First Stars

in the

First Structures

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Outline

Gas evolution
- atoms and molecules

Simulations
- N-body hydro
- stellar evolution
- non-equilibrium chemistry
- star formation and feedback

Results
- Ω parameters, t_{depl}, Z, UVBs

Rationale: Understand the drivers of cosmic gas evolution, high-redshift galaxy formation and the role of feedback effects for popIII regimes over cosmological epochs

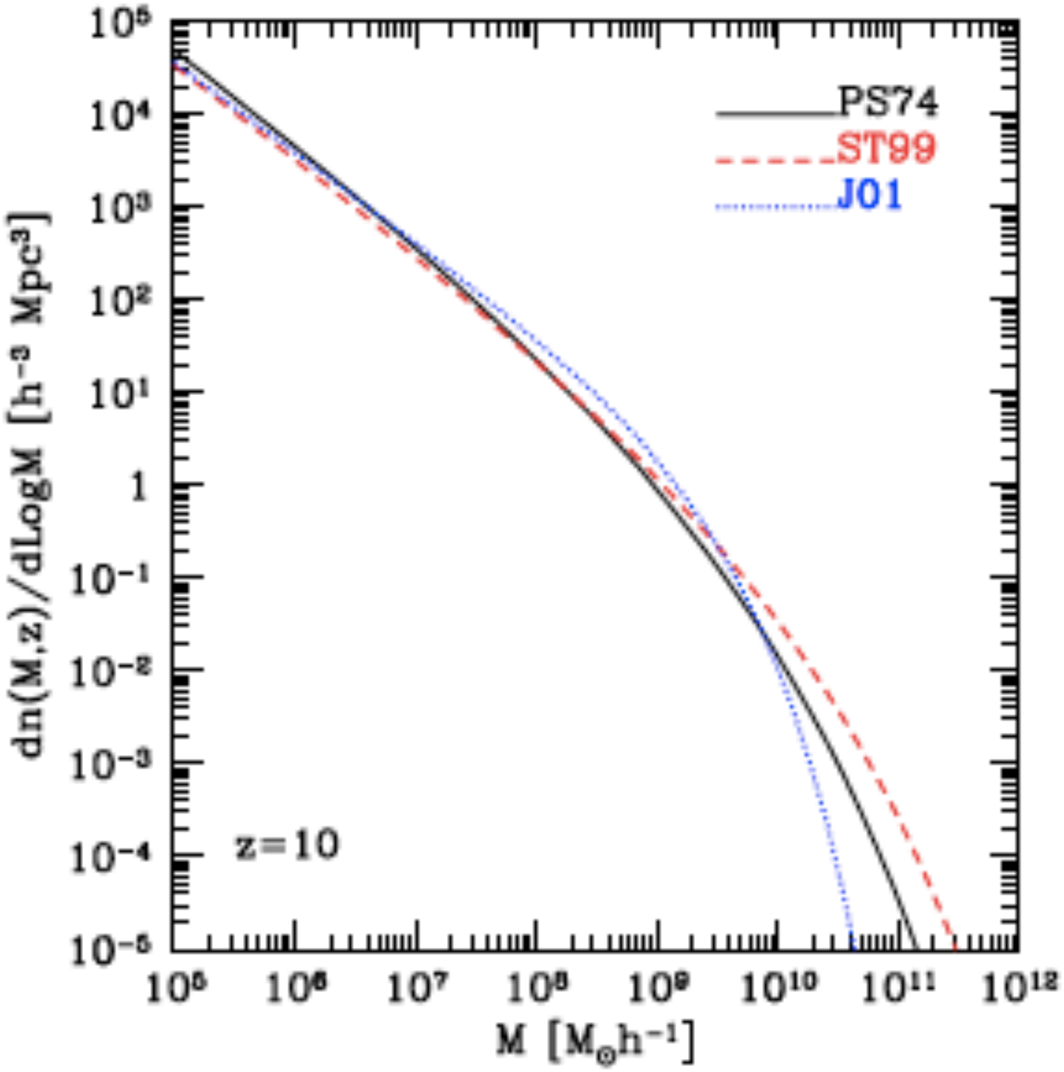
→ Formation epoch of high-z objects?
→ Has cosmic gas enough time to collapse?
→ What drives HI and H_2 evolution?
→ What is the role of early populations (popIII)?
→ What are the effects of different feedback/IMFs?
→ How do they impact gas metallicities and BH formation?

Requirements: Study thermal and chemical properties of the cosmic medium and cold gas in the most *general conditions*

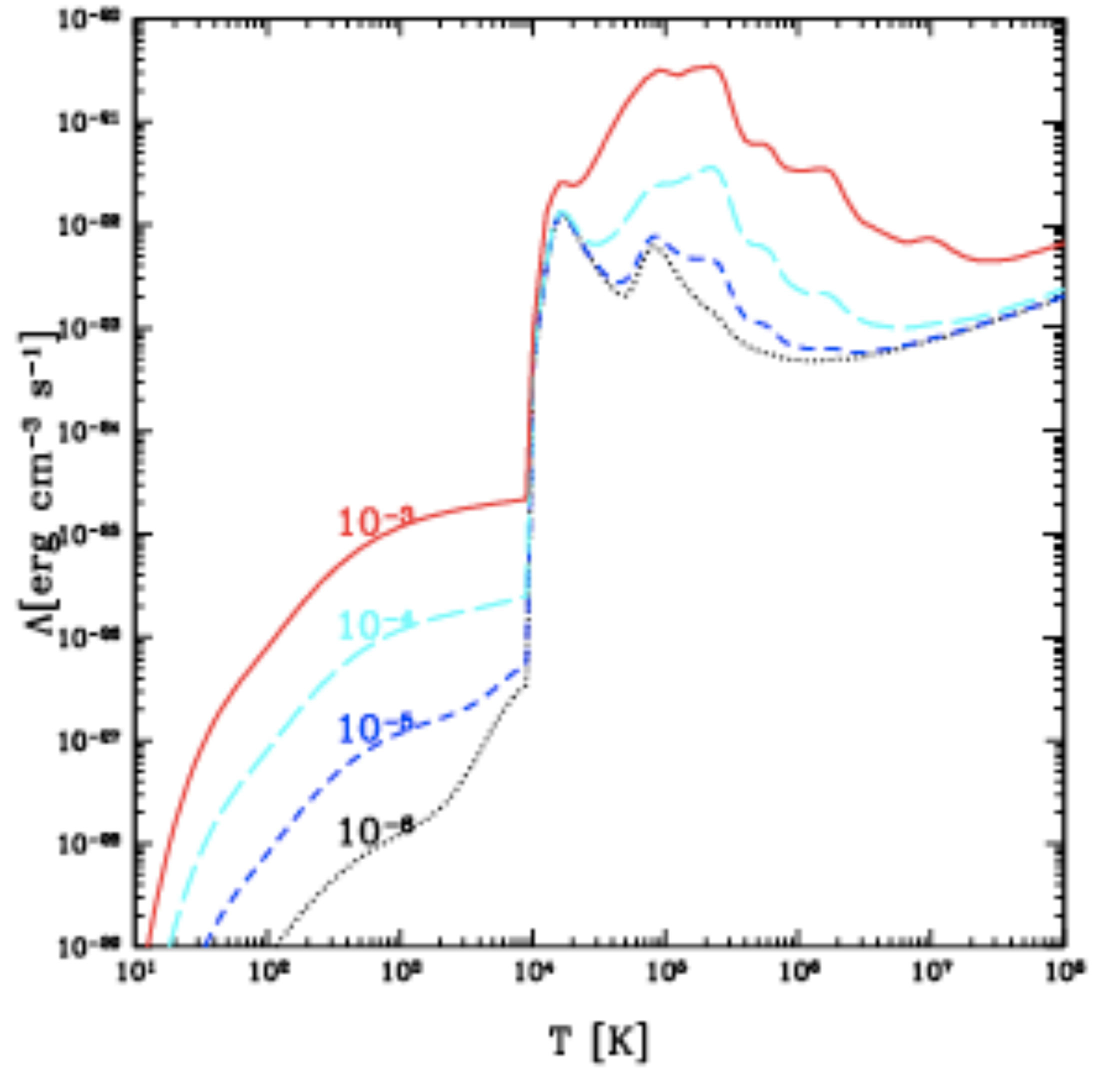
Techniques: Cosmological hydrodynamic and chemical numerical simulations

Primordial environments

Small dark-matter haloes hosting



molecular and metal cooling

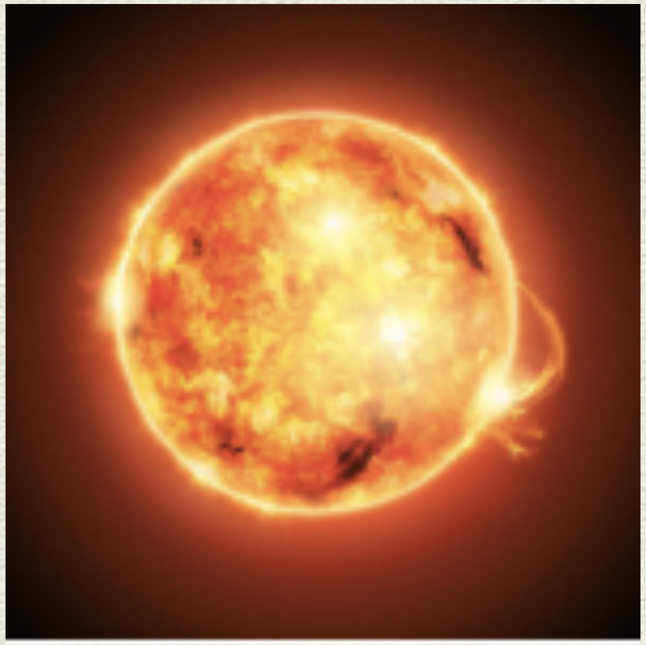


Maio et al. (2007)

H-cooling haloes: $T_{vir} \geq 10^4\,K$

H_2-cooling haloes: $T_{vir} < 10^4\,K$

$\longrightarrow$ gas in-fall and star formation



PopIII regimes

pristine or very metal poor

mass range: ? ? ?

explosion energies: ? ? ?

driving reionization: ? ? ?

early MBH seeds: ? ? ?

PopII regimes

metal enriched

mass range: ~[0.1, 100]Msun

explosion energies: ~10^{51}erg

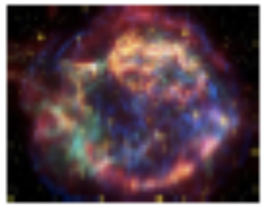
driving reionization: NO

early MBH seeds: NO

For a complete picture

⟶ follow gravity and hydrodynamics *coupled* to molecule formation and metal production from stellar evolution through cosmic time

molecules determine *first* gas collapsing events



metals determine *subsequent* structure formation

stellar evolution determines *yields*, γ and *timescales*

(Springel, 2001, 2005;Dolag+2009;Tornatore+2007,2010; Maio+2007,2010,2016,2019,2022,2023; etc.)

