Employing Dwarf Galaxies to Assess Star Formation Regulation on Galactic Scales

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the SAGA survey

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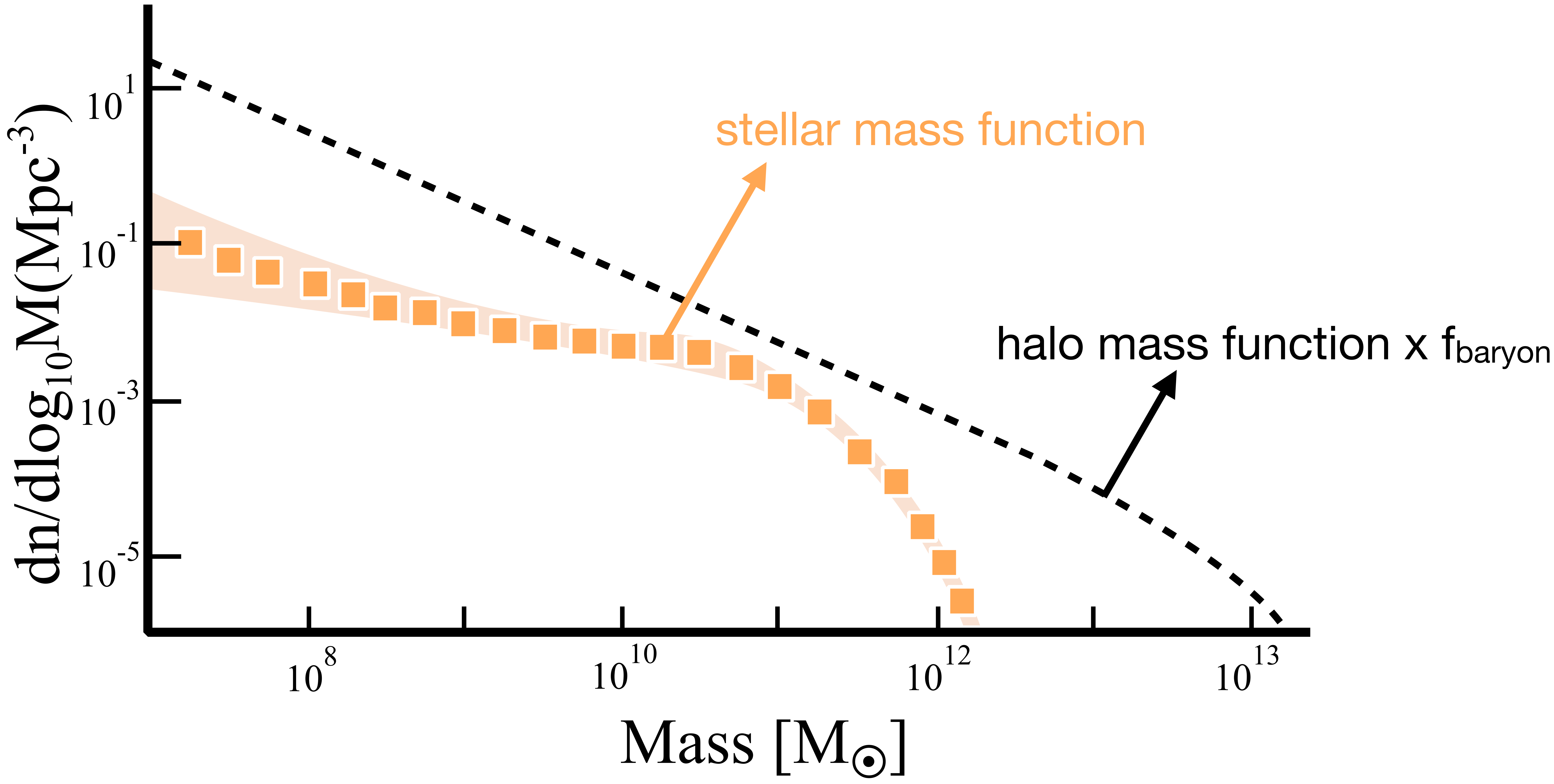
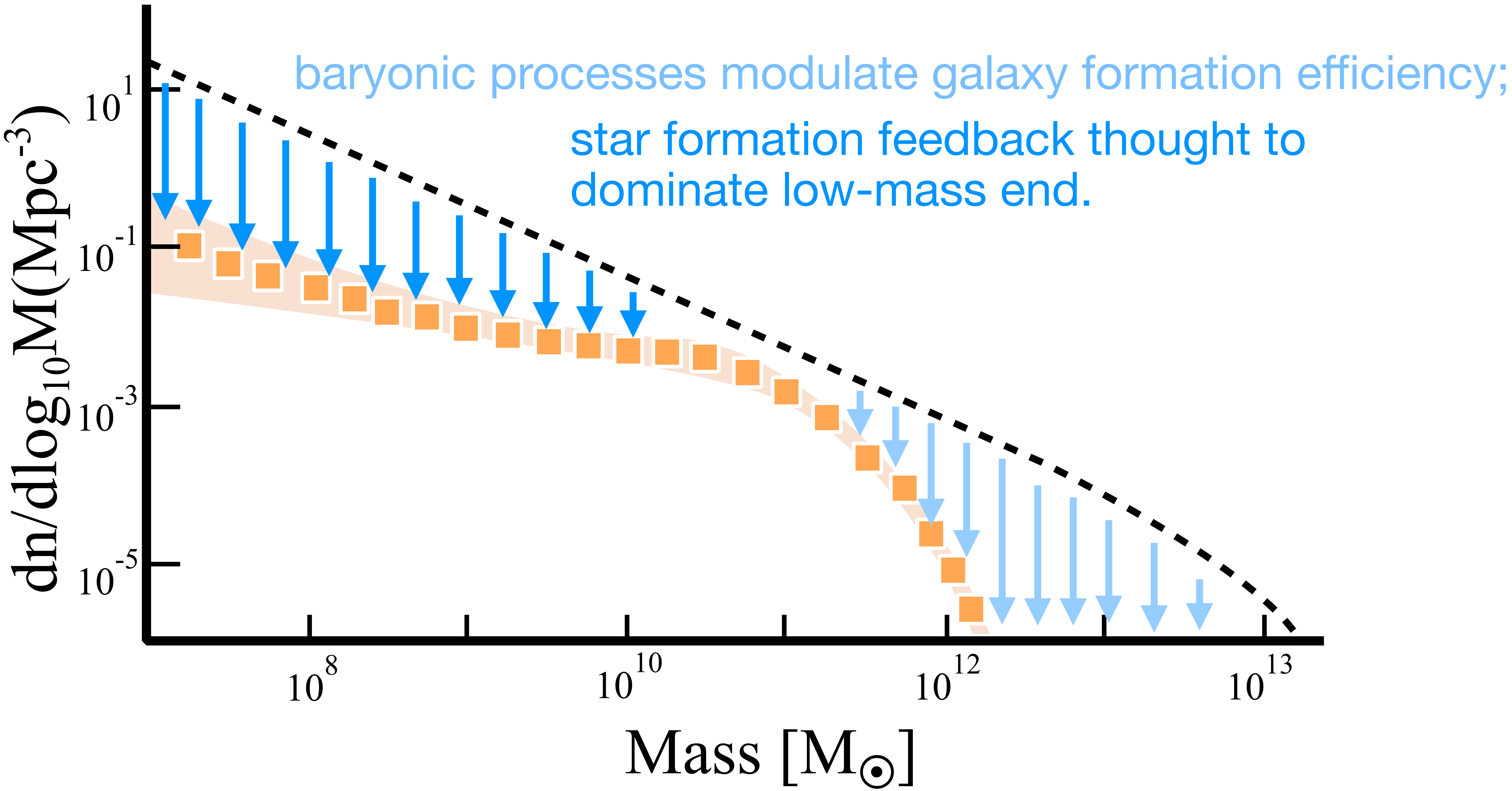
DGSCG2024 (2024/07/09)

We would like to understand the laws that govern the Universe.



ADAPTED FROM BULLOCK & BOYLAN-KOLCHIN 2017



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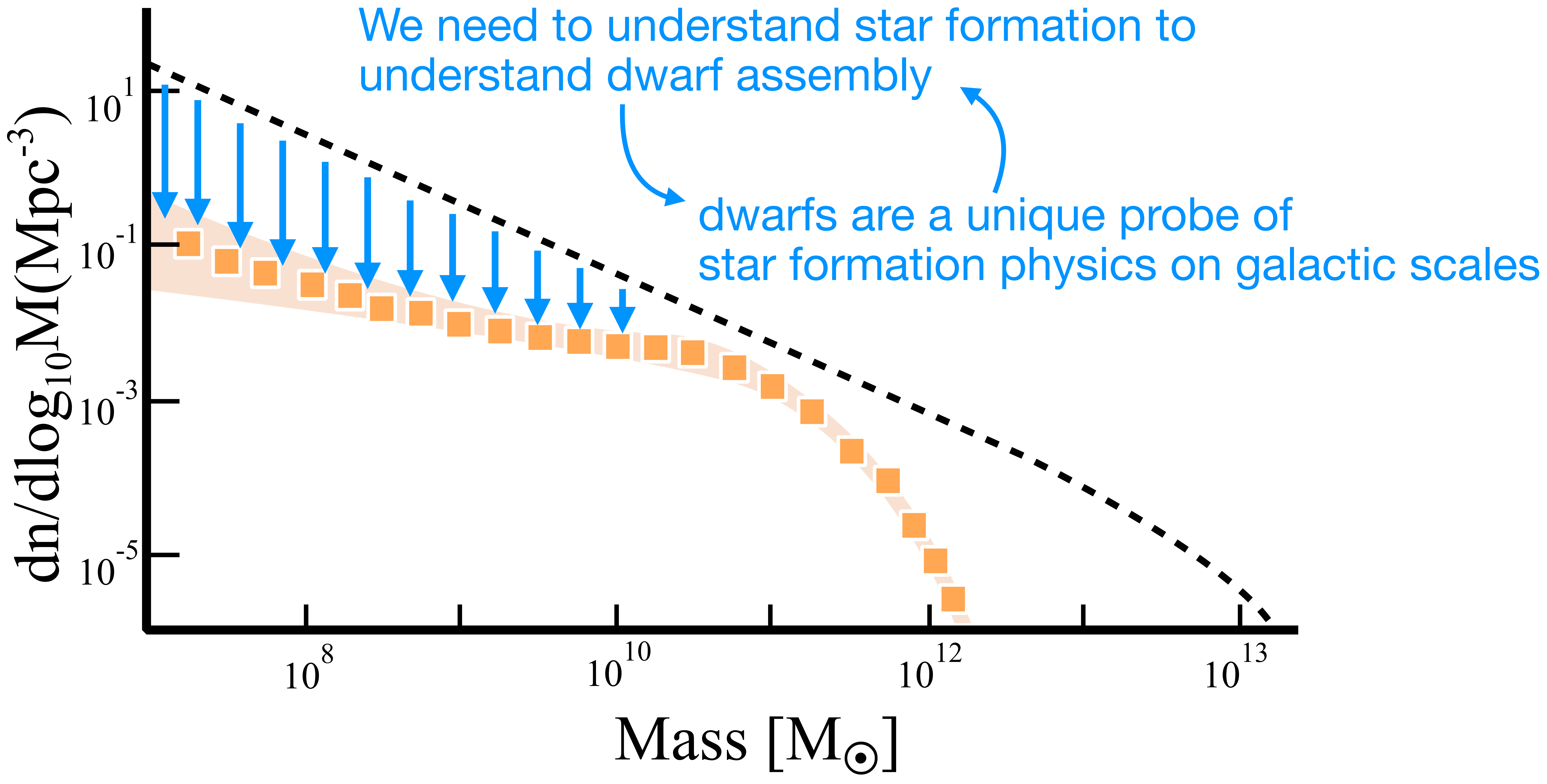
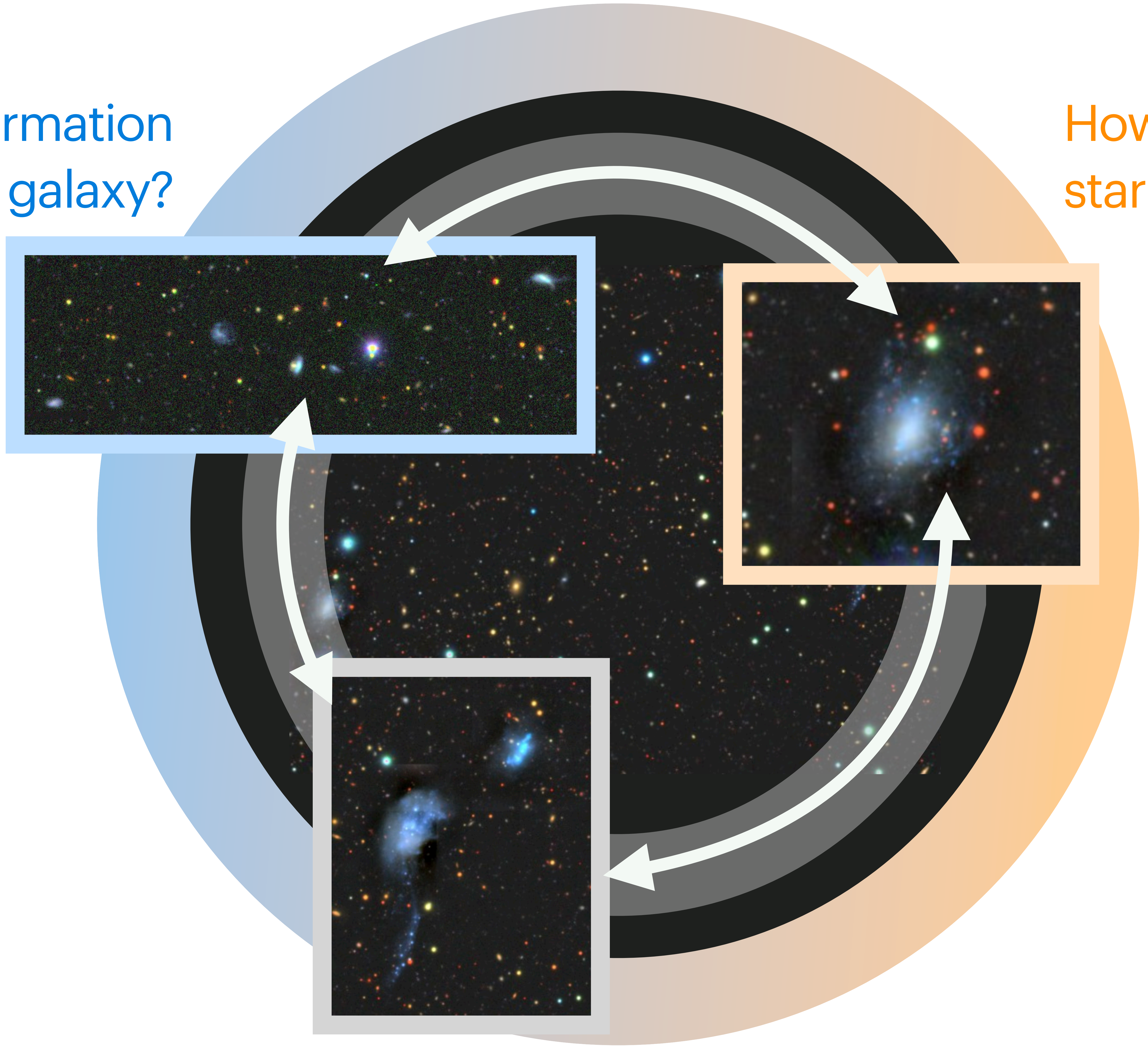


ADAPTED FROM BULLOCK & BOYLAN-KOLCHIN 2017

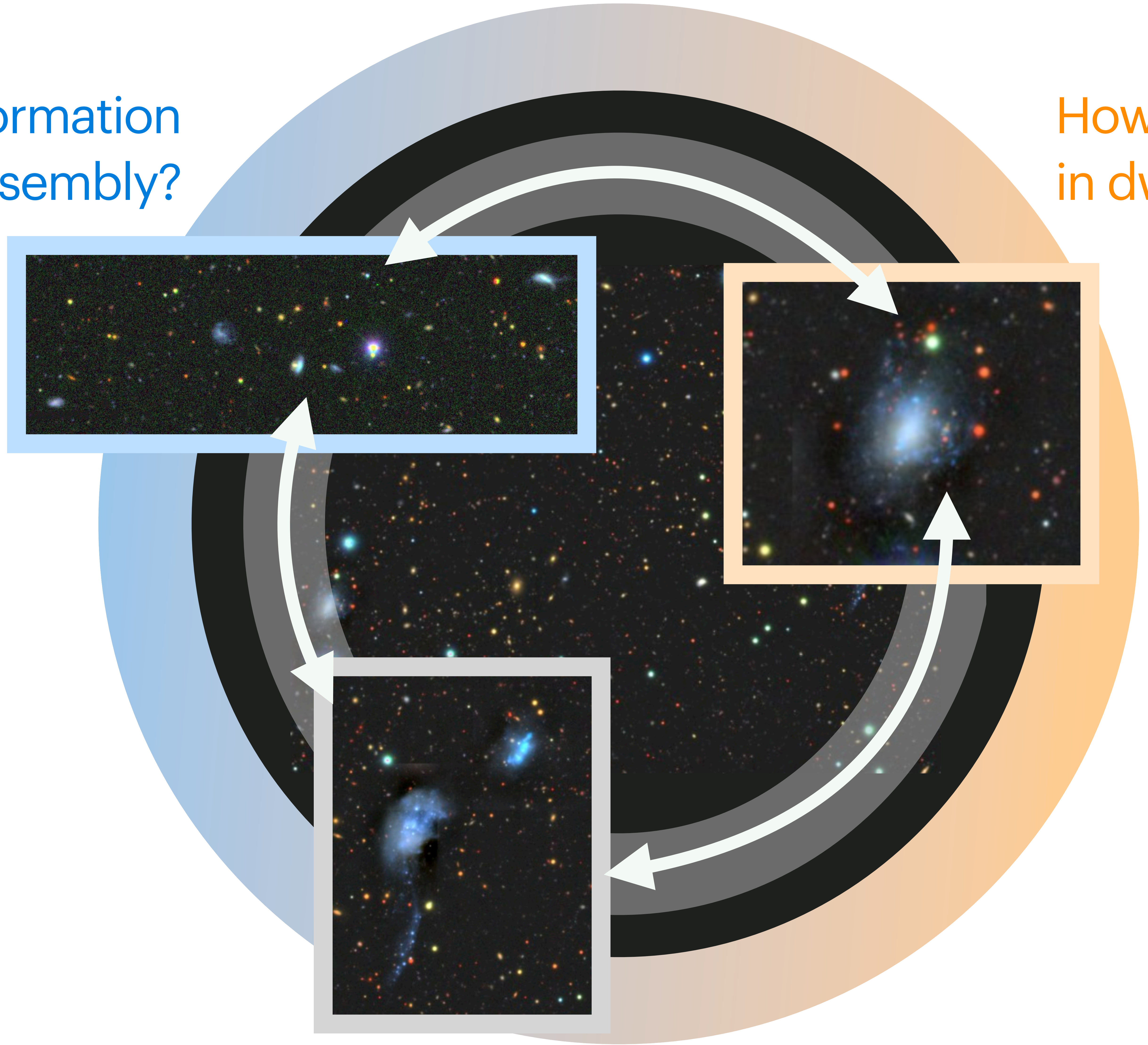
Star Formation and the Galactic-Extragalactic Ecosystem



