Gravitational lensing of individual Population III stars in the early Universe

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JWST detection of lensed, individual Pop III stars is possible if:

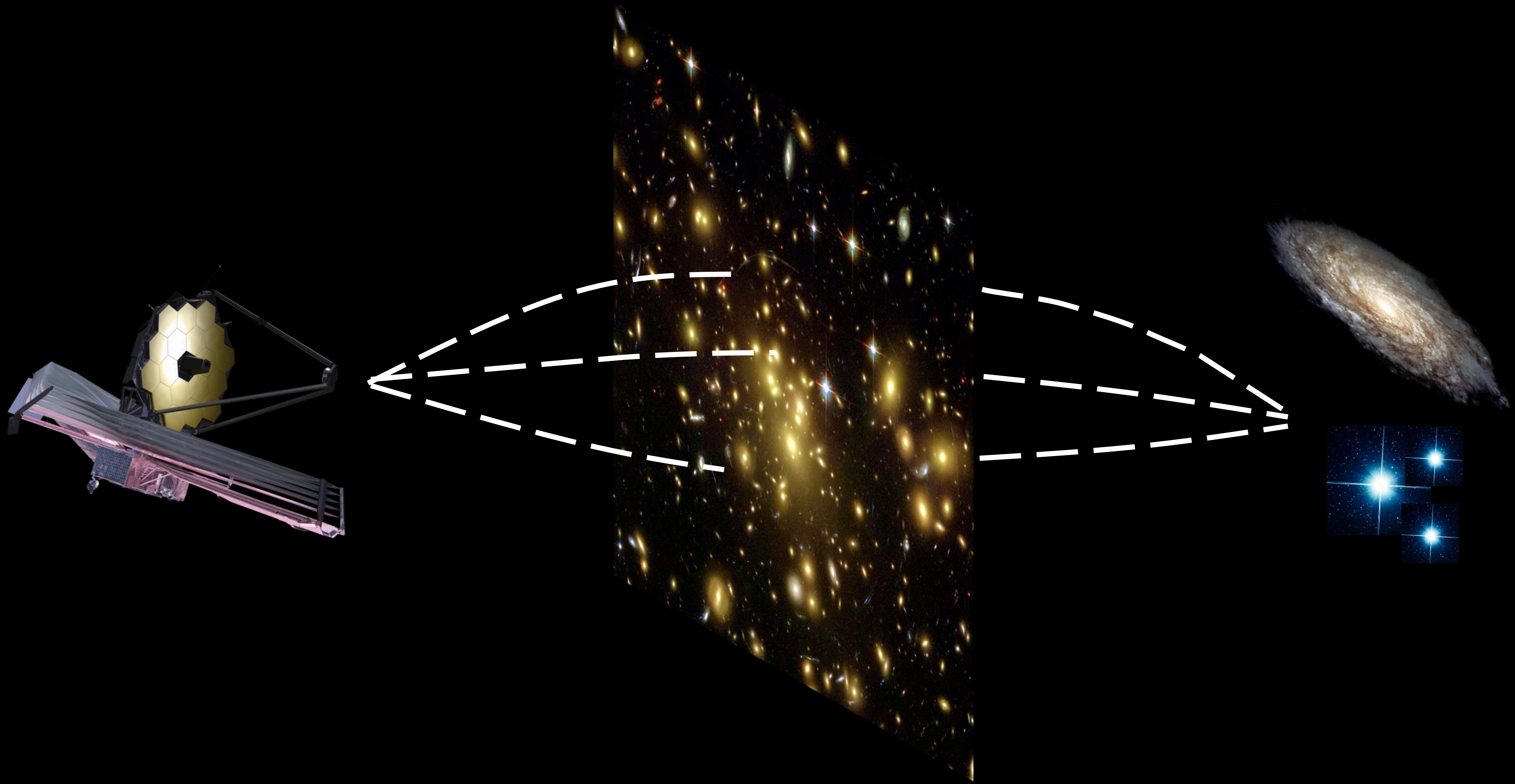
1. Pop III stars keep forming until $z \approx 6$-10, at a SFRD level of $\sim 10^{-4}\ M_{\odot}\ yr^{-1}\ cMpc^{-3}$

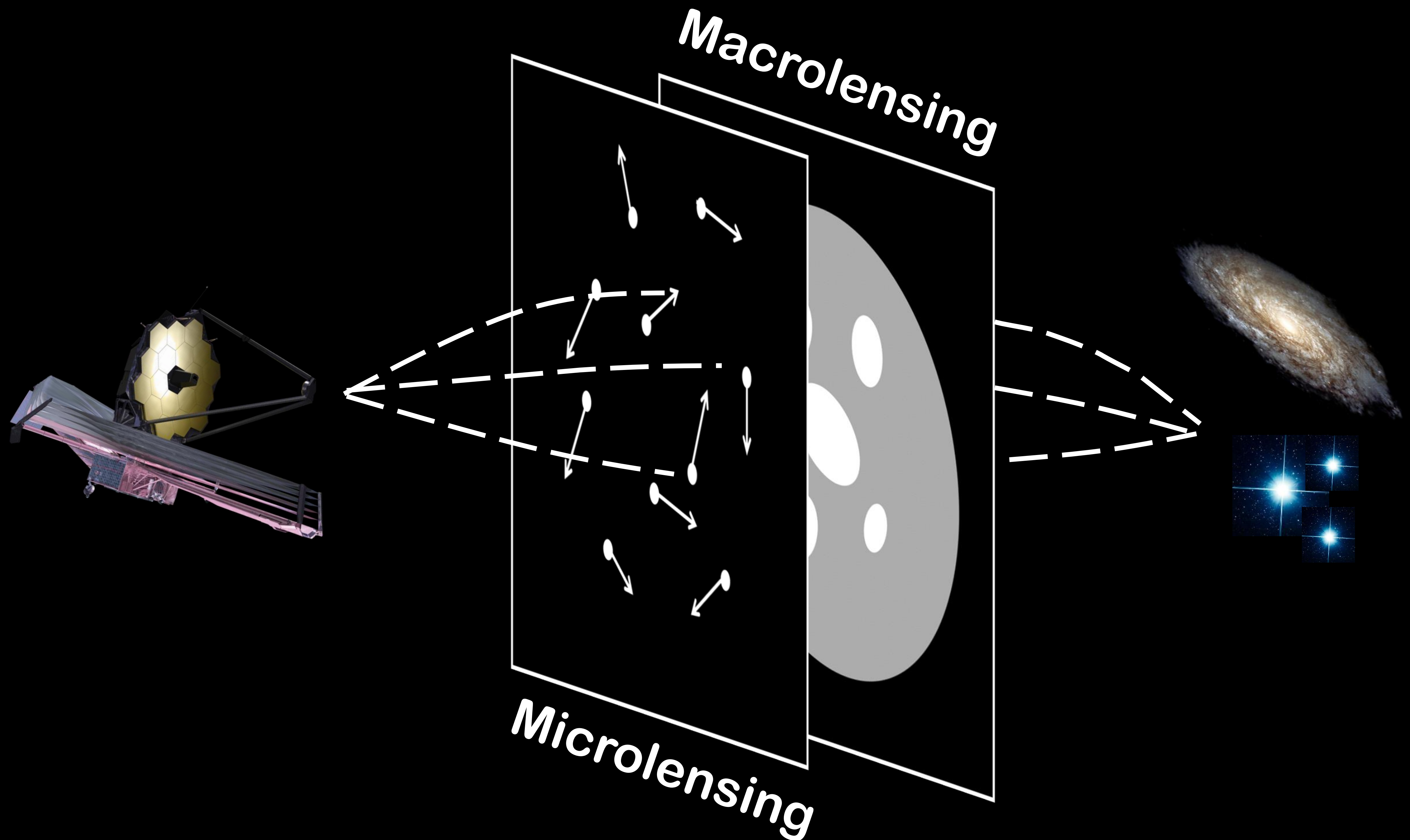
2. Pop III stars have a relatively top-heavy IMF (significant mass fraction in $>100\ M_{\odot}$ stars)

3. Massive Pop III stars evolve to $T_{eff} < 30000$ K

4. You observe 30+ cluster-lensing fields

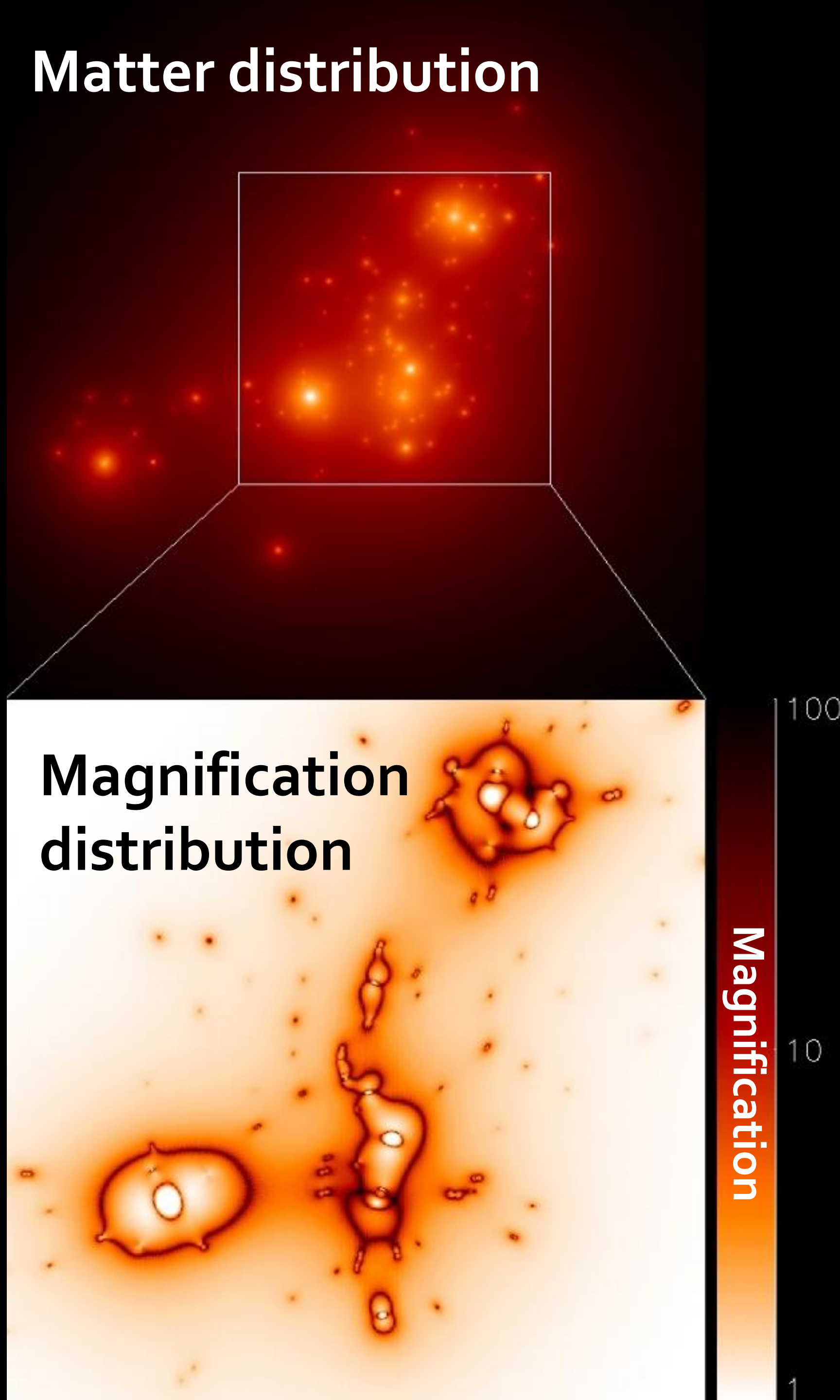

SMACS 0723




Macrolensing
Microlensing

- High-redshift galaxies can get magnified by factors up to ~10^2 (5 mag)
- Smaller high-redshift objects (stars, black hole accretion disks) can get magnified by factors up to ~10^4 (10 mag)

