Université Paris Cité

Unveiling the hidden side of galaxy formation

PhD defense presented by Lucas Leroy

Johan Richard	Professeur	Université de Lyon	Président du jury
Laurence Tresse	Professeur	Aix-Marseille Université	Rapportrice
Amélie Saintonge	Professeur	University College London	Rapportrice
Simona Mei	Professeur	Université Paris Cité	Examinatrice
Laure Ciesla	Chargé de Recherche	Aix-Marseille Université	Examinatrice
David Elbaz	Directeur de recherche	UMR AIM - CEA Paris Saclay	Directeur de thèse
Benjamin Magnelli	Chargé de Recherche	UMR AIM - CEA Paris Saclay	Invité

23 October 2023

Galaxies

01

Galaxies

Elliptical galaxy - NGC 4150

Credit: NASA, ESA, R.M. Crockett (University of Oxford, U.K.), S. Kaviraj (Imperial College London and University of Oxford, U.K.), J. Silk (University of Oxford), M. Mutchler (Space Telescope Science Institute, Baltimore, USA), R. O'Connell (University of Virginia, Charlottesville, USA), and the WFC3 Scientific Oversight Committee

Galaxies

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Spiral galaxy - NGC 1376

Credit: NASA, ESA, and the Hubble Heritage Team (STScI/AURA). Acknowledgment: R. Thompson (University of Arizona)

Galaxies

Elliptical galaxy - NGC 4150

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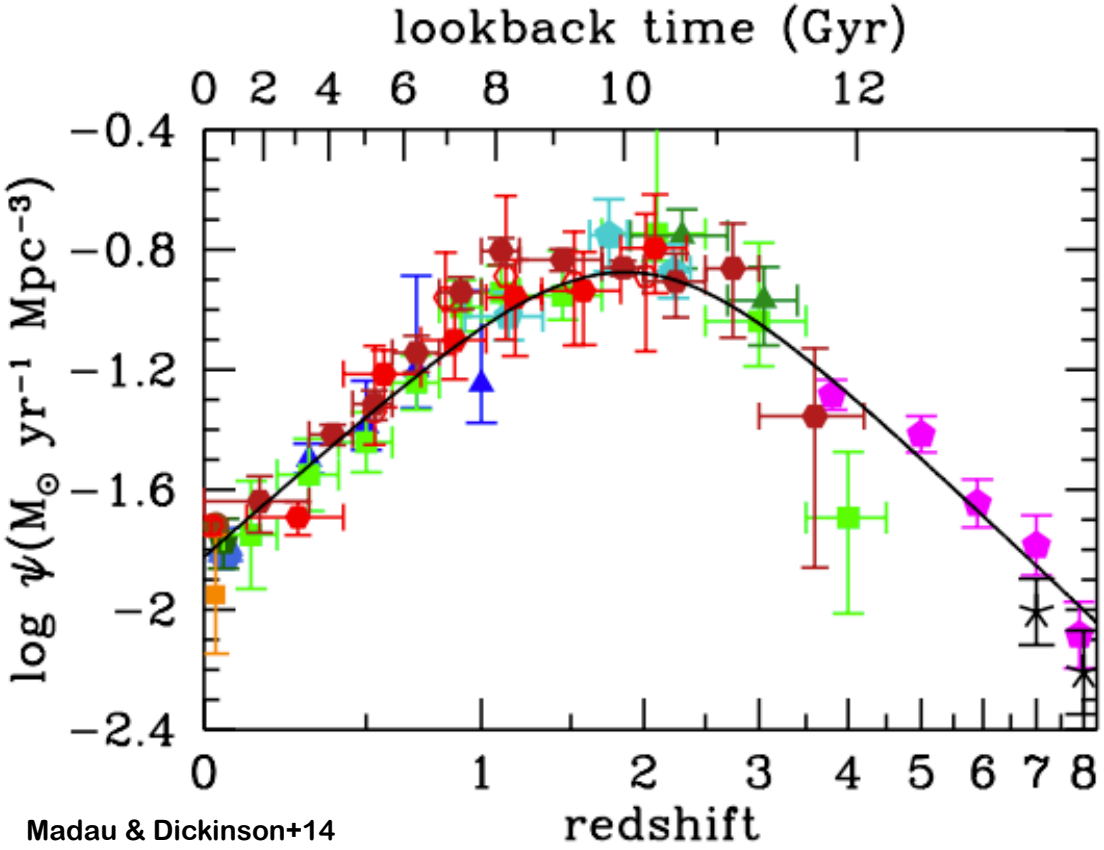
Spiral galaxy - NGC 1376

Credit: NASA, ESA, and the Hubble Heritage Team (STScI/AURA). Acknowledgment: R. Thompson (University of Arizona)

Starburst galaxy - M82

Credit: NASA, ESA and the Hubble Heritage Team (STScI/AURA). Acknowledgment: J. Gallagher (University of Wisconsin), M. Mountain (STScI) and P. Puxley (NSF).

The cosmic star formation history

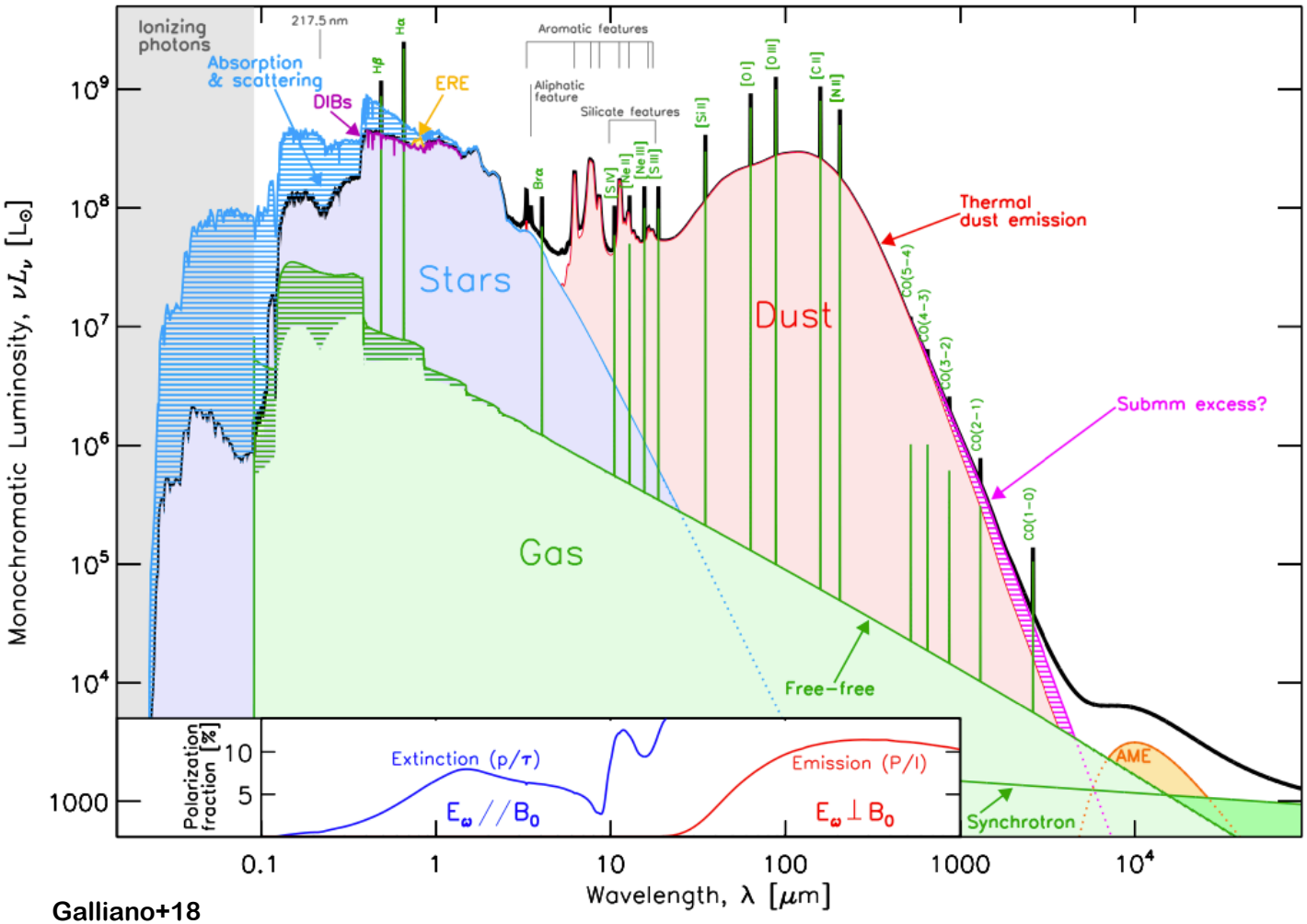


Madau & Dickinson+14

- How did galaxies build their mass?

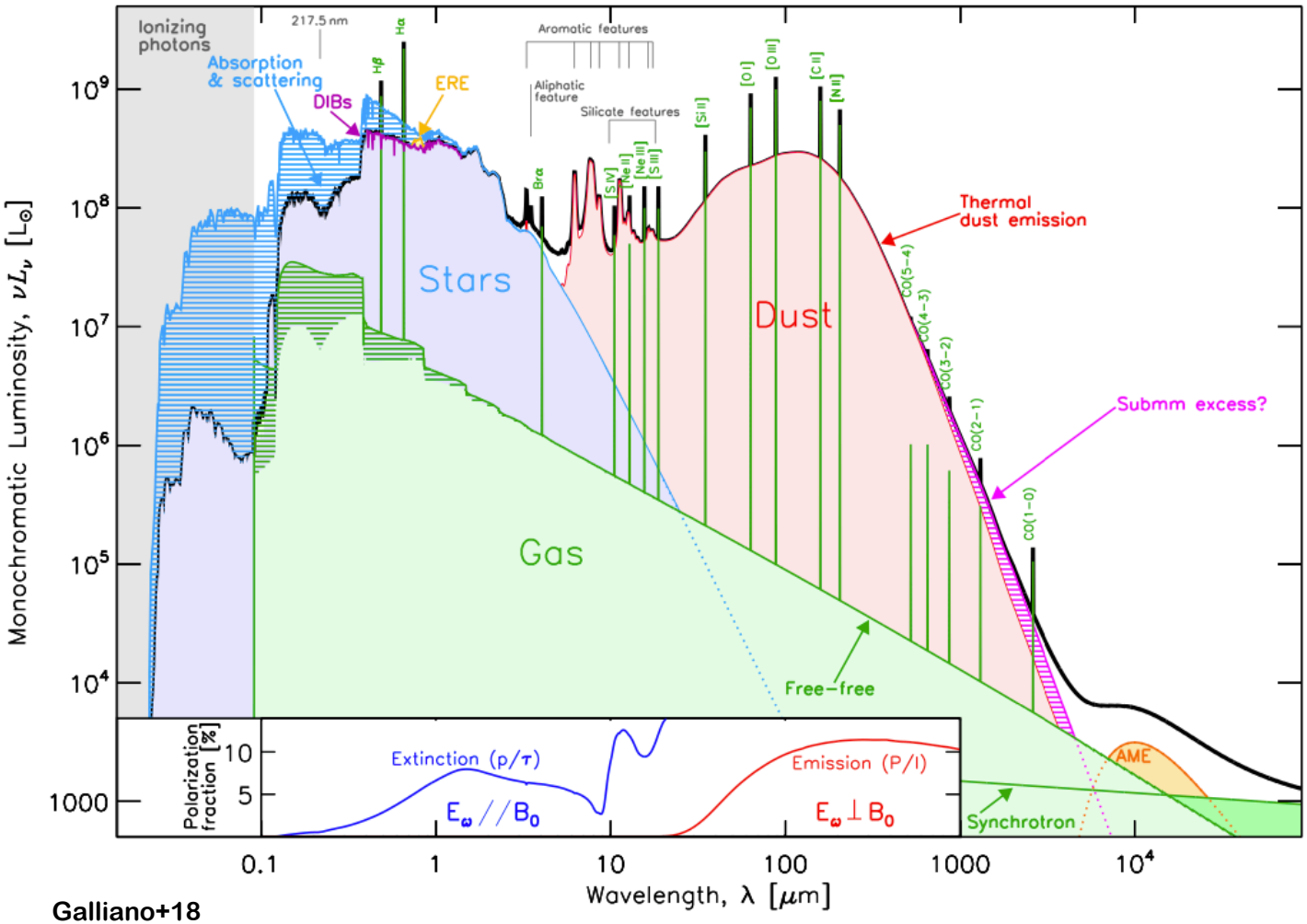
e.g., Sanders+03, Takeuchi+03, Schiminovich+05, Wyder+05, Dahlen+07, Reddy & Steidel+09, Magnelli+11, Robotham & Driver+11, Bouwens+12a,b, Cucciati+12, Gruppioni+13, Magnelli+13, Schenker+13

SED of a galaxy



Galliano+18

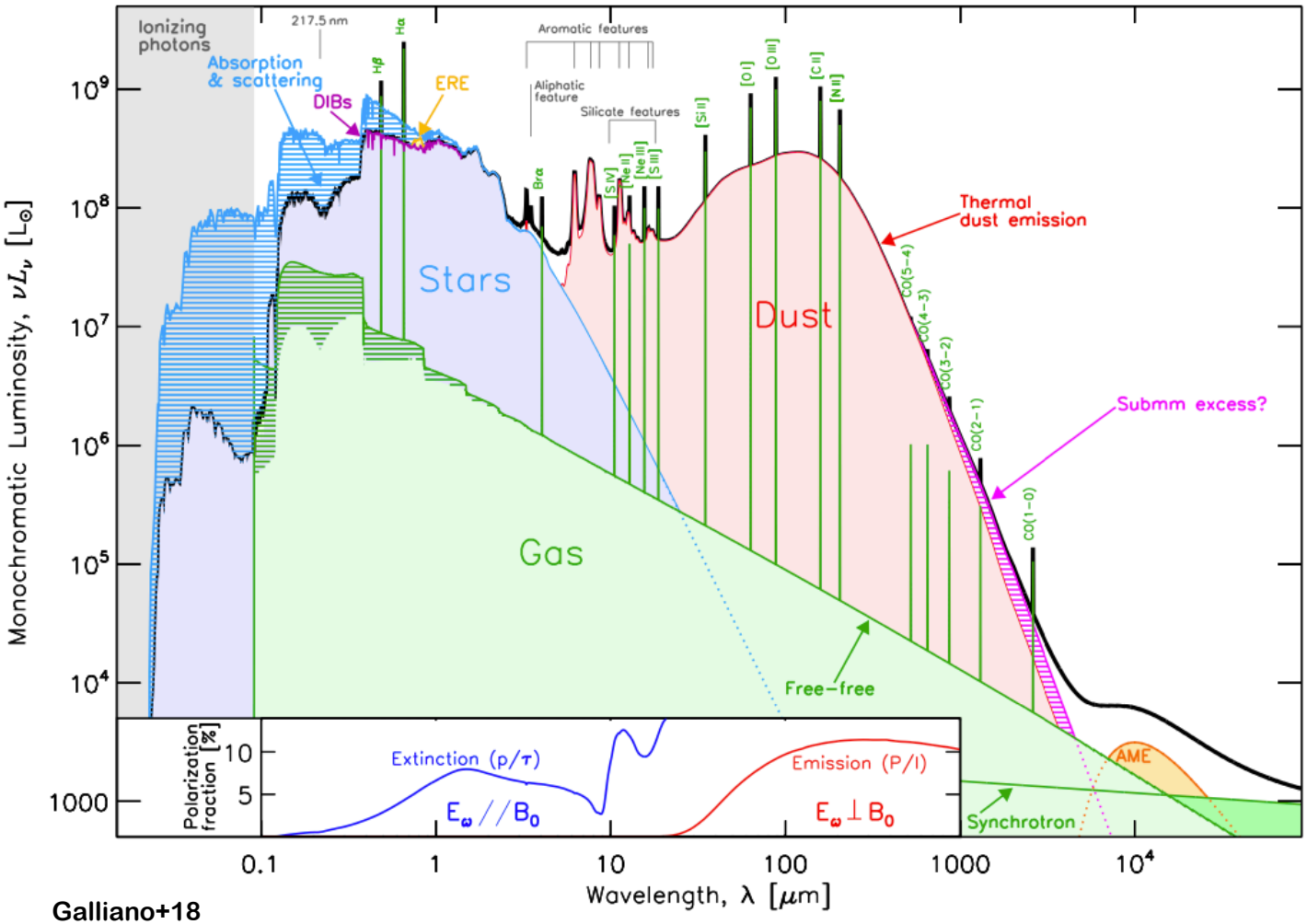
SED of a galaxy



Galliano+18

- Stellar emission absorbed by dust

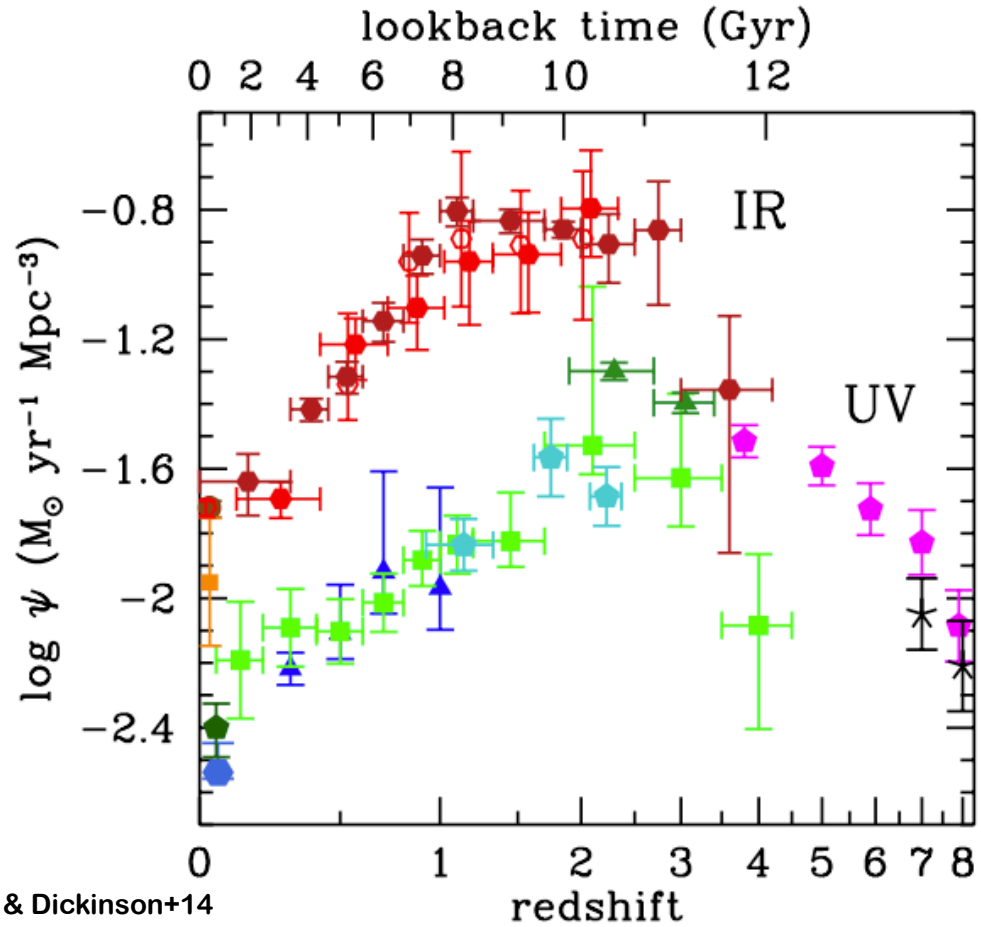
SED of a galaxy



Galliano+18

- Stellar emission absorbed by dust
- Re-emitted in the IR

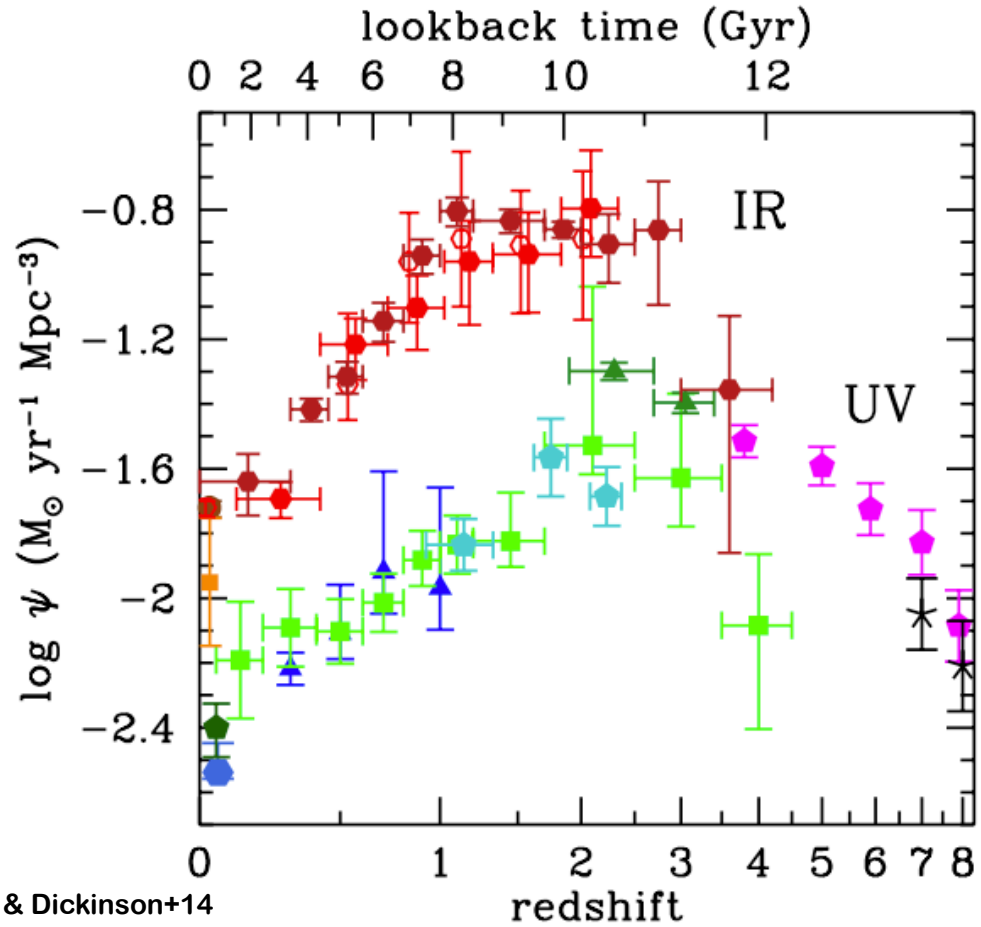
The cosmic star formation history



Madau & Dickinson+14

e.g., Sanders+03, Takeuchi+03, Schiminovich+05, Wyder+05, Dahlen+07, Reddy & Steidel+09, Magnelli+11, Robotham & Driver+11, Bouwens+12a,b, Cucciati+12, Gruppioni+13, Magnelli+13, Schenker+13

The cosmic star formation history



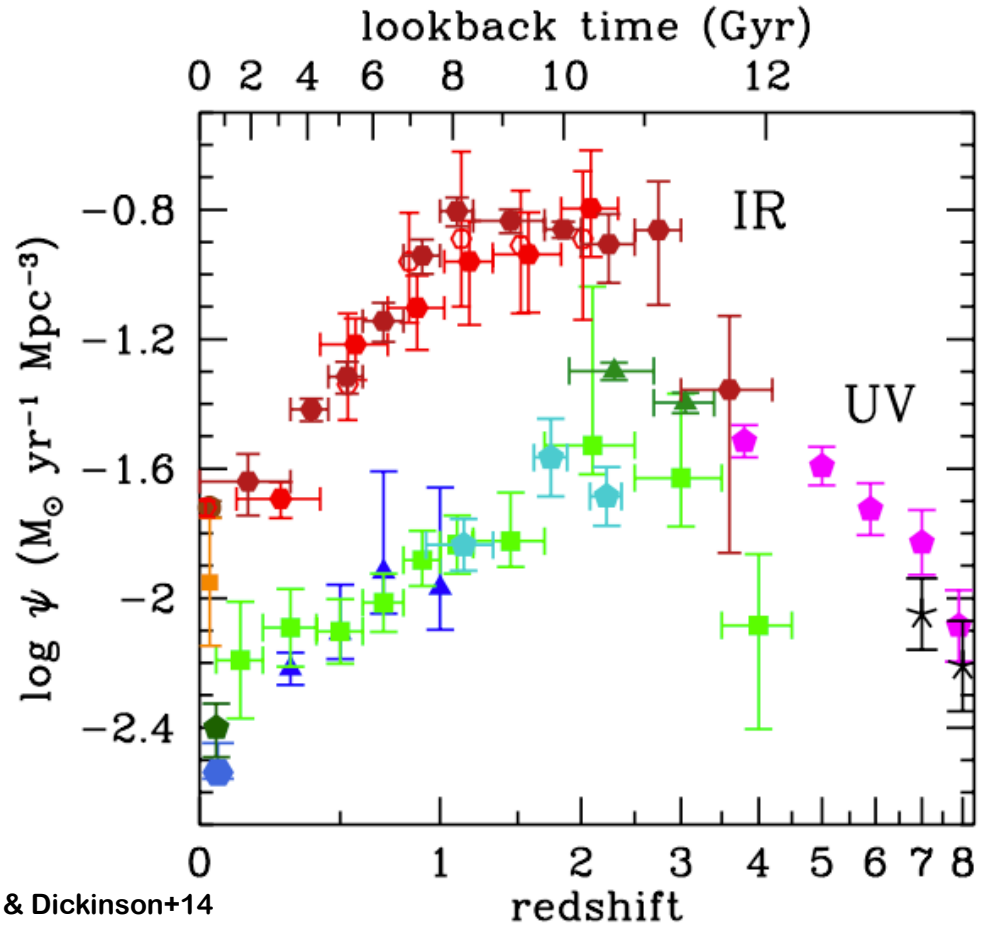
Madau & Dickinson+14

Dust-uncorrected SFRD derived from the FUV data

e.g., Sanders+03, Takeuchi+03, Schiminovich+05, Wyder+05, Dahlen+07, Reddy & Steidel+09, Magnelli+11, Robotham & Driver+11, Bouwens+12a,b, Cucciati+12, Gruppioni+13, Magnelli+13, Schenker+13

04

The cosmic star formation history



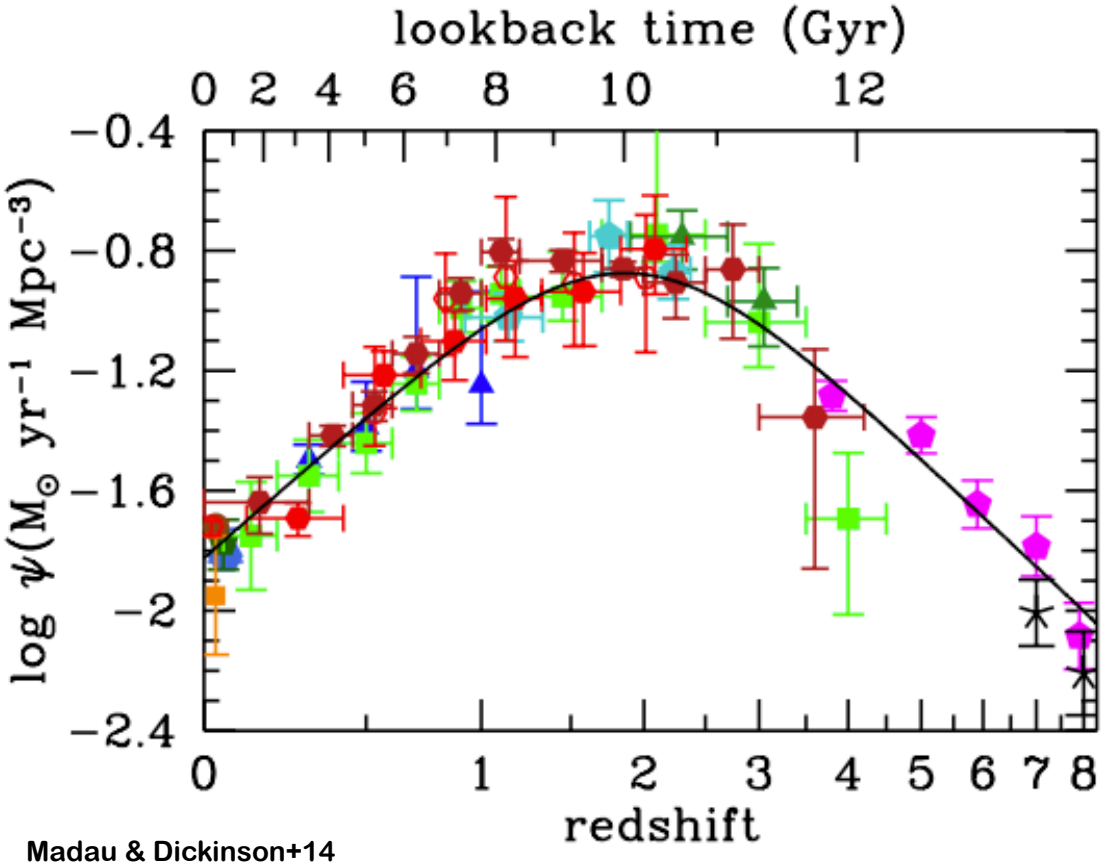
Madau & Dickinson+14

Dust-uncorrected SFRD derived from the FUV data

SFRD derived from dust emission from the IR

e.g., Sanders+03, Takeuchi+03, Schiminovich+05, Wyder+05, Dahlen+07, Reddy & Steidel+09, Magnelli+11, Robotham & Driver+11, Bouwens+12a,b, Cucciati+12, Gruppioni+13, Magnelli+13, Schenker+13

The cosmic star formation history



Madau & Dickinson+14

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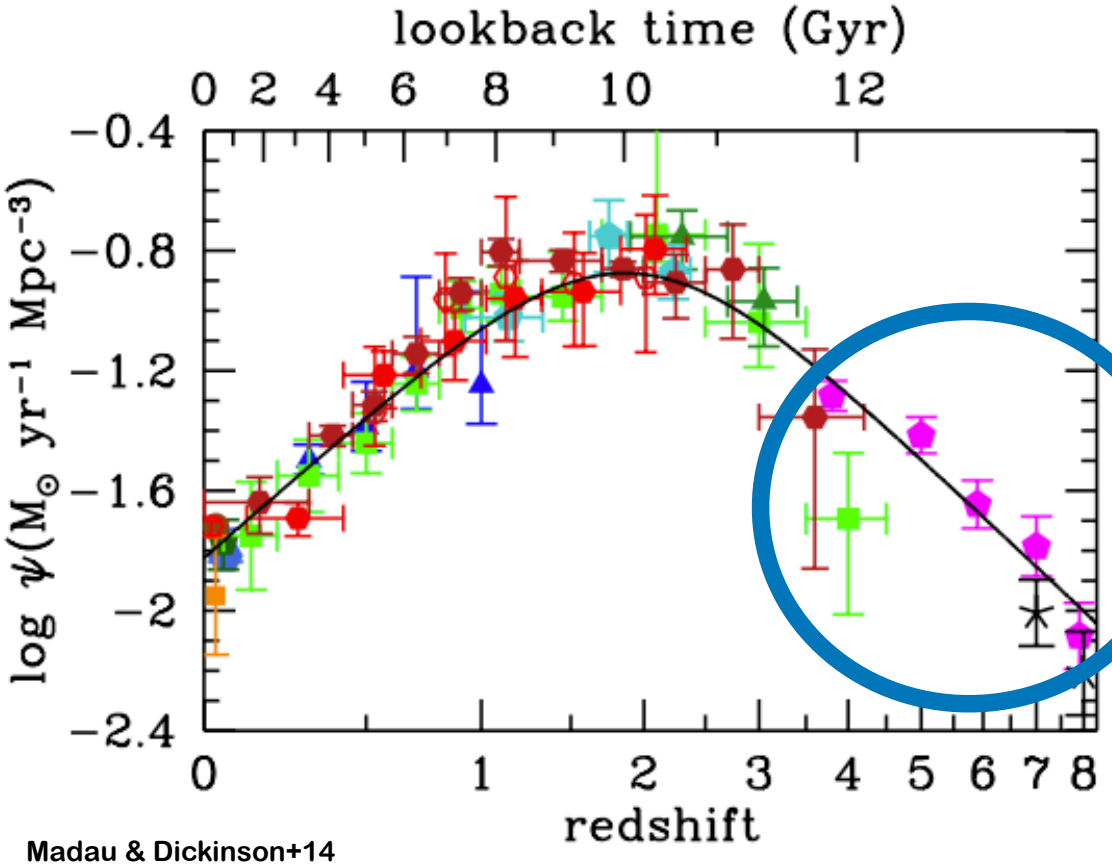
e.g., Sanders+03, Takeuchi+03, Schiminovich+05, Wyder+05, Dahlen+07, Reddy & Steidel+09, Magnelli+11, Robotham & Driver+11, Bouwens+12a,b, Cucciati+12, Gruppioni+13, Magnelli+13, Schenker+13

The cosmic star formation history



Madau & Dickinson+14

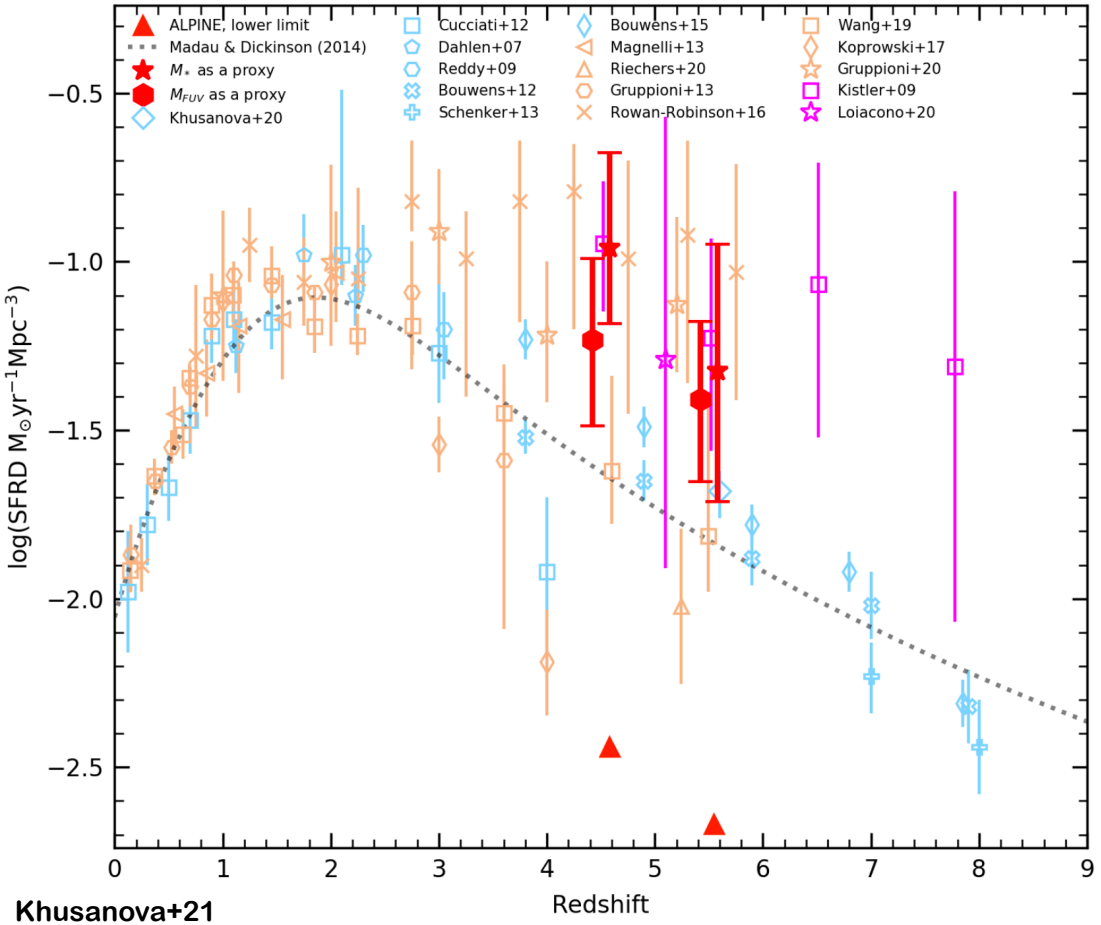
Dust-corrected SFRD derived from the FUV data

SFRD derived from dust emission from the IR

Mostly derived from the FUV at high redshift

e.g., Sanders+03, Takeuchi+03, Schiminovich+05, Wyder+05, Dahlen+07, Reddy & Steidel+09, Magnelli+11, Robotham & Driver+11, Bouwens+12a,b, Cucciati+12, Gruppioni+13, Magnelli+13, Schenker+13

The cosmic star formation history



Khusanova+21

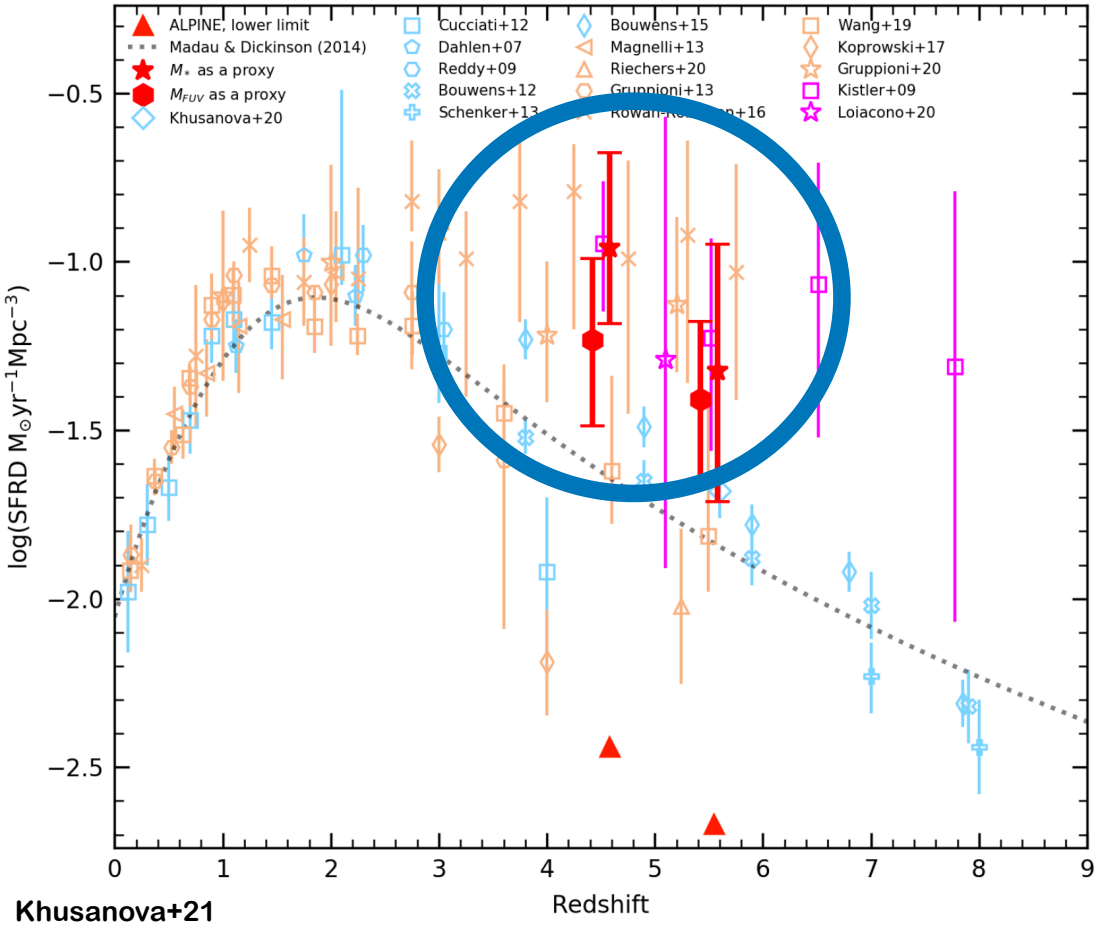
Dust-corrected SFRD derived from the FUV data

SFRD derived from dust emission from the IR

SFRD derived [CII] and γ ray bursts

e.g., Dahien+07, Reddy+09, Kistler+09, Bouwens+12, Cucciati+12, Gruppioni+13, Magnelli+13, Schenker+13, Madau&Dickinson+14, Bouwens+15, Schreiber+15, Rowan-Robinson+16, Bethermin+17, Koprowski+17, Lagache+18, Wang+19, Gruppioni+20, Loiacono+20, Riechers+20, Khusanova+21

The cosmic star formation history



Khusanova+21

Dust-corrected SFRD derived from the FUV data

SFRD derived from dust emission from the IR

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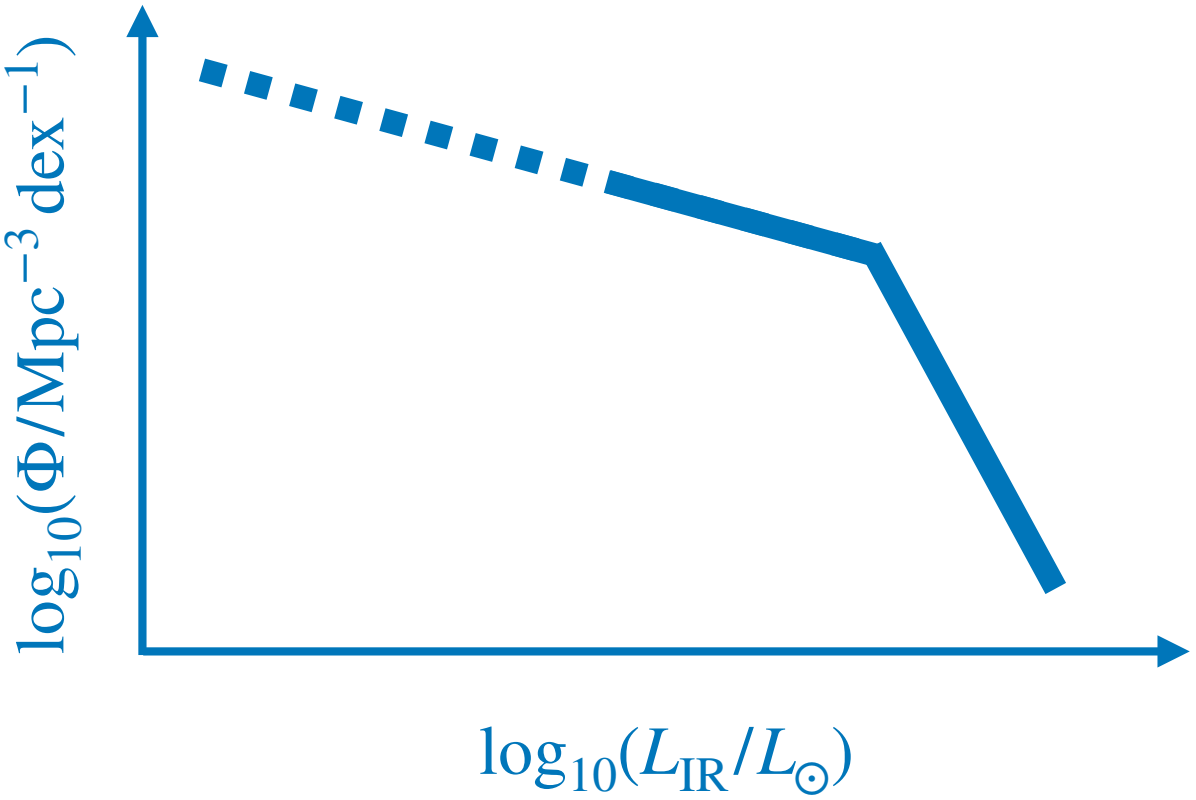
e.g., Dahien+07, Reddy+09, Kistler+09, Bouwens+12, Cucciati+12, Gruppioni+13, Magnelli+13, Schenker+13, Madau&Dickinson+14, Bouwens+15, Schreiber+15, Rowan-Robinson+16, Bethermin+17, Koprowski+17, Lagache+18, Wang+19, Gruppioni+20, Loiacono+20, Riechers+20, Khusanova+21

The first question

- How much of the dust obscured SFR are we missing at $z > 3$?

