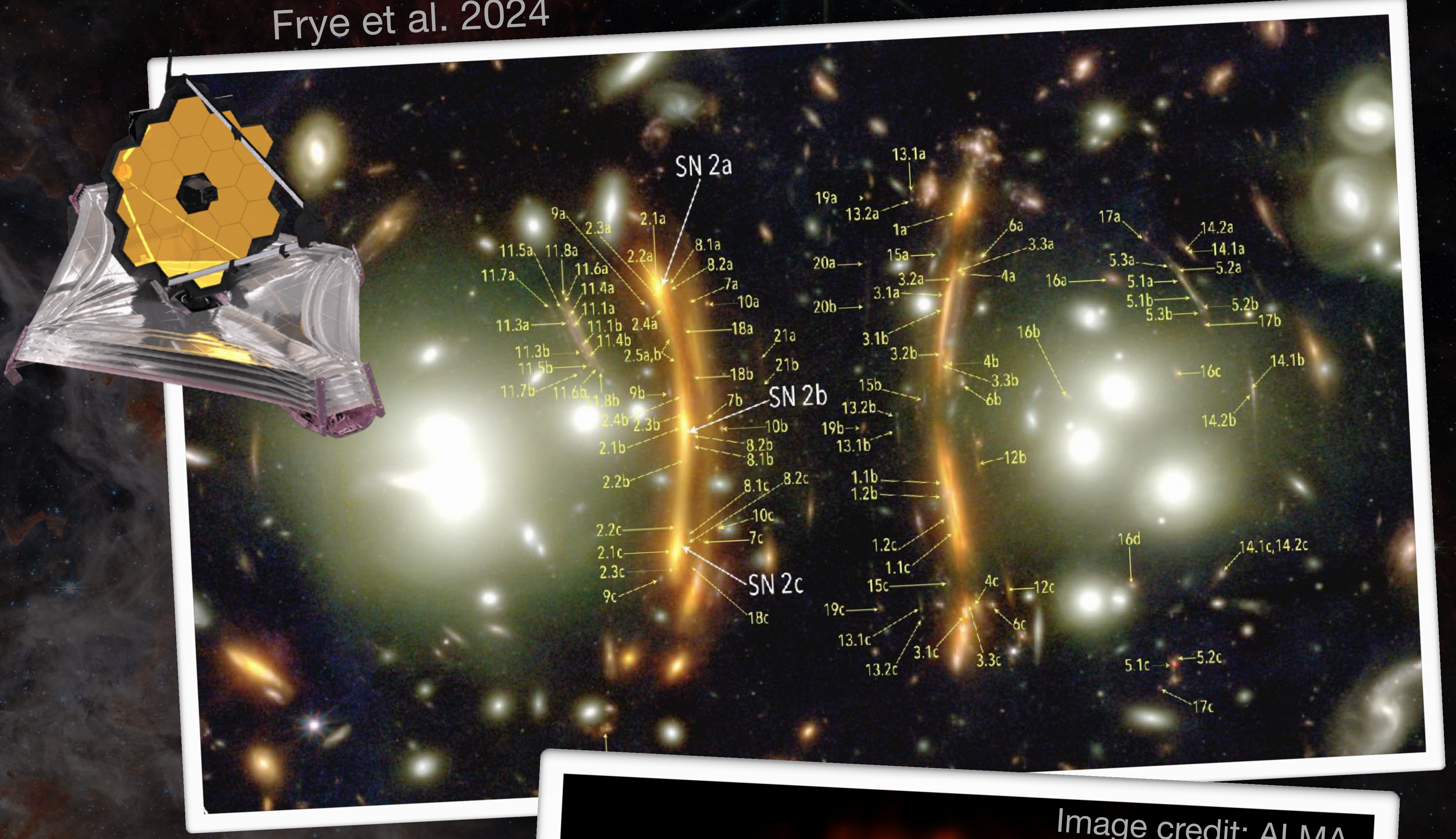
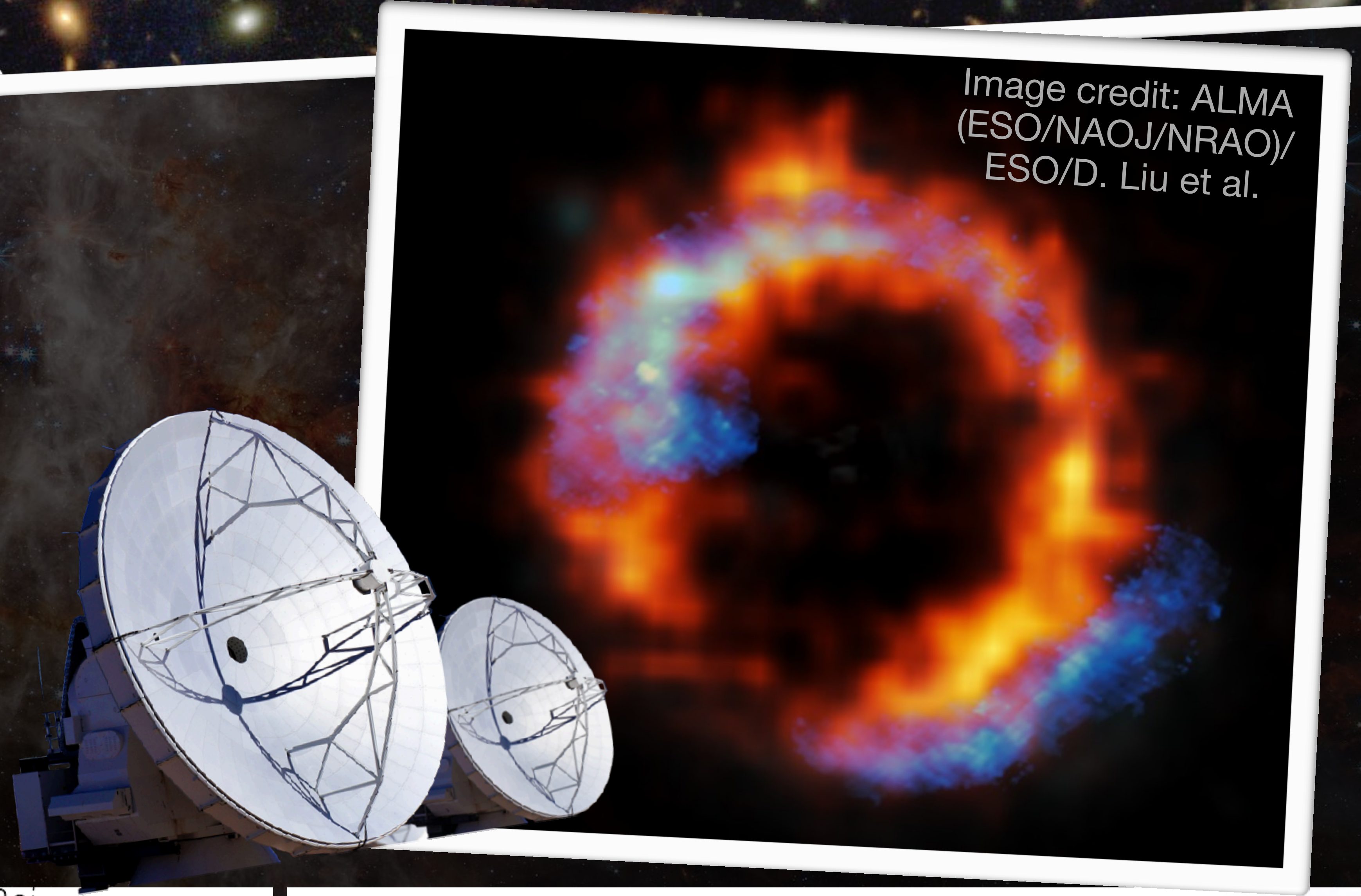
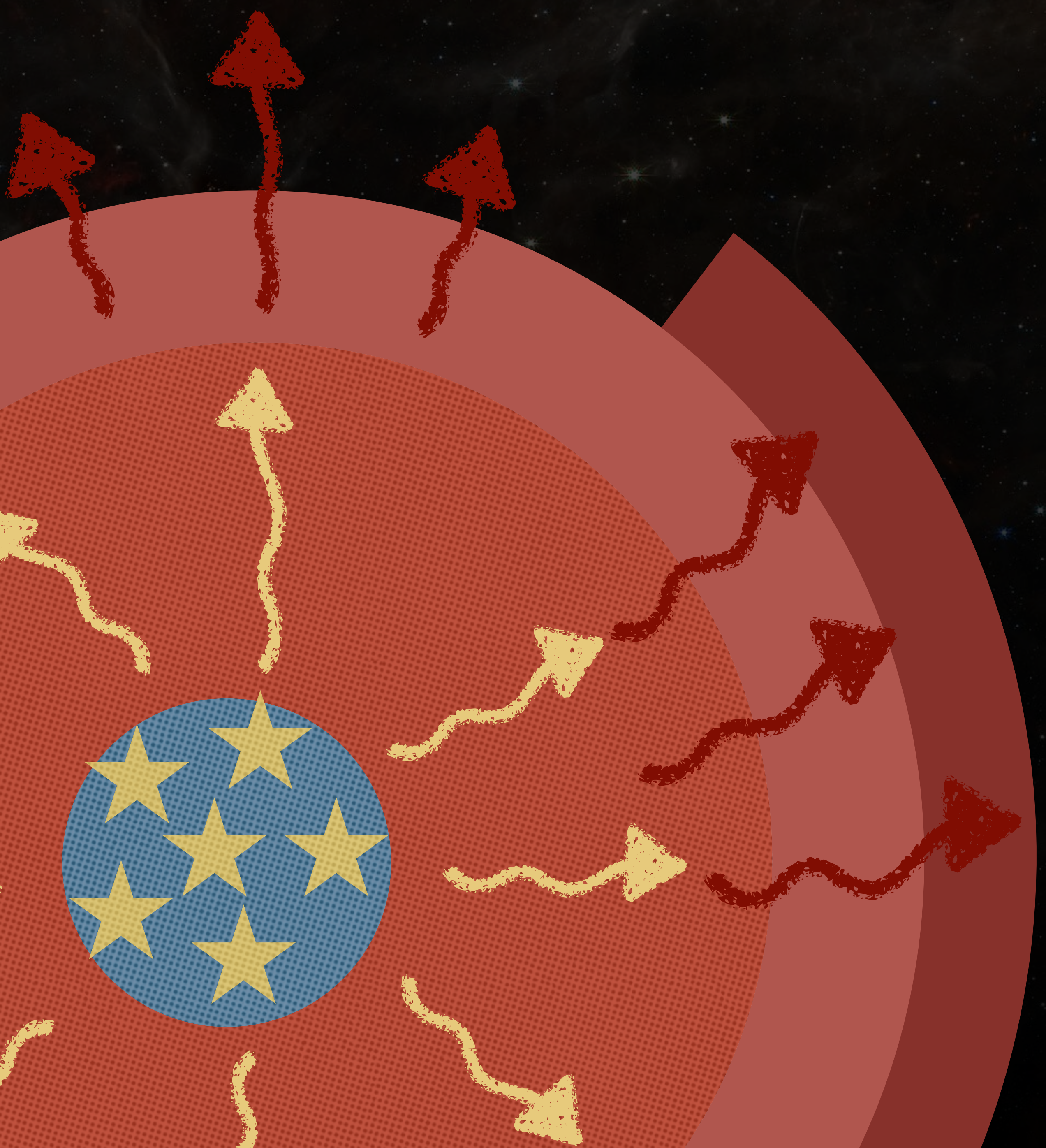
Monsters Under the Magnifying Glass:

Star Formation in Gravitationally Lensed Dusty Starbursts

Frye et al. 2024







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NM Symposium 2024

Prime Extragalactic Areas for Reionization and Lensing Science
PEARLS

PASSAGES
Planck All-Sky Survey to Analyze Gravitationally-Lensed Extreme Starbursts

What factors determine the *maximal* rate of star formation in a galaxy?