Cold-gas simulations *"ColdSim"*

Simulation runs including relevant gas physical and chemical processes

'Non-equilibrium' chemistry, H, D, He and H_2 channels, H_2 grain catalysis, PE heating, CR heating, gas HI/H_2 self-shielding, UVB, IMFs for popIII-popII SE and metal enrichment from PISN, SNII, AGB, SNIa…

NB: <u>No HI/H_2 partition recipe adopted</u>

Time-dependent HI and H_2 abundances are calculated from gas T, ϱ and Z at each timestep

No-UV
HM-HISSmed-DB2
HM-HISSmed-WG
HM-HISSmed-3b
HM-HISSmed-H_2^+
HM-HISSmed-none
HM-HISSmed-cat-75-Zevol
HM-HISSmed-cat-75-Zevol-pe
HM-HISS-cat-40-Zevol
HM-HISS-cat-75-Zevol
HM-HISS-cat-120-Zevol
HM-HISS-cat-Tcmb-Zevol
HM-HISS-cat-Tbeta-Zevol
HM-HISS-cat-75-0.01Zsun
HM-HISS-cat-75-Zsun
HM-cat-75-Zevol
HM-HISSmed-cr
HM-HISSmed-cr-P18
HM-HISSmed-cr-P18sfr

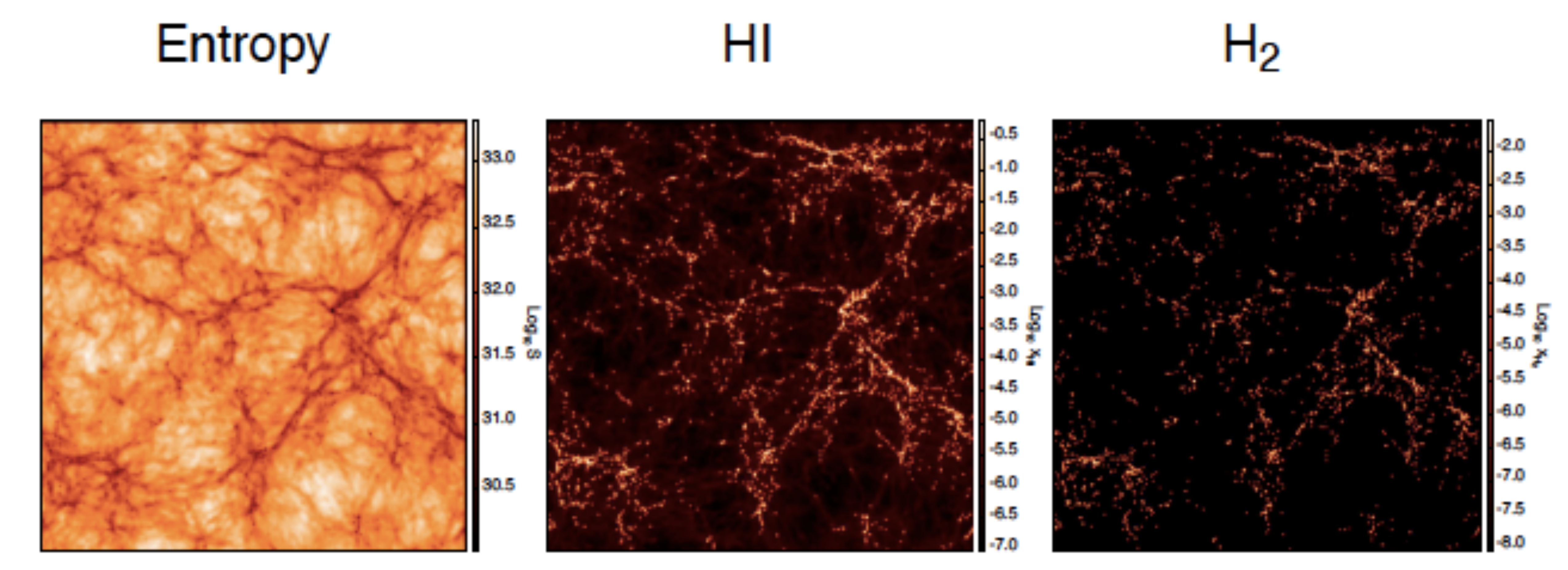
HM
HM-HISS
HM-HISSmed (ref)
P19
P19-HISS
P19-HISSmed
FG20
FG20-HISS
FG20-HISSmed
FG20thin
HM-std
HM-HISSmed-std
HM-HISSmed-H2

HM-1
HM-0.5
HM-0.01
HM-w700
HM-wf
HM-Chabrier
HM-1-Chabrier
P19-1
P19-Chabrier
P19-1-Chabrier