Extrapolation through the luminosity function

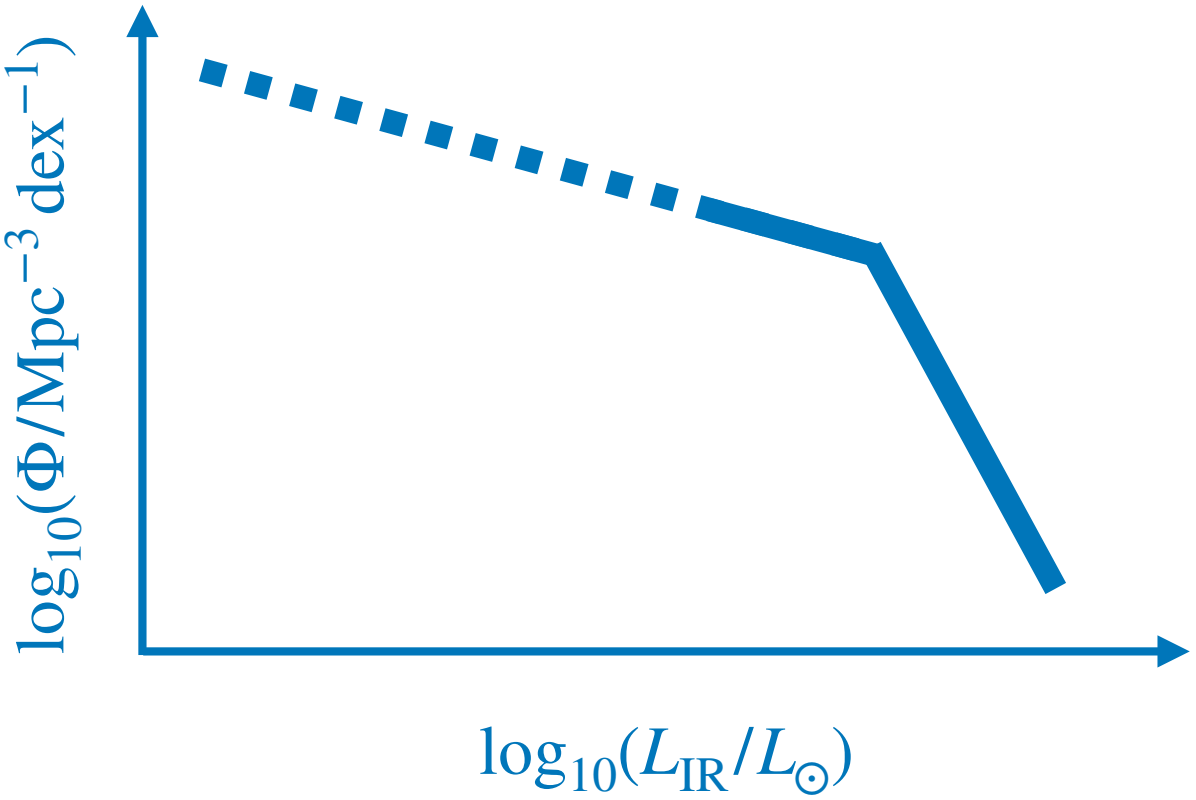


L_{IR} is a proxy for SFR

Detected

Extrapolated

Extrapolation through the luminosity function



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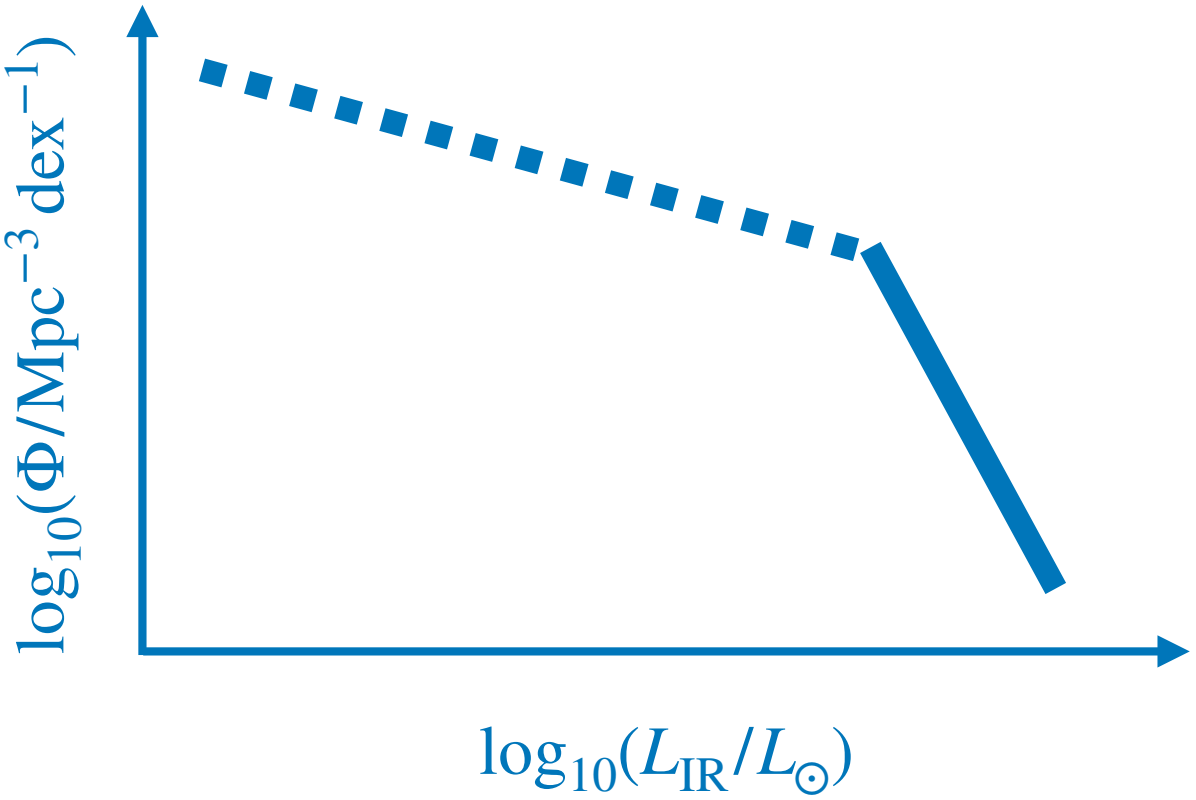
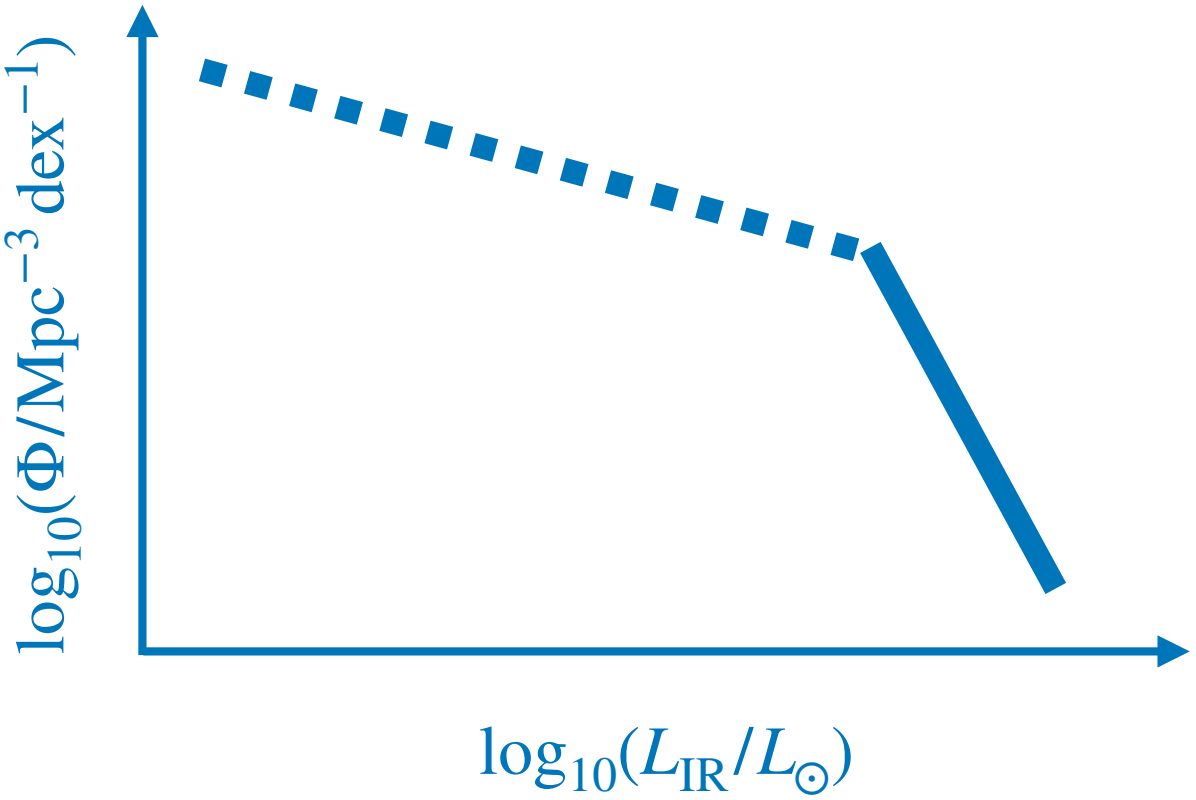


L_{IR} is a proxy for SFR

Detected

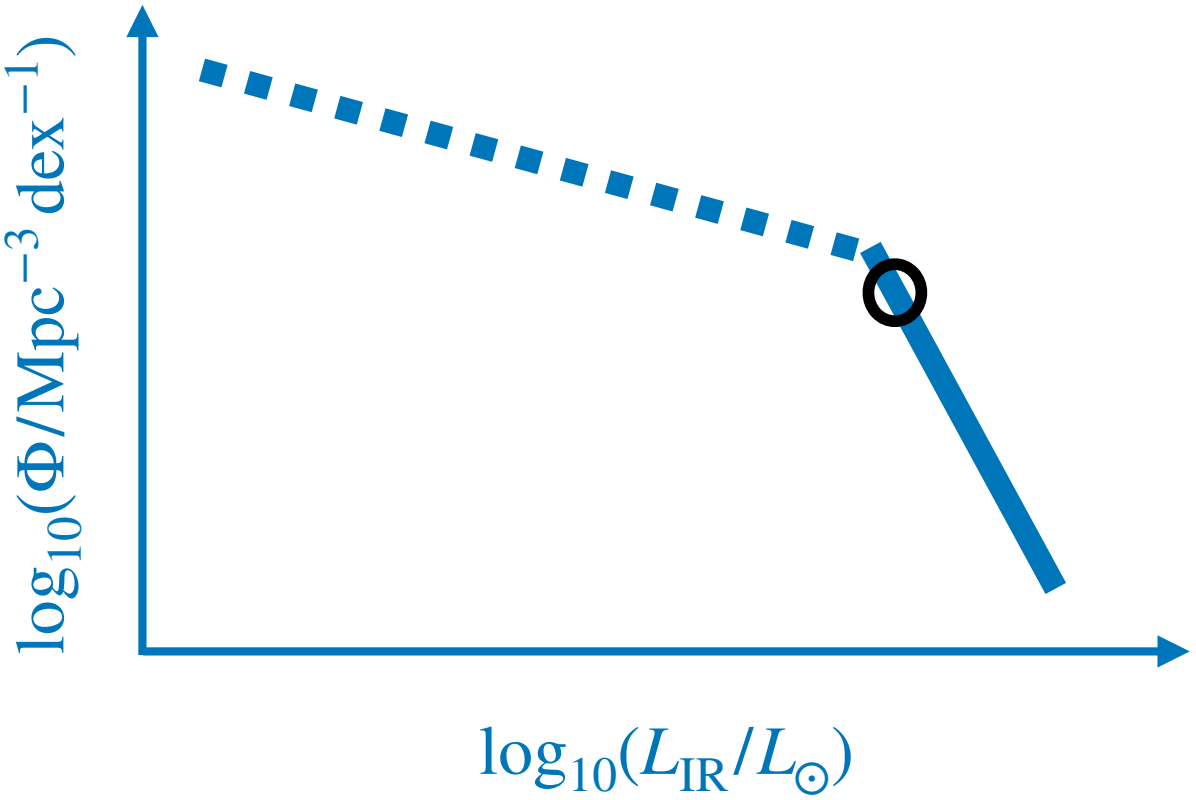
Extrapolated

Extrapolation through the luminosity function



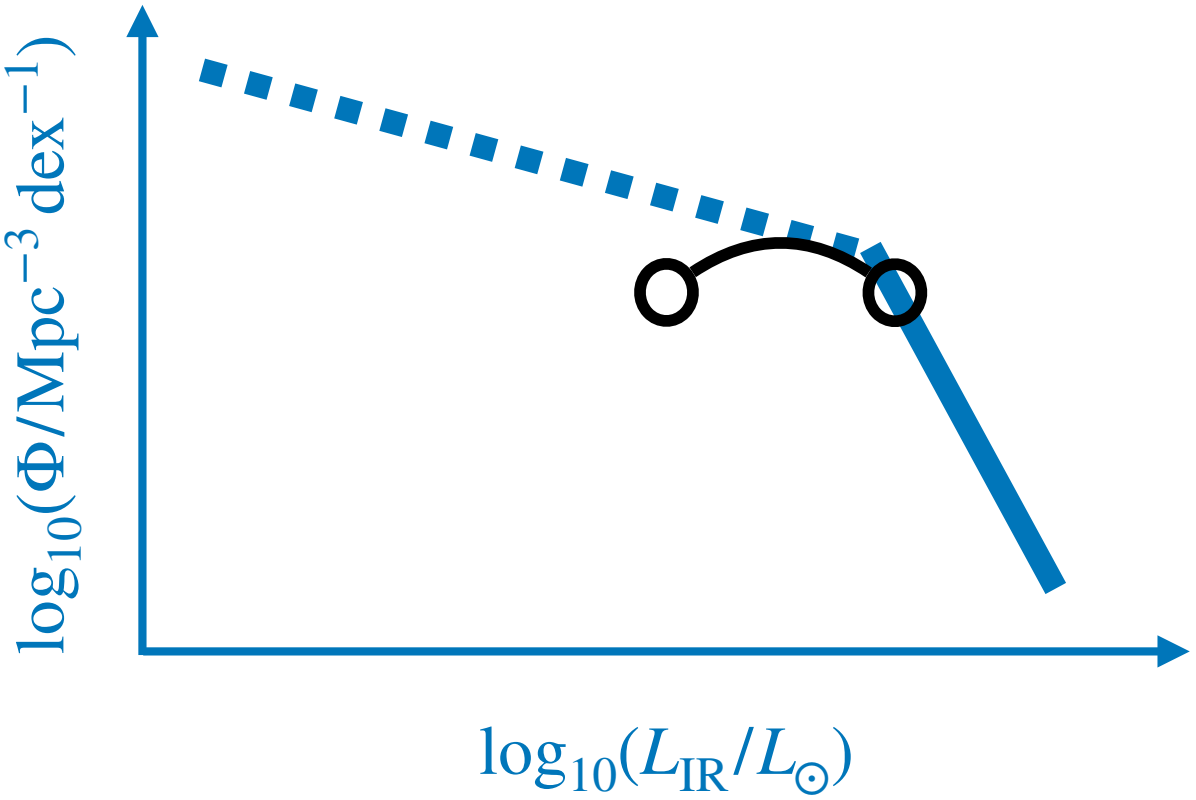
- L_{IR} is a proxy for SFR
- Detected
- Extrapolated
- Biased toward galaxies with high L_{IR}

Extrapolation through the luminosity function



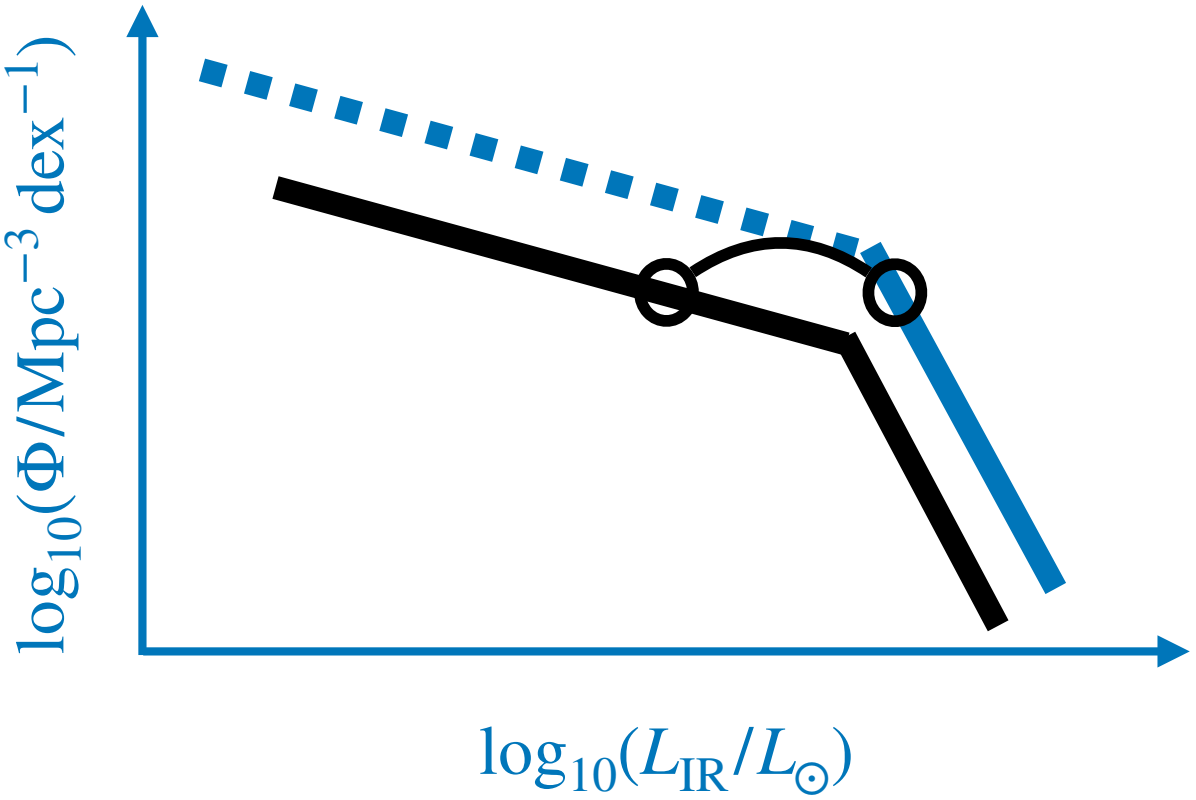
- L_{IR} is a proxy for SFR
- Detected
- Extrapolated
- Biased toward galaxies with high L_{IR}

Extrapolation through the luminosity function



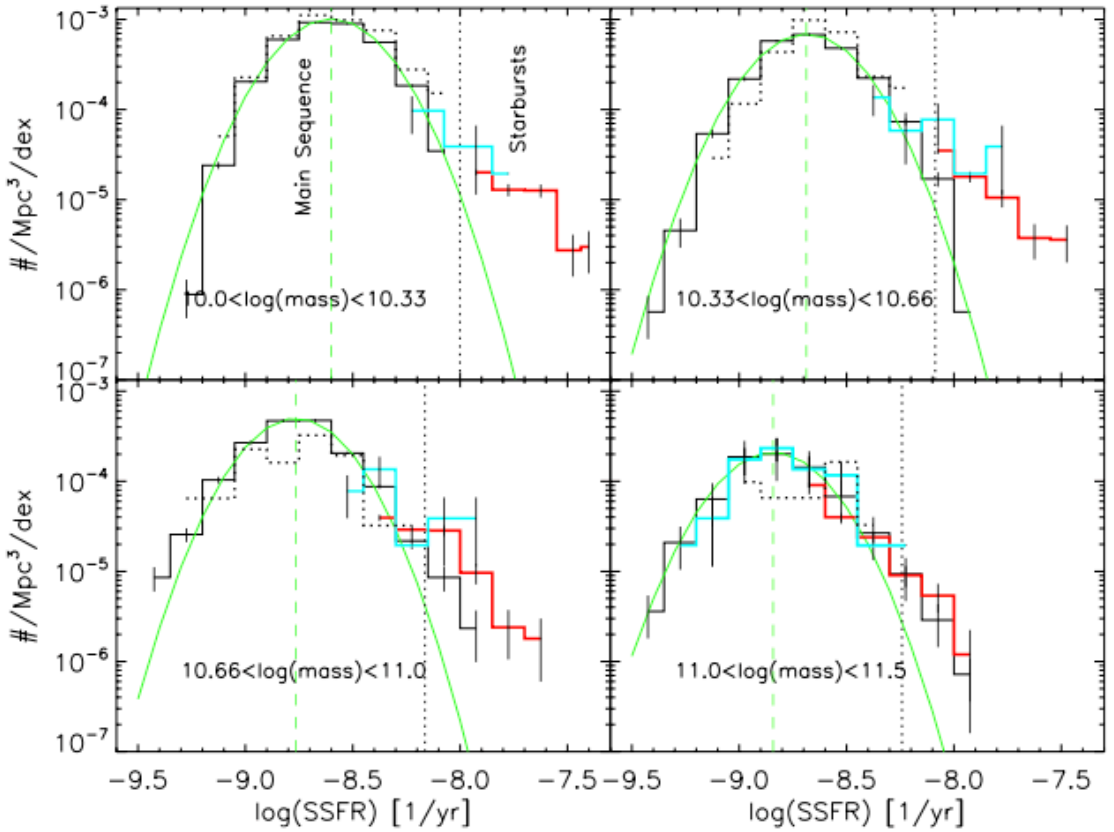
- L_{IR} is a proxy for SFR
- Detected
- Extrapolated
- Biased toward galaxies with high L_{IR}

Extrapolation through the luminosity function



- L_{IR} is a proxy for SFR
  - Detected
  - Extrapolated
  - True luminosity function
- Biased toward galaxies with high L_{IR}

Star formation main sequence

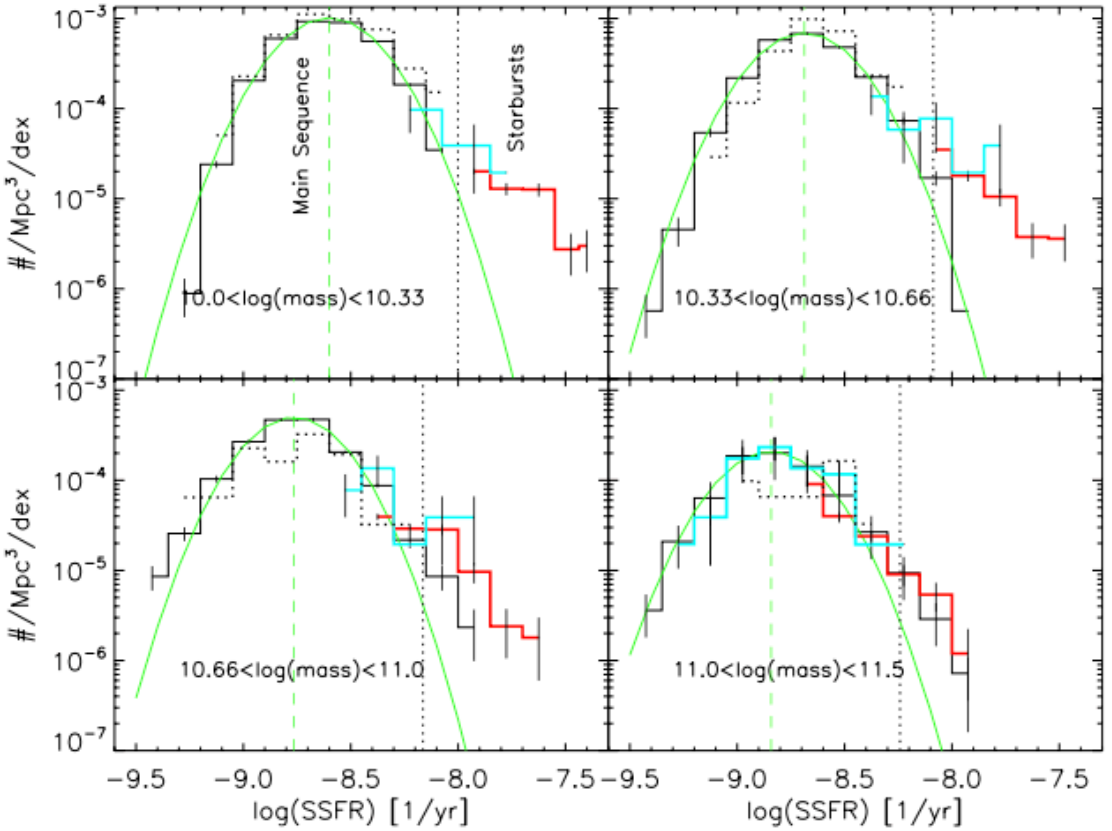


Rodighiero+11

e.g., Rodighiero+11, Schreiber+15

Star formation main sequence

- Starbursts represent only 3% of galaxies at a given instant

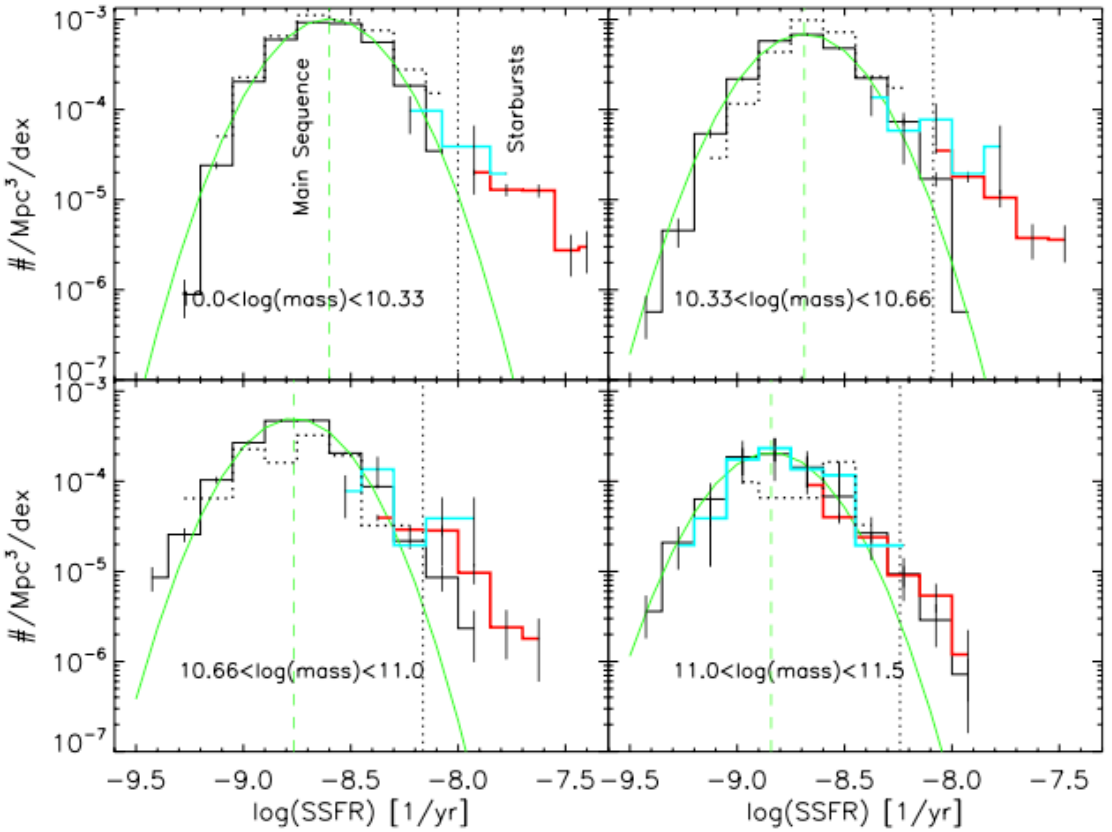


Rodighiero+11

e.g., Rodighiero+11, Schreiber+15

Star formation main sequence

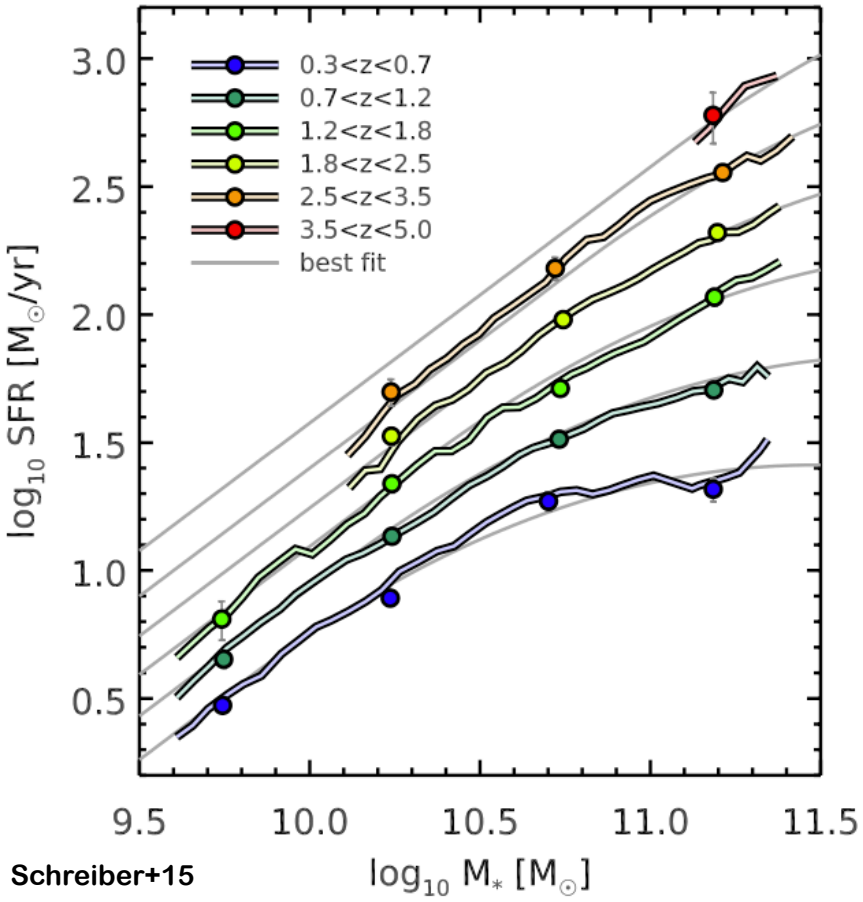
- Starbursts represent only 3% of galaxies at a given instant
- Starbursts account for 10-15% of stars formed at a given instant



Rodighiero+11

e.g., Rodighiero+11, Schreiber+15

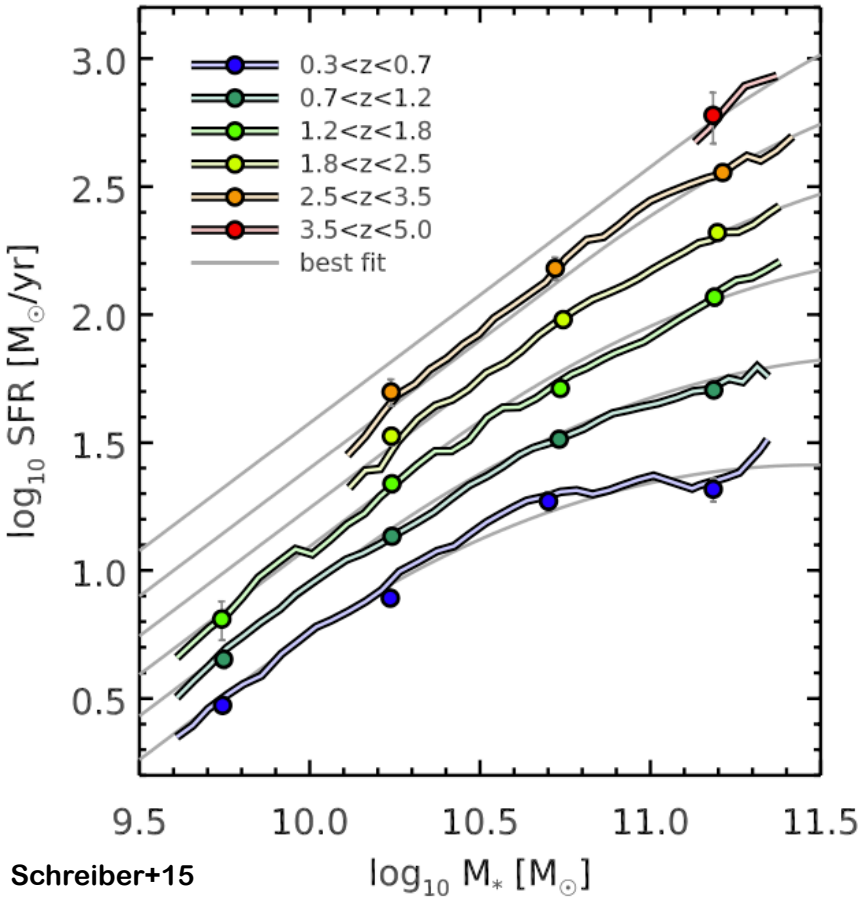
Star formation main sequence



Schreiber+15

e.g., Noeske+07, Elbaz+07; Daddi +07; Whitaker+12; Speagle+14; Whitaker+14; Screiber+15; Lee +15; Delvecchio+21; Leslie+20; Popesso+23

Star formation main sequence

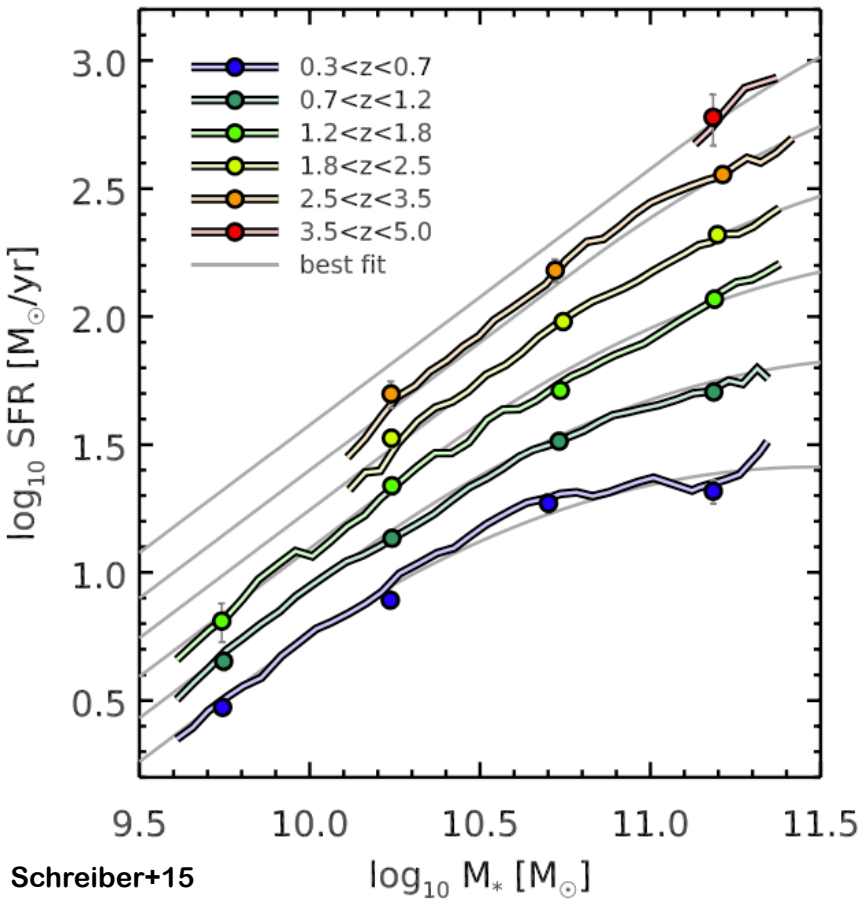


Schreiber+15

- Increase of SFR with stellar mass

e.g., Noeske+07, Elbaz+07; Daddi +07; Whitaker+12; Speagle+14; Whitaker+14; Screiber+15; Lee +15; Delvecchio+21; Leslie+20; Popesso+23

Star formation main sequence

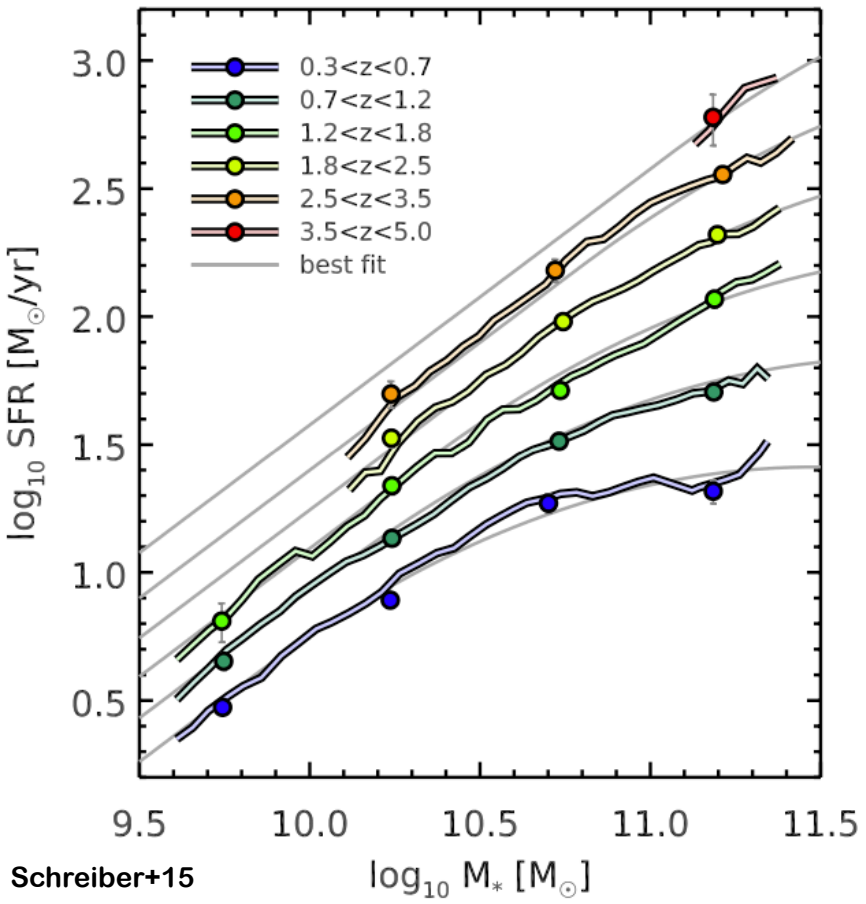


Schreiber+15

- Increase of SFR with stellar mass
- Increase of SFR with redshift

e.g., Noeske+07, Elbaz+07; Daddi +07; Whitaker+12; Speagle+14; Whitaker+14; Screiber+15; Lee +15; Delvecchio+21; Leslie+20; Popesso+23

Star formation main sequence

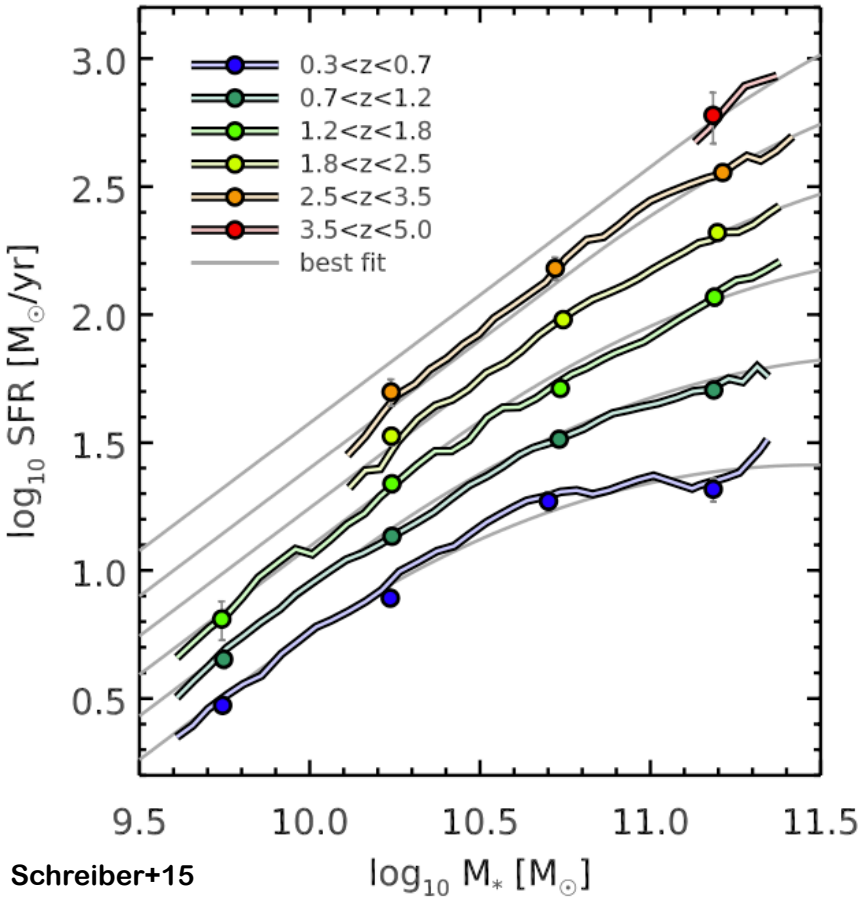


Schreiber+15

- Increase of SFR with stellar mass
- Increase of SFR with redshift
- Bending on the high mass end

e.g., Noeske+07, Elbaz+07; Daddi +07; Whitaker+12; Speagle+14; Whitaker+14; Screiber+15; Lee +15; Delvecchio+21; Leslie+20; Popesso+23

Star formation main sequence

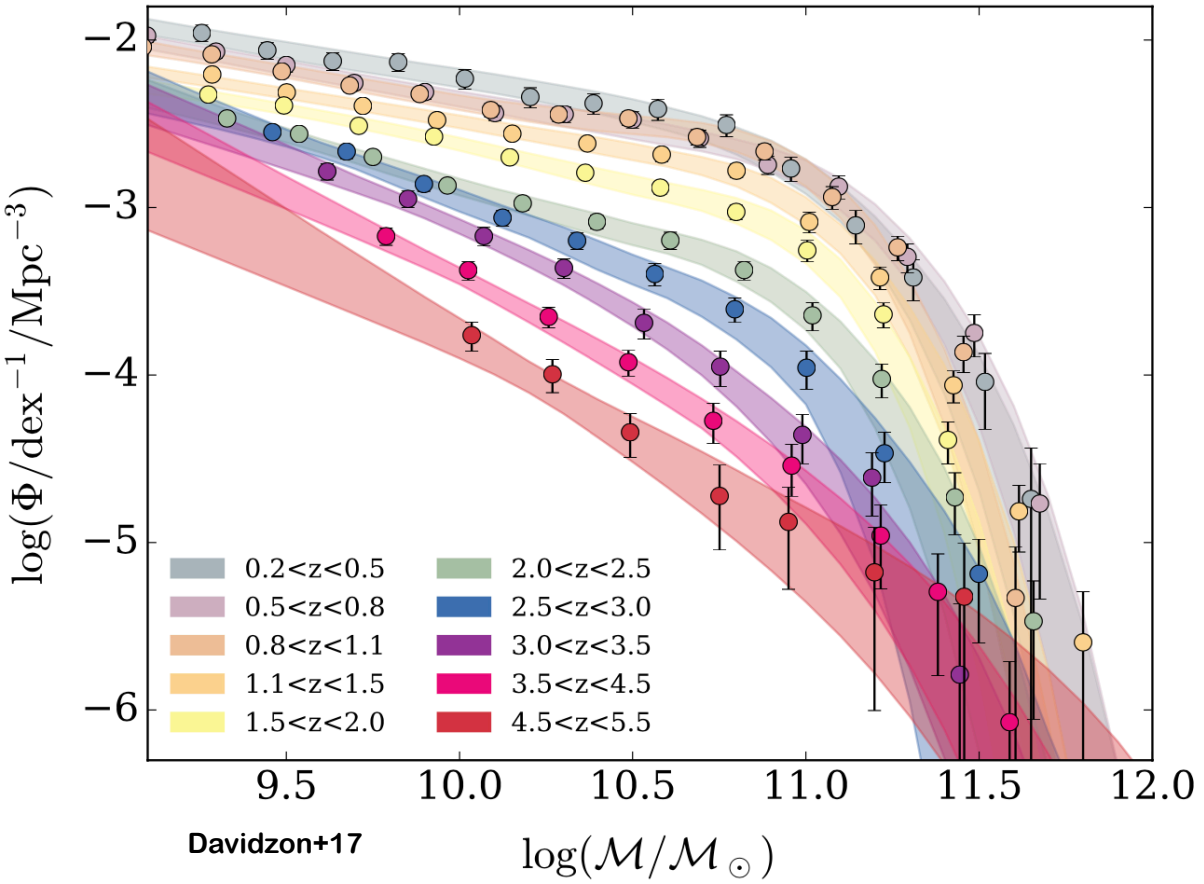


Schreiber+15

- Increase of SFR with stellar mass
- Increase of SFR with redshift
- Bending on the high mass end
- Scatter of 0.3 dex

e.g., Noeske+07, Elbaz+07; Daddi +07; Whitaker+12; Speagle+14; Whitaker+14; Screiber+15; Lee +15; Delvecchio+21; Leslie+20; Popesso+23

Extrapolation through the stellar mass function

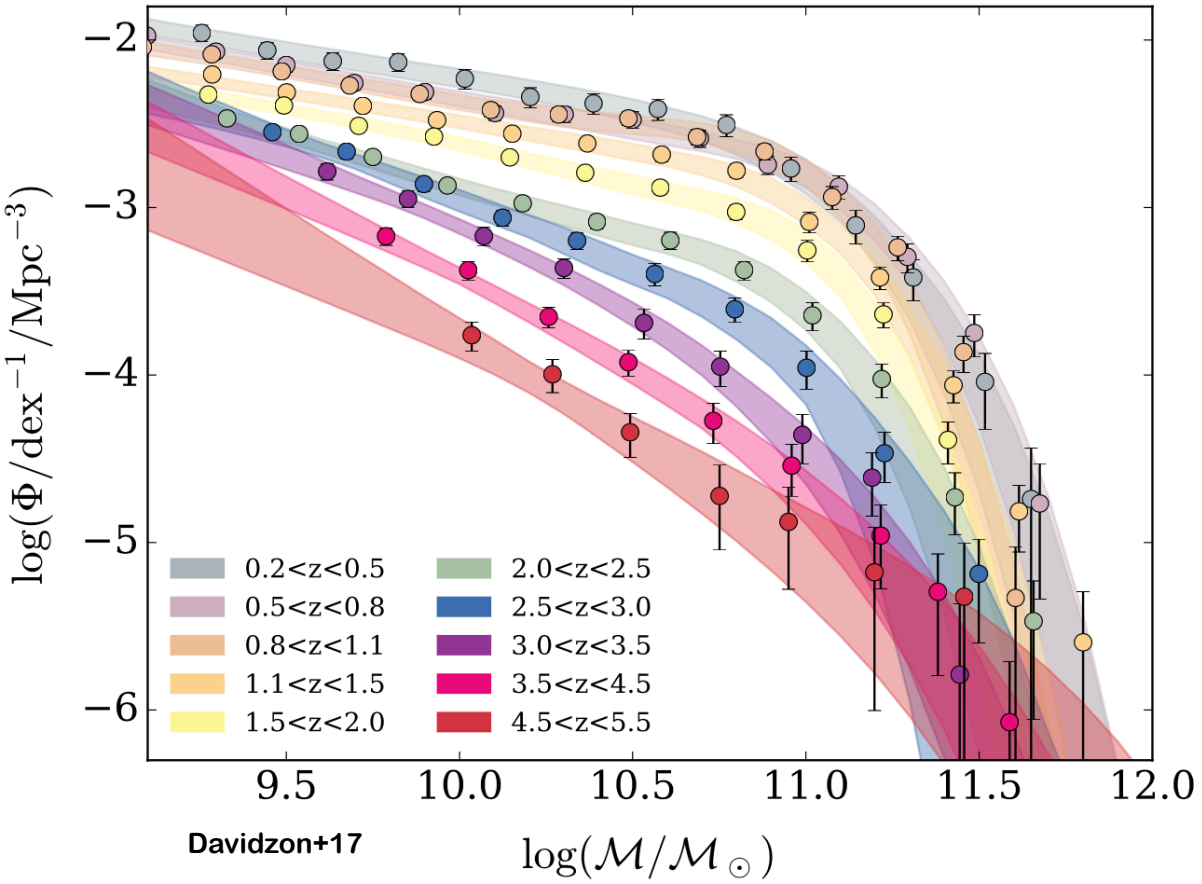


Davidzon+17

e.g., Caputi+11, González+11, Mortlock+11, Reddy+12, Santini+12, Ilbert+13, Muzzin +13, Duncan+14, Tomczak+14, Caputi+15, Grazian+15, Mortlock+15, Song+16