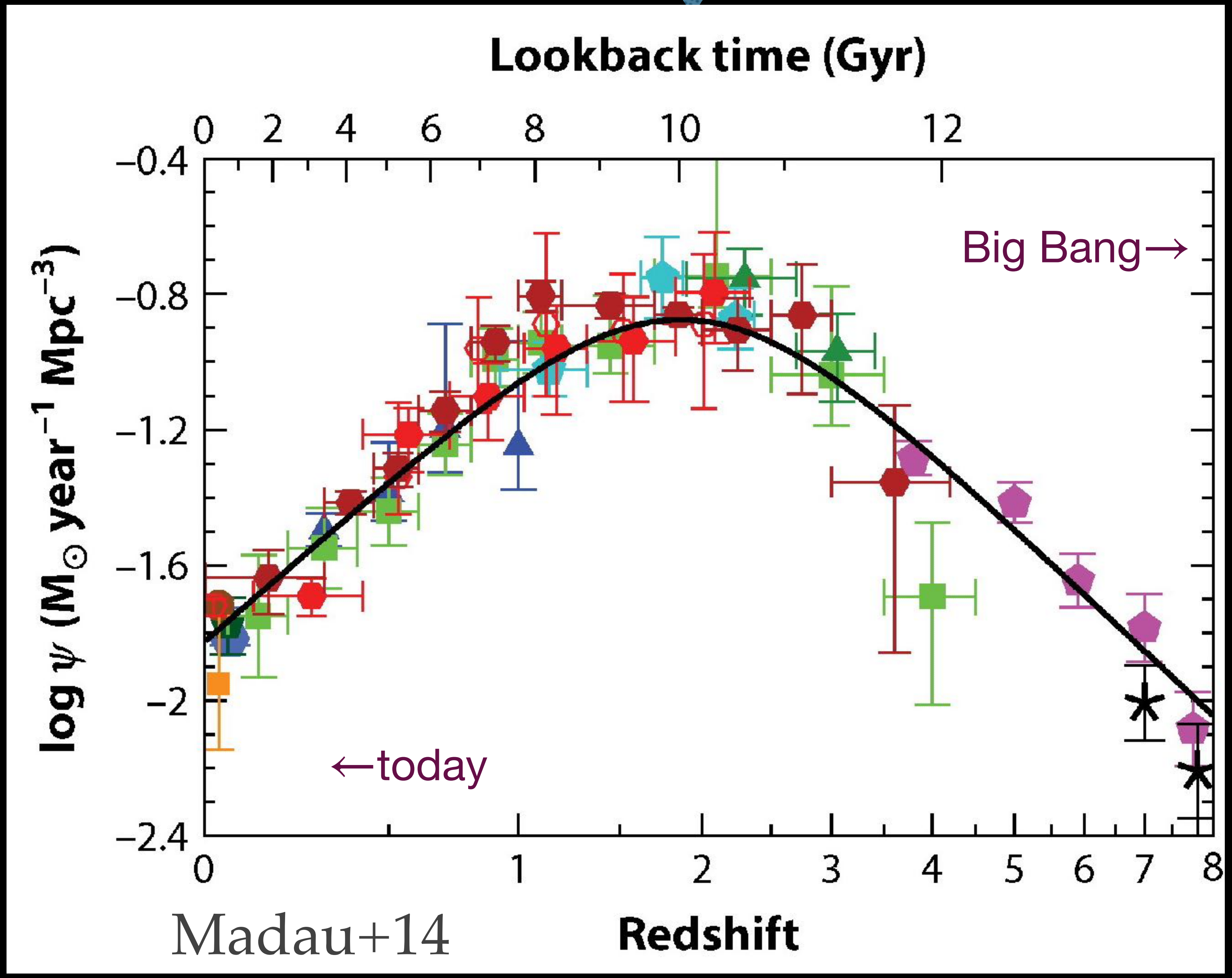
- **Available gas reservoir near to the galaxy ready to form stars**
- **Ability to accrete and replenish this fuel from the surrounding medium**
- **Efficiency in converting gas into stars—and overcome stellar feedback…**

ARTIST'S RENDITION: James Josephides, Swinburne Astronomy Productions

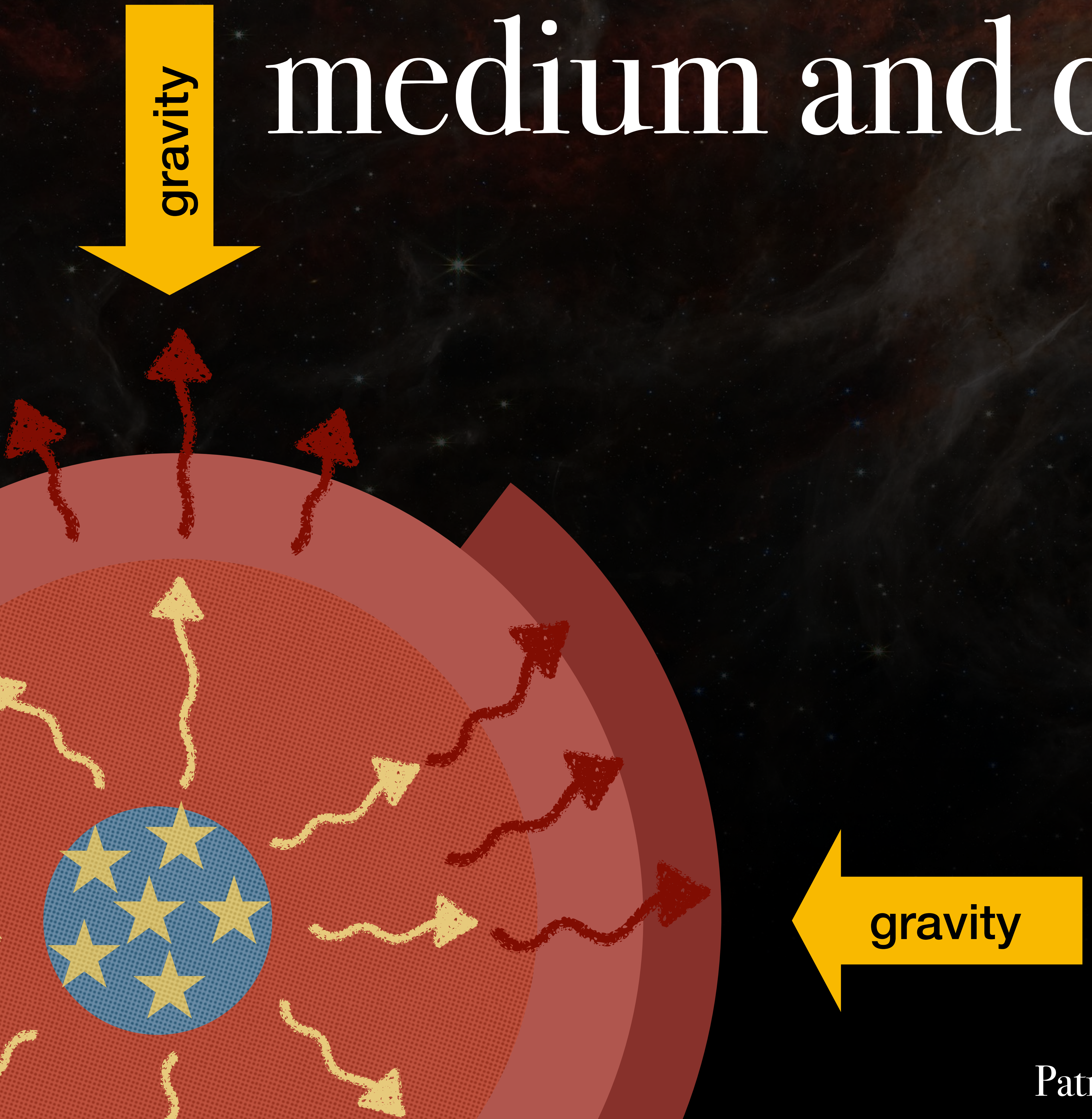
The rate of average star formation of the Universe is on the decline (and has been for 10 billion years).

- Galaxies are star-making factories, but they are not all equally efficient.
- 10 billion years ago, the Universe was at peak productivity– forming stars at 10x the rate of today.
- Part of this is due to galaxies expending their gas supply… but there are other mechanisms at play.

Star formation in the Universe reaches a peak 3 billion years after the Big Bang— **Cosmic Noon**.



Stellar feedback: the formation of massive stars in a galaxy can deposit energy/momentum into the surround interstellar medium and disrupt future star formation.



The fraction of obscured star formation correlates with SFR, so starbursts are also typically very dusty, providing the ingredients for *radiation pressure* to contribute significantly and overcome gravity.

SFR = star formation rate

Stellar feedback: the formation of massive stars in a galaxy can deposit energy/momentum into the surround interstellar medium and disrupt future star formation.

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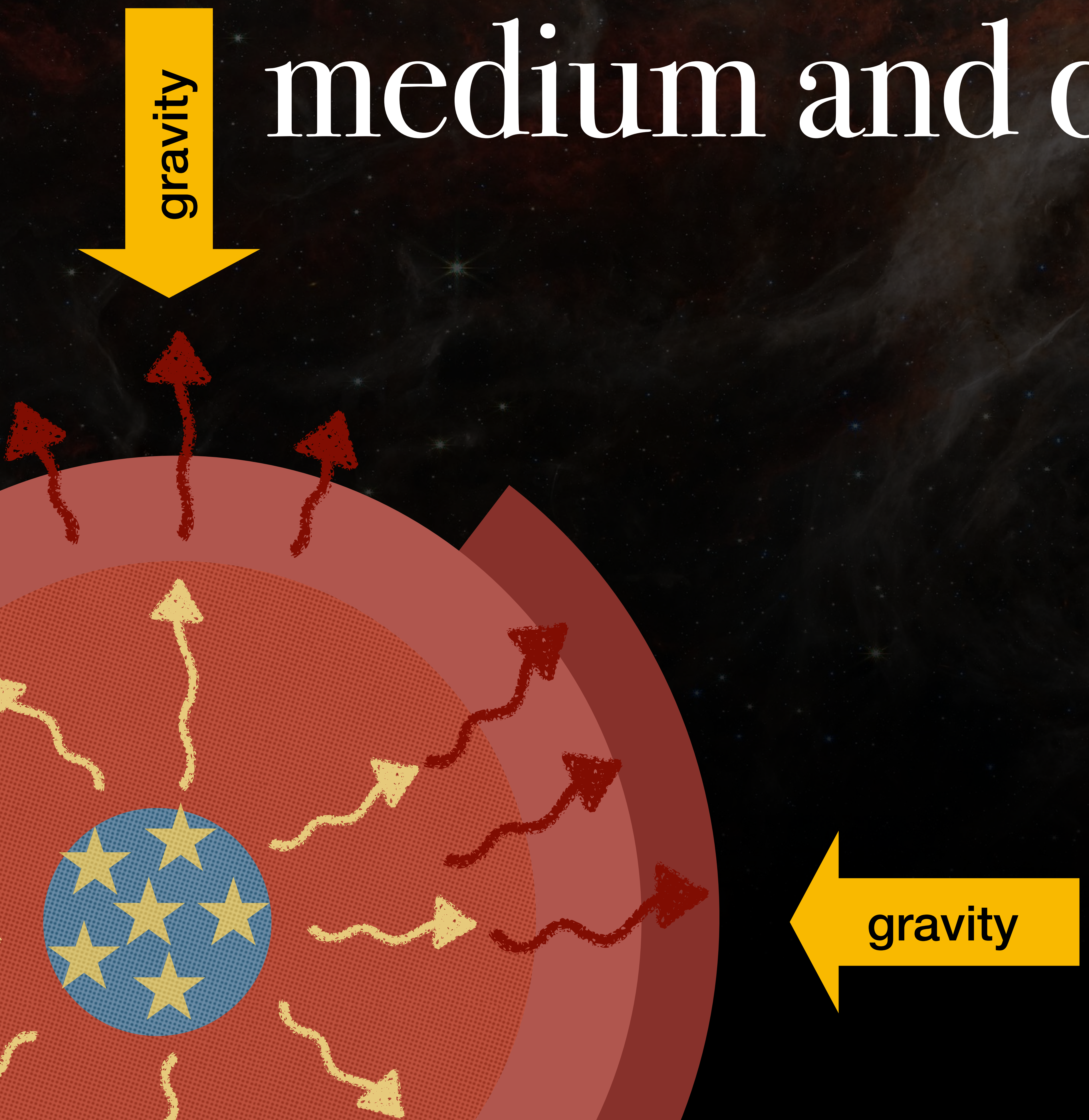
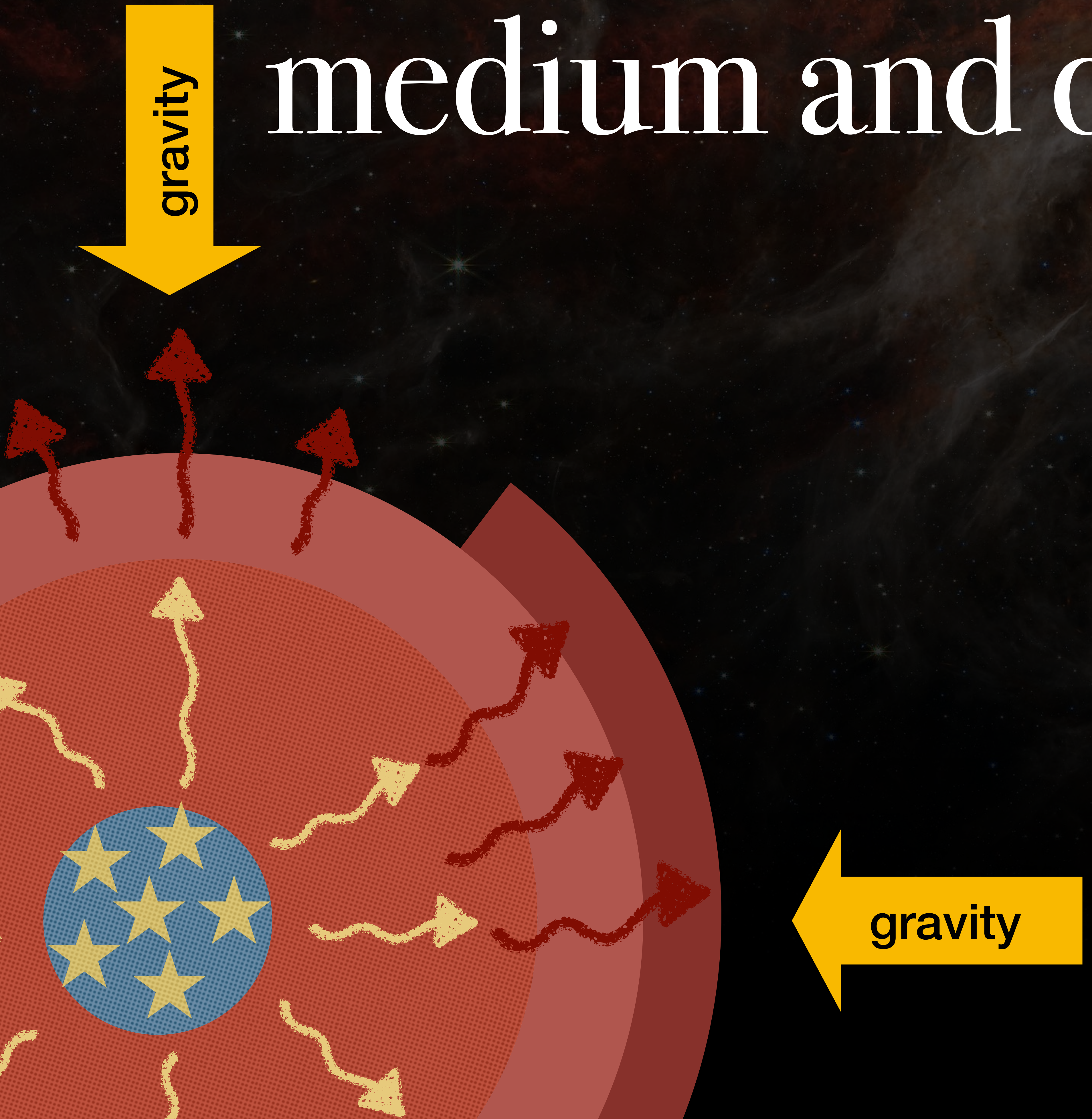


