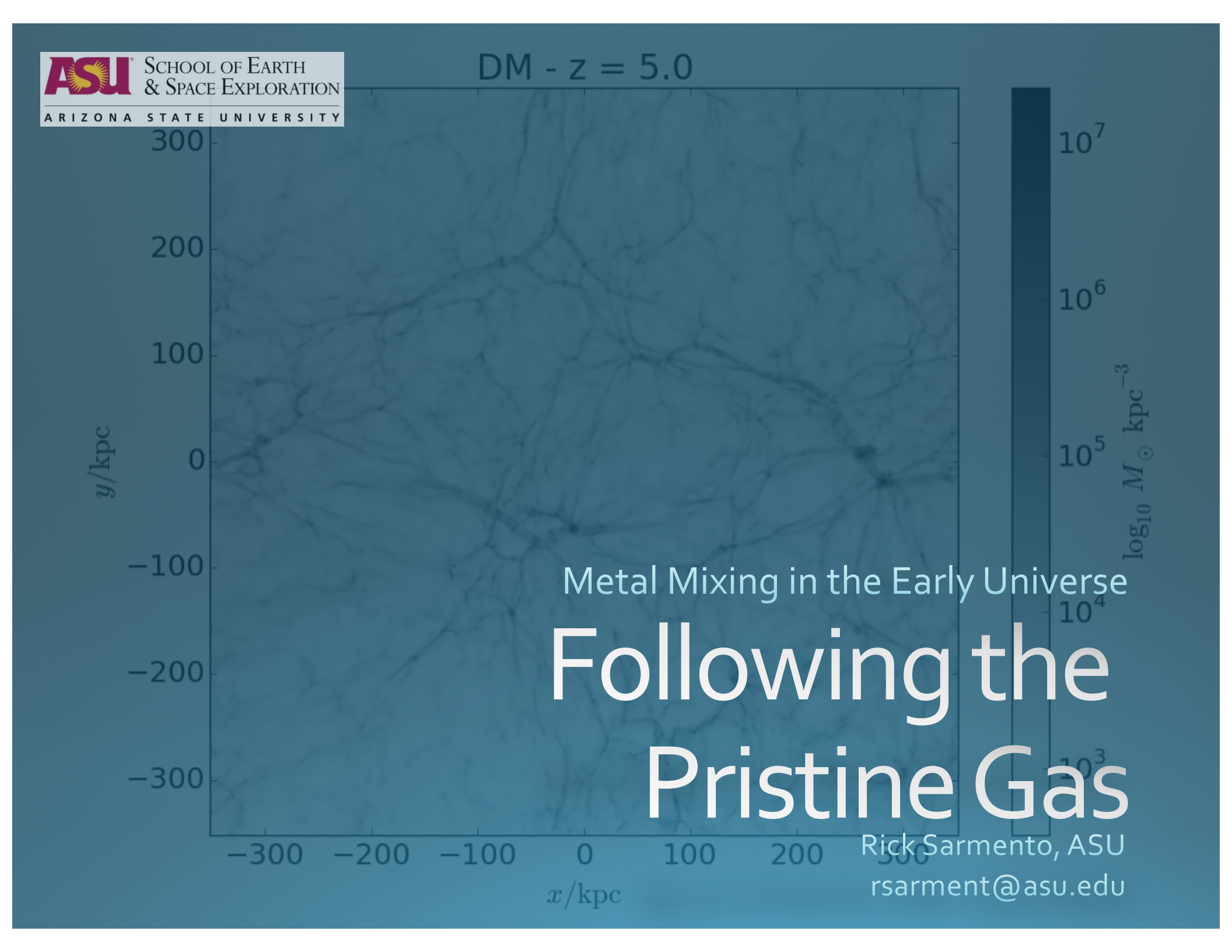

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Metal Mixing in the Early Universe

Following the Pristine Gas

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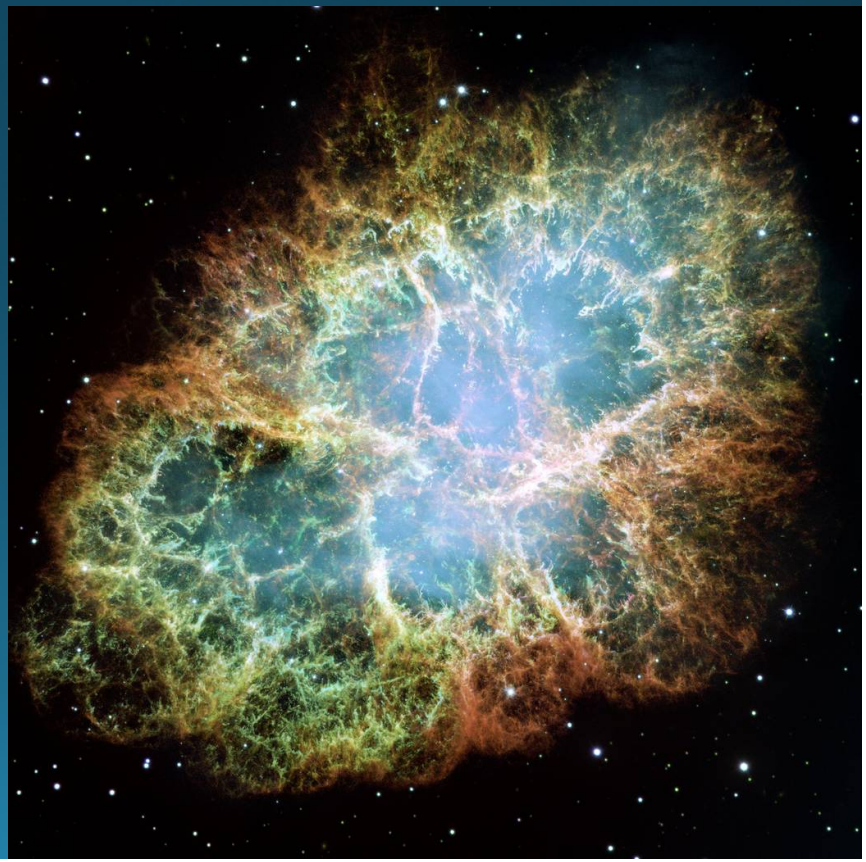
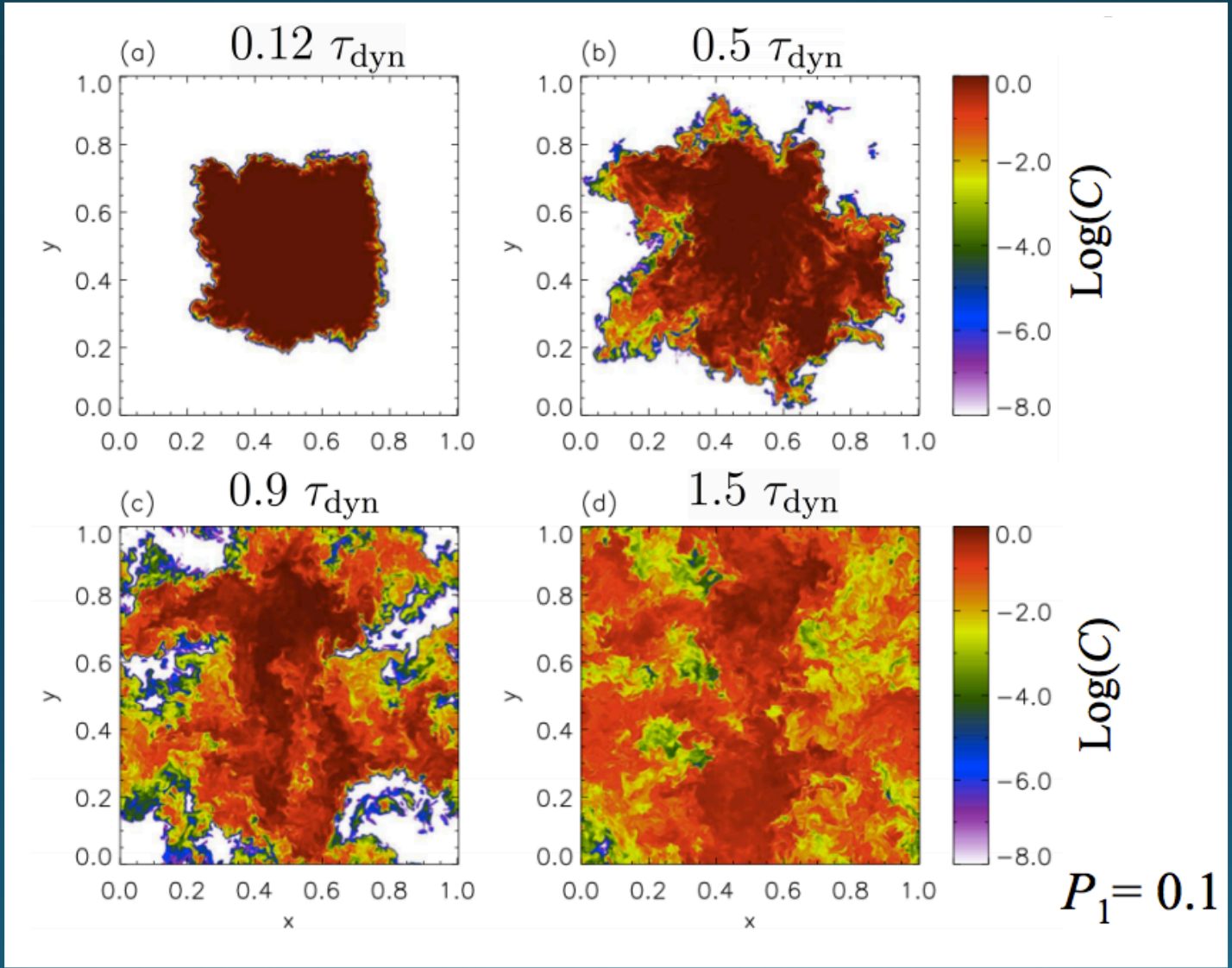
Pollution of the pristine gas