Extrapolation through the stellar mass function

- Better constrained than luminosity functions from the IR



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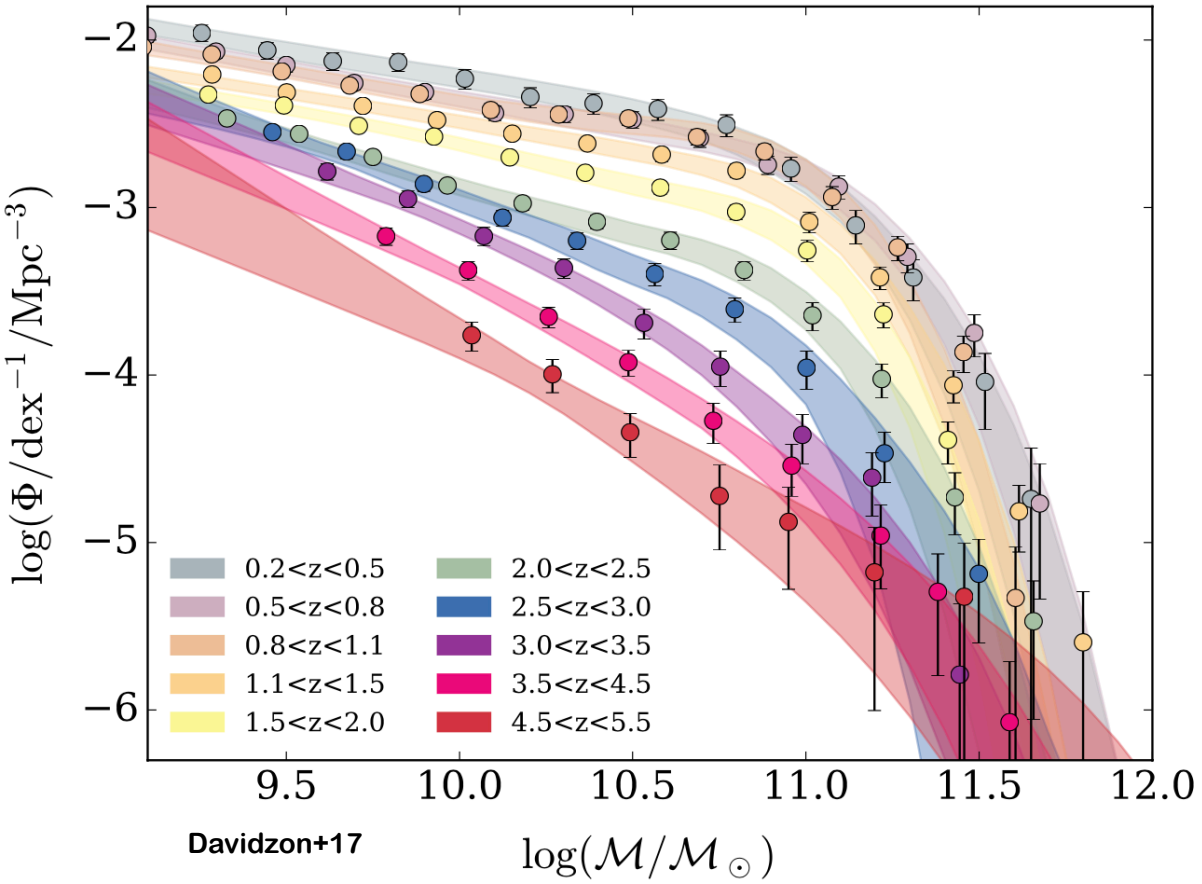
Extrapolation through the stellar mass function

- Better constrained than luminosity functions from the IR
- Built from data in the optical/NIR



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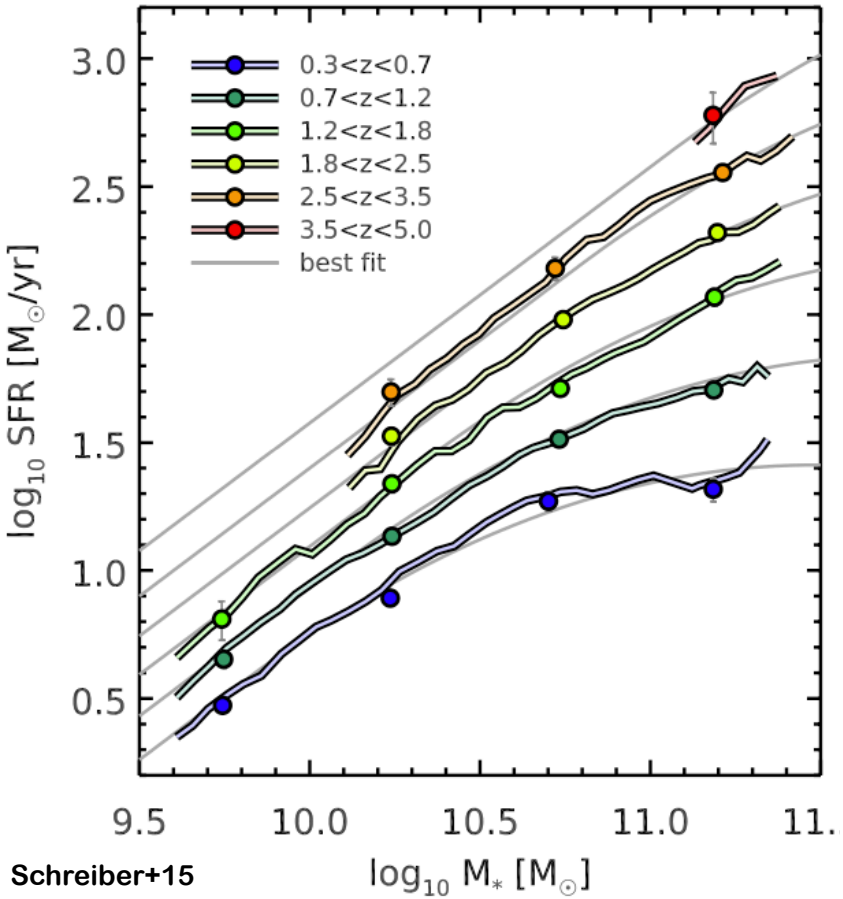

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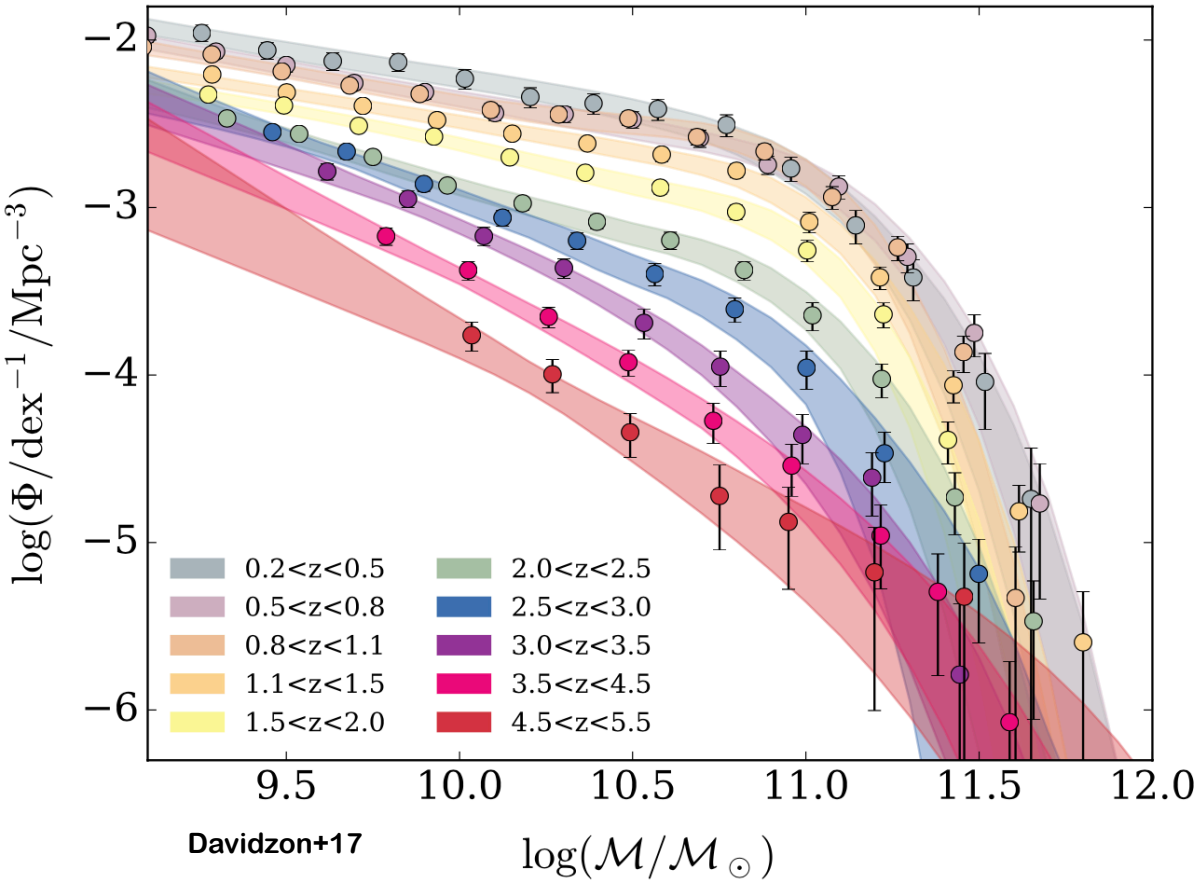

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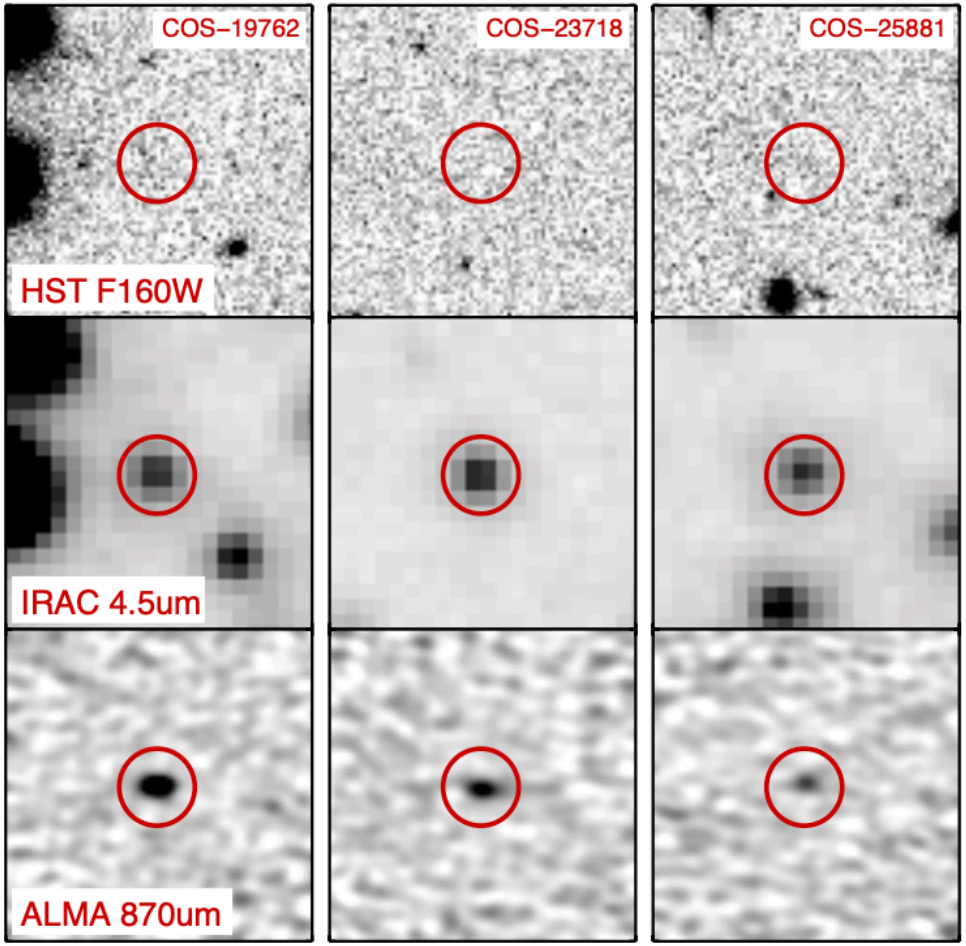
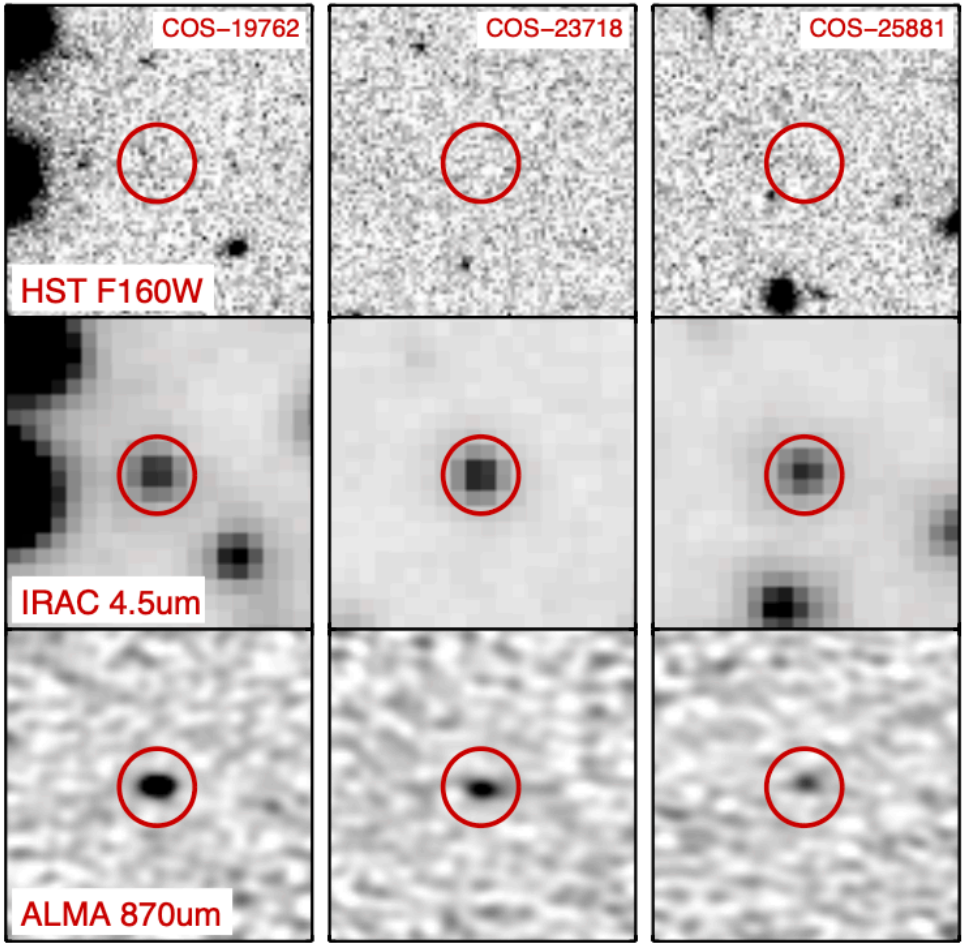
H-dropout galaxies (or HST-dark, OFGs…)



Wang+19

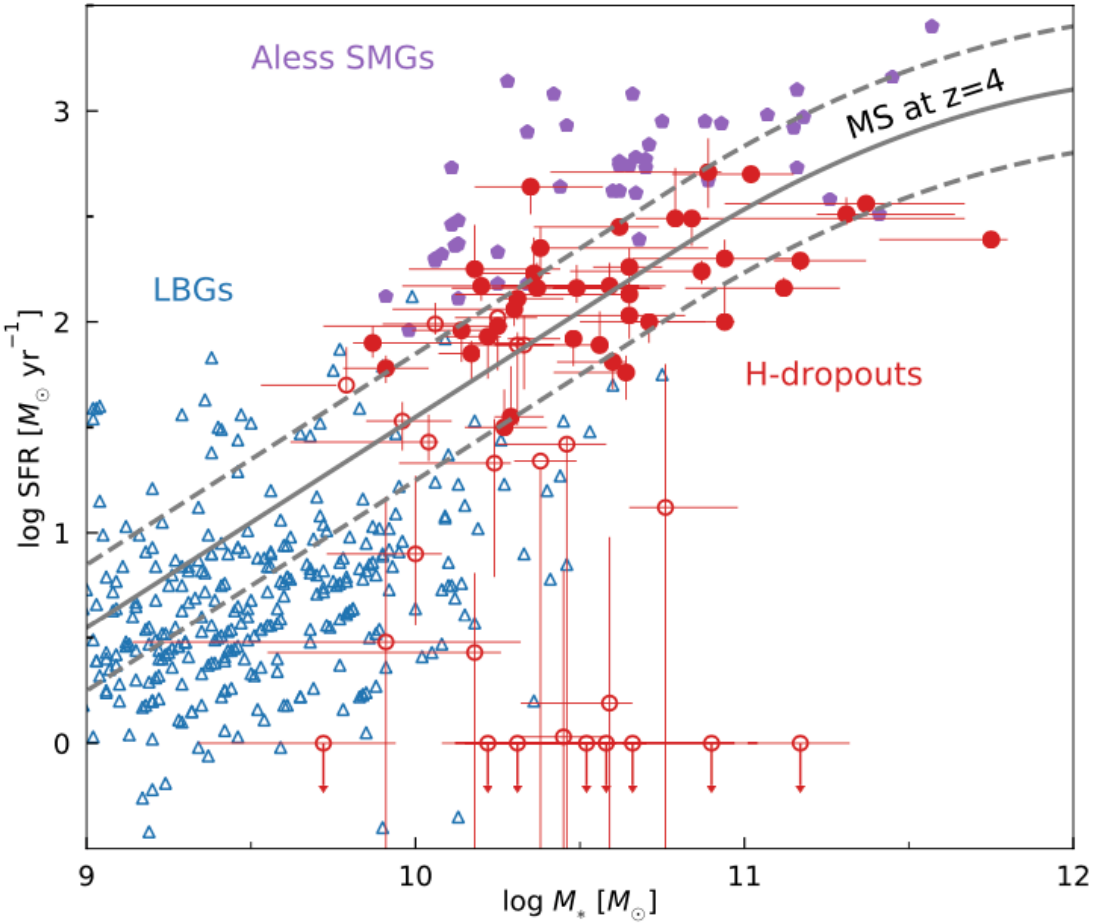
H-dropout galaxies (or HST-dark, OFGs…)



- Invisible in the UV

Wang+19

H-dropout galaxies (or HST-dark, OFGs…)



Wang+19

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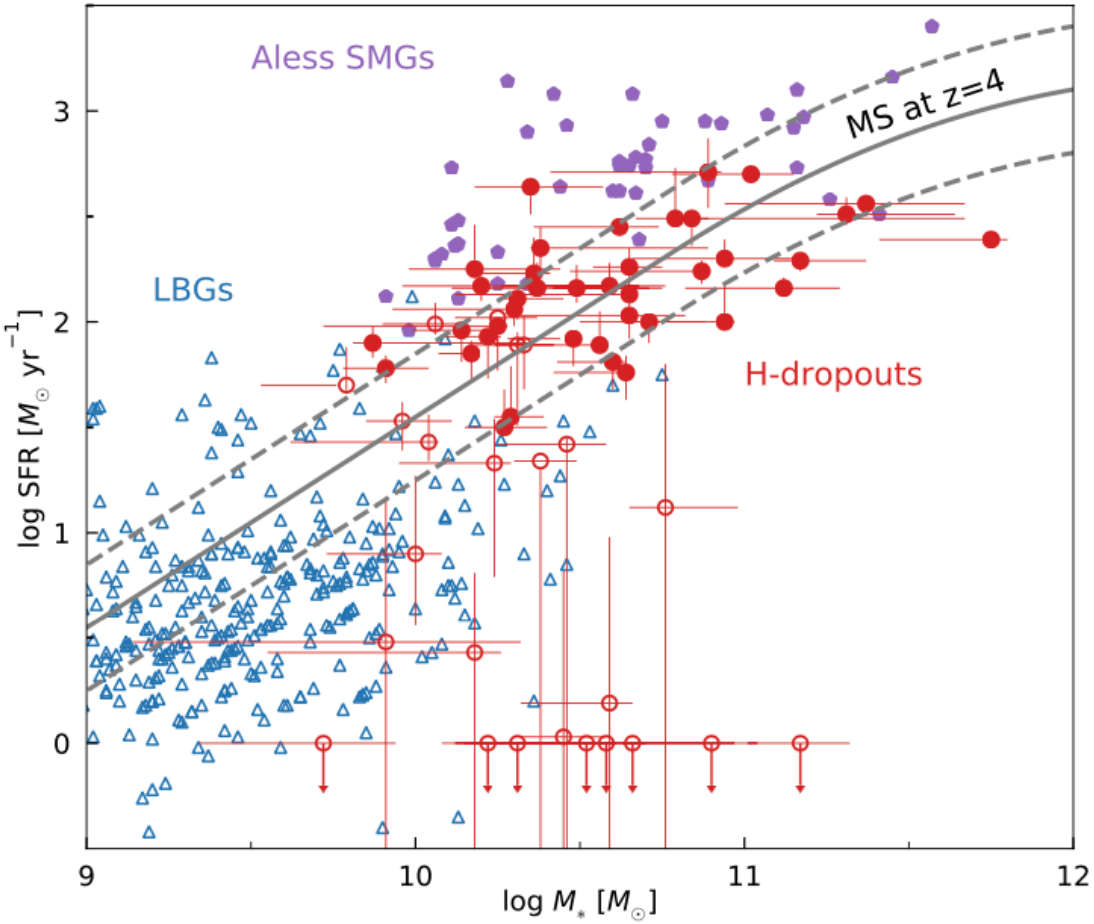
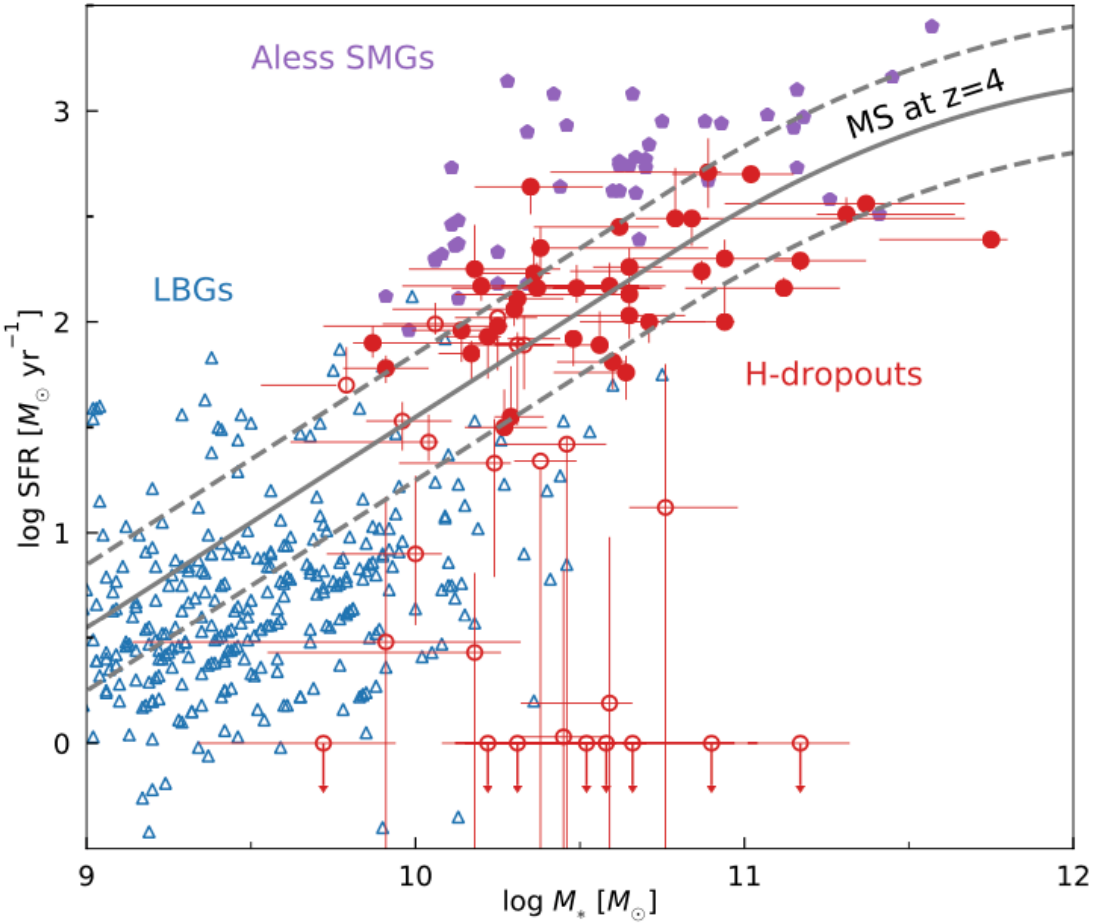


Wang+19

- Invisible in the UV
- Massive galaxies (i.e. $M_\star > 10^{10.3}\,M_\odot$)

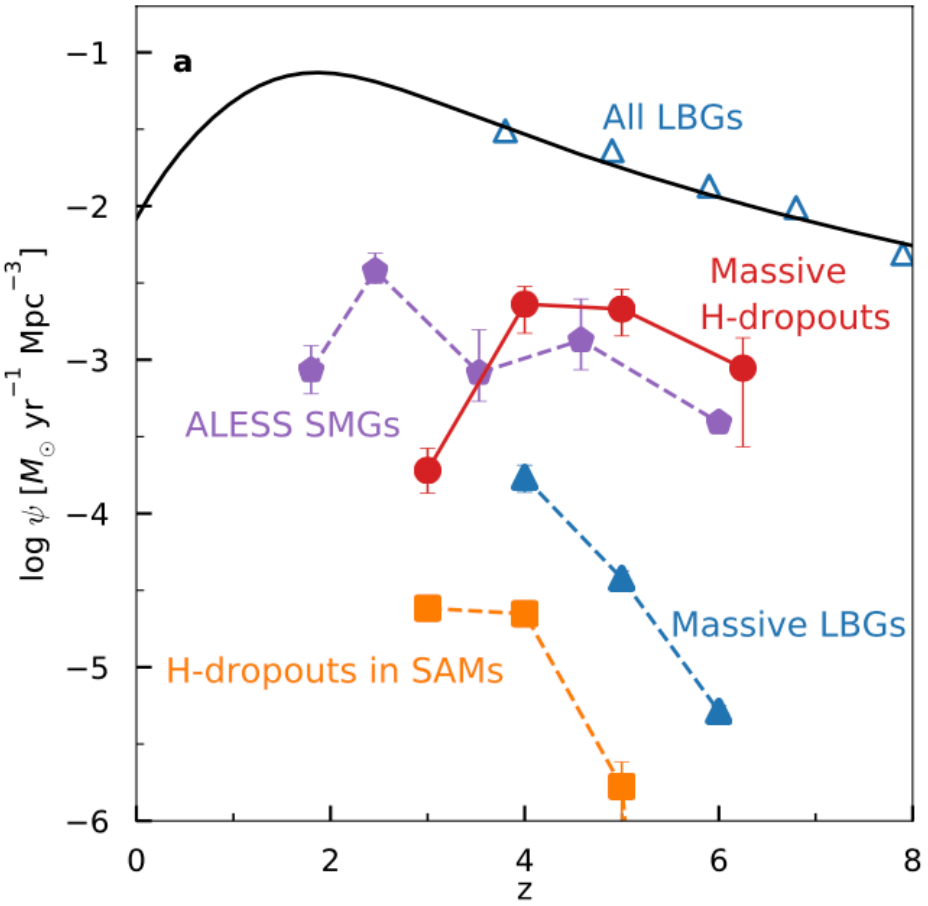
H-dropout galaxies (or HST-dark, OFGs…)



Wang+19

- Invisible in the UV
- Massive galaxies (i.e. $M_\star > 10^{10.3}\,M_\odot$)
- Main sequence galaxies

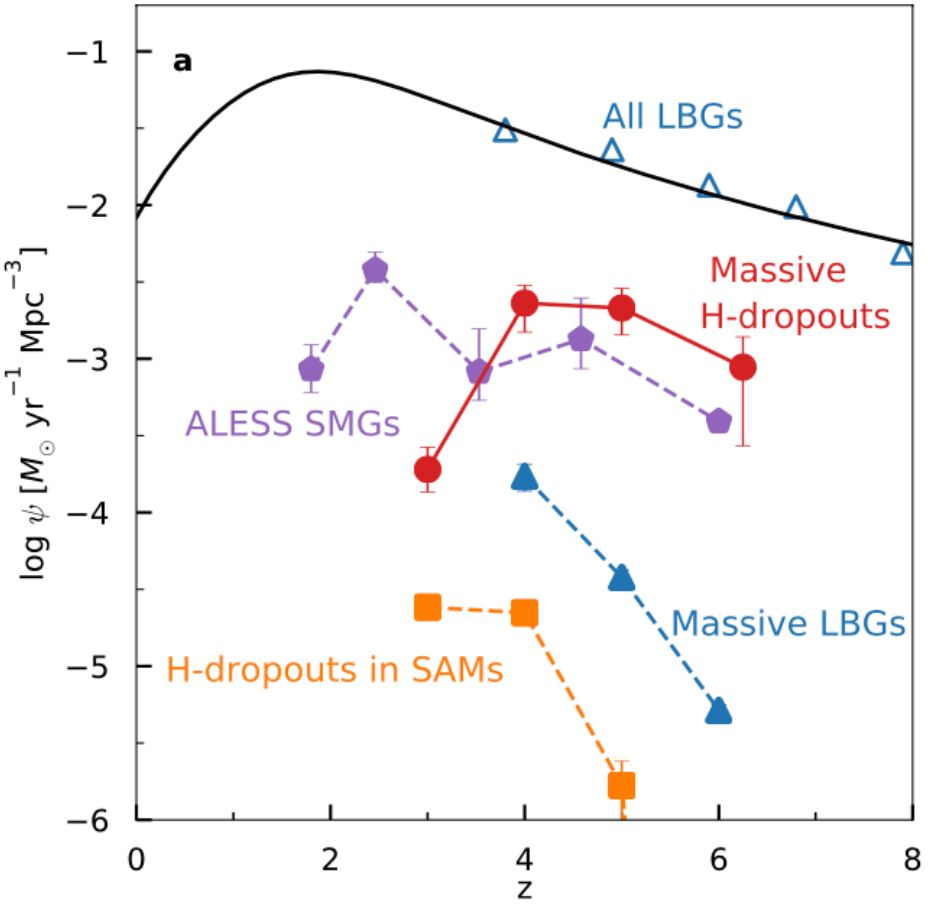
H-dropout galaxies (or HST-dark, OFGs…)



Wang+19

- Invisible in the UV
- Massive galaxies (i.e. $M_\star > 10^{10.3}\,M_\odot$)
- Main sequence galaxies

H-dropout galaxies (or HST-dark, OFGs…)



Wang+19

- Invisible in the UV
- Massive galaxies (i.e. $M_\star > 10^{10.3}\,M_\odot$)
- Main sequence galaxies
- Estimated to account for $\sim 10\,\%$ at $z = 5$ of the total SFRD

The second question

- How much of the dust obscured SFR are we missing at $z > 3$?

- How much massive galaxies contribute to the SFRD? Can we add a dimension in stellar mass to the Madau plot?

The link between the SFR and gas content of SFGs

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- Do galaxies have more gas at high redshift?

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- Do galaxies have more gas at high redshift?
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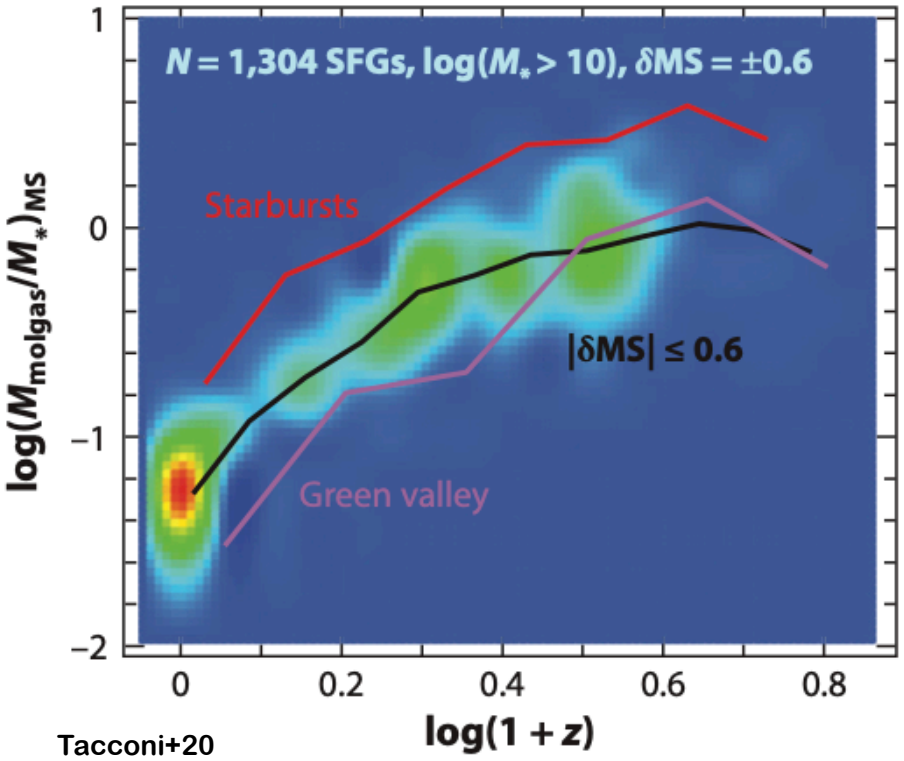
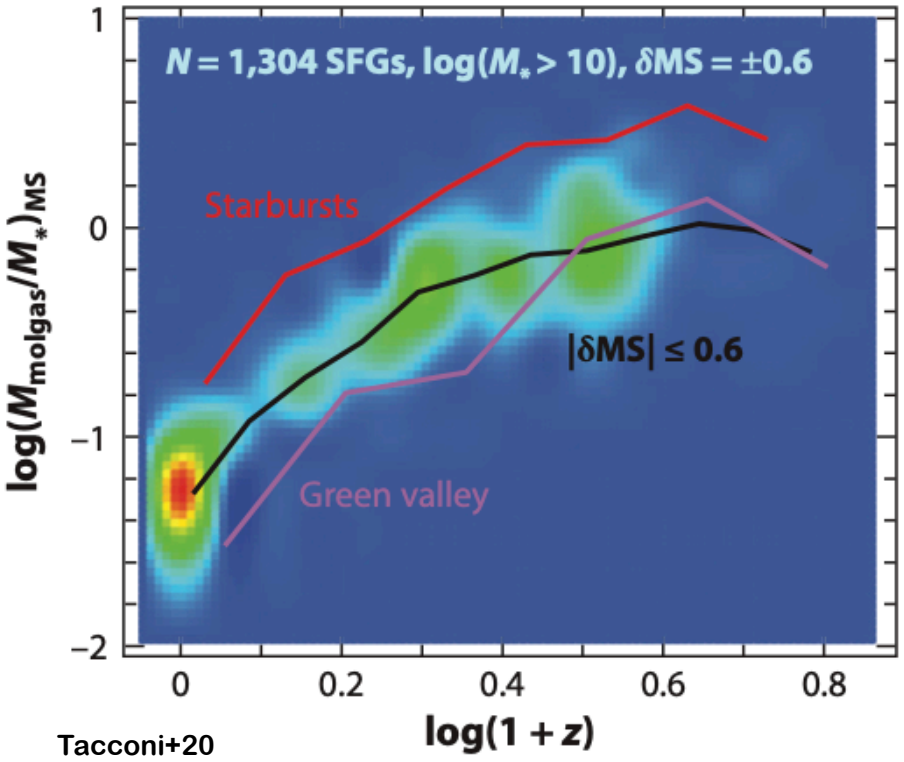


Tacconi+20

e.g., Saintonge+11a,b, Santini+14 , Saintonge+16, Scoville+16, Bolatto+17, Fujimoto+17, Saintonge+17, Utomo+17, Cowie+18, Tacconi+18, Tacconi+20, Saintonge+22

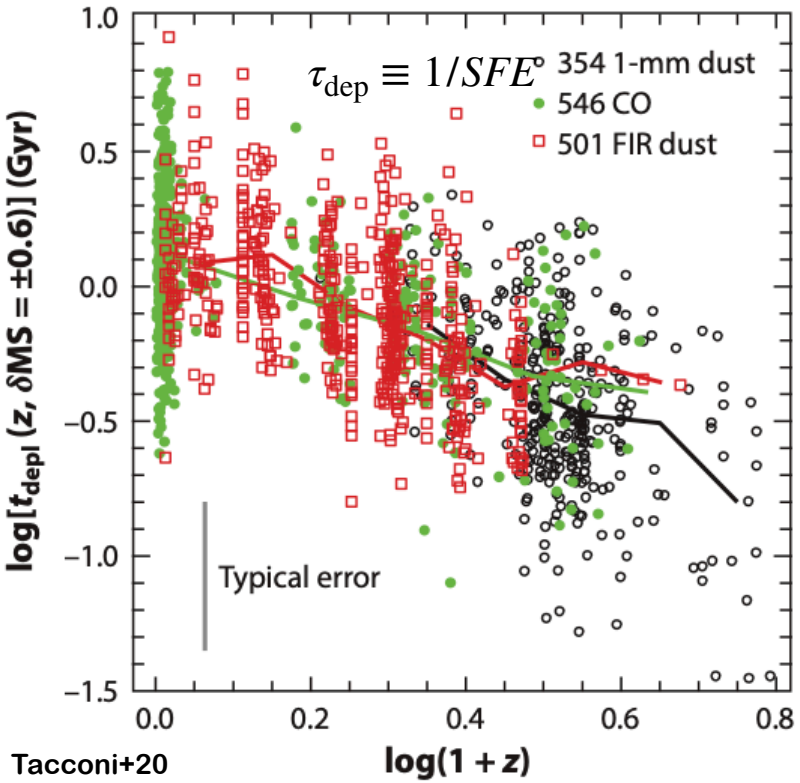
The link between the SFR and gas content of SFGs

- Do galaxies have more gas at high redshift?



Tacconi+20

- Or are they more efficient at converting gas into stars?



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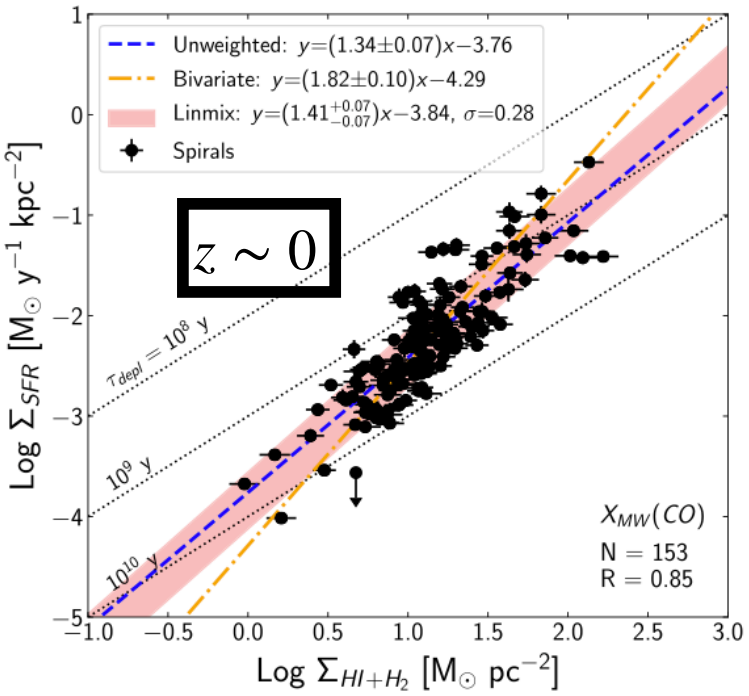
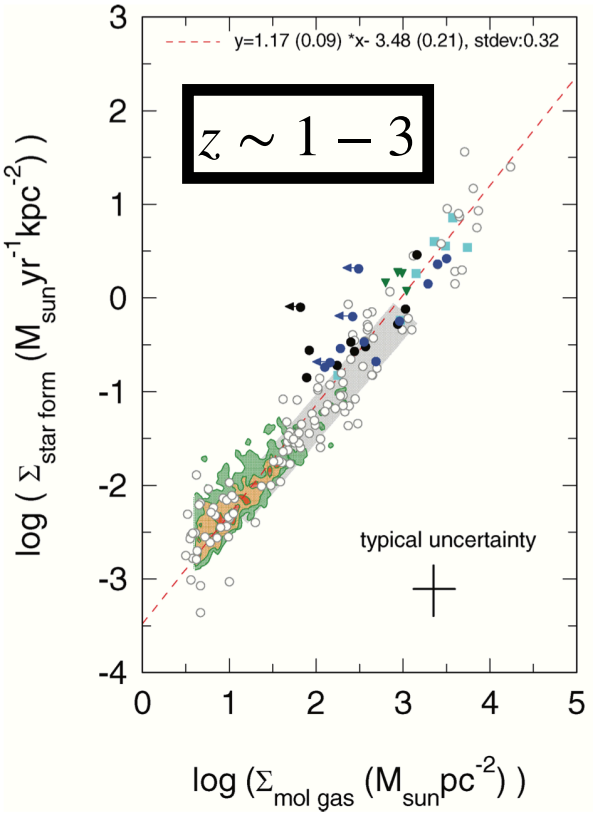
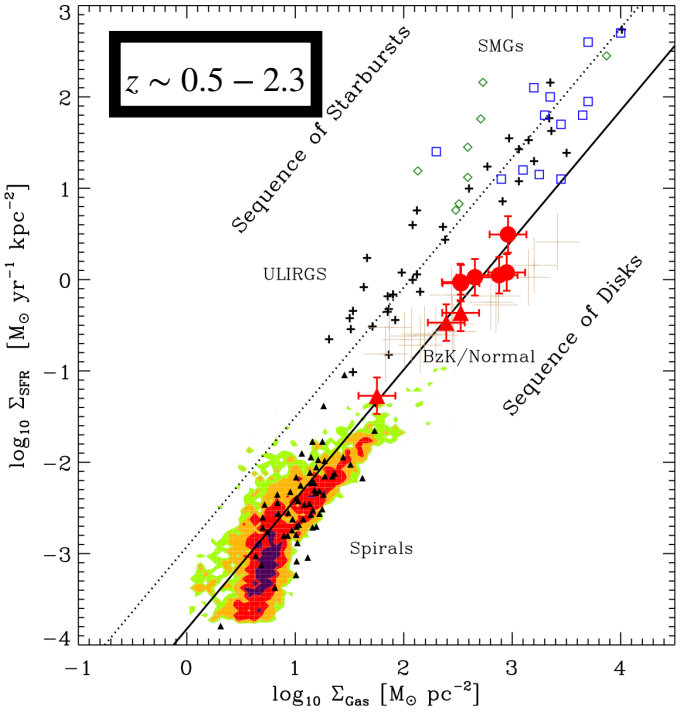


de los Reyes & Kennicutt+19



Genzel+10



Daddi+10

e.g., Schmidt1959; Kennicutt1998; Bouché+07; Bothwell+09; Genzel+10; Heiderman+10; Tacconi+10; de los Reyes & Kennicutt+19; Wang+22

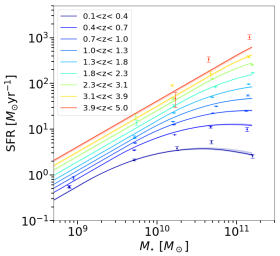
The third question

- How much of the dust obscured SFR are we missing at $z > 3$?
- How much massive galaxies contribute to the SFRD? Can we add a dimension in stellar mass to the Madau plot?
- Are some galaxies more efficient at forming stars than others?

What we are looking for

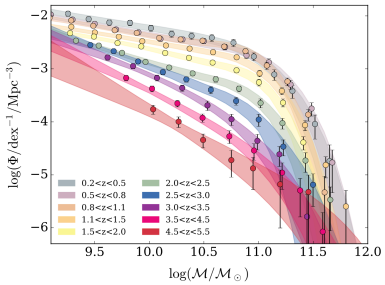
- How much of the dust obscured SFR are we missing at $z > 3$?
- How much massive galaxies contribute to the SFRD? Can we add a dimension in stellar mass to the Madau plot?
- Are some galaxies more efficient at forming stars than others?

What is the plan?



