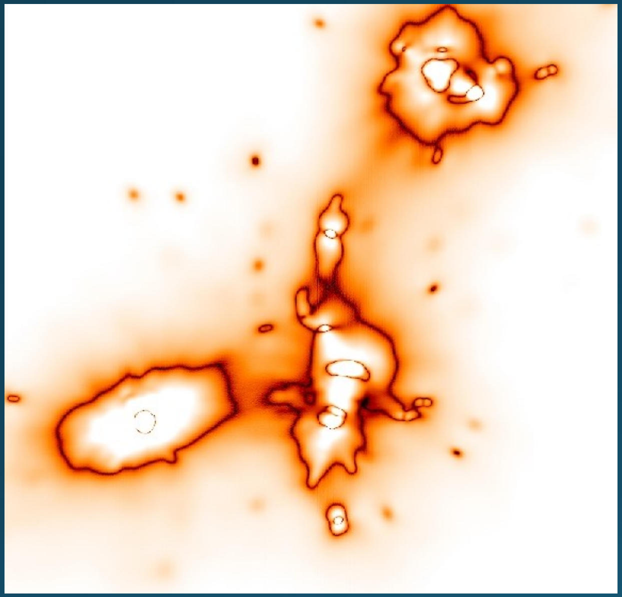
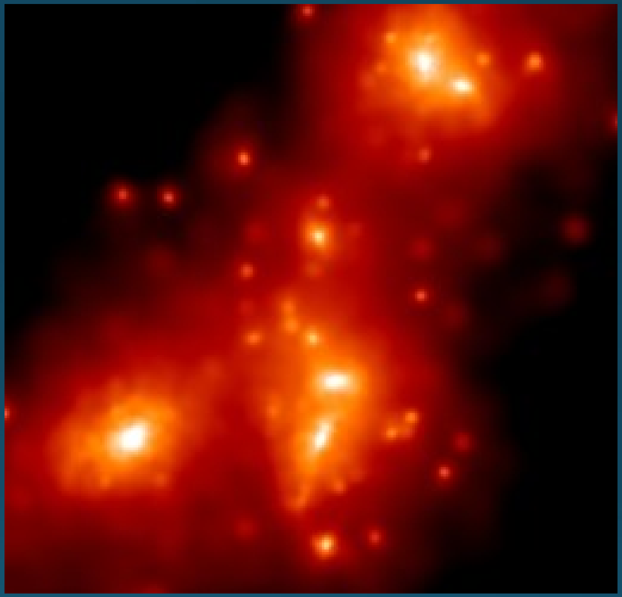
Primordial Star Clusters at Extreme Magnification





Erik Zackrisson
Stockholm University
Juan González, Simon Eriksson, Saghar Asadi,
Daniel Schaerer, Michele Trenti , Chalence Safranek-Shrader

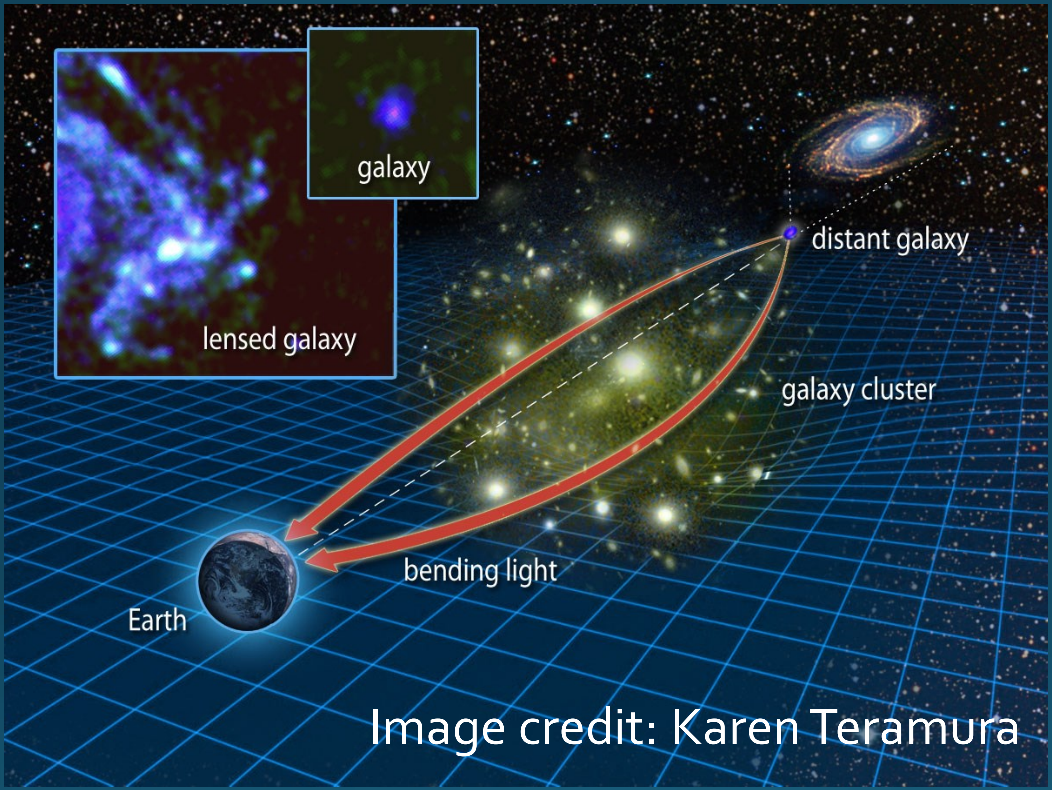
Punchline

The WISH Ultra Deep Survey may be able to detect $\sim 10^4\ M_\odot$ Population III star clusters at redshift $z > 7$ and magnification $\mu \approx 1000$

Follow-up JWST observations $\rightarrow$ IMF constraints

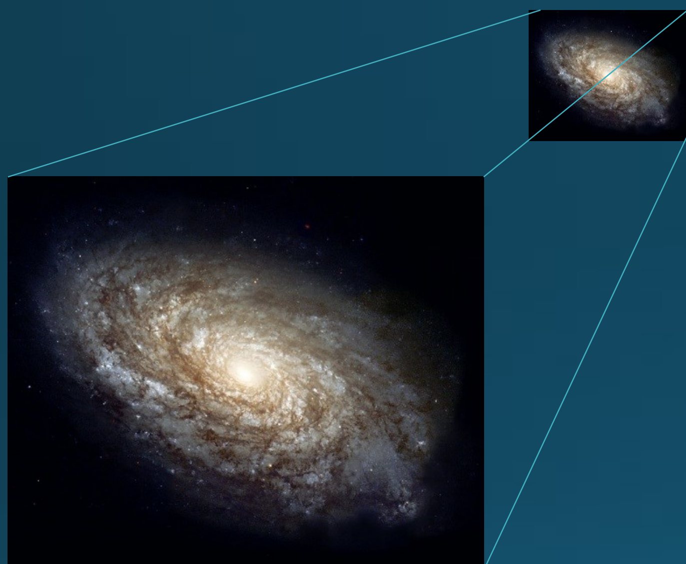
Zackrisson et al. 2014, in prep.

