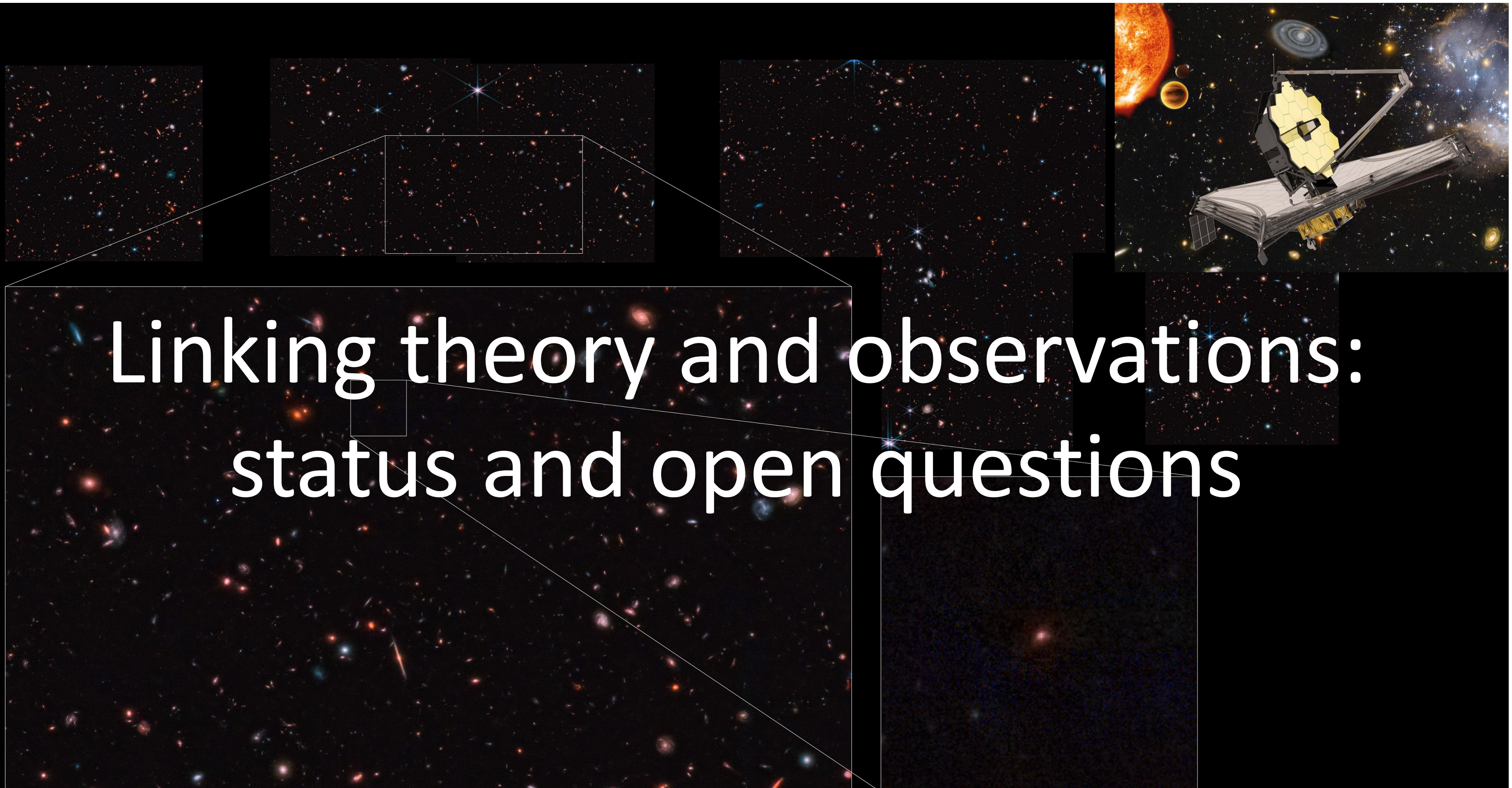
Linking theory and observations: status and open questions



CEERS JWST/NIRCam F115W F150W F200W F277W F356W F410M F444W NASA/STScI/CEERS/TACC/S. Finkelstein/M. Bagley/Z. Levay

- *rachel somerville*

Center for Computational Astrophysics

FLATIRON INSTITUTE

54th Saas-Fee Advanced Course

Galaxies and Black Holes in the First Billion Years as seen by the JWST

Jan 27-31, 2025

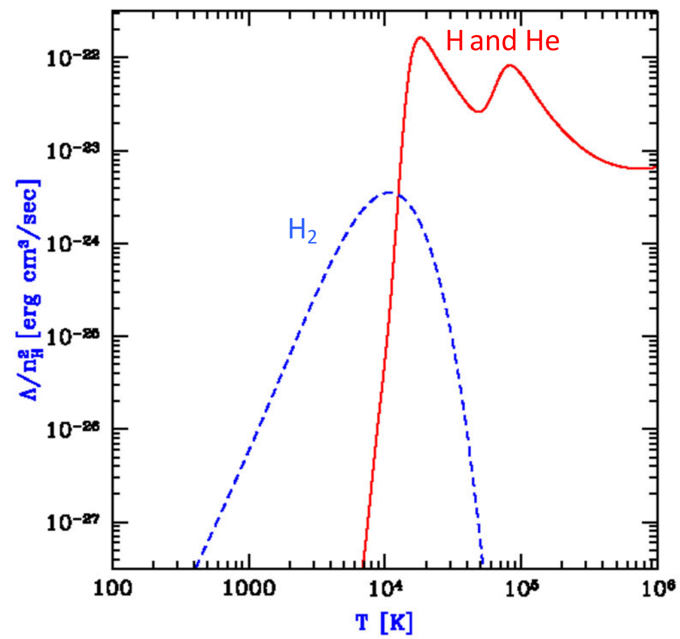
Swiss National Science Foundation · EPFL · scnat swiss academy of sciences · UNIVERSITÉ DE GENÈVE · SSAA

outline

- Pop III star formation
- bridging theory and observations
  - modeling the SEDs of (unattenuated) stellar populations
  - modeling nebular emission from HII regions
  - modeling dust attenuation and emission
  - estimating physical quantities from SED fitting
- challenges and puzzles in the FBY revealed by JWST

formation of the first stars

cooling rate of primordial gas



Barkana & Loeb 2001

$$\mathrm{H} + \mathrm{e}^- \rightarrow \mathrm{H}^- + \gamma,$$

$$\mathrm{H}^- + \mathrm{H} \rightarrow \mathrm{H}_2 + \mathrm{e}^-.$$

$$\mathrm{H} + \mathrm{H}^+ \rightarrow \mathrm{H}_2^+ + \gamma,$$

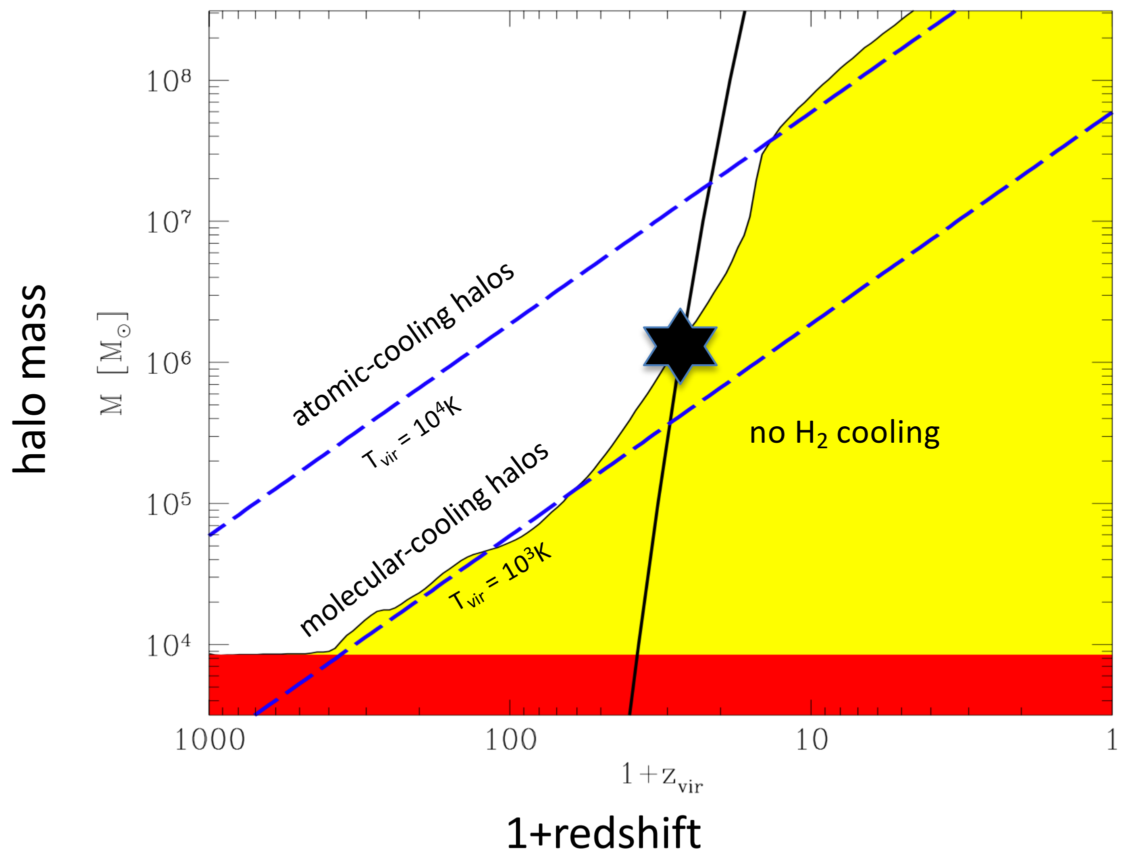
$$\mathrm{H}_2^+ + \mathrm{H} \rightarrow \mathrm{H}_2 + \mathrm{H}^+.$$

Klessen & Glover 2023, ARAA

huge thanks to R. Schneider for sharing slides from her KITP review on this topic

when and where did the first stars form?

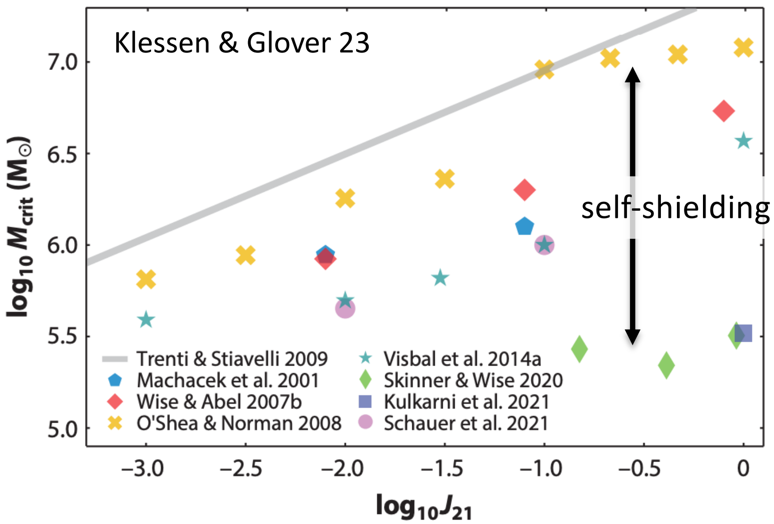
at $z \approx 30$ in primordial dark matter **mini-halos** $M \approx M(T_{vir} \approx 10^3 - 10^4\ K) \approx 10^6\ M_{sun}$



Tegmark et al. (1997)

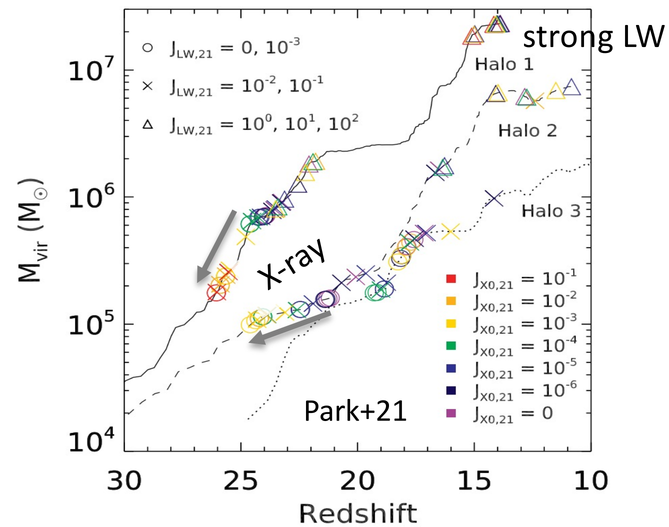
additional important processes: radiation fields

in the Lyman-Werner UV band (LW, 11.2–13.6 eV)
photo-dissociate H_2 and suppress cooling



$J_{21} = J_{LW}$ in units of 10^{-21} erg s^{-1} cm^{-2} Hz^{-1} sr^{-1}

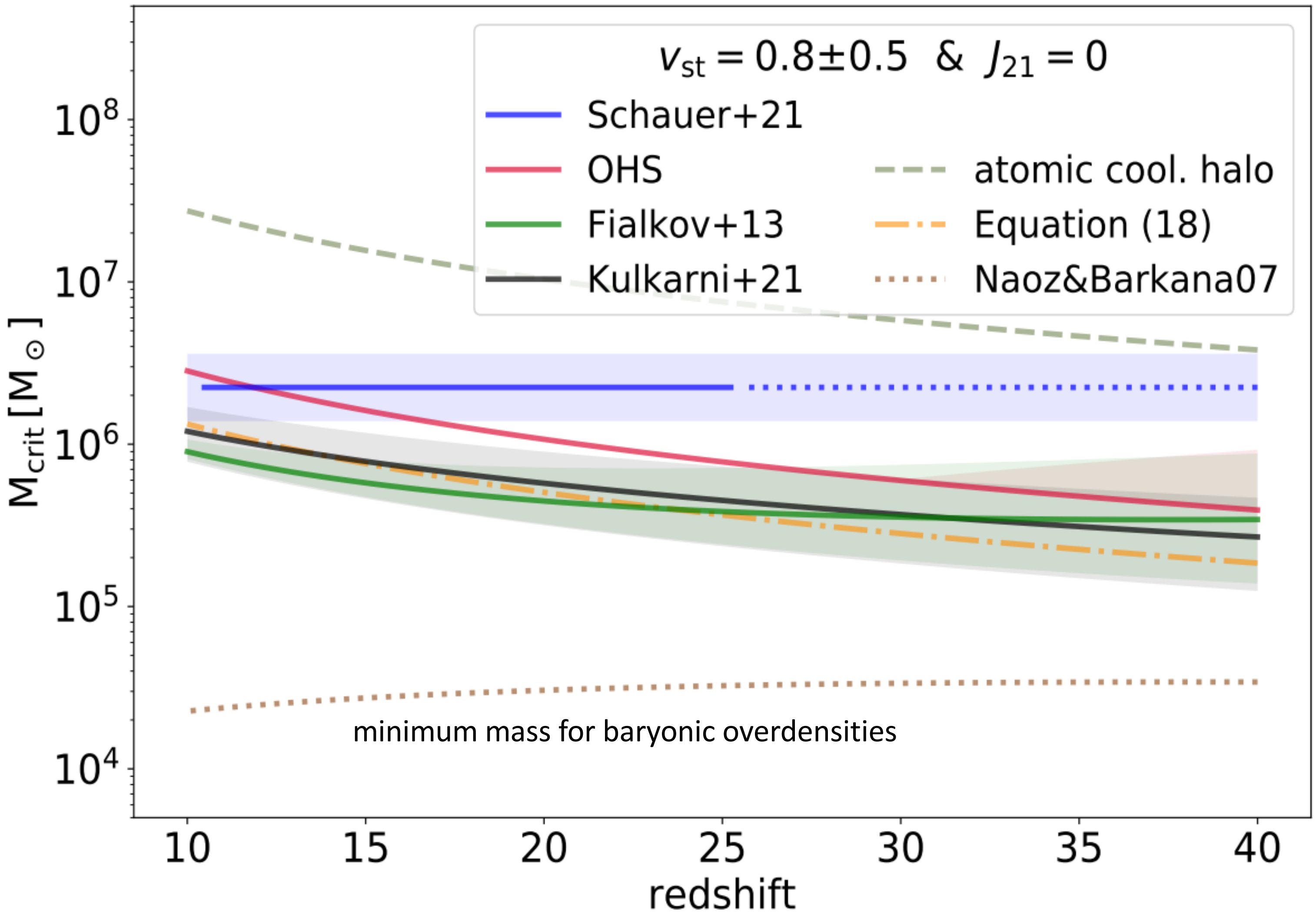
in the X-ray band (0.2 – 2 keV and 1– 10 keV)
increase free electron fraction, promote H_2
formation and cooling



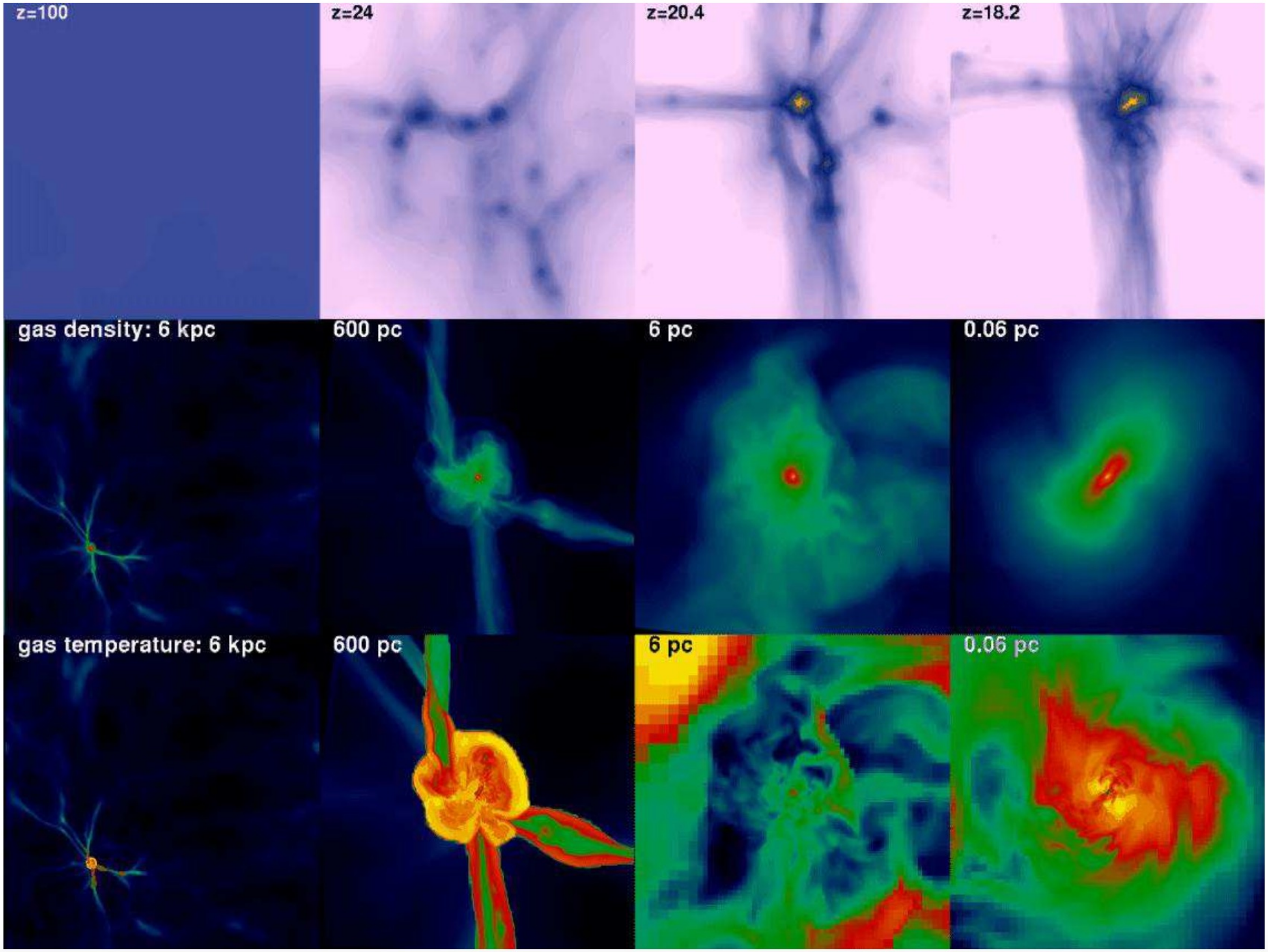
$J_{x021} = J_{x21}(E_0 = 0.2$ keV) units of 10^{-21} erg s^{-1} cm^{-2} Hz^{-1} sr^{-1}

see also Gnedin 00; Haiman+00; O'Shea & Norman 08; Johnson+13; Regan+20; Venkatesan+01; Jeon+14; Xu+16; Ricotti+16; Ricotti+21; Correa-Magnus+24

impact of relative streaming velocities on first stars

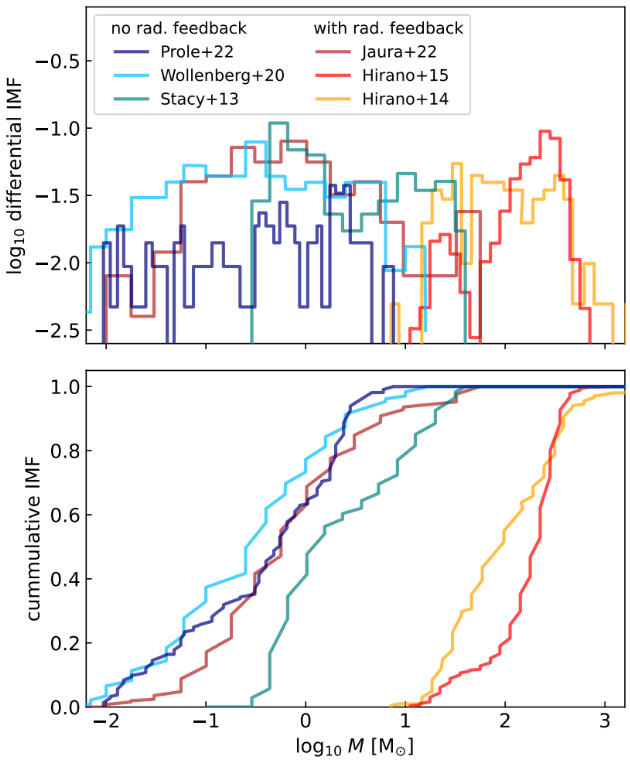


Klessen & Glover 2023



Abel et al. 2001; Bromm et al. 1999; 2002; Yoshida et al. 2003

the initial mass function of Pop III stars



Klessen & Glover 2023, ARAA

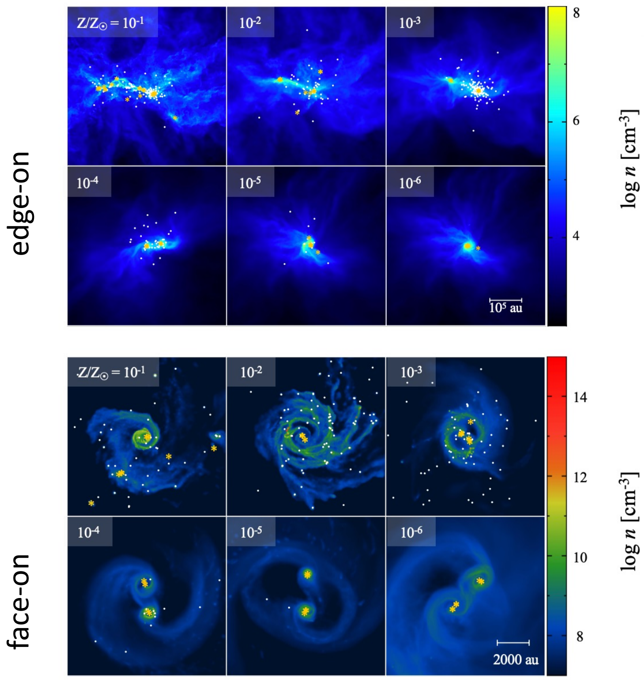
- large variation in the mass range (resolution,
- integration time, etc)

