Cold atomic and molecular gas in simulations of early galaxy formation: *coldSIM*

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Outline

Motivations

Rationale Understand the evolution of cold atomic and molecular gas (HI and H_2) during galaxy formation

→ *How does cold gas evolve with z?*

→ *What is the residual neutral HI gas after reionization?*

→ *Can large amounts of H_2 form at different z and at low Z?*

→ *Are HI and H_2 depletion times compatible with gas collapse and structure formation?*

→ *What is the impact of different UVBs on cold neutral gas?*

→ *How theoretical predictions compare with HI and H_2 data?*

Requirements Study gas time-dependent composition and cooling/heating processes

Techniques *Ad hoc* implementations and simulations

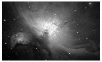
A short recap

- Well known HI abundances up to $z \simeq 5$ (via QSO spectra and 21cm analysis) in terms of $\rho_{\rm HI}$ or $\Omega_{\rm HI}$
- Increasing amounts of H_2 determinations until $z \simeq 7$ from IR and (sub)mm data (via CII/CO conversion) in terms of $\rho_{\rm H_2}$ or $\Omega_{\rm H_2}$
- Weak dependence of H_2 masses on environment up to $z \simeq 3.5$
- Large local H_2 fractions of $\sim$ 50-60% reached at $z \simeq$ 4-6
- Uncertainties about H_2 formation at different metallicities (H^- channel, grain catalysis, 3-body interactions?)

Peroux & Howk 2020, Reichers+2019, Decarli+2020, Tacconi+2020, Garratt+2021, Hamanowicz+2021, etc.

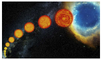
For a complete picture: *coldSIM*

$\longrightarrow$ follow gravity and hydrodynamics *coupled* to molecule formation and metal spreading from stellar evolution in LCDM box L=10Mpc/*h*



molecules determine *first* gas collapsing events

metals determine *subsequent* structure formation



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

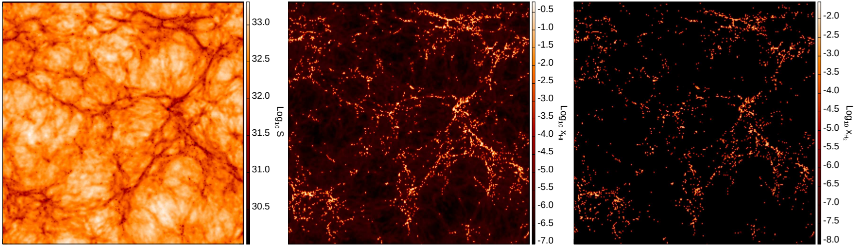
Implementing gas evolution during structure formation (Gadget3ext)

i.e. time-dependent 'non-equilibrium' abundance calculations; atomic and molecular cooling; H_2 grain catalysis; UVB, cosmic-ray and photoelectric heating; metal spreading from SNII/AGB/SNIa; winds; various IMF/UVB; etc.

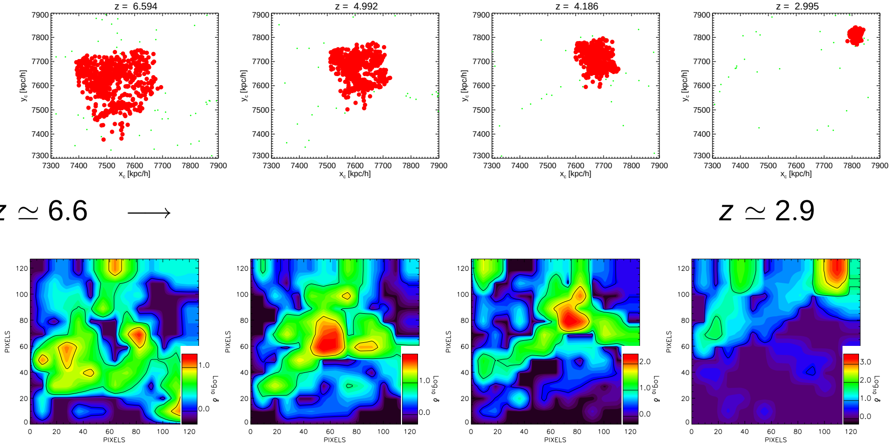
Springel,2001,2005; Yoshida+2003; Tornatore+2007; Maio+2007,2010,2016,2019,2021 ...

