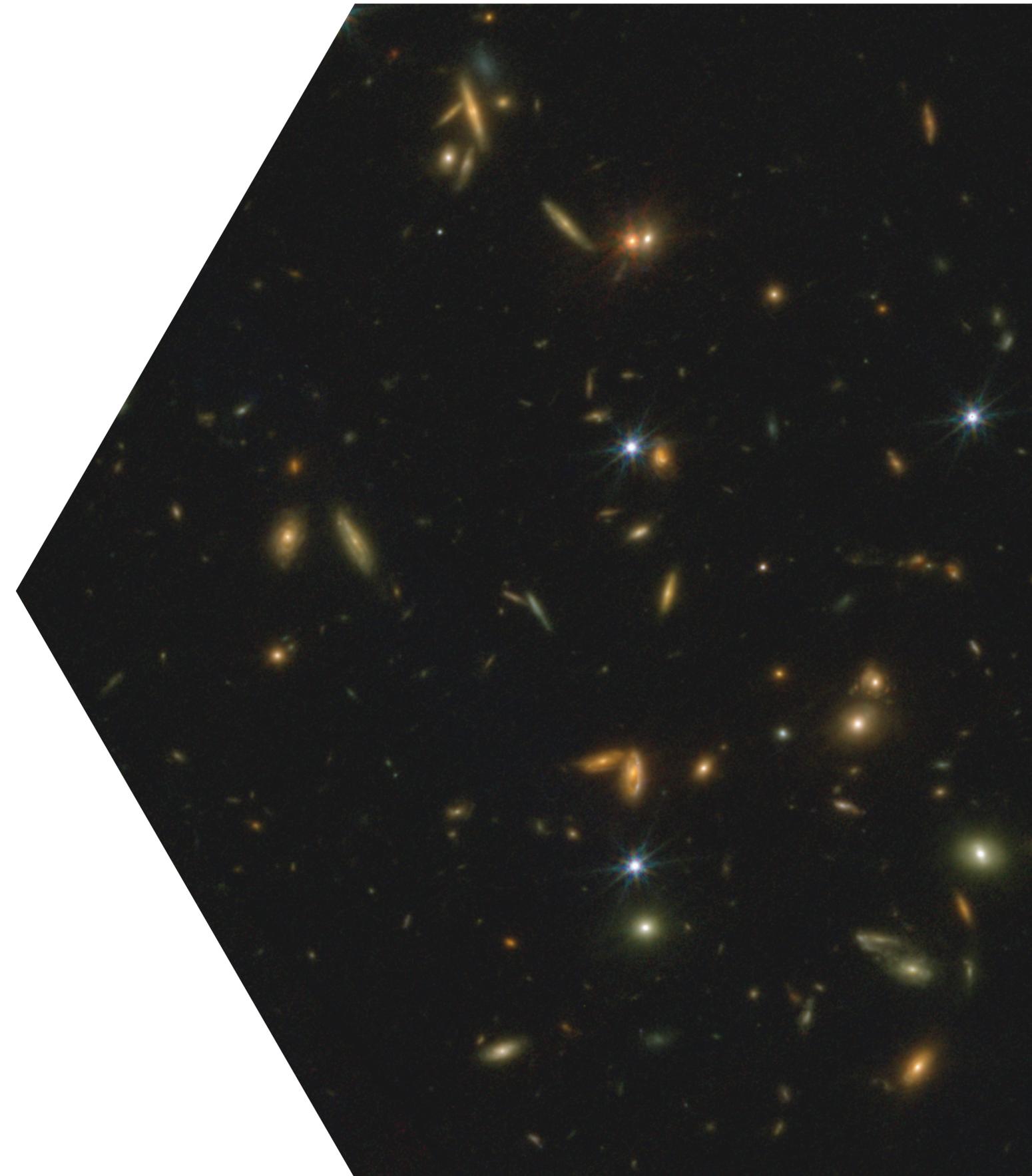# Galaxy growth in dark matter halos
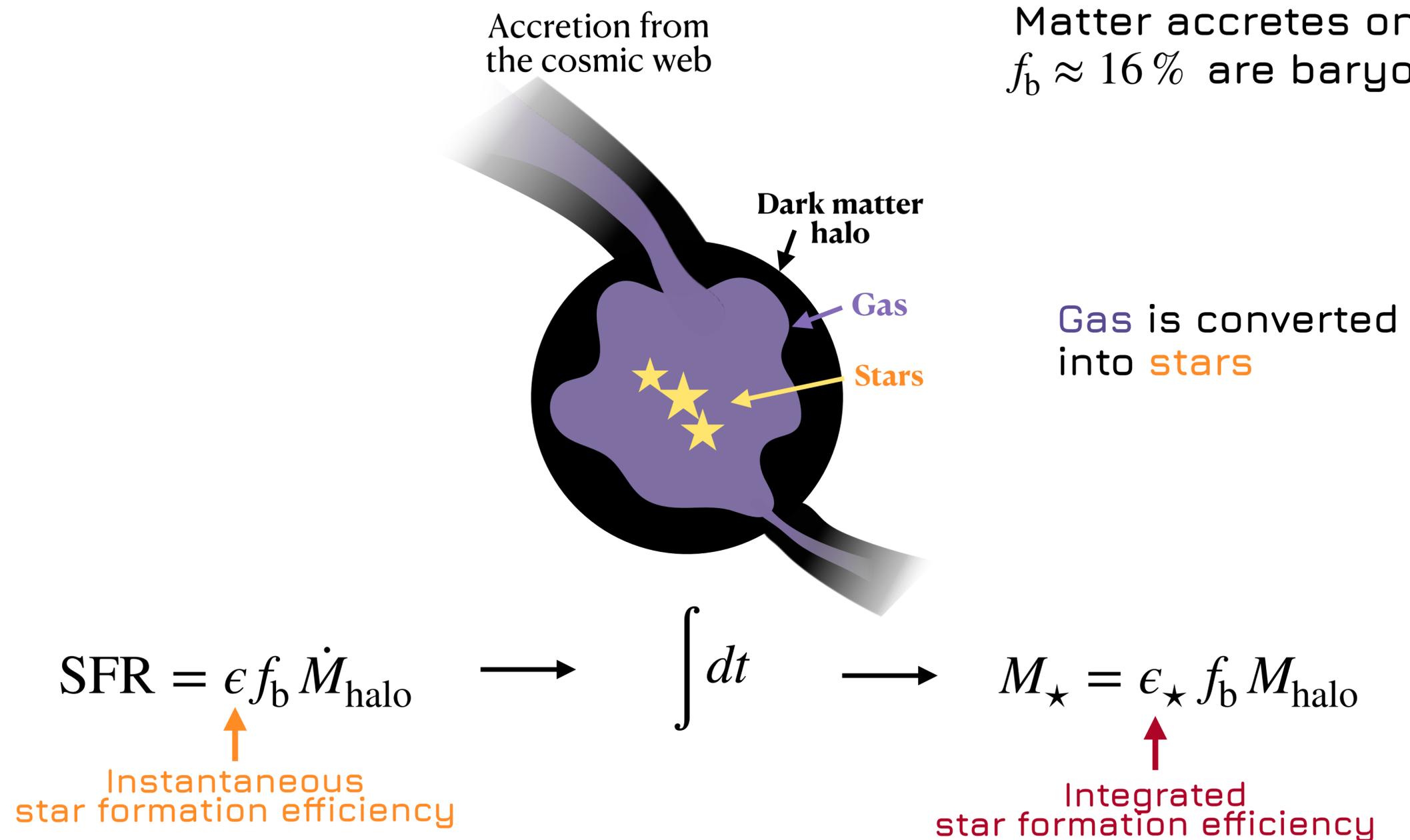## Insights from COSMOS-Web and FRESCO

Marko Shuntov
Postdoc at DAWN

+ Sune Toft, Olivier Ilbert,, Louise Paquereau, Hollis Akins, Rafael Arango-Toro, Max Franco, Henry Joy McCracken, Clotilde Laigle, Jeyhan Kartaltepe
+ Pascal Oesch, Alba Covelo-Paz, Romain Meyer, Andrea Weibel

DAWN

Danmarks
Grundforskningsfond
Danish National
Research Foundation

A simple model of galaxy formation within dark matter halos

A simple model of galaxy formation within dark matter halos

Accretion from
the cosmic web

Matter accretes onto halos
$f_{\rm b} \approx 16\,\%$ are baryons

**Dark matter
halo**

Gas

Gas is converted
into stars

Stars

$$\mathrm{SFR} = \epsilon f_{\rm b} \dot{M}_{\rm halo} \quad \longrightarrow \quad \int dt \quad \longrightarrow \quad M_\star = \epsilon_\star f_{\rm b} M_{\rm halo}$$

Instantaneous
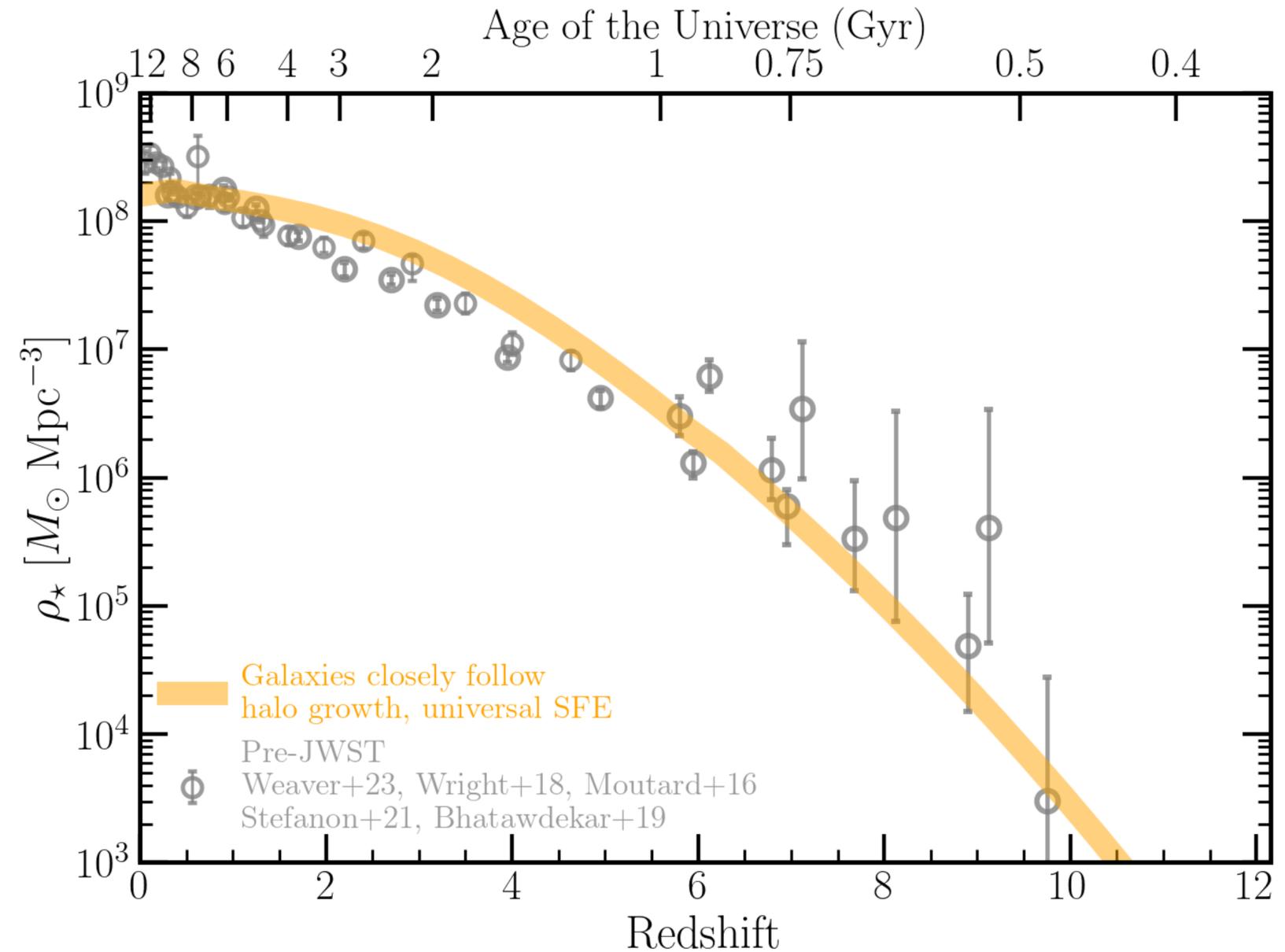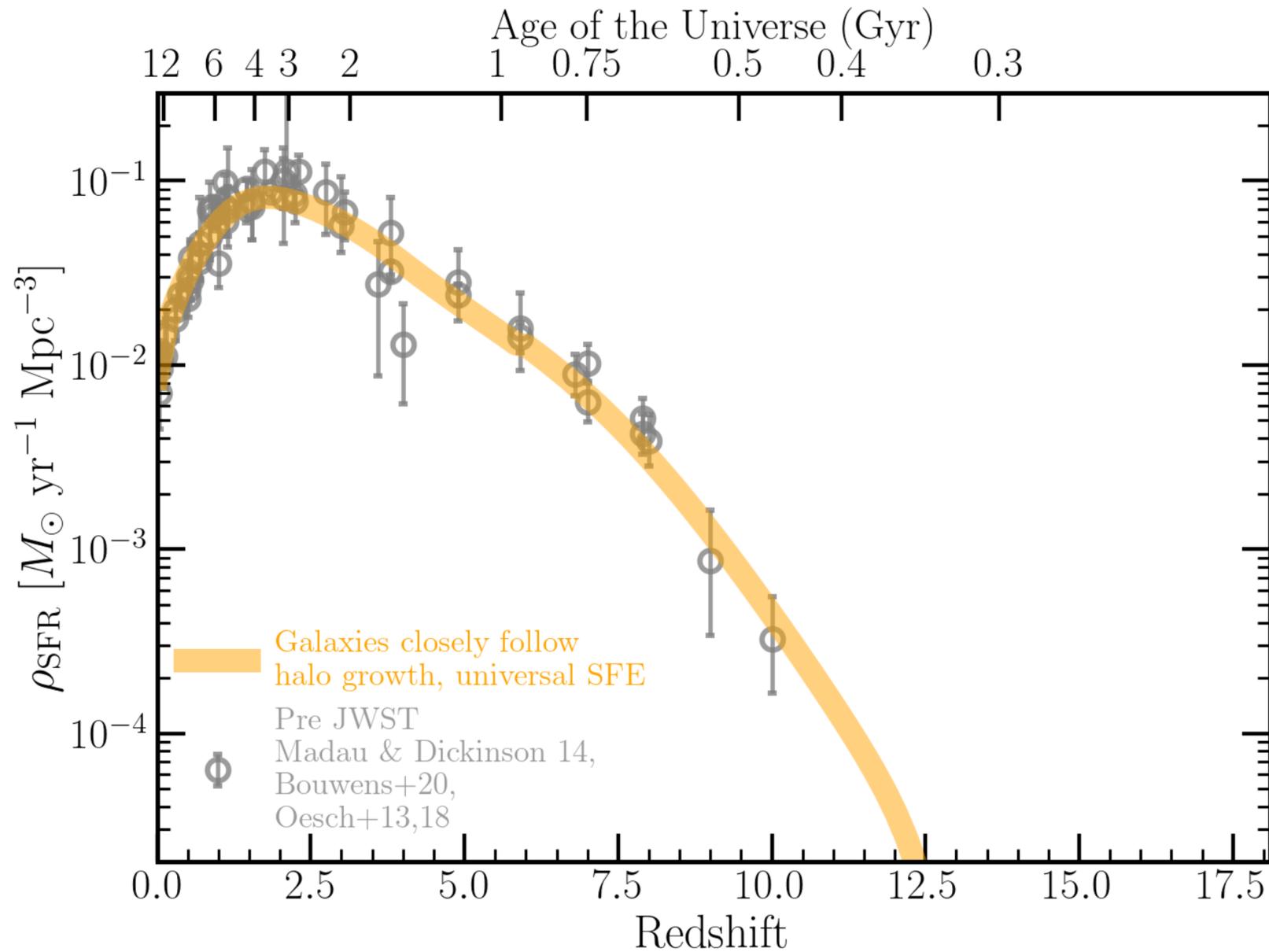star formation efficiency

Integrated
star formation efficiency

One of the central quests in astronomy has been accurately measuring the star formation history of our Universe and building our theoretical models of galaxy formation within the cosmological context
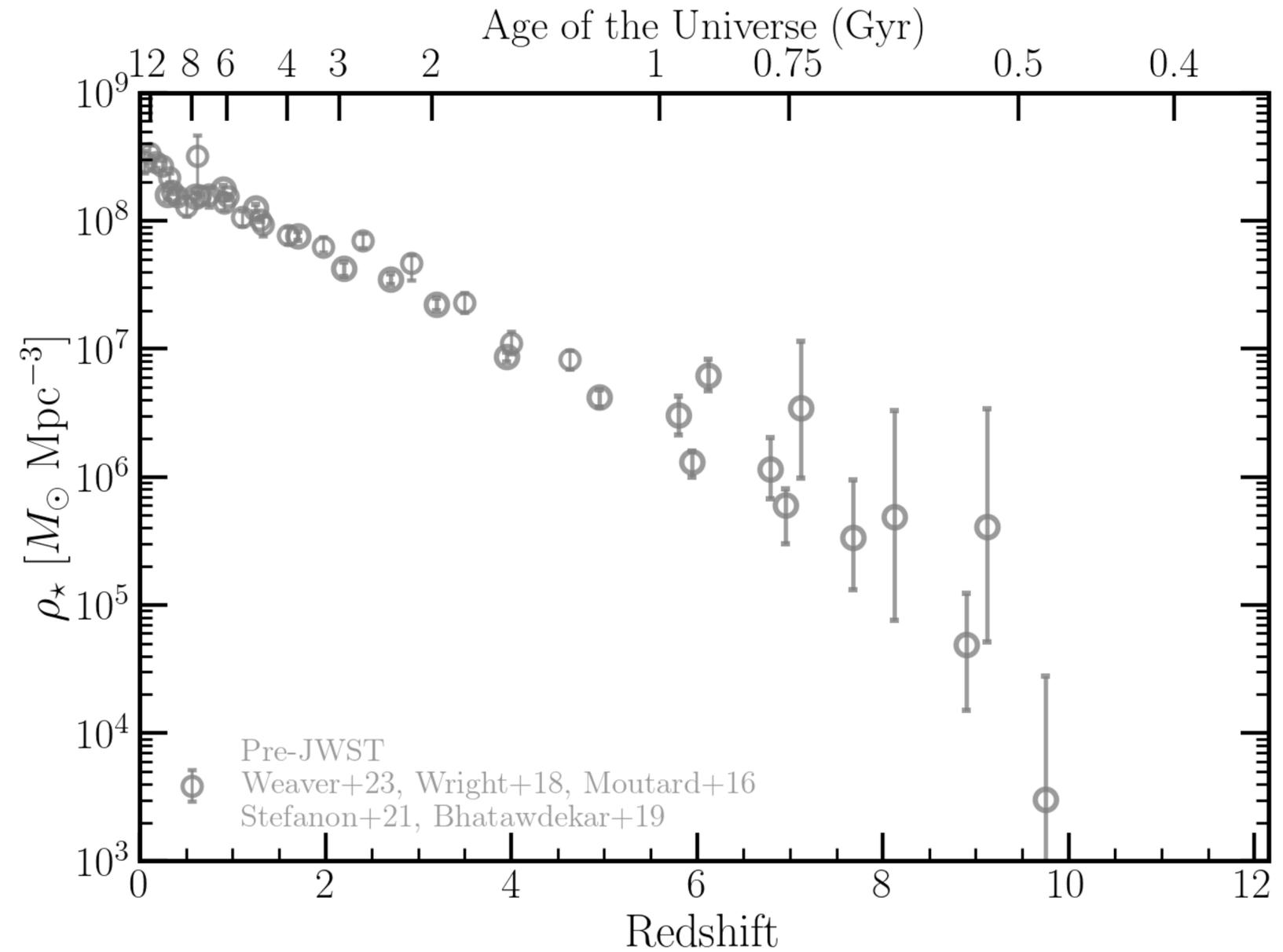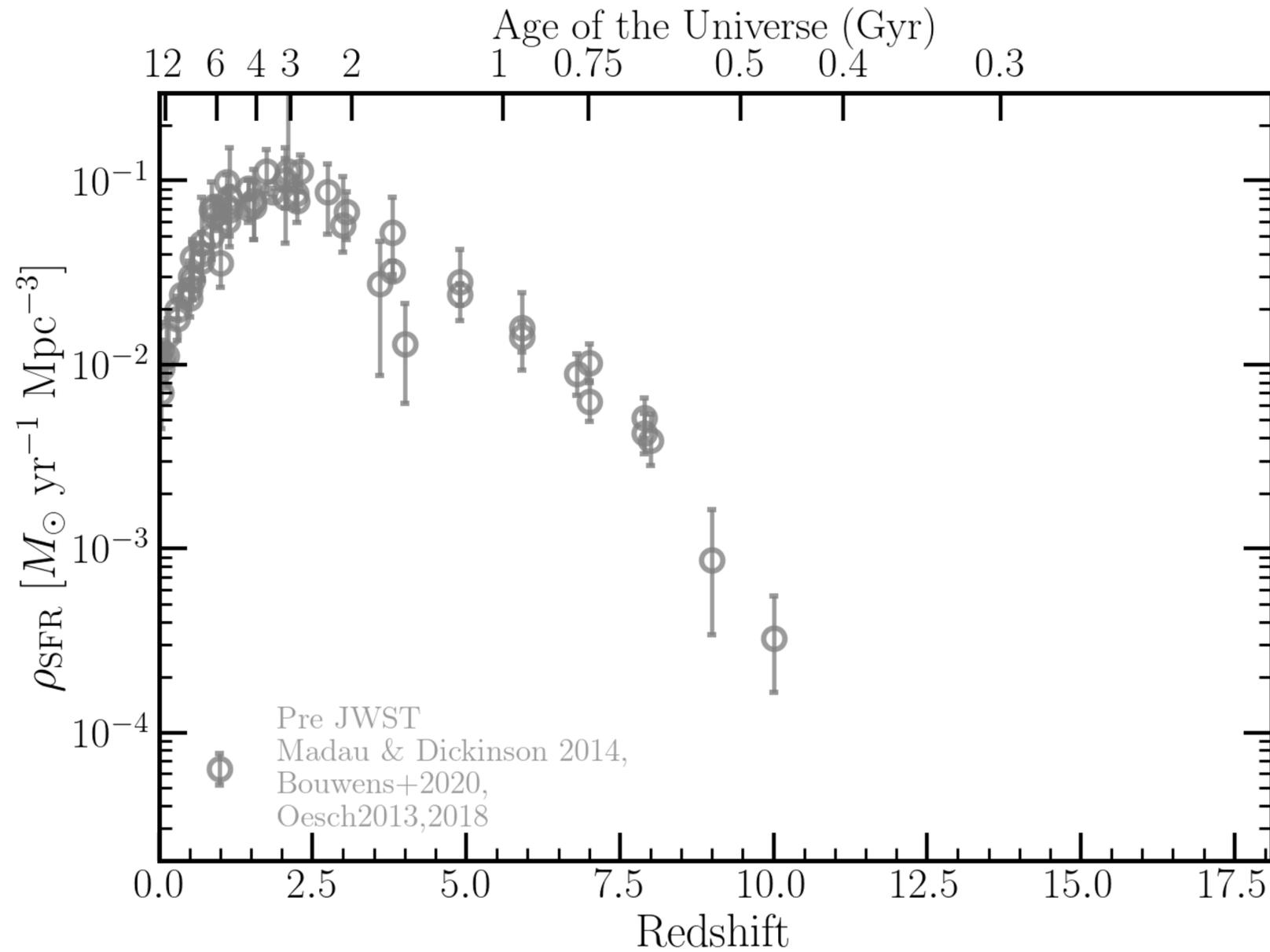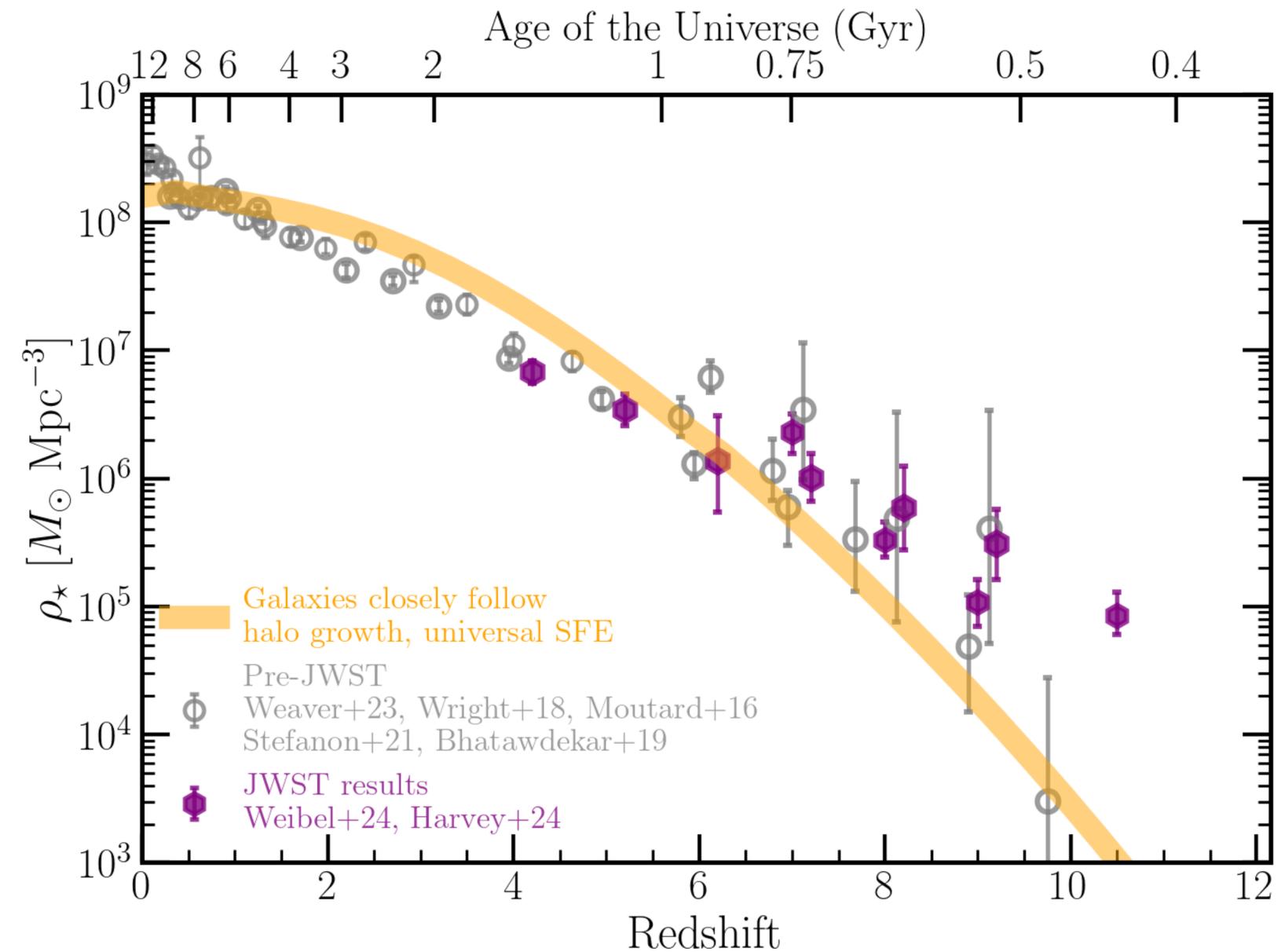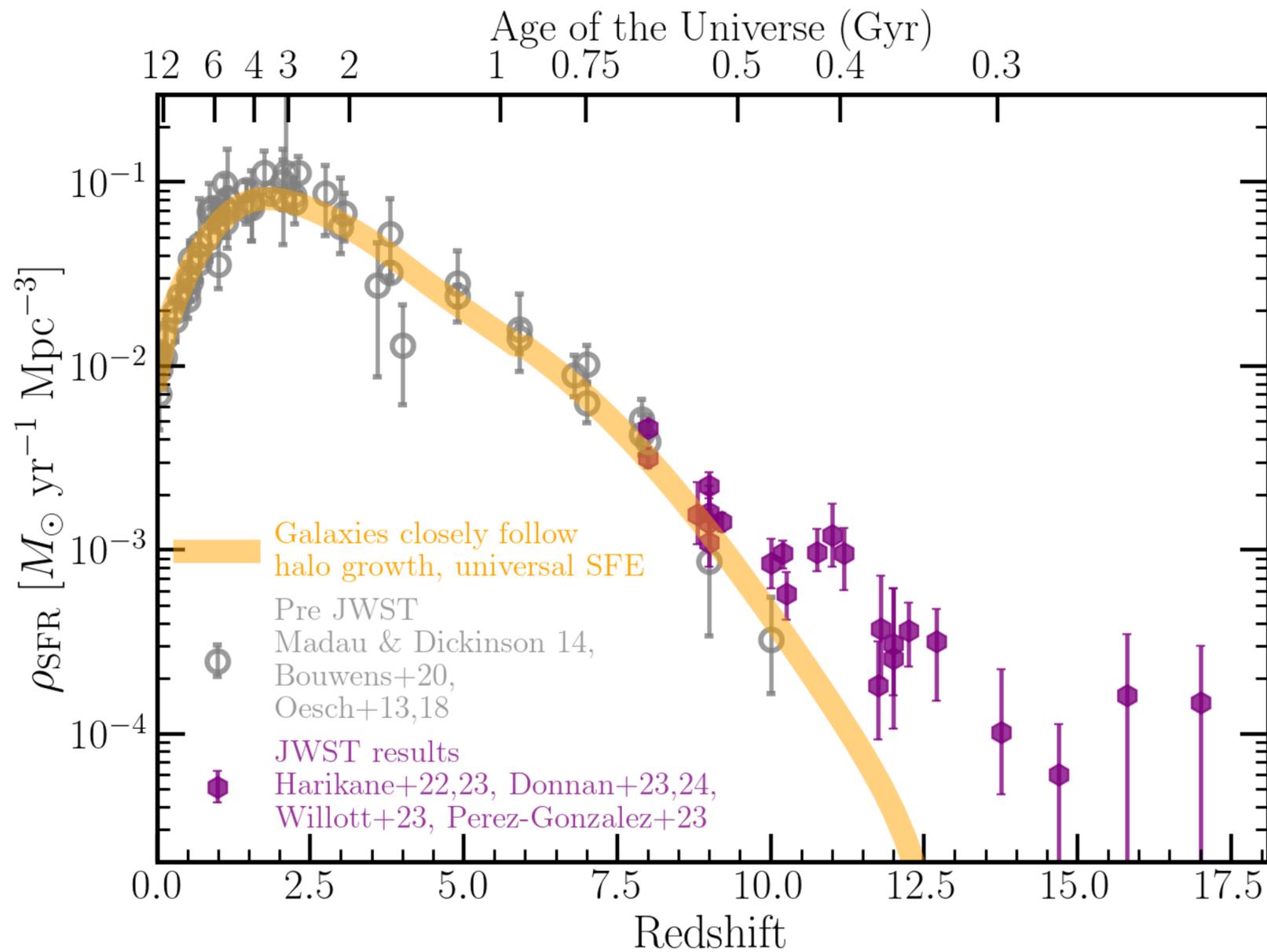
Pre-JWST measurements consistent with galaxies and halos growing at the same rate with universal star formation efficiency <20%