- approximately Log Flat distribution
- → top-heavy wrt present-day IMF

strongest existing constraints from stellar archaeology in nearby Universe

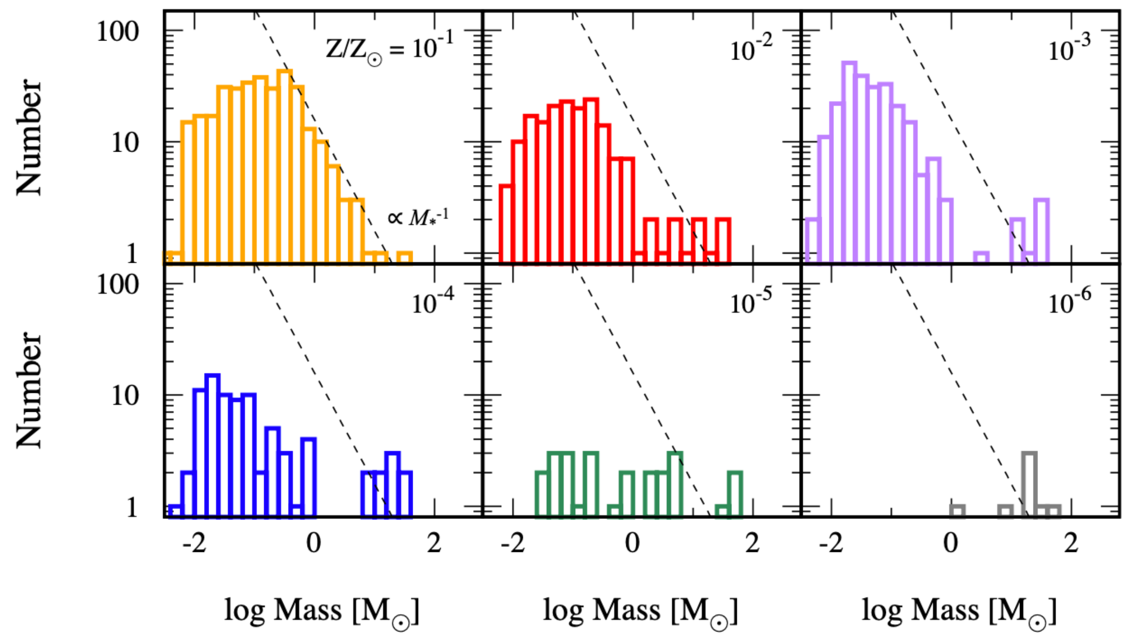
IMF transition in metal-poor environments

projected gas density at $t_{end} = 10^4 – 10^5$ yr



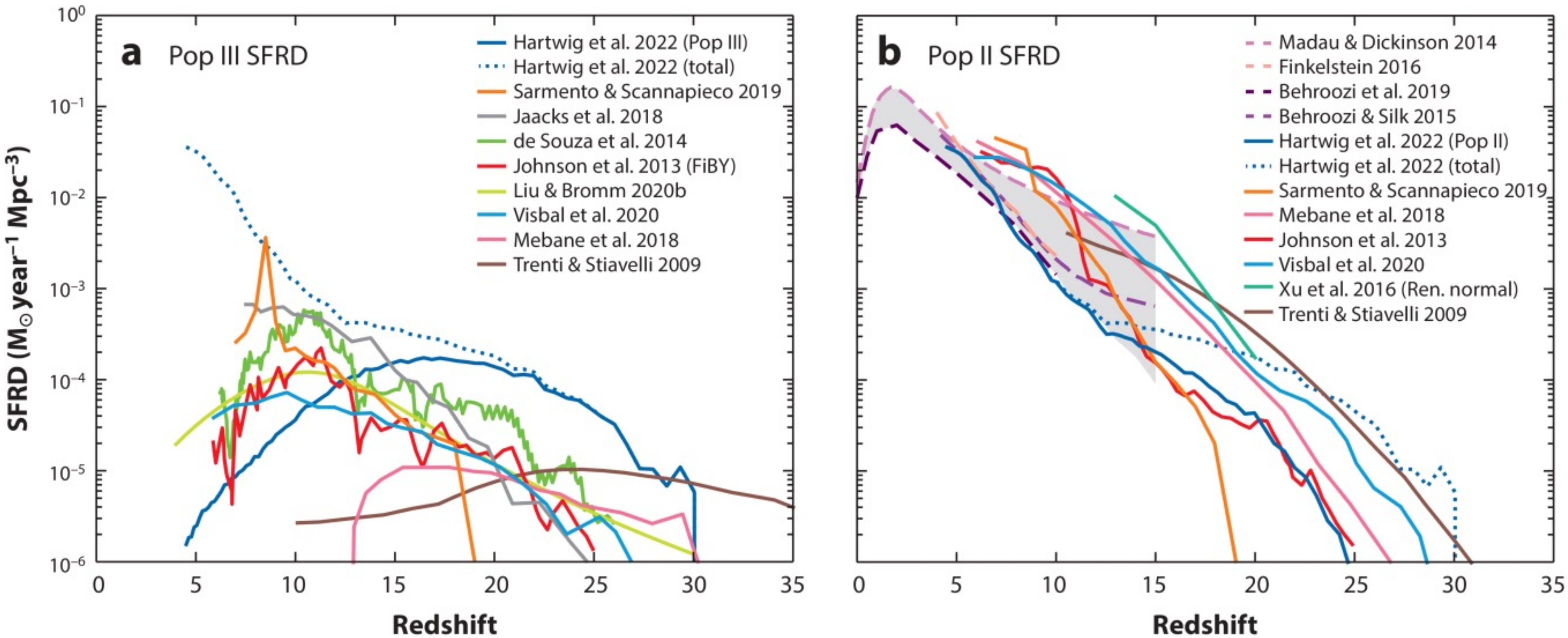
stars < 1 M_{sun} stars > 1 M_{sun}

$M_{star,tot}$ = 150 M_{sun}



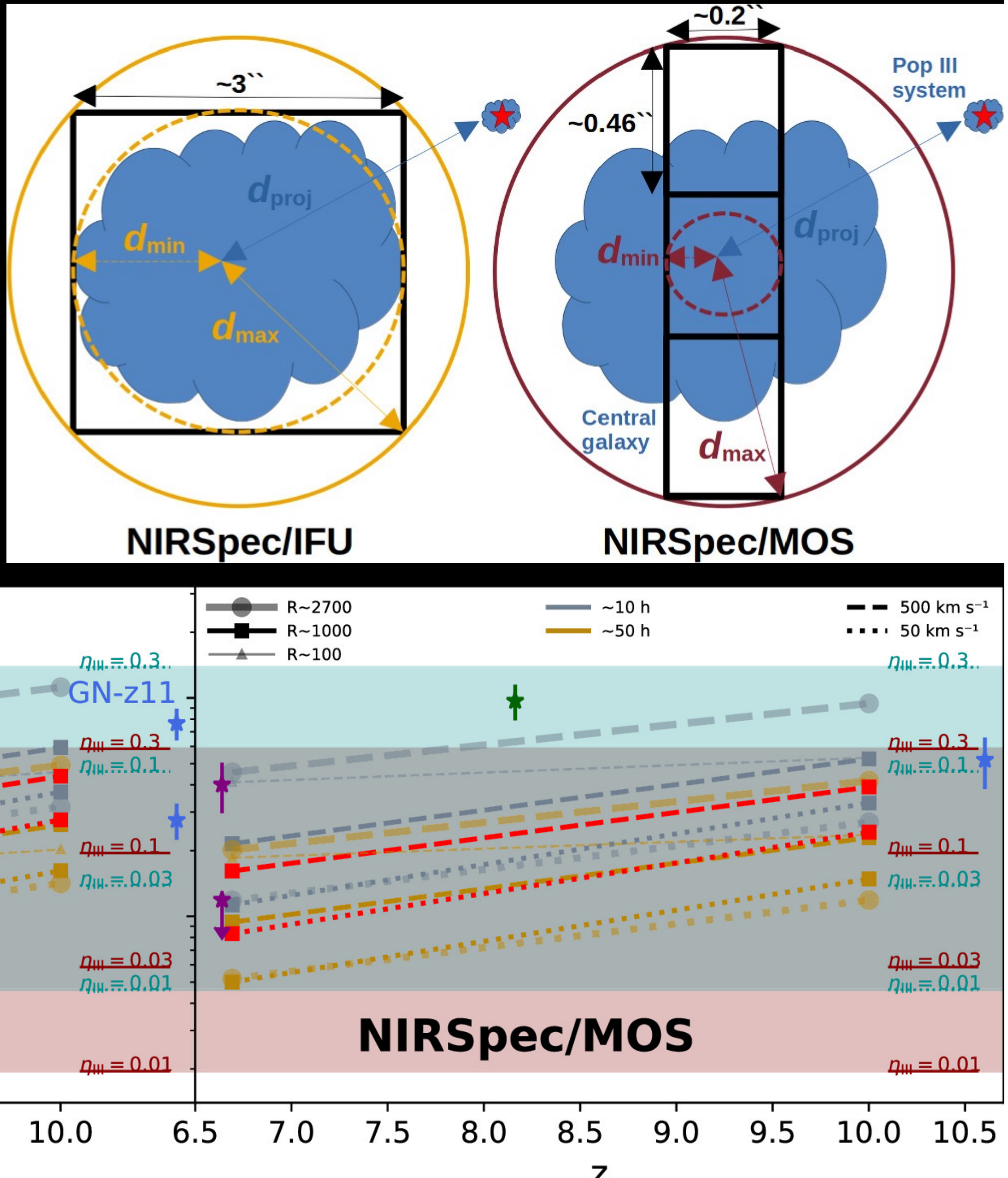
Chon+2021

Pop III formation may continue into the epoch that can be observed with JWST!



Klessen RS, Glover SCO. 2023
Annu. Rev. Astron. Astrophys. 61:65–130

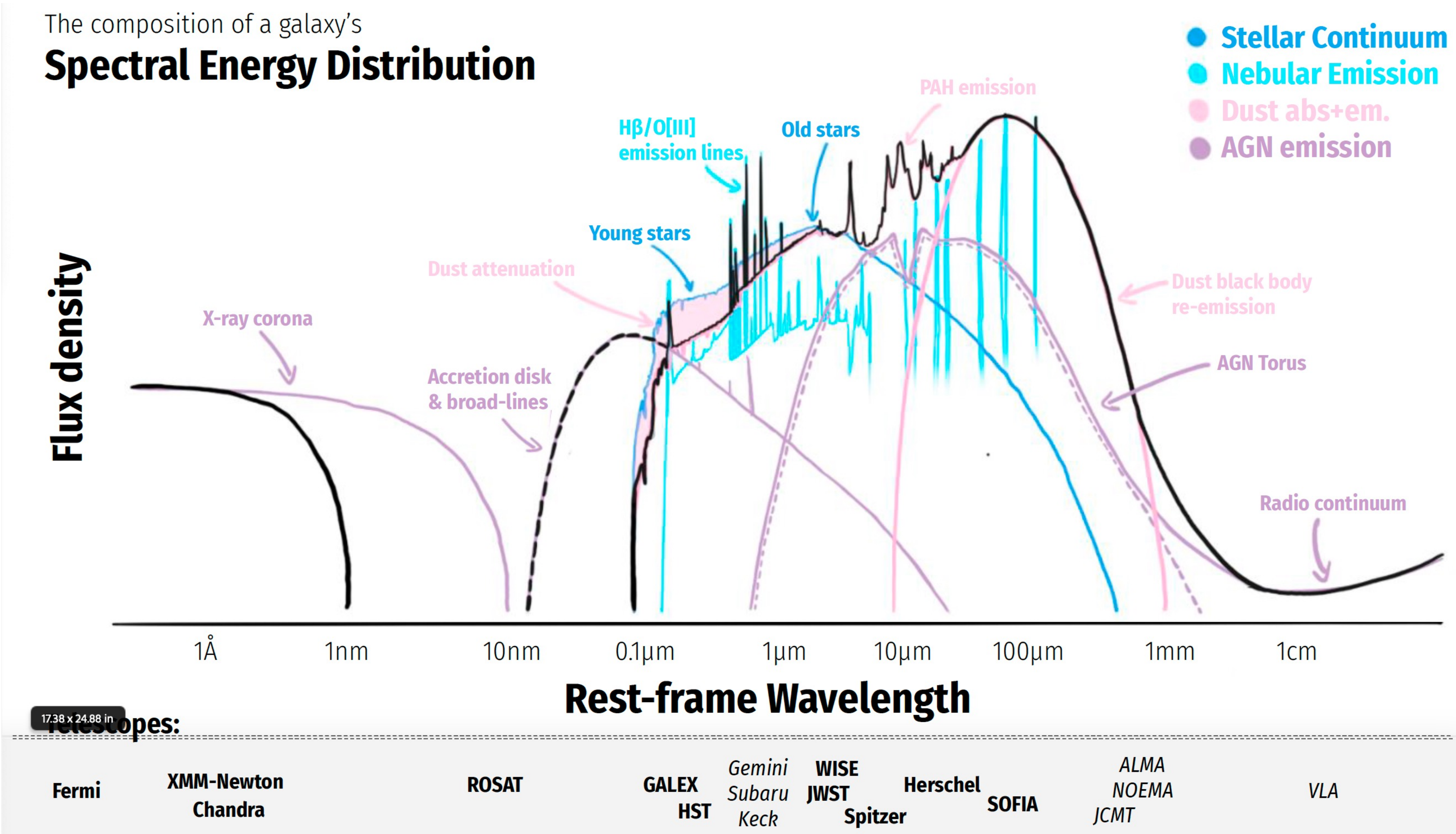
can JWST find observational signatures of Pop III stars?



Venditti et al. 2024

take-away points

- Pop III stars likely start forming in mini-halos with masses ~few 10^5-10^6 M_{sun} at z~25-30
- Pop III stars likely form in multiples/clusters; the masses are determined by radiation feedback
- the IMF of Pop III stars is still uncertain but is likely ‘top heavy’ relative to the local IMF
- Pop III may continue to occur in rare pockets (perhaps offset from luminous galaxies) down to redshifts as low as z~6 – possibly detectable with JWST?



The composition of a galaxy's
Spectral Energy Distribution
Stellar Continuum
Nebular Emission
Dust abs+em.
AGN emission
PAH emission
Hβ/O[III]
emission lines
Old stars
Young stars
Dust attenuation
X-ray corona
Accretion disk
& broad-lines
Dust black body
re-emission
AGN Torus
Radio continuum
Flux density
1Å
1nm
10nm
0.1μm
1μm
10μm
100μm
1mm
1cm
Rest-frame Wavelength
Telescopes:
Fermi
XMM-Newton
Chandra
ROSAT
GALEX
HST
Gemini
Subaru
Keck
WISE
JWST
Spitzer
Herschel
SOFIA
ALMA
NOEMA
JCMT
VLA

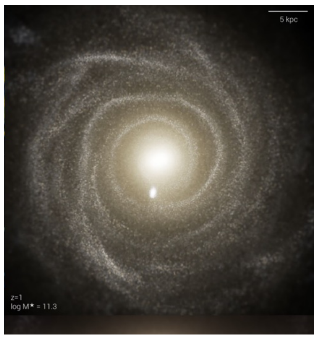
K. Iyer

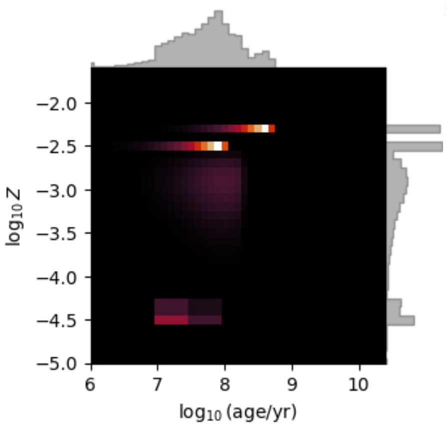
two types of SED modeling: forwards and backwards

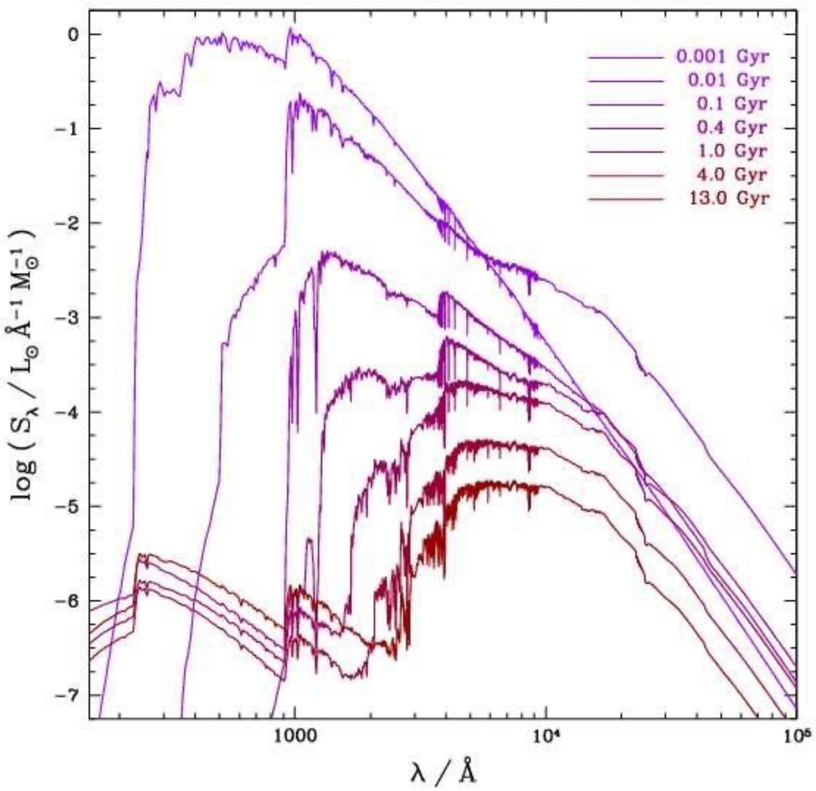
- forward modeling: ***predict SED*** based on physical properties/conditions from a physics-based simulation (such as numerical hydro/SAM) coupled with appropriate modeling tools
- backwards modeling: estimate the underlying ***physical properties*** (e.g. m_*, SFR, m_{dust}) of a real galaxy by fitting an idealized model to the observed SED

stellar population synthesis

stellar ages
& metallicities

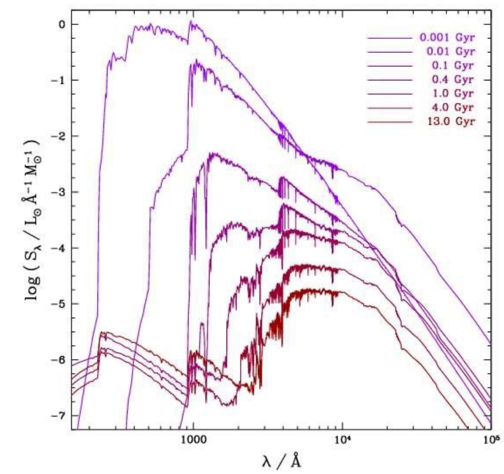






Bruzual & Charlot 2003

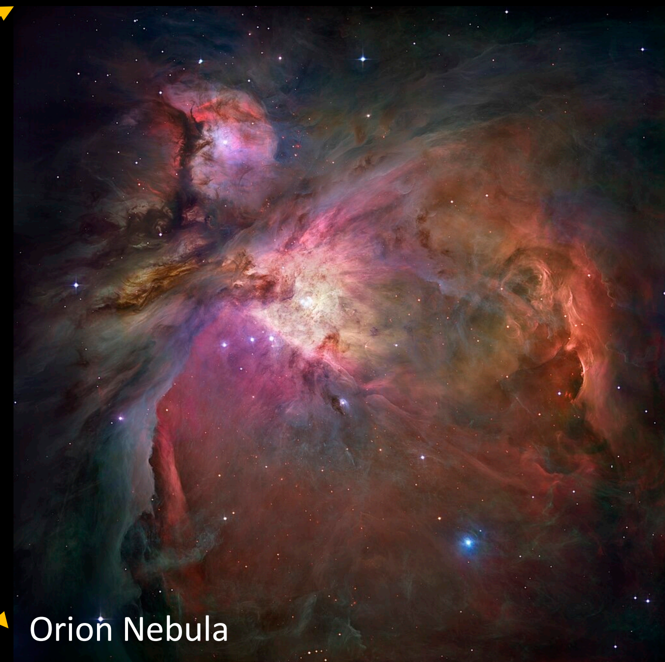
SSP models:
primary challenges/uncertainties

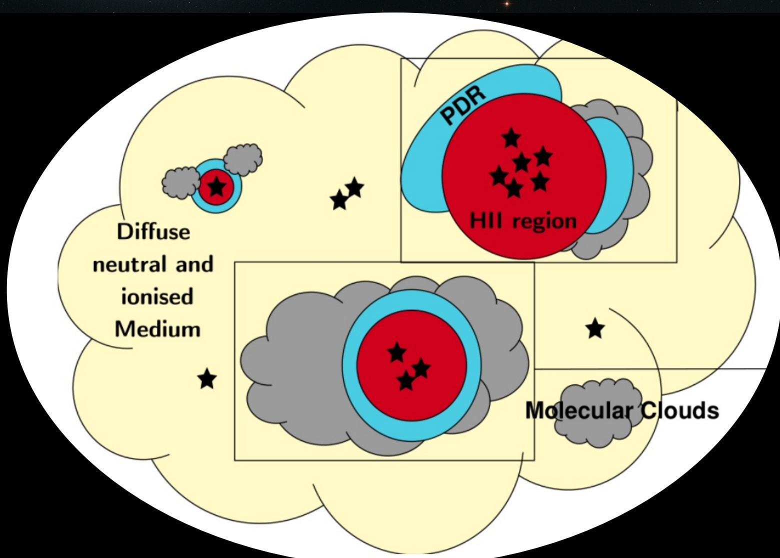


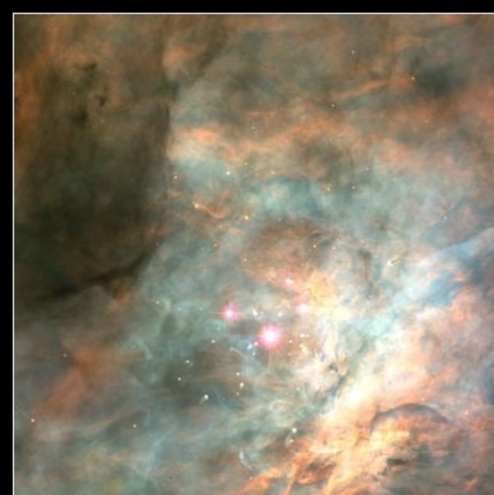
- stellar initial mass function
- isochrones/stellar evolution physics
- stellar atmosphere models
- abundance ratios
- binary/multiple star physics

uncertainties are particularly large for low metallicity massive stars, for which we have few nearby examples

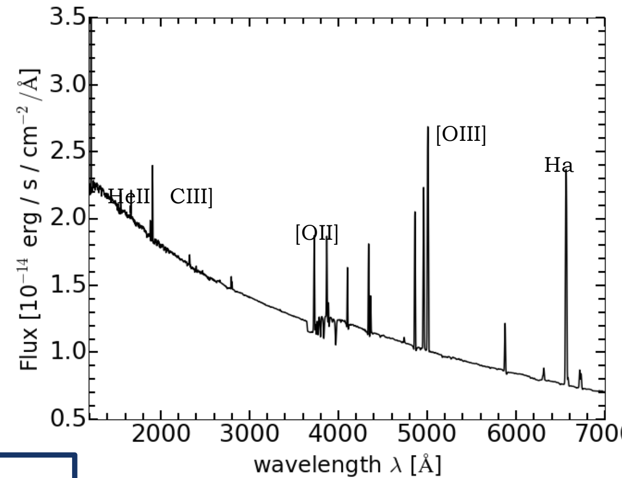
emission from the ISM

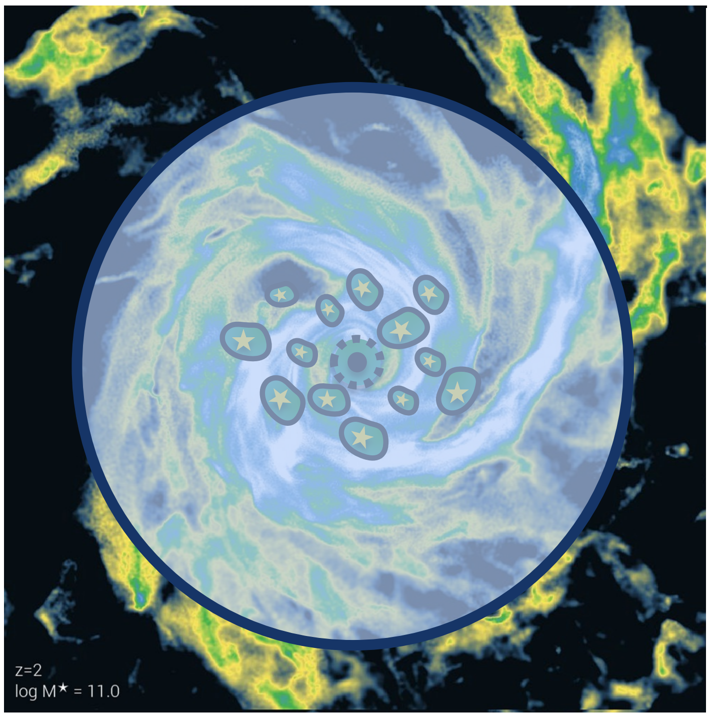






modeling emission from the ISM in cosmological simulations





ionizing spectrum
ISM metallicity
ionization parameter
dust/metal ratio
ionized gas density
ISM abundance ratios

photoionization code (e.g. CLOUDY, MAPPINGS)

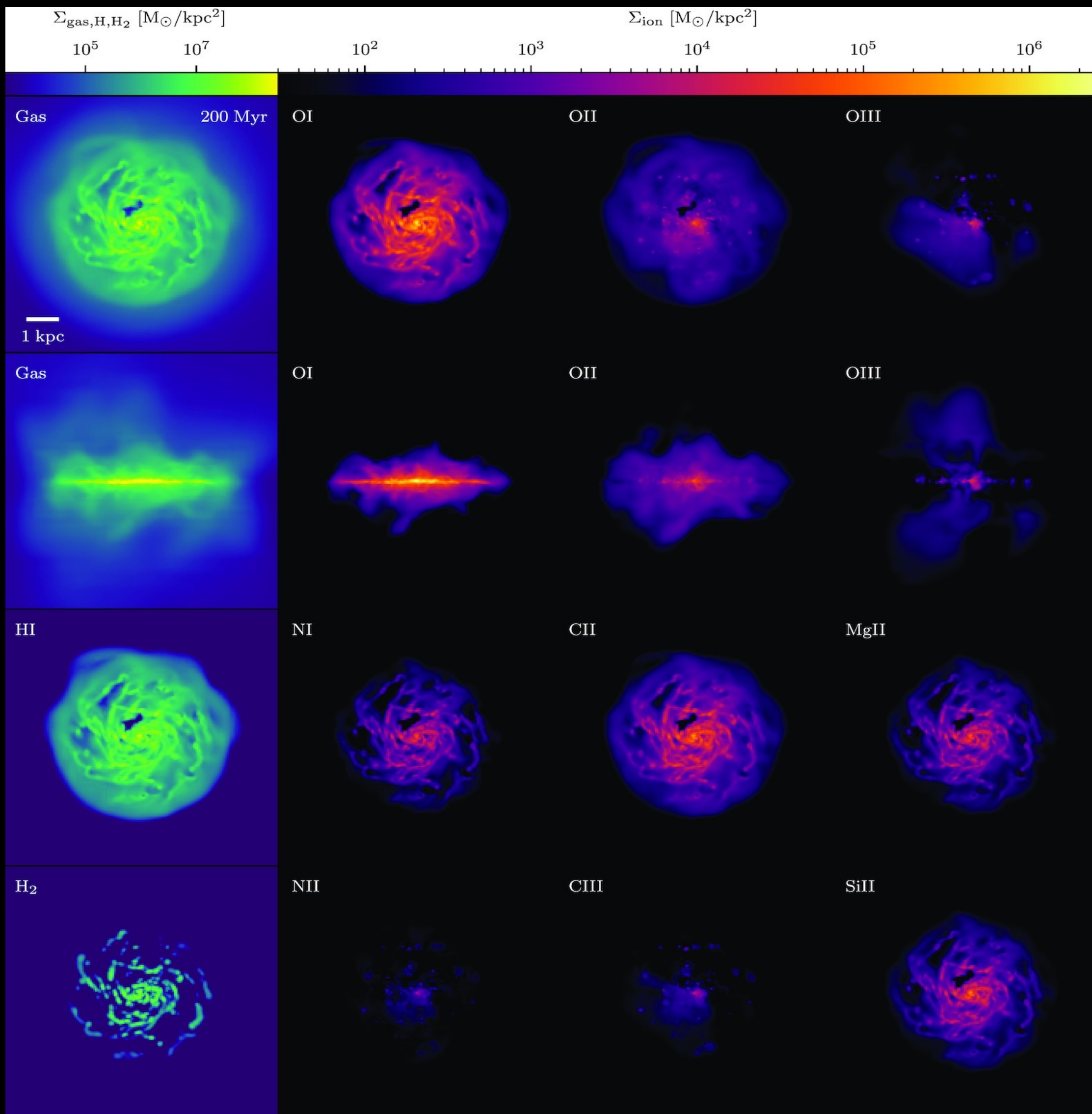
fairly good agreement with line ratios and line luminosity functions at low and intermediate redshifts

Hirschmann+2017; 2019; 2022; 2023
see also Wilkins et al. 2020,2022; Garg et al. 2023

slide adapted from M. Hirschmann

see poster by L. Scharré

simulations with non-equilibrium thermo-chemistry + on the fly radiative transfer



