Core-collapse supernovae as probes of cosmic star formation history

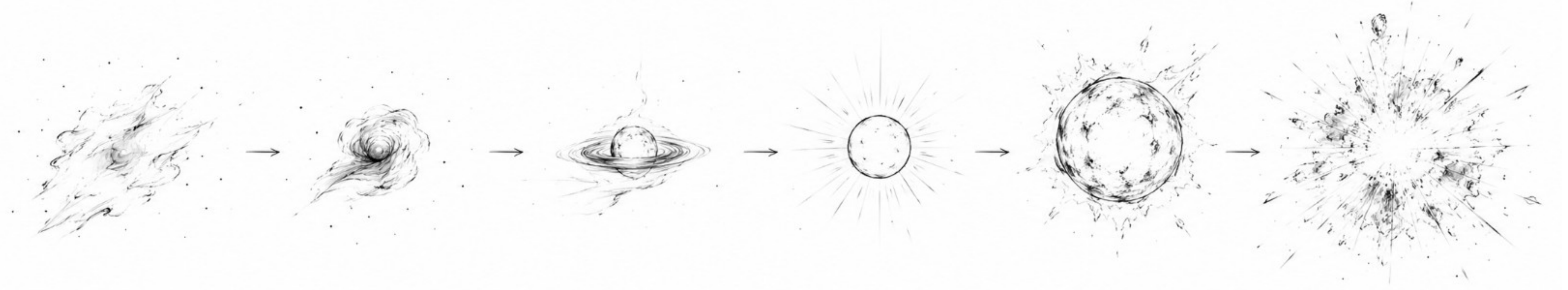
Christian Vassallo[1], Seppo Mattila[1], Christa DeCoursey[2], Lou Strolger[3], Erkki Kankare[1], Max Briel[4], Eiichi Egami[2], Iikka Mäntynen[1]
+ JADES, STScI collaboration

Nordic Baltic 28.05

[1]University of Turku, [2]University of Arizona, [3]Space Telescope Science Institute, [4]University of Geneva

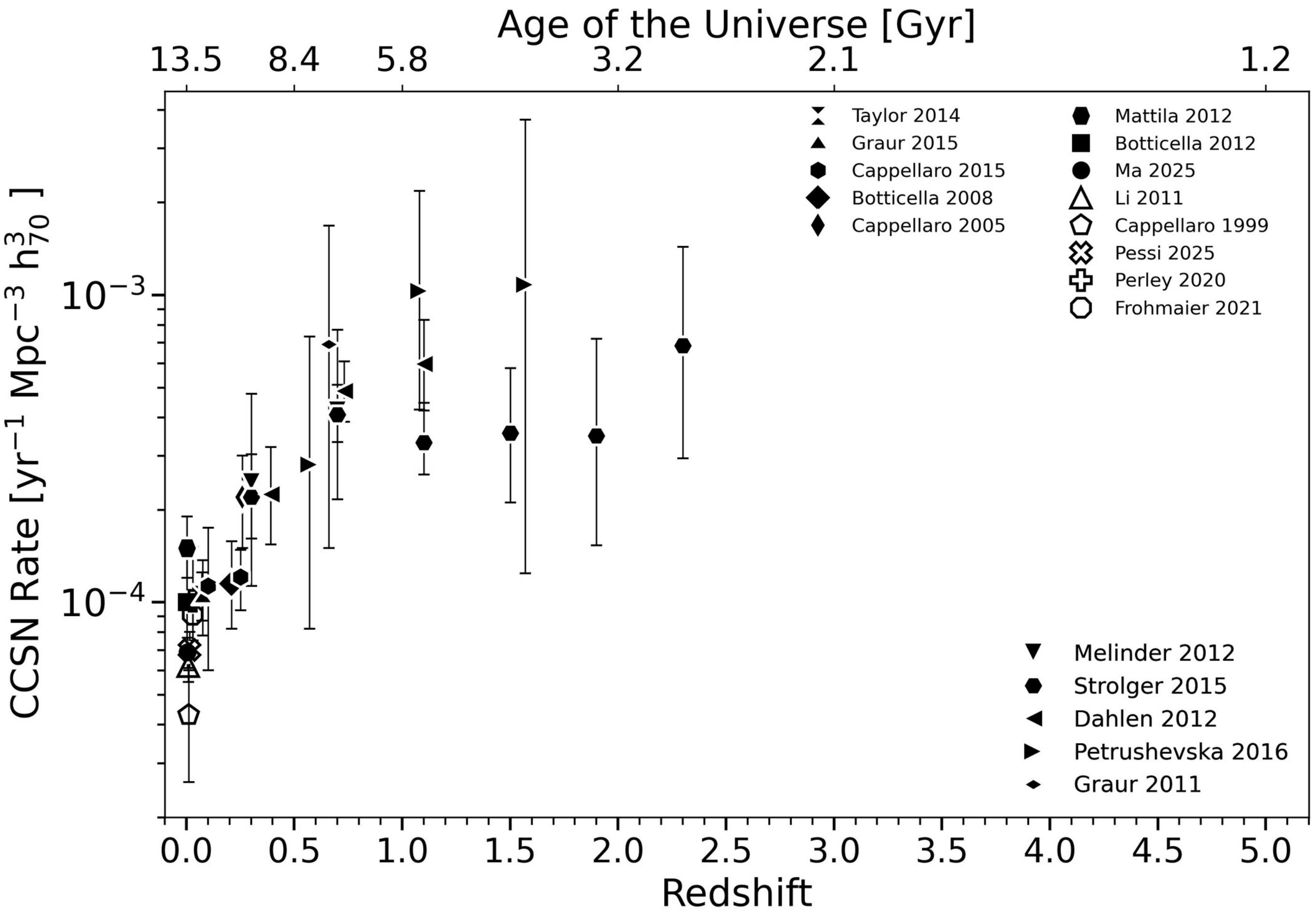
JWST ADVANCED DEEP EXTRAGALACTIC SURVEY

UNIVERSITY OF TURKU

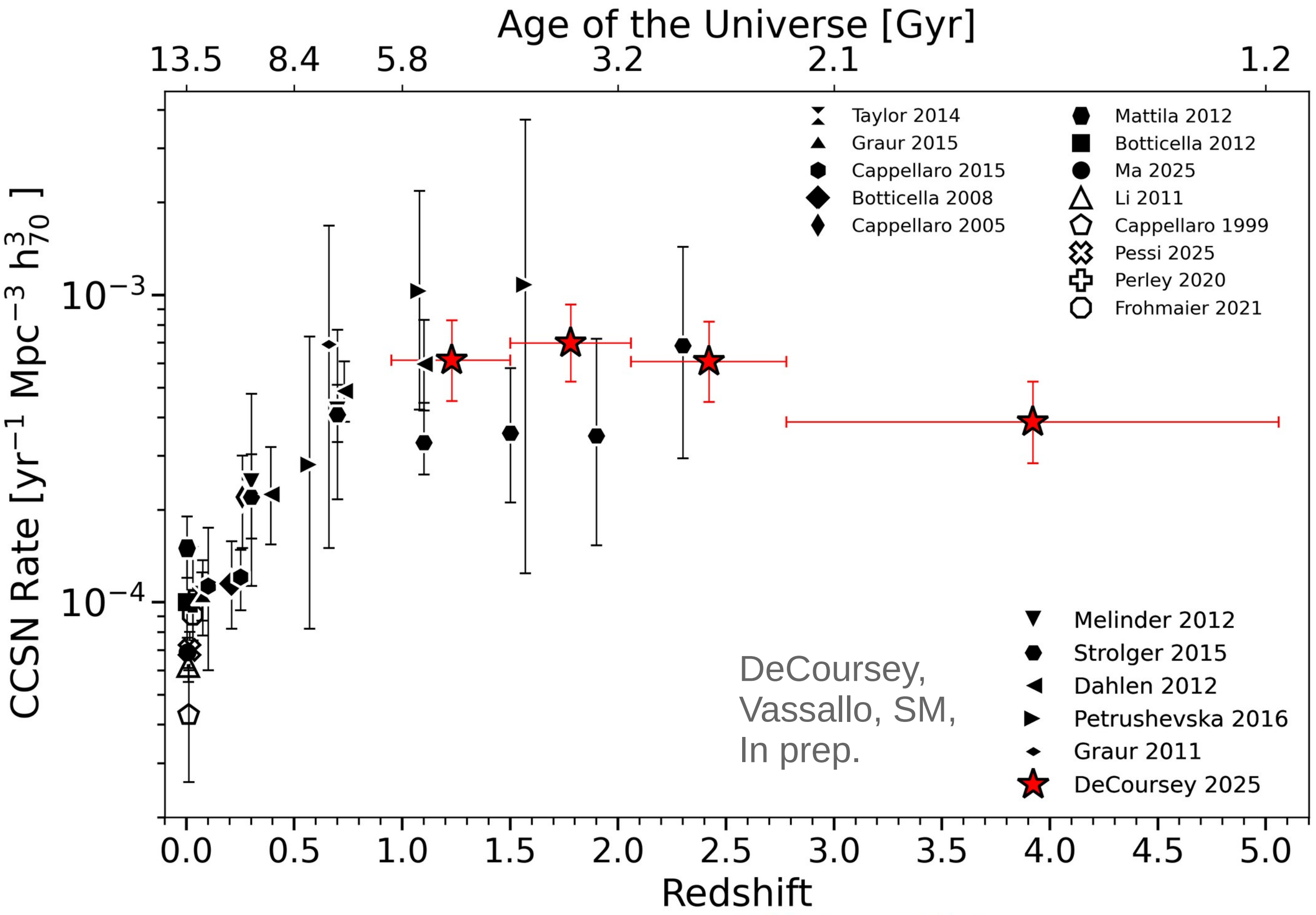


- CCSNe result from short-lived massive stars ($M \gtrsim 8\ M_\odot$, lifetimes below 50Myr)
- Therefore the volumetric CCSN rate directly traces the cosmic star-formation history (CSFH).
- Mapping the CSFH is a central goal of extragalactic astronomy. Evolution of galaxies through cosmic time.
- Using CCSN rates as an independent probe of the CSFH up to redshifts ≈ 5.