Sufficient for detection of M_{ZAMS}>10 $M_\odot$ stars at z>1



Welch et al. (2022, Nature 603, 815)

Article

A highly magnified star at redshift 6.2

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Check for updates

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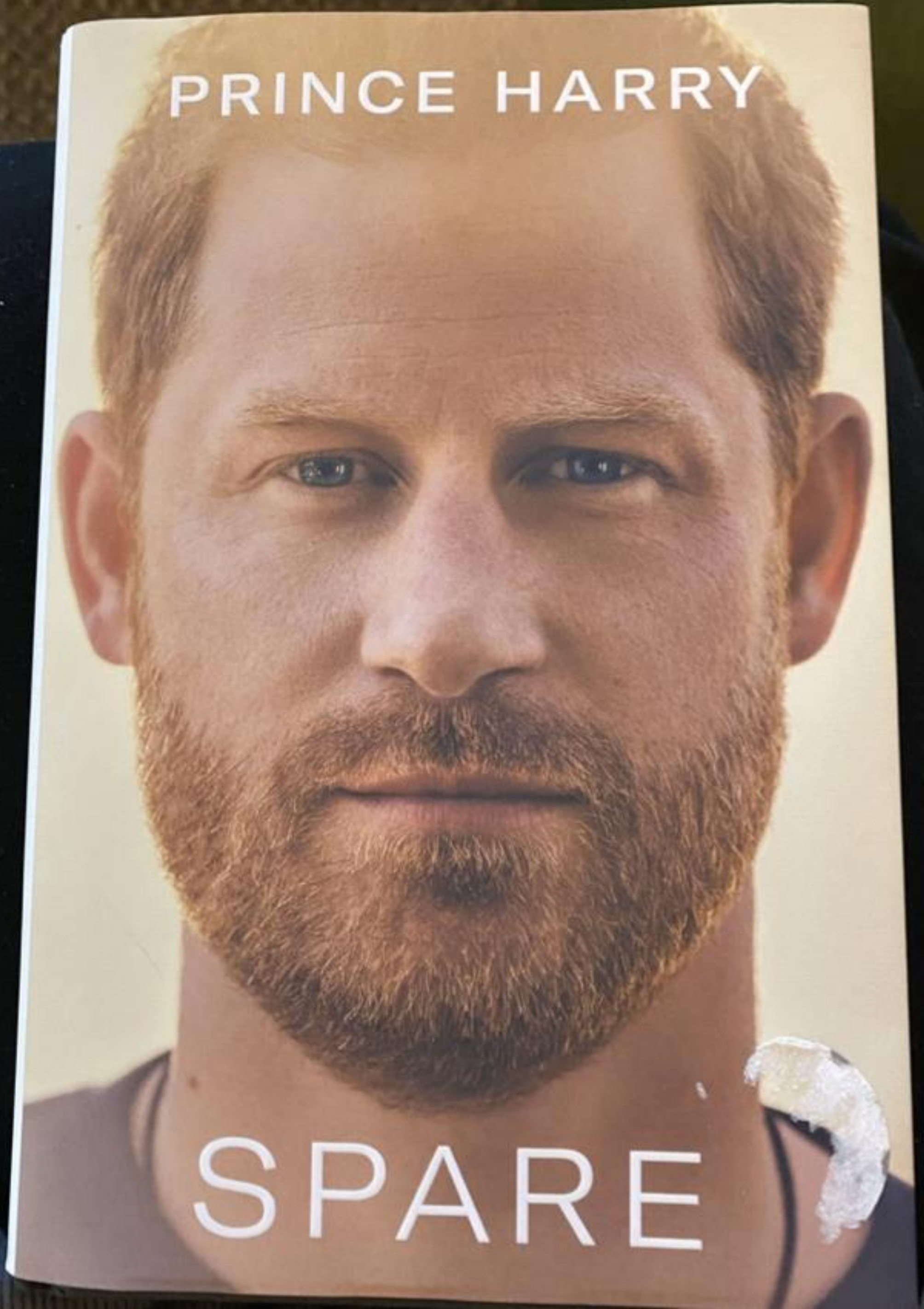
Galaxy clusters magnify background objects through strong gravitational lensing. Typical magnifications for lensed galaxies are factors of a few but can also be as high as tens or hundreds, stretching galaxies into giant arcs[1,2]. Individual stars can attain even higher magnifications given fortuitous alignment with the lensing cluster. Recently, several individual stars at redshifts between approximately 1 and 1.5 have been discovered, magnified by factors of thousands, temporarily boosted by microlensing[3–6]. Here we report observations of a more distant and persistent magnified star at a redshift of 6.2 ± 0.1, 900 million years after the Big Bang. This star is magnified by a factor of thousands by the foreground galaxy cluster lens WHL0137−08 (redshift 0.566), as estimated by four independent lens models. Unlike previous lensed stars, the magnification and observed brightness (AB magnitude, 27.2) have remained roughly constant over 3.5 years of imaging and follow-up. The delensed absolute UV magnitude, −10 ± 2, is consistent with a star of mass greater than 50 times the mass of the Sun. Confirmation and spectral classification are forthcoming from approved observations with the James Webb Space Telescope.

Earendel

(≈ eorendel, earendil), old English for “Rising Star”

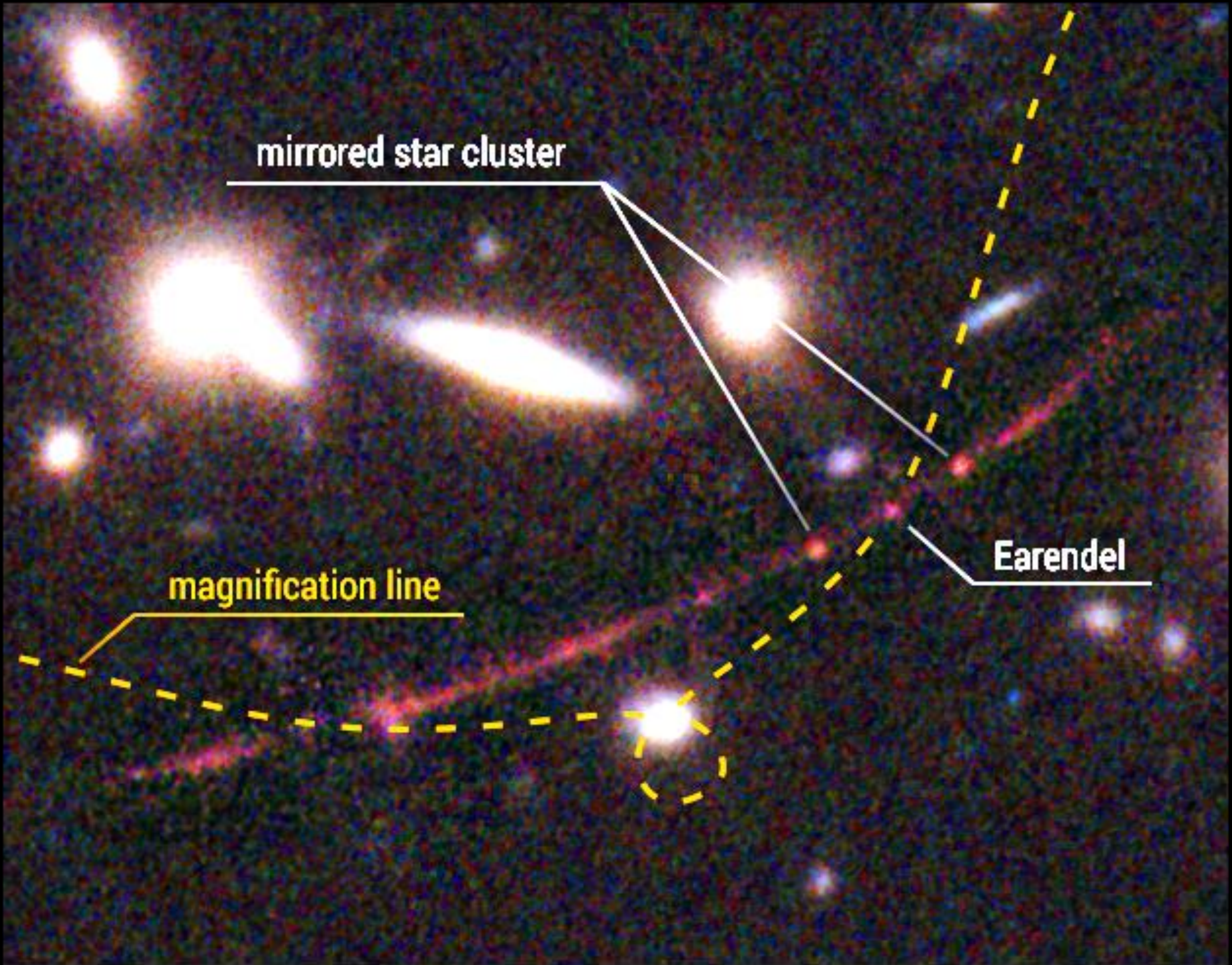
"I give you the light of Earendil, our most beloved star.
May it be a light for you in dark places, when all other lights go out."



Maybe she was omnipresent for the very same reason that she was indescribable—because she was light, pure and radiant light, and how can you really describe light? Even Einstein struggled with that one. Recently, astronomers rearranged their biggest telescopes, aimed them at one tiny crevice in the cosmos, and managed to catch a glimpse of one breathtaking sphere, which they named Earendel, the Old English word for Morning Star. Billions of miles off, and probably long vanished, Earendel is closer to the Big Bang, the moment of Creation, than our own Milky Way, and yet it's somehow still visible to mortal eyes because it's just so awesomely bright and dazzling

That was my mother.


