Photons under the rug:
Hiding the ionizing photon surplus in the Cosmic Infrared Background

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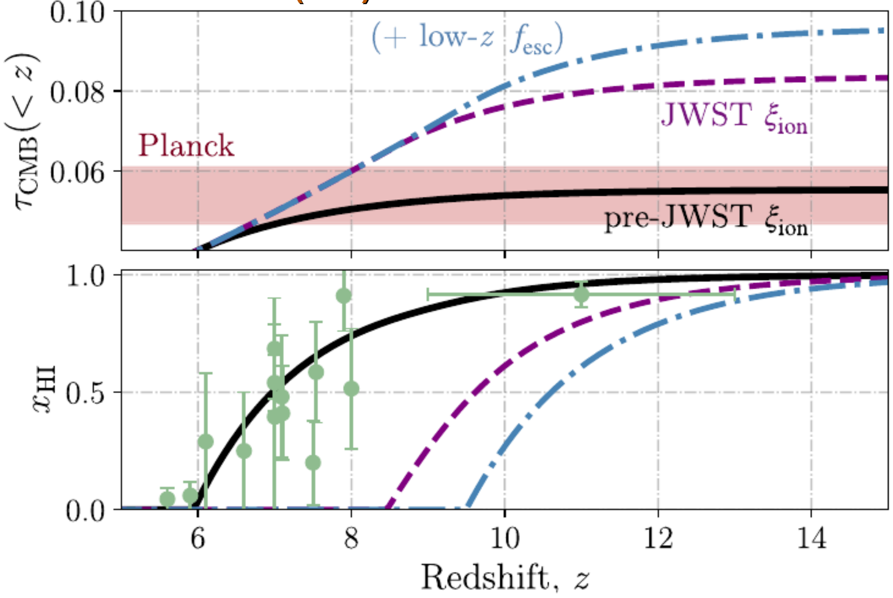
with Julian B. Munoz and Volker Bromm

Escape of Lyman radiation from galactic labyrinths

Reionization after JWST: a photon budget crisis?

Munoz et al. (2024)



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$f_{esc} = 20\%$
$M_{uv,cut\text{-}off} = -13$

(Robertson et al. 2015)

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Potential tension between **JWST** and **Planck** constraints on the **reionization timeline**

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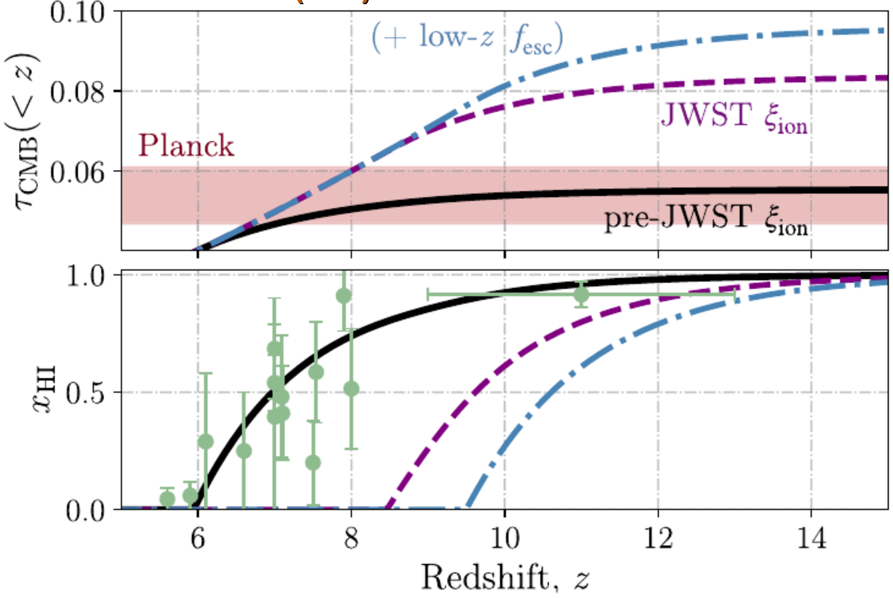

+ Log [ξ_{ion} /(Hz/erg)] ≈ 25.8 + 0.11(M_{UV} + 17) + 0.05(z − 7)
up to ~26 at M_{UV} = -16

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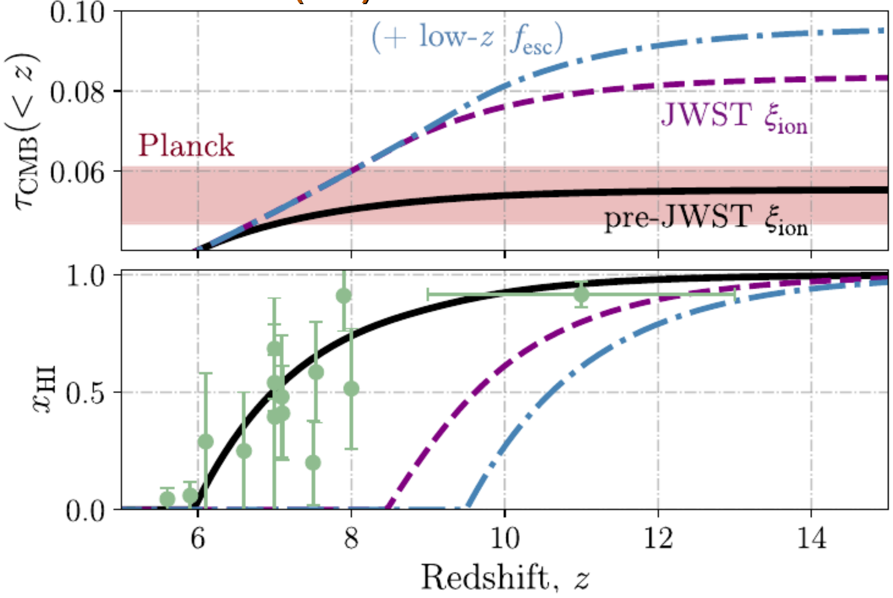

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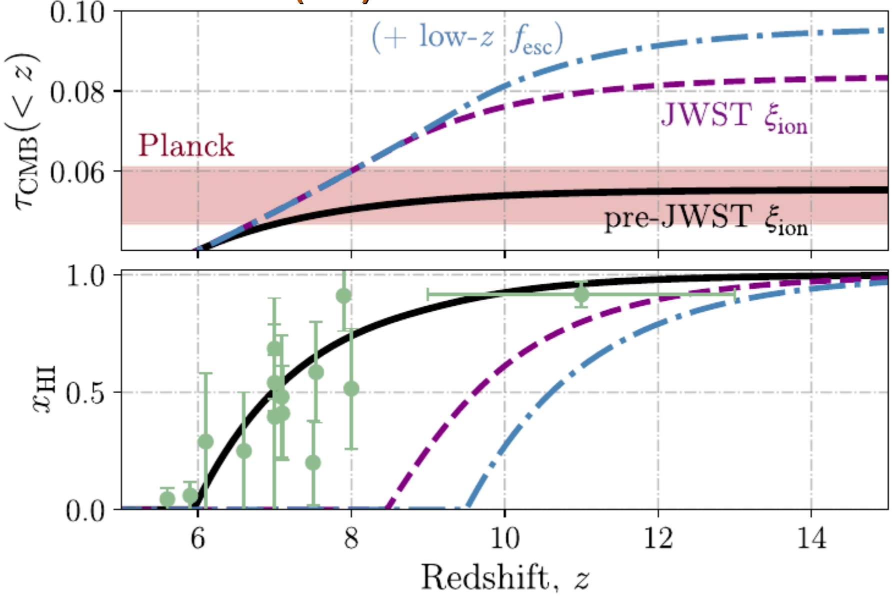

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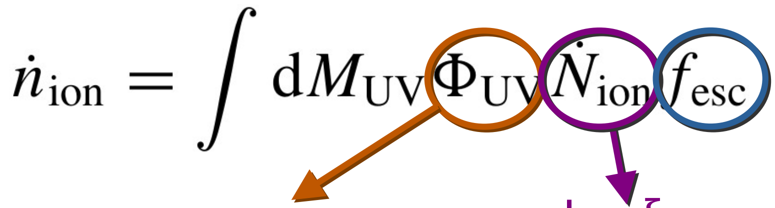

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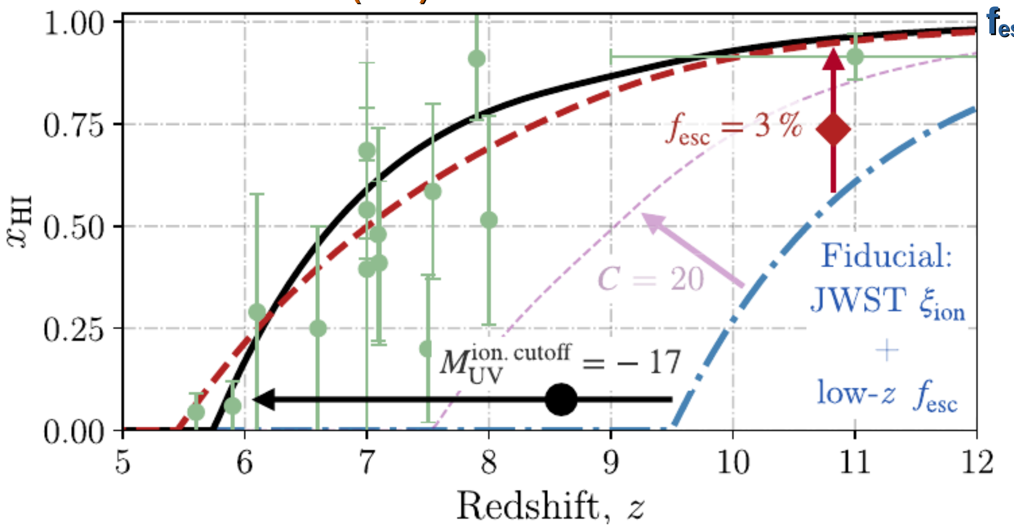
Potential tension between **JWST** and **Planck** constraints on the **reionization timeline**

Observed galaxies would drive an <u>earlier reionization</u> than expected from CMB measures

Low escape fractions?

Munoz et al. (2024)



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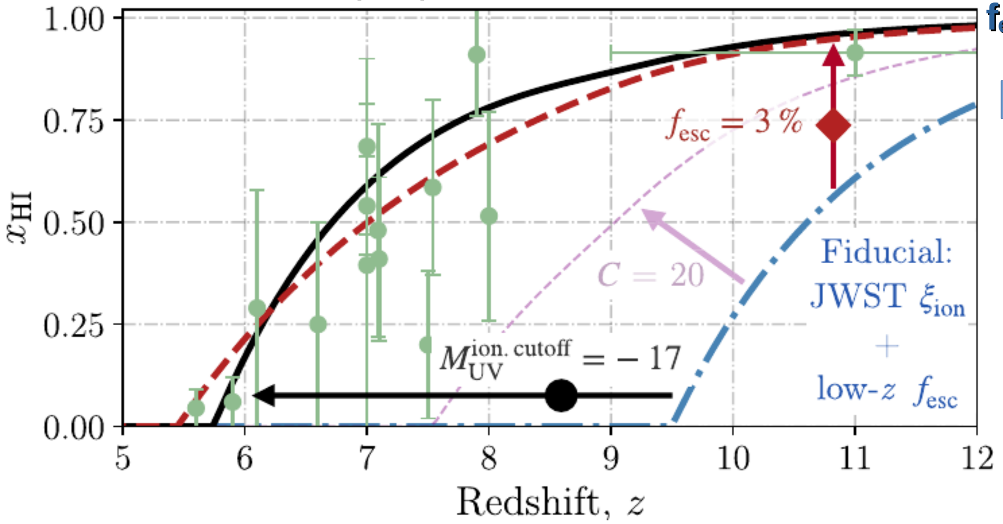

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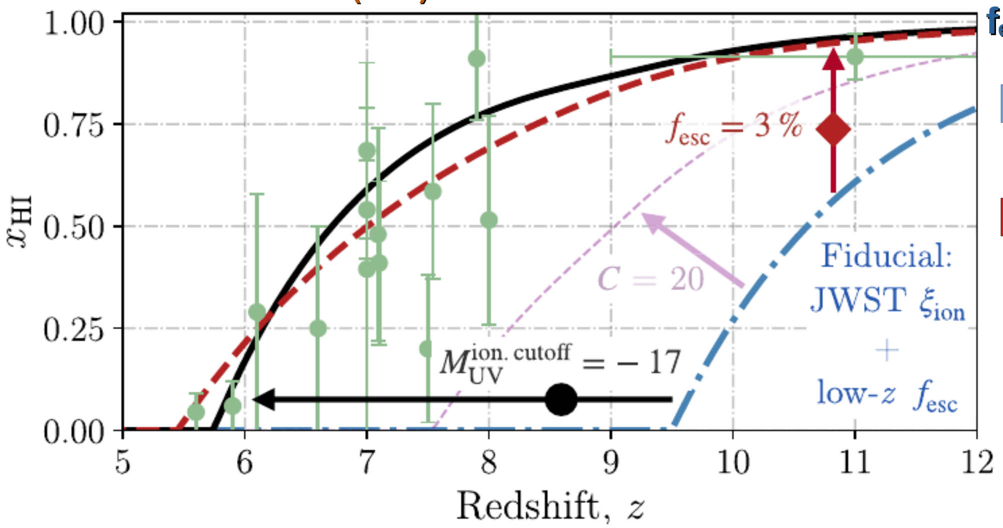

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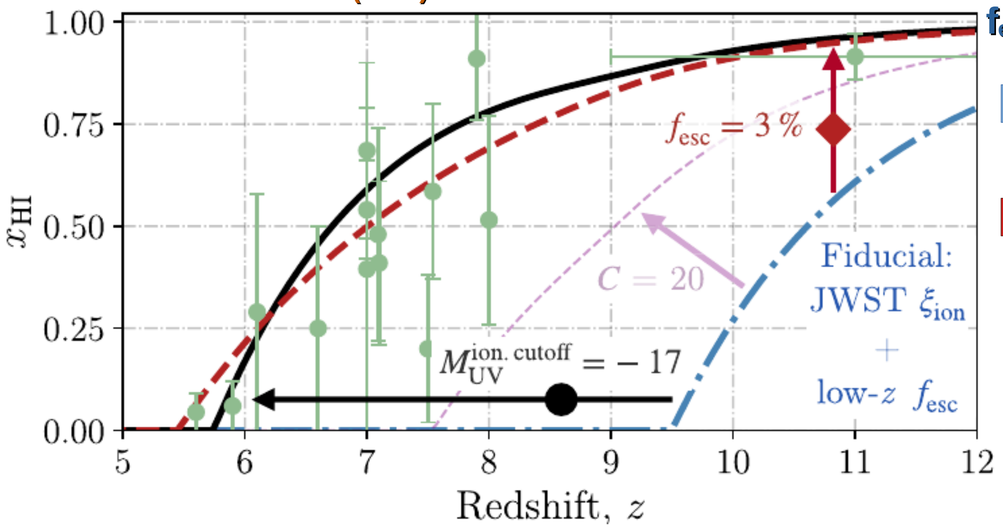

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The ionizing photons must end up somewhere...

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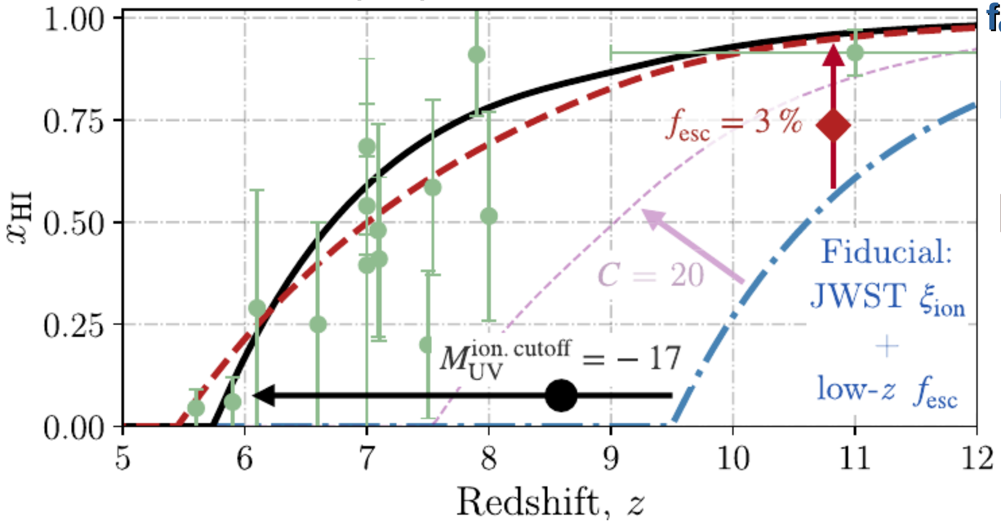

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Ionizing radiation from
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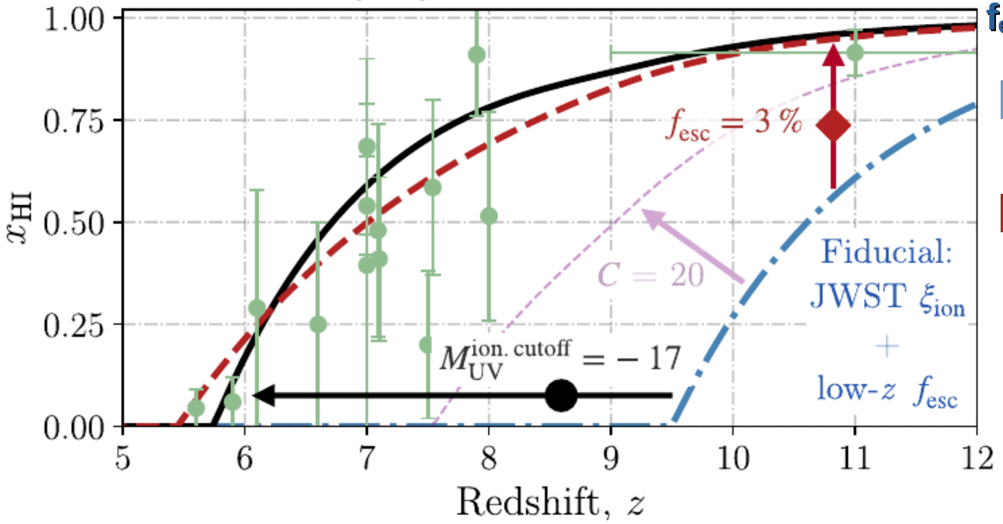

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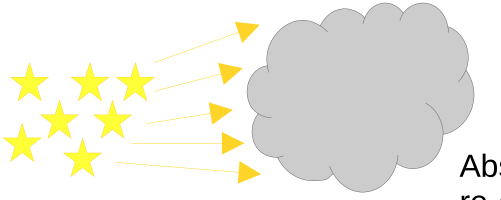

Absorbed by ISM and
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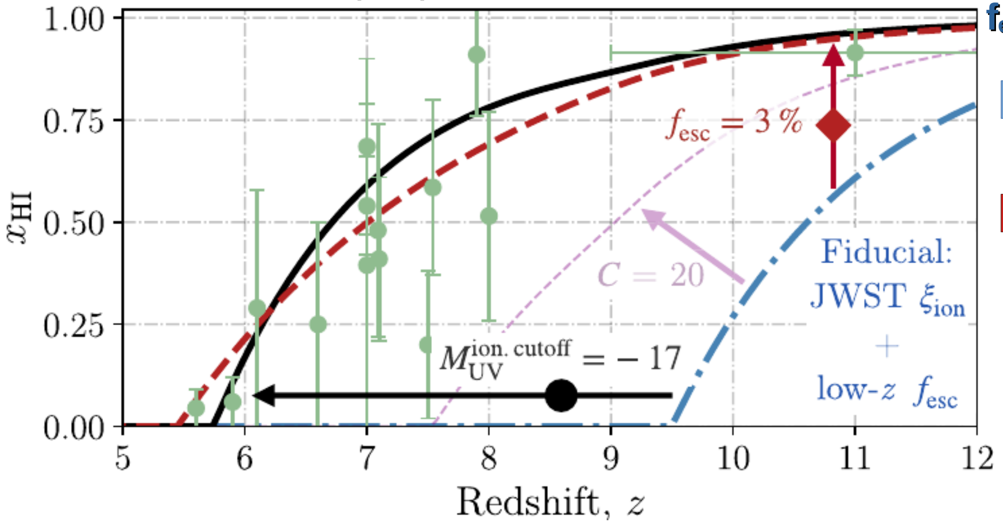

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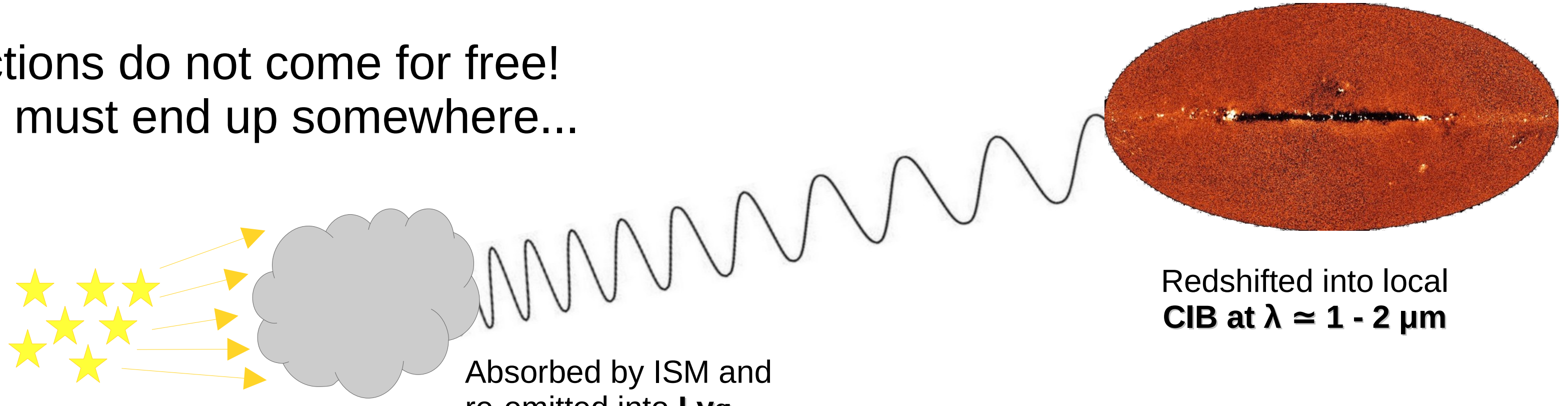