- ~25 years of CCSN rate measurements
- Large statistical uncertainties
- Previously up to redshift of 2.5



- ~25 years of CCSN rate measurements
- Large statistical uncertainties
- Previously up to redshift of 2.5
- JADES CCSN rates extend up to redshift of ~5.
- Depth of ~30 AB mag
- Filters from 0.9 to 4.4 microns



E. Egami, the PI of the JADES transient program. See: C. DeCoursey et al. 2025

- Relation between the CCSN rate and SFR

$$R_{\mathrm{CCSN}}(z) = \frac{\int_{m_l}^{m_u} \phi(m)\,\mathrm{d}m}{\int_{m_{\mathrm{min}}}^{m_{\mathrm{max}}} m\,\phi(m)\,\mathrm{d}m}\,\rho_{\mathrm{SFR}}(z) \equiv k_{\mathrm{CCSN}}\,\rho_{\mathrm{SFR}}(z)\,.$$

$$\rho_{\mathrm{SFR}}(z) = \frac{A(1+z)^B}{1+[(1+z)/C]^D},$$

- Relation between the CCSN rate and SFR

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- $R_{\rm CCSN}$: expected CCSN rate based on SFR density

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$$\equiv k_{\rm CCSN}\,\rho_{\rm SFR}(z)\,.$$

- R_{CCSN}: expected CCSN rate based on SFR density

- k_{CCSN}: number of CCSN per solar mass

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- R_{CCSN}: expected CCSN rate based on SFR density

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$$\rho_{\rm SFR}(z) = \frac{A(1+z)^B}{1+[(1+z)/C]^D},$$

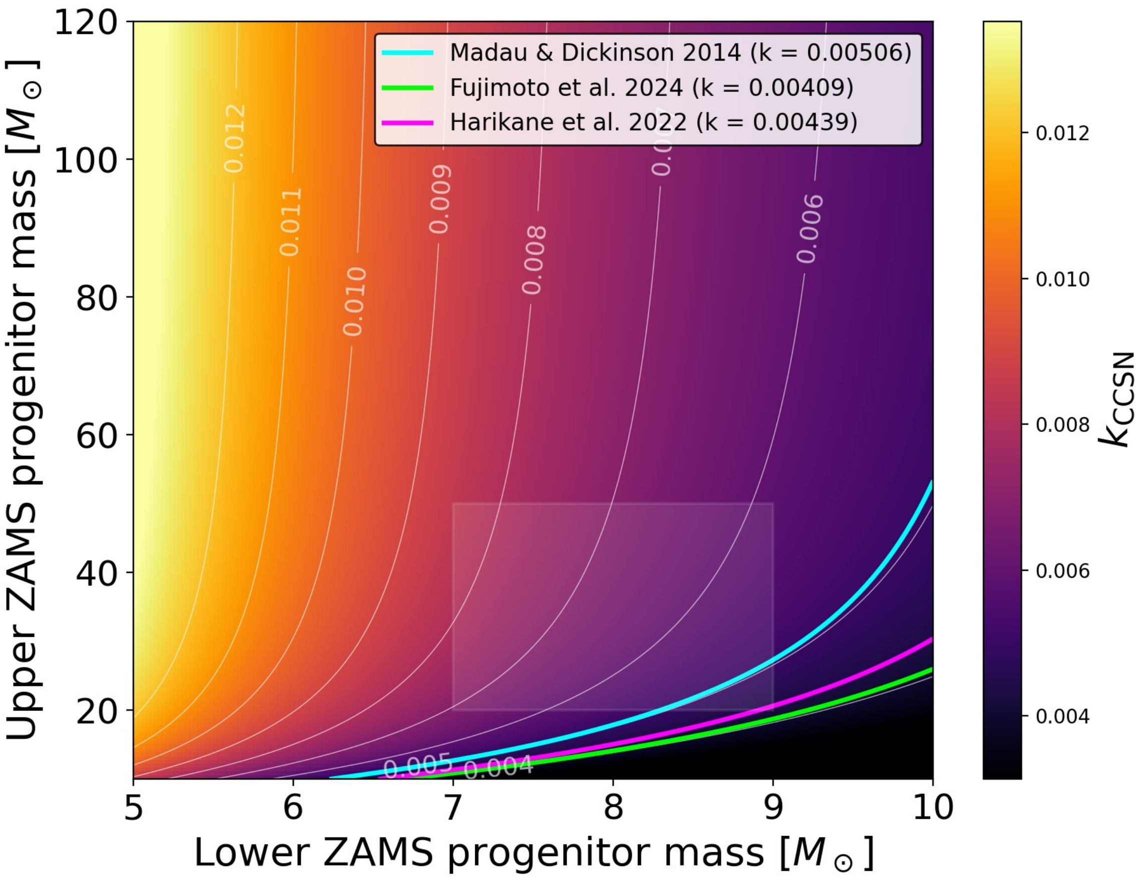
- Depends on upper and lower progenitor mass limits, and the Initial Mass Function (IMF)

k_{CCSN}

- We fit the k_{CCSN} against the observed CCSN rates, assuming various (SFRDs)

- Compare with expectations (progenitor mass limits) from literature.

[Smartt 2009, Smartt 2015, Eldridge 2013, Van Dyk 2018]



Vassallo, SM, In prep.

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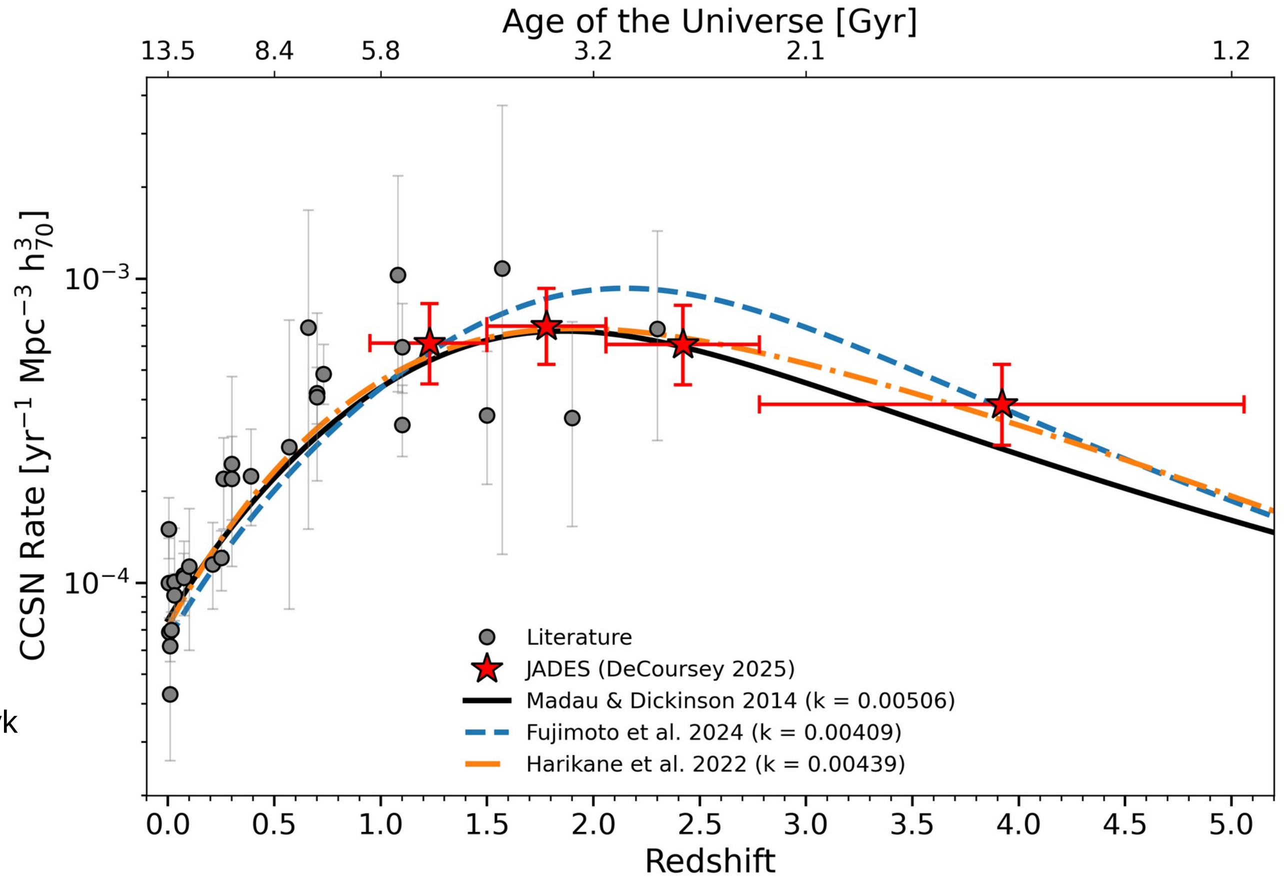
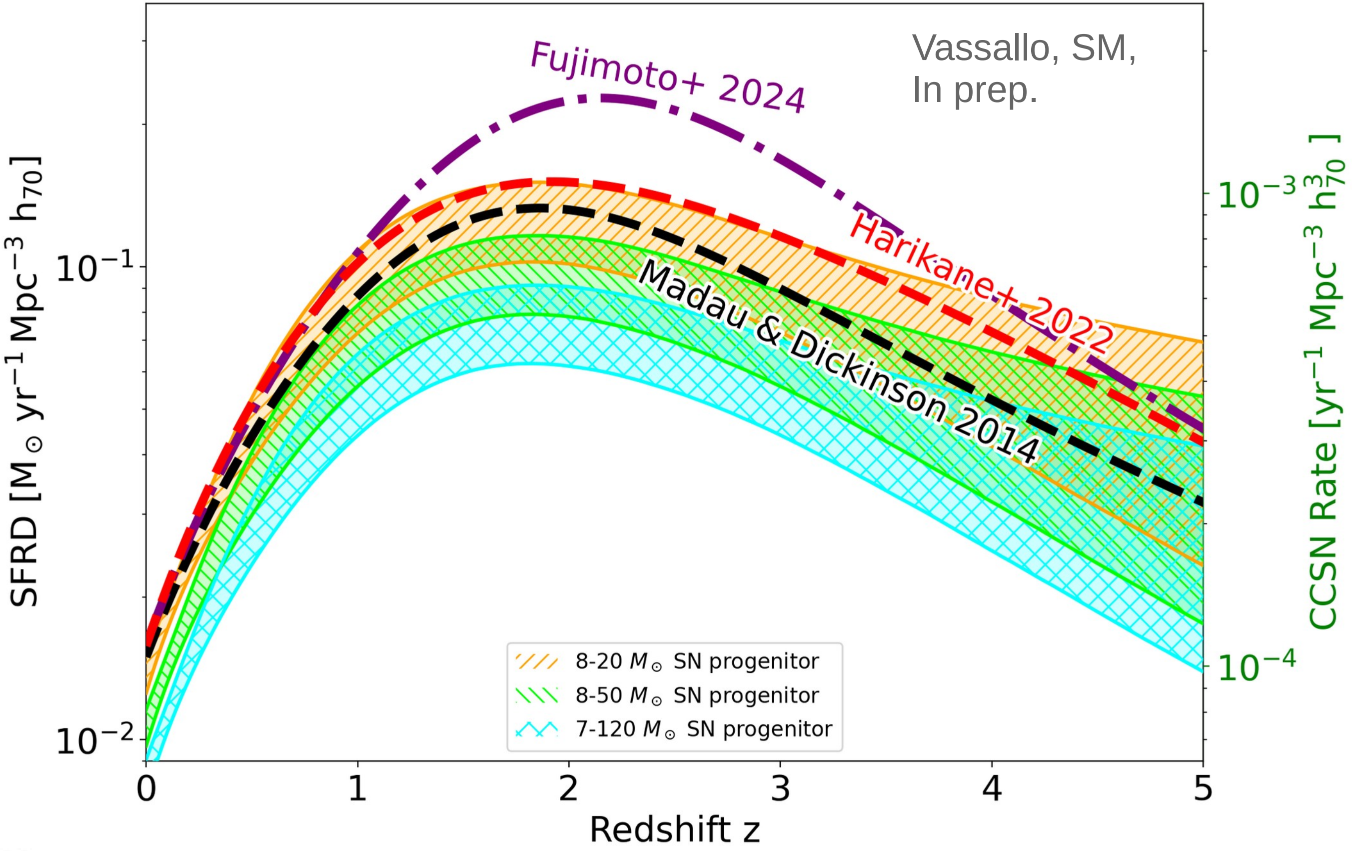


