Following the Pristine Gas: The Pop III/II transition

JINA-CEE - *Gala of GALAH*

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Motivation

Understand & characterize the transition from Pop III to Pop II star formation

- No Pop III stars observations!

Near-field cosmology/Stellar archeology... & simulation

- Pop III – Progenitors of the *first* metals
- Link elemental abundances in Carbon-Enhanced Metal-Poor (CEMP-no) stars to Pop III progenitor
- Characteristic mass, *IMF*

- *Sneak-peek? (CEMP-r)*

Cosmological simulations

Simulating a chunk of the universe…

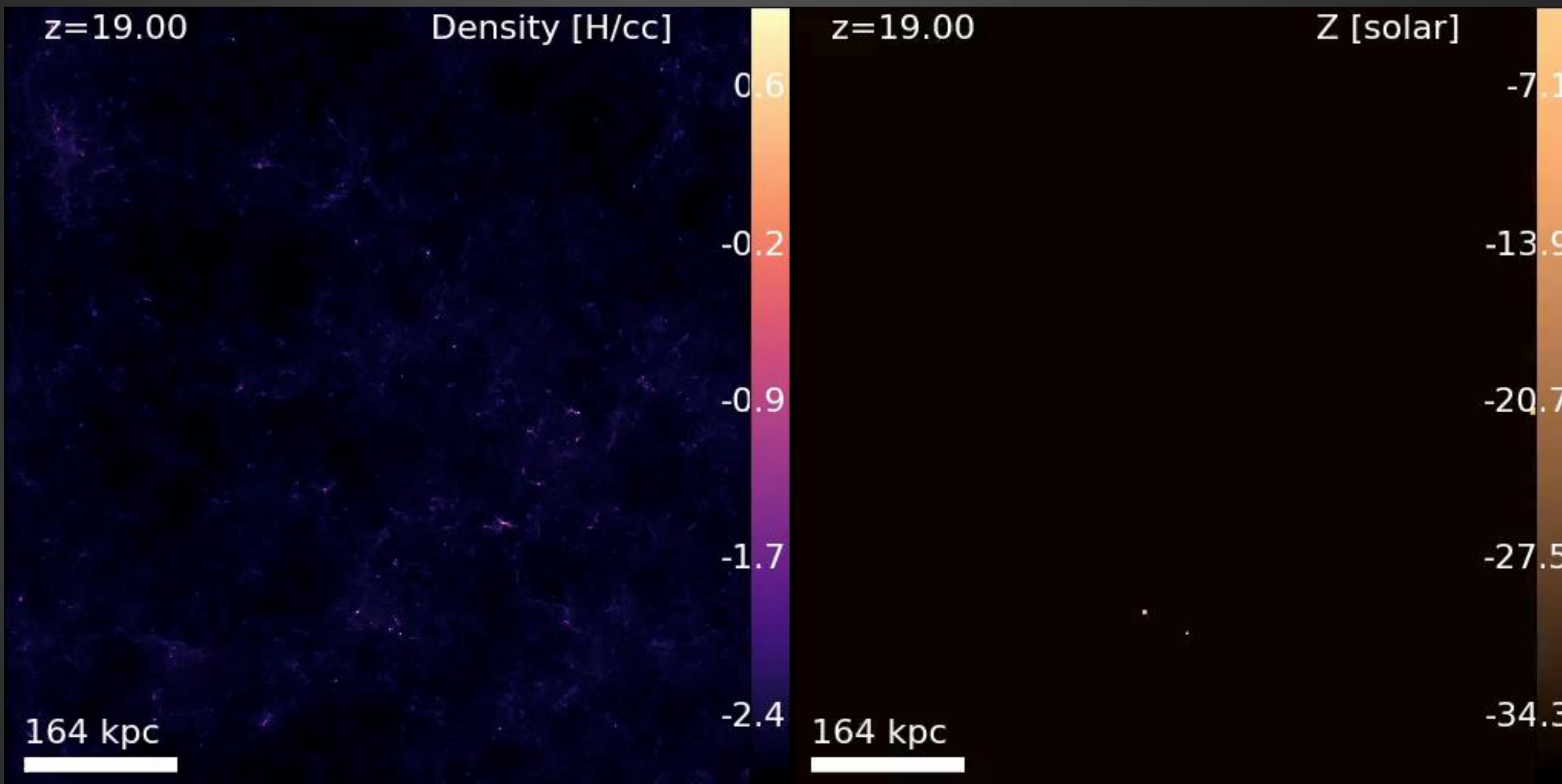
- Self-gravitating fluid dynamics with AMR
  - Cells model the gas
  - Particles model stars and DM
  - Star (particle) formation
  - Supernova feedback
- Setup
  - $(17\ \mathrm{Mpc})^3$, 1024^3 cells ➔ 16 kpc init grid resolution
  - 65 pc resolution (cmv)
  - $M_{DM} = 5.59 \times 10^5\ M_\odot$, 10^9 DM particles
  - $3.2 \times 10^3 < M_{SP}/M_\odot < 6.3 \times 10^4$ – each SP is an IMF of stars
  - $Z_{crit} = 10^{-5}\ Z_\odot$

Refine cells as they become over-dense

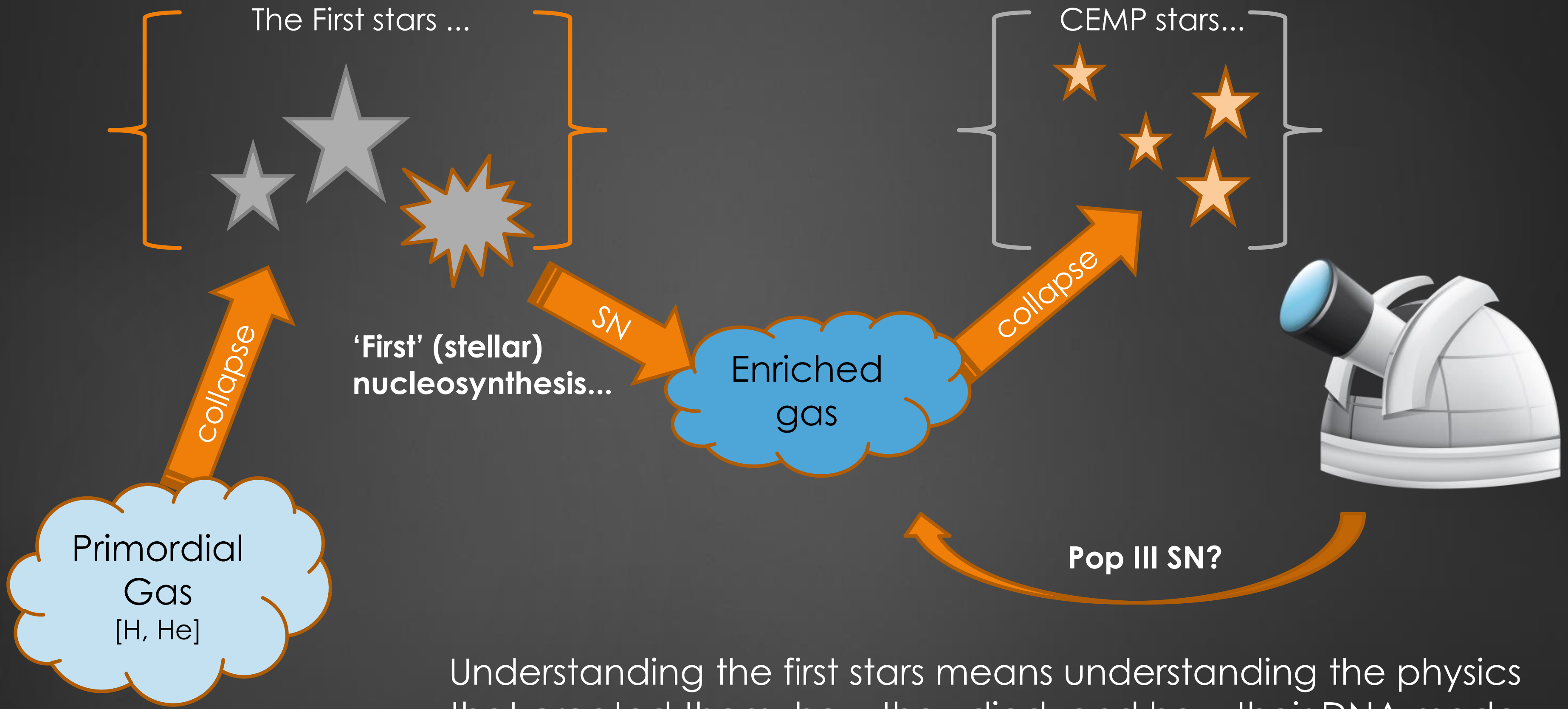
440,000 CPU-hours ➔ z=6.6

50 CPU-years

Projected Density & Z



The Story to date...



Understanding the first stars means understanding the physics that created them, how they died, and how their DNA made its way into the second generation of stars (that we can see).