Star Formation and the Galactic-Extragalactic Ecosystem

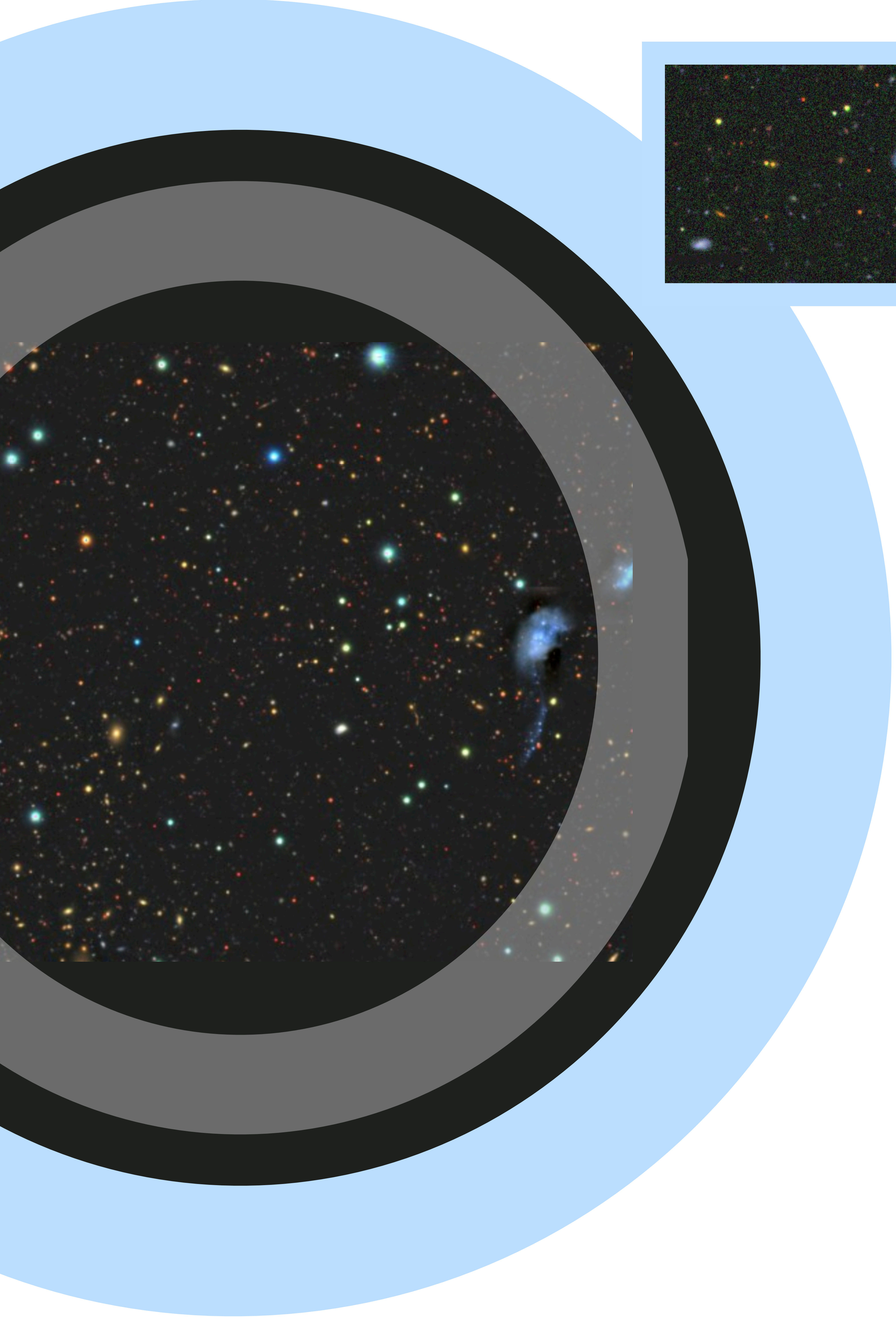
How does star formation influence dwarf assembly?

How does star formation proceed in dwarf-like conditions?

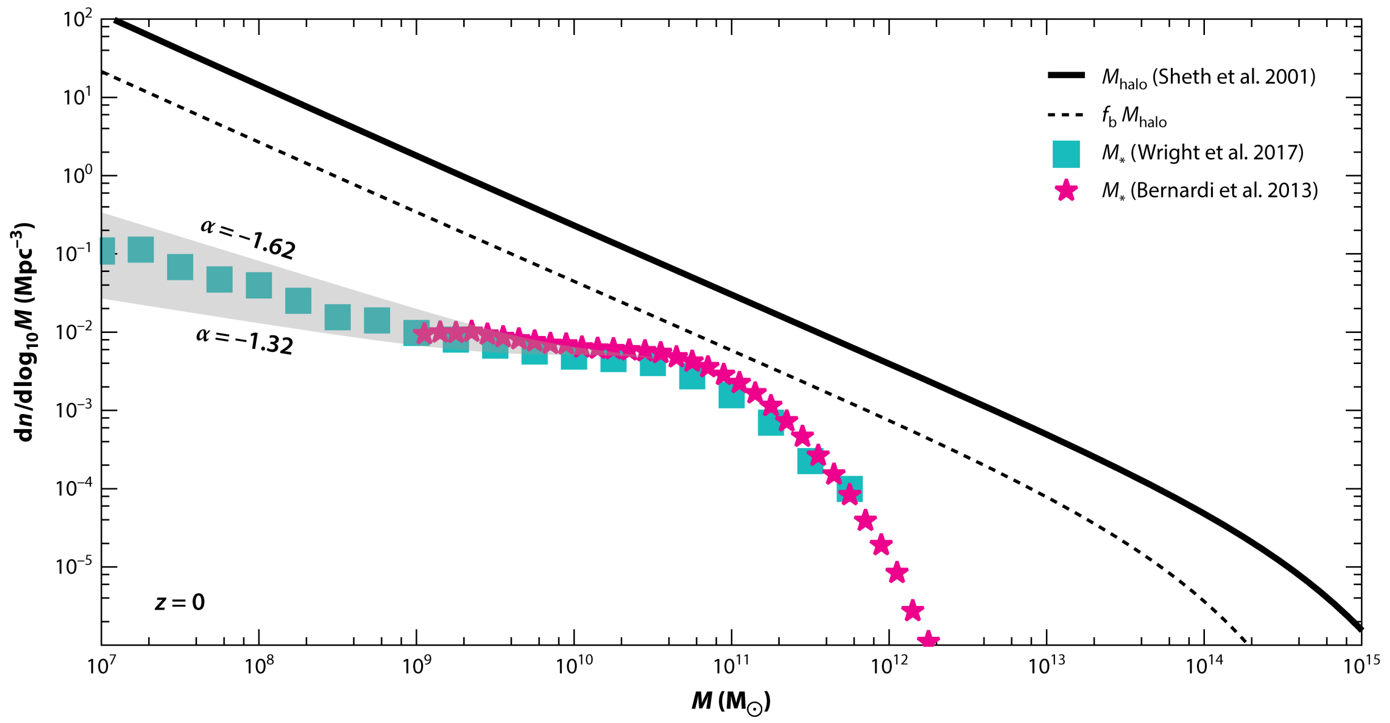


How does star formation participate in environmental processing of dwarfs?

Star Formation and the Galactic-Extragalactic Ecosystem

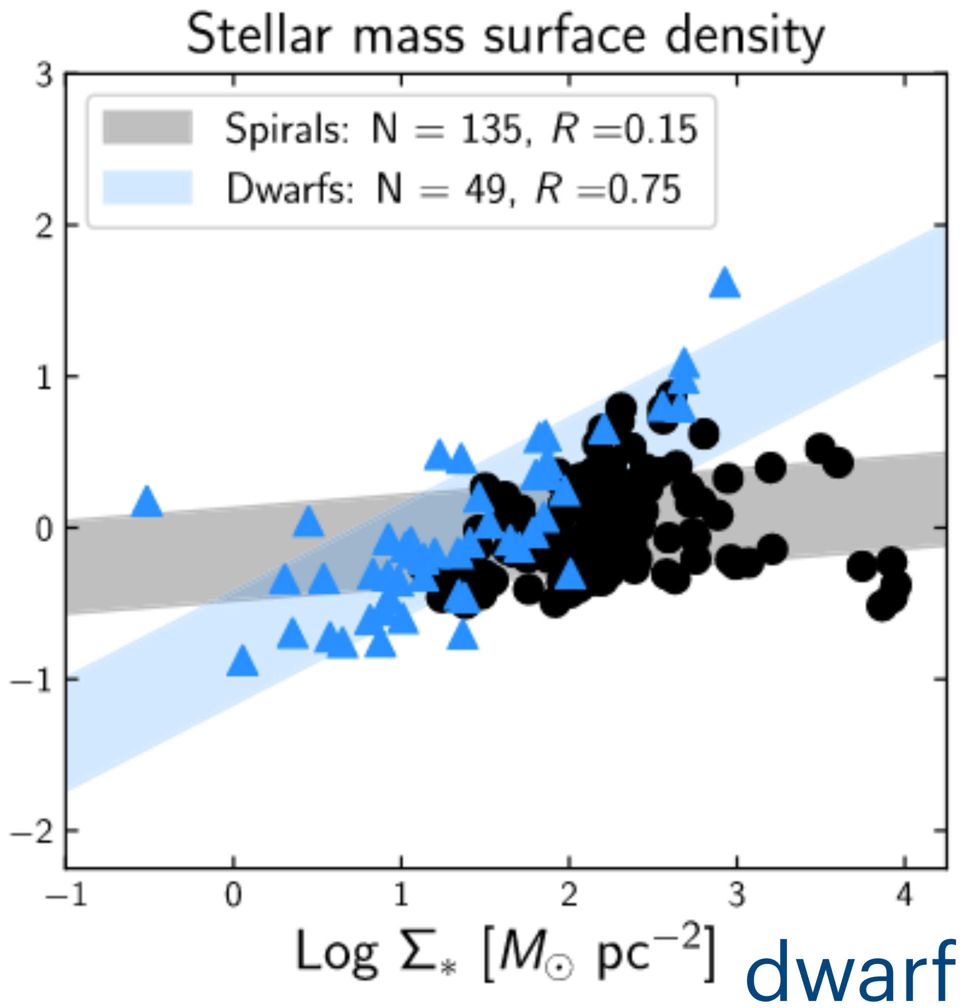


How does star formation influence dwarf assembly?



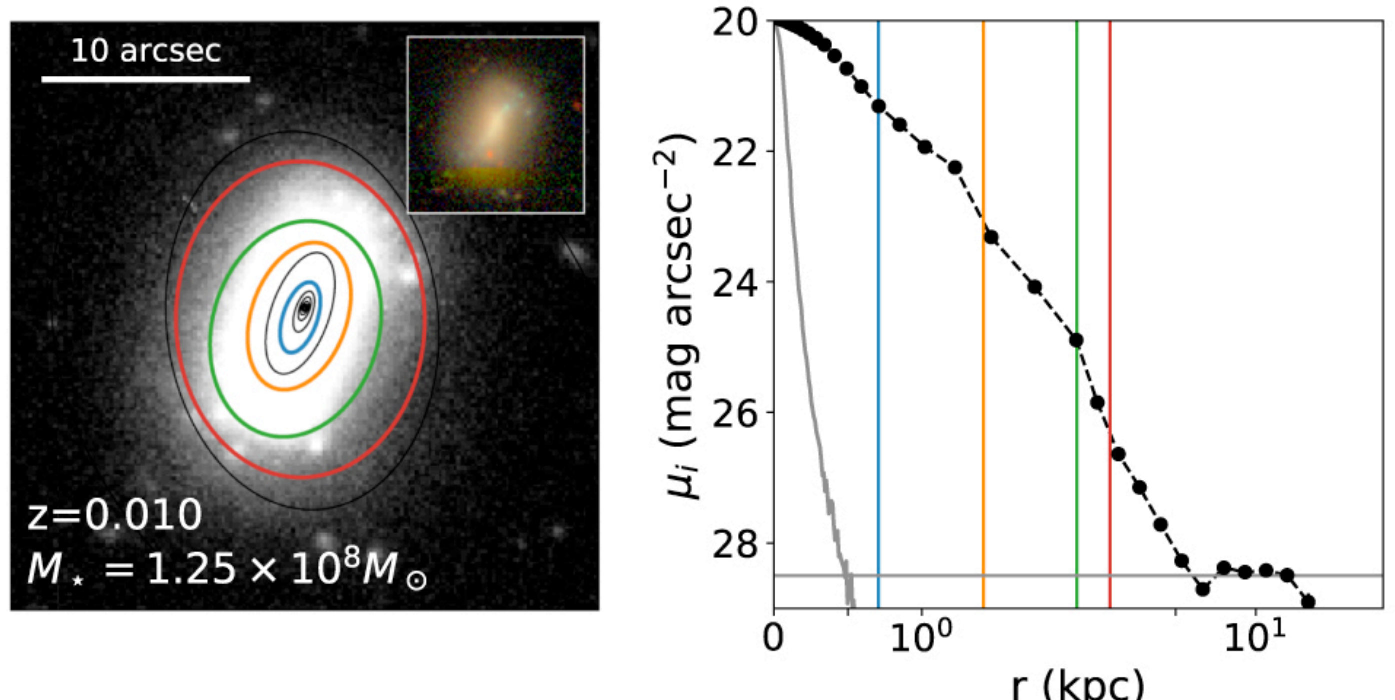
SF feedback modulates the SHMR

[Review by Bullock & Boylan-Kolchin 2017]



dwarf stellar structure traces deviation from Kennicutt-Schmidt

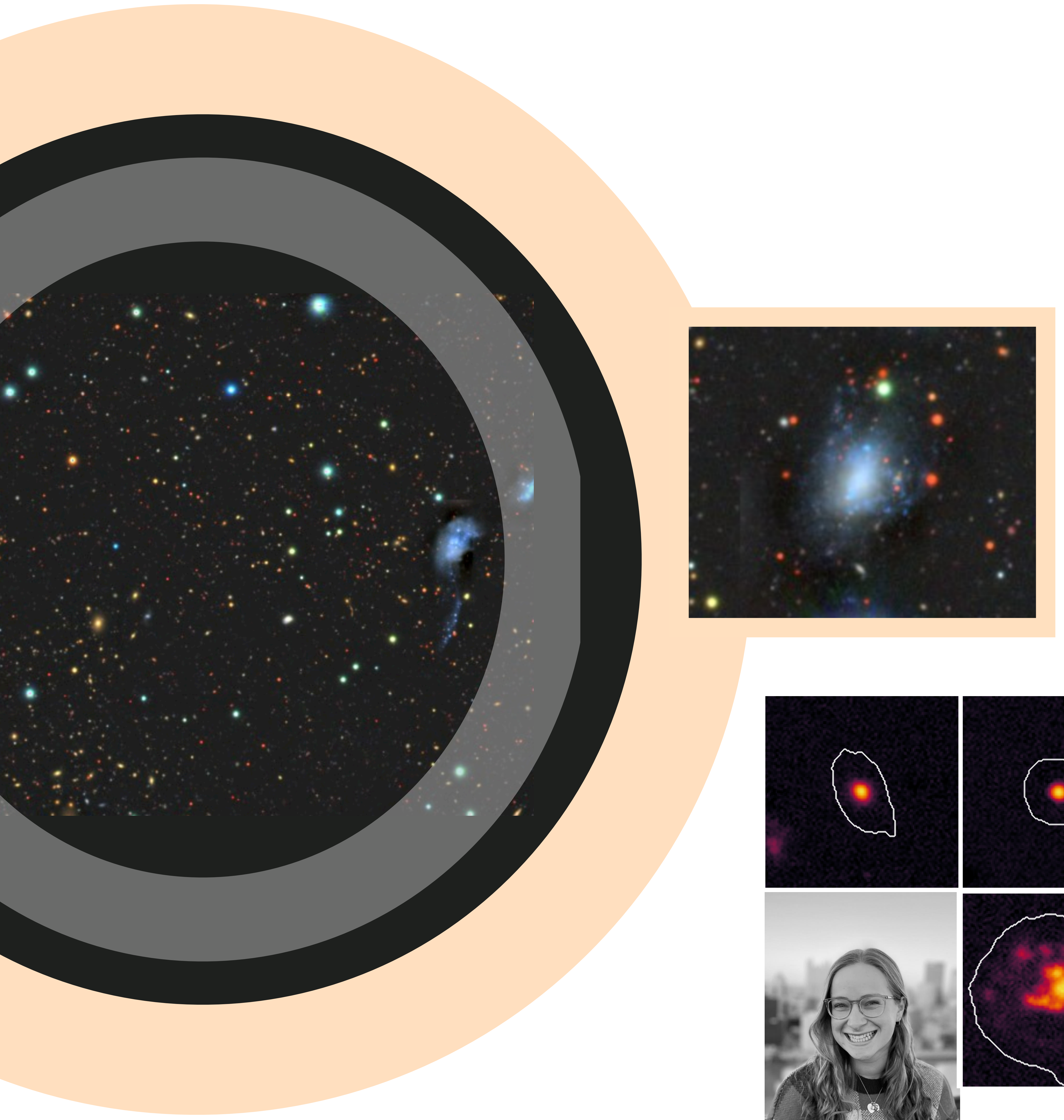
[de los Reyes+2019]

