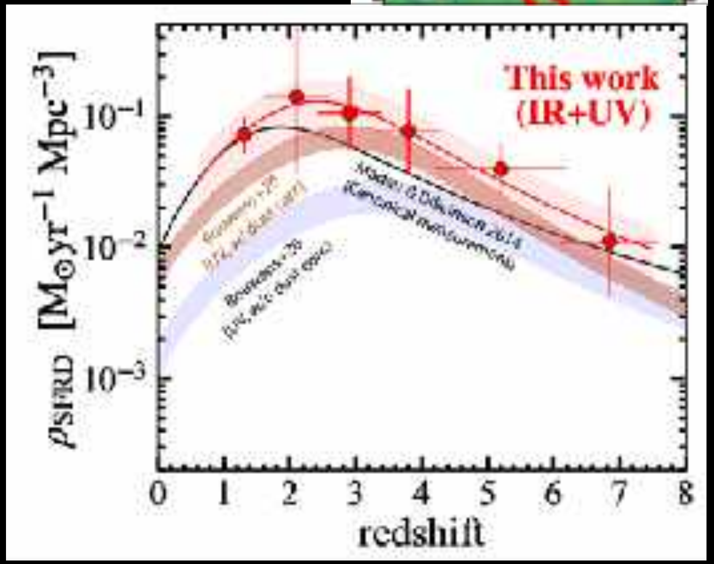


- **Additional (~ 60%) obscured SF component at z~4-8**

Summary

Gas and dust at early epochs





High abundance of bright galaxies at z>10?

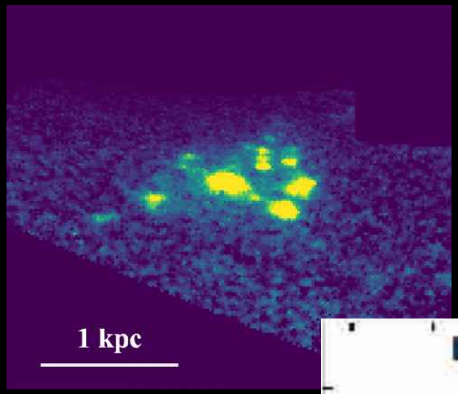
Star

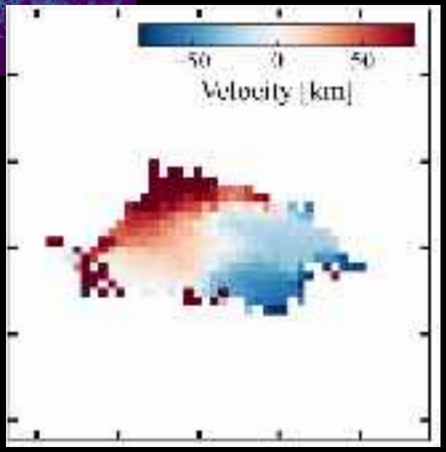
Dust

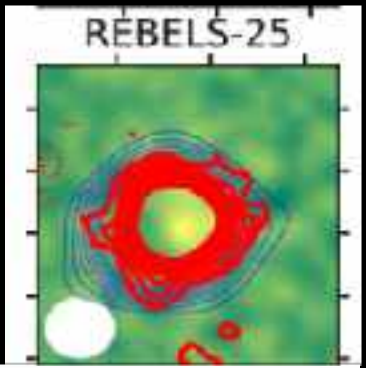
- **Additional (~ 60%) obscured SF component at z~4-8**
- **High M_{dust}/M_{star} at z>7 → *Efficient* dust growth (+SN eject)**

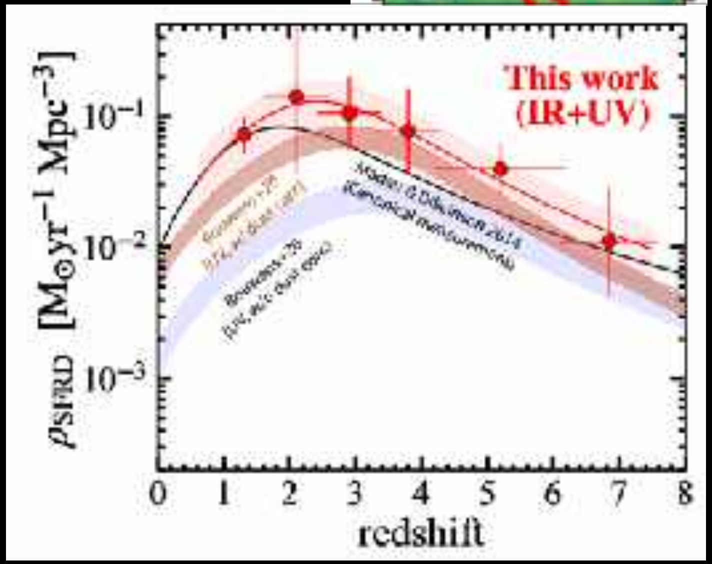
Summary

Gas and dust at early epochs









High abundance of bright galaxies at z>10?