Earendel

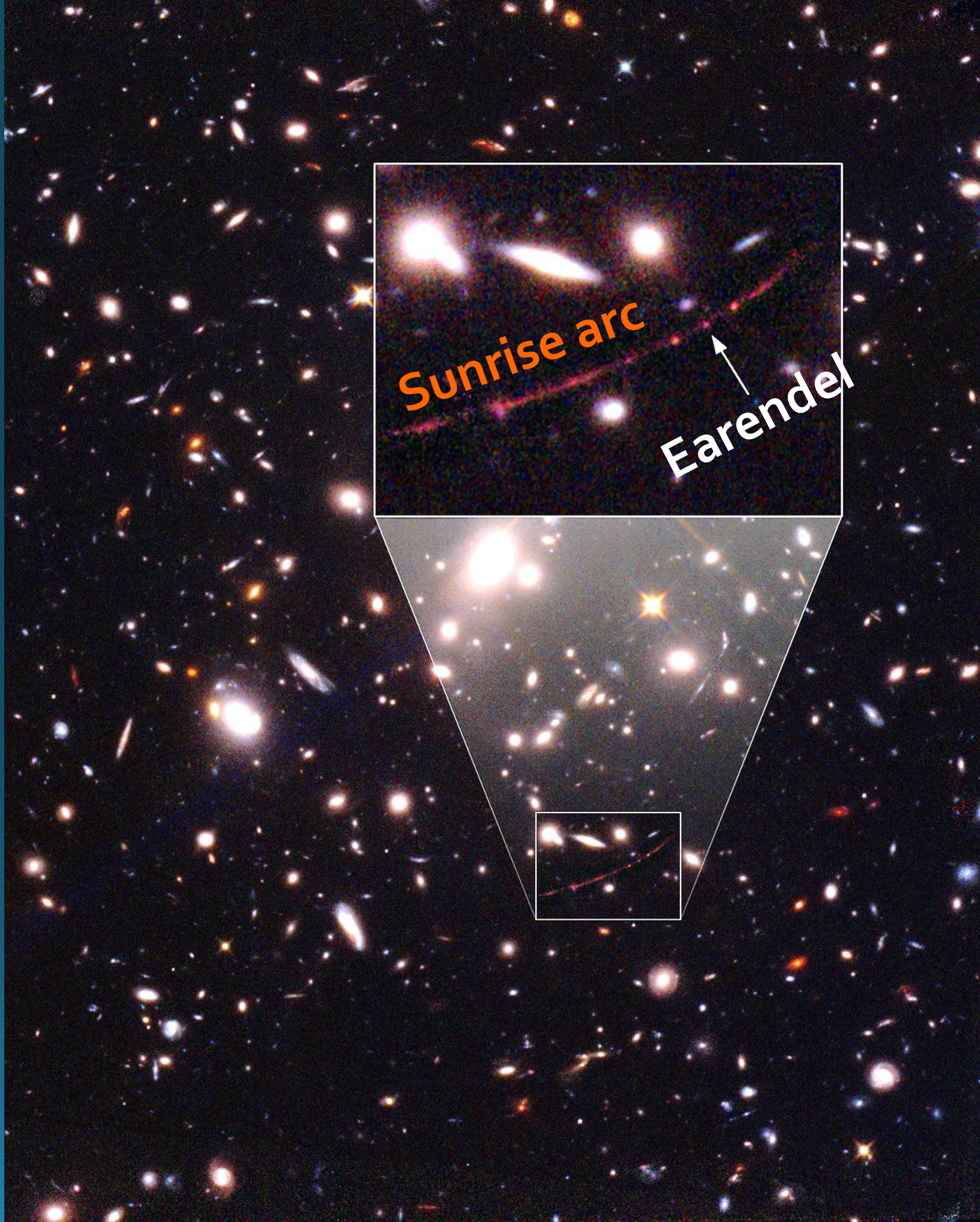

mirrored star cluster
Earendel
magnification line

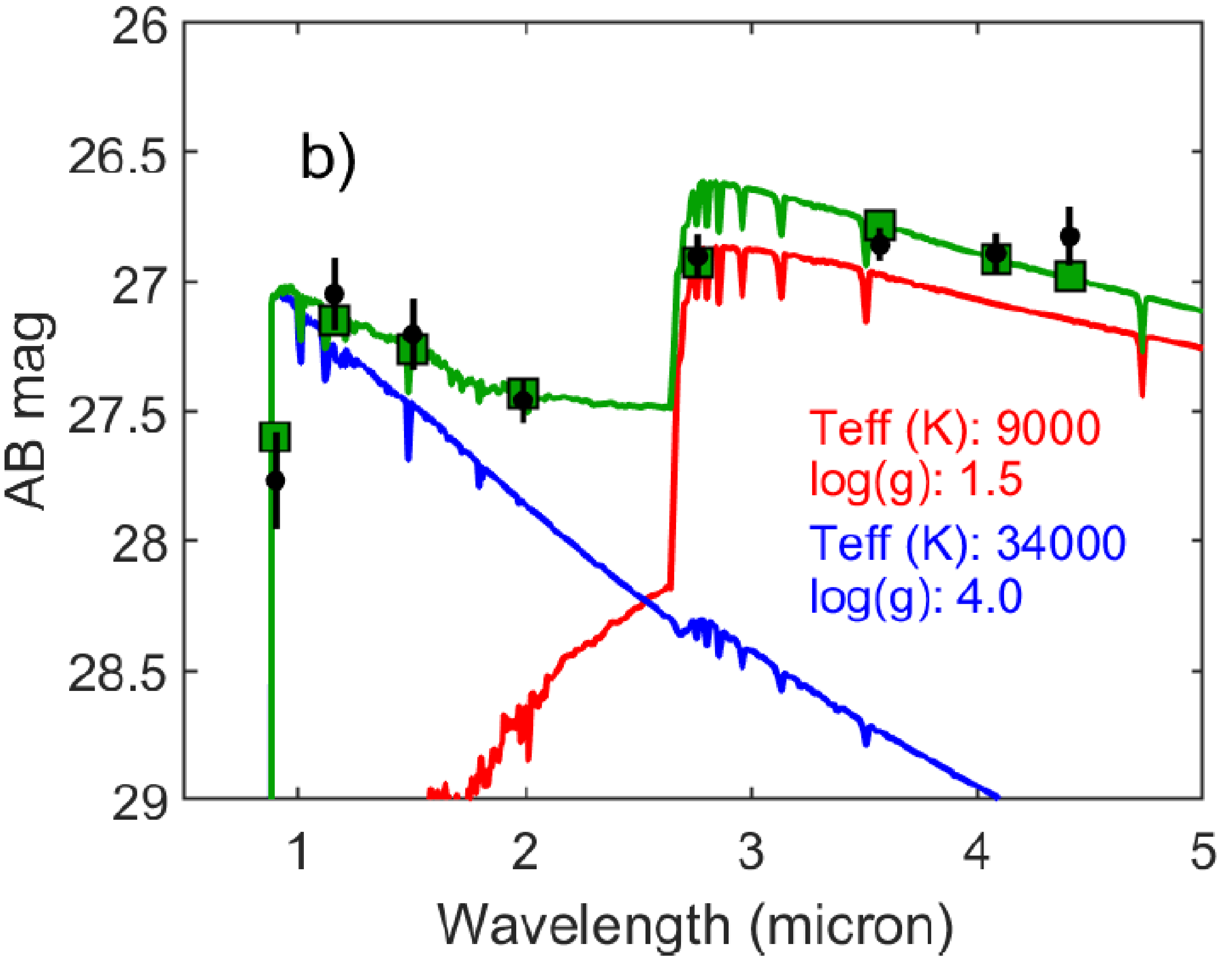
Earendel: Properties

- Magnification of Earendel uncertain, but definitely high $\mu \approx 4000\text{-}35000$

- Delensed flux emitted from within ~0.02 pc (4000 AU) → Likely single star or binary

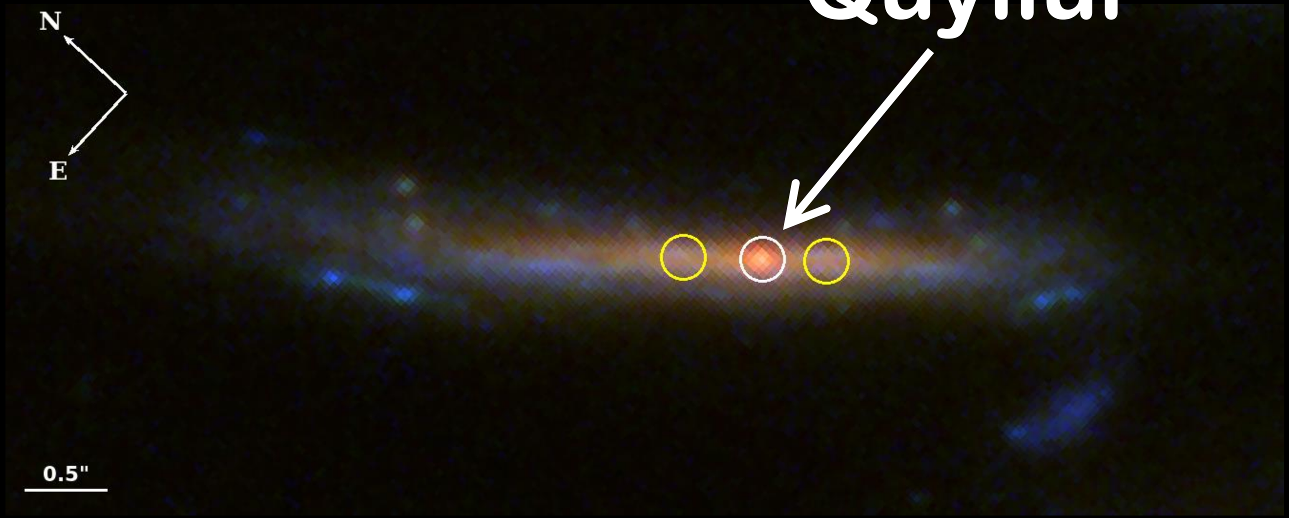
- Likely stellar mass at birth: 20-150 $M_{\odot}$