e.g., Tacchella+13,18; Mason+15; Oesch+18; Harikane+22, Stefanon+21

However, JWST discovers increased abundances of $z \gtrsim 8$ galaxies challenges our theories and suggest more efficient star formation

How can we study the galaxy-halo connection, and infer quantitatively the cosmic star formation efficiency?
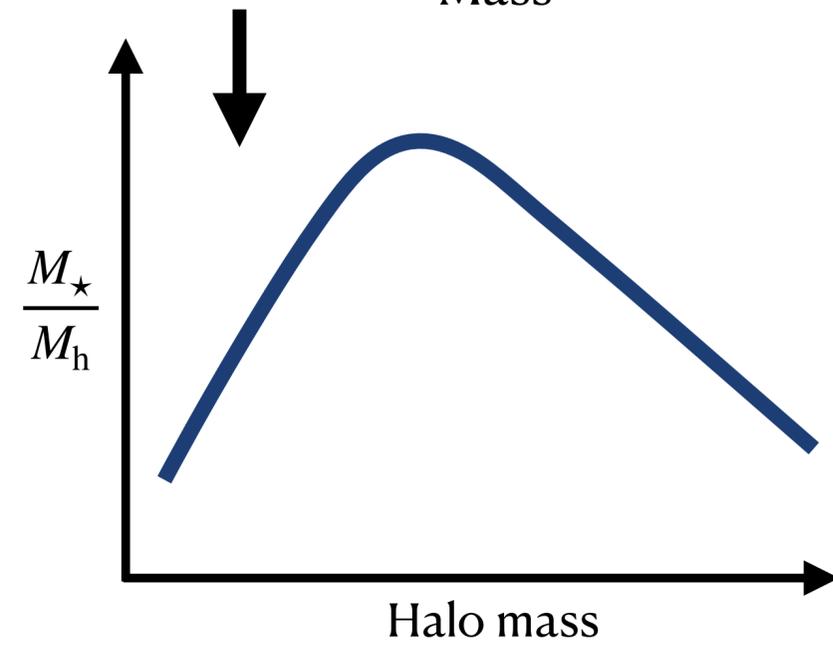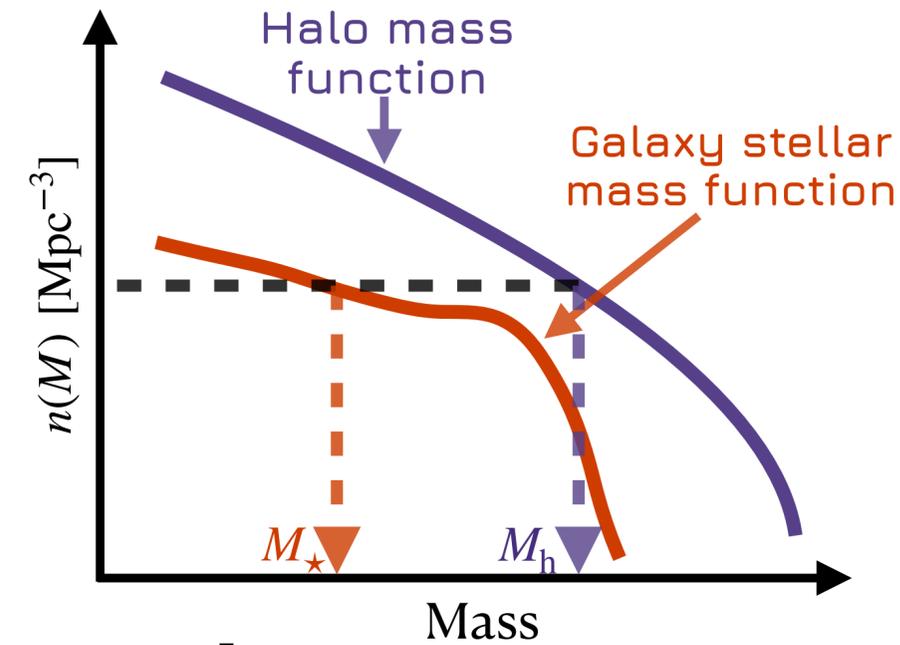
1. Abundance matching

→ Stellar-to-halo mass relationship

Halo mass function

Galaxy stellar mass function

$n(M)$ [Mpc^{-3}]

$M_\star$ M_h

Mass

$\frac{M_\star}{M_\mathrm{h}}$
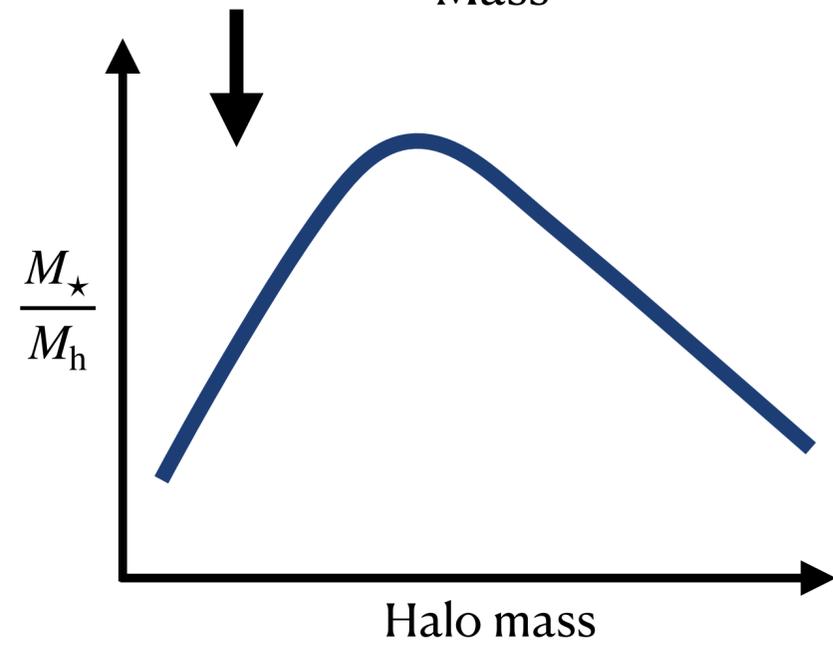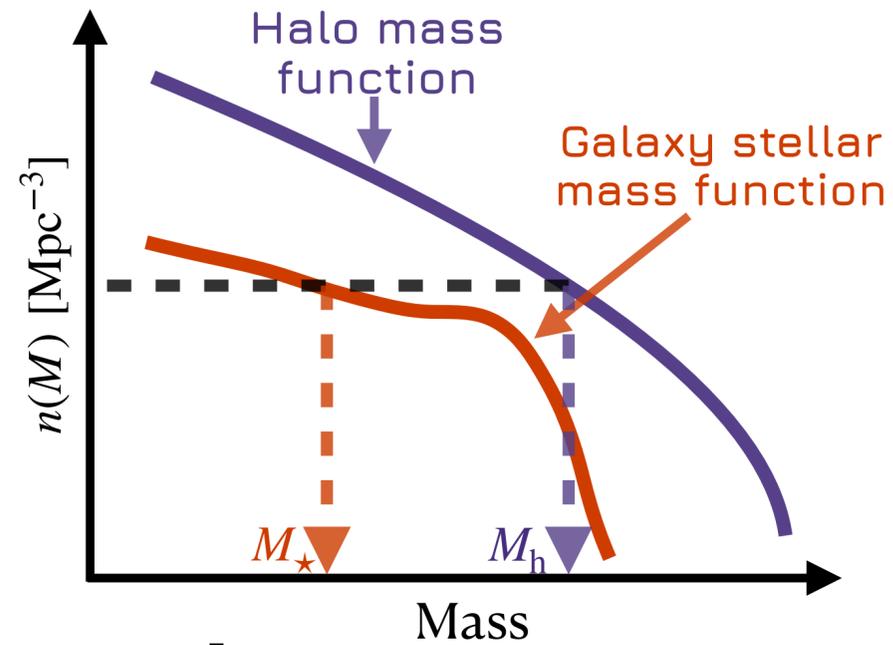
Halo mass

Measures the integrated star formation efficiency $\epsilon_\star = \dfrac{M_\star}{M_\mathrm{h}\, f_\mathrm{b}}$

1. Abundance matching
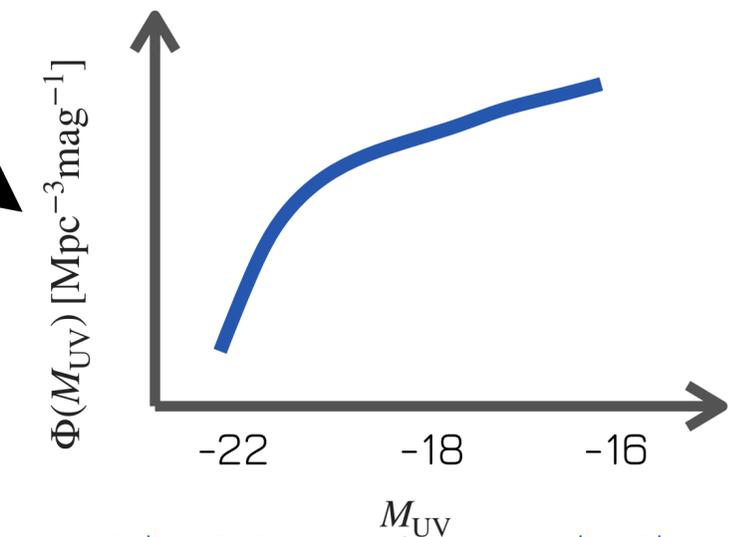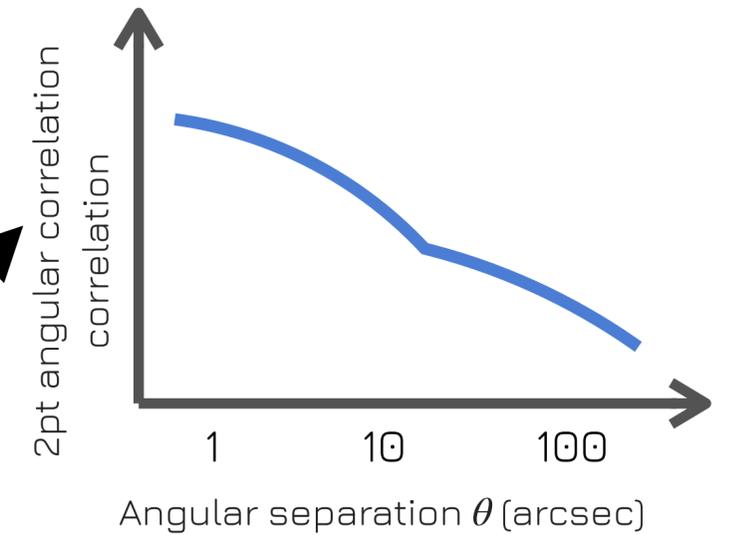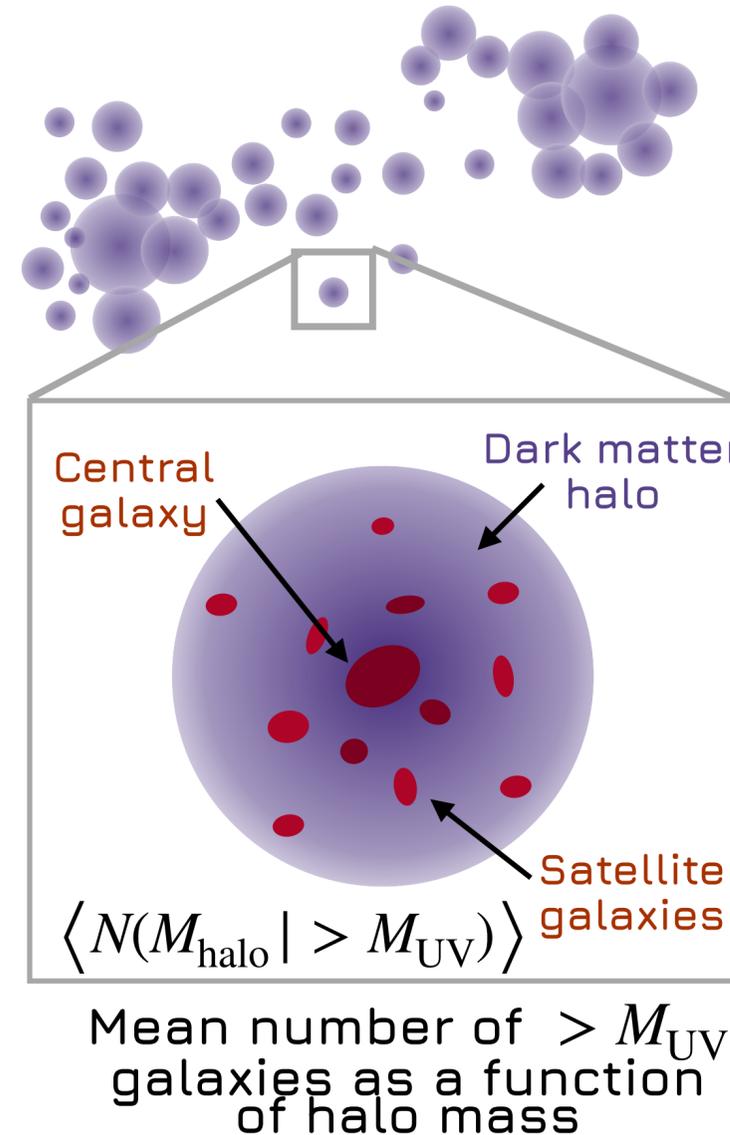→ Stellar-to-halo mass relationship

Measures the integrated star formation efficiency

$$\epsilon_\star = \frac{M_\star}{M_h\, f_b}$$

2. Halo occupation distribution (HOD) modelling

Analytical model that can predict
→ **galaxy clustering**
   (2pt correlation function)
→ **UV luminosity functions**
→ **Stellar mass functions**

$$\langle N(M_{\mathrm{halo}}\,|\,>M_{\mathrm{UV}})\rangle$$

Mean number of $>M_{\mathrm{UV}}$ galaxies as a function of halo mass

What can we infer from COSMOS-Web

By measuring the stellar mass assembly from $z \sim 0$ to $z \gtrsim 10$

COSMOS-Web

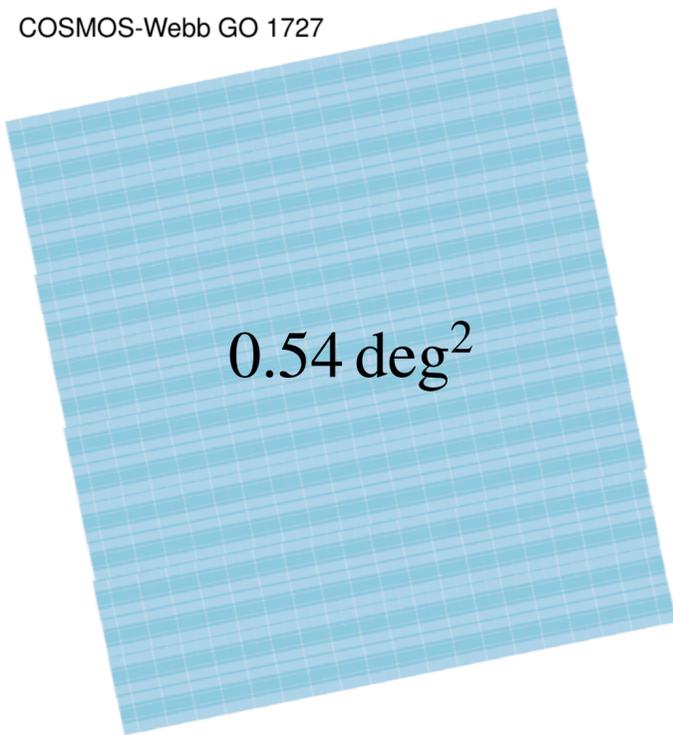## One of the best datasets to study stellar mass assembly from $z \sim 0$ to $z \gtrsim 10$

JWST Programs

COSMOS-Webb GO 1727

$0.54 \, \mathrm{deg}^2$
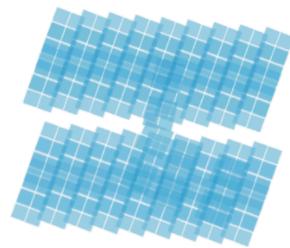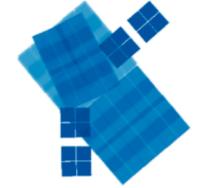
0.1 Degree

PRIMER COSMOS GO 1837
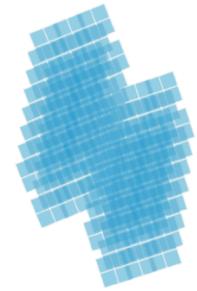
PRIMER UDS GO 1837