→ Most applicable when galaxy is optically thick to even re-radiated far-infrared photons

→ All momentum of photons from star formation gets transferred to the ISM!

e.g. Scoville+01, Thompson+05, Andrews+11

Stellar feedback: the formation of massive stars in a galaxy can deposit energy/ momentum into the surround interstellar medium and disrupt future star formation.



These processes predominate at spatial scales of Giant Molecular Clouds and smaller, ~10-100 pc in size.

How can we have any hope of resolving them at $z \gtrsim 1$ without just waiting for the ngVLA??

Strong gravitational lensing is key to both *finding* and *investigating* the most extreme starburst events in the Universe— and in turn, the role of stellar feedback.

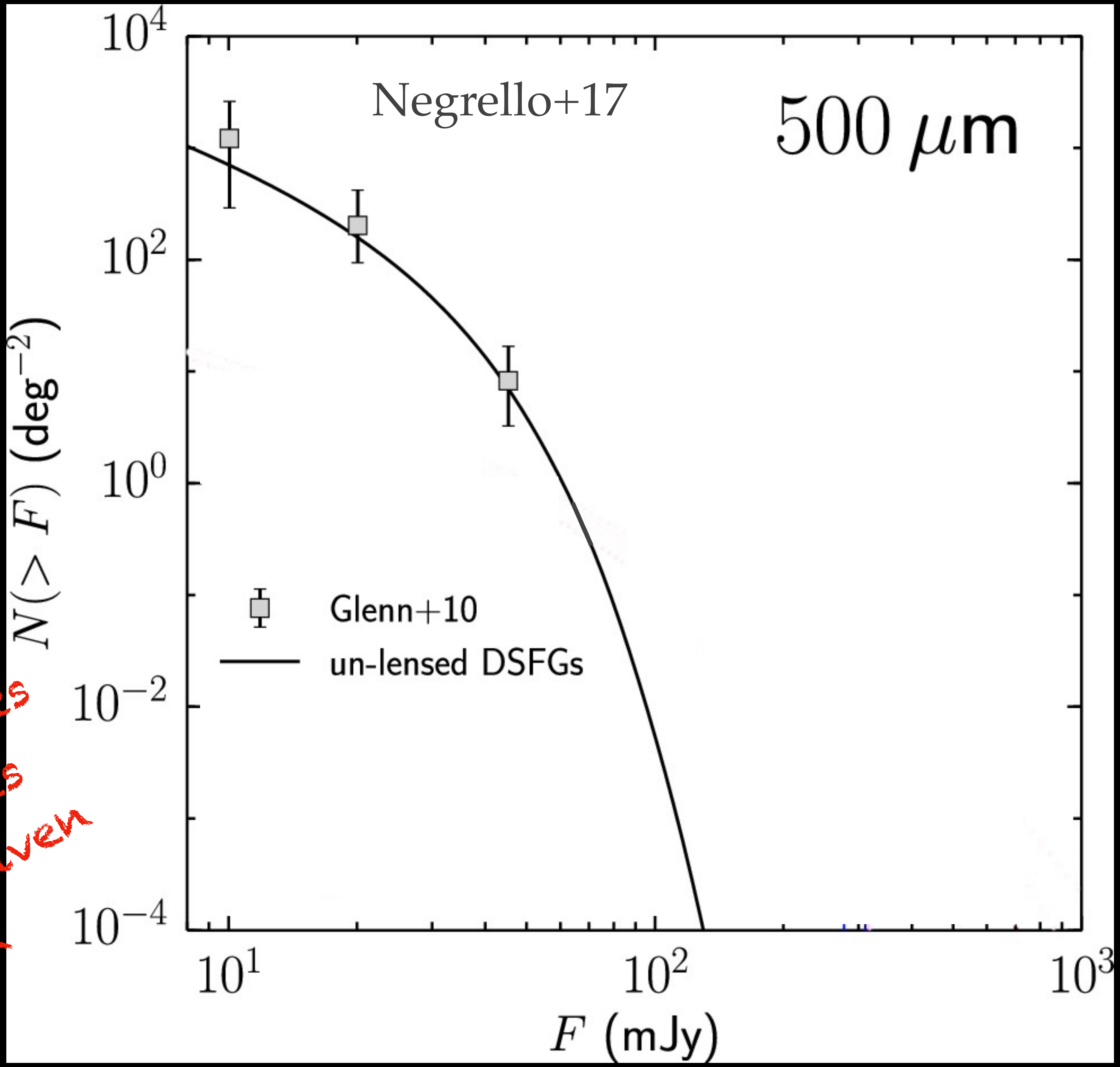
Image: ALMA / NRAO / ESO / NAOJ / B. Saxton / AUI / NSF / NASA / ESA / Hubble / T. Hunter

Identifying lensed, submm-bright objects is efficient

Why submillimeter?

- Intrinsic sub-mm number counts are very steep at the bright end
- Few low-z interlopers at $\lambda > 500\mu m$

number counts of galaxies above a given flux

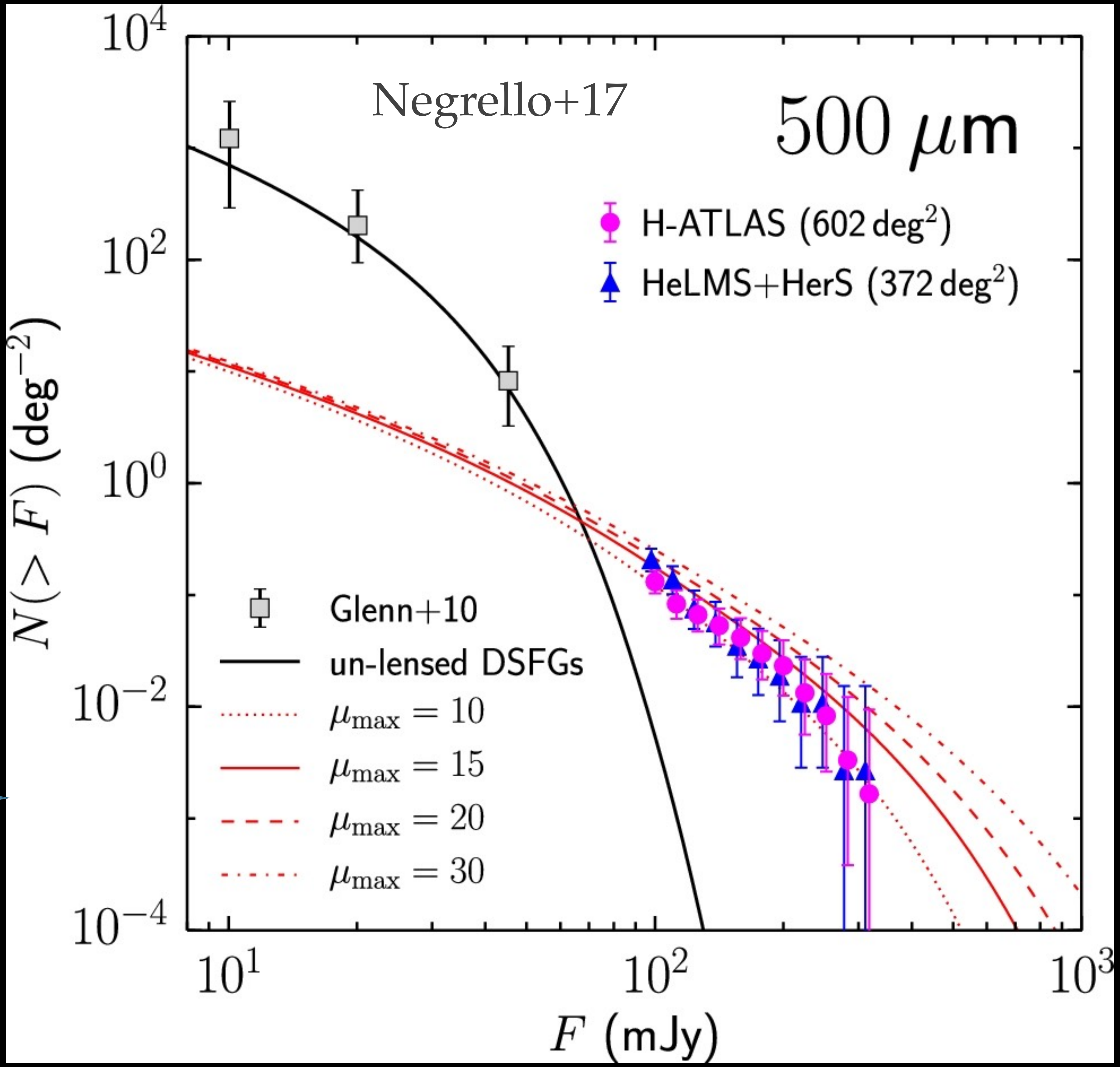


Identifying lensed, submm-bright objects is efficient

Why submillimeter?

- Intrinsic sub-mm number counts are very steep at the bright end
- Few low-z interlopers at $\lambda > 500\mu m$

Gravitational lensing shifts objects to larger apparent fluxes—beyond S_{500} = 0.1 Jy, it's >10x more likely that objects are lensed.