… … …

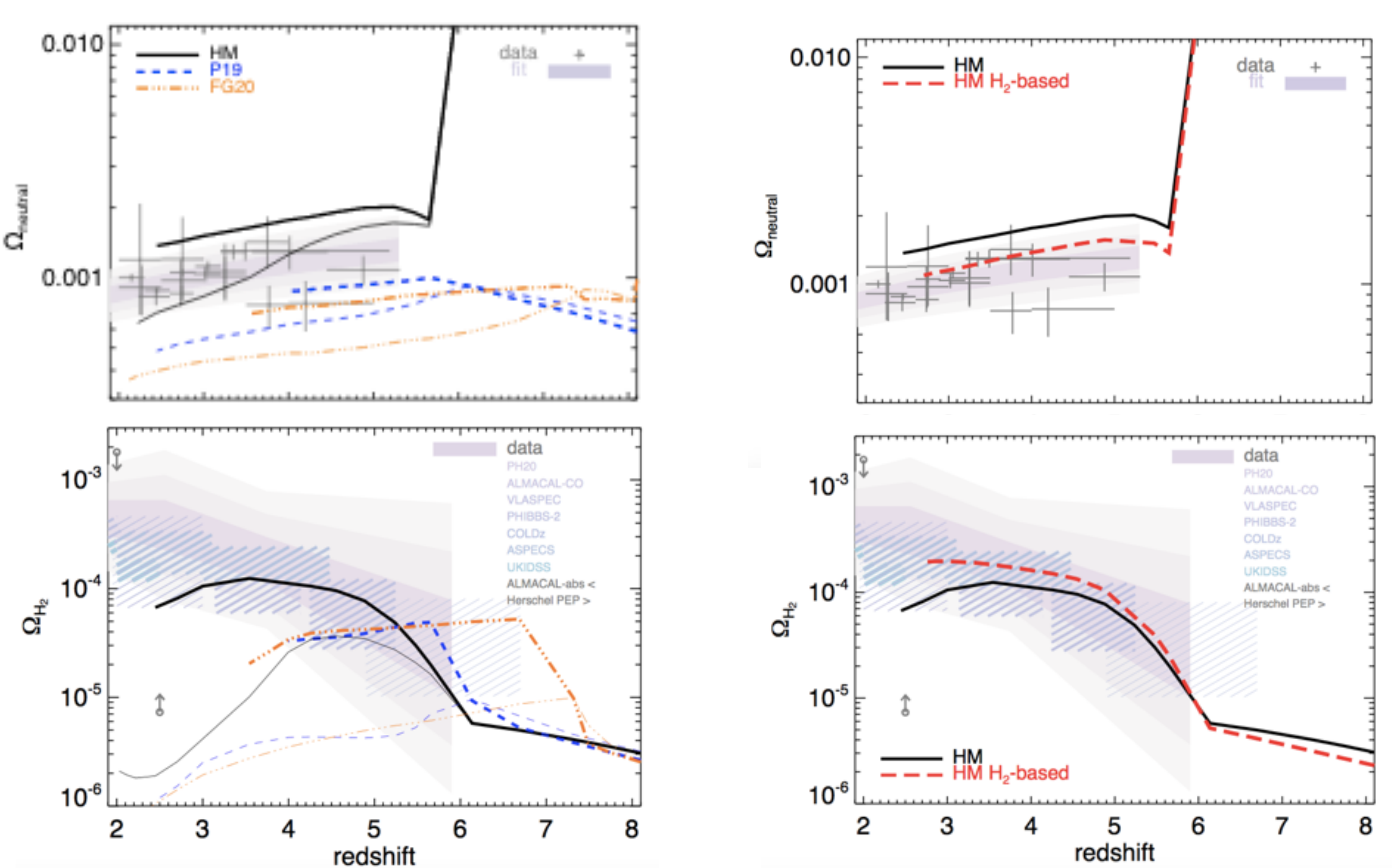
Details in
Maio, Péroux, Ciardi 2022

Distribution of atoms and molecules



Reproduce expected vs. observed $\Omega_{neutral}$ and Ω_{H_2}

for different UVBs, w or w/o HI/H2 shielding, HI/H2-based SF…

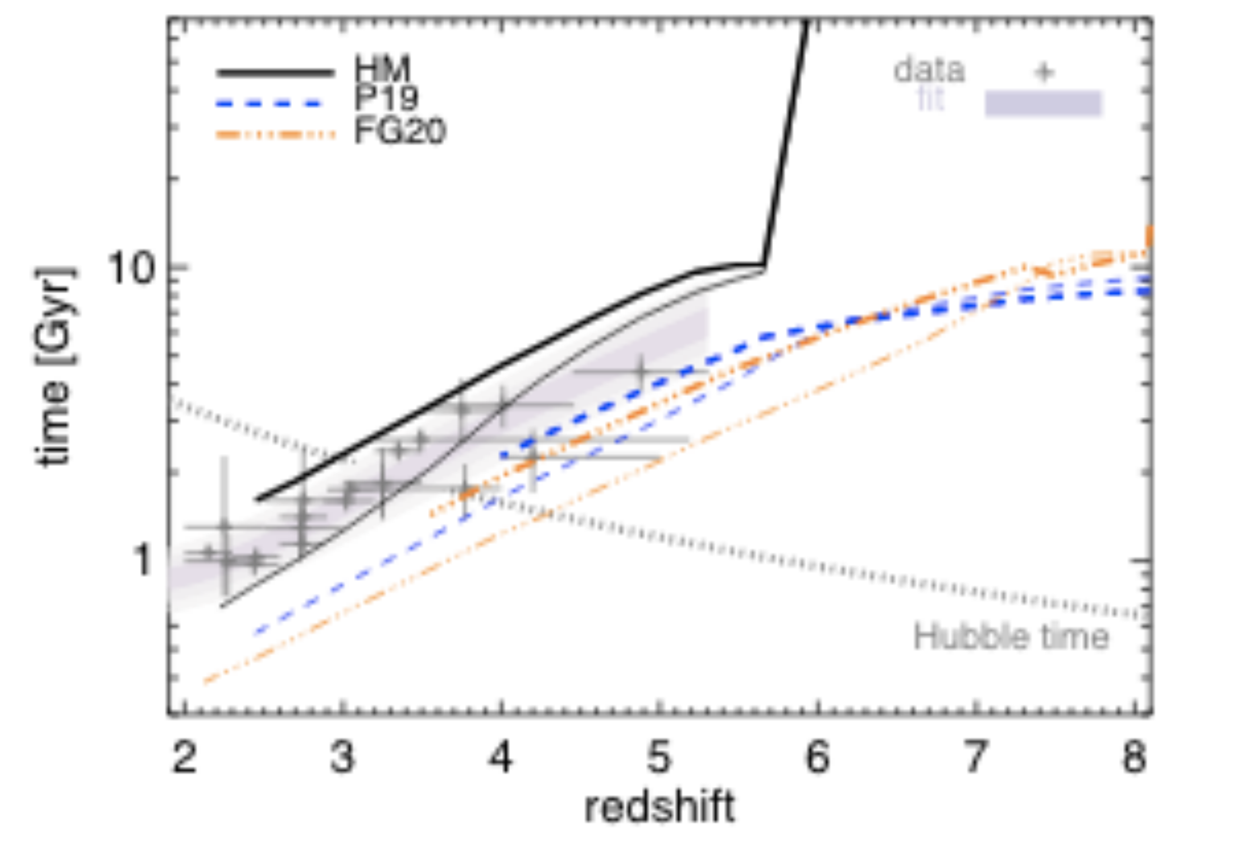


Maio, Péroux, Ciardi 2022

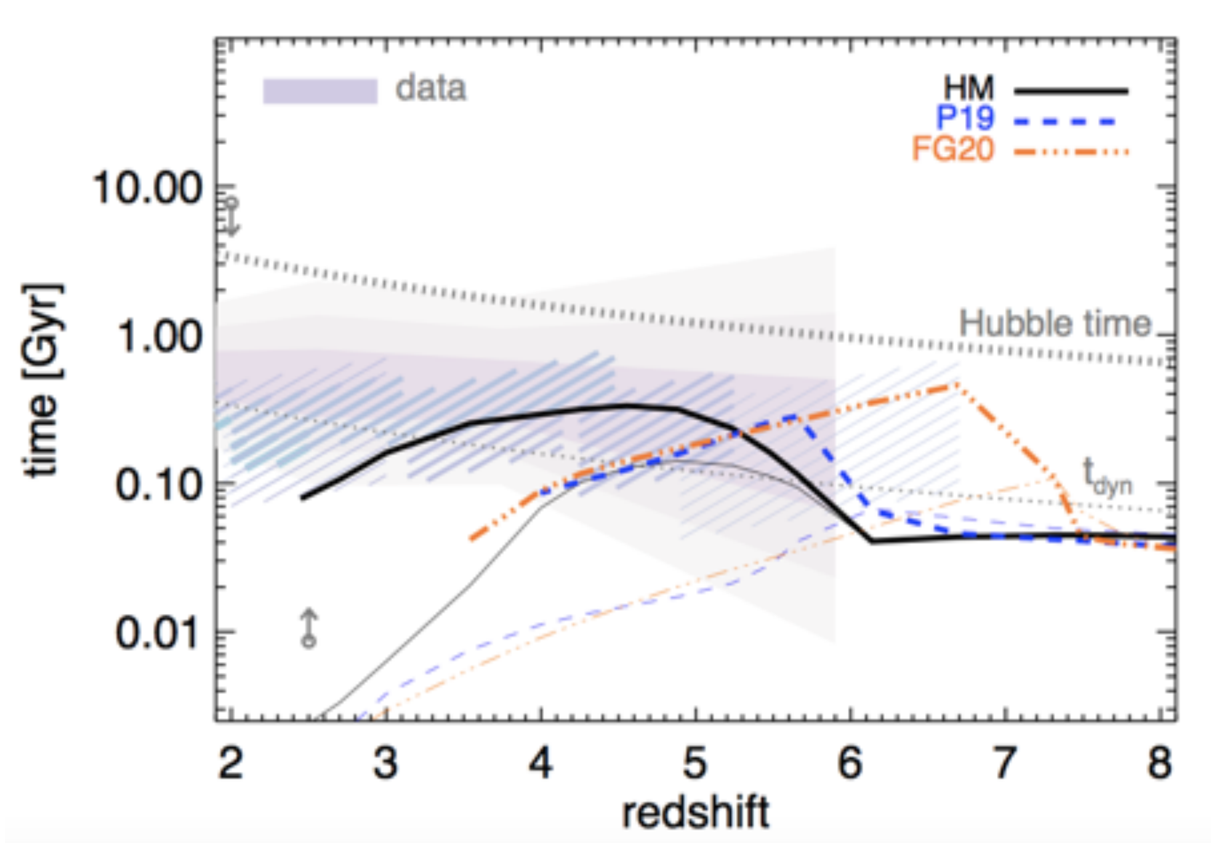
Expected vs. observed depletion times

for different UVBs w or w/o HI/H_2 shielding

HI



H_2



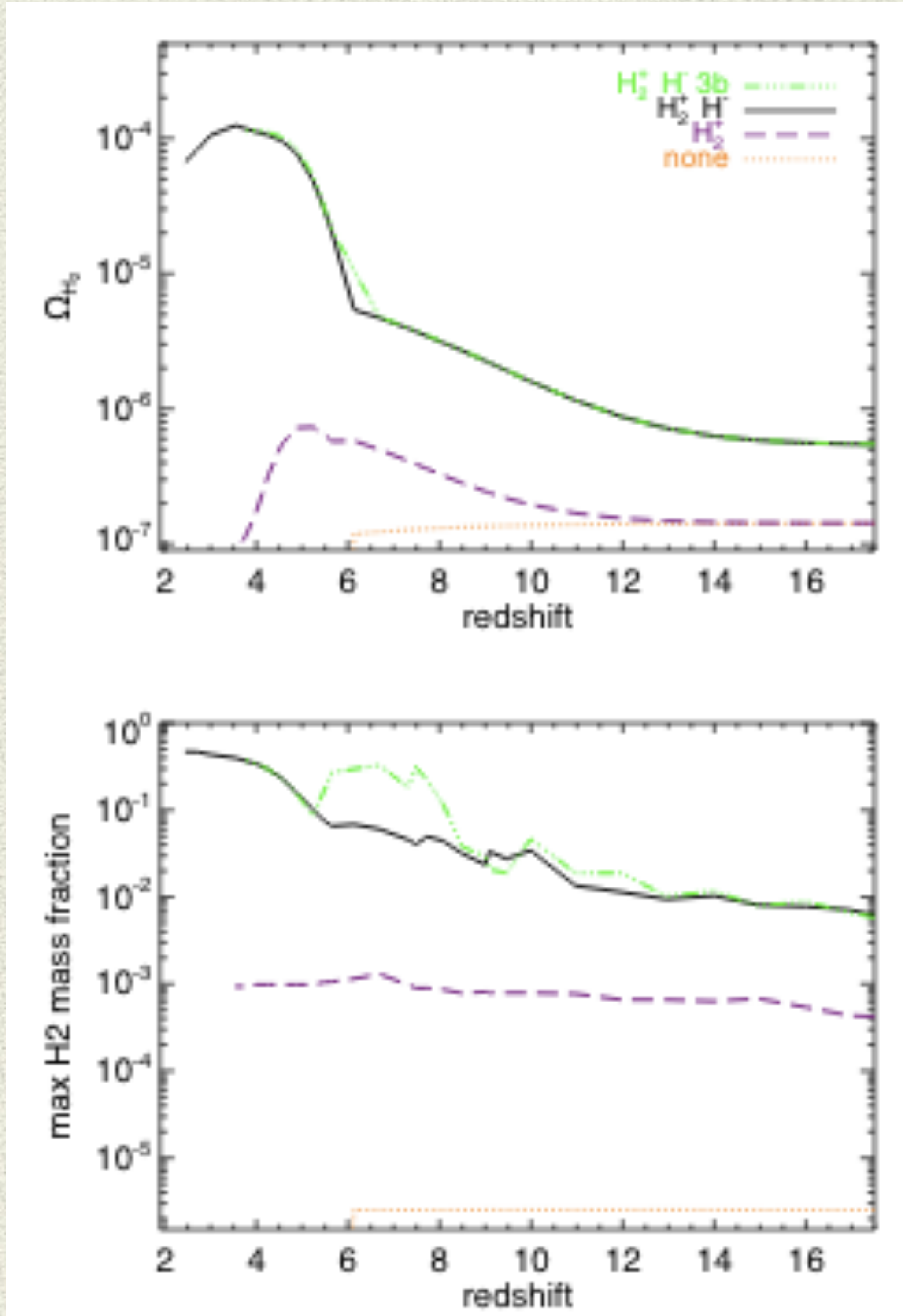
Early depletion times are short (t_{depl}<<t_H)

and dominated by molecular gas!