JADES GOODS-S
GTO 1180,1210,1287

JADES GOODS-N
GTO 1181

CEERS DD-ERS 1345
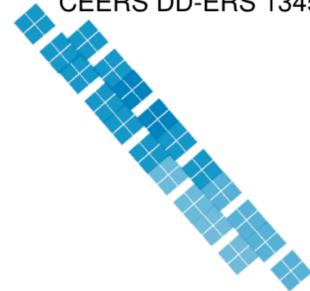
WDEEP GO 2079

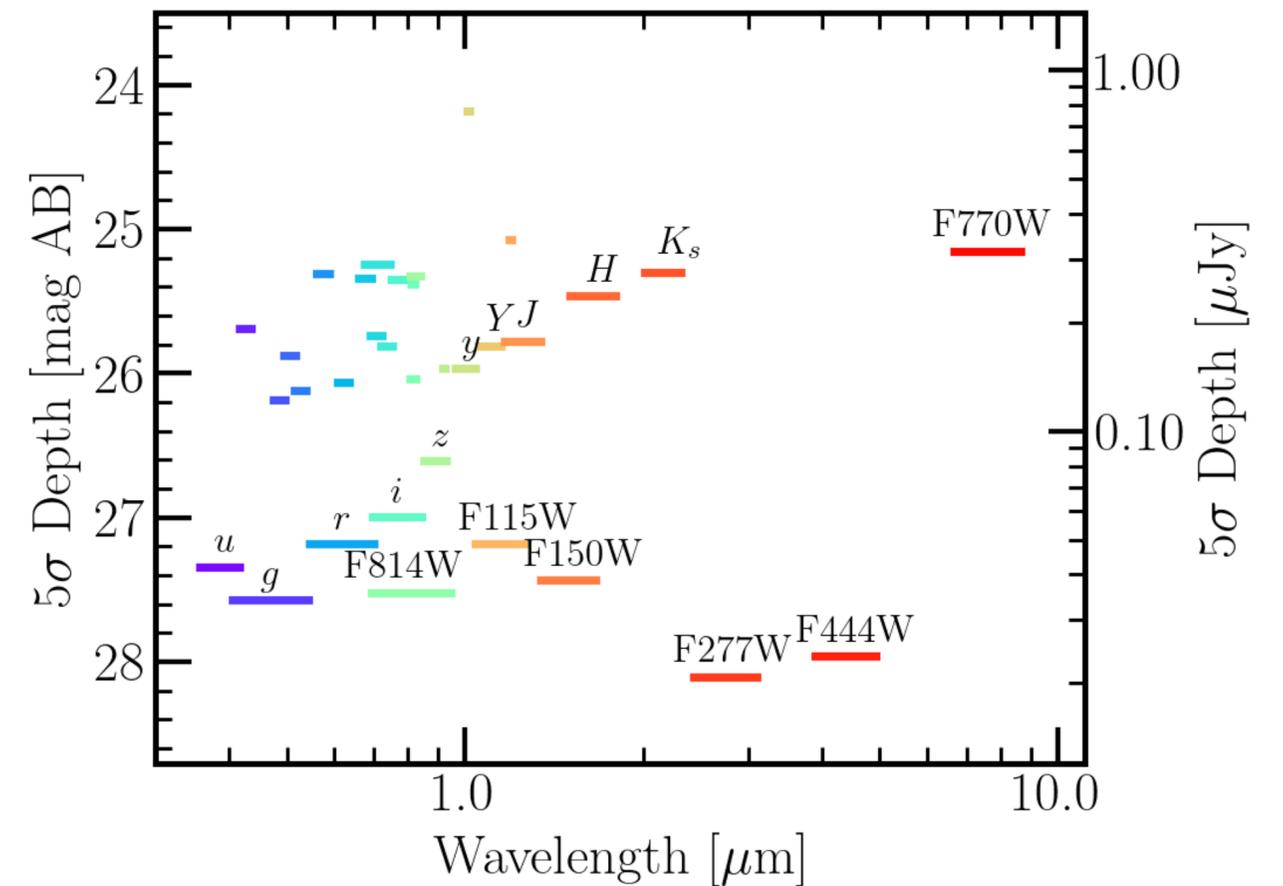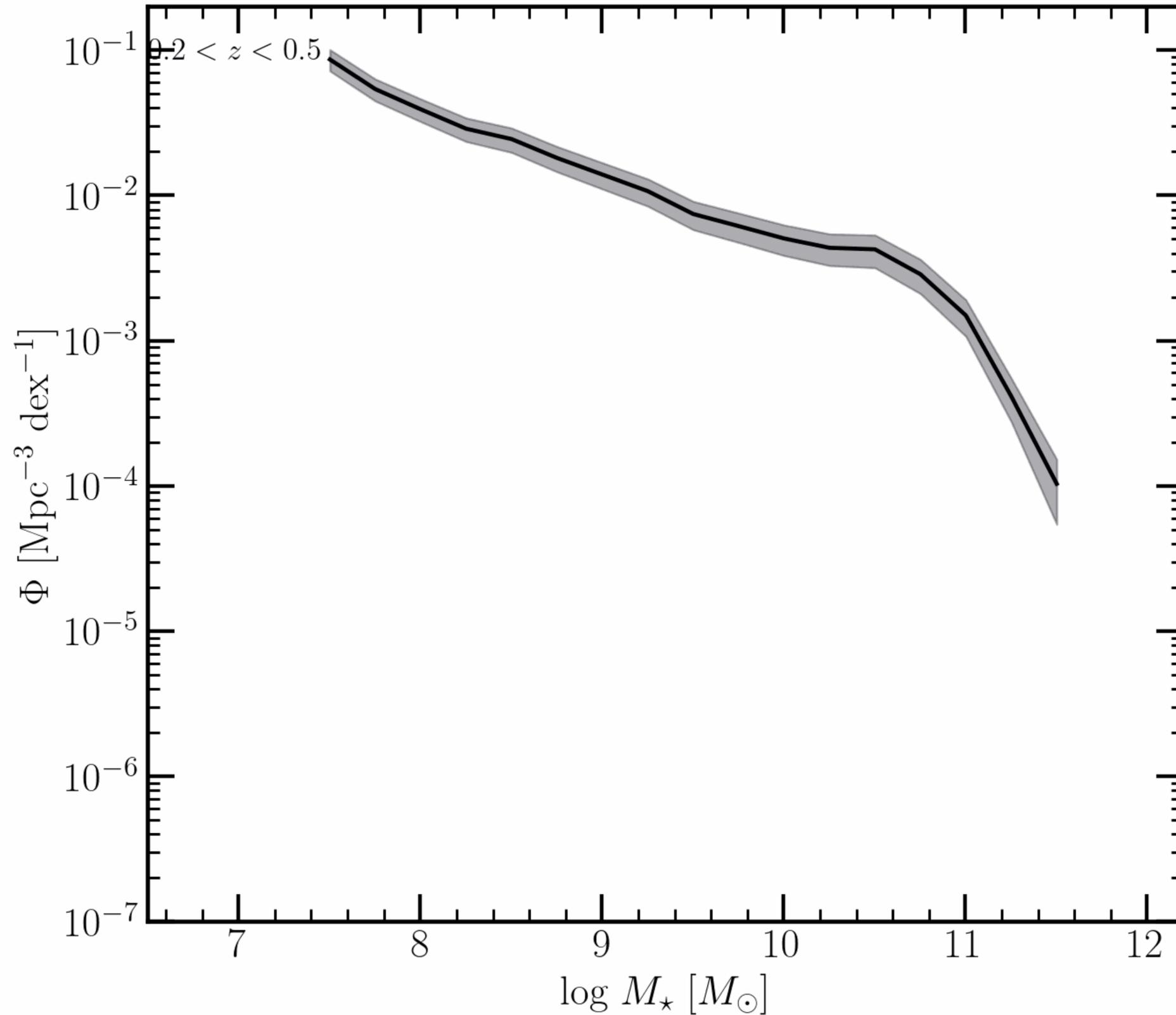Robertson 2022

Large areas give good statistics, low cosmic variance and probe some of the rarest and most massive objects

Over 30 photometric bands spanning $0.3 - 7.7 \, \mu\mathrm{m}$

Stellar mass functions at 0.2 < z < 12

Shuntov et al. 2024,
preprint arXiv:2410.08290

$0.2 < z < 0.5$

Stellar mass functions at 0.2 < z < 12

Shuntov et al. 2024,
preprint arXiv:2410.08290

AP Symposium, Marko Shuntov
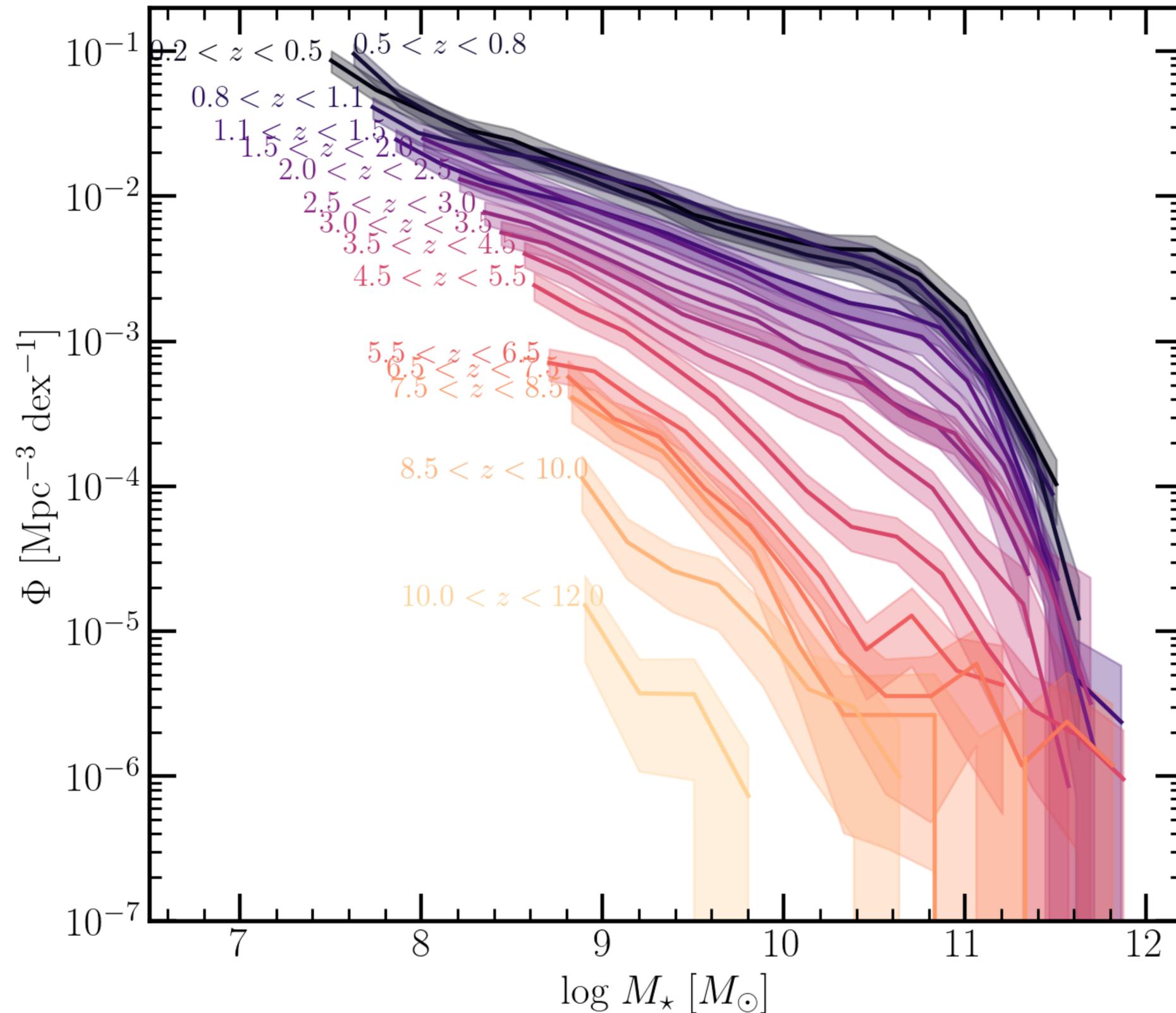
Comparison with previous measurements

This work, Shuntov+2024 · Weaver+23 · Navarro-Carrera+23 · Harvey+24 · Stefanon+21 · Weibel+24 · Gottumukkala+24