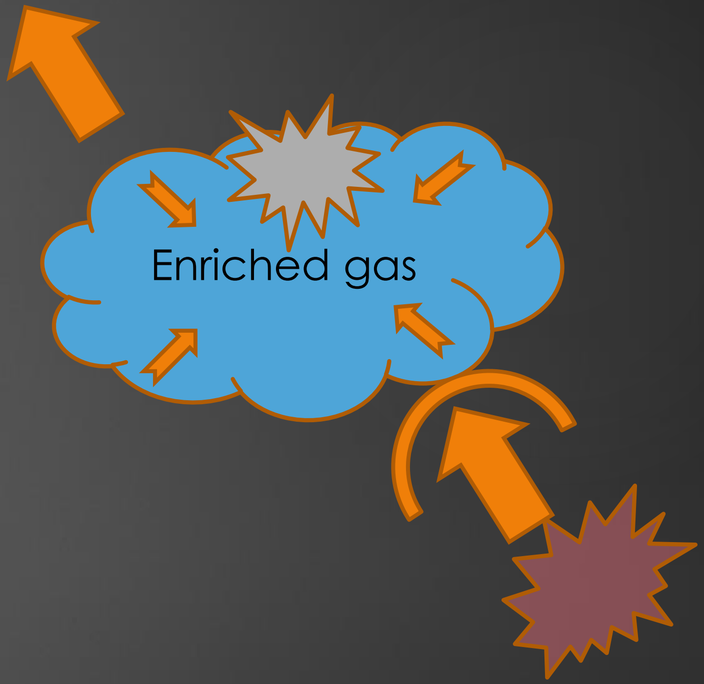
Modeling Considerations

Critical metallicity

- $Z > Z_{crit}$

Mixing of metals in the ISM

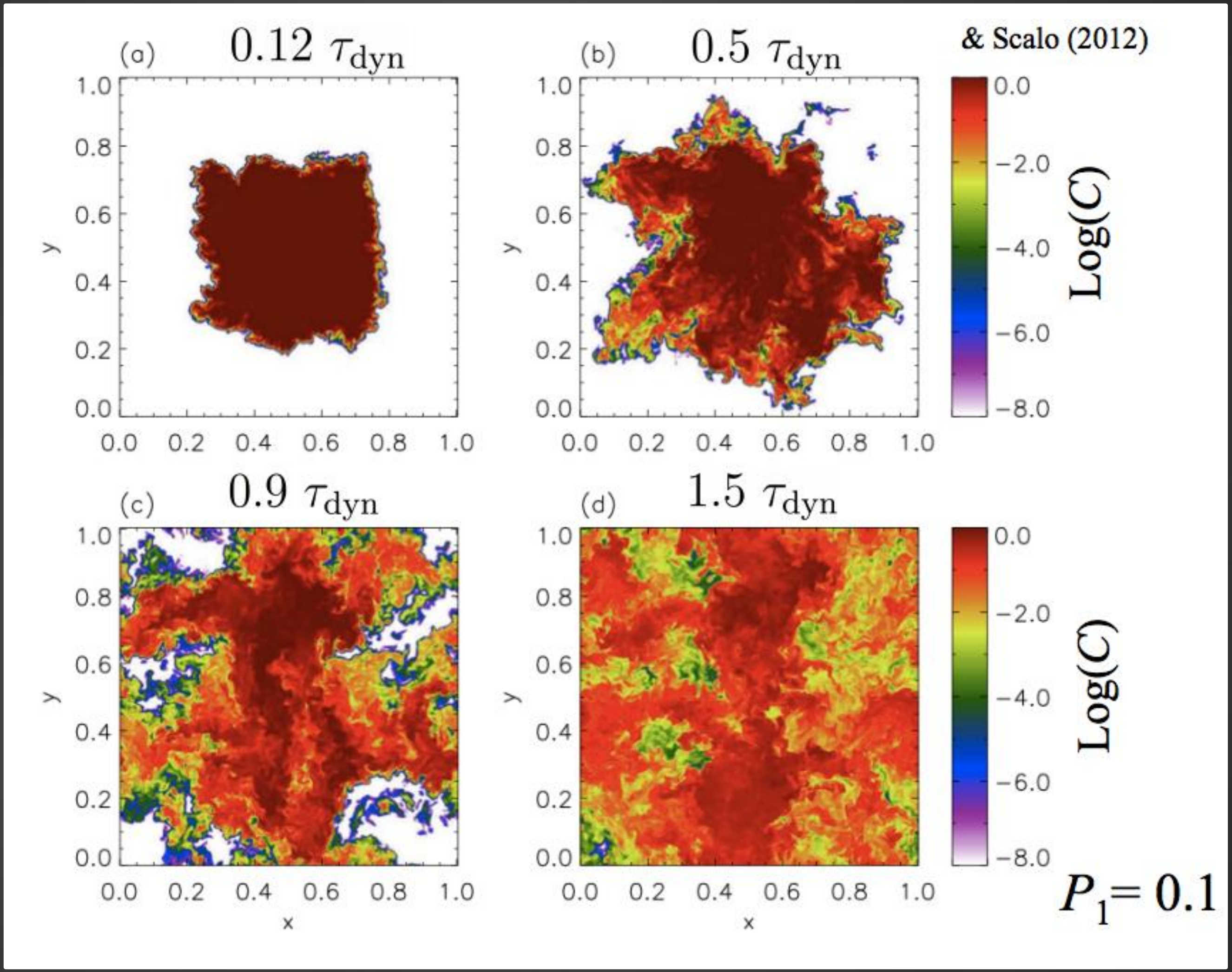
- SN rate & ejecta (metal) mass
- Gravity
- Hydrodynamic flow



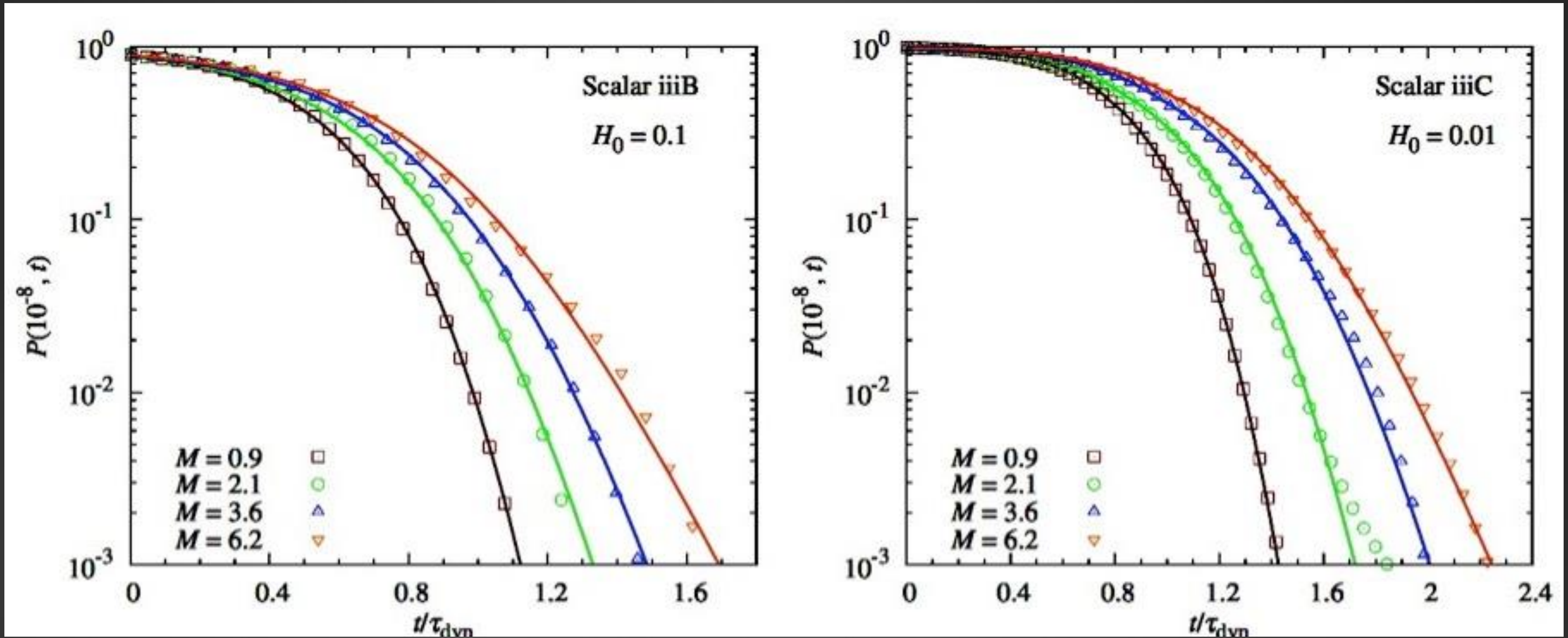
Additional Factor - Small Scale Mixing

Typically a problem in cosmo sims… scale disparity ~10^6

Mixing…



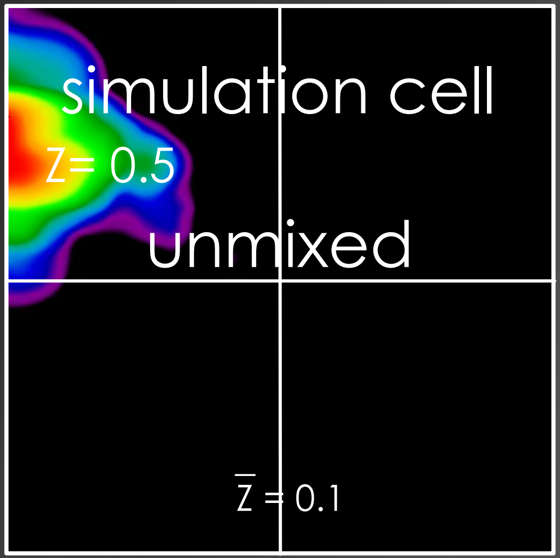
Pan, ES, & Scalo (2012)



$$\frac{dP}{dt} = -\frac{n}{\tau_{\rm con}} P(1 - P^{1/n}).$$

Pan, ES, & Scalo (2013)