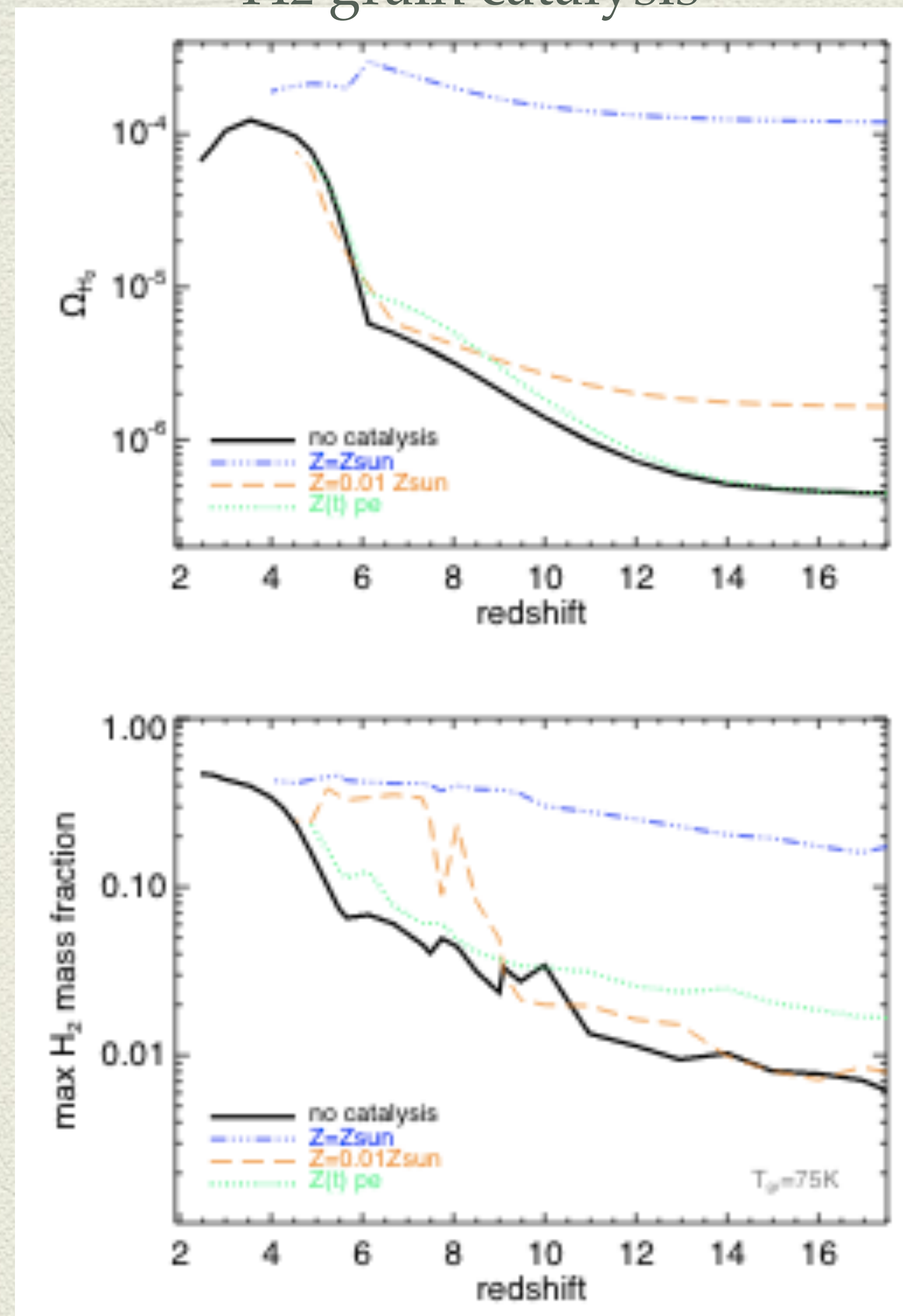
On the origin of H_2

contributions from different physical/chemical mechanisms

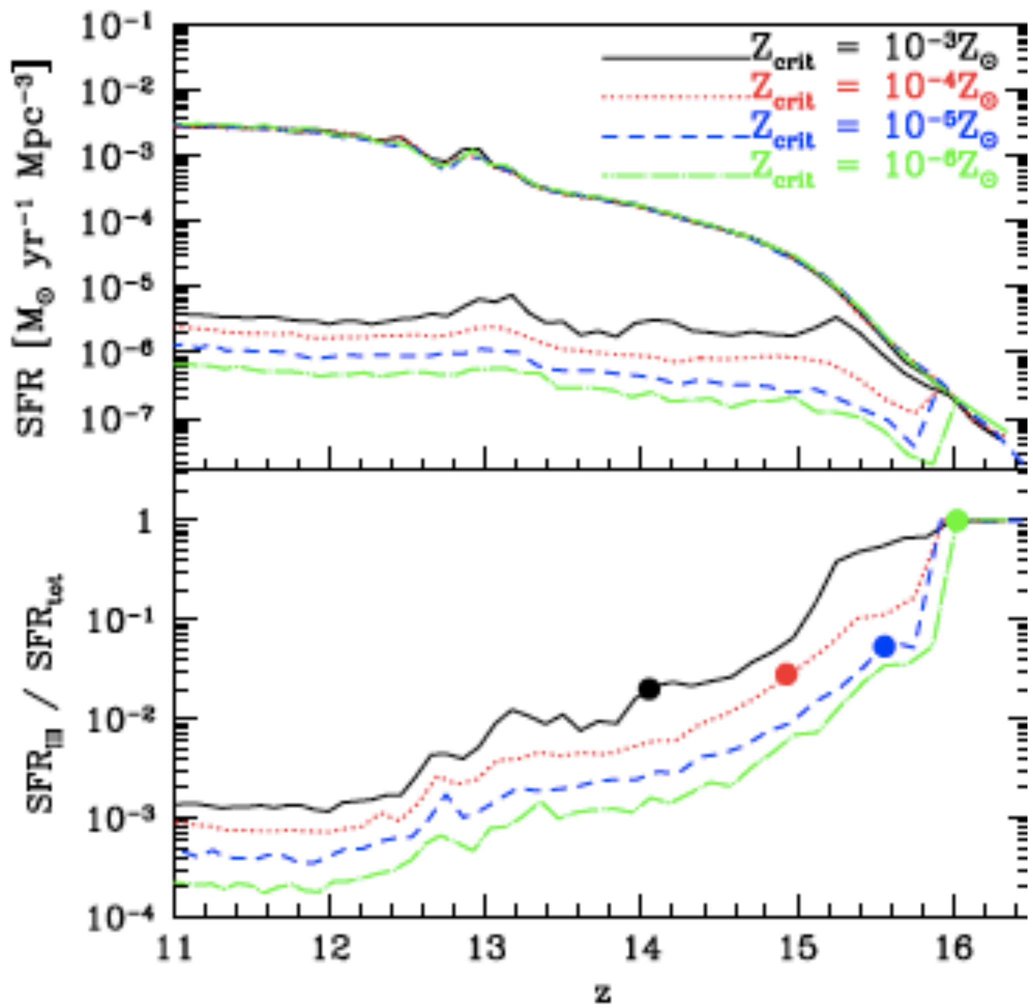
H_2 formation channels

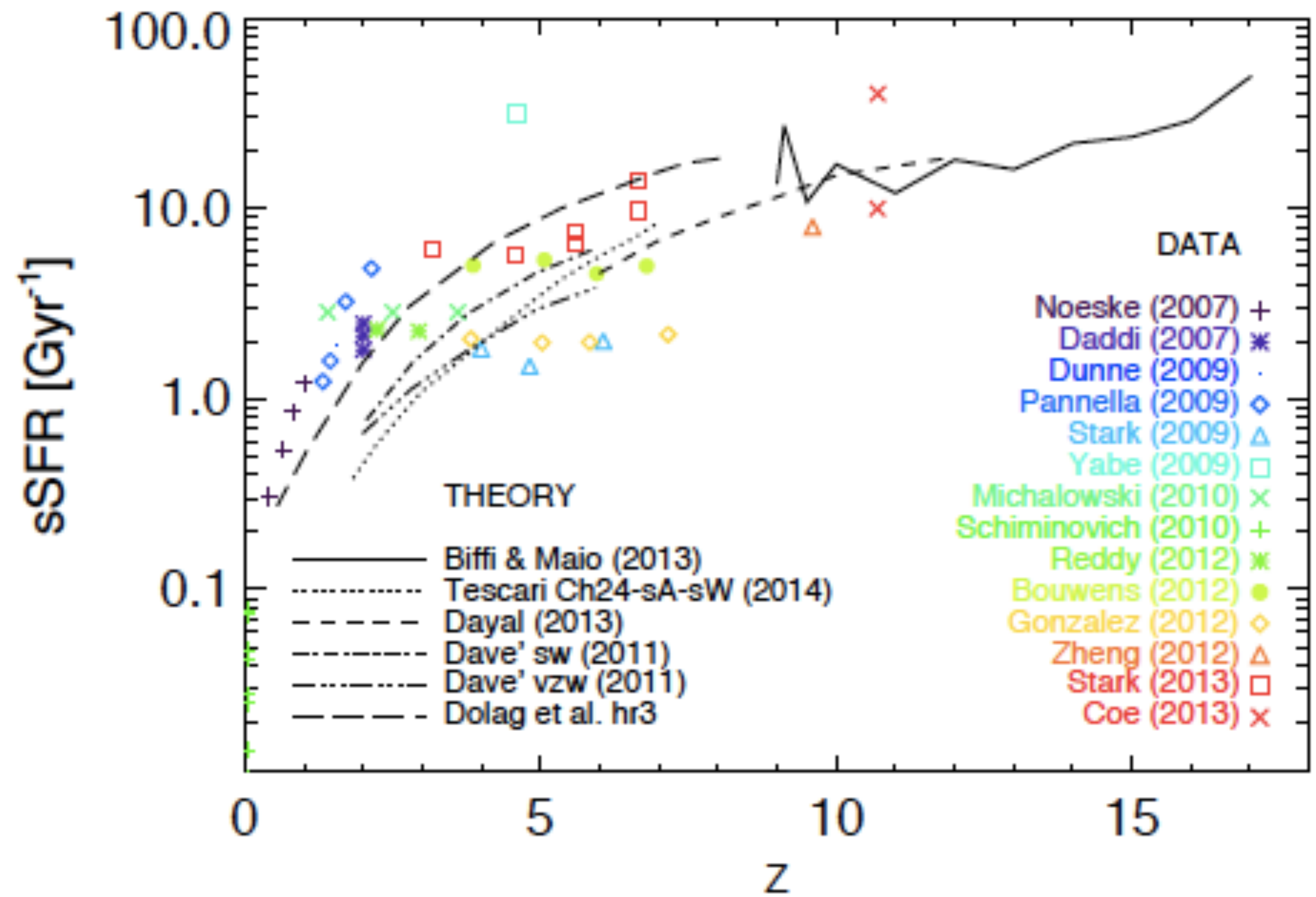


H_2 grain catalysis



Early star formation and popIII regimes



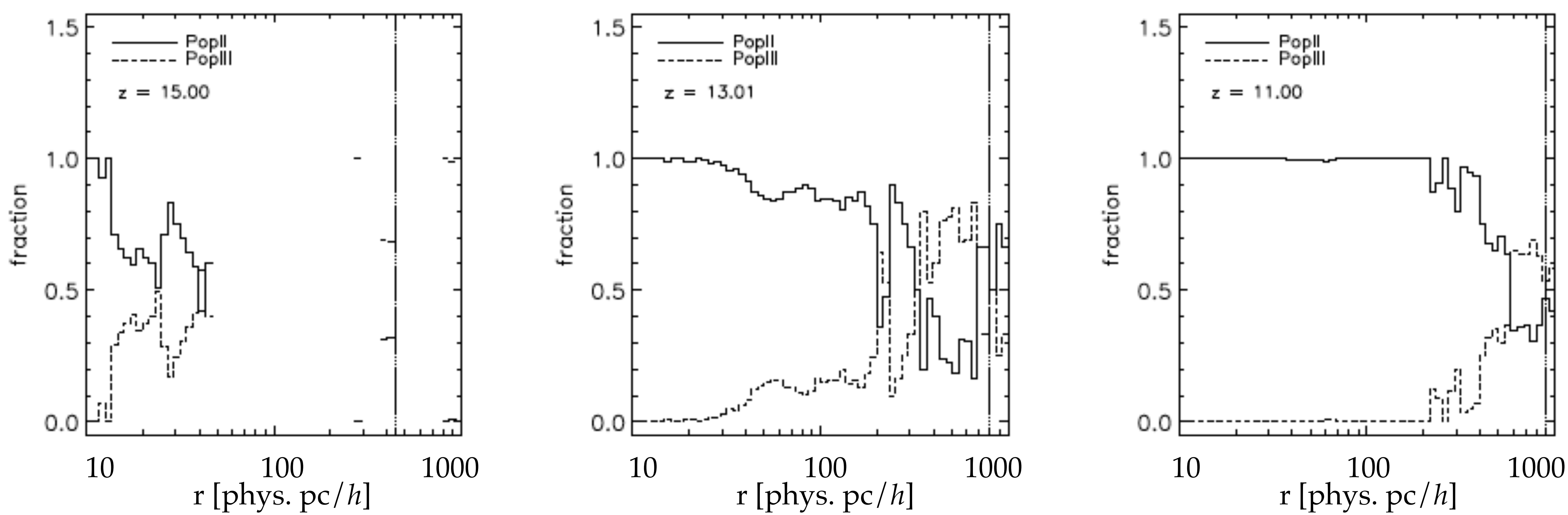


Maio+2010,2011; Biffi & Maio 2013

Radial distribution

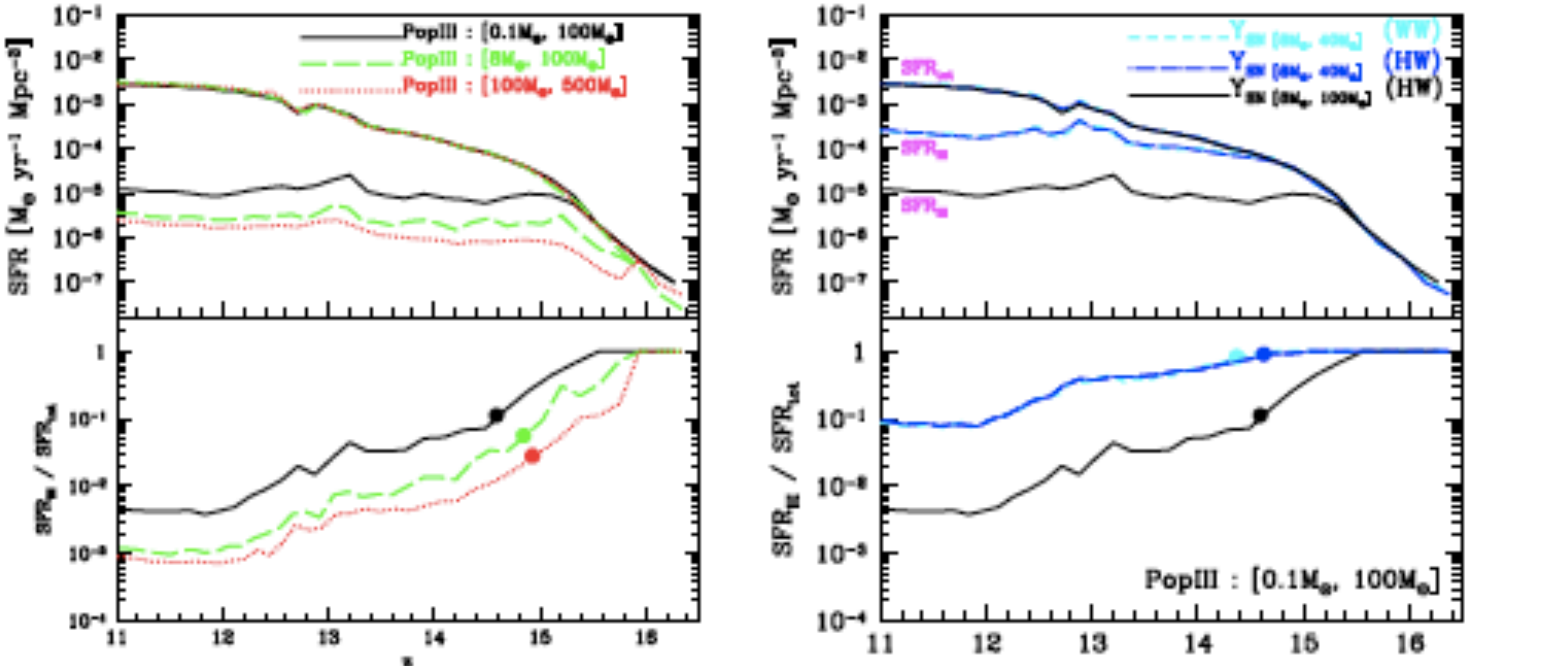
Radial fractions of popII ($Z \geq Z_{crit}$) and popIII ($0 < Z < Z_{crit}$) enriched gas in the most massive halo at $\sim 10 - 1000$ pc (physical)