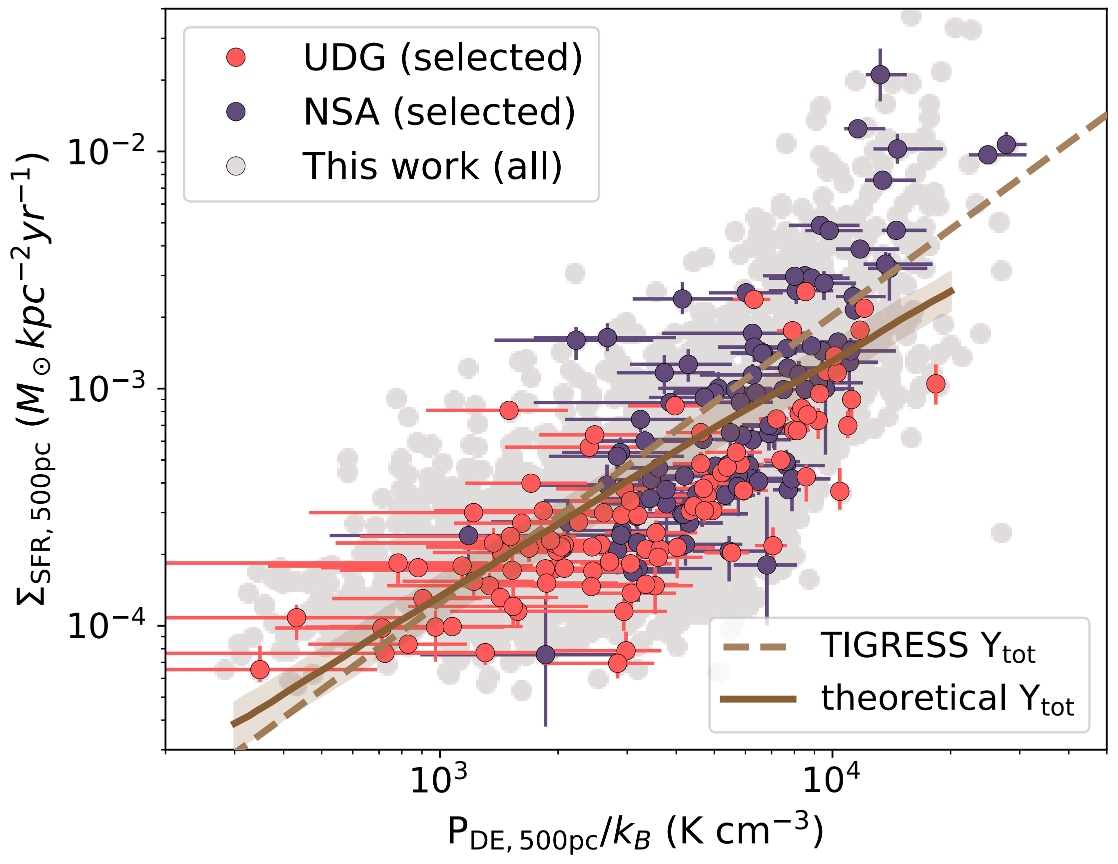


Inner stellar halos of dwarfs may be in-situ, feedback-driven structures.

[EKF+2020b,2022a]

Star Formation and the Galactic-Extragalactic Ecosystem

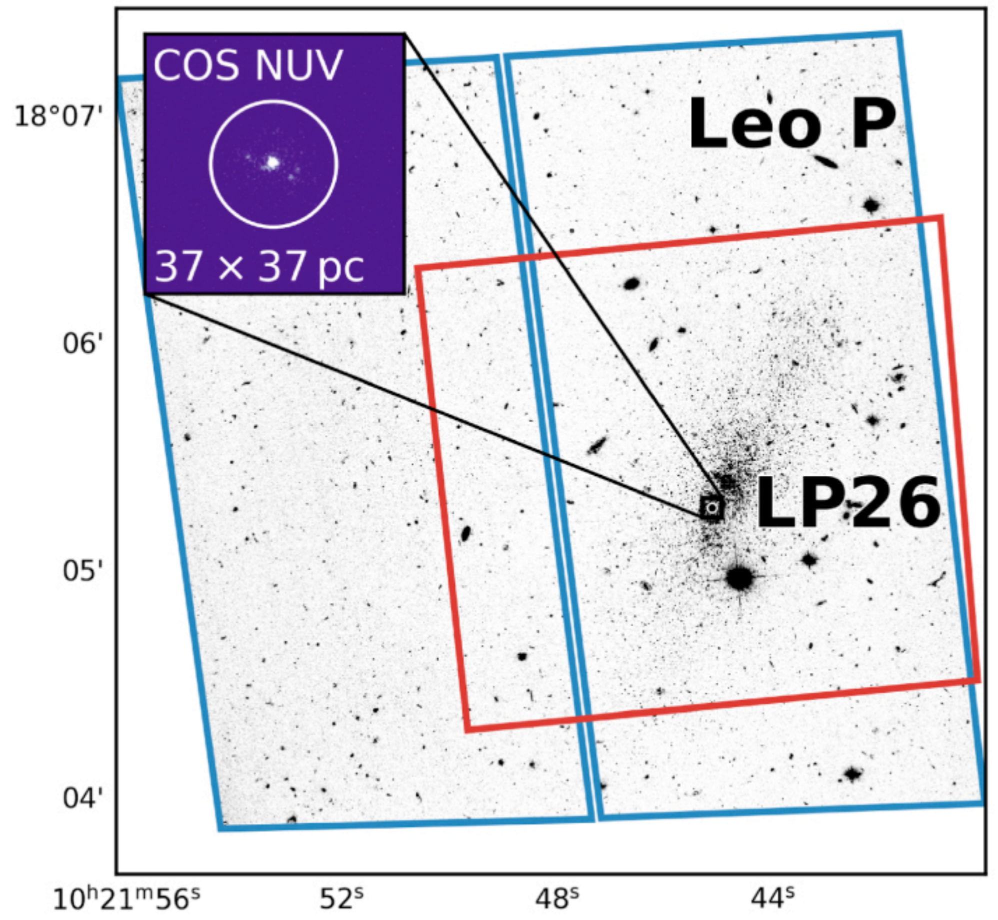




Star formation feedback strength in UDGs is typical compared to HSB dwarfs.

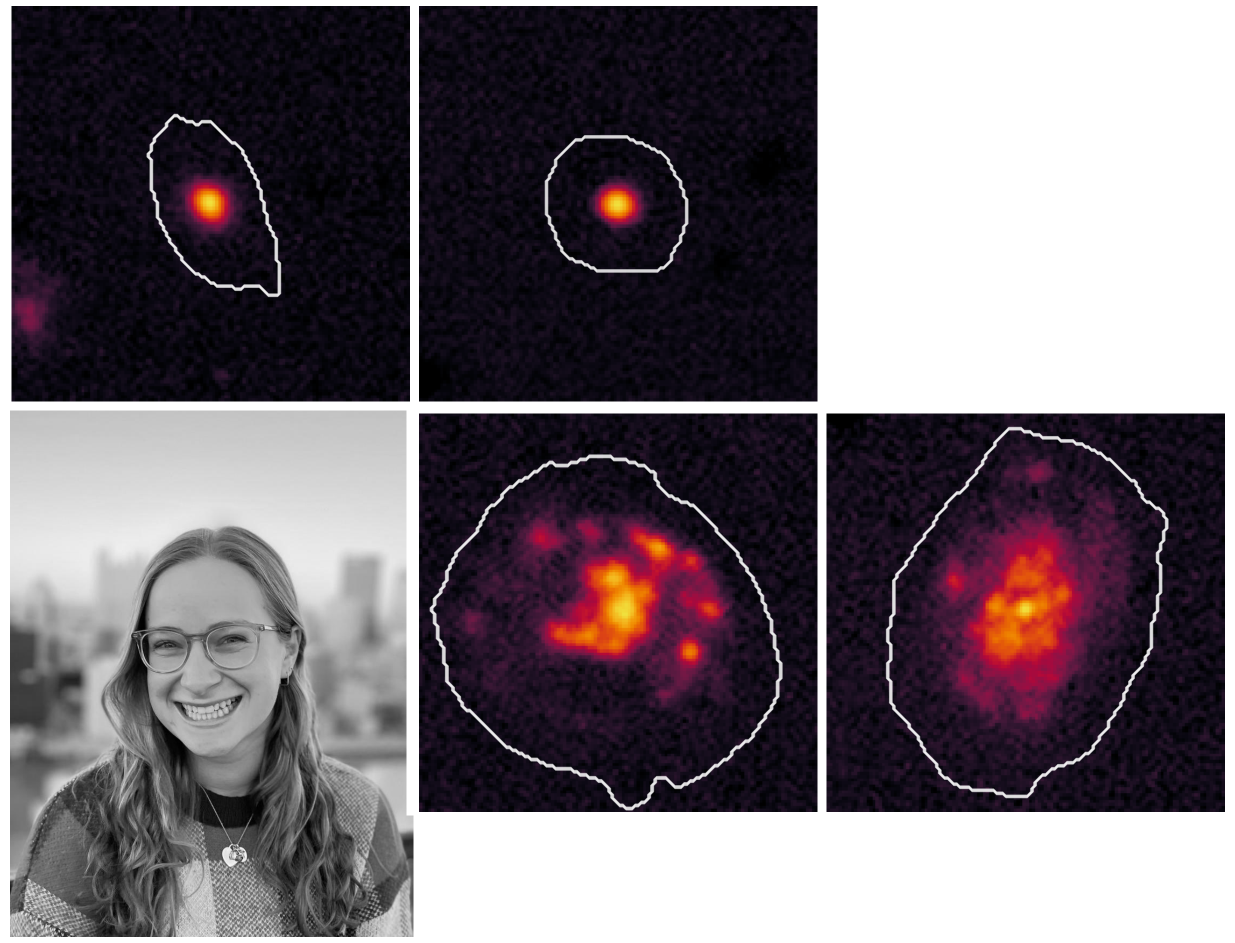
[EKF+2022b,c]

How does star formation proceed in dwarf-like conditions?



dwarfs host low-metallicity massive stars

[Telford+2021,2023]

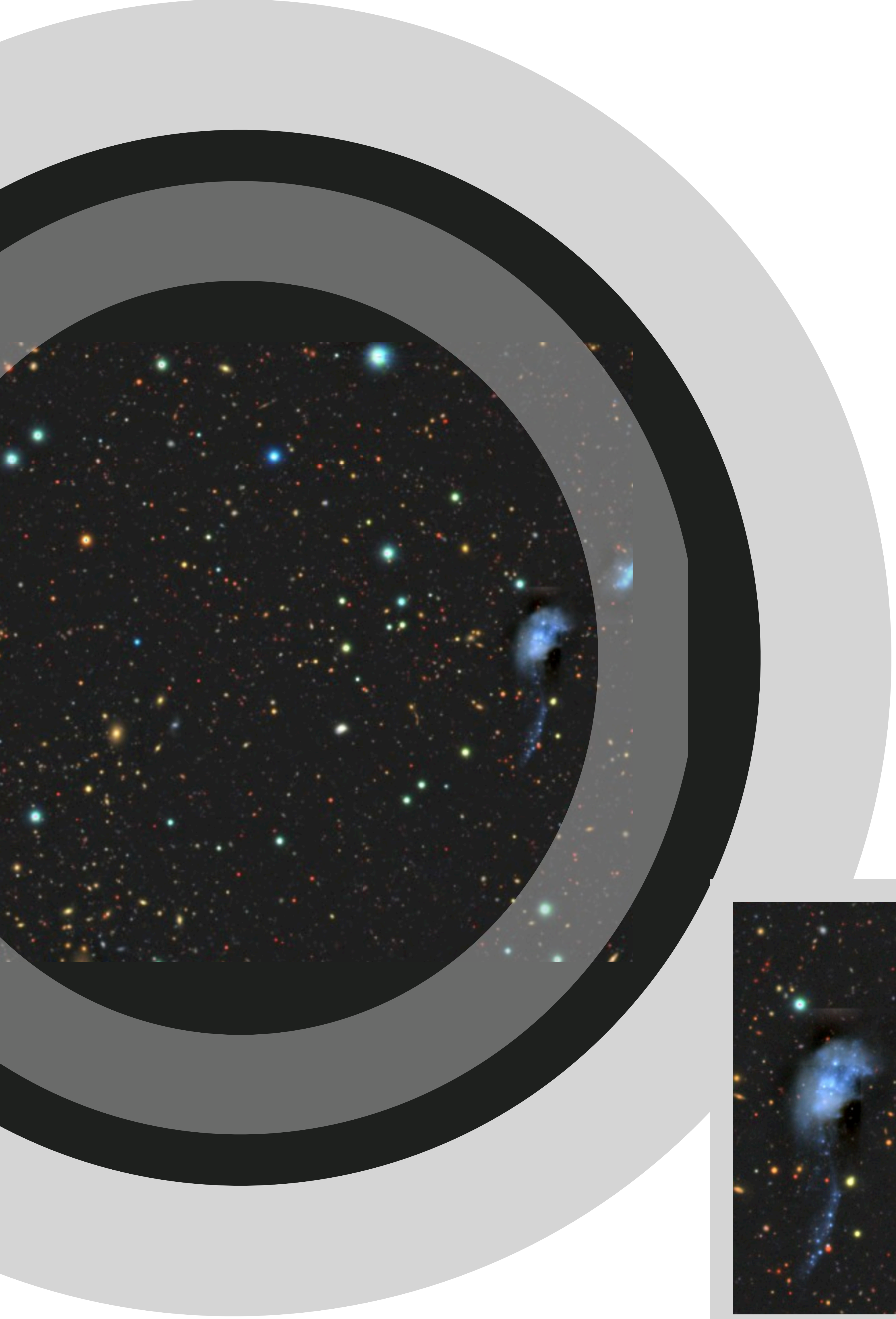


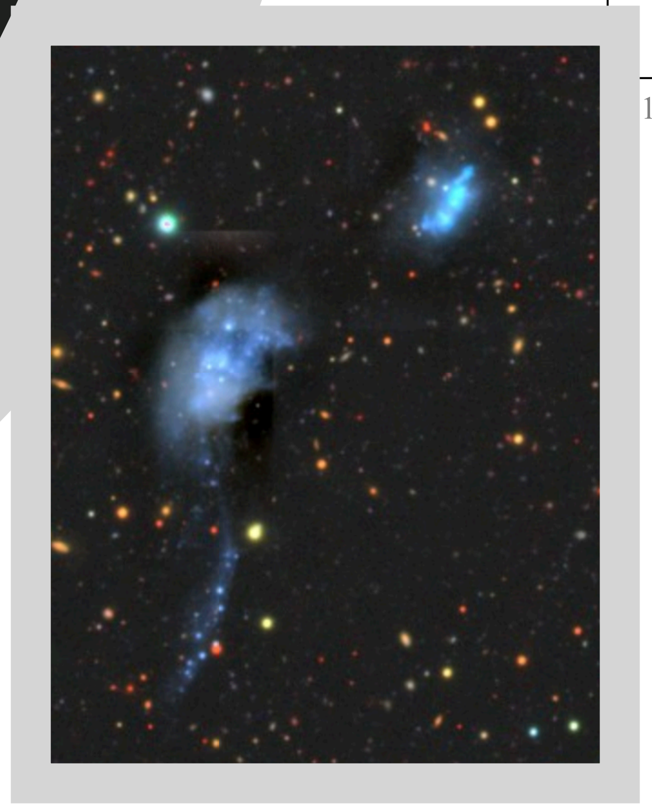
dwarf starbursts are more compact than massive starbursts

[Mintz, Greene, EKF+submitted]

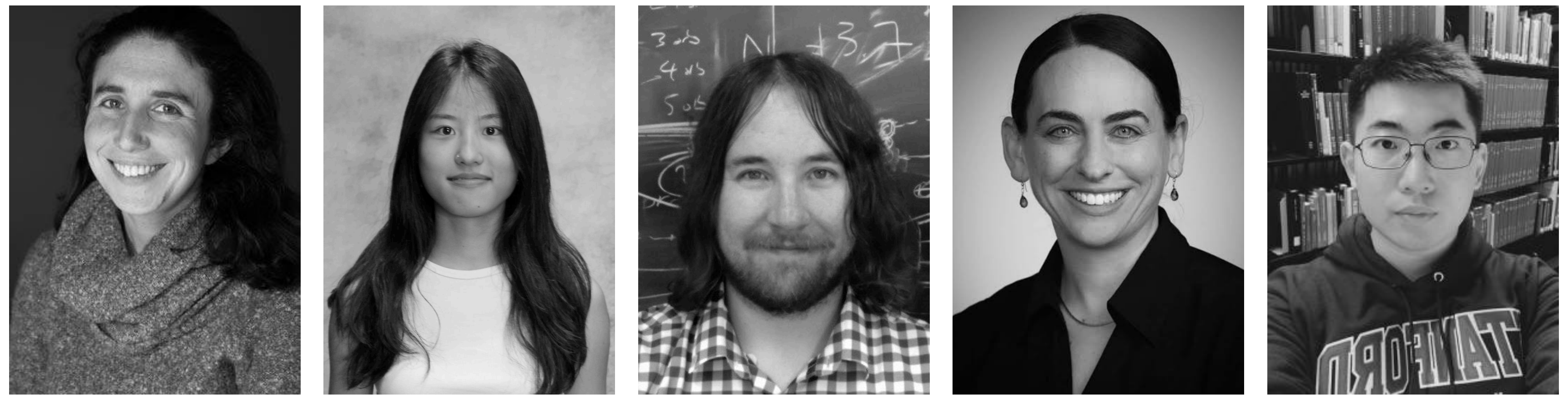
(see Abby's poster!)