Main sequence from Leroy+23 Submitted

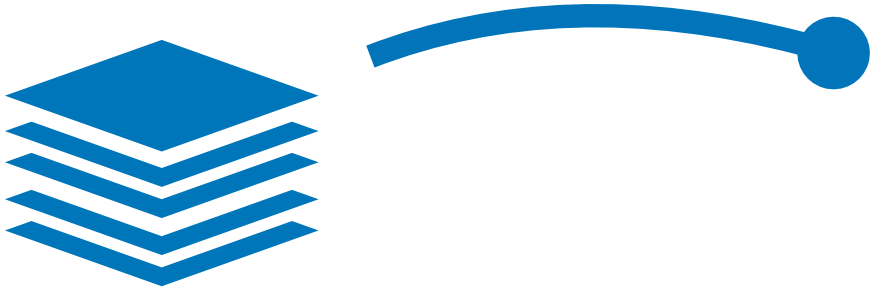
The mass function from Davidzon+17



SFR and M_{gas}

The stacking method

Stacking of N galaxies

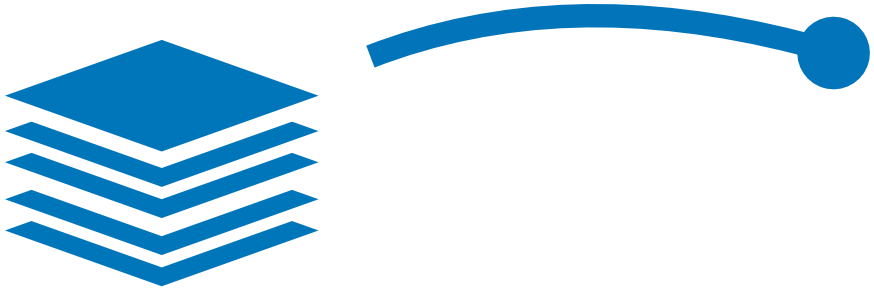


- Improve the S/N by about $\sqrt{N}$

e.g., Magnelli+09, Béthermin+10,14, Magnelli+14,15, Schreiber+15,18, Jin+18, Delvecchio+21

The stacking method

Stacking of N galaxies



- Improve the S/N by about $\sqrt{N}$
- Great for studying galaxies too faint to be looked at individually

e.g., Magnelli+09, Béthermin+10,14, Magnelli+14,15, Schreiber+15,18, Jin+18, Delvecchio+21

The method

Catalogues of H-band selected SFGs

z, $M_\star$ and $SFR_{\rm UV}$

The method

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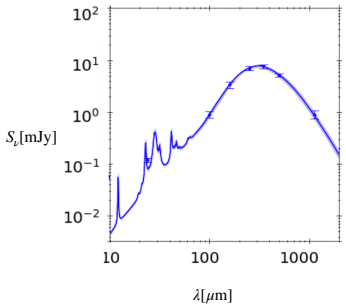
MIPS+Herschel+ALMA

The method

Catalogues of H-band selected SFGs
z, $M_\star$ and $SFR_{\rm UV}$

Improving photometry limits through stacking

MIPS+Herschel+ALMA



The method

Catalogues of H-band selected SFGs
z, $M_\star$ and $SFR_{\rm UV}$

Improving photometry limits through stacking

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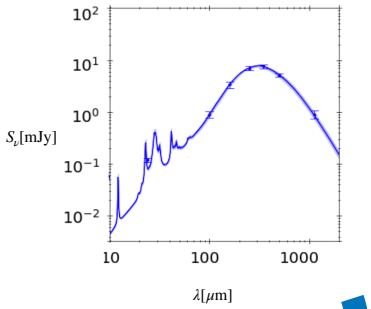

Deducing galaxies properties :
SFR, $T_{\rm dust}$, $M_{\rm dust}$, $M_{\rm gas}$, $\rho_{\rm SFR}$, $\rho_{\rm gas}$…

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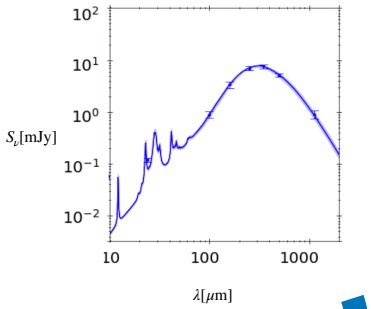

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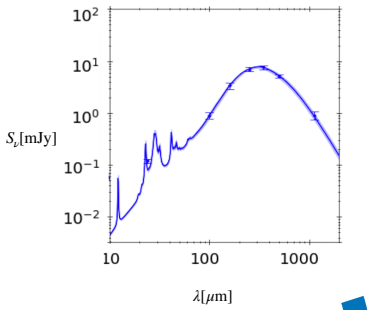

Deducing galaxies properties :
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H-dropout properties from Wang+19

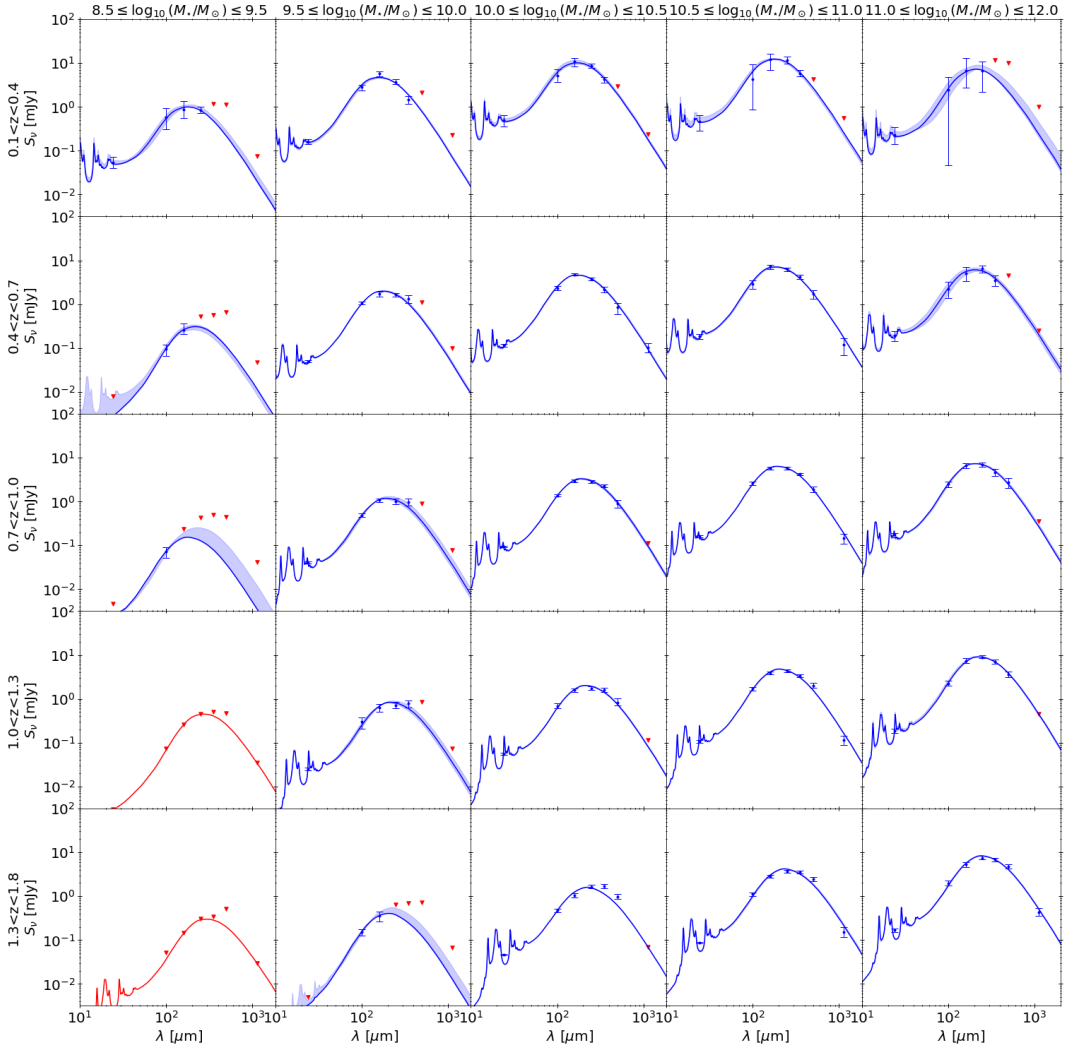
Stacking method

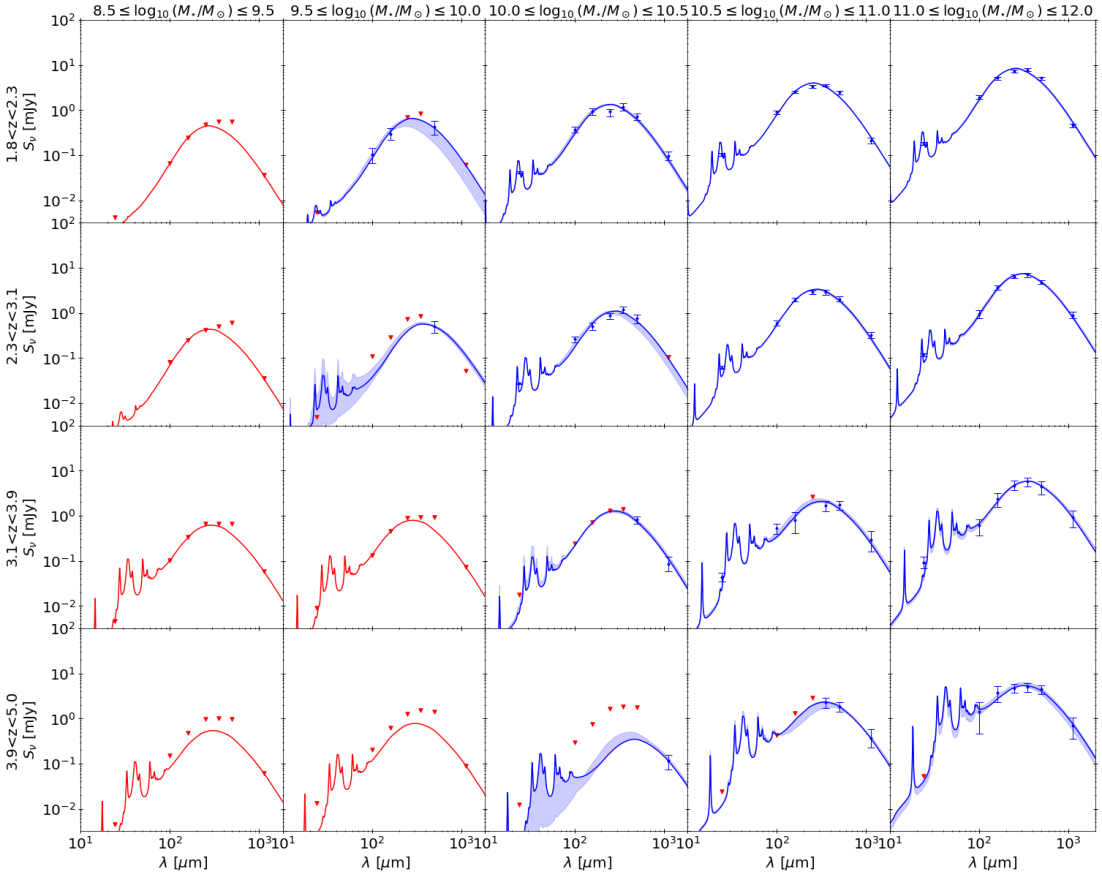
- Gradient in maps
- Clustering bias in Herschel bands
- PSF fitting and aperture photometry
- Measure of S/N and flux errors

SED fitting method

- Schreiber+18 template library and correction table
- Simulations for averaging biases
- AGN bias and transmission windows

Best fit SEDs





Leroy+23 Submitted

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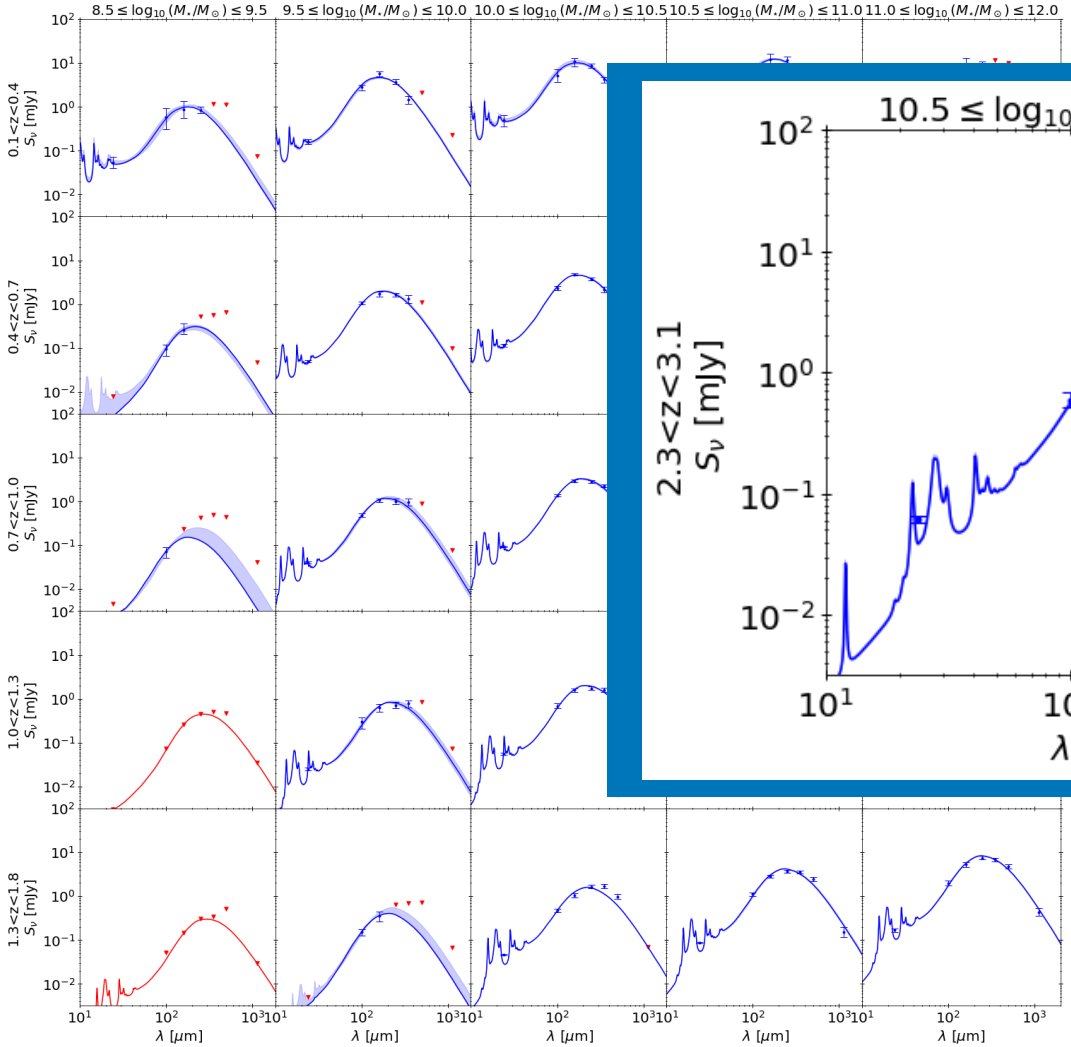

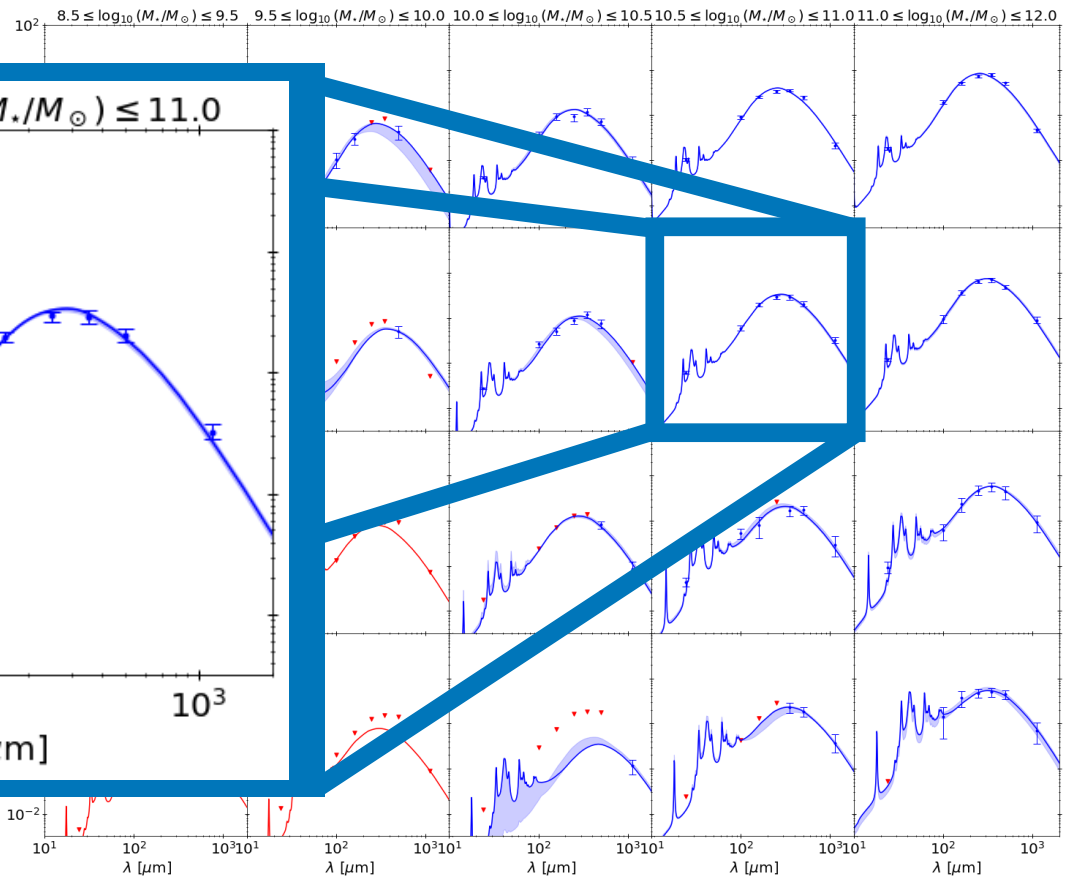

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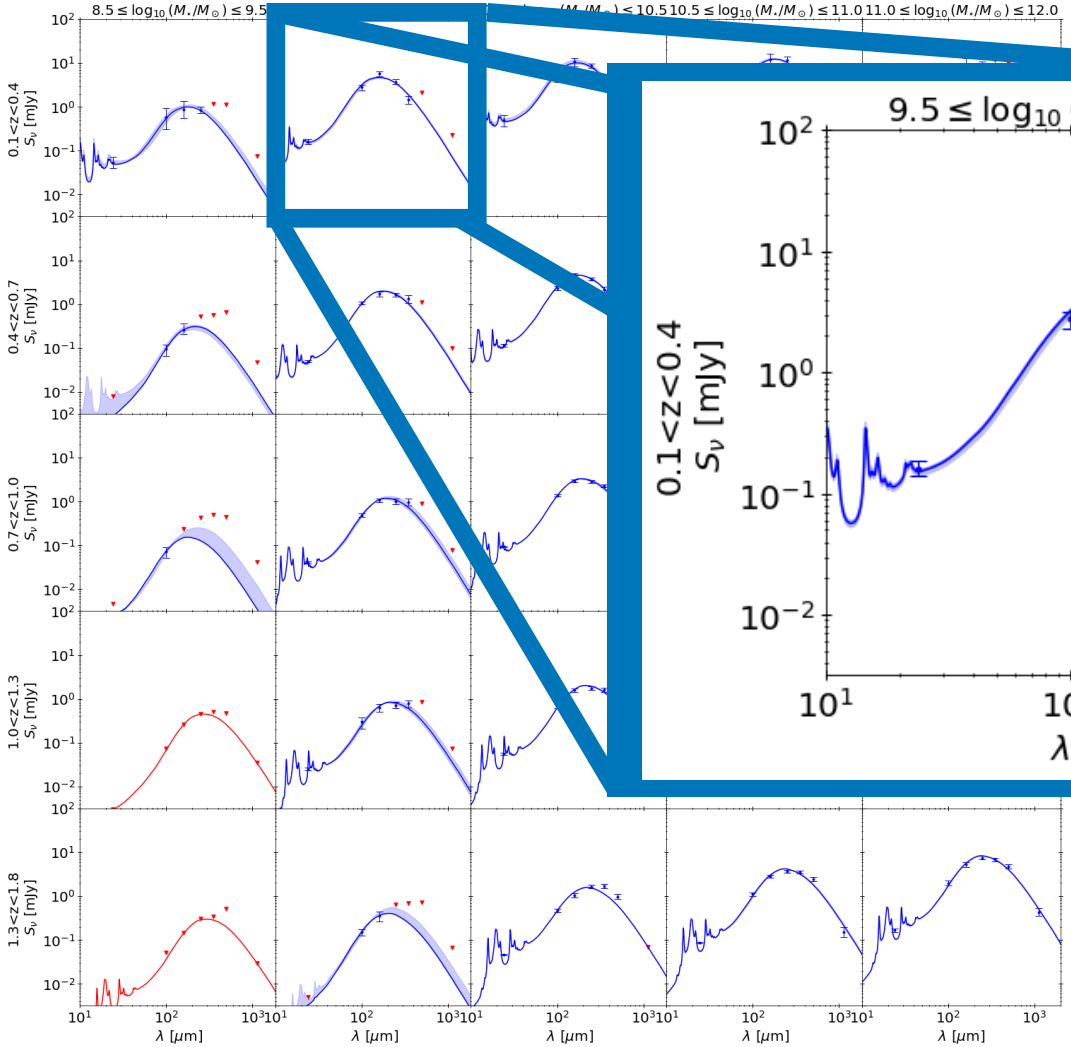

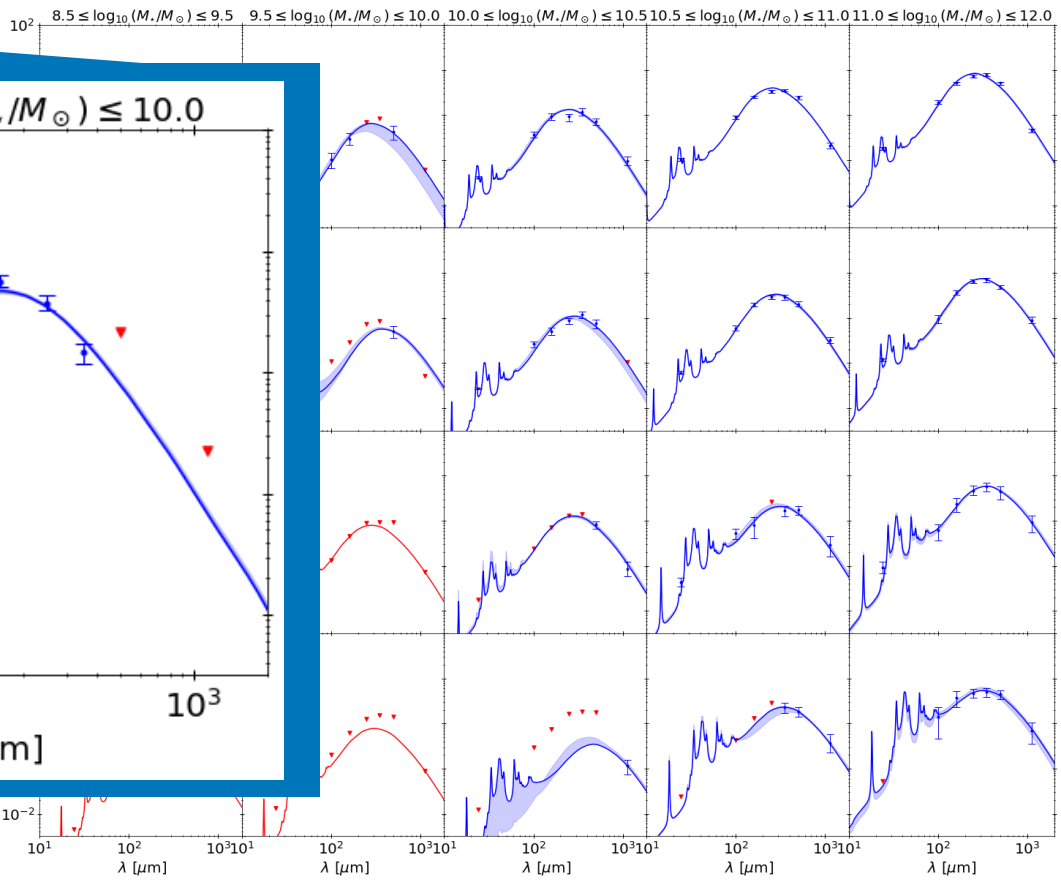

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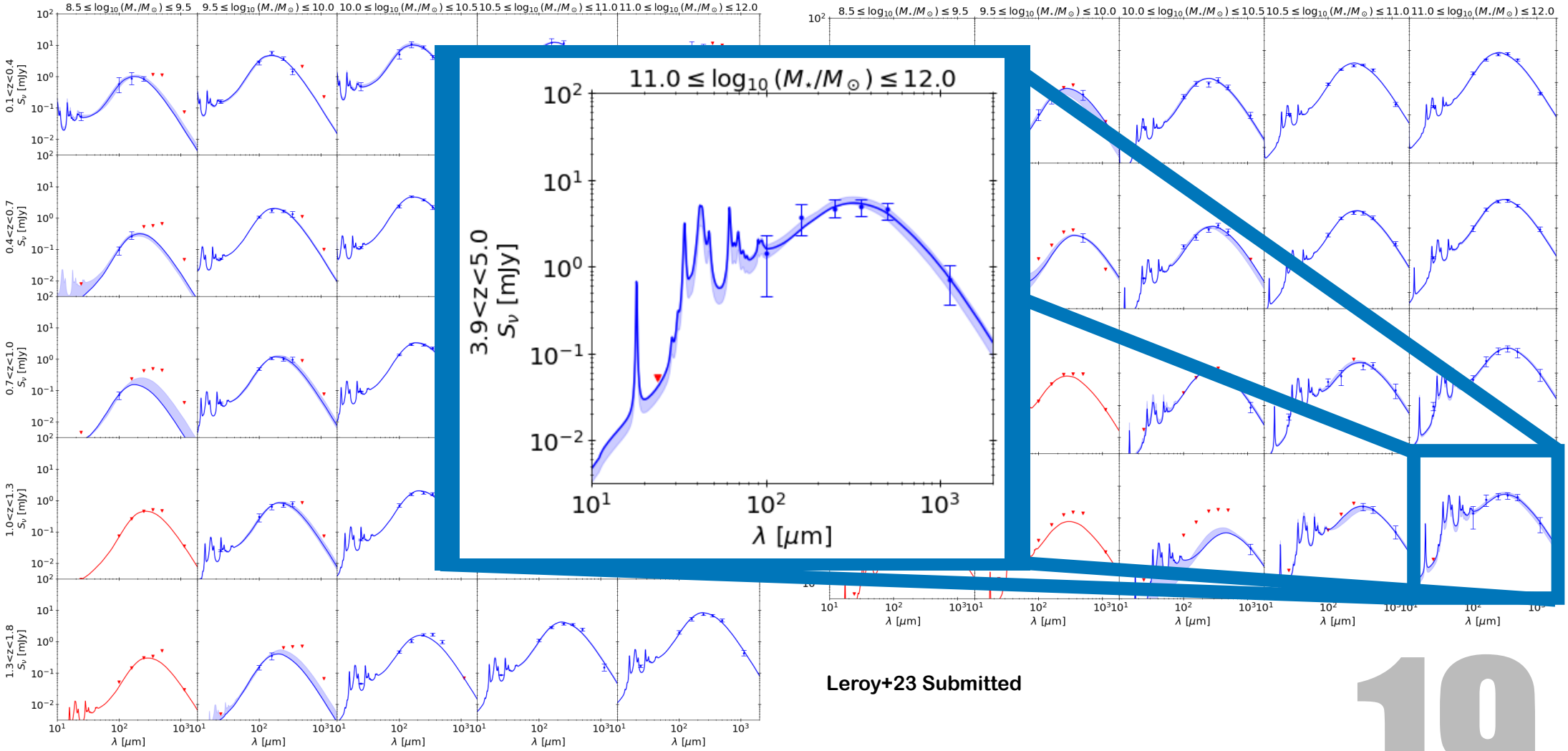

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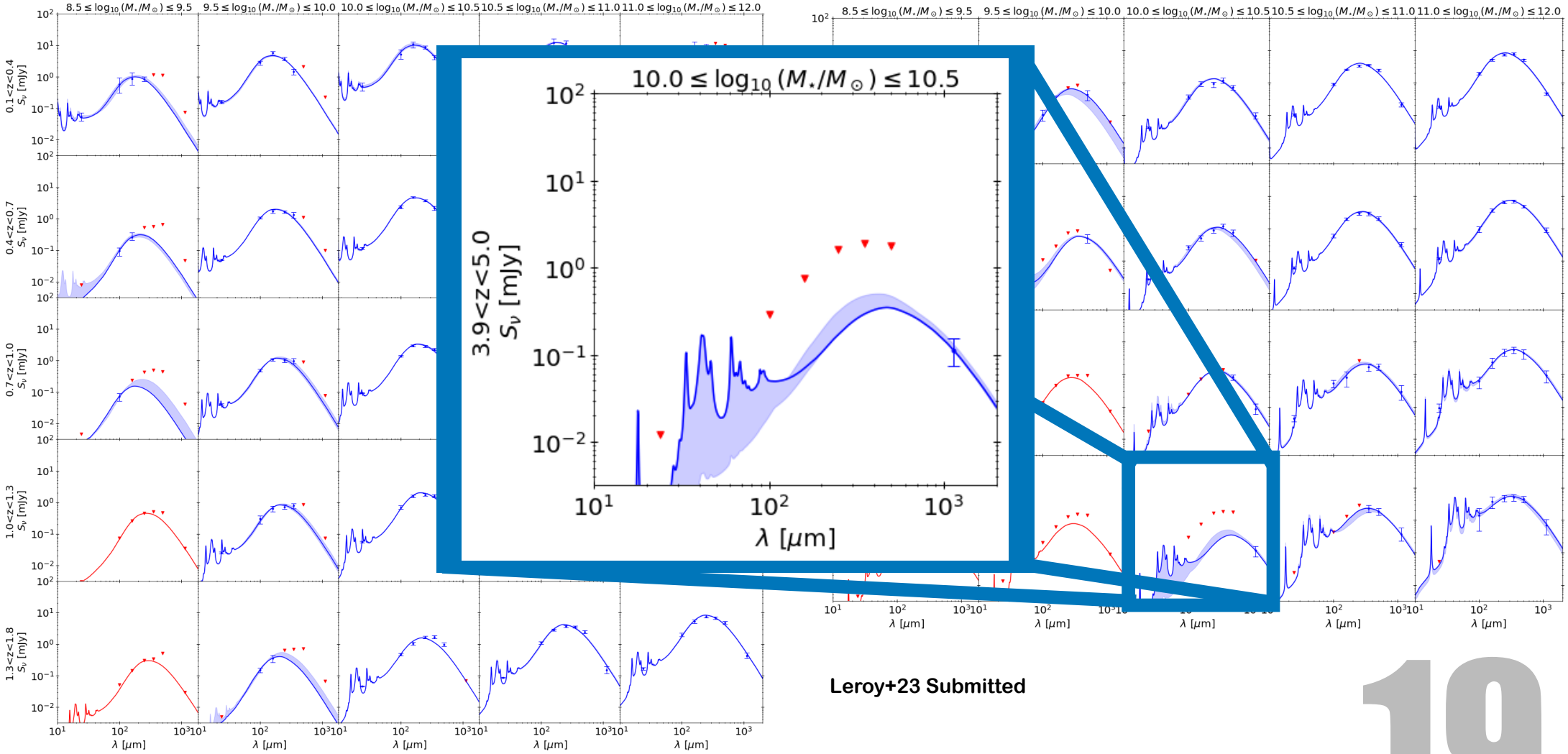
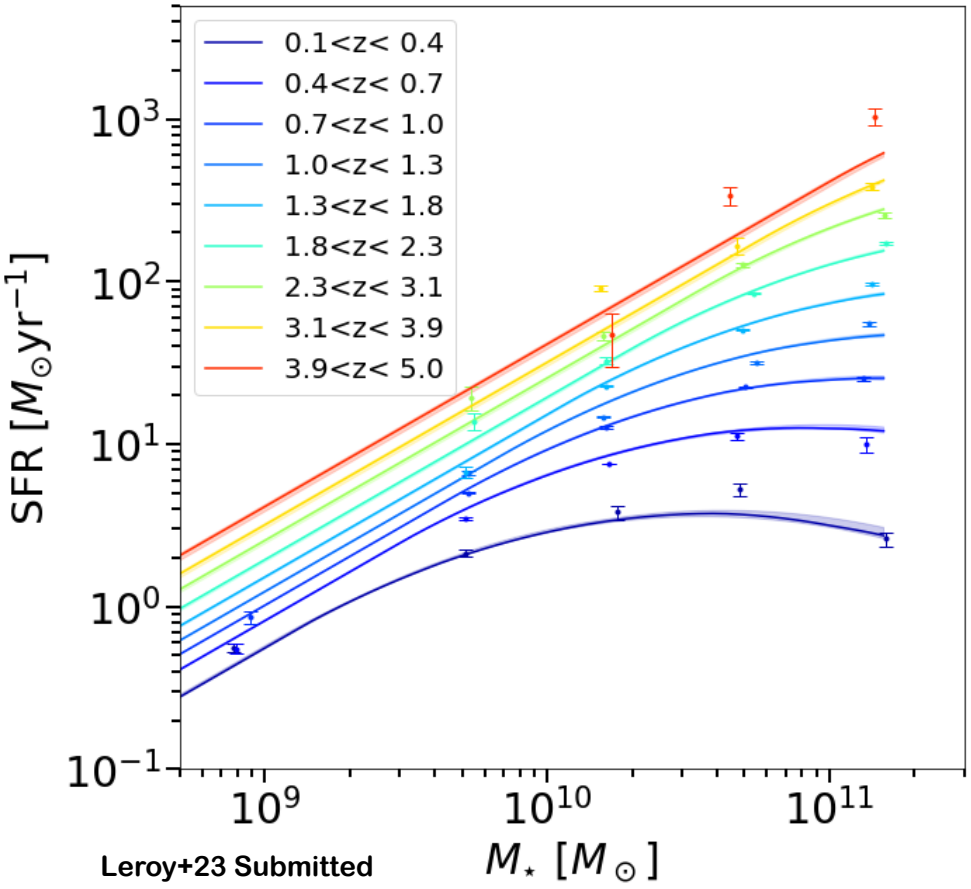


Leroy+23 Submitted

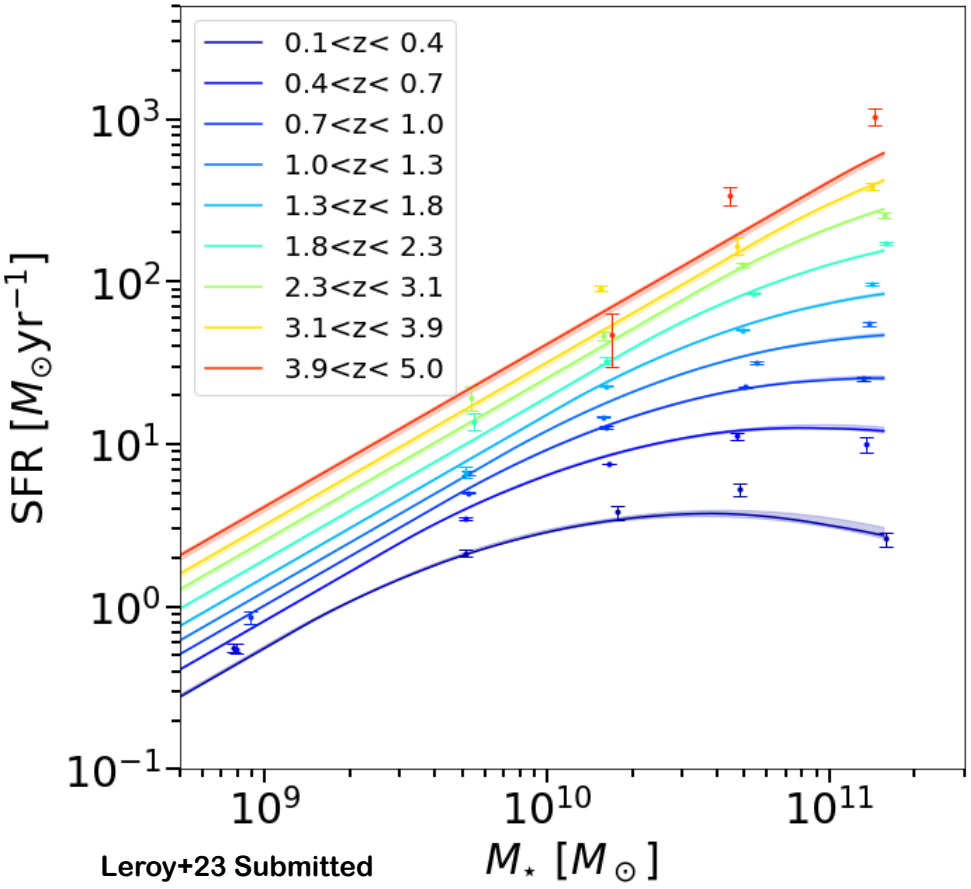
The main sequence of SFGs



Leroy+23 Submitted

$SFR_{\rm MS}$ as a function of $M_\star$ over different redshift bins.

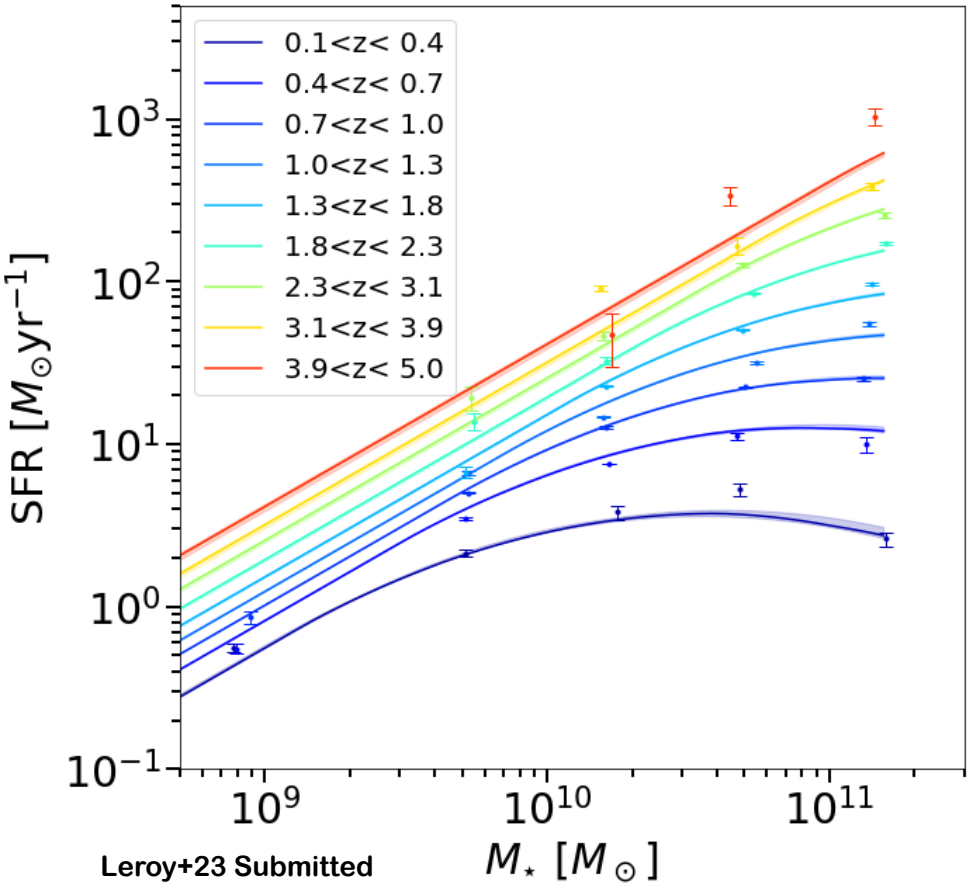
The main sequence of SFGs



$SFR_{\rm MS}$ as a function of $M_\star$ over different redshift bins.

- Increase of SFR with stellar mass

The main sequence of SFGs

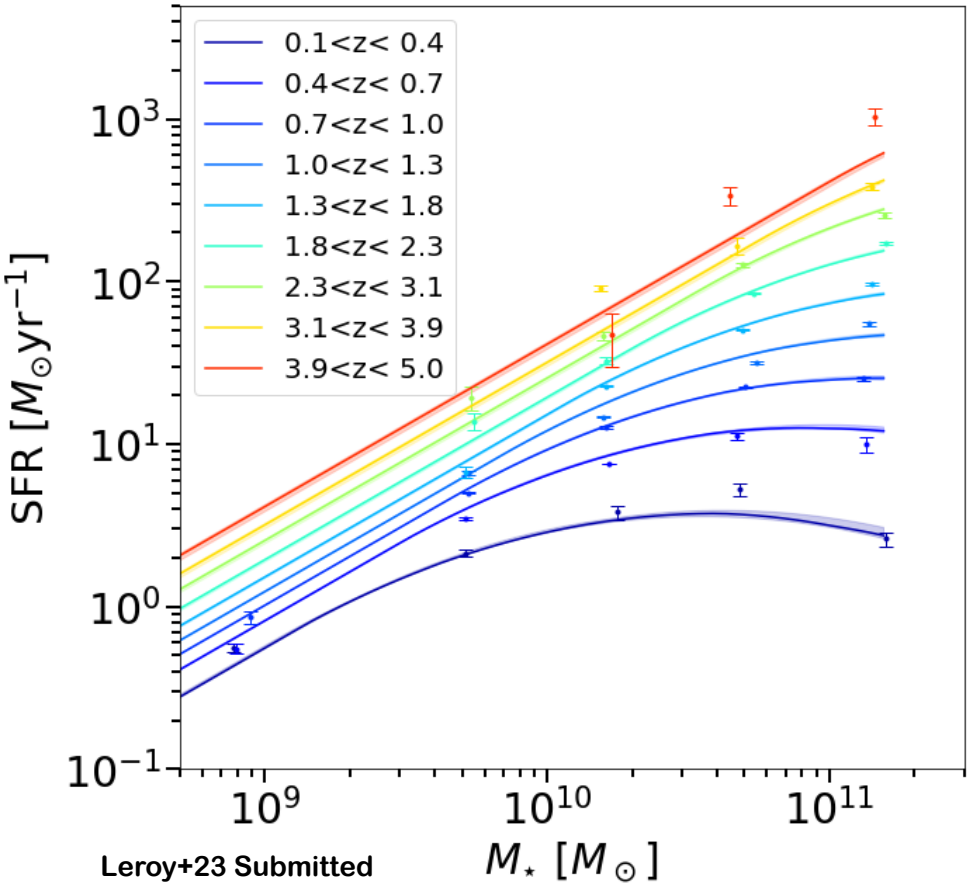


Leroy+23 Submitted

$SFR_{\rm MS}$ as a function of $M_\star$ over different redshift bins.

- Increase of SFR with stellar mass
- Increase of SFR with redshift

The main sequence of SFGs

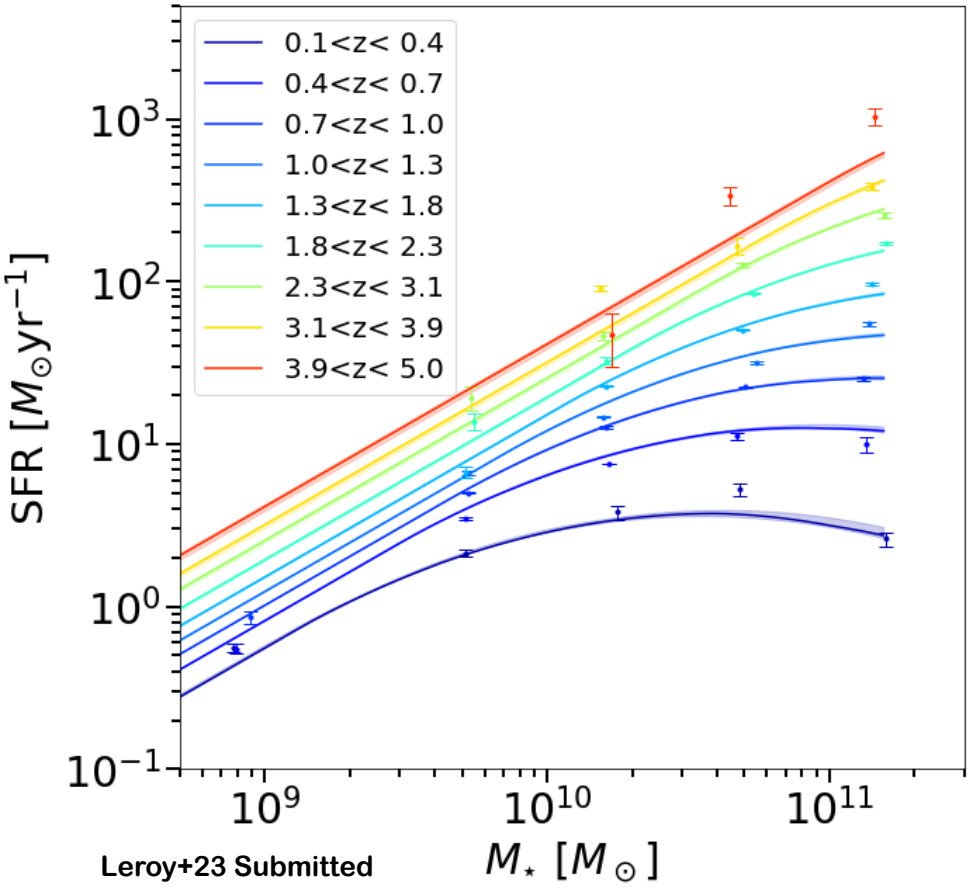


Leroy+23 Submitted

$SFR_{\rm MS}$ as a function of $M_\star$ over different redshift bins.

- Increase of SFR with stellar mass
- Increase of SFR with redshift
- Bending at the high mass end

The main sequence of SFGs

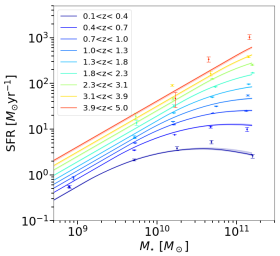


Leroy+23 Submitted

$SFR_{\rm MS}$ as a function of $M_\star$ over different redshift bins.