- Why?
  - Effects on Pop III SFRD
  - Transition to normal star formation…
- Considerations
  - Asymmetrical SN blast/Distribution of metals
  - Pre-SN stellar structure
  - Clumpy, turbulent, etc.
  - Turbulent mixing !
- Turbulence is resolved at scales > resolution scale
  - Typical scales of 10-1000 pc
- What about subgrid scales?
- Our approach
  - Turbulence is unresolved – but we can still characterize mixing at *subgrid* scales

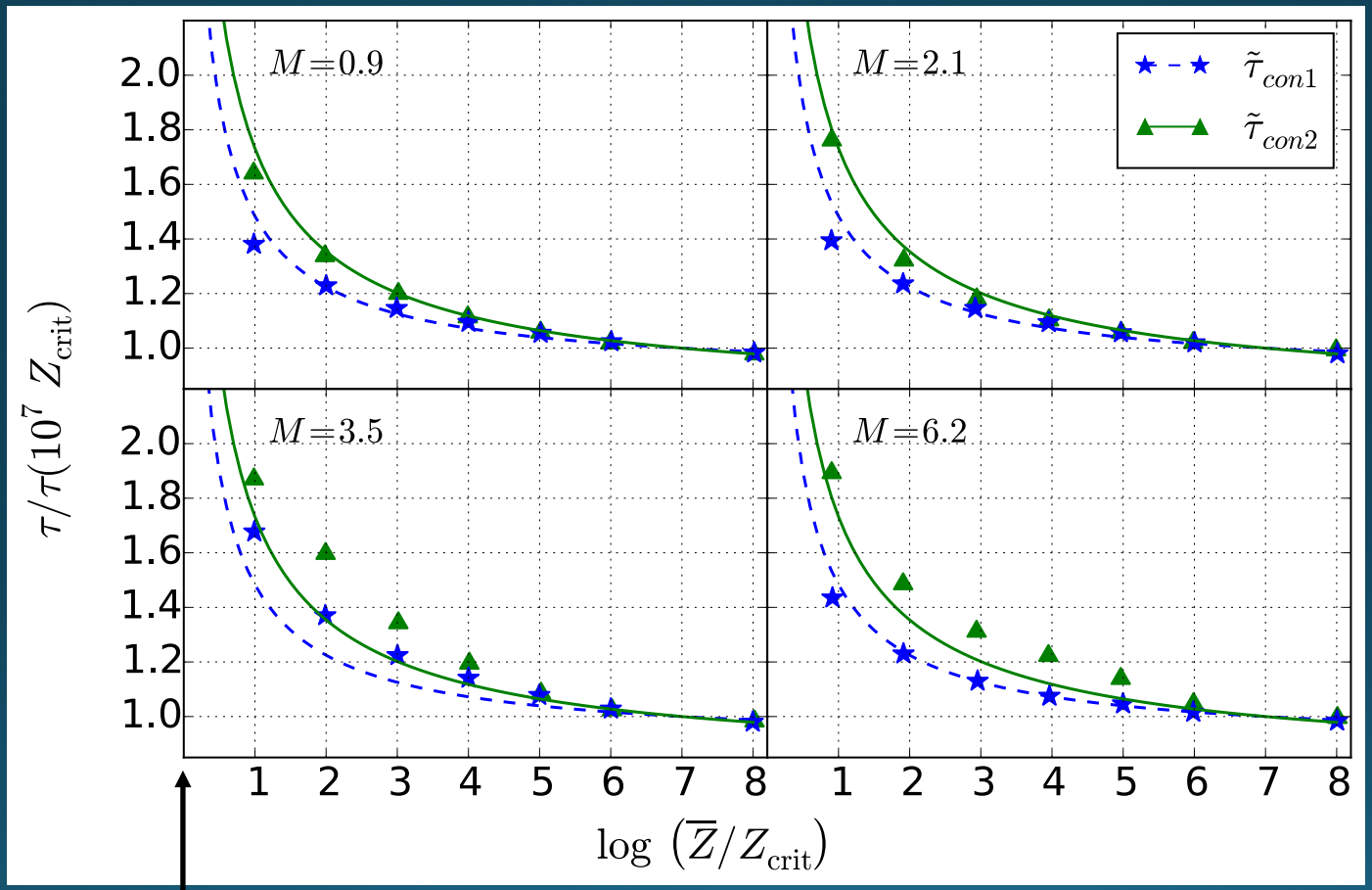


Modeling Turbulence…



Pan, ES, & Scalo (2012,2013)

