Simulations of feedback effects in the cosmic gas

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Outline

Motivations

Goal: Structure formation: cosmic gas, stars, galaxies and their effects:

→ *What is the formation epoch of cosmic objects?*
→ *What is the role of molecules and metals?*
→ *How does structure growth proceed?*
→ *How relevant is pristine “popIII” star formation?*
→ *How fast is the transition to metal-enriched “popII” regime?*
→ *What are the effects of different IMFs on SFR?*
→ *What are the effects of the underlying matter distribution?*
→ *What are the effects on cosmic re-ionization, GRBs, BHs?...*

Requirements: Study the properties of cosmic gas and metal enrichment from stars, during cosmic evolution.

Techniques: N-body/SPH simulations (with Gadget).

- Cosmic structures originate from the growth of matter perturbations at early times (inflation), in an expanding, flat Universe, containing *"dark"* matter and *"baryonic"* matter.
- Baryonic structures form from in-fall and cooling of gas into DM potential well.
- Eventually, a "cloud" can form if radiative losses are sufficient to make the gas condense and fragment:

$$t_{cool} = \frac{3}{2}\frac{nkT}{\mathcal{L}(n,T)} \quad \ll \quad t_{ff} = \sqrt{\frac{3\pi}{32G\rho}}$$

- Under a cosmological point of view, at early times, the cooling function is dominated by molecules ! After pollution from formed (baryonic) structures (→ *chemical feedback*) metals dominate.

Molecules and metals

For a complete picture: necessity to follow gravity and hydrodynamics joined to molecular evolution and metal production during cosmic time (e.g. Galli& Palla, 1998; Abel et al., 1997)

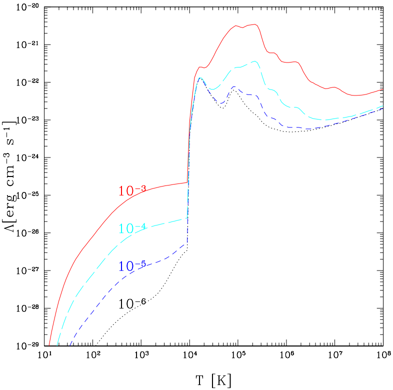
- molecules determine *first* structure formation
- metals determine *subsequent* structure formation
- stellar evolution determines *timescales* and *yields*

Following and implementing metal and molecule evolution in numerical codes (N-body/SPH Gadget) required
(Yoshida et al., 2003; Tornatore et al., 2007; Maio et al., 2006, 2007, 2009, 2010, 2011a,b,c)

Gas cooling function ⟶

In primordial regimes, the main coolants are H, He and molecules (H_2 and HD).

In metal enriched ones, metal fine-structure transitions from C, O, Fe, Si (dominant over molecules at low temperatures).



(Maio et. al, 2007)

Cooling leads the gas in-fall into DM potential wells.

Z_{crit}: transition from popIII to popII-I star formation

We study the effects connected to the existence of a critical metallicity Z_{crit} (e.g. Bromm & Loeb, 2003; Schneider et al., 2003) and the transition from popIII SF ($Z < Z_{crit}$) to popII-I SF ($Z \geq Z_{crit}$).

In order to address such issues, we perform several numerical simulations of early structure formation adopting different values for Z_{crit} and exploring different scenarios.

Simulation set-up

(Maio et al., 2010, 2011b, Maio & Iannuzzi, 2011; Maio, 2011; Maio & Khochfar, 2012)

- standard-ΛCDM cosmology (1,7,14,43,143Mpc side);
- molecular and metal chemistry;
- assume $Z_{crit} = (10^{-6}, 10^{-5}, 10^{-4}, 10^{-3})\ Z_{\odot}$
- assume different popIII IMFs (→ top-heavy/Salpeter)
- assume different matter distributions (→ G vs non-G)

Simulations of structure formation (example)

Example of structure formation

Metal enrichment in the Universe

Z (absolute)

Total enrichment

O (absolute)

O enrichment

Fe (absolute)