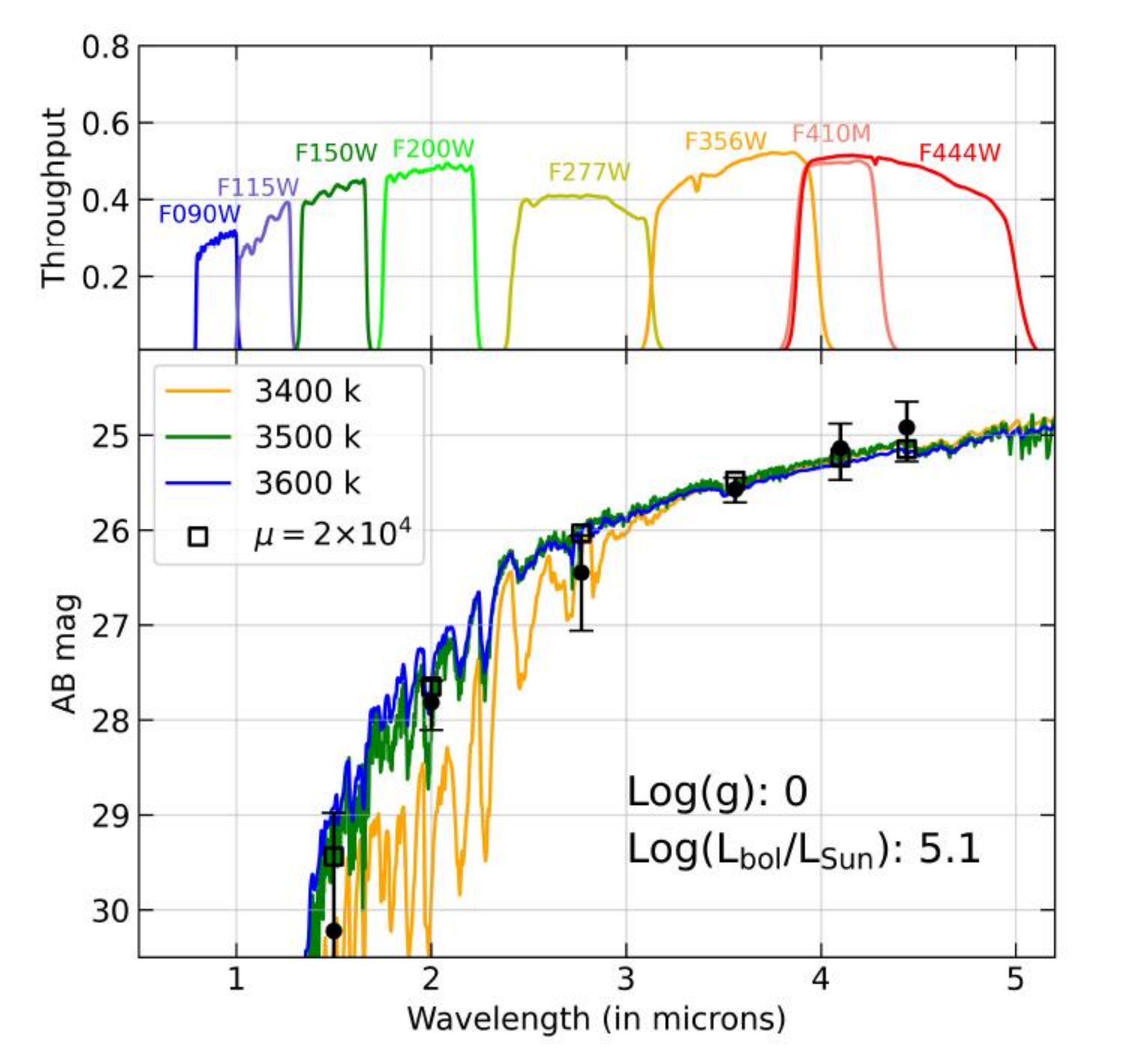

b)
Teff (K): 9000
log(g): 1.5
Teff (K): 34000
log(g): 4.0
AB mag
Wavelength (micron)
26
26.5
27
27.5
28
28.5
29
1
2
3
4
5

Quyllur: Betelgeuse-like star 10.7 billion years ago (z≈2.2)

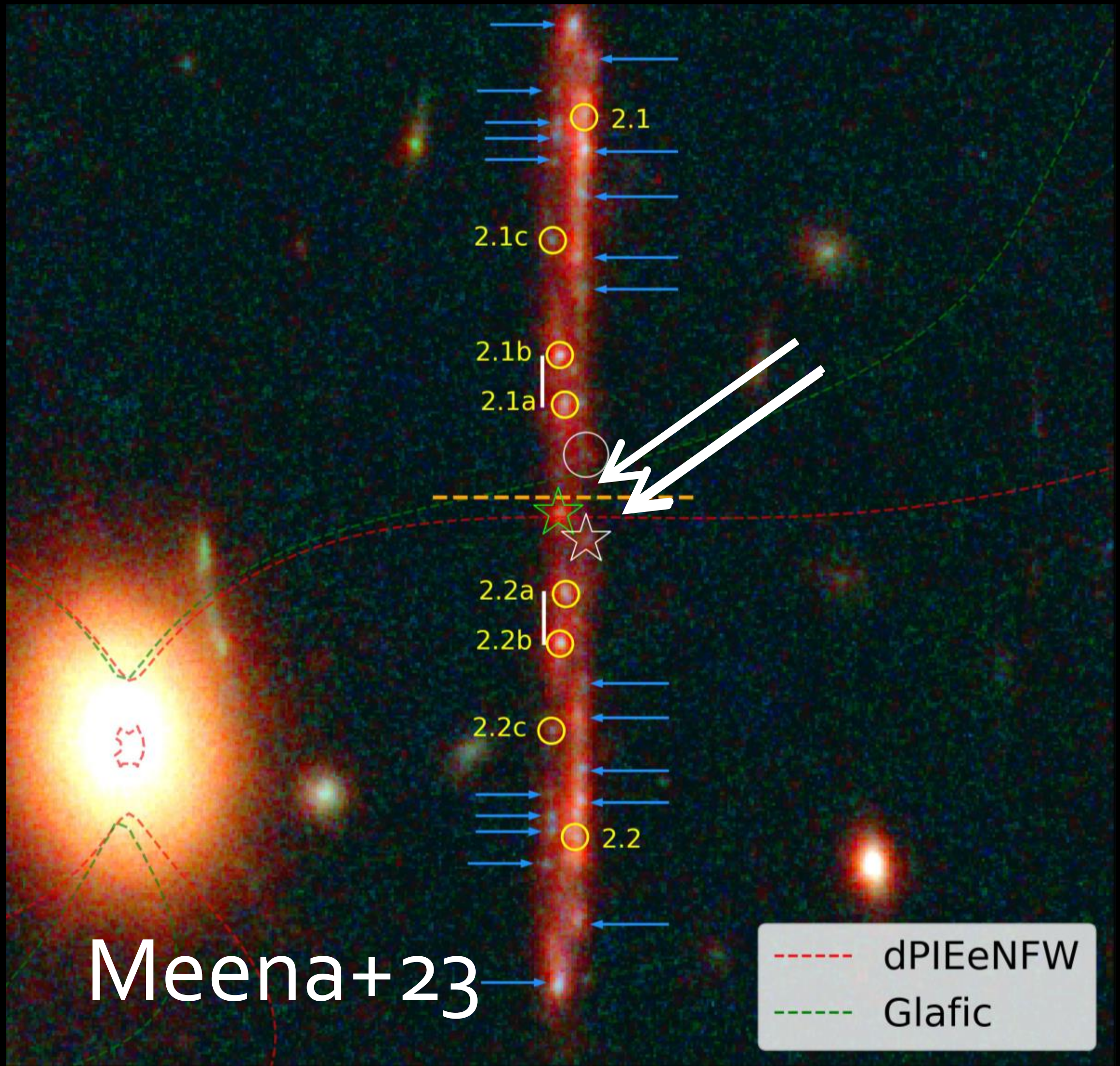
Quyllur

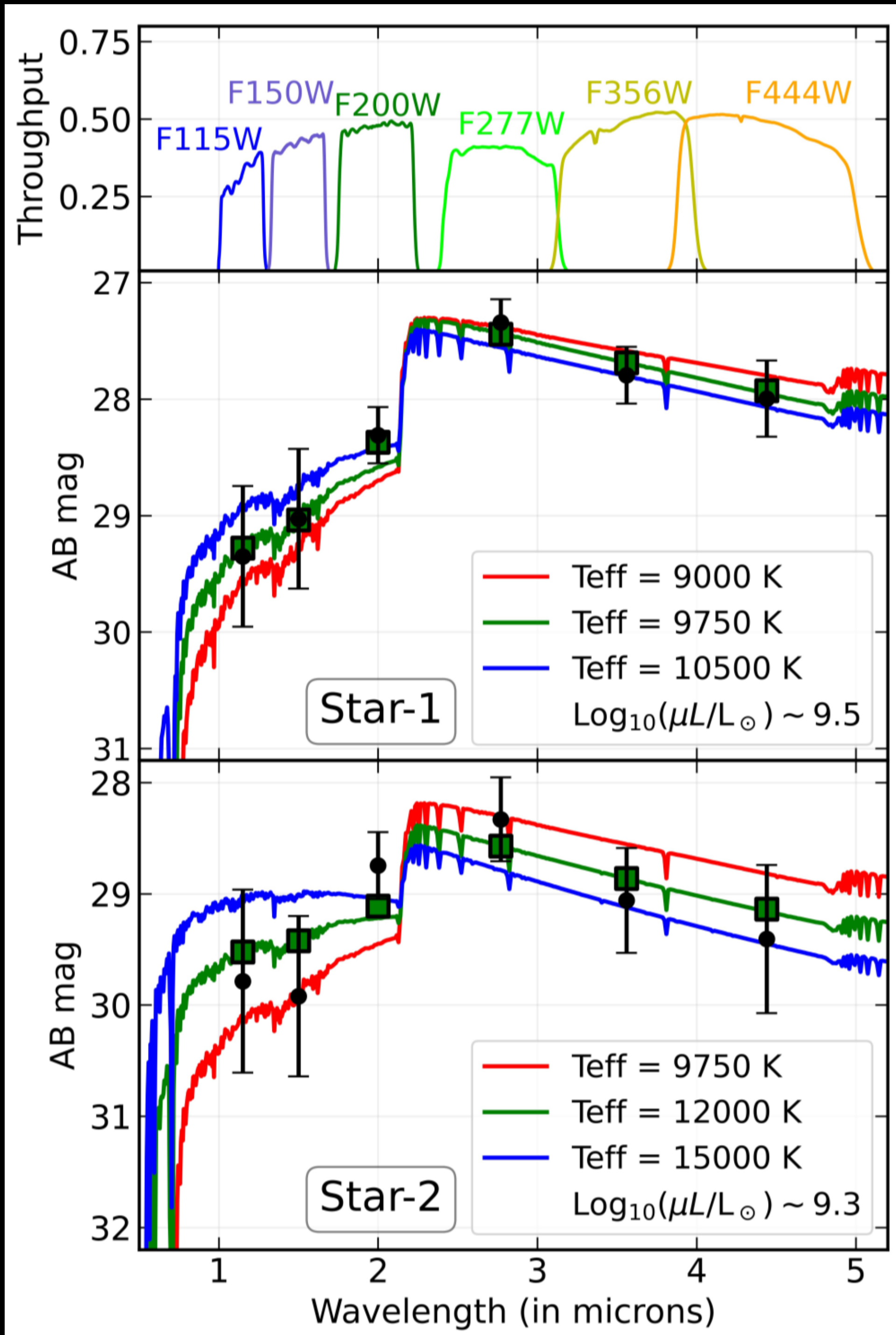


Diego+23



Two lensed stars 12.5 billion years ago (redshift z≈4.8)