Dynamical mixing time…



Parameters: Δx, $\overline{Z}$, v_t, c_s

$\overline{Z}$: The average metallicity of the cell

Pan, et al. 2013

Dynamical mixing time…

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

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

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

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

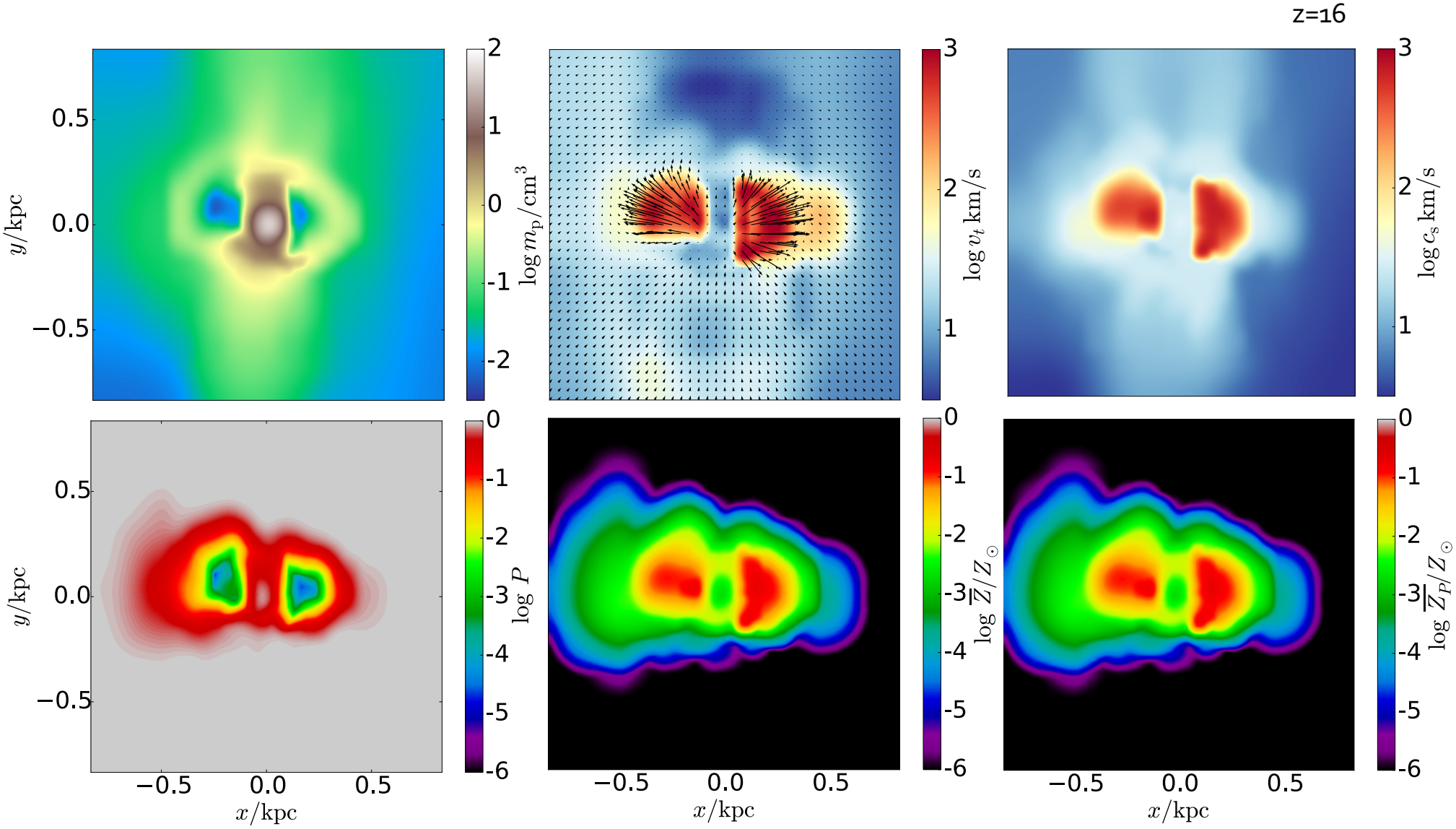
$$v_t = |S_{ij}|\,\Delta x.$$

Pan, et al. 2013

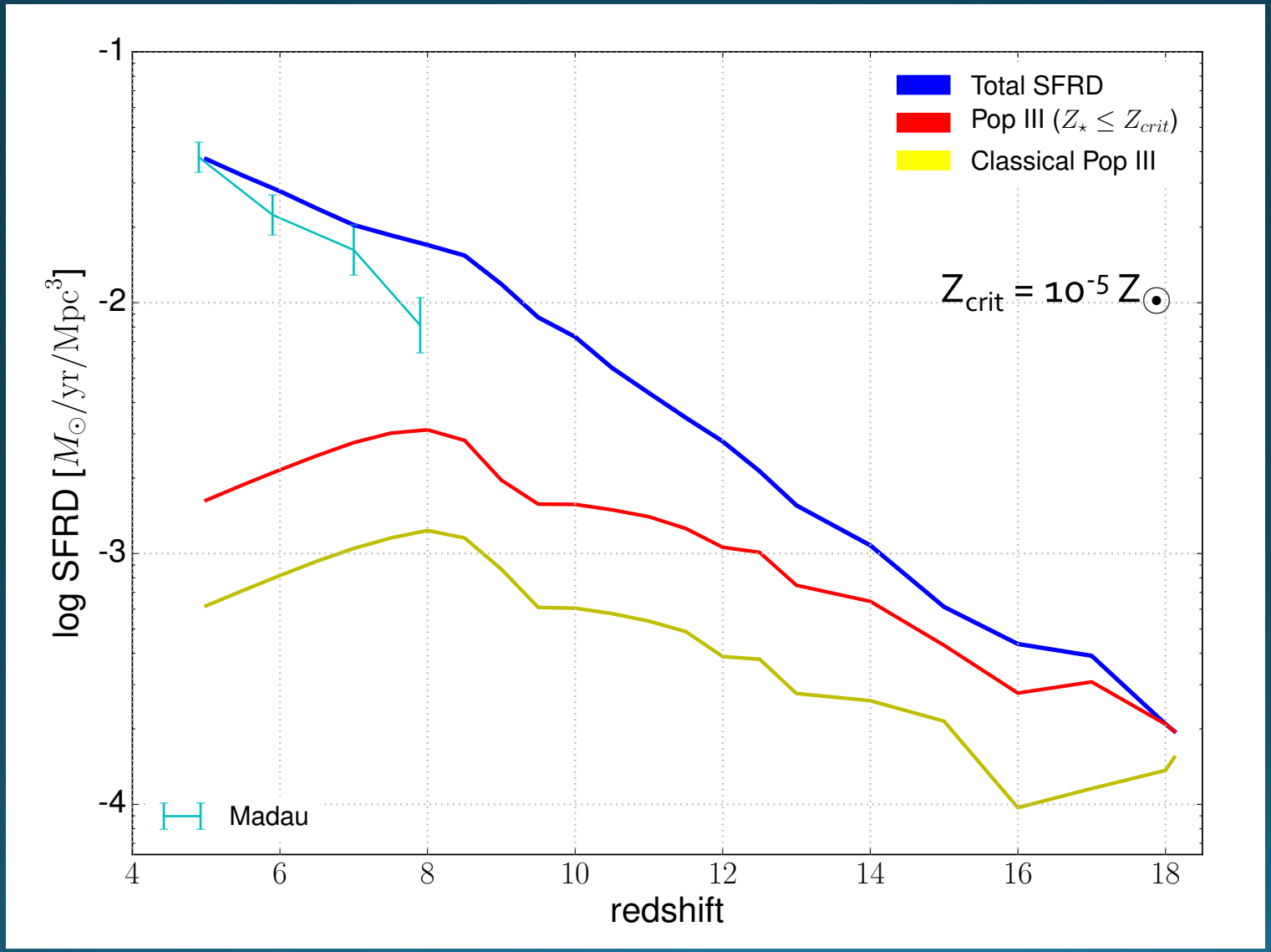
New RAMSES scalars

- v_t – turbulent velocity
  - Based on a Smagorinsky's formulation
  - gas
- P – pristine gas fraction
  - tracks the fraction of gas in each cell $Z < Z_{crit}$
  - both gas and star particles
- Z_P – primordial metal fraction
  - tracks the fraction of metals in the cell that come from Pop III SN
  - both gas and star particles