Gravitational lensing

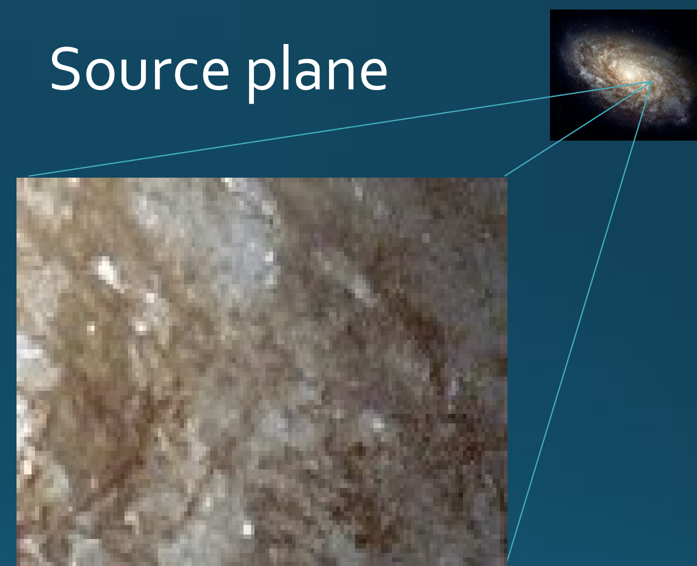


High-redshift galaxies are routinely detected with magnifications up to $\mu \approx 100$, but no higher than that. *Why not?*

Extreme magnification: size issues



$\mu \approx 10$



$\mu \approx 1000$

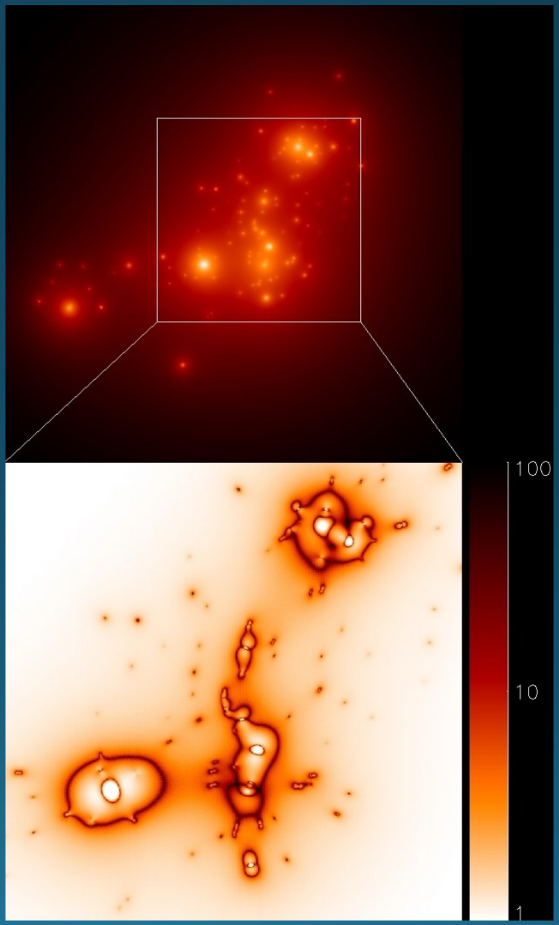
Magnification $\mu > 100$ not realistic for normal (kpc-scale) galaxies.
but for objects the size of a star cluster (<10 pc), this could work!

Extreme magnification: probability

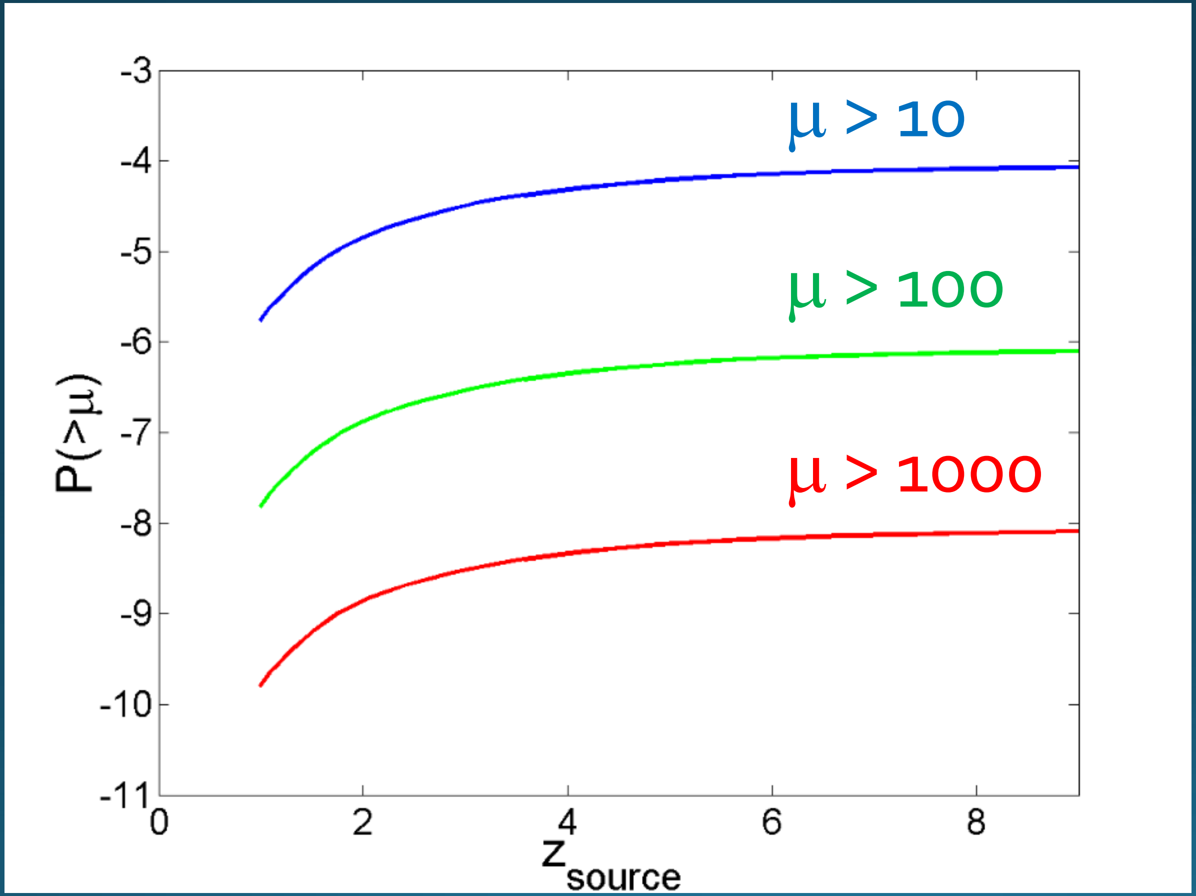
- The high magnification tail:

  $P(>\mu) \propto \mu^{-2}$

- The probability for extreme magnifications ($\mu \sim 1000$) is tiny, but with a sufficiently large survey area (WISH UDS), objects along such sightlines may still be discovered
- Ray-tracing through the Millenium simulation $\rightarrow$ $P(>\mu)$ as a function of redshift



Extreme magnification: probability



Ray-tracing through the Millenium simulation

Extreme magnification in the WISH UDS

Extreme magnifications may be relevant for objects with **small intrinsic sizes** (<10 pc) and **large number densities** at **high redshifts**

Population III star clusters!

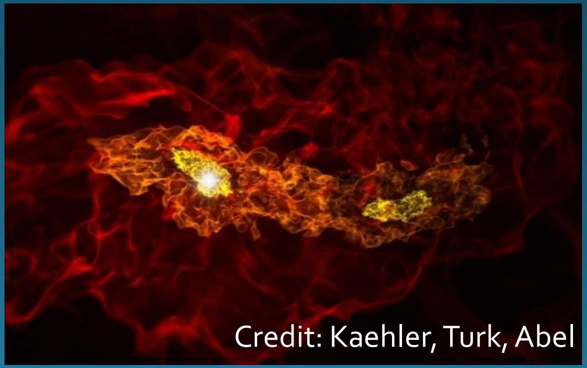
But you also need huge survey areas to find them…

The WISH 100 deg^2 UDS!

Population III stars

- First generation of stars
- Metallicity $Z \approx 0 \rightarrow$ Very hot ($T_{eff} \sim 10^5$ K)
- Start forming at $z \approx 30$, in 10^5-10^6 M_{solar} minihalos
- May continue to form until $z \approx 2$ (in 10^9 M_{solar} halos)
- Typical stellar mass ~ 10 M_{solar} (top-heavy IMF)

Key question: Can we observationally confirm that the IMF really was top-heavy?



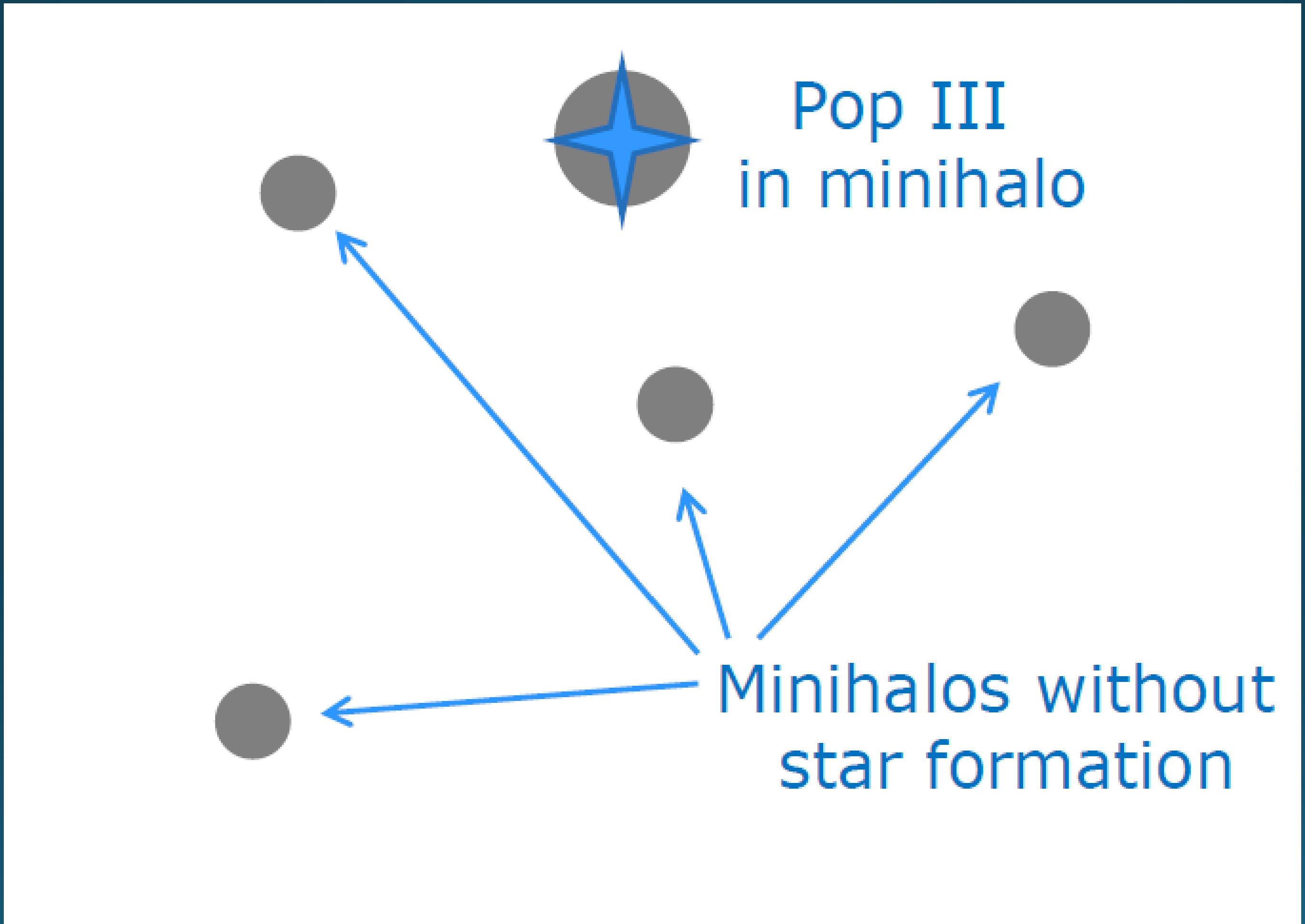
Detecting Population III stars

Individual Pop III stars in minihalos:
Undetectable even in superdeep JWST exposures of lensed fields (e.g. Rydberg et al. 2013)