(Maio et al., 2011b)



Parameter dependences

PopIII range (Salpeter IMF – top-heavy IMF)　　　　SN range (Salpeter IMF)



Mass ranges for popIII IMF and/or massive SN have significant impacts:

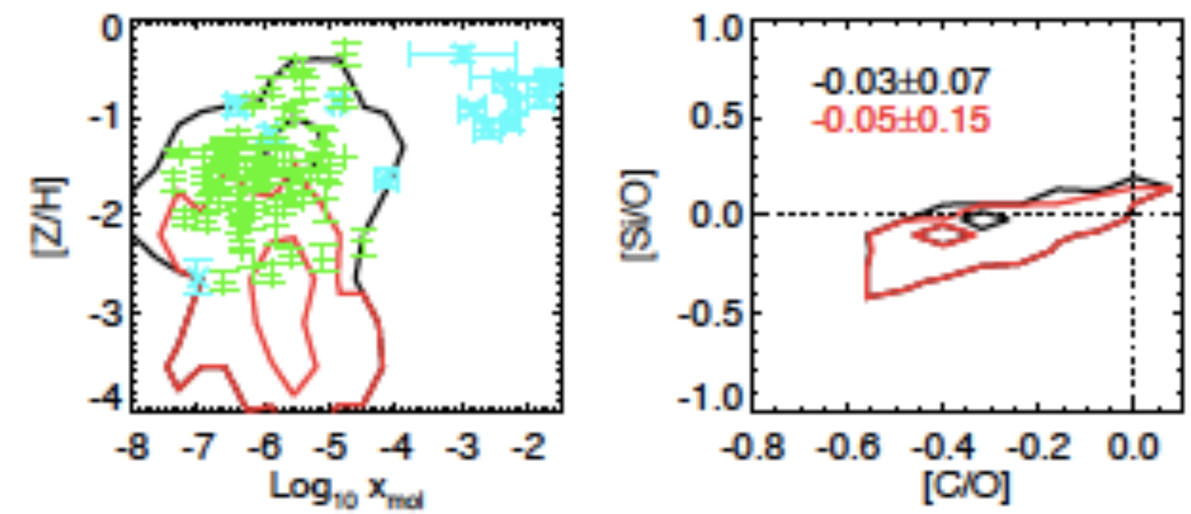
Larger masses → Shorter stellar lifetimes → Earlier enrichment → Shorter “popIII epoch”

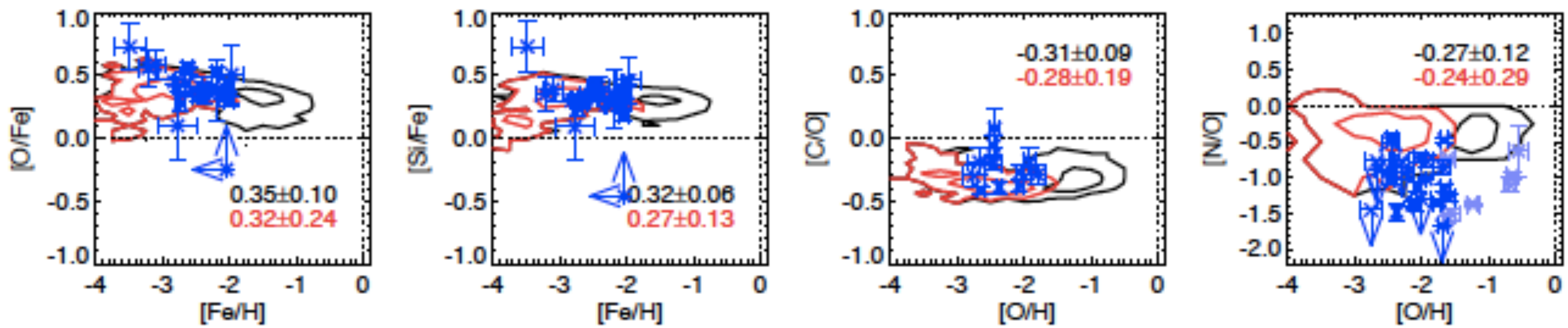
Gas metal abundance ratios

$z \simeq 3$

DLA (or GRB) **data** vs. **simulations** at different *z* are useful to check *gas abundance ratios* and the effects of different IMFs (Salpeter / top-heavy,…)