Gas characteristics …

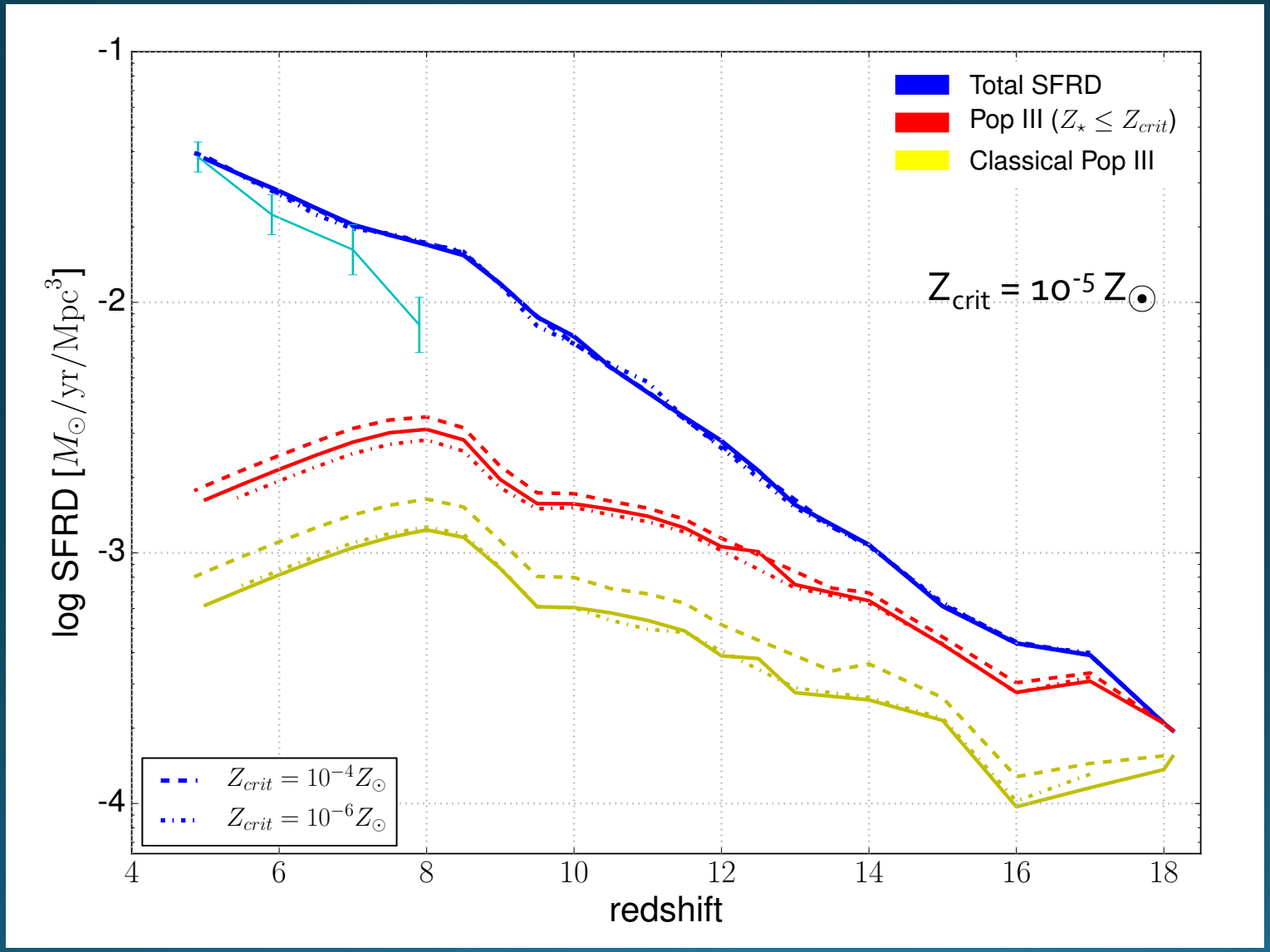


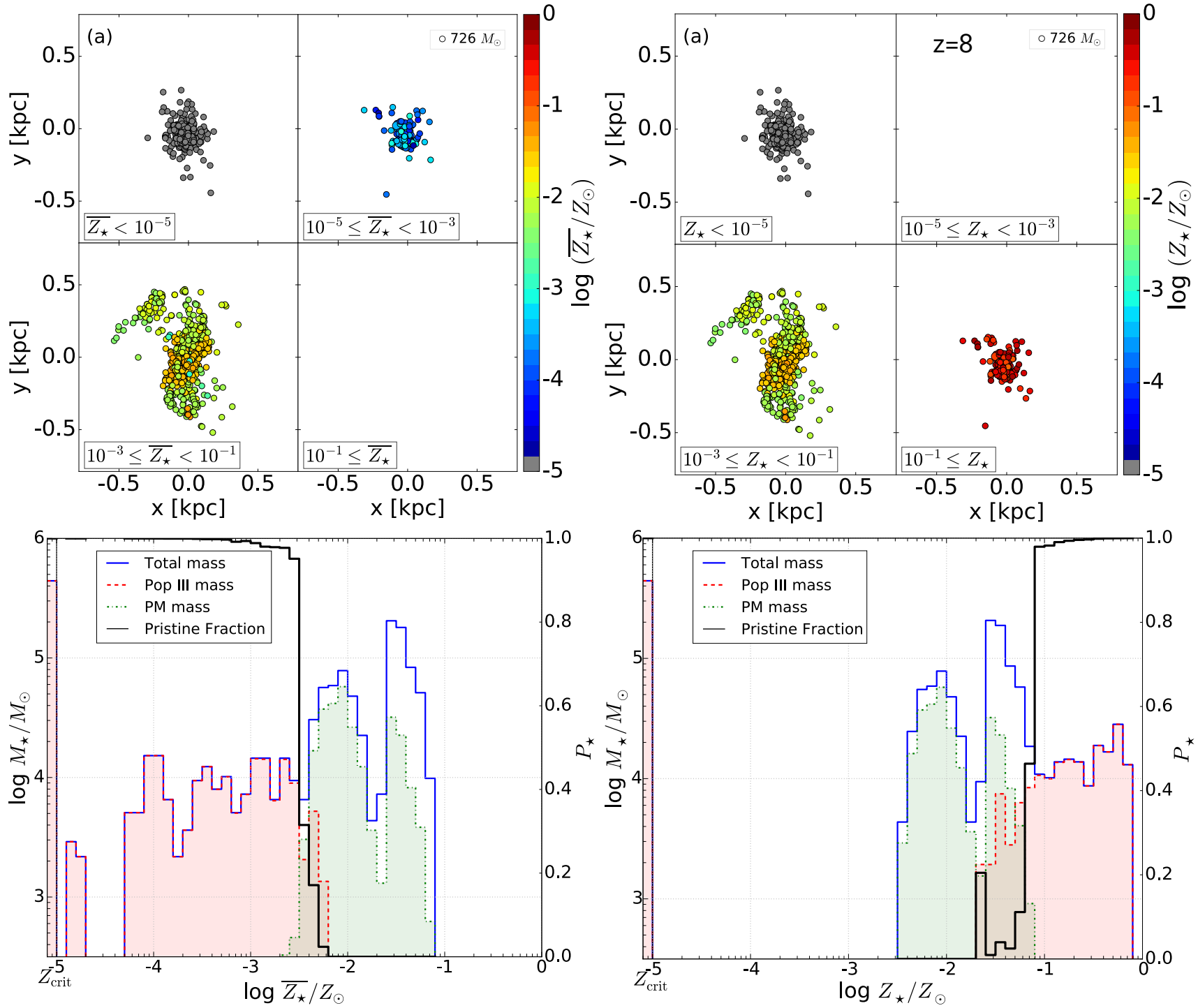
SFRD – With/Without Mixing

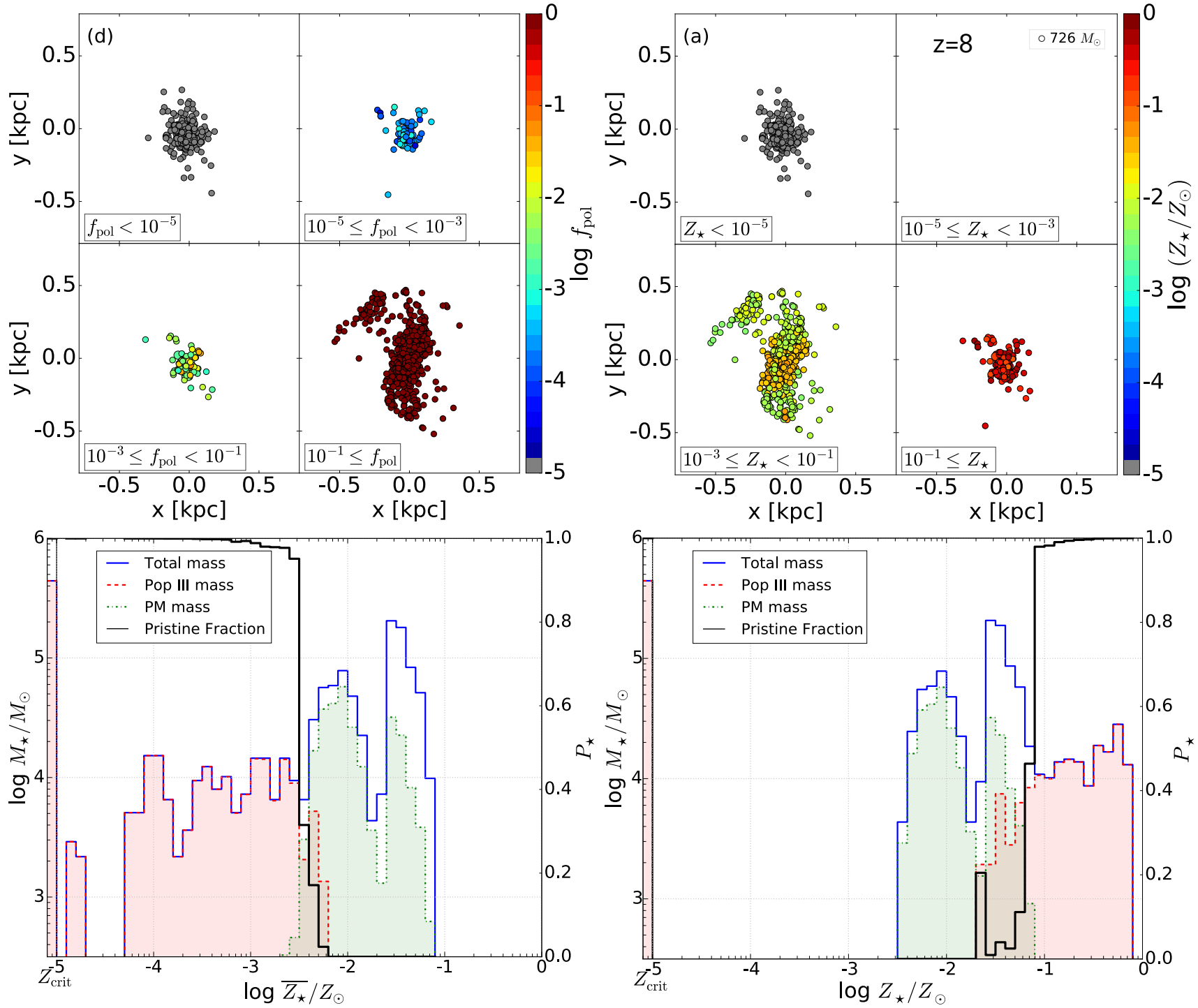


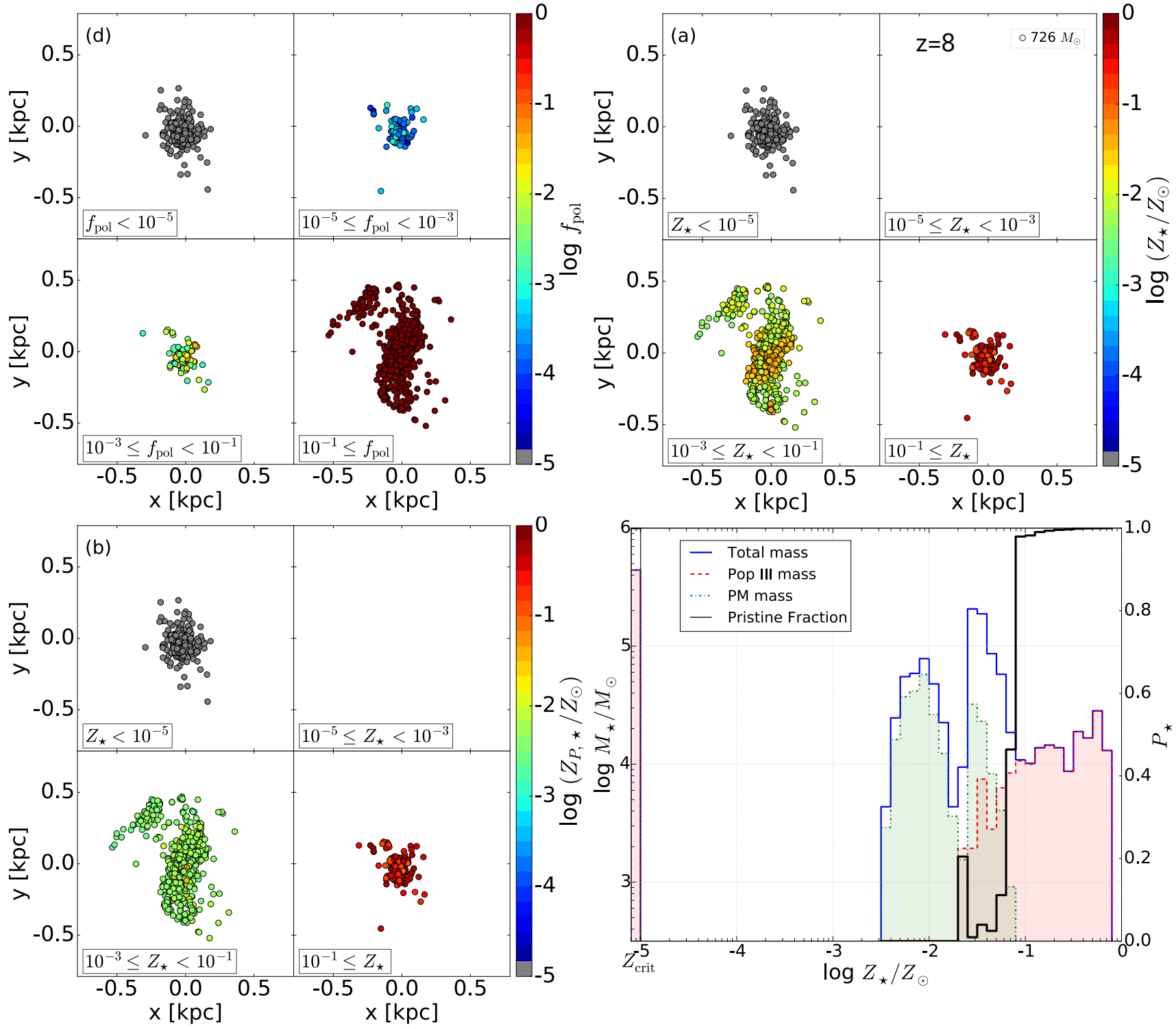
Madau & Dickenson, 2014

Varying Z_{crit}…

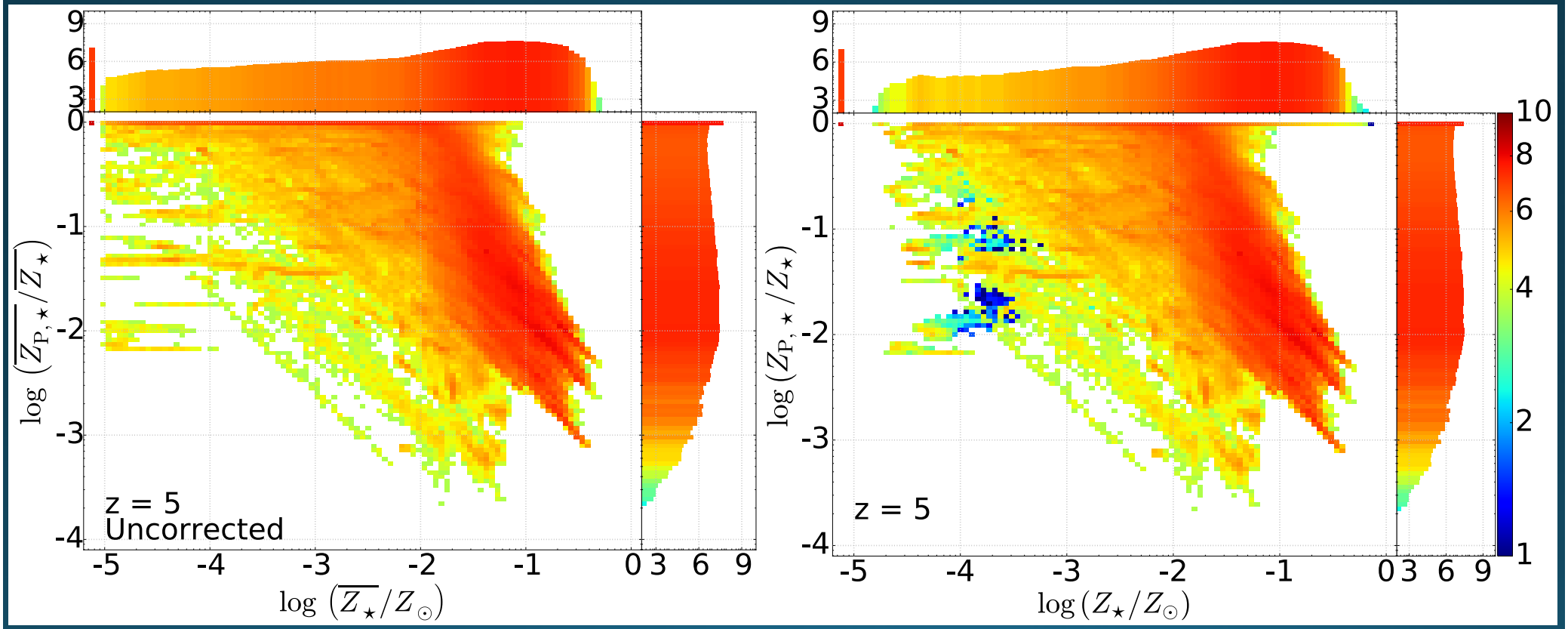



(a)
○ 726 $M_\odot$
$\overline{Z_\star} < 10^{-5}$
$10^{-5} \leq \overline{Z_\star} < 10^{-3}$
$10^{-3} \leq \overline{Z_\star} < 10^{-1}$
$10^{-1} \leq \overline{Z_\star}$
y [kpc]
x [kpc]
log $(\overline{Z_\star}/Z_\odot)$
(a)
z=8
○ 726 $M_\odot$
$Z_\star < 10^{-5}$
$10^{-5} \leq Z_\star < 10^{-3}$
$10^{-3} \leq Z_\star < 10^{-1}$
$10^{-1} \leq Z_\star$
log $(Z_\star/Z_\odot)$
Total mass
Pop III mass
PM mass
Pristine Fraction
log $M_\star/M_\odot$
$P_\star$
$\bar{Z}_{\rm crit}$
log $\overline{Z_\star}/Z_\odot$
log $Z_\star/Z_\odot$