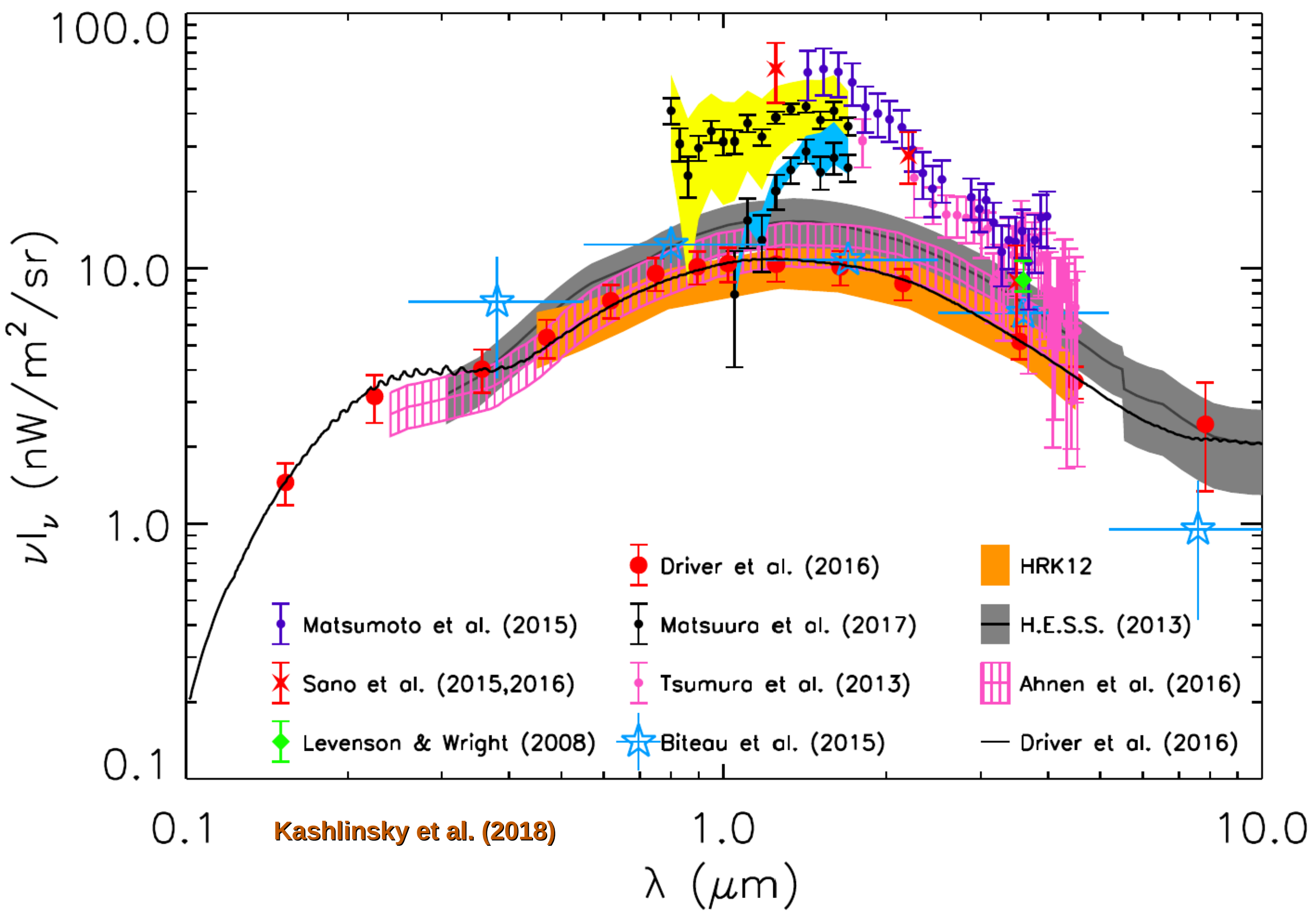
Ionizing radiation from **sources at 7 ≲ z ≲ 15**

Absorbed by ISM and re-emitted into **Lyα**

Redshifted into local **CIB at λ ≃ 1 - 2 μm**

The CIB excess

Emission accumulated over the entire history of our Universe



Kashlinsky et al. (2018)

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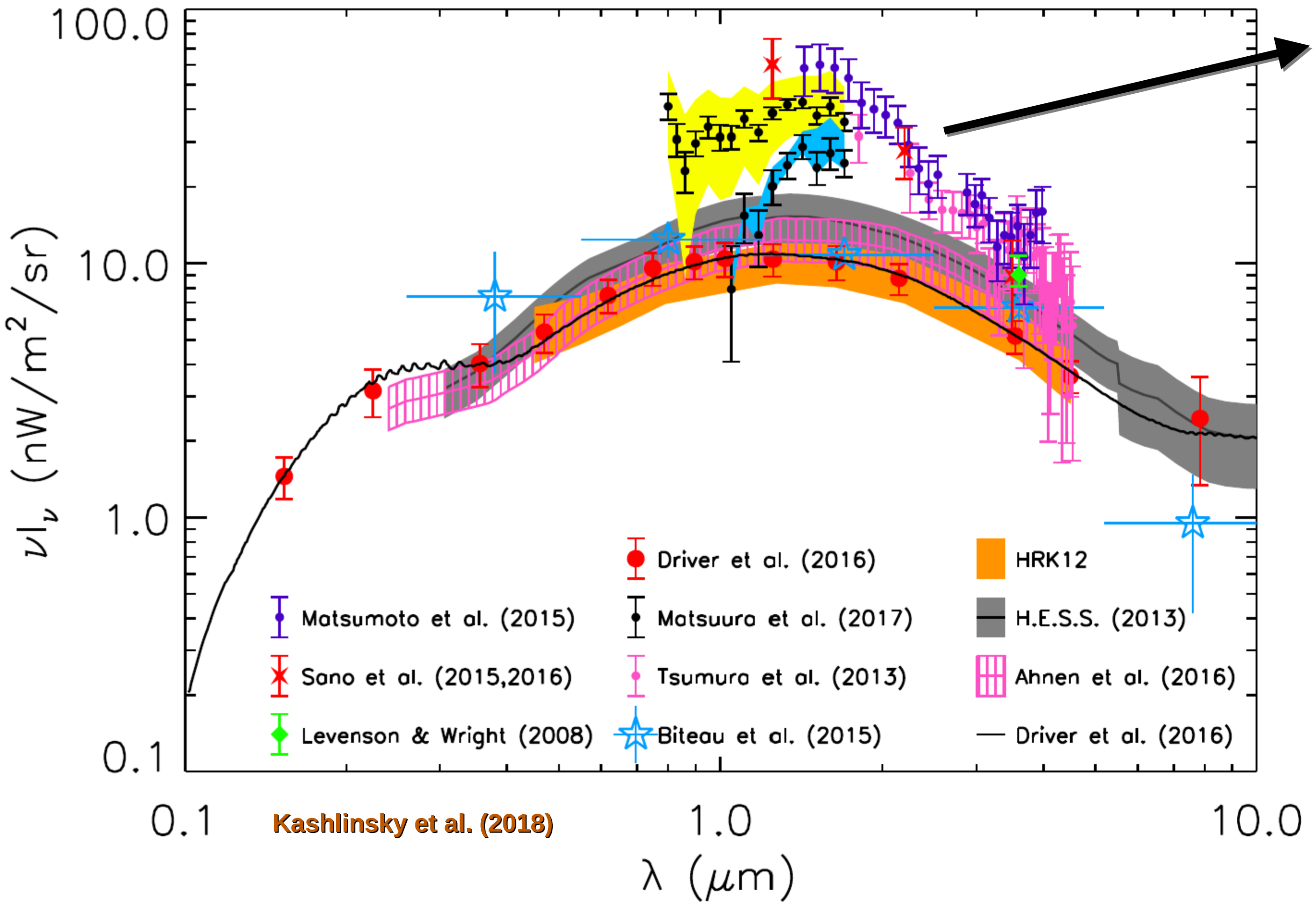

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CIB measures
averaged over large sky areas

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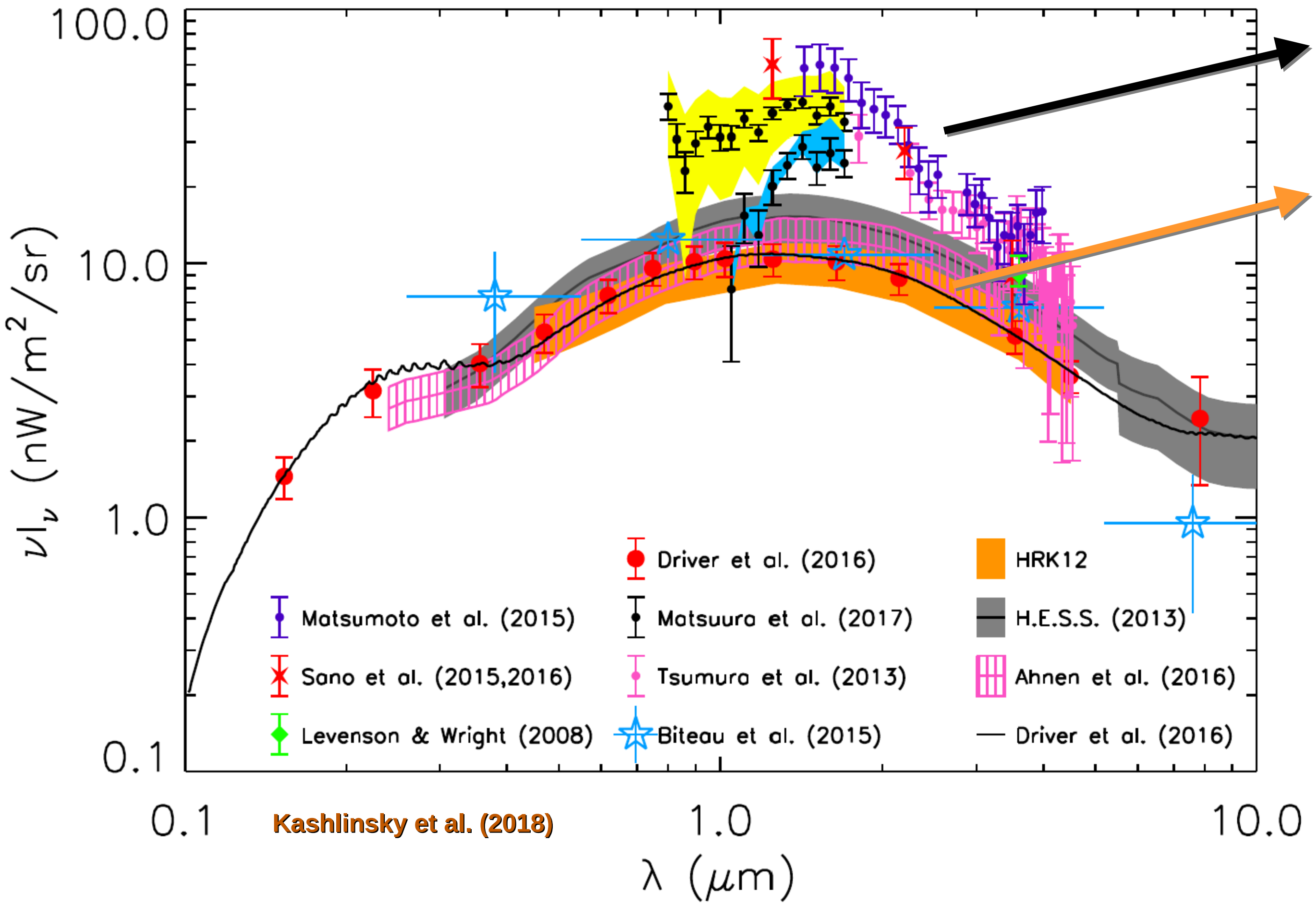

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Resolved galaxies
out to z ~7 - 8

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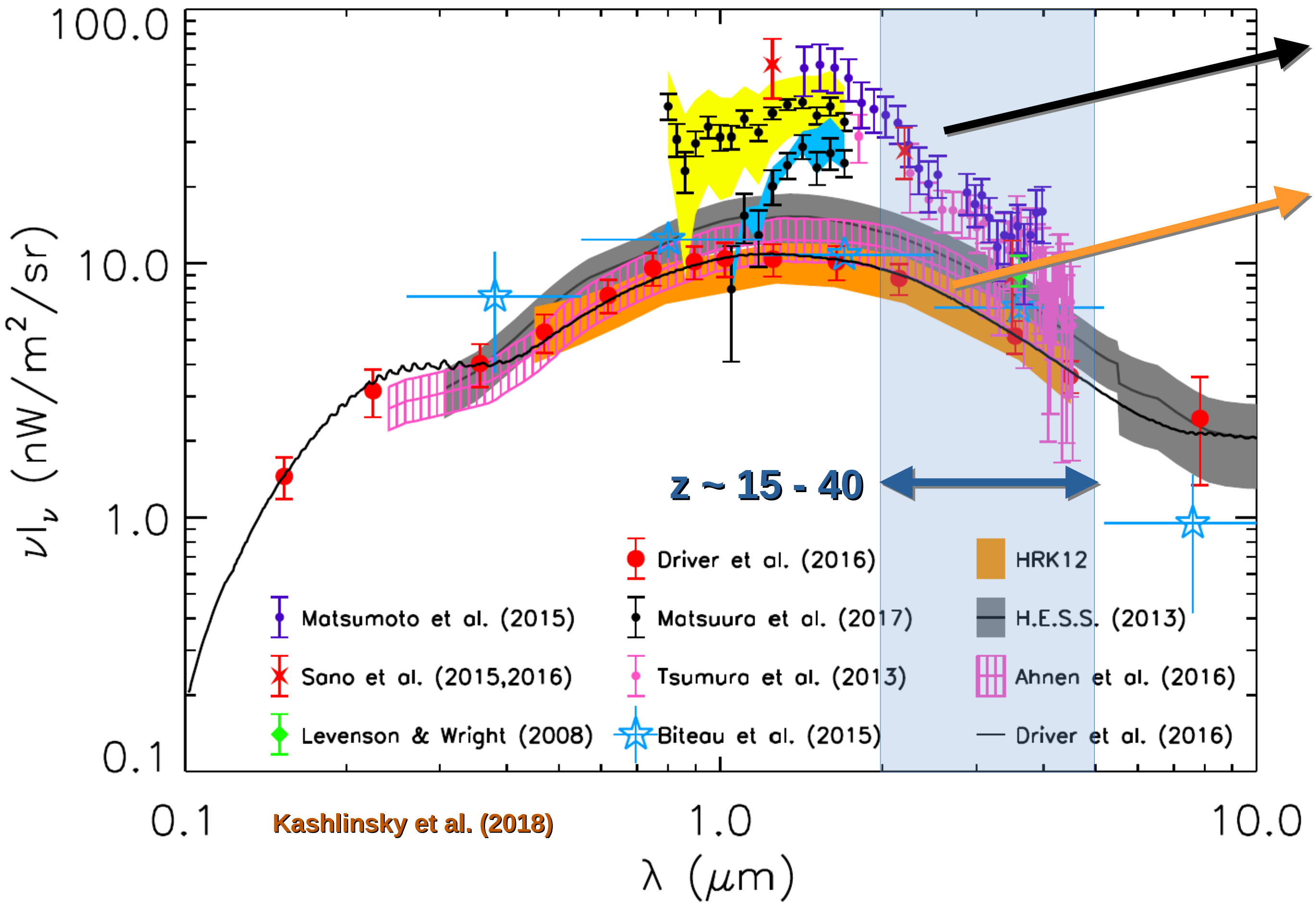

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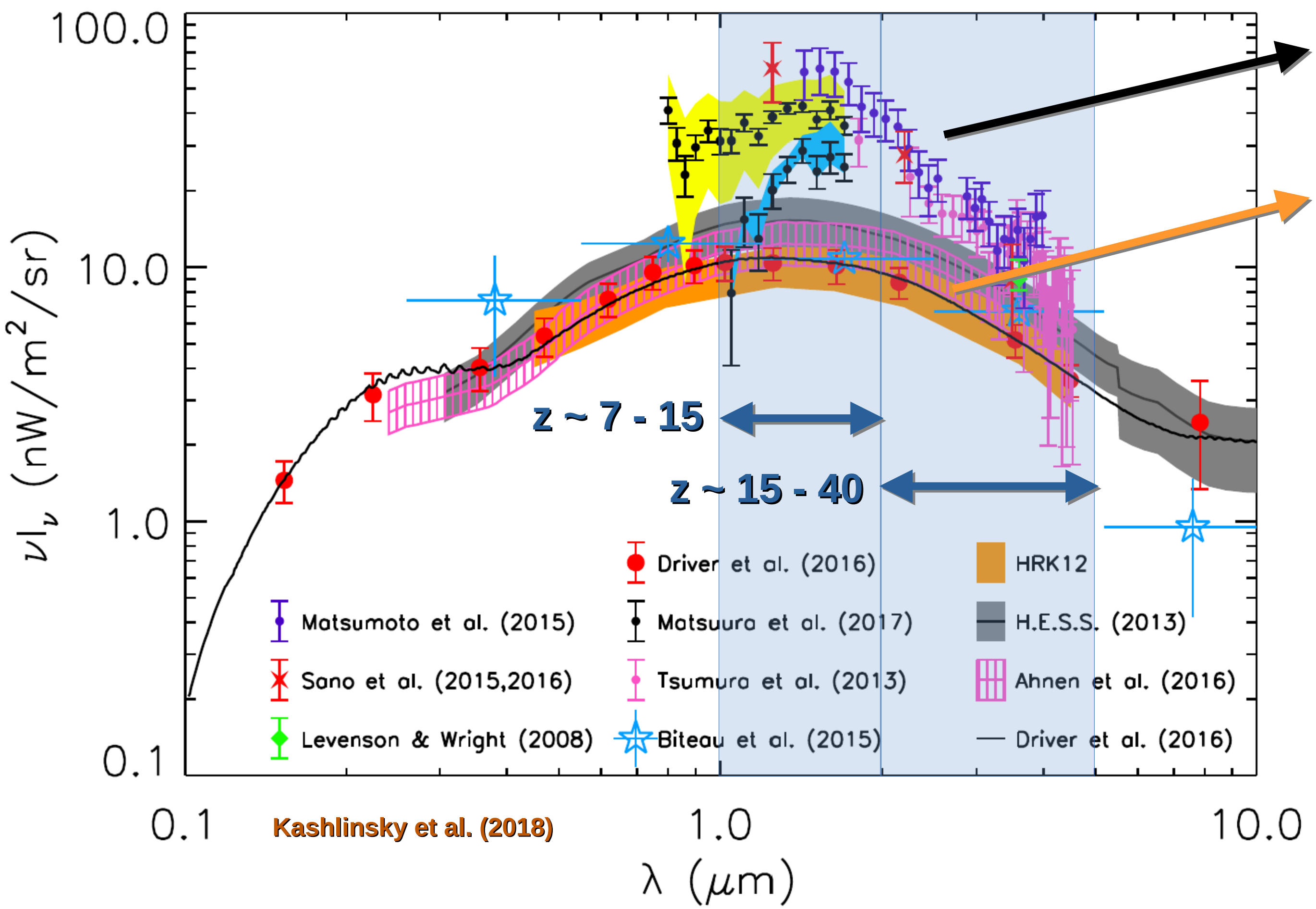

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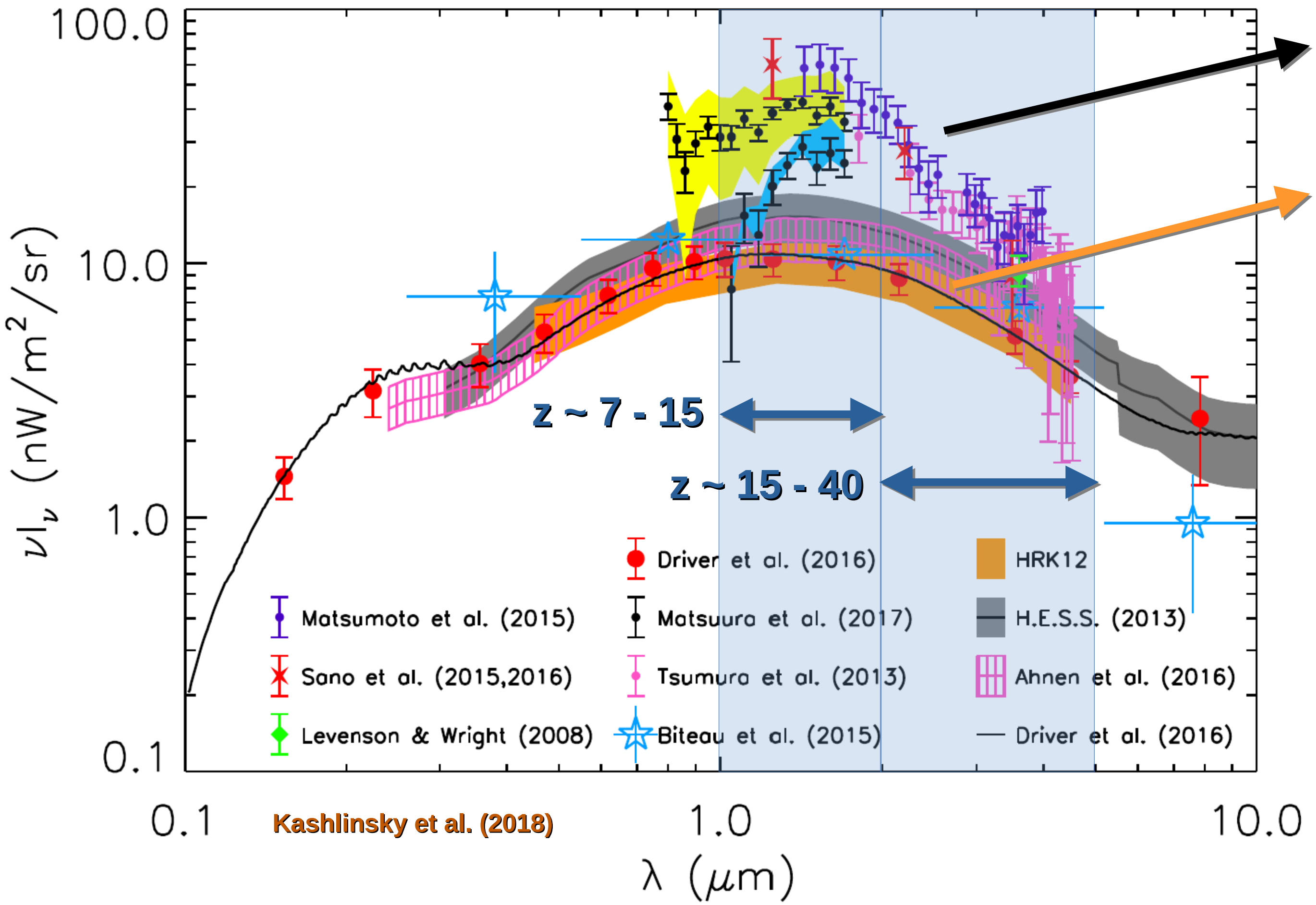