See also Anna De Graaf's talk

JWST measurements agree on the enhanced abundances of massive galaxies
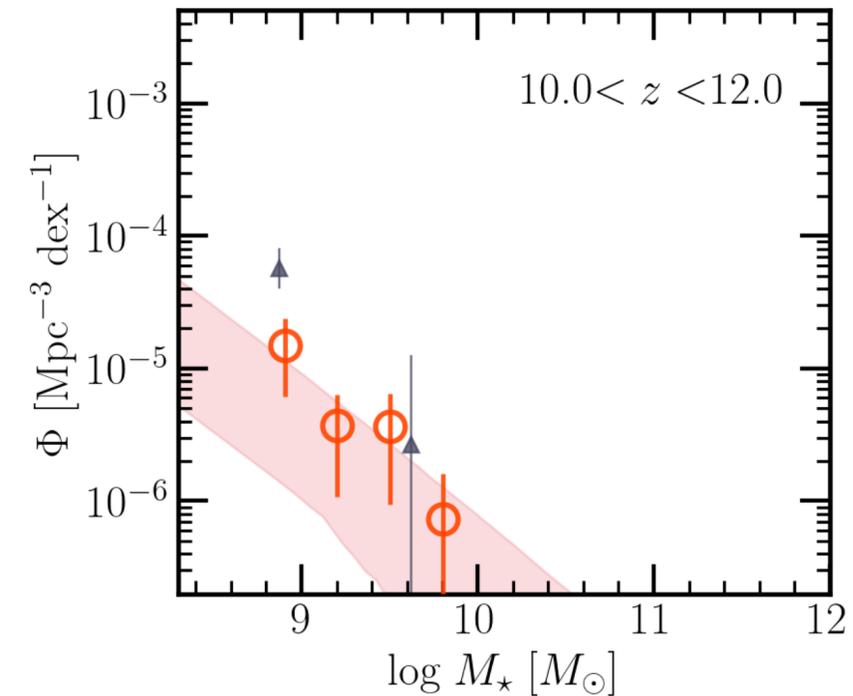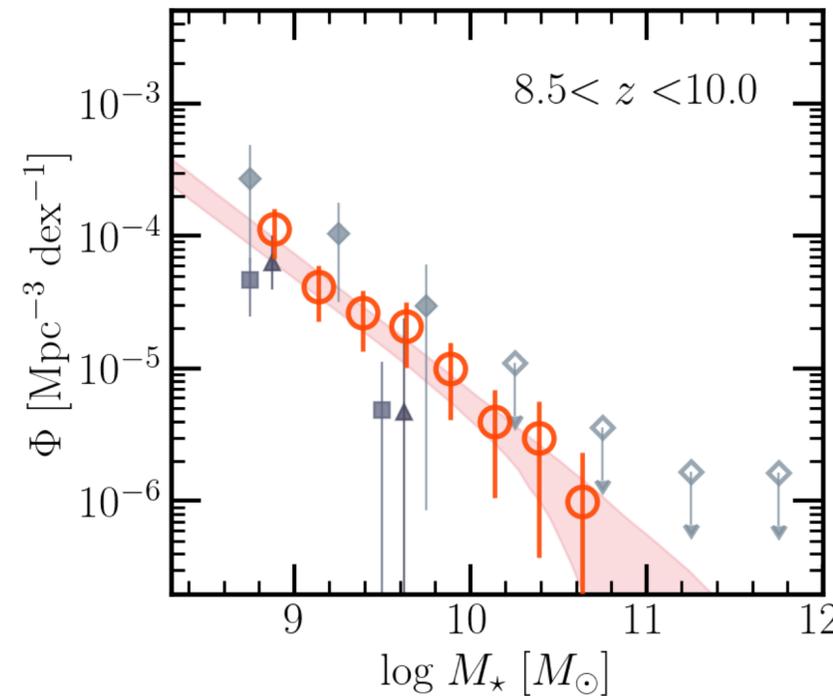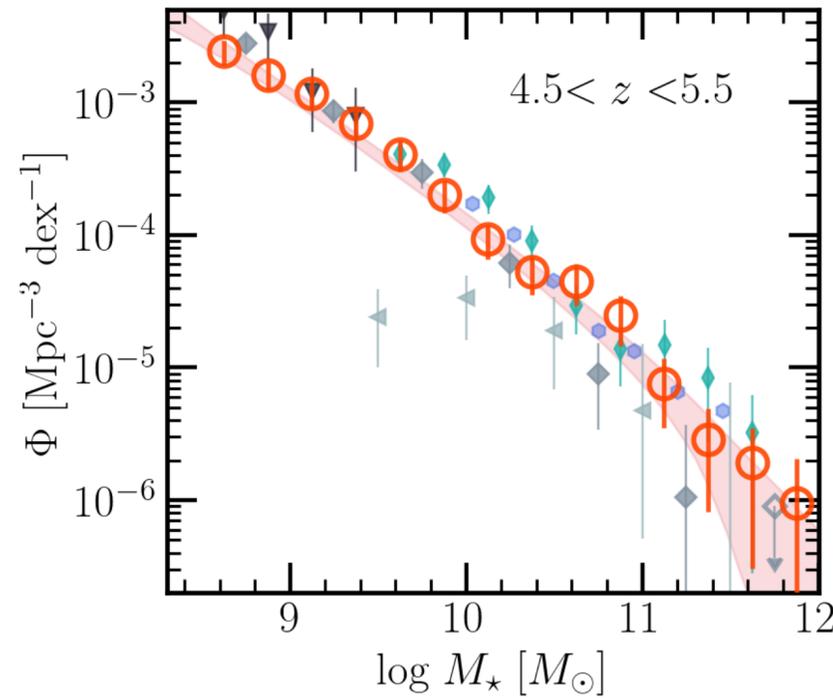
The cosmic stellar mass density and star formation history
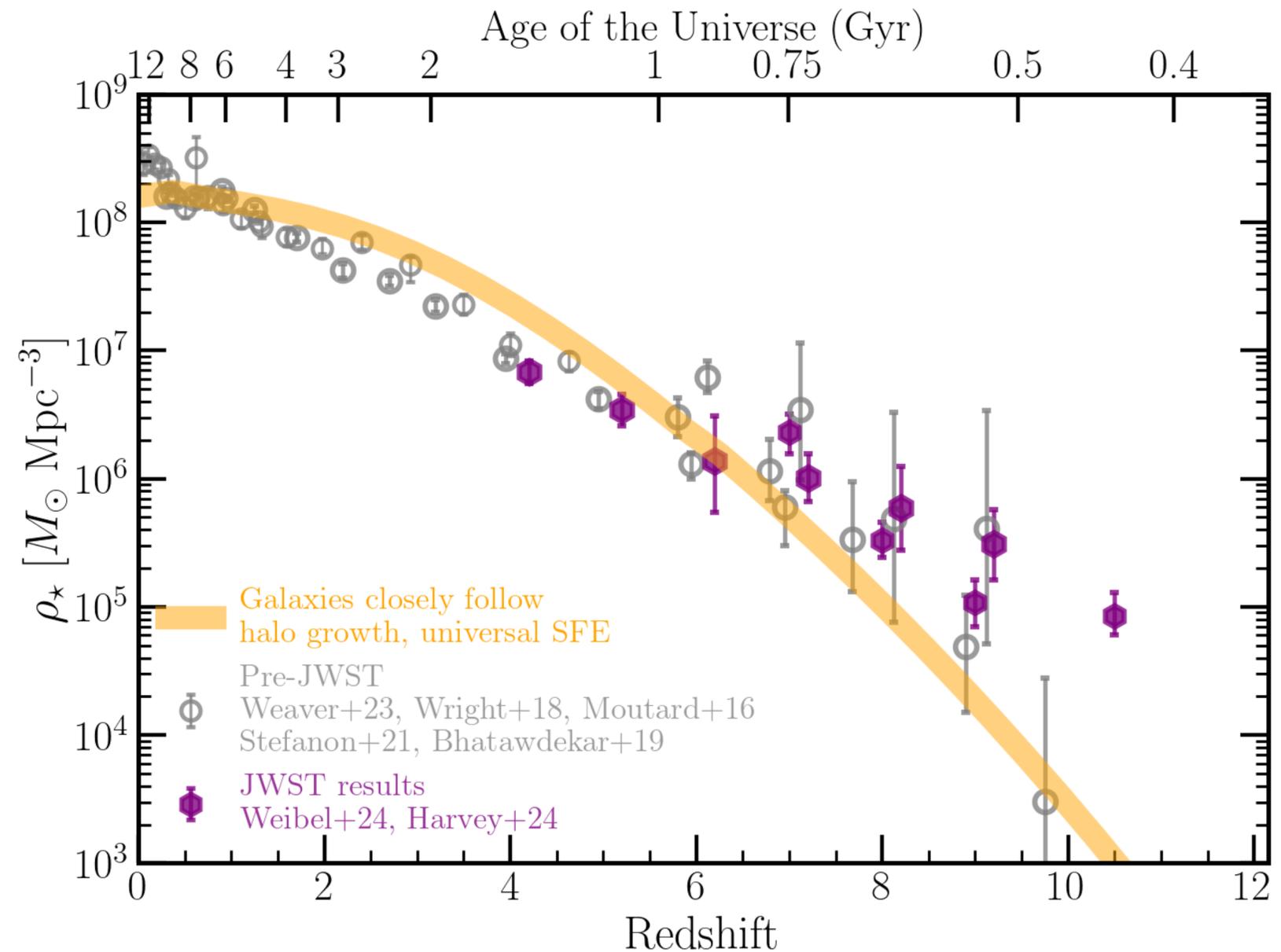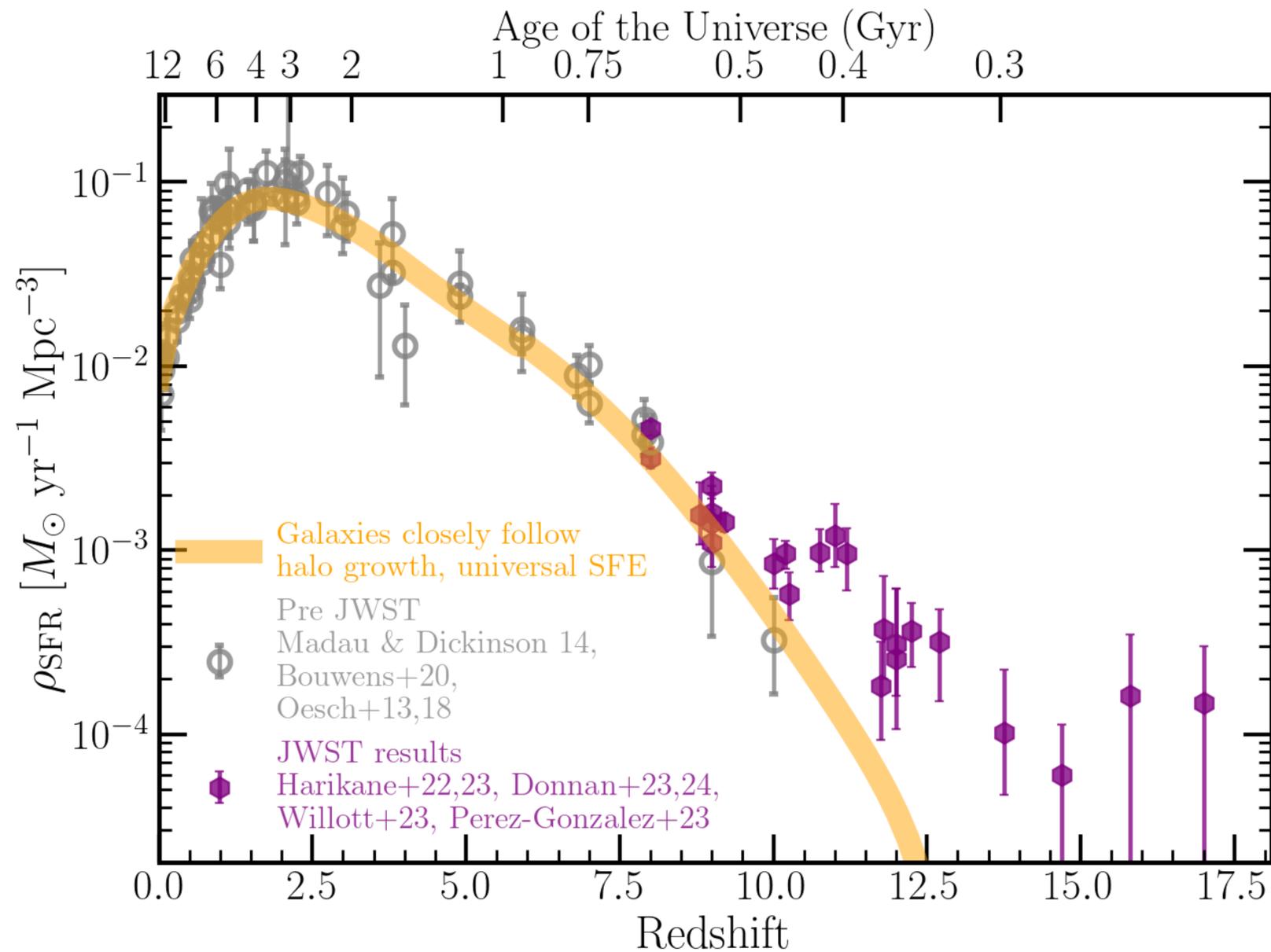
COSMOS-Web probes 13.4 Gyr of cosmic star formation history and mass assembly
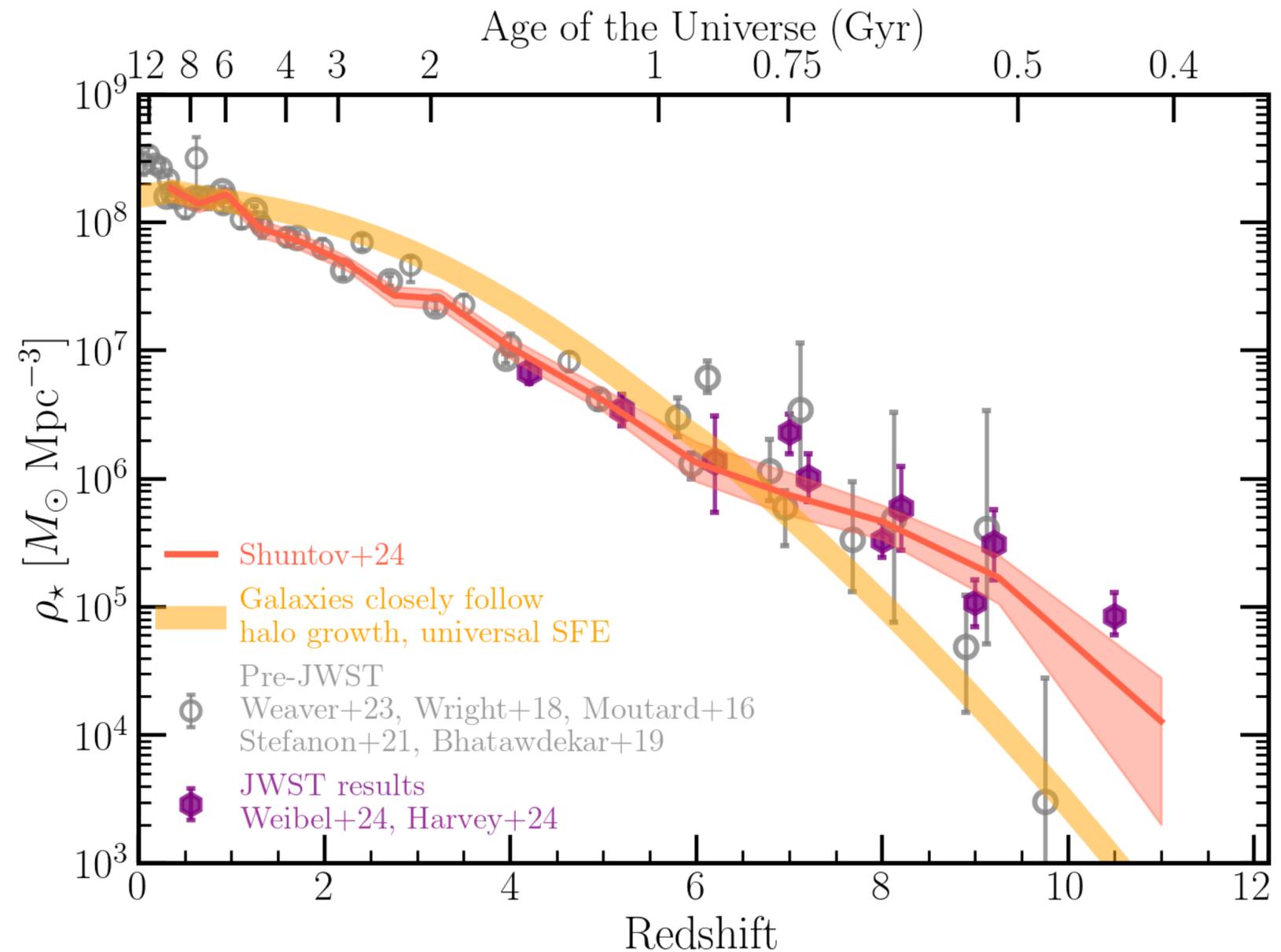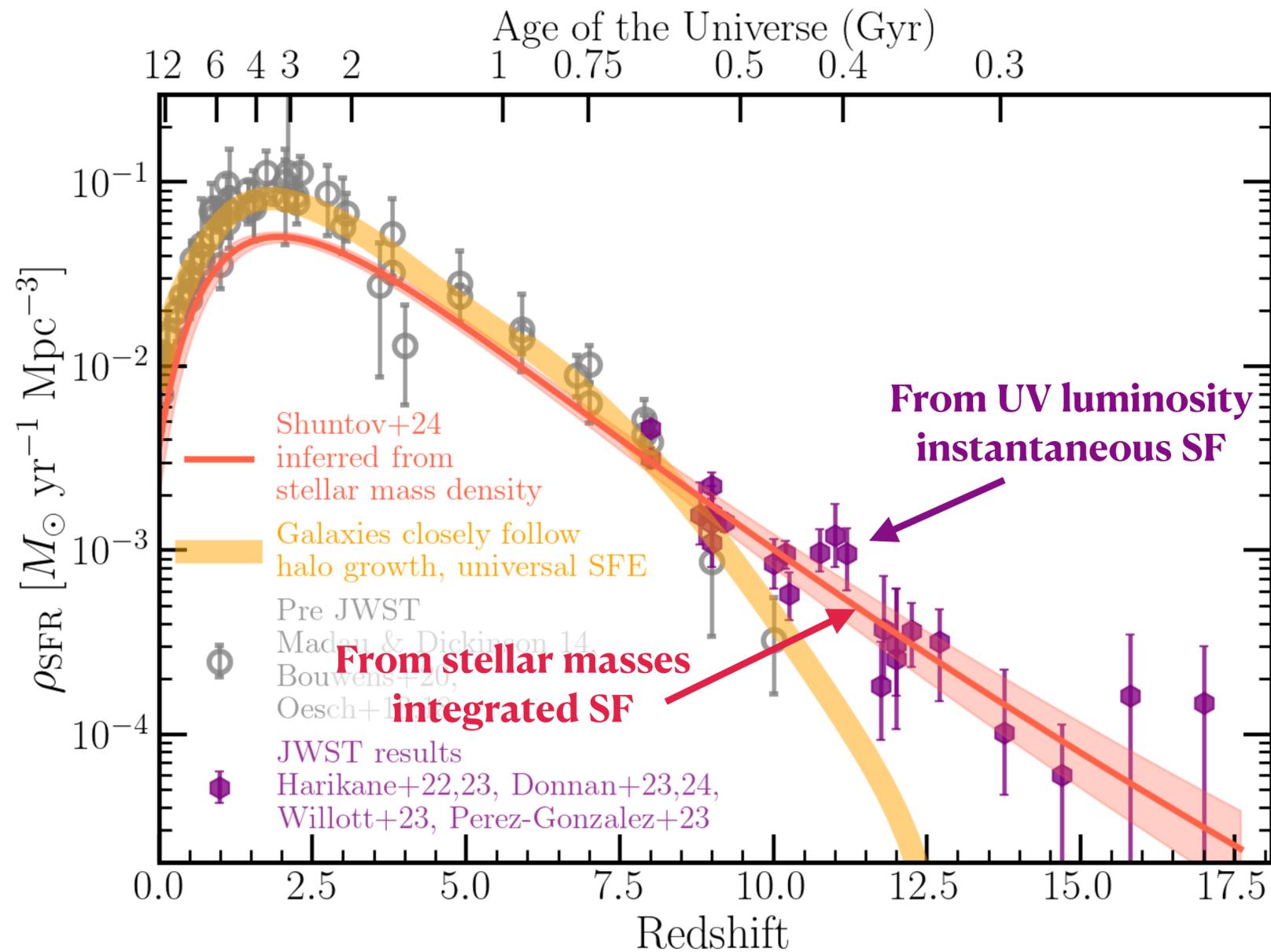
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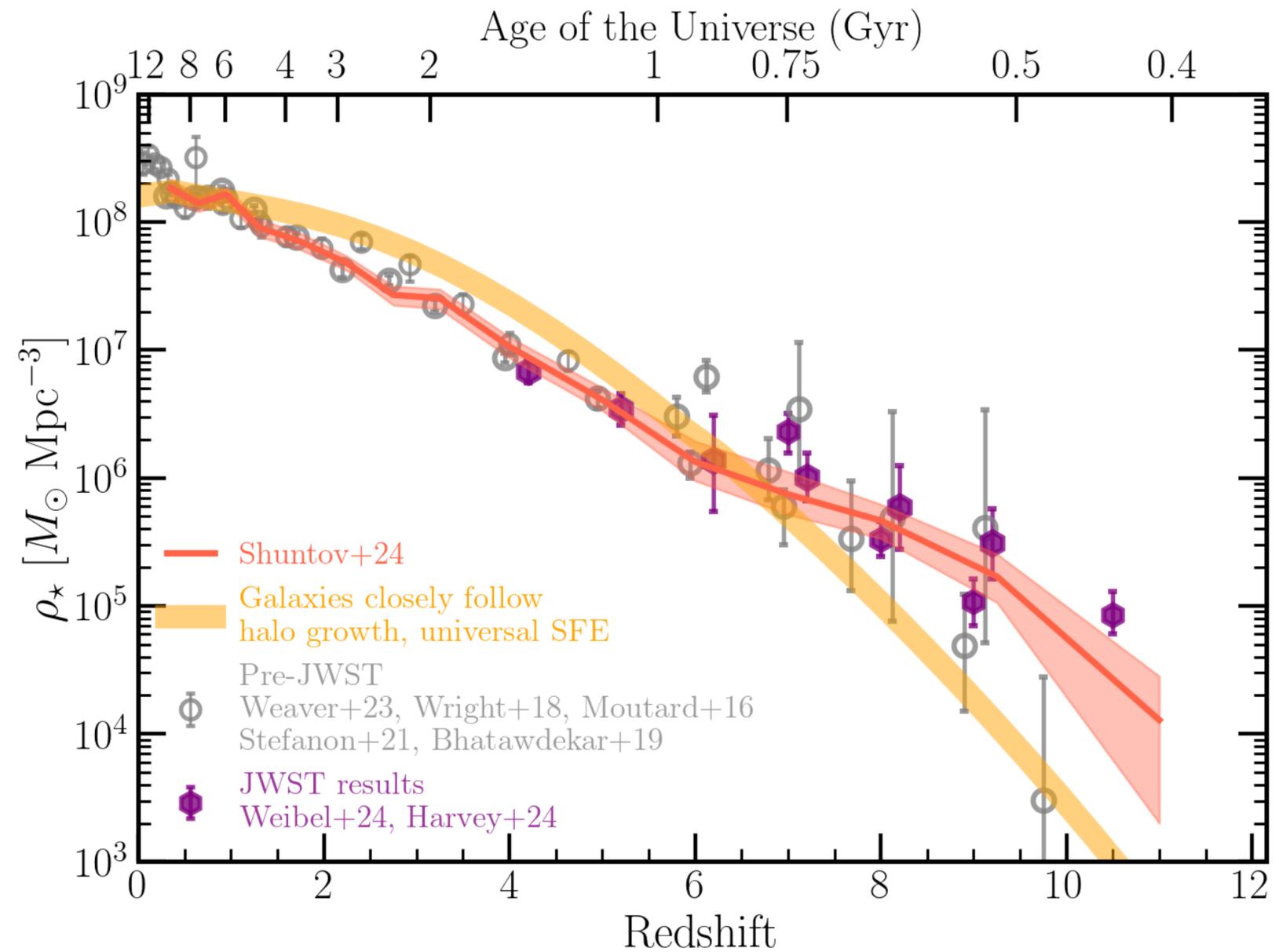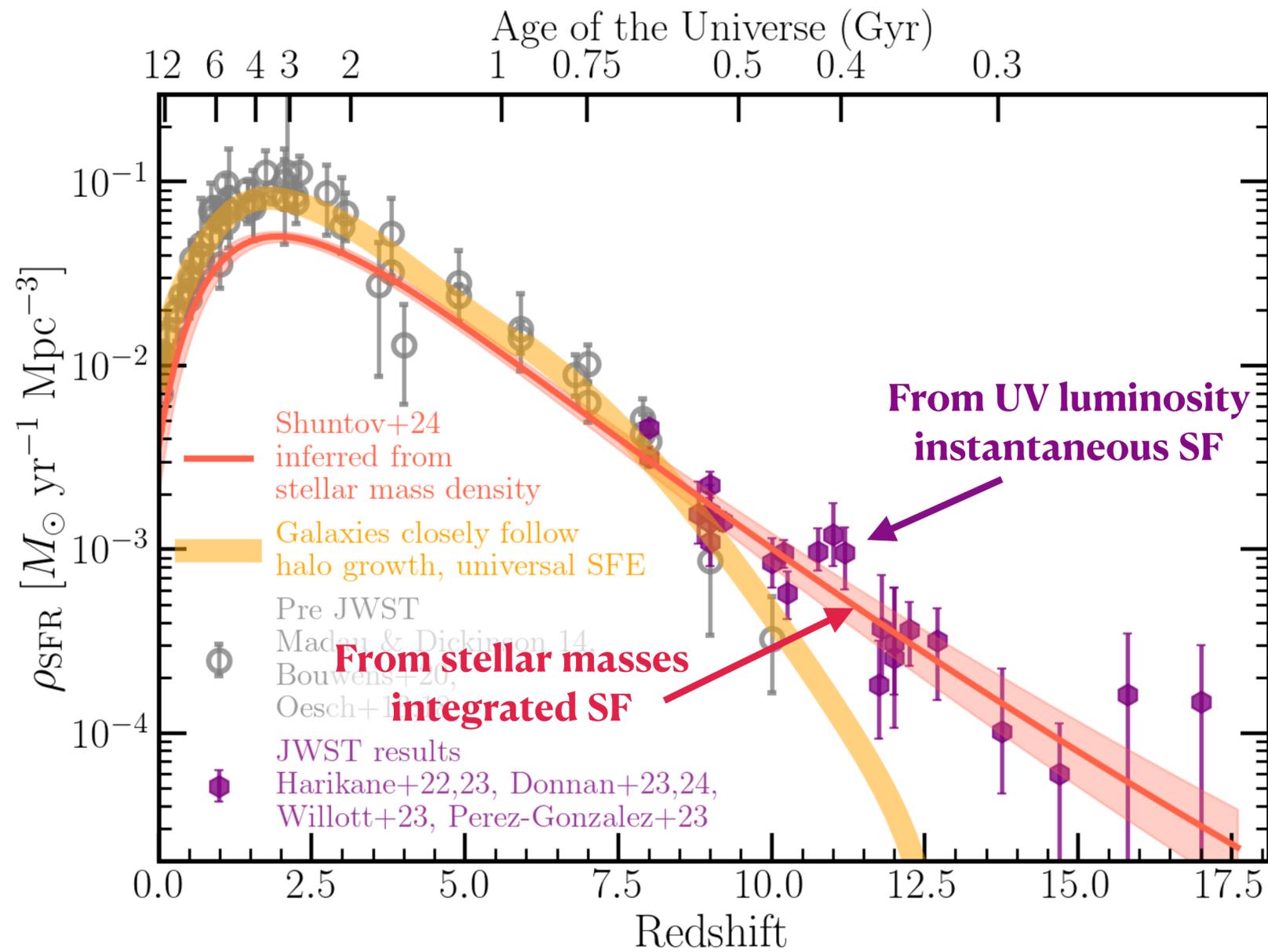
These measurements corroborate the need for increased SF efficiencies in the early Universe

What does this imply quantitatively for the cosmic star formation efficiency?

↓

Stellar-to-halo mass relationship
via abundance matching

The SHMR in 15 z-bins at 0.2 < z < 12
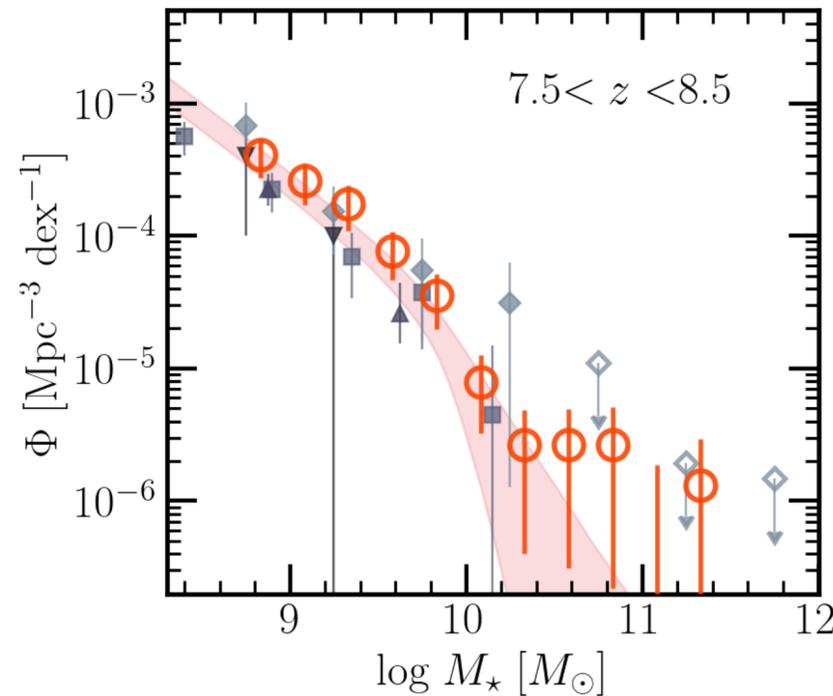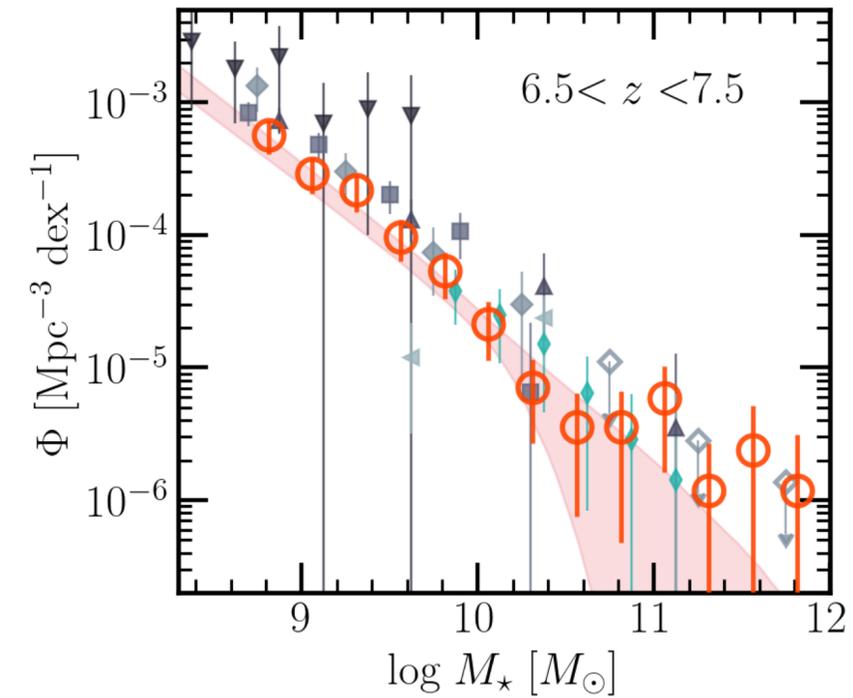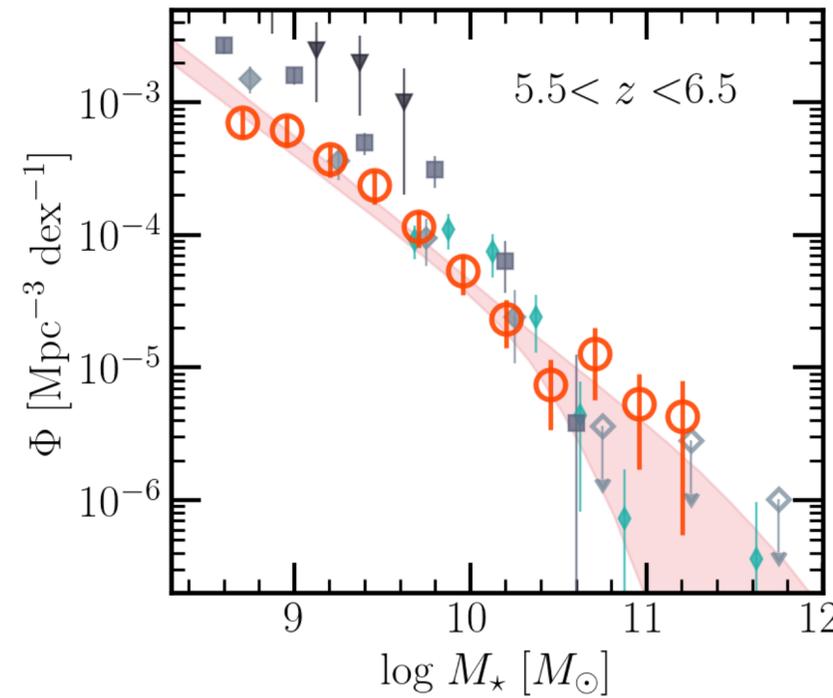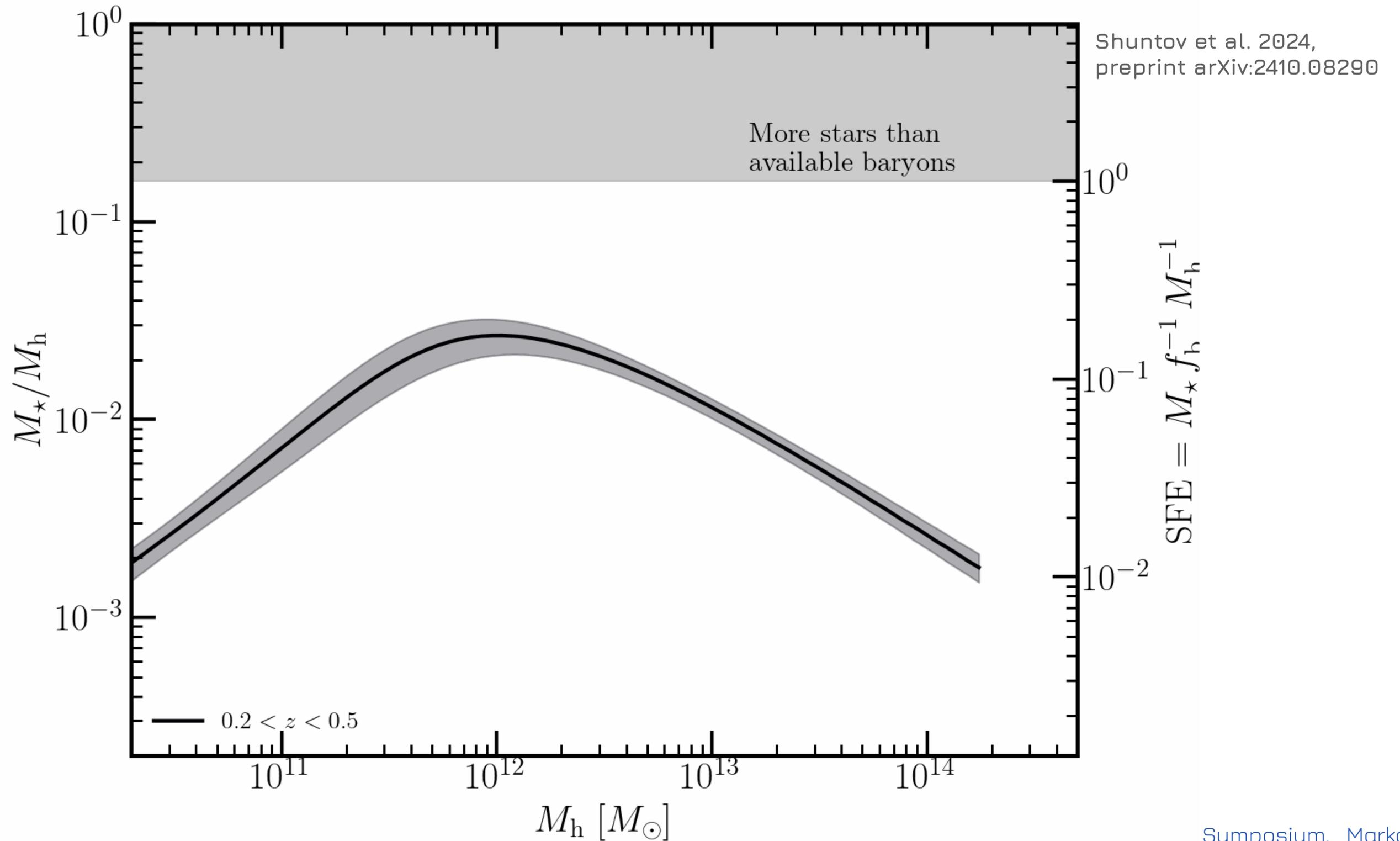
Non-monotonic evolution of the integrated SFE an upturn at $z \sim 3.5$