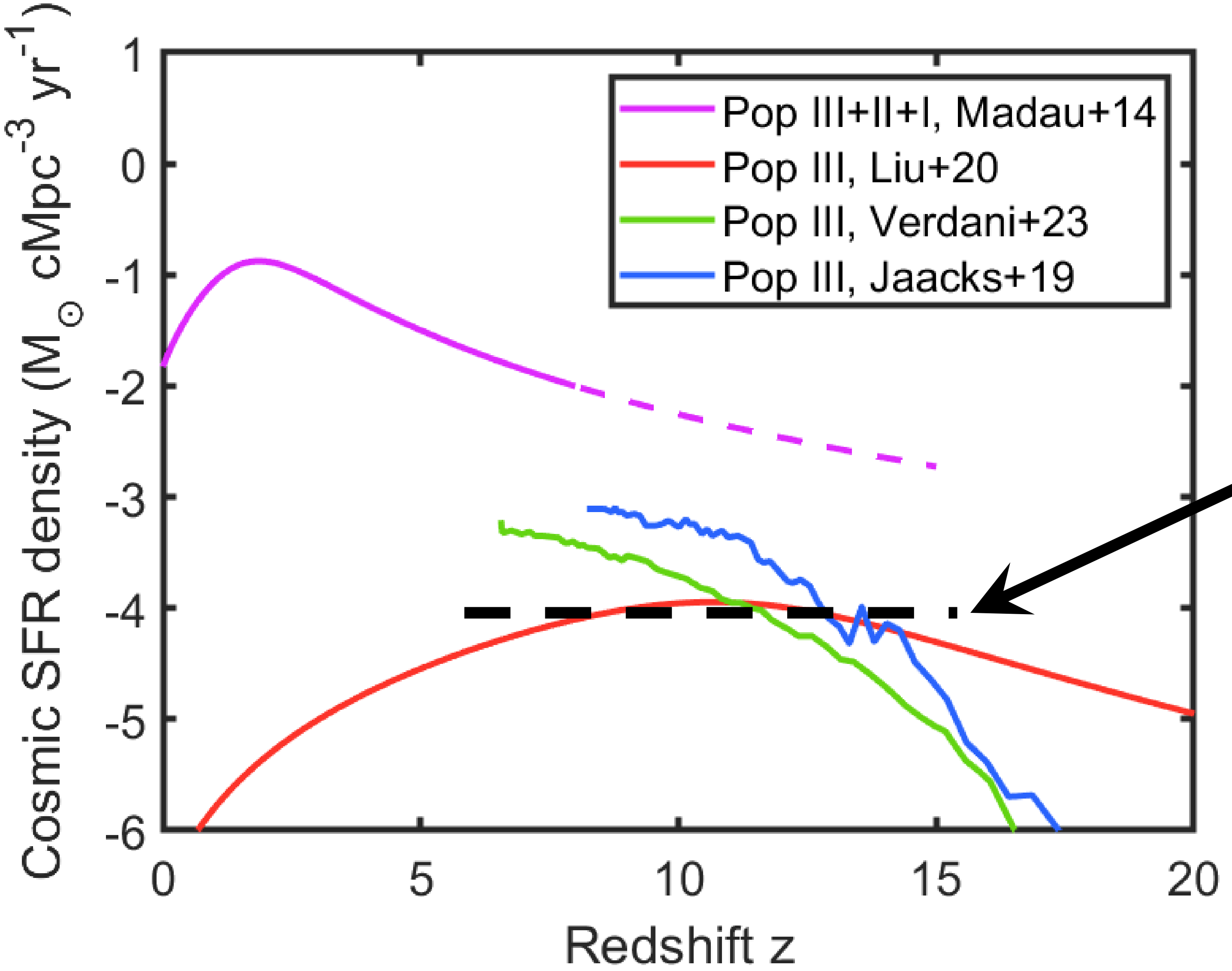


Can we detect Pop III stars this way?

Primarily depends on:

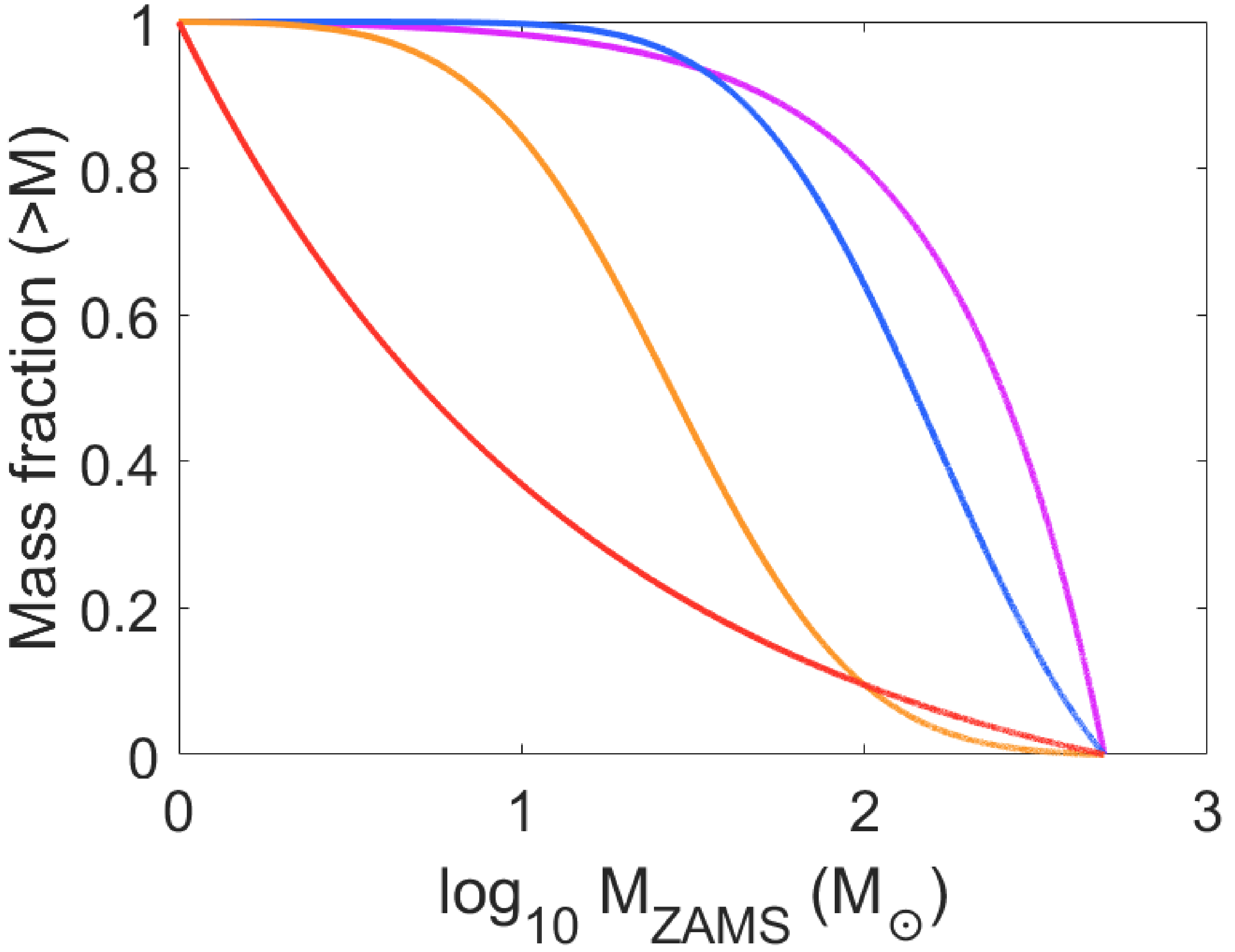
- Star formation rate density
- Stellar initial mass function
- Evolution across the HR diagram

Pop III star formation rate density (z)