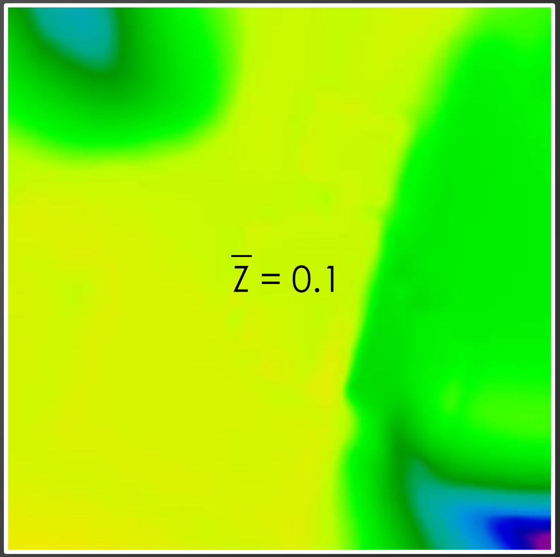
Corrected Metallicity



f_{pol} = 0.2

$$f_{\rm pol} \equiv 1 - P,$$

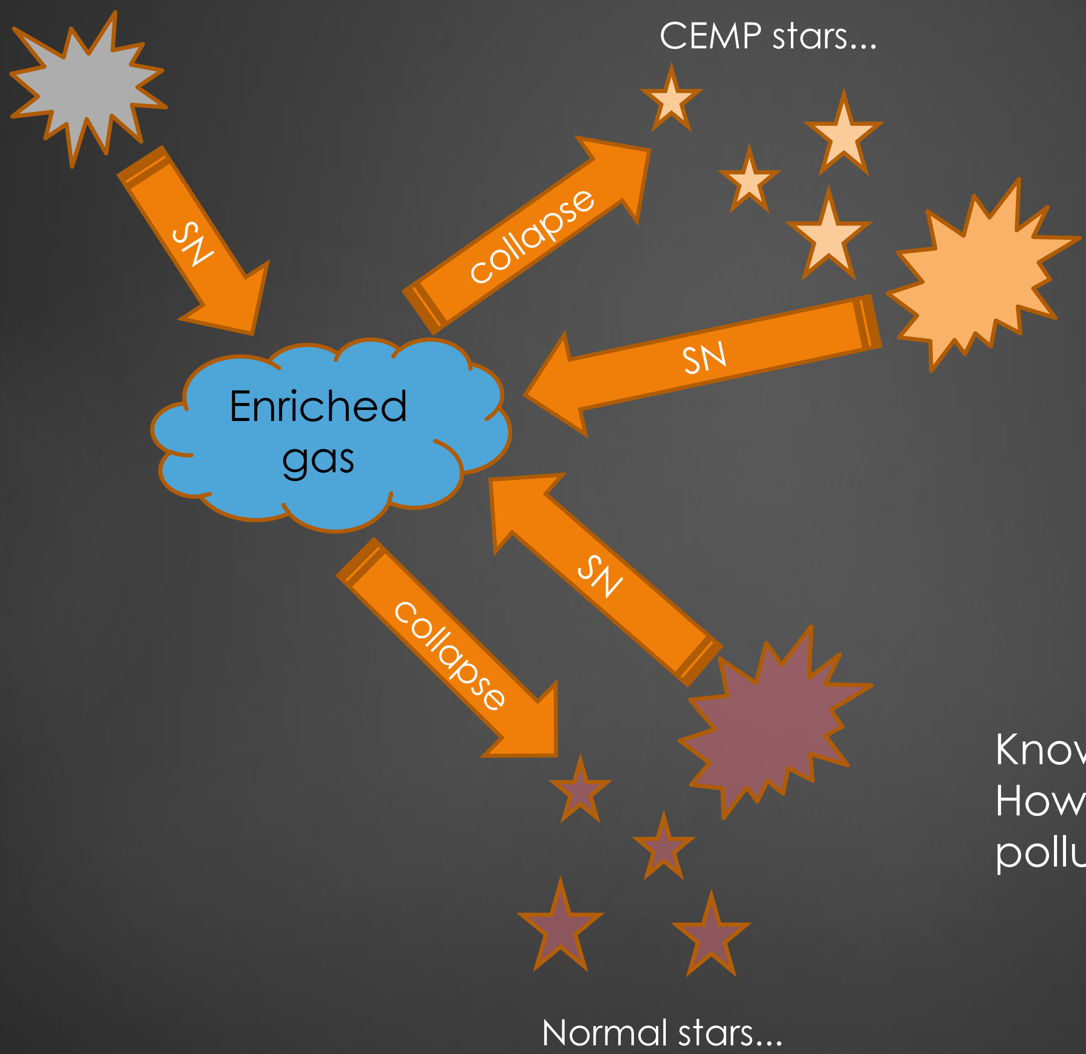
f_{pol} = 1



$$Z \equiv \frac{\overline{Z}}{f_{\rm pol}},$$

Trying to correct for incomplete mixing

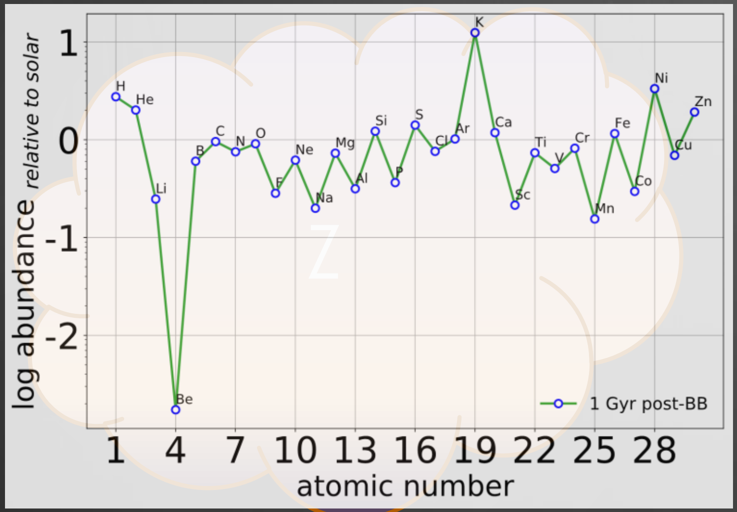
Identifying CEMP-no stars



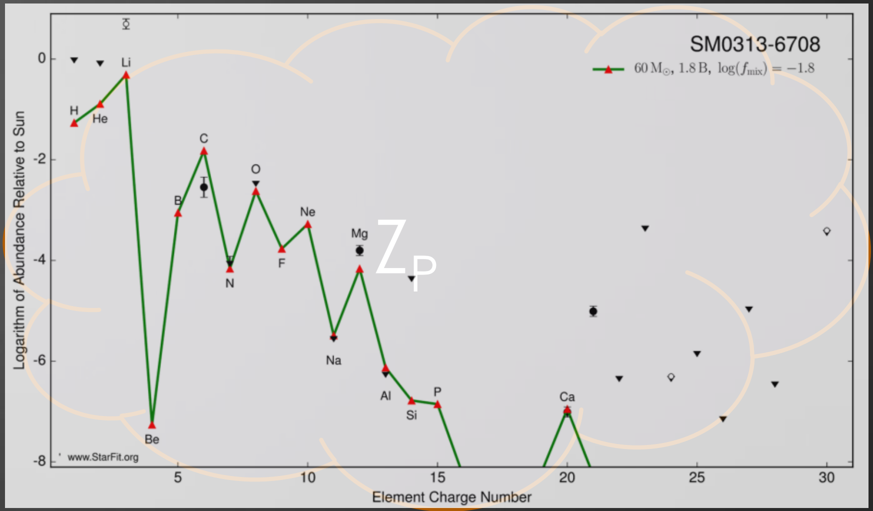
Knowing Z isn't enough ...
How to identify stars that are polluted with ONLY Pop III ejecta?