DeCoursey, Vassallo, SM, In prep.

- SFRDs based on CCSN rates
- Depends on chosen k_{ccsn}
- Suggests a decrease after cosmic noon



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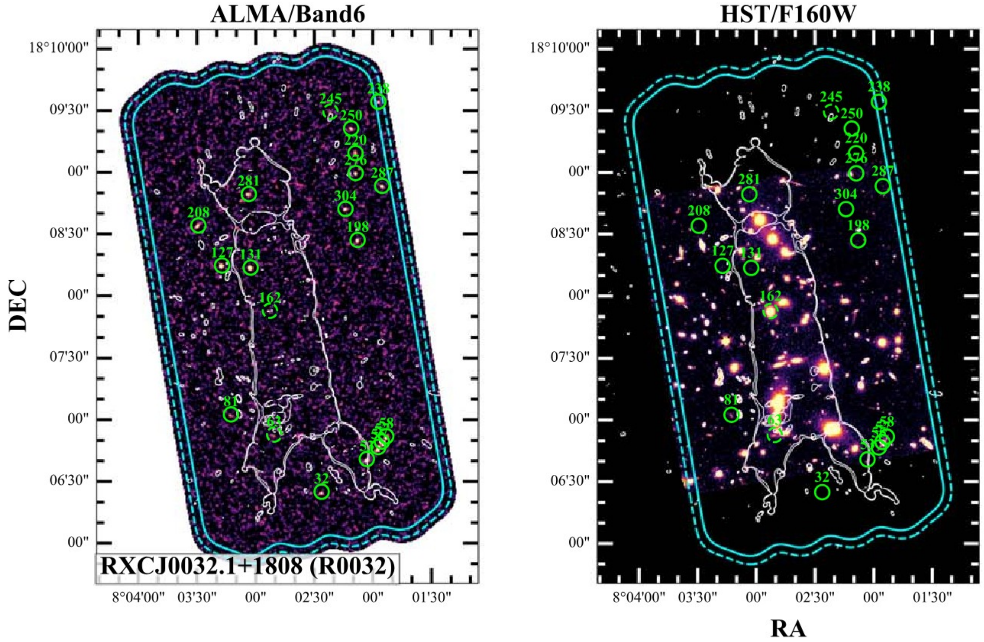
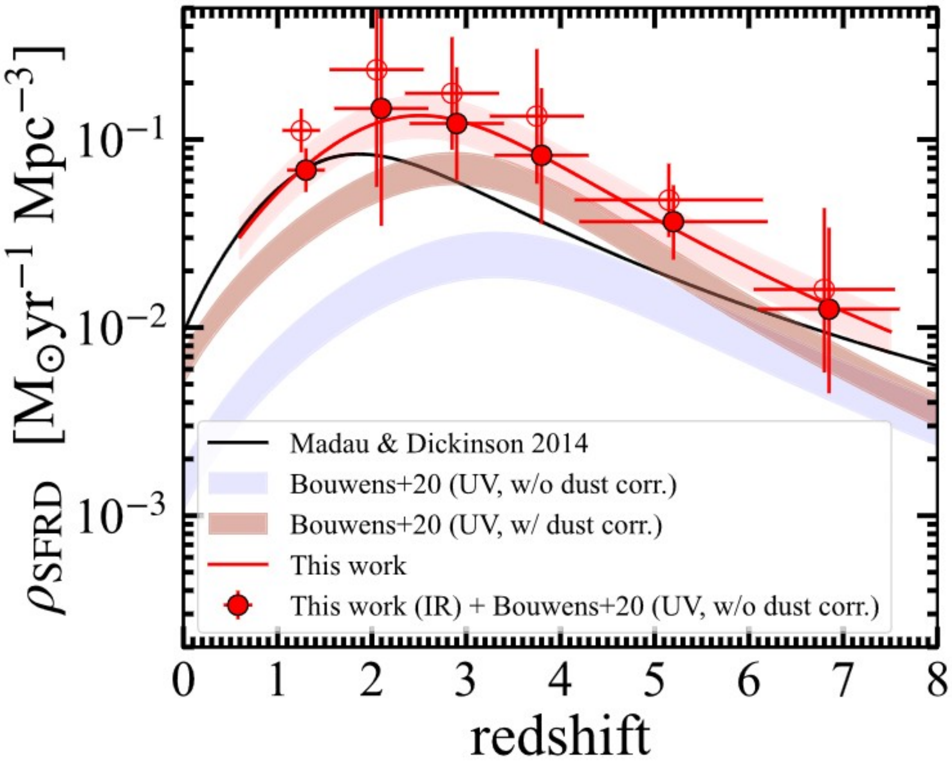
$$\rho_{\mathrm{SFR}}(z) = \frac{A(1+z)^B}{1+[(1+z)/C]^D},$$

- Very faint ALMA mm sources - a missing SFRD component contributed by near-IR dark dust obscured galaxies

- Total SFRD ~1.6 x M&D2014 SFRD





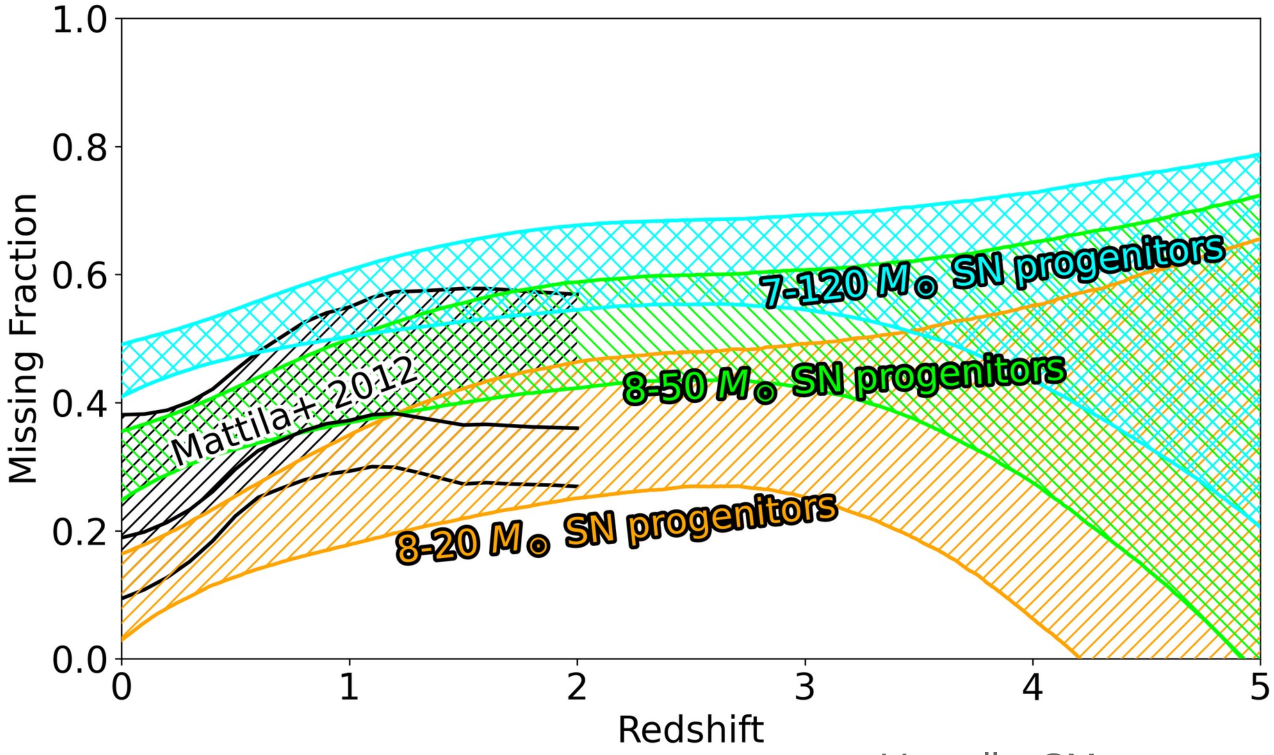
Fujimoto et al. 2024

- Using the more complete SFRDs of F24 and plausible progenitor mass limits for k_{ccsn}