Pop III supernovae:
May well be detectable with JWST and WFIRST out to $z \approx 20\text{-}30$ (e.g. Whalen et al. 2013abc) even without lensing

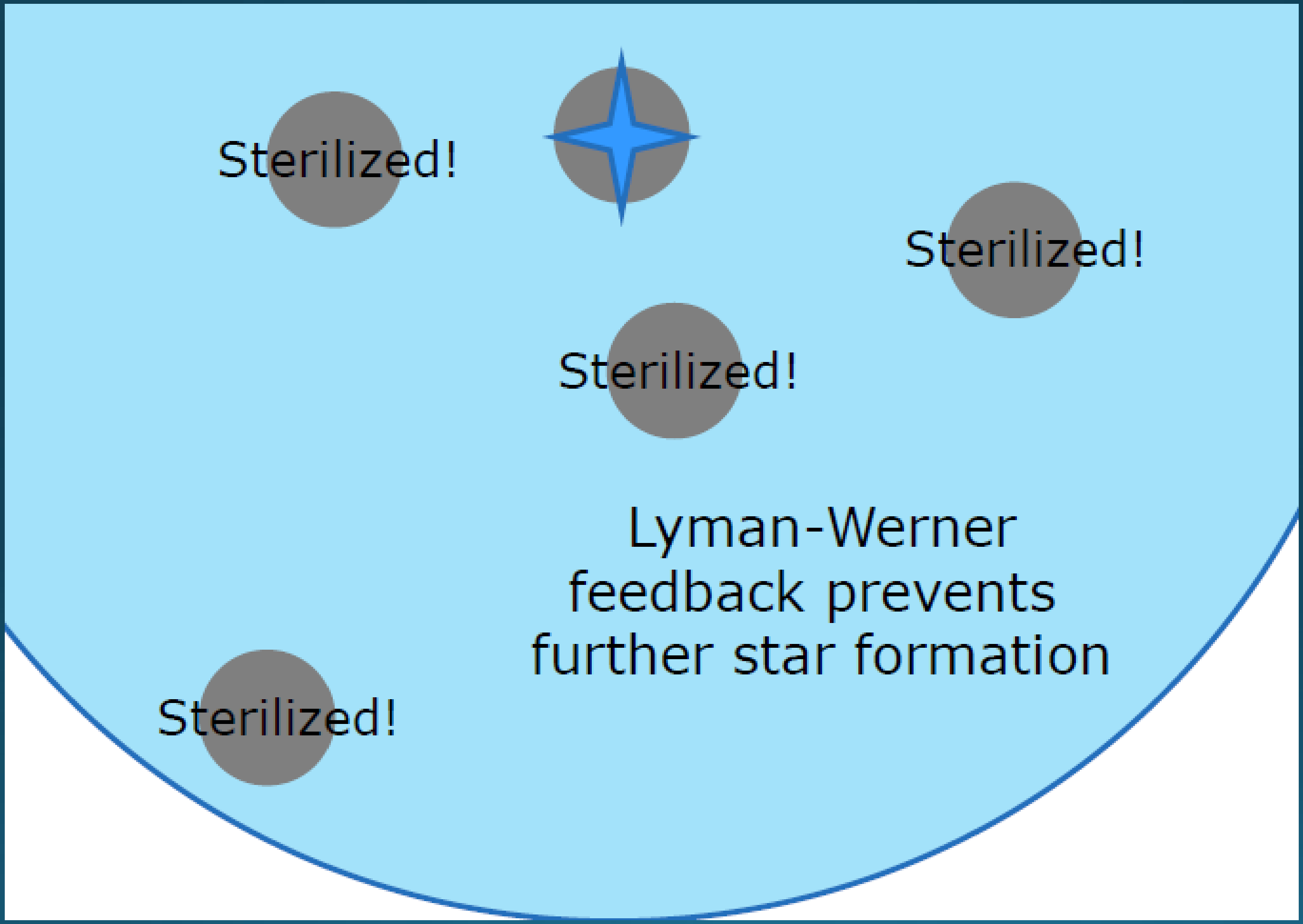
Pop III galaxies/star clusters:
May well be detectable with HST, JWST, WISH & WFIRST when lensed, but this depends on the combined mass in Pop III stars within each object (Zackrisson et al. 2012)

How to form a Pop III galaxy



E.g. Stiavelli & Trenti (2010)