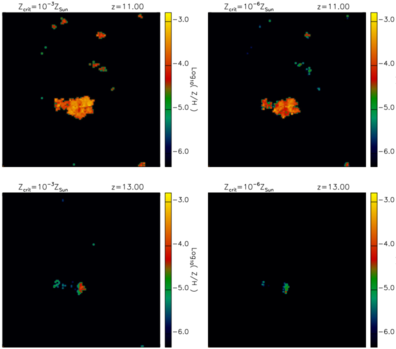
Fe enrichment

Metal enrichment led by stellar evolution: SNII/PISN $\longrightarrow$ O, SNIa $\longrightarrow$ Fe

Results (1/11): effects for different $Z_{\rm crit}$

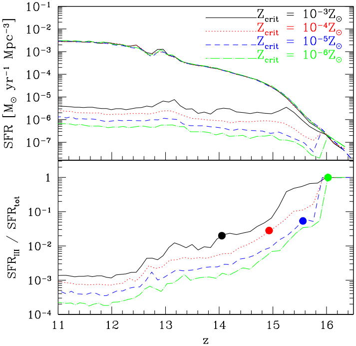
Z_{crit} :

$10^{-3}\,Z_\odot$ $10^{-6}\,Z_\odot$



z=11

z=13



box: $1\mathrm{Mpc}^3$; popIII IMF: top-heavy with slope=-1.35, range=[$100M_\odot$,$500M_\odot$]

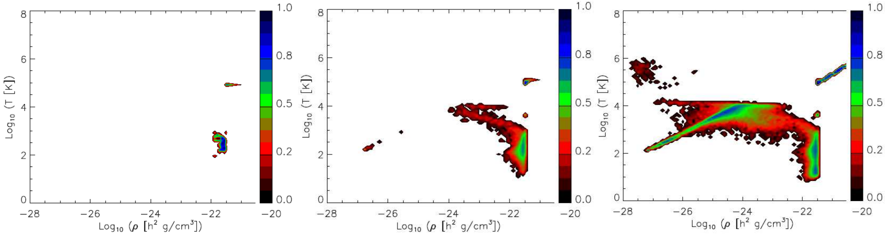
(Maio et al., 2010)

Results (2/11): polluting the surrounding medium

Phase diagrams with color contours for enriched gas

($Z_{crit} = 10^{-4} Z_\odot$, box side = 1 Mpc)

z=16 z=14 z=11



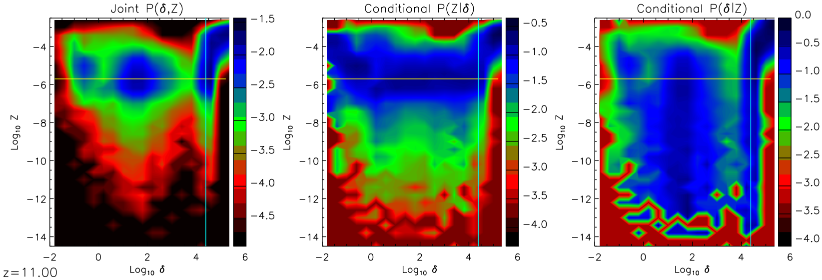
Metals produced by stellar evolution pollute the surrounding, pristine gas with an *“inside-out”* mode.

(Maio et al, 2011b)

Results (3/11): metallicity distribution

Metallicity distributions with color contours for enriched gas at $z = 11$

($Z_{crit} = 10^{-4} Z_{\odot}$, box side = 1 Mpc)

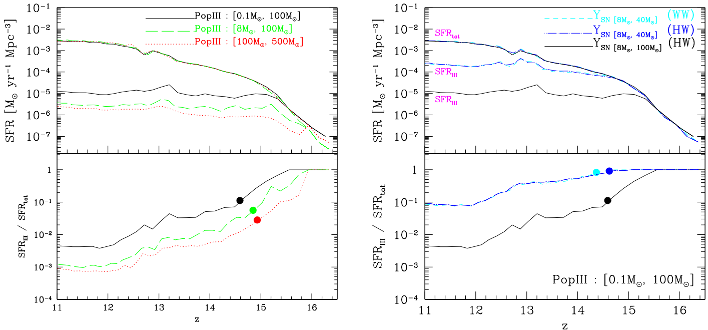


At $z \sim 11$, after $\sim 10^8$ yr from the onset of star formation, most of the enriched mass has $Z > Z_{crit}$.