Shuntov et al. 2024, preprint arXiv:2410.08290

More stars than available baryons

$M_\star / M_{\rm h}$

10^0 10^{-1} 10^{-2} 10^{-3}

$M_{\rm h}\ [M_\odot]$

10^{11} 10^{12} 10^{13} 10^{14}

$\mathrm{SFE} = M_\star\, f_{\rm h}^{-1}\, M_{\rm h}^{-1}$

10^0 10^{-1} 10^{-2}

$0.2 < z < 0.5$	$2.0 < z < 2.5$	$5.5 < z < 6.5$
$0.5 < z < 0.8$	$2.5 < z < 3.0$	$6.5 < z < 7.5$
$0.8 < z < 1.1$	$3.0 < z < 3.5$	$7.5 < z < 8.5$
$1.1 < z < 1.5$	$3.5 < z < 4.5$	$8.5 < z < 10.0$
$1.5 < z < 2.0$	$4.5 < z < 5.5$	$10.0 < z < 12.0$

Similar picture from clustering and HOD analysis: in COSMOS-Web Paquereau et al., in prep

Implied integrated SFE in the EoR are high $\sim 0.5 - 1$
Challenging traditional models, but can be explained by some

Shuntov et al. 2024,
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More stars than
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Legend:
$0.2 < z < 0.5$
$0.5 < z < 0.8$
$0.8 < z < 1.1$
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$1.5 < z < 2.0$
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$3.0 < z < 3.5$
$3.5 < z < 4.5$
$4.5 < z < 5.5$
$5.5 < z < 6.5$
$6.5 < z < 7.5$
$7.5 < z < 8.5$
$8.5 < z < 10.0$
$10.0 < z < 12.0$

Axes: $M_\star / M_{\rm h}$ (left), $M_{\rm h}\ [M_\odot]$ (bottom), $\mathrm{SFE} = M_\star\, f_{\rm h}^{-1}\, M_{\rm h}^{-1}$ (right)

Similar picture from clustering and HOD analysis: in COSMOS-Web Paquereau et al., in prep
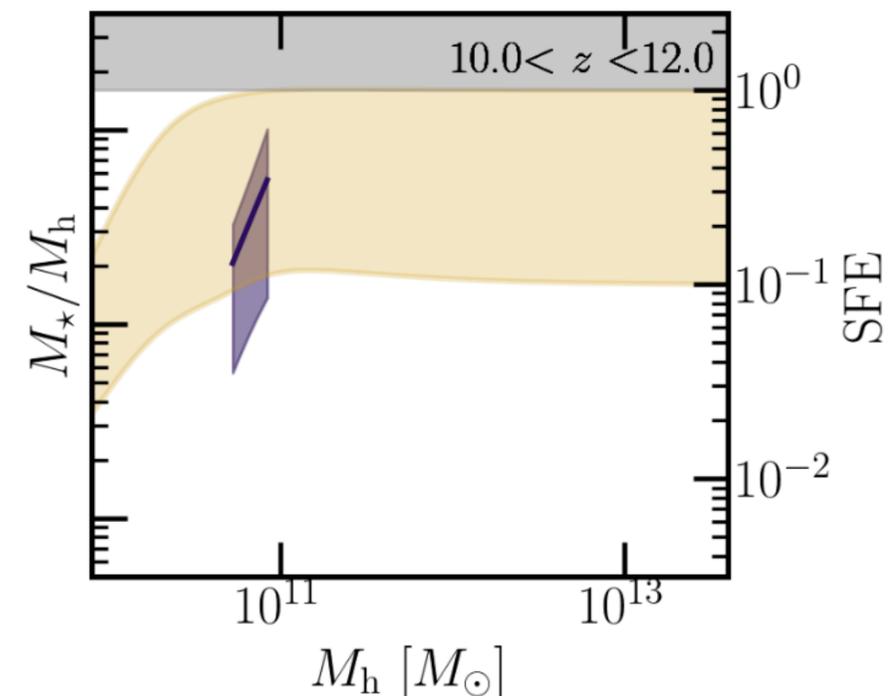
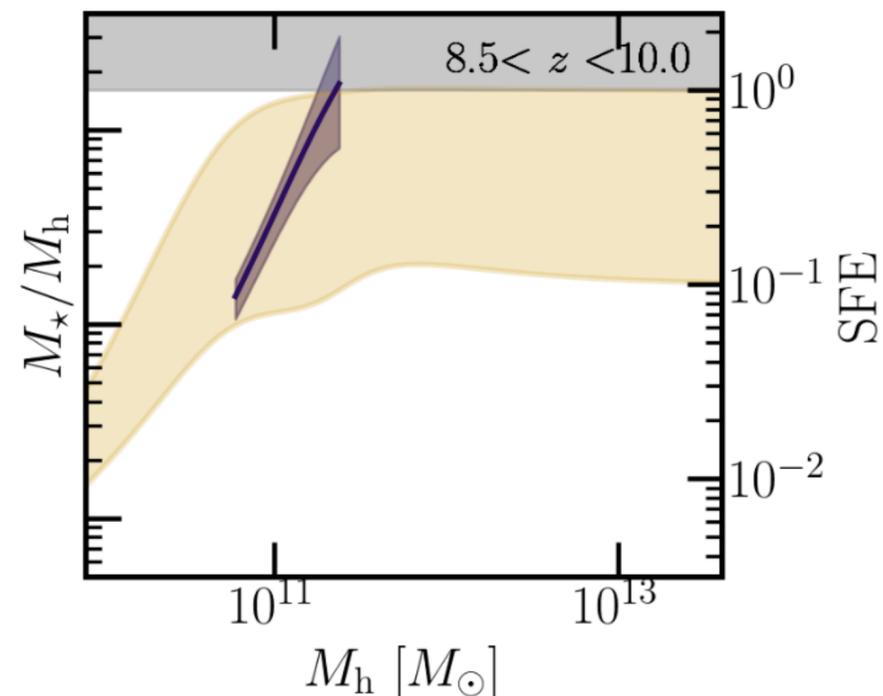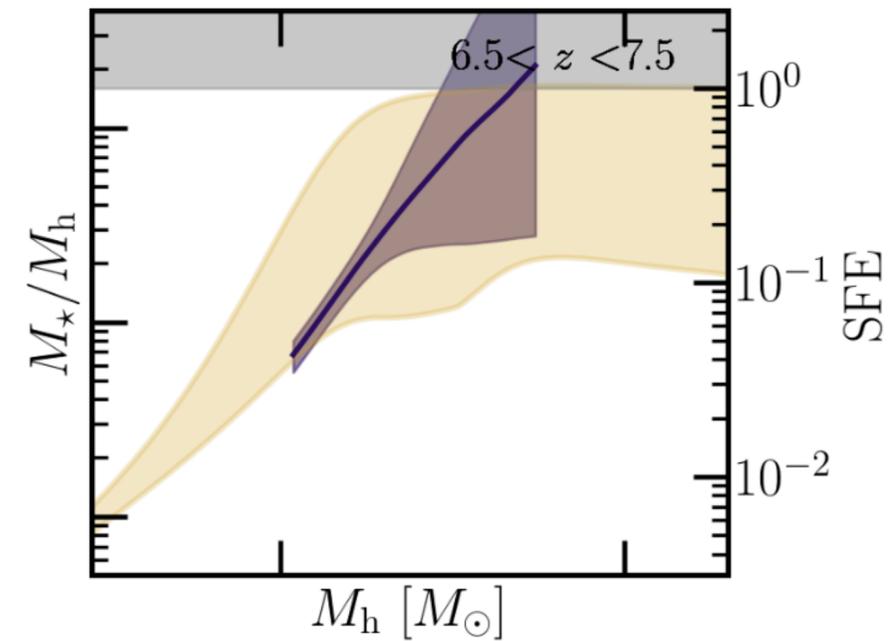# Implied integrated SFE in the EoR are high $\sim 0.5 - 1$
Challenging traditional models, but can be explained by some

Mechanisms to enhance abundances/SFE

- **Feedback-free bursts**
  (Dekel+23, Li+23, Torrey+17, Grudic+18)

- **Positive AGN feedback**
  (Silk+24)

- **Stochastic/bursty star formation**
  (Mason+23, Pallottini&Ferrara+23, Shen+23, Sun+24, Gelli+24, Ciesla+24)

Or mass estimates can be wrong

- **Top heavy initial mass function**
  (Inayoshi+22, Harikane+22, Yung+24)

- **Contribution from AGN, nebular continuum**
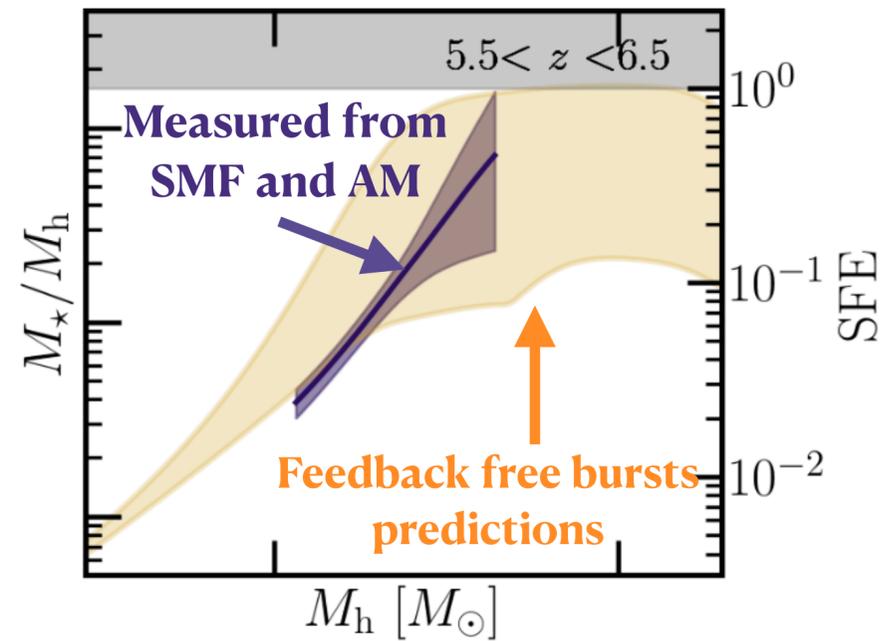 (Maiolino+23, Tachella+23, Cameron+24)

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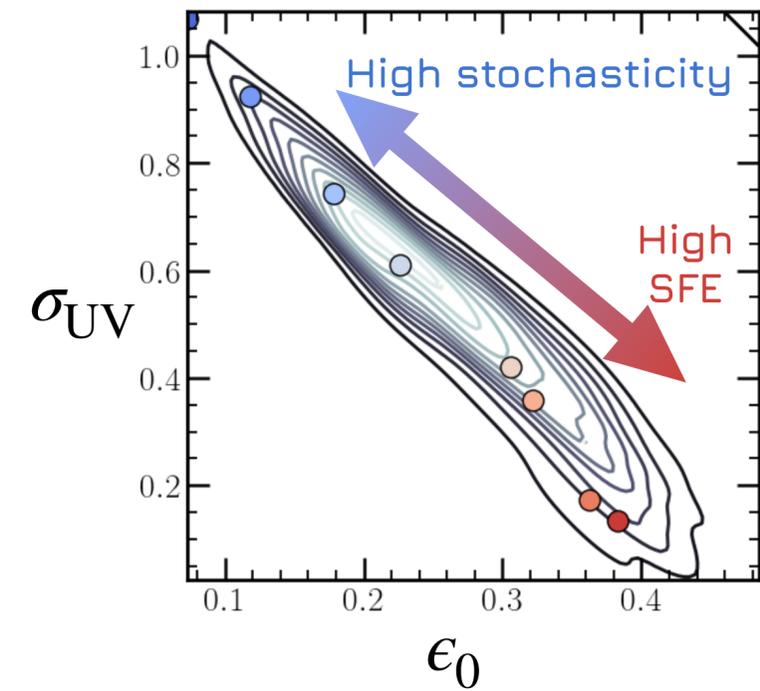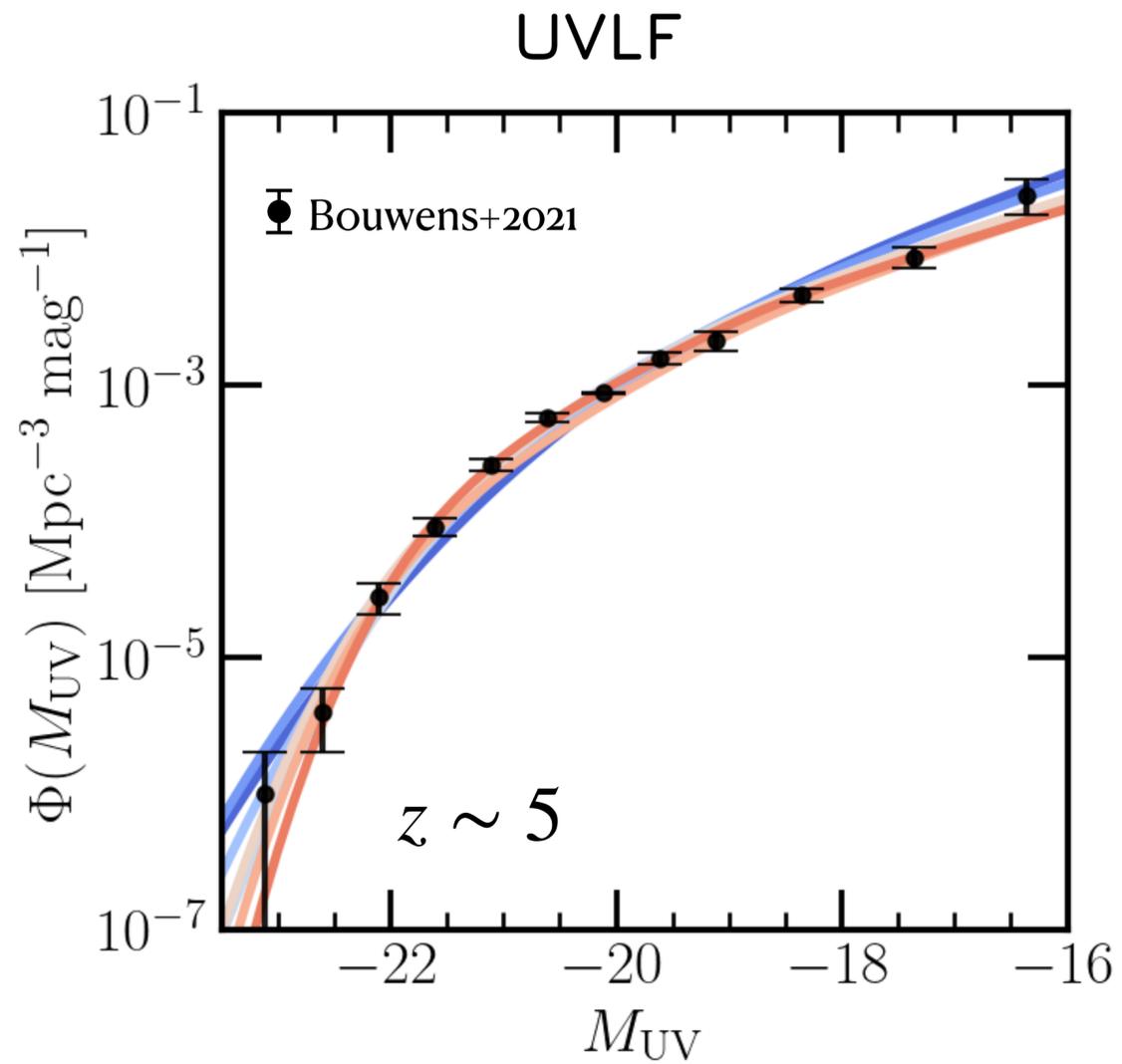 (Mason+23, Pallottini&Ferrara+23, Shen+23, Sun+24, Gelli+24, Ciesla+24)

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Enhanced SFE can be degenerate with e.g., **increased scatter** in the $M_\star - M_{\rm halo}$ and $M_{\rm UV} - M_{\rm halo}$ relationships
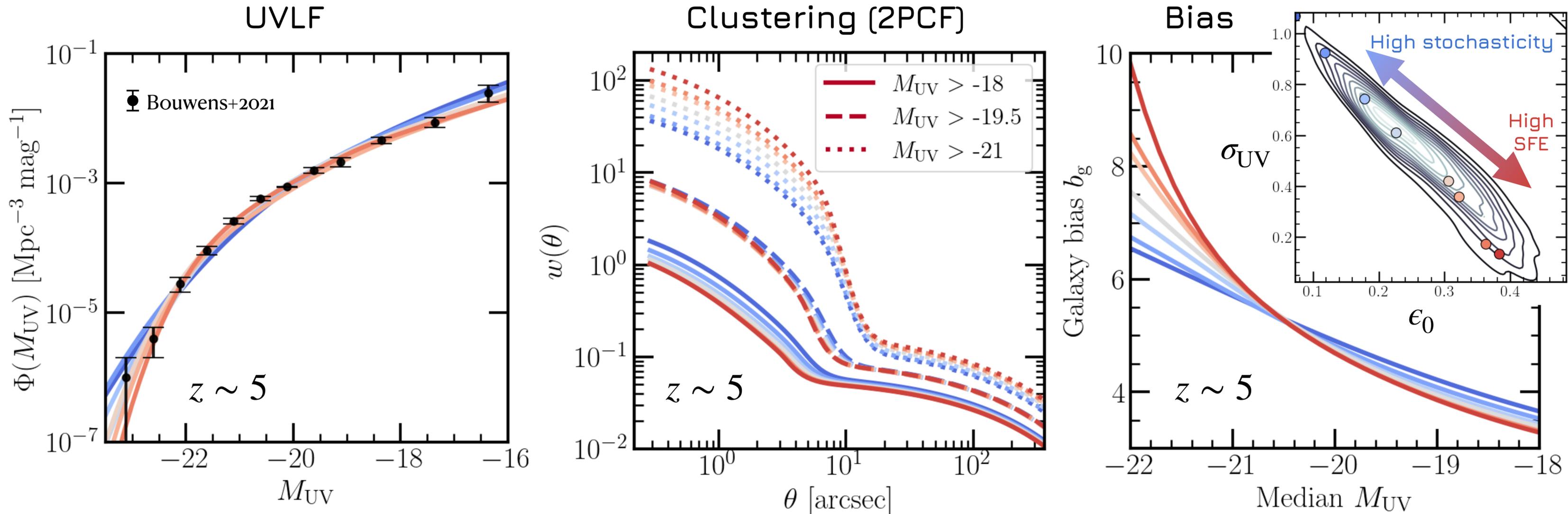
Stochastic/bursty SF or enhanced SFE?

Enhanced SFE can be degenerate with increased scatter in the and $M_{\rm UV} - M_{\rm halo}$ relationship in the resulting galaxy abundances

UVLF

Bouwens+2021

$z \sim 5$

High stochasticity

High SFE

$\sigma_{\rm UV}$

ϵ_0

Stochastic/bursty SF or enhanced SFE?

Enhanced SFE can be degenerate with increased scatter in the
and $M_{\rm UV} - M_{\rm halo}$ relationship in the resulting galaxy abundances

UVLF

Clustering (2PCF)

Bias

$\Phi(M_{\rm UV})$ [Mpc^{-3} mag^{-1}]

Bouwens+2021

$z \sim 5$

$M_{\rm UV}$

$w(\theta)$

$M_{\rm UV} > -18$
$M_{\rm UV} > -19.5$
$M_{\rm UV} > -21$

$z \sim 5$

θ [arcsec]

Galaxy bias $b_{\rm g}$

$z \sim 5$

Median $M_{\rm UV}$

High stochasticity

High SFE

$\sigma_{\rm UV}$

ϵ_0

Clustering can break this degeneracy!
(Muñoz+23)

Joint HOD-based model of the UVLF and 2PCF
to measure SFE and scatter

Yang+2009
Moster+2010
Leauthaud+2011
Shuntov+2022

UV-Halo mass relation, f_{UVHMR}

$$M_{\mathrm{UV}} \propto \mathrm{SFR} = \epsilon f_{\mathrm{b}} \dot{M}_{\mathrm{halo}}$$

Parametric model of the SFE

$$\epsilon(M_{\mathrm{h}}) = 2\,\epsilon_0 \left[\left(\frac{M_{\mathrm{h}}}{M_c}\right)^{-\beta} + \left(\frac{M_{\mathrm{h}}}{M_c}\right)^{\gamma} \right]^{-1}$$
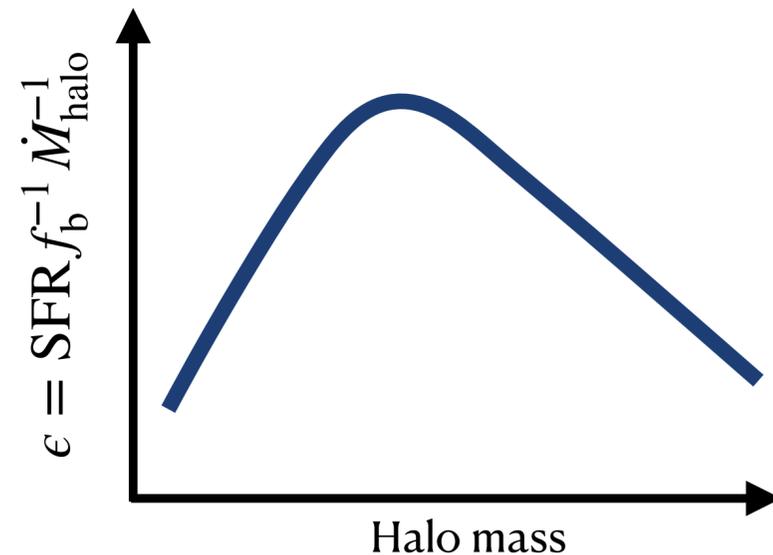
Conditional UVLF

$$P(M_{\mathrm{UV}}\,|\,M_{\mathrm{h}}) \sim \mathcal{N}\left[f_{\mathrm{UVHMR}}(M_{\mathrm{h}}), \sigma_{\mathrm{UV}} \right]$$

Scatter in the $M_{\mathrm{UV}} - M_{\mathrm{halo}}$ relation

+   **HOD**

Clustering (2PCF)
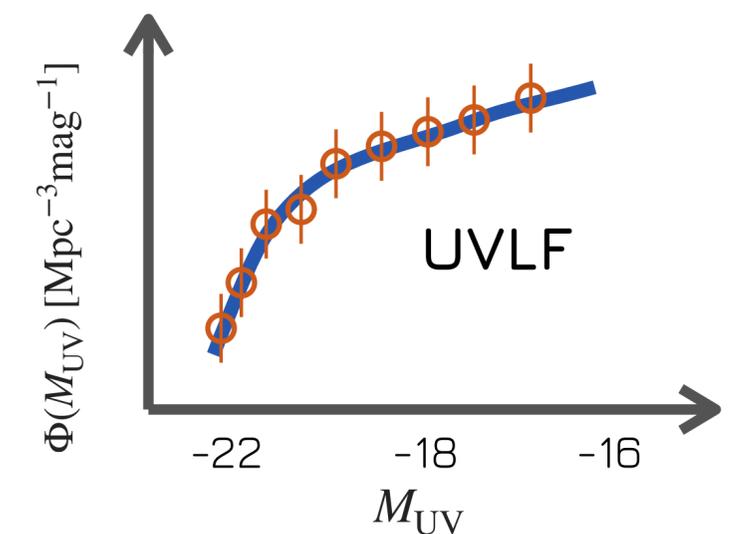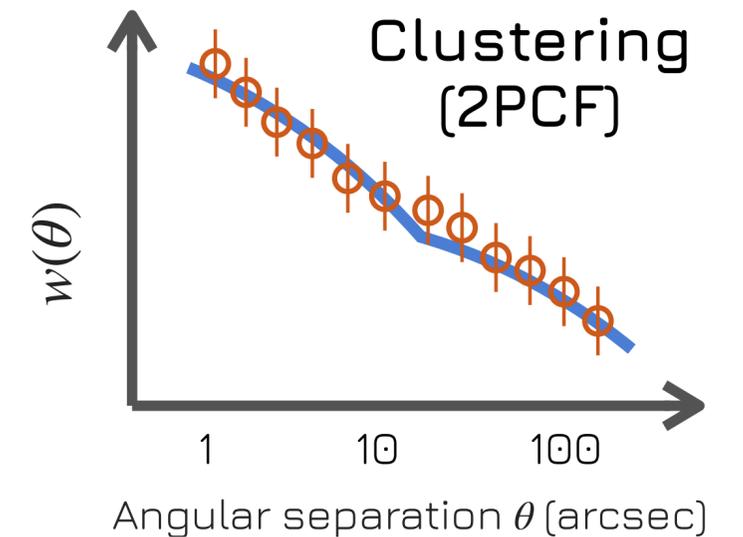
UVLF