How to form a Pop III galaxy



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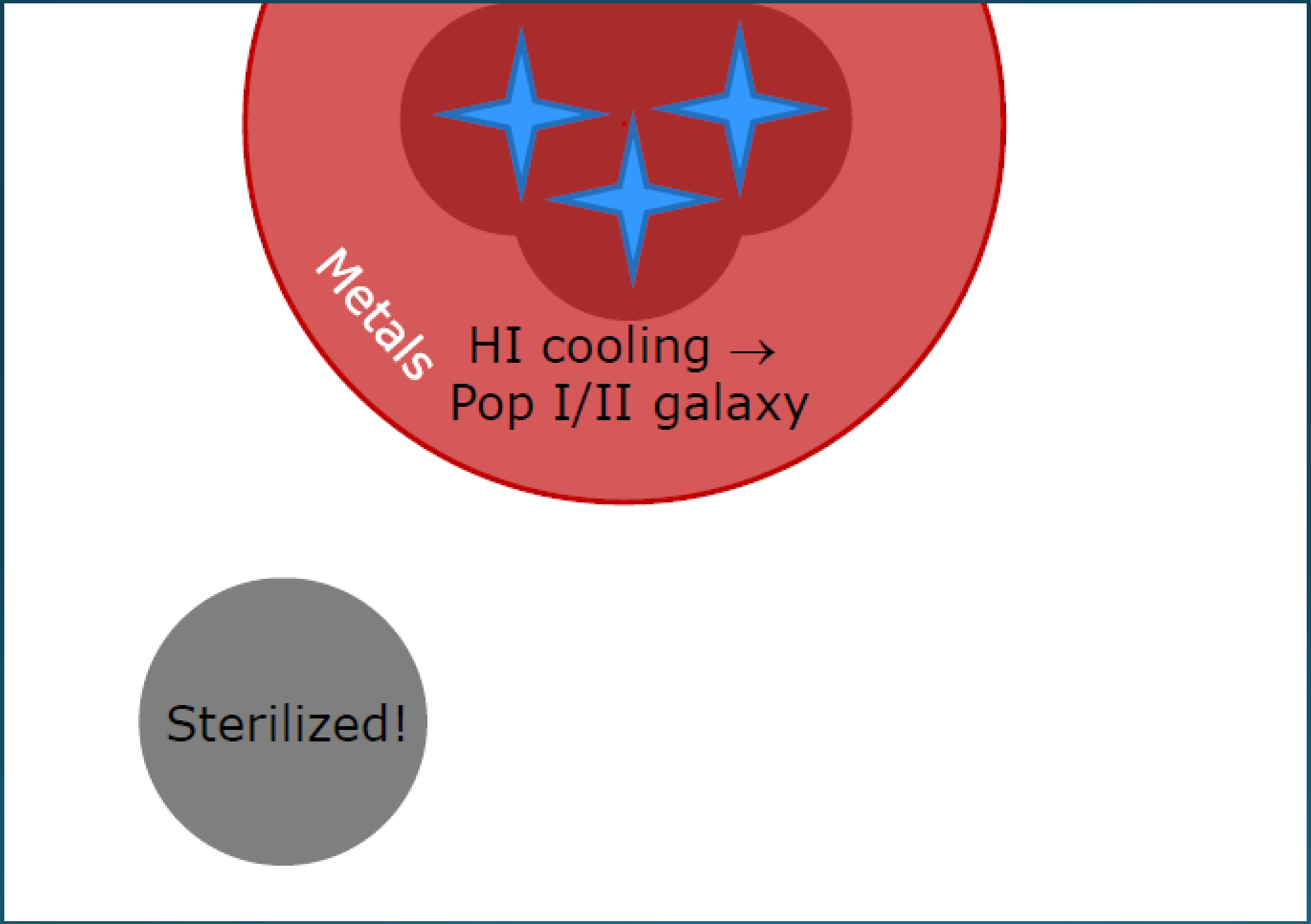

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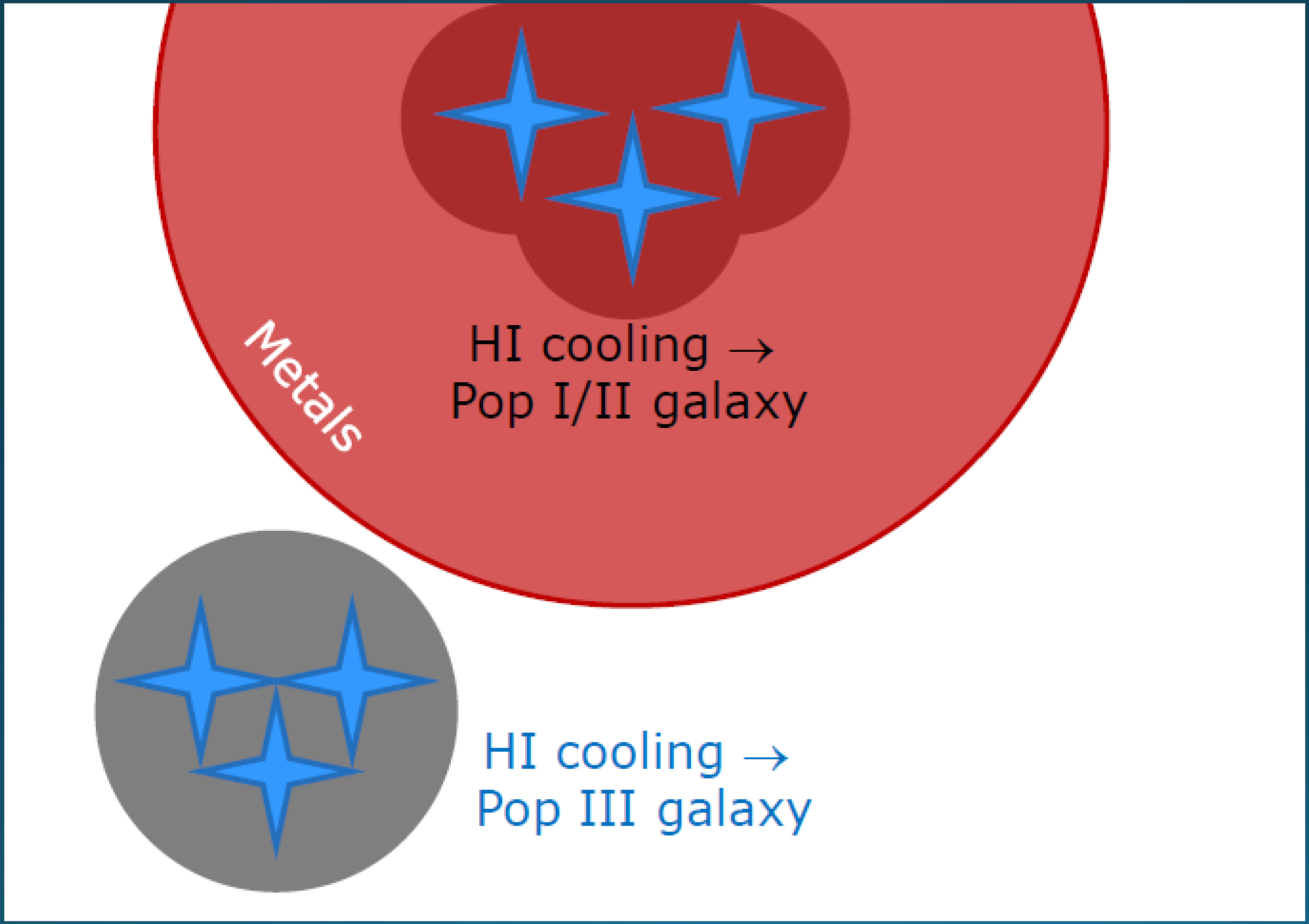
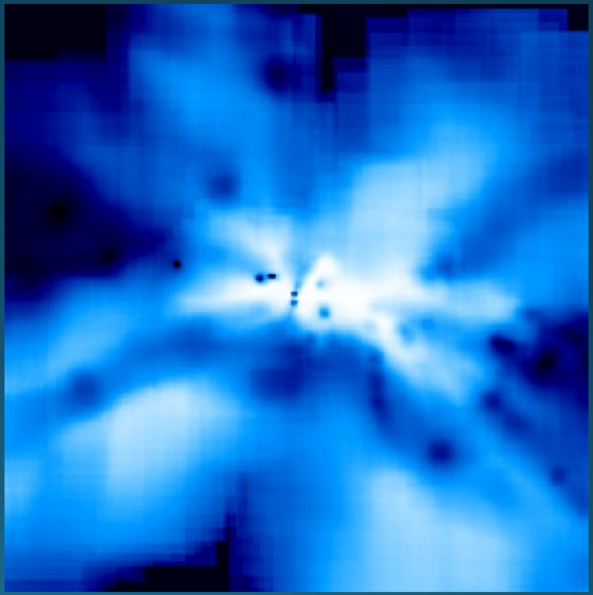