Identifying a large sample of hyperluminous infrared galaxies at Cosmic Noon

aka "HyLIRGs"
$L_{\mathrm{IR}} > 10^{13}\ L_{\odot}$

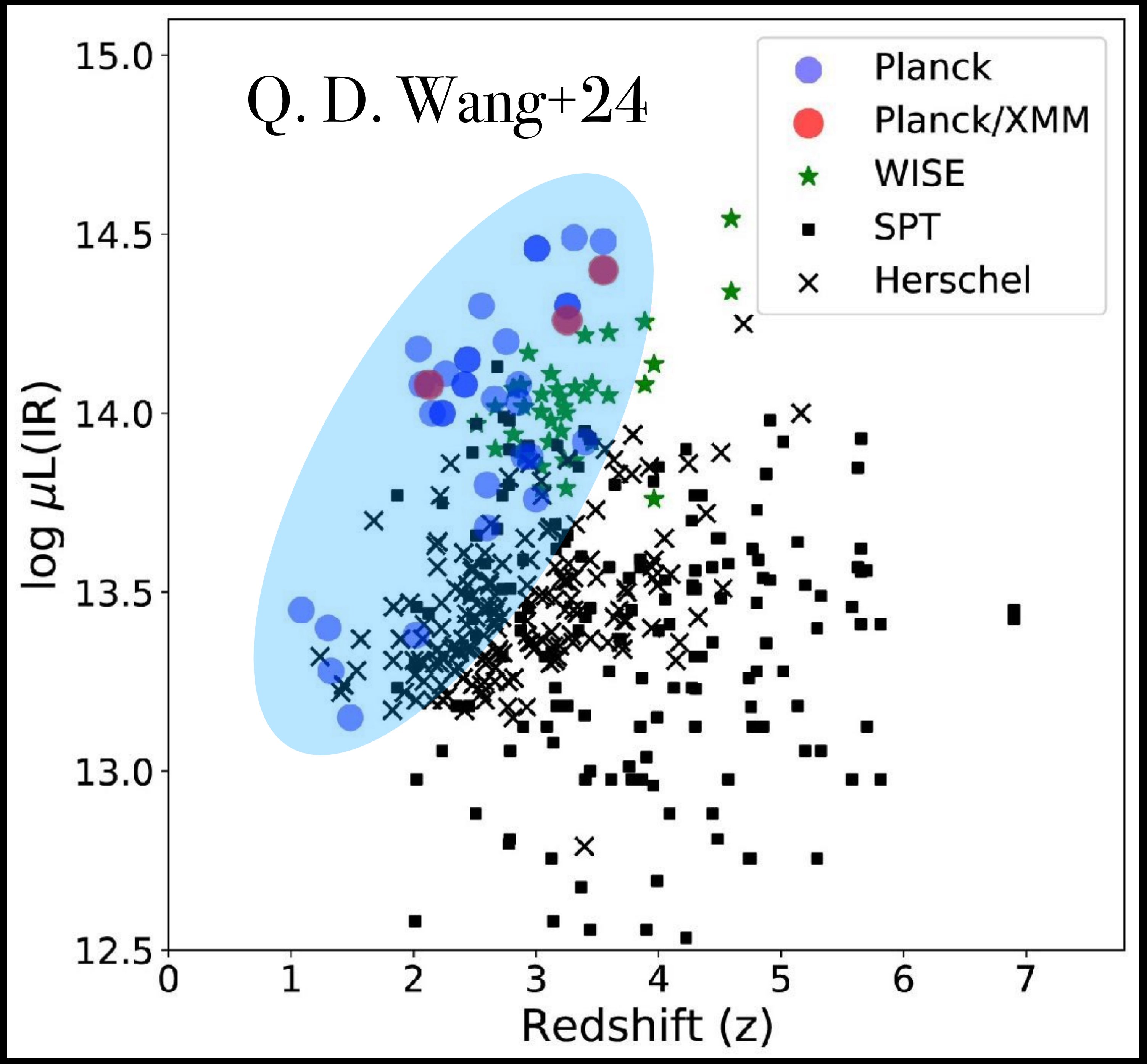
- **Selecting the brightest objects in the submillimeter is efficient at identifying gravitationally-lensed dusty star forming galaxies** (DSFGs)
- **PASSAGES:** *Planck* All-Sky Survey to Analyze Gravitationally Lensed Extreme Starbursts– approx. 30 lensed DSFGs at $z \sim 1 - 3.5$

see also e.g. Harrington+16, +21; Berman+22; Kamieneski+24a; independent work by Cañameras+15; Frye+19

Why lensed galaxies?

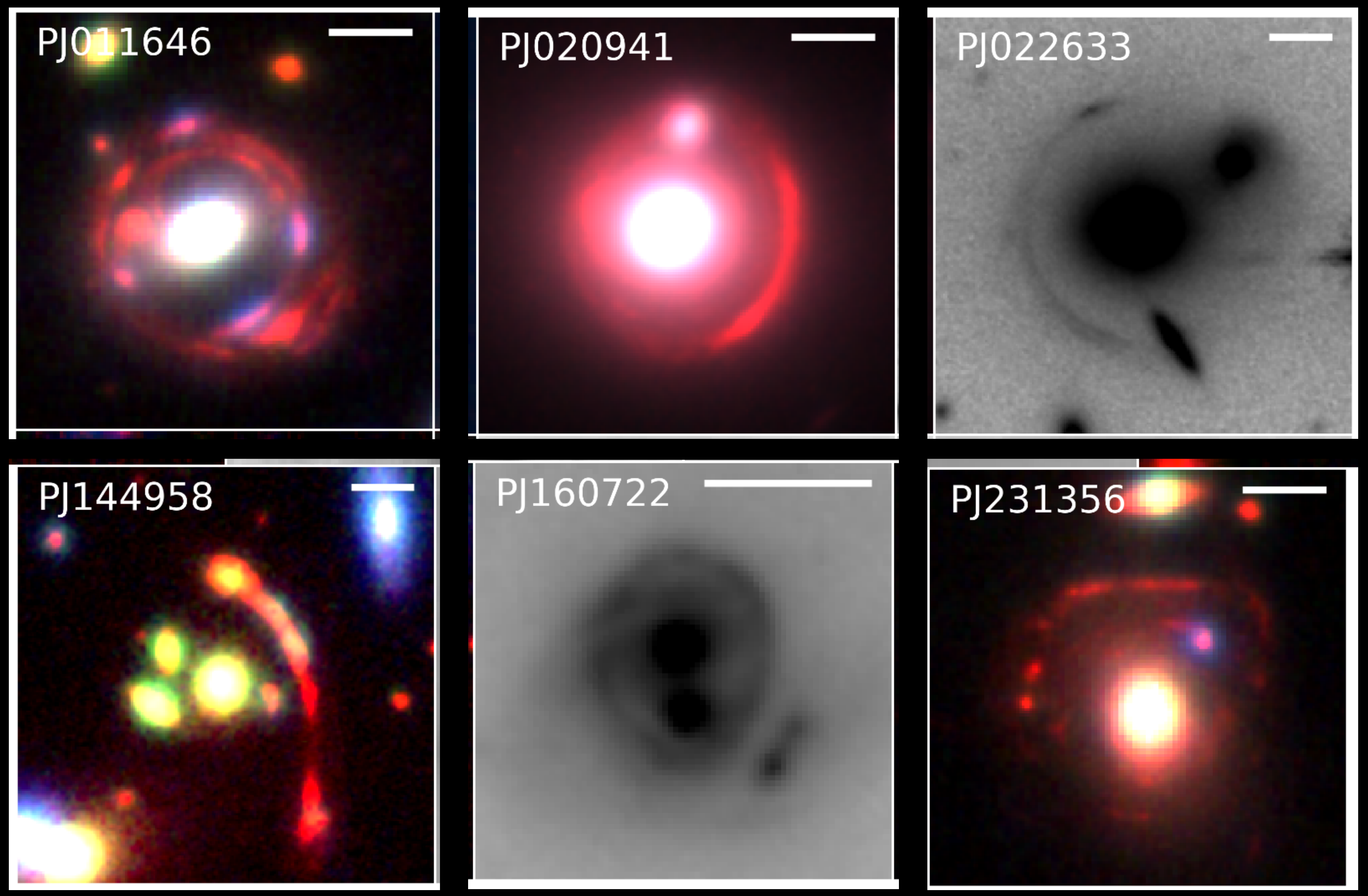
- Efficient selection method
- Magnification size bias means magnification is typically only $\lesssim 10 - 20$
  - So the *brightest* are also among the *most intrinsically luminous*
- **"Cosmic telescope" to reach crucial sub-kpc scales of stellar mass assembly at $z > 1$**

PASSAGES
PLANCK ALL-SKY SURVEY TO ANALYZE GRAVITATIONALLY-LENSED EXTREME STARBURSTS



Diverse sample of (mostly galaxy/group-scale) lenses

SFR $\sim 100 - 3000\ M_\odot\ \mathrm{yr}^{-1}$



Kamieneski+24a

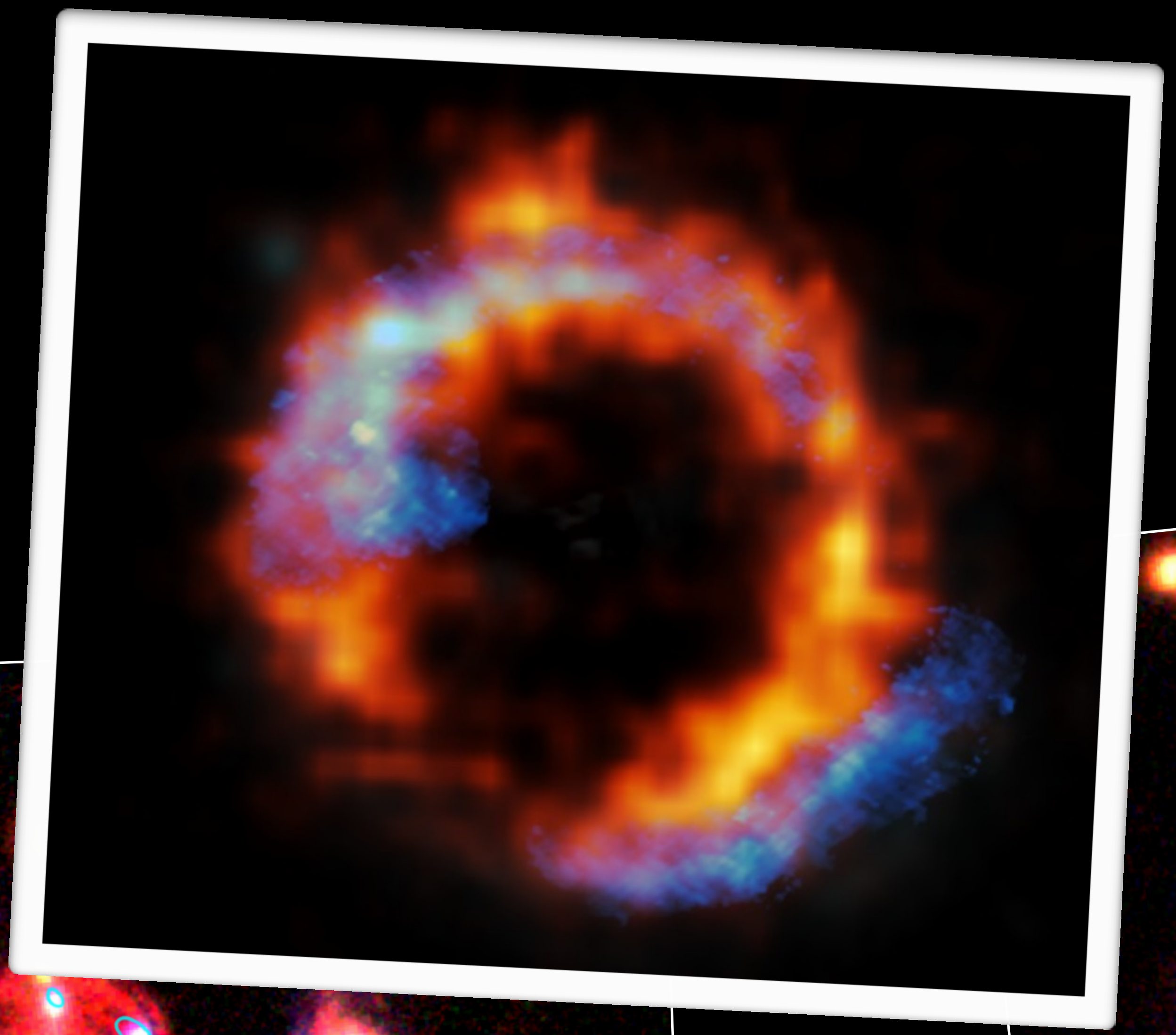
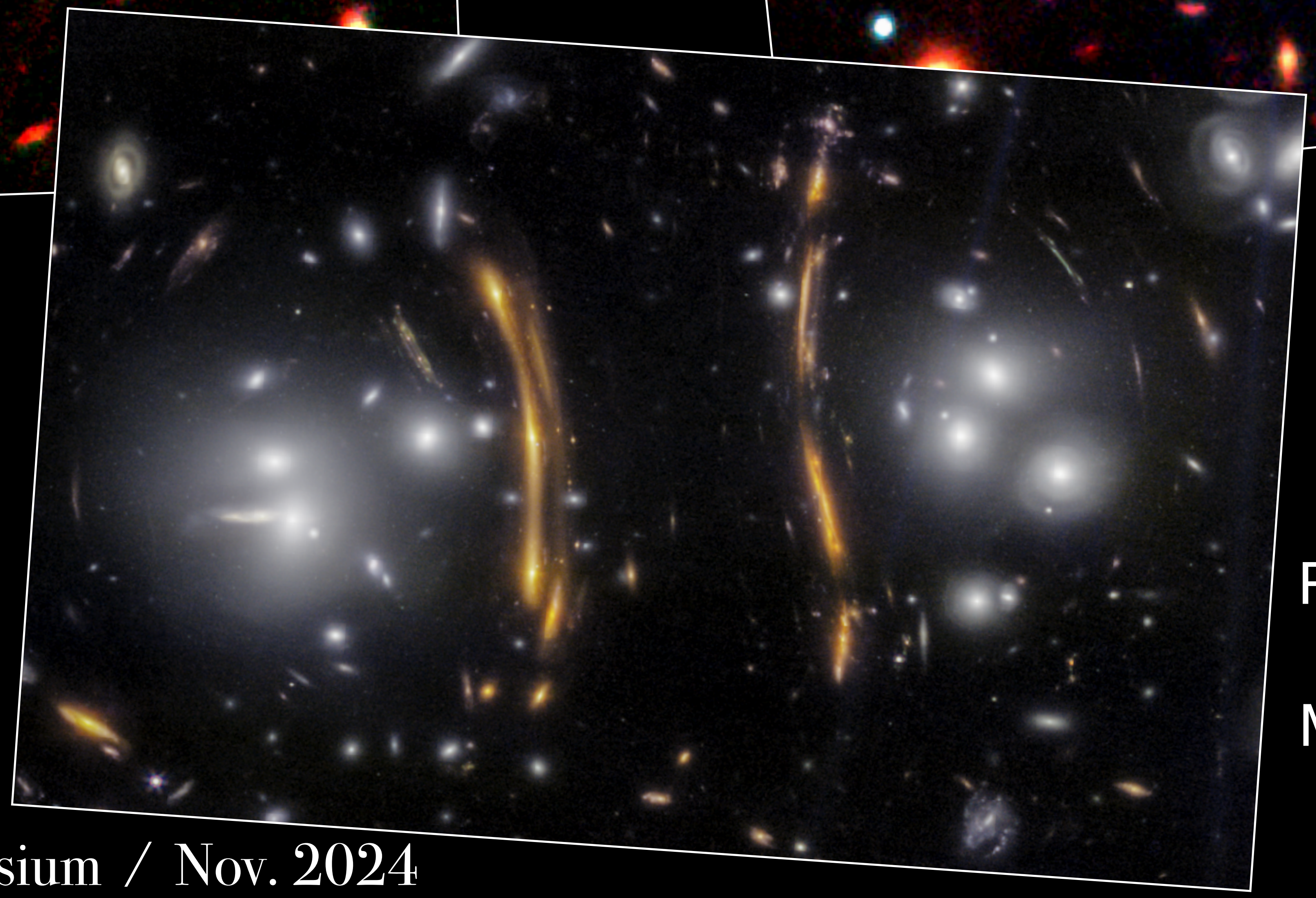