(Maio et al, 2011b)

Results (4/11): changing the popIII IMF

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”

(Maio et al., 2010)

Results (5/11): Luminosity functions

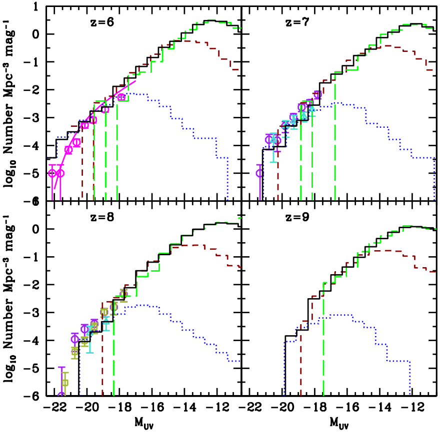
For each galaxy: $L_\lambda = L_\lambda^{\mathrm{II}} + L_\lambda^{\mathrm{III}}$
in L5, L10, L30

PopII-I SEDs from Starbust99, by Vazquez & Leitherer (2005).
PopIII SEDs from Schaerer (2002).
No dust assumed
Pop III objects have little relevance

Observational data points from:

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

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



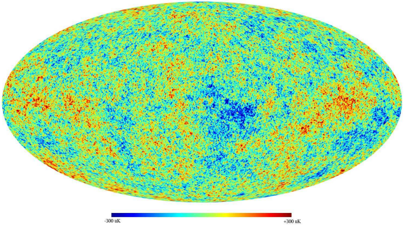
(see also Salvaterra et al., 2012)

Results (6/11): primordial matter distributions and Non-Gaussianities

Basic assumption: Gaussian perturbations → evidences for non-Gaussianities (CMB). Primordial non-Gaussianities are introduced via (Salopek & Bond, 1990

$$\Phi = \Phi_L + f_{\rm NL} \left(\Phi_L^2 - < \Phi_L^2 >\right)$$

Φ is the Bardeen potential (Newton potential at sub-Hubble scales), Φ_L is the *linear* (Gaussian) part, and $f_{\rm NL}$ the non-Gaussian parameter.



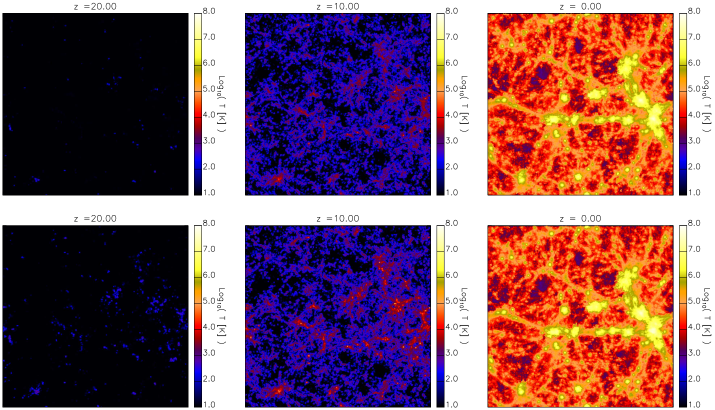
credit: WMAP

$f_{\rm NL}$ = 0, 10, 50, 100, 1000
box sides: 0.5 and 100 Mpc/h
number of particles: 2×320^3
gas mass resolution: $42\ {\rm M}_\odot/h$ and $3 \times 10^8\ {\rm M}_\odot/h$

Maio & Iannuzzi (2011); Maio (2011); Maio et al. (2012)