Track 2 kinds of metals…

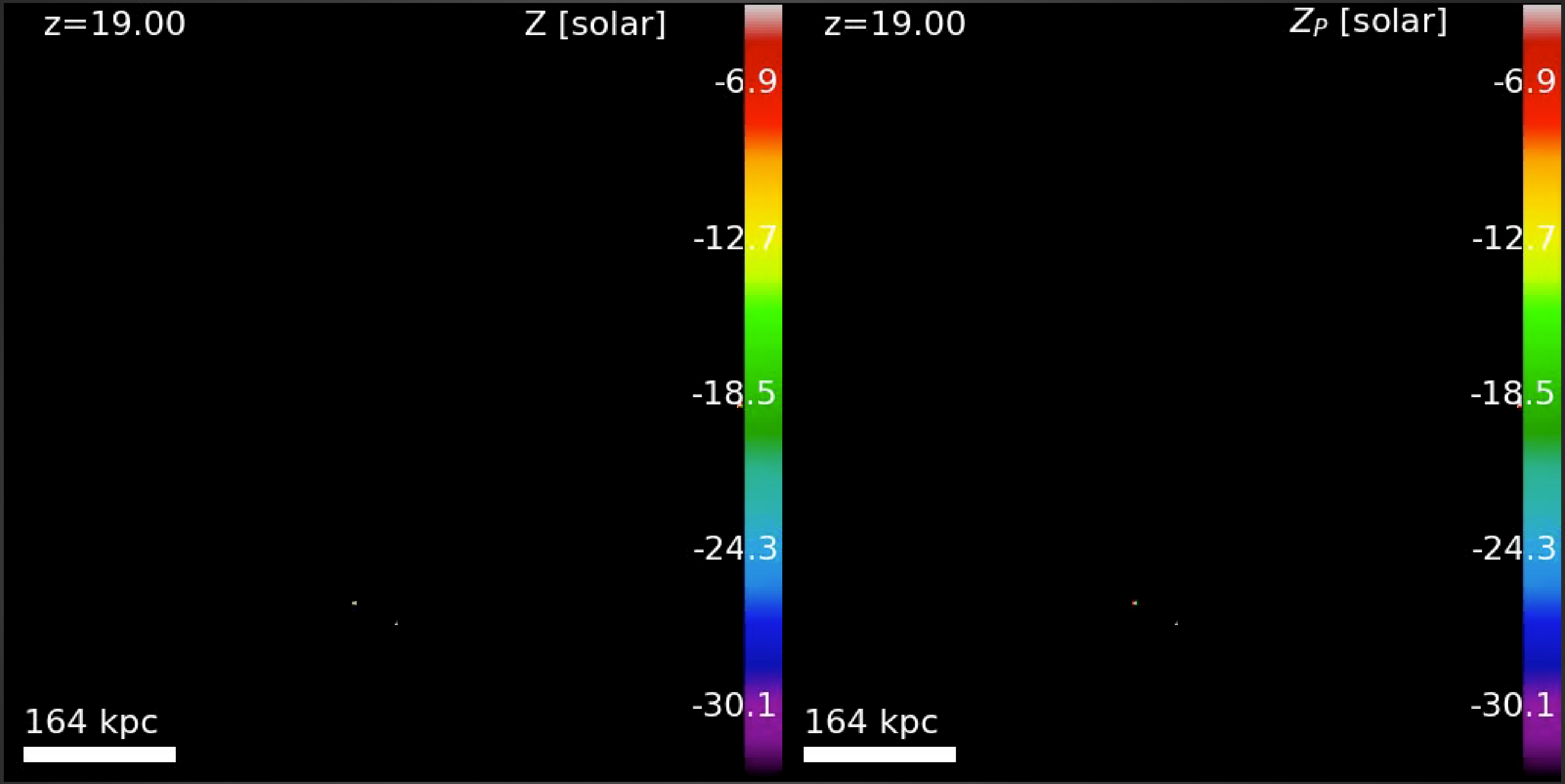
- Elemental yields from Pop III SN vs Pop II
  - CEMP abundances likely due to subset of Pop III SN
- Ratio, in each star particle, is important for understanding the final chemical composition stars
  - $\frac{Z_P}{Z} \cong 1$ → CEMP-no



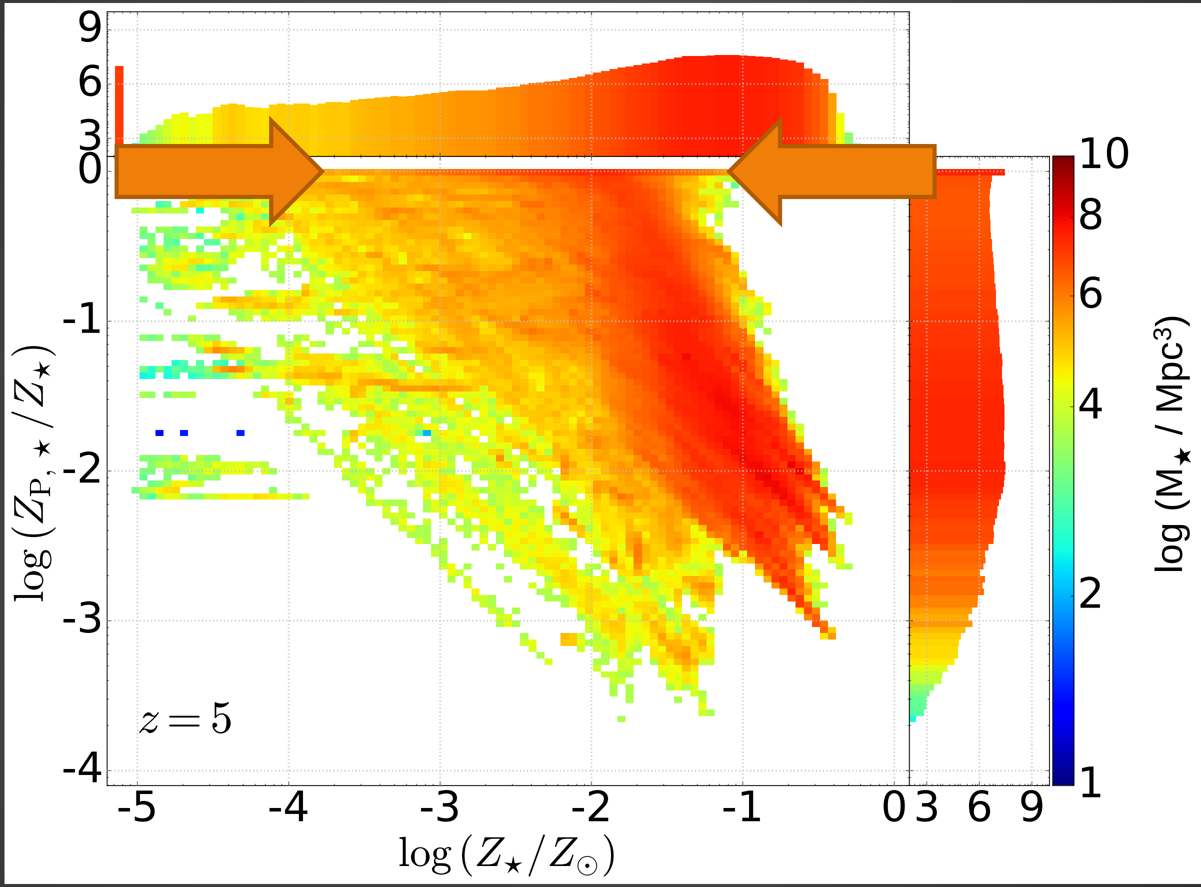
Z - Z_P



Timmes, 2015, Heger, StarFit 2016

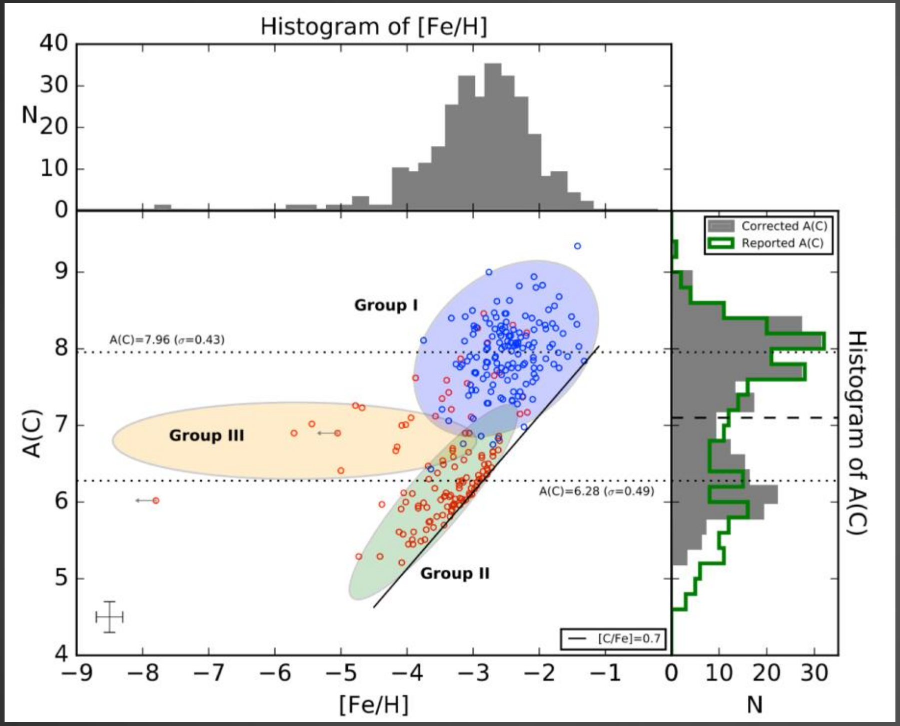

z=19.00
Z [solar]
-6.9
-12.7
-18.5
-24.3
-30.1
164 kpc
z=19.00
Z_P [solar]
-6.9
-12.7
-18.5
-24.3
-30.1
164 kpc