E.g. Stiavelli & Trenti (2010)

Pop III *Galaxy* or *Star Cluster*?

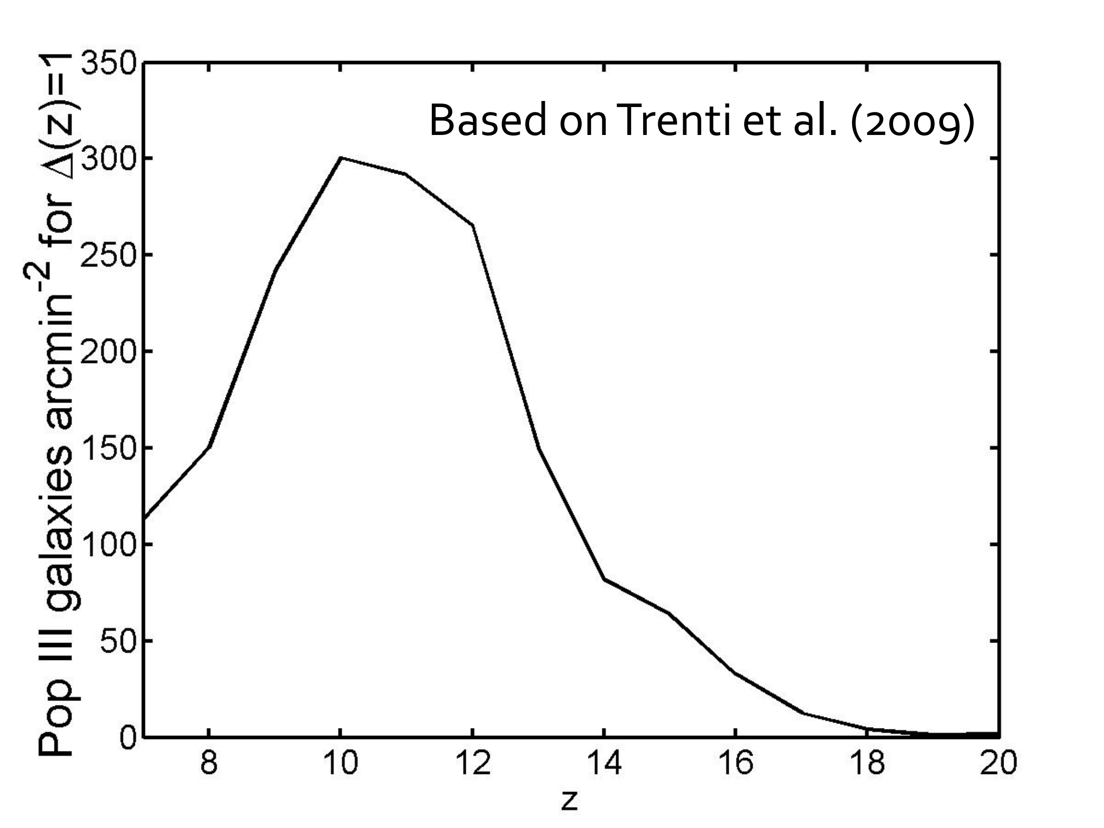
Both expressions are used, for the same type of objects…

- Sitting inside their own dark matter halos, so galaxy-like…
- But the halo mass is $\sim 10^8\ M_\odot$ at $z>7$, and with only ~0.1% of the baryons forming stars (Safranek-Shrader+12) → **Combined Pop III stellar mass: $\sim 10^4\ M_\odot$, i.e. similar to a star cluster**



Johnson+09

The predicted formation history of Pop III galaxies



Zackrisson et al. 2012, MNRAS, 427, 2212

Huge number densites but very faint → Good for lensing!

Lensed Pop III star clusters

No lensing

Central star cluster (≈ 10 pc)

Nebula (≈ 1 kpc)