Star Formation and the Galactic-Extragalactic Ecosystem

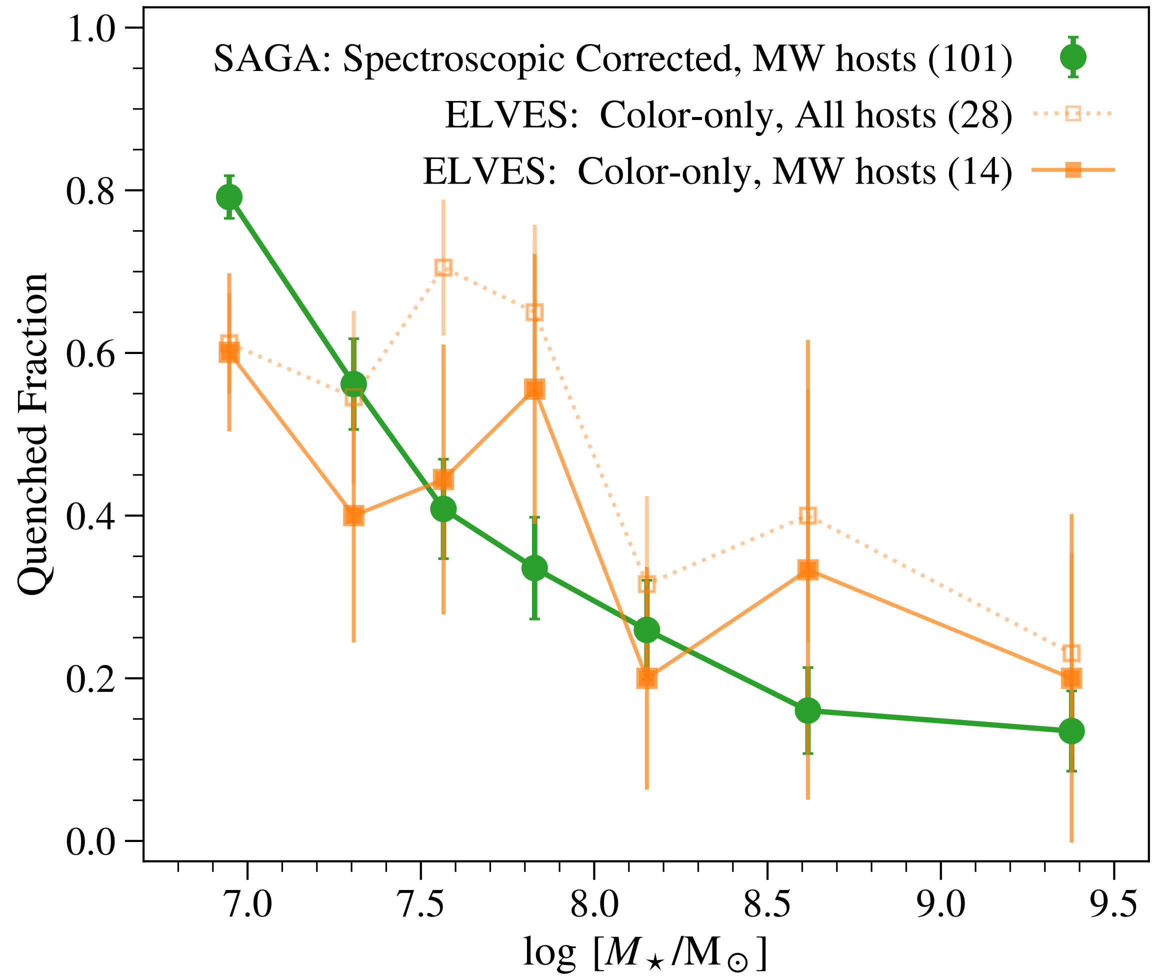


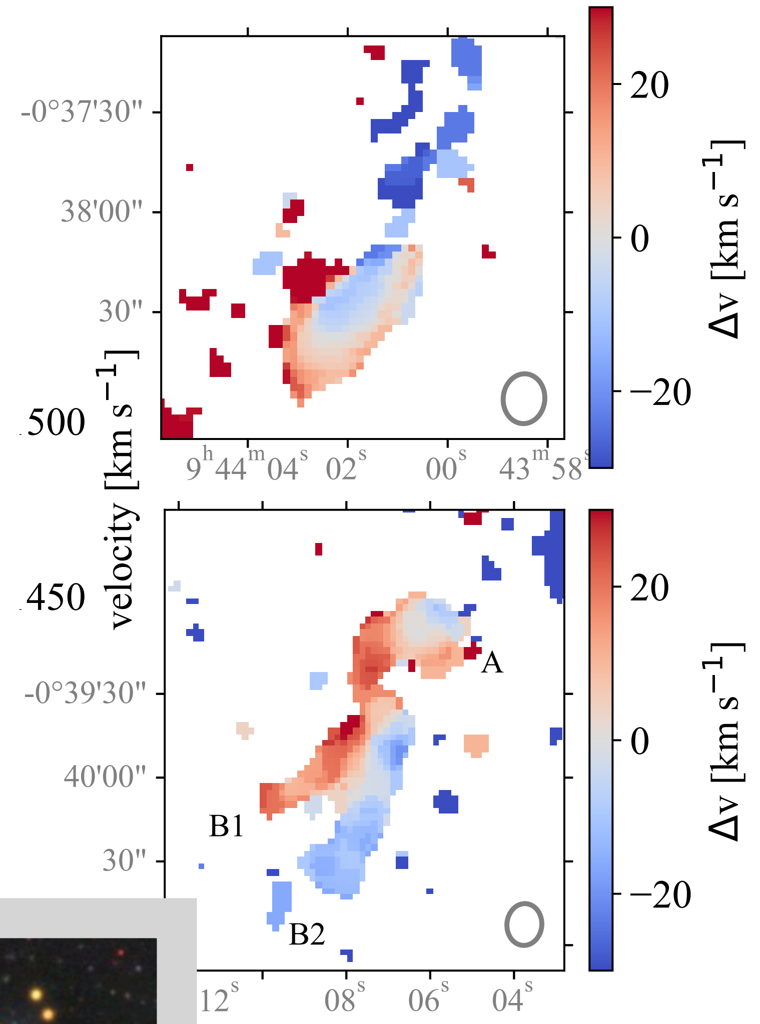


SAGA, ELVES, Merian ++
shed light on environmental
processing of MW-like satellites



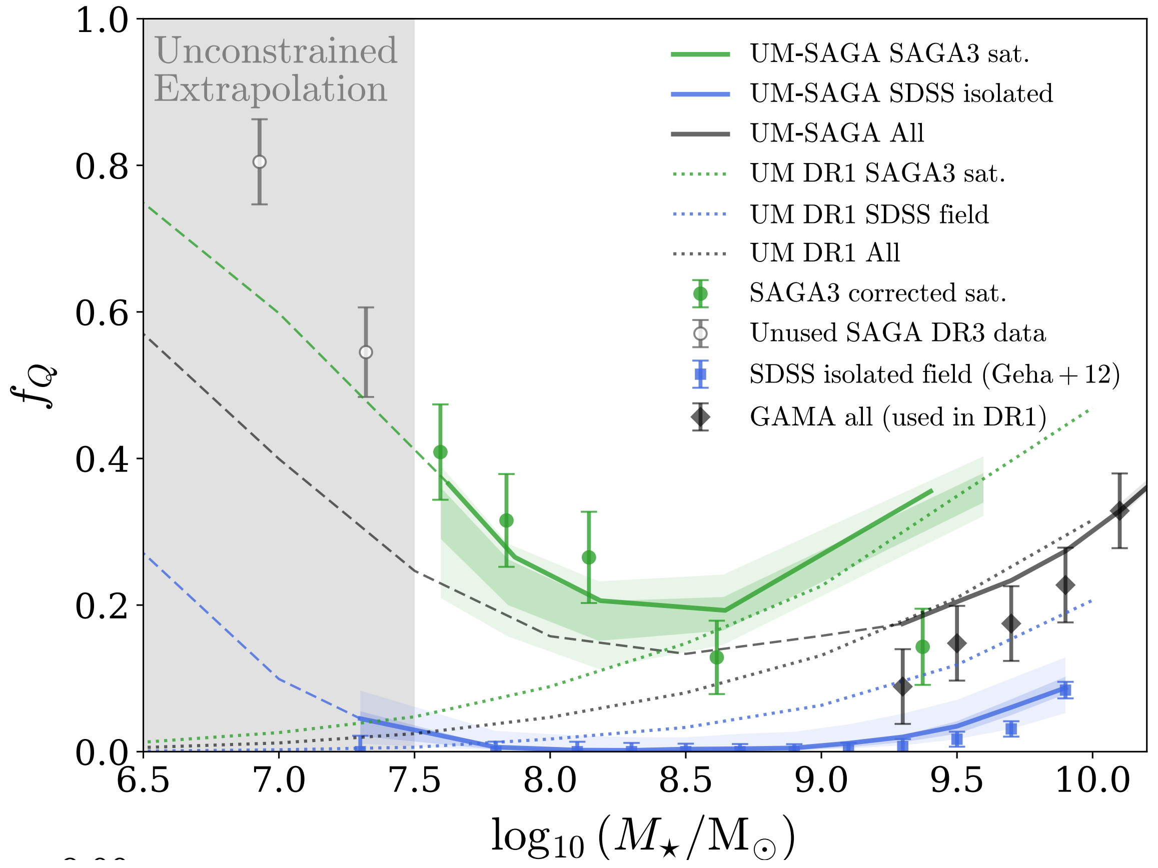
[see Marla & Jenny's talks,
Erik, Richie & Yue's posters]



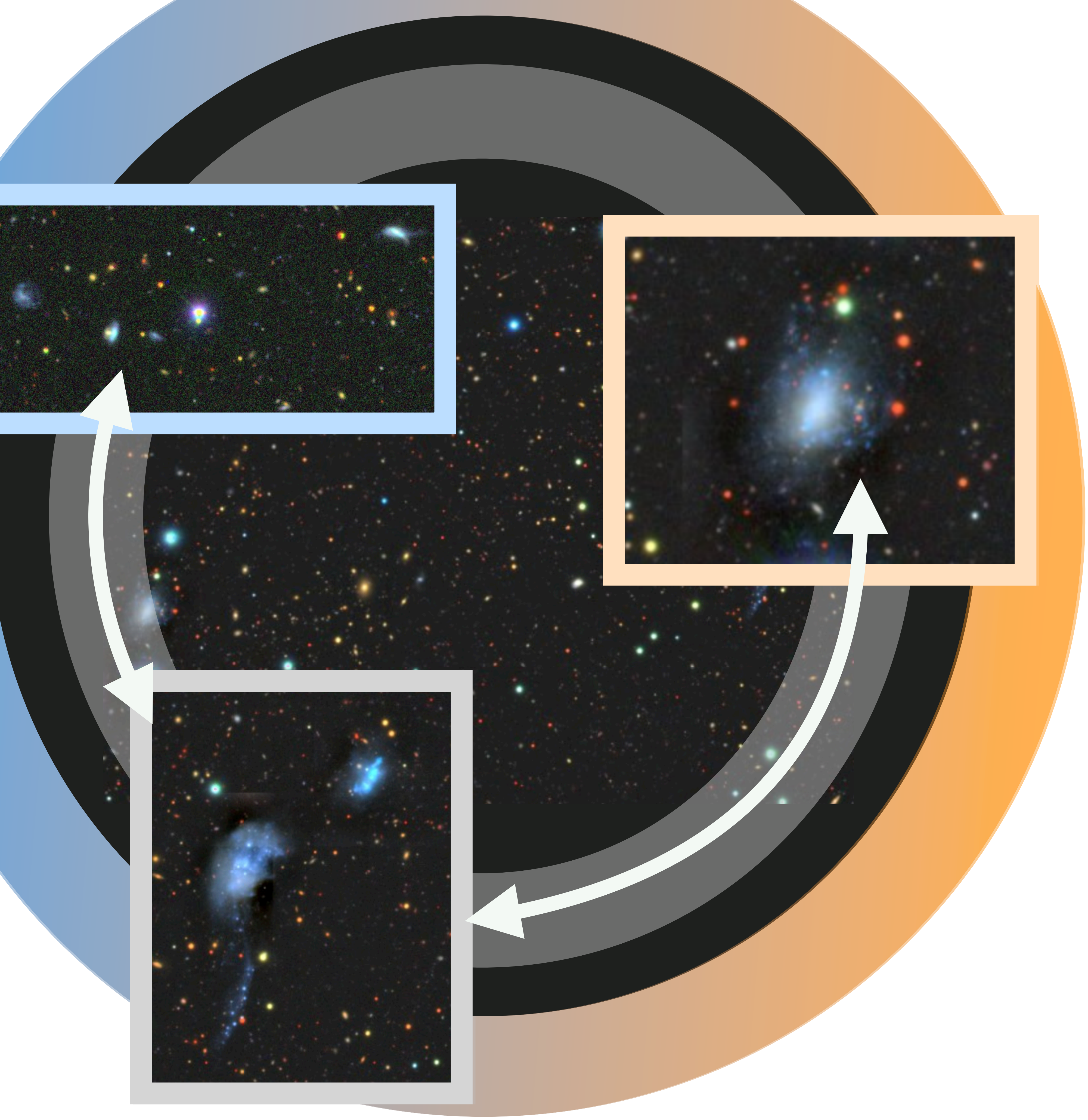


Interactions between dwarfs
can both trigger and (temporarily)
quench star formation

[Stierwalt+2015,
Paudel+2019, EKF+2020a,2024a]



How does star formation participate
in environmental processing of dwarfs?



Statistical Measures of Star Formation Regulation in Dwarfs, Two Ways:

Driving galactic winds.

How efficiently does star formation in dwarfs displace mass in outflows?

Evolution in the “low-z” Star-Forming Sequence of dwarfs.

Star formation feedback drives galactic winds.

e.g. Martin+1998, Chisholm+2015, Heckman+2017, McQuinn+2019, Marasco+2023++

These winds remove gas for future star-formation; i.e., self-regulation of star formation.

e.g. Lynden-Bell+1975, Pagel+1975, Maiolino+2017, Matteucci+2021 ++

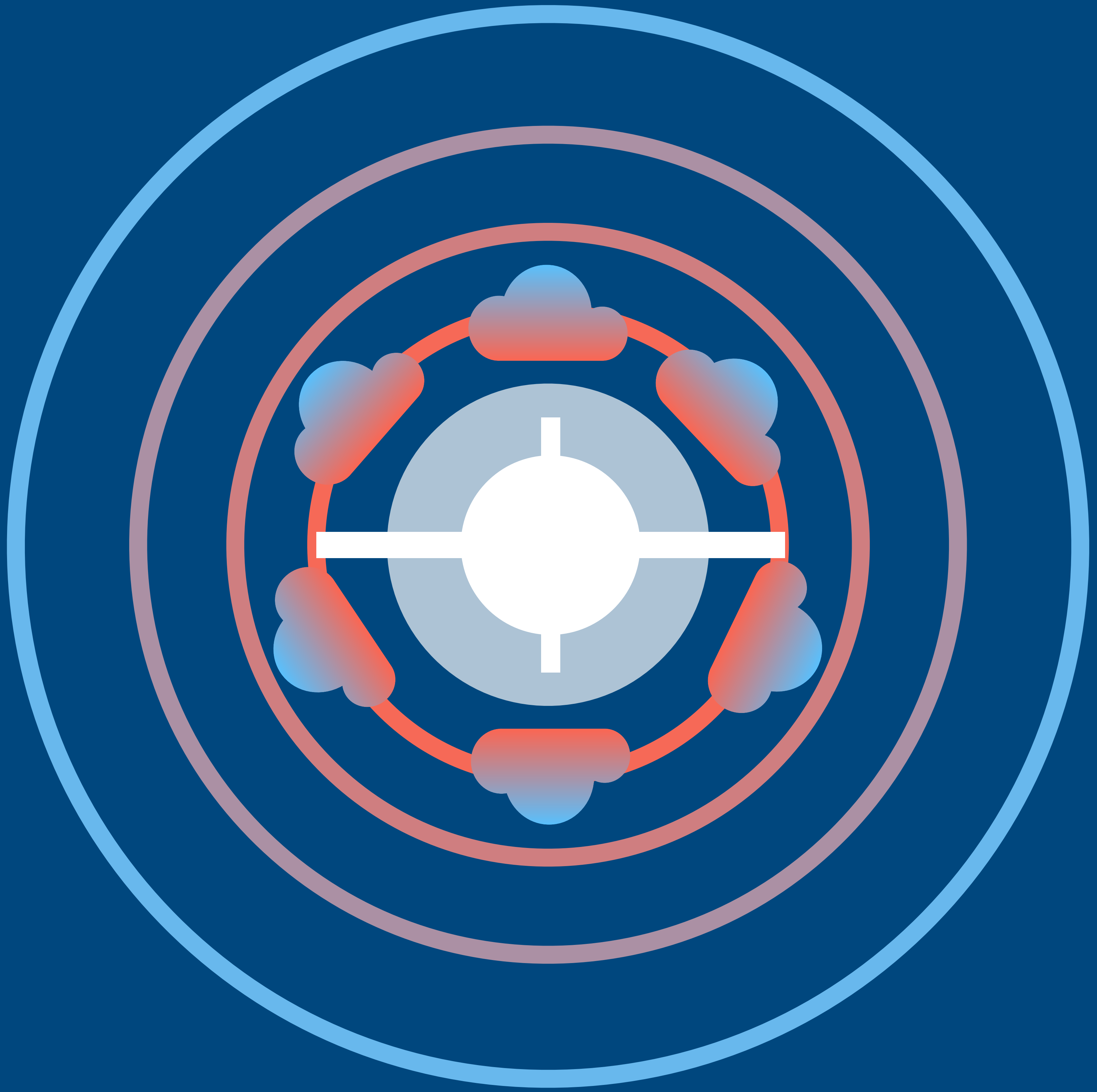
Wind-driving efficiency is thus key to our understanding of star formation regulation,

e.g. Lily+2013, Fielding+2017, Fielding+2022, Carr+2023, C.G Kim+2023 ++

but theoretical predictions vary by factors of ~1000 for dwarfs!

e.g. Muratov+2015, Hu+2019, Nelson+2019, C.G. Kim+2020, Steinwandel+2022, Pandya+2021