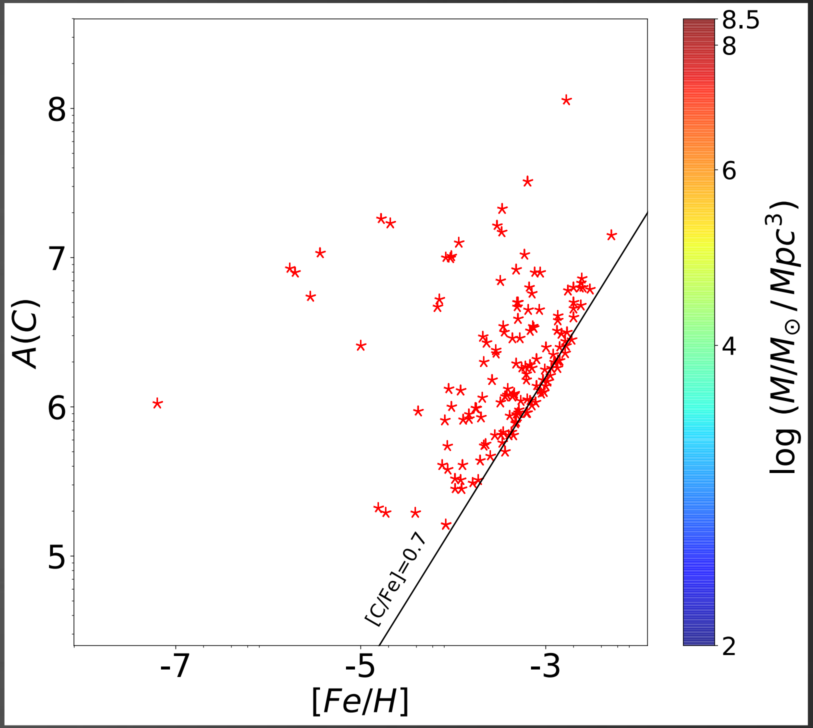
Chemical composition...



Sarmento et al., 2017a

Compare to Observations





Observations of CEMP-no stars
(red circles)

$A(C) = \log(N_C/N_H) + 12$
$A(C)_\odot = 8.43$

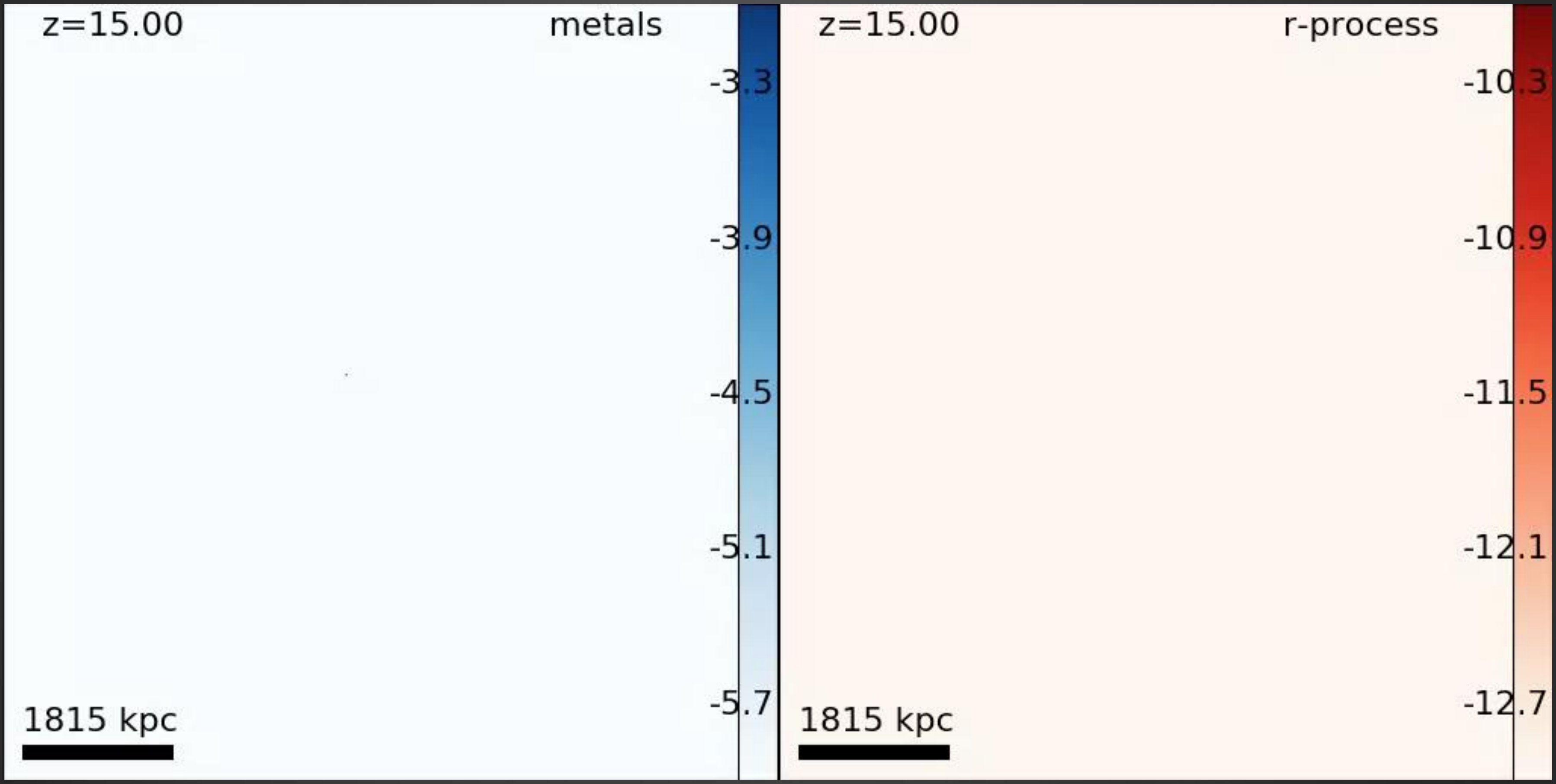
Simulation Stars
Z_P = 60 $M_\odot$ SN abundances
Z = 'gas at z=5'

Yoon et al. 2016 Heger (StarFit) 2016, Timmes, 2016 Sarmento et al., 2017b

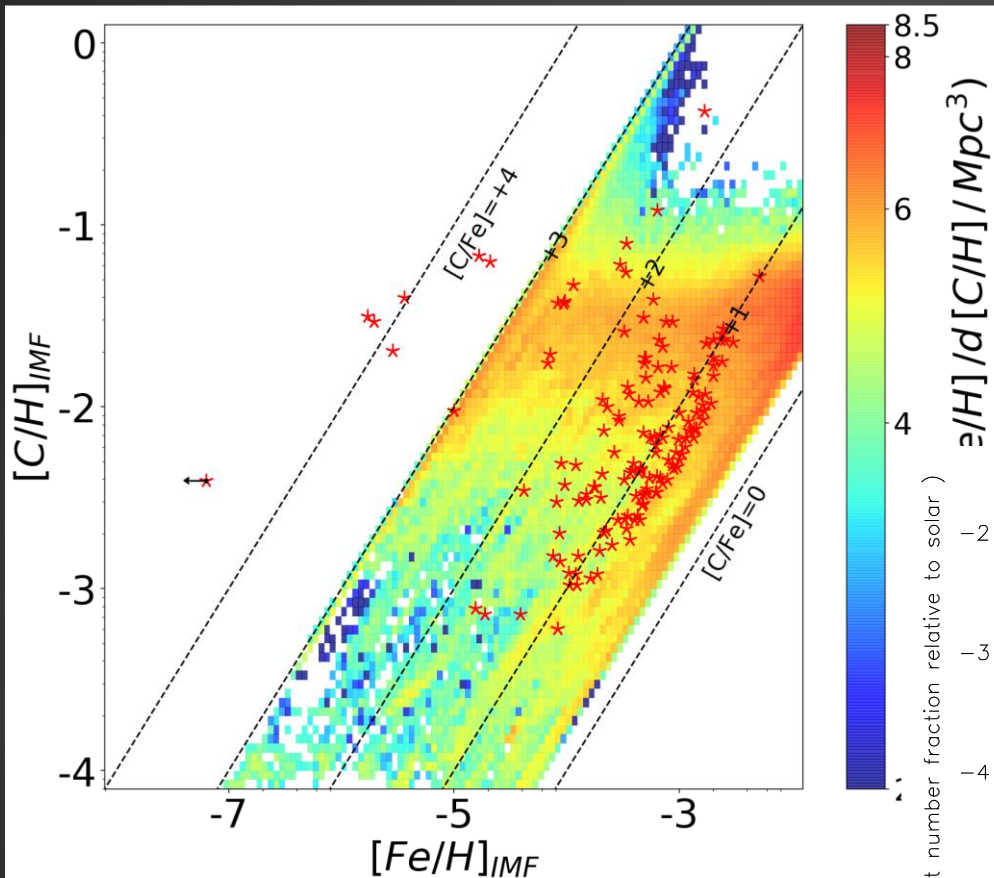
Summary

- Inexpensively track fraction of pristine gas at subgrid scales
  - Improved Pop III SFRD model
- Efficiently track two kinds of pollutants with different characteristics -
  - Far less cost than following detailed chemical evolution – still evaluate specific yield models
  - Quickly determine which progenitor models show promise wrt observations.
    - Need large Fe to C spread to explain observations... of lowest Z CEMP-no stars
- **Future work –**
  - Parameter study
    - **SN energy**, SN energy partition, SN mass loading, Z_{crit}
  - What else could produce those abundances? (Spin stars, Low-mass Pop III companion, etc.)