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Resolved galaxies
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- Dependent on foreground removal
  (e.g. zodiacal light)
- Further constraints from Euclid

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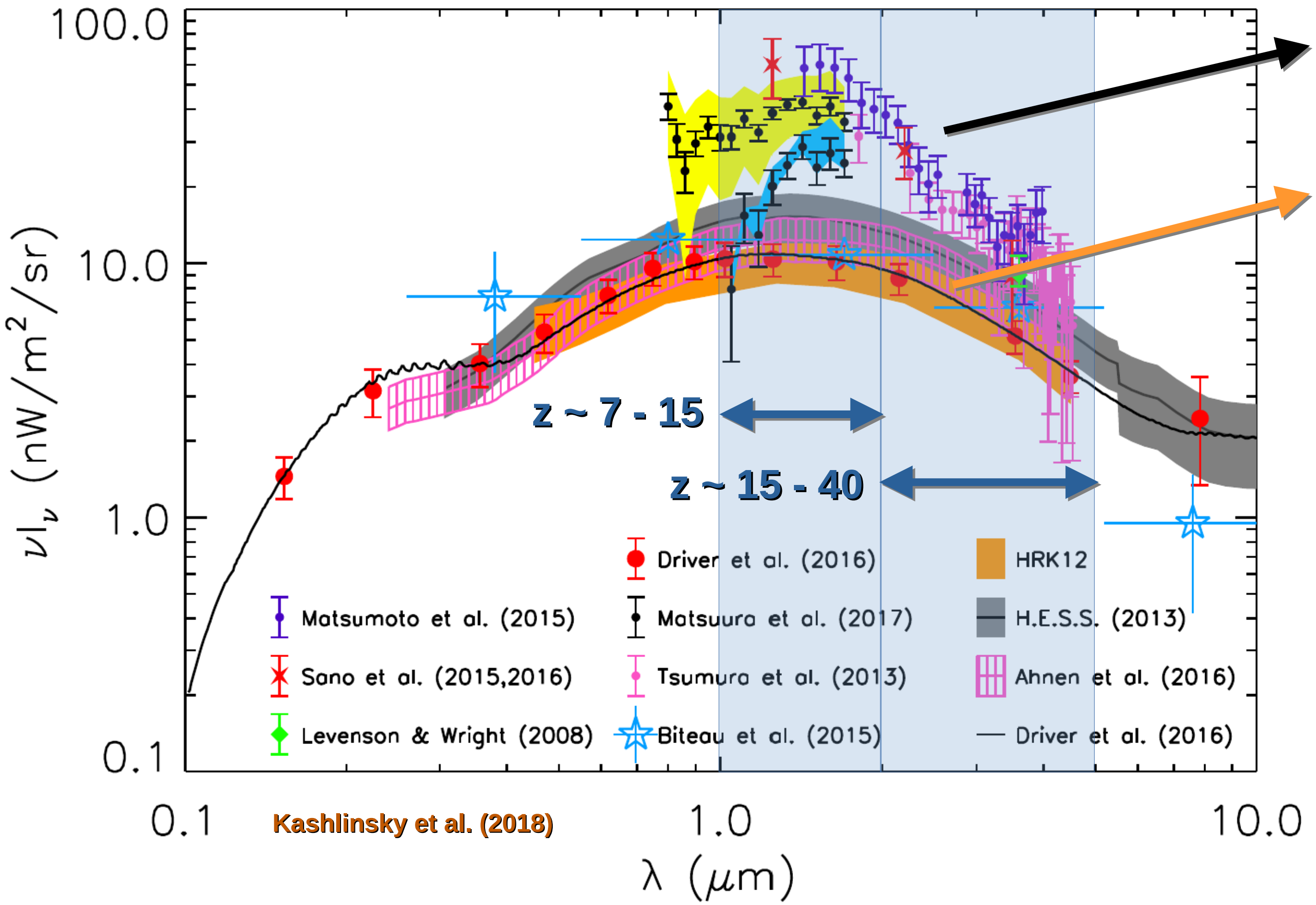

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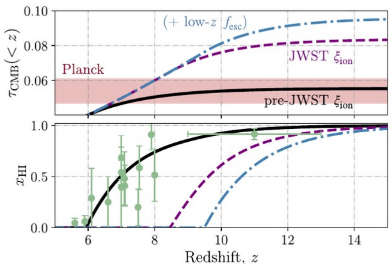
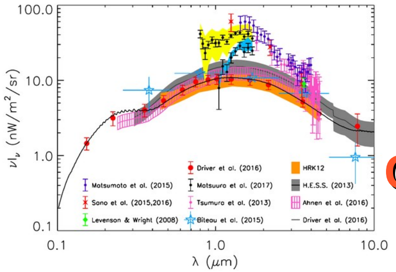
Excess **~few nW m^{-2} sr^{-1}**

Unresolved
high-z component?



Early reionization problem



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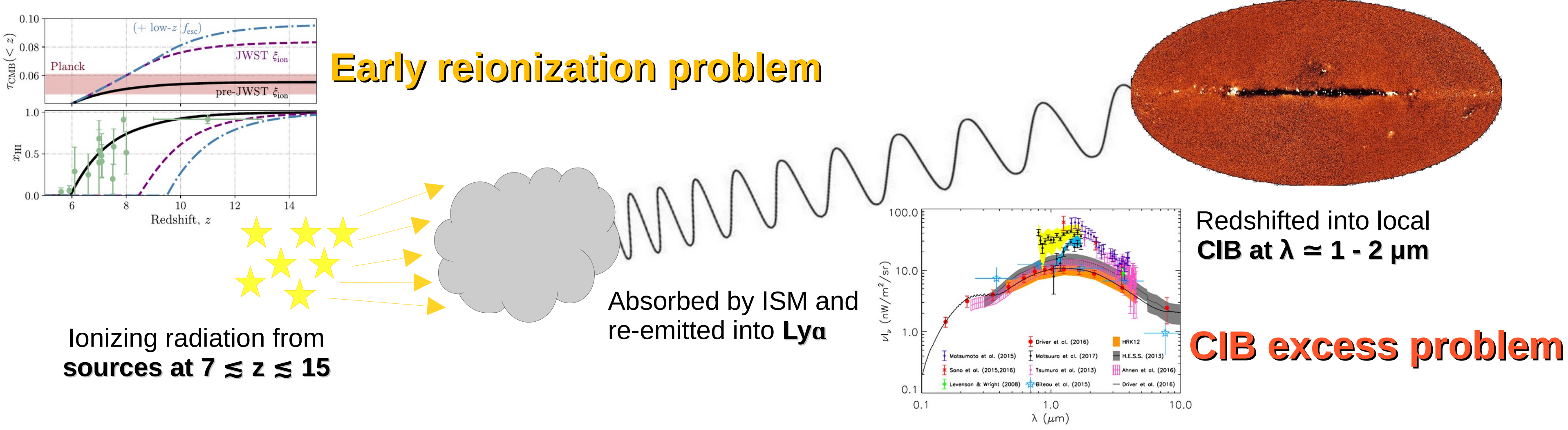

Early reionization problem
Planck
JWST ξ_{ion}
pre-JWST ξ_{ion}
(+ low-z f_{esc})
$\tau_{CMB}(<z)$
x_{HI}
Redshift, z
Ionizing radiation from
sources at 7 ≲ z ≲ 15
Absorbed by ISM and
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Redshifted into local
CIB at λ ≃ 1 - 2 μm
CIB excess problem
νI_ν (nW/m^2/sr)
λ (μm)
Driver et al. (2016)
Matsumoto et al. (2015)
Matsuura et al. (2017)
Sano et al. (2015,2016)
Tsumura et al. (2013)
Levenson & Wright (2008)
Biteau et al. (2015)
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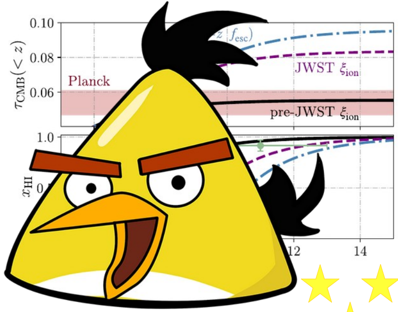

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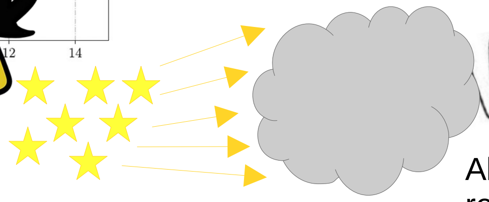

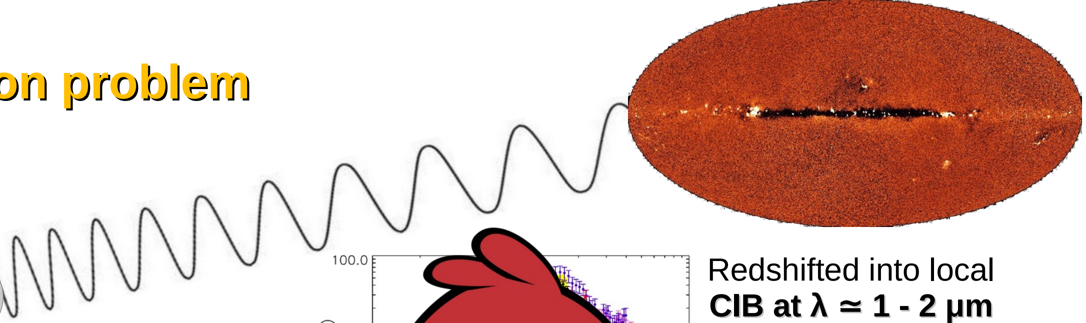

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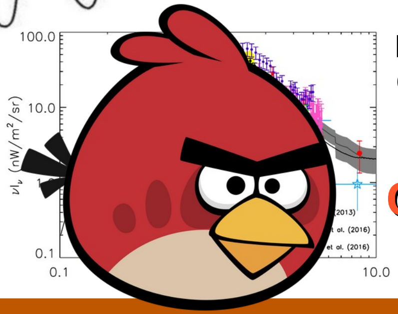
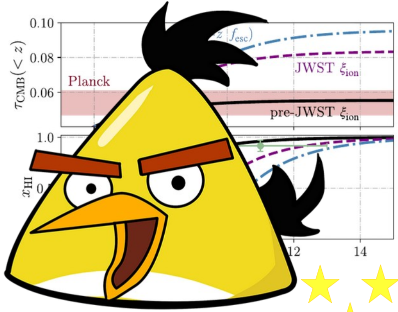


Redshifted into local
CIB at λ ≃ 1 - 2 μm

CIB excess problem

Two birds with one stone?



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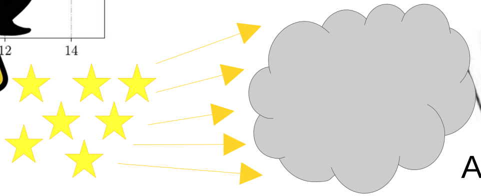

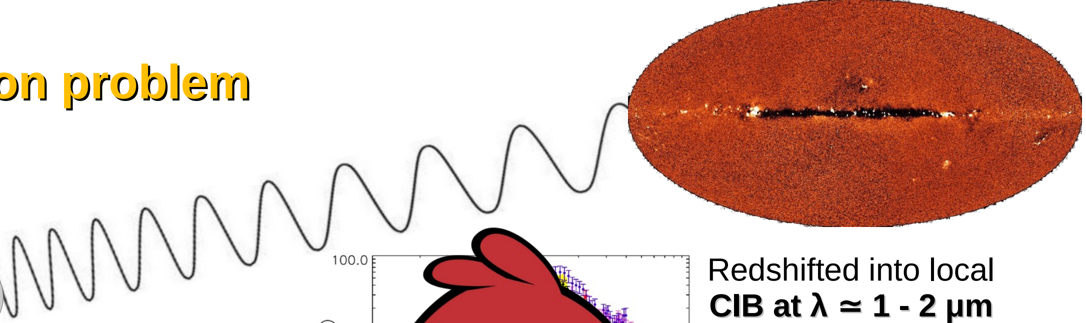

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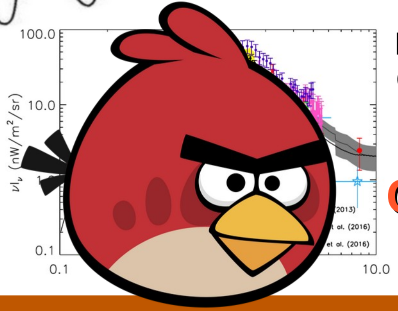

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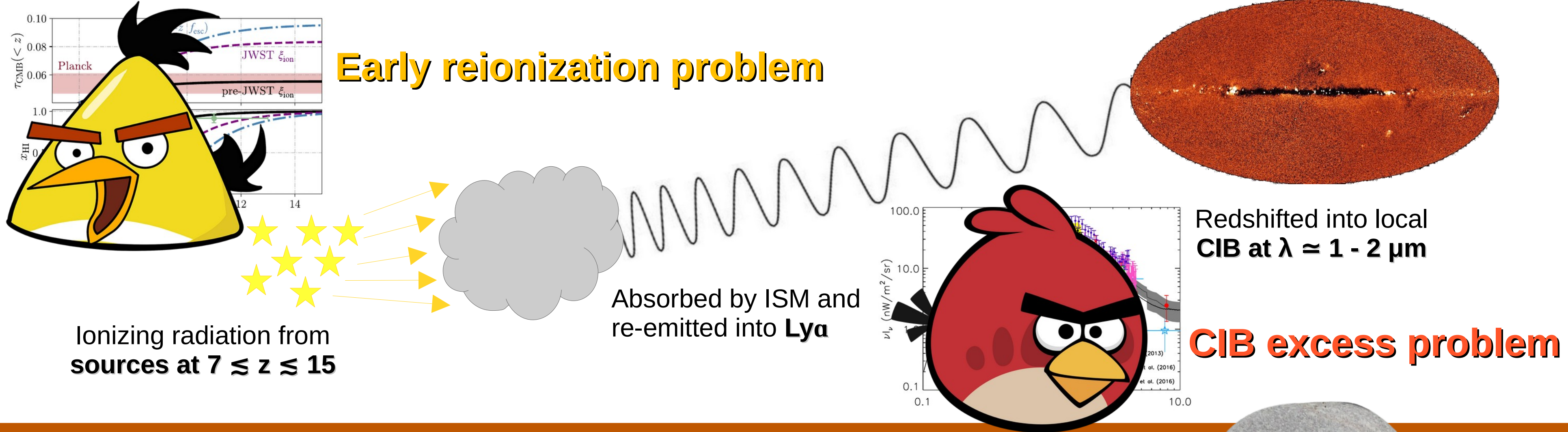

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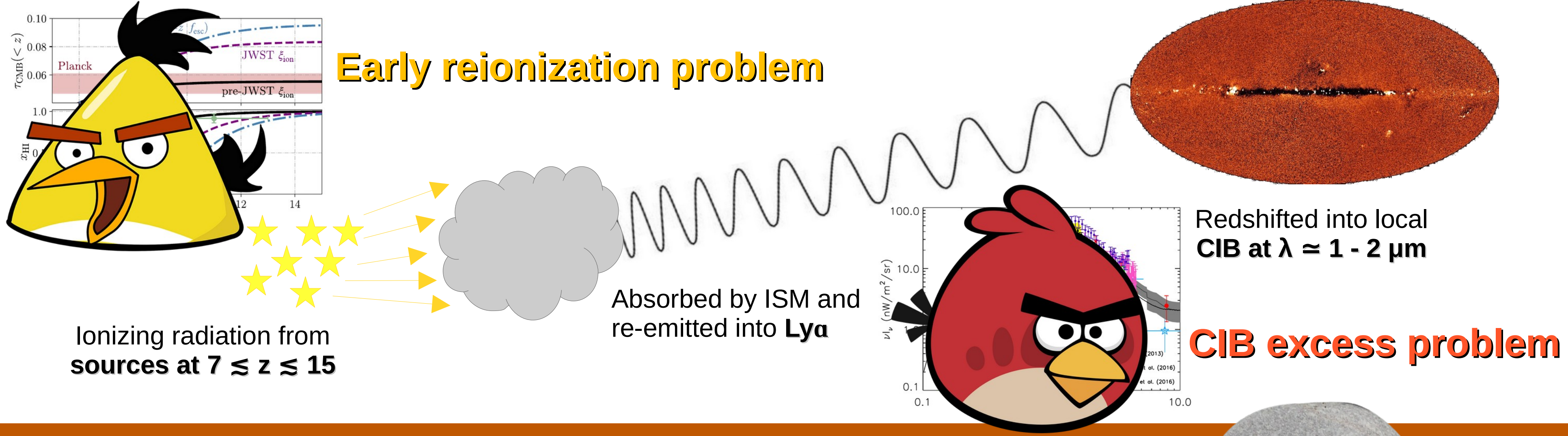

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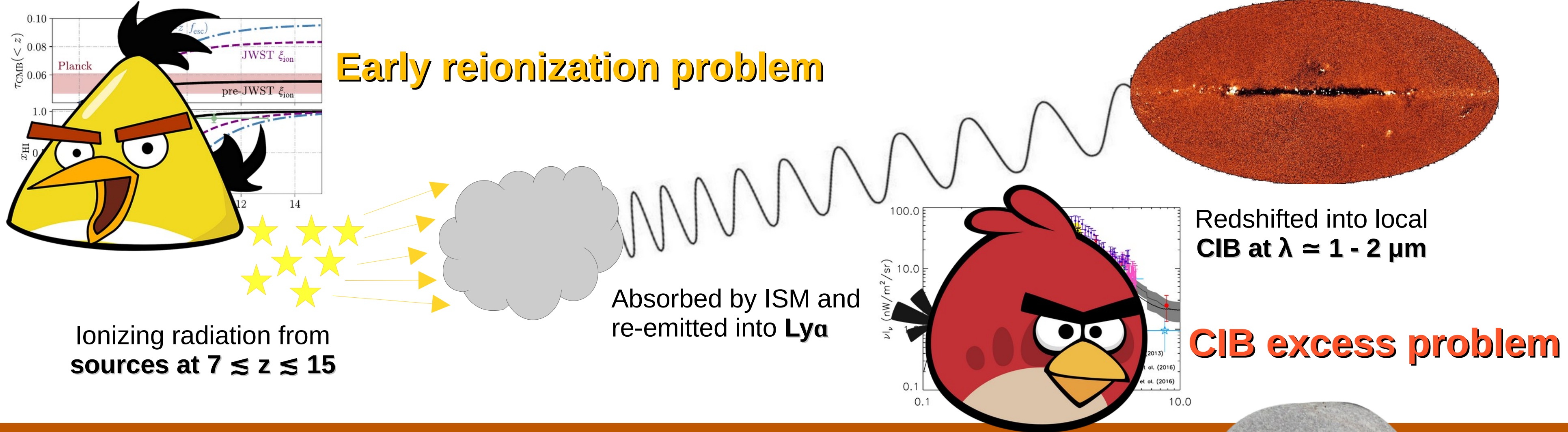
max. f_{esc} to not reionize the Universe too early

min. f_{esc} to not over-produce local CIB



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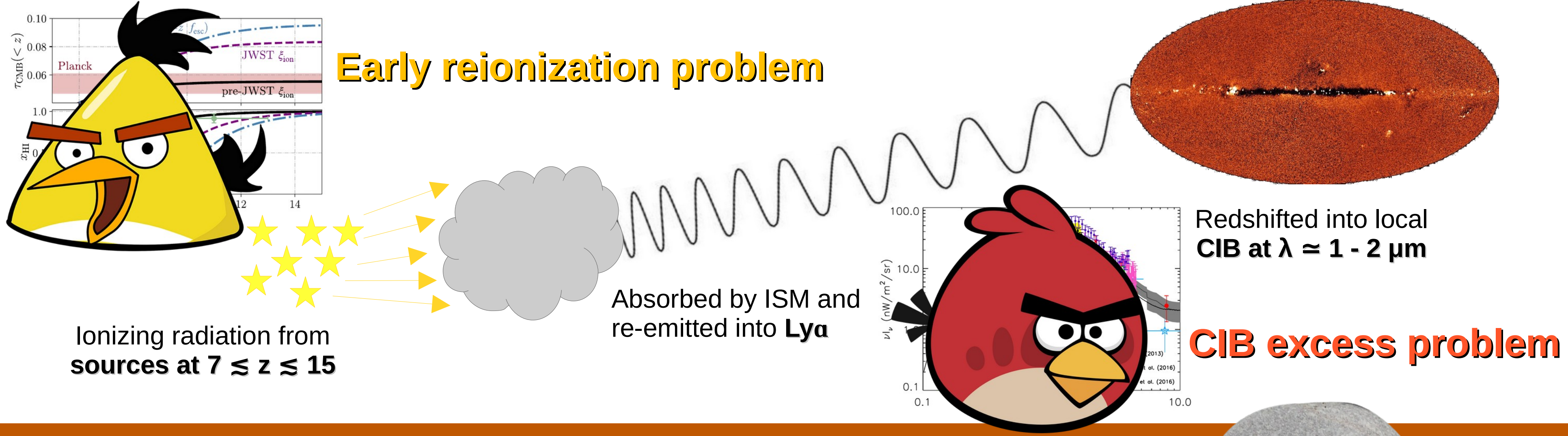

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[CASE 2] **"CIB undershoot":** CIB excess even beyond JWST galaxies

→ We can throw the <u>excess ionizing photons into Lyα</u>, no tension with CIB measures

→ However, no constraints on escape fractions
+ Other mechanisms needed to account for the CIB excess

Our theoretical framework

$$\rho_{\mathrm{Ly}\alpha}(z) = \int_{-24}^{M_{\mathrm{UV}}^{\mathrm{ion.\ cutoff}}} L_{\mathrm{Ly}\alpha}(M_{\mathrm{UV}}) \Phi_{\mathrm{UV}}(M_{\mathrm{UV}}, z) \mathrm{d}M_{\mathrm{UV}}$$

Intrinsic Lyα luminosity density

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Intrinsic Lyα luminosity density