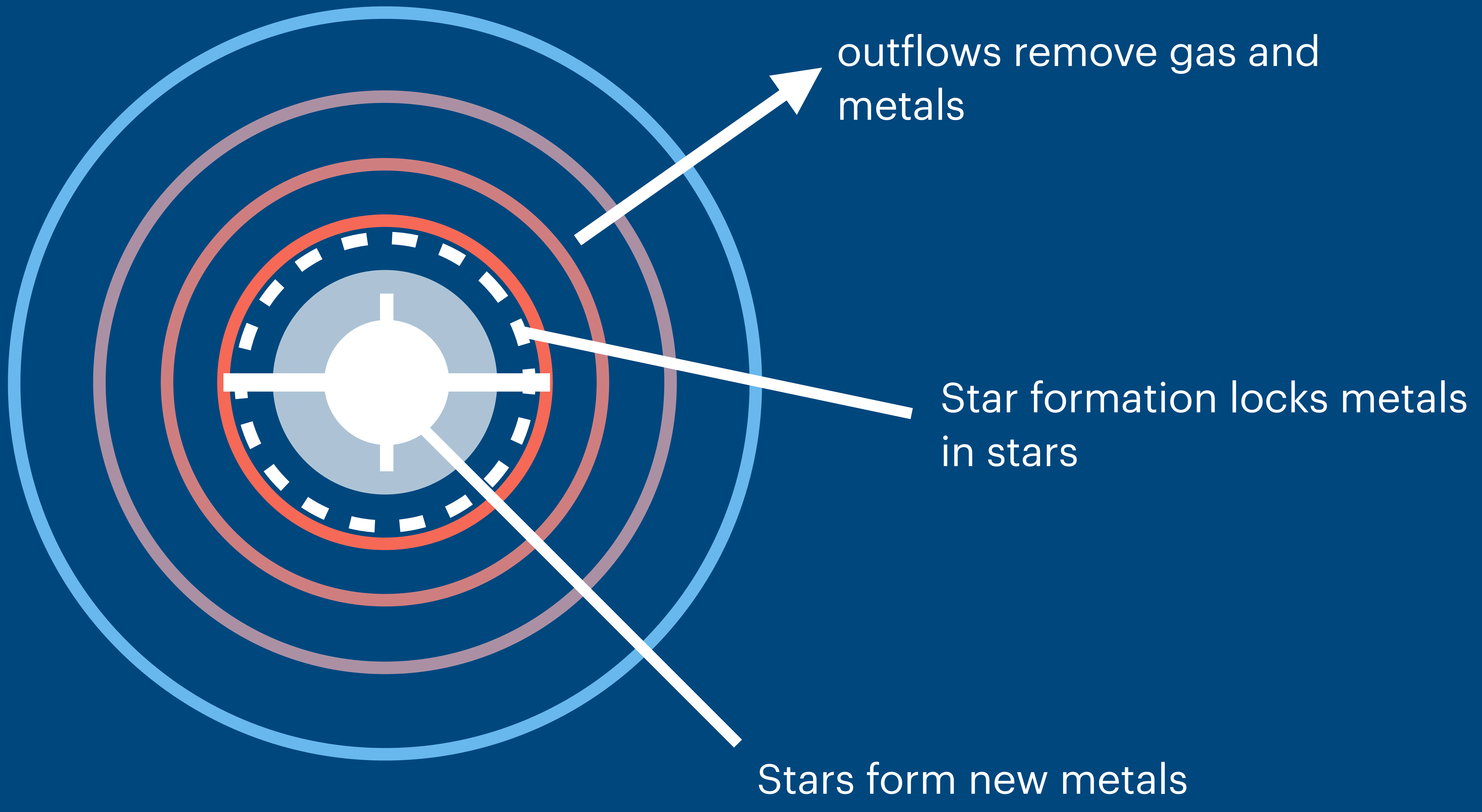
HOW EFFICIENTLY DOES STAR FORMATION DRIVE WINDS IN LOW-MASS GALAXIES?



The efficiency at which star formation drives outflows can be measured via the mass-loading factor:

$$\eta_m \equiv \frac{\dot{\mathrm{M}}_{\mathrm{out}}}{\mathrm{SFR}}$$

We can spatially resolve these outflows only for vigorous + nearby cases.



The efficiency at which SF drives outflows also governs chemical enrichment

Ergo, chemical evolution can also tell us something about outflows.

But, making realistic galaxies is hard...

Working backwards to measure η_m from chemical enrichment

Observed: $\{M_\star(t_{lb}), SFR(t_{lb}), Z_O(t_{lb}), M_{HI}(z=0)\}$

oxygen abundance, by mass

(statistical)

Using $z \sim 0$ sample as a boundary condition,

(They must be realistic galaxies, because they are real galaxies)

(Heavily simplified model for a very restricted part of stellar mass & redshift space!)

$$\dot{M}_\star(t_{lb}) = SFR(t_{lb}=0)(1 + a_{SFH} t_{lb})$$

$$\dot{M}_g(t_{lb}) = 0$$ equilibrium assumption

$$\dot{M}_O(t_{lb}) = p_O \dot{M}_\star(t_{lb}) - Z_O(t_{lb})(1 - f_{rec})\dot{M}_\star(t_{lb}) - Z_O(t_{lb}) y_z \eta_m \dot{M}_\star(t_{lb})$$

Kado-Fong+2024b

Working backwards to measure η_m from chemical enrichment

Observed: $\{M_\star(t_{lb}), SFR(t_{lb}), Z_O(t_{lb}), M_{HI}(z=0)\}$

Using $z \sim 0$ sample as a boundary condition,

Star formation … makes stars.

$$\dot{M}_\star(t_{lb}) = SFR(t_{lb}=0)(1 + a_{SFH} t_{lb})$$

$$\dot{M}_g(t_{lb}) = 0$$ equilibrium assumption*

$$\dot{M}_O(t_{lb}) = p_O \dot{M}_\star(t_{lb}) - Z_O(t_{lb})(1 - f_{rec})\dot{M}_\star(t_{lb}) - Z_O(t_{lb}) y_z \eta_m \dot{M}_\star(t_{lb})$$

Kado-Fong+2024b

Working backwards to measure η_m from chemical enrichment

Observed: $\{M_\star(t_{lb}), SFR(t_{lb}), Z_O(t_{lb}), M_{HI}(z=0)\}$

Using $z \sim 0$ sample as a boundary condition,

Star formation … drives outflows.

$$\dot{M}_\star(t_{lb}) = SFR(t_{lb}=0)(1 + a_{SFH} t_{lb})$$

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Kado-Fong+2024b

Working backwards to measure η_m from chemical enrichment

Observed: $\{M_\star(t_{lb}), SFR(t_{lb}), Z_O(t_{lb}), M_{HI}(z=0)\}$

Using $z \sim 0$ sample as a boundary condition,

Star formation ... produces metals.

$$\dot{M}_\star(t_{lb}) = SFR(t_{lb} = 0)(1 + a_{SFH} t_{lb})$$

$\dot{M}_g(t_{lb}) = 0$ equilibrium assumption

$$\dot{M}_O(t_{lb}) = p_O \dot{M}_\star(t_{lb}) - Z_O(t_{lb})(1 - f_{rec})\dot{M}_\star(t_{lb}) - Z_O(t_{lb}) y_z \eta_m \dot{M}_\star(t_{lb})$$

Kado-Fong+2024b

Working backwards to measure η_m from chemical enrichment

Observed: $\{\mathrm{M}_\star(\mathrm{t_{lb}}), \mathrm{SFR}(\mathrm{t_{lb}}), \mathrm{Z_O}(\mathrm{t_{lb}}), \mathrm{M_{HI}}(\mathrm{z}=0)\}$

Using $z \sim 0$ sample as a boundary condition,

Estimate $\{\dot{M}_\star, \dot{M}_g, \dot{Z}_O\}$

(+ observational constraints)

Predict: $\{\mathrm{M}_\star(\mathrm{t_{lb}}), \mathrm{SFR}(\mathrm{t_{lb}}), \mathrm{Z_O}(\mathrm{t_{lb}})\}$

What is the probability we would put a fiber on a galaxy with the predicted properties?

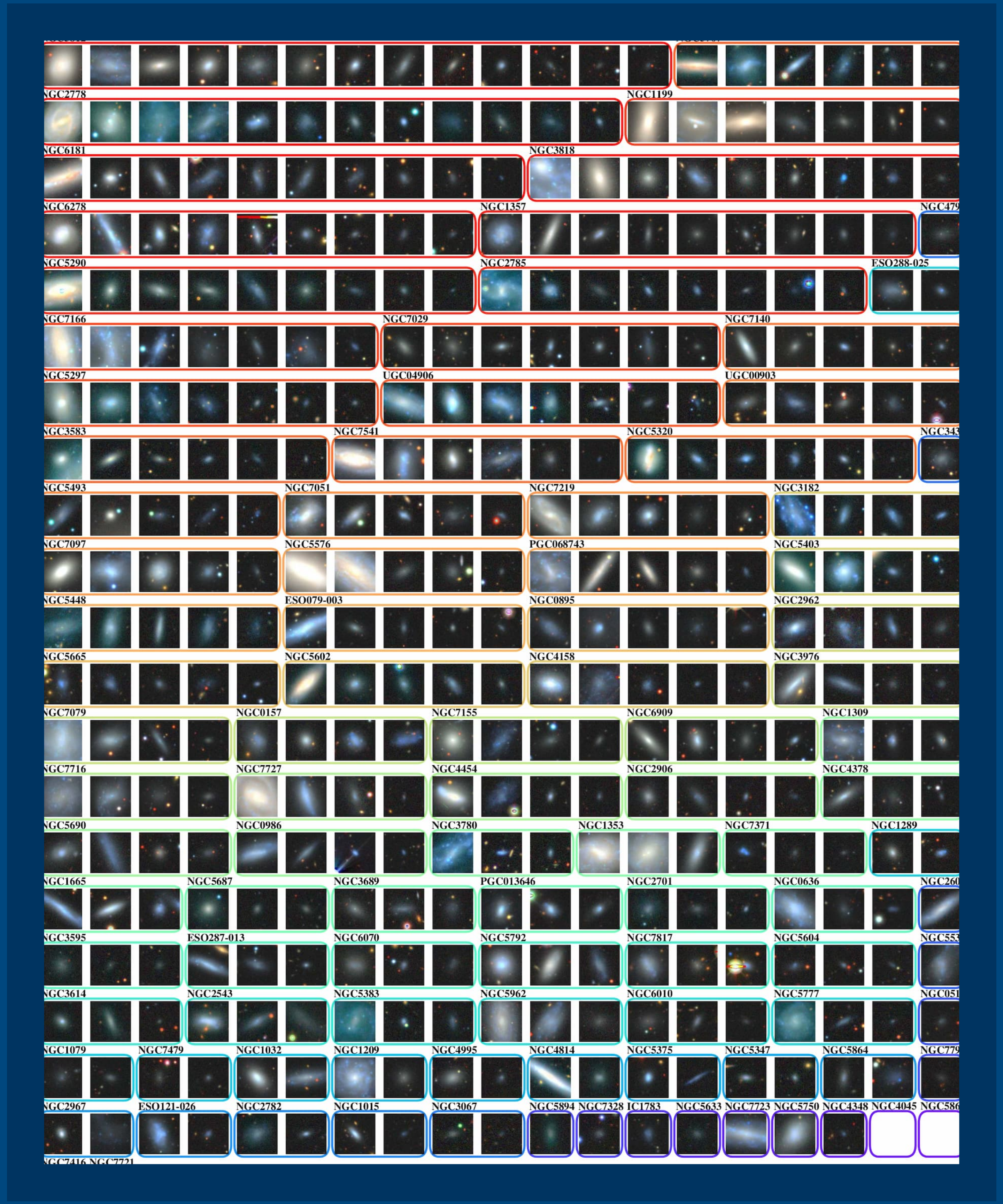
What is the probability that we will achieve redshift success for this galaxy?

We need a large sample of low-mass, low-redshift galaxies with a well-understood selection function.

Kado-Fong+2024b

the SAGA survey

DATA RELEASE 3



the

SAGA

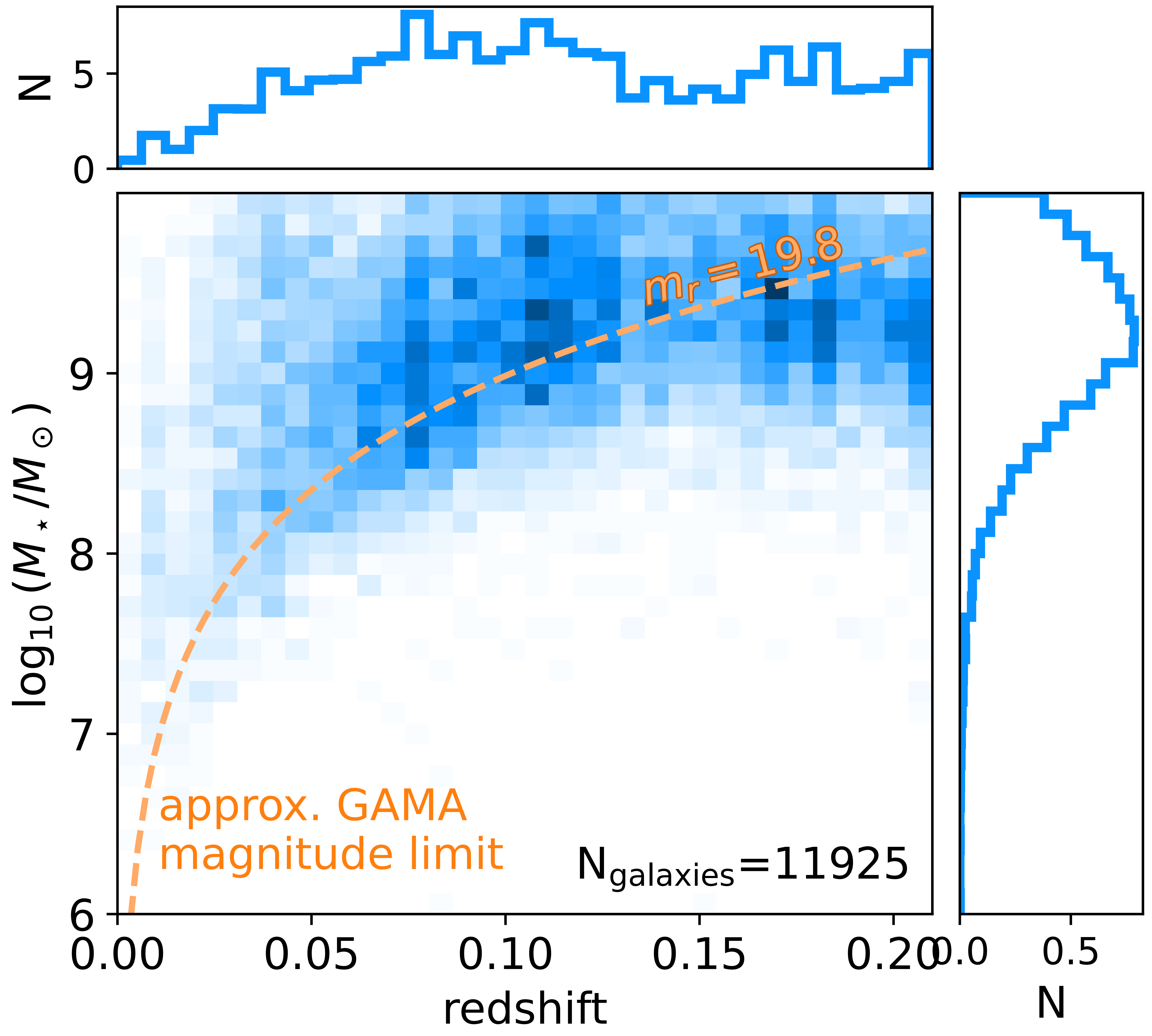
survey

DATA RELEASE 3

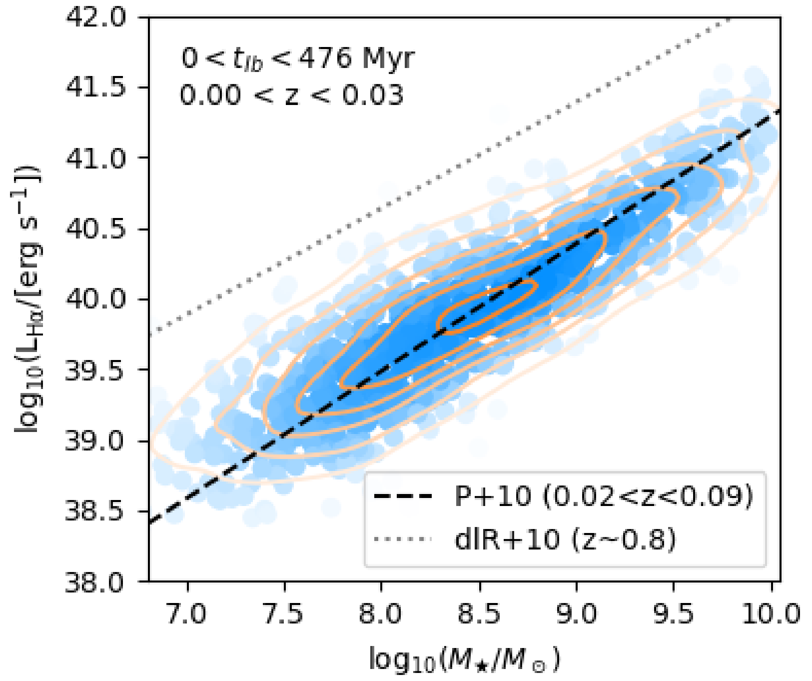
378 satellites,
but took 40,000+ spectra.

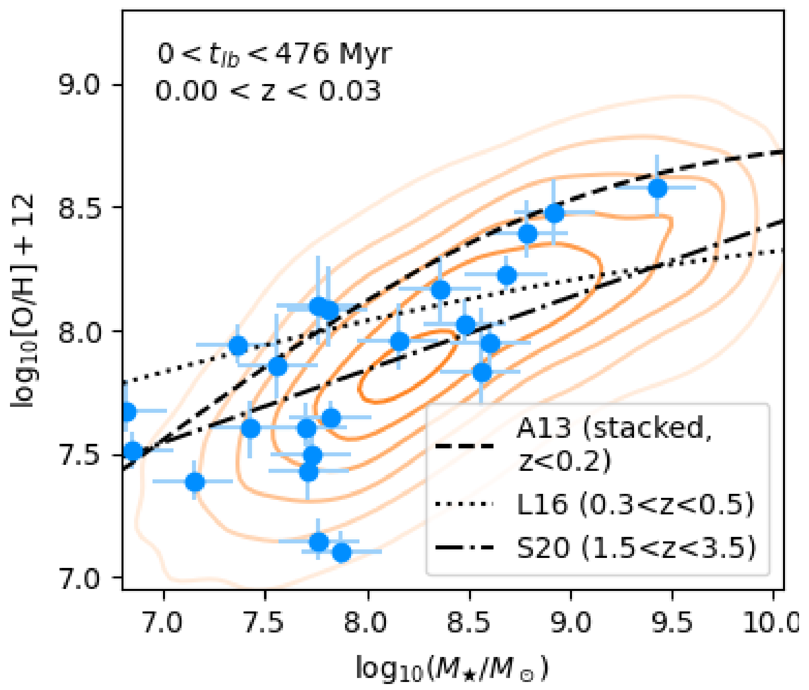
These background spectra are low-mass, low-redshift galaxies,

and have a well-characterized selection function.