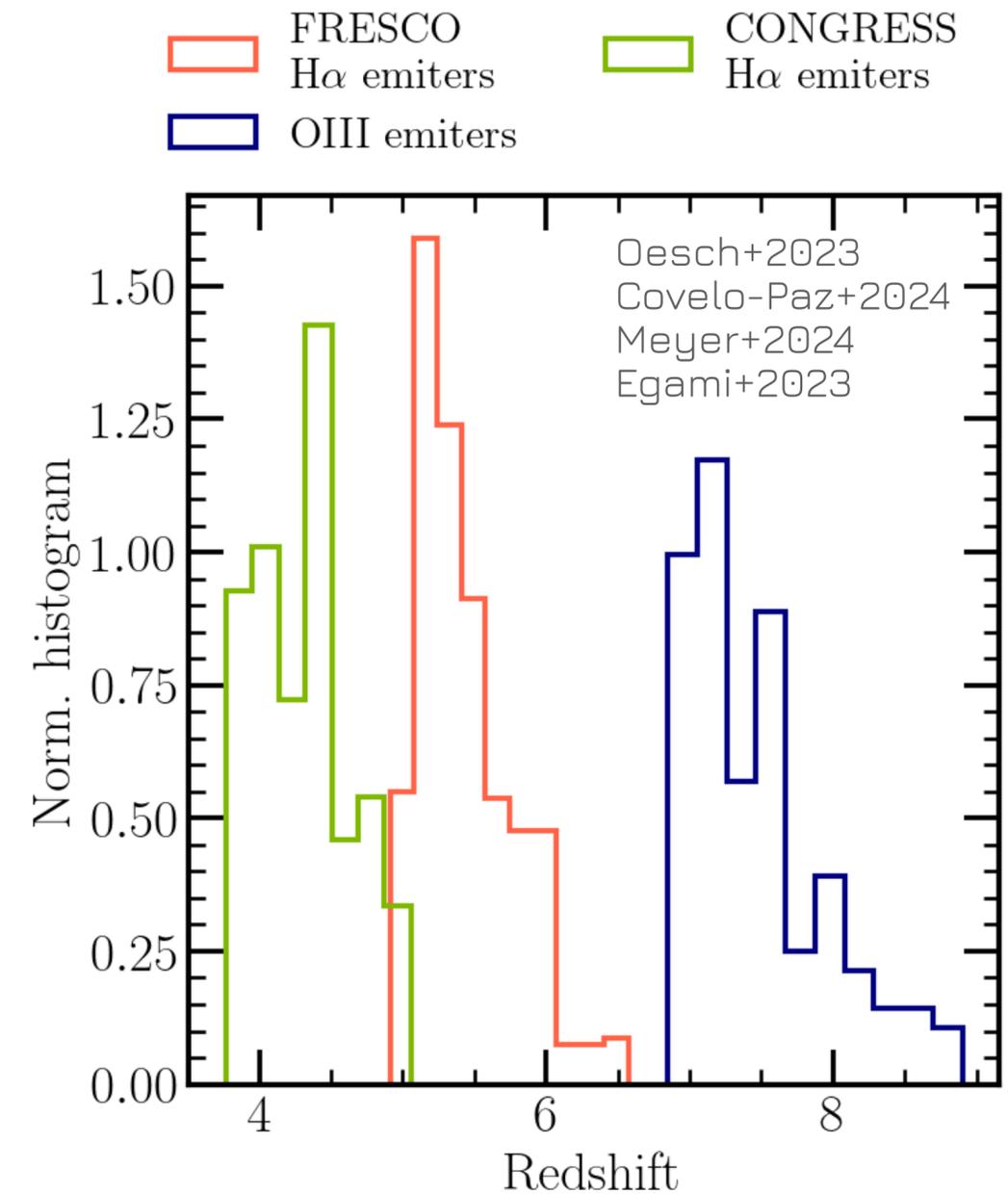SFE and σ_{UV} measured by fitting 2PCF and UVLF
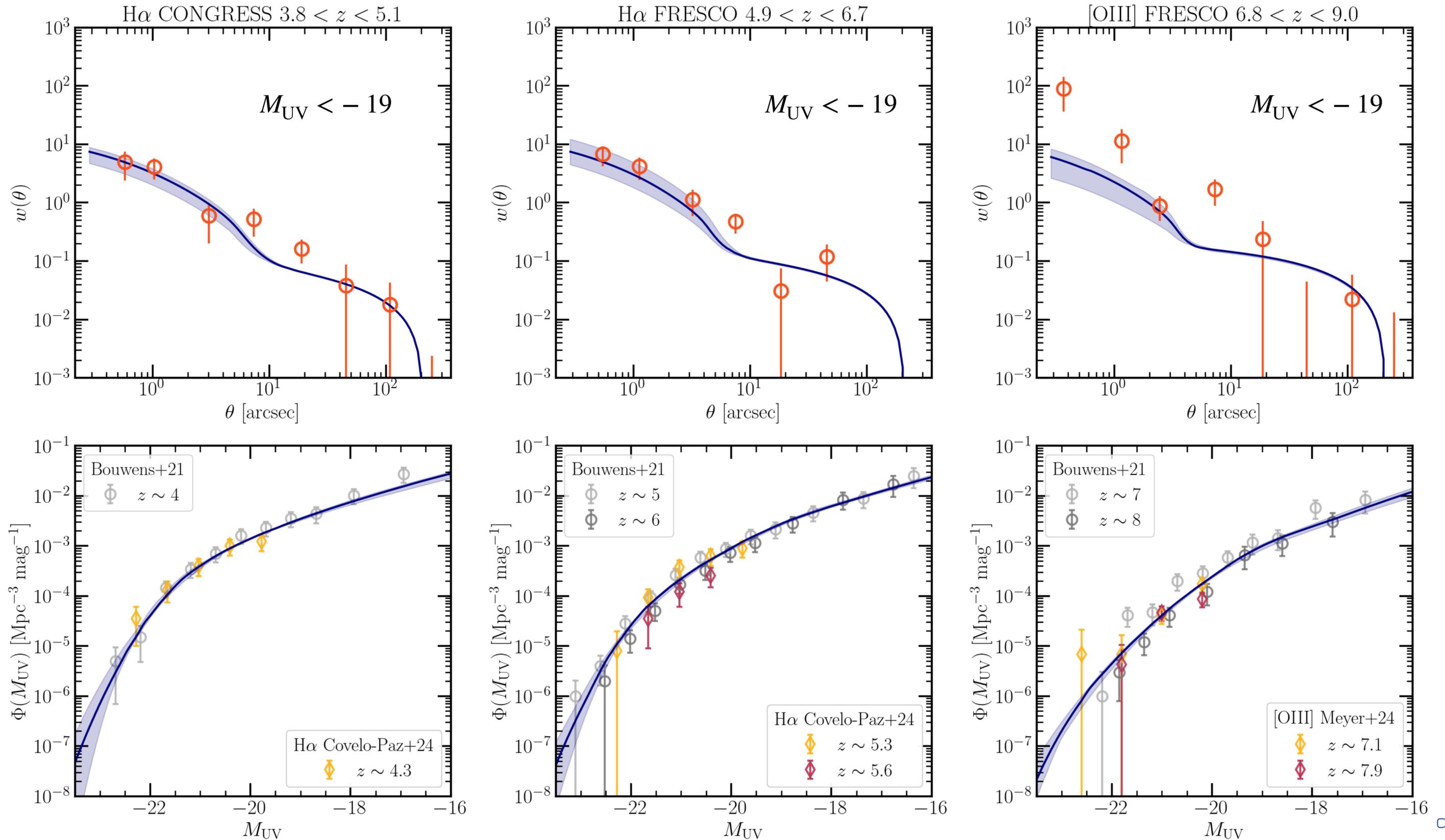
FRESCO: putting this formalism to the test

FRESCO (Oesch+2023) provides a ~small but robust sample of spec-z galaxies to measure **clustering via the 2pcf**

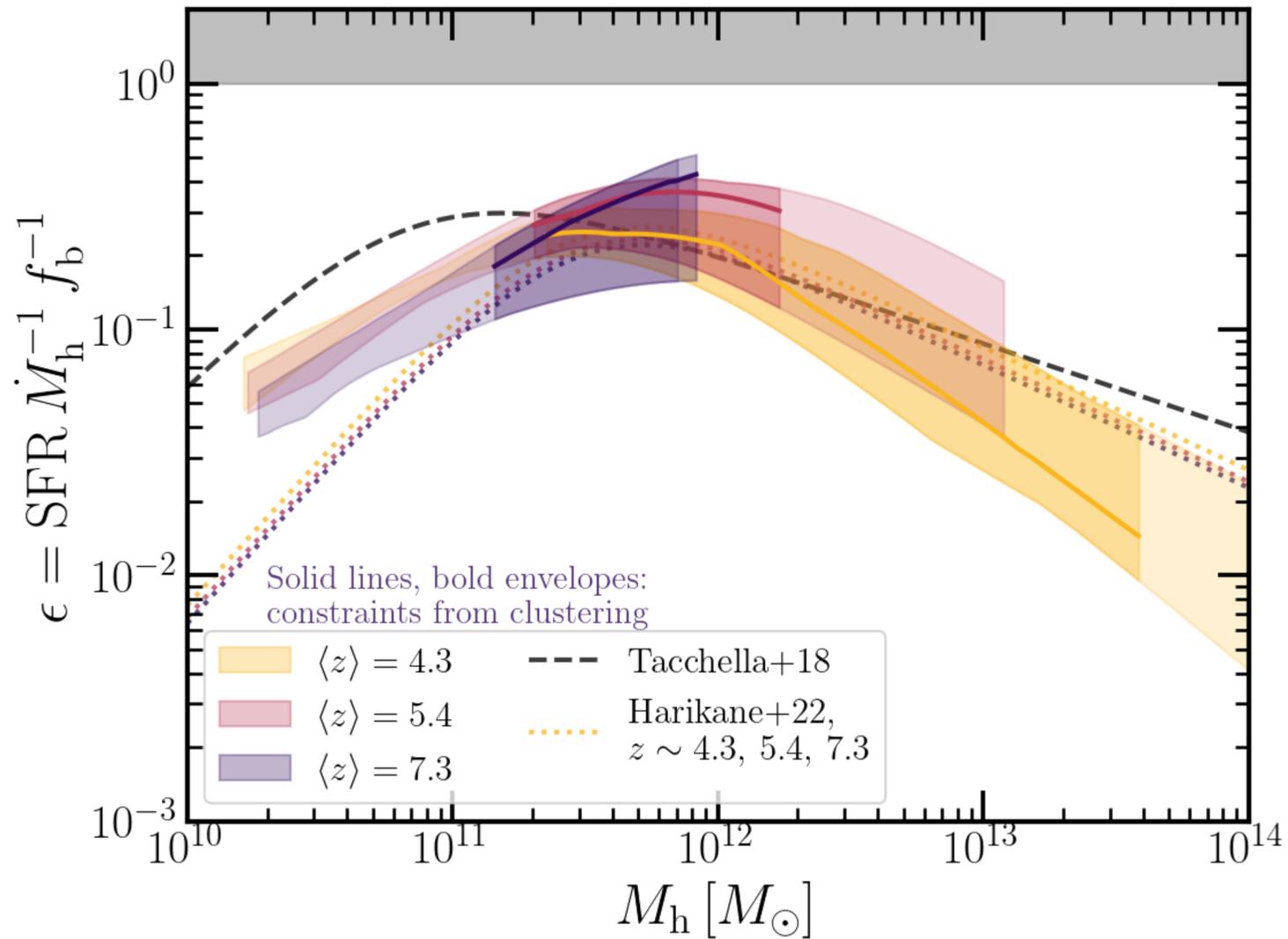Hα emitters at $z \sim 4.3$, $z \sim 5.5$ (Covelo-Paz+2024)
[OIII] emitters at $z \sim 7.5$ (Meyer+2024)

FRESCO: first and preliminary results

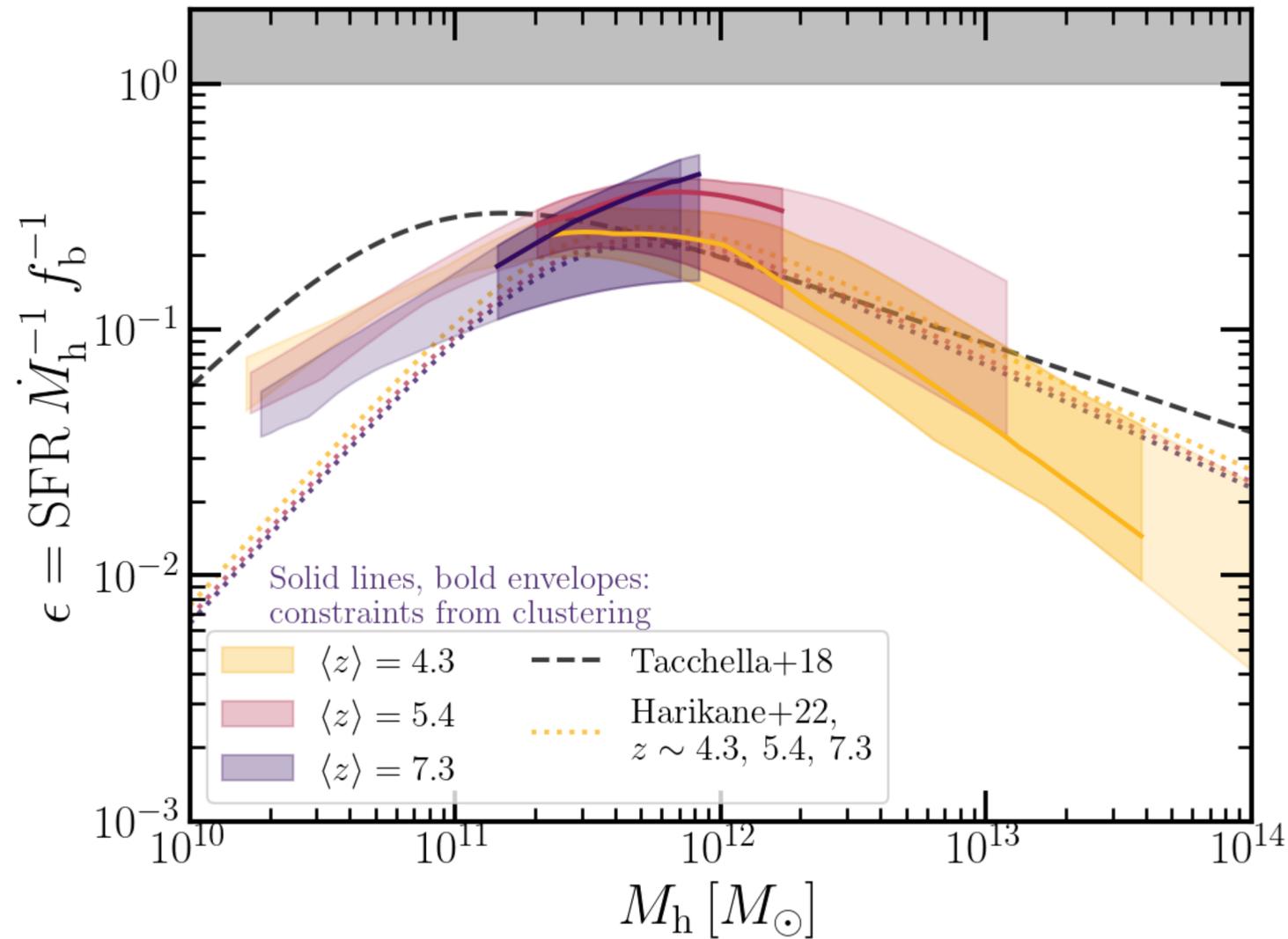arko Shuntov

FRESCO: first and preliminary results

Little evolution of the
SFE over $4.3 < z < 7.3$
in agreement with previous finds
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Evidence for an increasing SFE in massive
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but constrains still mainly come from UVLF, need
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Constant and modest scatter, increasing SFE
with redshift
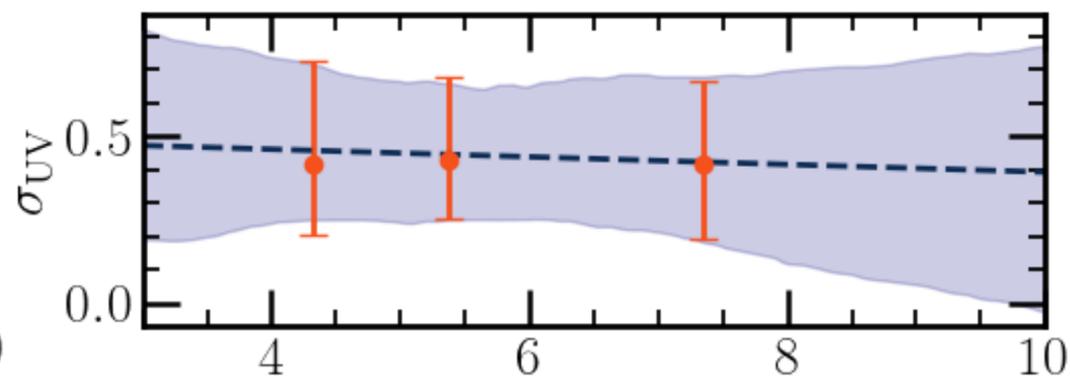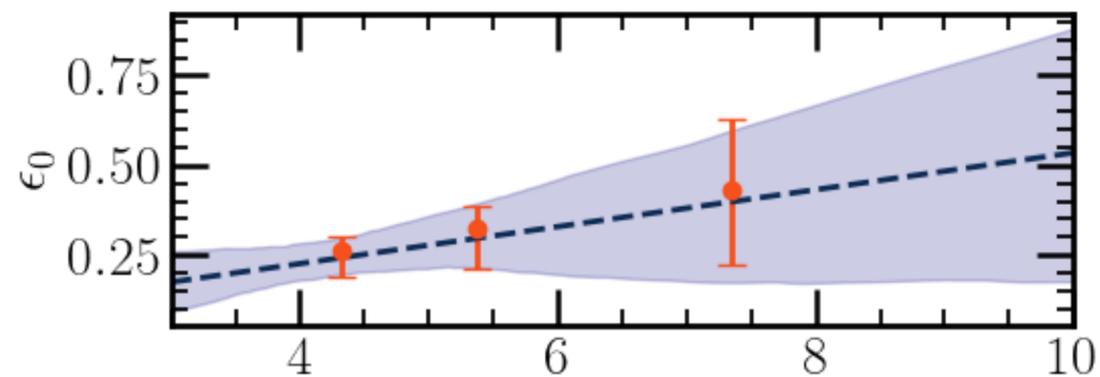
Conclusions

- COSMOS-Web: $0.5\,\mathrm{deg}^2$ and 30+ bands allow us to study the stellar mass assembly history at $0.2 < z < 12$

- Non-monotonous evolution of the integrated SFE (SHMR) with an upturn at $z \sim 3.5$, $\epsilon_\star \sim 50 - 100\,\%$ at $z \gtrsim 6$.

- Promising, highly flexible and predictive HOD-based joint model of UVLF, 2PCF (and soon other statistics e.g., SMF, SFH)

- FRESCO: Evidence for an increasing instantaneous SFE $(\epsilon_0 \sim 20 - 40\,\%)$ in massive halos and with redshift $(4.3 < z < 7.3)$, constant and modest scatter $(\sigma_{\mathrm{UV}} \sim 0.5)$

Thank you for your attention

SMF Paper on ADS

arXiv:2410.08290

Github repository
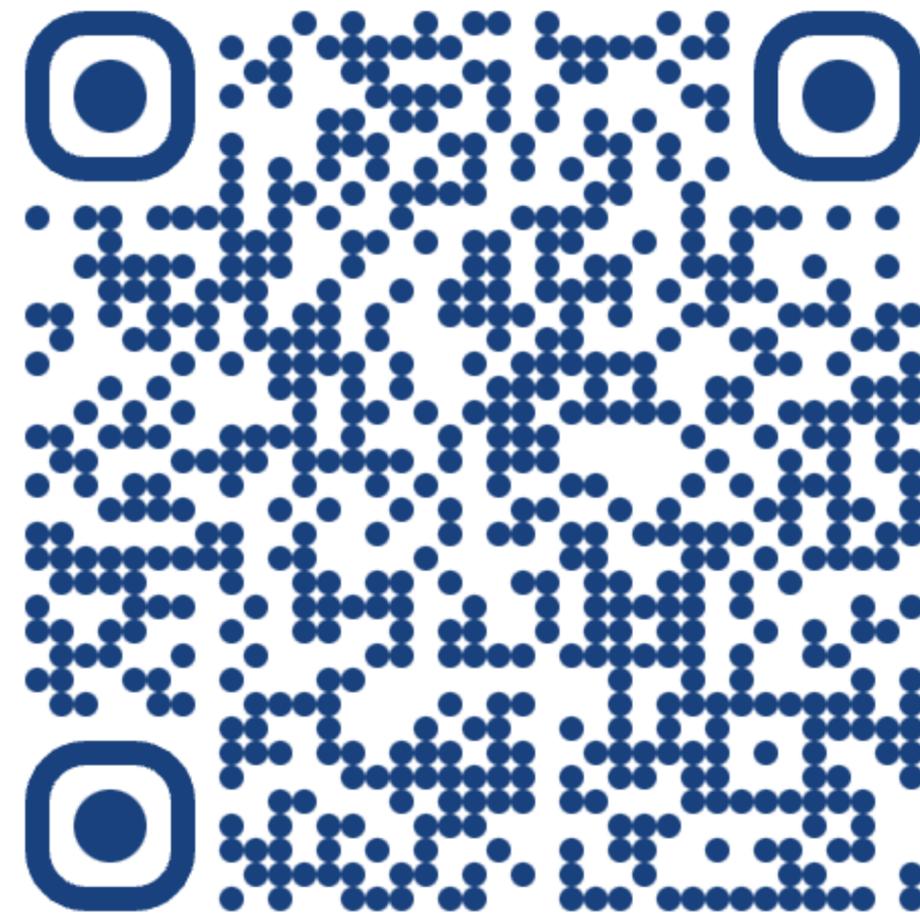
Tables of all paper data,
figures and more