(d)
$f_{\rm pol} < 10^{-5}$
$10^{-5} \leq f_{\rm pol} < 10^{-3}$
$10^{-3} \leq f_{\rm pol} < 10^{-1}$
$10^{-1} \leq f_{\rm pol}$
y [kpc]
x [kpc]
log $f_{\rm pol}$
(a)
z=8
○ 726 $M_\odot$
$Z_\star < 10^{-5}$
$10^{-5} \leq Z_\star < 10^{-3}$
$10^{-3} \leq Z_\star < 10^{-1}$
$10^{-1} \leq Z_\star$
log $(Z_\star/Z_\odot)$
Total mass
Pop III mass
PM mass
Pristine Fraction
log $M_\star/M_\odot$
$P_\star$
$Z_{\rm crit}$
log $\overline{Z_\star}/Z_\odot$
log $Z_\star/Z_\odot$

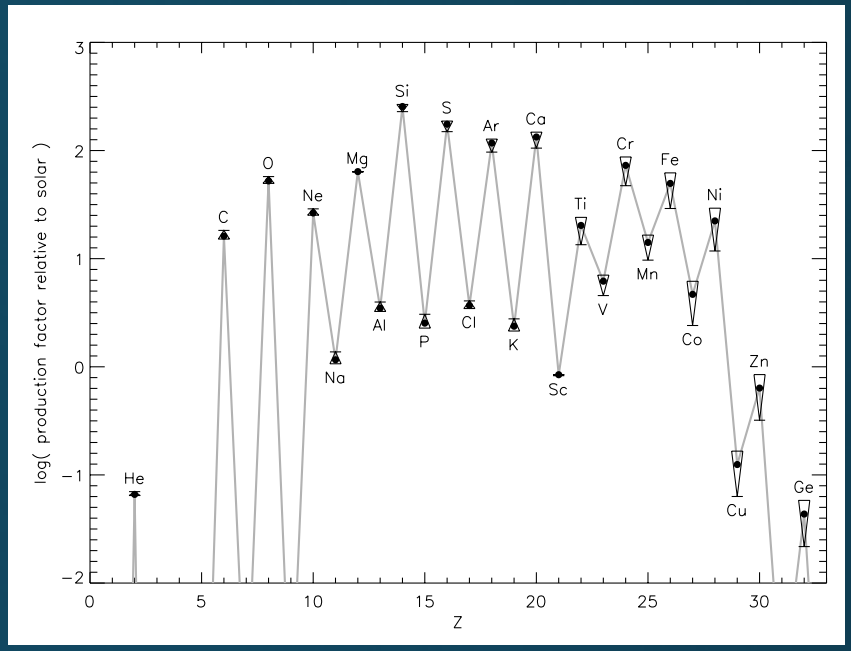

(d)
$f_{\rm pol} < 10^{-5}$
$10^{-5} \leq f_{\rm pol} < 10^{-3}$
$10^{-3} \leq f_{\rm pol} < 10^{-1}$
$10^{-1} \leq f_{\rm pol}$
log $f_{\rm pol}$
(a)
z=8
○ 726 $M_\odot$
$Z_\star < 10^{-5}$
$10^{-5} \leq Z_\star < 10^{-3}$
$10^{-3} \leq Z_\star < 10^{-1}$
$10^{-1} \leq Z_\star$
log $(Z_\star/Z_\odot)$
(b)
$Z_\star < 10^{-5}$
$10^{-5} \leq Z_\star < 10^{-3}$
$10^{-3} \leq Z_\star < 10^{-1}$
$10^{-1} \leq Z_\star$
log $(Z_{P,\star}/Z_\odot)$
Total mass
Pop III mass
PM mass
Pristine Fraction
log $M_\star/M_\odot$
$P_\star$
$Z_{\rm crit}$
log $Z_\star/Z_\odot$
x [kpc]
y [kpc]

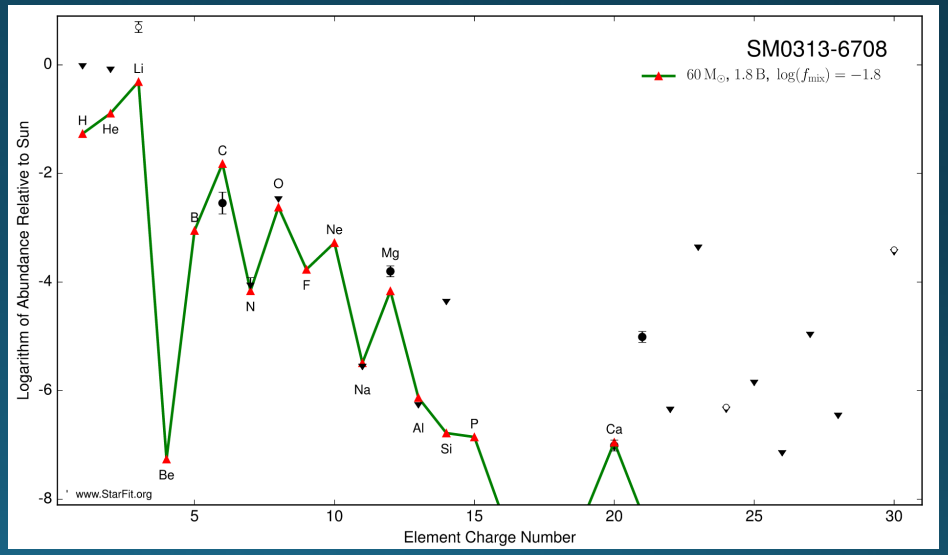
Correcting SP Z with the polluted fraction



So what?

- SPs have two kinds of metallicity:
  - Z - Corrected metallicity
  - Z_P - Primordial metallicity
- Combine Z and Z_P to model composition of SPs
- Tie progenitor models to observations – quickly!

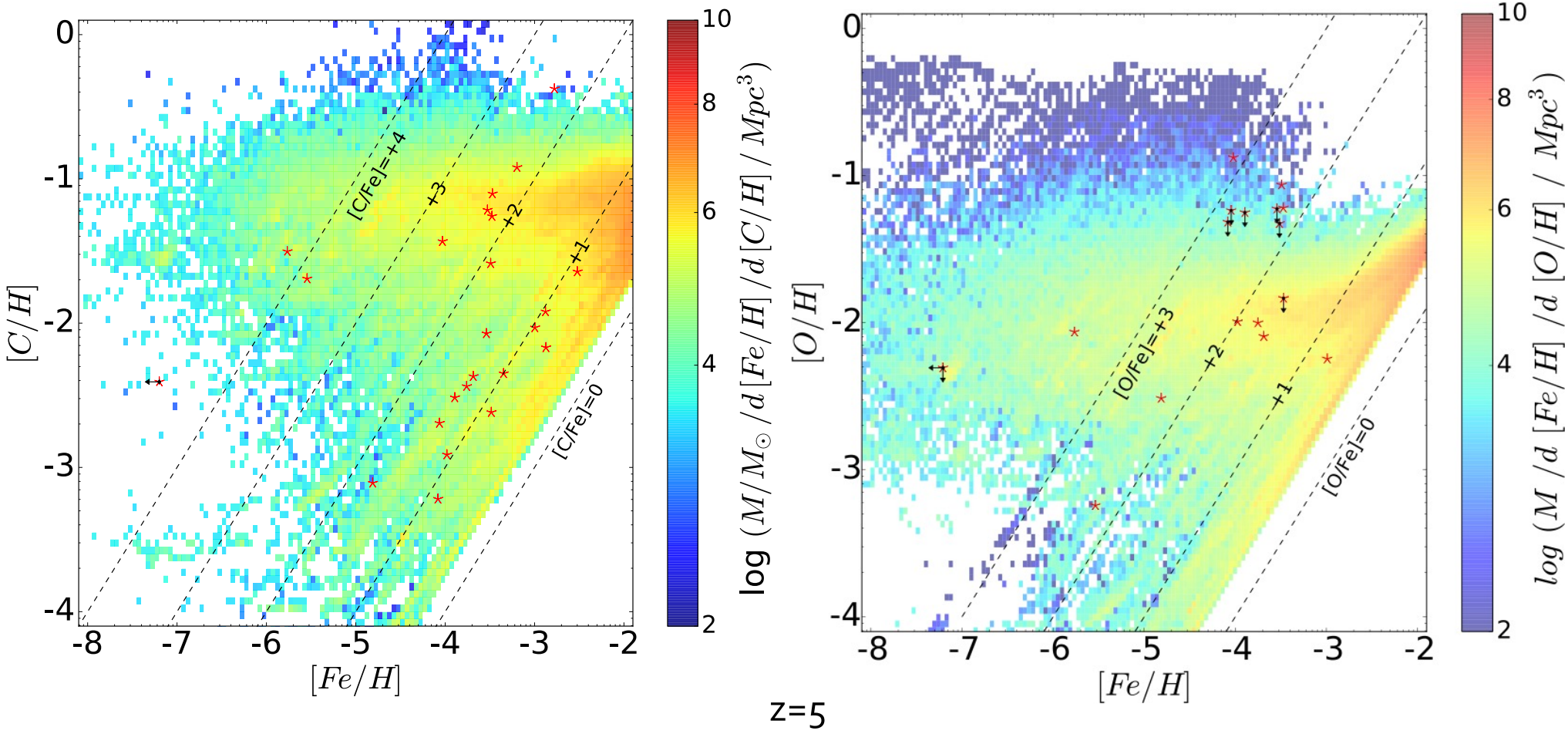




No expensive chemical evolution runs
Explore possible progenitor yield models without re-running

Heger and Woolsey, 2002, Heger; StarFit 2016

MW Halo CEMP Stars



Keller et al. 2014, Heger (StarFit) 2016, Timmes, 2016

Conclusions…

- New technique for modeling subgrid turbulence in a cosmological context
  - Inexpensively track mixing of pollutants at subgrid scales
  - 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
  - Improved (?) Pop III SFRD model
  - Future work –
    - Predictions for the luminosity function/observational characteristics of high-z galaxies

Backup slides

Halo characteristics...