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$z \leq 9$: pre-JWST (Bouwens et al. 2021)

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Intrinsic Lyα luminosity density

faint-end cut-off
> -15 from HST+JWST (Atek+18)

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Lyα luminosity

$L_{\mathrm{Ly}\alpha} = h\nu_{\mathrm{Ly}\alpha}\,\dot{N}_{\mathrm{Ly}\alpha}$,

$\dot{N}_{\mathrm{Ly}\alpha} \simeq 0.75\,\dot{N}_{\mathrm{ion}}$

$\dot{N}_{\mathrm{ion}} = \xi_{\mathrm{ion}}(M_{\mathrm{UV}}, z)\,L_{\mathrm{UV}}$

(ionizing → Lyα photon production rate with **escape fraction f_{esc} ≃ 0**)

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~~(Chisolm et al. 2022, **LzLCS**)~~

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~~(Chisolm et al. 2022, **LzLCS**)~~

ionizing efficiency

Log [ξ_{ion} /(Hz/erg)] ≈ 25.8 + 0.11(M_{UV} + 17) + 0.05(z − 7)
up to ~26 at M_{UV} = -16 (Simmonds et al. 2024, **JADES**)

Our theoretical framework

$$\rho_{\mathrm{Ly}\alpha}(z) = \int_{-24}^{M_{\mathrm{UV}}^{\mathrm{ion.\,cutoff}}} L_{\mathrm{Ly}\alpha}(M_{\mathrm{UV}})\,\Phi_{\mathrm{UV}}(M_{\mathrm{UV}}, z)\,\mathrm{d}M_{\mathrm{UV}}$$

Intrinsic Lyα luminosity density

faint-end cut-off

> -15 from HST+JWST (Atek+18)

Lyα luminosity

$L_{\mathrm{Ly}\alpha} = h\nu_{\mathrm{Ly}\alpha}\,\dot{N}_{\mathrm{Ly}\alpha}$,

$\dot{N}_{\mathrm{Ly}\alpha} \simeq 0.75\,\dot{N}_{\mathrm{ion}}$ → (ionizing → Lyα photon production rate with **escape fraction $f_{esc} \simeq 0$**)

$\dot{N}_{\mathrm{ion}} = \xi_{\mathrm{ion}}(M_{\mathrm{UV}}, z)\,L_{\mathrm{UV}}$

UV LF

z ≤ 9: pre-JWST (Bouwens et al. 2021)

z > 9: post-JWST (Donnan et al. 2024)

~~$f_{esc} = 1.3 \times 10^{-4} \times 10^{-1.22\,\beta_{UV}}$~~

~~(Chisolm et al. 2022, **LzLCS**)~~

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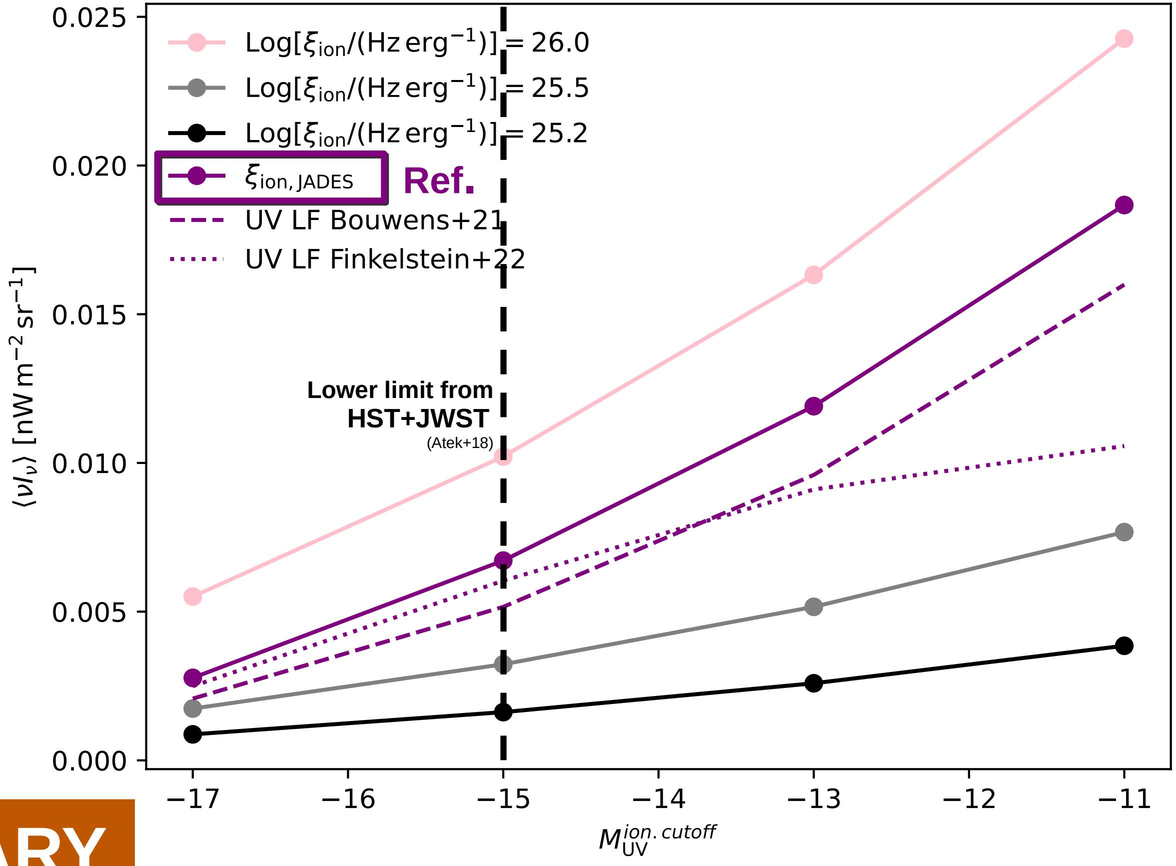
$$I_{\mathrm{NIR,tot}}(1-2\ \mu\mathrm{m}) = \int_{z_{\min}\simeq 7.2}^{z_{\max}\simeq 15.5} \frac{\rho_{\mathrm{Ly}\alpha}(z)}{4\pi D_{\mathrm{L}}(z)^2}\frac{\mathrm{d}V}{\mathrm{d}z}\mathrm{d}z$$

Integrated flux observed locally at λ ~ 1 − 2 μm

An out to the reionization timeline tension



PRELIMINARY

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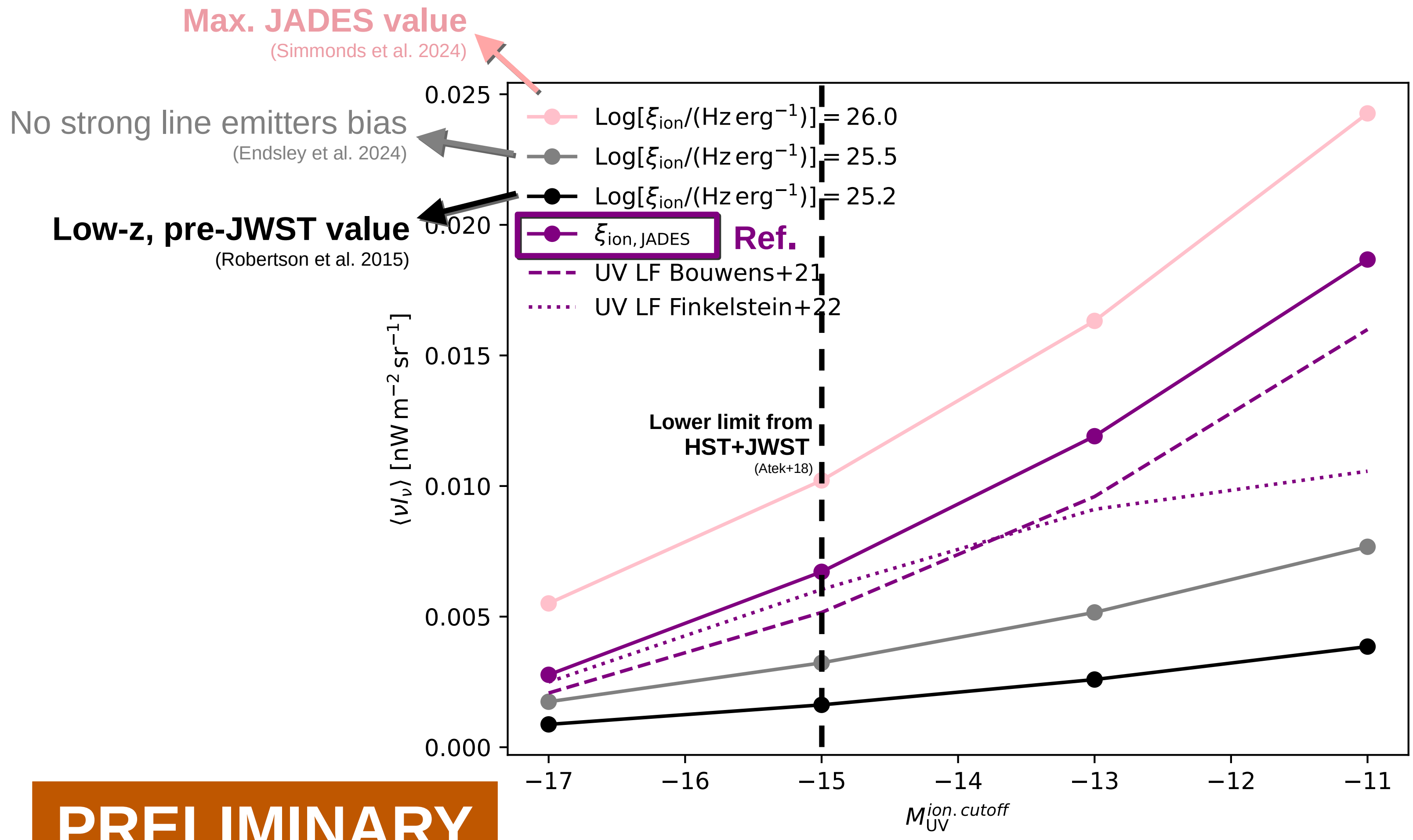

PRELIMINARY

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No strong line emitters bias
(Endsley et al. 2024)

Low-z, pre-JWST value
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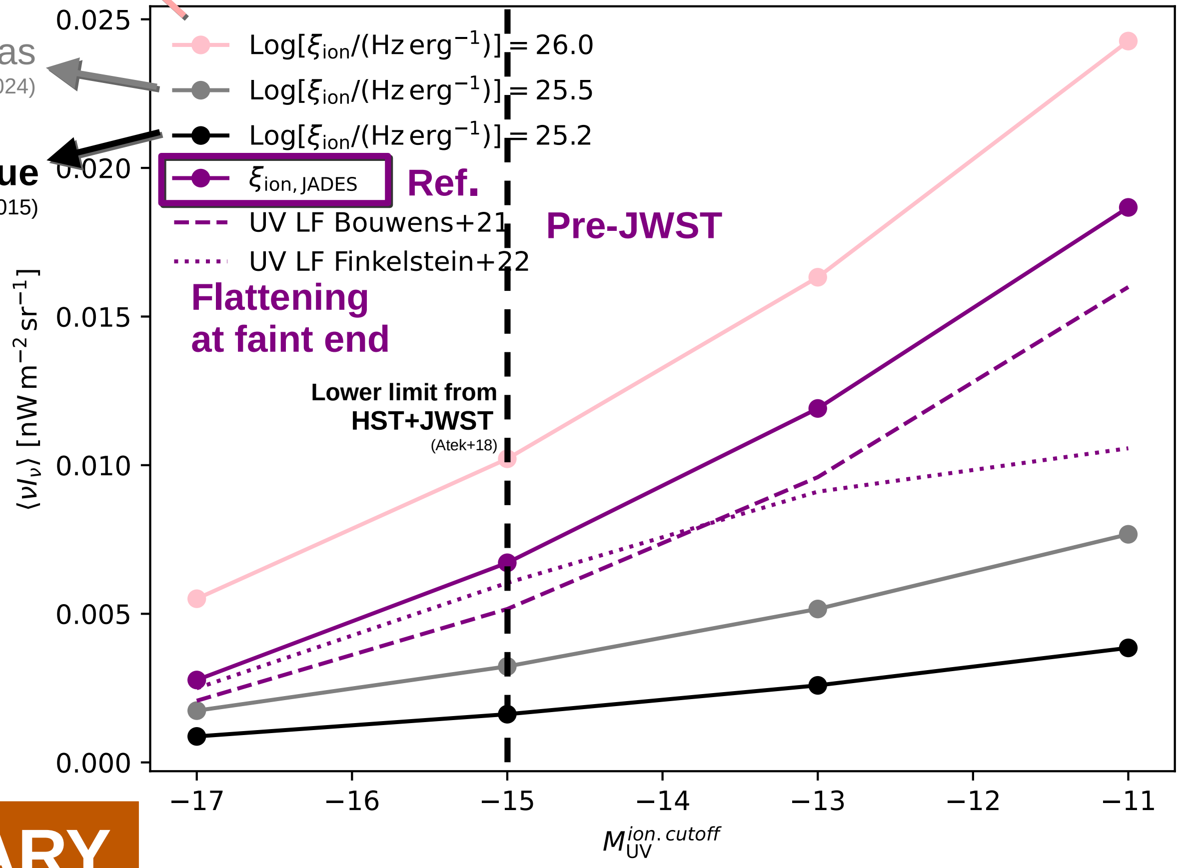

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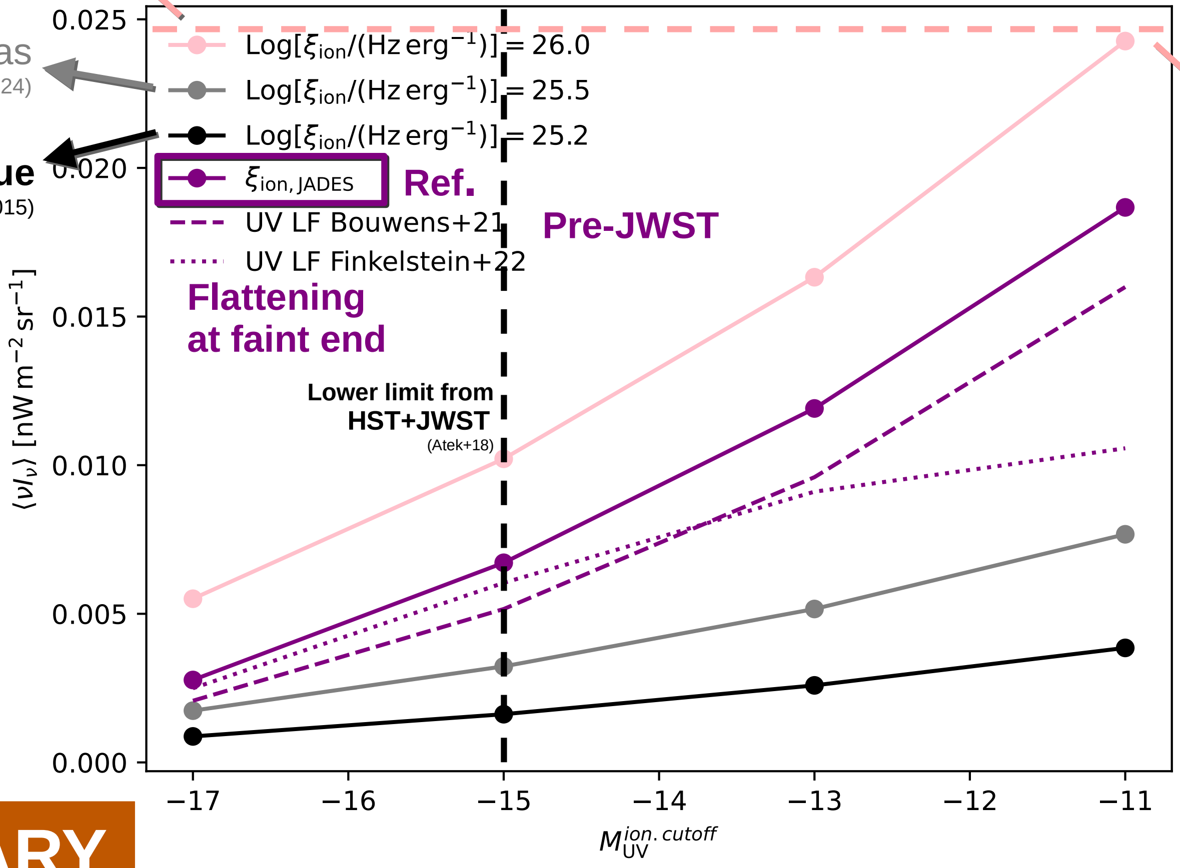

$\langle \nu I_\nu \rangle \simeq \langle \lambda \rangle I_{NIR,tot}/\Delta\lambda$
<< **1 nW m^{-2} sr^{-1}!**
=> "undershoot" case

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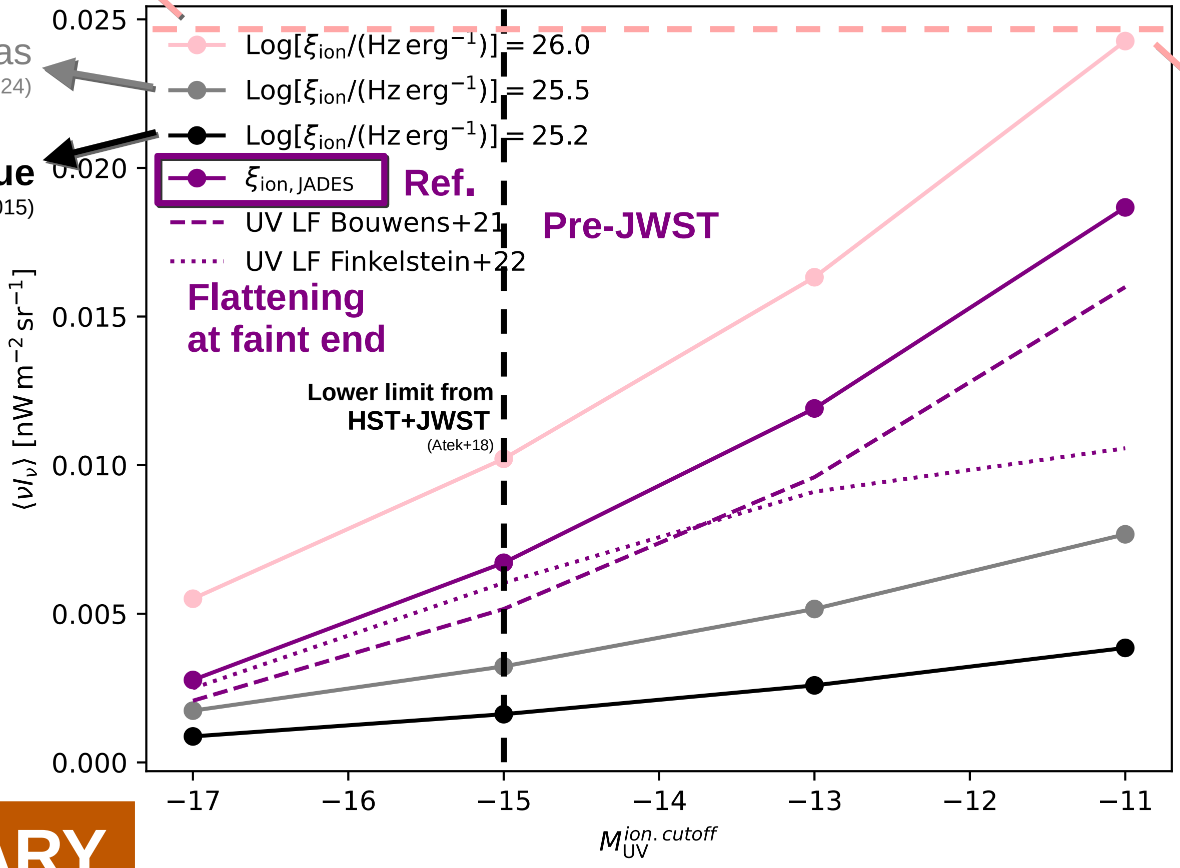

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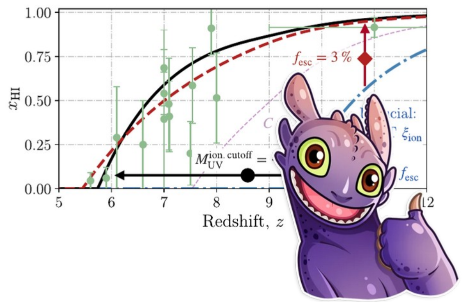

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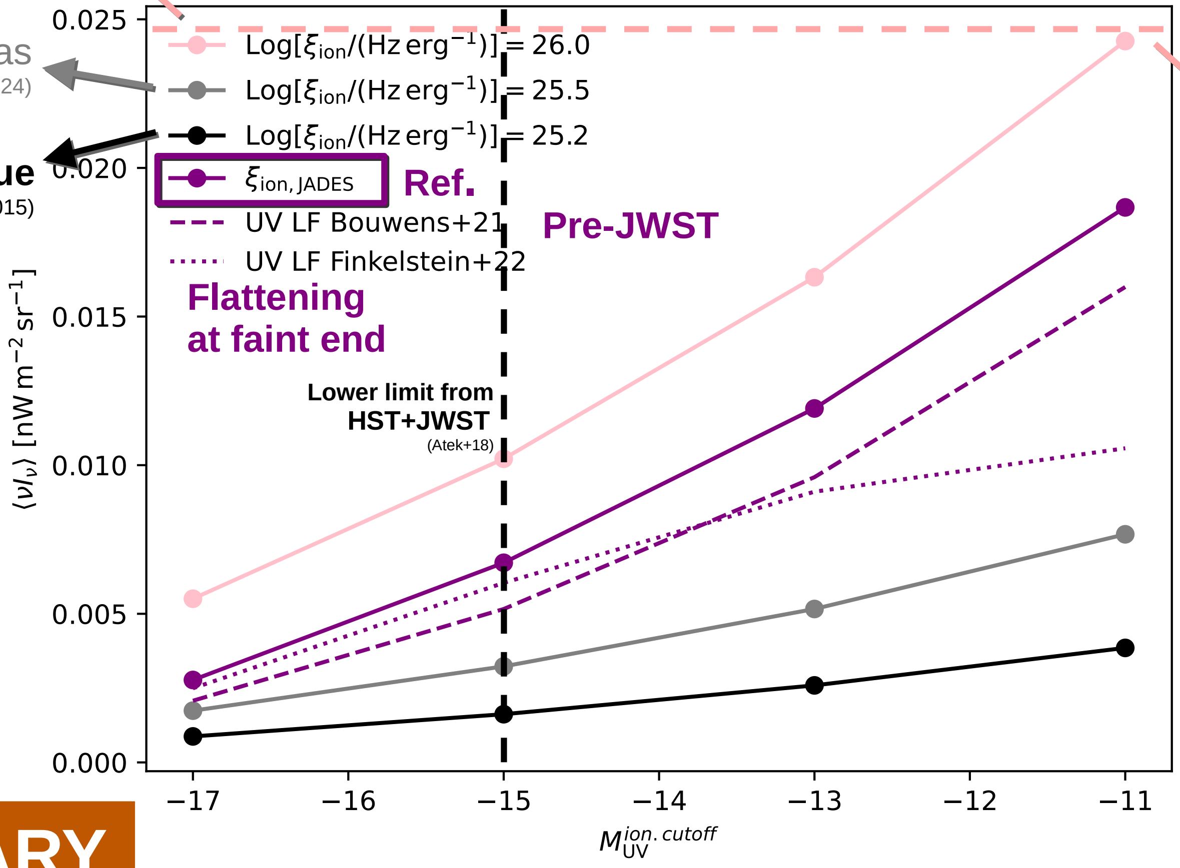

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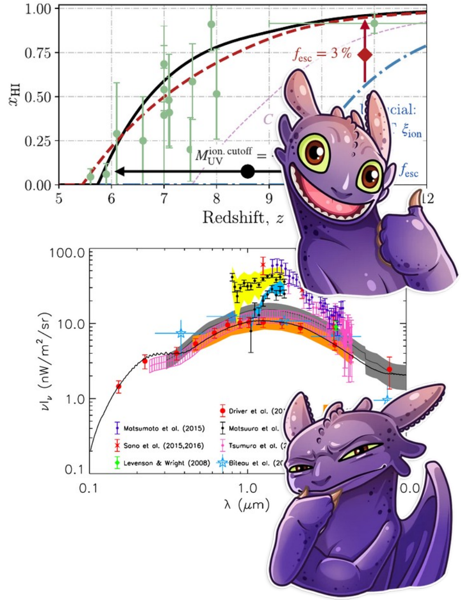

PRELIMINARY

What about the rest of the IR photons?