Star

Dust

Gas

- **Numerous clumps embedded in a smooth (σ~20km/s) rotating gas disk**

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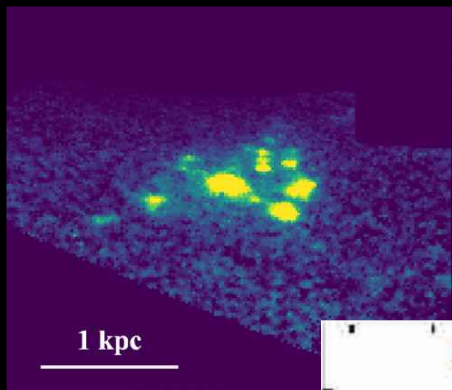
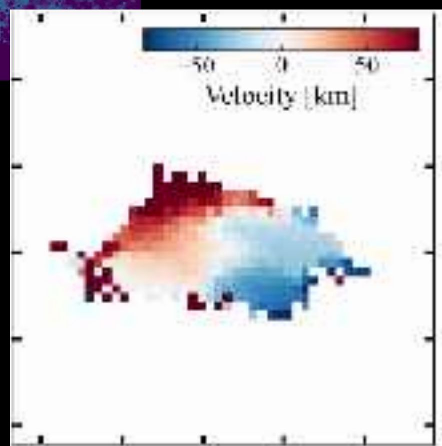
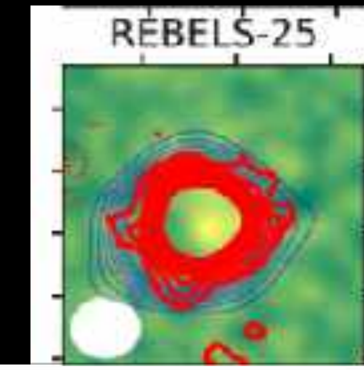
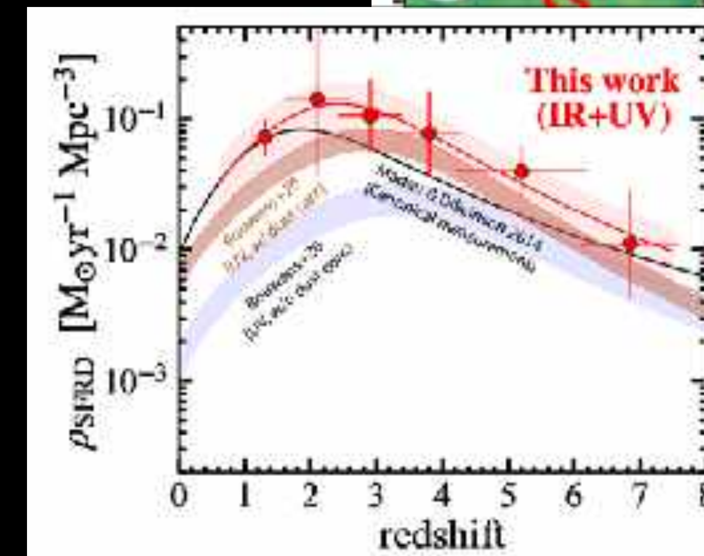
Gas and dust at early epochs









High abundance of bright galaxies at z>10?

Star → **Dust** → **Gas**

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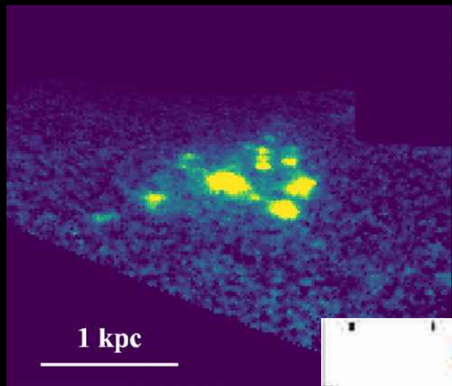

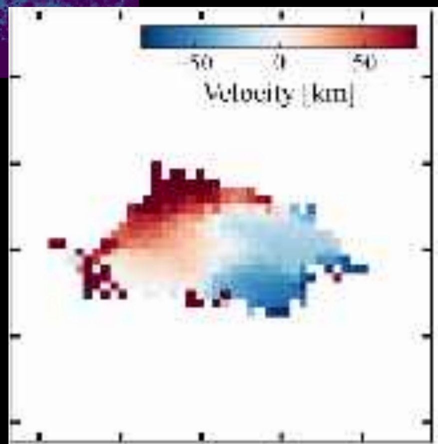

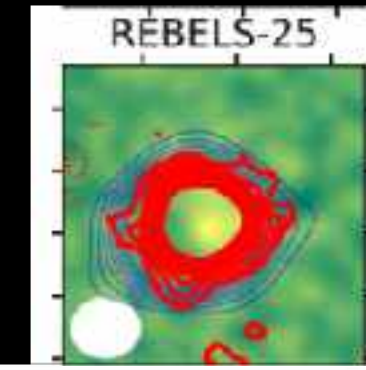

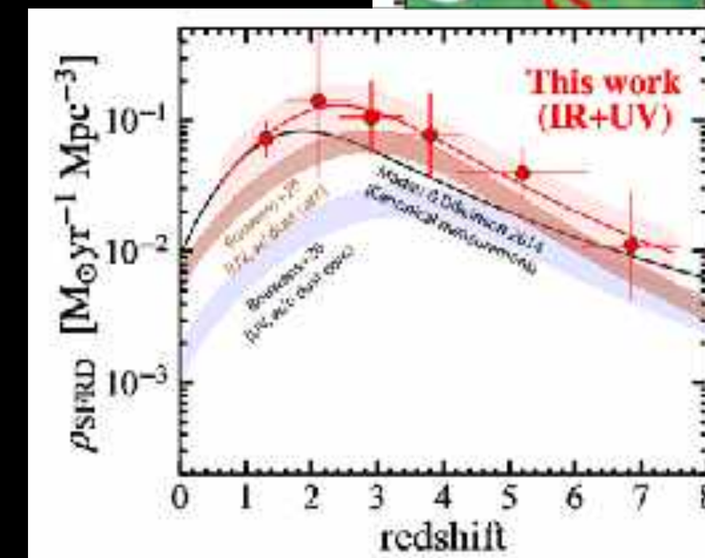

High abundance of bright galaxies at z>10?

Star

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High ISM gas density ~ High SFE