Image credit: ALMA (ESO/NAOJ/NRAO)/ESO

D. Liu+24

N. Foo+ in prep.

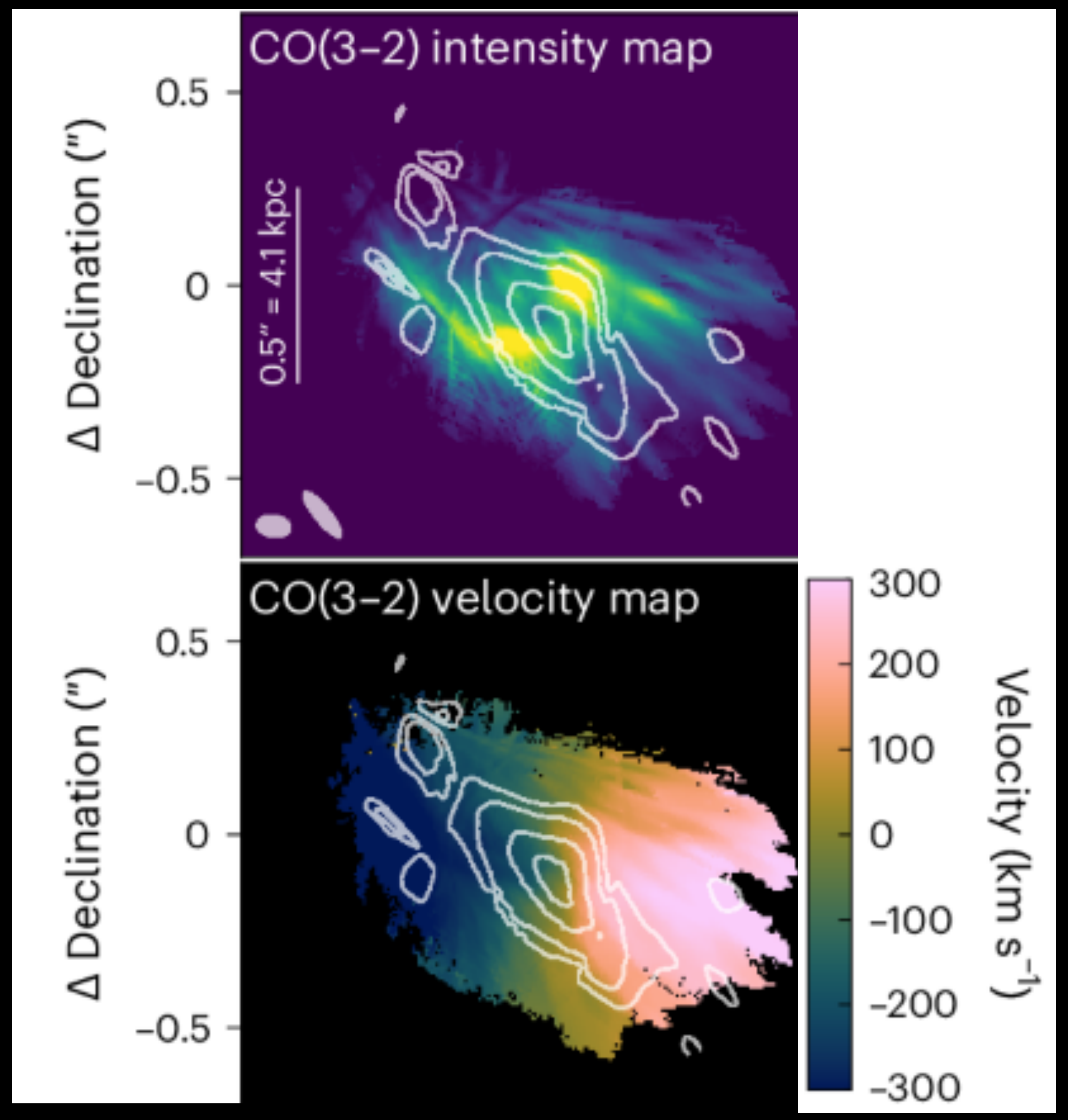


G165
R. Cañameras+18
B. Frye+19,24
M. Pascale+22,24
Kamieneski+24b

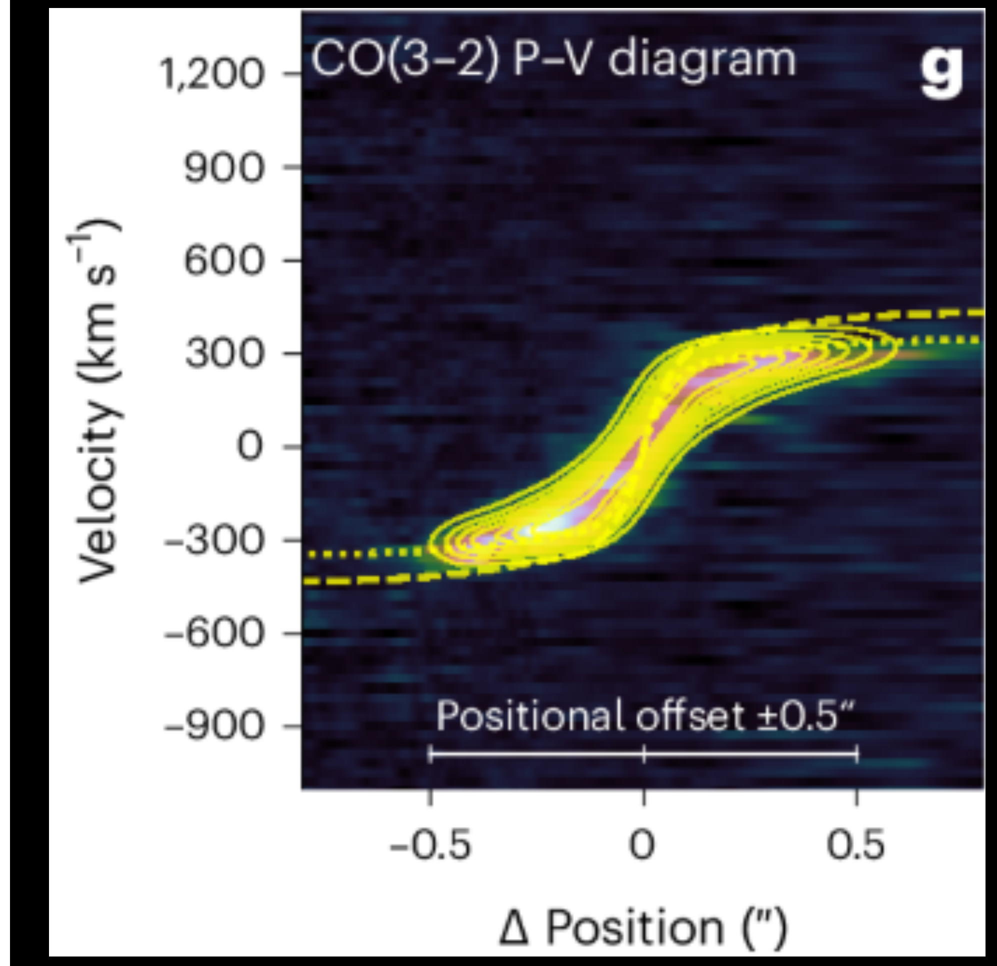
Diverse sample of (mostly galaxy/group-scale) lenses

SFR $\sim 100 - 3000\ M_\odot\ \mathrm{yr}^{-1}$

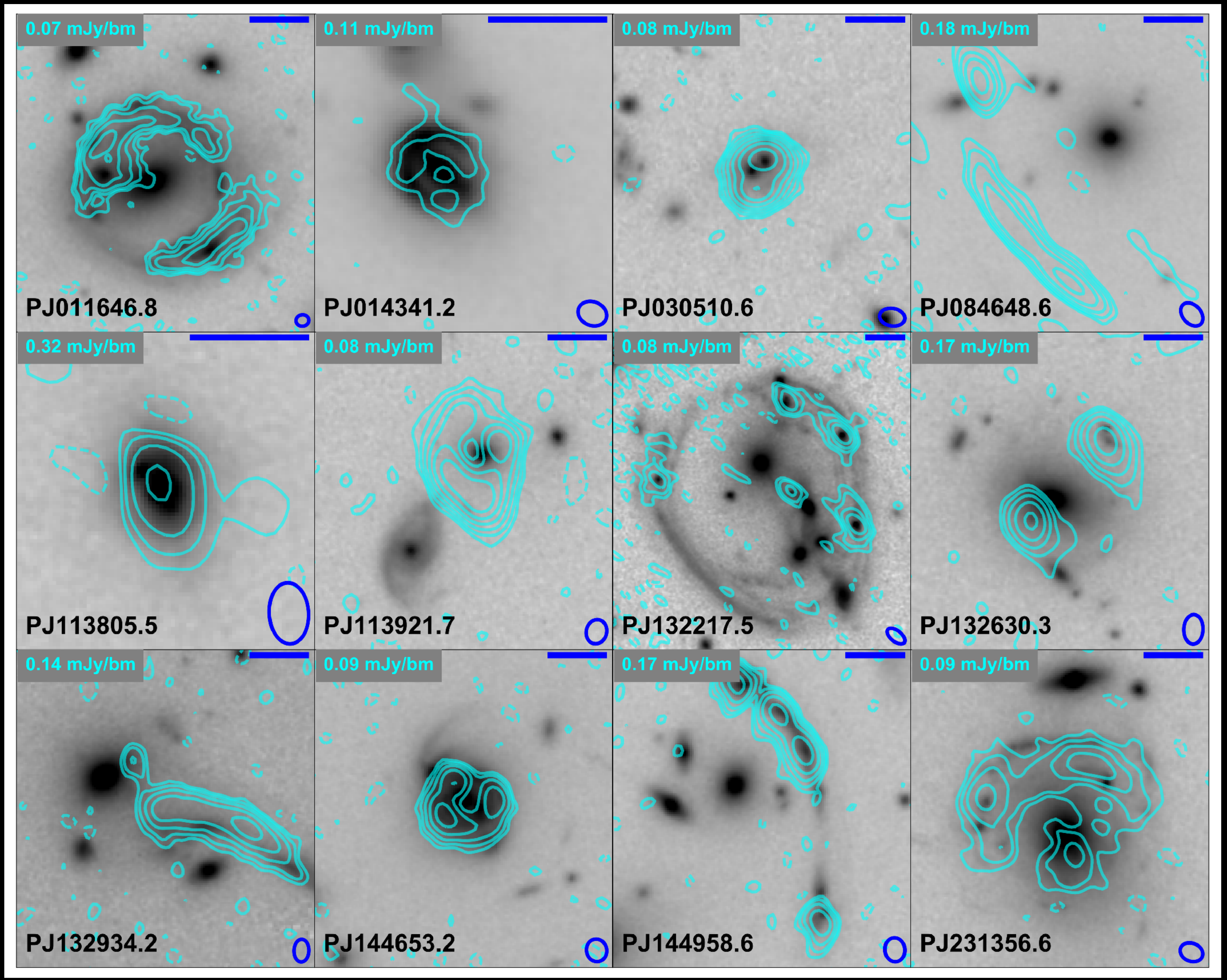
- Incredibly gas-rich: $\sim 10^{12}\ M_\odot$ molecular gas mass (Harrington+21)
- Ongoing work: kinematic modeling to determine degree of rotational support



D. Liu+24, NatAs



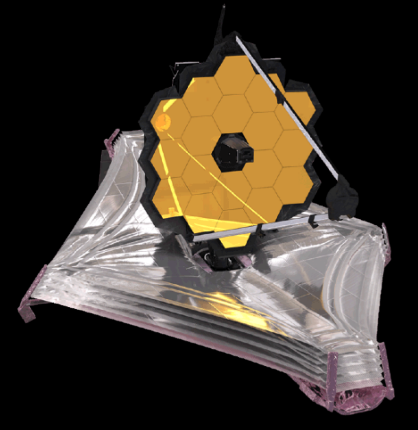
Molecular gas reveals where stars are actively forming