- Underestimated contribution from high-z, JWST galaxies?
- Additional contributions?

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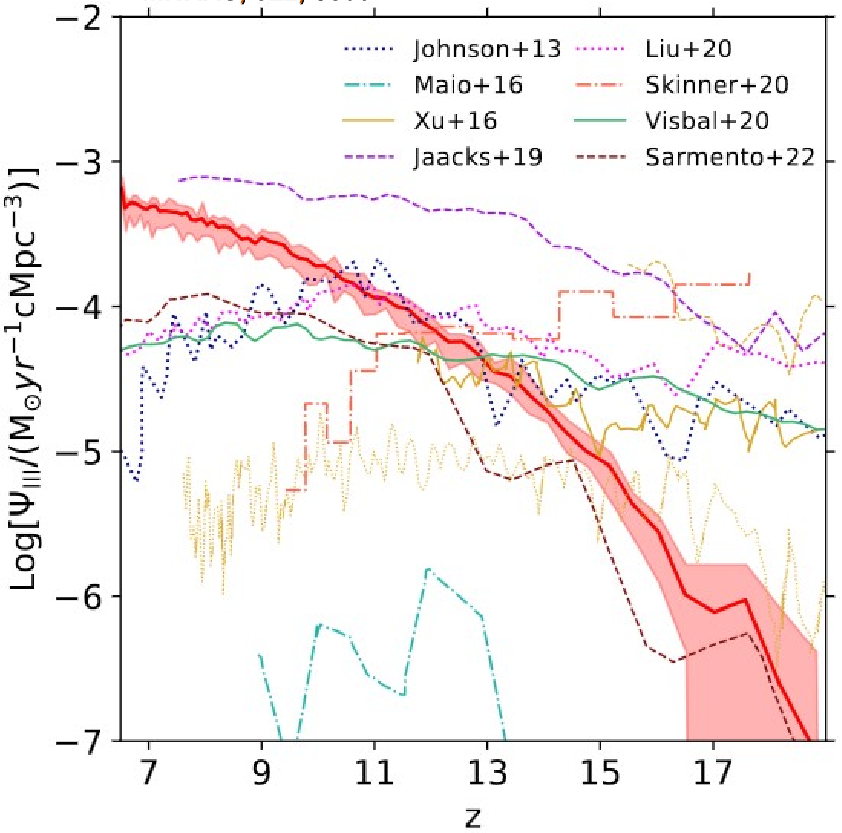
Venditti et al. (2023), MNRAS, 522, 3809



Late Pop III SF down to the EoR, due to in-homogeneous enrichment

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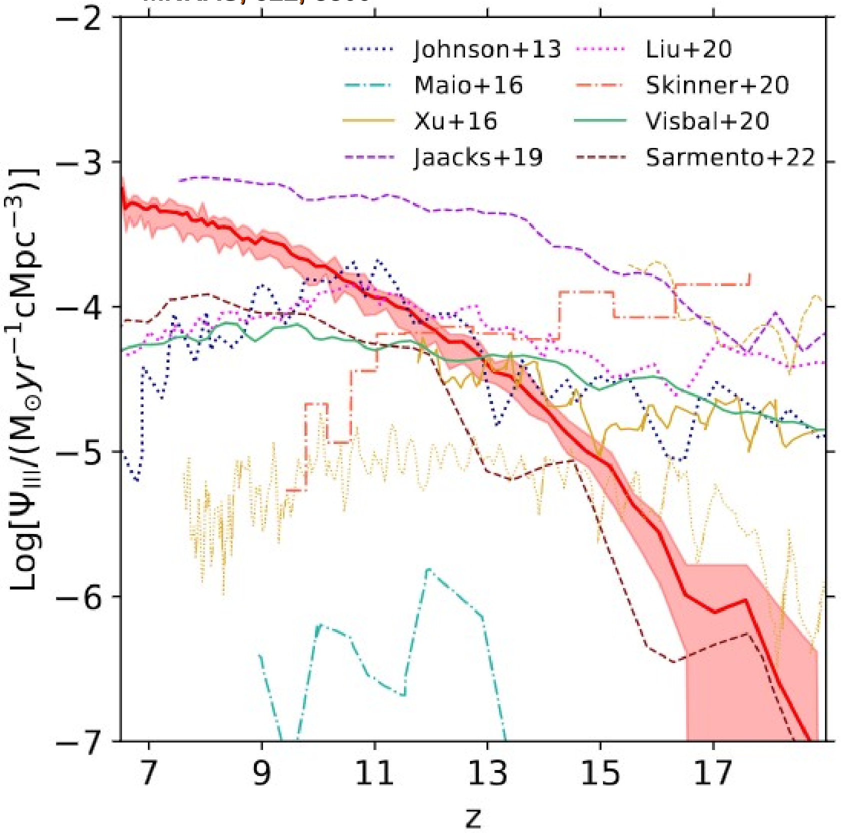

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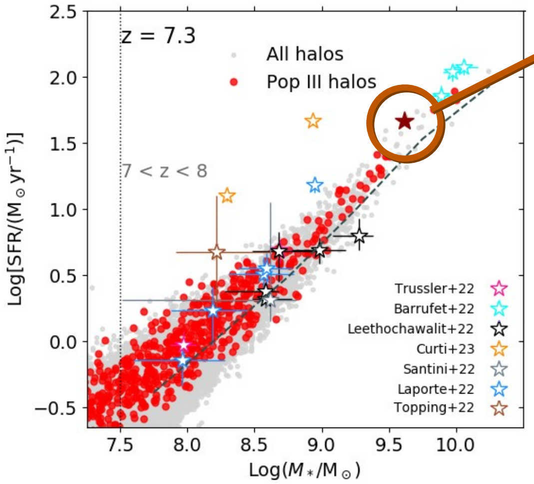

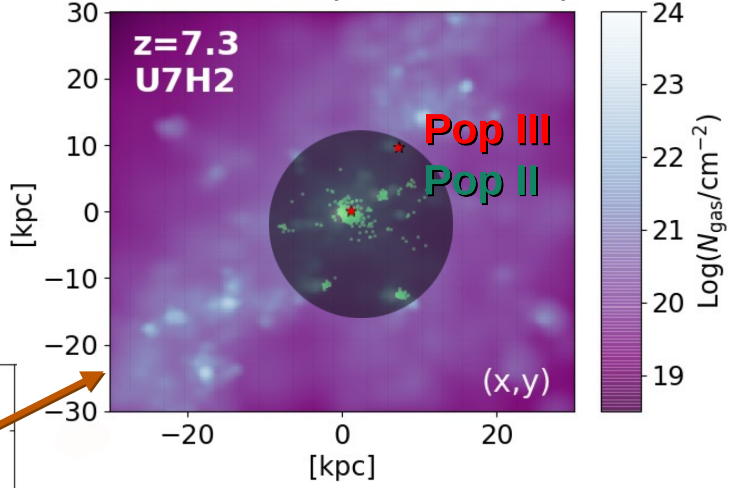

Even in **massive, evolved galaxies**

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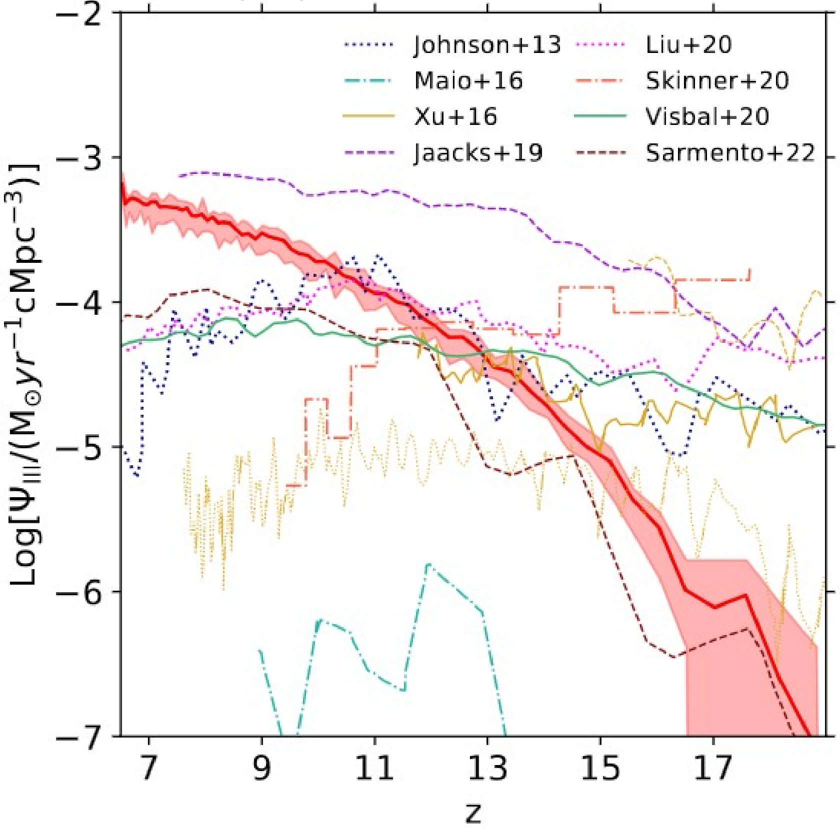
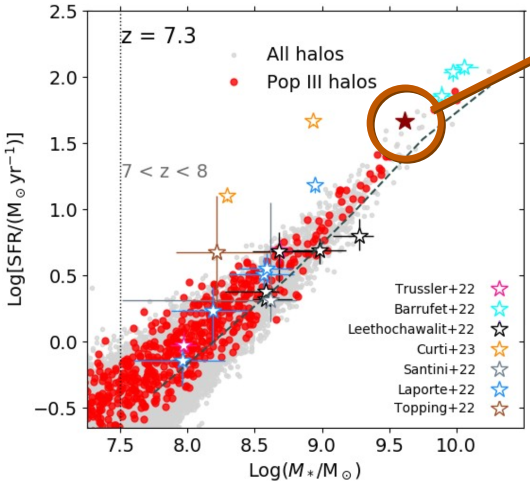
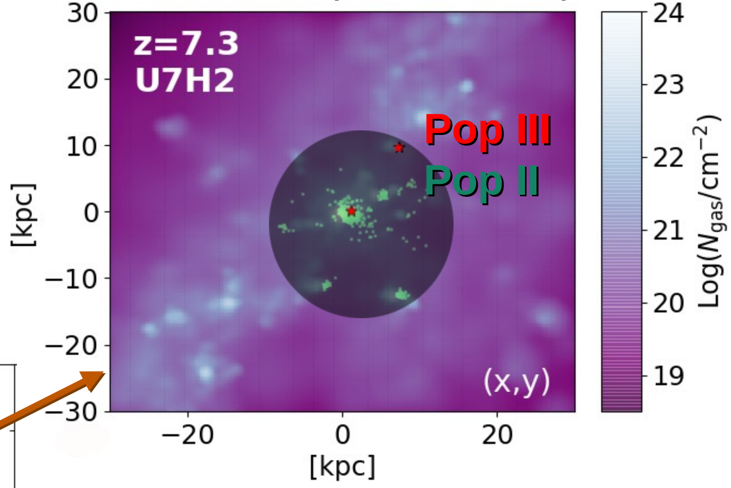


Late Pop III SF down to the EoR, due to in-homogeneous enrichment





Even in **massive, evolved galaxies**

May be missed for **geometry/sensitivity!**

Venditti et al. (2024), APJL, 973, L12

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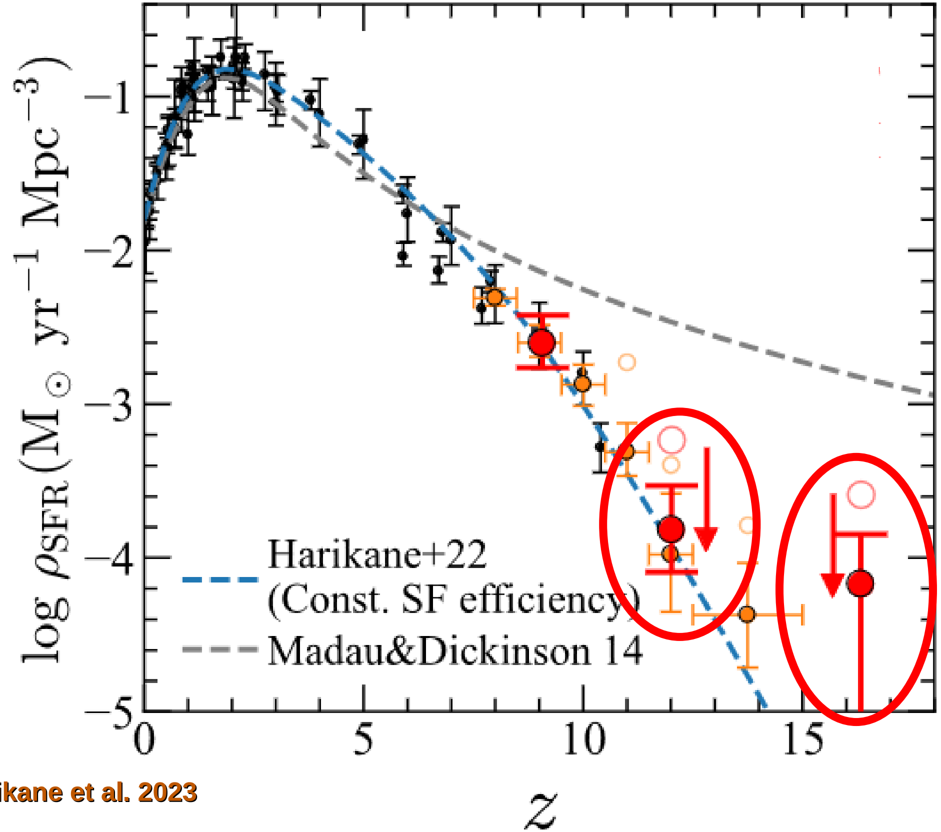
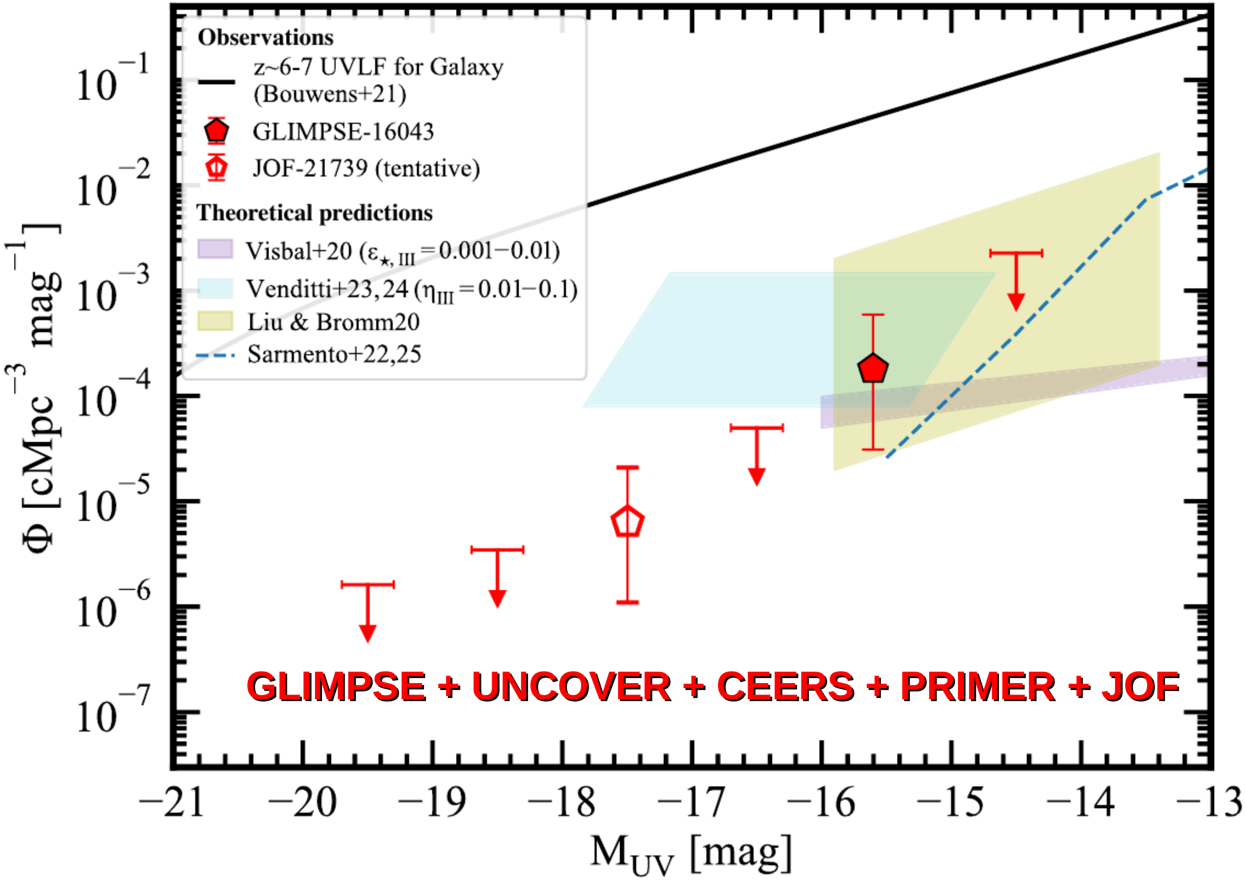


Top-heavy IMF?