Results (7/11): Non-G and the cosmic web

$f_{NL}=0$



$f_{NL}=1000$

Results (8/11): Implications for LGRBs

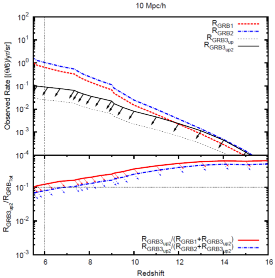
LGRB rate:

different progenitors
i.e. stars with

1: $Z > Z_{crit}$
$\rightarrow$*any popII-I*

2: $Z_{crit} < Z \leq 0.5 Z_\odot$
$\rightarrow$*low-Z popII*

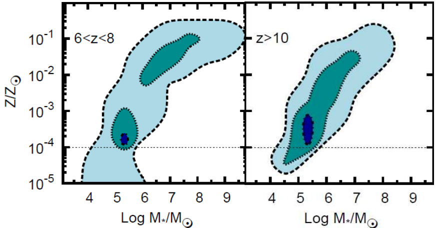
3: $Z \leq Z_{crit}$
$\rightarrow f_{GRBup} = 0.006$
$\rightarrow f_{GRBup2} = 0.022$
(upper limits from
Swift sample, 2011)



Detectable *fraction* (by BAT/Swift) of popIII GRBs:
$\sim$ 10% at $z > 6$
$\gtrsim$ 40% at $z > 10$
of the whole population

GRB-hosts:
the highest probability of finding popIII GRBs is in hosts with $\mathrm{M}_\star < 10^7\,\mathrm{M}_\odot$ and $Z \gtrsim Z_{crit}$ (efficient pollution)

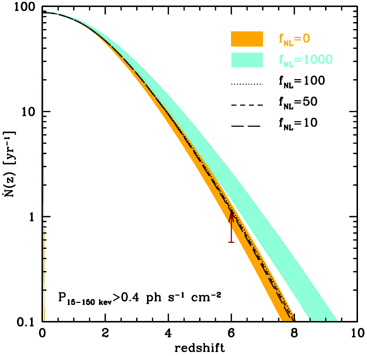
See Campisi, Maio, Salvaterra, Ciardi (2011) and Salvaterra, Maio, Ciardi, Campisi (2013)

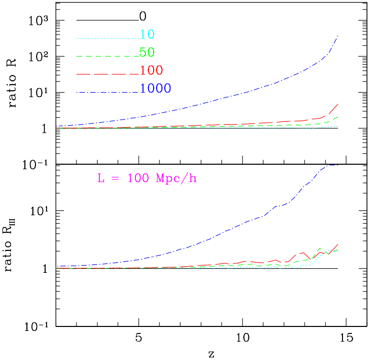


$$R_{GRB} = \frac{\gamma_b \zeta_{BH} f_{GRB}}{4\pi} \int_z \dot{\rho}_\star \frac{dz'}{(1+z')} \frac{dV}{dz'} \int_{L_{th}(z')} \Psi(L') dL'$$

R_{GRB}: gamma-ray burst rate, γ_b: beaming factor, ζ_{BH}: fraction of expected BH (IMF), f_{GRB}: fraction of expected GRB from collapse onto a BH (Swift), $\dot{\rho}_\star$: star formation rate density (simulation), $\Psi(L)$: Schechter luminosity fct. (assumption), L_{th}: instrumental sensitivity (Swift)
PopIII IMF: top-heavy over [100, 500]$\mathrm{M}_\odot$
PopII IMF: Salpeter over [0.1, 100]$\mathrm{M}_\odot$

Results (9/11): GRBs as probe of non-G





From Swift data

See Maio, Salvaterra, Moscardini, Ciardi (2012)

Results (10/11): radiative feedback on cosmic gas

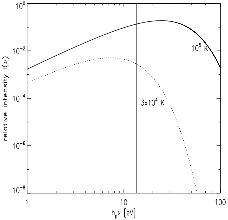
RT from ionizing sources:

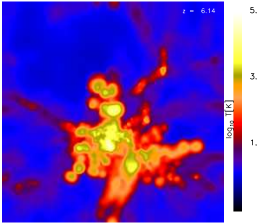
(Petkova & Springel, 2009, 2011; Petkova & Maio, 2012)

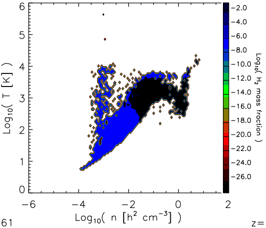
- stars are sources of photons
- Planck spectrum $s_{\gamma}(\nu)$
- multi-frequency method sampling the spectrum with $\sim$ 150 frequency bins
- molecules are self- shielded

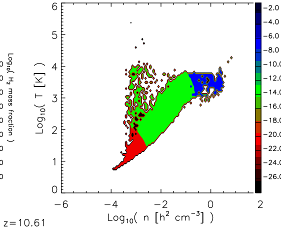
  from **LW** (Draine & Bertoldi, 1996)

- NB: RT is coupled with hydro and chemistry self-consistently, and NOT run on post-processing
- see also: Abel & Gnedin (2001); Ricotti et al. (2001); Ahn & Shapiro (2007); Whalen & Norman (2009); etc.









Results (11/11): effects on re-ionization

No RT

With RT

(Preliminary results!!!)

Summary...

- We have presented results from N-Body, hydrodynamical, chemistry and radiative simulations.
- We have studied the growth of cosmic structures, and their implications for Z, SFR, IMF, LF, non-G, GRBs, RT, BHs, etc..

Conclusions...

- Early ($z \sim 15-20$) metal enrichment from the first stars is very strong and the transition from pristine to standard popII regime is very rapid ($\sim 10^7 - 10^8\,\mathrm{yr}$), with a residual popIII contribution to the total SFR at $z \sim 10$ of only $\sim 10^{-3} - 10^{-1}$.
- Radiation from early stars can easily dissociate molecules (mostly where not shielded), heat surrounding gas, and inhibit further SF.
- Feedback effects can affect metal pollution in primordial objects (chemical feedback), and impact significantly on the thermodynamical state of the IGM (radiative feedback).

The End

Thank you...

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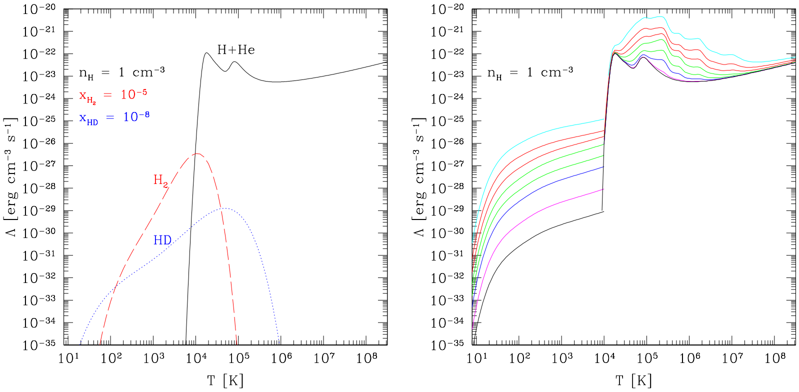
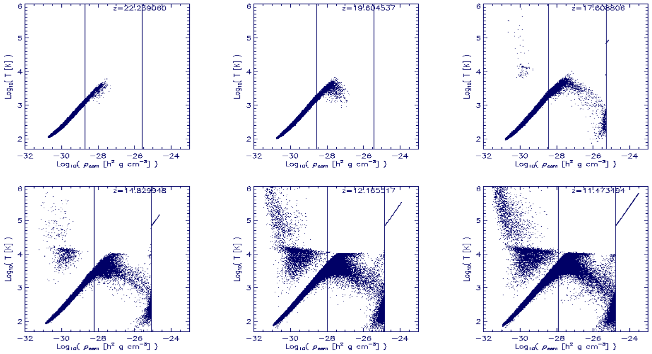
Extra: cooling functions...