Maio+2013,2015;   Ma+2015,2017

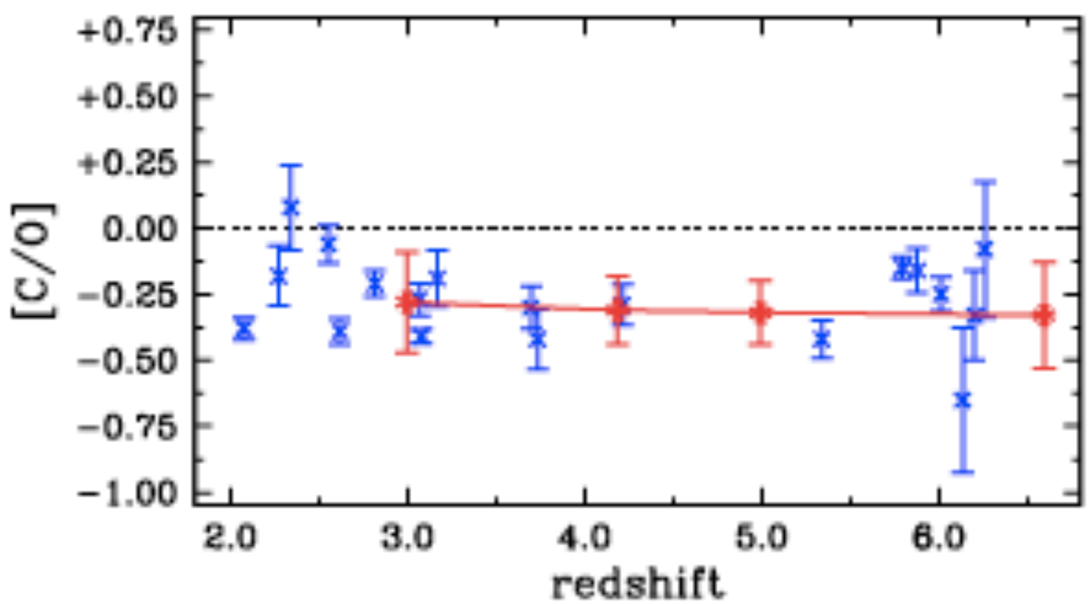




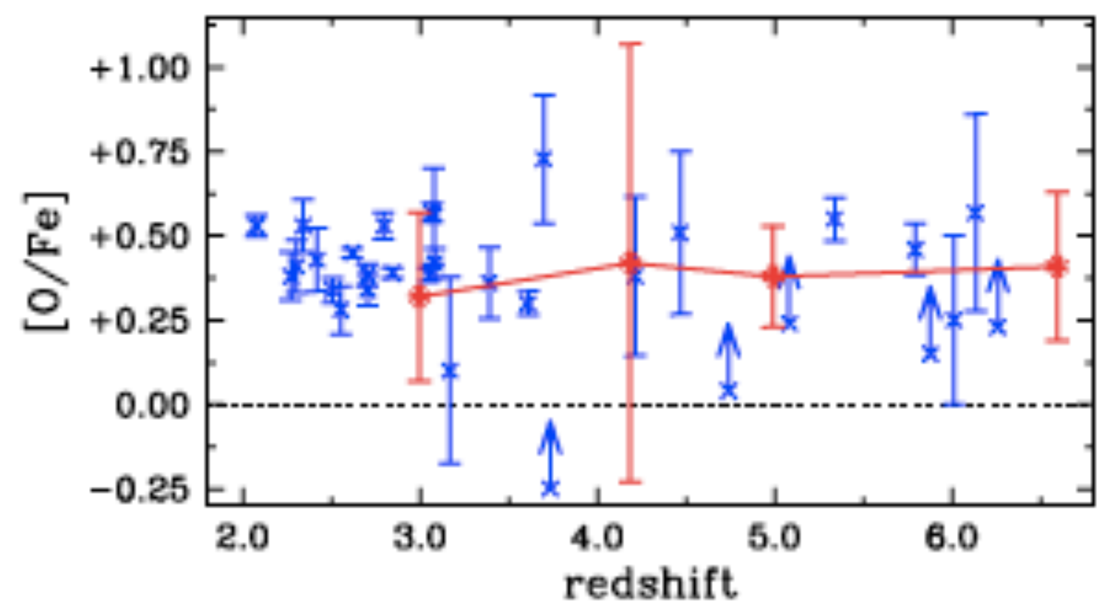
DLA data: Dessauges-Zavadsky et al. (2001), Becker et al. (2012); Cooke et al. (2015); Noterdaeme et al. (2008, 2012), Srianand et al. (2010), Albornoz Vásquez et al. (2013), Zafar et al. (2014)

DLA abundance evolution

mean [C/O] vs z



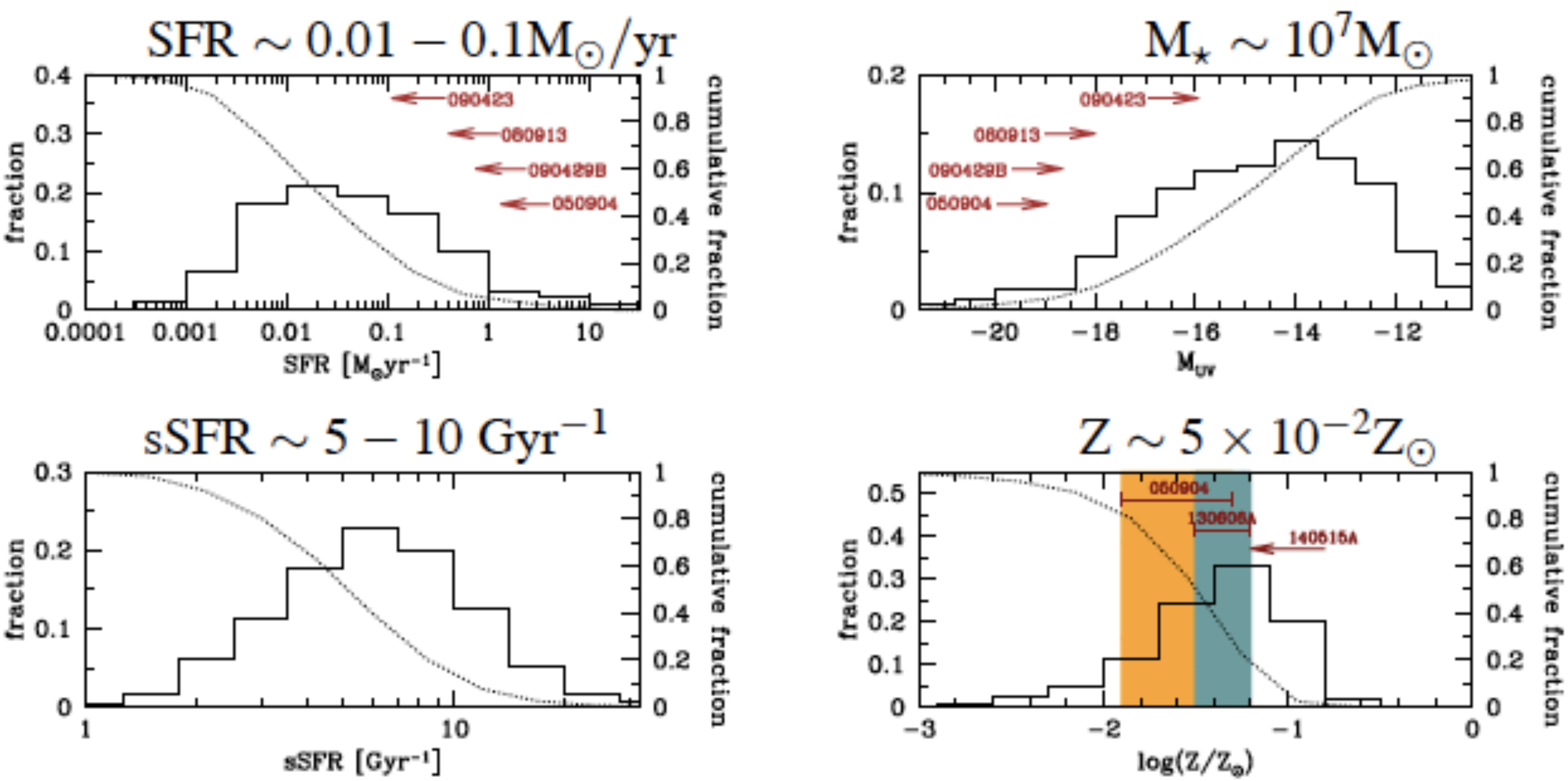
mean [O/Fe] vs z



SNII/AGB $\longrightarrow$ left; SNIa $\longrightarrow$ right (more line broadening at $z < 5$?)

No PopIII needed to explain current low-z DLA data

Statistical properties of the first GRB hosts



GRB Data: Tanvir et al. (2012); Thöne et al. (2013); Hartoog et al. (2014); Chornock et al. (2014)

Numerical models: Campisi et al. (2011); Salvaterra et al. (2013, 2015); Ma et al. (2015, 2017)

GRB abundance ratios: stellar populations at high z

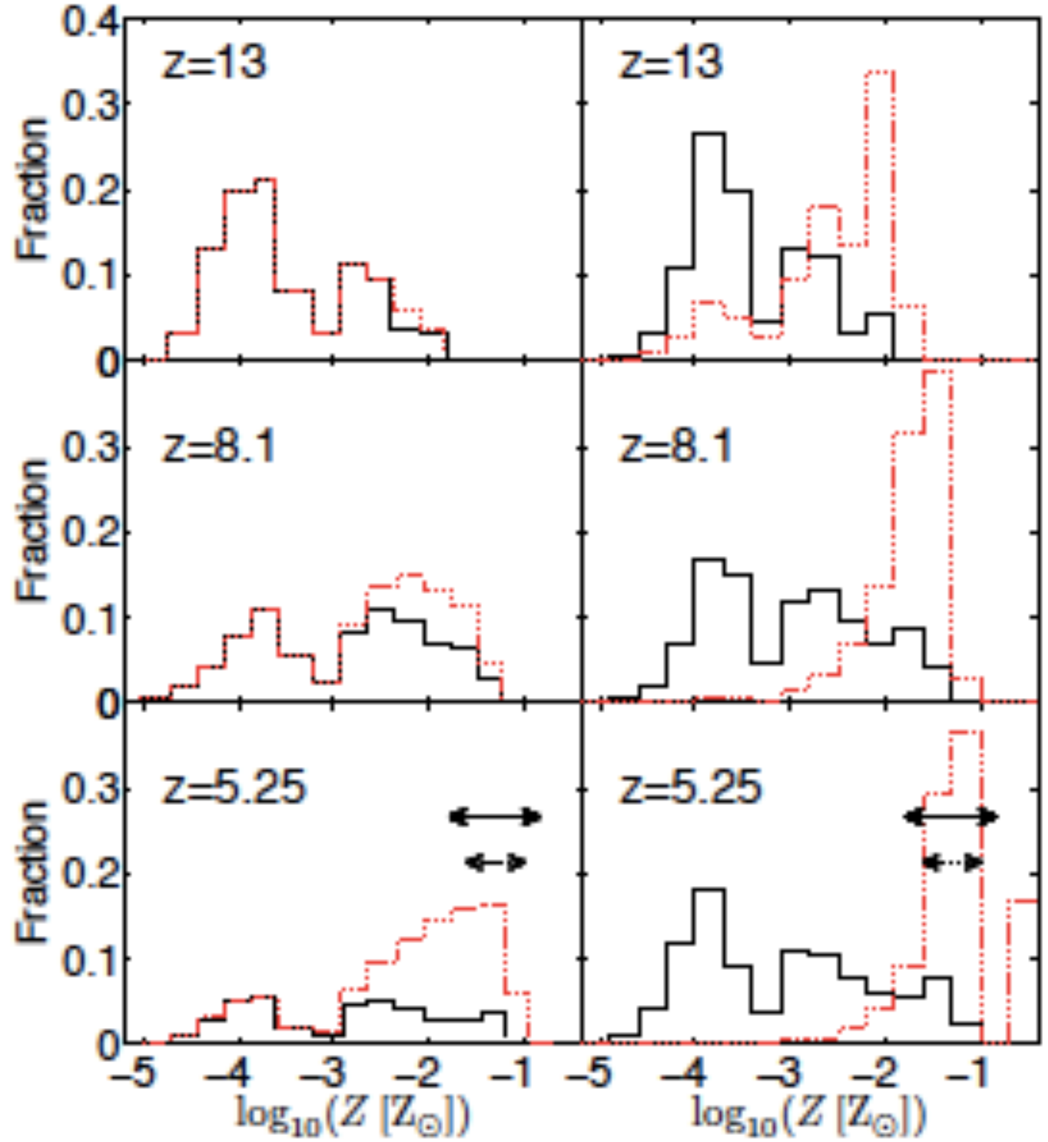
Indirect signatures:
abundance ratios

GRB 050904 ($z = 6.3$): no PopIII
$[\mathrm{C/O}] = -0.1$, $[\mathrm{S/O}] = 1.3$
$[\mathrm{Si/O}] = -0.3$, $Z \simeq 0.03\, Z_\odot$
(Kawai et al., 2006; Thöne et al., 2013)