- Increase of SFR with stellar mass
- Increase of SFR with redshift
- Bending at the high mass end
- Extended to higher z and lower $M_\star$

ρ_{SFR}



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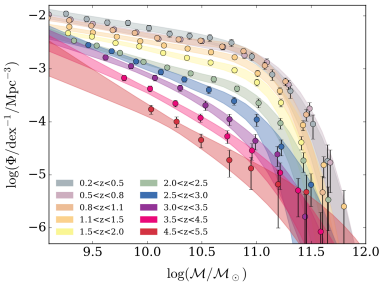
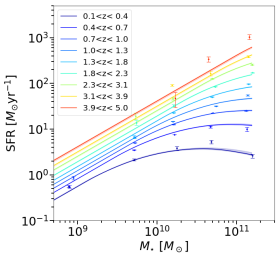


$\rho_{\rm SFR}$



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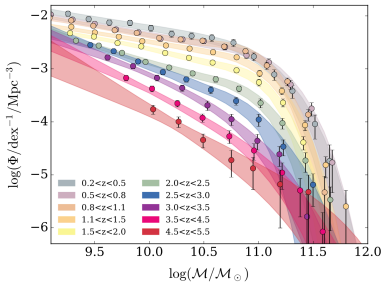
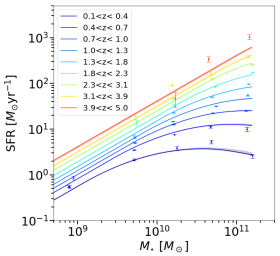


Mock galaxies

ρ_{SFR}



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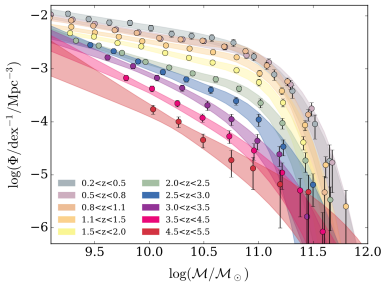
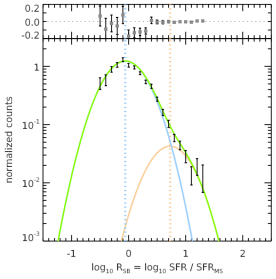
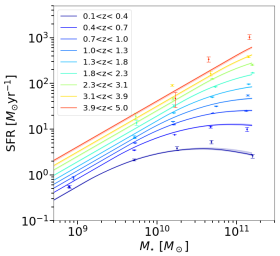


Take starburst into account (Schreiber+15)



Mock galaxies

ρ_{SFR}



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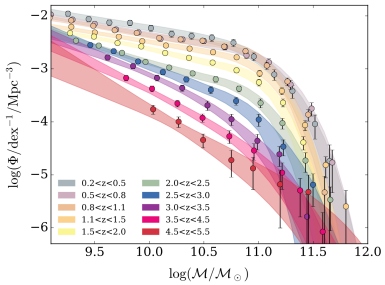

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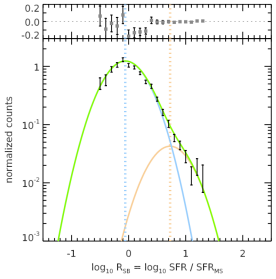
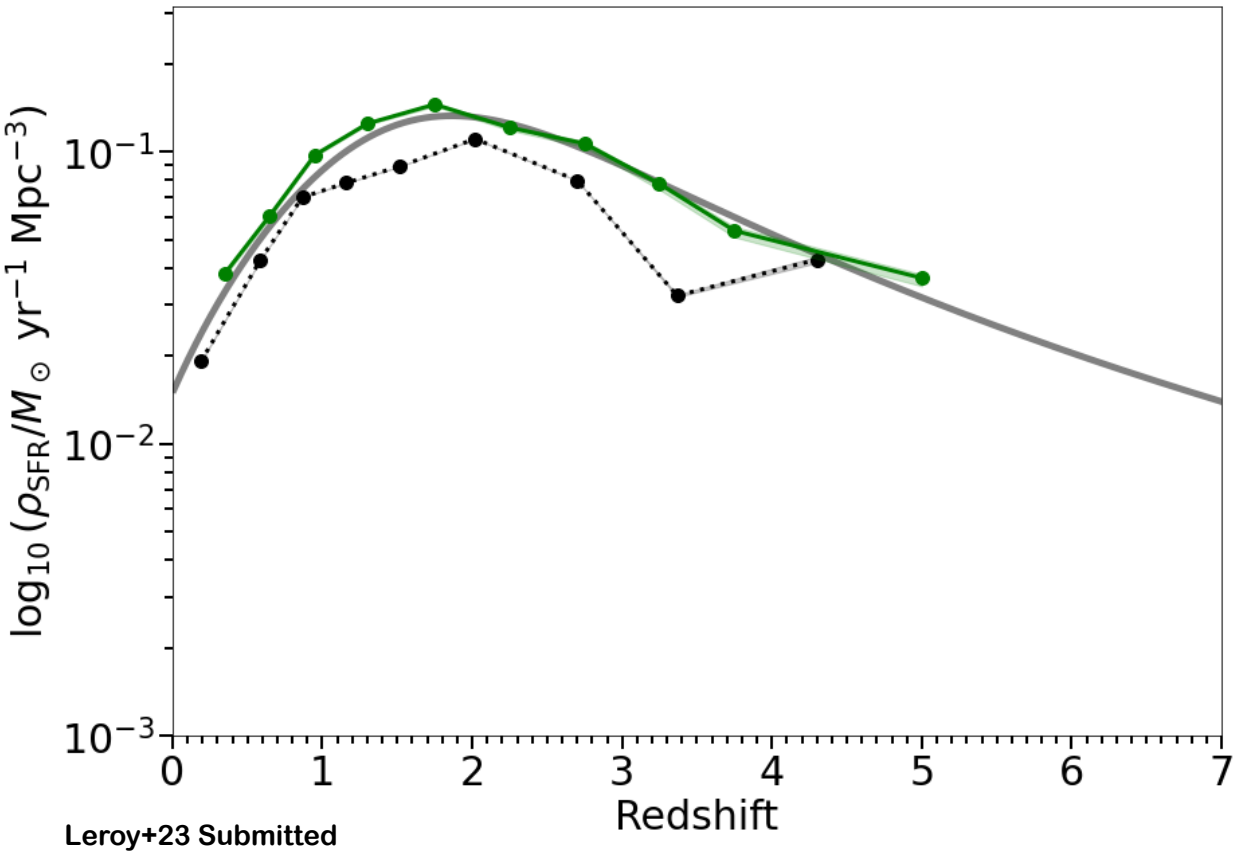


Mock galaxies

ρ_{SFR}

The cosmic star formation history ($\rho_{\rm SFR}$)



Leroy+23 Submitted

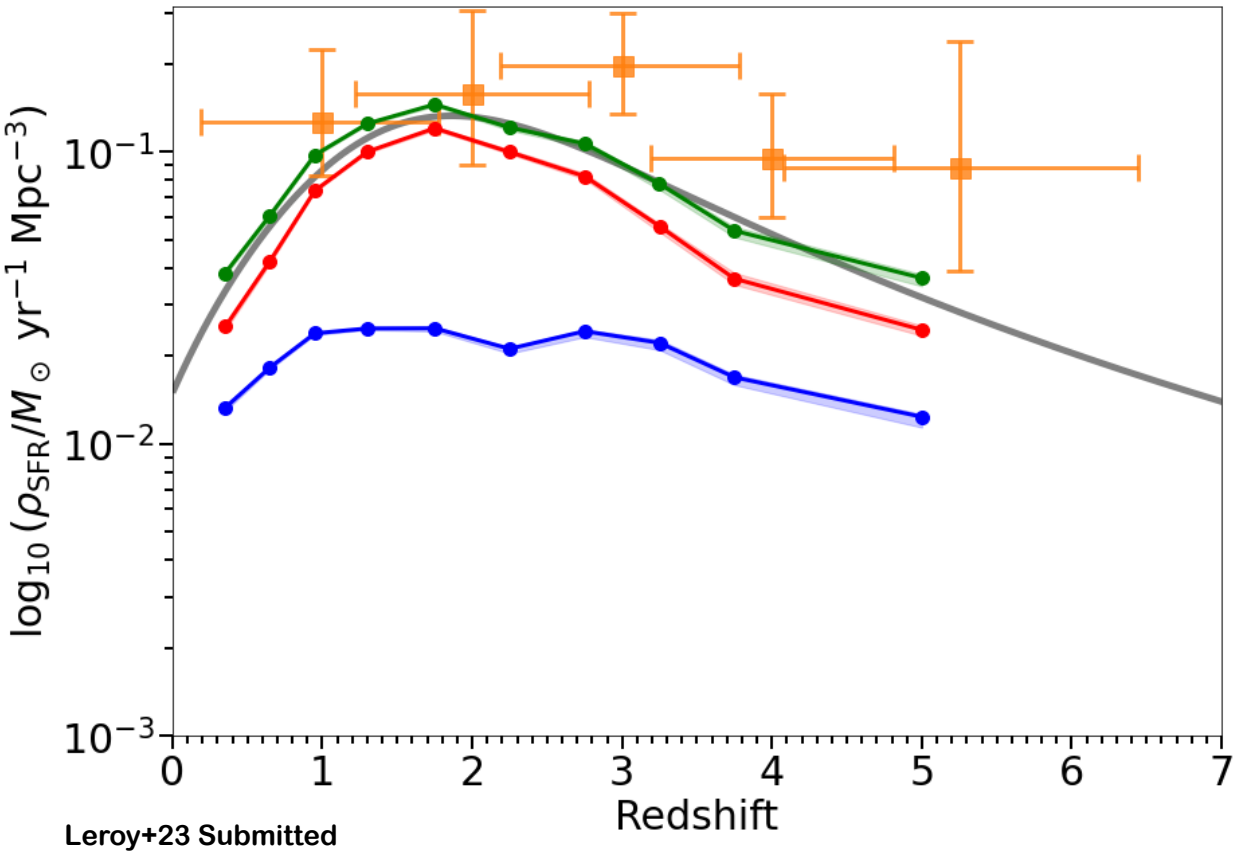
Madau & Dickinson+14

This work

This work detected with stacking

Cosmic star formation rate density ($\rho_{\rm SFR}$) as a function of redshift

The cosmic star formation history ($\rho_{\rm SFR}$)



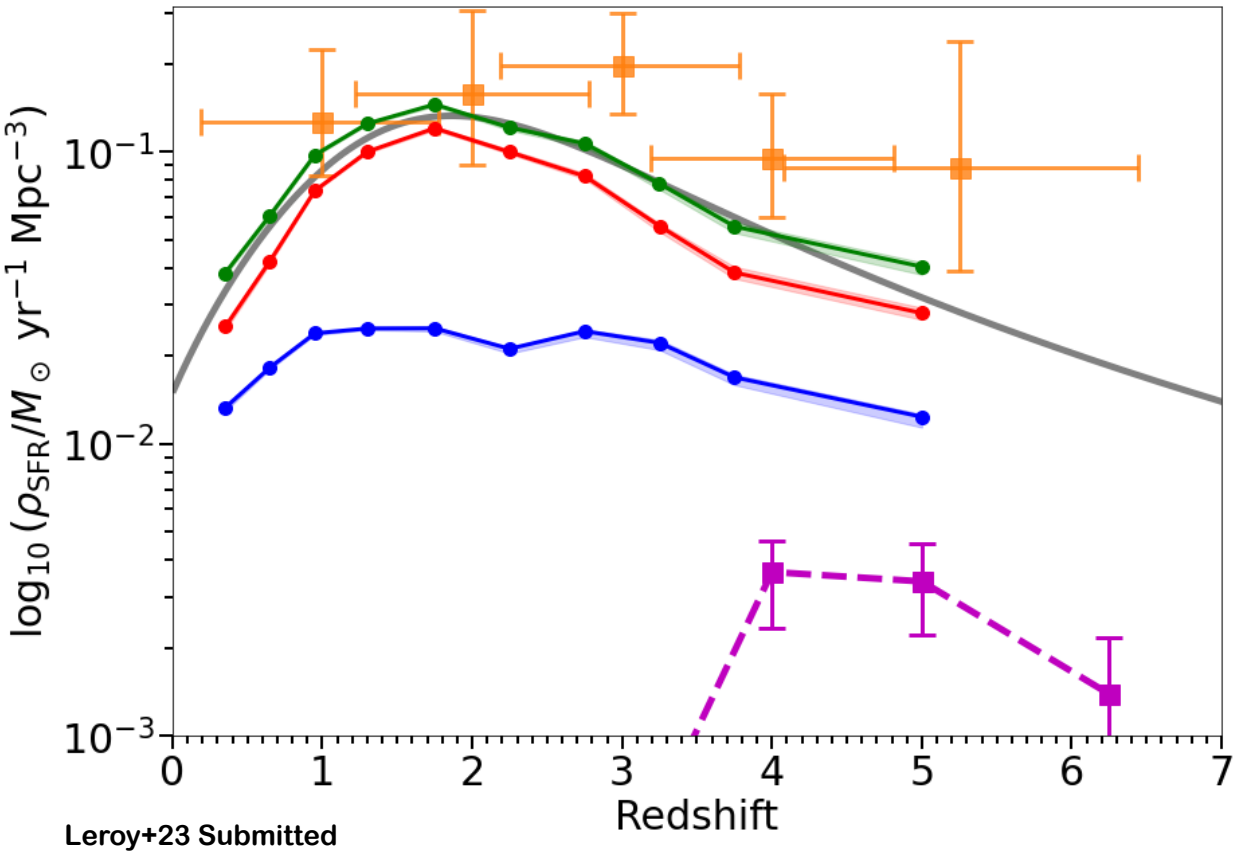
Leroy+23 Submitted

Cosmic star formation rate density ($\rho_{\rm SFR}$) as a function of redshift

How much of the SFRD are we missing?

- Madau & Dickinson+14
- This work
- This work for $M_\star \geq 10^{10}\,M_\odot$
- This work for $M_\star < 10^{10}\,M_\odot$
- Gruppioni+20

The cosmic star formation history ($\rho_{\rm SFR}$)



Leroy+23 Submitted

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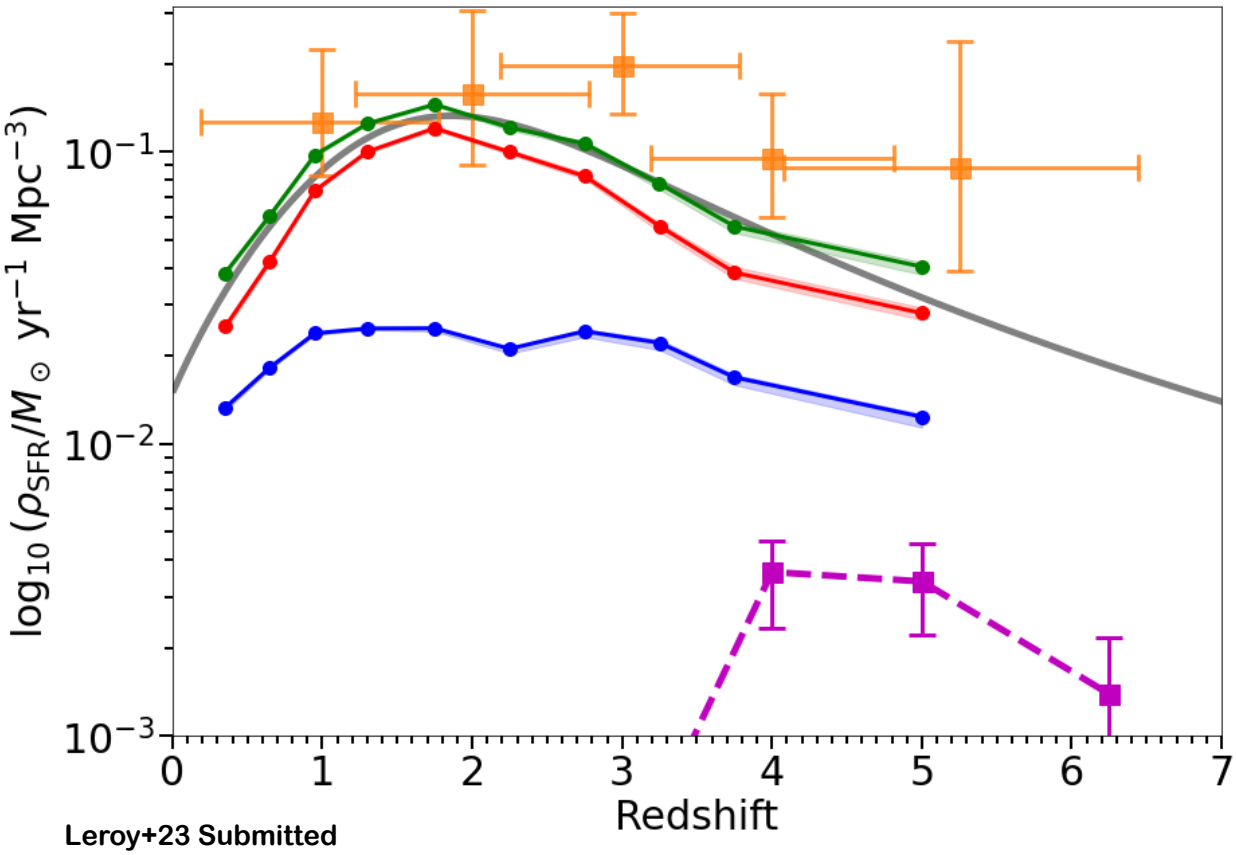

Leroy+23 Submitted

Cosmic star formation rate density ($\rho_{\rm SFR}$) as a function of redshift

How much of the SFRD are we missing?

Not much optically thick

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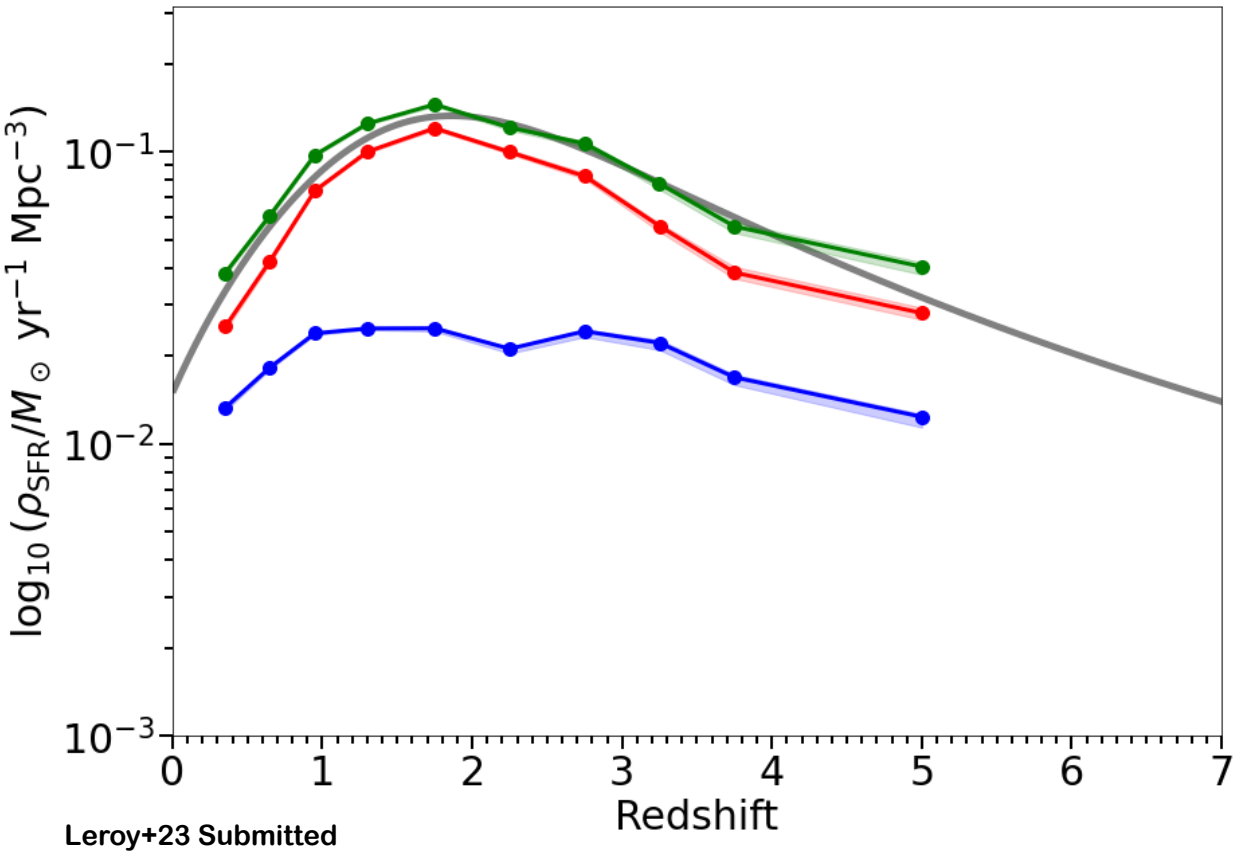
The cosmic star formation history ($\rho_{\rm SFR}$)



Leroy+23 Submitted

Madau & Dickinson+14

This work

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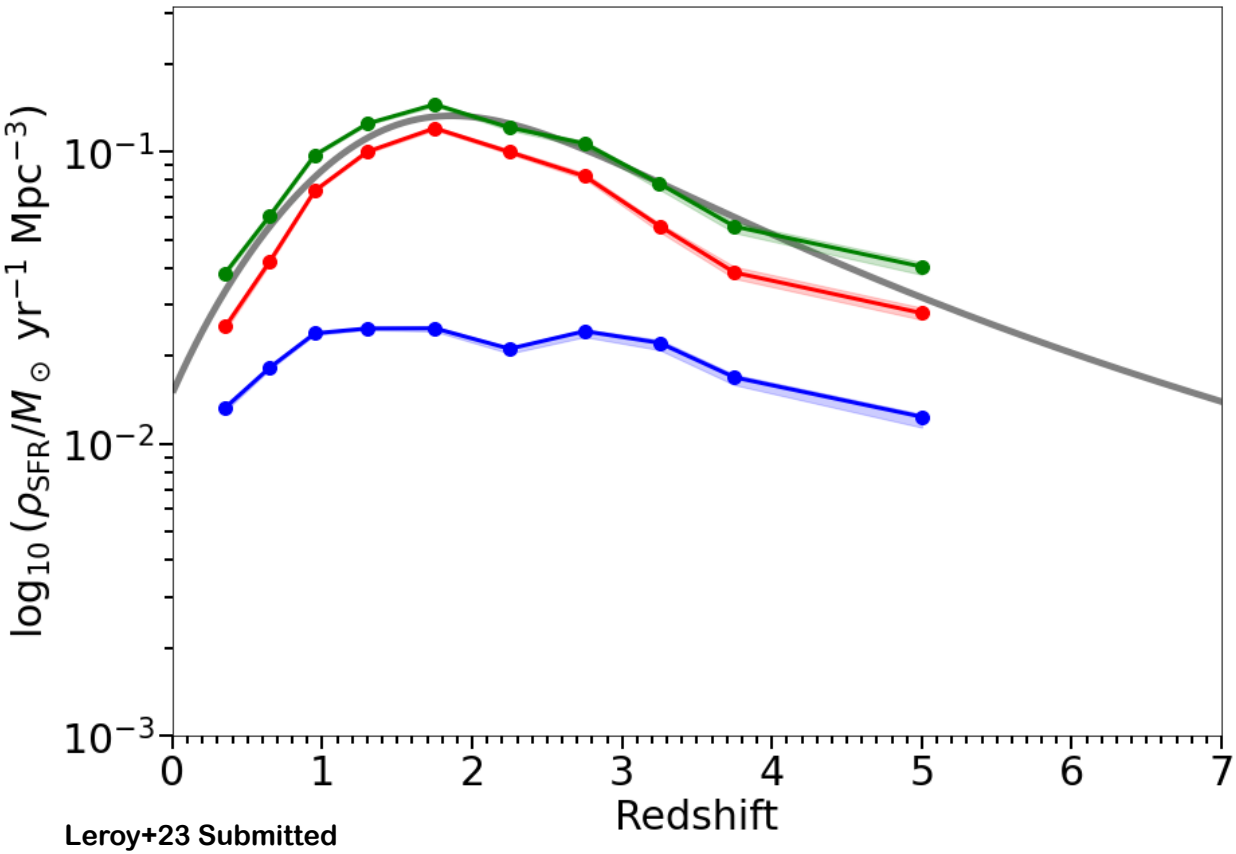


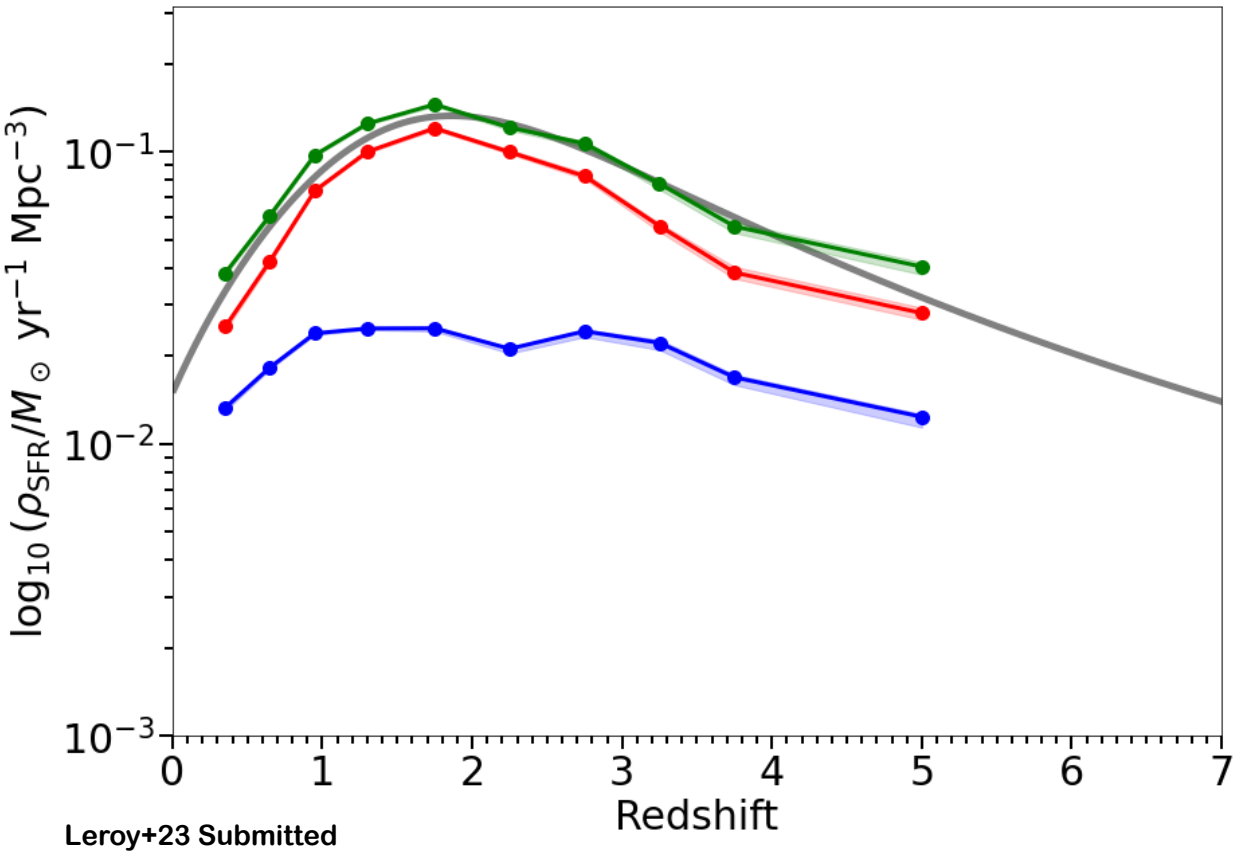
Leroy+23 Submitted

- High masses account for most of the $\rho_{\rm SFR}$

- Madau & Dickinson+14
- This work
- This work for $M_\star \geq 10^{10}\,M_\odot$
- This work for $M_\star < 10^{10}\,M_\odot$

Cosmic star formation rate density ($\rho_{\rm SFR}$) as a function of redshift

The cosmic star formation history ($\rho_{\rm SFR}$)



Leroy+23 Submitted

- High masses account for most of the $\rho_{\rm SFR}$
- Low masses contribution is fairly constant over z

Madau & Dickinson+14

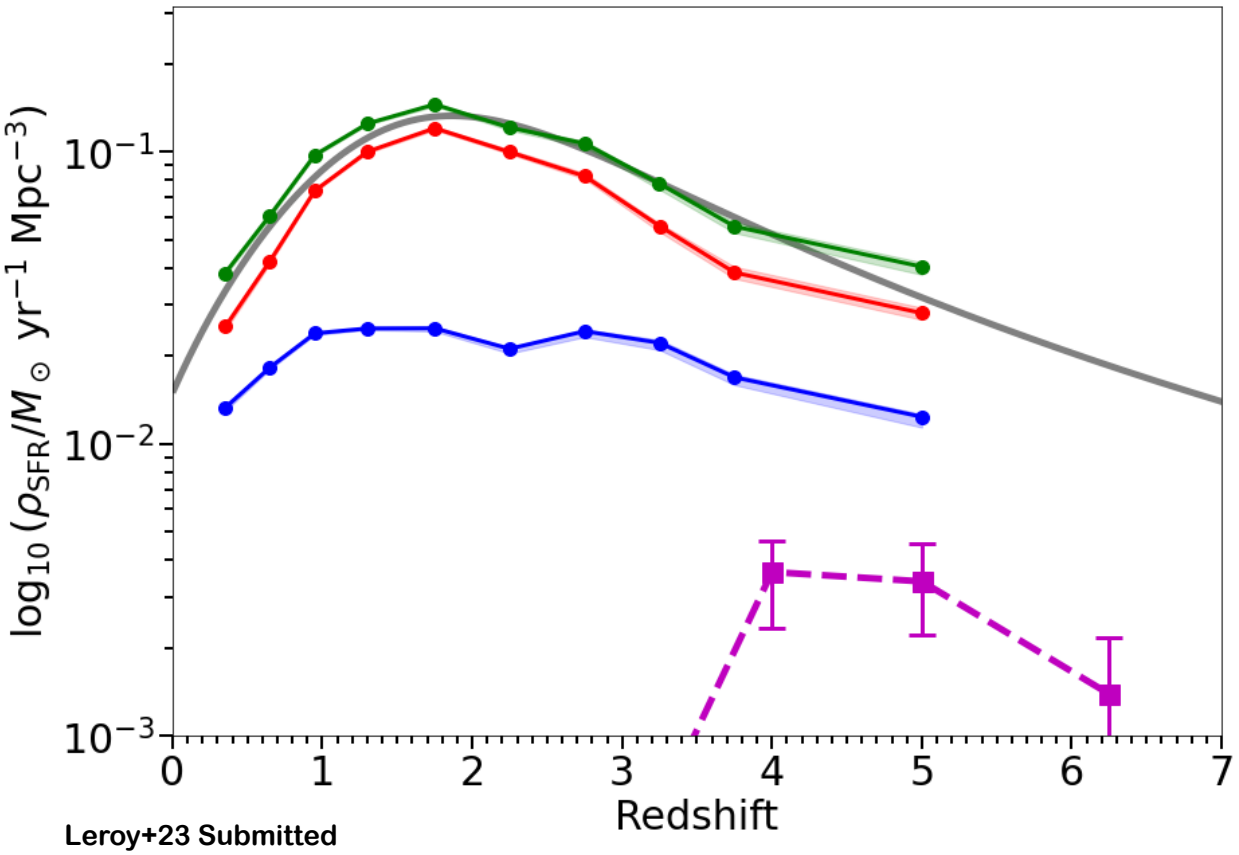
This work

This work for $M_\star \geq 10^{10}\,M_\odot$

This work for $M_\star < 10^{10}\,M_\odot$

Cosmic star formation rate density ($\rho_{\rm SFR}$) as a function of redshift

The cosmic star formation history ($\rho_{\rm SFR}$)



Leroy+23 Submitted

Madau & Dickinson+14

This work

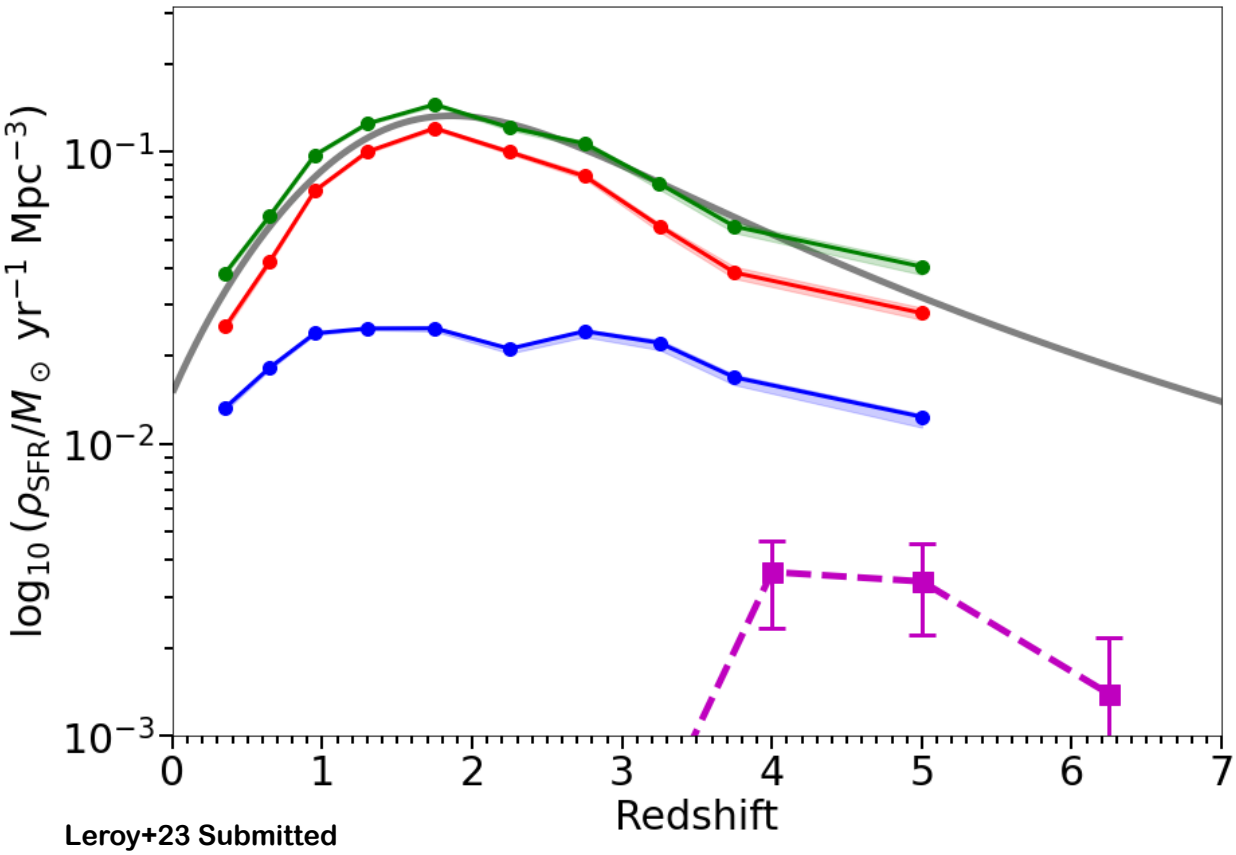
This work for $M_\star \geq 10^{10}\,M_\odot$

This work for $M_\star < 10^{10}\,M_\odot$

Wang+19

Cosmic star formation rate density ($\rho_{\rm SFR}$) as a function of redshift

The cosmic star formation history ($\rho_{\rm SFR}$)



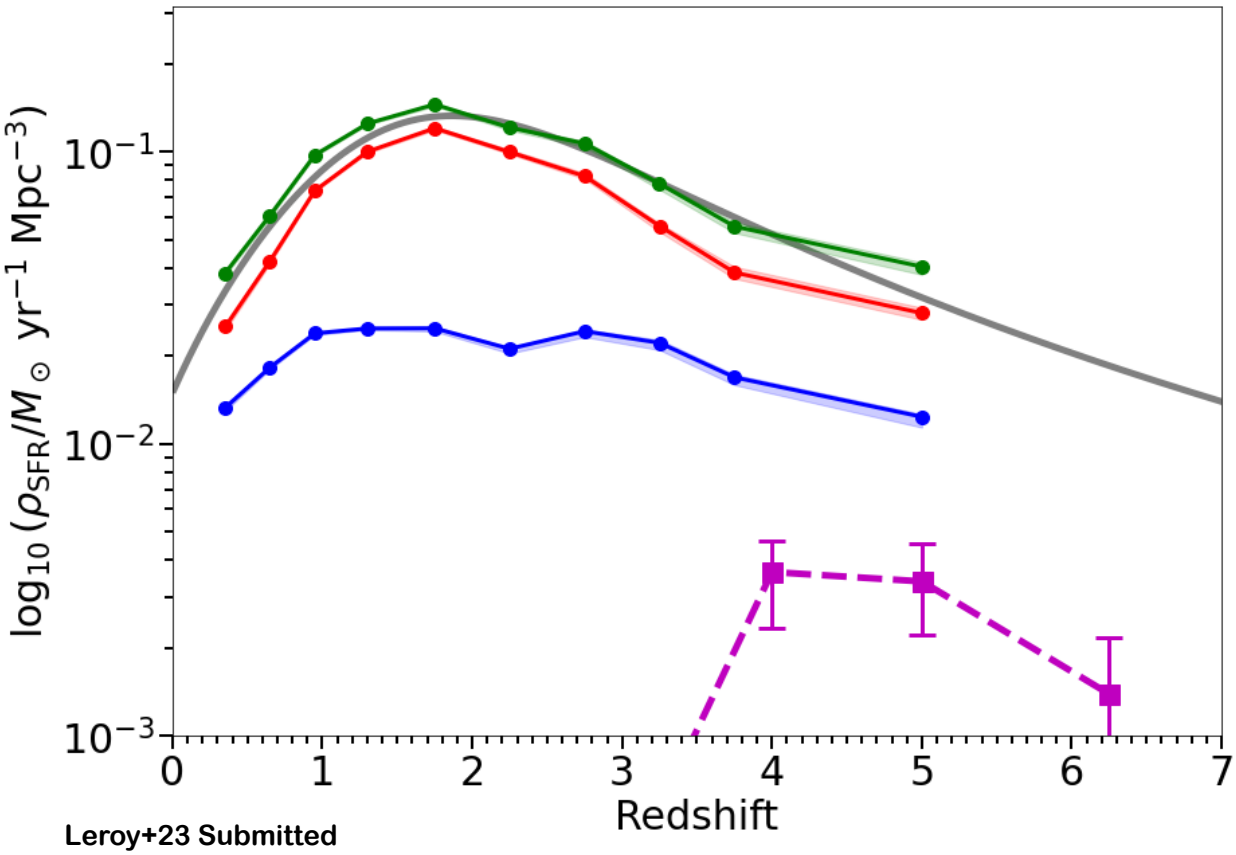
Leroy+23 Submitted

- H-dropout galaxies account for 13% of the total $\rho_{\rm SFR}$

- Madau & Dickinson+14
- This work
- This work for $M_\star \geq 10^{10}\,M_\odot$
- This work for $M_\star < 10^{10}\,M_\odot$
- Wang+19

Cosmic star formation rate density ($\rho_{\rm SFR}$) as a function of redshift

The cosmic star formation history ($\rho_{\rm SFR}$)



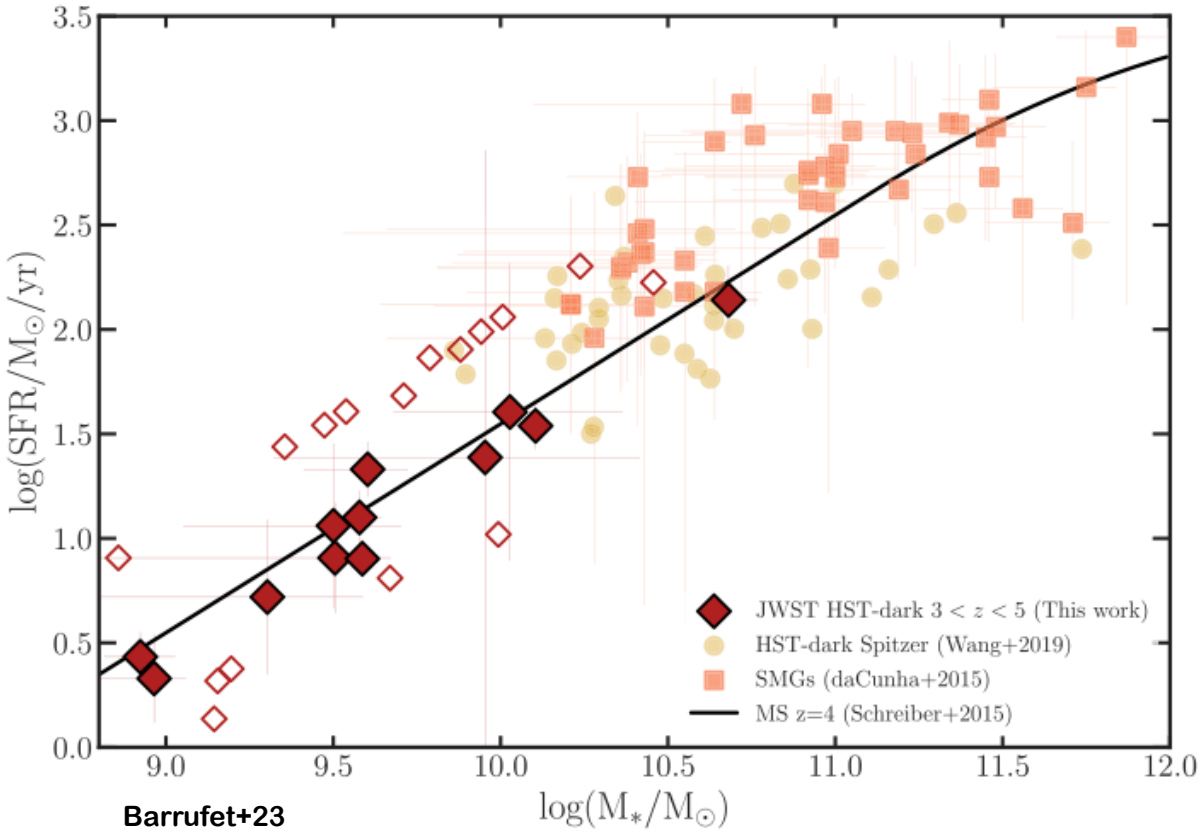
Leroy+23 Submitted

- H-dropout galaxies account for 13% of the total $\rho_{\rm SFR}$
- H-dropout galaxies account for 23% of the $\rho_{\rm SFR}$ of galaxies with $M_\star \geq 10^{10.3} M_\odot$ at z=5

Madau & Dickinson+14
This work
This work for $M_\star \geq 10^{10}\,M_\odot$
This work for $M_\star < 10^{10}\,M_\odot$
Wang+19

Cosmic star formation rate density ($\rho_{\rm SFR}$) as a function of redshift

A better characterization of HST-dark galaxies with JWST

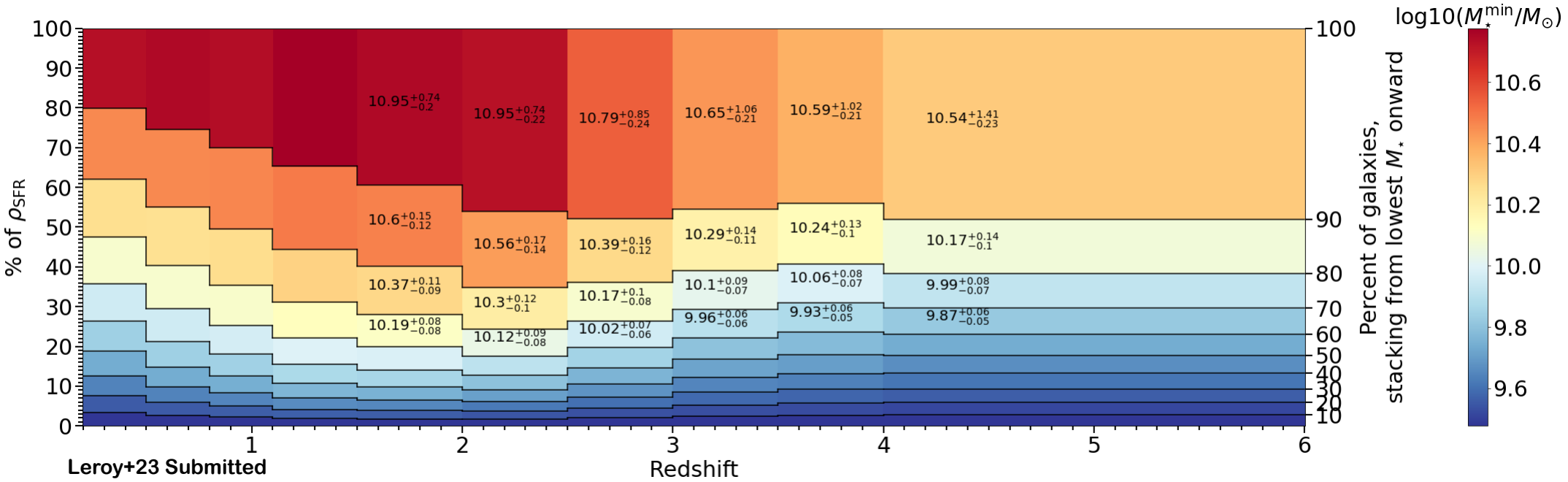


Barrufet+23

SFR as a function stellar mass.

e.g., Simpson+14, Wang+19, Williams+19, Toba+20, Umehata+20, Zhou+20, Fudamoto+21, Enia+22, Manning+22, Gomez-Guijarro+23, Barrufet+23, Xiao+23

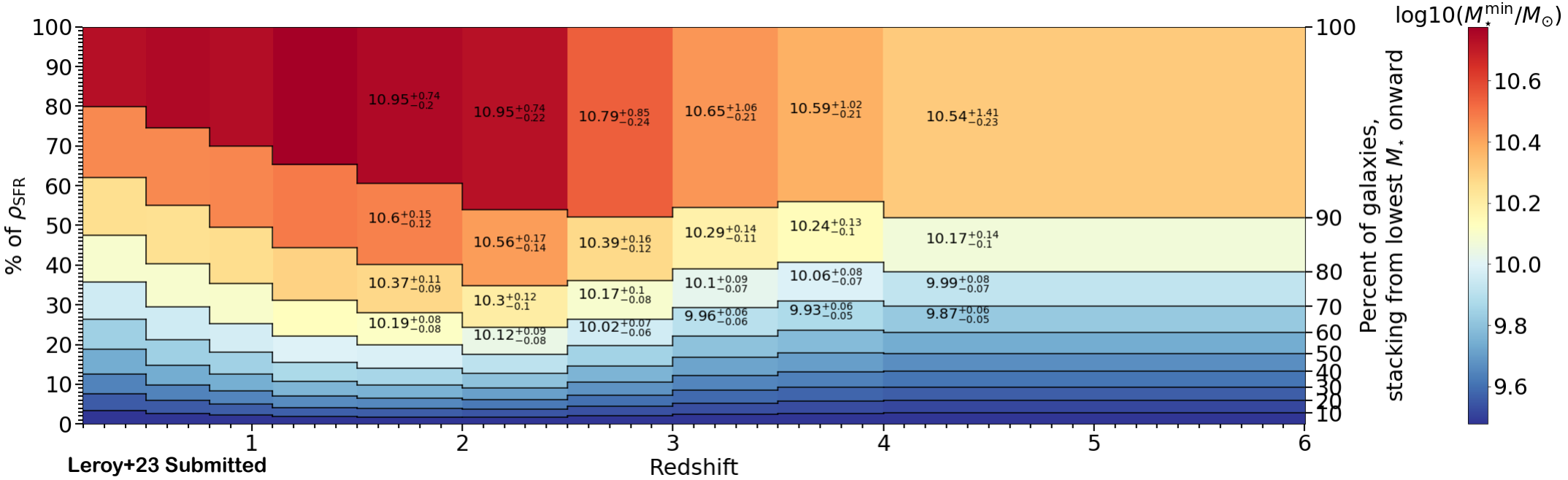
The cosmic star formation history ($\rho_{\rm SFR}$)



Leroy+23 Submitted

Contribution to $\rho_{\rm SFR}$ of SFGs as a function of redshift. Each bin includes 10% of the galaxies in number, picking from the lowest $M_\star$ onwards. The minimum $M_\star$ in the bin defines the colour. The numbers give the median $M_\star$ within the bin along with the lower and maximum extension of the bin.

The cosmic star formation history ($\rho_{\rm SFR}$)

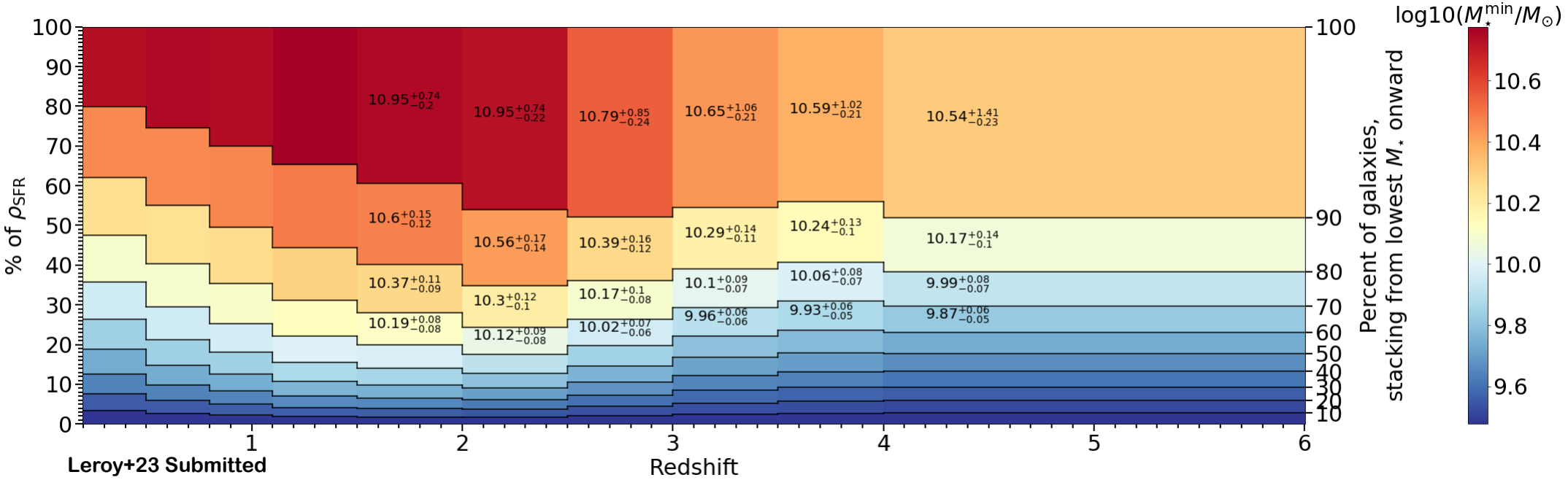


Leroy+23 Submitted

Contribution to $\rho_{\rm SFR}$ of SFGs as a function of redshift. Each bin includes 10% of the galaxies in number, picking from the lowest $M_\star$ onwards. The minimum $M_\star$ in the bin defines the colour. The numbers give the median $M_\star$ within the bin along with the lower and maximum extension of the bin.