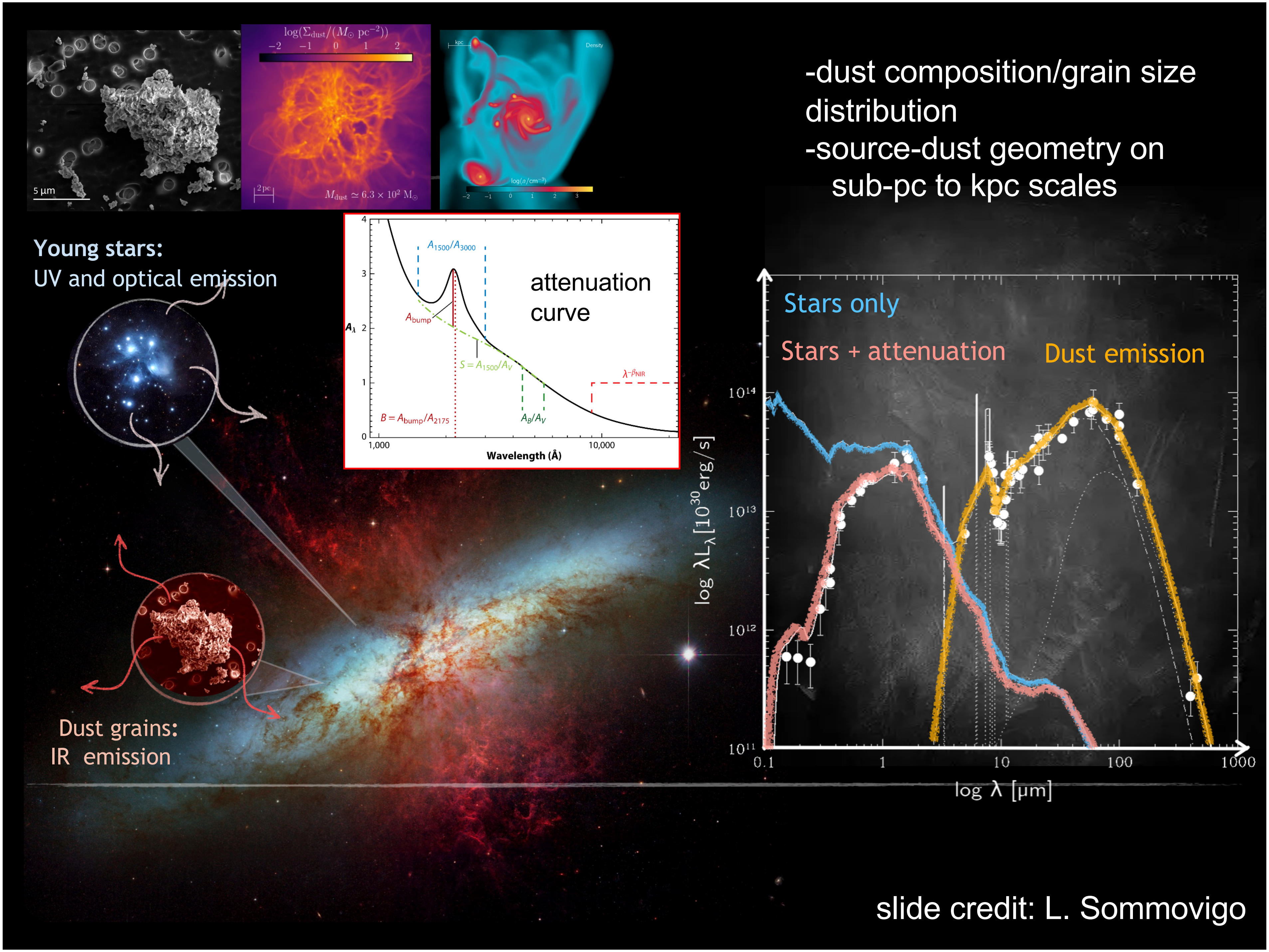
RAMSES-RTZ → MEGATRON

line ratios observable with JWST are very sensitive to conditions in the ISM and hence to details of star formation & feedback physics implementations in sims

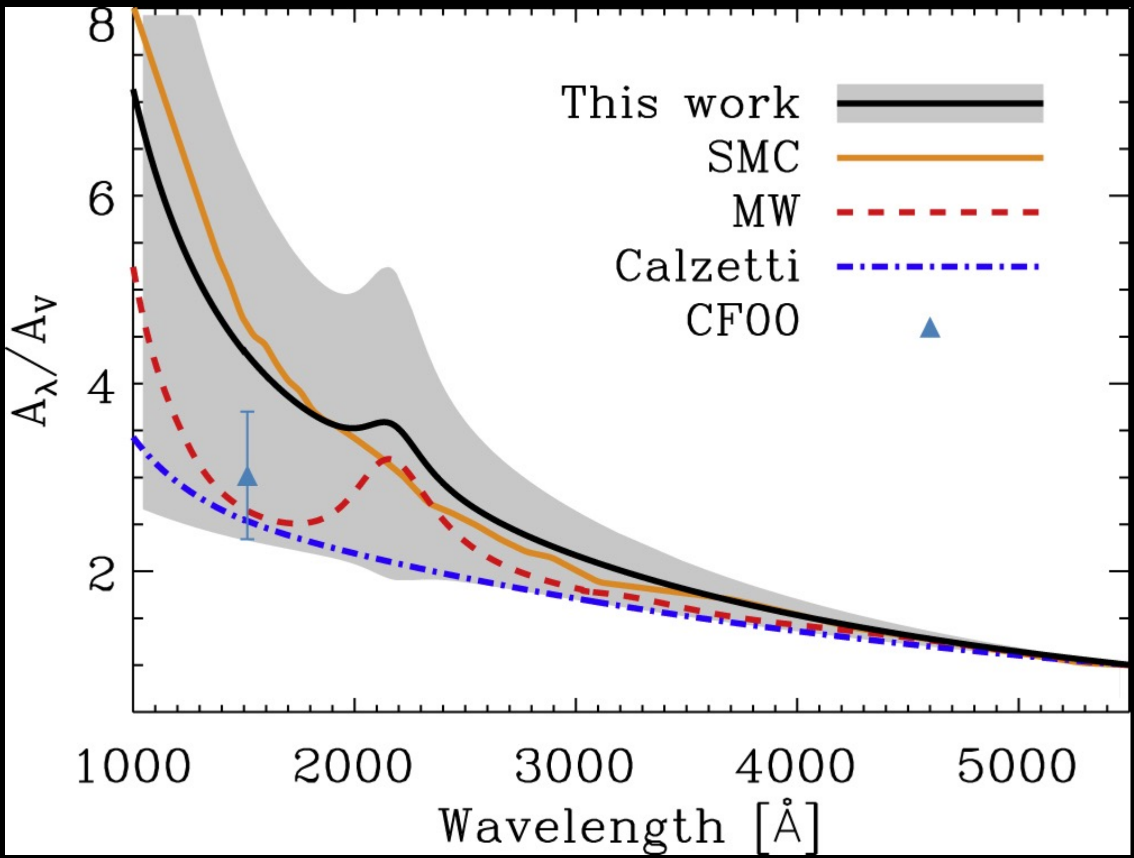
e.g. [O III] λ5007 / [O II] λλ3727
C IV λλ1550/[C III] λλ1908
[OIII]4363/5007

(Katz et al. 2024)

Katz 2022


-dust composition/grain size distribution
-source-dust geometry on sub-pc to kpc scales
Young stars:
UV and optical emission
Dust grains:
IR emission
attenuation curve
Wavelength (Å)
1,000
10,000
A_λ
A_{1500}/A_{3000}
A_{bump}
$S = A_{1500}/A_V$
A_B/A_V
$B = A_{bump}/A_{2175}$
$\lambda^{-\beta_{NIR}}$
5 μm
2 pc
$\log(\Sigma_{dust}/(M_\odot\ pc^{-2}))$
$M_{dust} \simeq 6.3 \times 10^2\ M_\odot$
Density
Stars only
Stars + attenuation
Dust emission
log $\lambda L_\lambda [10^{30}$erg/s]
log λ [μm]
0.1
1
10
100
1000
10^{11}
10^{12}
10^{13}
10^{14}
slide credit: L. Sommovigo

dust attenuation



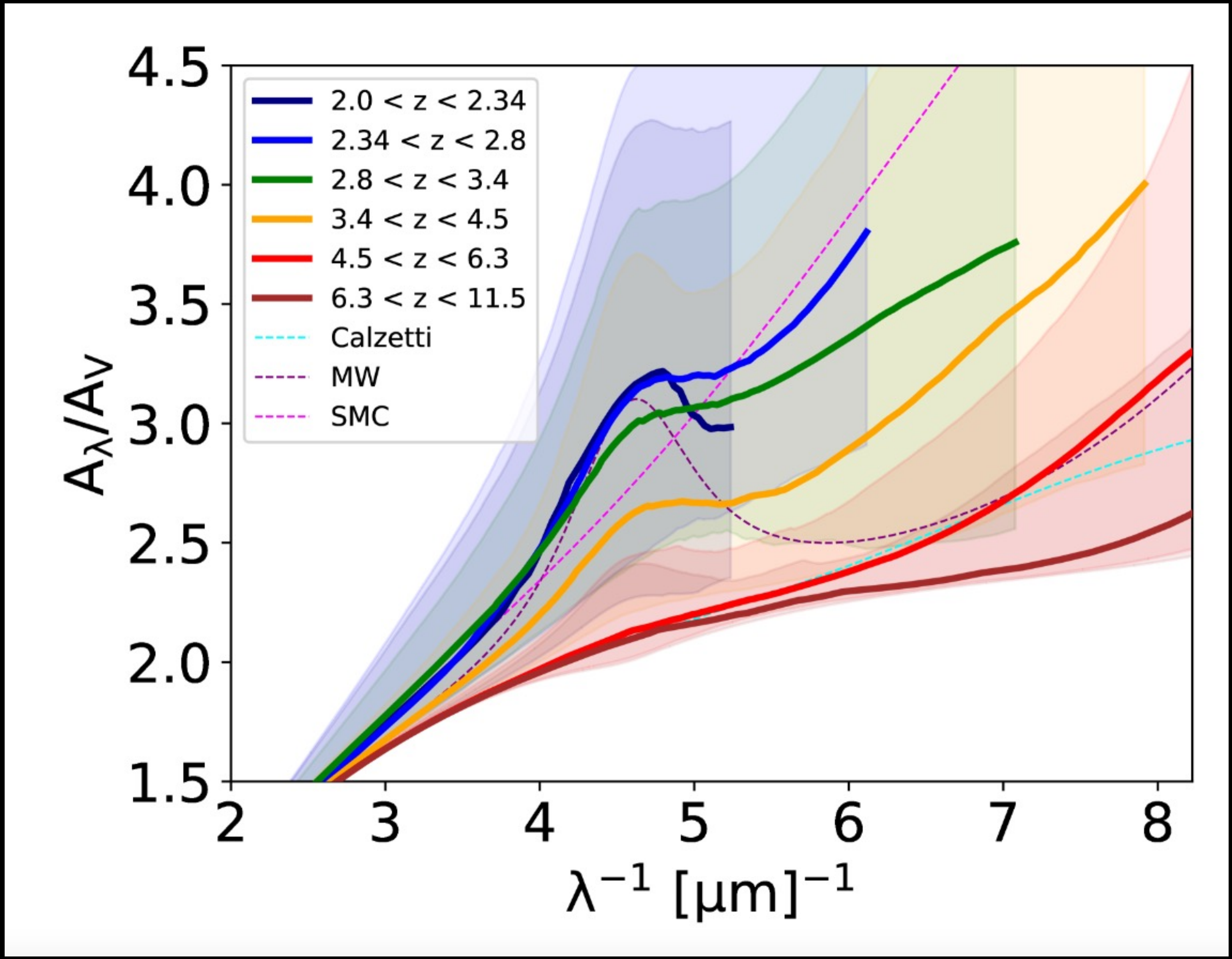
Salim et al. 2018; Salim & Narayanan 2020

-wide spread in attenuation curves even in local galaxies

-attenuation curve parameters correlated with each other

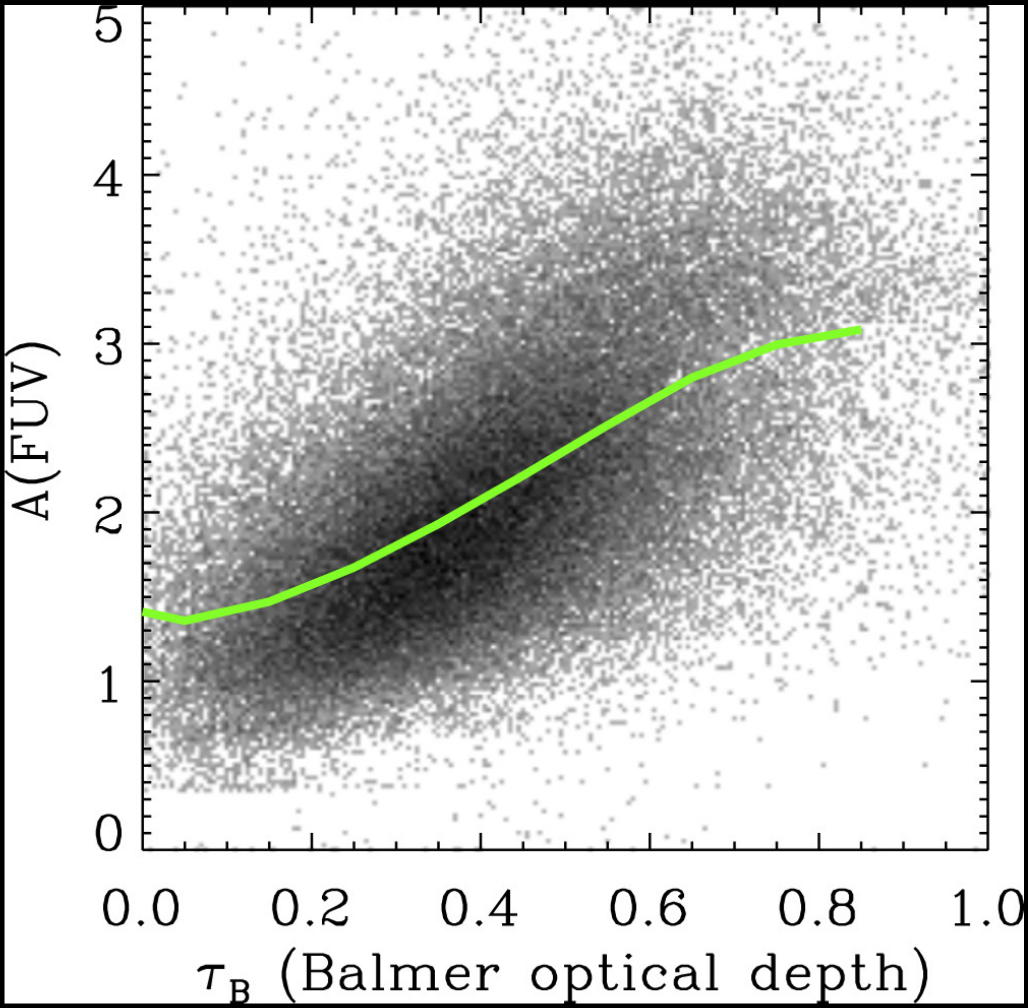
-attenuation curve parameters are correlated with physical properties of the galaxy

-all three of the above are seen empirically in observations AND predicted from dust+radiative transfer simulations of galaxies hints of redshift evolution in average attenuation curves



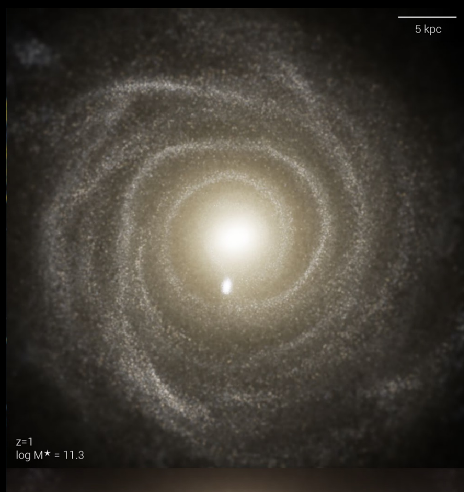
Markov et al. 2024

beware: dust attenuation of stellar continuum and nebular emission need NOT be the same...

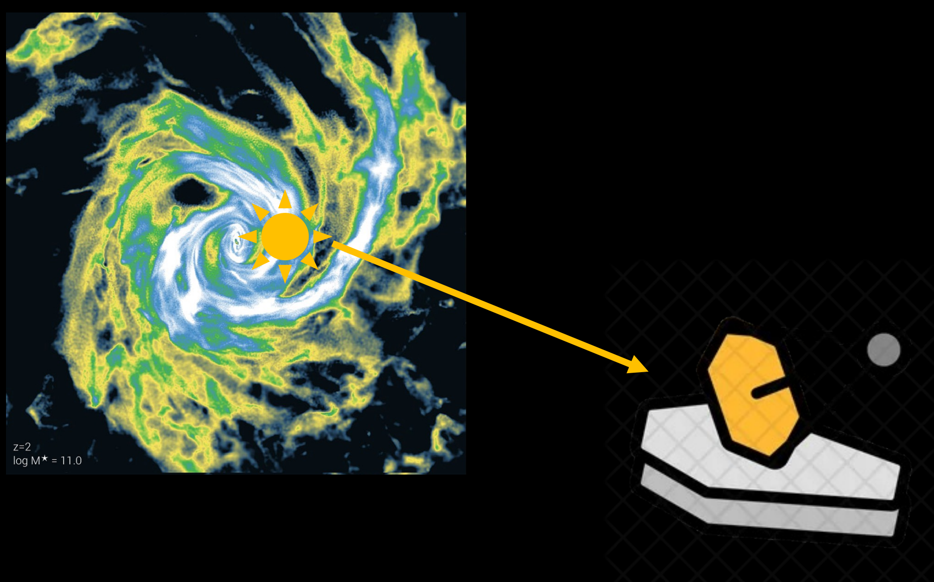


Salim et al. 2018

dust+RT simulations



- most cosmo sims do not explicitly model the formation and destruction of dust, so a dust-to-metal ratio is assumed
- solve RT equation along line of sight
- mostly in post-processing (some OTF RT simulations now coming)



RT codes commonly used for galaxy sims:

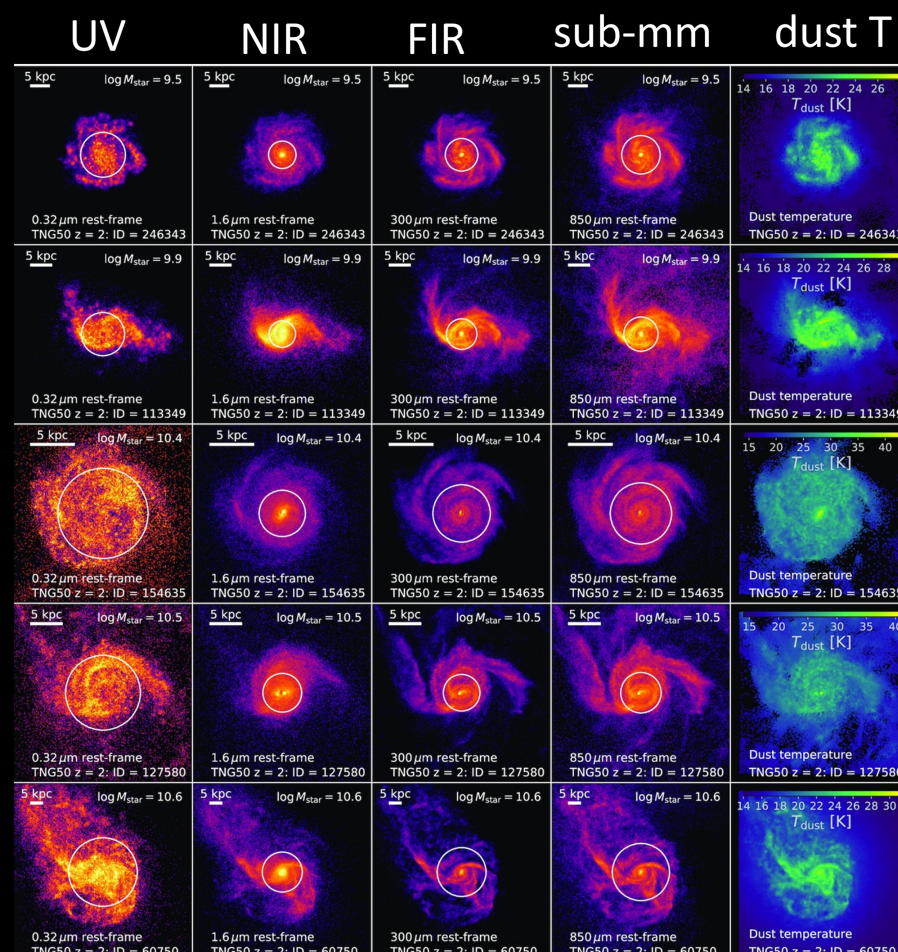
powderday
https://github.com/dnarayanan/powderday

Narayanan et al. 2021

RADMC-3D
(Dullemond et al. 2012)

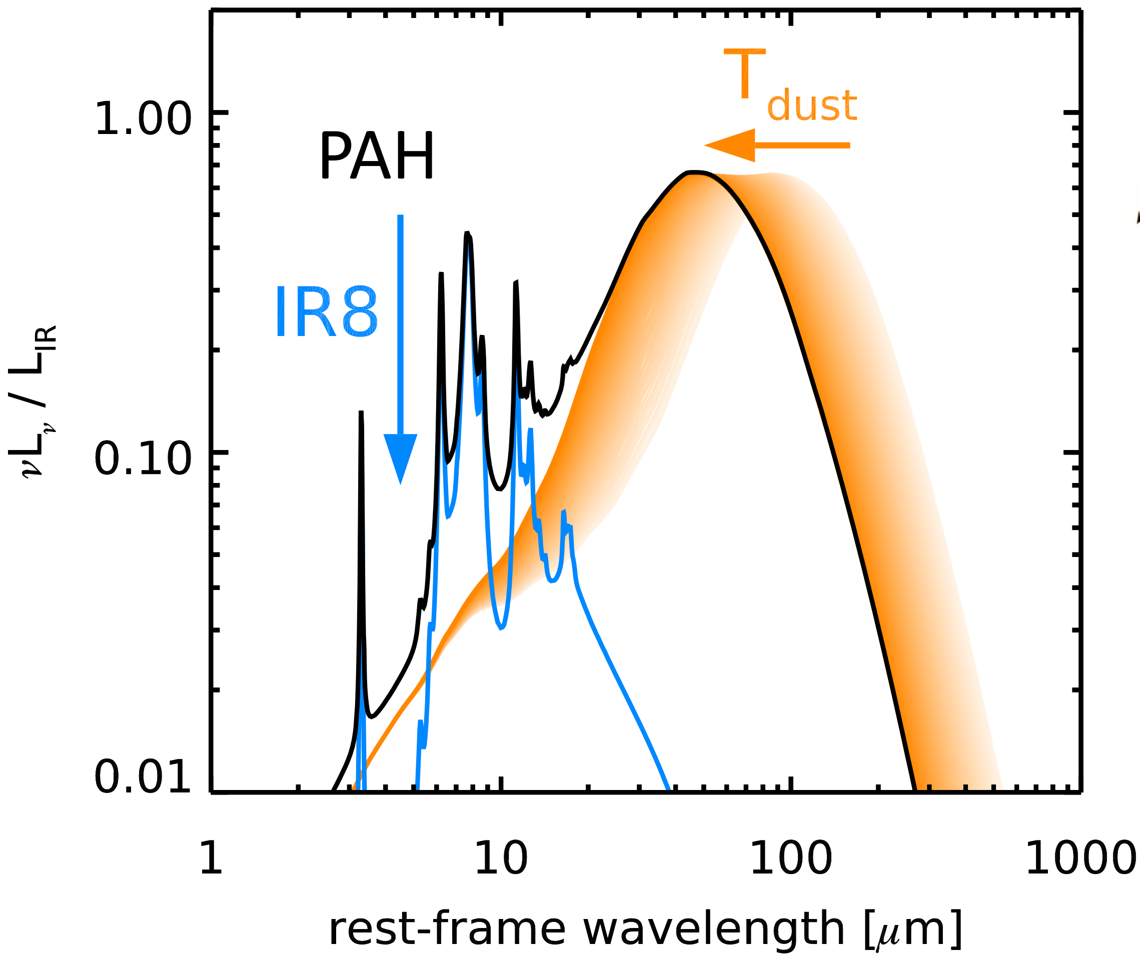
Hyperion (Robitaille 2011)

ART2 (Li et al. 2020)



Popping et al. 2021

dust emission



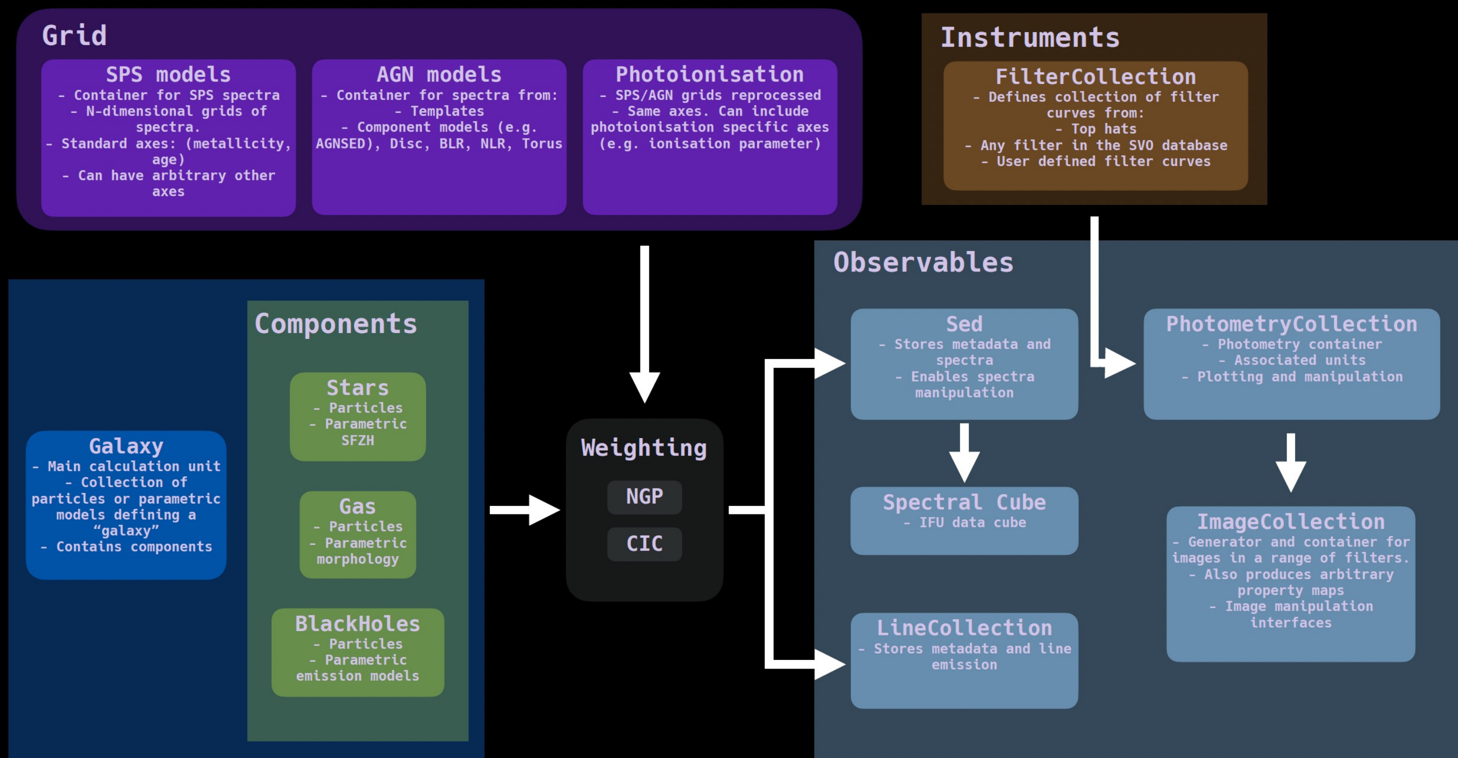
$$S_{\rm ot}(\nu) \propto \nu^{\beta} B_\nu(T) = \frac{\nu^{\beta+3}}{e^{h\nu/kT} - 1}$$