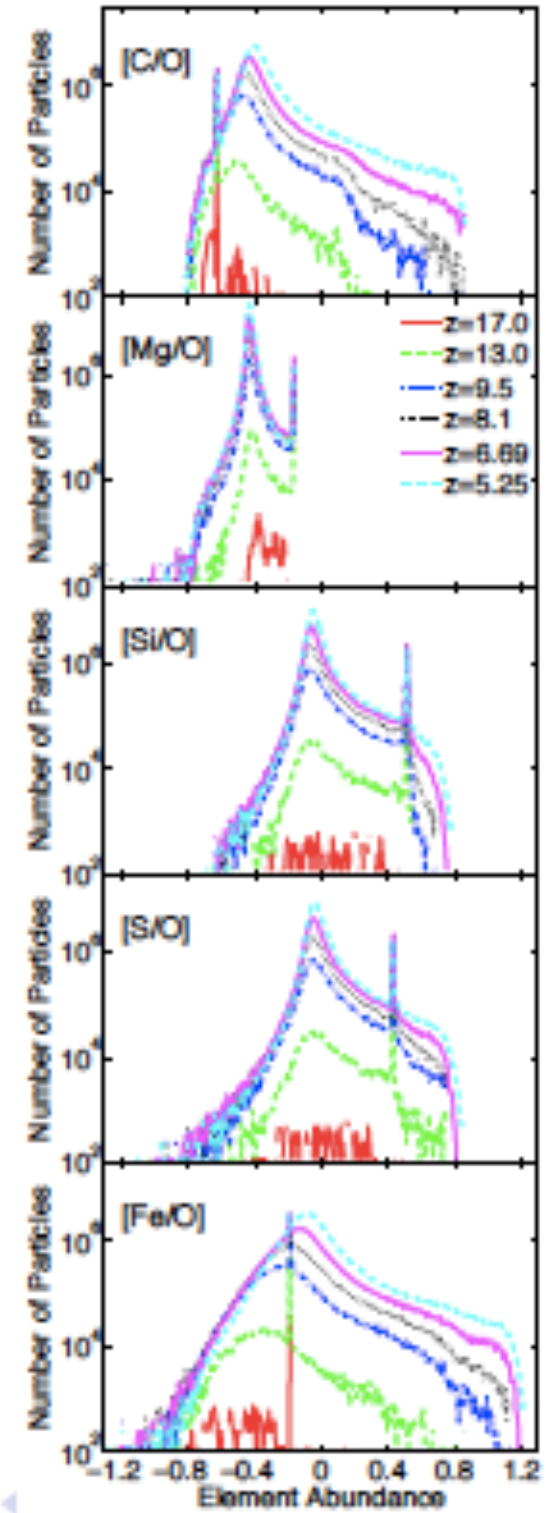
GRB 130606A ($z = 5.9$): unlikely PopIII
$[\mathrm{S/O}] < 1.24$, $[\mathrm{Si/O}] < 0.55$
$[\mathrm{Fe/O}] < -0.34$,
$Z \simeq 0.1\, Z_\odot - 0.01\, Z_\odot$
(Castro-Tirado et al., 2013)

GRB 111008A ($z = 5.0$): unlikely PopIII
$[\mathrm{S/H}] = -1.7$, $Z \gtrsim 0.01\, Z_\odot$
(Sparre et al., 2014)

GRB 100219A ($z = 4.7$): unlikely PopIII
$[\mathrm{C/H}] = -2.0$, $[\mathrm{Fe/H}] = -1.9$
$[\mathrm{O/H}] = -0.9$, $[\mathrm{S/H}] = -1.1$
$Z \simeq 0.1\, Z_\odot$
(Thöne et al., 2013)



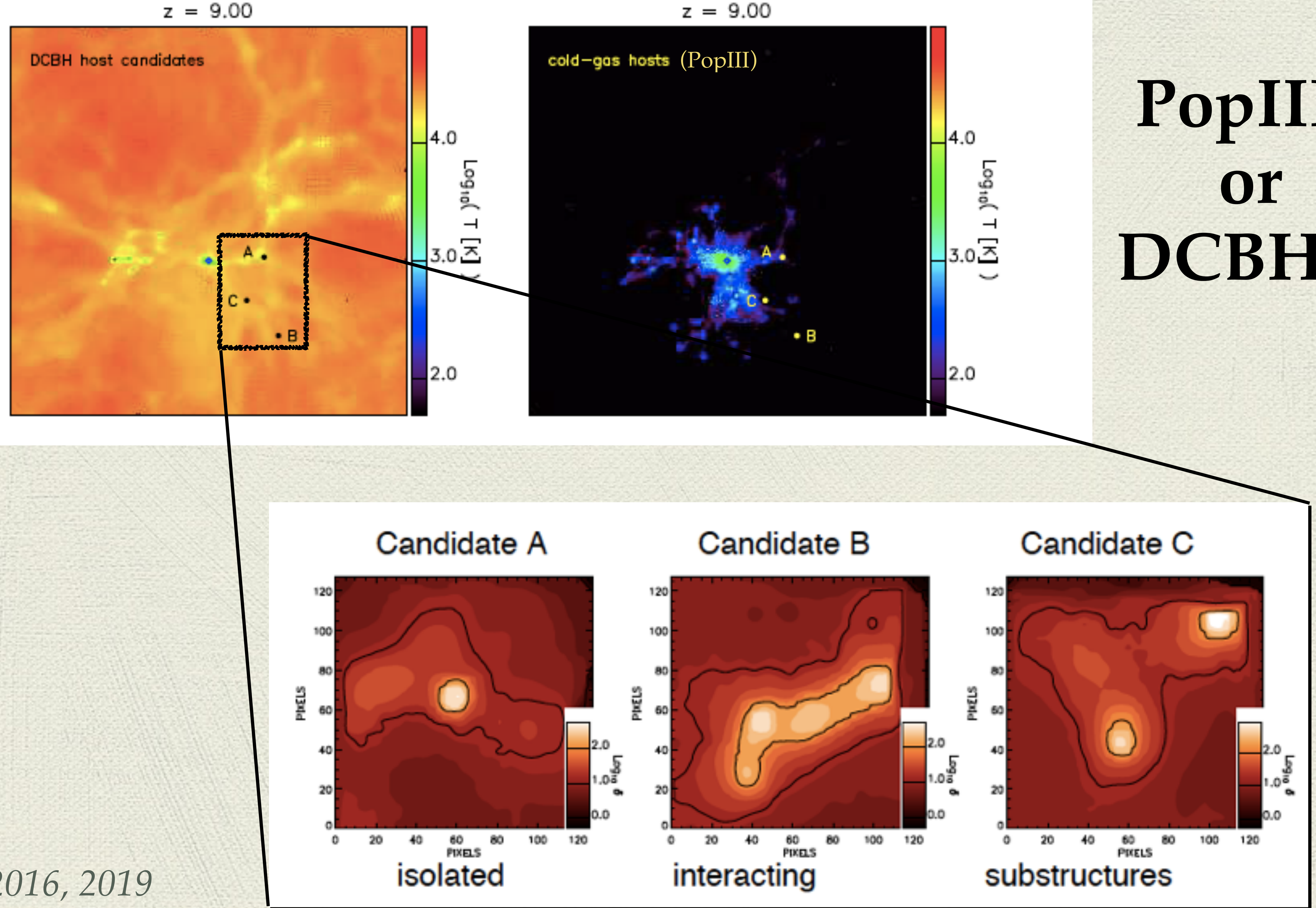
PopII-I star forming haloes
PopII-I star forming haloes pre-enriched by popIII



Ma, Maio, et al. (2015,2017)

MBHs: DCBHs as seeds of SMBHs at $z \gtrsim 6$?

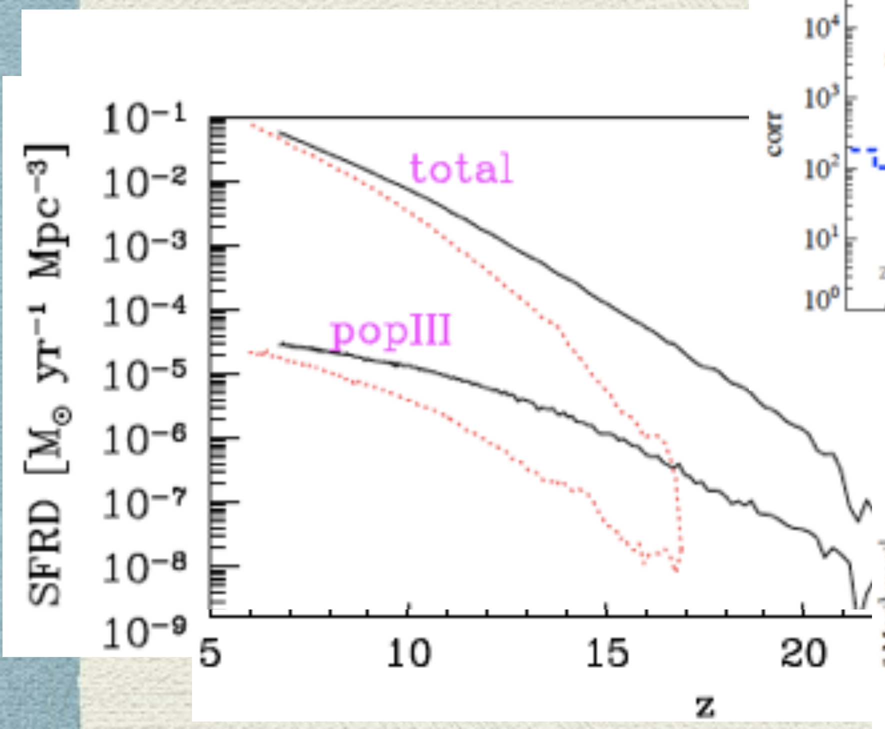
Look for haloes which host gas direct collapse (no fragmentation!):
$\longrightarrow$ pristine non-SF haloes with $\mathrm{T} \sim 10^4$ K, dark mass $\gtrsim 2 \times 10^6\,\mathrm{M}_\odot$, no H_2 content (destroyed by nearby LW radiation)