Cold neutral gas

Entropy HI H_2

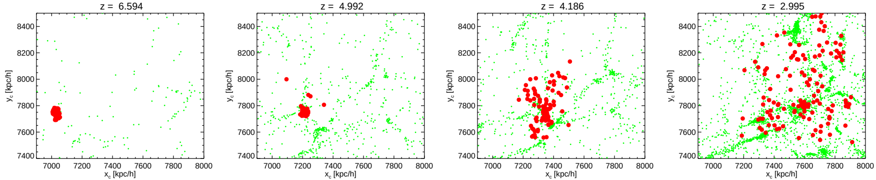


H/H_2-driven gas collapse (inflows)...



$z \simeq 6.6 \quad \longrightarrow \quad z \simeq 2.9$

... star formation and disruption (outflows)...



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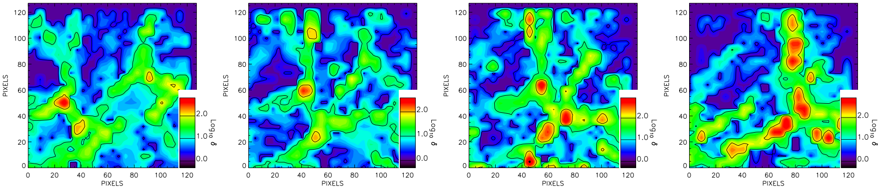


... with metal spreading

Metal enrichment and stellar evolution: massive SN $\rightarrow \alpha$, SNIa $\rightarrow$ Fe

Observables

Theoretical models must be compared against observational findings, such as:

– galaxy LFs (SFRs)
– chemical abundances (HI, H_2, DLAs, GRBs, etc.)
– UVB and reionization

Luminosity functions

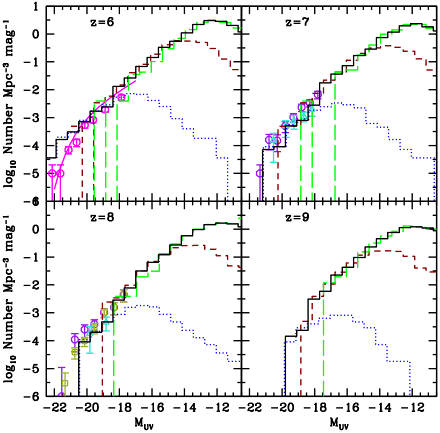
For each galaxy: $L_\lambda = L_\lambda^{\mathrm{II}} + L_\lambda^{\mathrm{III}}$
in L5, L10, L30

PopII-I SEDs from Starbust99 (Vazquez & Leitherer, 2005).
PopIII SEDs from Schaerer (2002).
No dust assumed: fair at $z > 6$

Observational data points from:

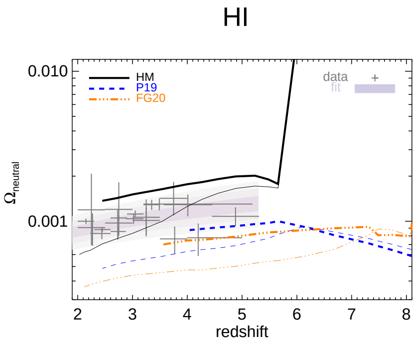
Bouwens et al., 2007 (circles); z=6
Bouwens et al., 2011 (circles); z=7-8
McLure et al., 2010 (triangles); z=7-8
Oesch et al., 2012 (squares); z=8

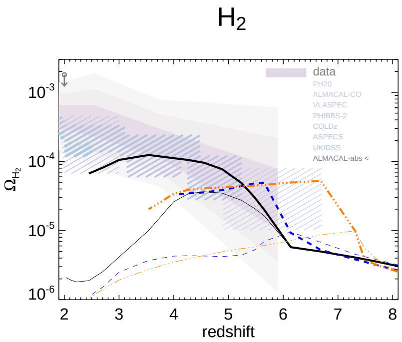
Fit: Su et al., 2012 (solid line); z=6.



Salvaterra,Maio+2013; Mancini+2016; Graziani+2020

HI and H_2 abundances for different UVBs





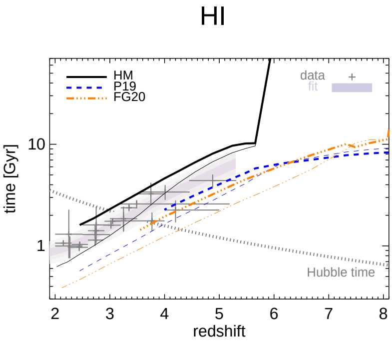
thick lines → HI and H_2 self-shielding included