Schreiber et al. 2018

$$S_\nu = M_{\rm dust}^{\rm cont}\,\bar{S}_\nu^{\rm cont} + M_{\rm dust}^{\rm PAH}\,\bar{S}_\nu^{\rm PAH}.$$

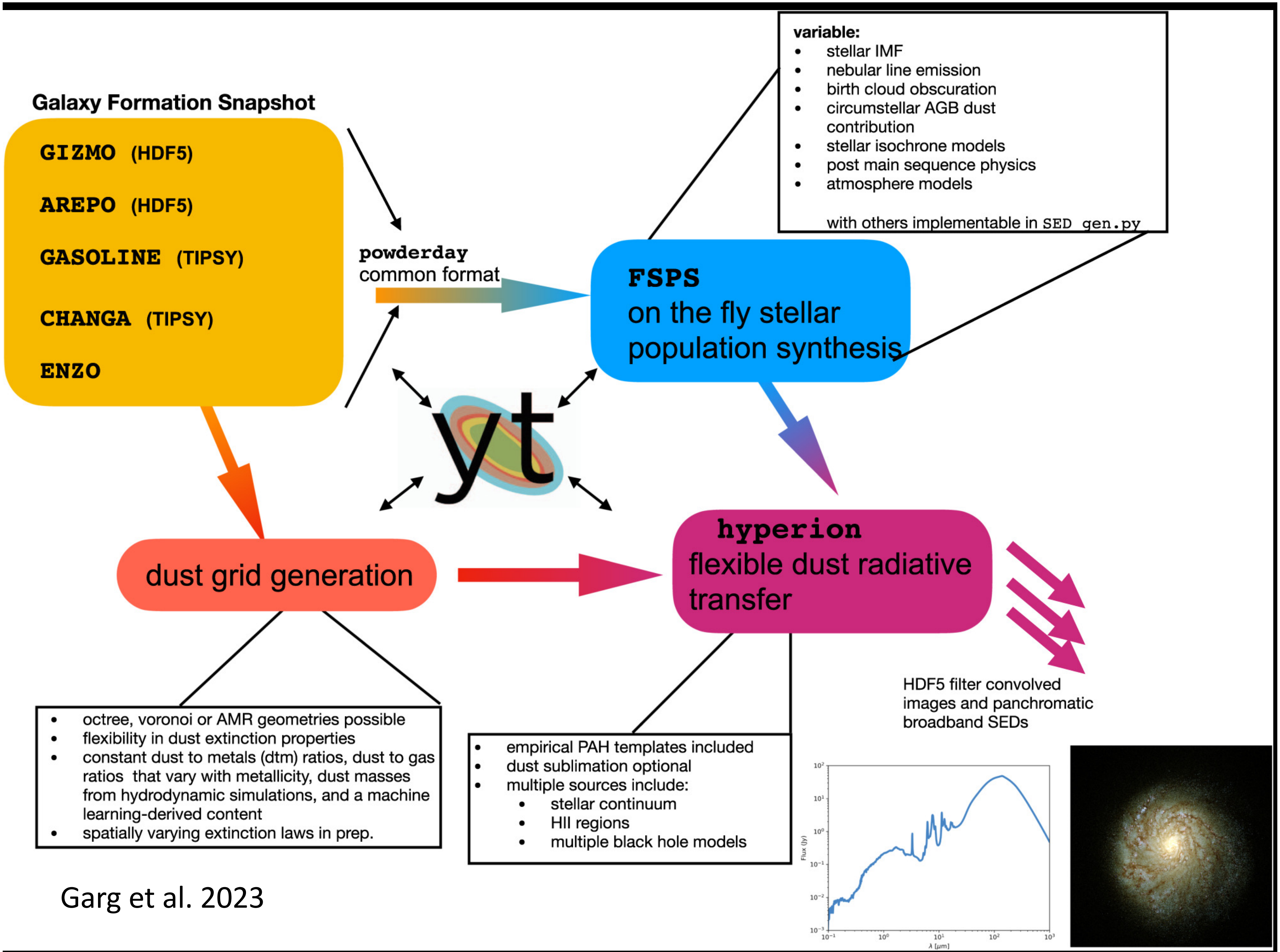
SYNTHESIZER

a fast, flexible generalized pipeline for creating synthetic images and spectra from hydro simulations or semi-analytic models



Chris Lovell, Steve Wilkins ++

https://flaresimulations.github.io/synthesizer/

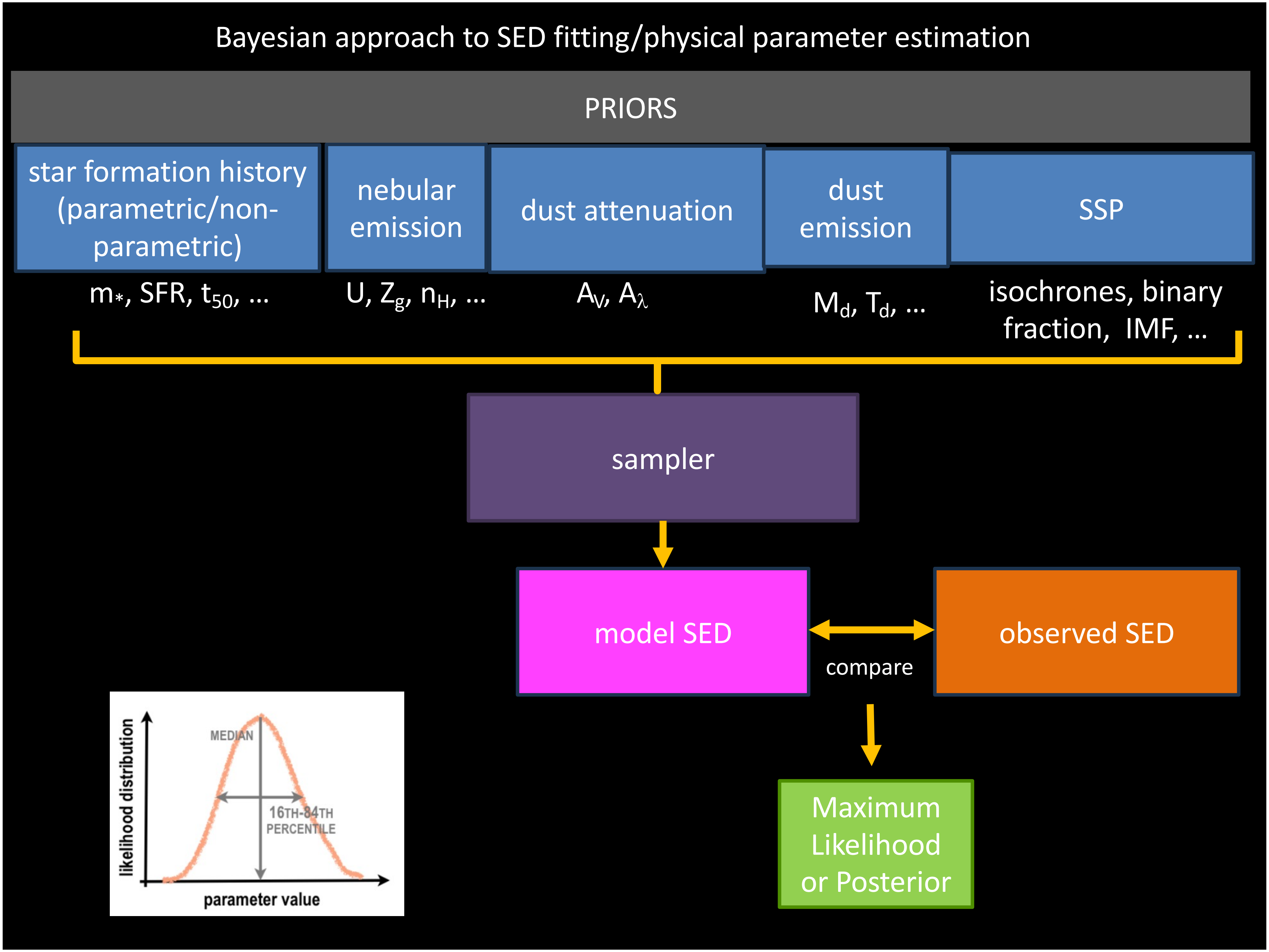


Garg et al. 2023

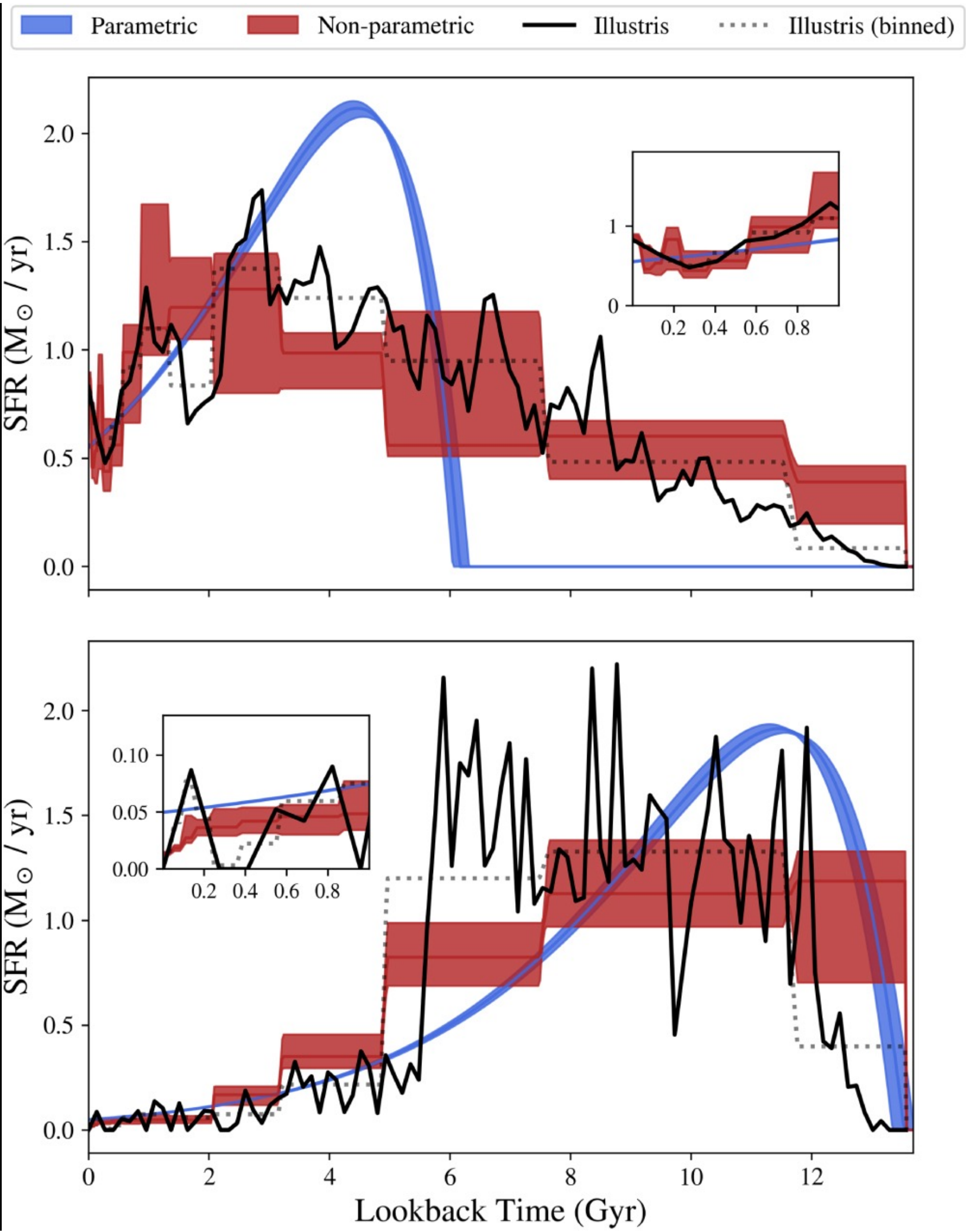
take away points

- nebular emission & effects of dust most commonly modeled in post-processing; some new simulations coming online with non-equilibrium thermo-chemistry & OTF radiation transport; models for dust formation + destruction
- simulations that do not resolve the multiphase ISM require sub-grid recipes to model nebular emission & dust

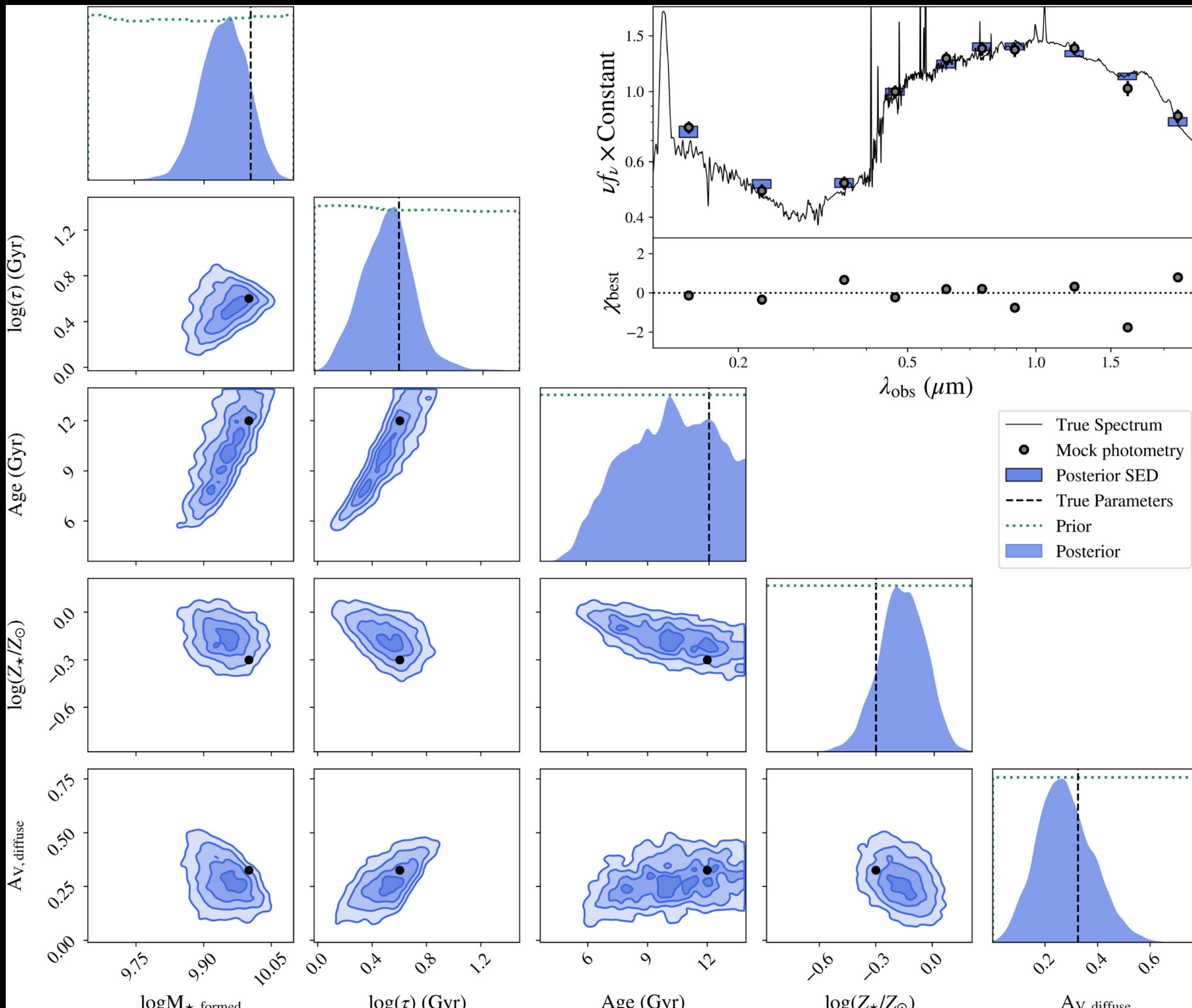
estimating physical parameters from SEDs


Bayesian approach to SED fitting/physical parameter estimation
PRIORS
star formation history (parametric/non-parametric)
nebular emission
dust attenuation
dust emission
SSP
m*, SFR, t50, ...
U, Zg, nH, ...
AV, Aλ
Md, Td, ...
isochrones, binary fraction, IMF, ...
sampler
model SED
observed SED
compare
Maximum Likelihood or Posterior
likelihood distribution
MEDIAN
16TH-84TH PERCENTILE
parameter value

parametric vs.
non-parametric
SFH



Johnson et al. 2021



Johnson et al. 2021

Table 2
Summary of Parameters, Hyperparameters, and Priors for Our Bagpipes SED Fitting

Common Parameters

Parameter	Prior/Value (Min, Max)	Description
z_{phot}	EAZY-py Posterior PDF ($\pm 3\sigma$)	Redshift
SPS Model	G. Bruzual & S. Charlot (2003); BPASS v2.2.1	Stellar population synthesis model
IMF	P. Kroupa (2001); default BPASS IMF	Stellar IMF
Dust-law Parameterization	D. Calzetti et al. (2000), S. Salim et al. (2018) S. Charlot & S. M. Fall (2000)	Dust law
A_V	Log-uniform: (10^{-3}, 10); uniform (0, 6)	V-band attenuation (all stars)
SFH	Log-normal; "continuity bursty"; delayed-τ	Star formation history
$\log_{10}(M_\star/M_\odot)$	Uniform: (5, 12)	Surviving stellar mass
$Z_\star/Z_\odot$	Log-uniform: (0.005, 5); uniform (0, 3)	Stellar metallicity
$Z_{gas}/Z_\odot$	Fixed to $Z_\star$	Gas-phase metallicity
$\log_{10} U$	Uniform: (-3, -1)	Ionization parameter

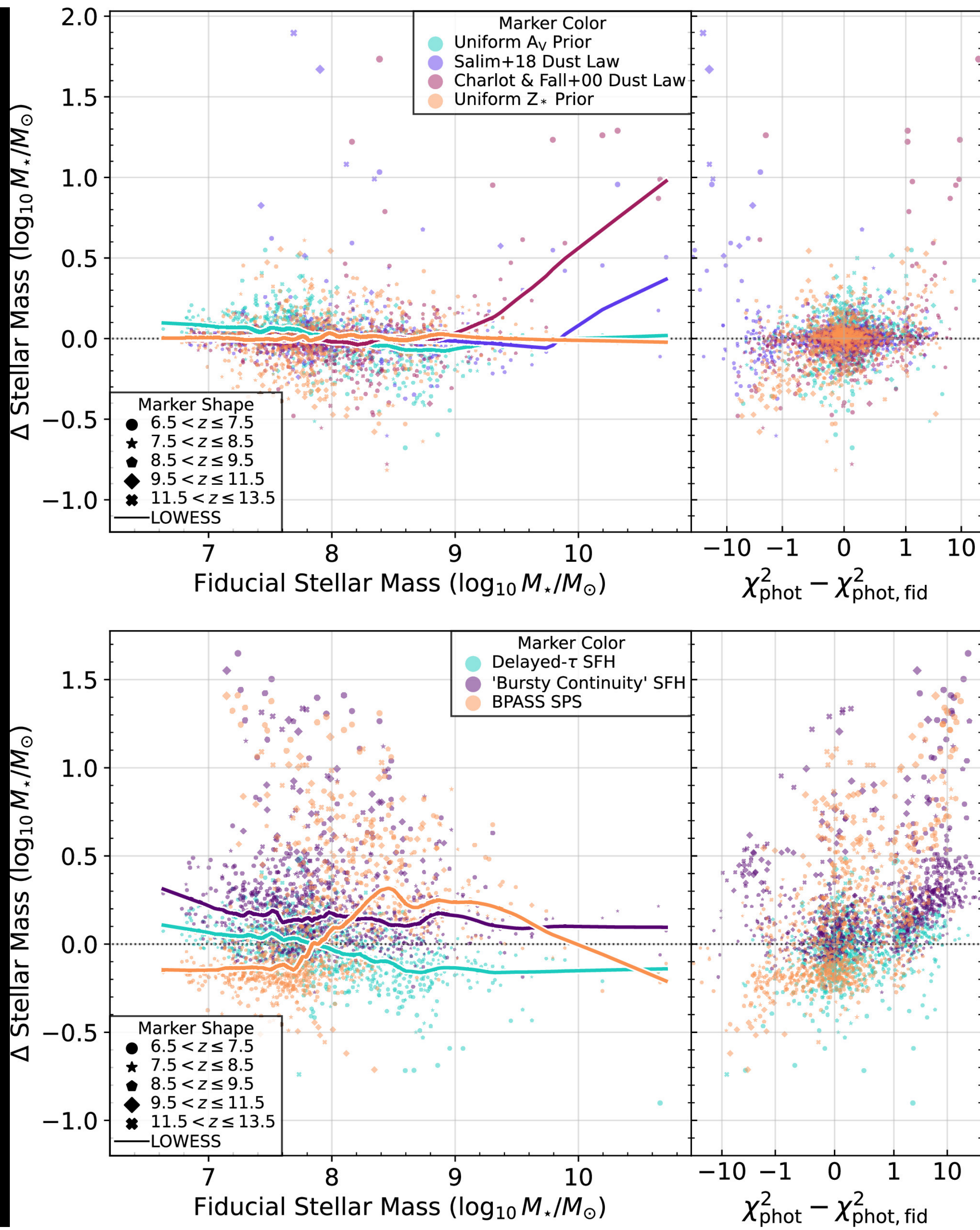
Model Specific Parameters

Model	Parameter	Prior/Value (Min, Max)	Description
Fiducial	t_{max}	Uniform: (10 Myr, 15 Gyr)	Age of Universe at peak SFR
	FWHM	Uniform: (10 Myr, 15 Gyr)	FWHM of SFH
Delayed-τ SFH	τ	Uniform: (10 Myr, 15 Gyr)	e-folding timescale
	Age	Log-uniform: (10 Myr, $t_{univ}(z_{phot})$)	Time since SF began
"Continuity Bursty" Nonparametric SFH	N_{bins}	Six bins (five fitted parameters)	First bin 0–10 Myr, SF begins at $z = 20$, others distributed equally in $\log_{10}$ lookback time
	$d_{\log_{10}\mathrm{SFR}}$	Student's t: $\nu = 2$, $\sigma = 1.0$	Ratio of $\log_{10}$SFR in adjacent bins, coupled by σ
S. Charlot & S. M. Fall (2000) Dust Law	n	Clipped normal: $\mu = 0.7$, $\sigma = 0.3$ (0.3, 2.5)	Power-law slope of attenuation curve ($A \propto \lambda^{-n}$) For D. Calzetti et al. (2000) $n \approx 0.7$
	η	clipped normal: $\mu = 2$, $\sigma = 0.3$ (1, 3)	$A_{V,<10\ \mathrm{Myr}}/A_V$ ratio between young and old stars
S. Salim et al. (2018) Dust Law	δ	Clipped normal: $\mu = 0$, $\sigma = 0.1$ (-0.3, 0.3)	Deviation from D. Calzetti et al. (2000) slope
	β	Uniform (0, 5)	Strength of 2175 Å bump
BPASS SPS Model			No additional components
Uniform A_V Prior			No additional components
Uniform $Z_\star$ Prior			No additional components

Notes. Parameters and priors for other iterations can be assumed to be the same as given for the "fiducial" bagpipes run unless otherwise specified. The top section of the table lists parameters that are common to all of our Bagpipes models, whereas the lower section gives the model-specific parameters for each of our chosen configurations.

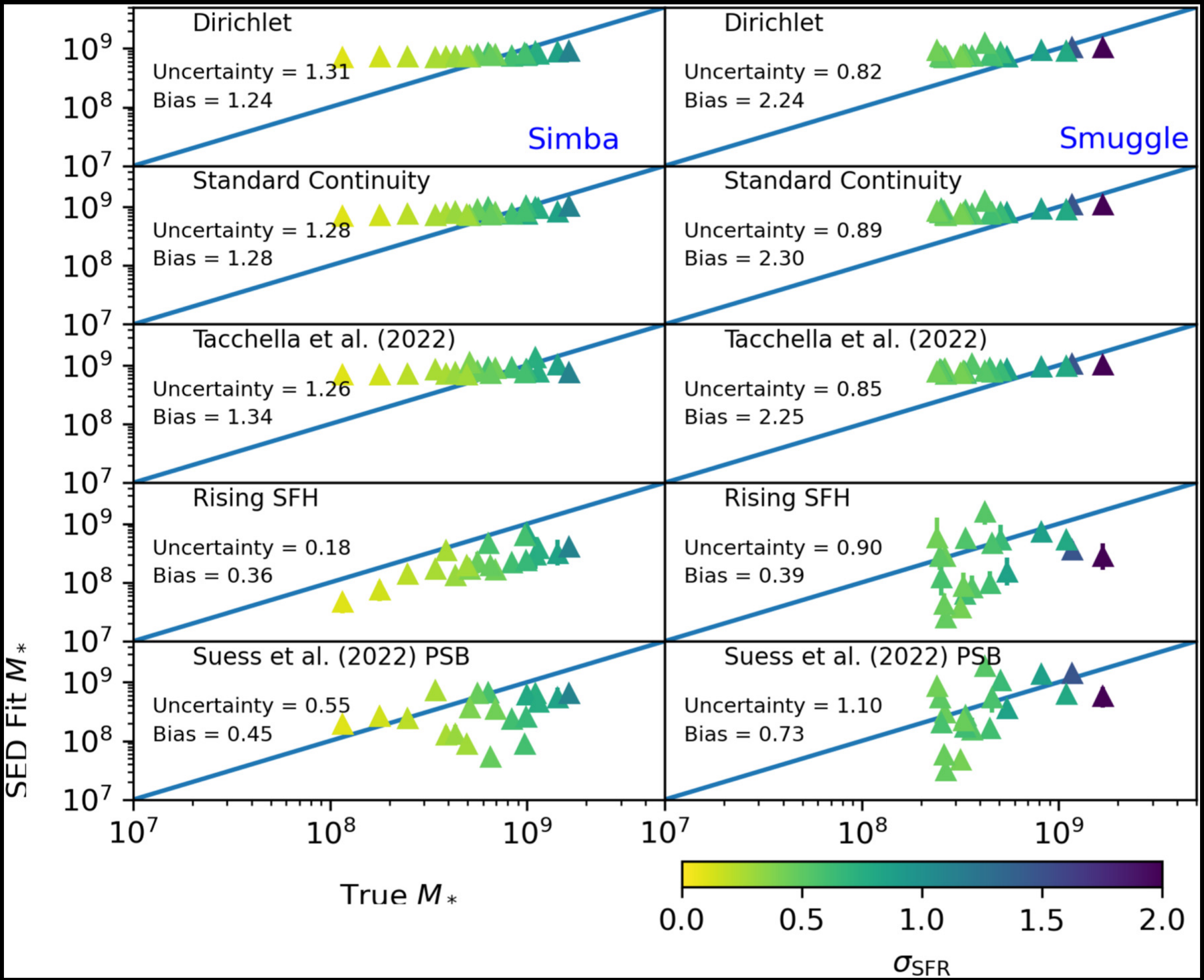
Harvey et al. 2024

validation method 1:
how robust are results to different priors/different modeling assumptions?