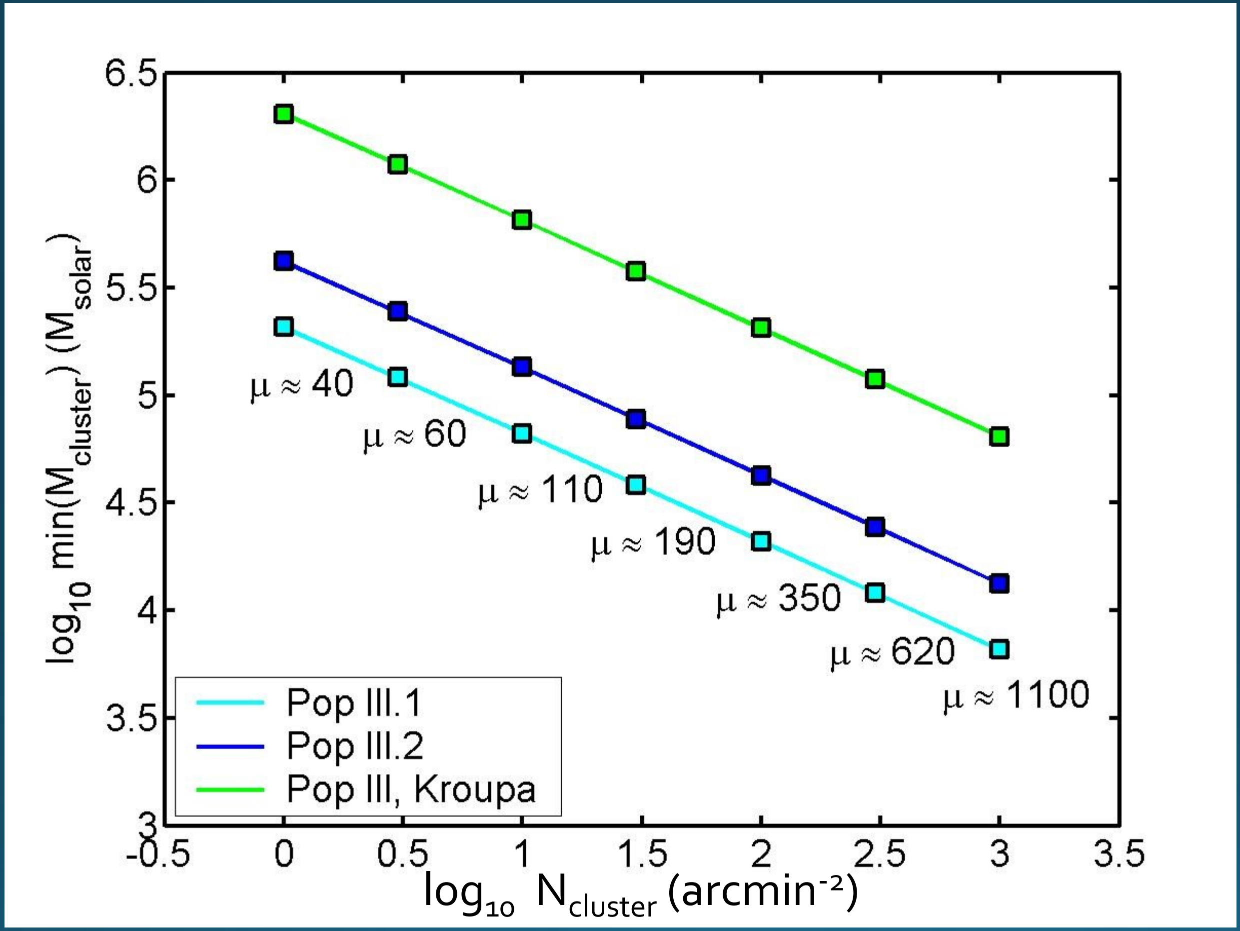
Both components largely unresolved (and blended) with WISH/JWST