Rewinding the Star Formation Cycle





$t_{lb} \lesssim 500$ Myr

From $z \sim 0$,

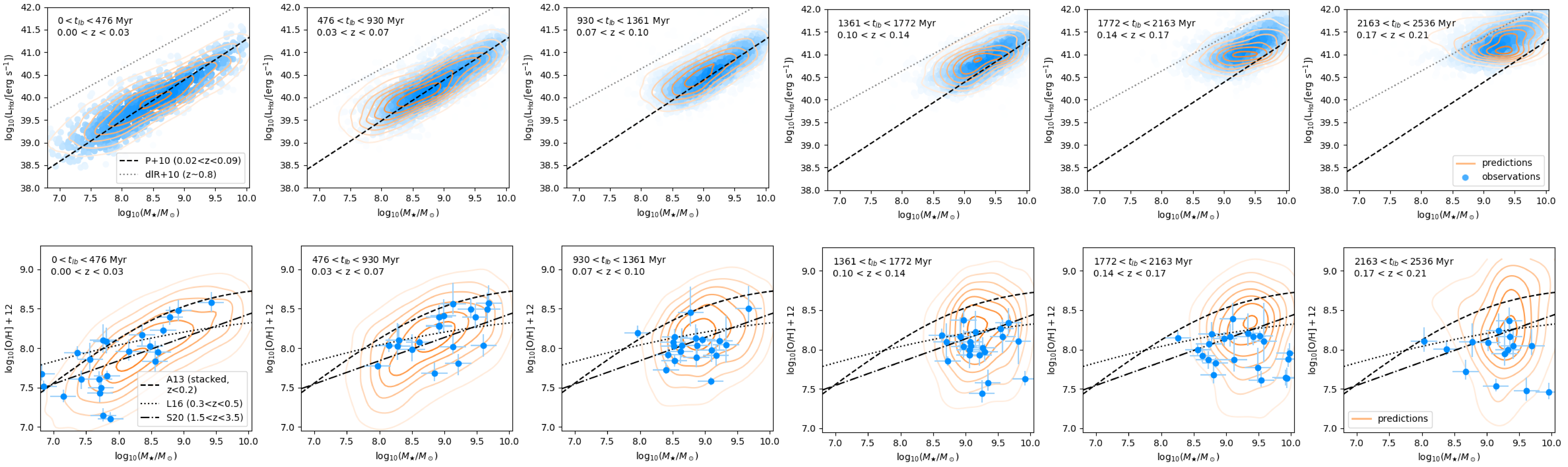
Observations

Predictions

Kado-Fong+2024b

Rewinding the Star Formation Cycle

predict evolution in $M_\star - \mathrm{SFR} - Z_O$ space



$t_{lb} \lesssim 500$ Myr

$t_{lb} \sim 2.5$ Gyr

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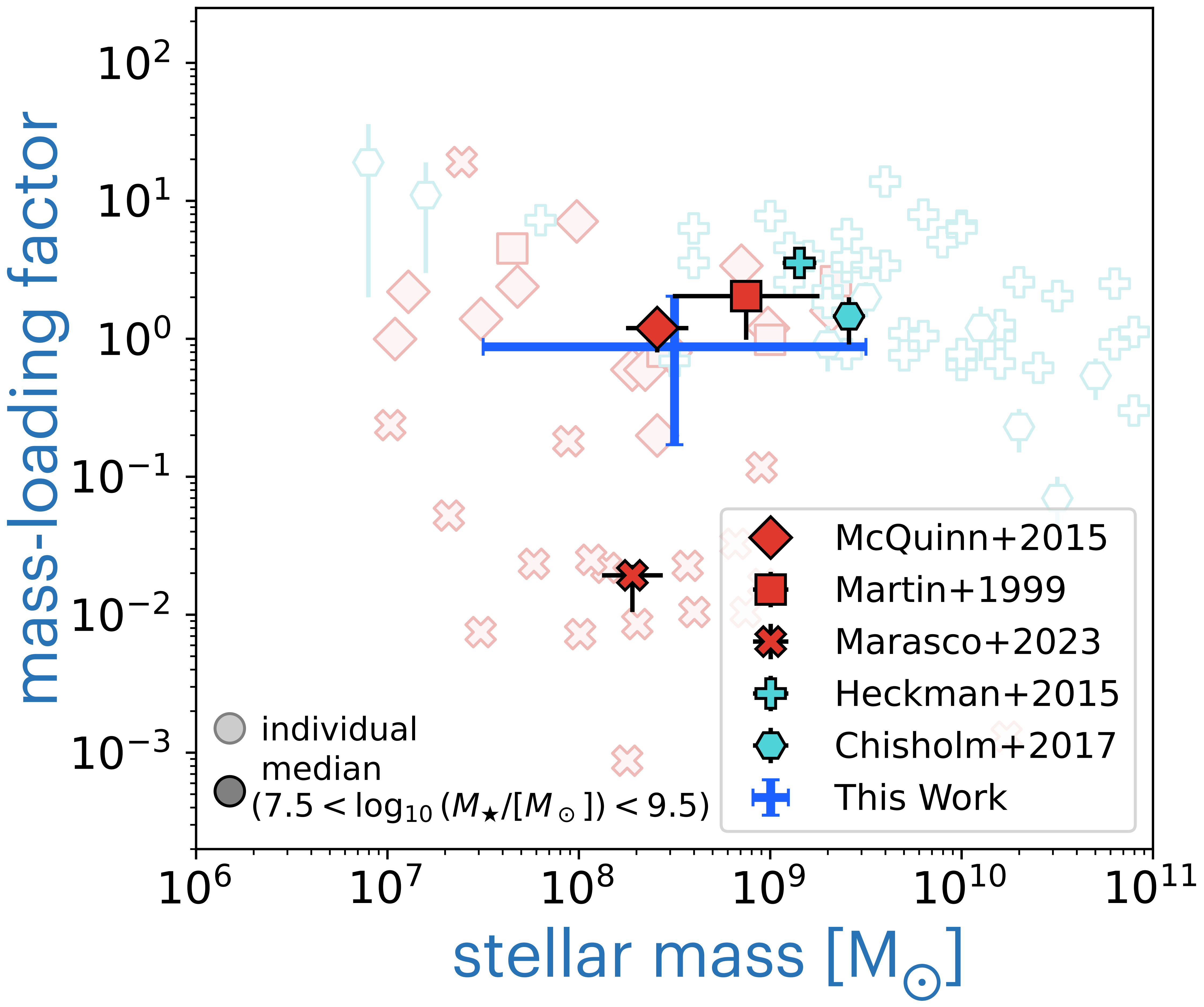


We find

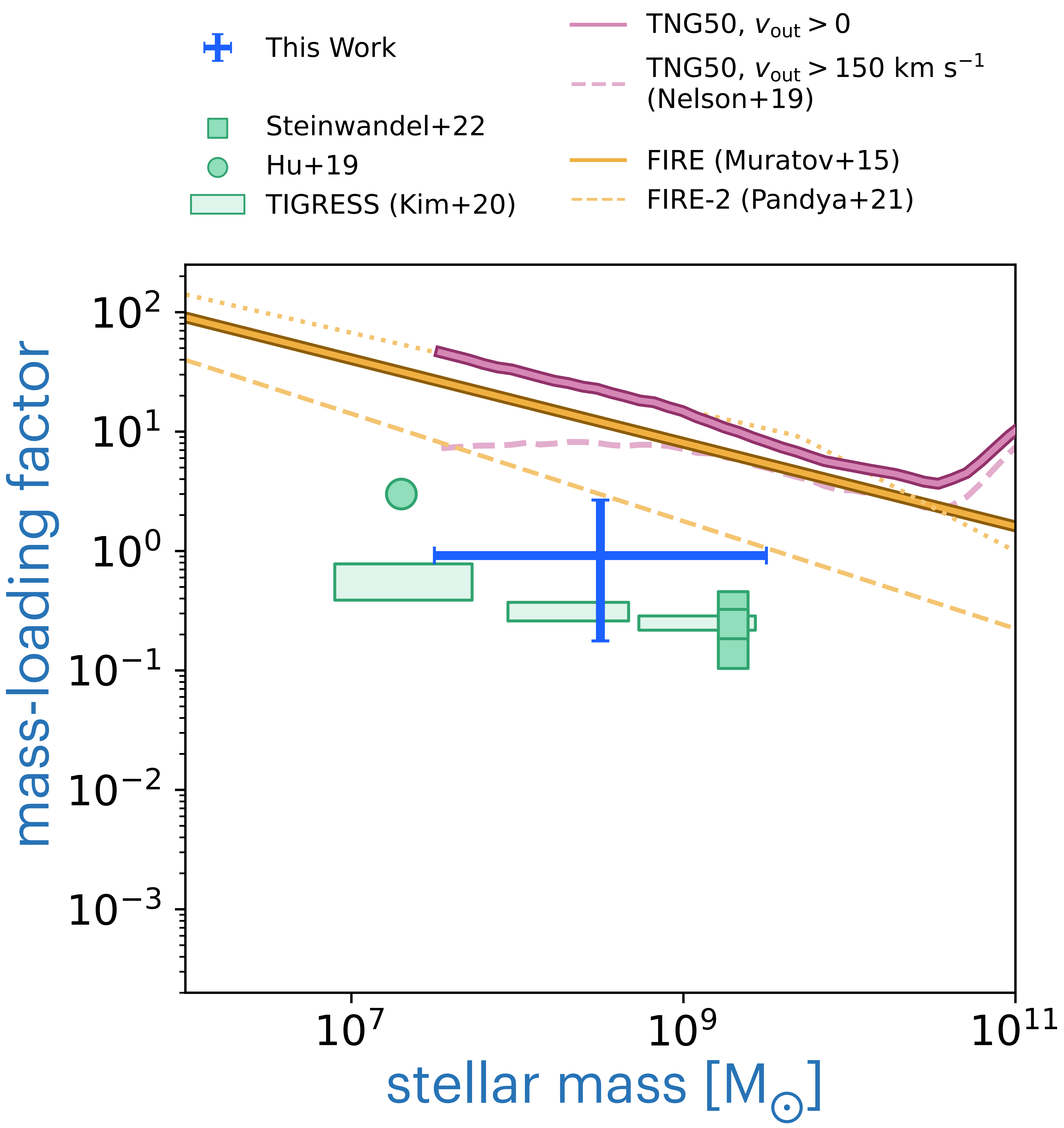
$\eta_m = 0.92 \pm 0.75,$

in good agreement with direct observations in

Hα and UV

despite very different assumptions!

Kado-Fong+2024b



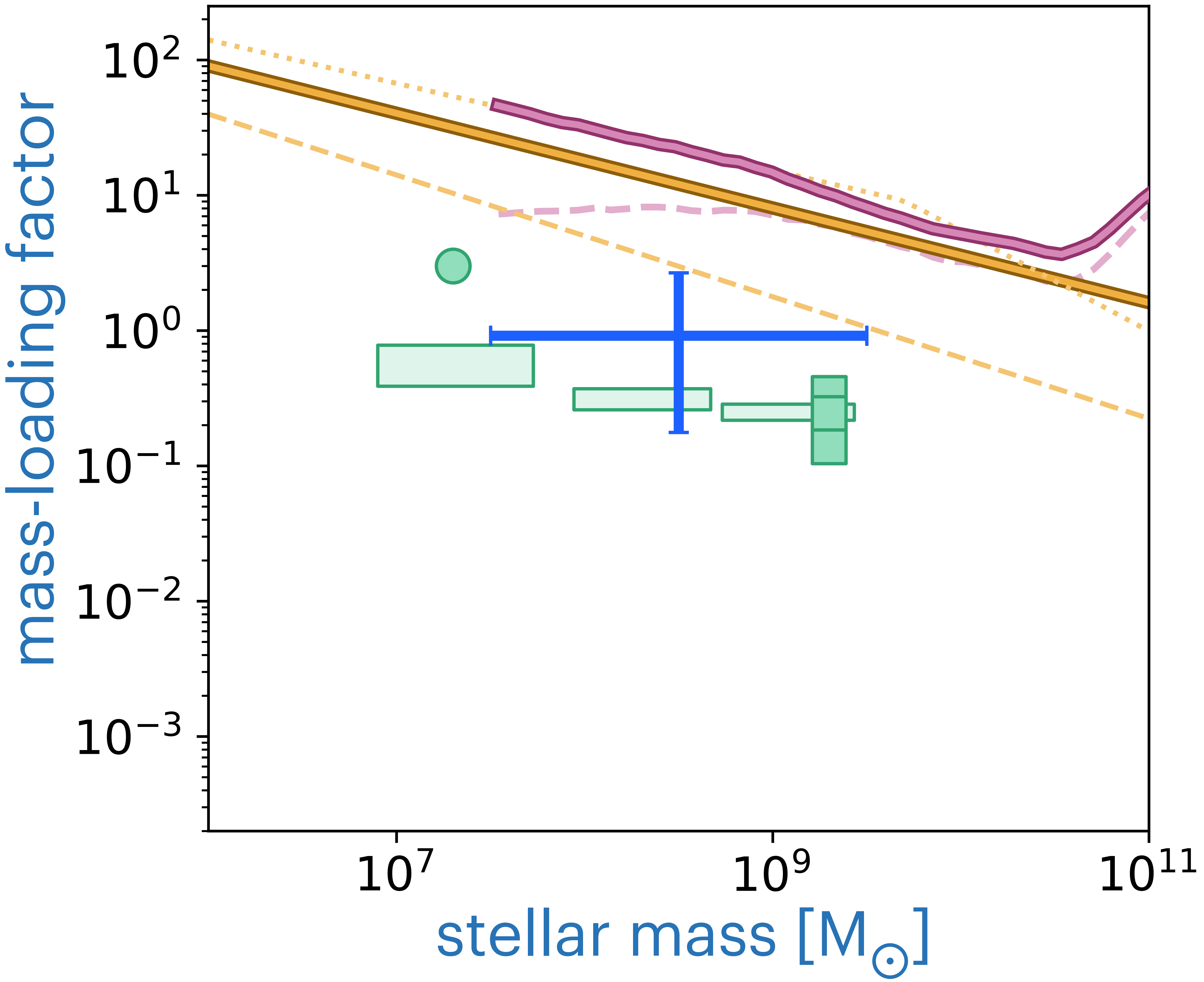
$\eta_m \approx 1$

in agreement with
ISM-scale sims

significantly lower than
cosmological simulations*
($\eta_m \approx 20 - 100$).

Kado-Fong+2024b

How efficiently does star formation drive winds in low-mass galaxies?

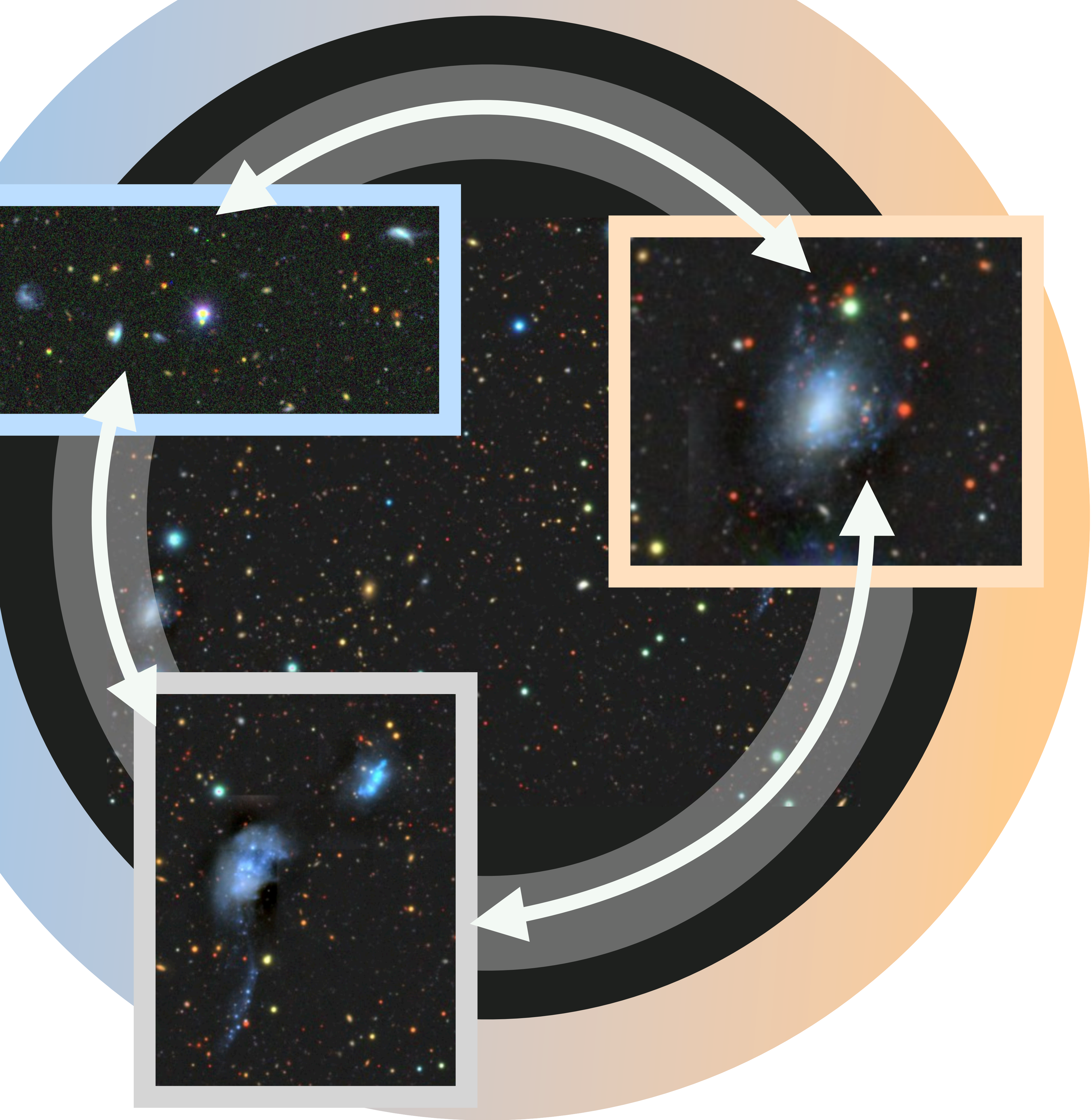


Star formation drives moderately efficient winds in low-mass galaxies ($\eta_m \approx 1$).