Harvey et al. 2024;
see also Tacchella et al. 2022;
Topping et al. 2022

validation method 2: apply SED fitting method to SED's from simulations where 'truth' known
→stellar masses can be off by ~1 dex



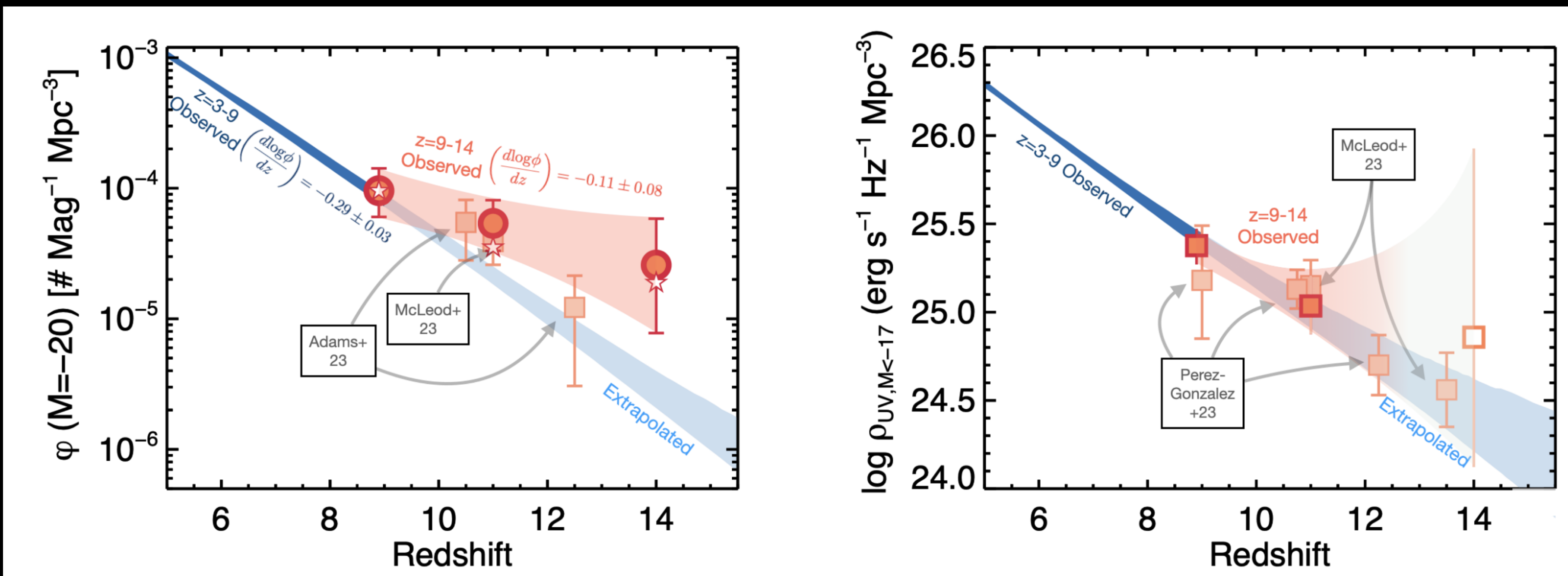
Narayanan et al. 2024

summary: estimating physical parameters from SEDs

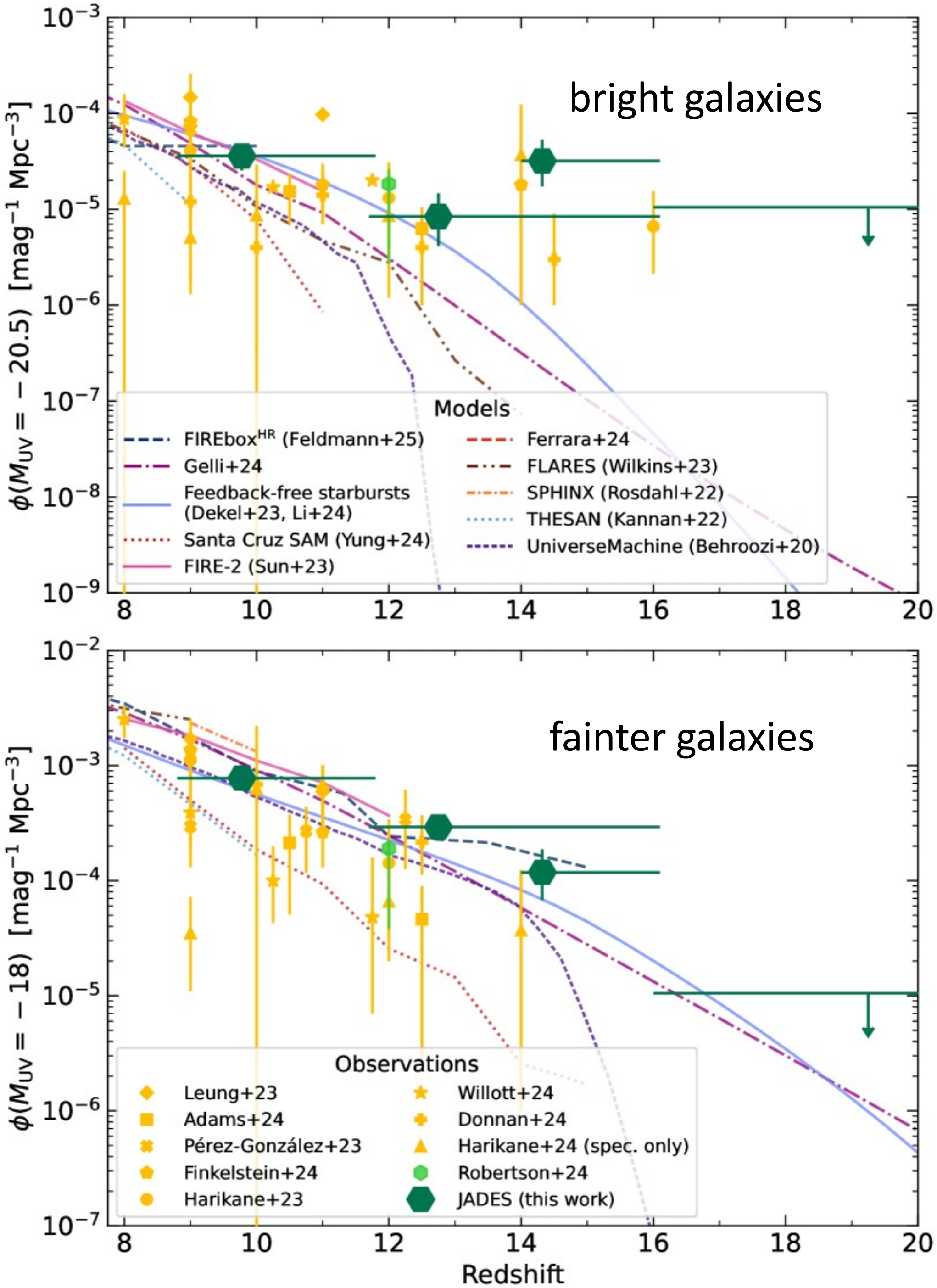
- stellar mass uncertainties *may be* up to 1 dex at high-z
- results dependent on SFH priors, choice of parametric vs. non. para SFH
- uncertainties/degeneracies associated with modeling of dust & nebular emission are not well quantified
- dust mass estimates sensitive to assumed temperature
- *bottom line: not only are these parameter estimates potentially highly uncertain, we do not even know how large the systematic uncertainties are!*

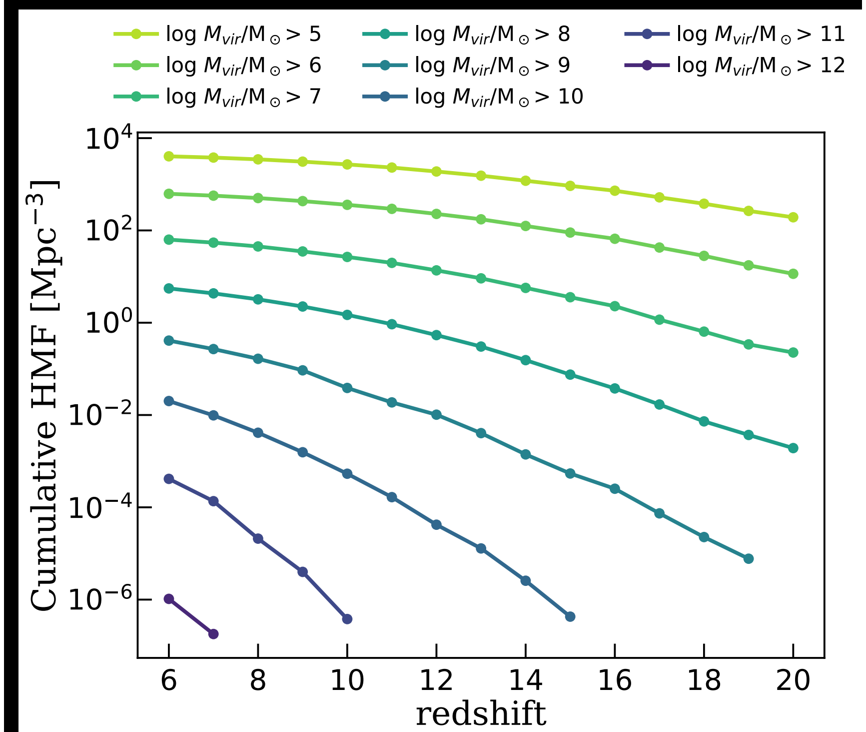
What have we learned about galaxy formation in the first billion years from JWST: insights and puzzles

JWST puzzle #1:
evolution of the number density of bright galaxies to z~14
is much shallower than expected



Finkelstein et al. 2024


bright galaxies
fainter galaxies
$\phi(M_{\rm UV} = -20.5)$ [mag^{-1} Mpc^{-3}]
$\phi(M_{\rm UV} = -18)$ [mag^{-1} Mpc^{-3}]
Redshift
Models
FIREbox$^{\rm HR}$ (Feldmann+25)
Gelli+24
Feedback-free starbursts (Dekel+23, Li+24)
Santa Cruz SAM (Yung+24)
FIRE-2 (Sun+23)
Ferrara+24
FLARES (Wilkins+23)
SPHINX (Rosdahl+22)
THESAN (Kannan+22)
UniverseMachine (Behroozi+20)
Observations
Leung+23
Adams+24
Pérez-González+23
Finkelstein+24
Harikane+23
Willott+24
Donnan+24
Harikane+24 (spec. only)
Robertson+24
JADES (this work)


log $M_{vir}/M_\odot > 5$
log $M_{vir}/M_\odot > 6$
log $M_{vir}/M_\odot > 7$
log $M_{vir}/M_\odot > 8$
log $M_{vir}/M_\odot > 9$
log $M_{vir}/M_\odot > 10$
log $M_{vir}/M_\odot > 11$
log $M_{vir}/M_\odot > 12$
Cumulative HMF [Mpc^{-3}]
redshift

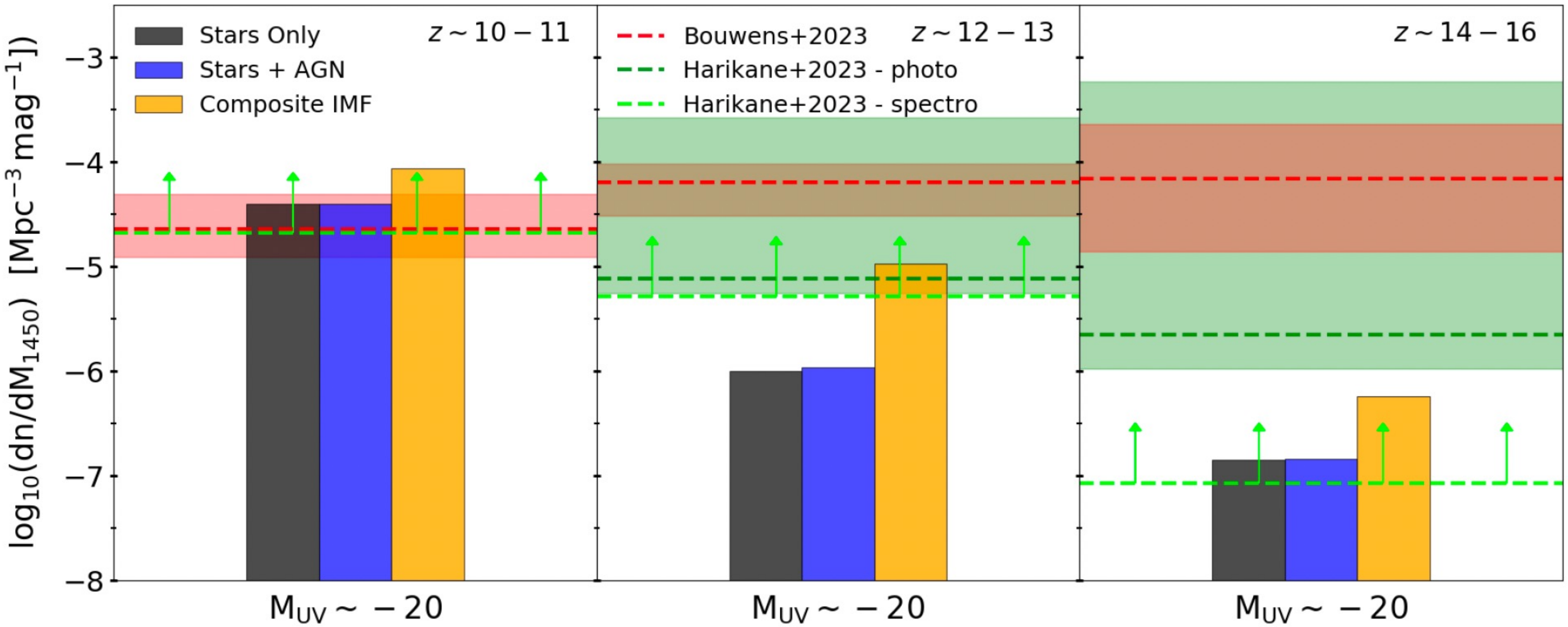
Whitler+25

proposed solutions to early galaxy problems

- 1) eject dust, top heavy IMF, AGN contribution to UV, bursty – *make galaxies brighter*
- 2) higher star formation efficiency/weaker feedback – *make more stars*

e.g. Ferrara+2023; Shen+2023; Yung+2024; Trinca+2023; Dekel+2023; Li+2024

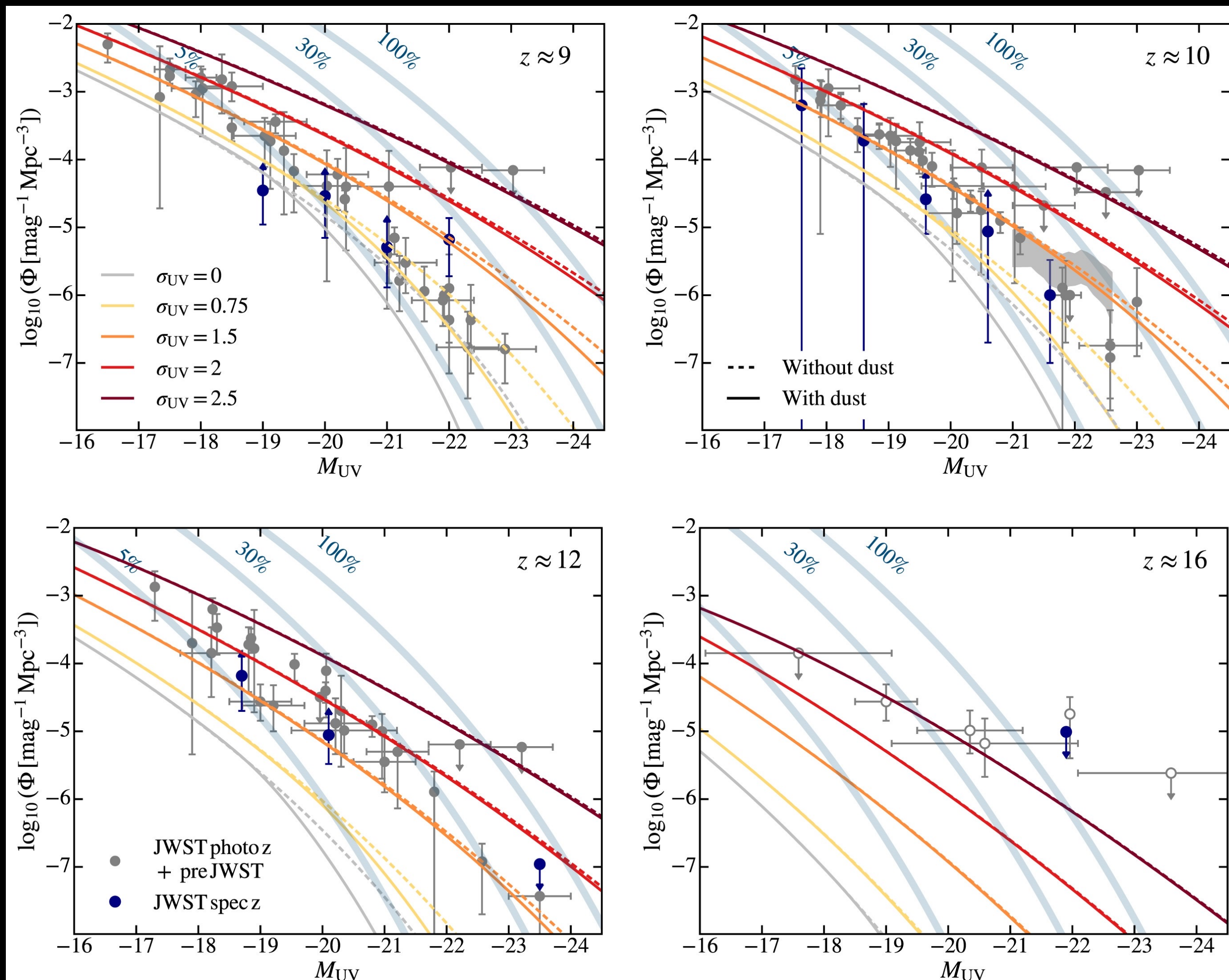
AGN contribution, IMF evolution?



CAT semi-analytic models

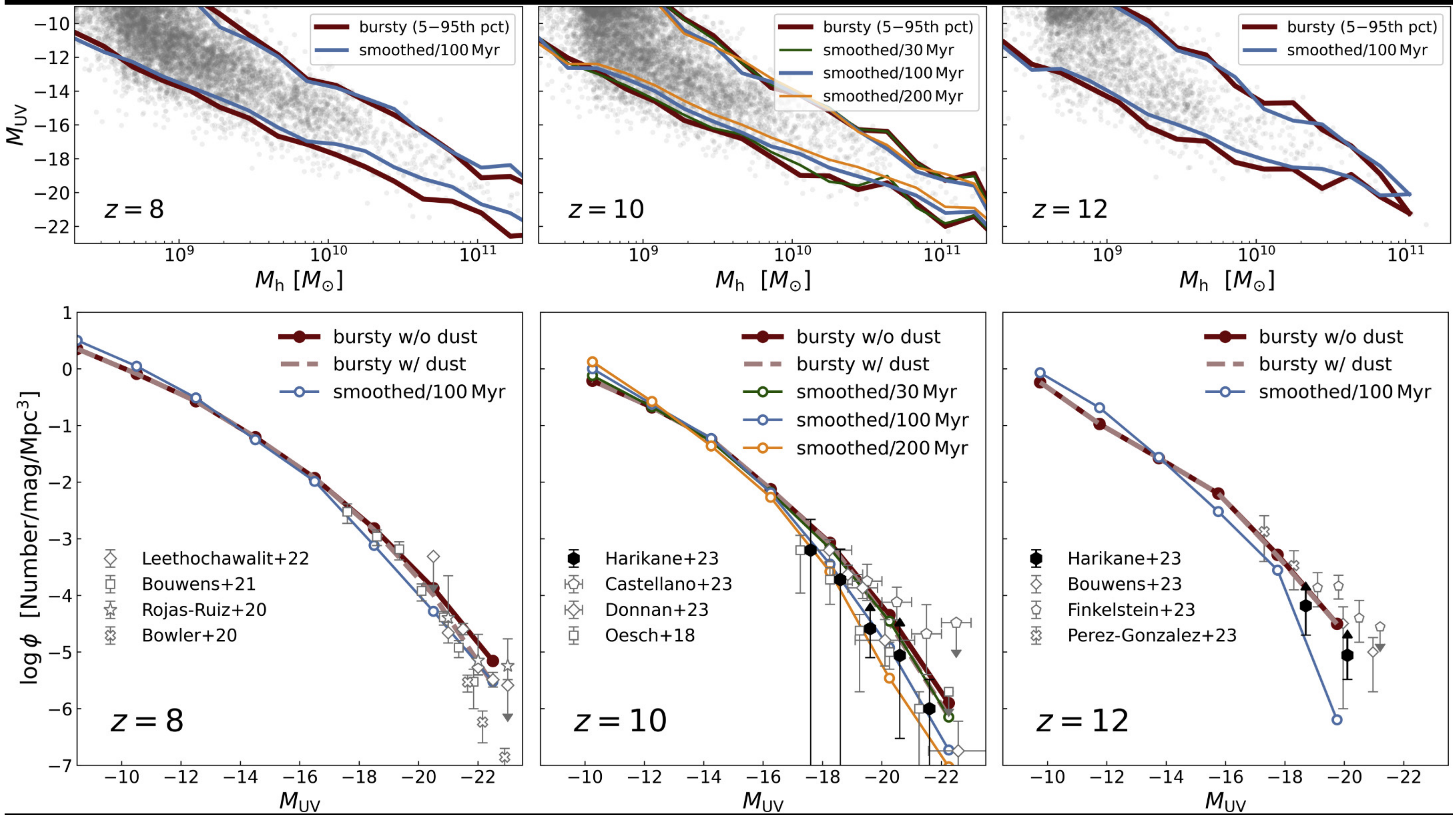
Trinca et al. 2023

impact of burstiness on UV LFs



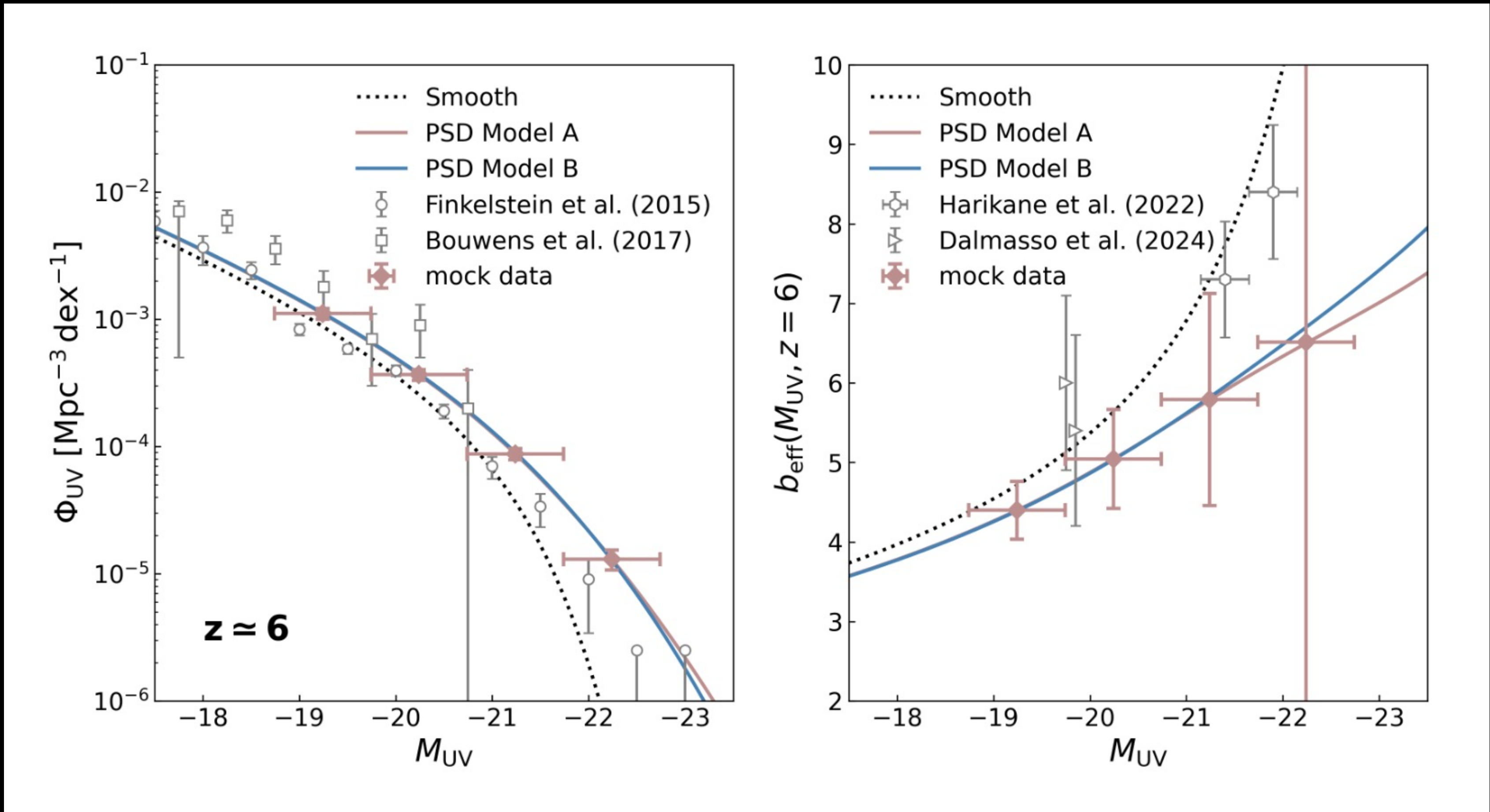
Shen et al. 2023

predicted SF burstyness in FIRE has a non-trivial effect on the bright end of the UVLF to z~12



