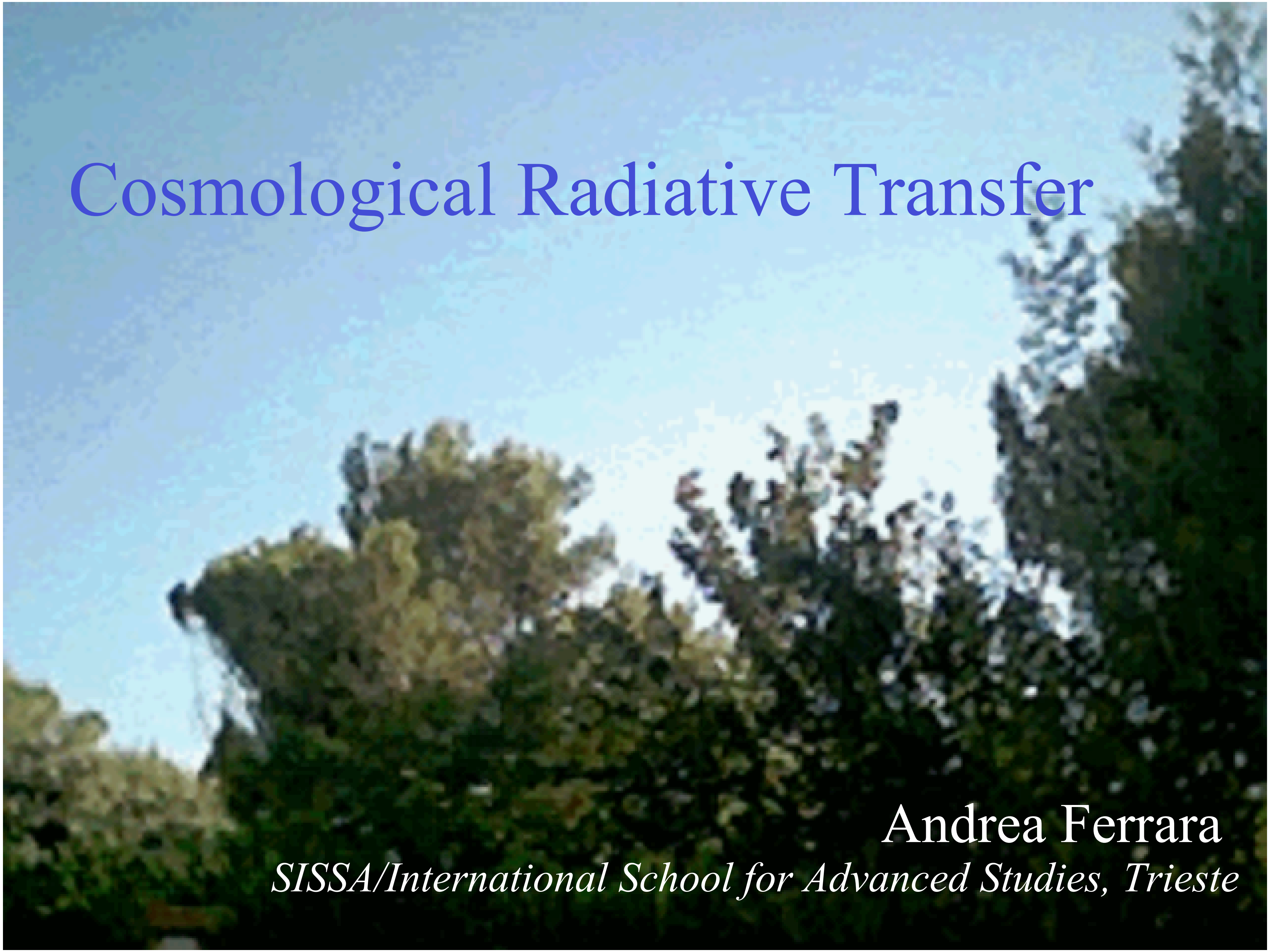

Cosmological Radiative Transfer

Andrea Ferrara

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Basic Introduction

Radiative Transfer Equation

$$I_\nu = I\,(t, \boldsymbol{x}, \boldsymbol{\omega}, \nu)$$

$$c^{-1}\frac{\partial I_\nu}{\partial t} + \frac{\hat{n}\cdot\nabla I_\nu}{a_{em}} - c^{-1}H(t)\left[\nu\frac{\partial I_\nu}{\partial \nu} - 3I_\nu\right] = \eta_\nu - \chi I_\nu$$