- **Downsizing : 10%, in number, of most massive galaxies contribute to a large fraction of $\rho_{\rm SFR}$ (24% at z=0, 48% at z=5)**

The cosmic star formation history ($\rho_{\rm SFR}$)

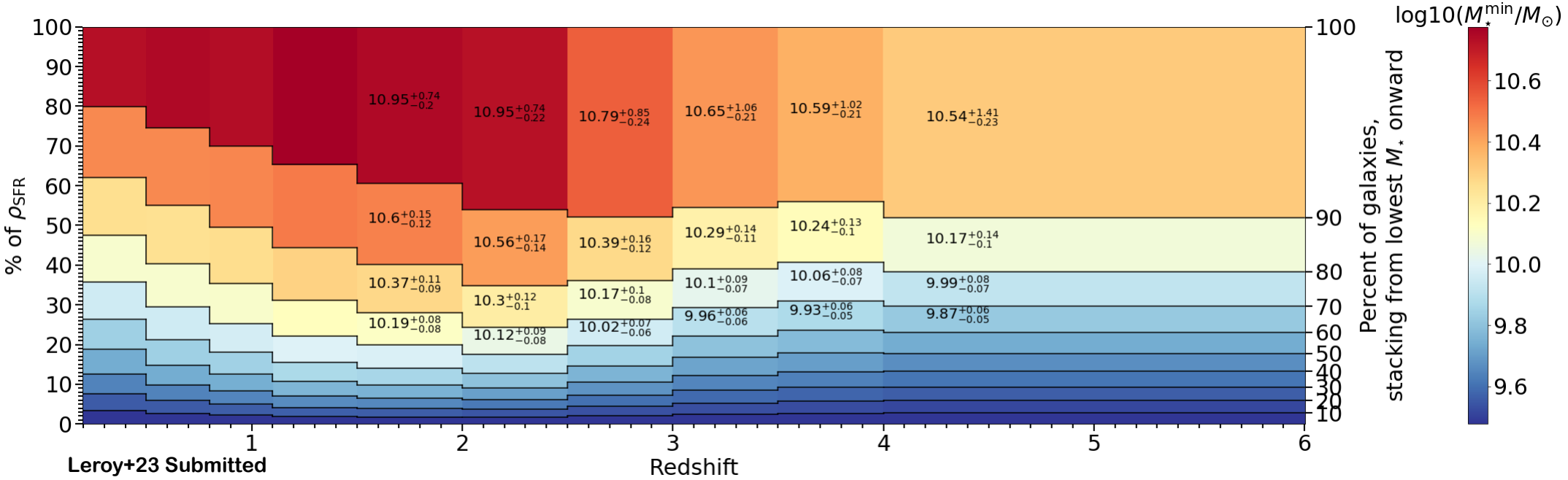


Leroy+23 Submitted

Contribution to $\rho_{\rm SFR}$ of SFGs as a function of redshift. Each bin includes 10% of the galaxies in number, picking from the lowest $M_\star$ onwards. The minimum $M_\star$ in the bin defines the colour. The numbers give the median $M_\star$ within the bin along with the lower and maximum extension of the bin.

- **Downsizing : 10%, in number, of most massive galaxies contribute to a large fraction of $\rho_{\rm SFR}$ (24% at z=0, 48% at z=5)**
- **Gradual quenching**

The cosmic star formation history ($\rho_{\rm SFR}$)

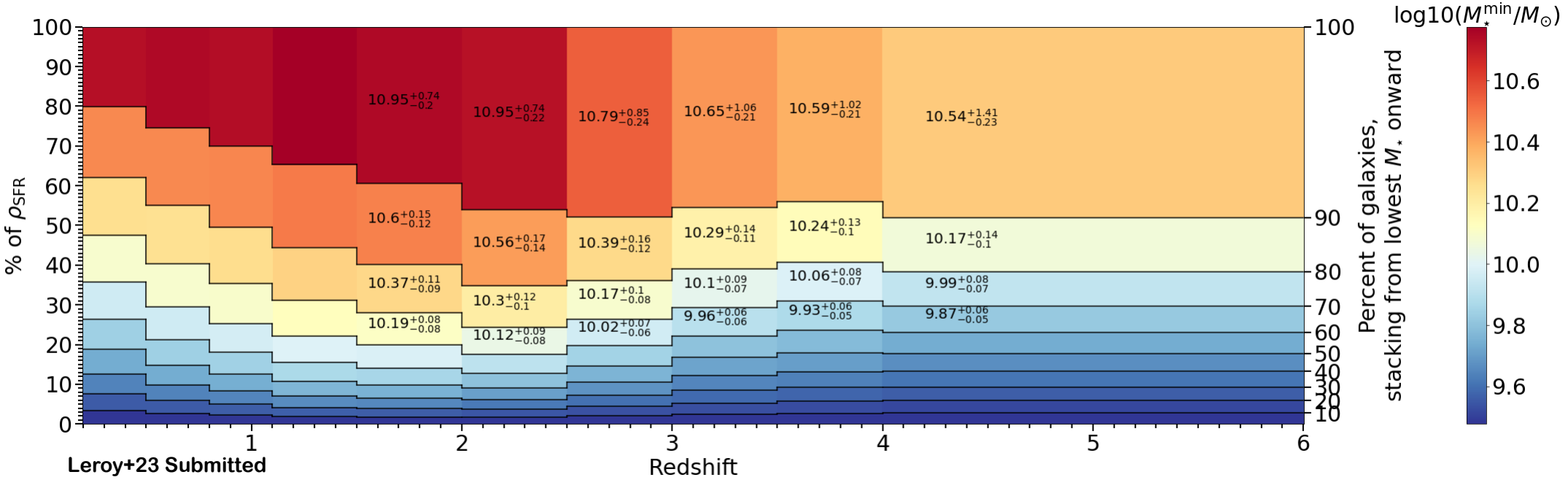


Leroy+23 Submitted

Contribution to $\rho_{\rm SFR}$ of SFGs as a function of redshift. Each bin includes 10% of the galaxies in number, picking from the lowest $M_\star$ onwards. The minimum $M_\star$ in the bin defines the colour. The numbers give the median $M_\star$ within the bin along with the lower and maximum extension of the bin.

- Downsizing : 10%, in number, of most massive galaxies contribute to a large fraction of $\rho_{\rm SFR}$ (24% at z=0, 48% at z=5)
- Gradual quenching
- Hierarchical growth

The cosmic star formation history ($\rho_{\rm SFR}$)

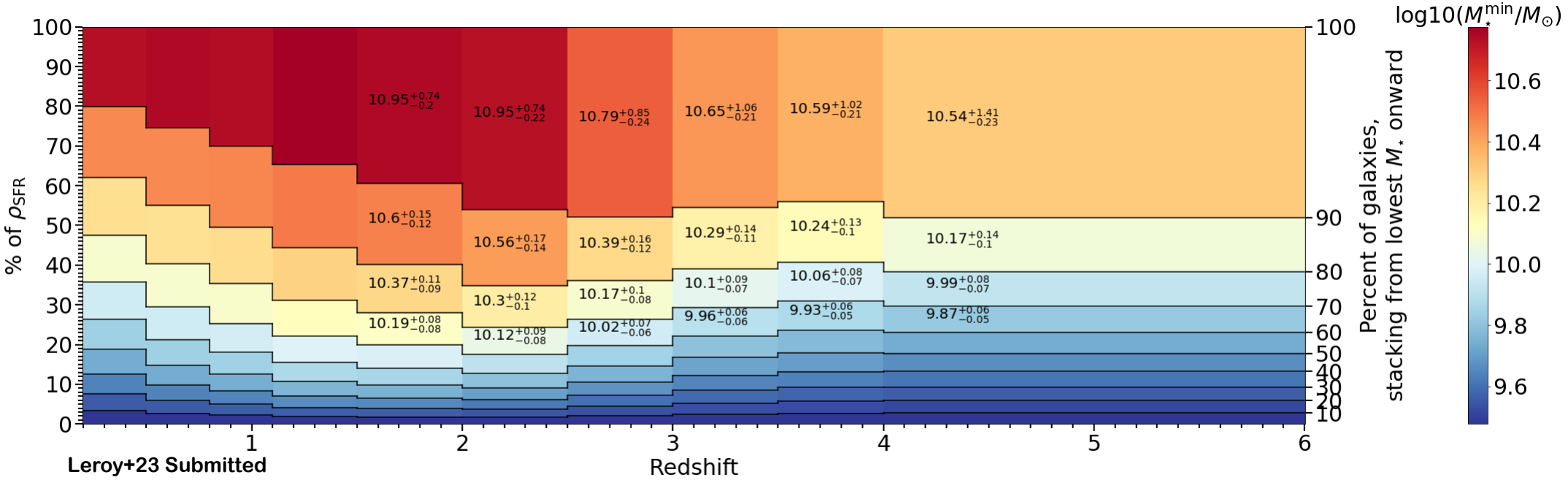


Leroy+23 Submitted

Contribution to $\rho_{\rm SFR}$ of SFGs as a function of redshift. Each bin includes 10% of the galaxies in number, picking from the lowest $M_\star$ onwards. The minimum $M_\star$ in the bin defines the colour. The numbers give the median $M_\star$ within the bin along with the lower and maximum extension of the bin.

- How much massive galaxies contribute to the SFRD?

The cosmic star formation history ($\rho_{\rm SFR}$)

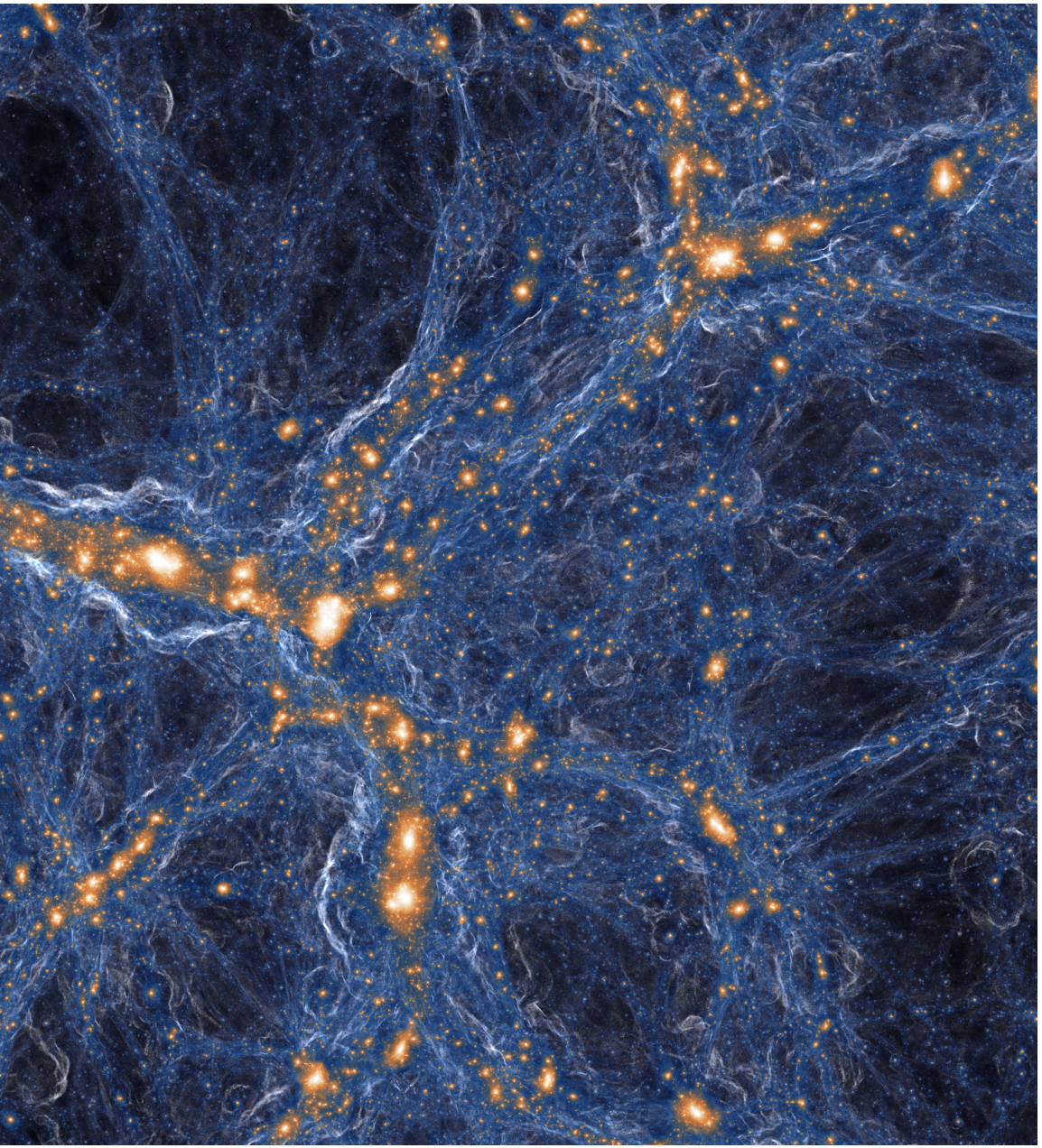


Leroy+23 Submitted

Contribution to $\rho_{\rm SFR}$ of SFGs as a function of redshift. Each bin includes 10% of the galaxies in number, picking from the lowest $M_\star$ onwards. The minimum $M_\star$ in the bin defines the colour. The numbers give the median $M_\star$ within the bin along with the lower and maximum extension of the bin.

How much massive galaxies contribute to the SFRD?

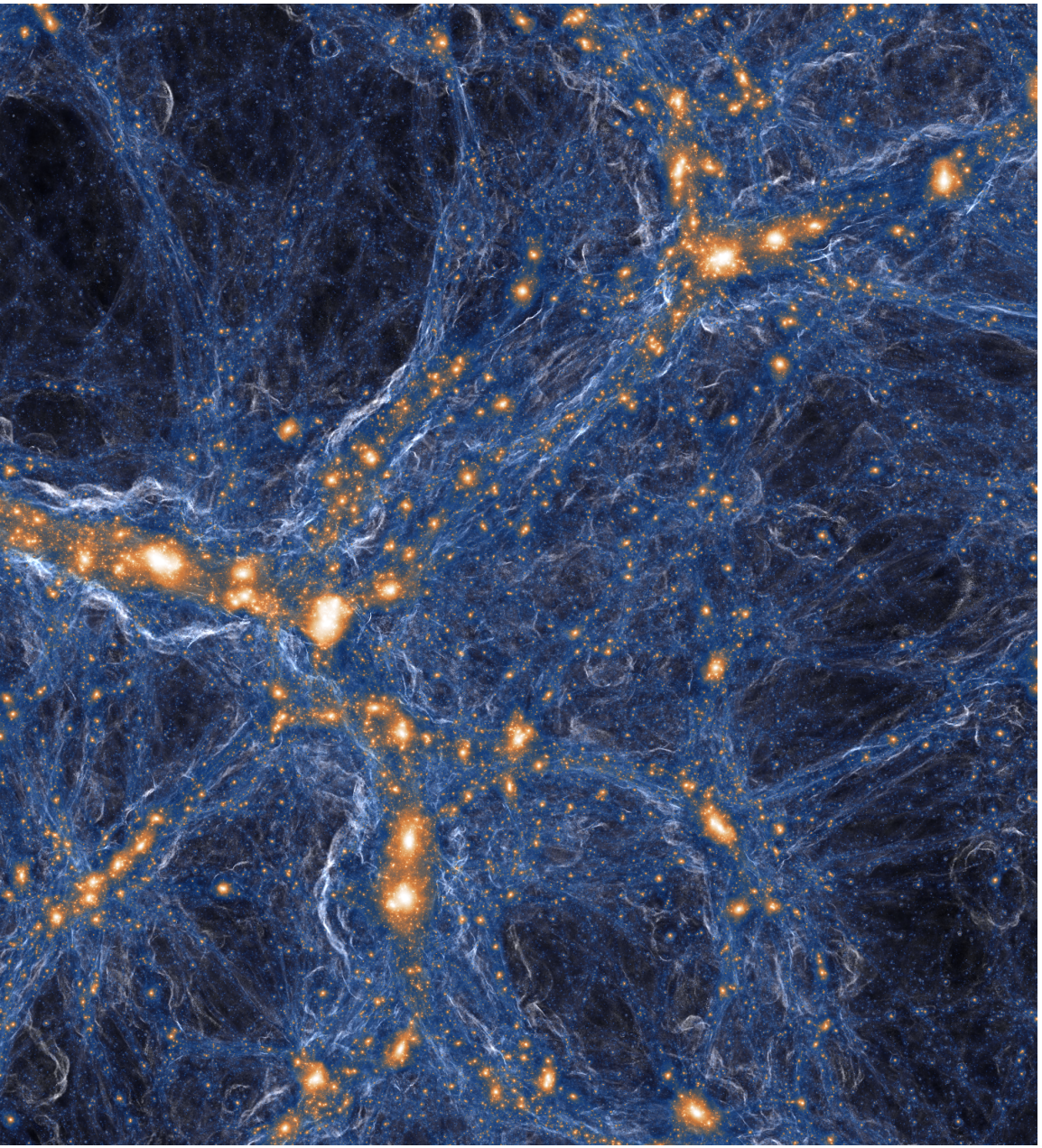
More than 40% at $z > 3$



TNG100

e.g., Weinberger+17, Marinacci+18, Naiman+18, Nelson+18, Pillepich+18a,b , Springel+18, Nelson+19

Credit: TNG Collaboration



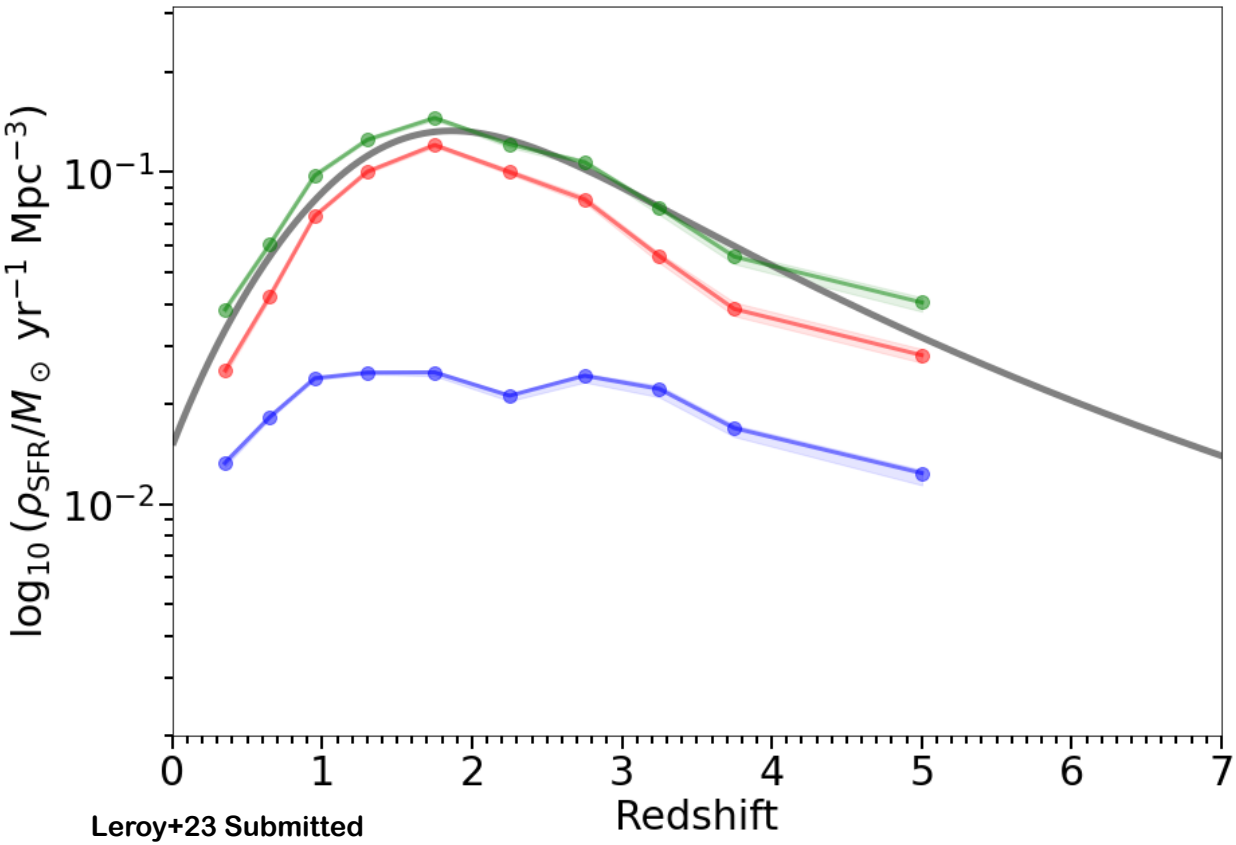
TNG100

Can it reproduce the contribution of massive galaxies to $\rho_{\rm SFR}$?

e.g., Weinberger+17, Marinacci+18, Naiman+18, Nelson+18, Pillepich+18a,b , Springel+18, Nelson+19

Credit: TNG Collaboration

The cosmic star formation history ($\rho_{\rm SFR}$)



Leroy+23 Submitted

Madau & Dickinson+14

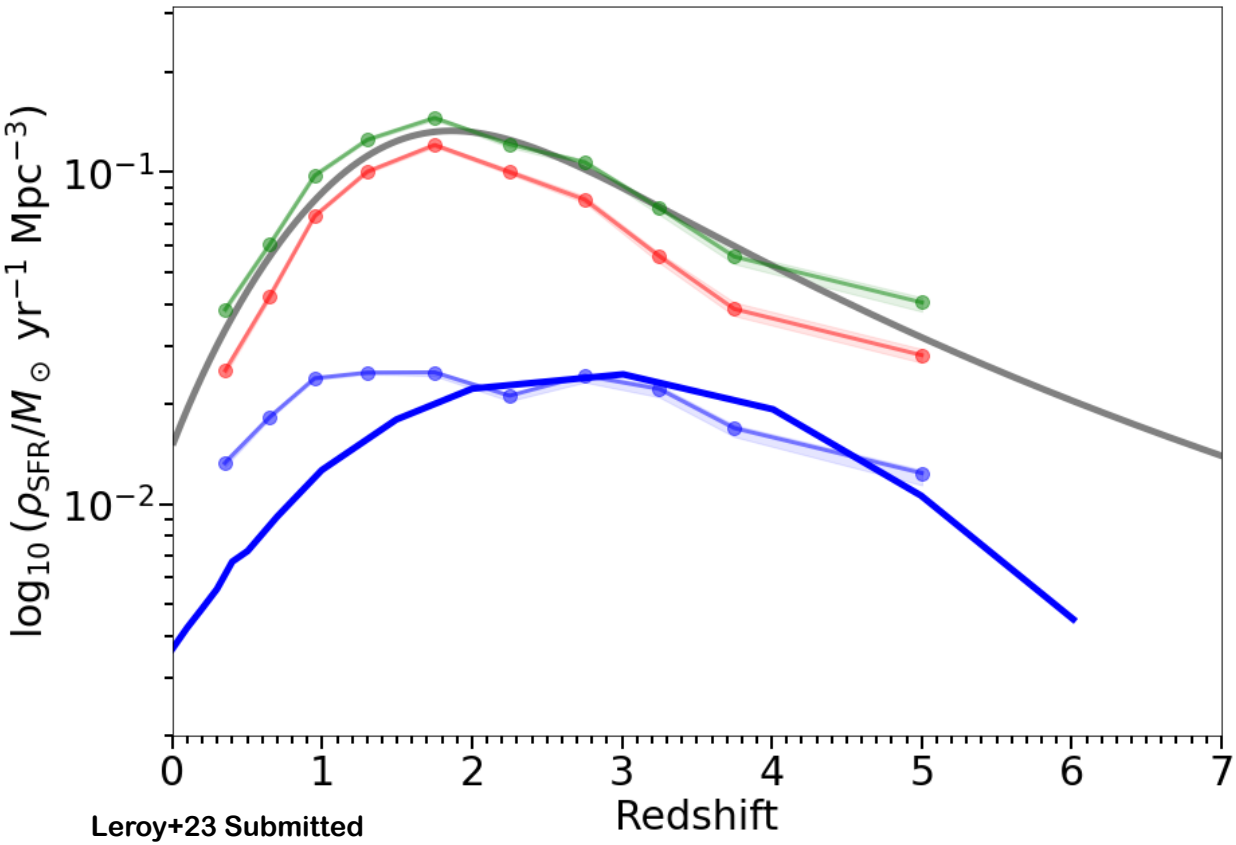
Total $\rho_{\rm SFR}$

$\rho_{\rm SFR}$ for $M_\star \geq 10^{10}\,M_\odot$

$\rho_{\rm SFR}$ for $M_\star < 10^{10}\,M_\odot$

Cosmic star formation rate density ($\rho_{\rm SFR}$) as a function of redshift

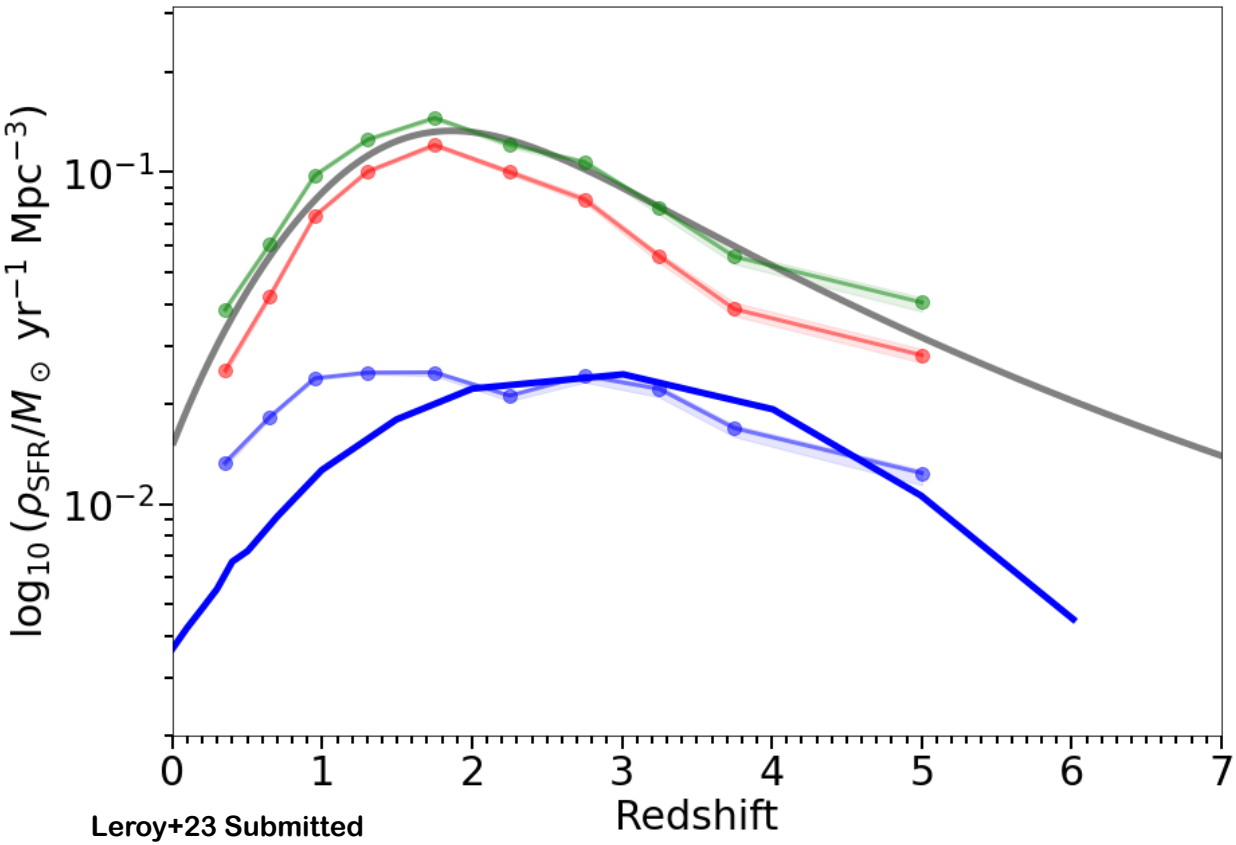
The cosmic star formation history ($\rho_{\rm SFR}$)



Leroy+23 Submitted

Cosmic star formation rate density ($\rho_{\rm SFR}$) as a function of redshift

The cosmic star formation history ($\rho_{\rm SFR}$)



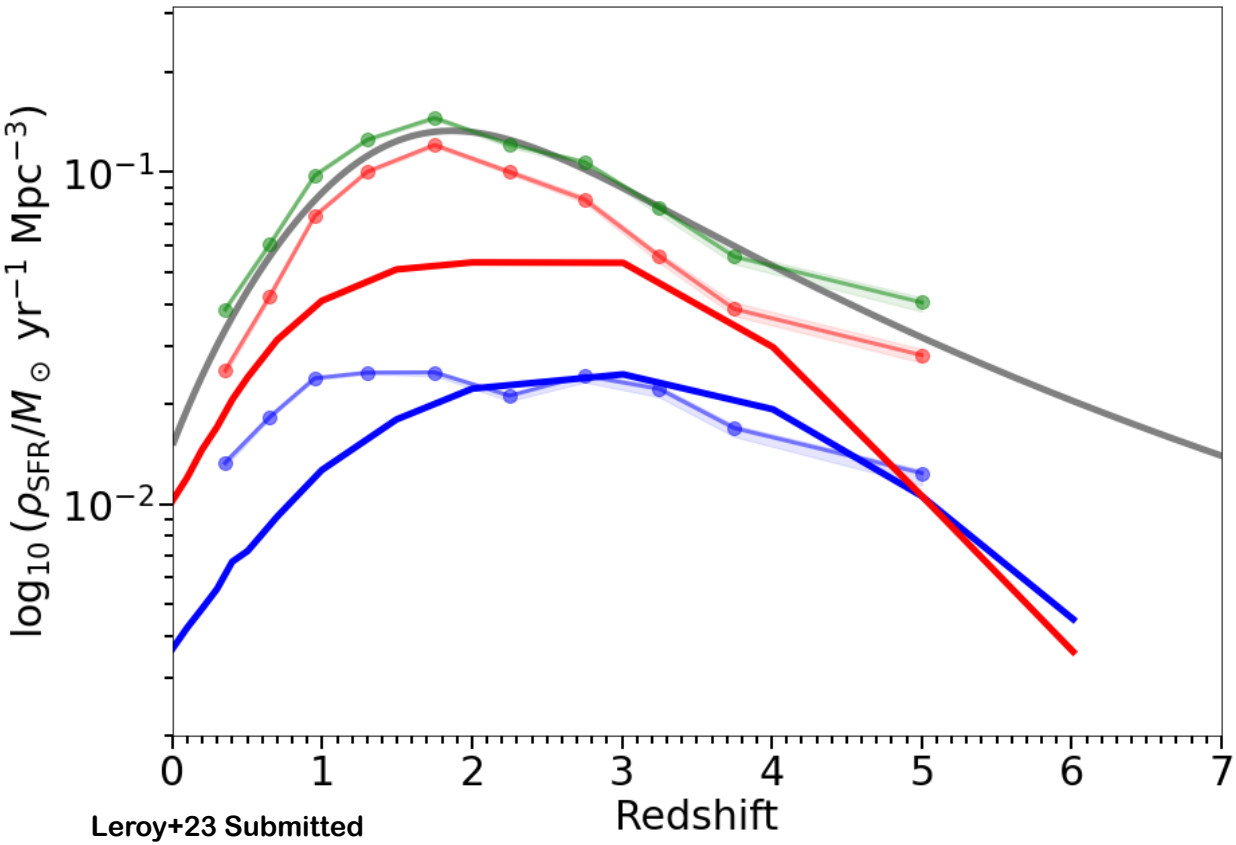
Leroy+23 Submitted

- Low mass galaxies contribution is quite well reproduced

- Madau & Dickinson+14
- Total $\rho_{\rm SFR}$
- $\rho_{\rm SFR}$ for $M_\star \geq 10^{10}\,M_\odot$
- $\rho_{\rm SFR}$ for $M_\star < 10^{10}\,M_\odot$

Cosmic star formation rate density ($\rho_{\rm SFR}$) as a function of redshift

The cosmic star formation history ($\rho_{\rm SFR}$)



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Cosmic star formation rate density ($\rho_{\rm SFR}$) as a function of redshift

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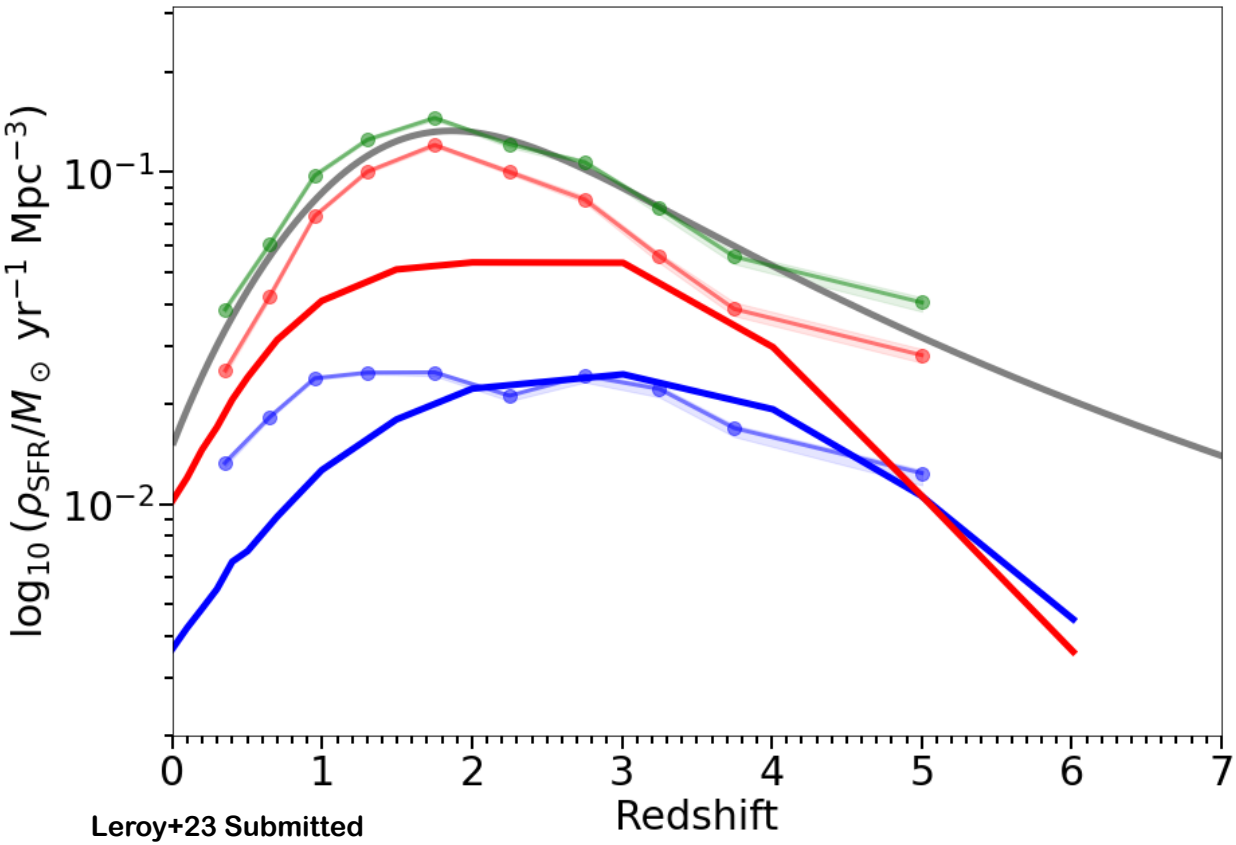


Leroy+23 Submitted

- Low mass galaxies contribution is quite well reproduced
- High mass galaxies contribution is under-estimated at most redshift

Madau & Dickinson+14

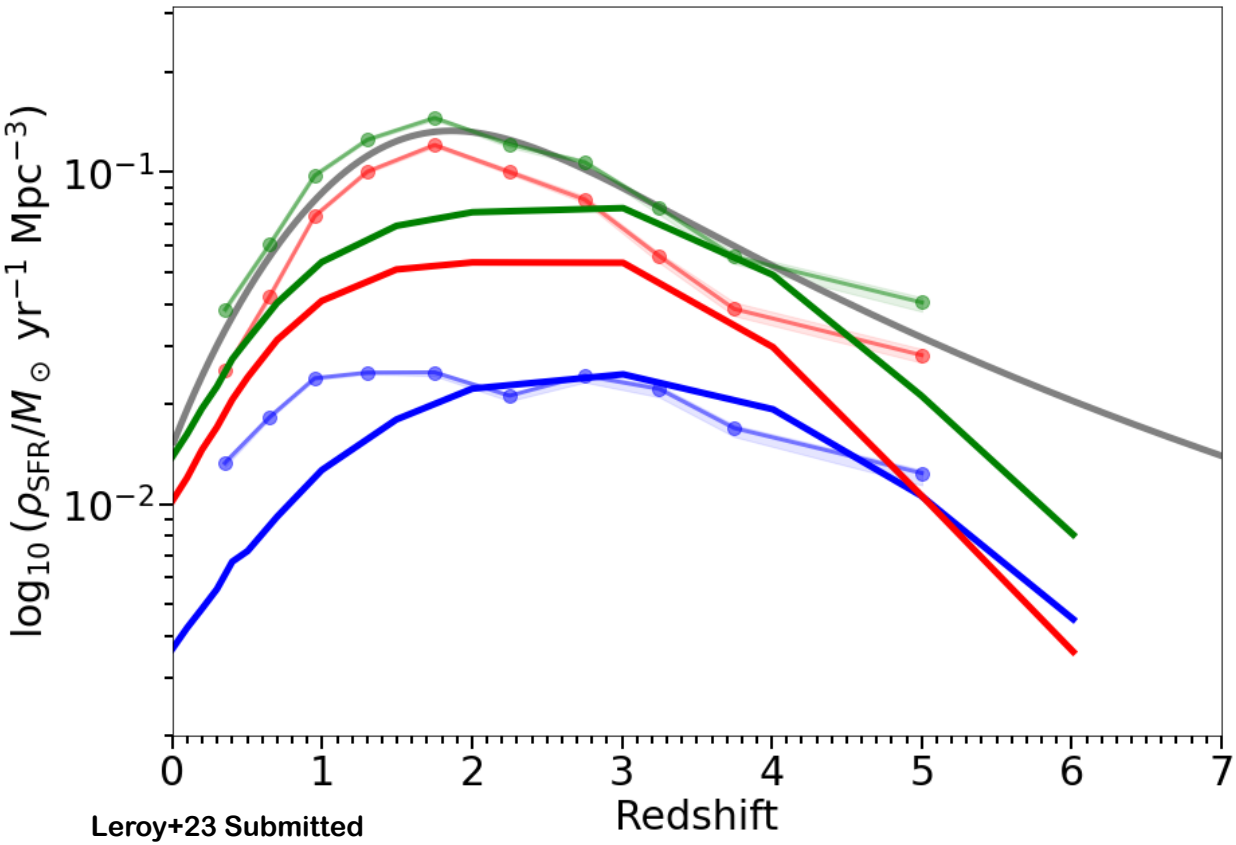
Total $\rho_{\rm SFR}$

$\rho_{\rm SFR}$ for $M_\star \geq 10^{10}\,M_\odot$

$\rho_{\rm SFR}$ for $M_\star < 10^{10}\,M_\odot$

Cosmic star formation rate density ($\rho_{\rm SFR}$) as a function of redshift

The cosmic star formation history ($\rho_{\rm SFR}$)



Leroy+23 Submitted

- Low mass galaxies contribution is quite well reproduced
- High mass galaxies contribution is under-estimated at most redshift

Madau & Dickinson+14

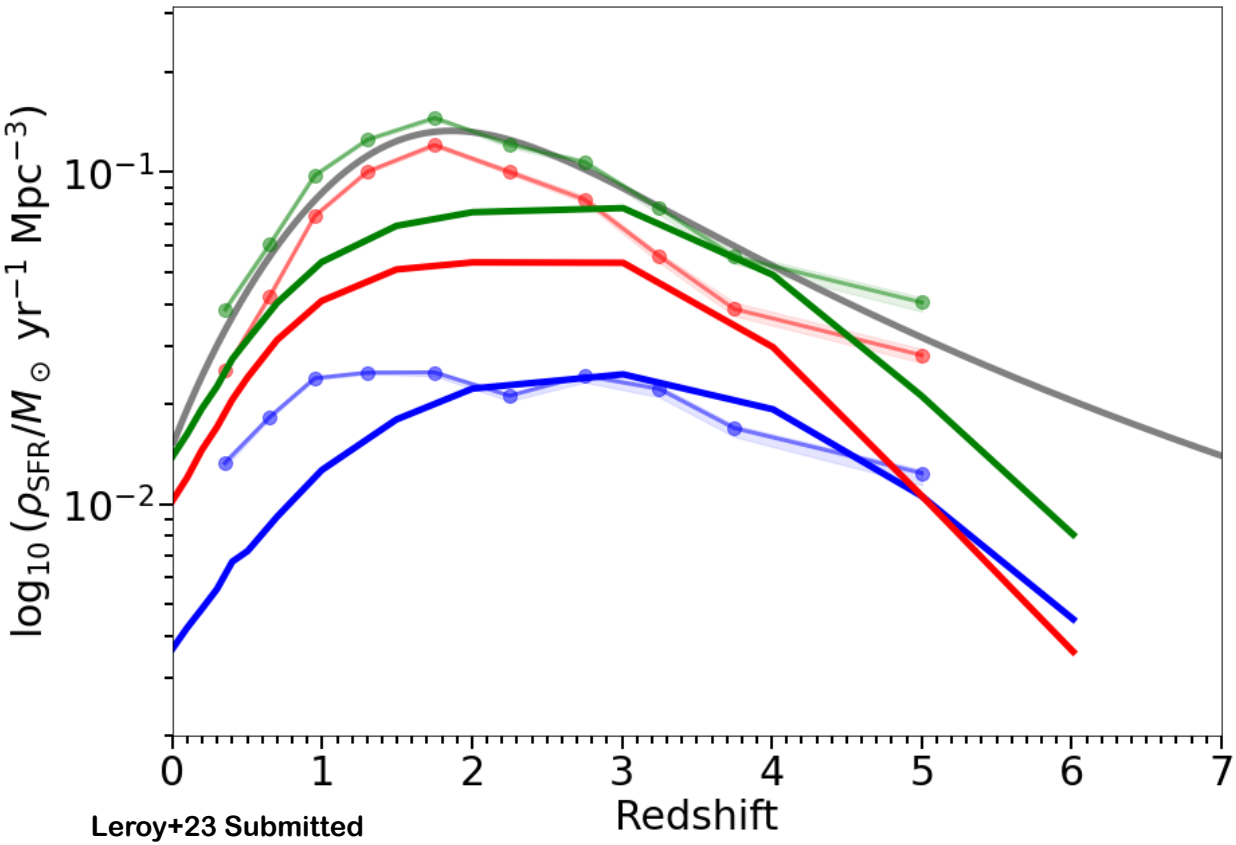
Total $\rho_{\rm SFR}$

$\rho_{\rm SFR}$ for $M_\star \geq 10^{10}\,M_\odot$

$\rho_{\rm SFR}$ for $M_\star < 10^{10}\,M_\odot$

Cosmic star formation rate density ($\rho_{\rm SFR}$) as a function of redshift

The cosmic star formation history ($\rho_{\rm SFR}$)



Leroy+23 Submitted

- Low mass galaxies contribution is quite well reproduced
- High mass galaxies contribution is under-estimated at most redshift
- Which results in an under-estimation at most redshift of the total $\rho_{\rm SFR}$

Madau & Dickinson+14

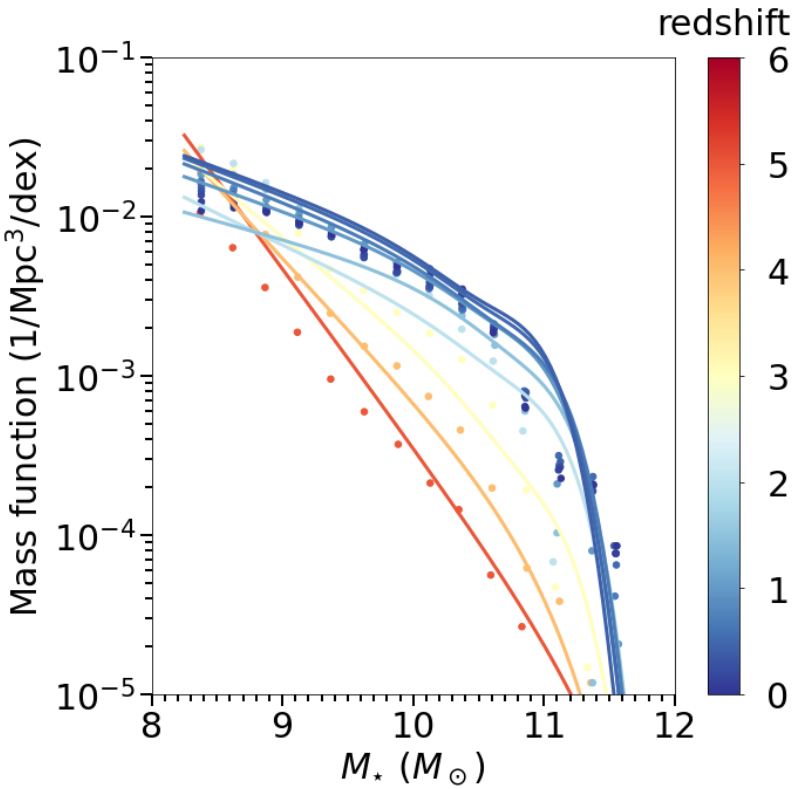
Total $\rho_{\rm SFR}$

$\rho_{\rm SFR}$ for $M_\star \geq 10^{10}\,M_\odot$

$\rho_{\rm SFR}$ for $M_\star < 10^{10}\,M_\odot$

Cosmic star formation rate density ($\rho_{\rm SFR}$) as a function of redshift

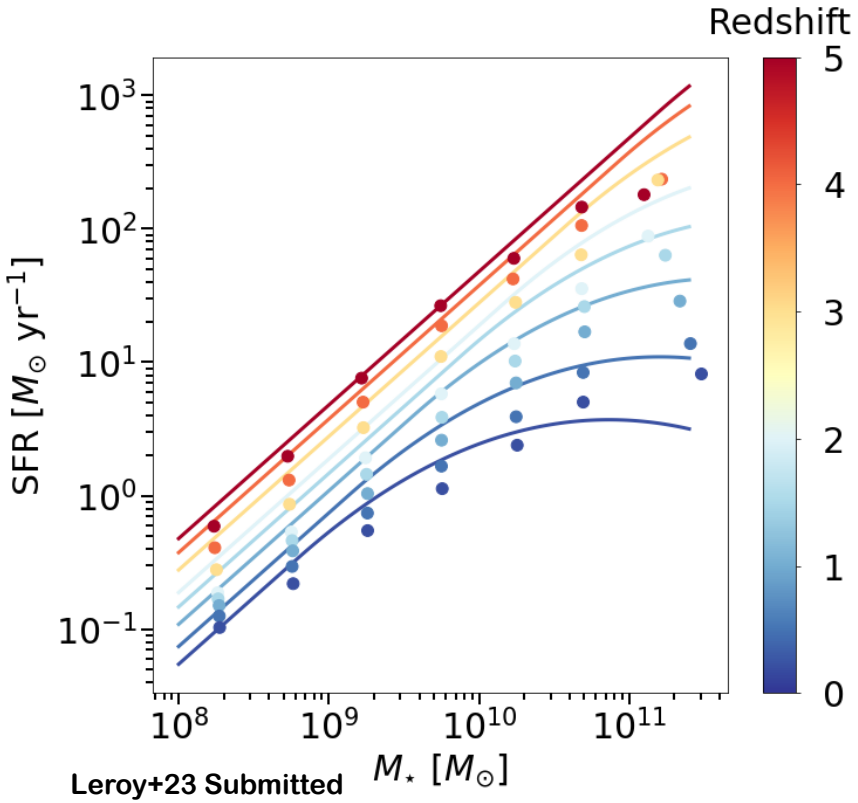
Why an under-estimation in massive galaxies