Harikane et al. 2023

Pop III UVLF

Fujimoto et al. (2025), arXiv:2501.11678

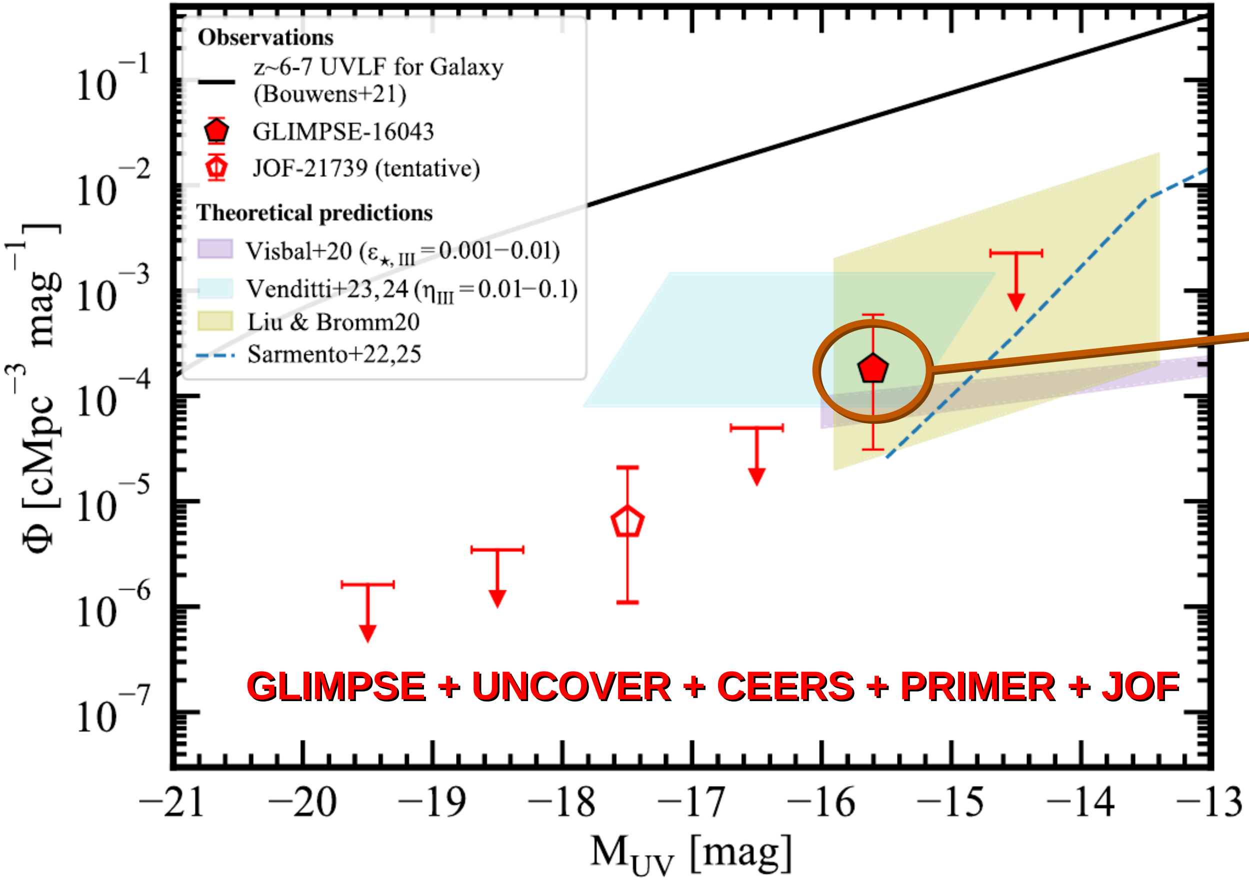


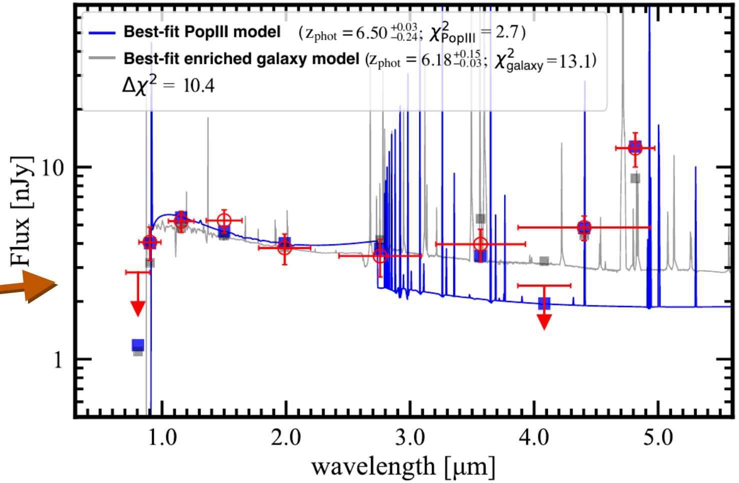
Pop III UVLF

Promising Pop III candidate **GLIMPSE-16043**:

- strong Hα
- Balmer jump
- no dust
- undetectable metal lines

Fujimoto et al. (2025), arXiv:2501.11678

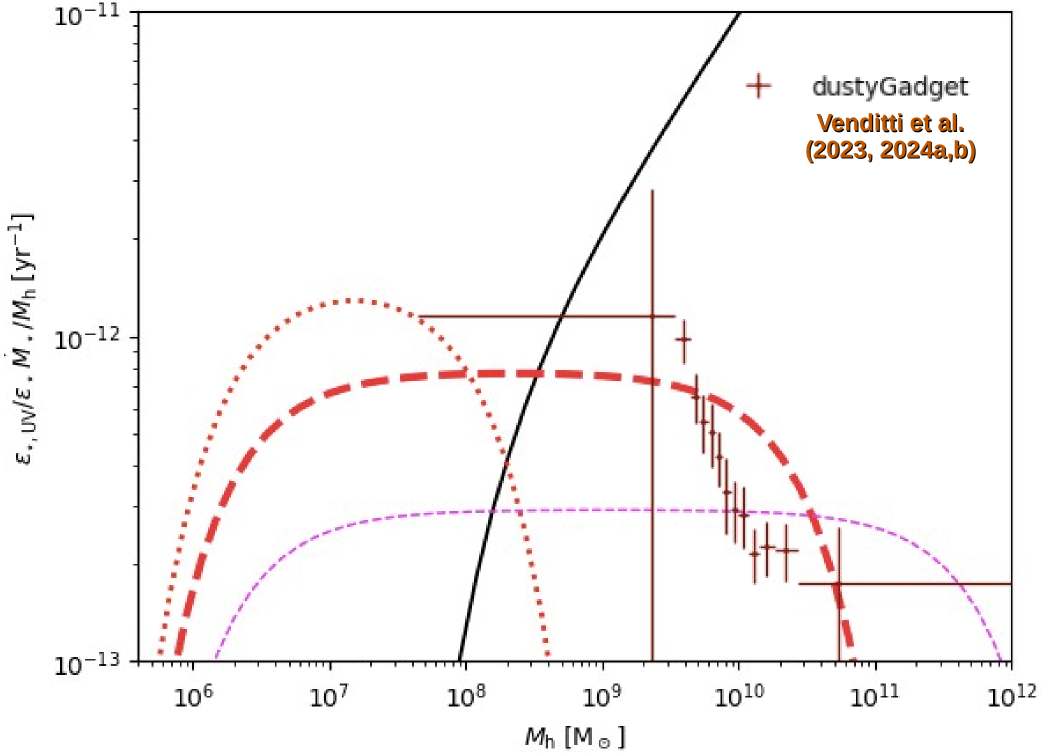




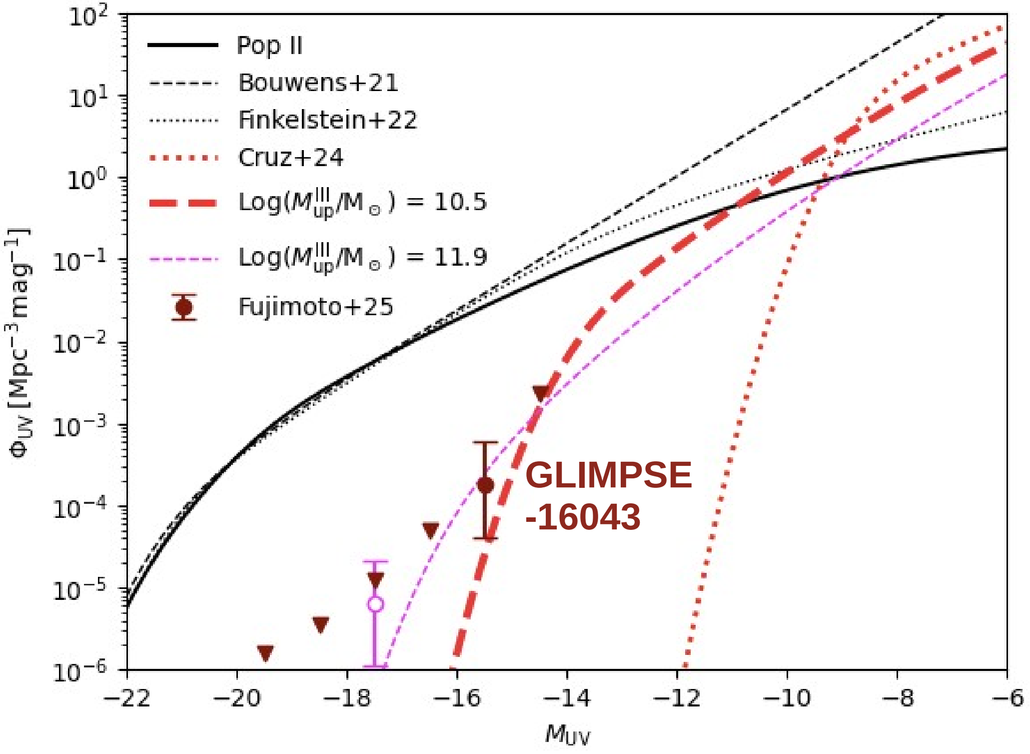
Property	Measurement
$z_{\rm phot}$	$6.50^{+0.03}_{-0.24}$
μ	$2.9^{+0.1}_{-0.2}$
β	-2.34 ± 0.36
$M_{\rm UV}$ [mag]	$-15.89^{+0.12}_{-0.14}$
$M_{\rm star}$ [$M_\odot$]	$\approx 10^5$
r_e [pc]	< 40
$t_{\rm age}$ [Myr]	2.8
Hα EW [Å]	2810 ± 550
OIII/H$\beta^\dagger$	< 0.44
12+log(O/H)†	< 6.4

Pop III UVLF: beyond mini-halos?

SFE



UVLF



PRELIMINARY

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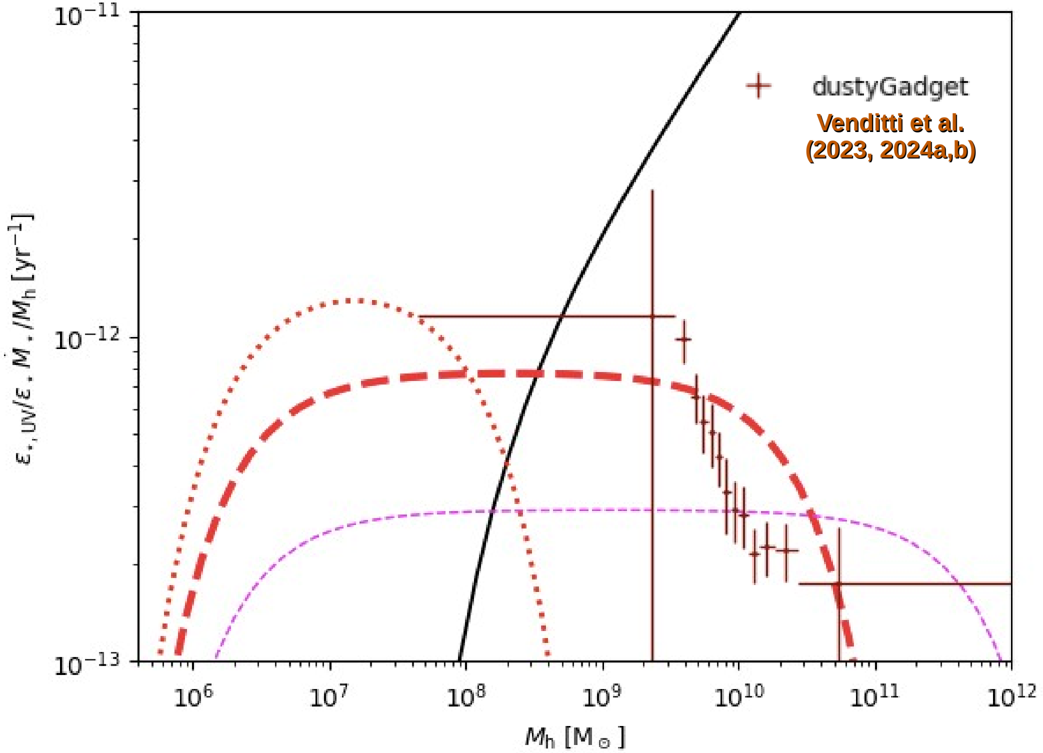

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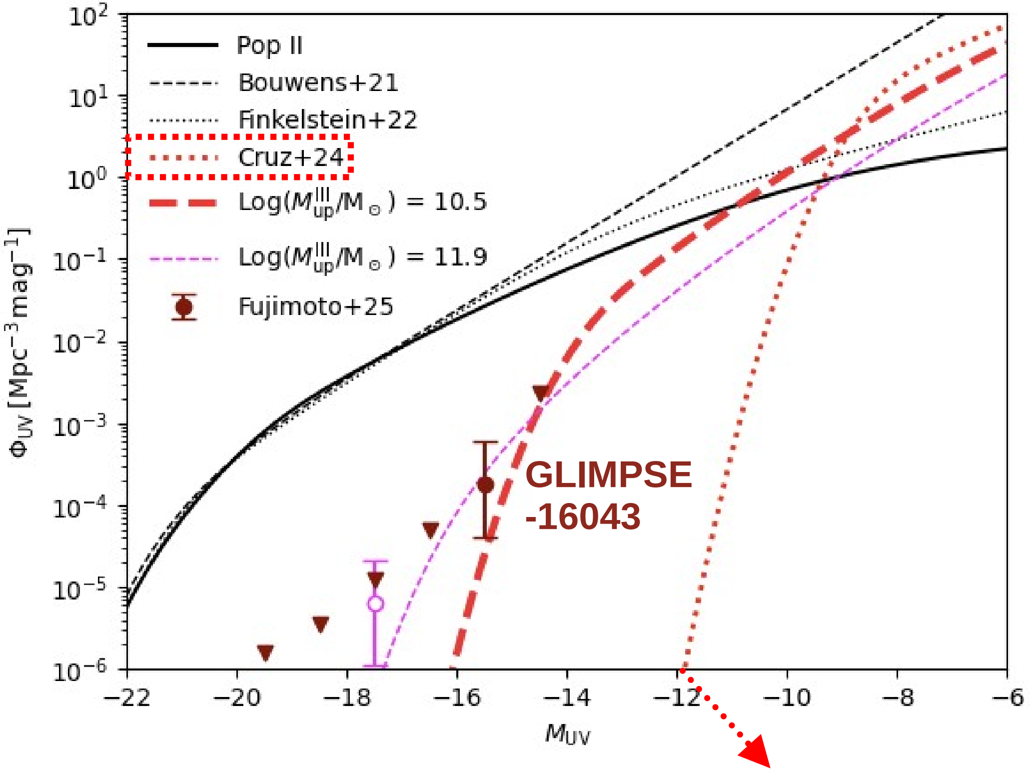

Hard to fit with Pop III SF confined in **molecular-cooling mini-halos**

(unless large stochasticity/burstiness)

PRELIMINARY

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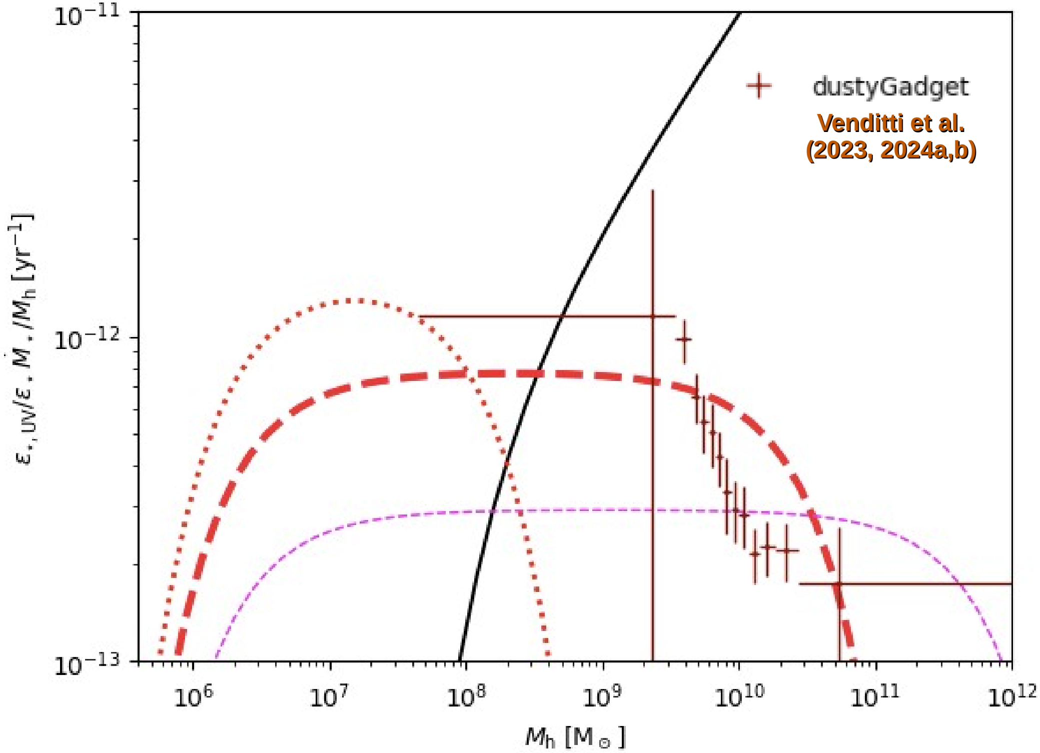
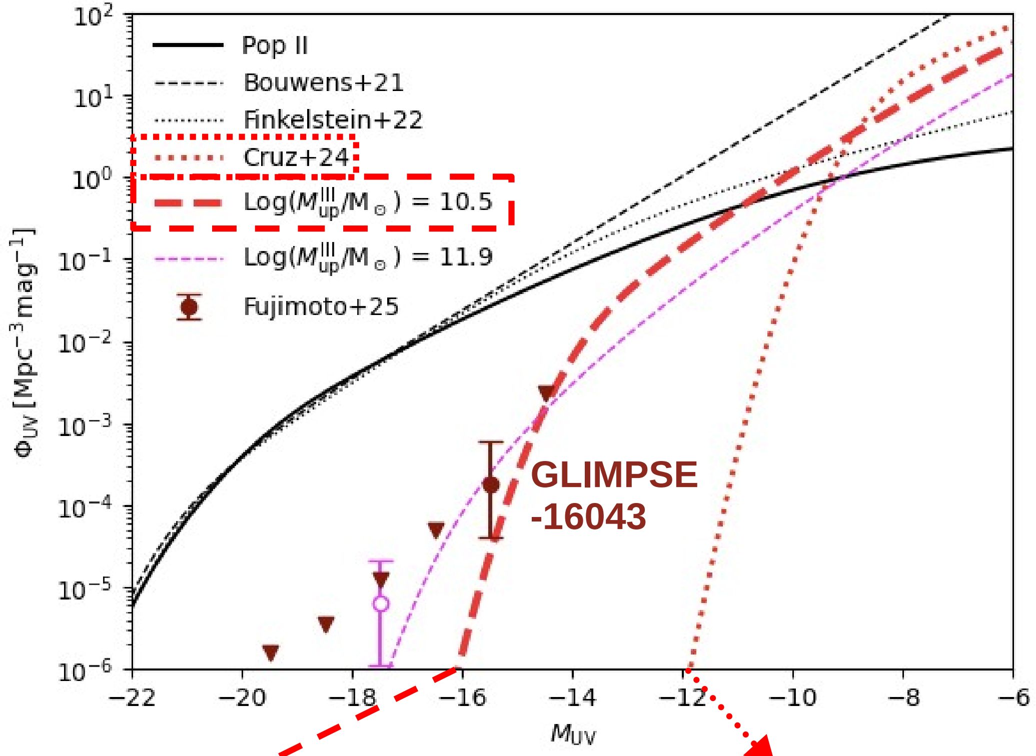
SFE



UVLF



Atomic-cooling Pop III halos can accommodate the data

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PRELIMINARY

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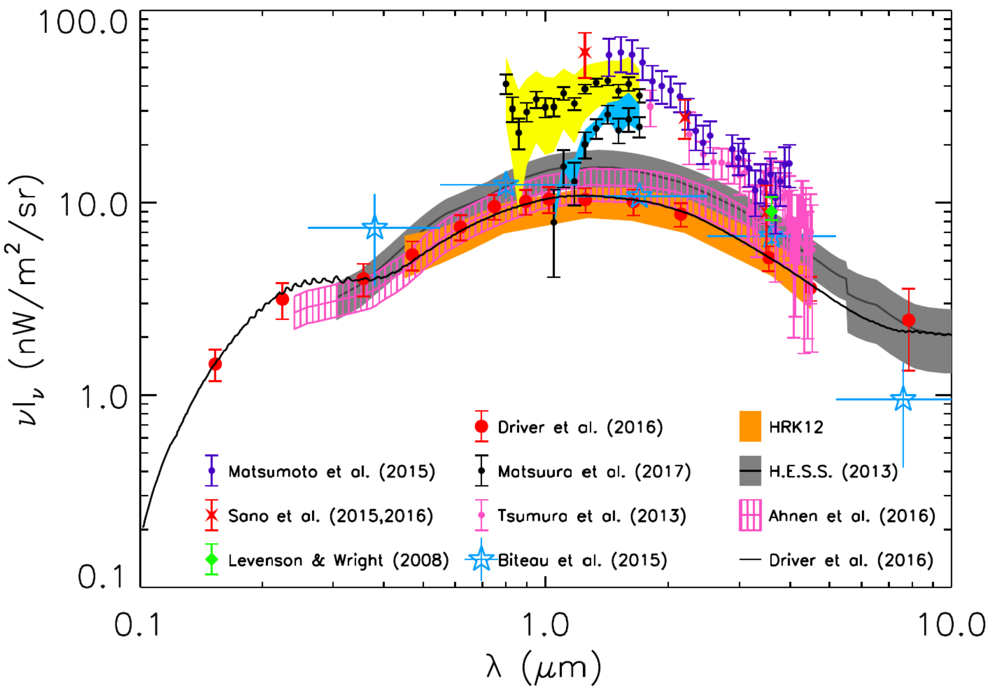

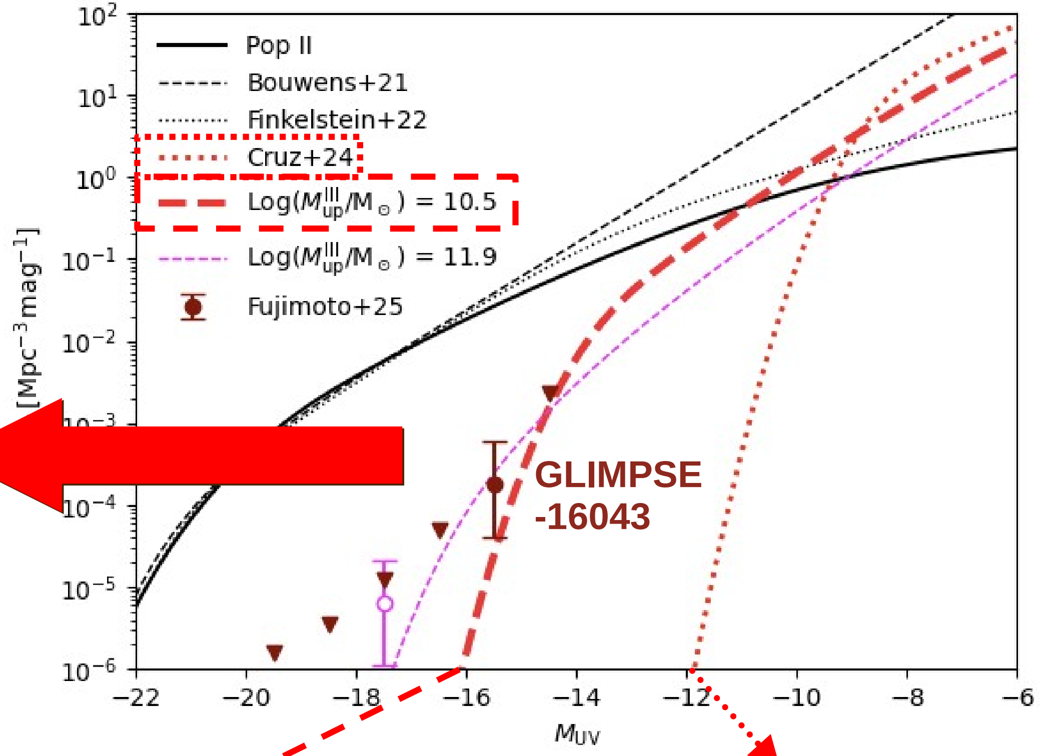

Atomic-cooling Pop III halos can accommodate the data

Hard to fit with Pop III SF confined in **molecular-cooling mini-halos**
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PRELIMINARY