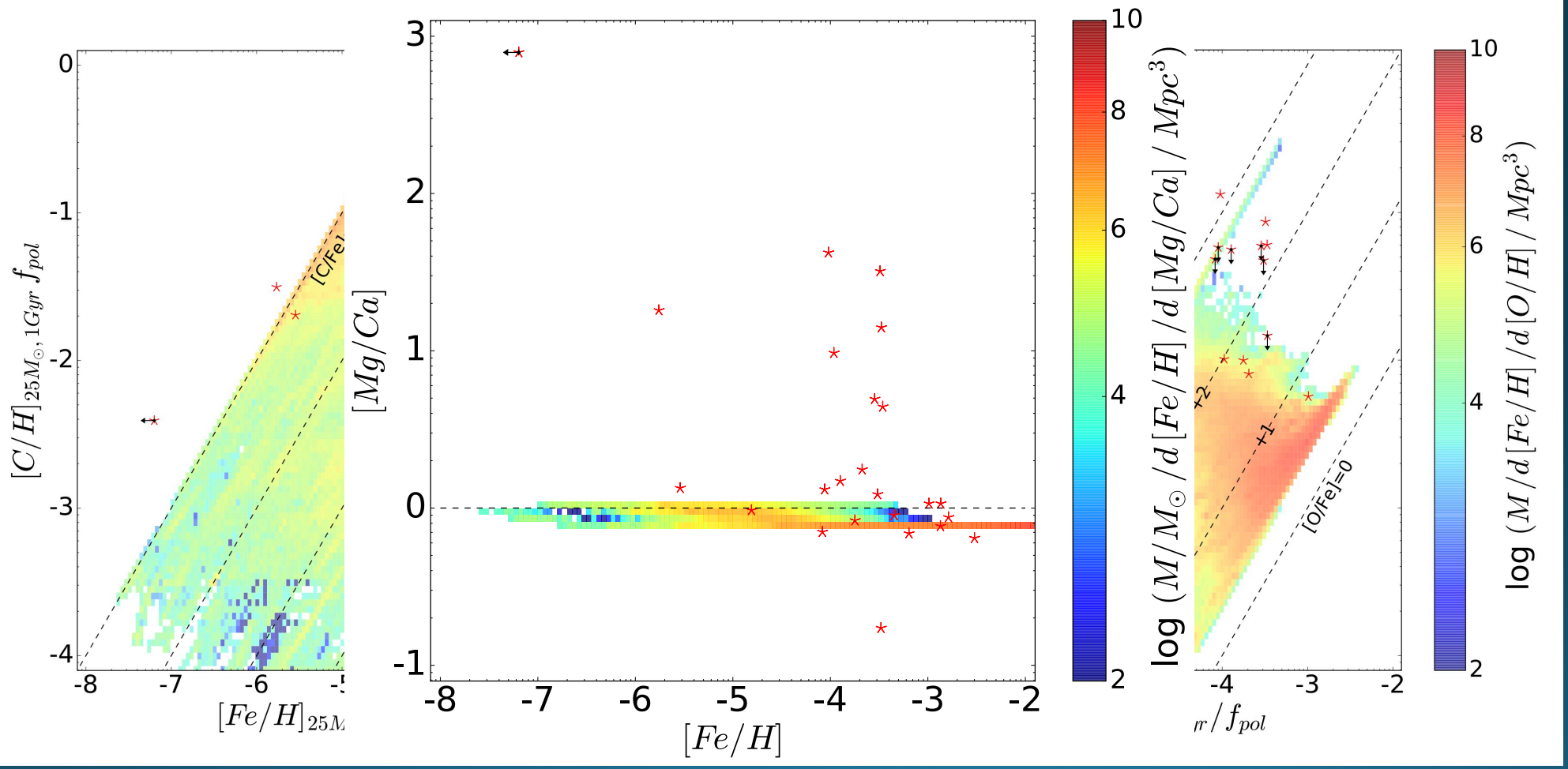
Table 2. Halo characteristics

Redshift	Total $M/M_\odot$	Pop III $M/M_\odot$	Classic PopIII / Pop III	$\langle Z_\star \rangle^{a}$	$\langle Z_{P,\star}/Z_\star \rangle^{b}$
16	5.35×10^5	3.04×10^5	0.300	3.07×10^{-3}	0.988
8	1.45×10^6	6.19×10^5	0.714	1.53×10^{-2}	0.322

[a]mass-weighted average metallicity for all stars in the halo.

[b]mass-weighted average primordial metal fraction for polluted stars in the halo.

Other Pop III progenitor models



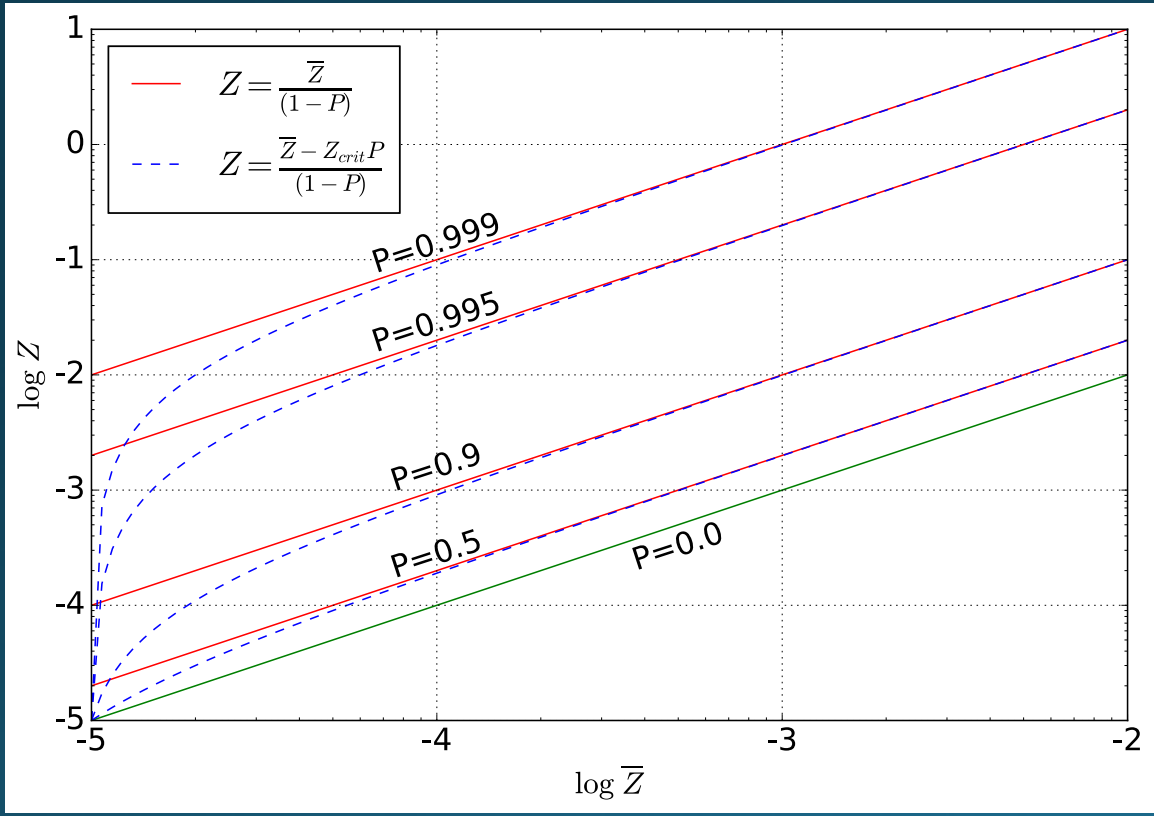
Yields, ISM

Table 3. Mass fractions of metals

Element	X/Z $1Gy$	X/Z_P $60M_\odot$ Pop III SN
C	1.68×10^{-1}	7.11×10^{-1}
O	5.29×10^{-1}	2.73×10^{-1}
Mg	2.49×10^{-2}	9.56×10^{-4}
Ca	3.00×10^{-3}	1.43×10^{-7}
Fe	5.39×10^{-2}	2.64×10^{-12}