  → Additional obscuration correction required

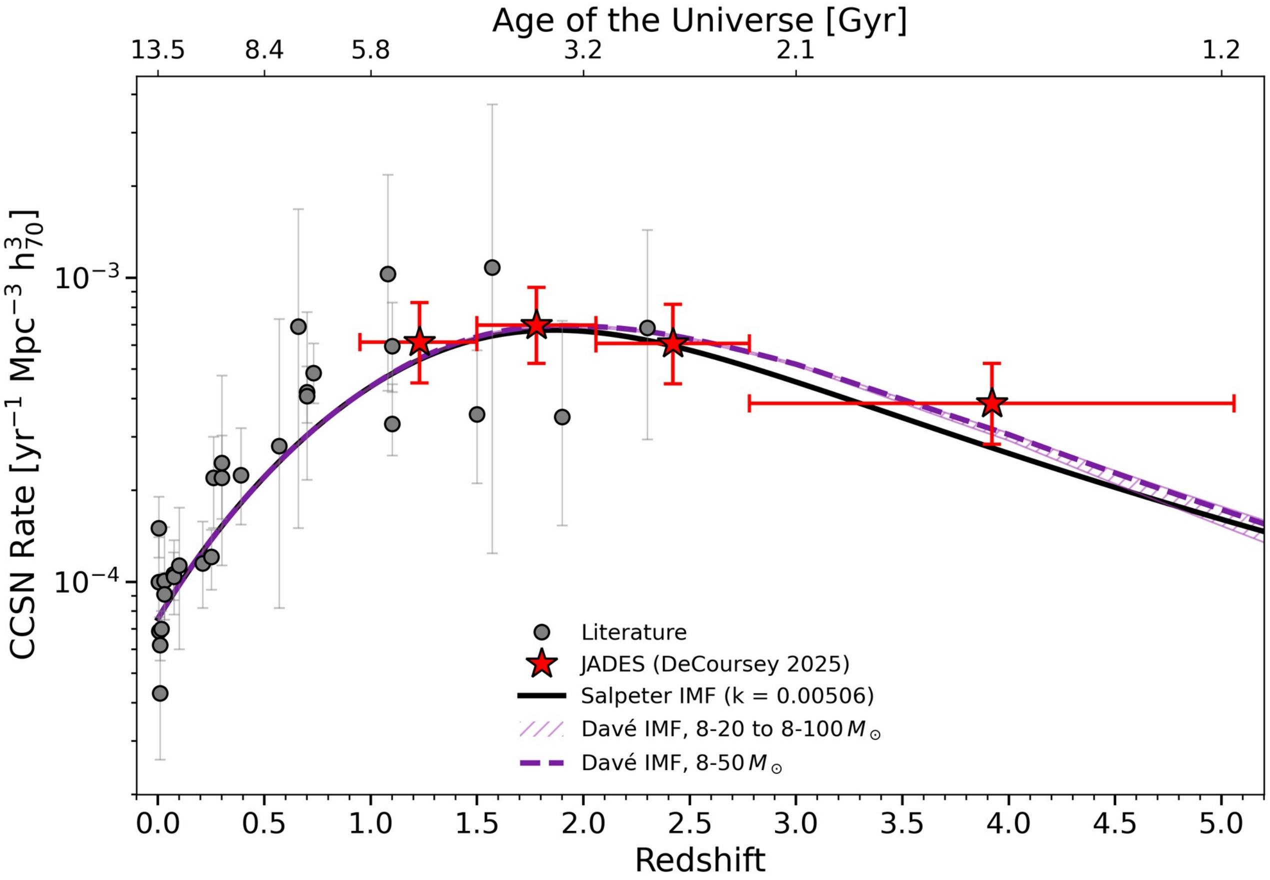
- Depends on chosen k_{ccsn}

- Increasing trend with redshift



Vassallo, SM,
In prep.

- Evolving IMF effect with Davé 2008.
- Top heavy IMF results in more CCSNe per solar mass
- Top heavy IMF results in less SFRD per solar mass (massive stars over-contribute to the luminosity)
- These effects cancel → total effect is small



$$\rho_{\rm SFR} = k_{\rm UV}({\rm IMF}) \times L_{\rm UV},$$

$$R_{\rm CCSN}({\rm IMF}) = k_{\rm CCSN}({\rm IMF}) \times k_{\rm UV}({\rm IMF}) \times L_{\rm UV}$$

Summary

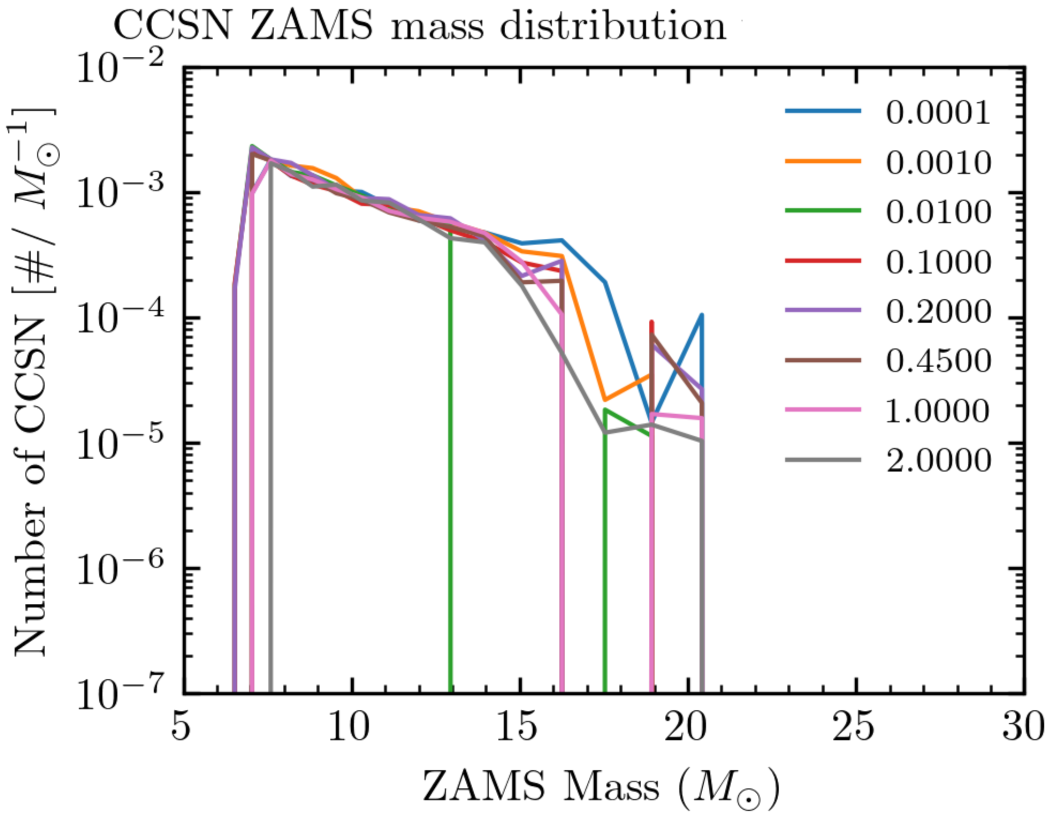
- JADES extends CCSN rates from $z \approx 2.5$ to $z \approx 5$ for the first time.
- CCSN rates consistent with MD14 SFRDs with plausible progenitor masses.
- Comparison with more complete F24 SFRDs require the CCSN rates to be corrected for dust obscuration.
- Top-heavy IMF (Davé 2008) raises k_{CCSN} and lowers SFRD - effects mostly cancel out.

More slides

Next study (preliminary)

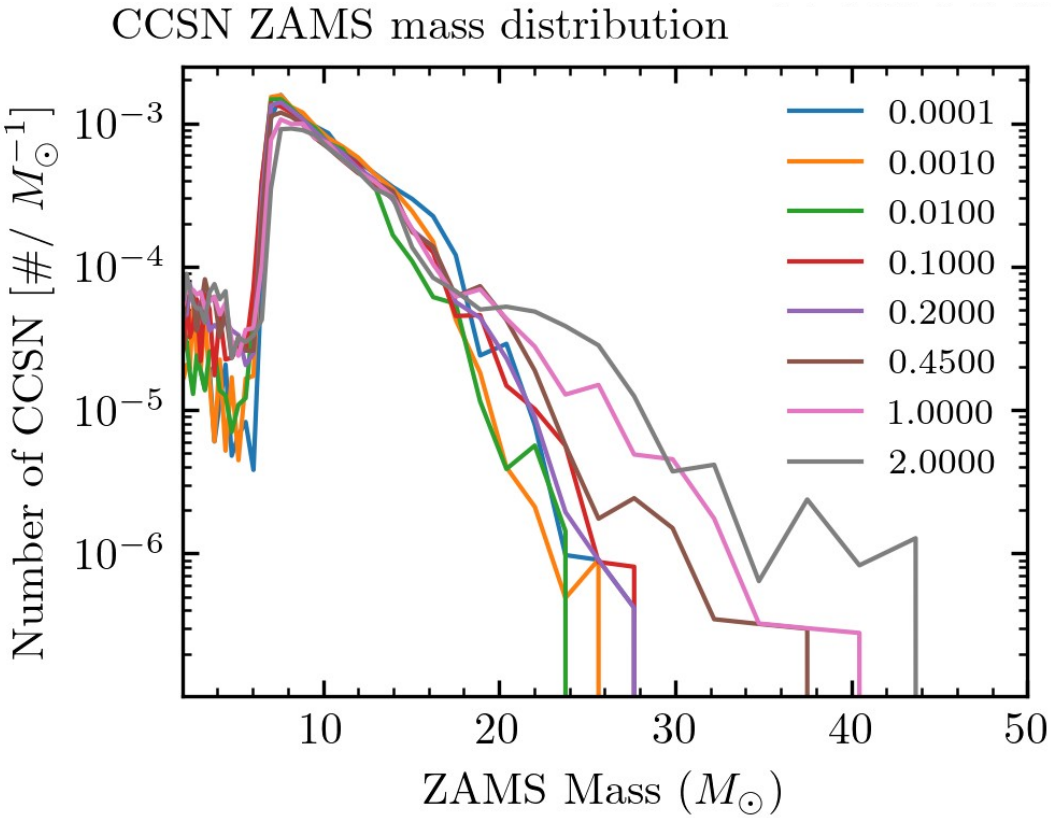
- Use POSYDON v2 to calculate k_{CCSN}
- Binary evolution and failed SN effects
- Do these change the conclusions compared to the simplistic single star case?