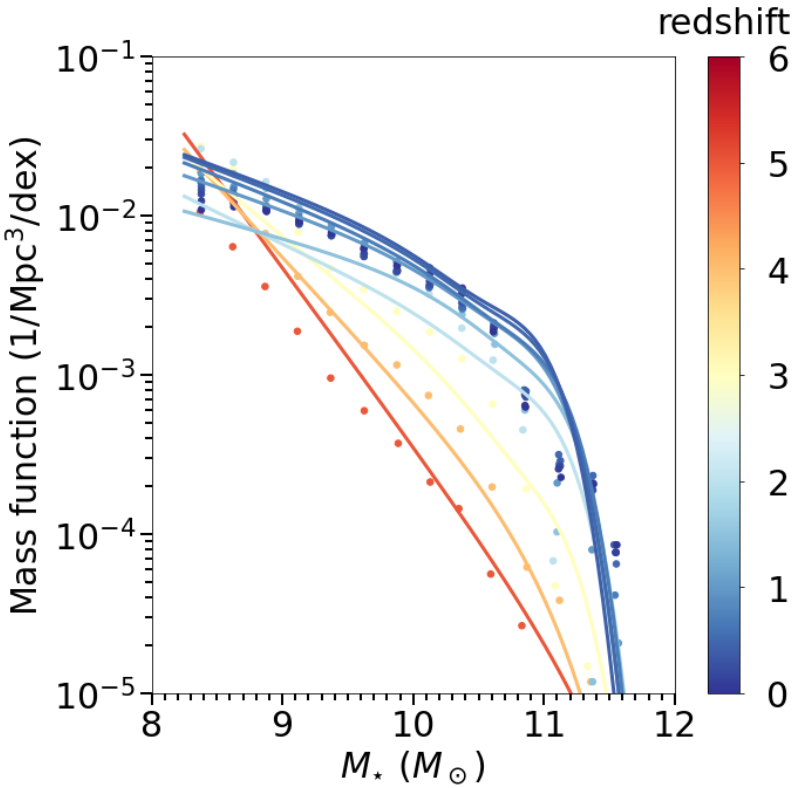
Leroy+23 Submitted

The mass function from TNG100

Why an under-estimation in massive galaxies

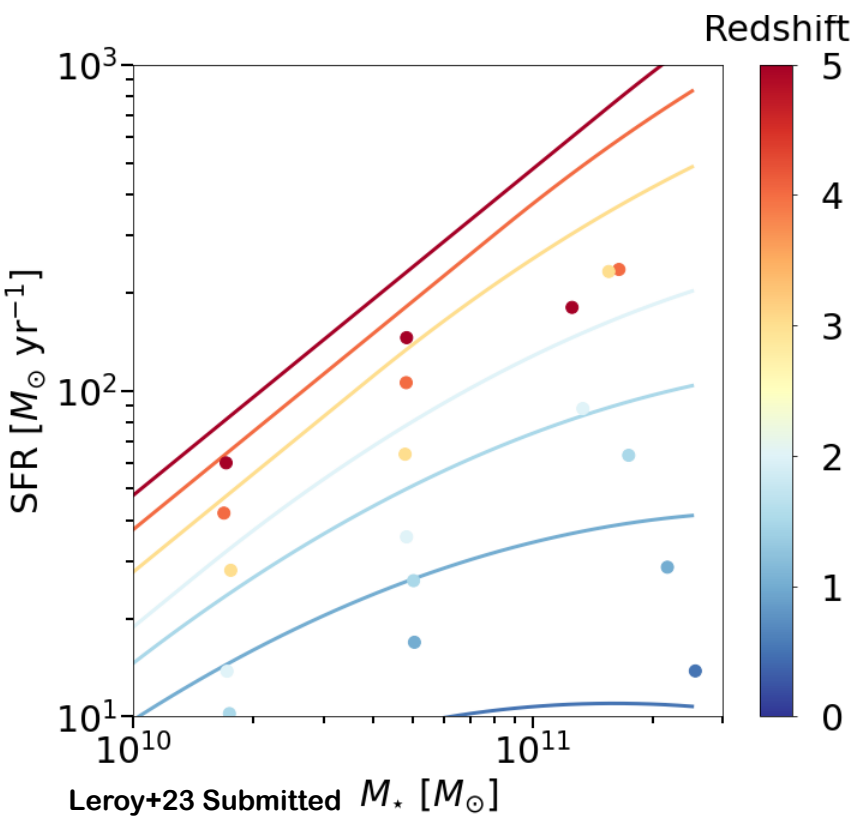


The star formation main sequence from TNG100



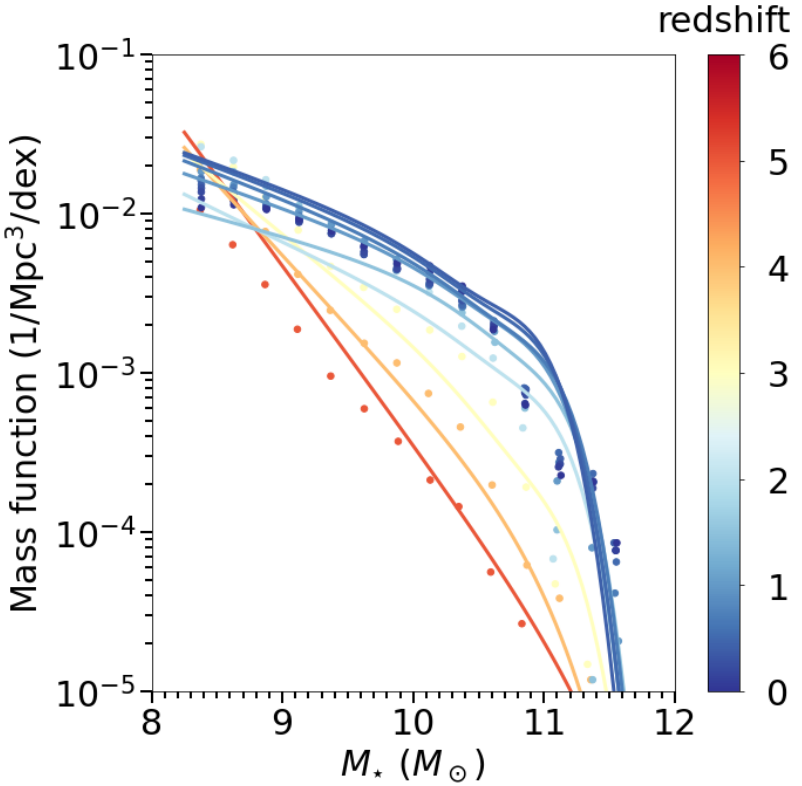
The mass function from TNG100

Why an under-estimation in massive galaxies



Leroy+23 Submitted

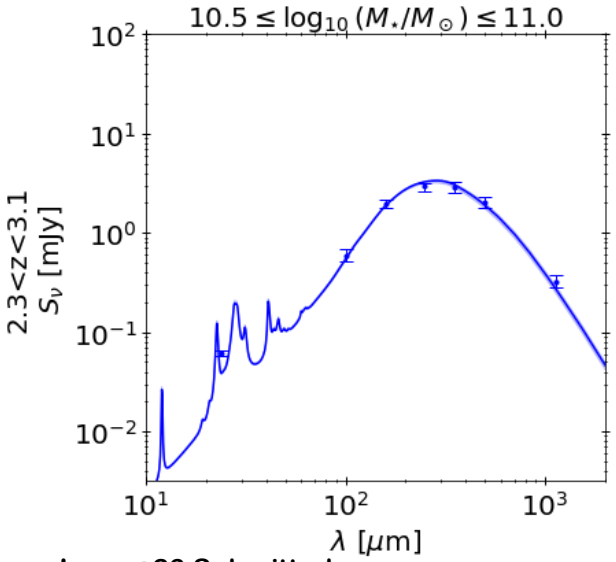
The star formation main sequence from TNG100



Leroy+23 Submitted

The mass function from TNG100

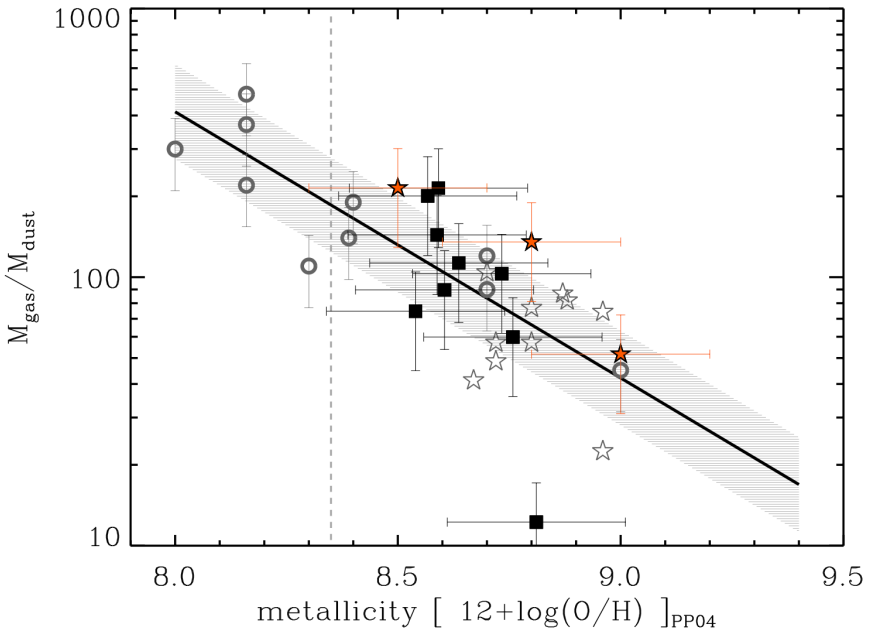
The gas mass evolution of SFGs



Leroy+23 Submitted

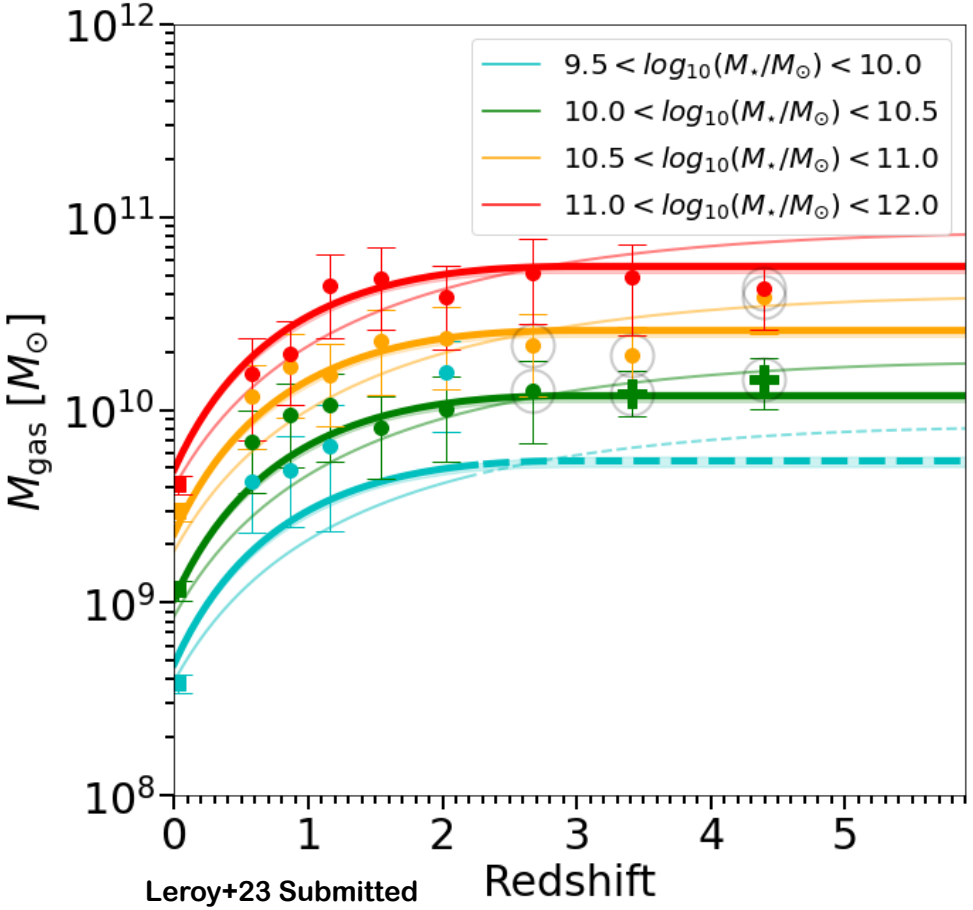
$M_{\rm dust}$

$M_{\rm gas}$



Magdis+12

The gas mass evolution of SFGs

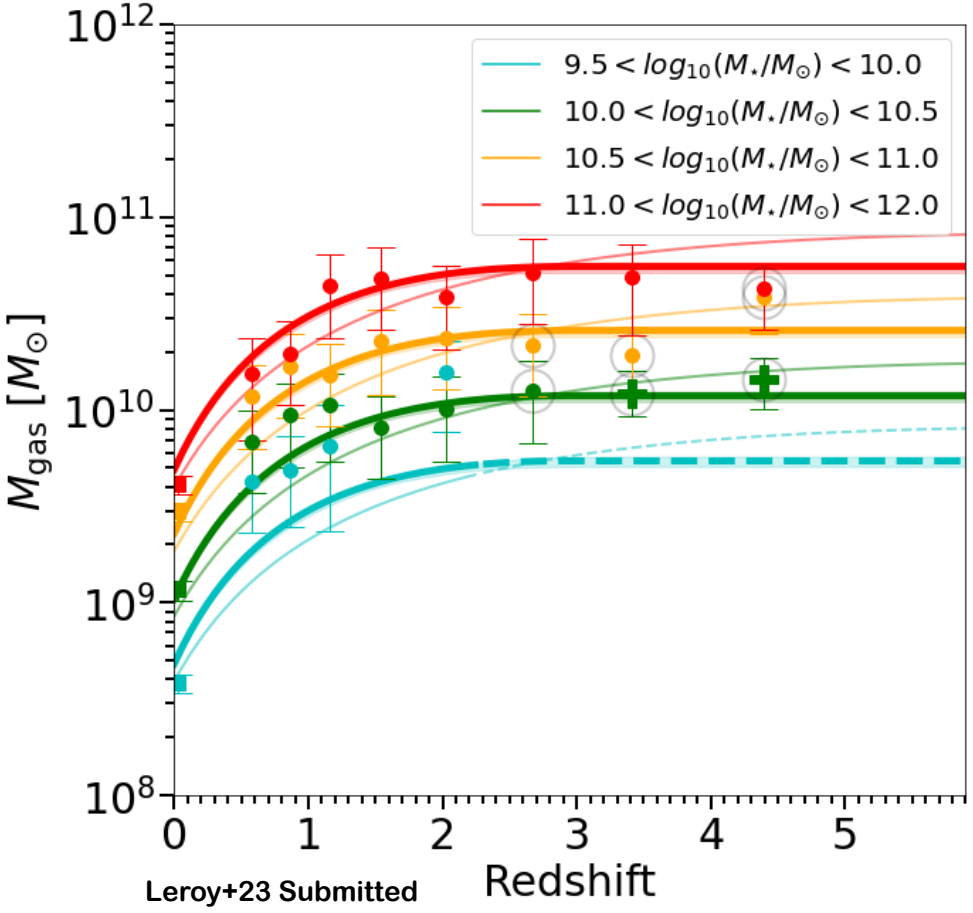


Leroy+23 Submitted

$M_{\rm gas}$ as a function of redshift for different $M_\star$

- $M_{\rm gas}$ from a δ_{GDR} − MZR method
- $M_{\rm gas}$ from a Scoville+16 method
- H-dropout contribution from Wang+19 is added
- $M_{\rm gas}$ measurements from Saintonge+17

The gas mass evolution of SFGs



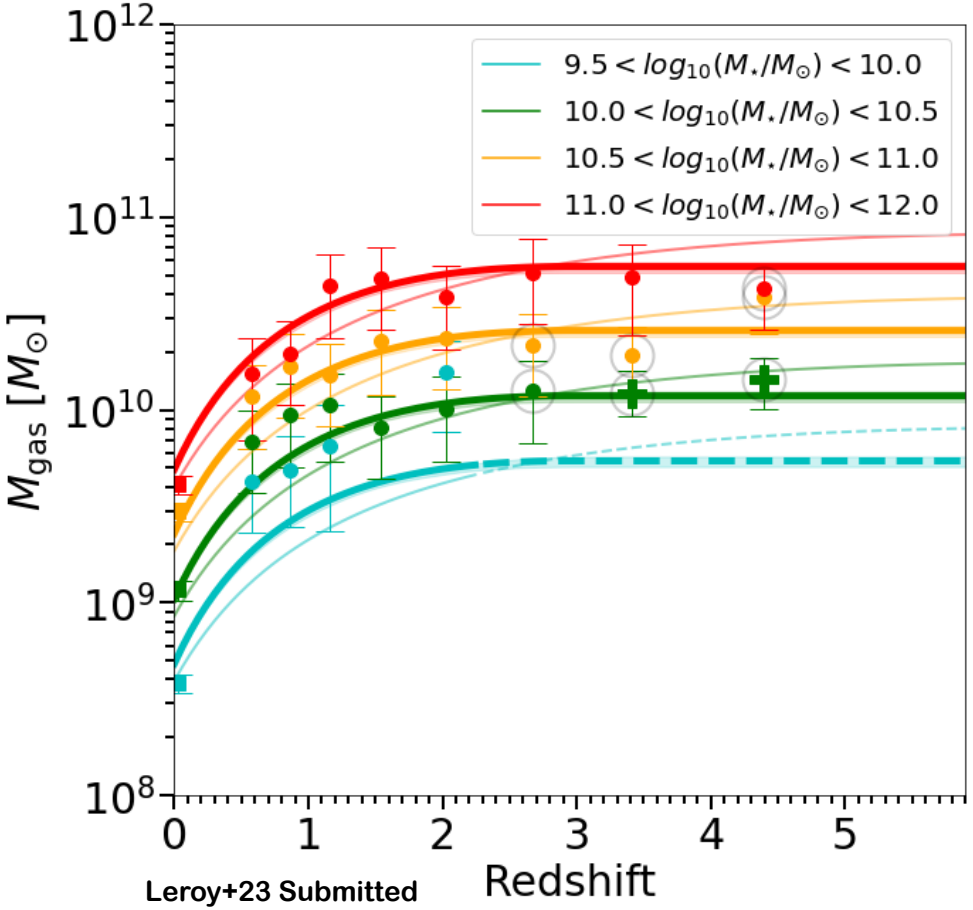
Leroy+23 Submitted

$M_{\rm gas}$ as a function of redshift for different $M_\star$

- Increase of $M_{\rm gas}$ with stellar mass

- $M_{\rm gas}$ from a $\delta_{GDR}-$ MZR method
- $M_{\rm gas}$ from a Scoville+16 method
- H-dropout contribution from Wang+19 is added
- $M_{\rm gas}$ measurements from Saintonge+17

The gas mass evolution of SFGs



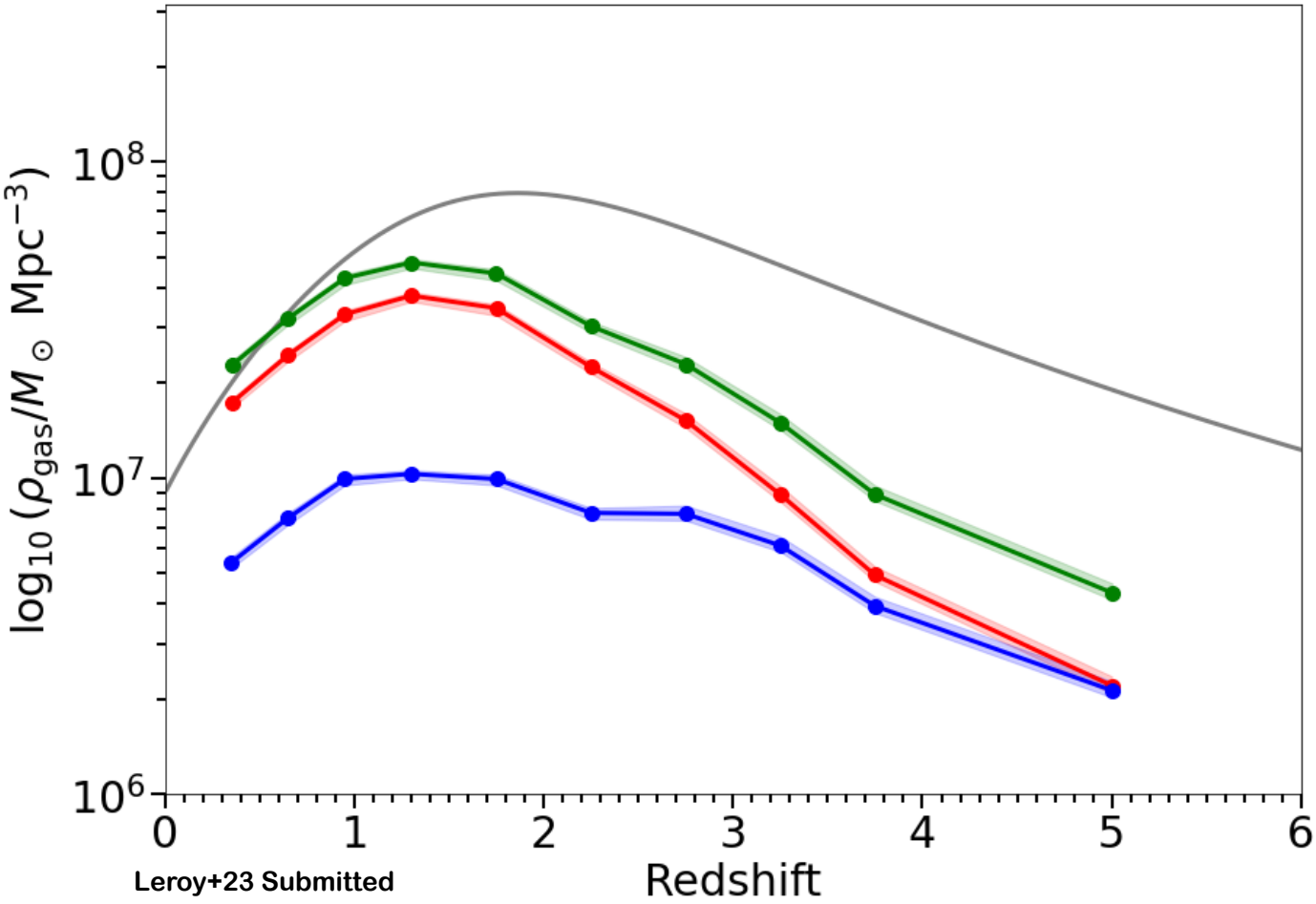
Leroy+23 Submitted

M_{gas} as a function of redshift for different $M_\star$

- Increase of M_{gas} with stellar mass
- Increase of M_{gas} with redshift up to $z \sim 2$

- M_{gas} from a δ_{GDR} − MZR method
- M_{gas} from a Scoville+16 method
- H-dropout contribution from Wang+19 is added
- M_{gas} measurements from Saintonge+17

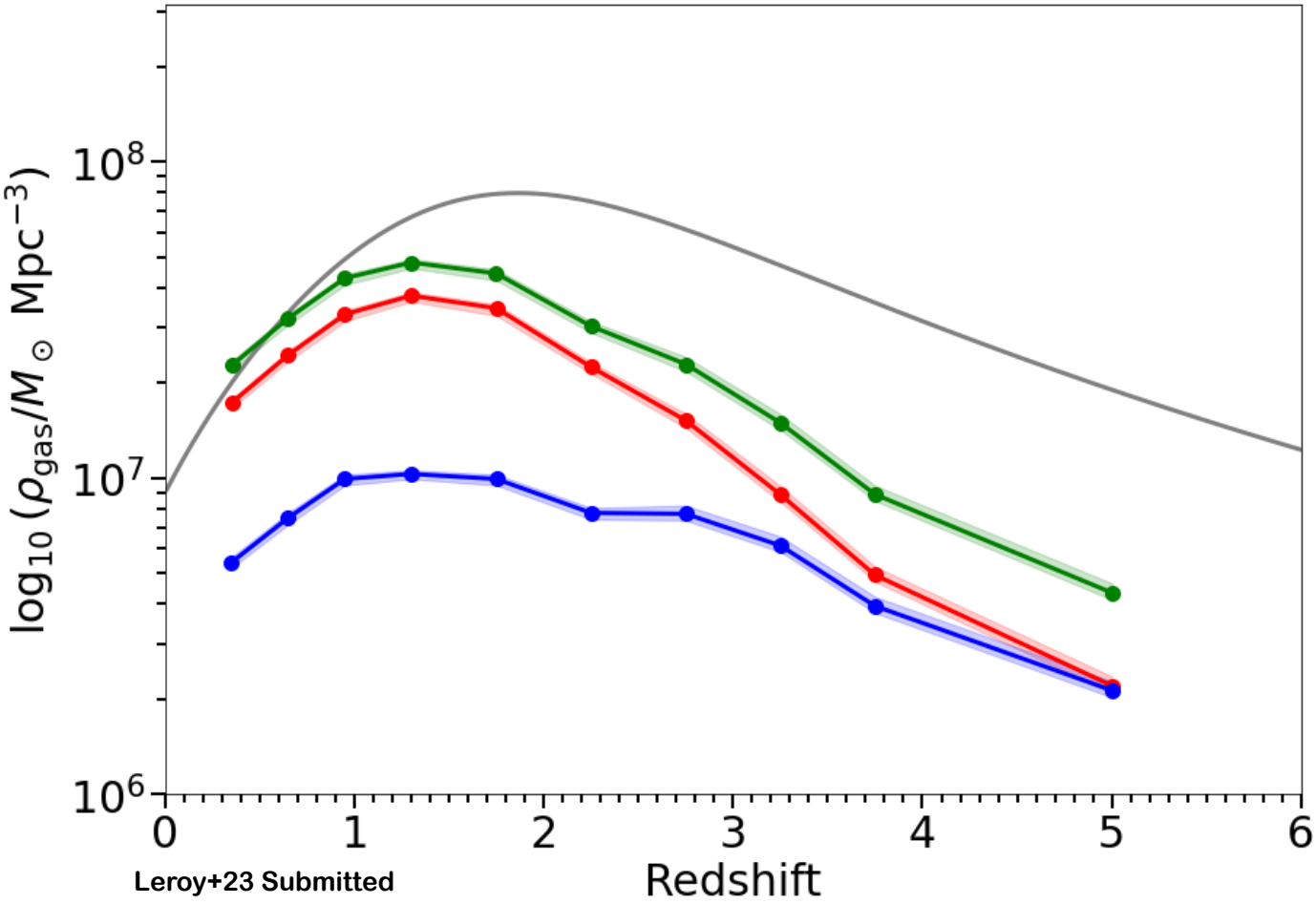
The cosmic evolution of the gas mass density ($\rho_{\rm gas}$)



The cosmic evolution of the gas mass density ($\rho_{\rm gas}$)

- Madau & Dickinson+14 $\times\ \tau_{\rm dep}^{600\,{\rm Myr}}$
- This work
- This work for $M_\star \geq 10^{10}\,M_\odot$
- This work for $M_\star < 10^{10}\,M_\odot$

The cosmic evolution of the gas mass density ($\rho_{\rm gas}$)



The cosmic evolution of the gas mass density ($\rho_{\rm gas}$)

Hints of higher SFE at high z

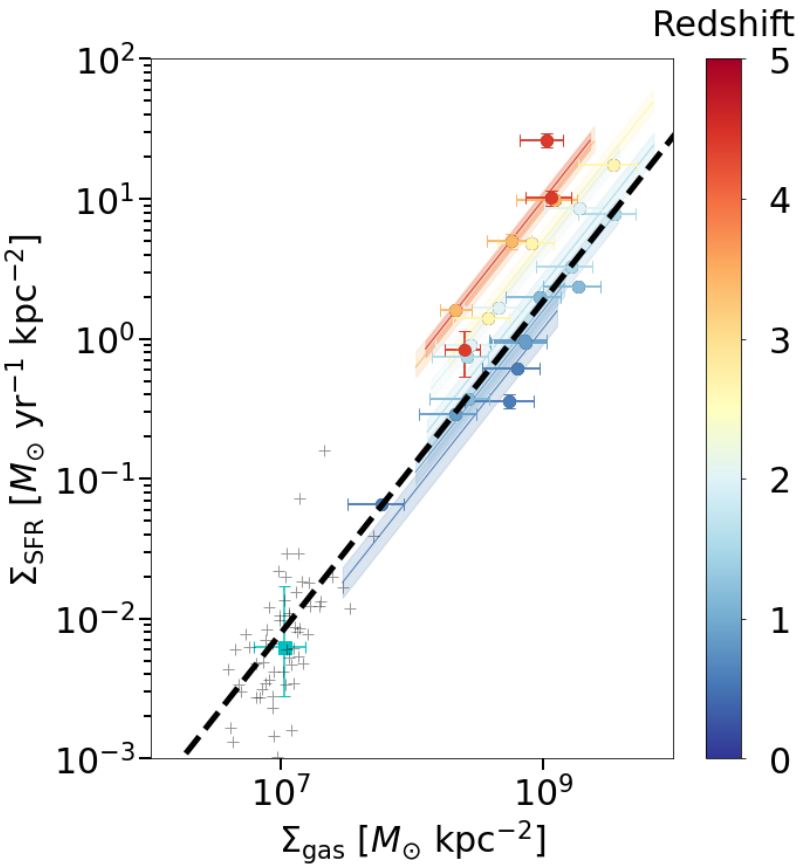
Madau & Dickinson+14 $\times\ \tau_{\rm dep}^{600\,{\rm Myr}}$

This work

This work for $M_\star \geq 10^{10}\,M_\odot$

This work for $M_\star < 10^{10}\,M_\odot$

The Kennicutt-Schmidt relation



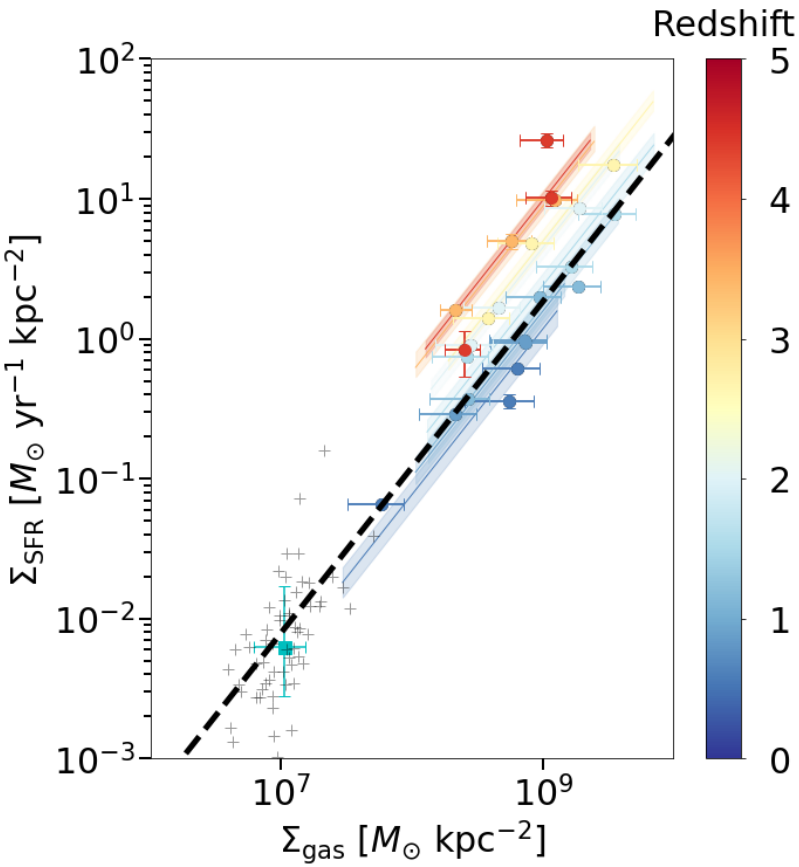
Leroy+23 Submitted

The Kennicutt-Schmidt relation

- Fitted with an equation of the form:

$$\log_{10}(\Sigma_{SFR}) = A + N \times \log_{10}(\Sigma_{gas})$$

The Kennicutt-Schmidt relation



Leroy+23 Submitted

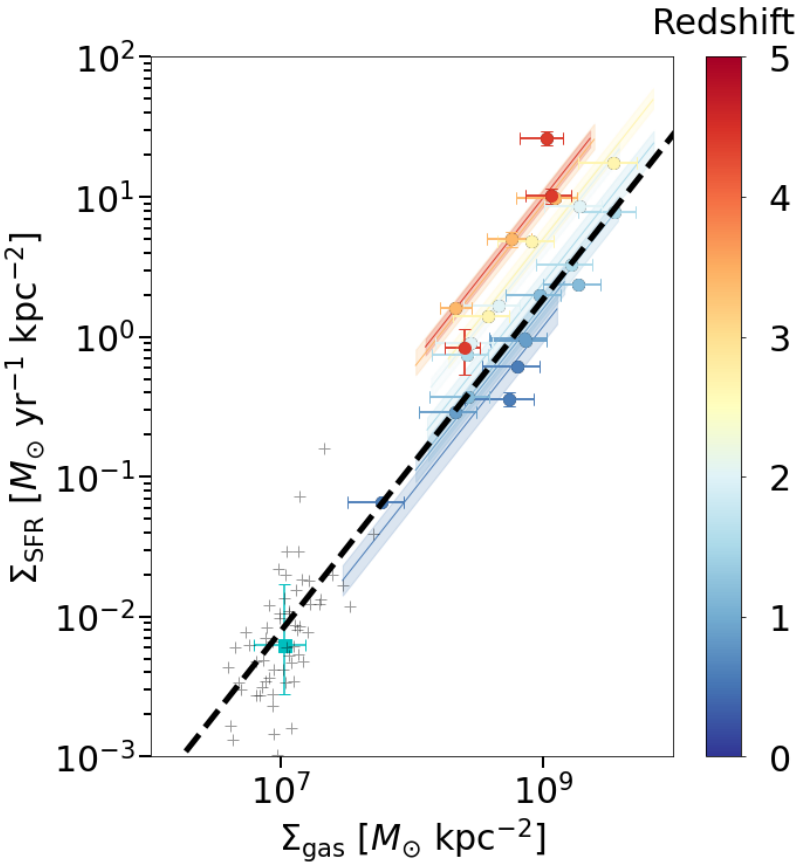
The Kennicutt-Schmidt relation

- Fitted with an equation of the form:

$$\log_{10}(\Sigma_{SFR}) = A + N \times \log_{10}(\Sigma_{gas})$$

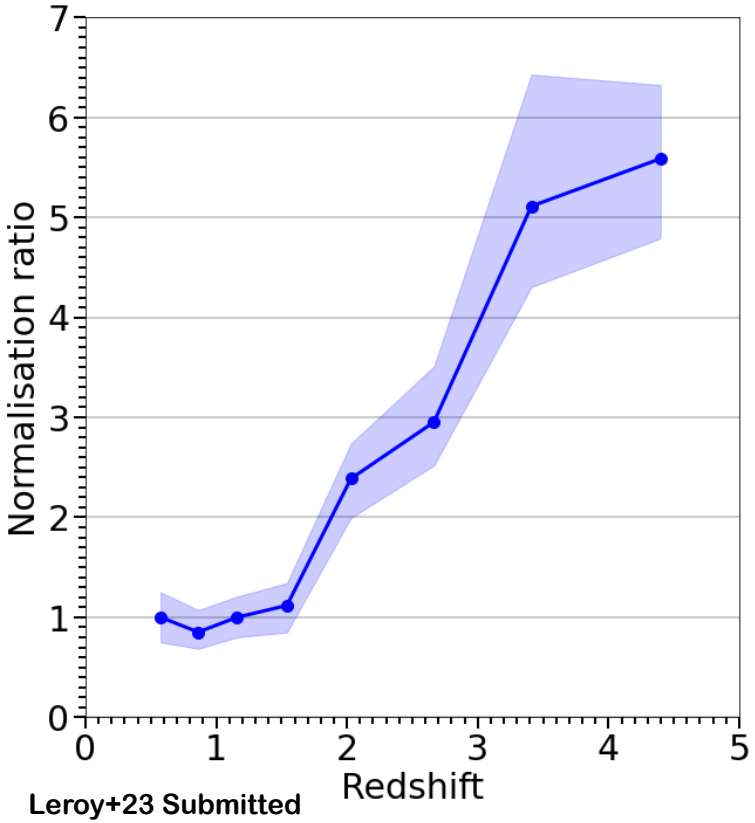
- Best fit gives N=1.18

The Kennicutt-Schmidt relation



Leroy+23 Submitted

The Kennicutt-Schmidt relation

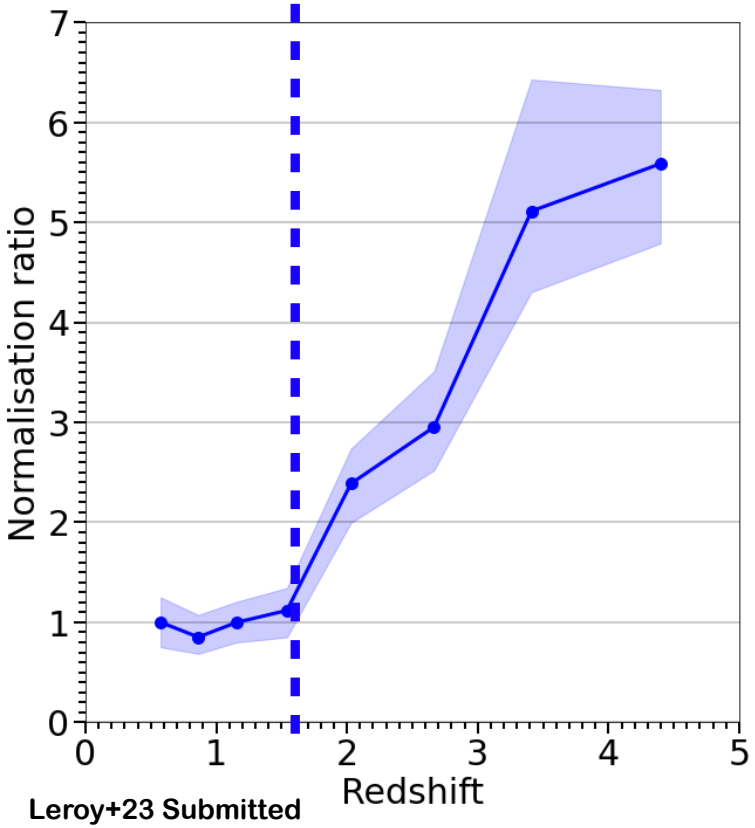


Leroy+23 Submitted

The evolution of the normalisation on the Kennicutt-Schmidt relation

The Kennicutt-Schmidt relation

- Two regimes:

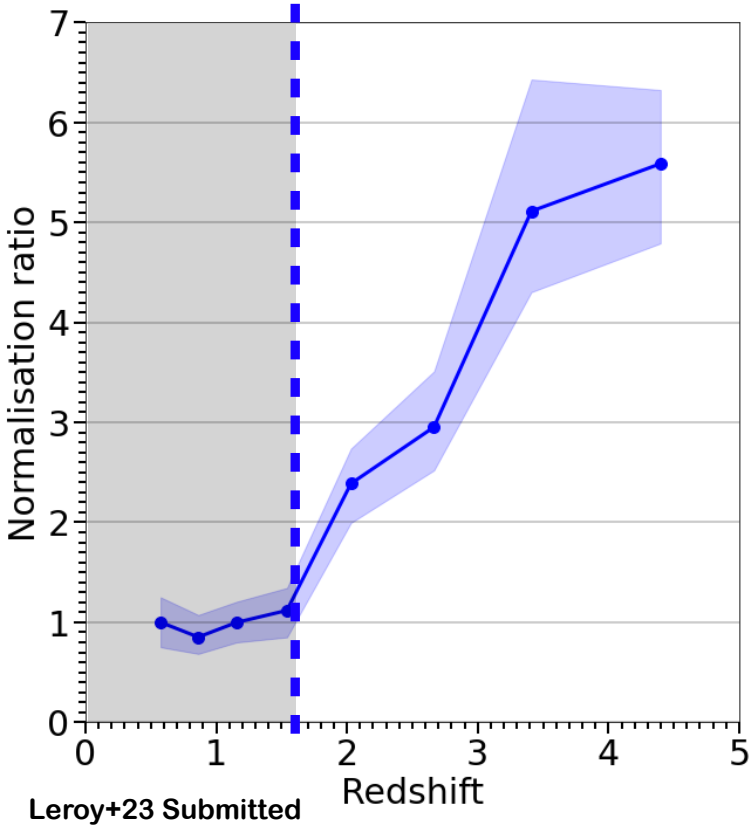


Leroy+23 Submitted

The evolution of the normalisation on the Kennicutt-Schmidt relation

The Kennicutt-Schmidt relation

- Two regimes:
  - At $z < 1.7$ increase in SFR is mainly due to variation in $M_{\rm gas}$



Leroy+23 Submitted

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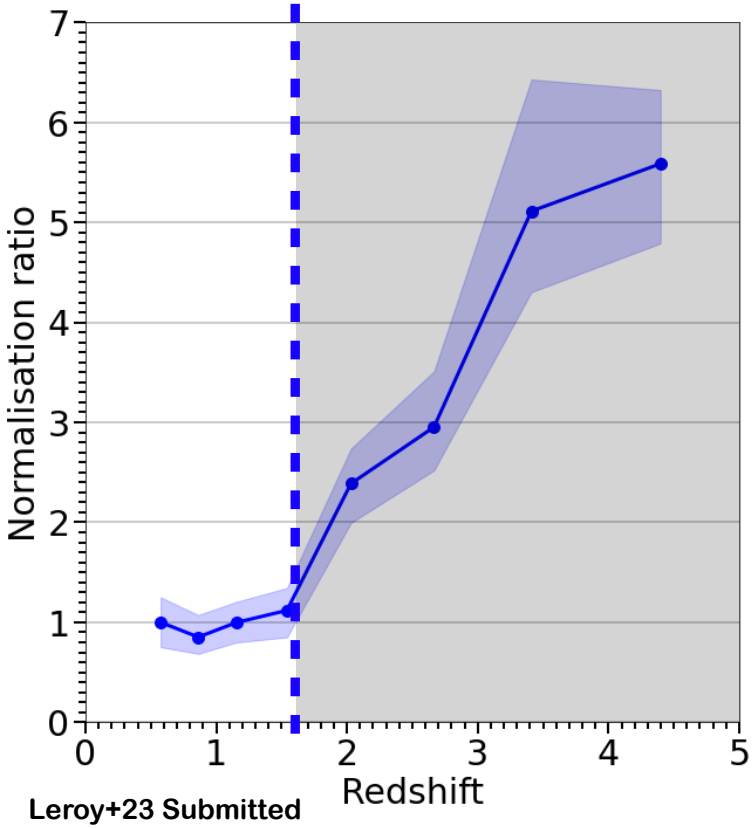
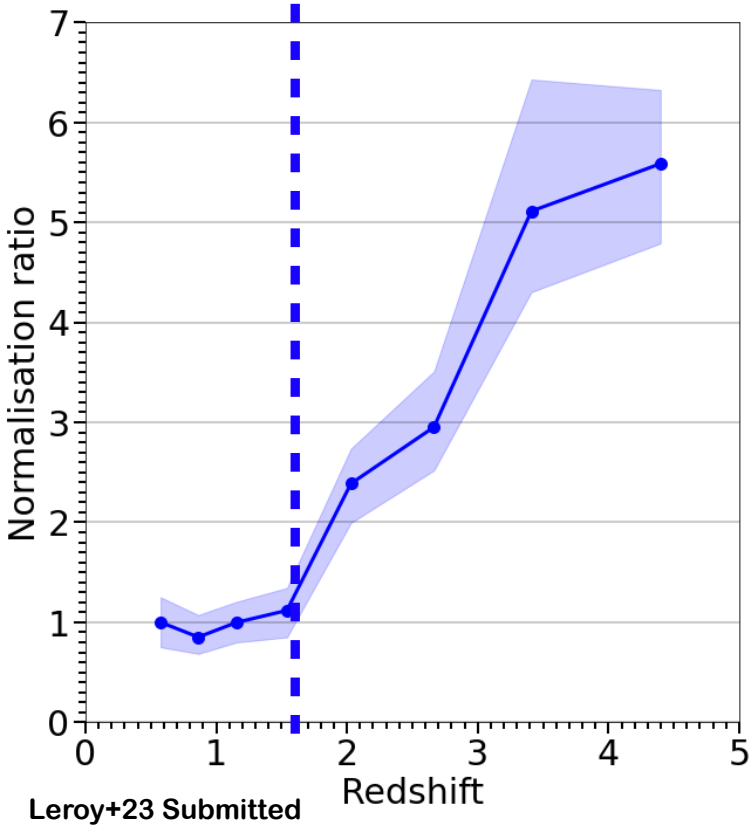


Leroy+23 Submitted

The evolution of the normalisation on the Kennicutt-Schmidt relation

The Kennicutt-Schmidt relation

- Two regimes:
  - At $z < 1.7$ increase in SFR is mainly due to variation in $M_{\rm gas}$
  - At $z > 1.7$ increase in SFR is partly due to variation in SFE
- High-redshift galaxies may be intrinsically more efficient at forming stars compared to low-redshift galaxies



Leroy+23 Submitted

The evolution of the normalisation on the Kennicutt-Schmidt relation

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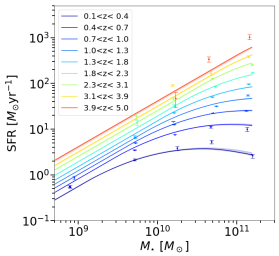
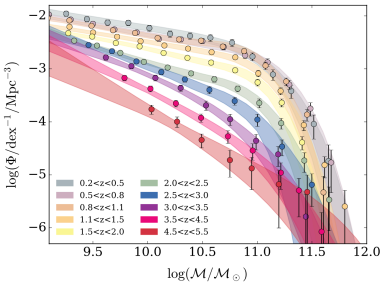
The James Webb Space Telescope

H-band selected galaxies

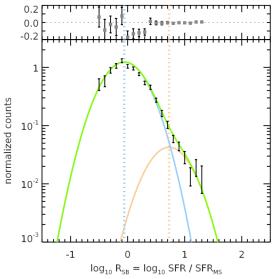


Deduce a main sequence

The mass function from Davidzon+17



Take starburst into account (Schreiber+15)