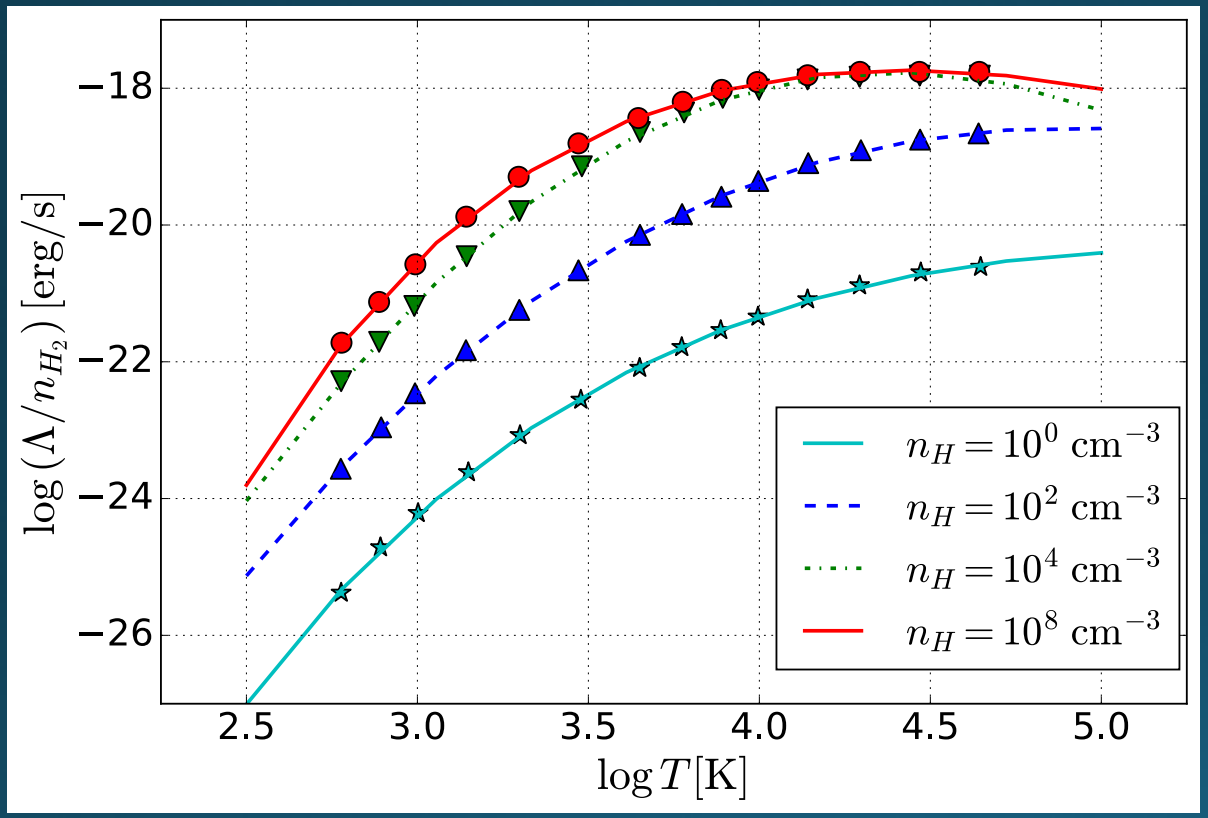
Note. — The mass fractions of metals for selected elements used to model the normal and primordial metallicity of star particles in our simulation. Data for gas typical of $1\,Gyr$ post BB provided by Timmes (2016). Data for $60M_\odot$ Pop III SN provided by Heger (2016).

Uncertainty in corrected metallicty

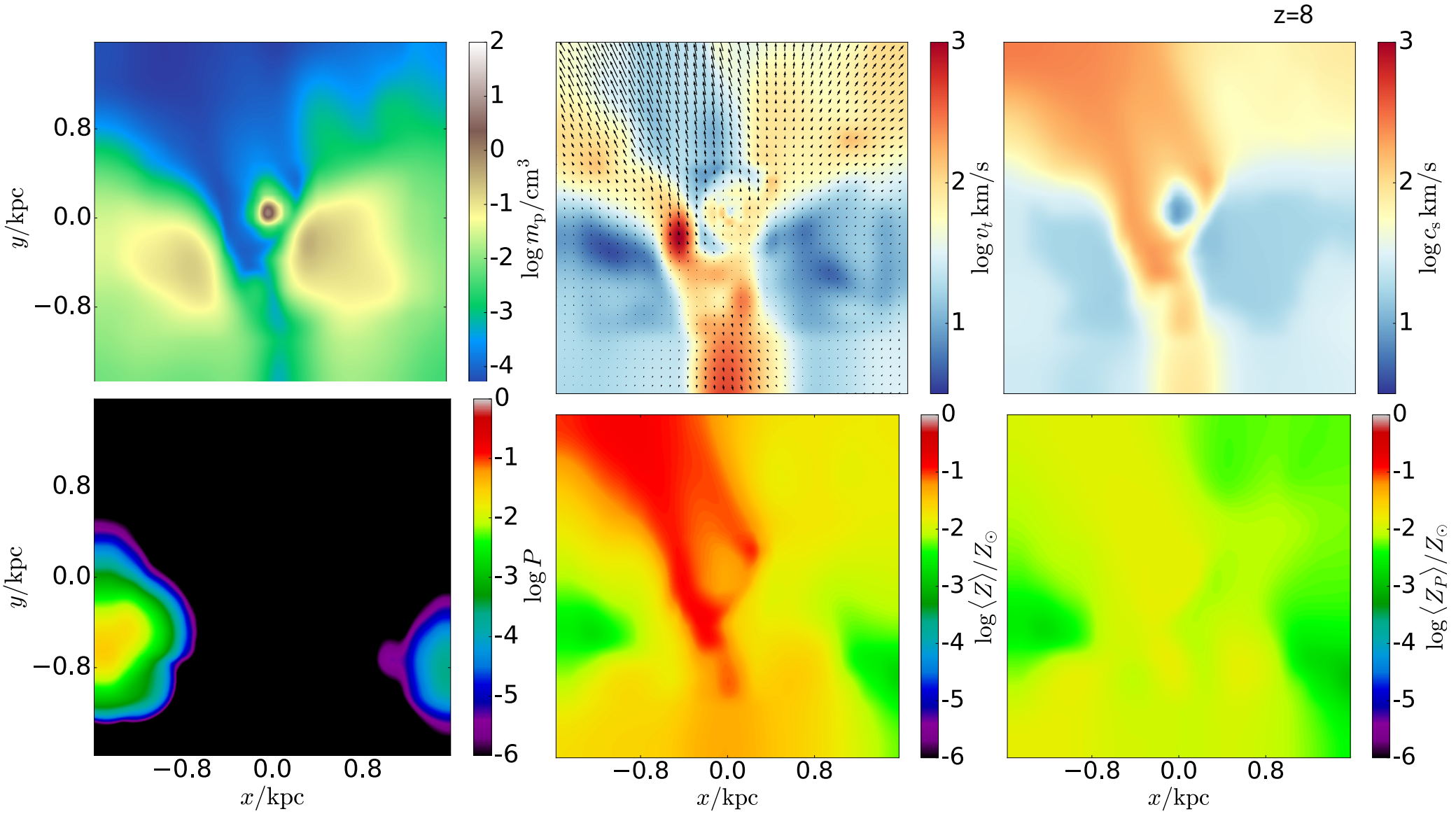


- Uncertainty in the metallicity of the pristine fraction
- We only know it is < Z_crit
- Early on, we know Z ~ 0.0
- Can bound the correction to get Z ...

Cooling in pristine gas



- H_2
- Based on data from Martin et al, 1996


z=8
y/kpc
x/kpc
0.8
0.0
−0.8
log $m_{\rm p}$/cm^3
log v_t km/s
log $c_{\rm s}$ km/s
log P
log $\langle Z \rangle / Z_\odot$
log $\langle Z_P \rangle / Z_\odot$