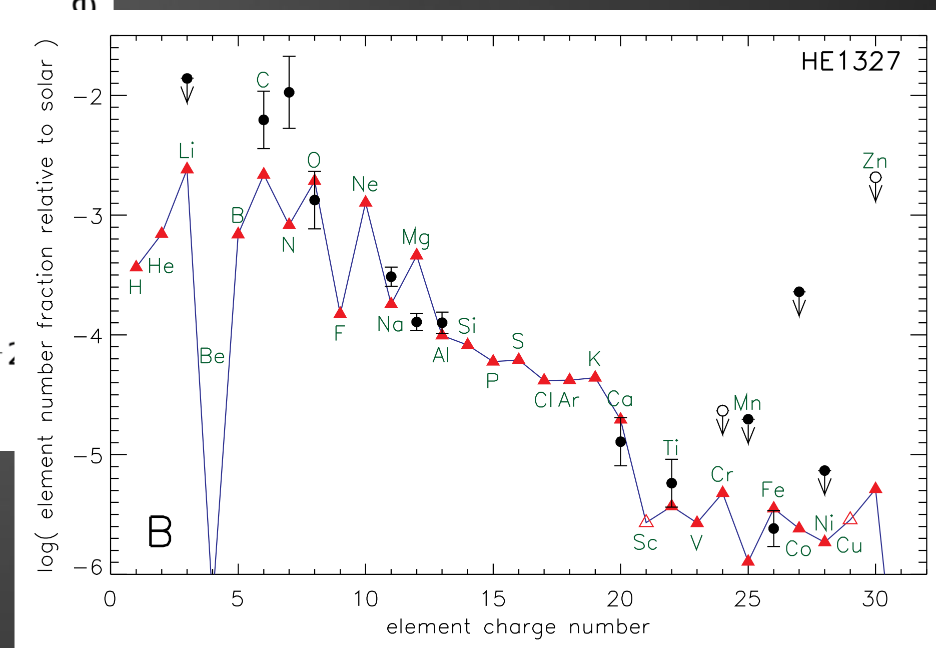
Following the r-process enhancement of the IS/GM



20-100 M⊙ IMF progenitors

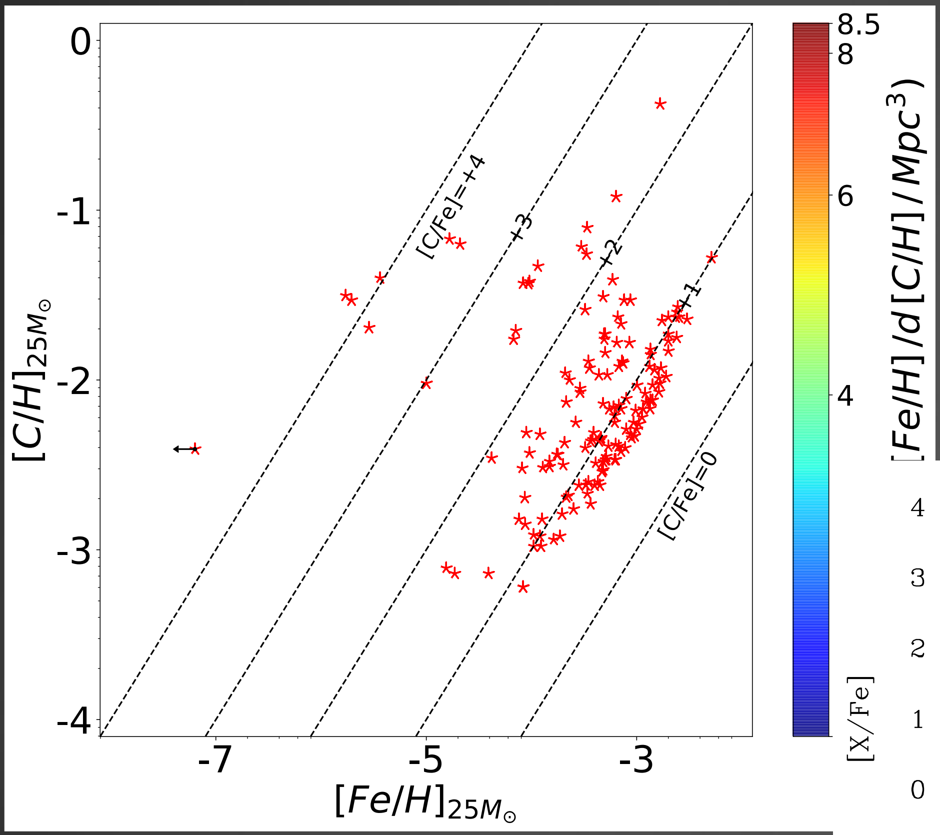


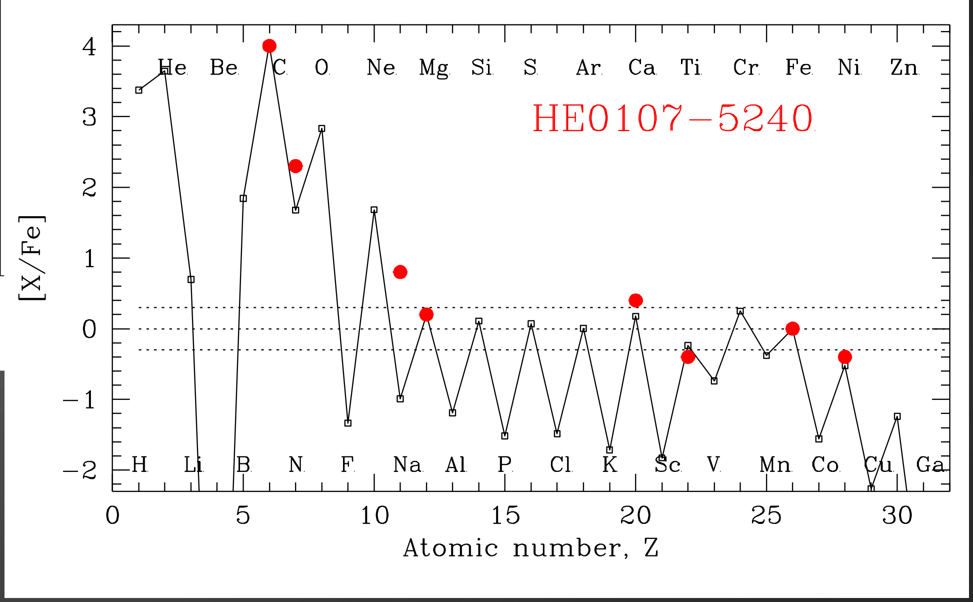
IMF M = 20 − 100 M⊙, Γ = 1.350, E = 1.2 B