Appendix

UVHMR
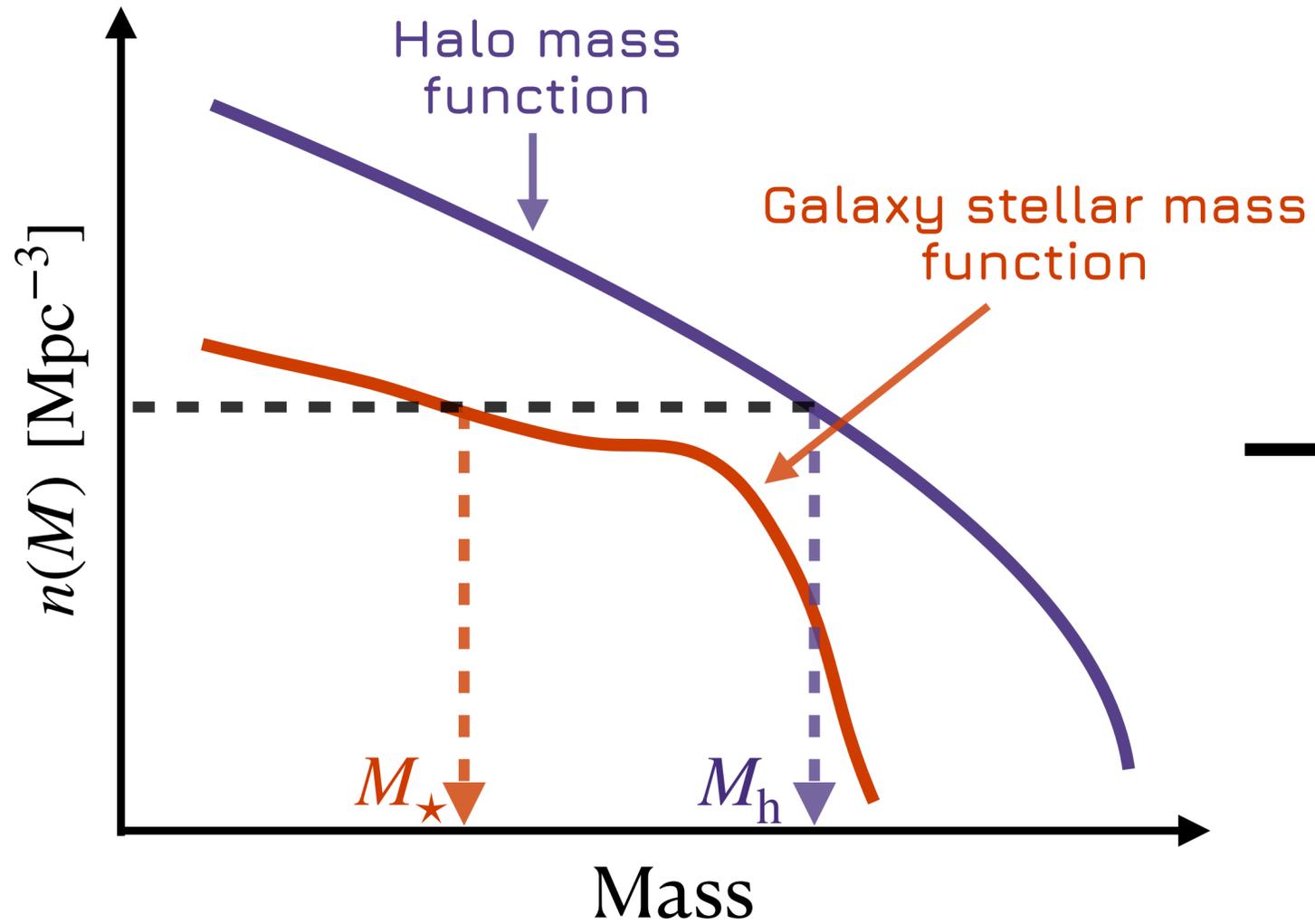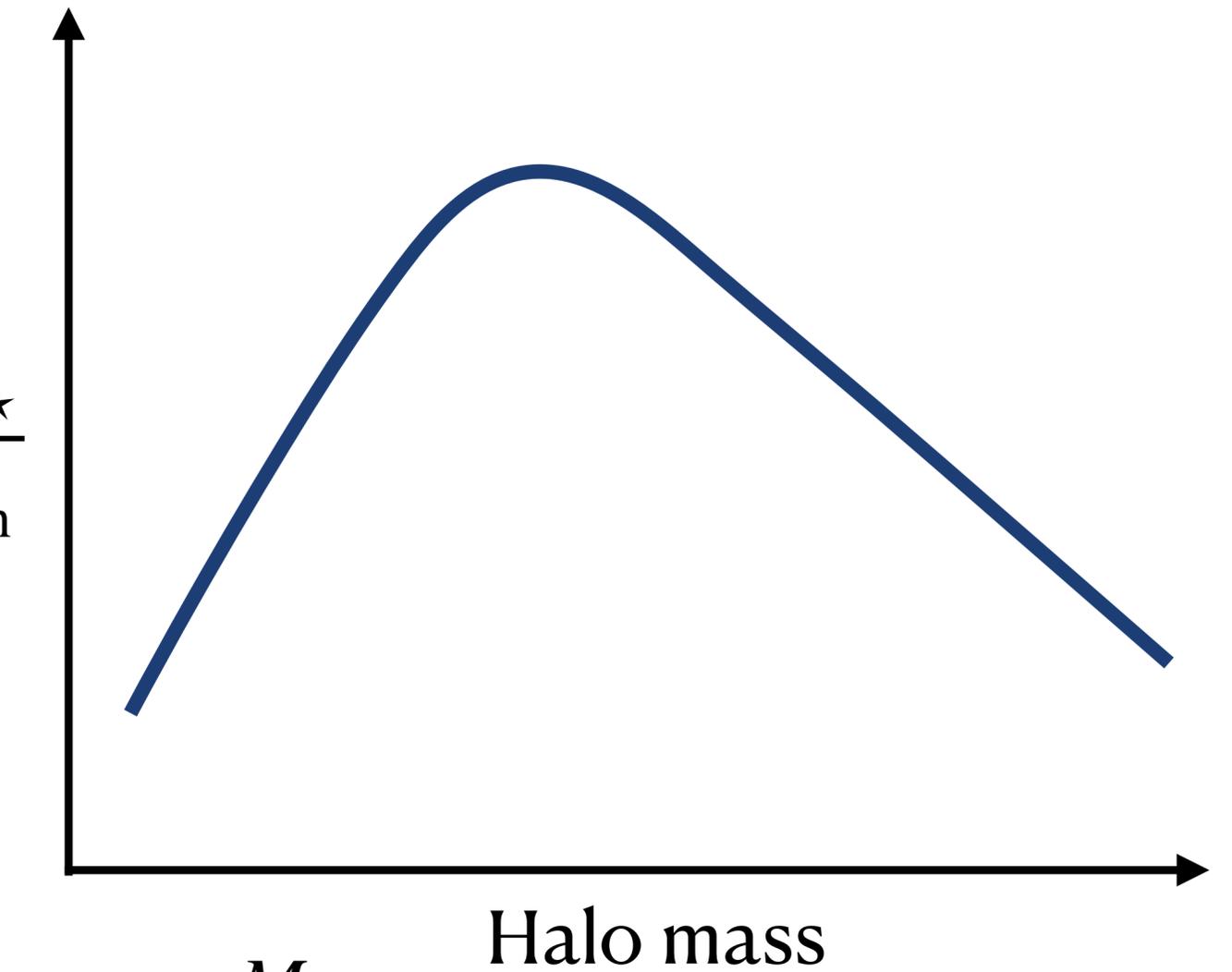
The stellar-to-halo mass ratio measures the integrated star formation efficiency
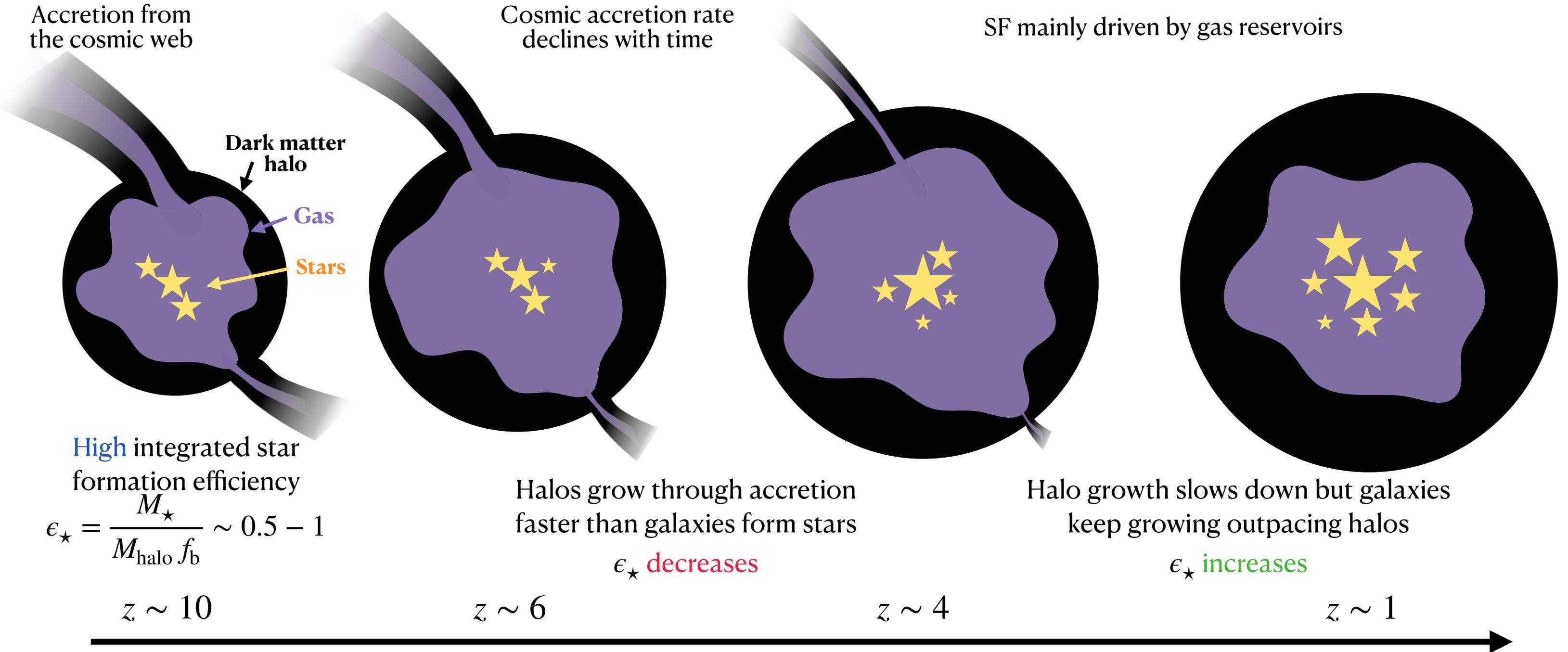
$$\epsilon_\star = \frac{M_\star}{M_{\rm h}\, f_{\rm b}}$$

The emerging picture from JWST/COSMOS-Web
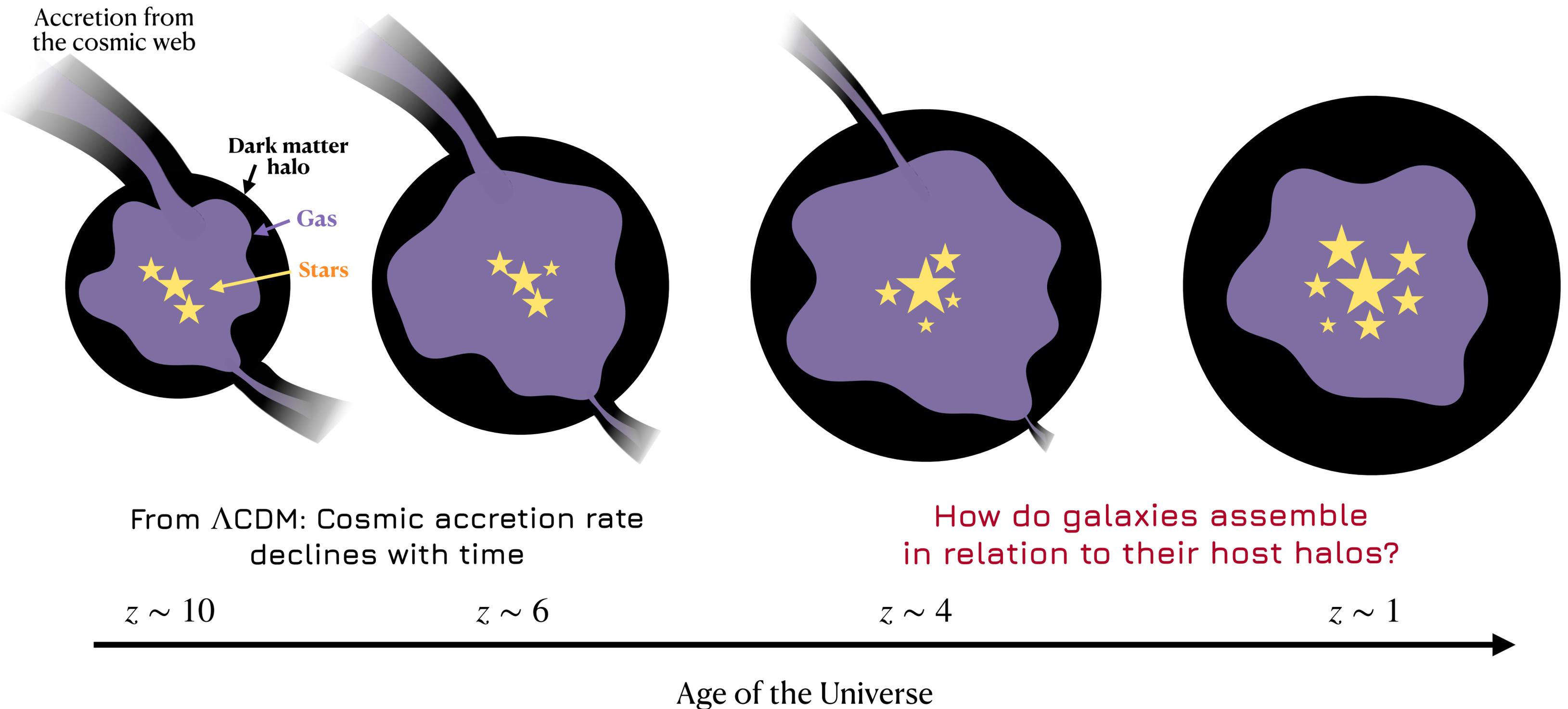## non-monotonic galaxy-halo coevolution

Accretion from the cosmic web

Dark matter halo

Gas

Stars

High integrated star formation efficiency
$$\epsilon_\star = \frac{M_\star}{M_{\mathrm{halo}}\, f_{\mathrm{b}}} \sim 0.5 - 1$$

$z \sim 10$

Cosmic accretion rate declines with time

Halos grow through accretion faster than galaxies form stars

$\epsilon_\star$ decreases

$z \sim 6$

$z \sim 4$

SF mainly driven by gas reservoirs

Halo growth slows down but galaxies keep growing outpacing halos

$\epsilon_\star$ increases

$z \sim 1$

Age of the Universe

A simple model of galaxy formation within dark matter halos

Accretion from the cosmic web

Dark matter halo

Gas

Stars

From ΛCDM: Cosmic accretion rate declines with time

How do galaxies assemble in relation to their host halos?

$z \sim 10$ $z \sim 6$ $z \sim 4$ $z \sim 1$

Age of the Universe

Stochastic/bursty SF or enhanced SFE?

Enhanced SFE can be degenerate with increased scatter in the
and $M_{\rm UV} - M_{\rm halo}$ and $M_\star - M_{\rm halo}$ relationships in the resulting galaxy abundances

Clustering can break
this degeneracy!