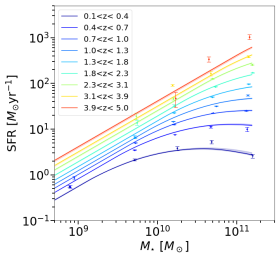
Mock galaxies

ρ_{SFR}

H-dropout

The James Webb Space Telescope

JWST selected galaxies



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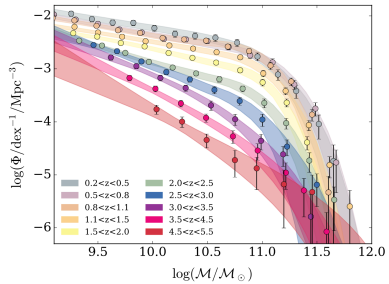

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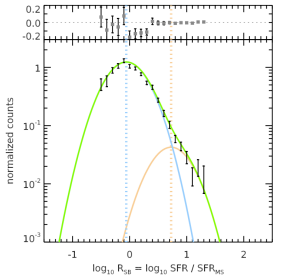


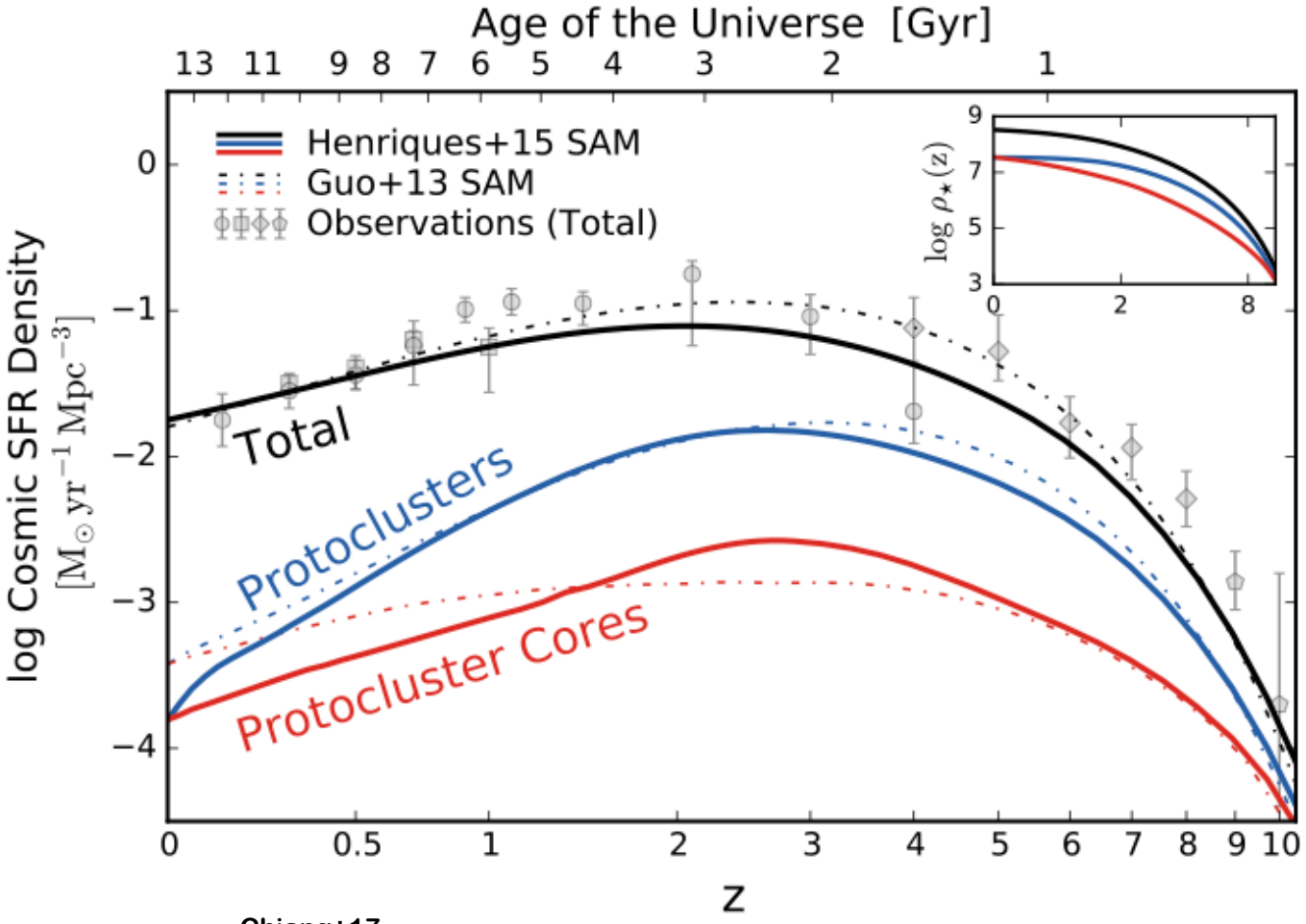
Mock galaxies

ρ_{SFR}

H ut

35

The impact of environment on galaxy evolution

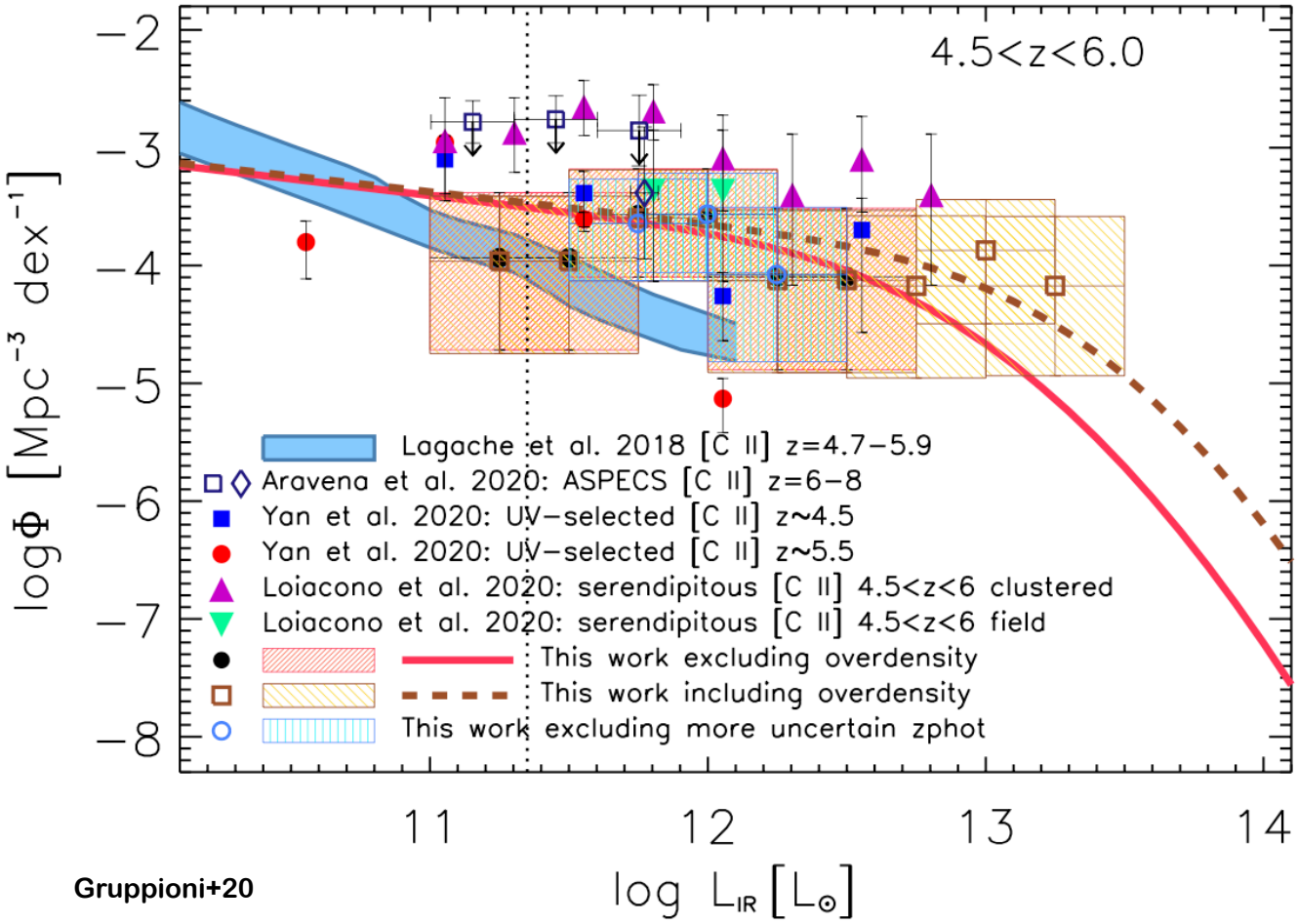


Chiang+17

Thanks

Backup slides

Extrapolation through the luminosity function



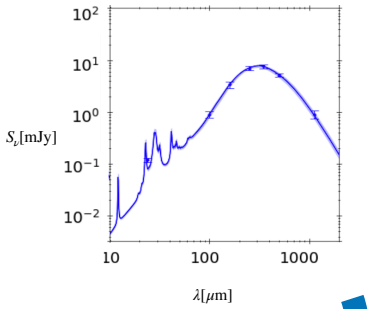
Gruppioni+20

The method

Catalogues of H-band selected SFGs
z, $M_\star$ and $SFR_{\rm UV}$

Improving photometry limits through stacking

MIPS+Herschel+ALMA



Deducing galaxies properties :
SFR, $T_{\rm dust}$, $M_{\rm dust}$

H-dropout properties from Wang+19

Stacking method

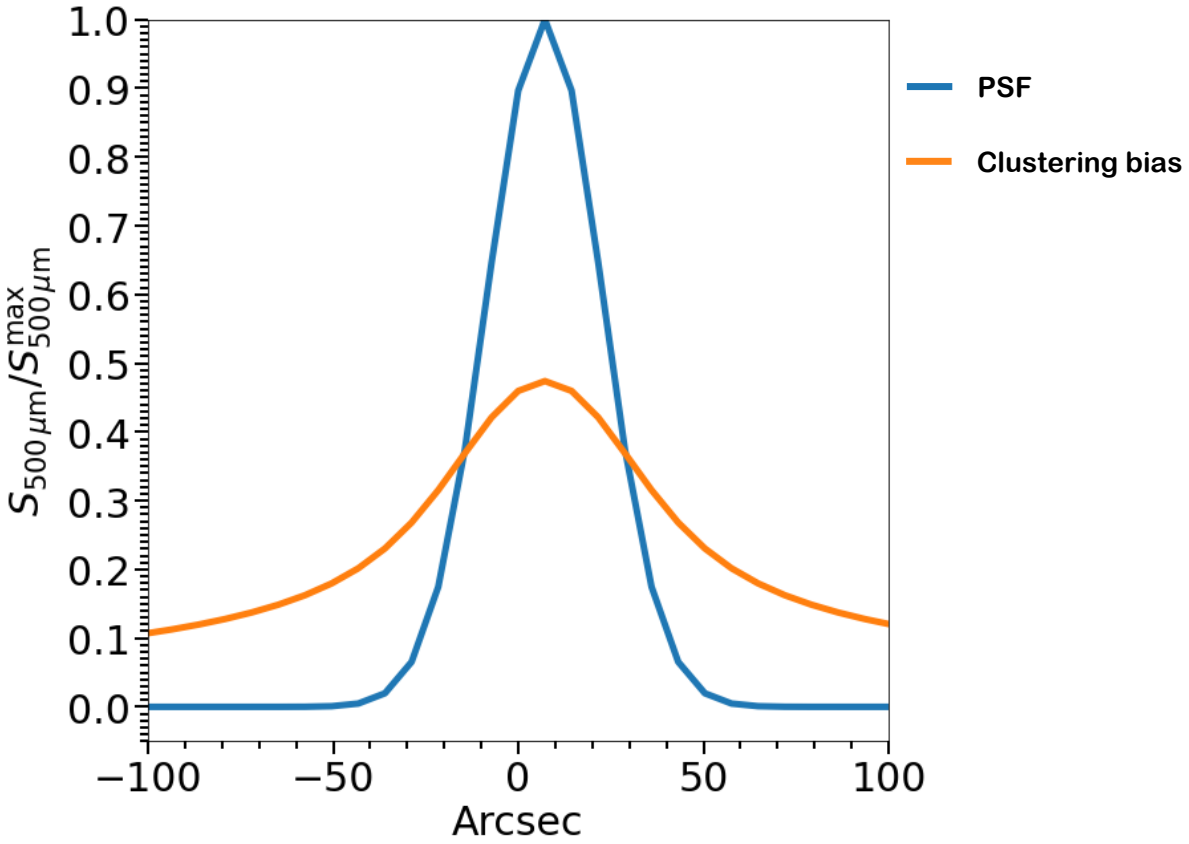
- Gradient in maps
- Clustering bias in Herschel bands
- PSF fitting and aperture photometry
- Measure of S/N and flux errors

SED fitting method

- Schreiber+18 template library and correction table
- Simulations for averaging biases
- AGN bias and transmission windows

Herschel: the clustering bias

- Signal contamination from true neighbouring sources
- Appears when the size of the PSF becomes comparable to the typical cluster length of SFGs



Example of clustering bias at $500\,\mu$m

Herschel: the clustering bias

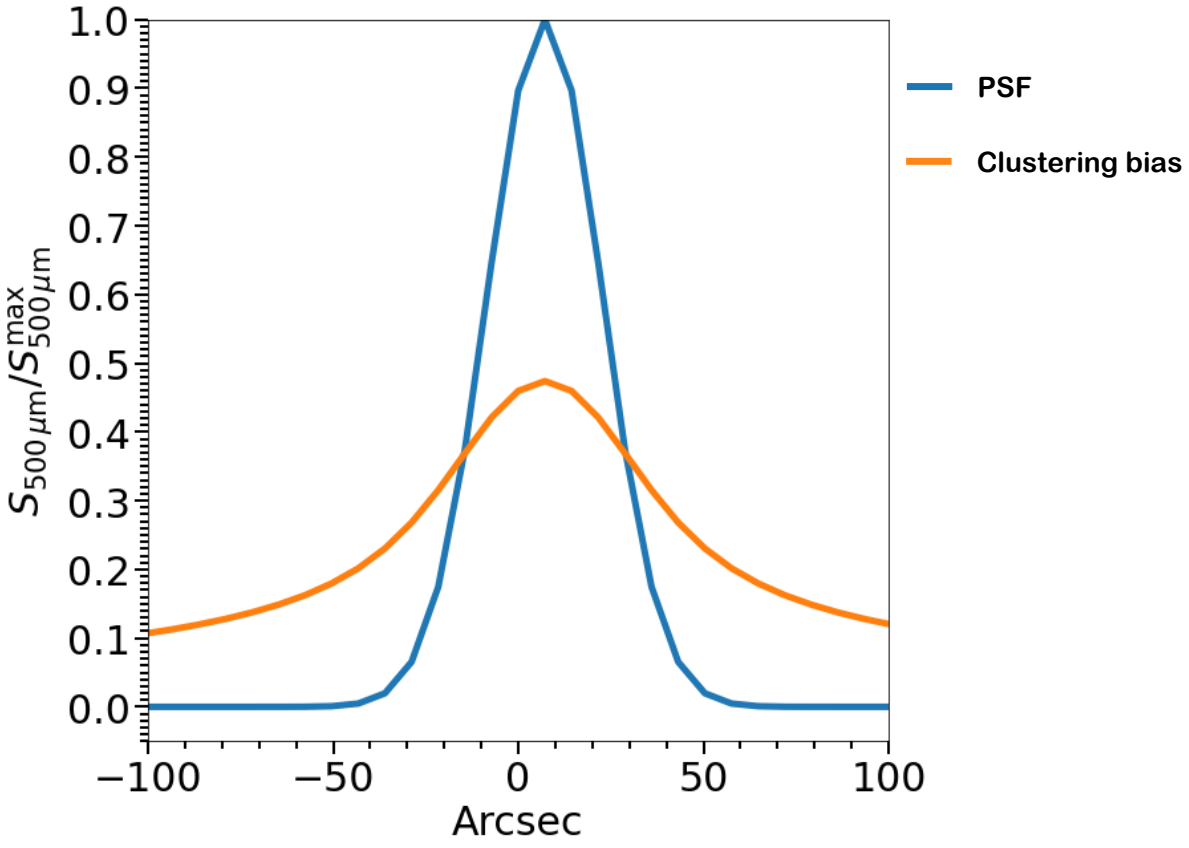
- Mesure the flux with PSF fitting:

$$S(x, y) = \varphi \times PSF(x, y) + \varepsilon$$

- Within a radius of 0.9xFWHM (Schreiber+15)

- Remove an extra factor (Schreiber+15):

Wavelenght (μm)	Correction
100	0%
160	3%
250	8%
350	13%
500	25%

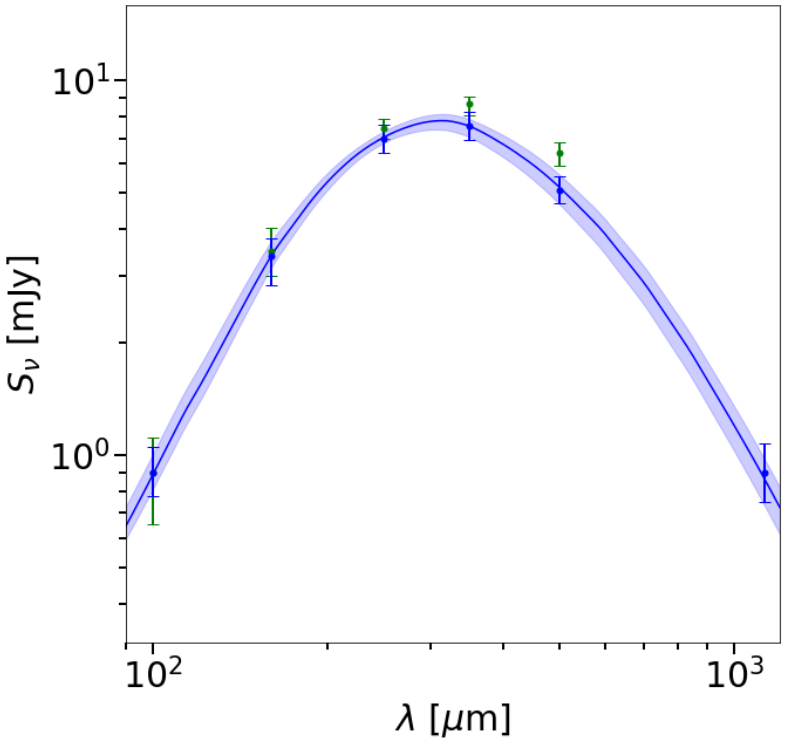


Example of clustering bias at $500\,\mu$m

Herschel and the clustering bias

If not corrected:

- Over estimation of L_{IR}
- Under estimation of T_{dust}



Original flux densities

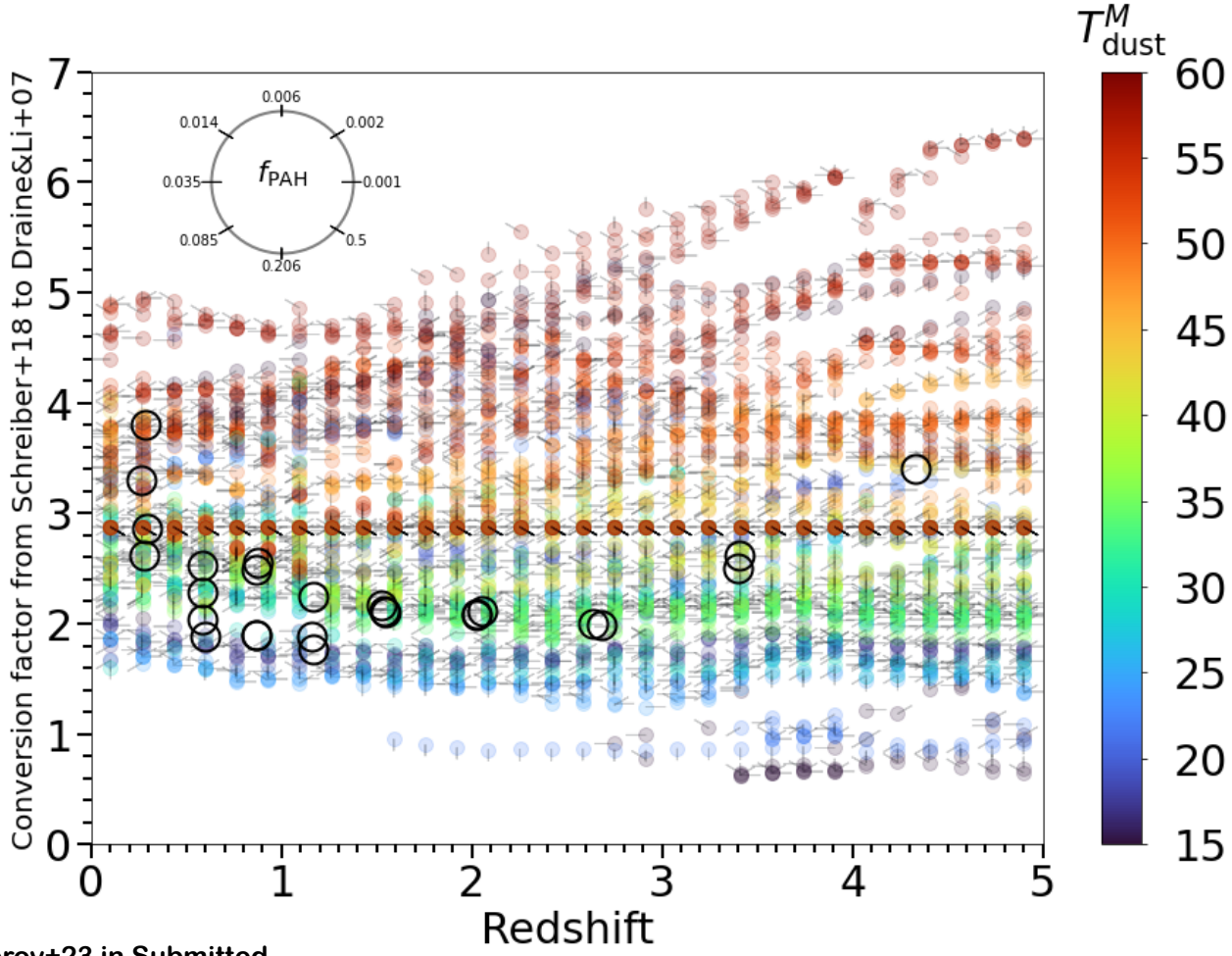
Flux densities corrected for the clustering bias

Best SED fit

68% uncertainty

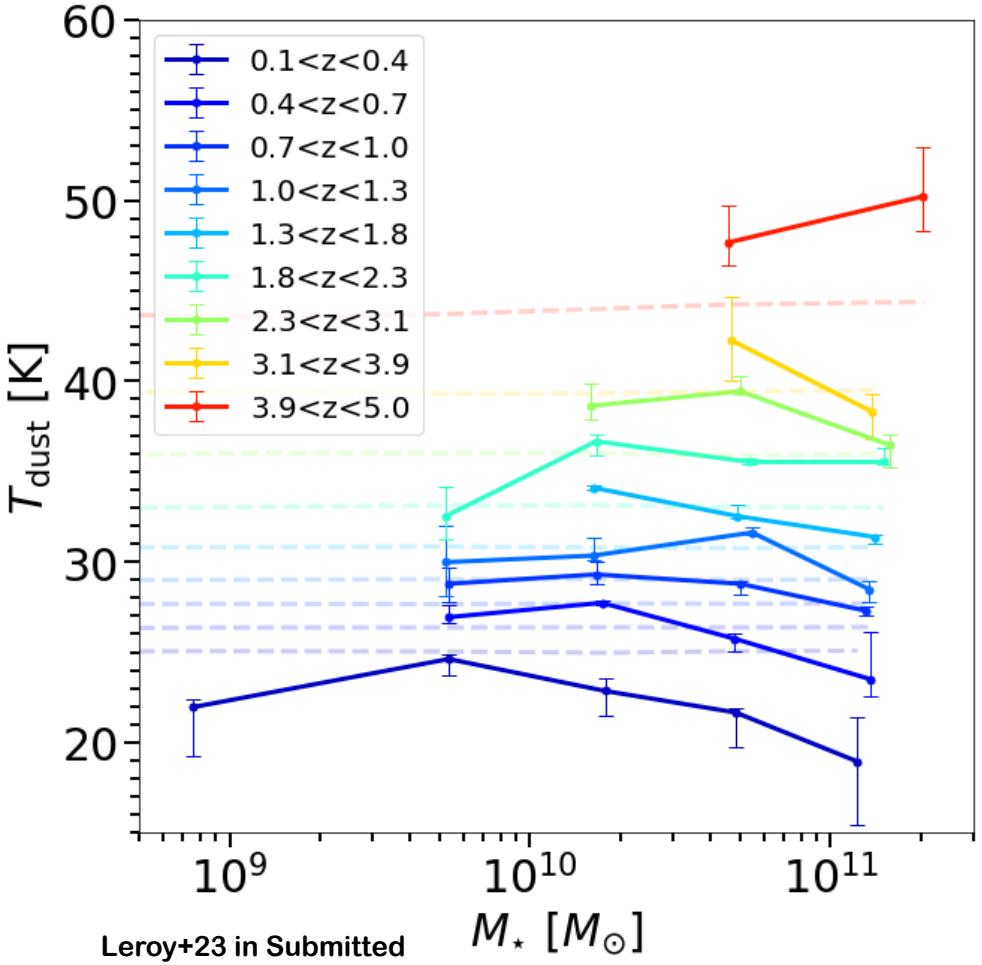
Flux density measurements for galaxies with $2.3 \leq z \leq 3.1$ and $11 \leq \log_{10}(M_\star/M_\odot) \leq 12$

$M_{\rm dust}$ correction factor between models



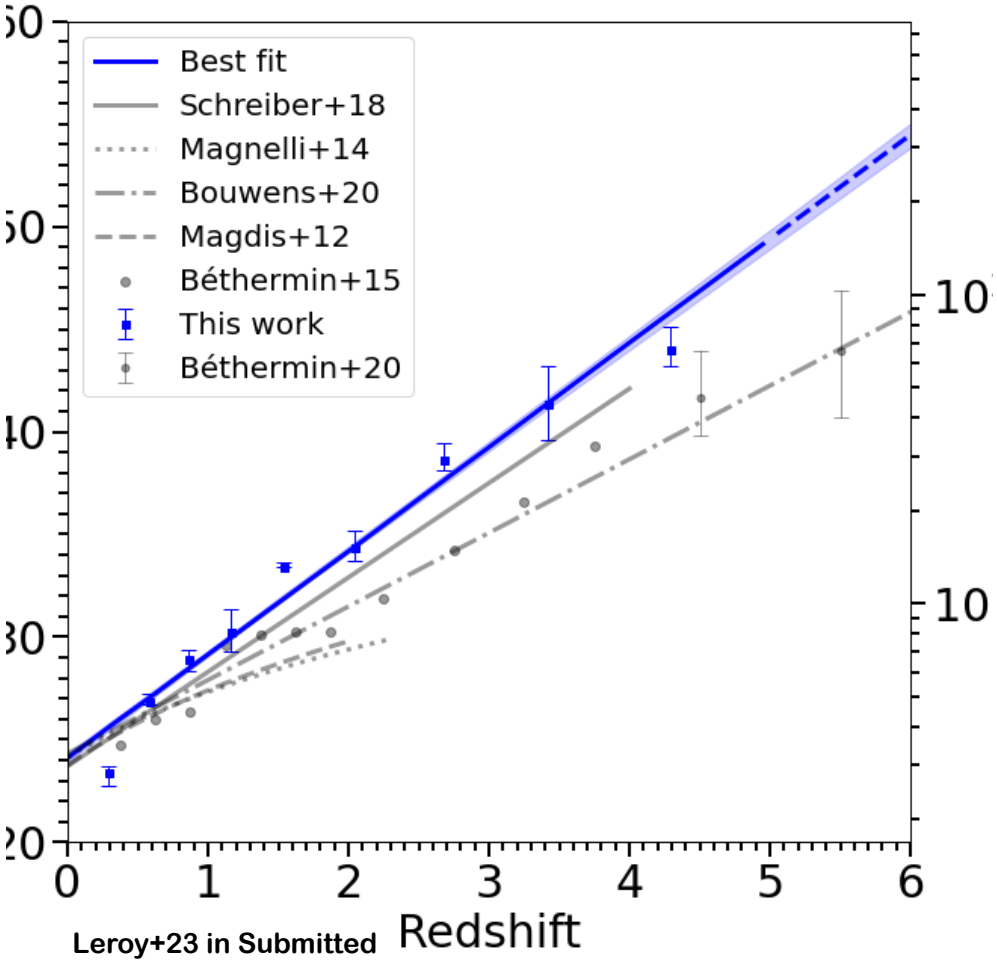
Leroy+23 in Submitted

$T_{\rm dust}$ as a function of $M_\star$



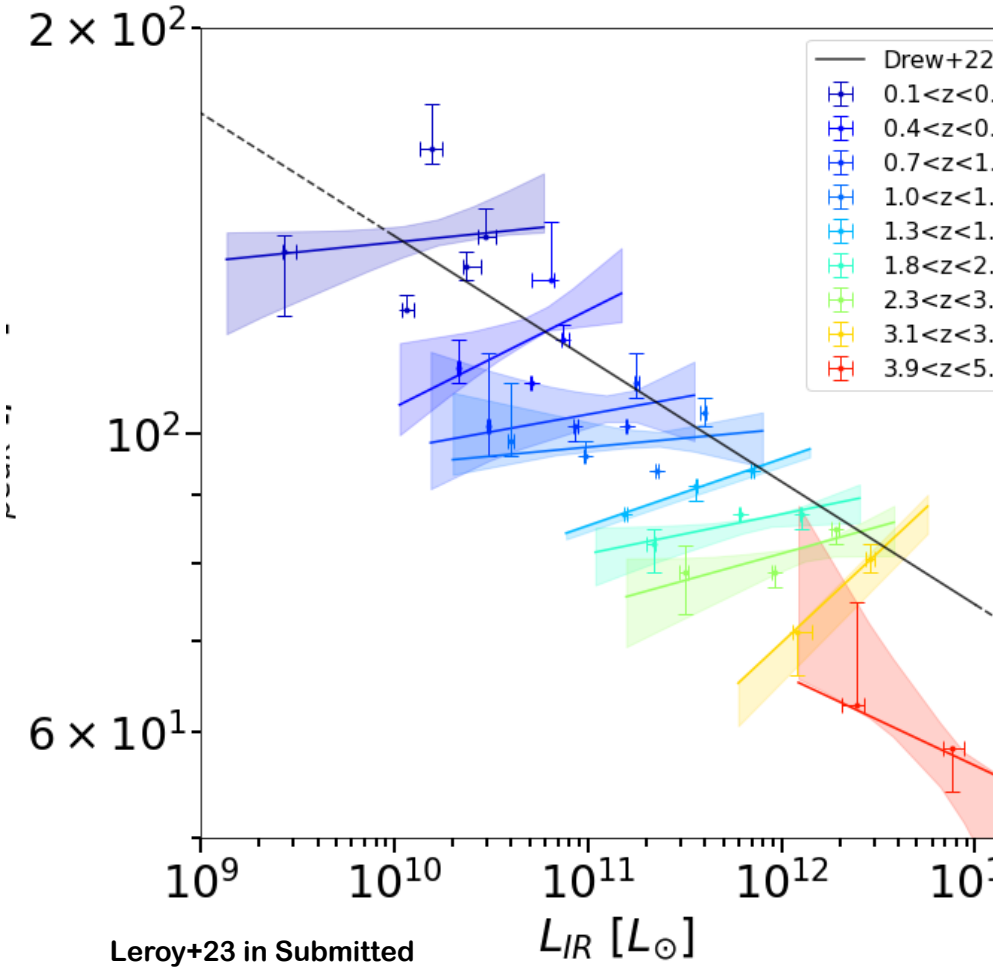
Leroy+23 in Submitted

$T_{\rm dust}$ as a function of z



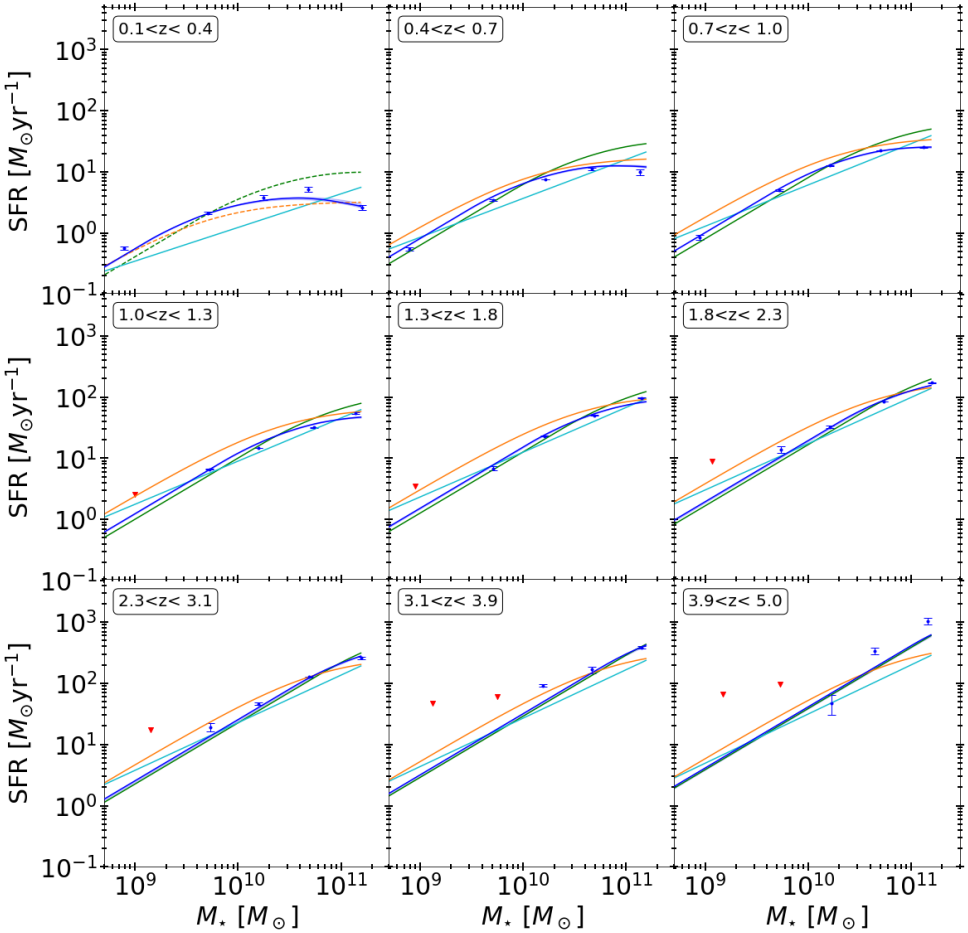
Leroy+23 in Submitted

$\lambda_{\rm peak}$ as a function of $L_{\rm IR}$



Leroy+23 in Submitted

The main sequence of SFGs

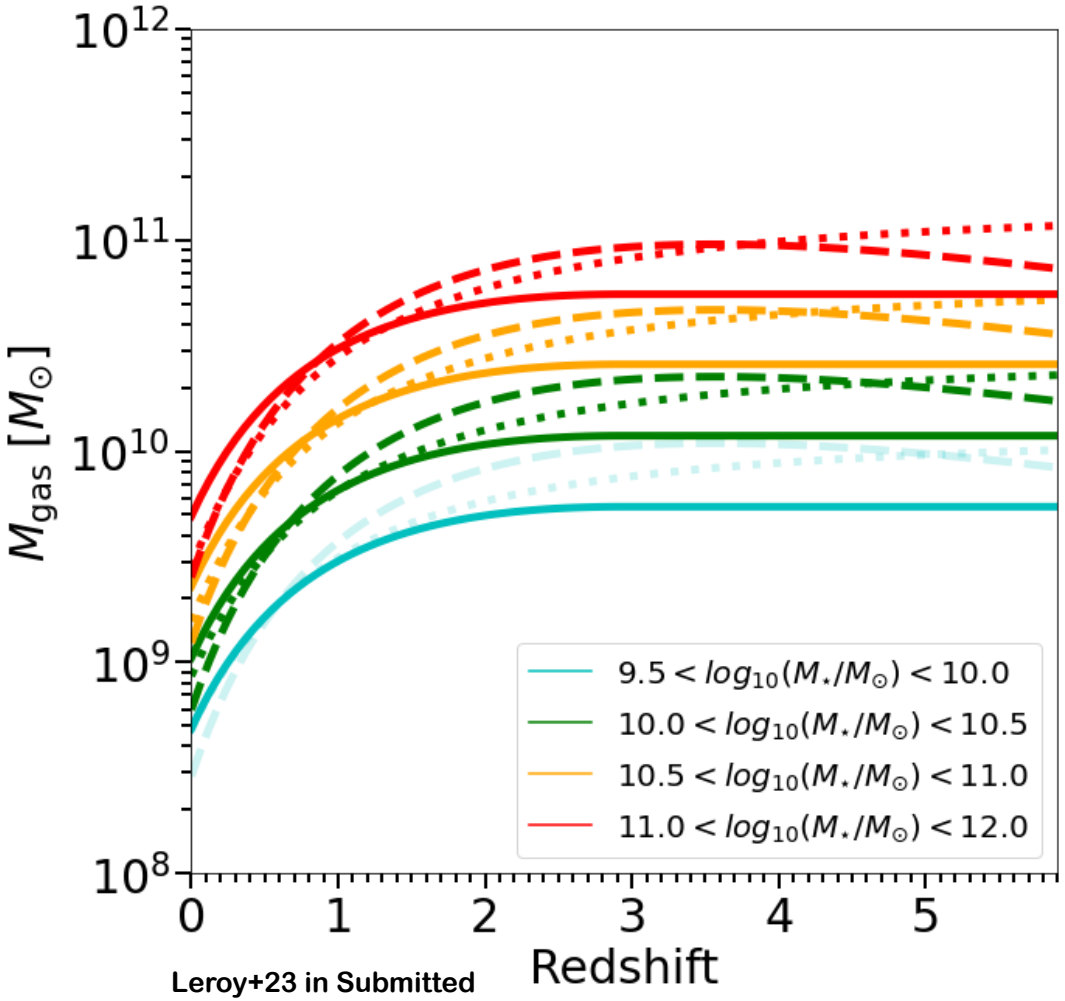


Leroy+23 Submitted

$SFR_{\rm MS}$ as a function of $M_\star$ over different redshift bins.

- Original flux densities
- Upper limits
- Best fit this work - UV+IR (MIPS+Herschel+ALMA)
- Schreiber+15 - UV+IR (MIPS+Herschel)
- Leslie+20 - 3 GHz radio continuum
- Speagle+14 - Combination of studies (UV, FUV, IR, H_α/H_β)

The gas mass evolution of SFGs



Leroy+23 in Submitted

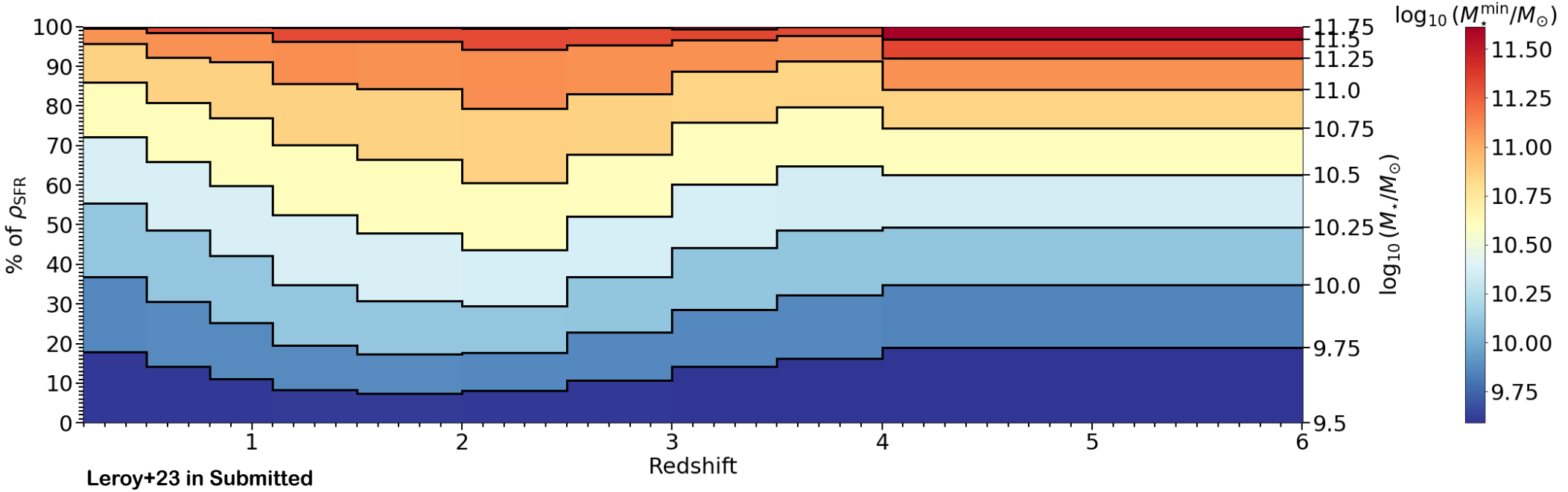
- Lower $M_{\rm gas}$ at $z \geq 2$

Best fit from this work (dust+ALMA)

Best fit from Taconni+18 (CO+dust)

Best fit from Wang+22 (ALMA)

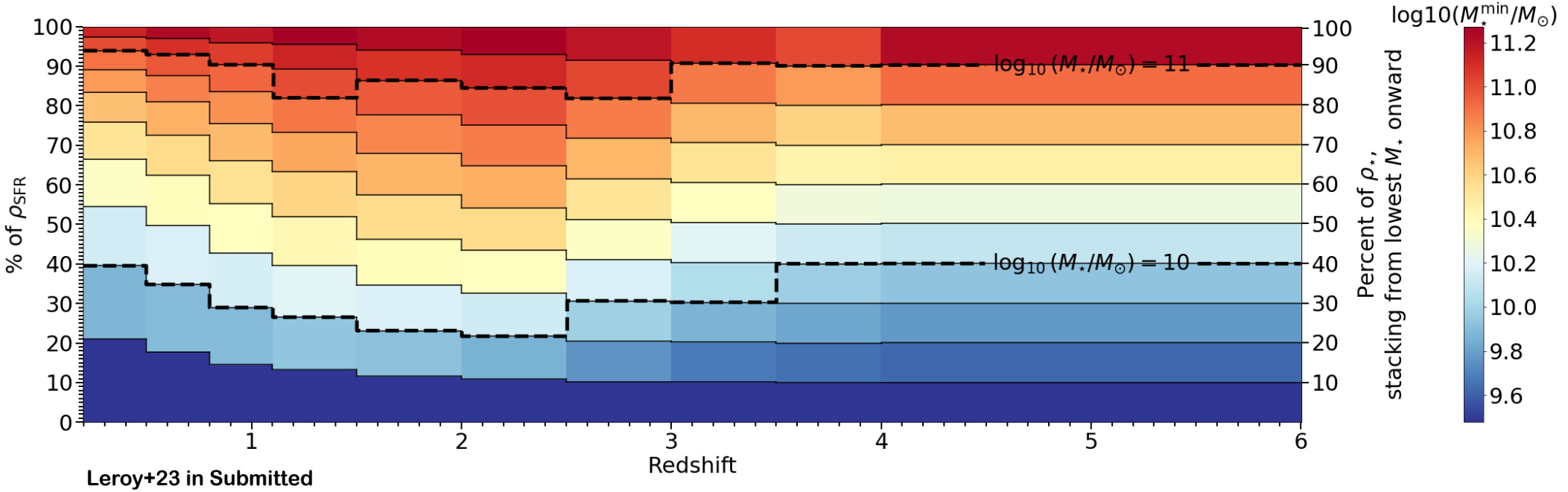
Per $M_\star$, Mmin in bin



Leroy+23 in Submitted

Contributions over the whole range of stellar masses to the total ρSFR as a function of redshift for SFGs.

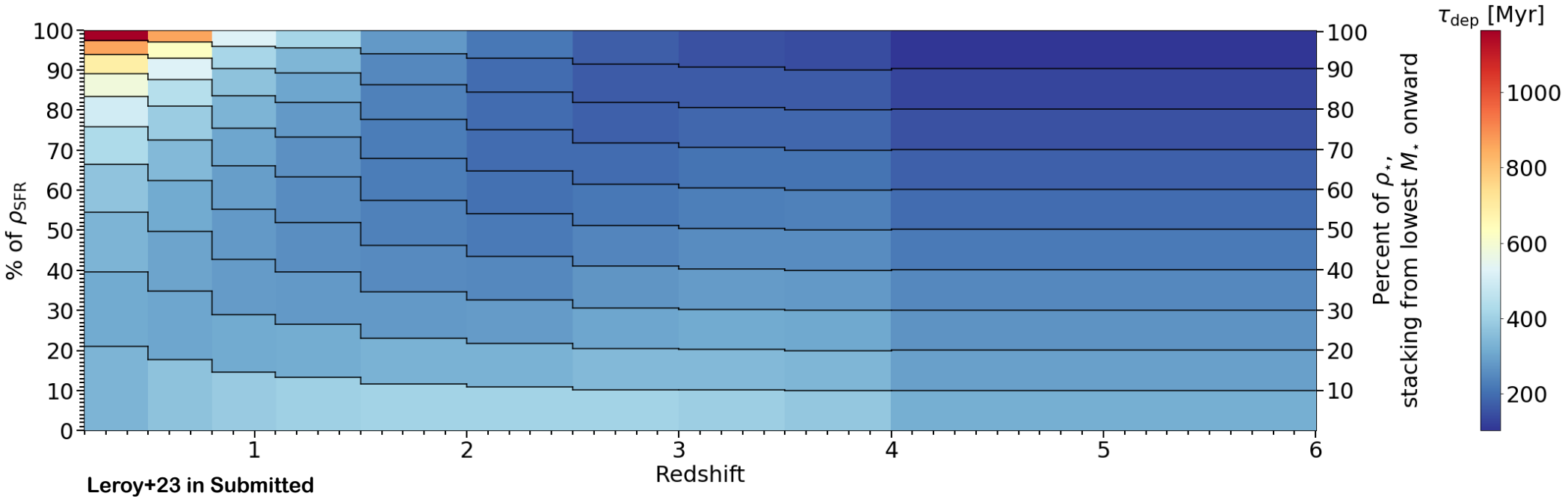
Percent of $\rho_\star$, Mmin in bin



Leroy+23 in Submitted

Each bin includes 10% of the total $M_\star$ of all galaxies, picking from the lowest $M_\star$ onwards. The minimum $M_\star$ in the bin defines the colour. Contours of $\log_{10}(M_\star/M_\odot) = 10$ and $\log_{10}(M_\star/M_\odot) = 11$ are added as black dashed lines..

Percent of $\rho_\star$, τ_{dep} in bin



Each bin includes 10% of the total M⋆ of all galaxies, picking from the lowest M⋆ onwards. The median τdep in the bin defines colour.