- Single stars: 8 metallicities nearly the same curve from ~7–20 $M_\odot$



Vassallo, SM, Briel
In prep.

- Single stars: 8 metallicities nearly the same curve from ~7–20 M⊙
- In binaries, mass transfer + mergers broaden the CCSN ZAMS mass window in both directions.
- Binary peak amplitude drops by ~×2
- Winds are stronger at high Z → more envelope removal → higher-mass stars still find a way to explode?
- Why this effect is only for binary case?



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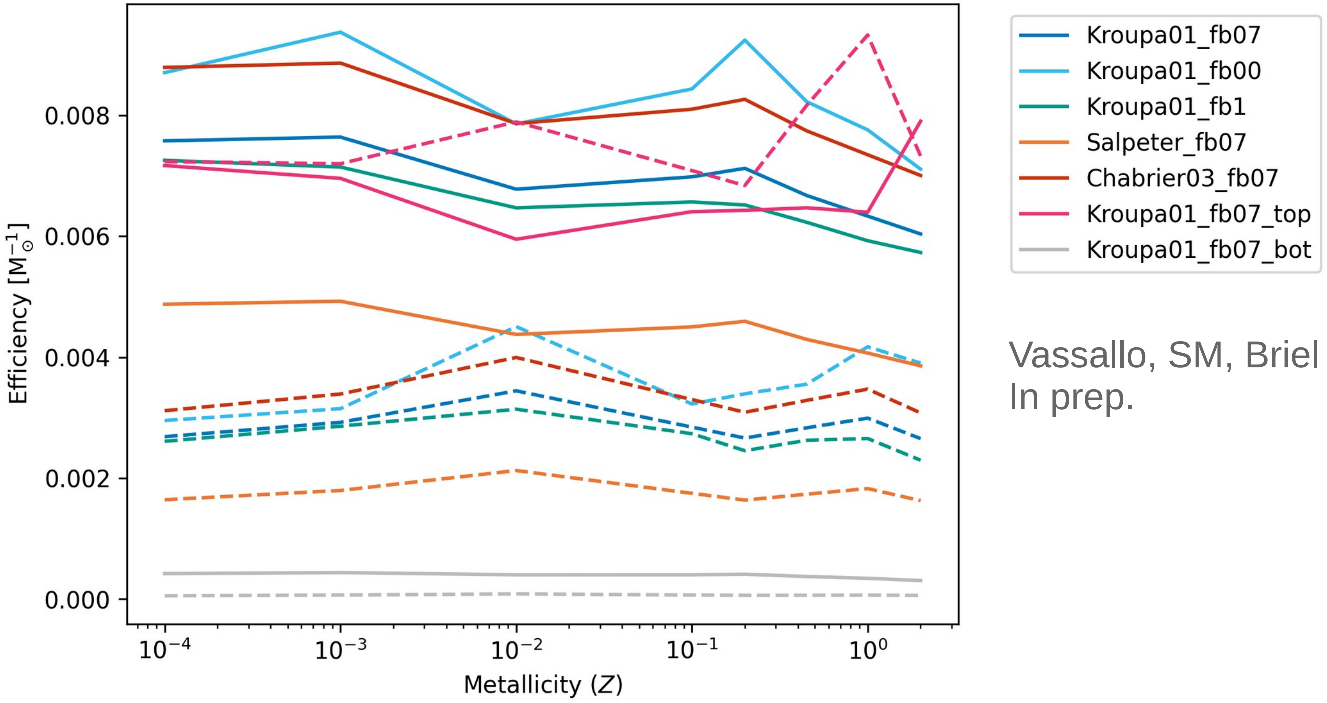
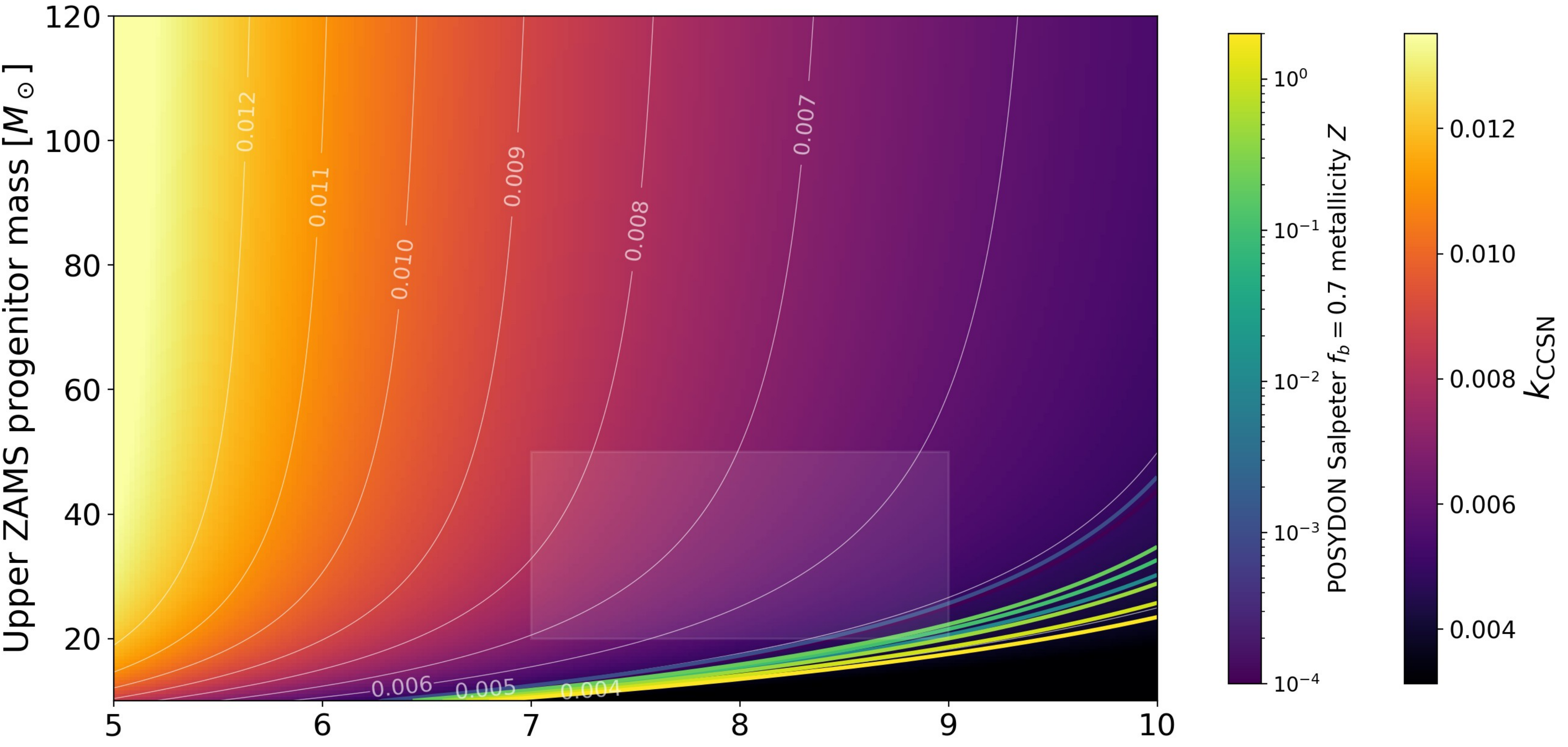


Vassallo, SM, Briel
In prep.

- Efficiency (k_{CCSN}), metallicities, IMFs
- Succeful CCSNe as solid
- Failed SN as dashed
- Salpeter CCSN eff. around 0.004 $M_\odot$

- Binary **lower** compared to 100% single stars (10-20% difference)
- Low Z **higher** than high Z (~20%)