Rough Pop III detection limit

Pop III stellar initial mass function



M_{ZAMS} = 1-500 $M_\odot$

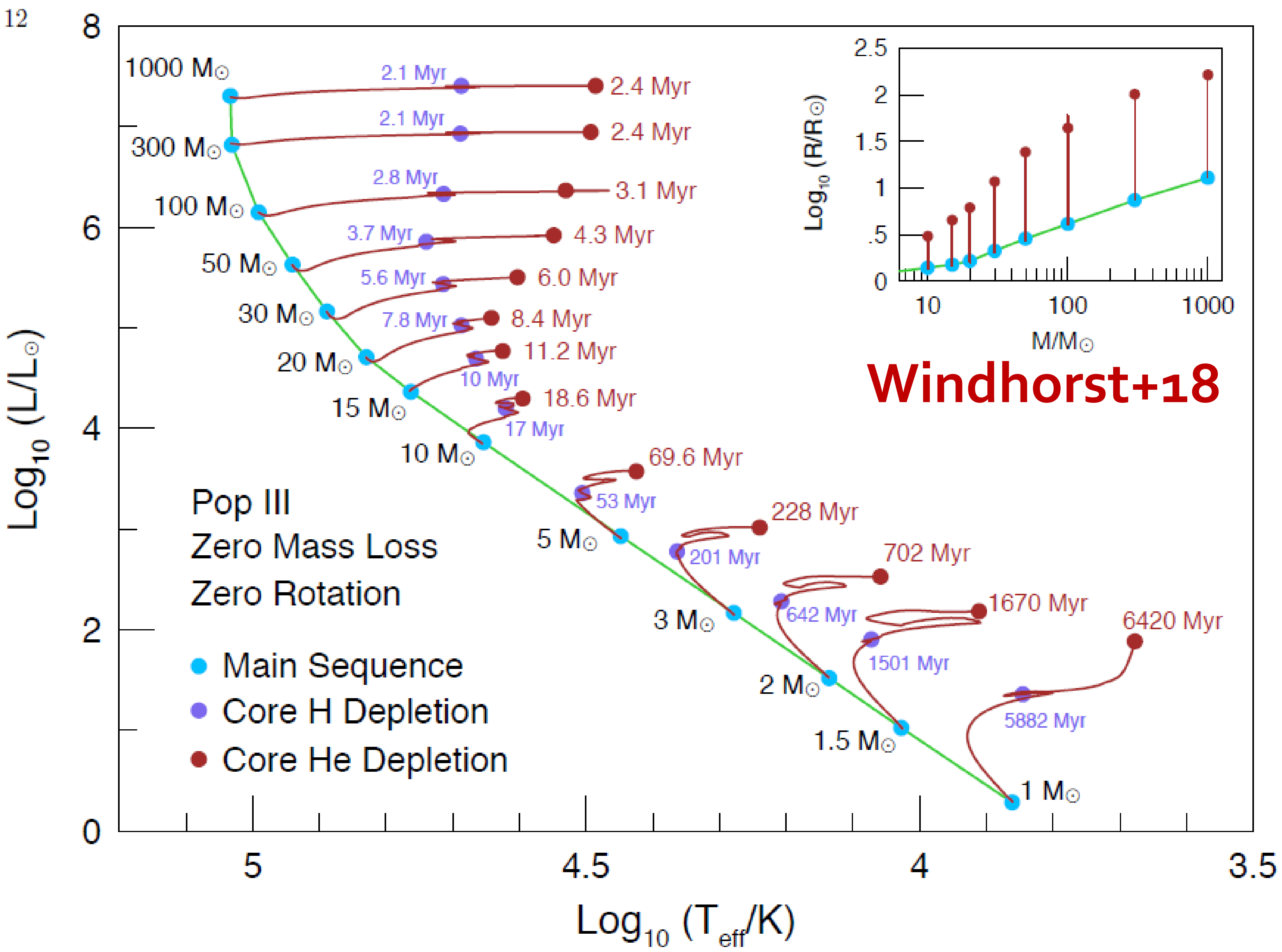
dN/dlogM = constant

Tumlinson+06, Mc=60 $M_\odot$, σ=1

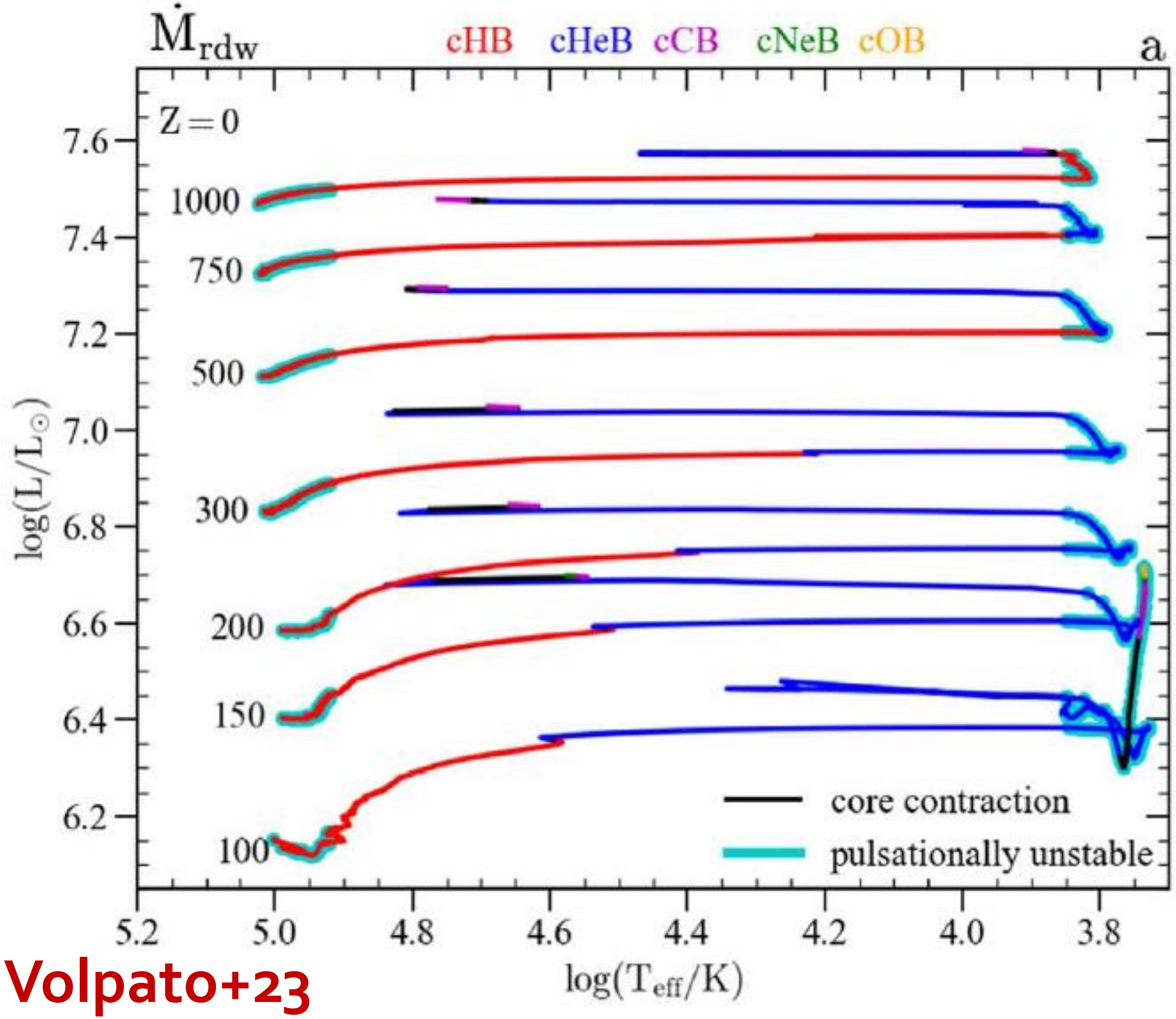
Tumlinson+06, Mc=10 $M_\odot$, σ=1

Salpeter, 1-500 M⊙

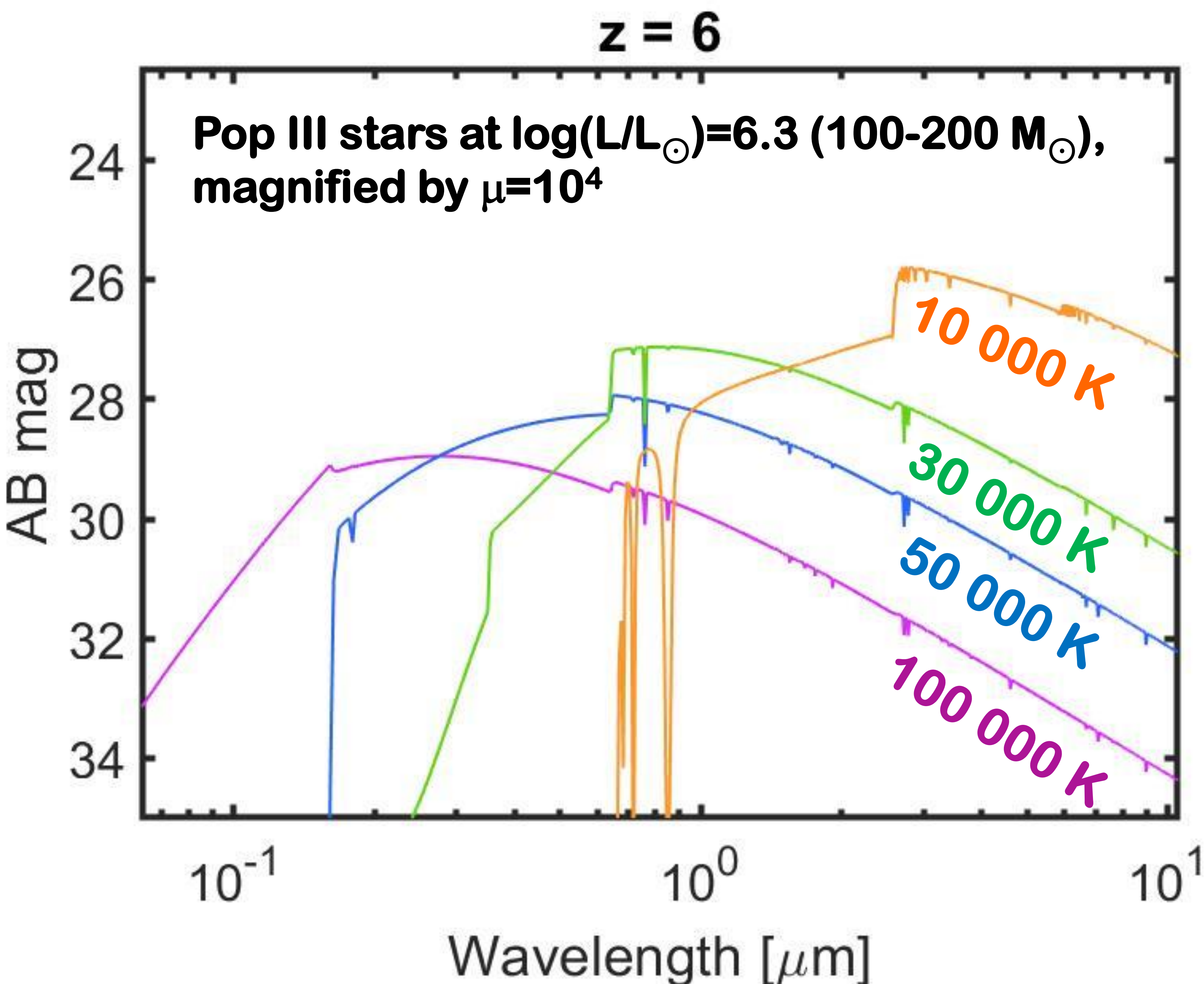
Pop III evolution across the HR diagram



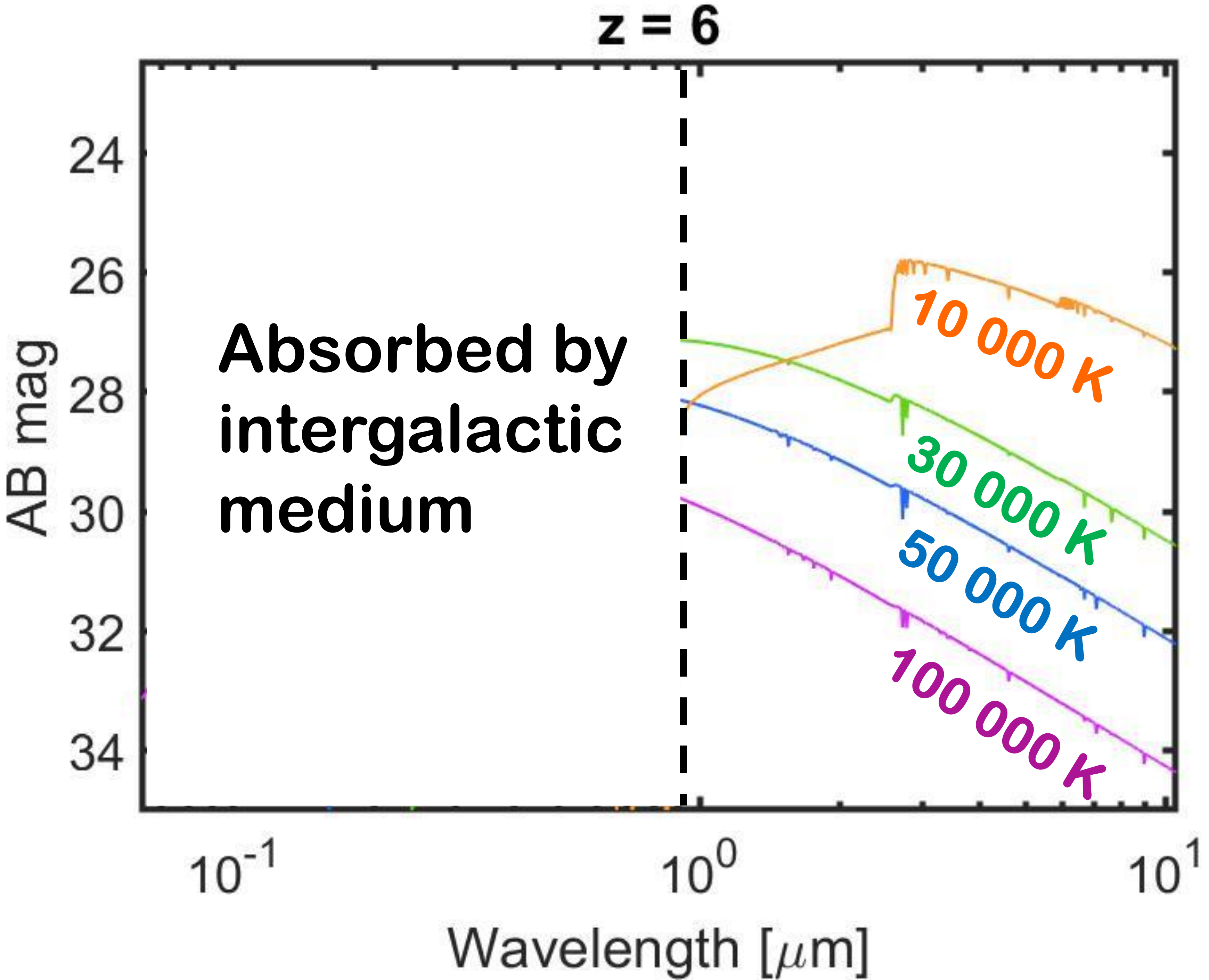
Pop III evolution across the HR diagram



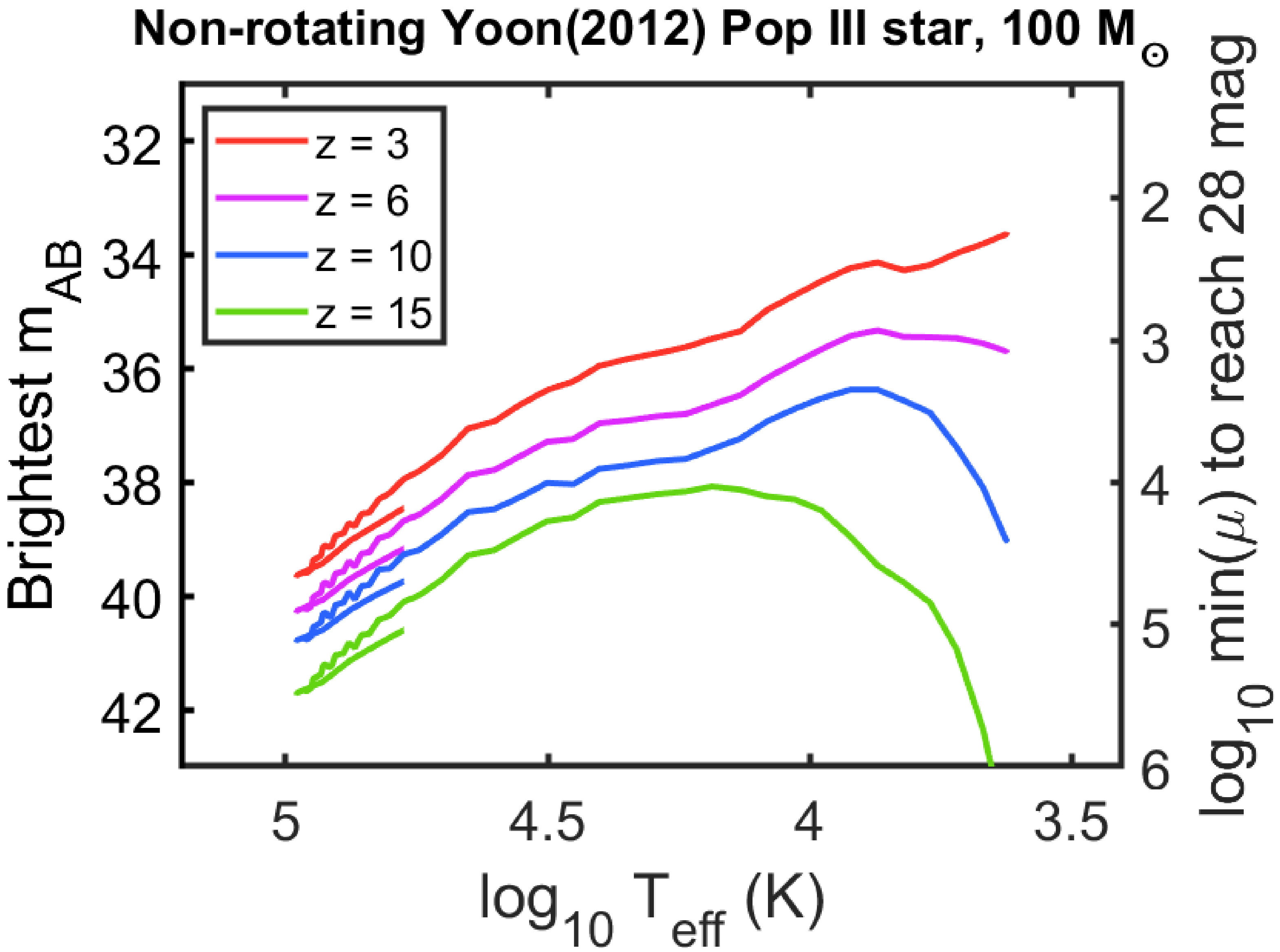