This mass-loading factor is in good agreement with direct observations of individual dwarfs,

and significantly lower than some predictions from cosmological simulations.

Kado-Fong+2024b



Statistical Measures of Star Formation Regulation in Dwarfs, Two Ways:

Driving galactic winds.

Evolution in the "low-z" Star-Forming Sequence of dwarfs.

How does the average star-forming dwarf change between z=0 and "z~0"?

Low redshift samples are often treated as context for Local (Group/Volume/etc.) samples.

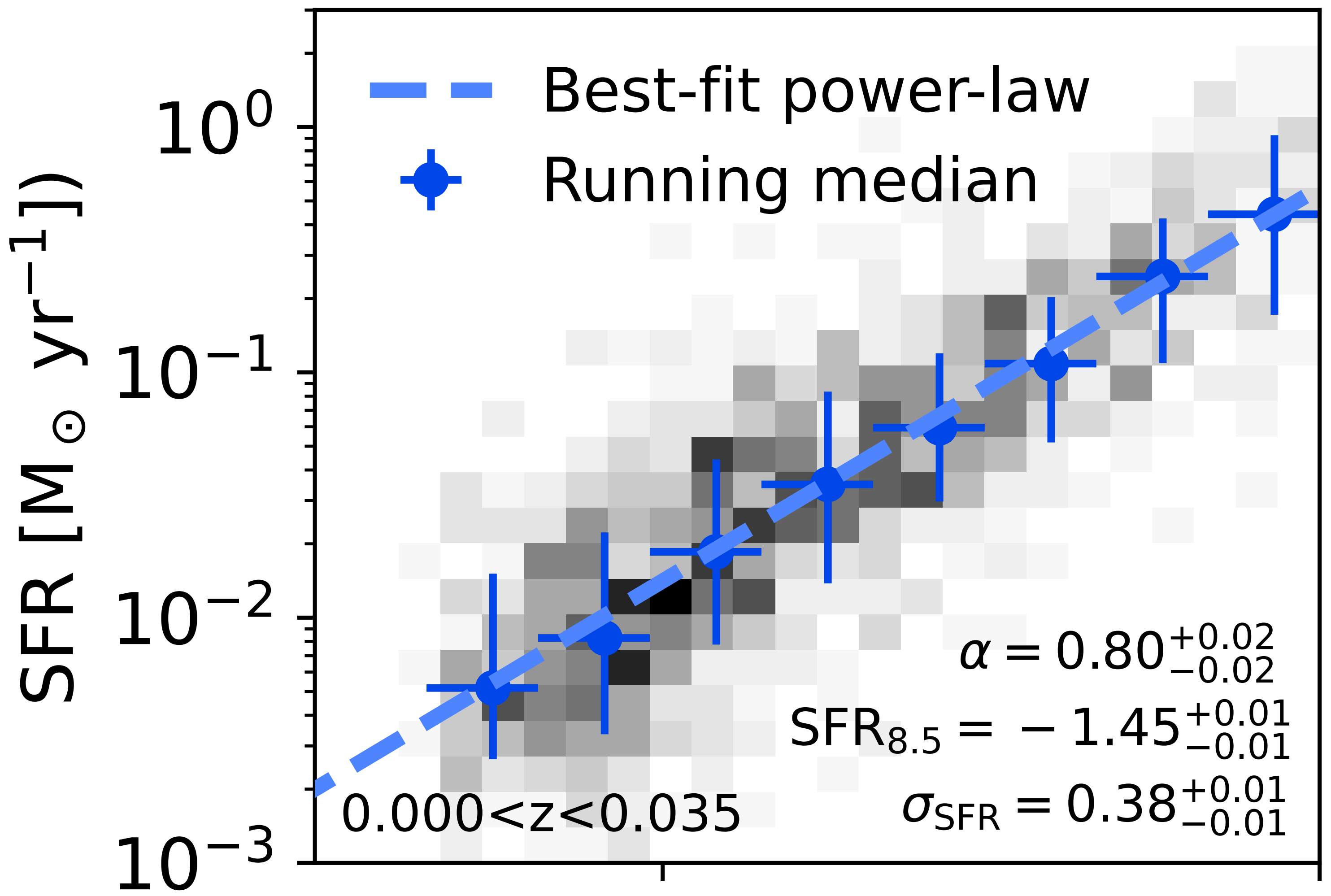
However, the Universe is always evolving.

In the era of high precision surveys of low-mass galaxies at both z=0 and z~0,

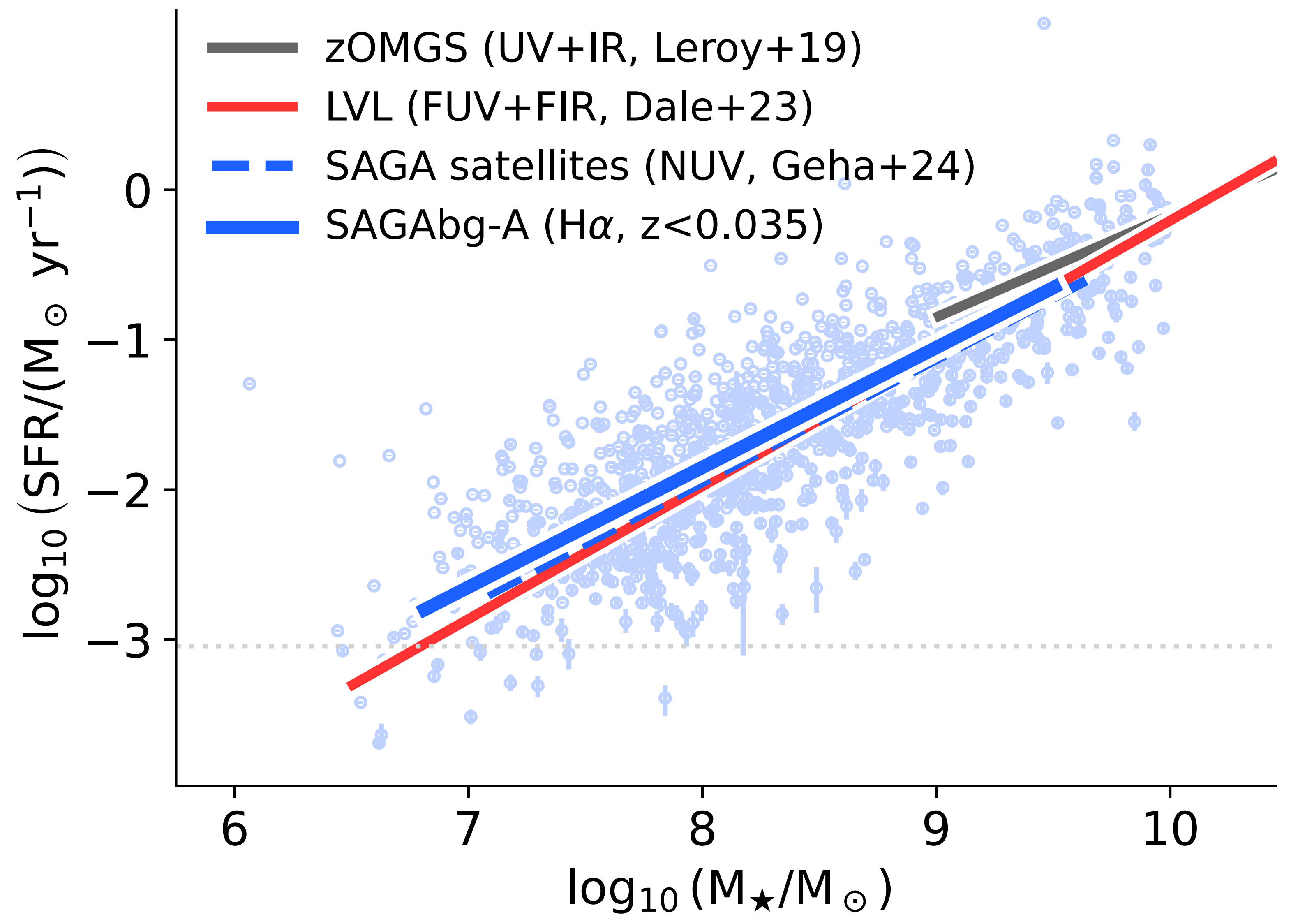
e.g. LVL, Z0MGs, SAGA, ELVES, ++ e.g. Merian, DESI LOW-Z, ++

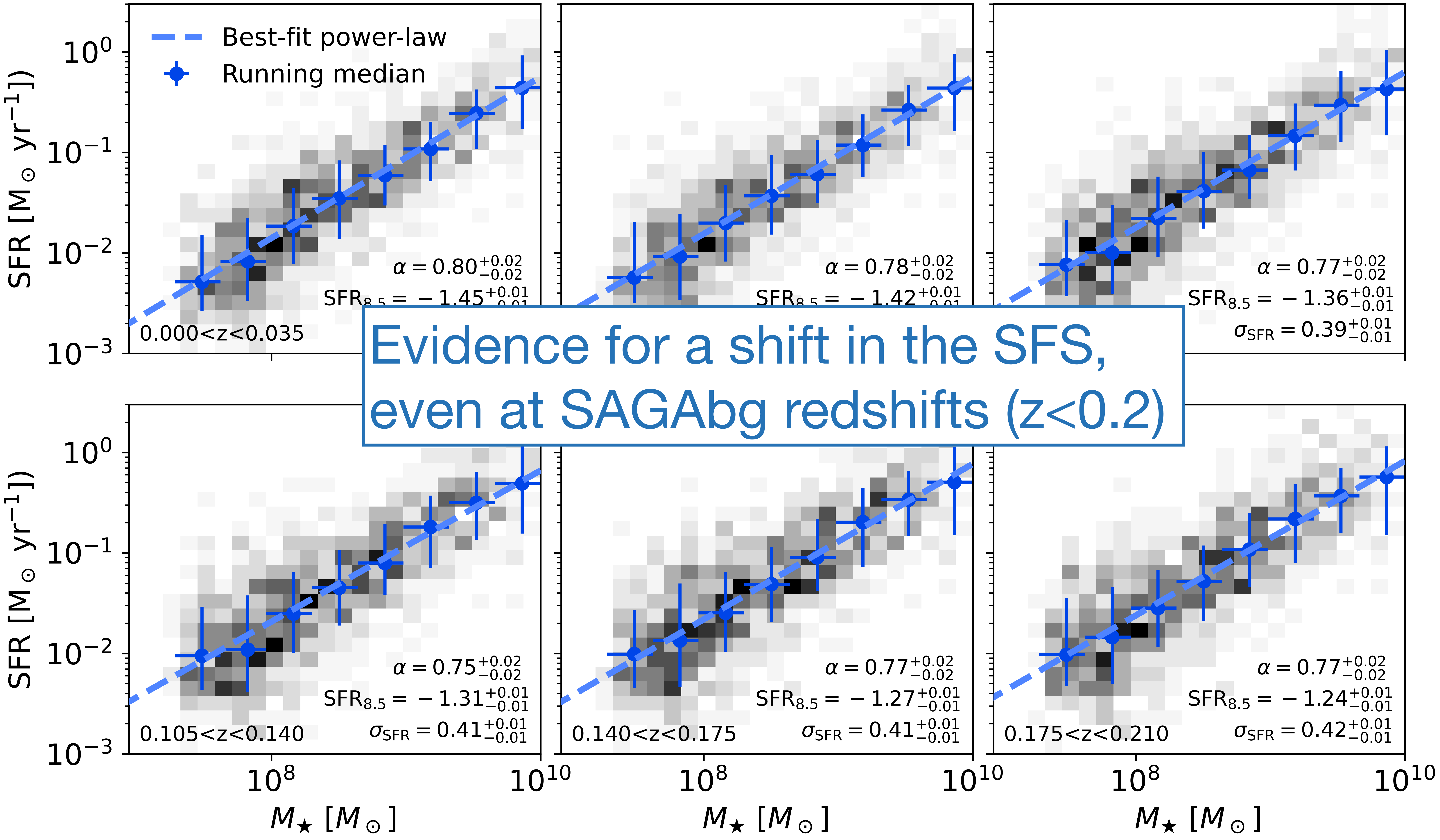
The low-redshift evolution of dwarf scaling relations becomes *statistically significant* and *cosmologically constraining*.

WHAT DOES THE LOW-Z EVOLUTION OF THE STAR-FORMING SEQUENCE MEAN FOR CONTEXTUALIZING DWARFS?

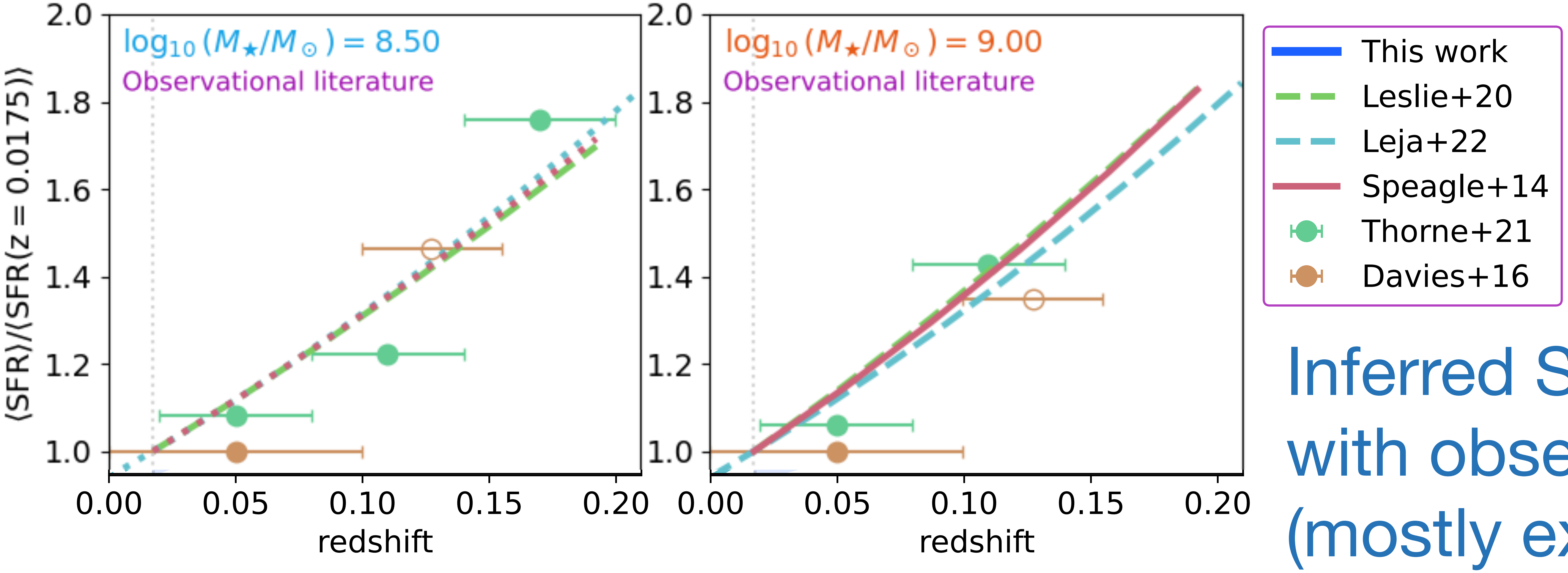


With the same retrogression framework, remove observational constraints to fit the intrinsic Star-Forming Sequence.



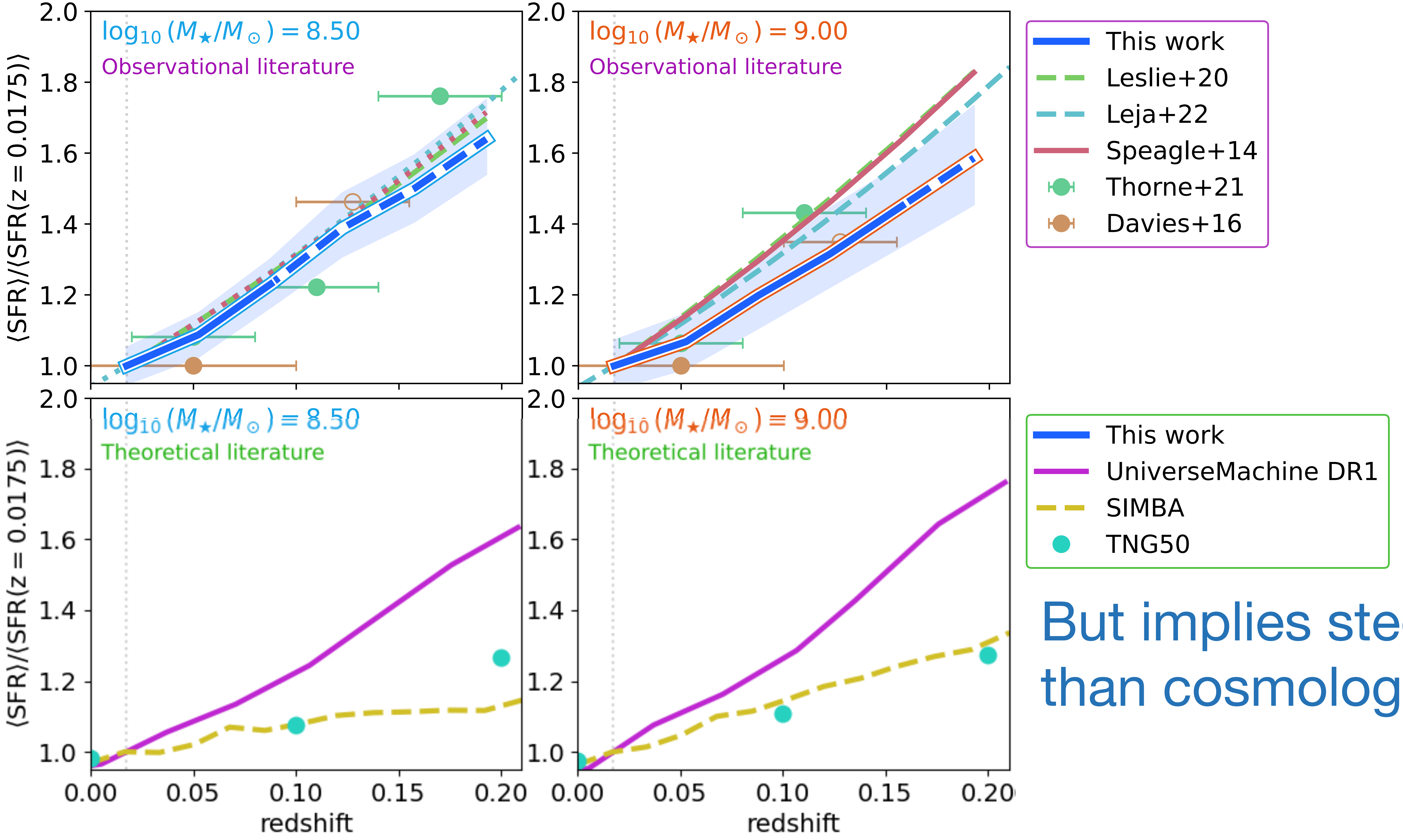


Best-fit power-law
Running median
SFR [M⊙ yr⁻¹]
$M_\star$ [$M_\odot$]
$\alpha = 0.80^{+0.02}_{-0.02}$
$\alpha = 0.78^{+0.02}_{-0.02}$
$\alpha = 0.77^{+0.02}_{-0.02}$
$\mathrm{SFR}_{8.5} = -1.36^{+0.01}_{-0.01}$
$\sigma_{\mathrm{SFR}} = 0.39^{+0.01}_{-0.01}$
0.000<z<0.035
Evidence for a shift in the SFS,
even at SAGAbg redshifts (z<0.2)
$\alpha = 0.75^{+0.02}_{-0.02}$
$\mathrm{SFR}_{8.5} = -1.31^{+0.01}_{-0.01}$
$\sigma_{\mathrm{SFR}} = 0.41^{+0.01}_{-0.01}$
0.105<z<0.140
$\alpha = 0.77^{+0.02}_{-0.02}$
$\mathrm{SFR}_{8.5} = -1.27^{+0.01}_{-0.01}$
$\sigma_{\mathrm{SFR}} = 0.41^{+0.01}_{-0.01}$
0.140<z<0.175
$\alpha = 0.77^{+0.02}_{-0.02}$
$\mathrm{SFR}_{8.5} = -1.24^{+0.01}_{-0.01}$
$\sigma_{\mathrm{SFR}} = 0.42^{+0.01}_{-0.01}$
0.175<z<0.210