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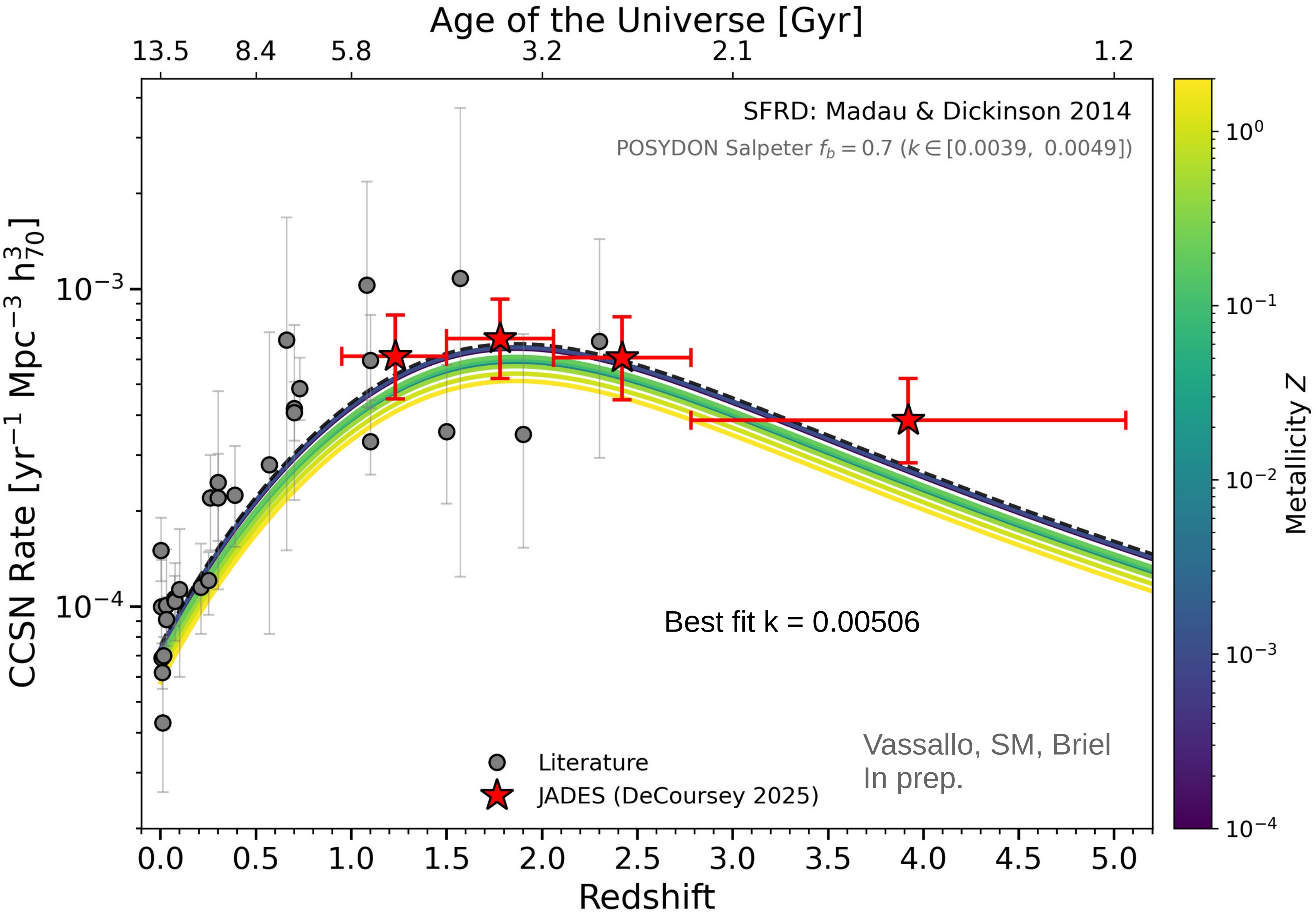
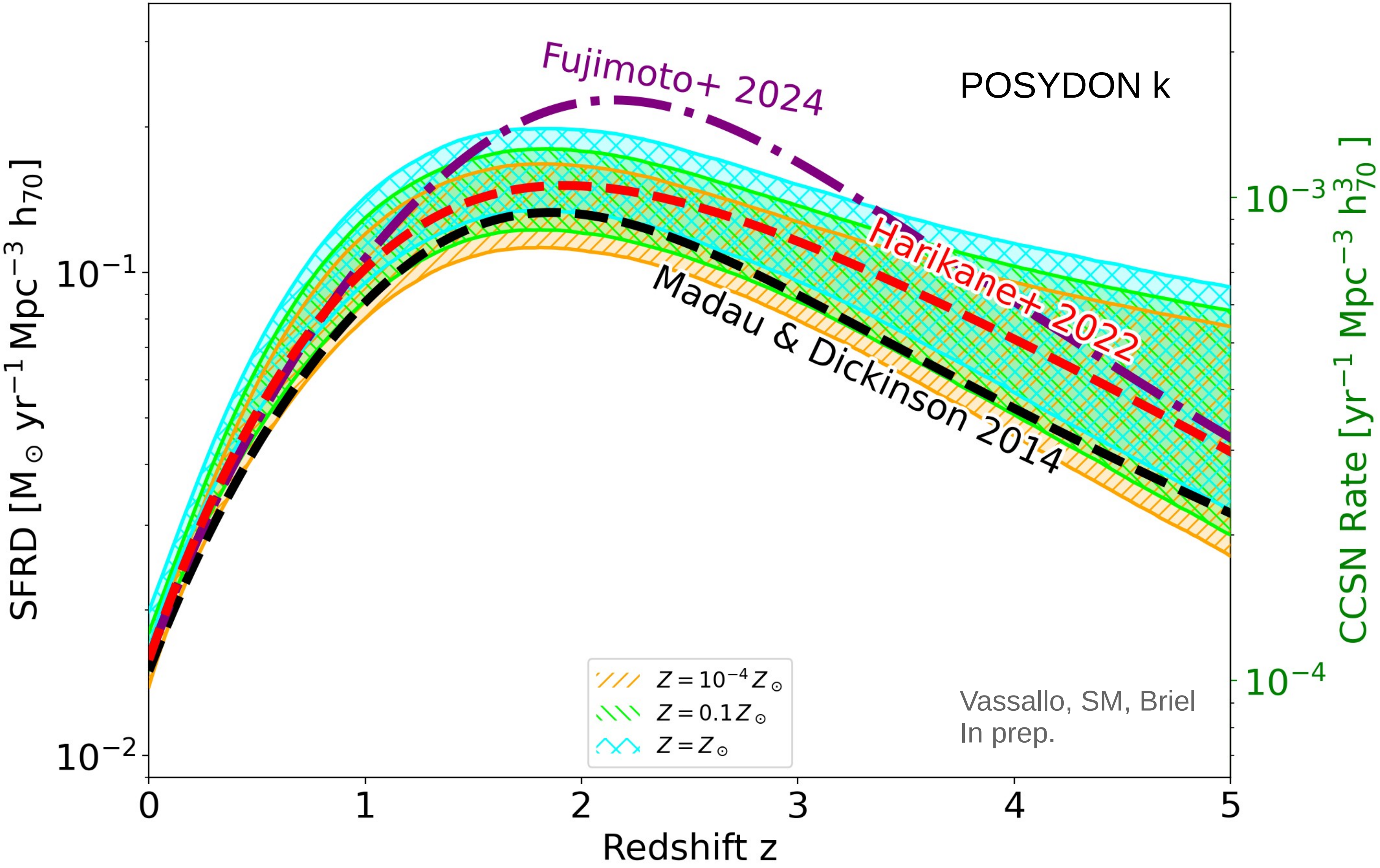
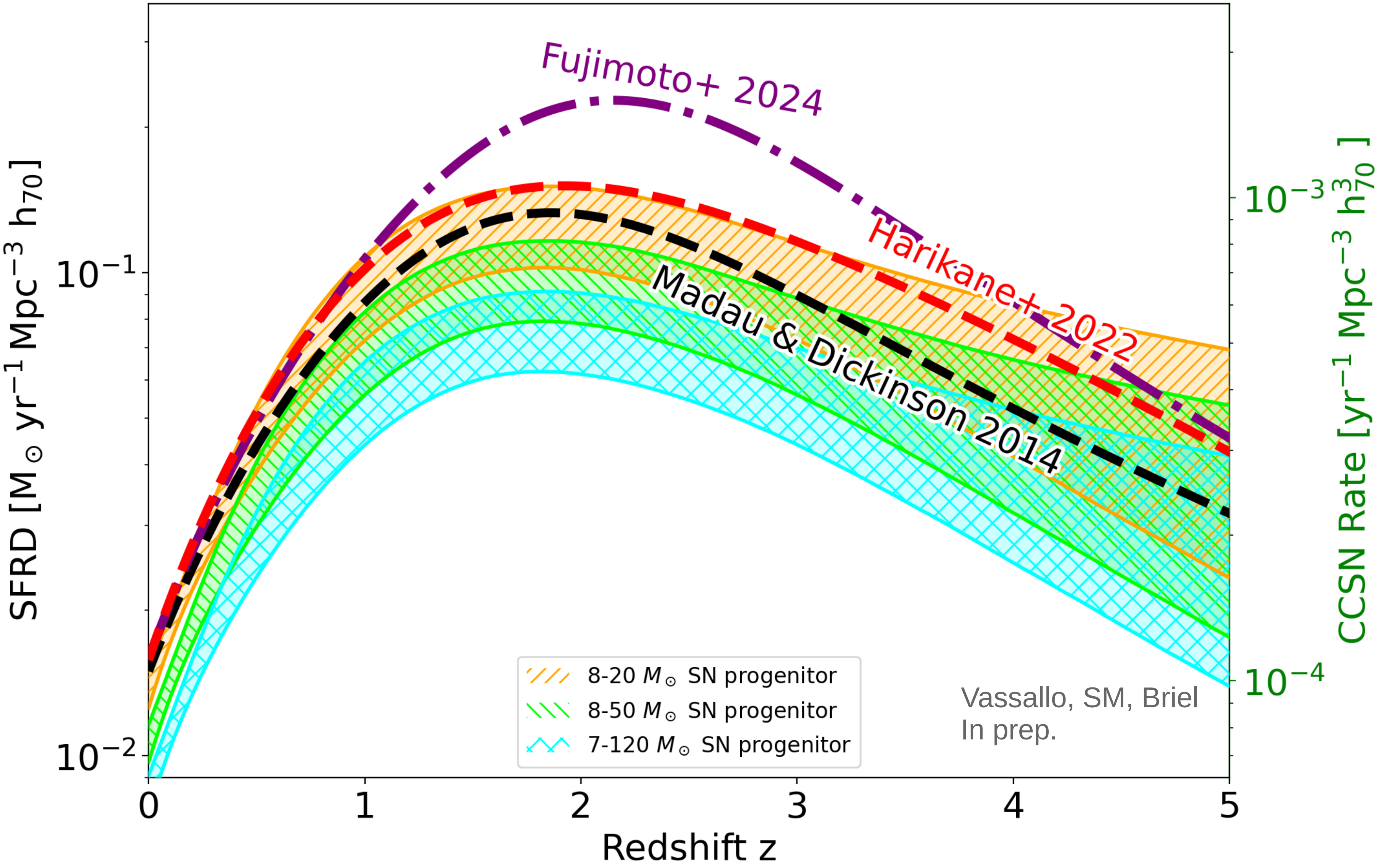
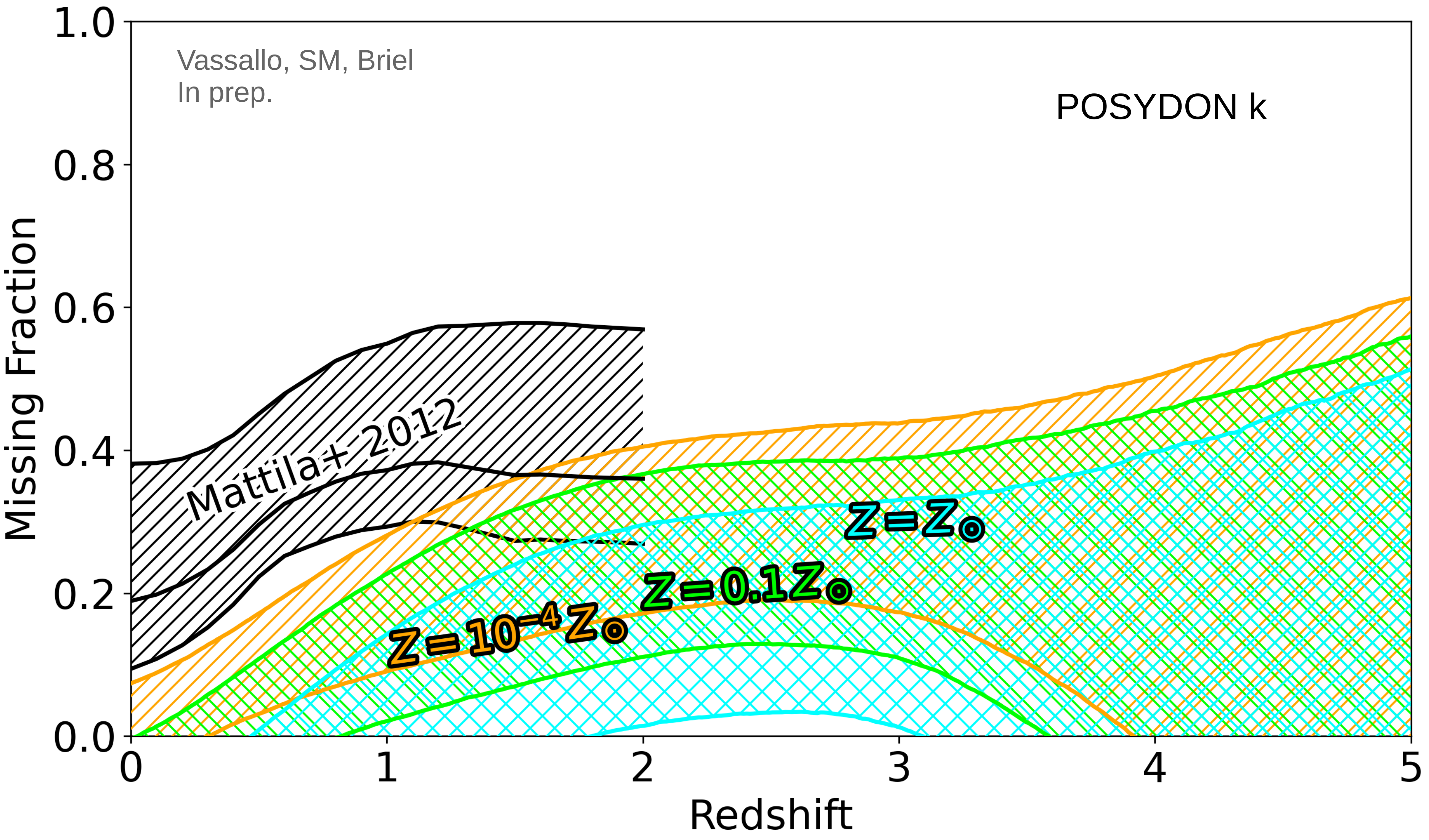