(Muñoz+23)
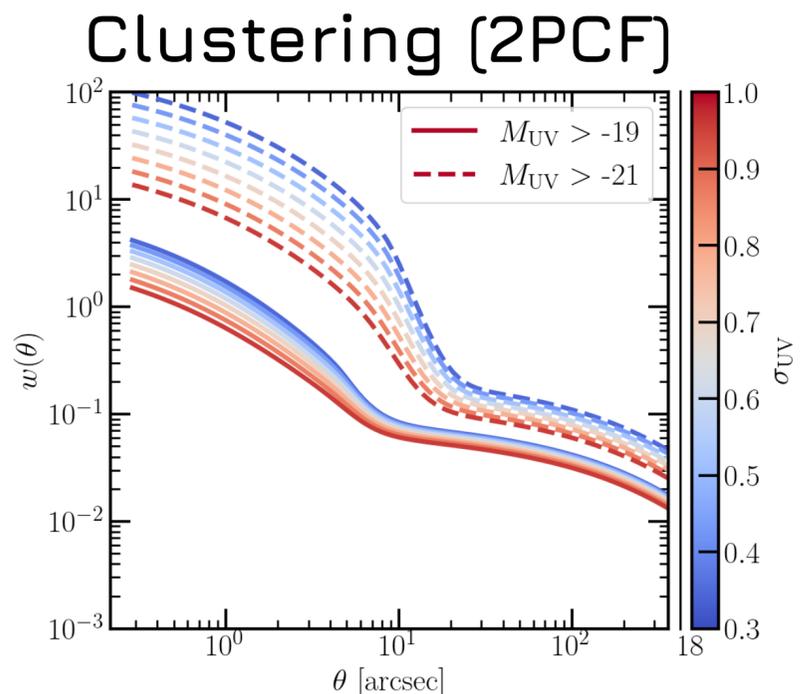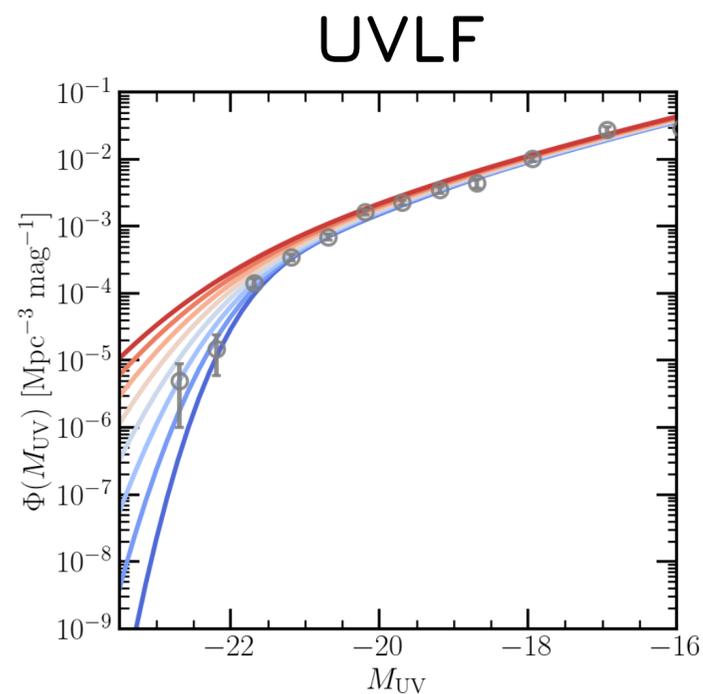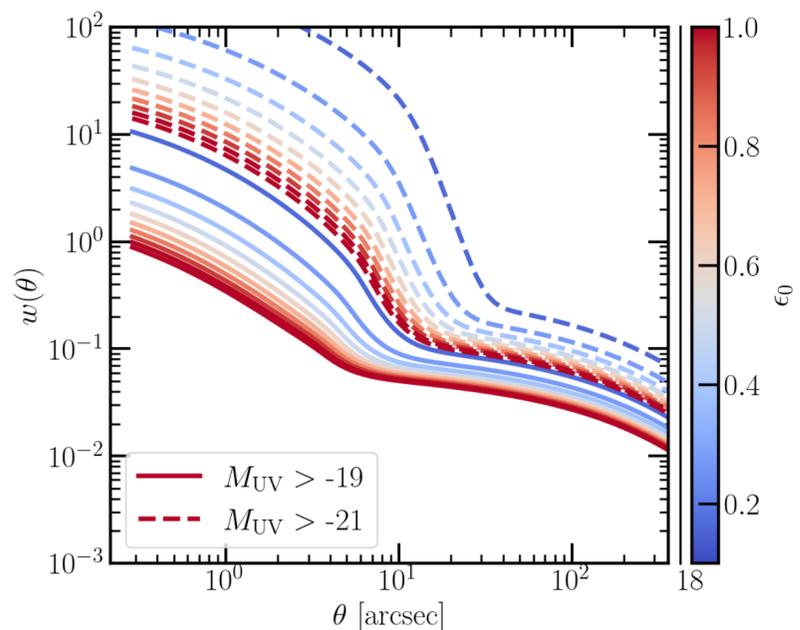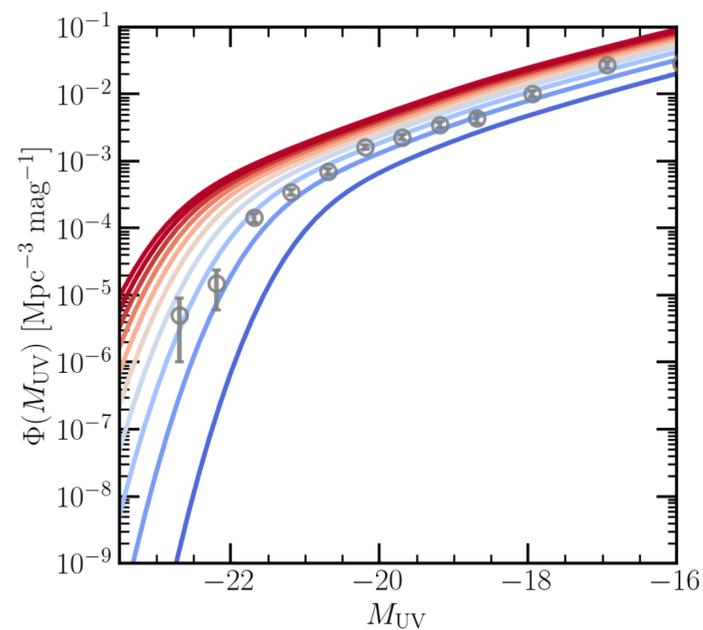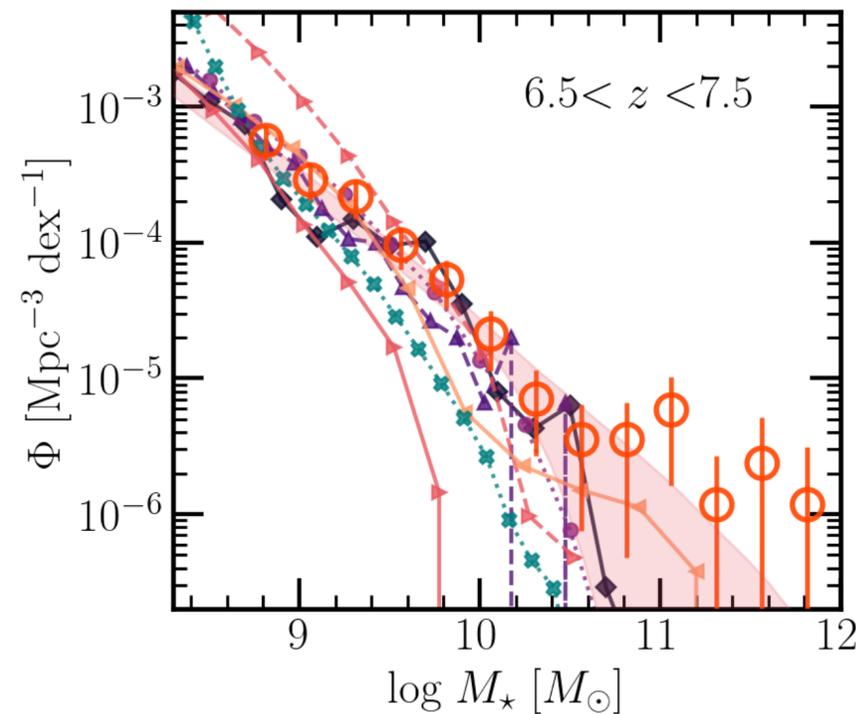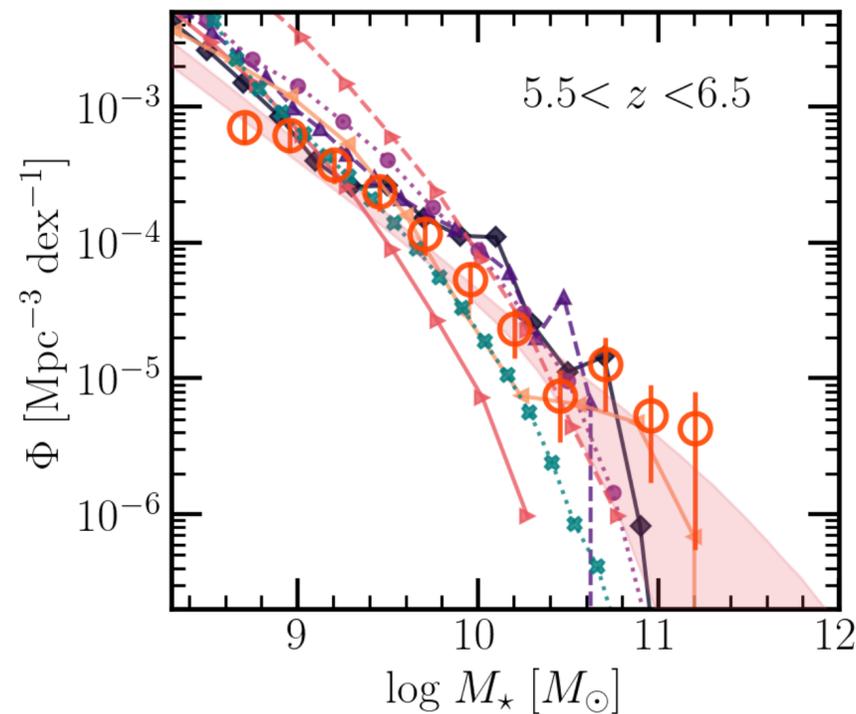
FRESCO: first and very preliminary results
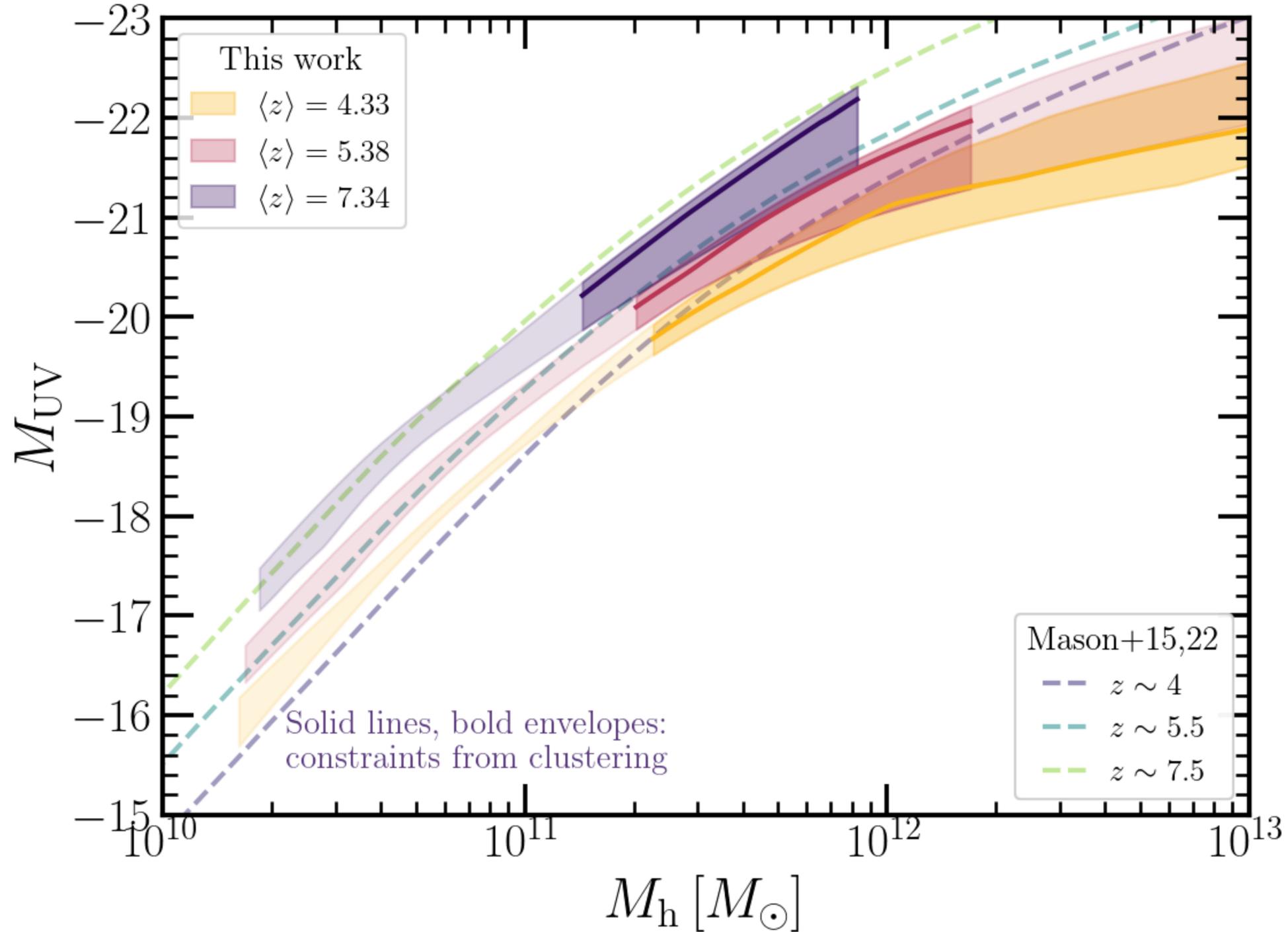
Increased abundances of massive galaxies at z>7 compared to simulations
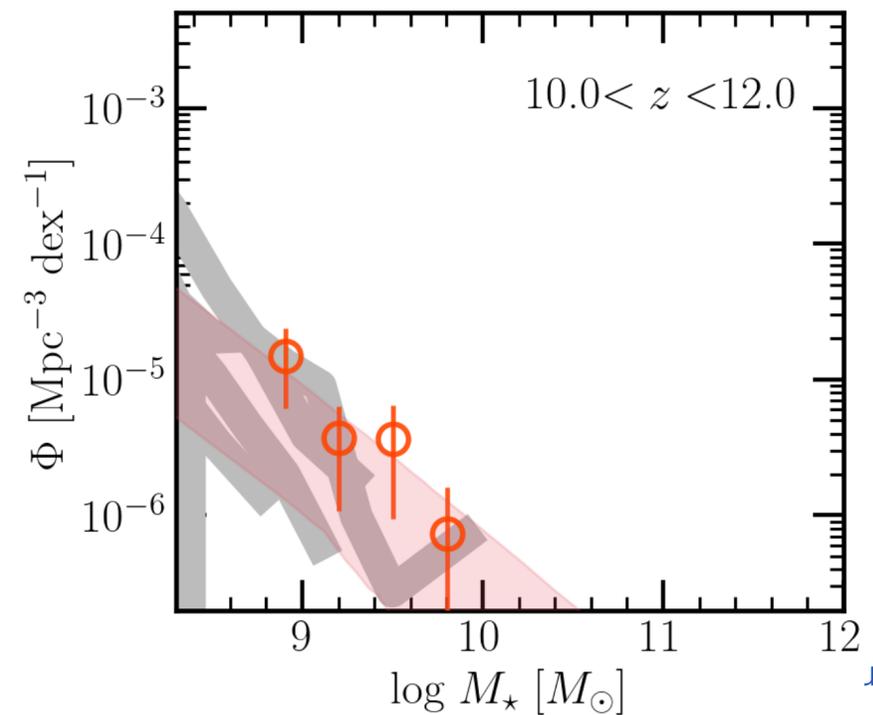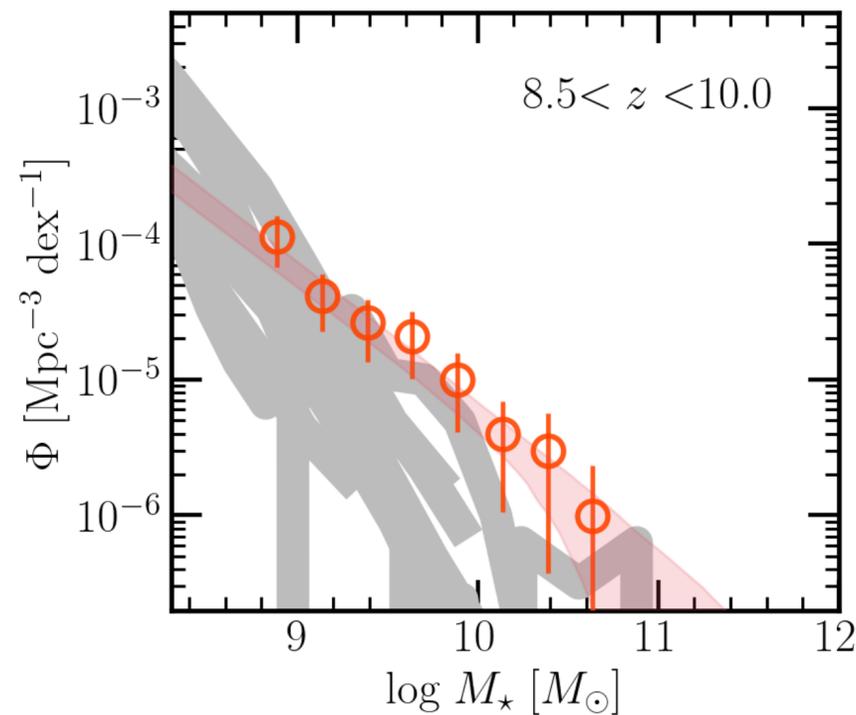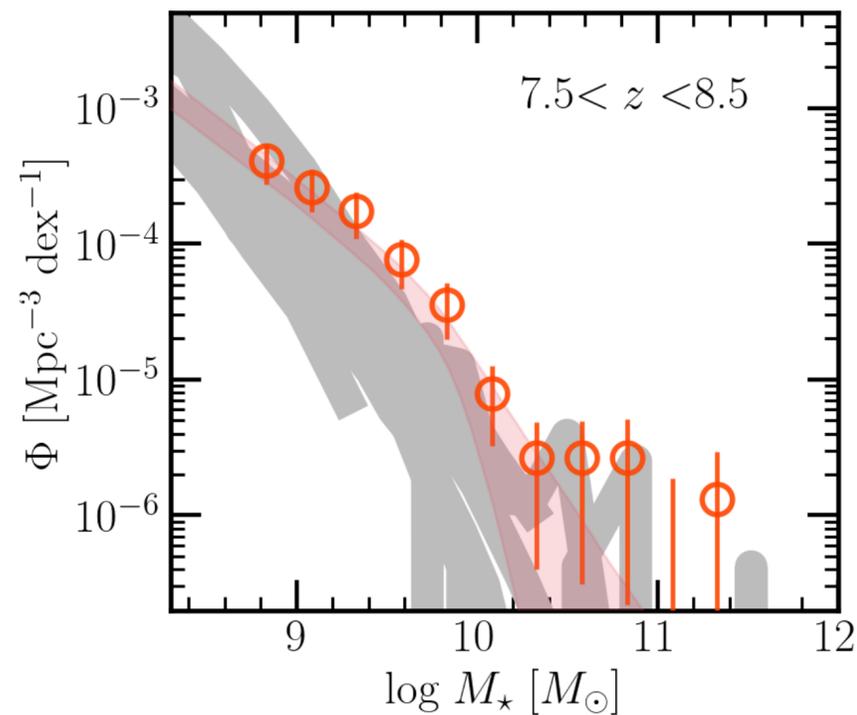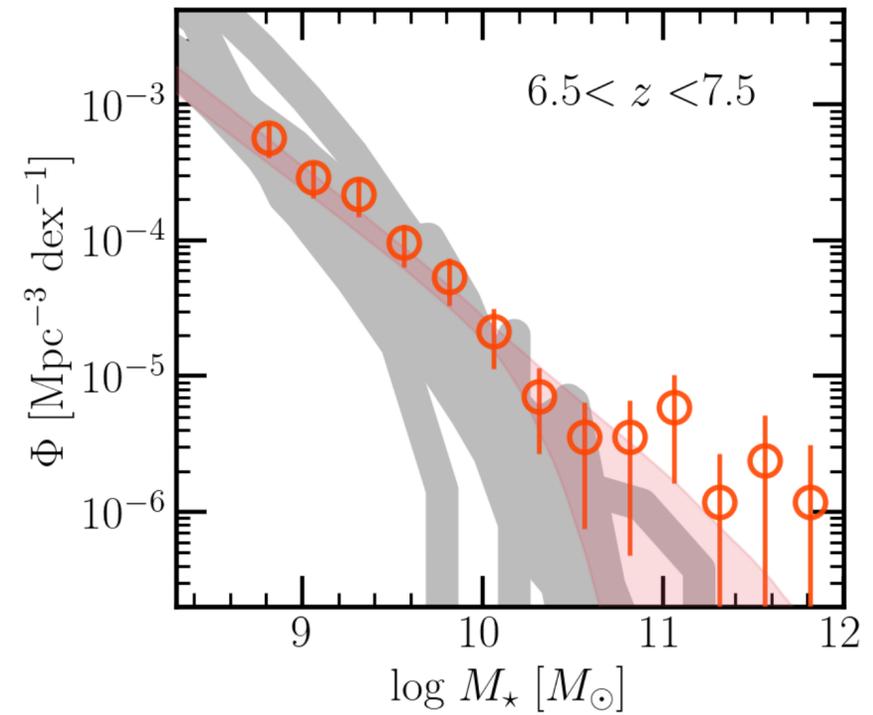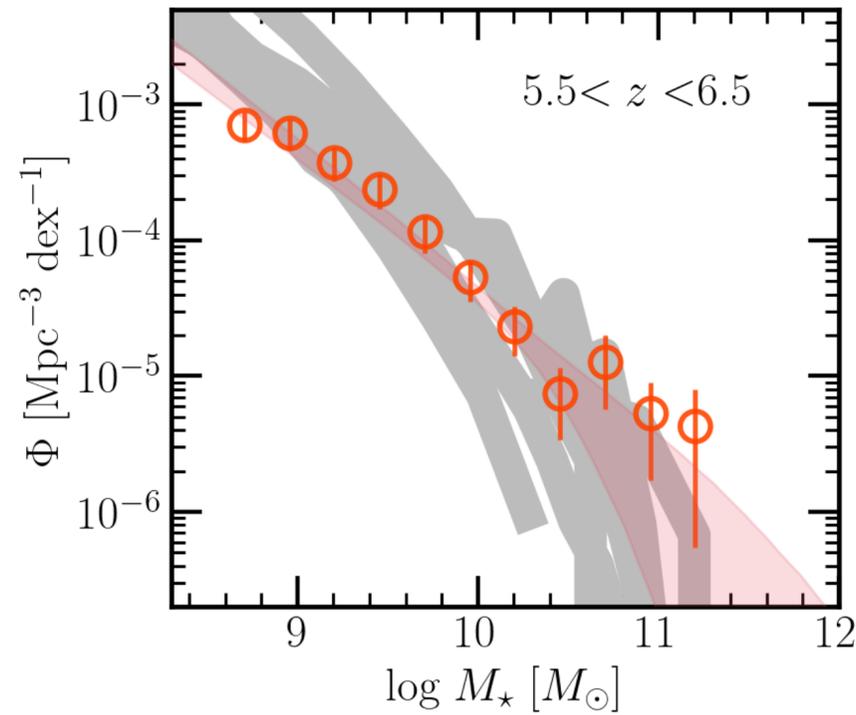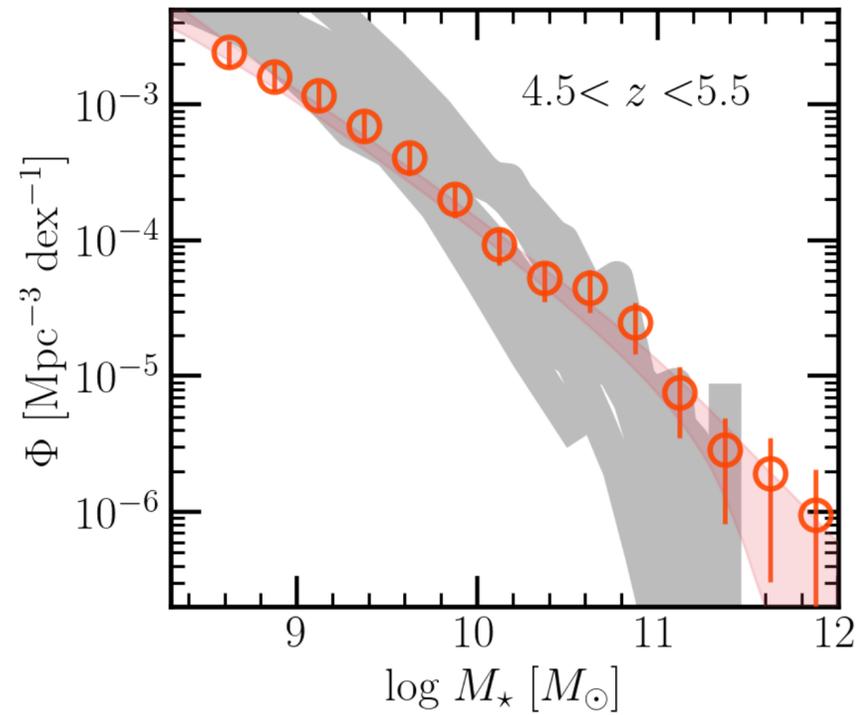
Increased abundances of massive galaxies at z>7 compared to simulations
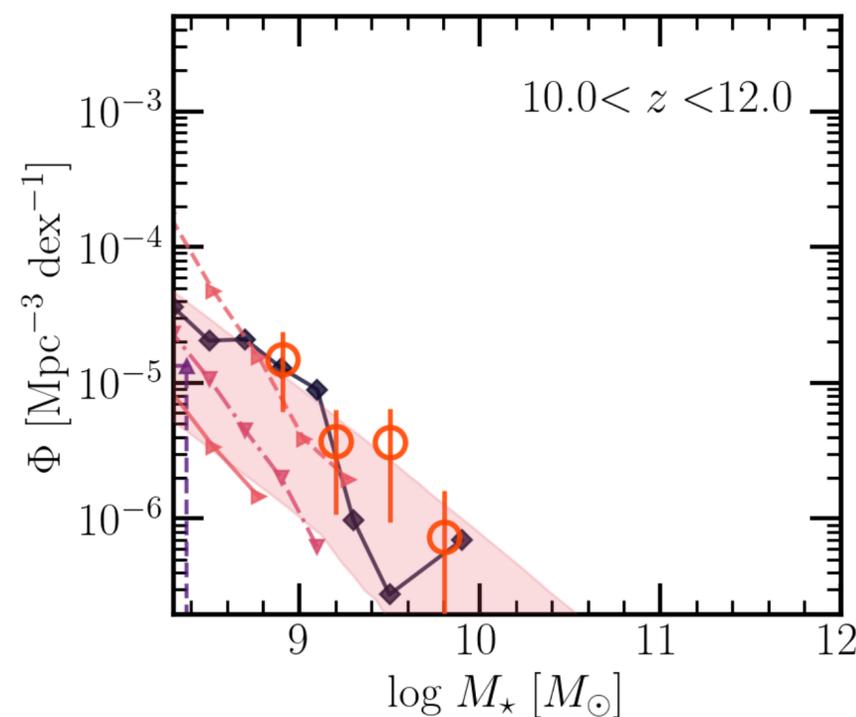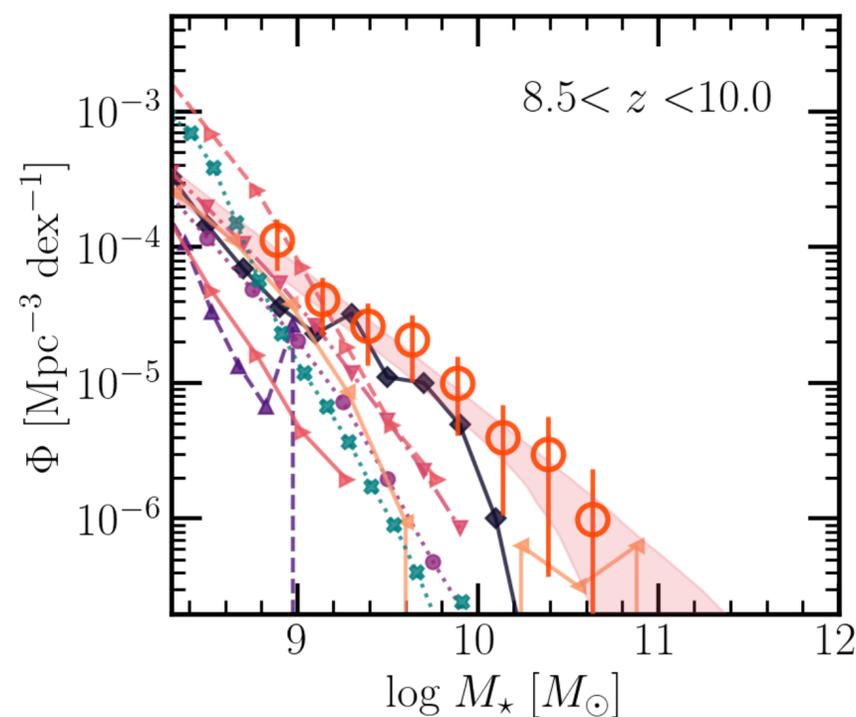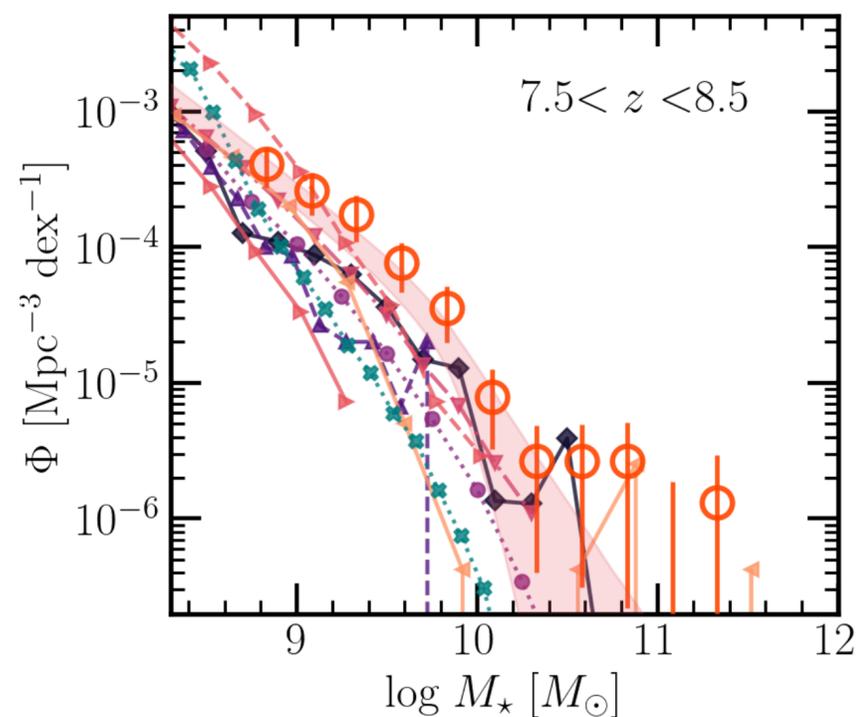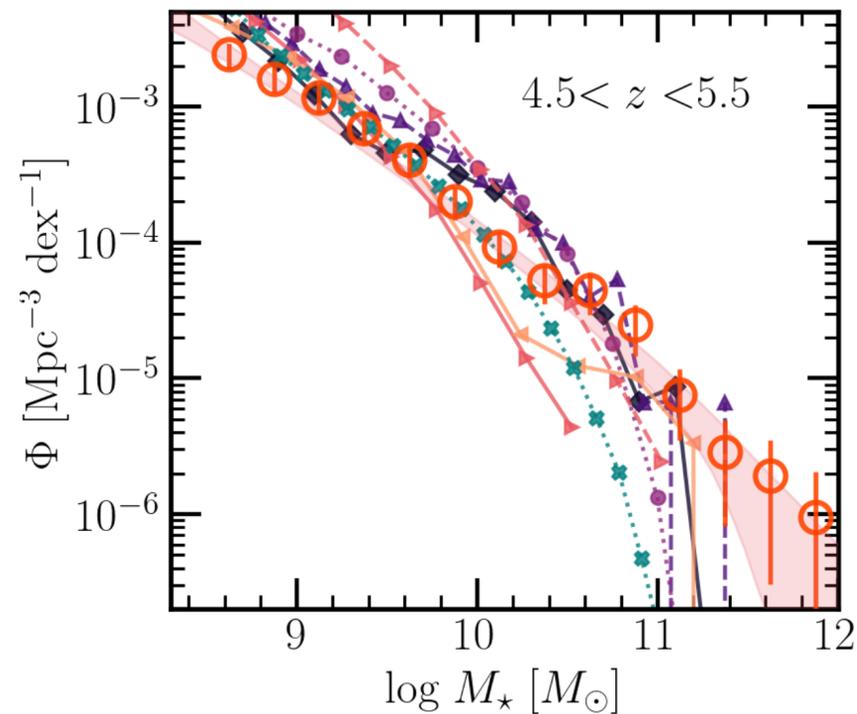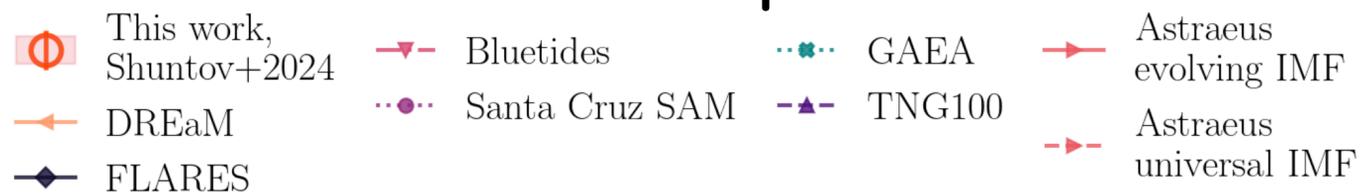
Comparison with theoretical models

Comparison with theoretical models

Li+2023
- $\epsilon_{max}^{FFB} = 0.0$, no FFB
- $\epsilon_{max}^{FFB} = 0.2$
- $\epsilon_{max}^{FFB} = 0.5$
- $\epsilon_{max}^{FFB} = 1$

This work, Shuntov+2024

$4.5 < z < 5.5$

$5.5 < z < 6.5$

$6.5 < z < 7.5$

$7.5 < z < 8.5$

$8.5 < z < 10.0$

$10.0 < z < 12.0$

Φ [Mpc^{-3} dex^{-1}]

$\log M_\star$ [$M_\odot$]