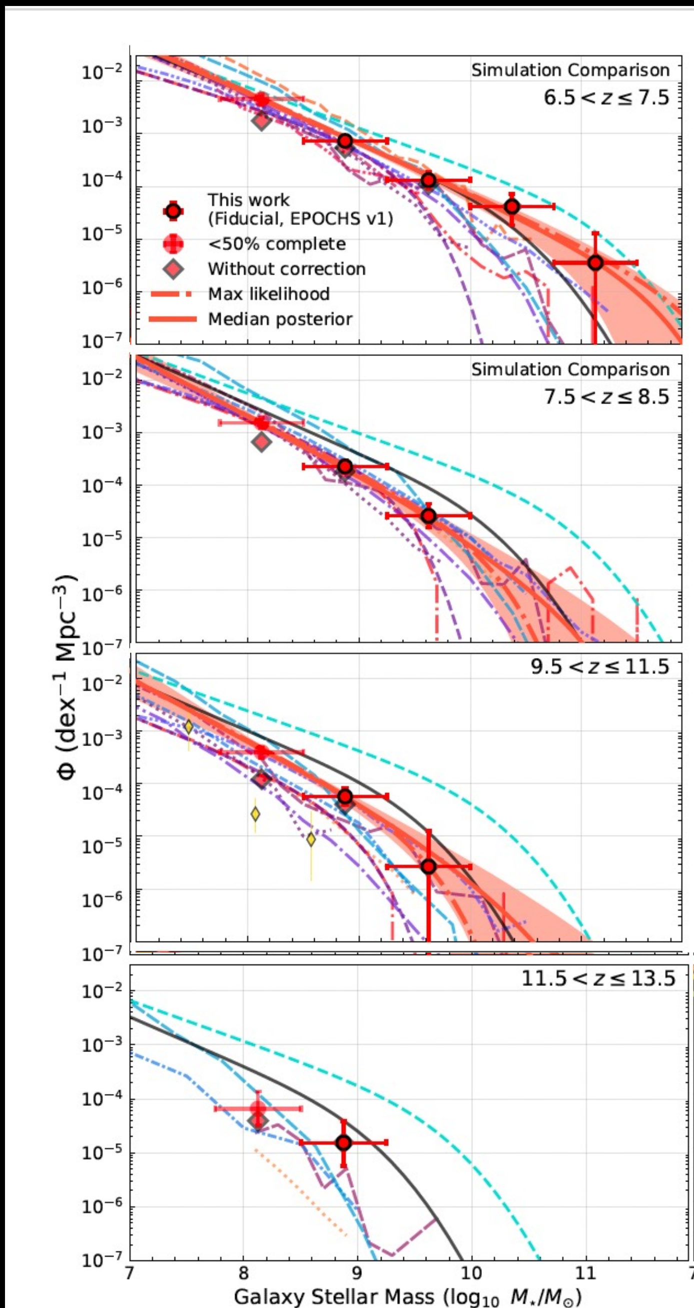
Sun et al. 2023

bursty star formation also has an impact on clustering



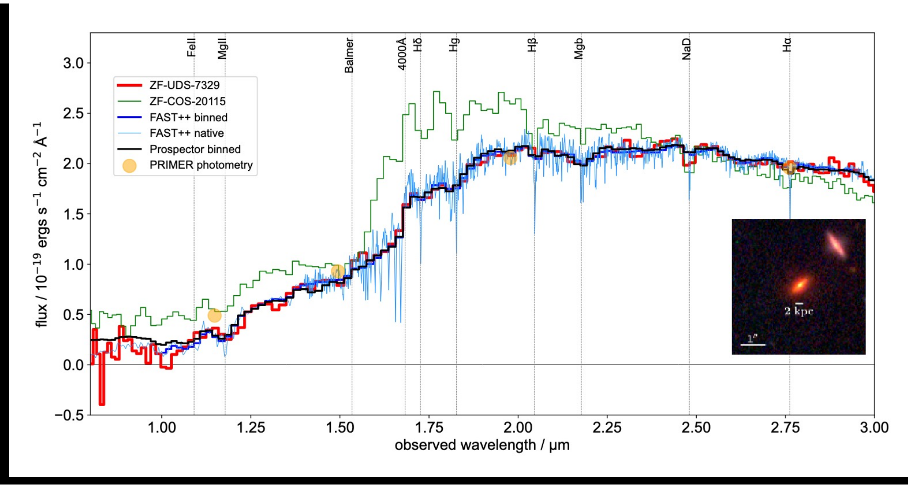
Sun et al. 2024

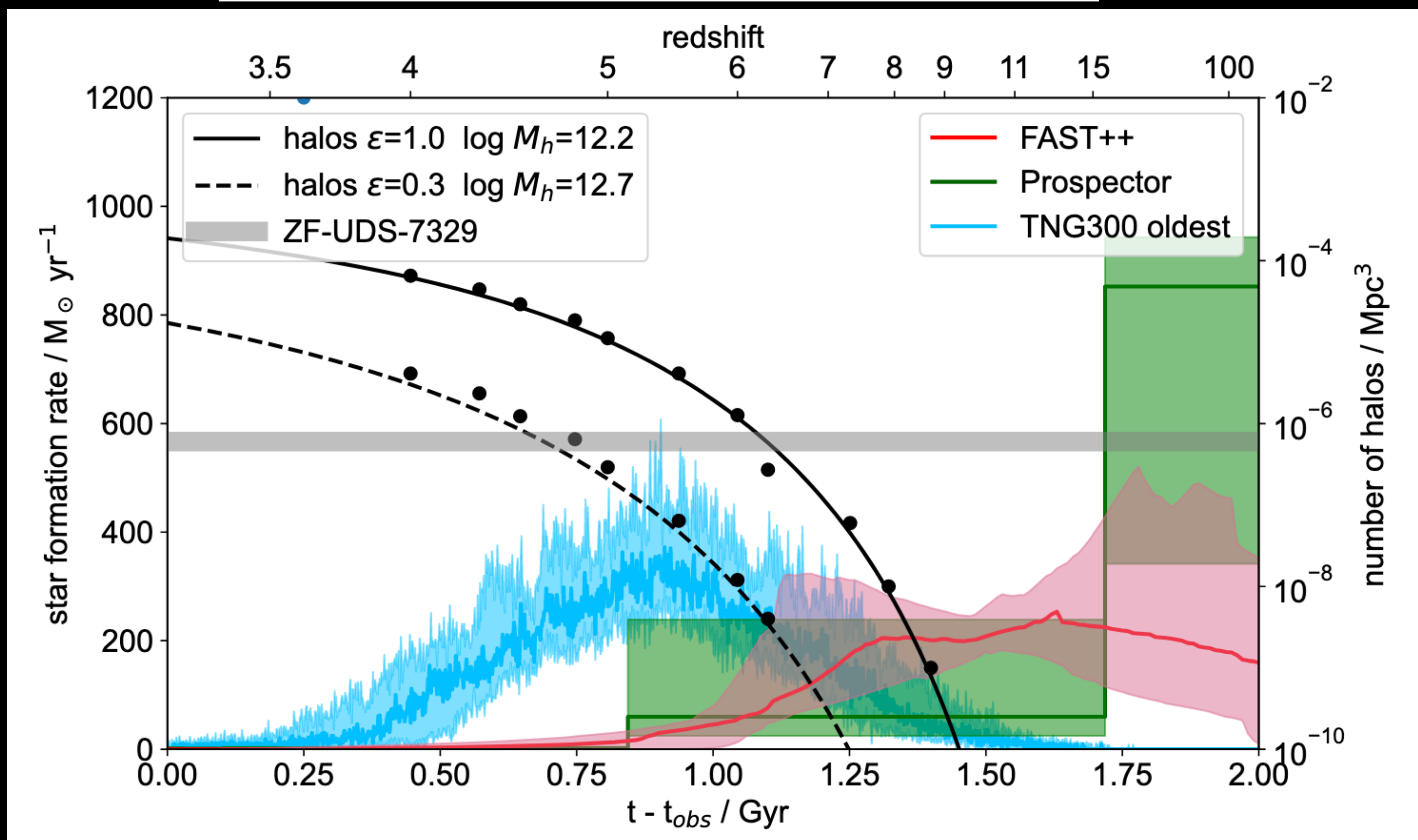
hint that some/most physics-based models are under-producing stellar masses of most massive galaxies at z>6, but uncertainties are v. large



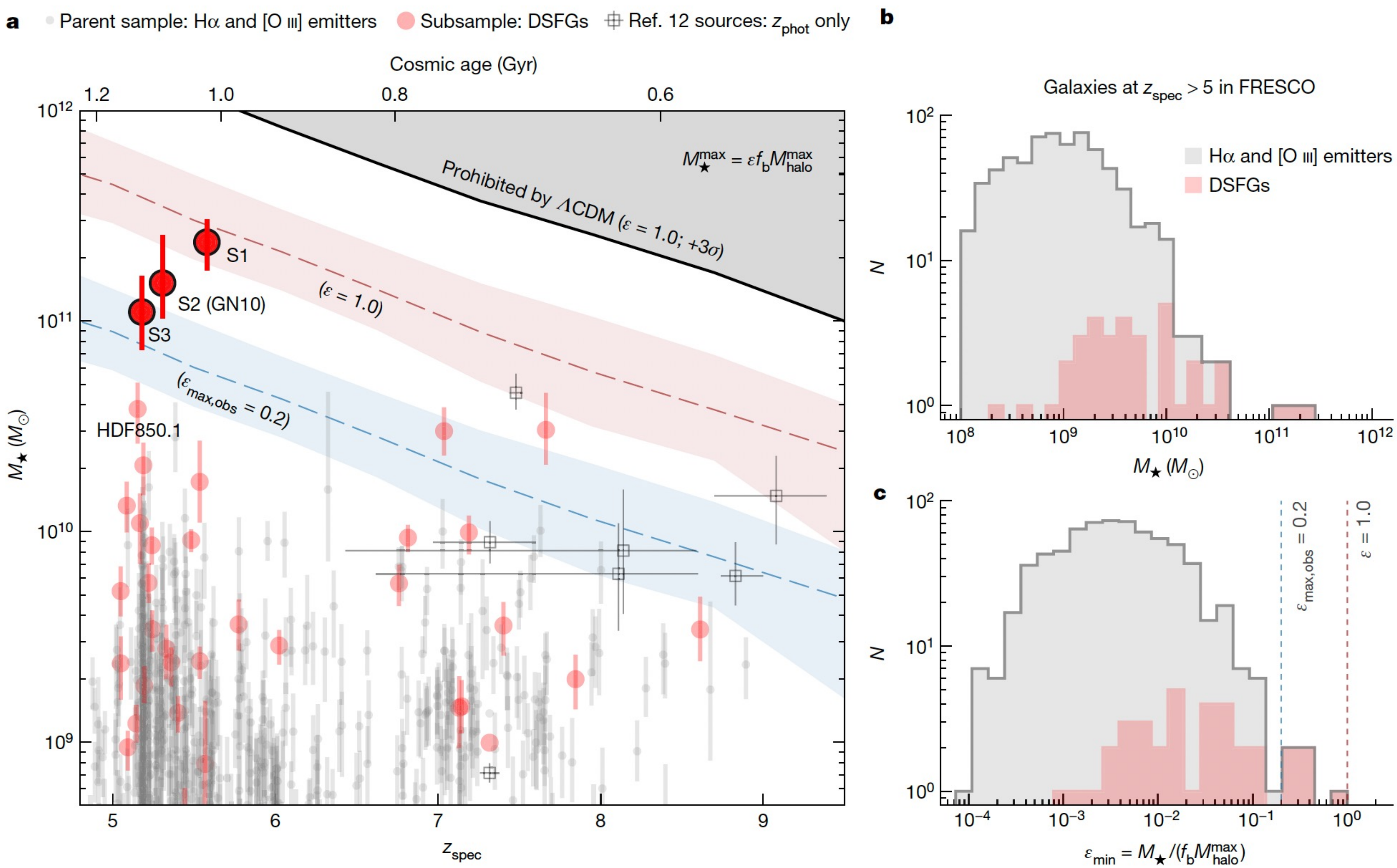
Harvey et al. 2024
see also Weibel+24

z=3.2





Glazebrook et al. 2024

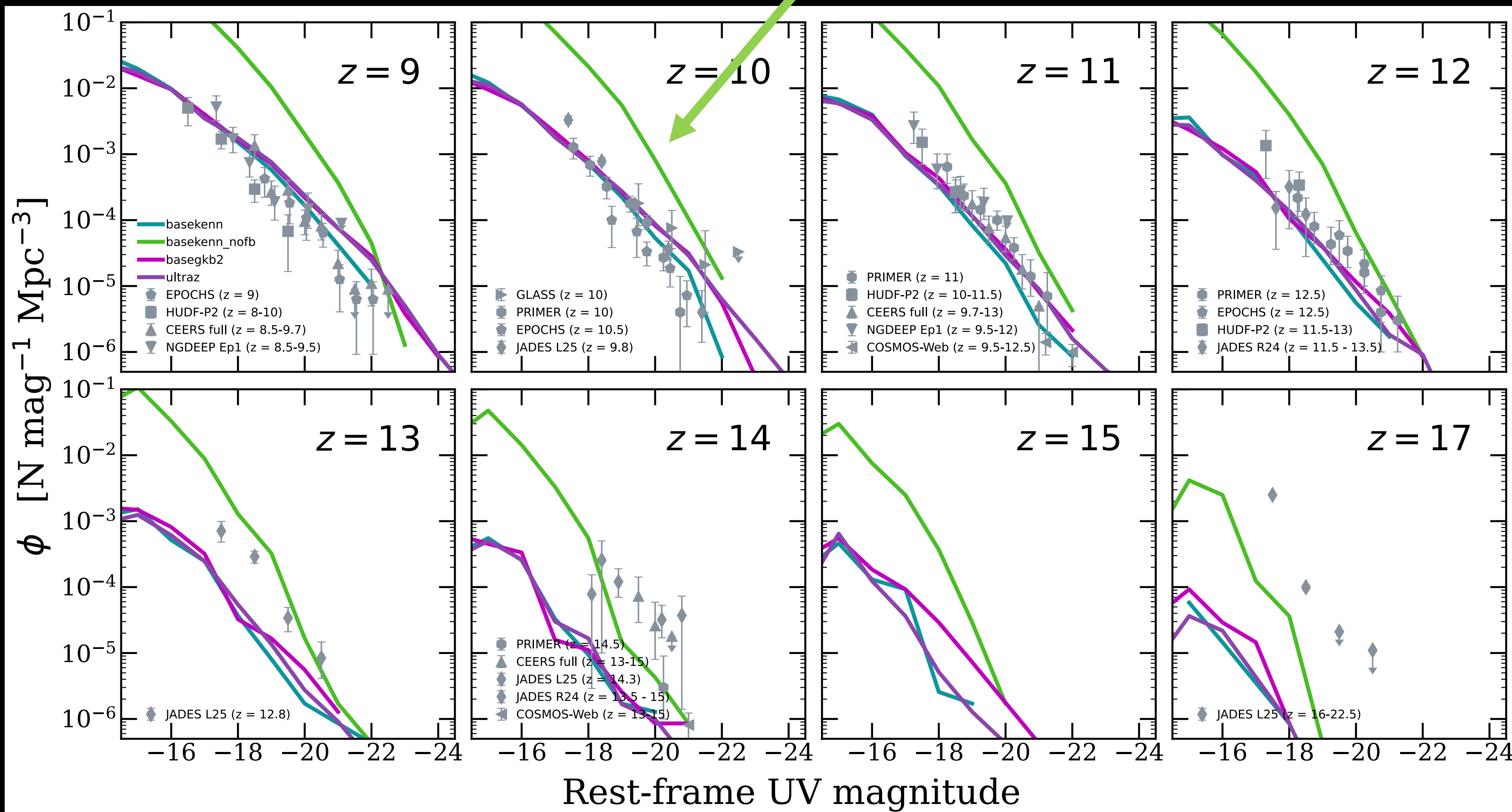


Xiao, Oesch et al. 2024

predictions from pre-launch `Santa Cruz' SAMs implemented in new high-z optimized GUREFT N-body simulation suite

NO DUST

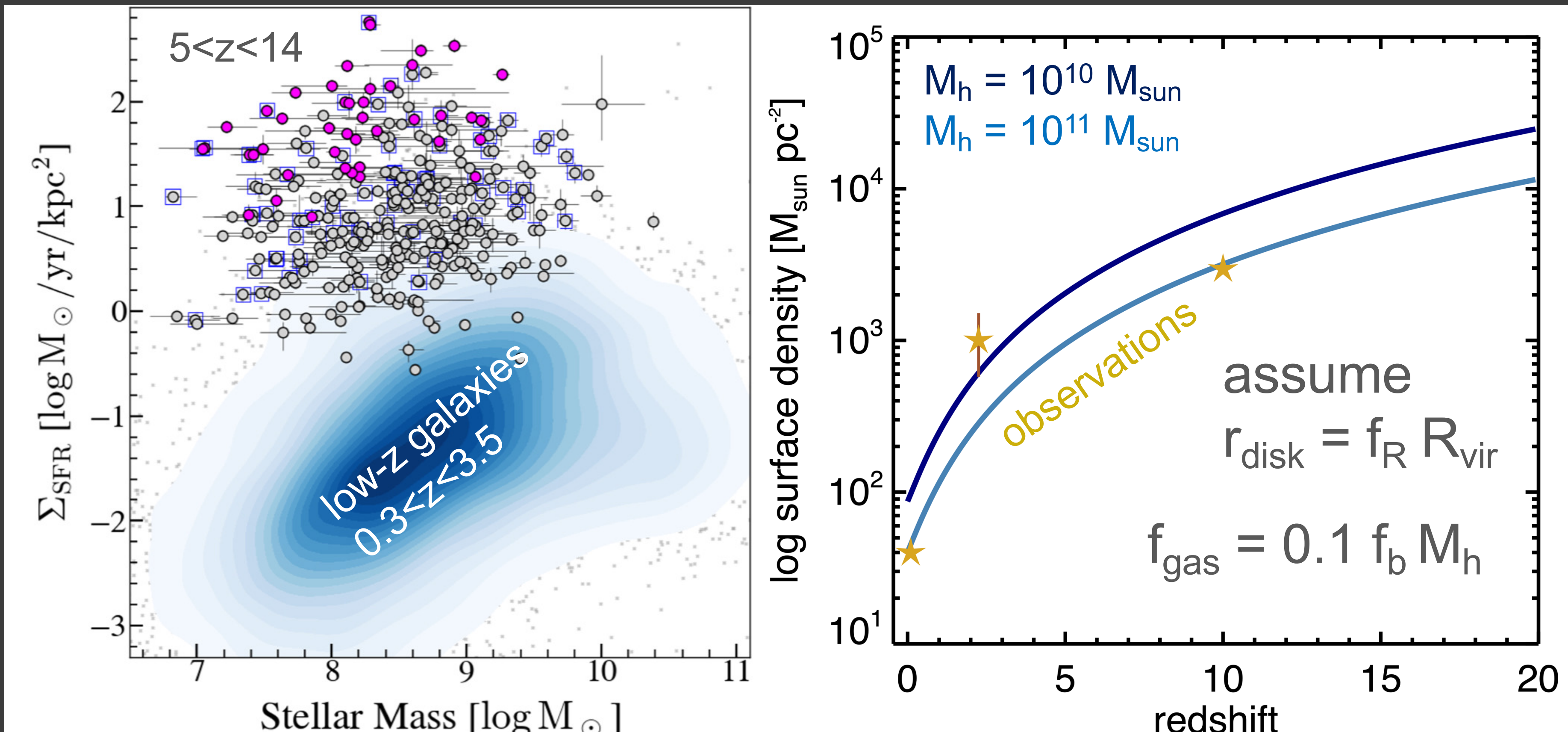
galactic winds switched off



rss, Yung et al.; + in prep

[bright end limited by volume of our biggest N-body box...]

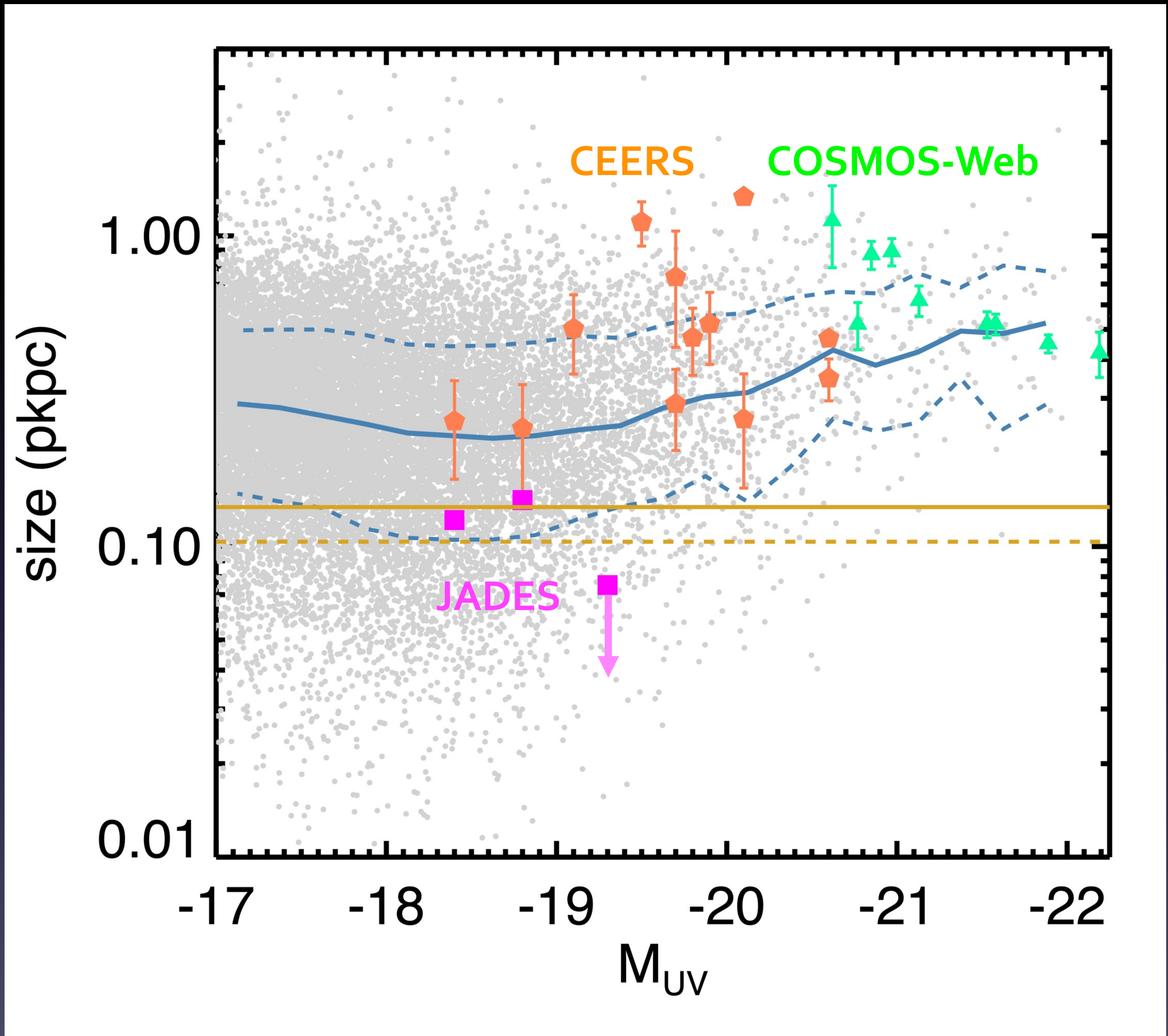
surface density of gas



Morishita et al. 2024

rss in prep

galaxy sizes at z=11: semi-analytic model



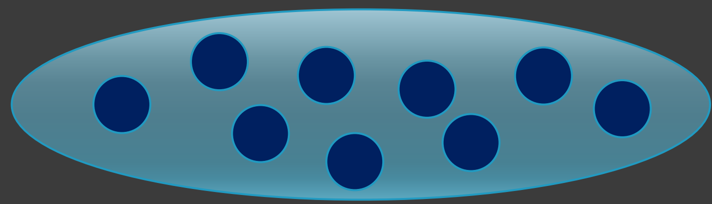
observations: 9<z<13
Robertson+23;
Finkelstein+23;
Casey+23

$r_{gal} = 2\lambda\, R_{halo}$

1 NIRCAM pixel z=9
z=13

rss, Yung et al. in prep

NEW density modulated “cloud/cluster” SF model

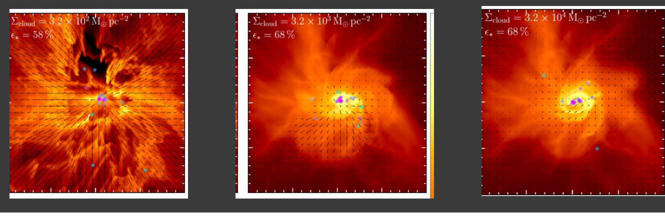


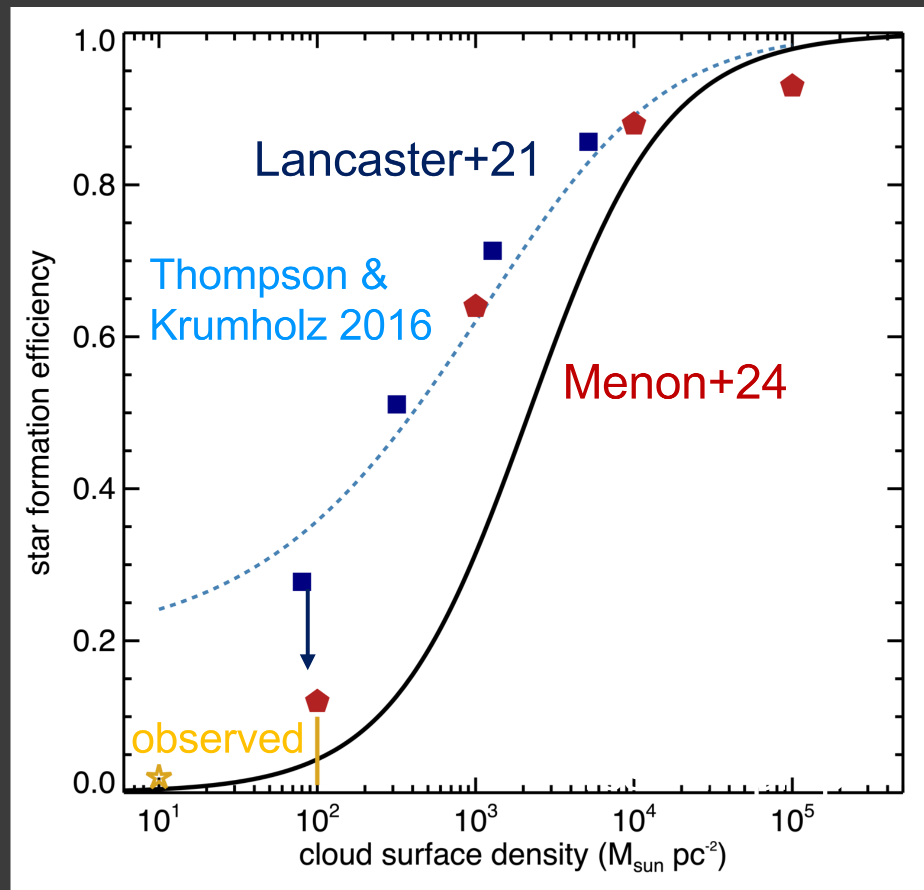
$$\epsilon_{*,\mathrm{cl}} = \frac{\Sigma_{\mathrm{cl}}/\Sigma_{\mathrm{crit}}}{(1.0 + \Sigma_{\mathrm{cl}}/\Sigma_{\mathrm{crit}})}$$

$$\Sigma_{\mathrm{crit}} = \frac{\langle \dot{p}/m_* \rangle}{\pi G}$$

$$\Sigma_{\mathrm{cl}} = \mathbf{c}\Sigma_{\mathrm{gal}}$$

$$m_{\mathrm{dense}} = \mathbf{f}_{\mathrm{dense}} m_{\mathrm{gas}} = N_{\mathrm{cl}} M_{\mathrm{cl}}$$





