Max Planck Institute for Astrophysics Garching

Early molecules, star formation and metal pollution

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We present results of structure formation studies derived by performing detailed N-body/hydrodynamical (SPH) numerical simulations. We implement in Gadget2 molecular and metal cooling (Maio et al. 2007), joined with metal enrichment and feedback schemes including winds and star formation (Tornatore et al. 2007; Springel & Hernquist, 2003).

In order to exactly follow star formation (SF) processes, it is necessary to consider all the relevant physical coolants (molecules and metals, if any) and to resolve at the same time very large and very small scales. Nowadays simulations do not allow that, so it is usual to fix some critical density threshold beyond which one assumes star formation. Once the stars are born they affect the surrounding medium with winds and metal ejection during their final stages.

The results of this approach (both in numerical and semi-analytical studies) are very sensitive to the density threshold adopted, which is the most critical parameter.

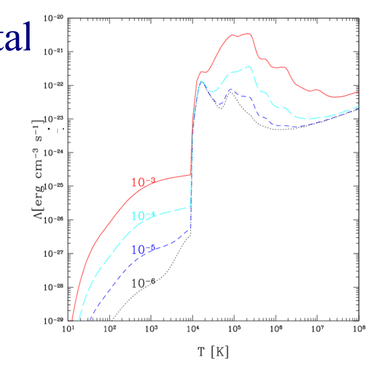
PHYSICS INCLUDED: gravity, molecular chemistry (reaction list below) and relative cooling with metal contribution from stellar pollution (e.g. plot on the very right for different metal number fractions), SF.

$H + e^- \rightarrow H^+ + 2e^-$
$H^+ + e^- \rightarrow H + \gamma$
$He + e^- \rightarrow He^+ + 2e^-$
$He^+ + e^- \rightarrow He + \gamma$
$He^+ + e^- \rightarrow He^{++} + 2e^-$
$He^{++} + e^- \rightarrow He^+ + \gamma$
$H + e^- \rightarrow H^- + \gamma$

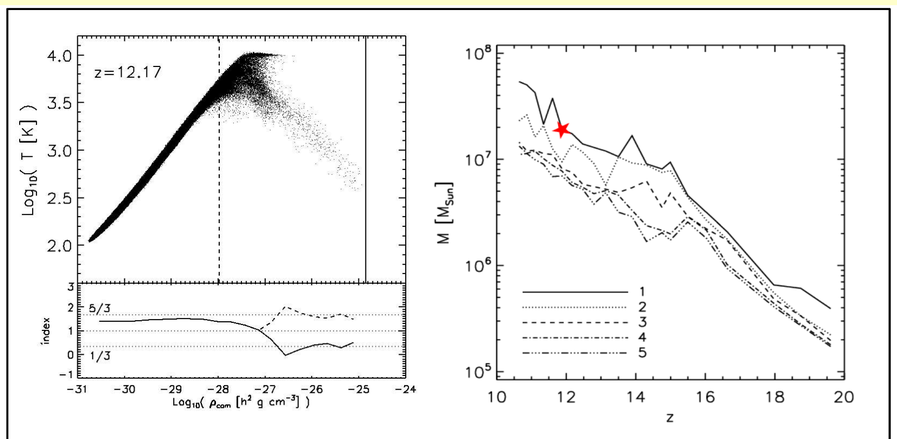
$H^- + H \rightarrow H_2 + e^-$
$H + H^+ \rightarrow H_2^+ + \gamma$
$H_2^+ + H \rightarrow H_2 + H^+$
$H_2 + H \rightarrow 3H$
$H_2 + H^+ \rightarrow H_2^+ + H$
$H_2 + e^- \rightarrow 2H + e^-$
$H^- + e^- \rightarrow H + 2e^-$

$H^- + H \rightarrow 2H + e^-$
$H^- + H^+ \rightarrow 2H$
$H^- + H^+ \rightarrow H_2^+ + e^-$
$H_2^+ + e^- \rightarrow 2H$
$H_2^+ + H^- \rightarrow H + H_2$
$D + H_2 \rightarrow HD + H$
$D^+ + H_2 \rightarrow HD + H^+$