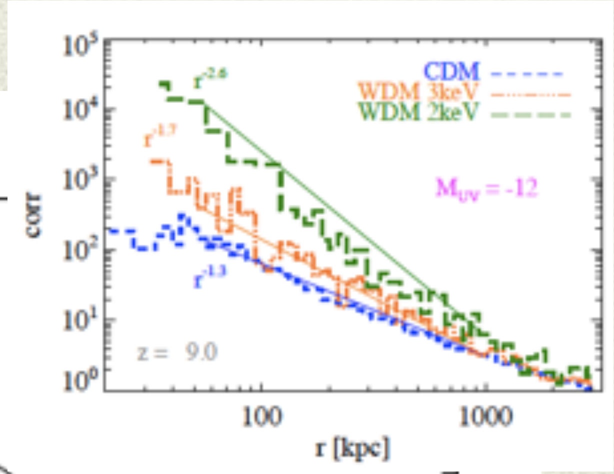


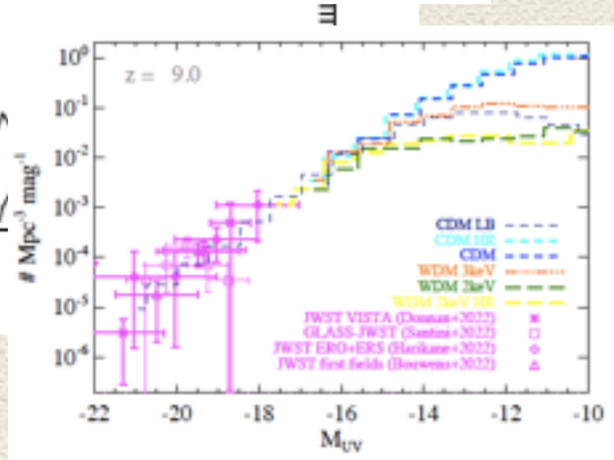
PopIIIs or DCBHs?

Maio+2016, 2019

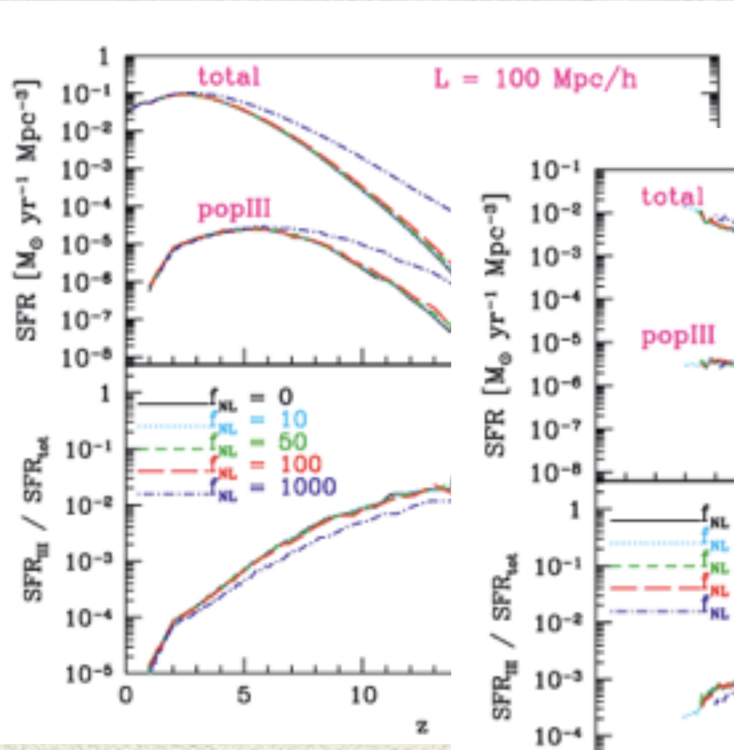
PopIII & alternative cosmological models

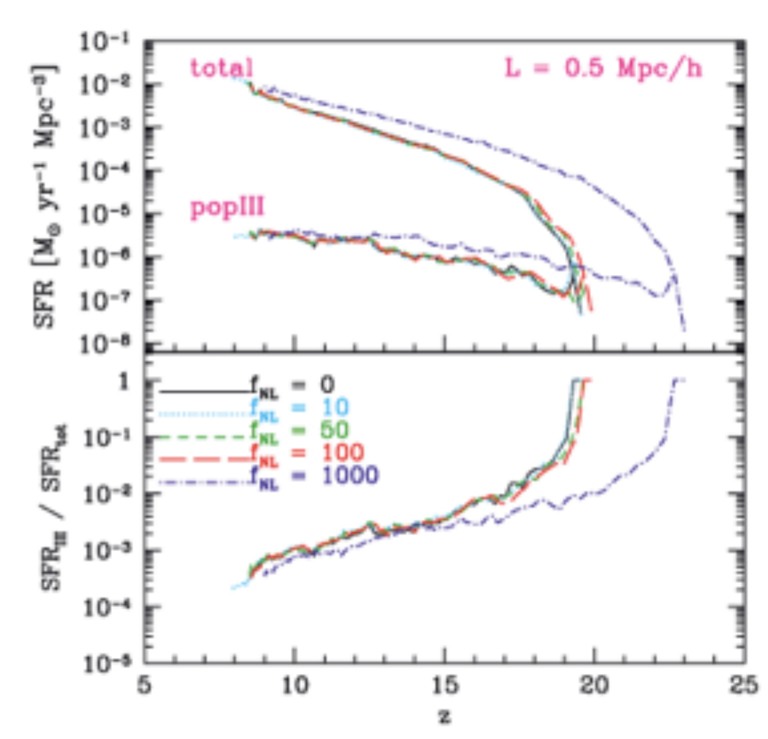




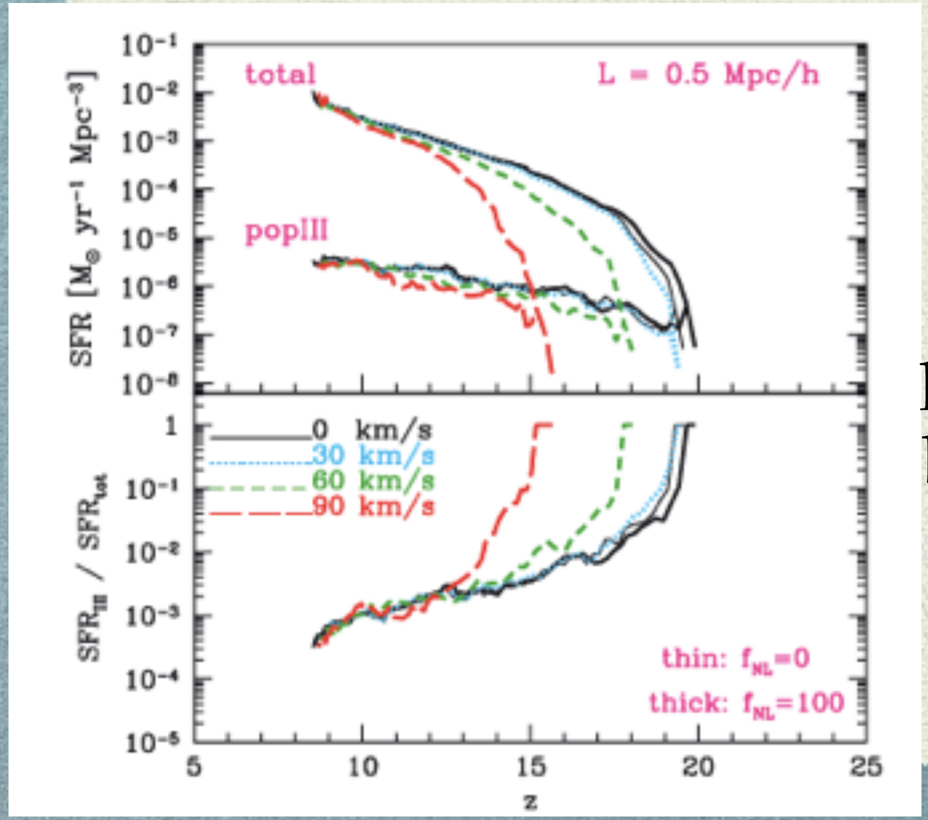


WDM-CDM



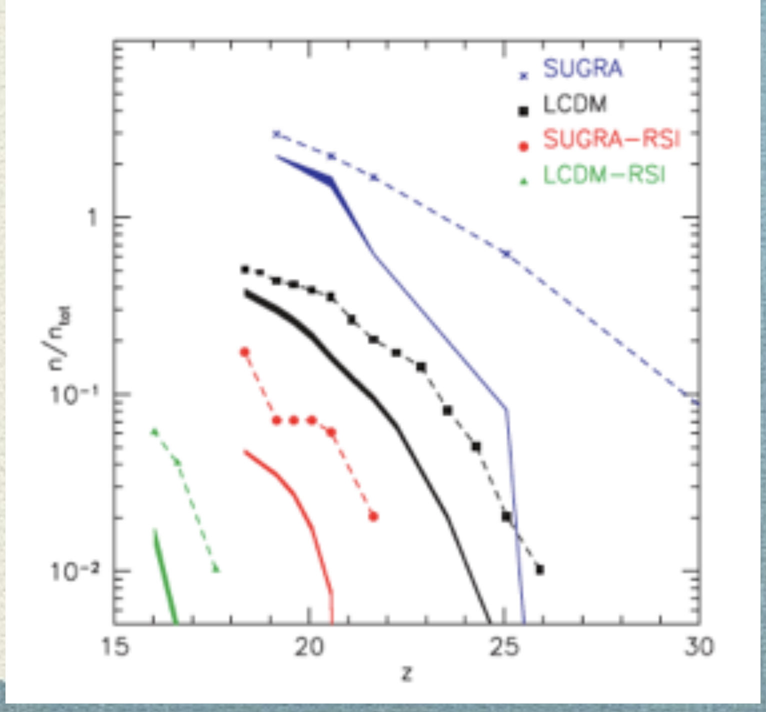


nonG



primordial bulk flows

Quintessence Dark Energy



Maio+2011,2006,2015, 2023

Summary

Gas physics and high-z structure formation can be studied effectively by means of cosmological time-dependent 'non-equilibrium' hydro-chemistry simulations

Conclusions

- Theoretical results suggest a limited contribution of primordial popIII stars to cosmic SF and a fast transition to popII regime
- Molecular-gas depletion times are 'short' already in the first half Gyr: this is crucial to explain e.g. the large reservoir of H_2 gas detected in high-z galaxies and early popIII metal enrichment
- Observed abundance ratios (DLAs, GRBs) are helpful to constrain stellar models (popIII/popII IMF, yields)
- PopIII stars can help disentangle different cosmological models