Heger & Woolsey, 08

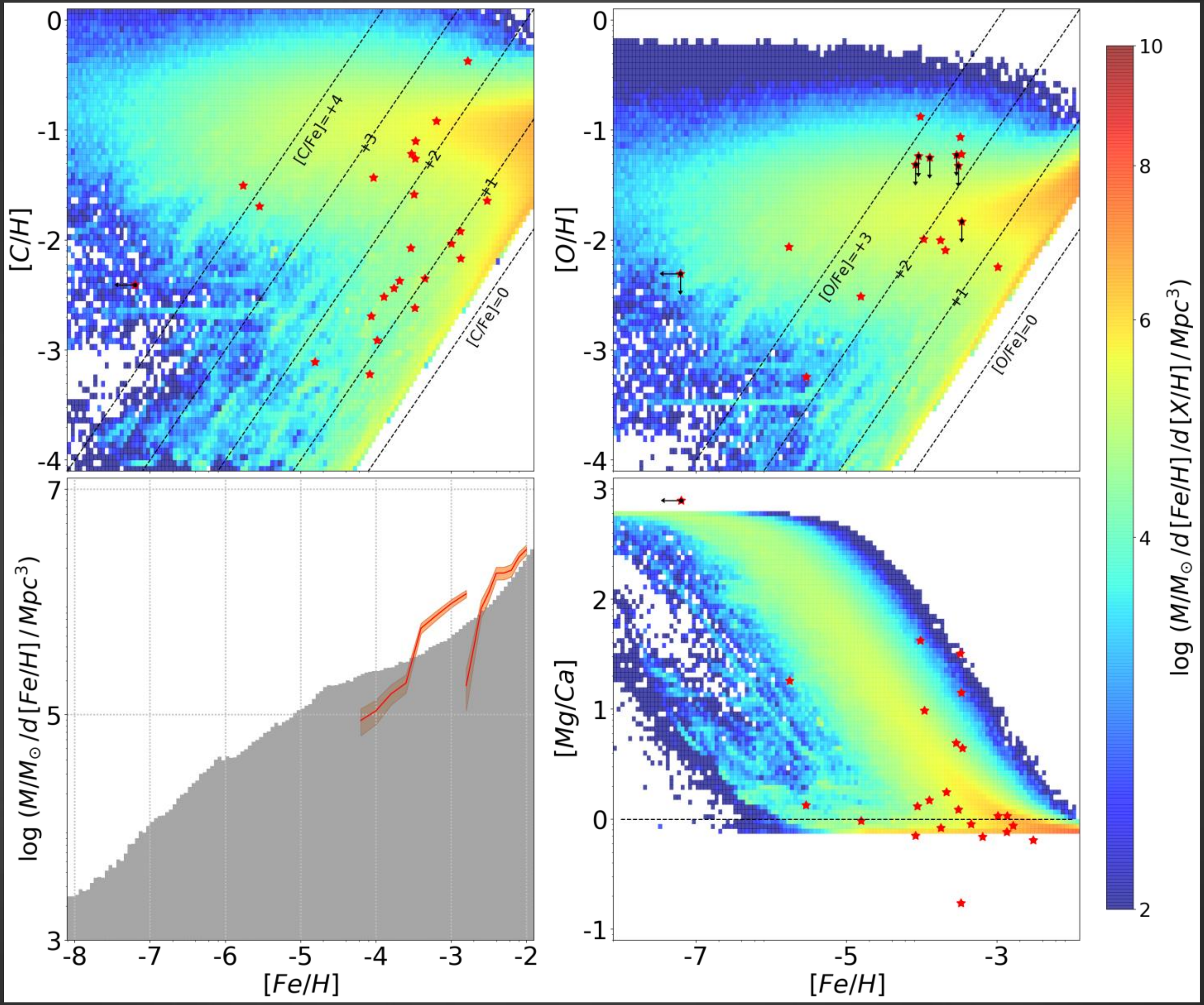
Final chemical composition



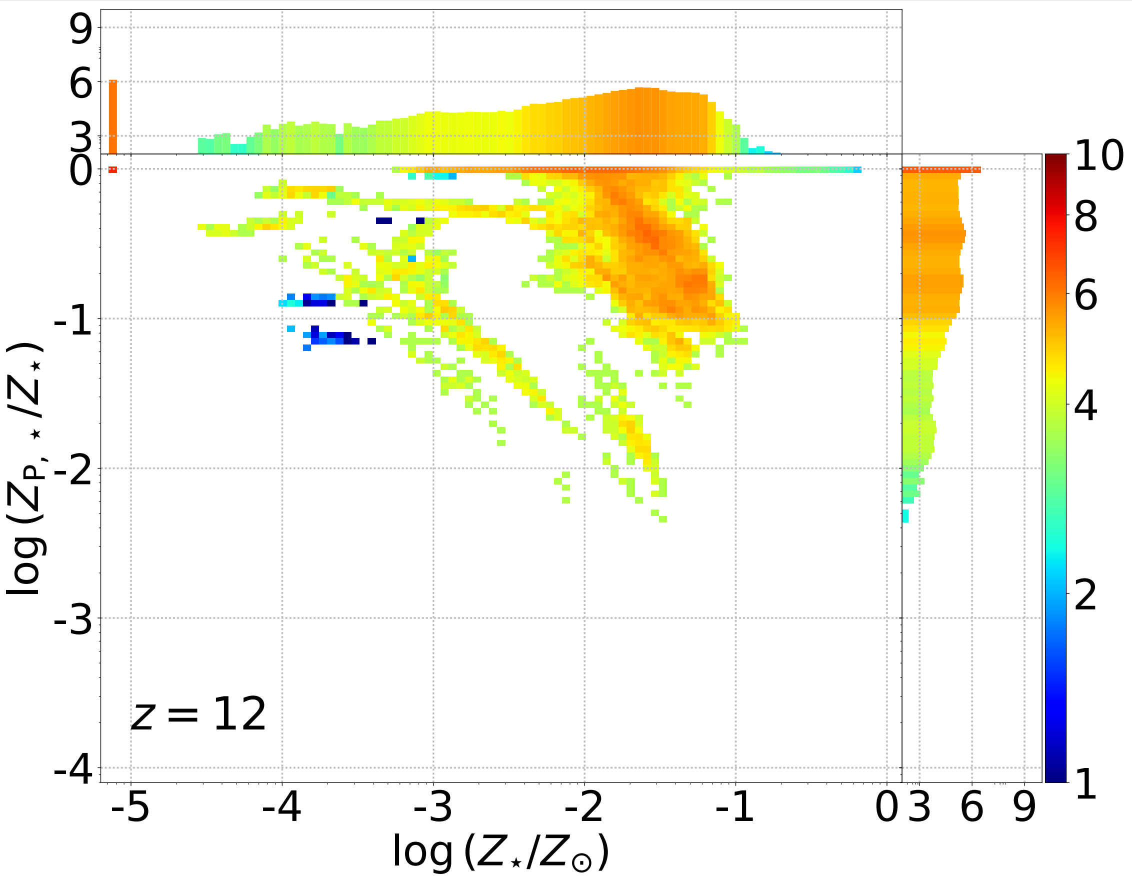


Simulation Stars
Z_P = 25 $M_\odot$ SN abundances
Z = 'gas at z=5'

Umeda & Nomoto, 2003



[C/H]
[C/Fe]=+4
+3
+2
+1
[C/Fe]=0
[O/H]
[O/Fe]=+3
+2
+1
[O/Fe]=0
log (M/M⊙ /d [Fe/H] / Mpc³)
[Mg/Ca]
[Fe/H]
[Fe/H]
log (M/M⊙ /d [Fe/H] /d [X/H] / Mpc³)



9
6
3
0
-1
-2
-3
-4
-5
-4
-3
-2
-1
0
3
6
9
10
8
6
4
2
1
$z = 12$
$\log(Z_{P,\star}/Z_\star)$
$\log(Z_\star/Z_\odot)$

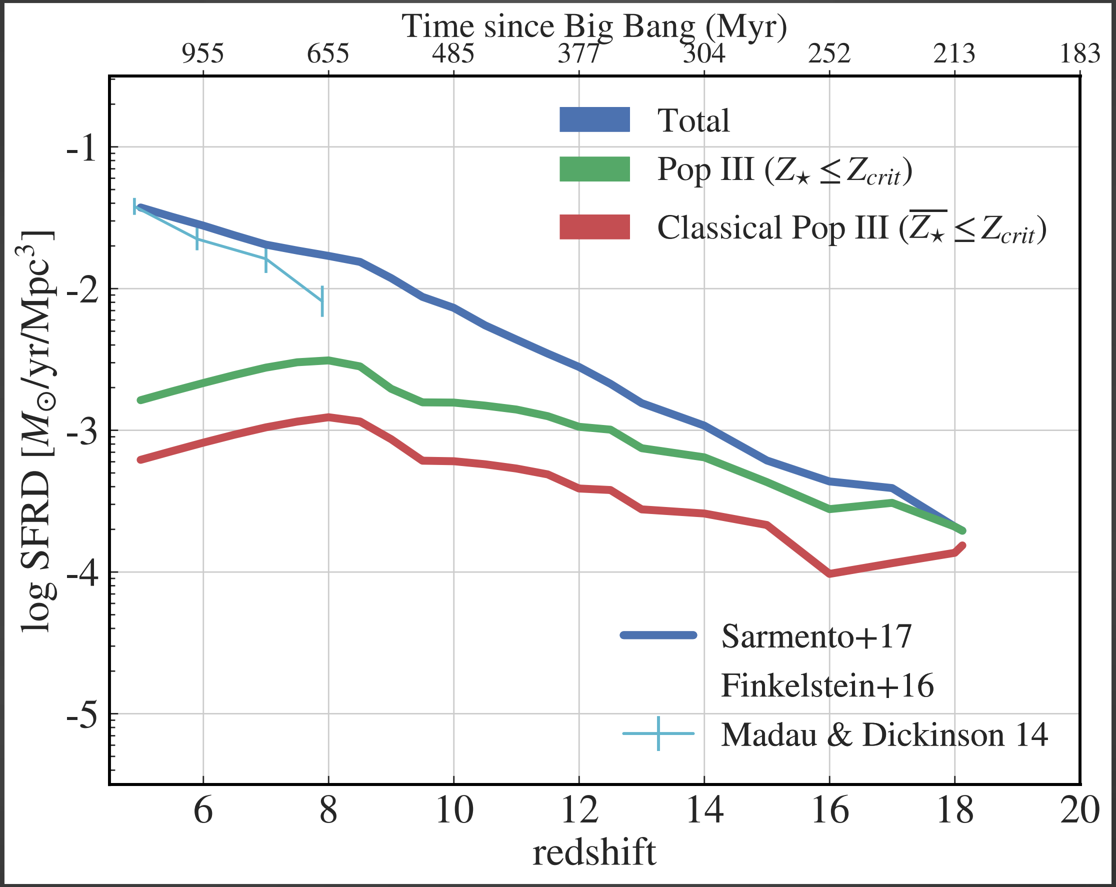
$$\tau_{\text{con}} = \frac{\Delta x}{v_t} \begin{cases} \tilde{\tau}_{\text{con1}} & \text{if } P \geq 0.9 \\ \tilde{\tau}_{\text{con2}} & \text{if } P < 0.9 \end{cases},$$

$$\tilde{\tau}_{\text{con1}} = \left[0.225 - 0.055 \exp\left(-\frac{M^{3/2}}{4} \right) \right] \sqrt{\frac{x}{5} + 1},$$