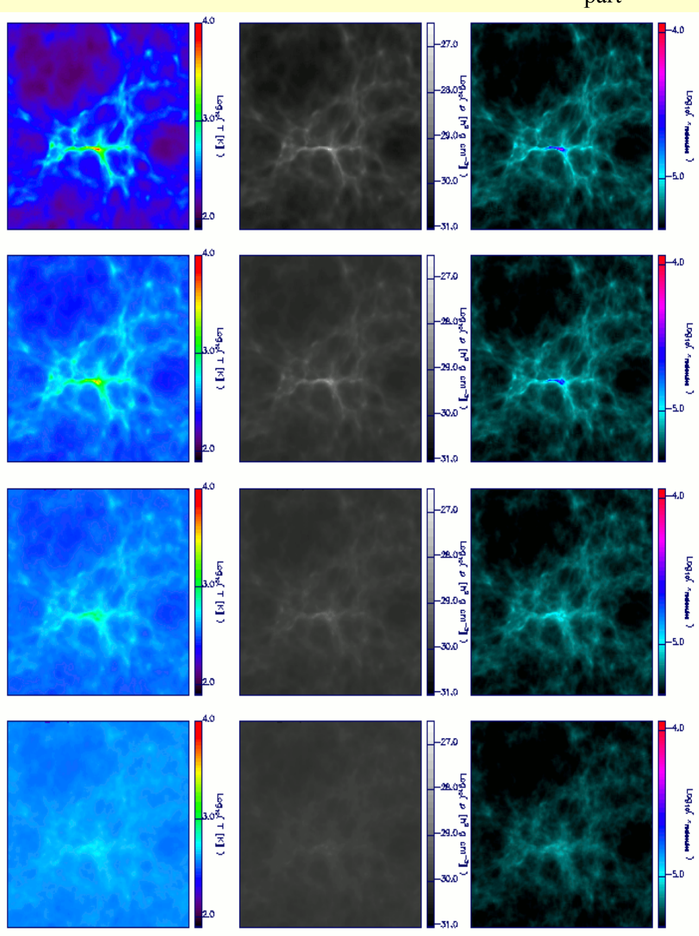
$HD + H \rightarrow D + H_2$
$HD + H^+ \rightarrow D^+ + H_2$
$H^+ + D \rightarrow H + D^+$
$H + D^+ \rightarrow H^+ + D$
$He + H^+ \rightarrow HeH^+ + \gamma$
$HeH^+ + H \rightarrow He + H_2^+$
$HeH^+ + \gamma \rightarrow He + H^+$



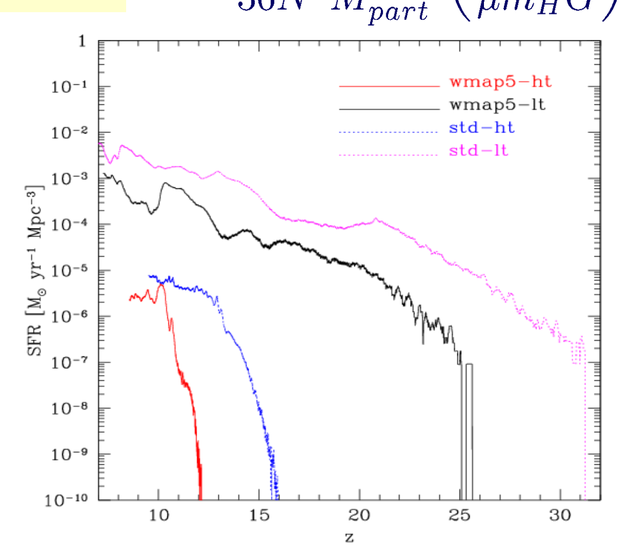
I. COSMOLOGICAL SET UP: we perform cosmological simulations fixing the star formation threshold according to the Jeans mass that we can resolve with at least N particles of mass M_{part}, namely: $\rho_{th} = \frac{\pi^2}{36 N^2 M_{part}^2} \left(\frac{k_B T_0}{\mu m_H G} \right)^3$



▲ Phase diagram, at z=12.17, with effective index in the bottom inset (left) and evolution of the five most massive haloes (right) for a simulation with WMAP5 parameters (Ω_{0m}=0.26, $\Omega_{0\Lambda}$=0.74, Ω_{0b}=0.04, h=0.72, σ_8=0.8, n=0.96). The dashed line refers to a physical number density of about 0.1 h^2cm^{-3}, the solid line to our modelling for resolving primordial objects (about 10^3 times higher). The red star signs the redshift when the first star is formed.