- Blue high-z, JWST galaxies may produce an overly **anticipated reionization** than allowed by Planck CMB data
  Munoz et al. (2024)

- This tension could be solved with **lower escape fractions** than measured at low z, with most ionizing photons re-emitted into Lyα and eventually redshifted into the local CIB ($\lesssim 0.03$ nW m^{-2} sr^{-1})

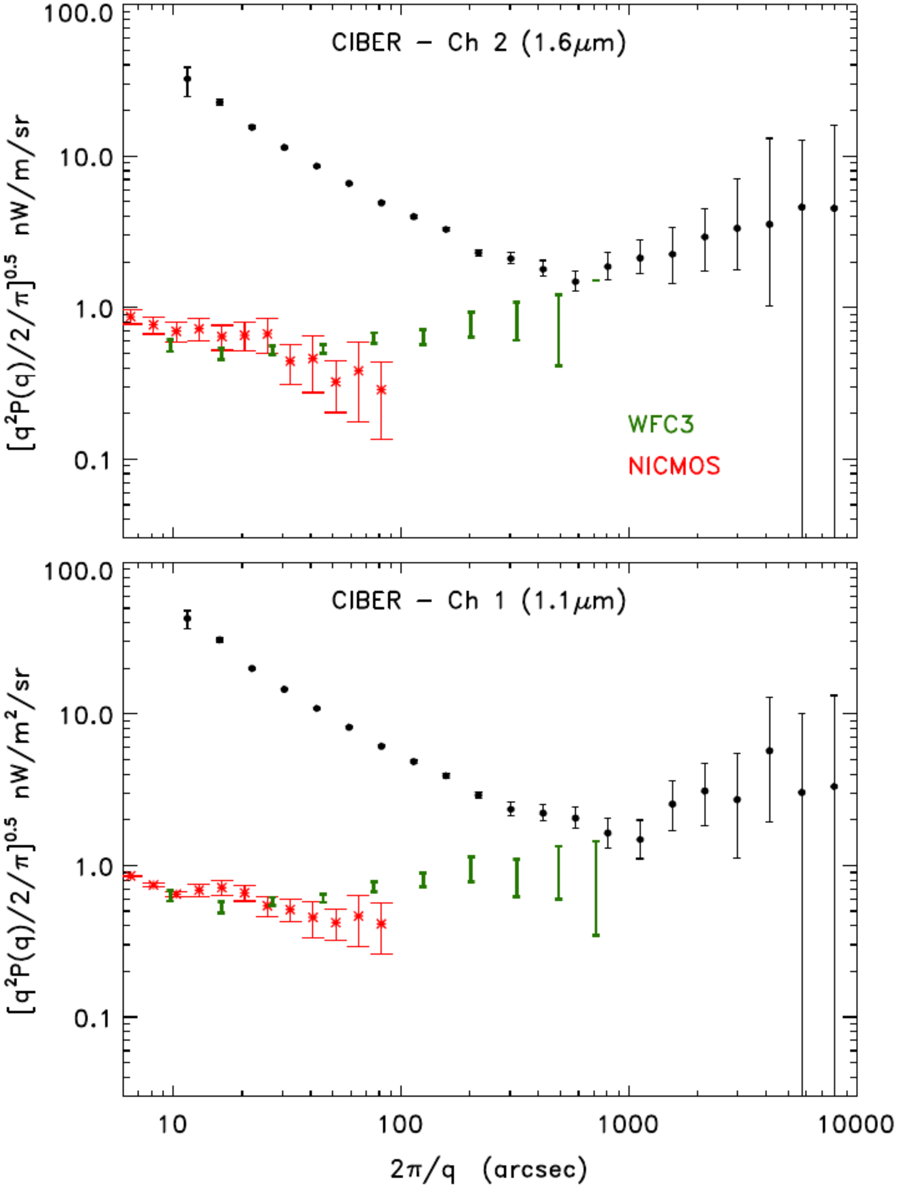
  Kashlinsky et al. (2018)

- However, measured **CIB excess** even beyond resolved low-z + high-z JWST galaxies
  → Other sources? (e.g. late Pop III star formation) Venditti et al. (2023, 2024a,b), Fujimoto et al. (2025)

Thank you for your attention!

"Photons under the rug:
Hiding the ionizing photon surplus in the Cosmic Infrared Background"
Escape of Lyman radiation from galactic labyrinths
Kolymbari, Orthodox Academy of Crete
April 11, 2025

Alessandra Venditti
University of Texas, Cosmic Frontier Center
alessandra.venditti@utexas.edu


CIBER – Ch 2 (1.6μm)
WFC3
NICMOS
[q²P(q)/2/π]^0.5 nW/m/sr
CIBER – Ch 1 (1.1μm)
[q²P(q)/2/π]^0.5 nW/m²/sr
100.0
10.0
1.0
0.1
10
100
1000
10000
2π/q (arcsec)

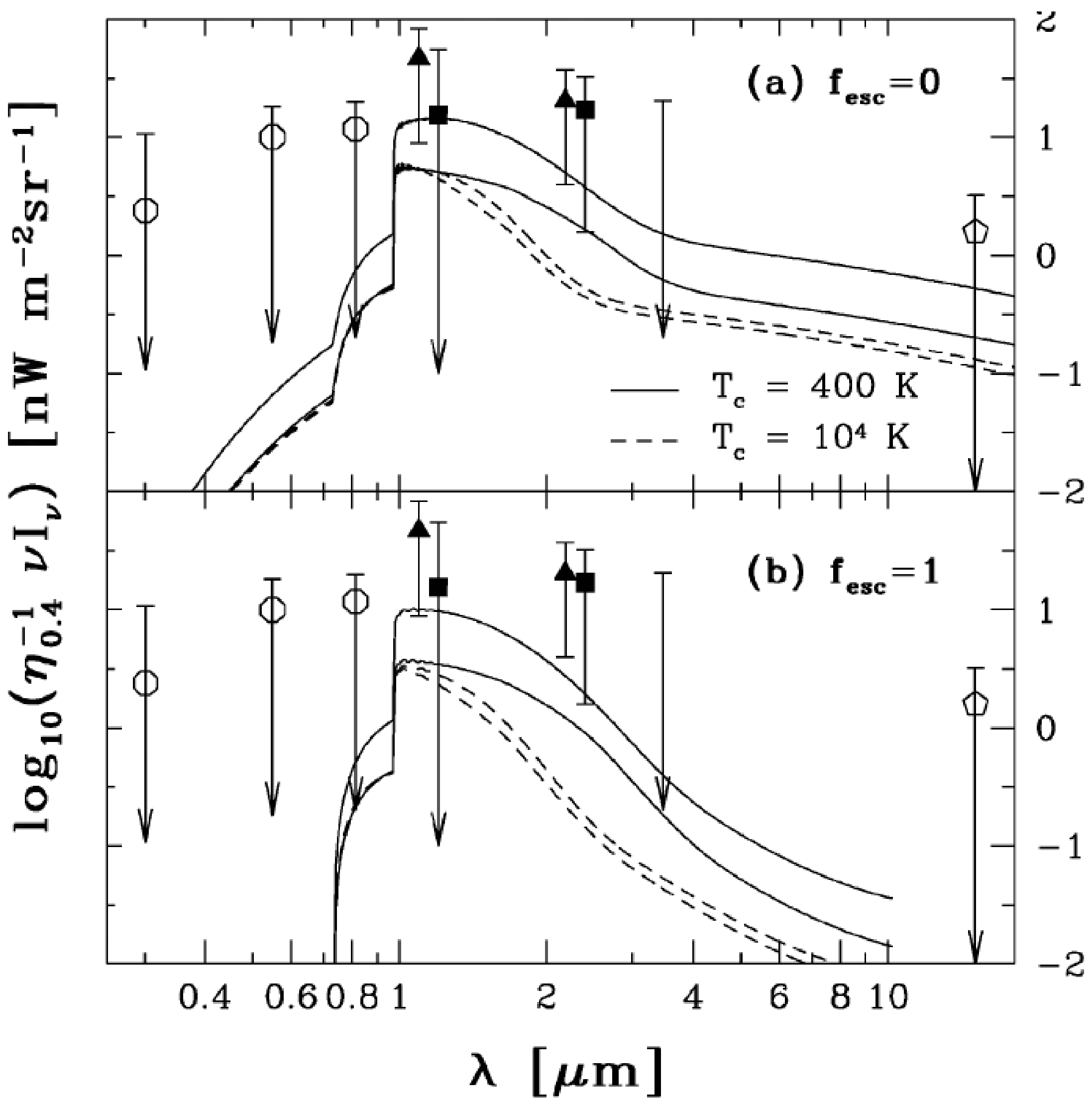


Figure 6. The cosmic infrared background from Pop III stars. The ordinate is the observed frequency multiplied by the observed specific intensity. Shown are curves for star formation in haloes with virial temperatures above the critical temperatures $T_{\rm crit} = 400$ K (molecular-hydrogen cooling, solid lines) and 10^4 K (atomic-hydrogen cooling, dashed lines). (a) $f_{\rm esc} = 0$; (b) $f_{\rm esc} = 1$. For both $f_{\rm esc}$ cases, there are two sets of two curves: the upper set is for the ongoing star formation model; the lower set is for the single-burst model. The properties of the curves are explained in Section 4.1; this figure shows $z_{\rm end} = 7$. The points show the excess CIRB, with 2σ errors, and are described in Section 4.2.

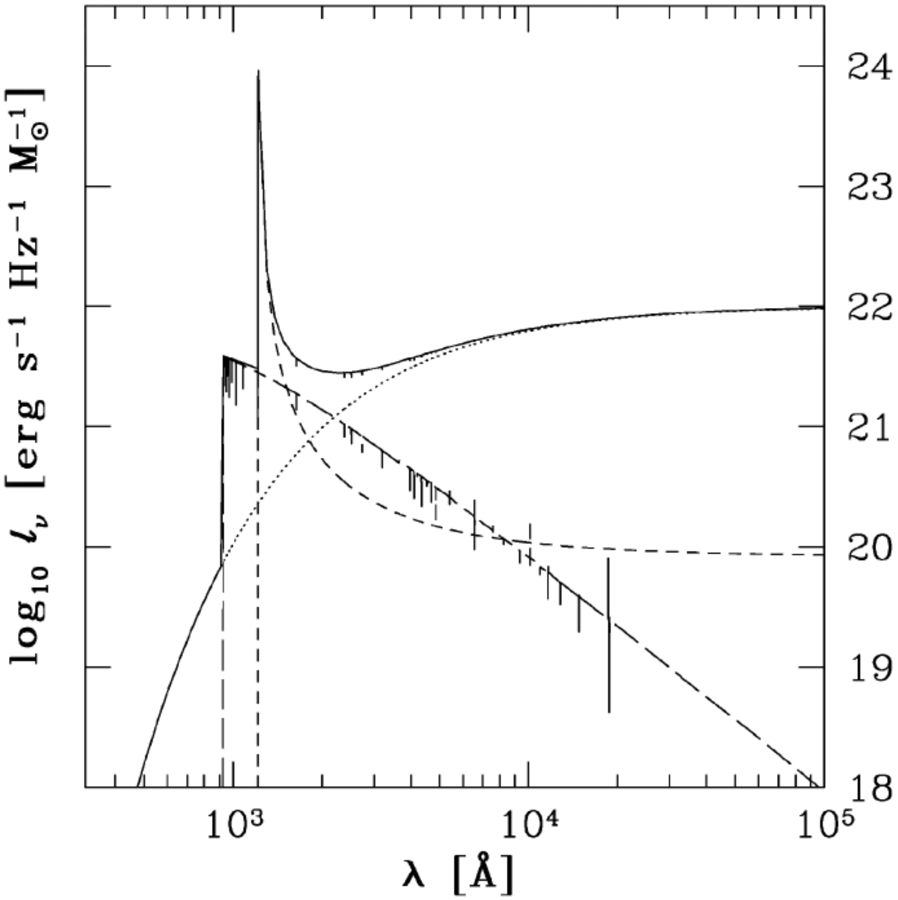


Figure 3. Spectrum of a $z = 15$ Pop III star plus nebular emission, for the $f_{esc} = 0$ case of Section 3.2. The long-dashed line is the spectrum of the star, cut-off for absorption shortward of the Lyman limit. The dotted line is the spectrum of free–free emission from the nebula. The short-dashed line is emission from Lyα recombination in the nebula at $z = 15$, corrected for scattering in the IGM. The solid line is the sum of the spectra. All spectra are in the rest frame of the star.

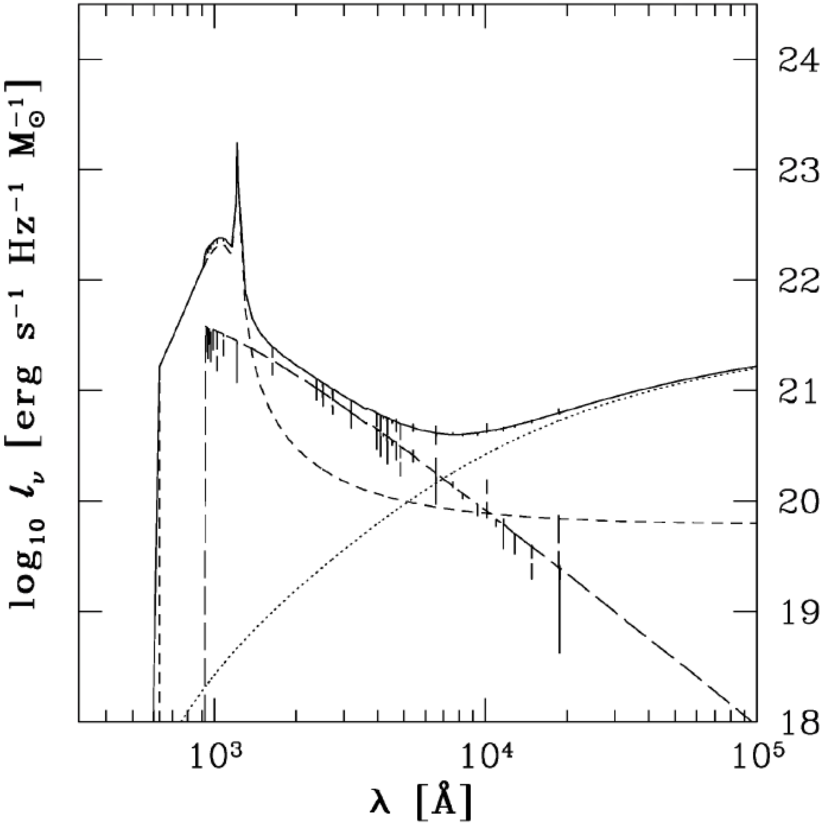
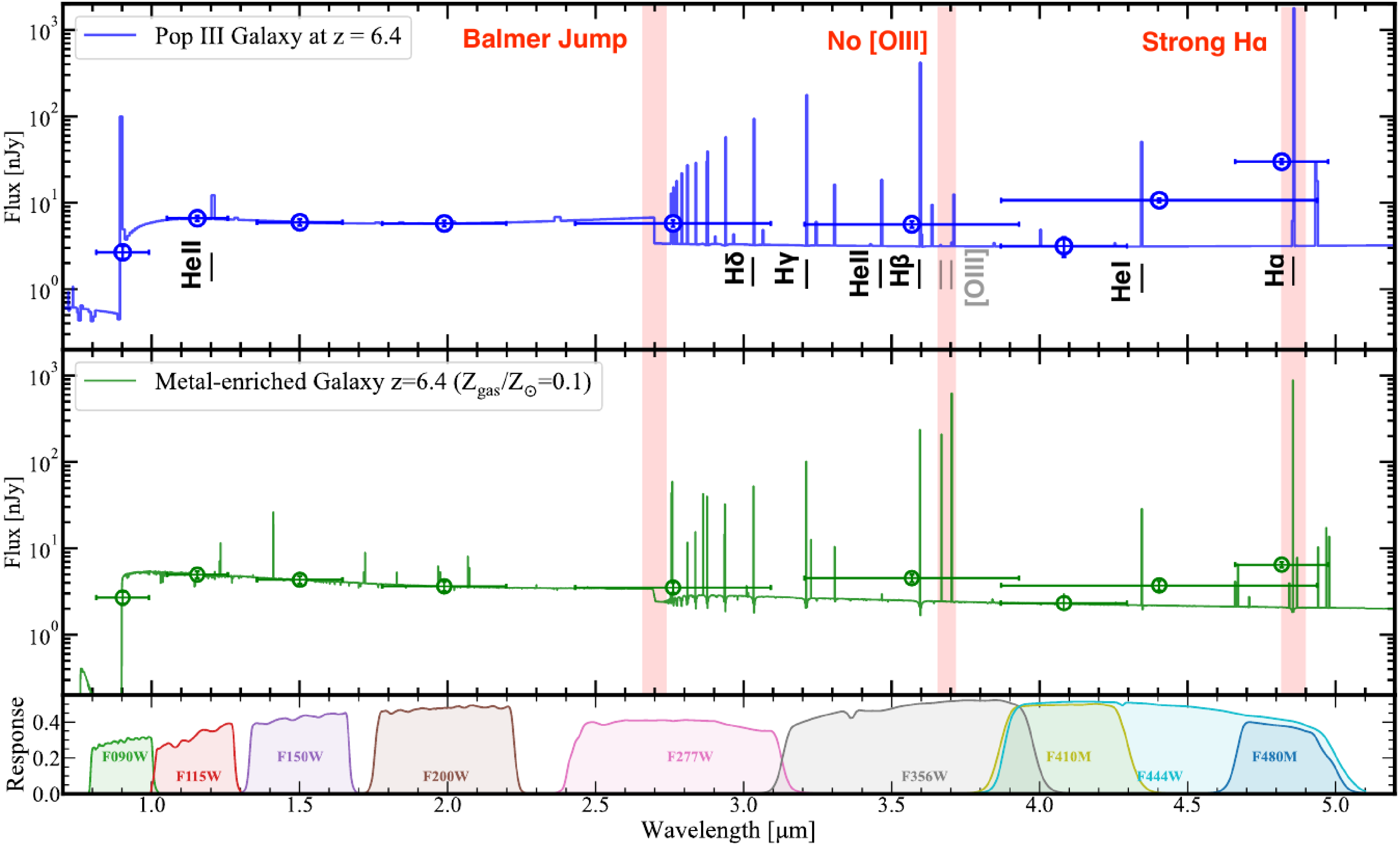
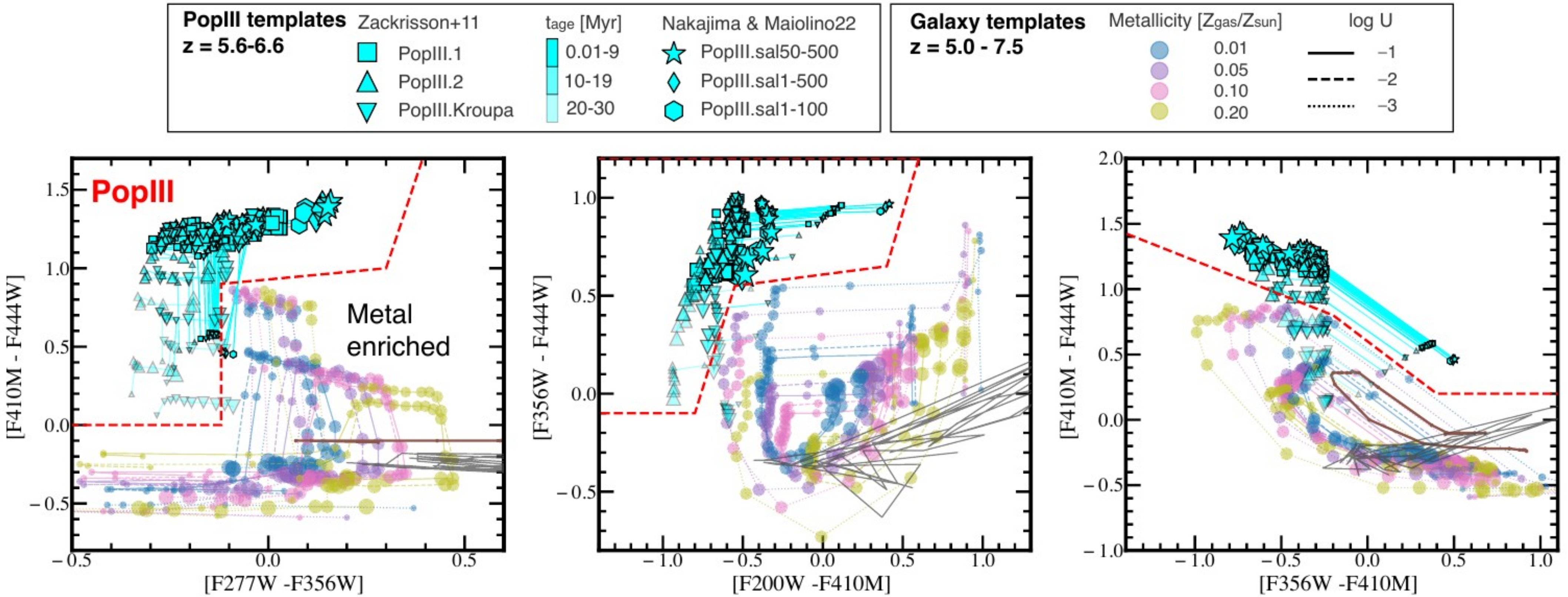


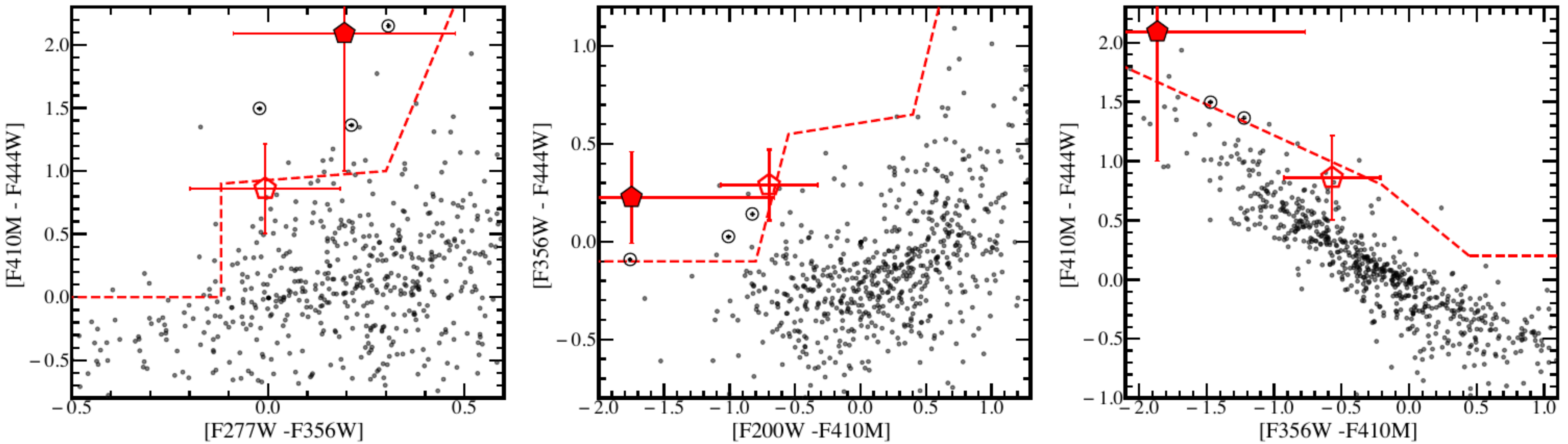
Figure 5. Spectrum of a $z = 15$ Pop III star plus emission from the IGM, for the $f_{esc} = 1$ case of Section 3.3. The long-dashed line is the spectrum of the star, cut-off for absorption shortward of the Lyman limit. The dotted line is the spectrum of free–free emission from the IGM. The short-dashed line is emission from Lyα recombination in the IGM, corrected for scattering. The free–free and Lyα spectra are integrated from $z = 15$ to 7, and divided by the lifetime of a Pop III star to give a useful normalization. The solid line is the sum of the spectra. The sharp peak at 1216 Å is collisionally excited Lyα emission; the broad peak at 1000 Å is Lyα from recombinations. All spectra are in the rest frame of the star (see Section 3.2.2 for an explanation).