Extreme magnification

μ ≈ 1000 but still unresolved

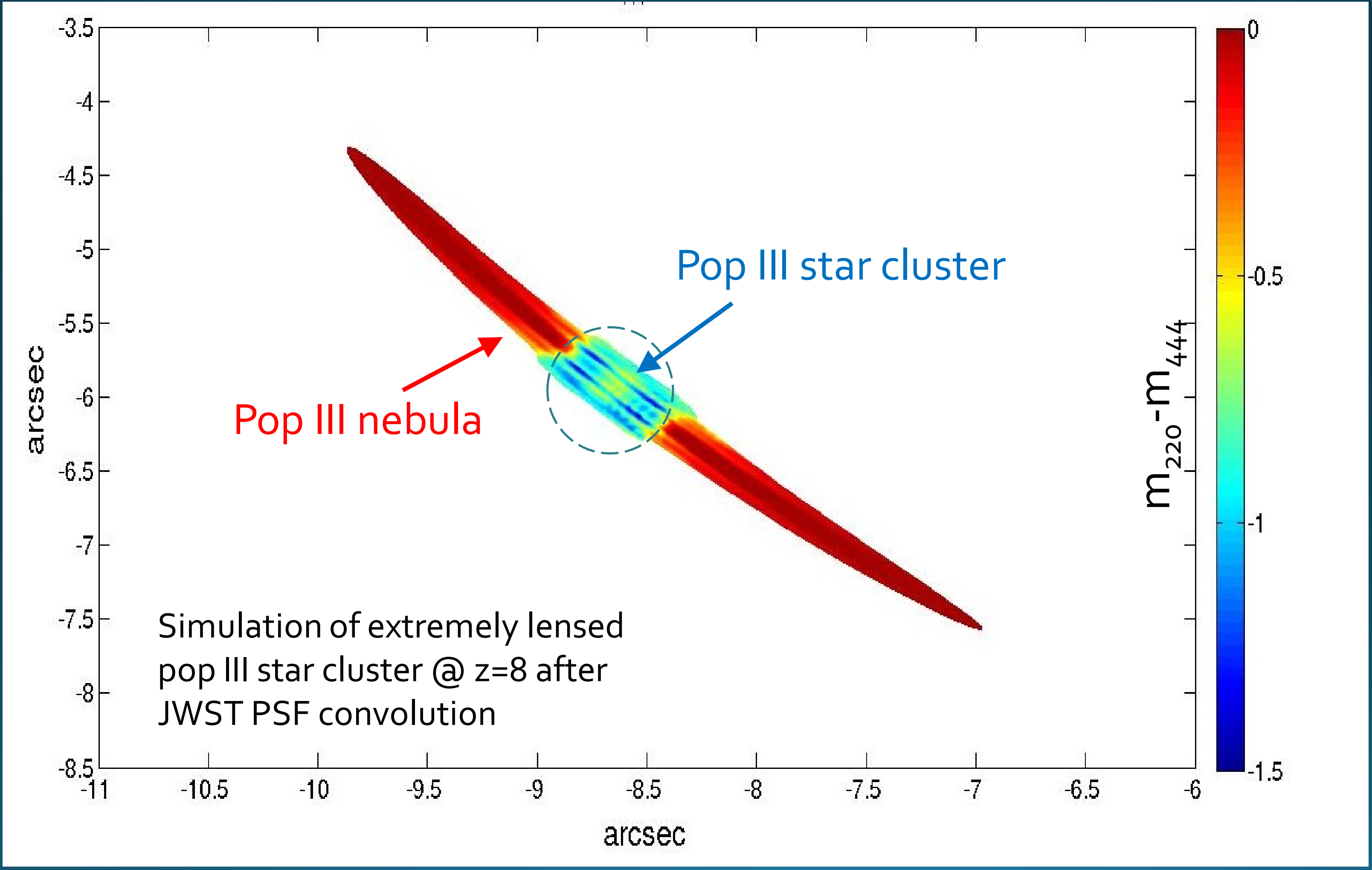
μ << 1000, huge, resolved arc

Conditions for detection in the WISH UDS



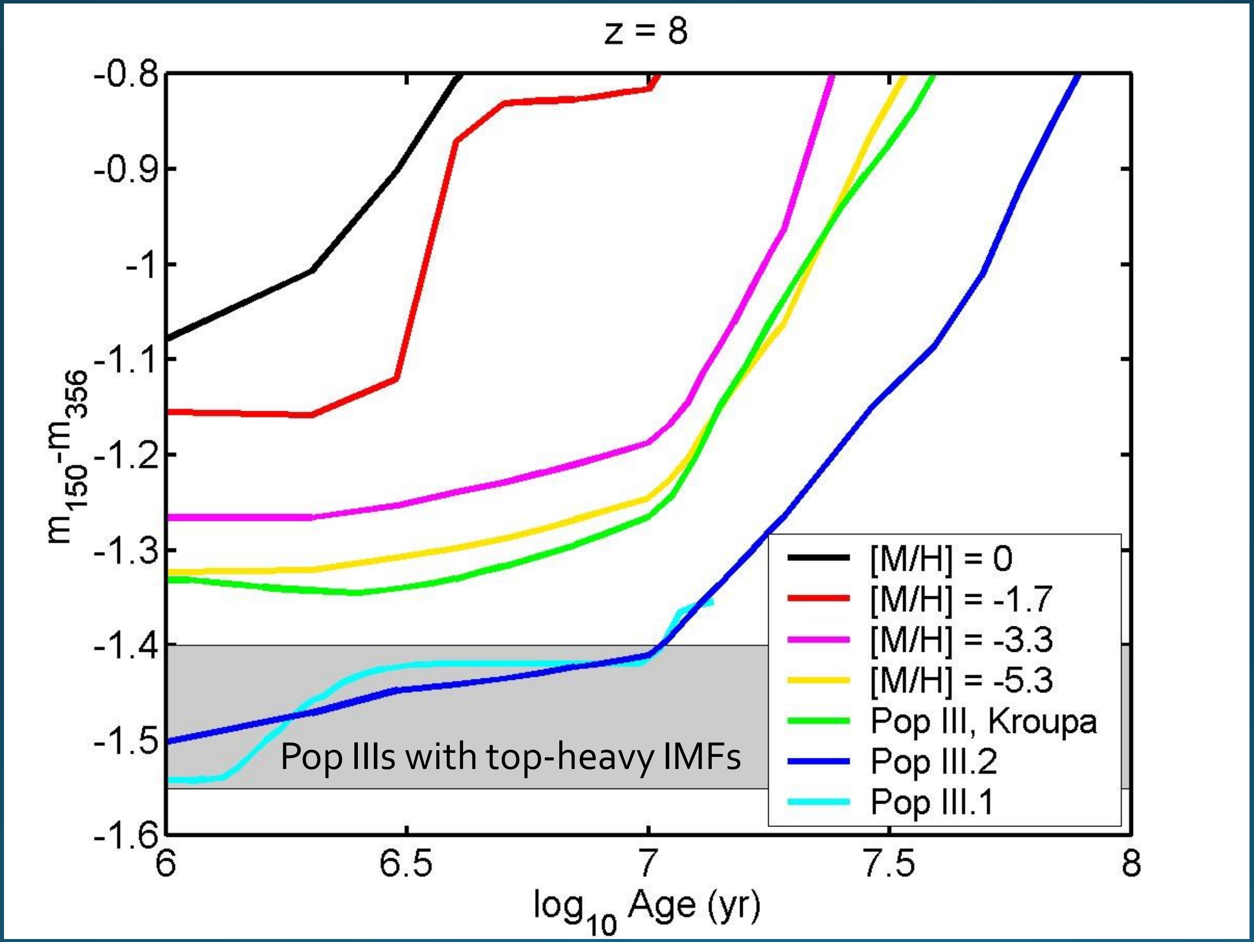
If these Pop III star clusters have small sizes (<10 pc), top-heavy IMFs and $M_{stars} \sim 10^4\ M_\odot$ in Pop IIIs, a handful may appear above the 5σ , m_{AB}<27.5 limit of the WISH 100 deg² UDS at μ ≈ 300-1000

JWST follow-up imaging



Probing the Pop III stellar IMF

"UV slope β"



10 Myr burst of constant SFR

JWST colour measurement towards central star cluster → Possible to confirm top-heavy IMF

- Pop I, II, III stars
- Nebular emission (Cloudy)
- Rest-frame SEDs (far-UV to near-IR)
- SDSS/HST/Spitzer/JWST/ WISH broadband fluxes @ z = 0-15

The Yggdrasil code

A spectral synthesis model for the first galaxies

Model grids available at: www.astro.su.se/~ez

Zackrisson et al. 2011, ApJ, 740, 13

Caveats

- Requirements to find these objects in the WISH 100 deg^2 UDS:

Typically ~10^4 $M_\odot$ of Pop III stars has to form in R<10 pc star clusters (provided that the IMF is reasonably top-heavy)

- Requirement to probe the Pop III IMF with JWST imaging:

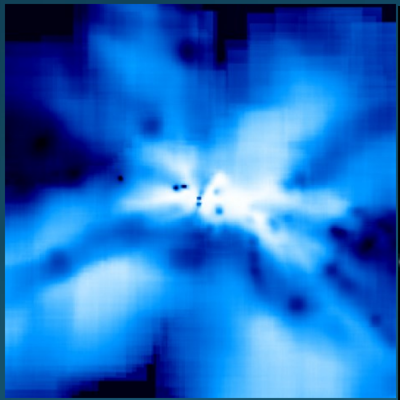
The nebular emission cannot be too centrally peaked, or the colour measurement may underestimate how top-heavy the IMF really is

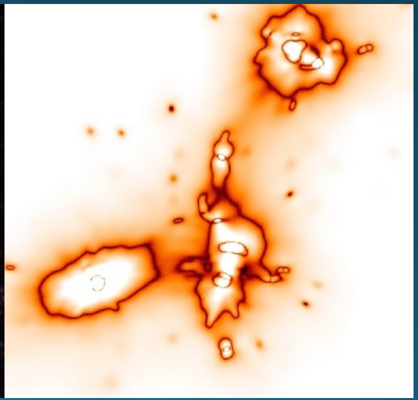
- Contaminants:

Foreground stars superposed on high-redshift arcs

Summary

- WISH has the potential to detect gravitationally lensed Population III star clusters at extreme magnifications
- Follow-up observations with JWST may constrain the Population III stellar initial mass function





Nebular emission made simple