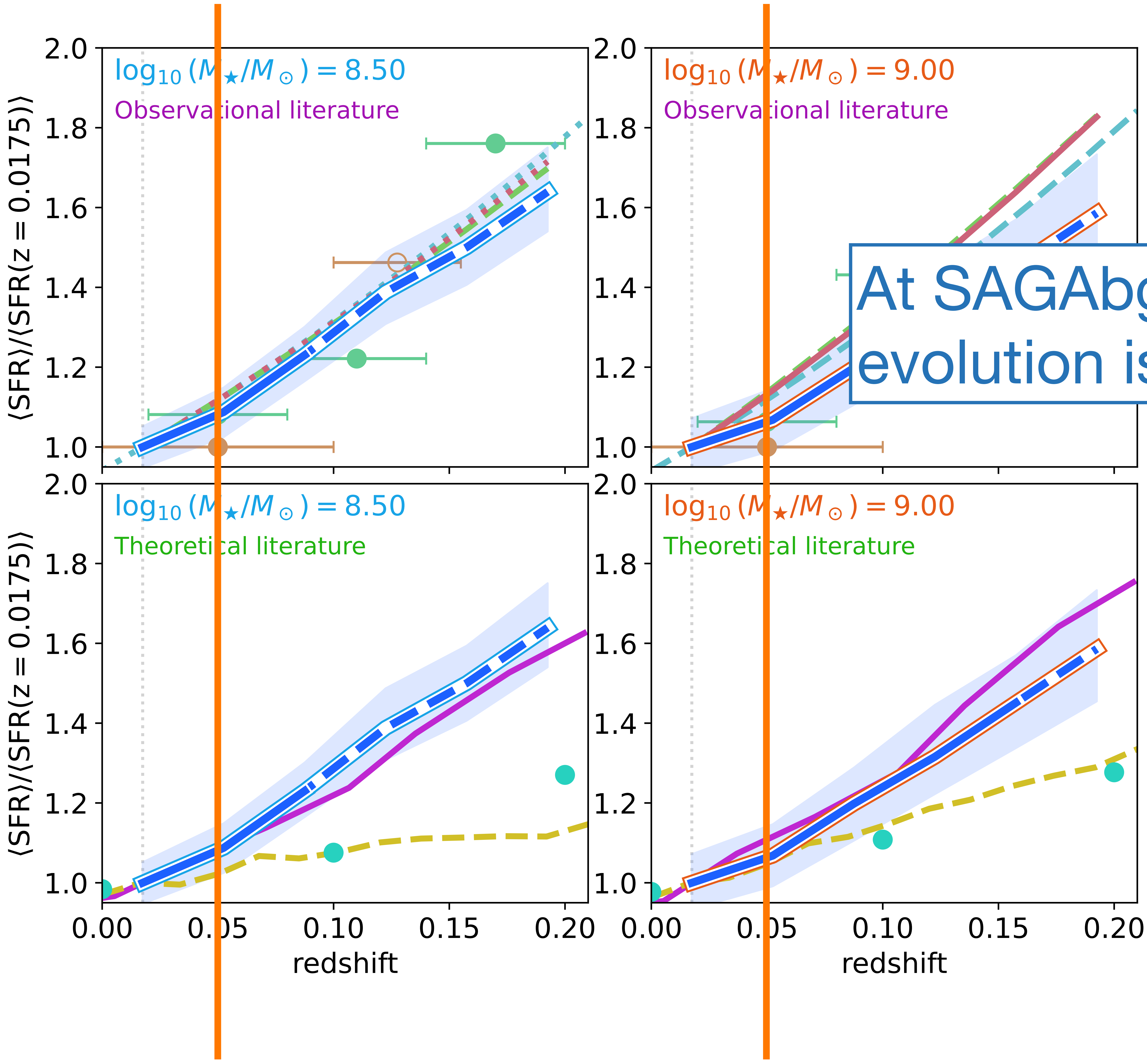
Inferred SFS agrees with observational literature (mostly extrapolations)

Kado-Fong+2024c, in prep.



But implies steeper evolution than cosmological simulations

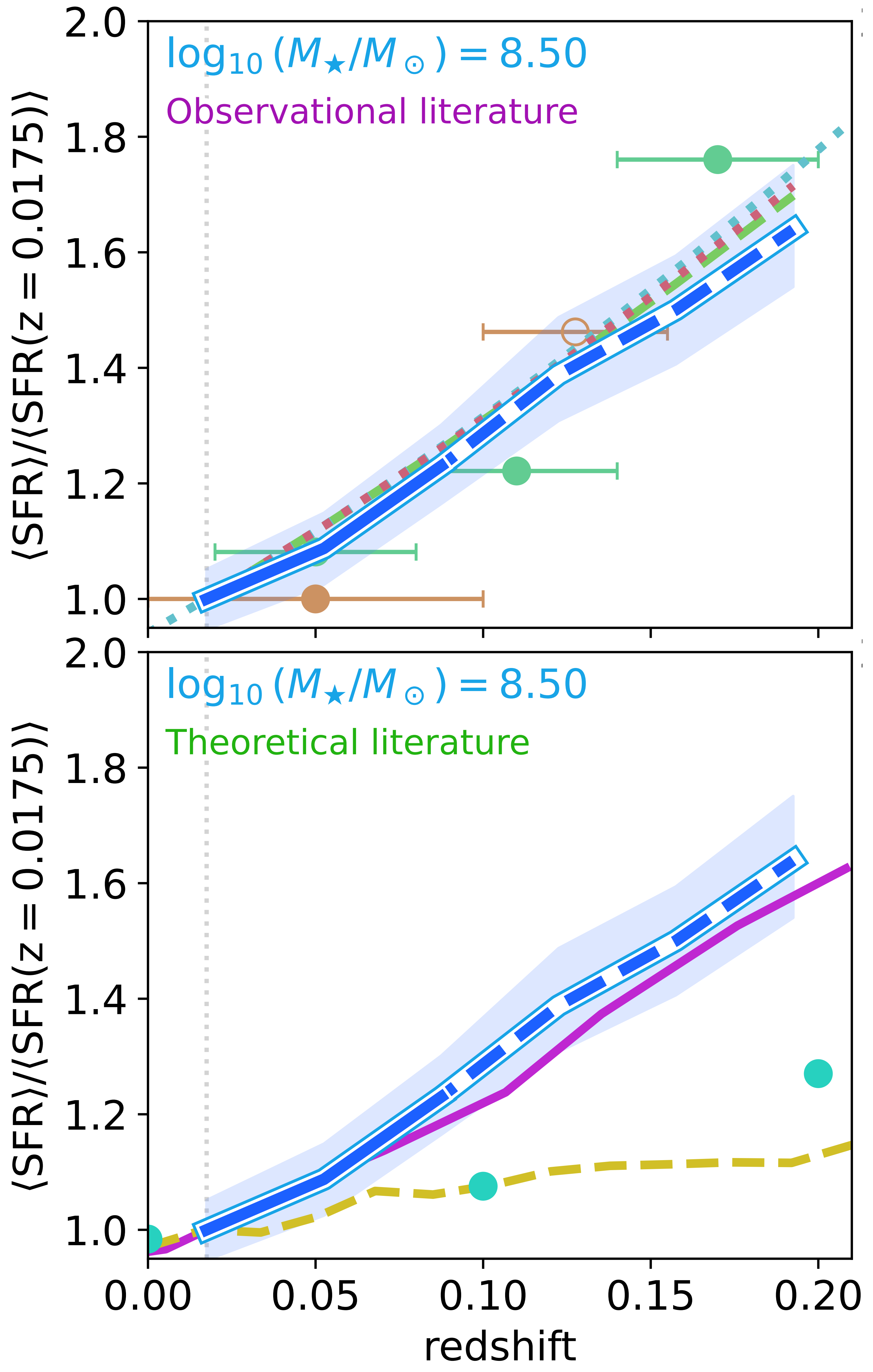
Kado-Fong+2024c, in prep.



At SAGAbg-A precision, redshift evolution is significant at z=0.05

A strict comparison between z=0 and z=0.05 samples can confound redshift evolution with other physics.

Kado-Fong+2024c, in prep.



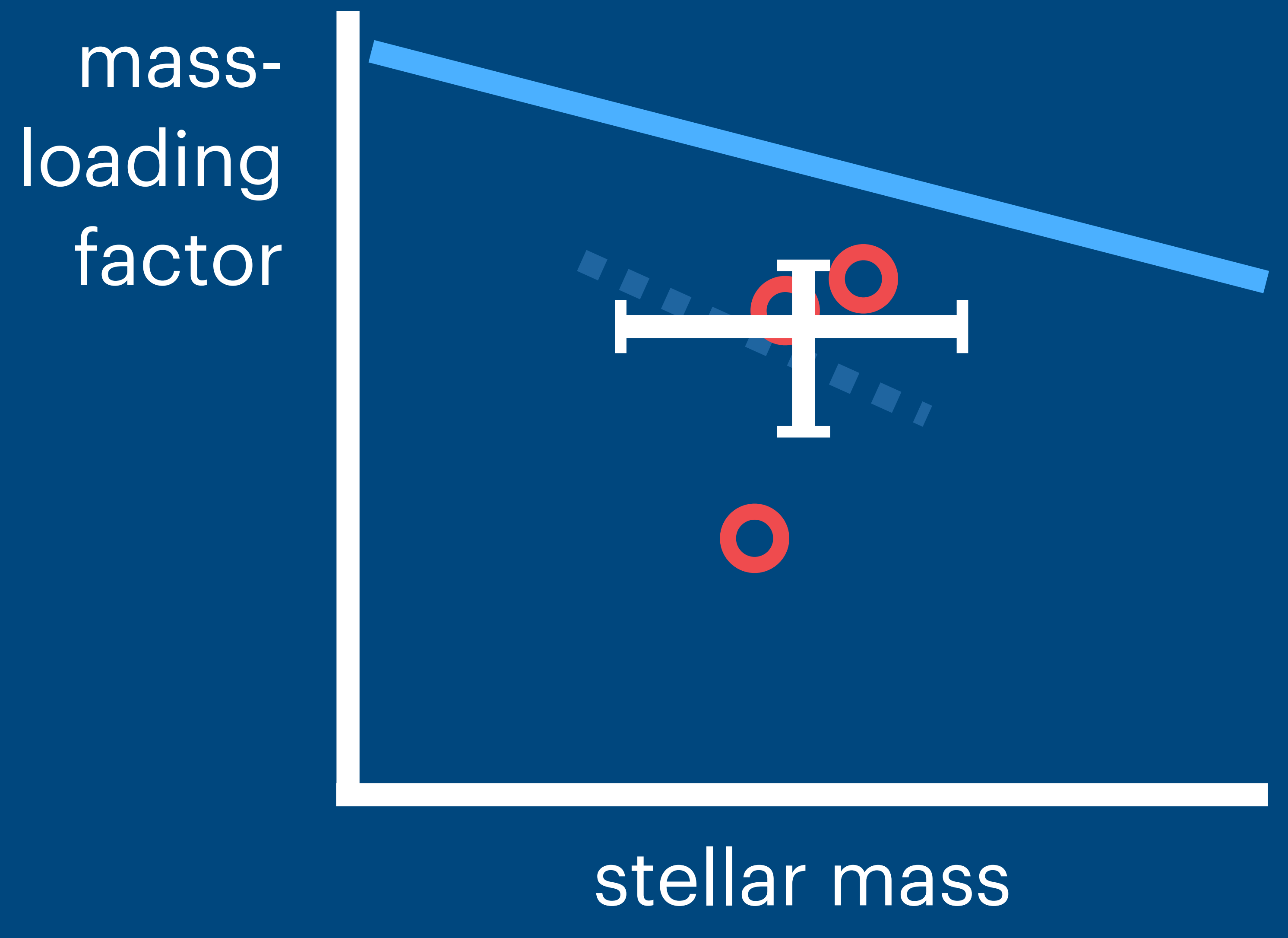
What does low-z SFS evolution mean for contextualizing dwarfs?

The evolution of the dwarf population continues down to z~0!

Simulated dwarf populations may underpredict the low-z evolution of the SFS.

In the era of precision extragalactic astrophysics, it is increasingly important to disambiguate z=0 and z~0.

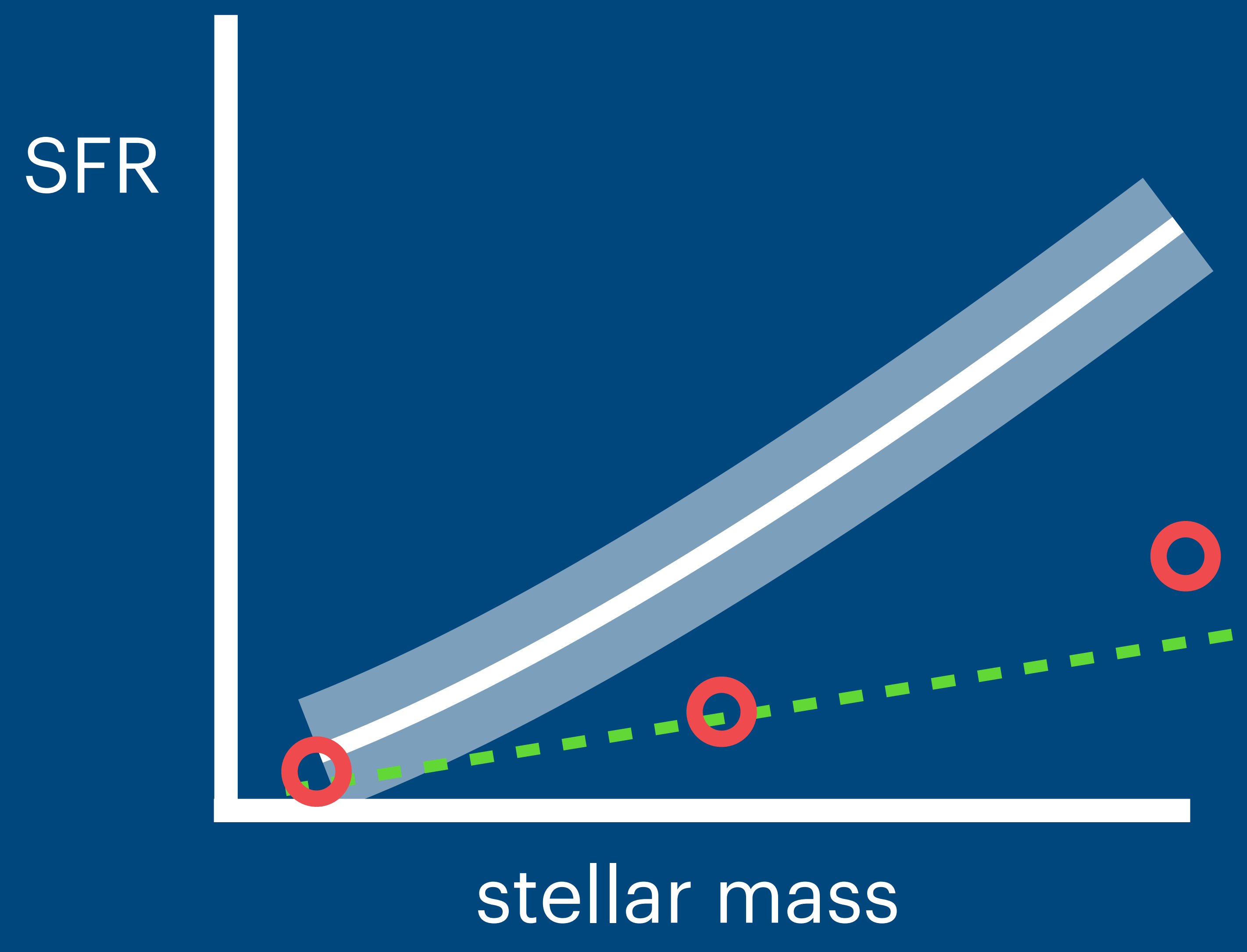
Star formation drives moderately efficient winds in low-mass galaxies; much lower than what some simulations use to make realistic dwarfs.
Kado-Fong +2024b



The low-redshift evolution of the low-mass Star Forming Sequence constrains dwarf assembly, and must be considered to disambiguate redshift evolution from other astrophysical processes.

(such as the effect of environment!)

Kado-Fong +2024c, in prep.



Dwarf galaxies are a unique and increasingly accessible probe of star formation physics on galactic scales