Volpato+23



z = 6
Pop III stars at log(L/L⊙)=6.3 (100-200 M⊙),
magnified by μ=10^4
10 000 K
30 000 K
50 000 K
100 000 K
24
26
28
30
32
34
AB mag
10^-1
10^0
10^1
Wavelength [μm]

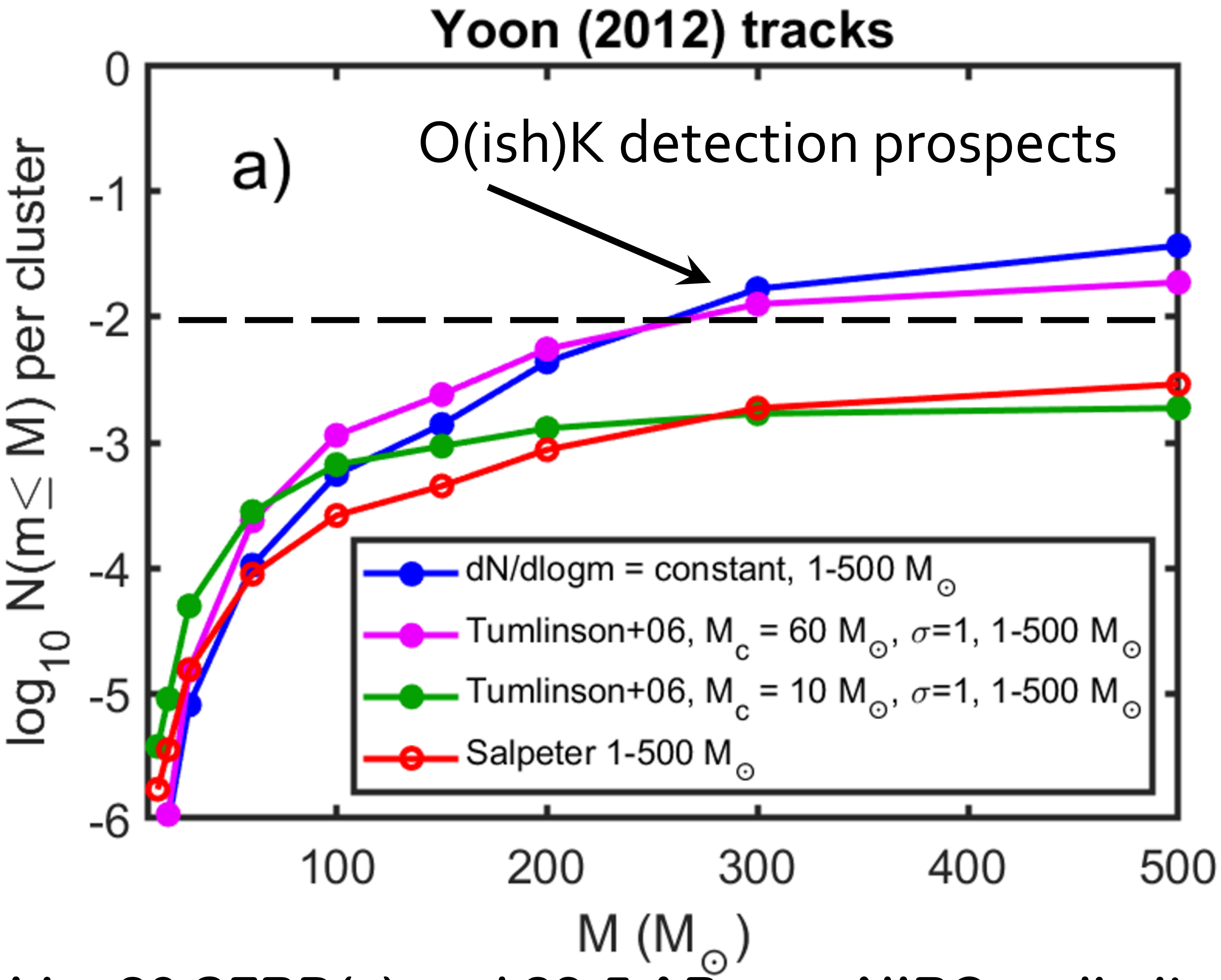


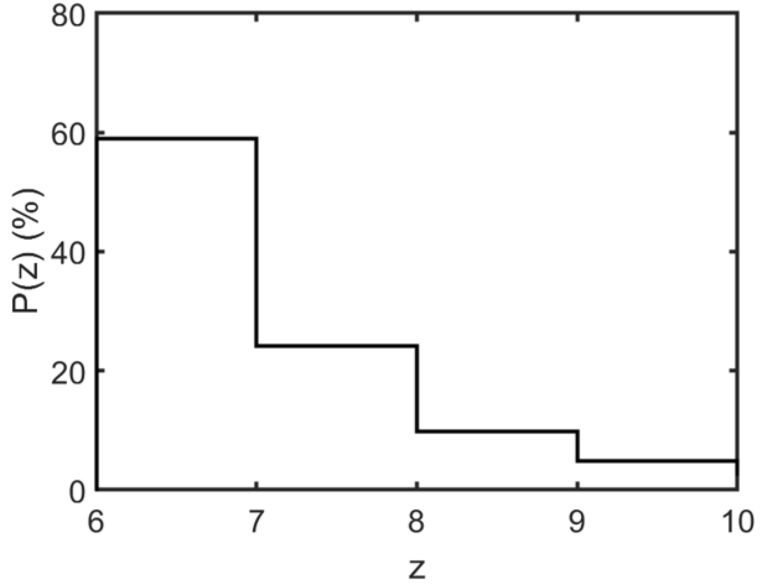
z = 6
24
26
28
30
32
34
AB mag
Absorbed by intergalactic medium
10 000 K
30 000 K
50 000 K
100 000 K
10^-1
10^0
10^1
Wavelength [μm]



Required magnification drops by factor of >10 at low Teff→ >100 times more likely; offsets timescale argument