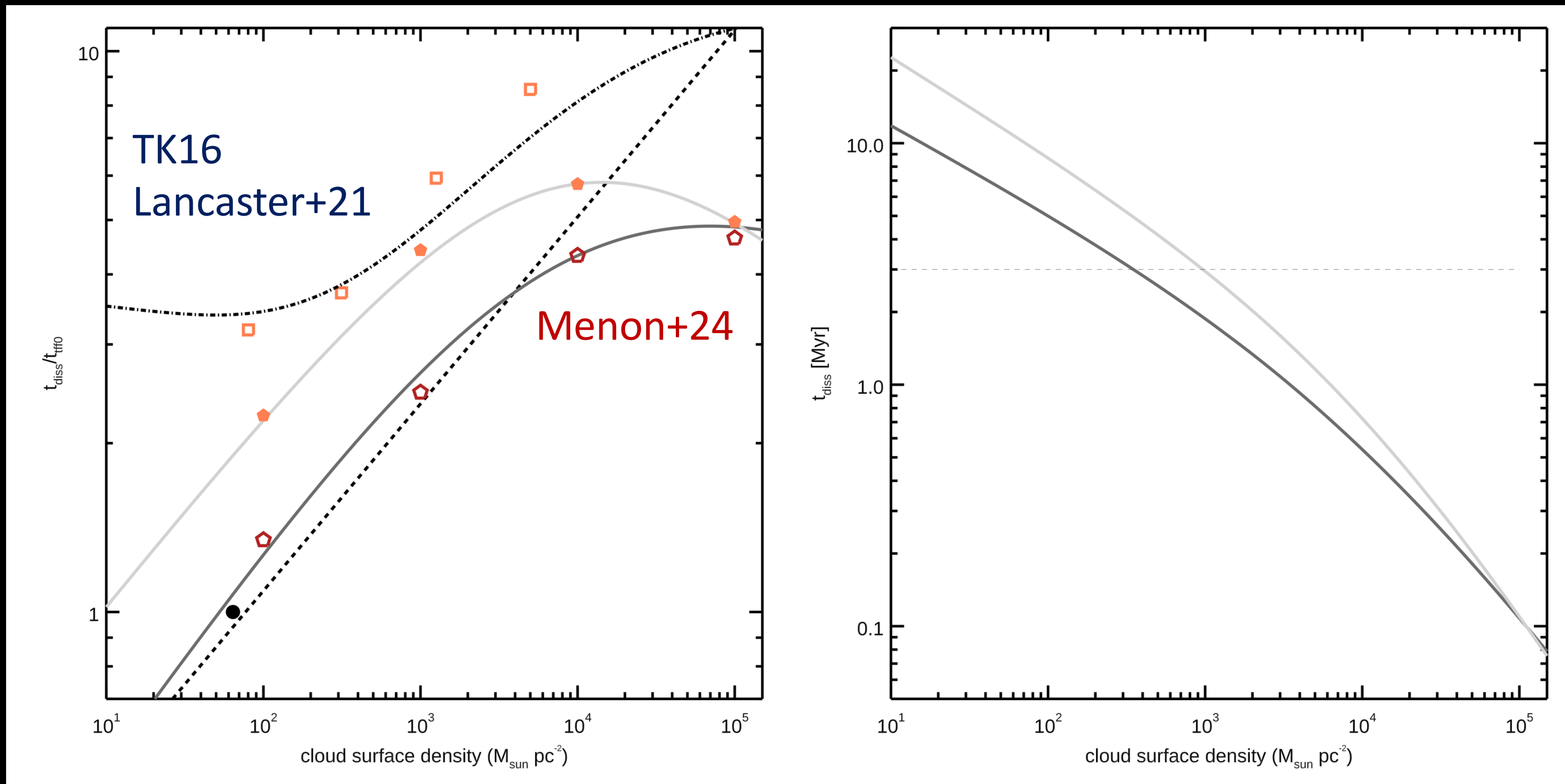
rss+ in prep

Grudic et al. 2018

in units of free fall time

in Myr

cloud lifetime



cloud surface density

cloud surface density

solid gray lines: empirical fit to cloud lifetimes in cloud-scale simulations

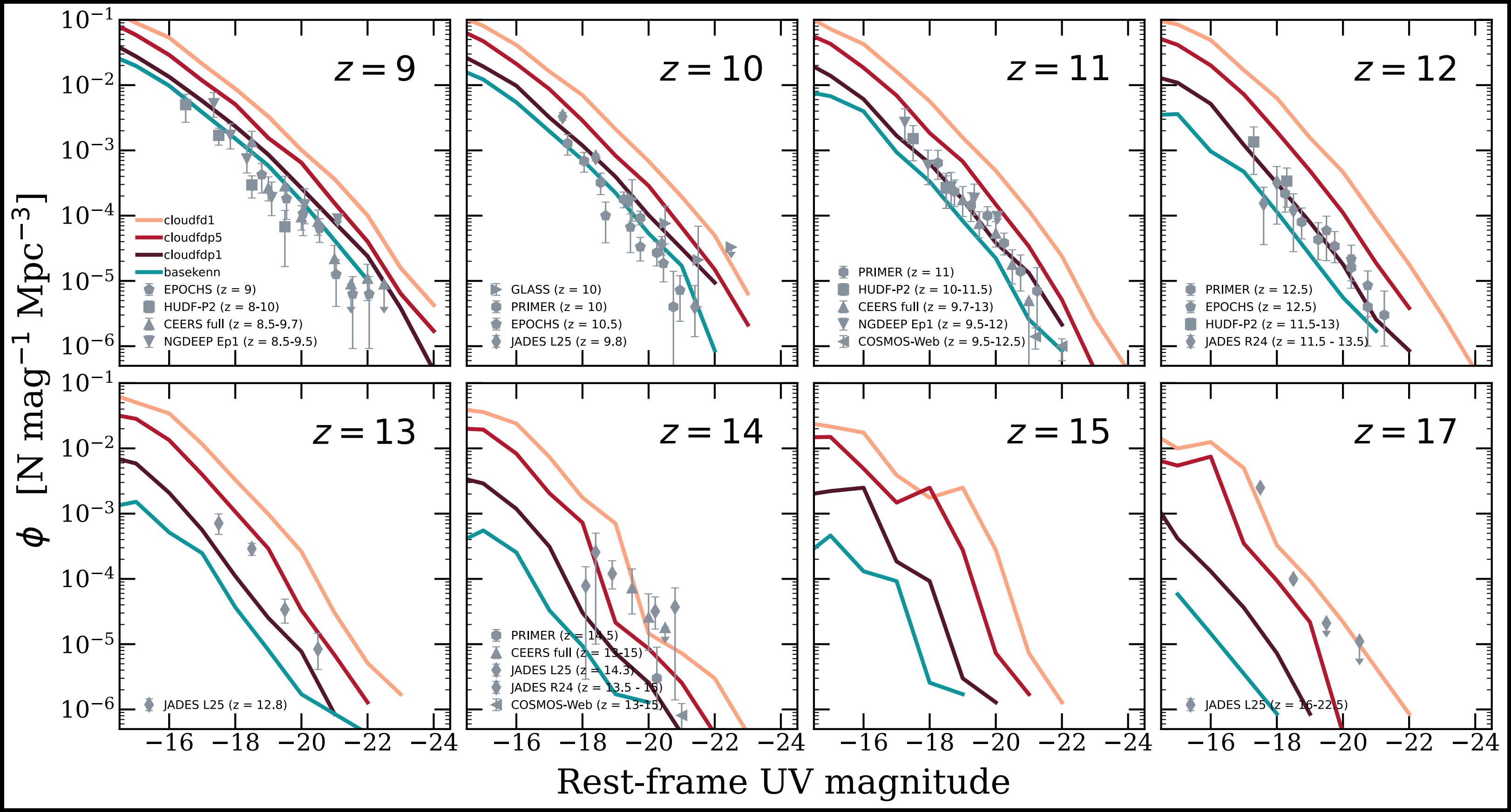
$$\langle SFR \rangle_{\rm cloud} = \frac{\epsilon_{*,\rm cl} M_{\rm cl,0}}{t_{\rm cl}}$$

rss + in prep

cluster based model with density modulated SFE:

NO DUST

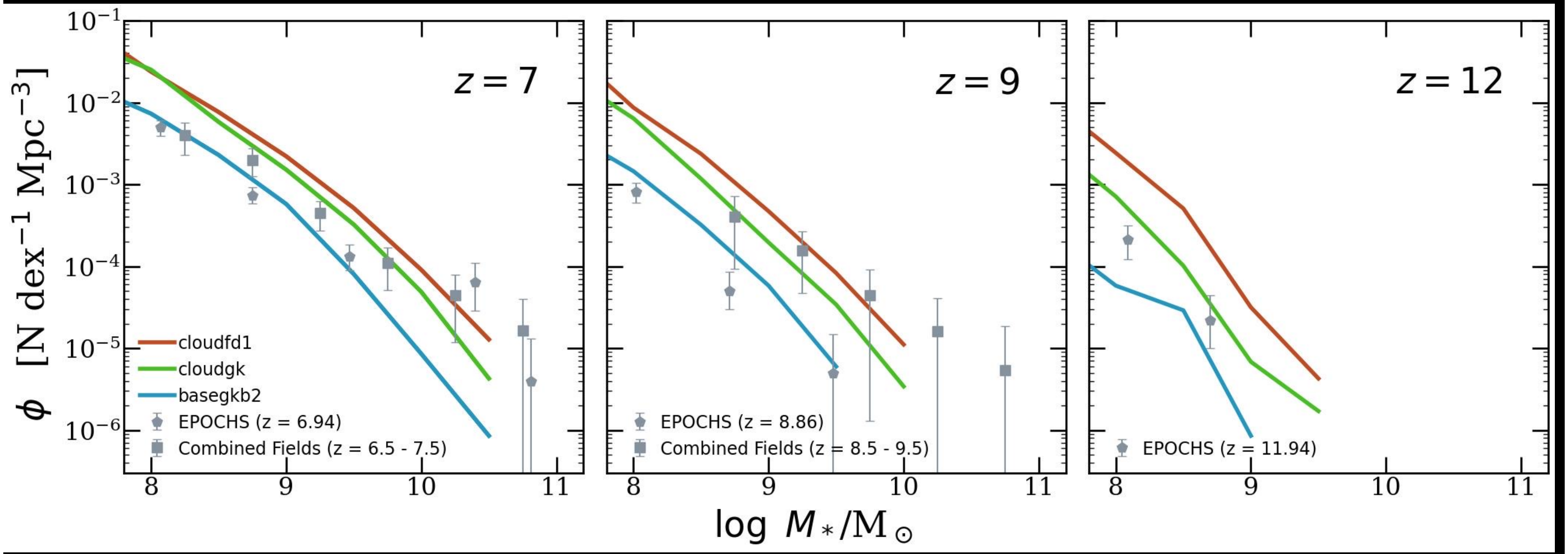
good agreement with observations to z~14 with 50% of SF in ‘clusters’



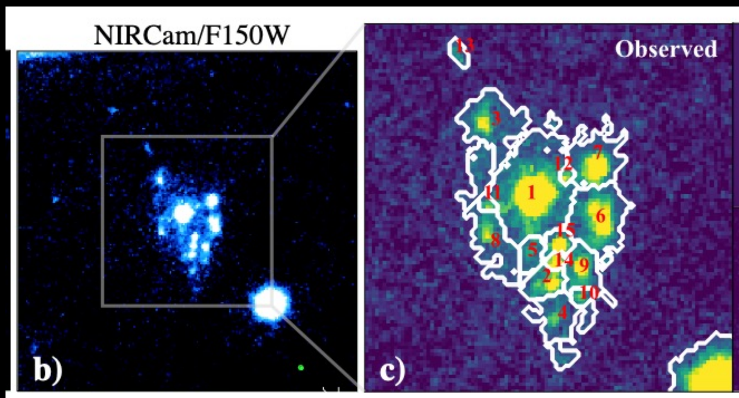
fraction of
gas in dense
clumps/clusters

rss, Yung et al. in prep

more early star formation: better agreement with stellar mass function estimates?

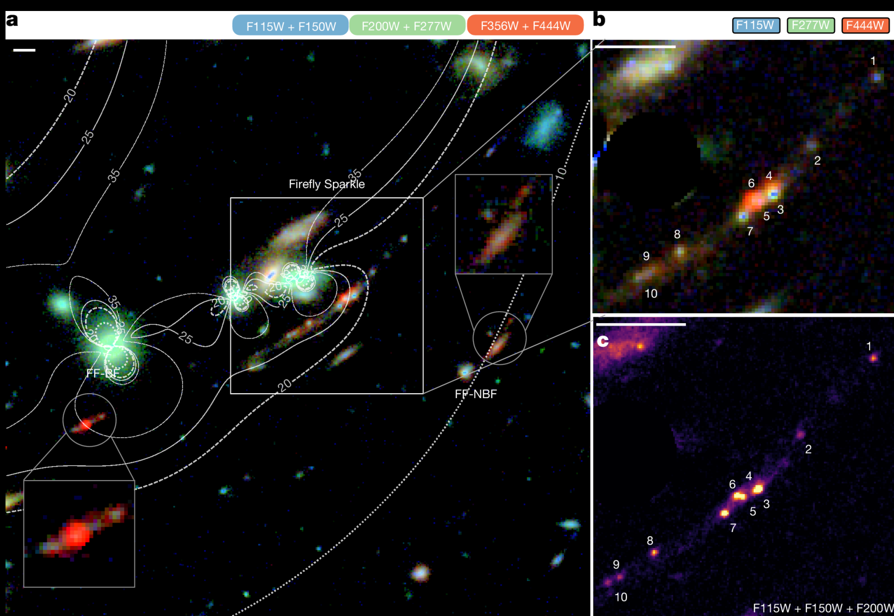


rss et al. in prep

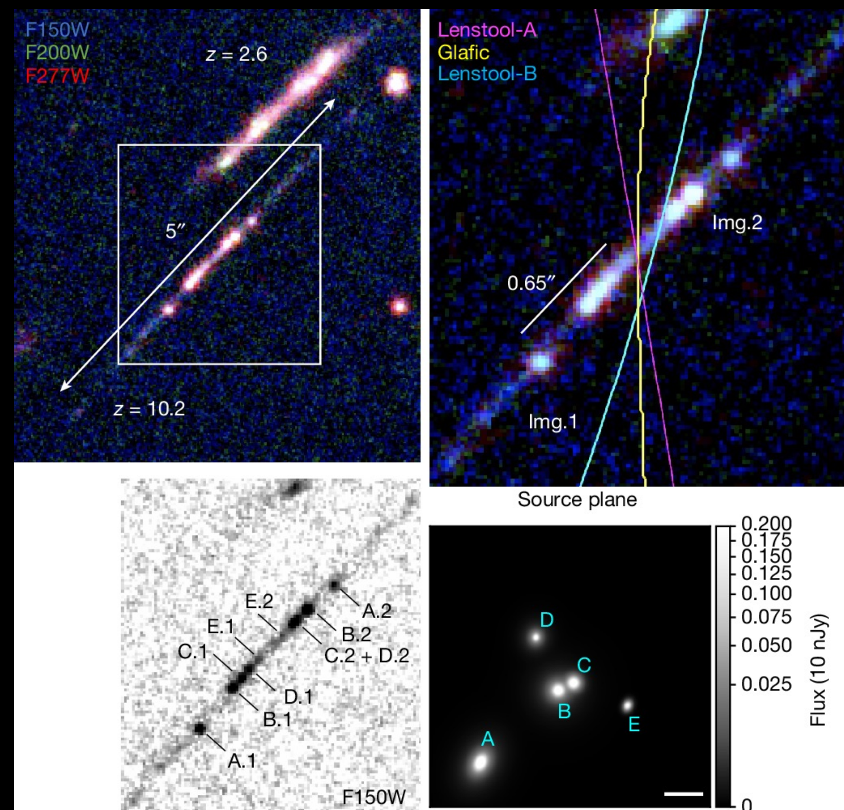


Fujimoto et al. 2024 ‘cosmic grapes’

fraction of SF in ‘super star clusters’ ~50%
consistent with lensed objects @ z~6-10



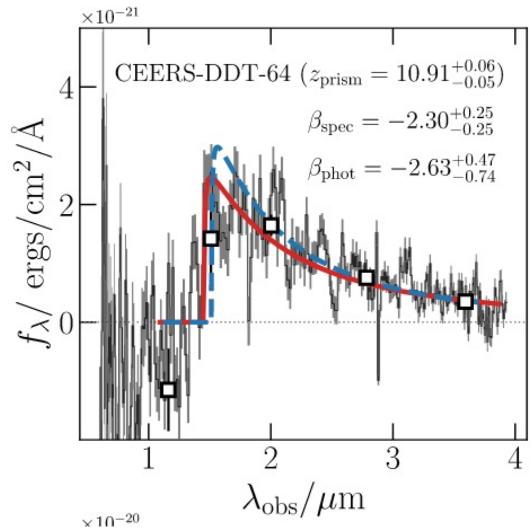
Mowla et al. 2024 ‘Firefly sparkle’

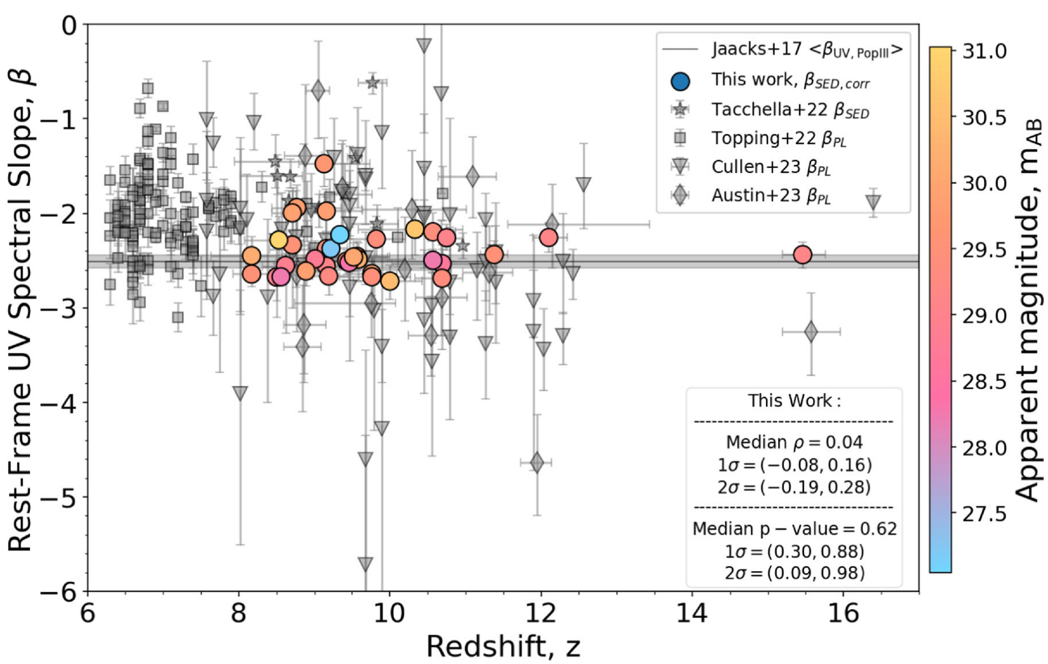


Adamo et al. 2024 ‘cosmic gems’

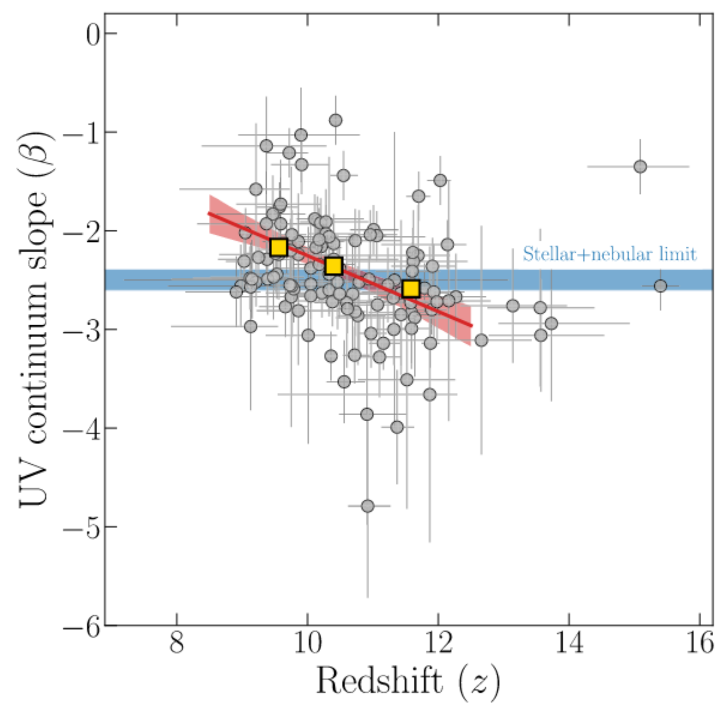
puzzle #2: Where is the dust?

extremely blue UV slopes at z>10 leave little (if any) room for dust reddening
evidence for lower and lower A_{UV} at z>10



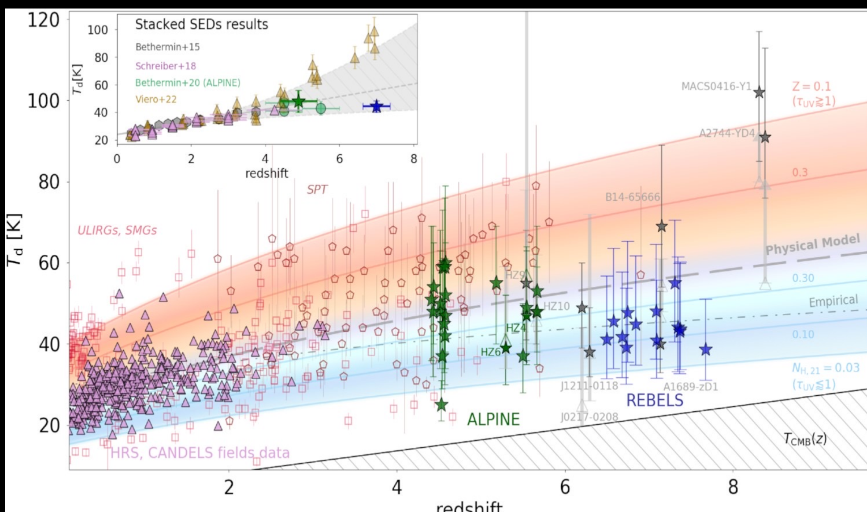


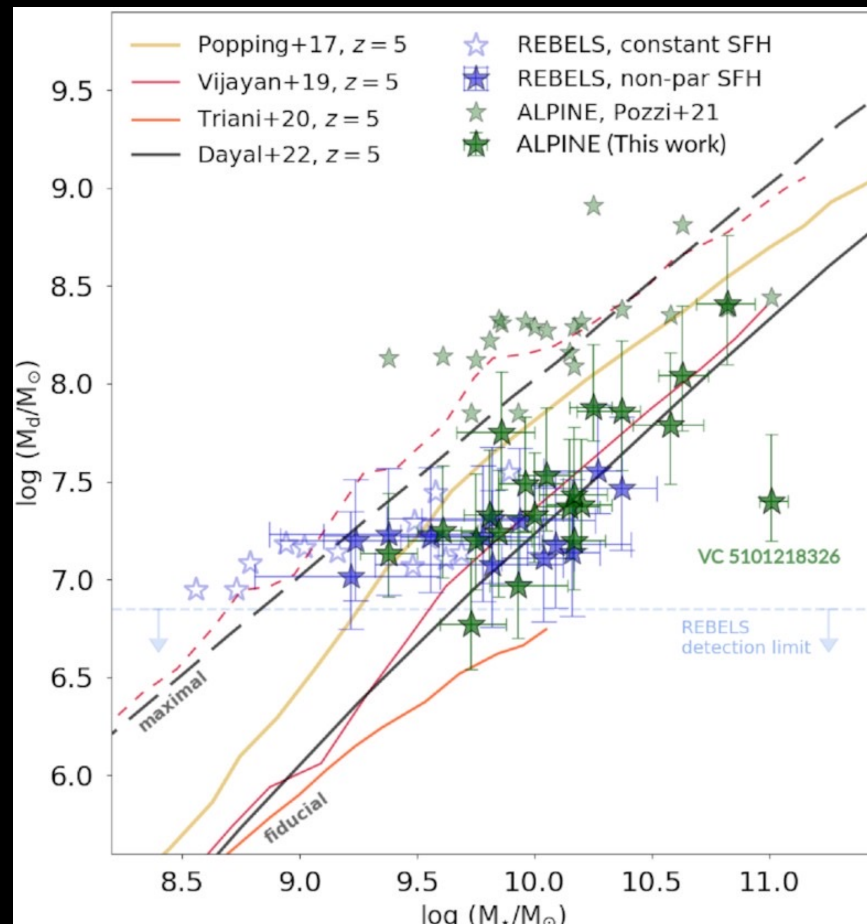
Morales et al. 2024



Cullen et al. 2024

but significant dust reservoirs in place by 750 Myr after Big Bang (z~7)