Resolving the gas in-fall: evolution in the ρ – T space

Hydrodynamic cosmological simulation with molecular chemistry and metal cooling/pollution; 2×128^3 particles in $(276\,\mathrm{kpc}/h)^3$ box: $M_{gas} \sim 10^2\,M_\odot/h$; $\Omega_{0,\Lambda} = 0.7$, $\Omega_{0,M} = 0.3$, $\Omega_{0,b} = 0.04$, $\sigma_8 = 1.2$, $n = 1$

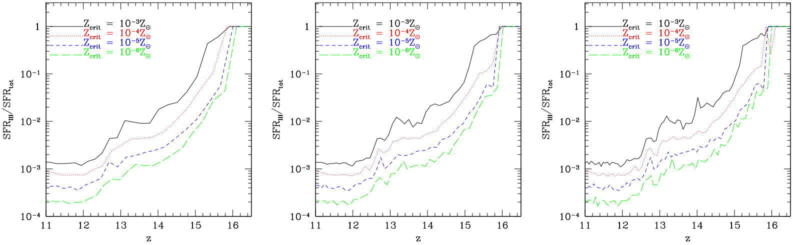


temperature: T [K] ⟶

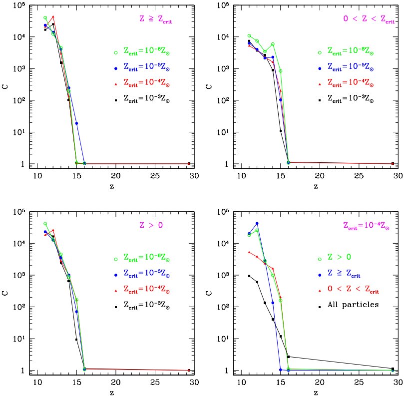
comoving density: ρ_{com} $[h^2\ \mathrm{g\,cm}^{-3}]$ ⟶

redshift interval: $z \simeq 22 - 11$

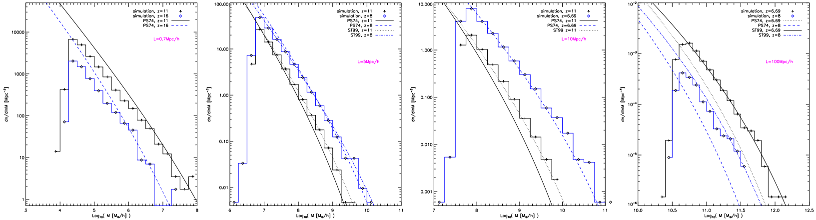
Extra: star formation ratio (box side = 1 Mpc)...



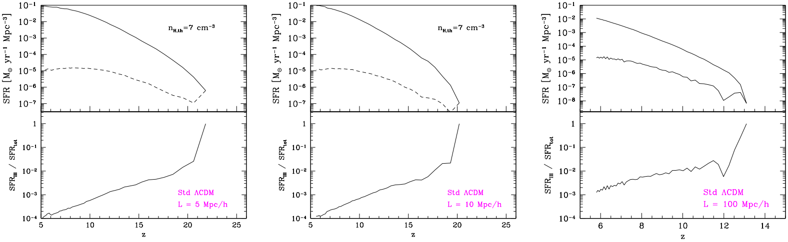
Extra: clumping factors (box side = 1 Mpc)



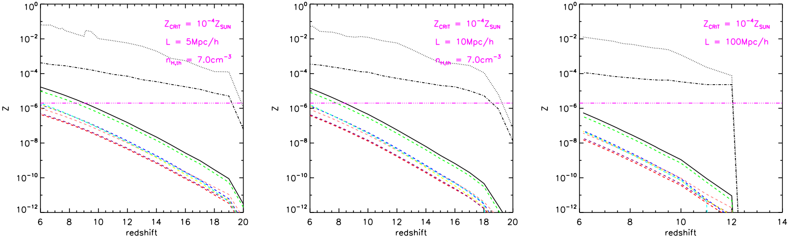
Extra: Mass functions (larger simulations)