Age of the Universe [Gyr]
13.5
8.4
5.8
3.2
2.1
1.2
SFRD: Madau & Dickinson 2014
POSYDON Salpeter $f_b = 0.7$ ($k \in [0.0039,\ 0.0049]$)
CCSN Rate [$\mathrm{yr^{-1}\ Mpc^{-3}\ h_{70}^{3}}$]
10^{-3}
10^{-4}
Best fit k = 0.00506
Literature
JADES (DeCoursey 2025)
Vassallo, SM, Briel
In prep.
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Redshift
Metallicity Z
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}



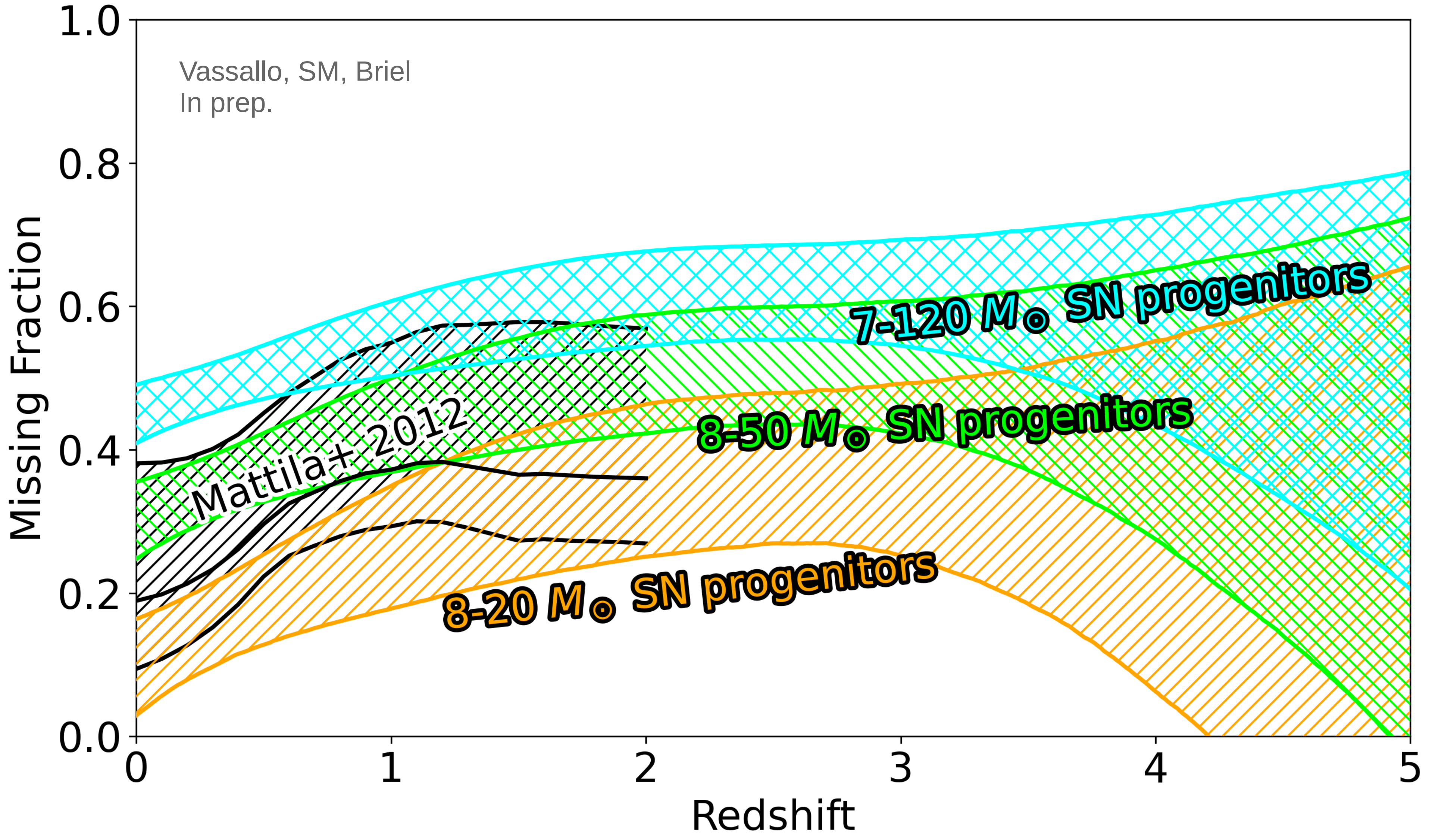
Fujimoto+ 2024
POSYDON k
Harikane+ 2022
Madau & Dickinson 2014
SFRD [$M_\odot$ yr^{-1} Mpc^{-3} h$_{70}$]
CCSN Rate [yr^{-1} Mpc^{-3} h$^3_{70}$]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$Z = 10^{-4}\,Z_\odot$
$Z = 0.1\,Z_\odot$
$Z = Z_\odot$
Vassallo, SM, Briel
In prep.
0
1
2
3
4
5
Redshift z



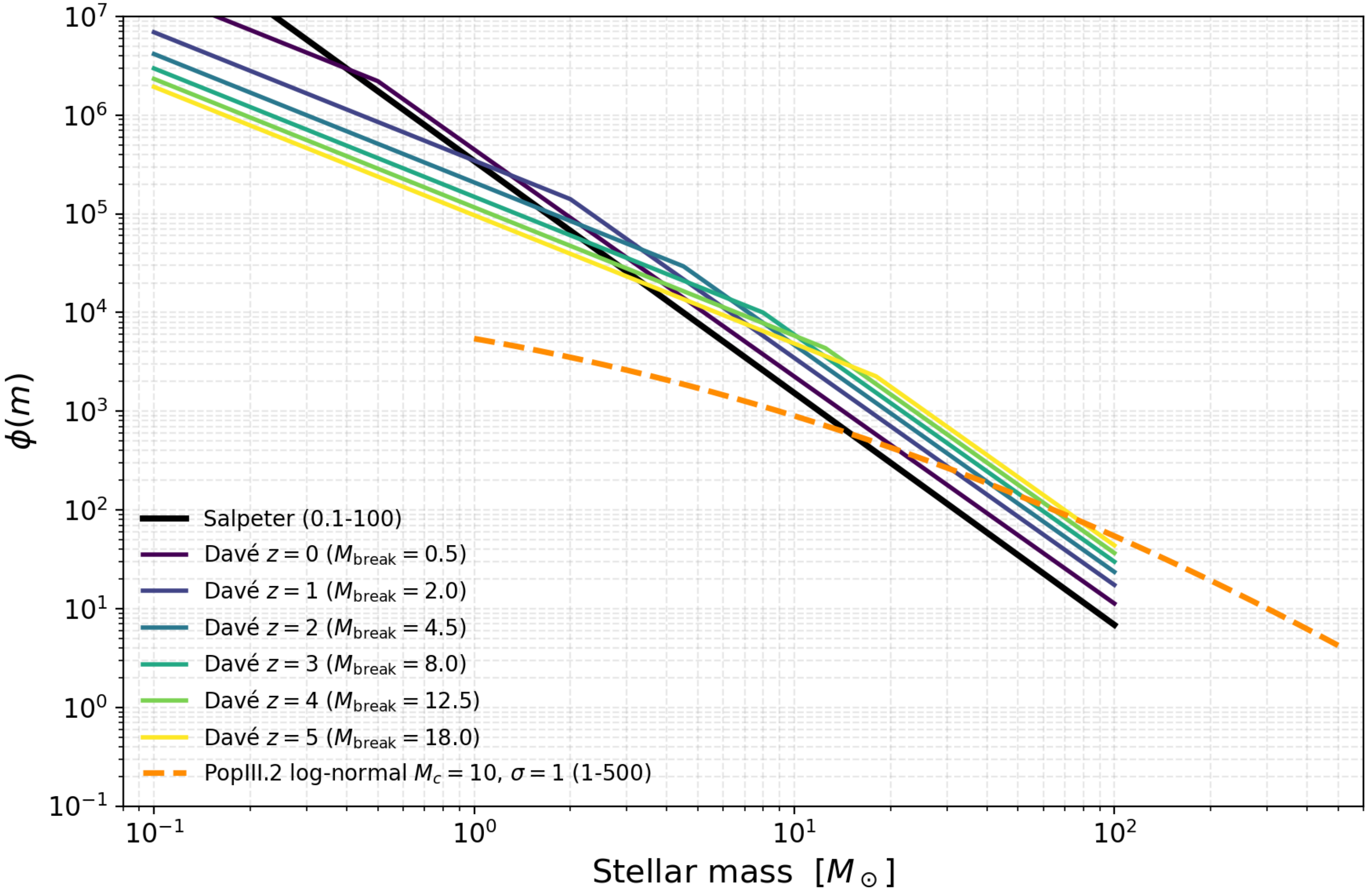
Fujimoto+ 2024
Harikane+ 2022
Madau & Dickinson 2014
8-20 $M_\odot$ SN progenitor
8-50 $M_\odot$ SN progenitor
7-120 $M_\odot$ SN progenitor
Vassallo, SM, Briel
In prep.
SFRD [$M_\odot$ yr^{-1} Mpc^{-3} h$_{70}$]
CCSN Rate [yr^{-1} Mpc^{-3} h$^3_{70}$]
Redshift z
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
1
2
3
4
5