Berman+22 (also Harrington+16)

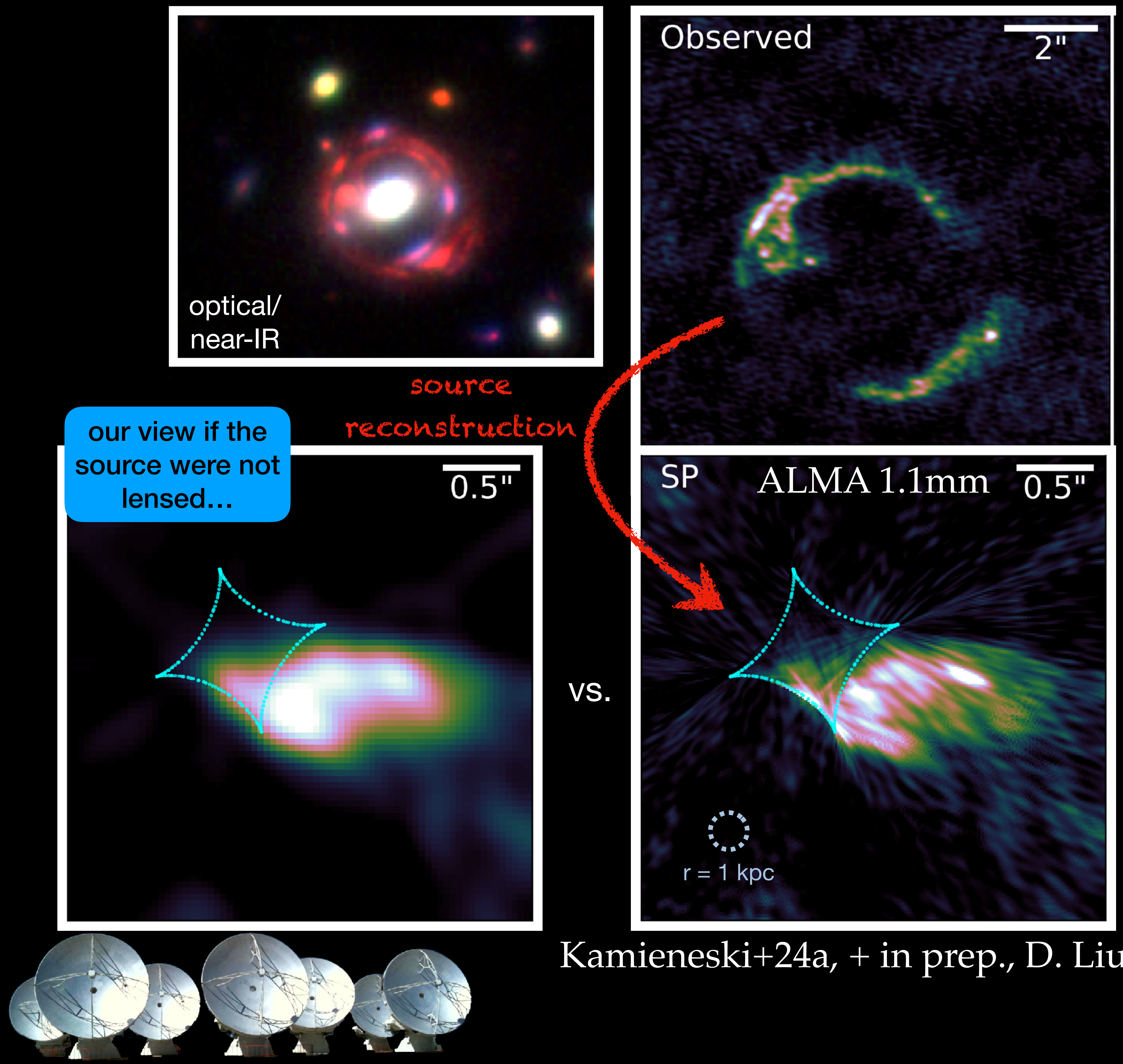
Some of these *monster galaxies* are forming stars at rates up to 1000+ times that of our Milky Way…

…an average of 1 Sun-like star every 9 hours!



ESA/Webb, NASA & CSA, L. Armus & A. Evans, R. Colombari

By modeling the foreground mass distribution, we can *de-lens* what we observe and recover each galaxy's intrinsic structure.



Kamieneski+24a, + in prep., D. Liu+24

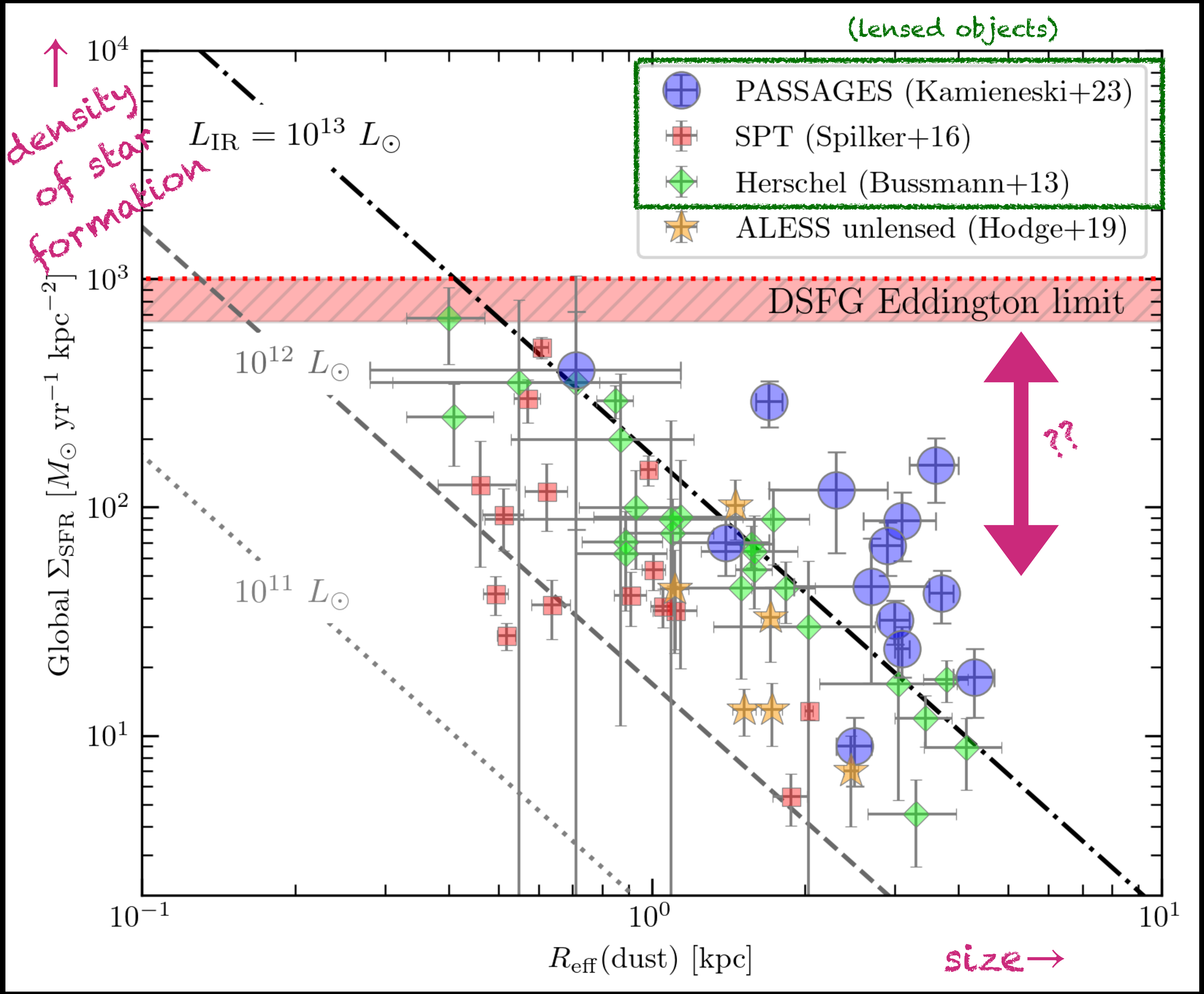
HyLIRGs are not forming stars at the Eddington limit— in fact they are 10x lower

… globally, at least.

Two main possibilities:

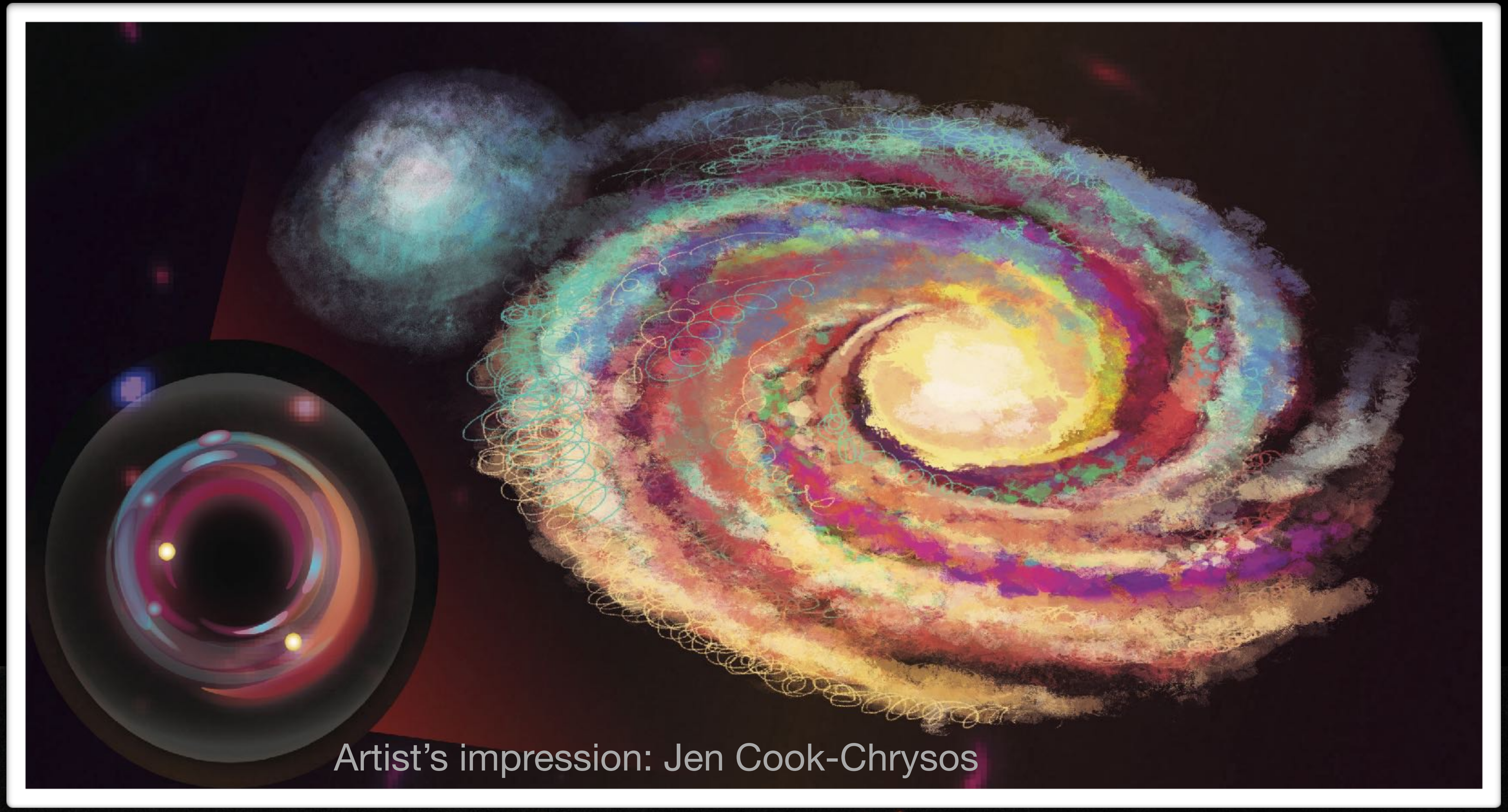
- Other feedback mechanisms are dominant in regulating these dusty starbursts instead of radiation pressure
  - Do they need to wait for supernovae?? e.g. C. G. Kim+20; Harrington+21; Reichardt Chu+24
- Star formation is **clumpy** and **widespread**, and closer to Eddington-limited in isolated unresolved regions