Pop III detection probability per cluster field

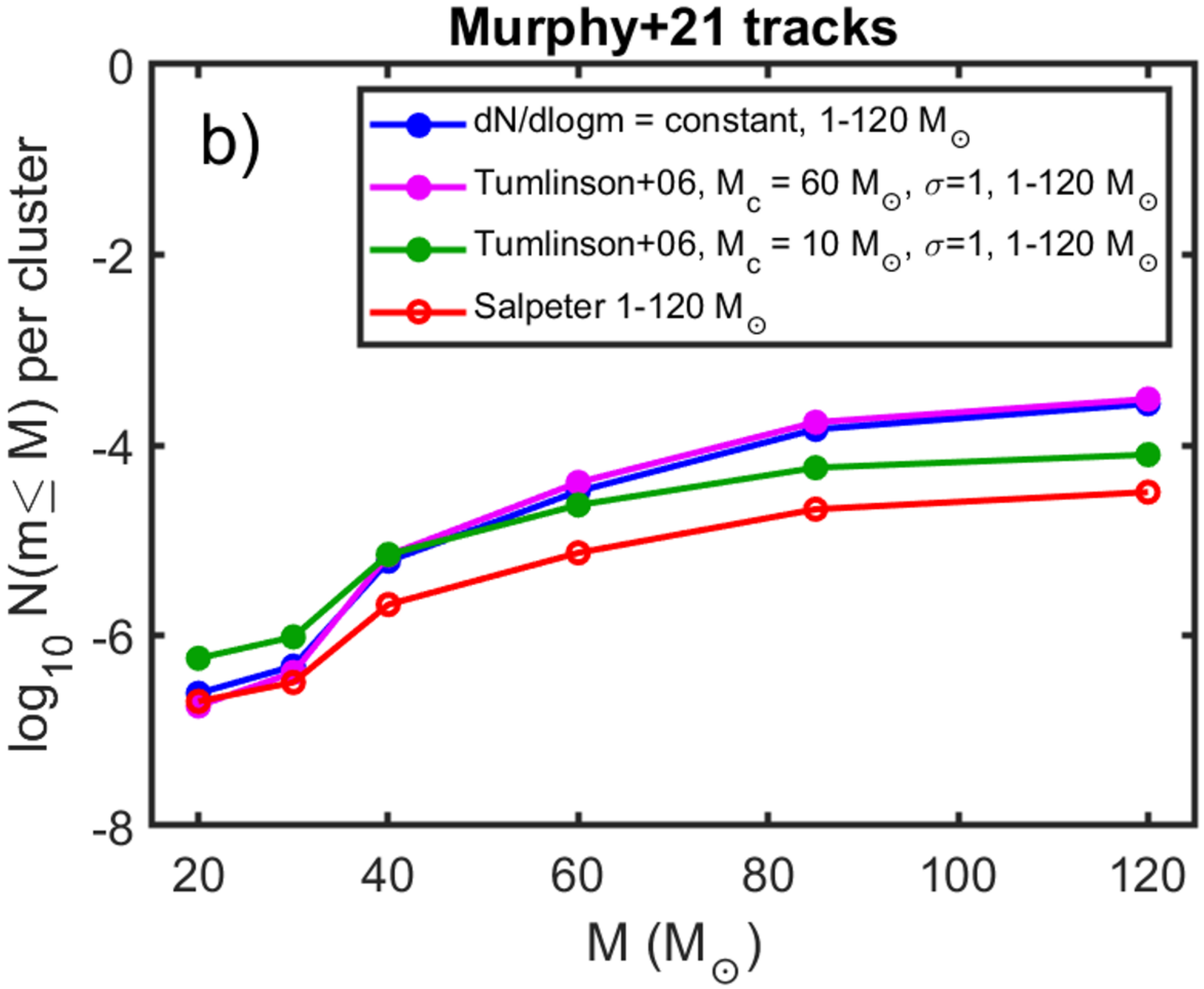


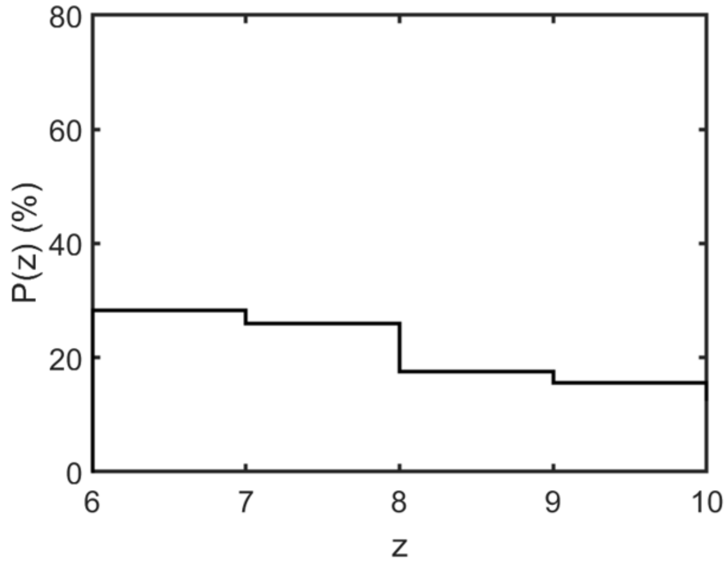


Only the most massive Pop III stars ($M \geq 300\ M_\odot$) are detectable at z>6

Liu+20 SFRD(z) and 28.5 AB mag NIRCam limit assumed

Pop III detection probability per cluster field

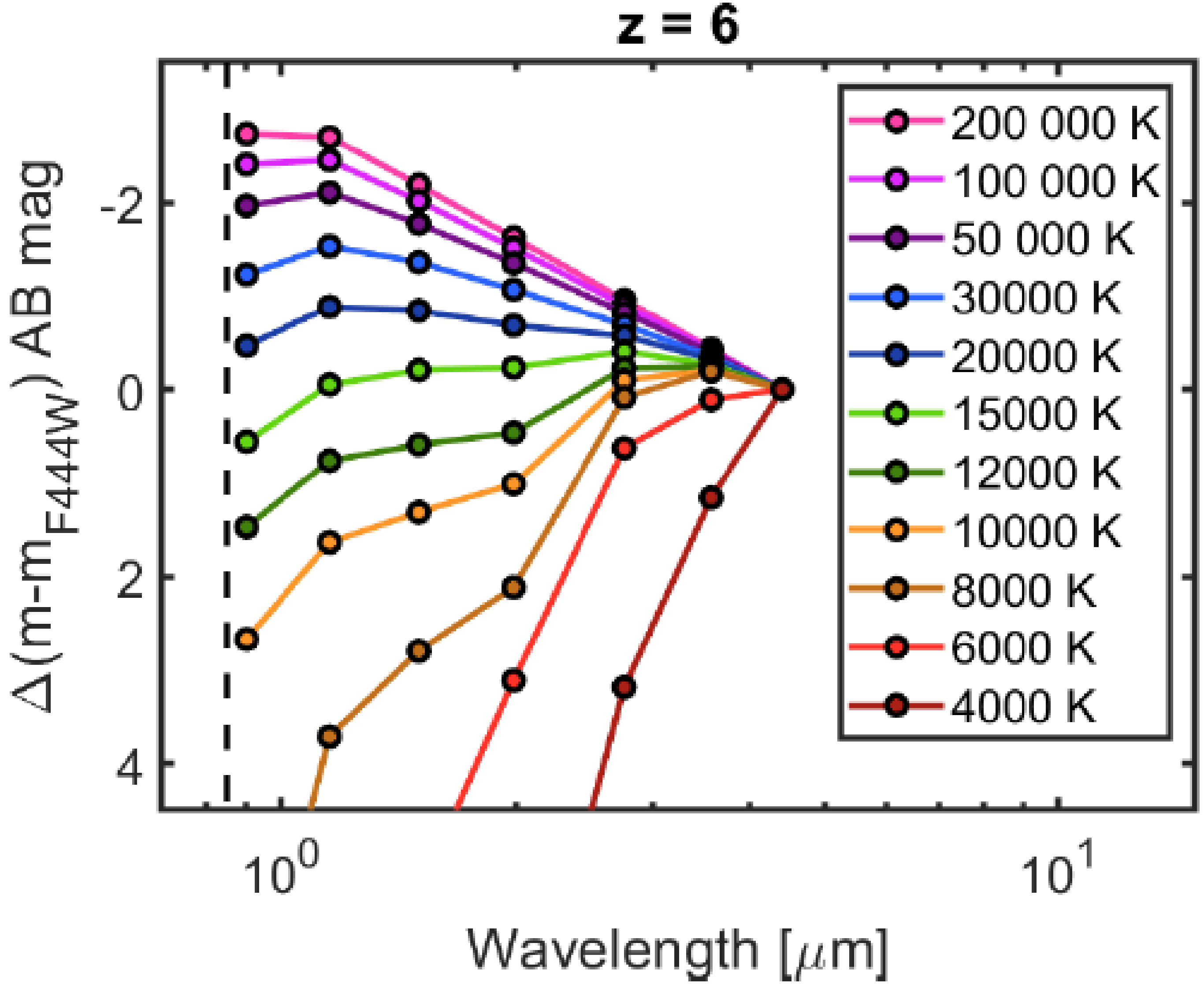




No Pop III stars at M>120 $M_\odot$ or at Teff<15000 K → Hopeless... ☹

Liu+20 SFRD(z) and 28.5 AB mag NIRCam limit assumed

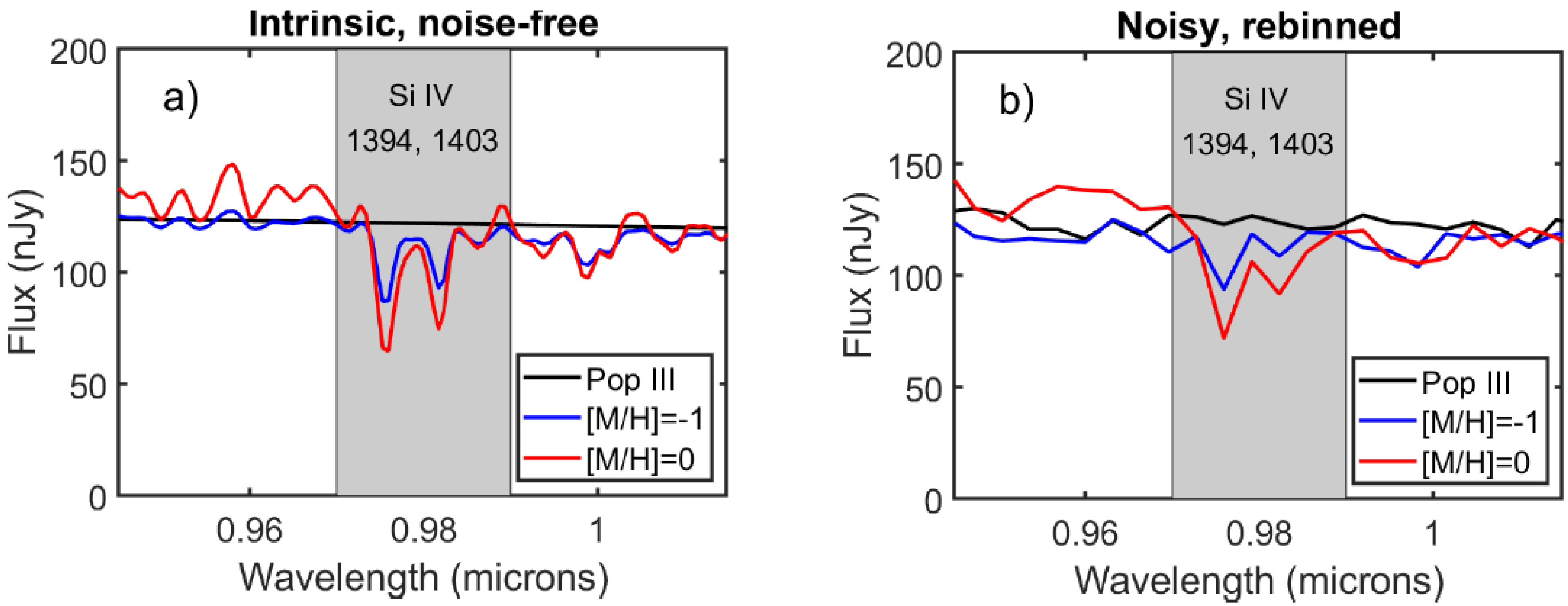
Characterizing lensed stars with JWST



Teff from photometry – easier for cool stars than hot stars

Metallicity of lensed stars from spectroscopy with JWST

Crazy-hard to even get $Z<0.1Z_{\odot}$ limits on metallicity
This is ELT territory!



26 AB mag, 30000 K star at z=6
after 100 h(!) of R~1000 spectroscopy

Pop III community input needed!

- What top-heavy IMFs can we already rule out?
- Stellar atmosphere spectra of evolved Pop III stars with surface pollution
- Stellar atmosphere spectra for rotating Pop III stars (with decretion disks?)
- Predictions on Pop III binary evolution
- HII-region evolution for late-forming Pop III stars