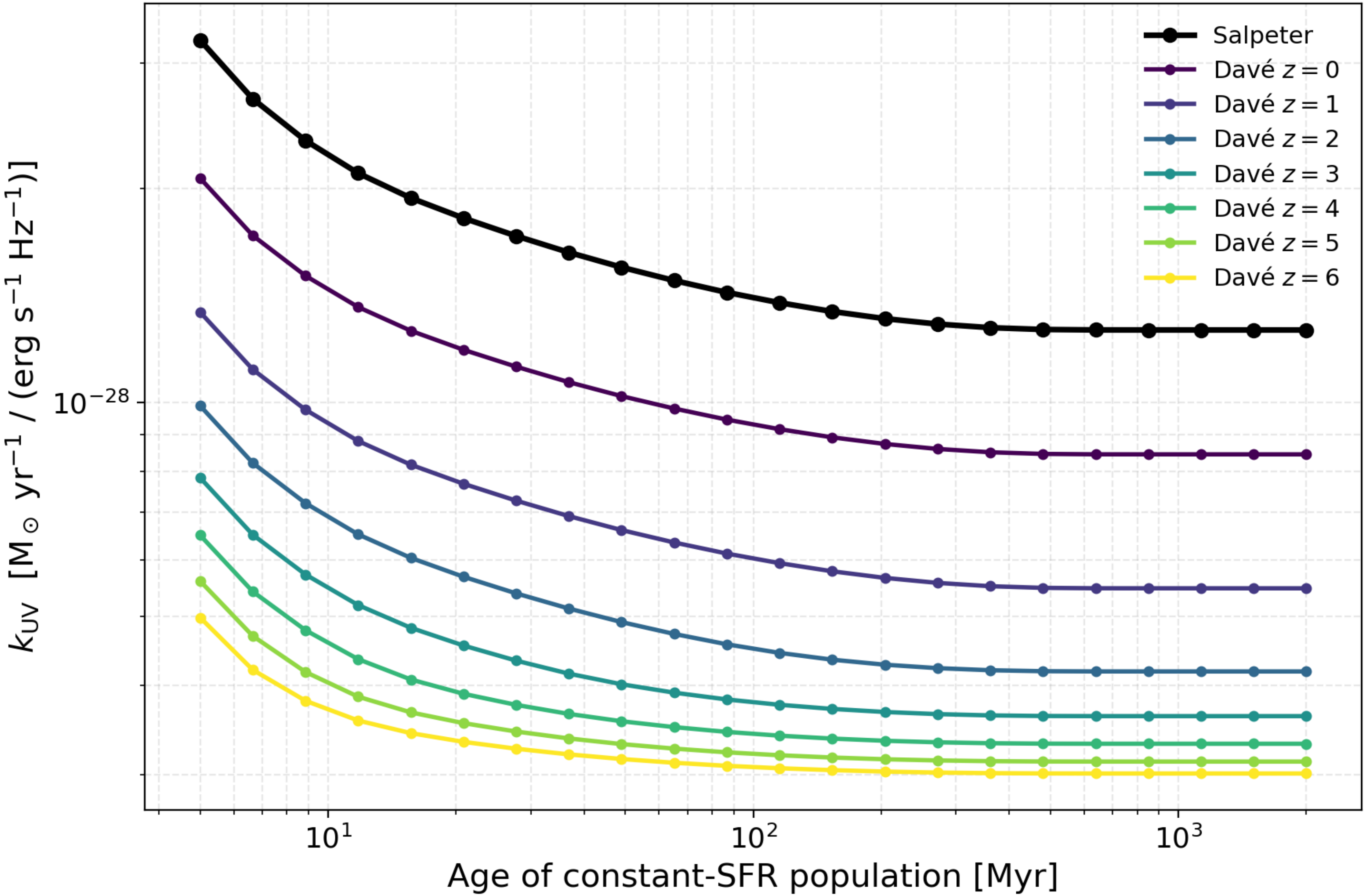
Vassallo, SM, Briel
In prep.
POSYDON k
Mattila+ 2012
Z=Z⊙
Z=0.1Z⊙
Z=10^-4 Z⊙
Missing Fraction
Redshift
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5



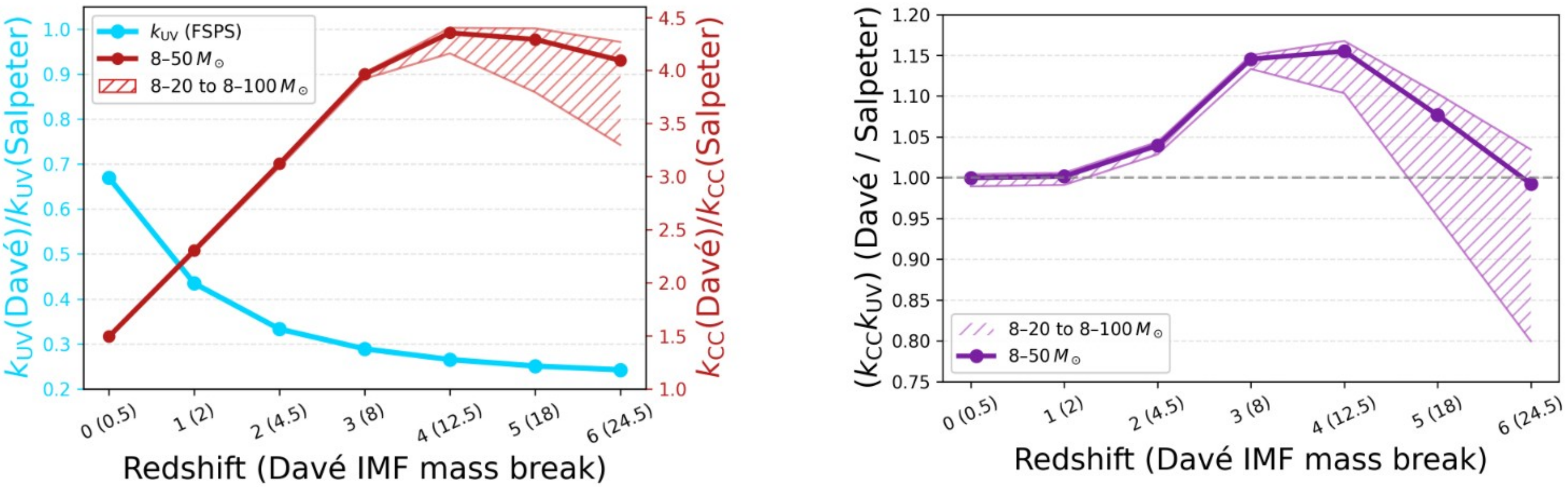
Vassallo, SM, Briel
In prep.
Missing Fraction
Redshift
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5
Mattila+ 2012
7-120 $M_\odot$ SN progenitors
8-50 $M_\odot$ SN progenitors
8-20 $M_\odot$ SN progenitors



$\phi(m)$
Stellar mass $[M_\odot]$
Salpeter (0.1-100)
Davé $z=0$ ($M_{\rm break}=0.5$)
Davé $z=1$ ($M_{\rm break}=2.0$)
Davé $z=2$ ($M_{\rm break}=4.5$)
Davé $z=3$ ($M_{\rm break}=8.0$)
Davé $z=4$ ($M_{\rm break}=12.5$)
Davé $z=5$ ($M_{\rm break}=18.0$)
PopIII.2 log-normal $M_c=10$, $\sigma=1$ (1-500)



Salpeter
Davé $z = 0$
Davé $z = 1$
Davé $z = 2$
Davé $z = 3$
Davé $z = 4$
Davé $z = 5$
Davé $z = 6$
10^{-28}
10^1
10^2
10^3
$k_{\rm UV}$ [$M_\odot$ yr^{-1} / (erg s^{-1} Hz^{-1})]
Age of constant-SFR population [Myr]



k_{UV} (FSPS)
8–50 $M_\odot$
8–20 to 8–100 $M_\odot$
k_{UV}(Davé)/k_{UV}(Salpeter)
k_{CC}(Davé)/k_{CC}(Salpeter)
($k_{CC}k_{UV}$) (Davé / Salpeter)
0 (0.5)
1 (2)
2 (4.5)
3 (8)
4 (12.5)
5 (18)
6 (24.5)
Redshift (Davé IMF mass break)