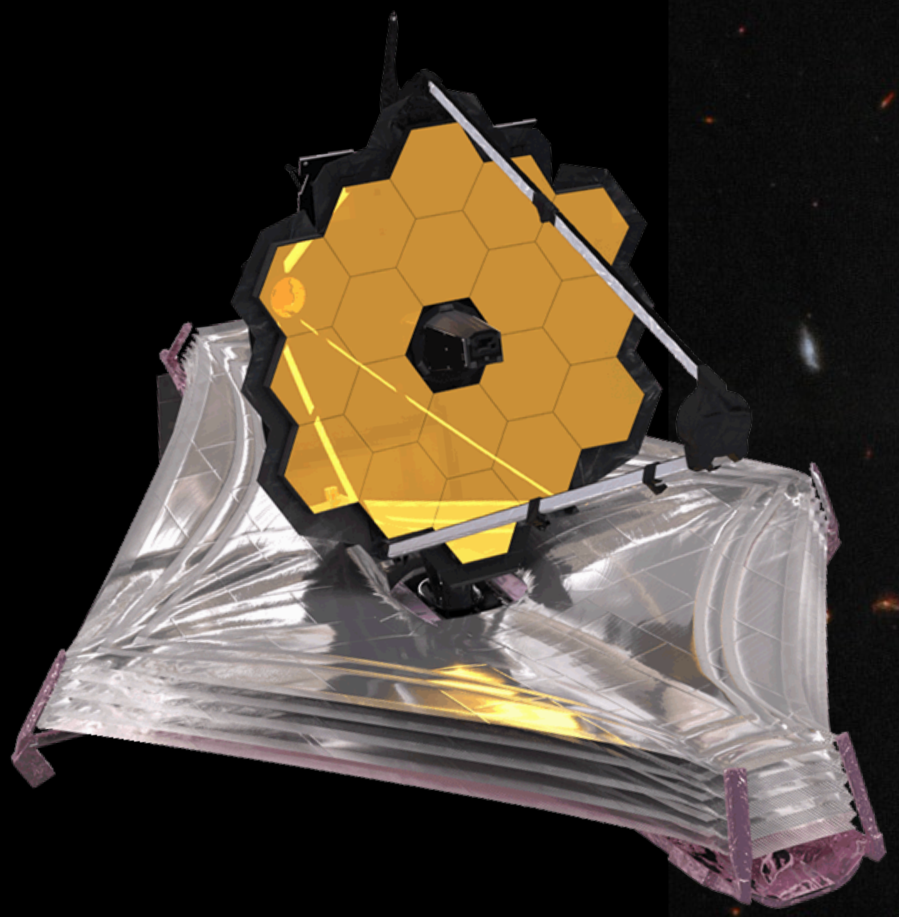
Kamieneski 2024 (IAUS 381)



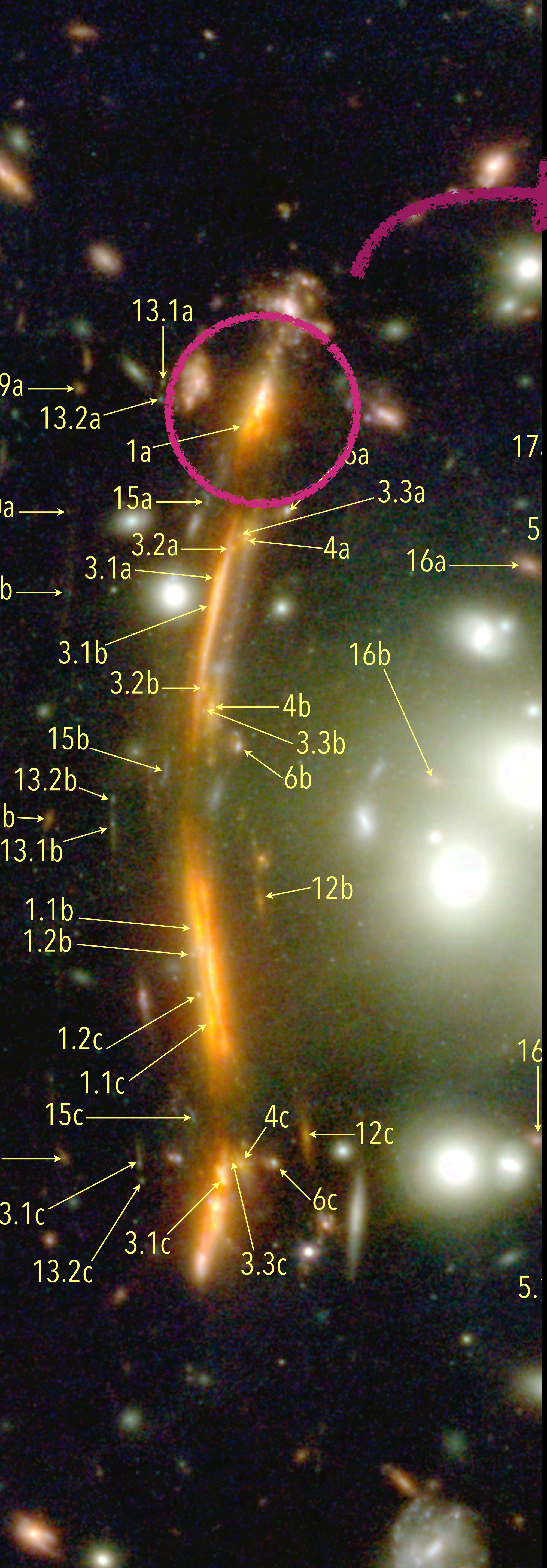
see also e.g. Kamieneski+24a, Hodge+19, Bakx+24e

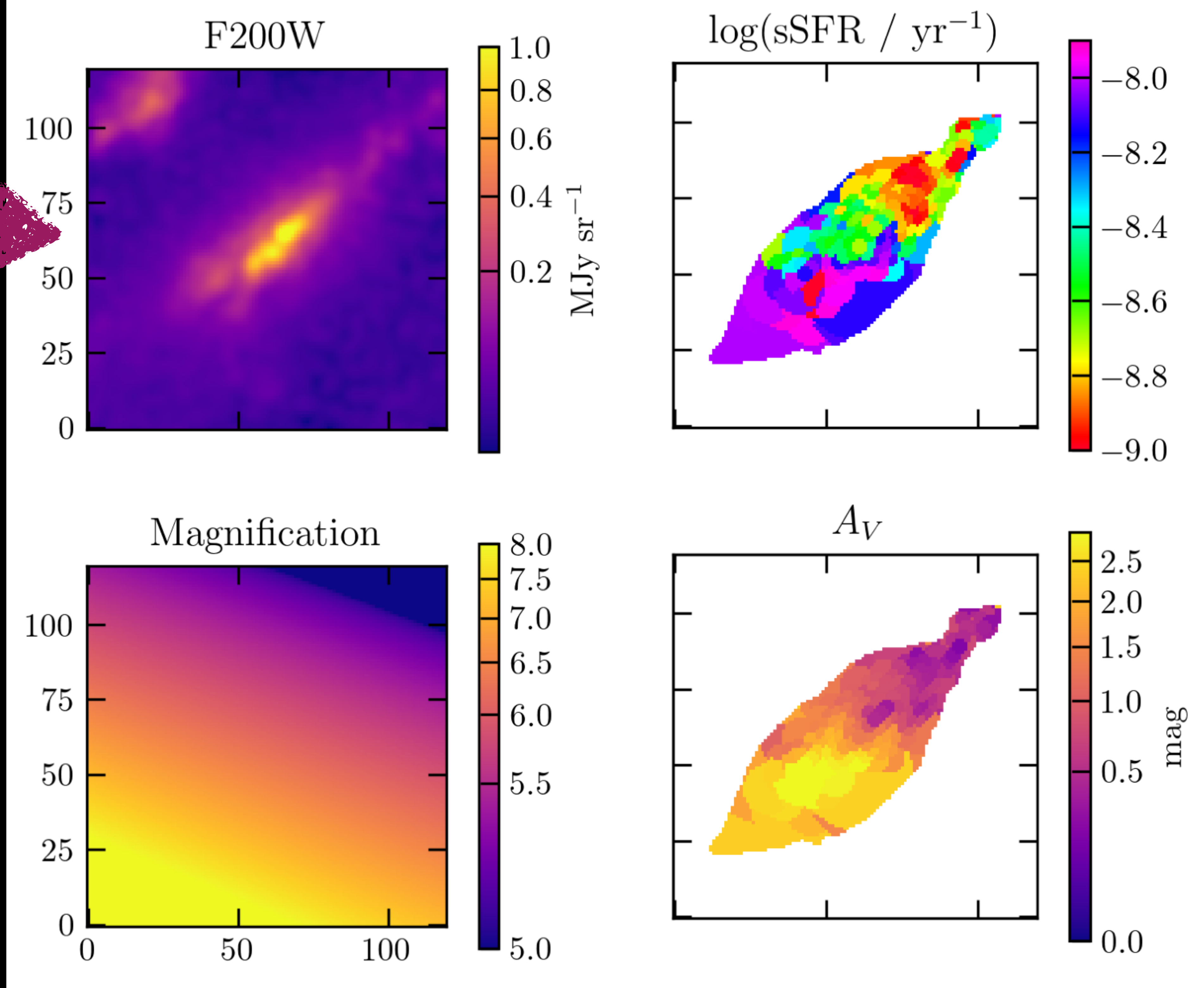
JWST is now revealing the *stellar mass skeleton* underpinning dusty star-forming galaxies— giving a sense of how widespread their starburst regions actually are.





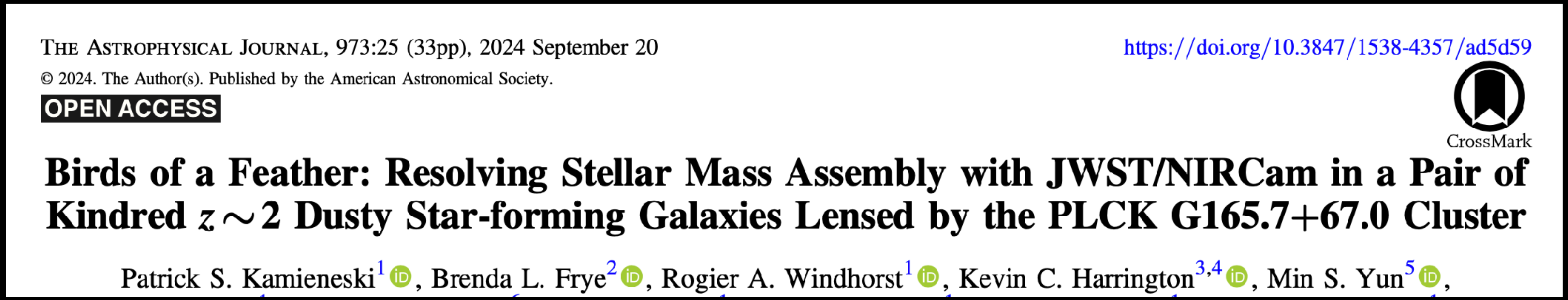
ESA/Webb, NASA & CSA, L. Armus & A. Evans