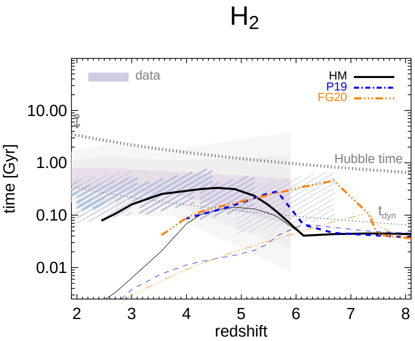
thin lines → HI self-shielding not included

+ data HI by PH20, H_2 by ALMA, VLA, NOEMA, UKIRT

Maio+2021

HI and H_2 depletion times



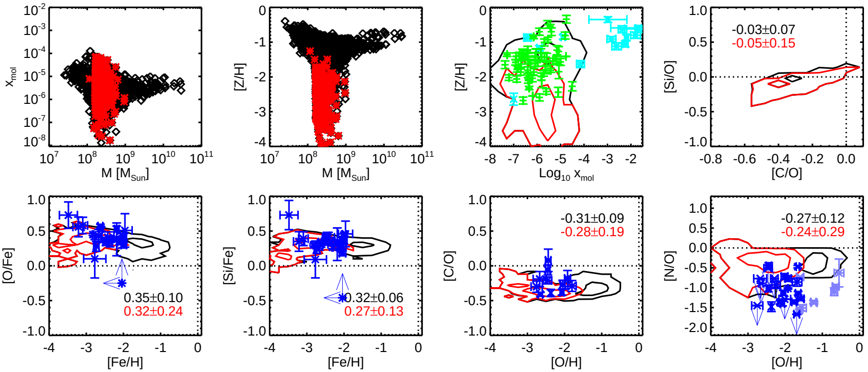


Maio+2021

dynamical time $t_{\rm dyn} = t_{\rm H}/10$

Abundance ratios: stellar populations from DLAs

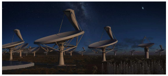
$z \simeq 3$



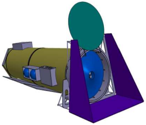
DLA data: Dessauges-Zavadsky et al. (2001), Becker et al. (2012); Cooke et al. (2015); Noterdaeme et al. (2008, 2012), Srianand et al. (2010), Albornoz Vásquez et al. (2013), Zafar et al. (2014)
Simulations with N-body/hydro + non-equilibrium chemistry + metals + feedback

Future perspectives

JWST space telescope: primordial Universe & reionization; launch: 2021+; costs: ~ 11 Bln \$ (NASA, ESA, Canadian Space Agency)



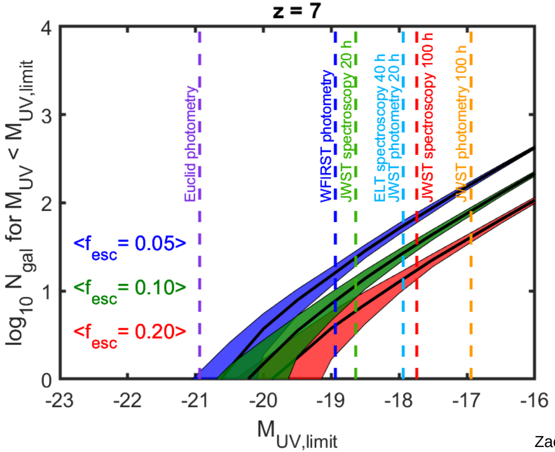
SKA radio telescope: HI gas, reionization, galaxy formation, radio transients; construction: 2020s; costs: ~ 8 Bln EUR (large Int. coll.)



Athena satellite: hot gas, clusters, z$\sim$6-10 GRB X-ray afterglows; launch 2028+; costs: ~ 1.3 Bln EUR (ESA, Airbus, Thales-Alenia)

Great Expectations ©

Promising tools to observe galaxies through ionized ‘bubbles’



Zackrisson et al., 2020

Summary...

- We have presented results from cosmological hydro chemistry simulations including detailed time-dependent ‘non equilibrium’ cold-gas modelling: coldSIM
- We study gas and galaxy evolution and their interplay

Conclusions...

- Non-equilibrium H_2 formation can easily justify the persistence of large molecular masses at high z and various environments (Z)
- UVB models are roughly consistent with $\Omega_{\rm neutral}$ data
- UVB models do not always agree with $\Omega_{\rm H_2}$ data $\rightarrow$?
- H_2 depletion times around or below $t_{\rm dyn}$ up to high z $\rightarrow$ cold gas in very early epochs is able to collapse!
- Metal abundance ratios helpful to constrain stellar models