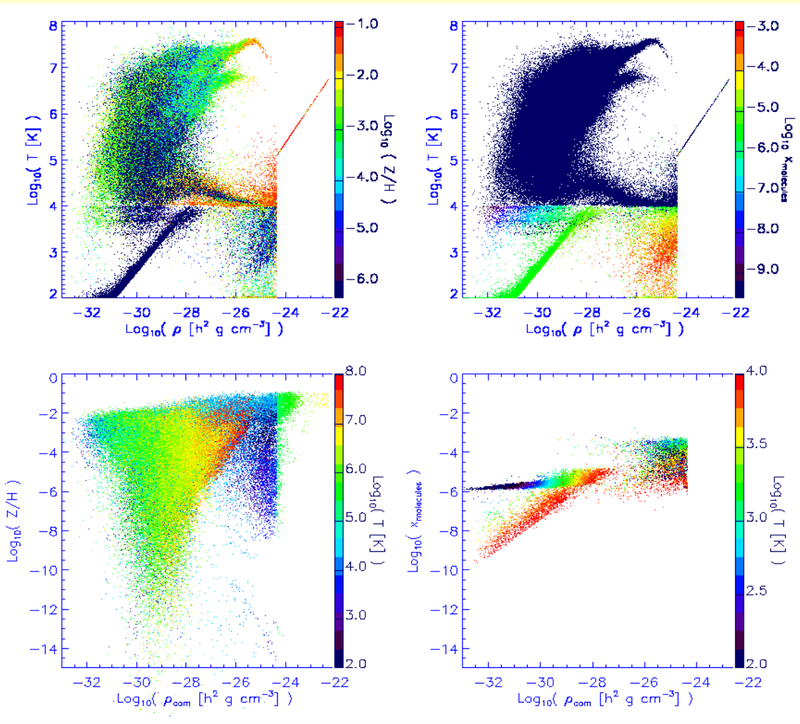


▶ Temperature (I column), density (II column) and molecule abundance (III column) maps for the same simulation when the age of the Universe is 0.1, 0.2, 0.3, 0.4 Gyr, from bottom to top.

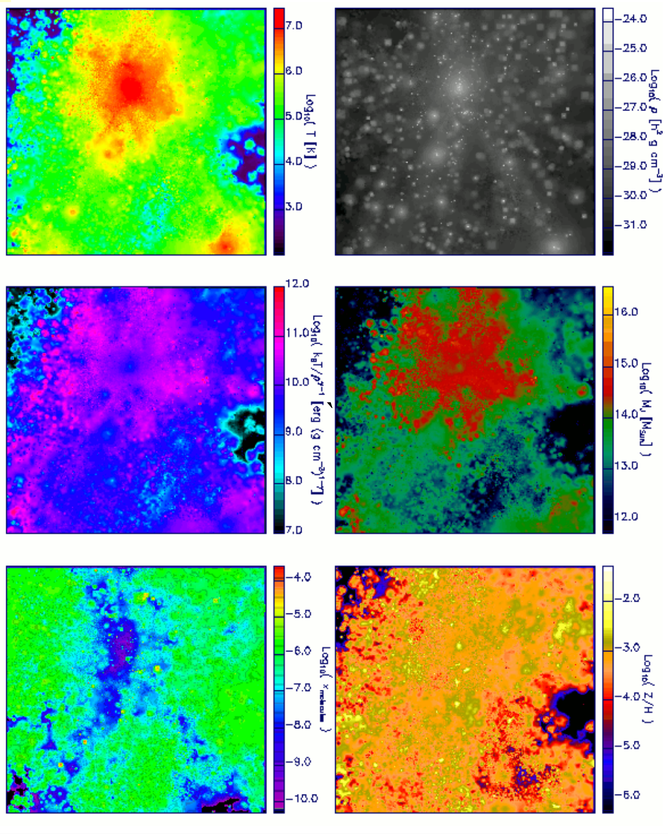


▲ Star formation rate (SFR) evolution for four different simulations (see labels). We compare Gadget low density threshold SF model (0.2 h^2cm^{-3}, 'lt') with our high threshold SF model (135 h^2cm^{-3}, 'ht'). The 'ht' model allows to follow gas condensation via molecular cooling, while the common 'lt' model assumes SF before the primordial gas can actually cool. The *delay* in the SF is evident.

II. GALAXY CLUSTER: we simulate a high density region extracted from a 479 Mpc/h cosmological simulation with standard parameters (Ω_{0m}=0.3, $\Omega_{0\Lambda}$=0.7, Ω_{0b}=0.04, h=0.7, σ_8=0.9, n=1).



◀ LEFT: phase diagrams (upper row) and density distribution (lower row) of metals (left panel) and molecules (right panel) at redshift z=0. While the spreading of metals happens randomly, molecules are very sensitive to temperature and a double tail is generated as a consequence of the SF history: molecules are destroyed during SF and reformed afterward, when particles which have experienced SF and/or winds reach cooler ($T<10^4$K), lower density regions. (It is possible to run up to z=0 only with a low density threshold).



▶ RIGHT: from top to bottom, from left to right, in order of row, we show temperature, density, entropy, Jeans mass, molecule and metal maps at redshift z=0. One can notice the anticorrelation (*negative feedback*) between molecules and hot star forming regions and the survival of few unpolluted regions, far from the cluster center.

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