Example: a pair of interacting DSFGs lensed by the G165 galaxy cluster

Kamieneski+24b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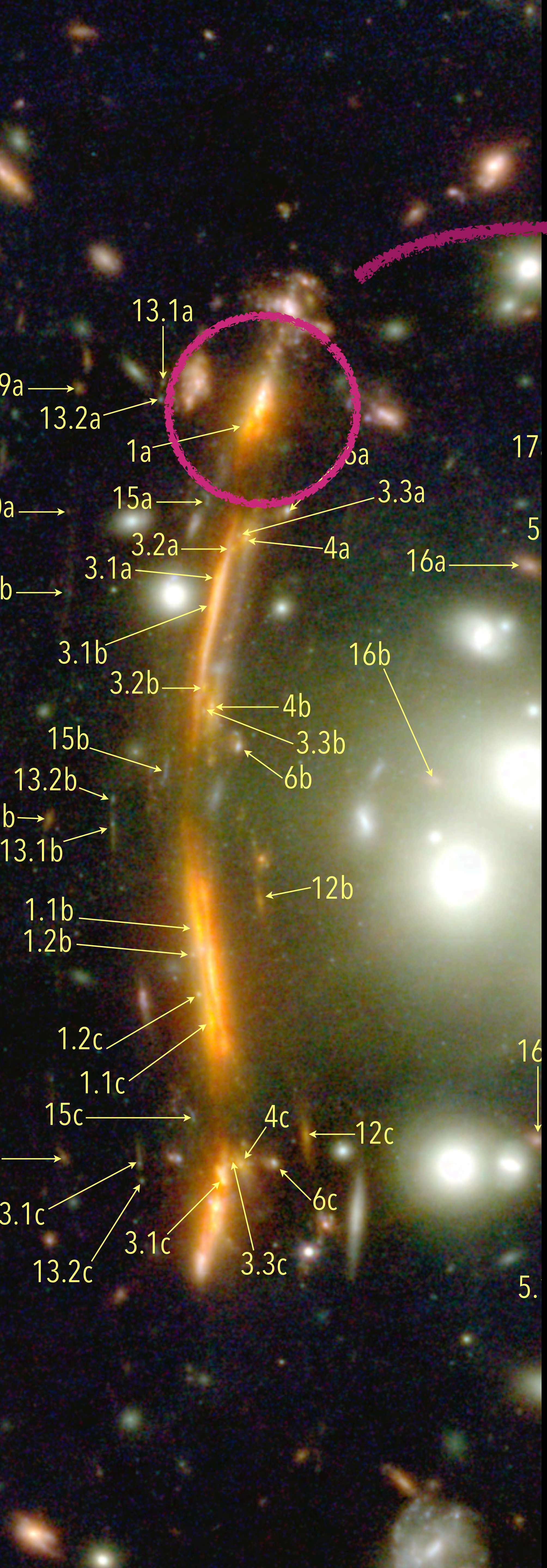
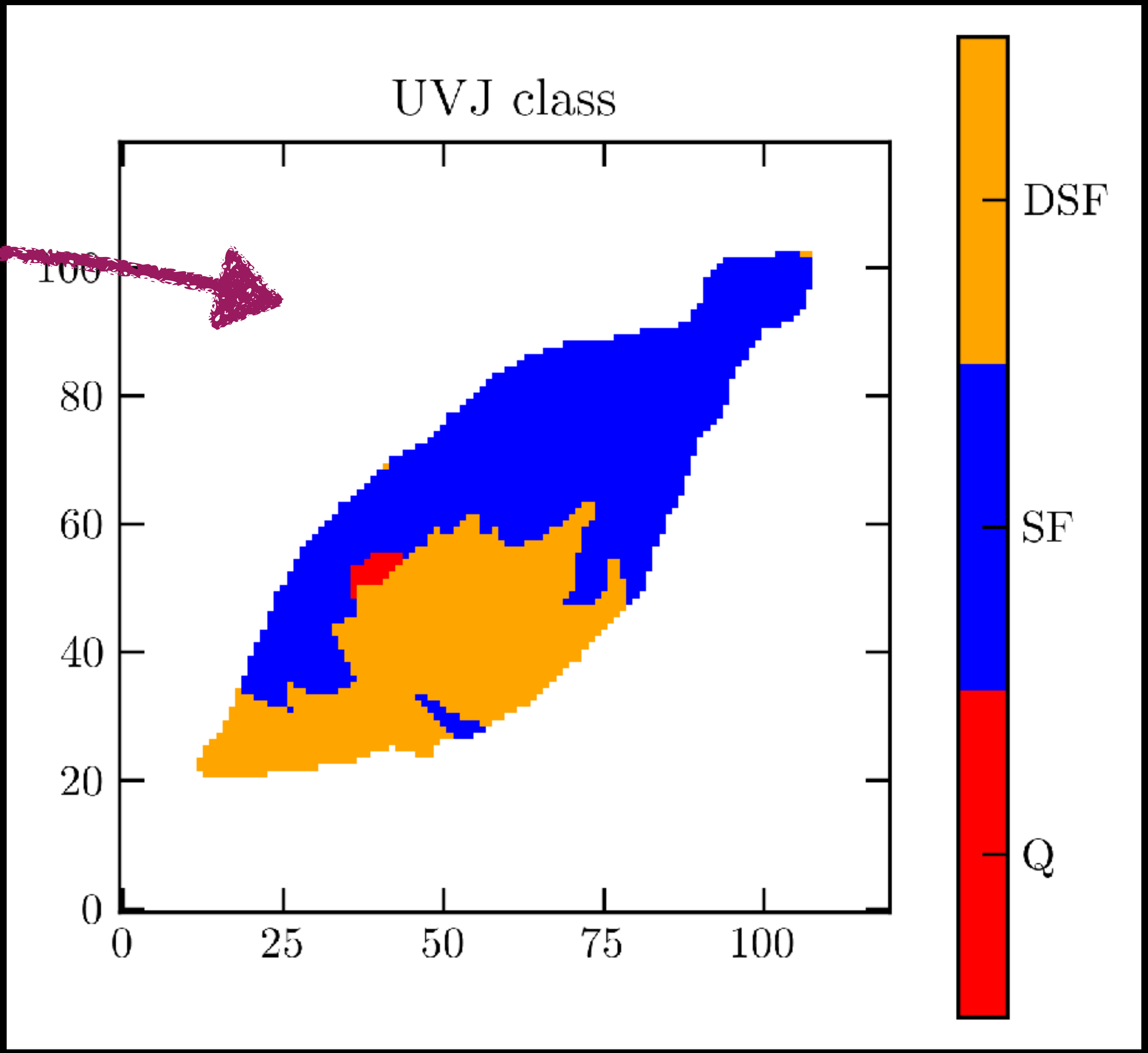
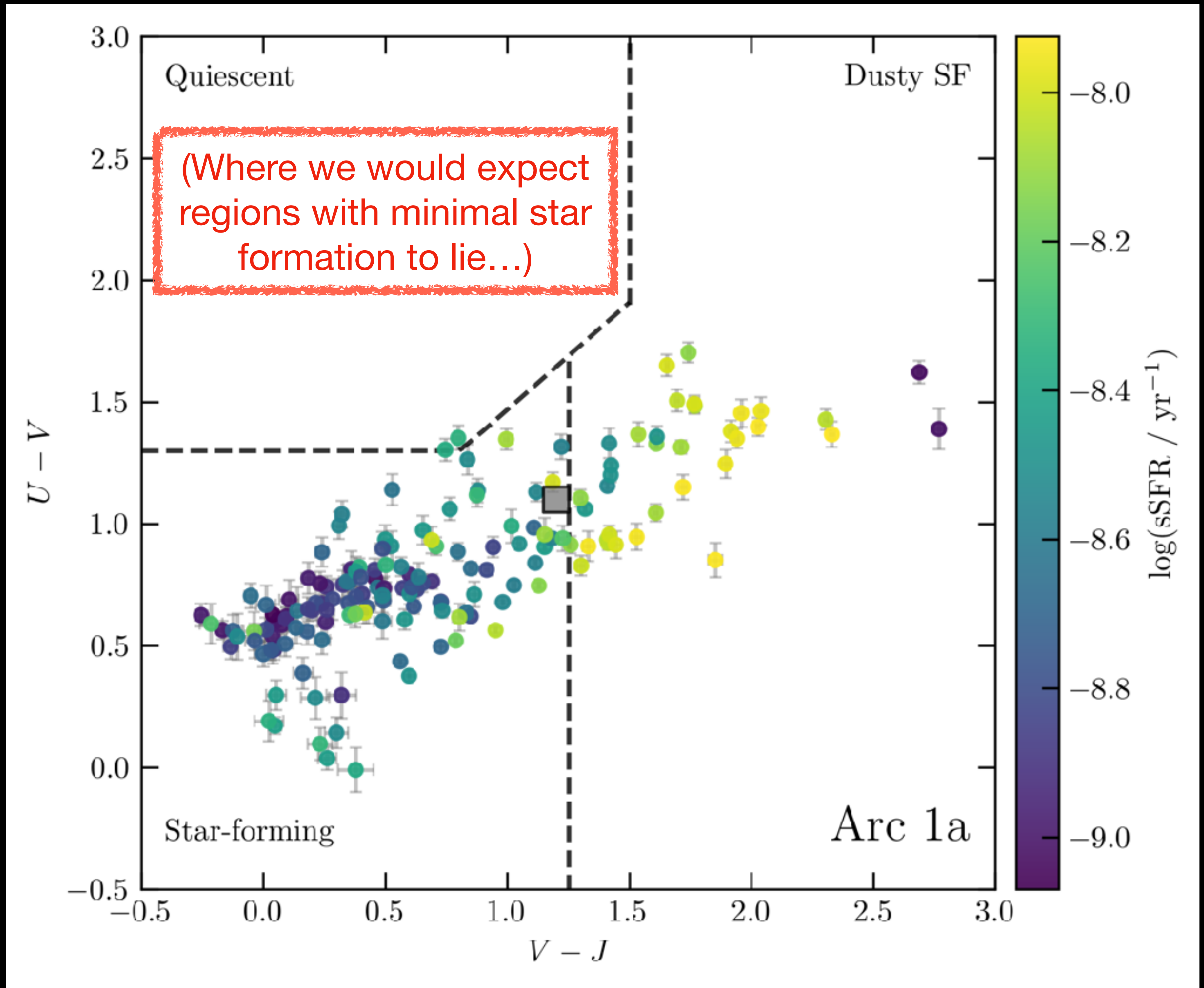
Birds of a Feather: Resolving Stellar Mass Assembly with JWST/NIRCam in a Pair of Kindred $z\sim2$ Dusty Star-forming Galaxies Lensed by the PLCK G165.7+67.0 Cluster

Patrick S. Kamieneski[1], Brenda L. Frye[2], Rogier A. Windhorst[1], Kevin C. Harrington[3,4], Min S. Yun[5],

Pixel-by-pixel SED fitting of rest-frame UV-NIR with JWST reveals very widespread starbursting conditions







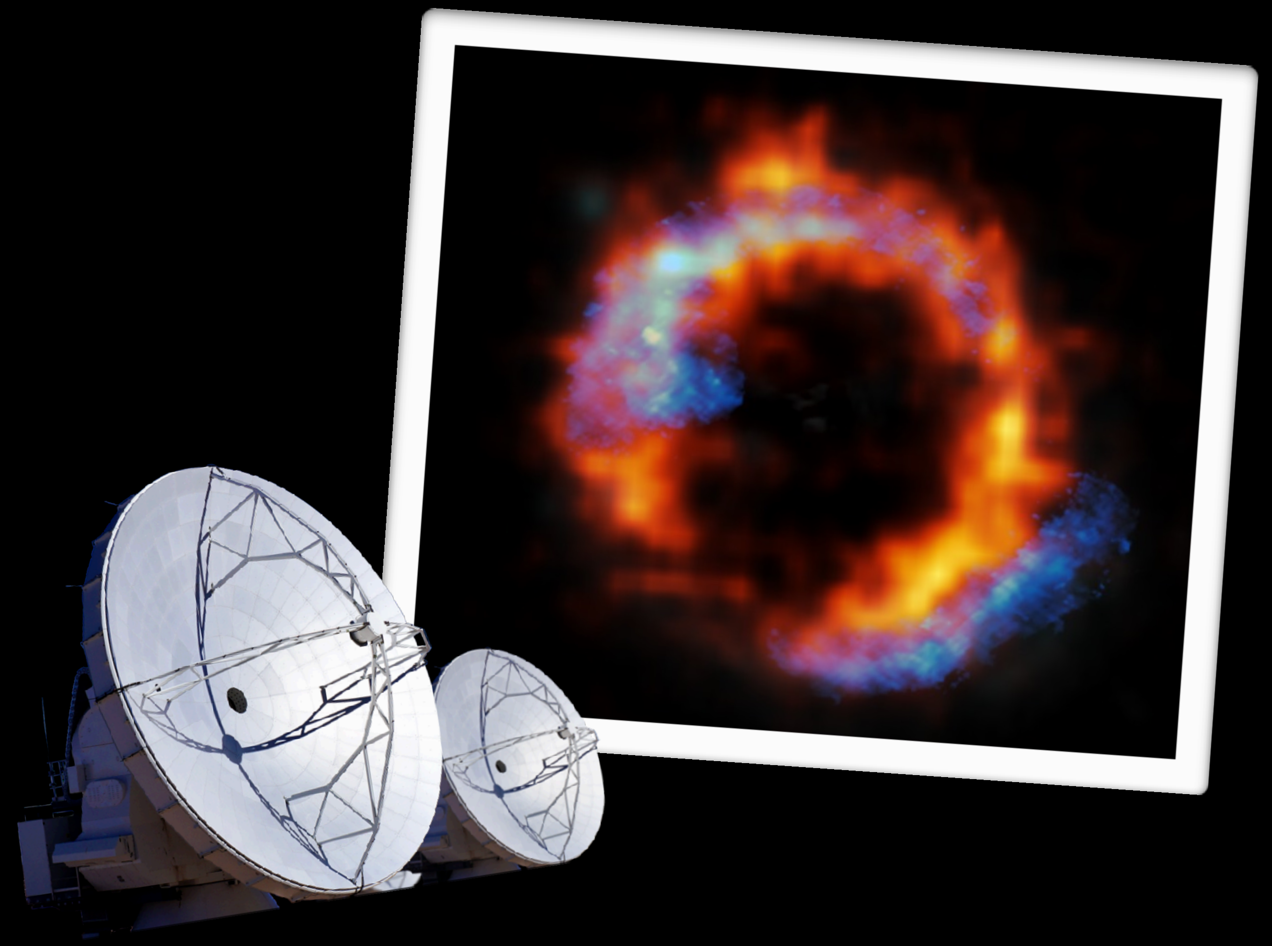
Kamieneski+24b

Resolved rest-frame UVJ diagram confirms the disk-wide star formation event.

Not simply a compact nuclear starburst!

Summary

- Gravitationally lensed dusty star-forming galaxies (like the PASSAGES sample) are a superb laboratory for testing the physics of star formation and the interstellar medium at Cosmic Noon, with a resolution that can usually only be achieved at low-*z*.
- Dusty starbursts have traditionally been thought to be regulated primarily by radiation pressure, but PASSAGES (and others) have densities ~10x lower than the theoretical maximum.
- Instead, they host widespread star formation at relatively low surface density of SFR, Σ_{SFR}, suggesting that supernovae play an outsized role in driving feedback.



Check out our team's (new) website!

bit.ly/astropassages

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Thanks for your attention!

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