Extra: SFR (larger simulations)



Extra: Metallicity evolution (larger simulations)



Results: metallicity evolution

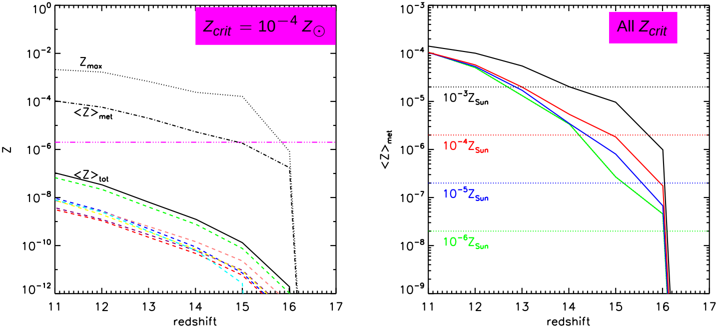
Dotted lines: maximum metallicity.

Dot-dashed lines: average metallicity over the enriched particles.

Solid lines: average metallicity over the whole box.

Dashed lines: average individual metallicities over the whole box.

(e.g., Maio et al, 2010)



$H + e^- \rightarrow H^+ + 2e^-$

$H^+ + e^- \rightarrow H + \gamma$

$H + \gamma \rightarrow H^+ + e^-$

$H^- + e^- \rightarrow H + 2e^-$

$H^- + \gamma \rightarrow H + e^-$

$He + e^- \rightarrow He^+ + 2e^-$

$He^+ + e^- \rightarrow He + \gamma$

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

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

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

$He + \gamma \rightarrow He^+ + e^-$

$H + e^- \rightarrow H^- + \gamma$

$H^- + H \rightarrow H_2 + e^-$

$H + H^+ \rightarrow {H_2}^+ + \gamma$

${H_2}^+ + H \rightarrow H_2 + H^+$

$H_2 + H \rightarrow 3H$

$H_2 + H^+ \rightarrow {H_2}^+ + H$

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

$H^- + H \rightarrow 2H + e^-$

$H_2 + \gamma \rightarrow H_2^+ + e^-$

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

$H_2 + \gamma \rightarrow 2H$

$H_2^+ + \gamma \rightarrow H + H^+$

$H^- + H^+ \rightarrow 2H$

$H^- + H^+ \rightarrow {H_2}^+ + e^-$

${H_2}^+ + e^- \rightarrow 2H$

${H_2}^+ + H^- \rightarrow H + H_2$

$D + \gamma \rightarrow D^+ + e^-$

$D^+ + e^- \rightarrow D + \gamma$

$D + H_2 \rightarrow HD + H$

$D^+ + H_2 \rightarrow HD + H^+$

$HD + H \rightarrow D + H_2$

$HD + H^+ \rightarrow D^+ + H_2$

$H^+ + D \rightarrow H + D^+$

$H + D^+ \rightarrow H^+ + D$

$He + H^+ \rightarrow HeH^+ + \gamma$

$HeH^+ + H \rightarrow He + H_2^+$

$HeH^+ + \gamma \rightarrow He + H^+$

Numerical RT – A Multi-Frequency Moment Method

Petkova & Springel (2009,2011), Petkova & Maio (2012)

- The RT equation for the photon number density per frequency

$$\frac{\partial n_\gamma(\nu)}{\partial t} = c\,\frac{\partial}{\partial x_j}\left(\frac{1}{\kappa(\nu)}\frac{\partial n_\gamma(\nu) h^{ij}}{\partial x_i}\right) - c\,\kappa(\nu)\,n_\gamma(\nu) + s_\gamma(\nu),$$

where

$$n_\gamma(\nu) = \frac{1}{c}\frac{4\pi I(\nu)}{h_p \nu}\,.$$

- Closure relation – Eddington tensor h^{ij} that gives effective radiation direction
- Stars are the sources of ionizing photons
- Source function $s_\gamma(\nu)$ – stellar luminosity has a black-body spectrum