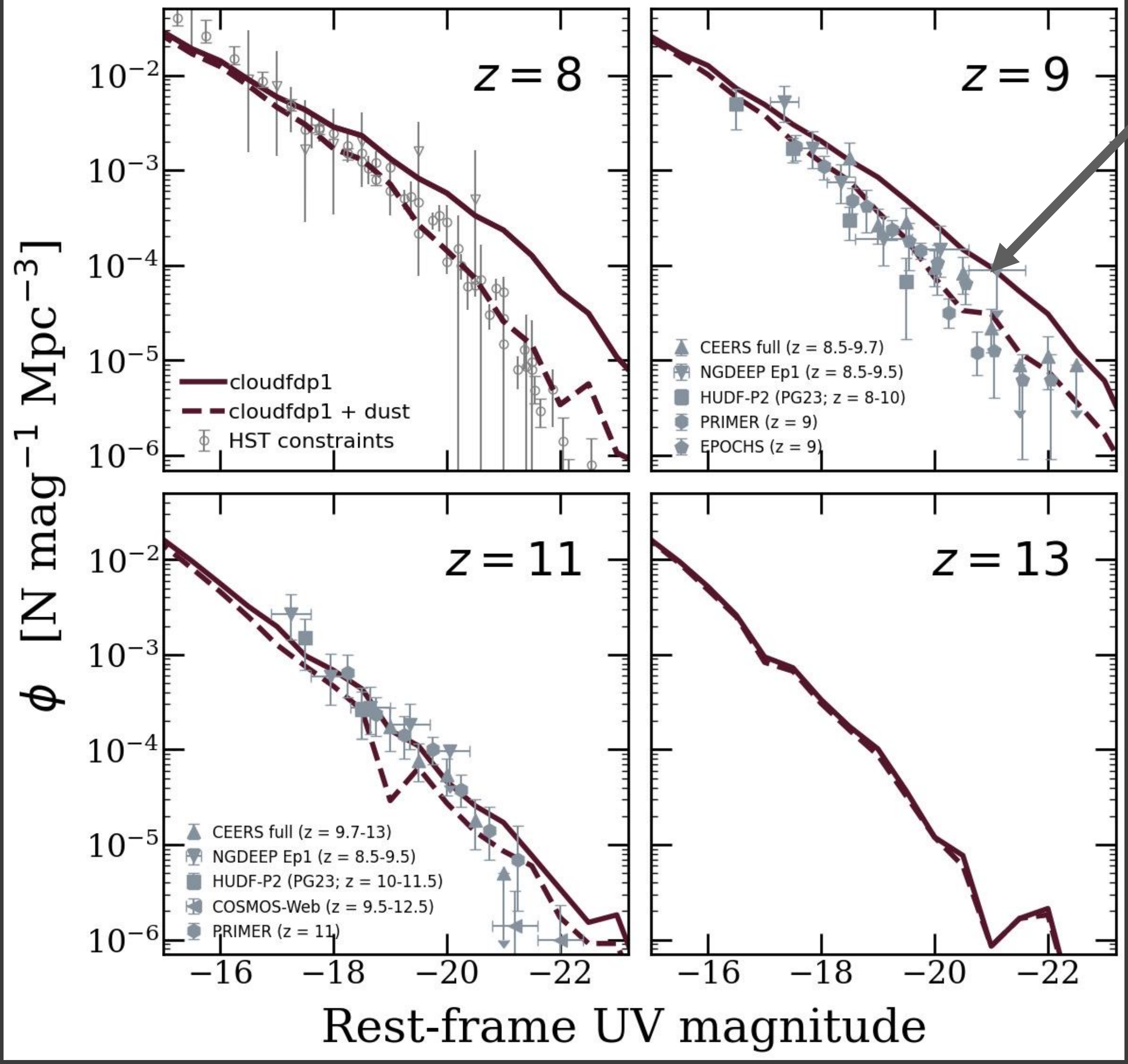


Sommovigo et al. 2022; see also Dayal et al. 2023

proposed solutions

- lower A_{UV} for a given m_{dust}: dust composition/grain size distribution was different at high-z, leading to *less efficient attenuation* (Narayanan et al. 2024)
- SNae dust yields are lower than we thought, and/or dust is destroyed by SNae shocks more efficiently than is generally assumed (R. Schneider et al.)
- dust is ejected by radiation pressure above a critical sSFR (Ferrara et al. 2022; 2023, 2024)

Santa Cruz SAM incorporating density dependent cloudscale SFE+

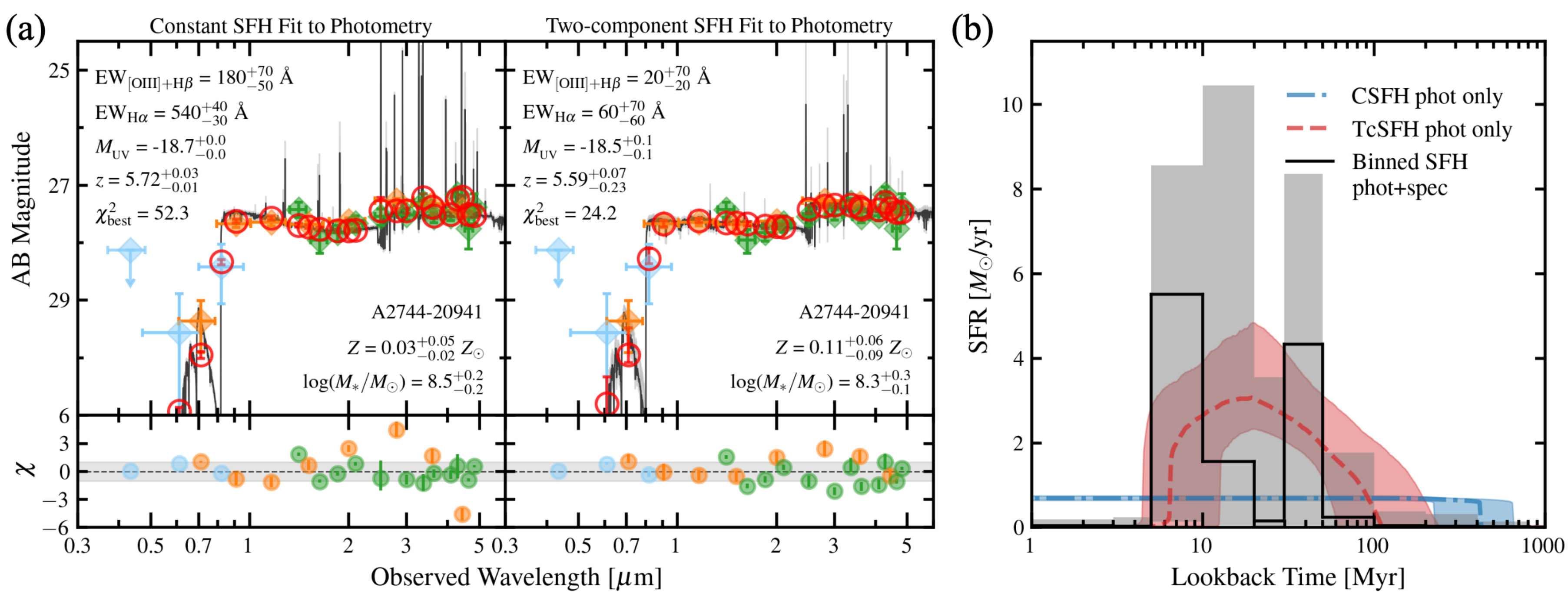


dust ejected when sSFR above critical value (Ferrara+23)

rss in prep

puzzle #3: emission line EW & line ratios: SF burstyness, abundances, abundance ratios, electron densities

quantifying bursty SF

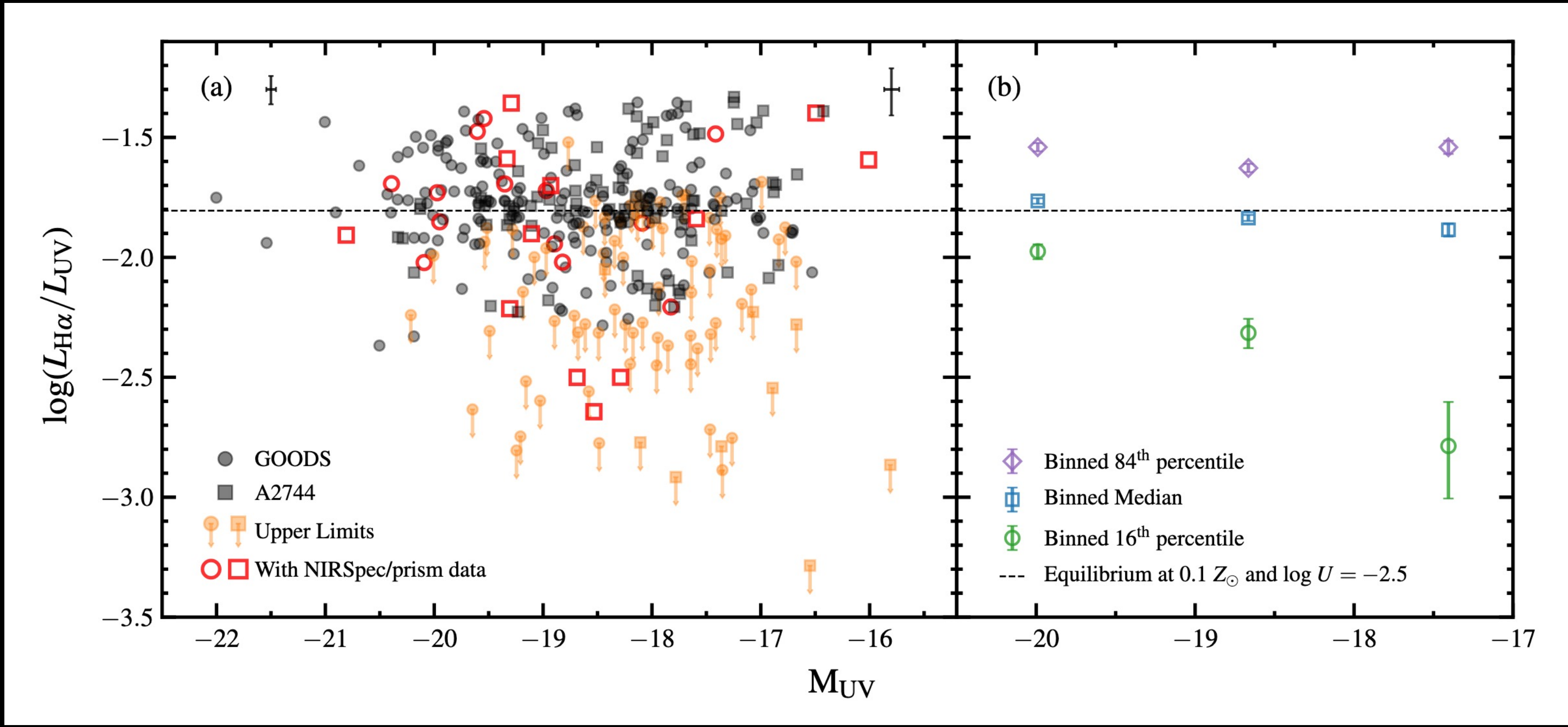


Endsley et al. 2024

quantifying bursty SF

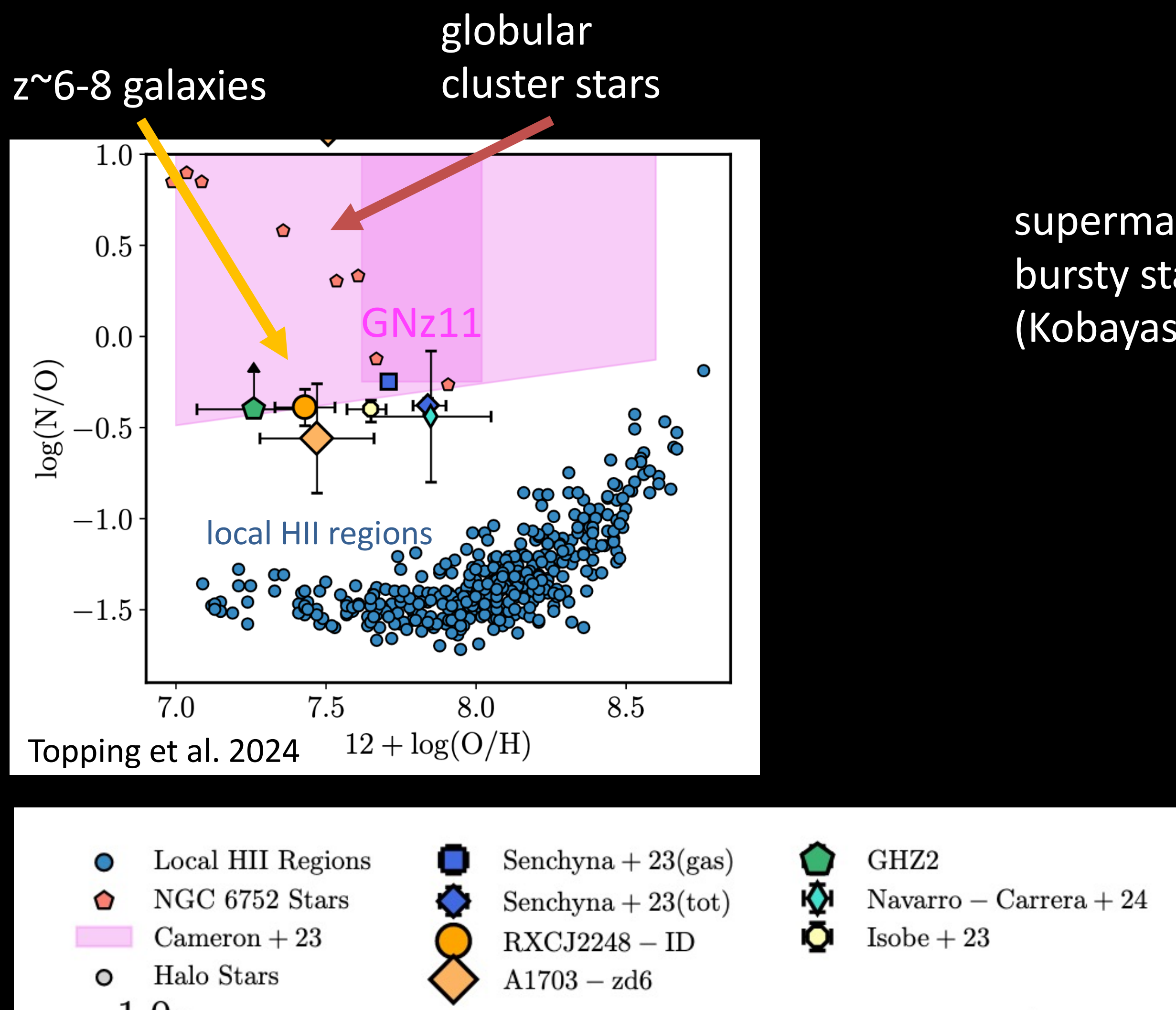
evidence for diverse/bursty SFH at z~6 → exciting to push to higher z!

~ SFR(10 Myr)/SFR(100 Myr)



Endsley et al. 2024

some (but not all) z>6 galaxies have high N/O, very different from local HII regions but similar to globular clusters

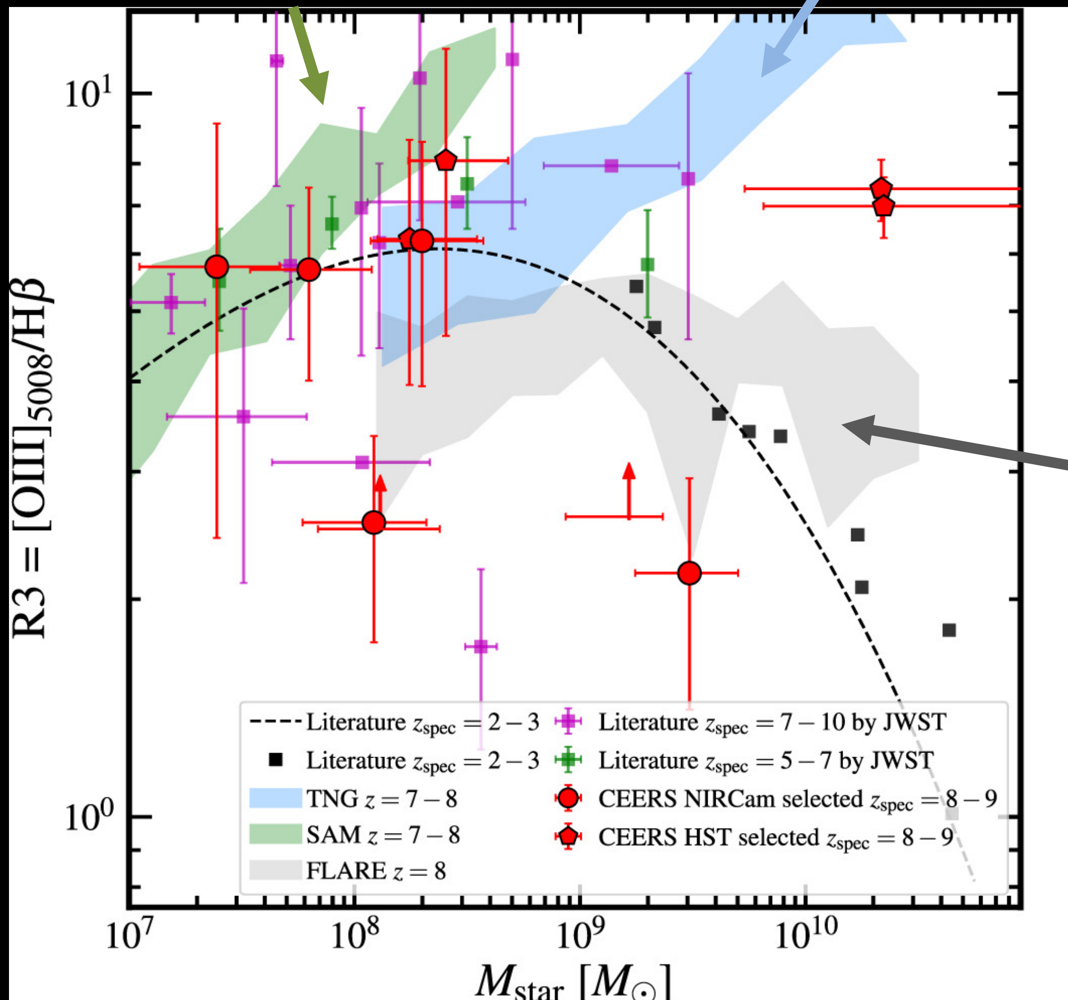


supermassive stars?
bursty star formation?
(Kobayashi & Ferrara 2024)

‘classic’ Santa Cruz SAM with Hirschmann EL models

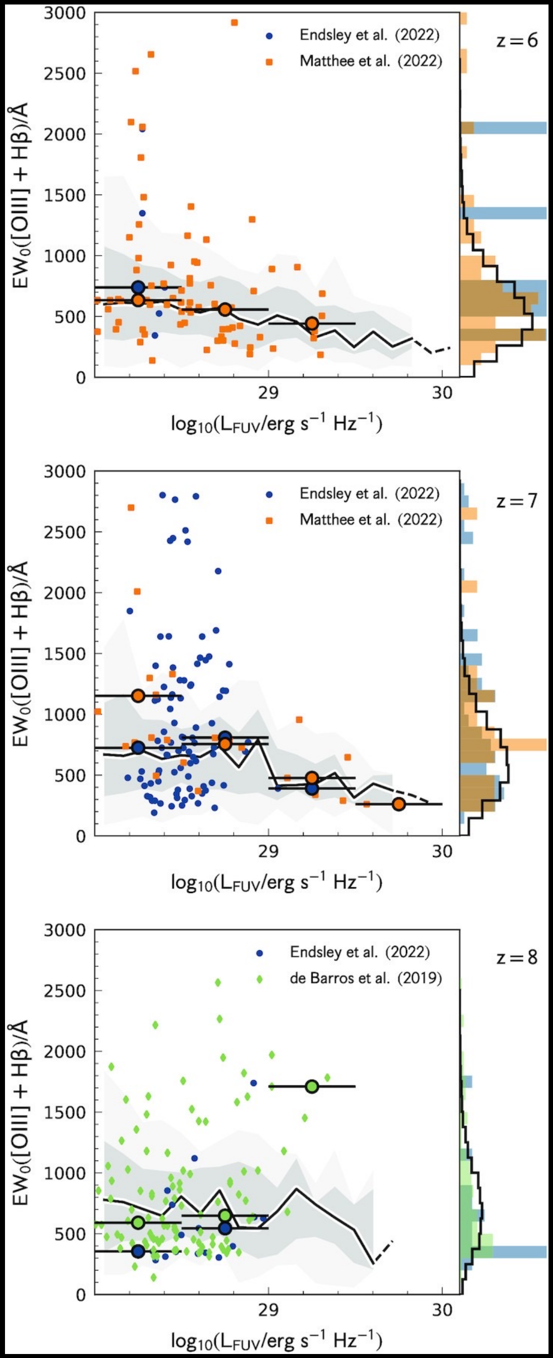
TNG with Hirschmann+ emission line models

predicted emission line properties quite sensitive to sub-grid modeling assumptions



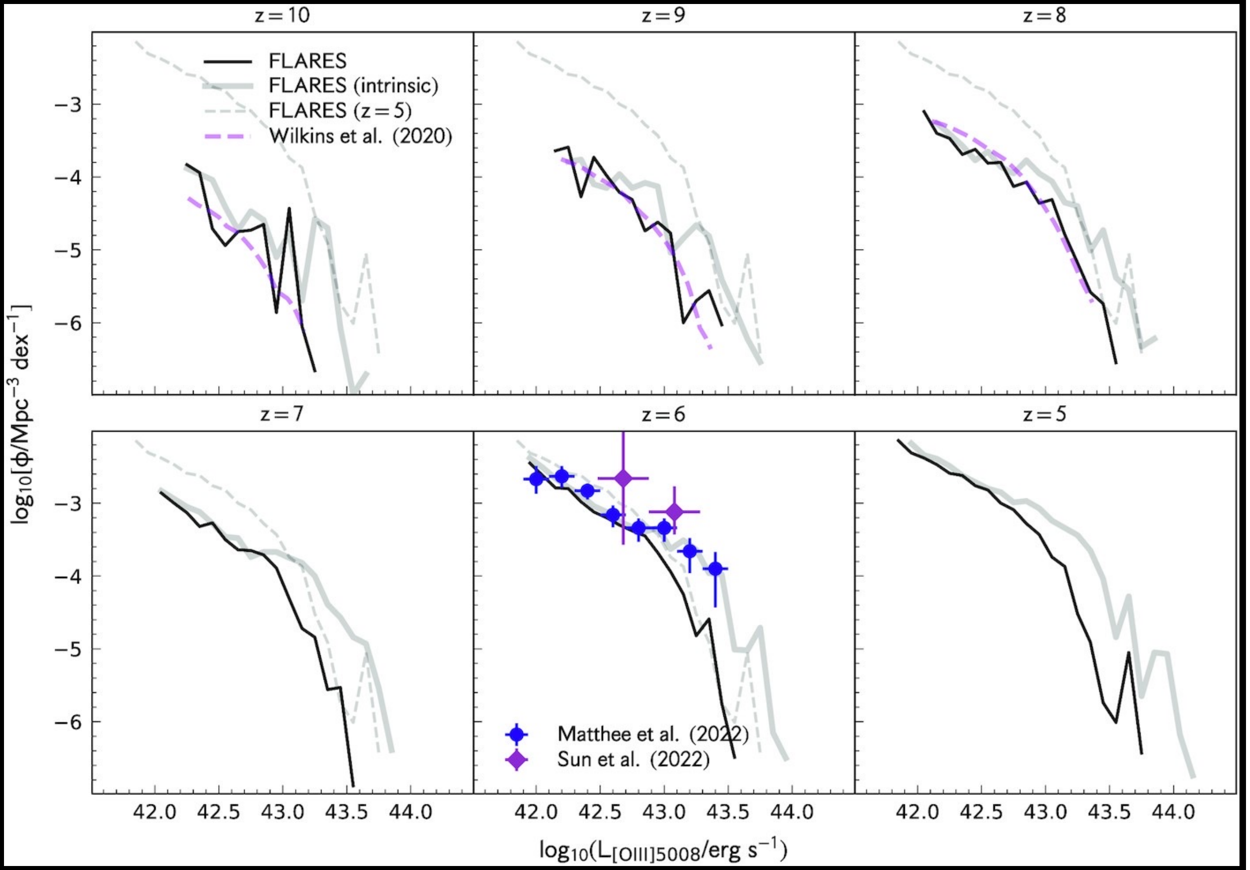
FLARES with synthesizer emission line models (Wilkins+)

Fujimoto et al. 2023



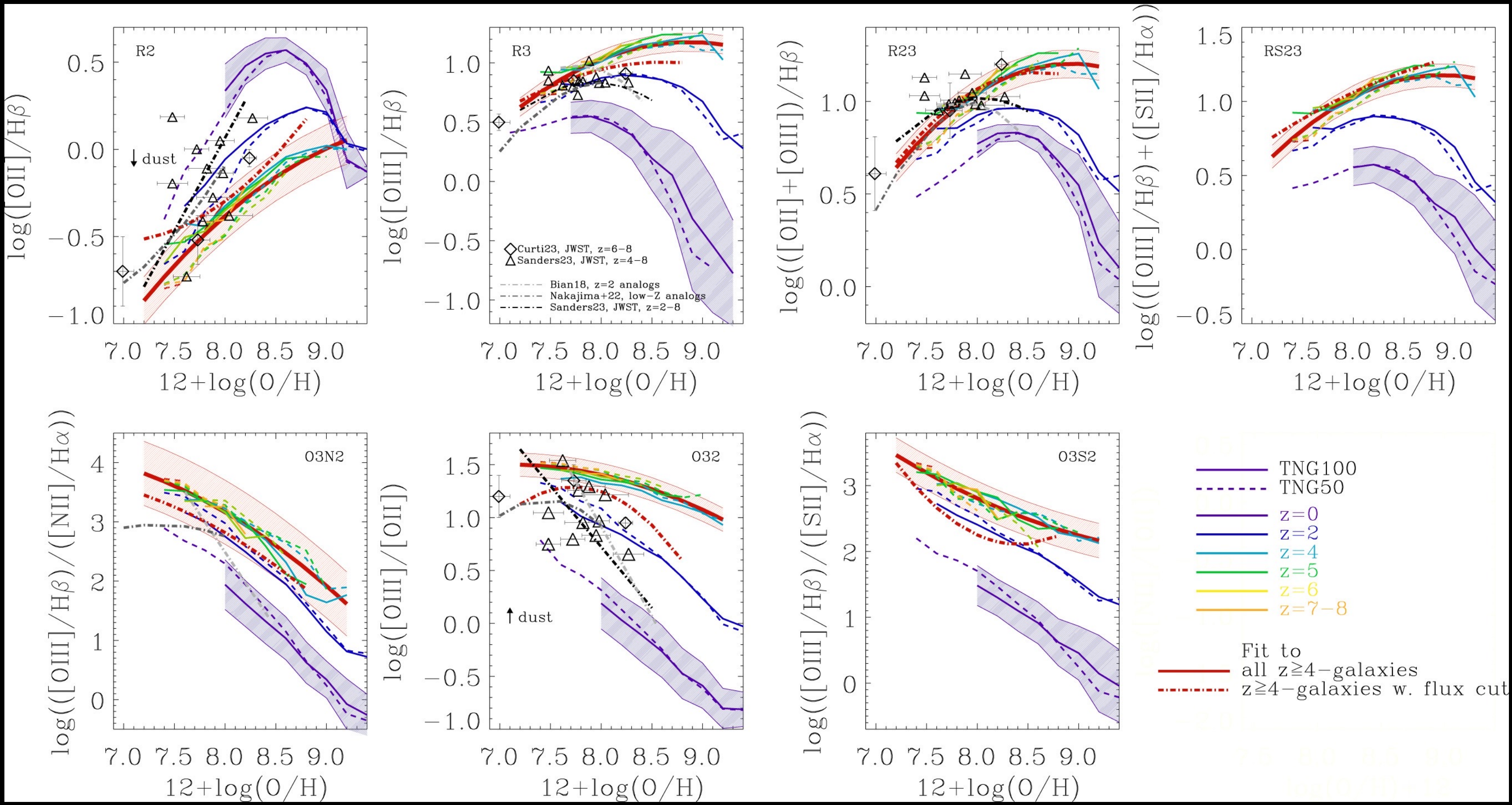
some models seem to struggle a bit to match extremely high equivalent widths at z>6

→ but predictions very sensitive to assumptions that go into nebular emission modeling



Wilkins et al. 2023

cautionary note: commonly used line ratios used as metallicity indicators may evolve strongly with redshift/ISM conditions



Hirschmann, Charlot & rss 2023

summary/take-away points

- JWST puzzle #1: more than expected UV-bright (massive?) galaxies at z>10
  - top heavy IMF, bursty star formation, more efficient SF/weaker feedback
- JWST puzzle #2: where is the dust?
  - evolving attenuation law/grain size distribution, lower dust yields, dust ejection
- JWST puzzle #3: emission lines
  - SF burstyness, chemical abundances & abundance ratios

- what new simulations need to be done to make progress towards solving these puzzles?
- what new observations need to be done to make progress towards solving these puzzles?

extra slides