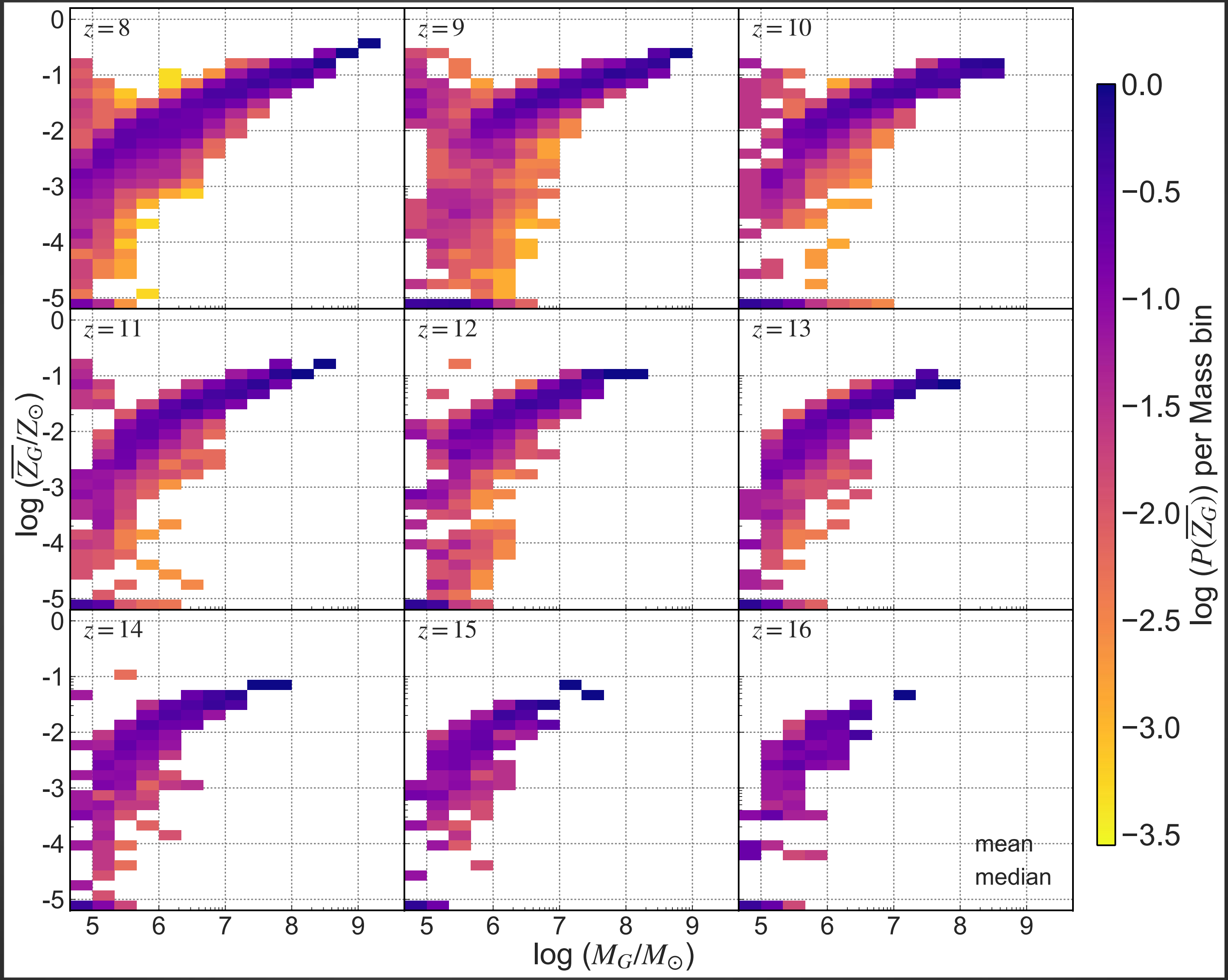
$$\tilde{\tau}_{\text{con2}} = \left[0.335 - 0.095 \exp\left(-\frac{M^{2}}{4} \right) \right] \sqrt{\frac{x}{3} + 1},$$

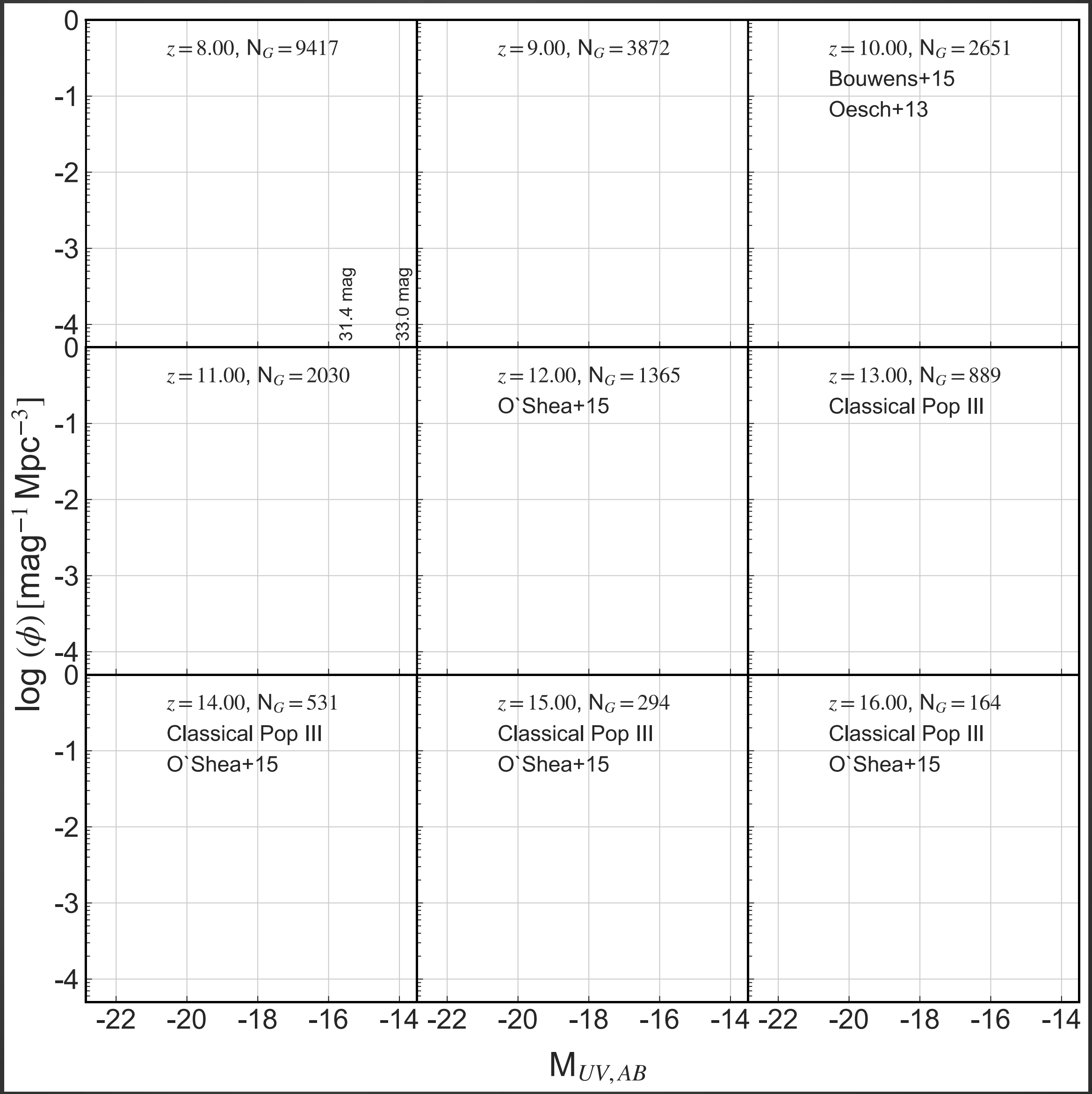
$$x \equiv -\log_{10}\left(\frac{\overline{Z}}{10^7 Z_{\text{crit}}} \right) \left[\log_{10}\left(\frac{\overline{Z}}{Z_{\text{crit}}} \right) \right]^{-1}$$

$$v_t = |S_{ij}|\, \Delta x.$$


Time since Big Bang (Myr)
955 655 485 377 304 252 213 183
Total
Pop III ($Z_\star \leq Z_{crit}$)
Classical Pop III ($\overline{Z_\star} \leq Z_{crit}$)
Sarmento+17
Finkelstein+16
Madau & Dickinson 14
log SFRD [$M_\odot$/yr/Mpc^3]
-1 -2 -3 -4 -5
6 8 10 12 14 16 18 20
redshift

Galaxy Mass-Metallicity




z = 8.00, N_G = 9417
31.4 mag
33.0 mag
z = 9.00, N_G = 3872
z = 10.00, N_G = 2651
Bouwens+15
Oesch+13
z = 11.00, N_G = 2030
z = 12.00, N_G = 1365
O`Shea+15
z = 13.00, N_G = 889
Classical Pop III
z = 14.00, N_G = 531
Classical Pop III
O`Shea+15
z = 15.00, N_G = 294
Classical Pop III
O`Shea+15
z = 16.00, N_G = 164
Classical Pop III
O`Shea+15
log (ϕ) [mag⁻¹ Mpc⁻³]
0
-1
-2
-3
-4
-22
-20
-18
-16
-14
M_UV,AB