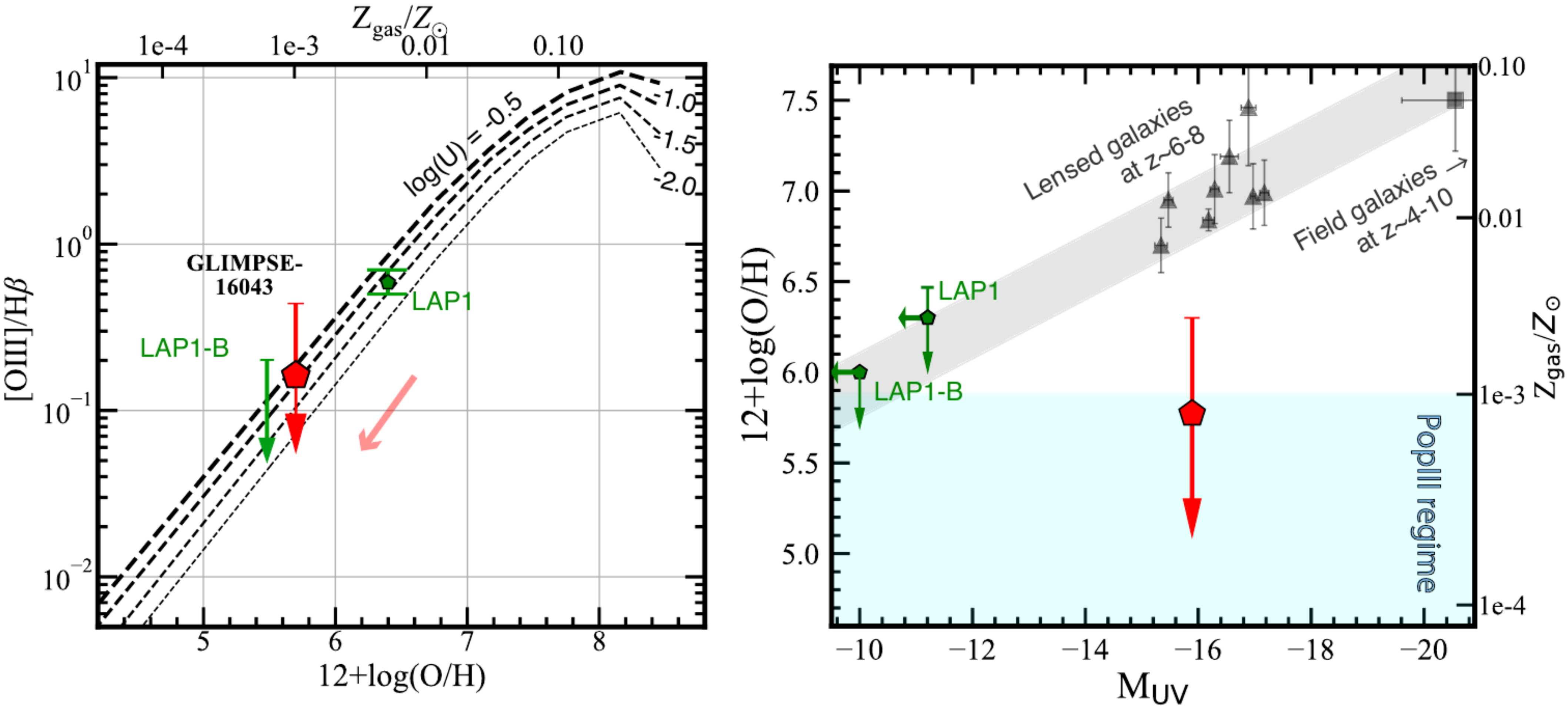
Pop III Galaxy at z = 6.4
Balmer Jump
No [OIII]
Strong Hα
HeII
Hδ
Hγ
HeII
Hβ
[OIII]
HeI
Hα
Flux [nJy]
Metal-enriched Galaxy z=6.4 ($Z_{gas}/Z_{\odot}$=0.1)
Flux [nJy]
Response
F090W
F115W
F150W
F200W
F277W
F356W
F410M
F444W
F480M
Wavelength [μm]



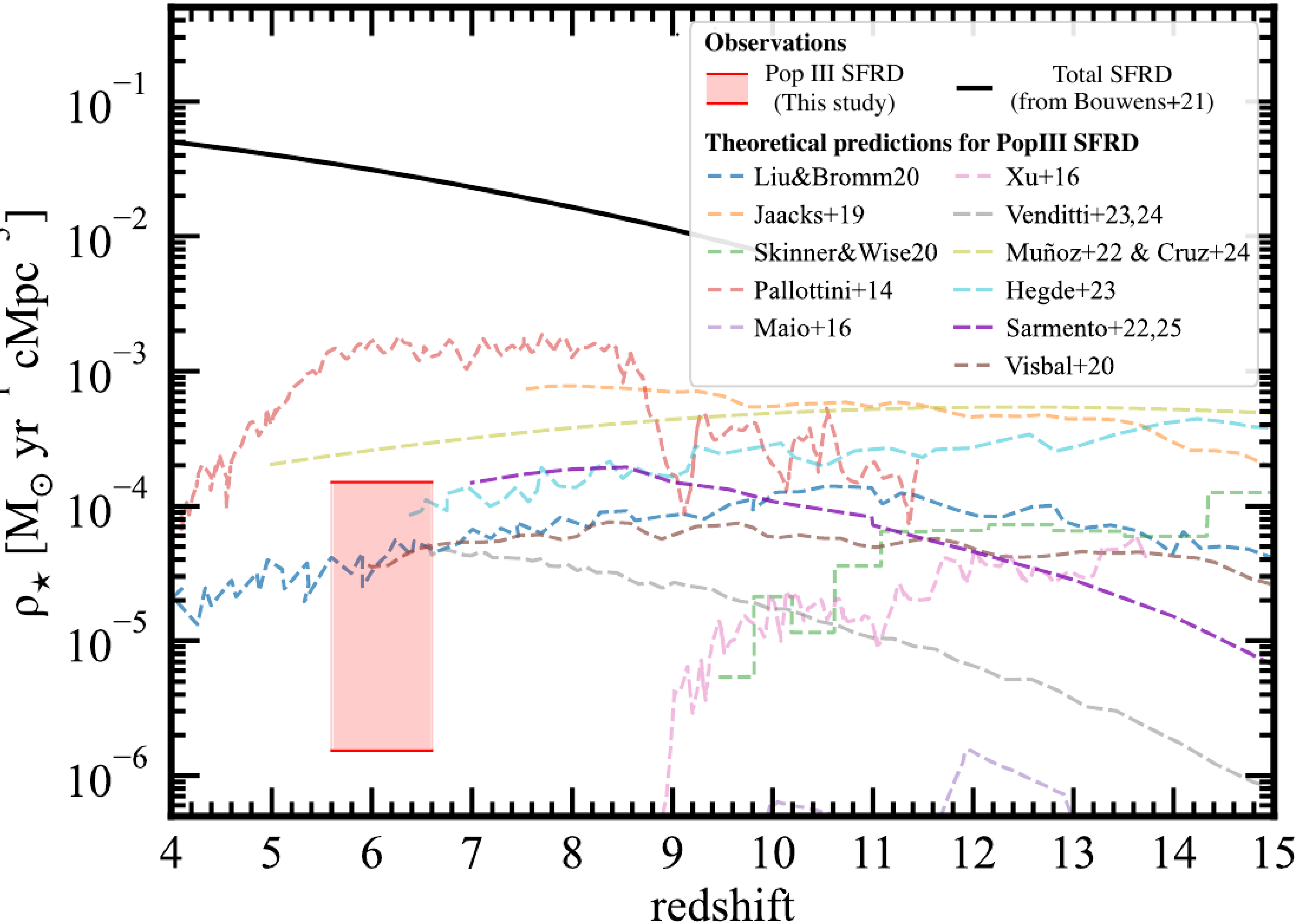
PopIII templates
z = 5.6-6.6
Zackrisson+11
PopIII.1
PopIII.2
PopIII.Kroupa
tage [Myr]
0.01-9
10-19
20-30
Nakajima & Maiolino22
PopIII.sal50-500
PopIII.sal1-500
PopIII.sal1-100
Galaxy templates
z = 5.0 - 7.5
Metallicity [Zgas/Zsun]
0.01
0.05
0.10
0.20
log U
−1
−2
−3
PopIII
Metal enriched
[F410M - F444W]
[F277W -F356W]
[F356W - F444W]
[F200W -F410M]
[F410M - F444W]
[F356W -F410M]

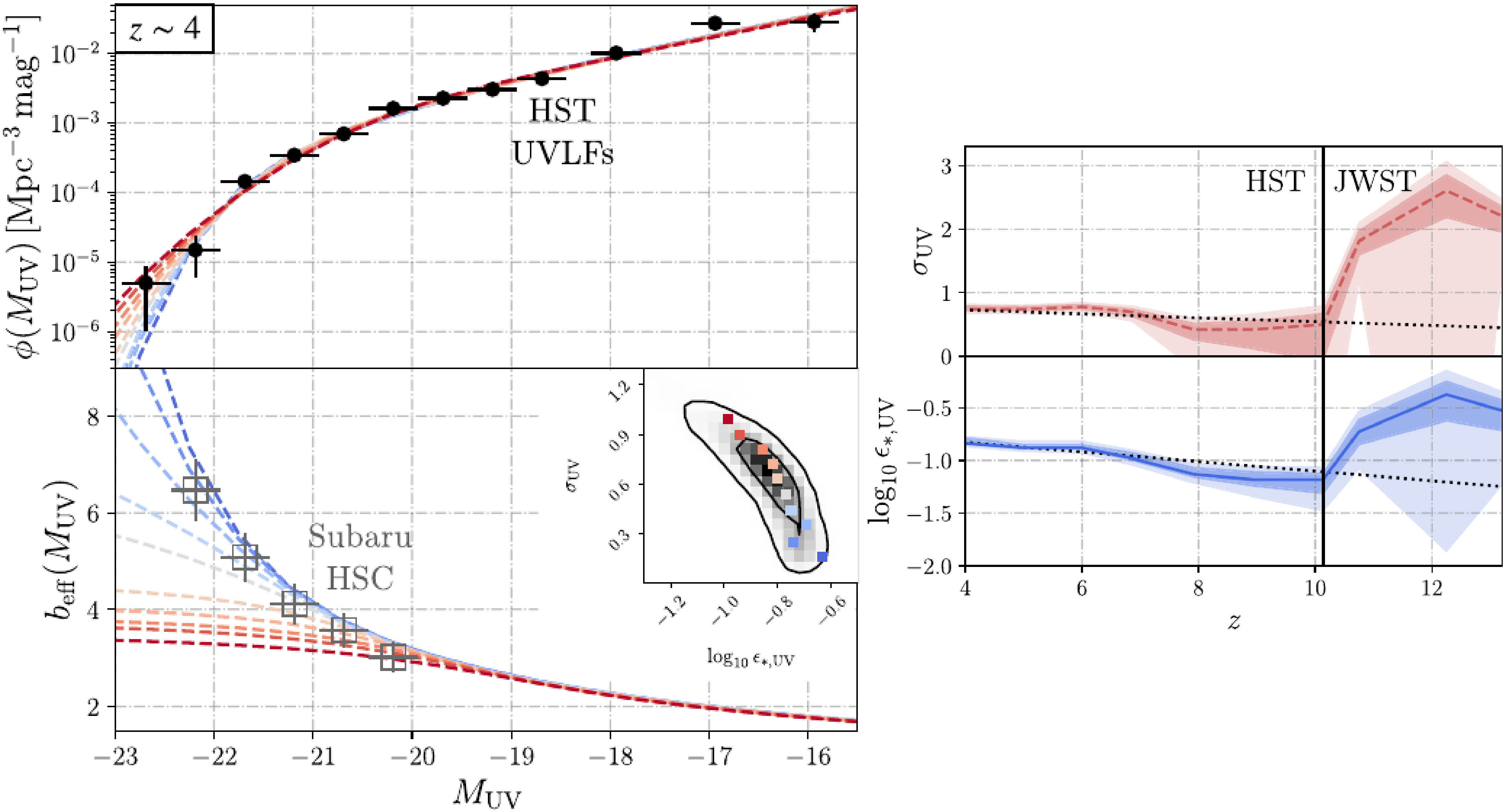


[F410M - F444W]
[F277W -F356W]
[F356W - F444W]
[F200W -F410M]
[F410M - F444W]
[F356W -F410M]

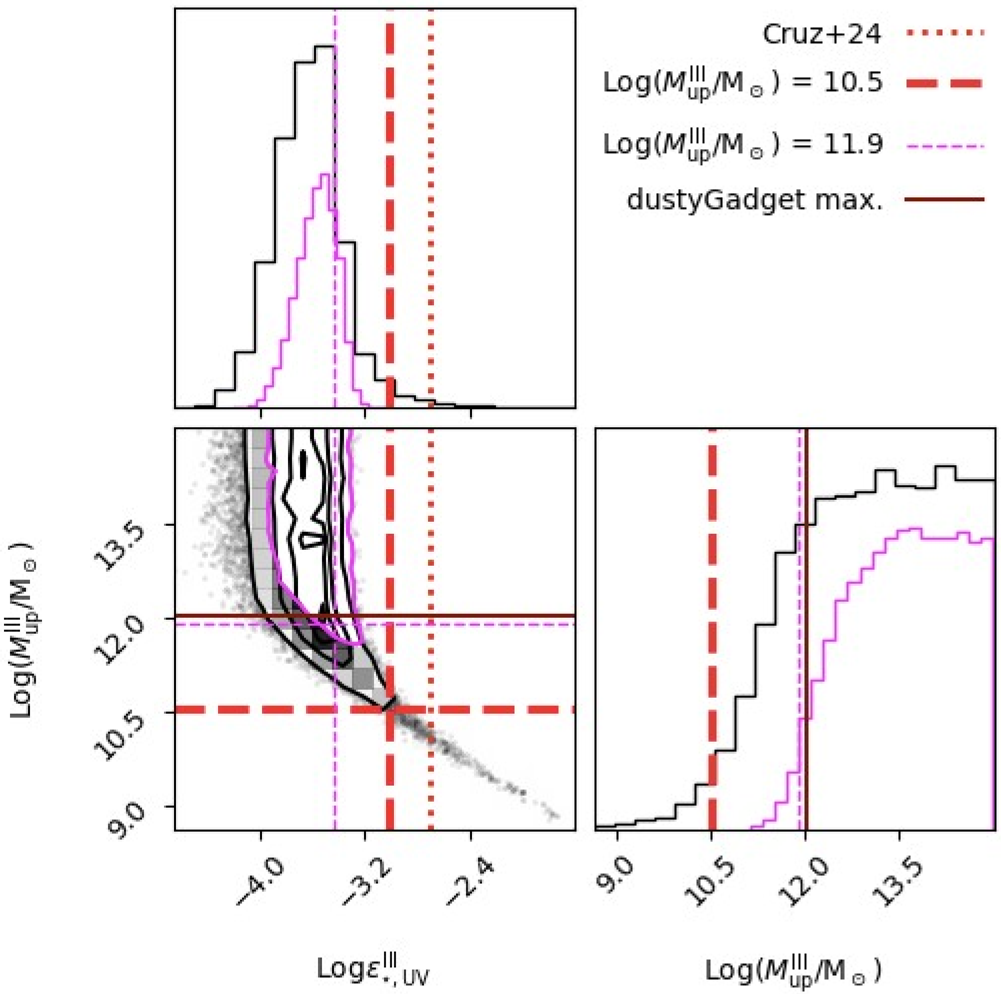


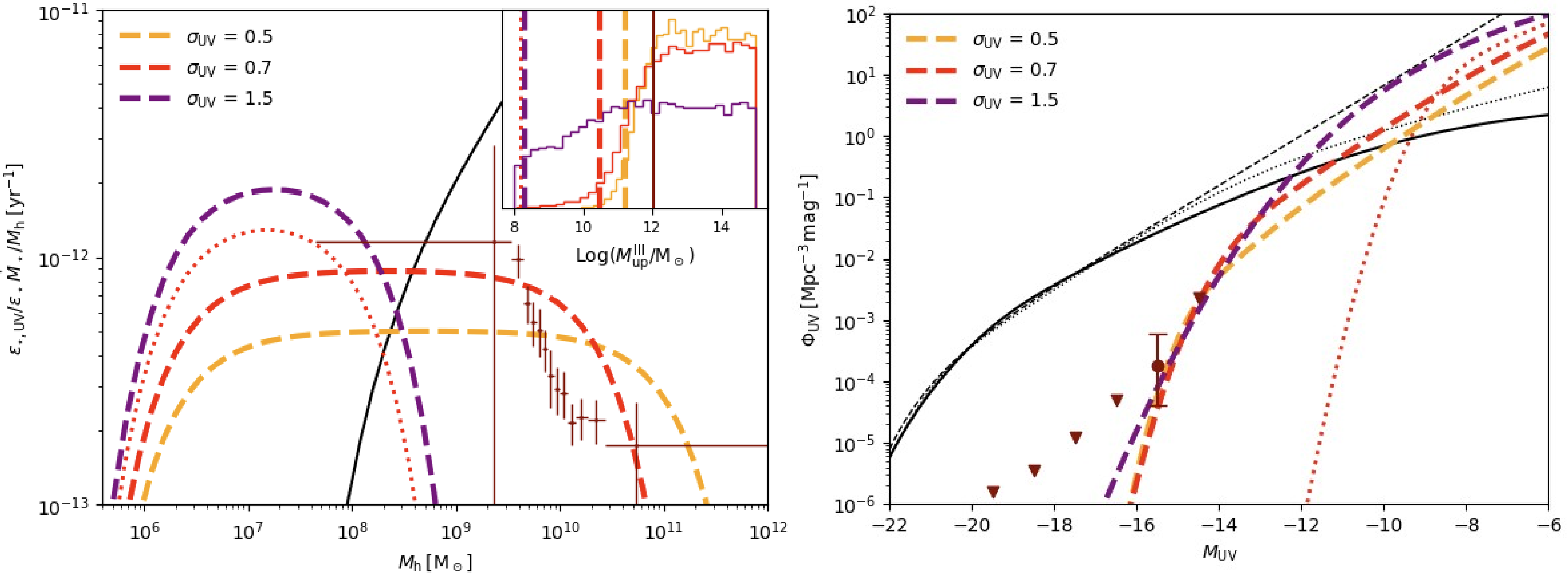
$Z_{gas}/Z_\odot$
1e-4
1e-3
0.01
0.10
10^1
10^0
10^{-1}
10^{-2}
[OIII]/Hβ
log(U) = -0.5
-1.0
-1.5
-2.0
GLIMPSE-16043
LAP1
LAP1-B
5
6
7
8
12+log(O/H)
7.5
7.0
6.5
6.0
5.5
5.0
Lensed galaxies at z~6-8
Field galaxies at z~4-10 →
PopIII regime
−10
−12
−14
−16
−18
−20
M_{UV}


Observations
Pop III SFRD (This study)
Total SFRD (from Bouwens+21)
Theoretical predictions for PopIII SFRD
Liu&Bromm20
Jaacks+19
Skinner&Wise20
Pallottini+14
Maio+16
Xu+16
Venditti+23,24
Muñoz+22 & Cruz+24
Hegde+23
Sarmento+22,25
Visbal+20
$\rho_\star$ [$M_\odot$ yr^{-1} cMpc^{-3}]
redshift



z ~ 4
HST
UVLFs
Subaru
HSC
HST
JWST
$\phi(M_{\rm UV})$ [Mpc^{-3} mag^{-1}]
$b_{\rm eff}(M_{\rm UV})$
$M_{\rm UV}$
$\sigma_{\rm UV}$
$\log_{10}\epsilon_{*,\rm UV}$
z


Cruz+24
$\mathrm{Log}(M_{\mathrm{up}}^{\mathrm{III}}/\mathrm{M}_\odot) = 10.5$
$\mathrm{Log}(M_{\mathrm{up}}^{\mathrm{III}}/\mathrm{M}_\odot) = 11.9$
dustyGadget max.
$\mathrm{Log}(M_{\mathrm{up}}^{\mathrm{III}}/\mathrm{M}_\odot)$
9.0
10.5
12.0
13.5
−4.0
−3.2
−2.4
$\mathrm{Log}\epsilon_{*,\mathrm{UV}}^{\mathrm{III}}$
$\mathrm{Log}(M_{\mathrm{up}}^{\mathrm{III}}/\mathrm{M}_\odot)$



σUV = 0.5
σUV = 0.7
σUV = 1.5
Log(M^III_up/M⊙)
ε⋆,UV/ε⋆ Ṁ⋆/Mh [yr−1]
Mh [M⊙]
σUV = 0.5
σUV = 0.7
σUV = 1.5
ΦUV [Mpc−3 mag−1]
MUV