Path Change

Redshifting

Dilution

Approximations

$I_\nu = I\,(t, \mathbf{x}, \boldsymbol{\omega}, \nu)$

I II III IV V

$$c^{-1}\frac{\partial I_\nu}{\partial t} + \frac{\hat{n}\cdot\nabla I_\nu}{a_{em}} - c^{-1}H(t)\left[\nu\frac{\partial I_\nu}{\partial \nu} - 3I_\nu\right] = \eta_\nu - \chi I_\nu$$

$a_{em} = 1+z_{em} / 1+z \approx 1 + 2/3\; L/L_H \approx 1$ Short photon crossing time

$$\frac{\text{Term III}}{\text{Term II}} \approx \frac{H L a_{em}}{c} \ll 1$$

Local approximation

Solution techniques

For a review see Ciardi & Ferrara 2005

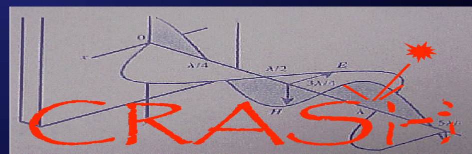
- Ray Tracing/Long characteristics *Abel, Norman & Madau 1999; Razoumov & Scott 1999; Sokasian, Abel & Hernquist 2001; Razoumov etal 2002*
- Ray Tracing/Short characteristics *Umemura etal 1999; Rijkhorst etal 2005*
- Flux-Eddington tensor *Gnedin & Abel 2001*
- Flux-limited diffusion *Turner & Stone 2001; Whitehouse & Bate 2004*
- Fourier transforms *Cen 2002*
- Unstructured grids *Ritzerveld etal 2004*
- Statistical methods *Ciardi etal 2001; Maselli, Ferrara & Ciardi 2003*

Cosmological

RAdiative Transfer

Scheme for

Hydrodynamics



Ciardi, AF, et al 2001

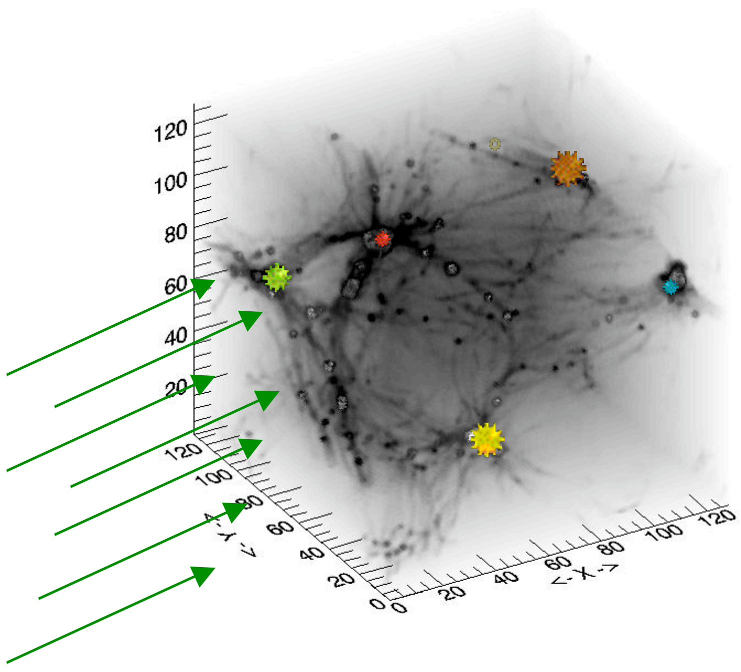
Maselli, AF & Ciardi 2003

WHAT CRASH DOES

Arbitrary 3-D precomputed cosmological H/He density field

+

Ionizing sources
- Multiple point souces
- Background (UVB)
- Diffuse radiation



OUTPUTS

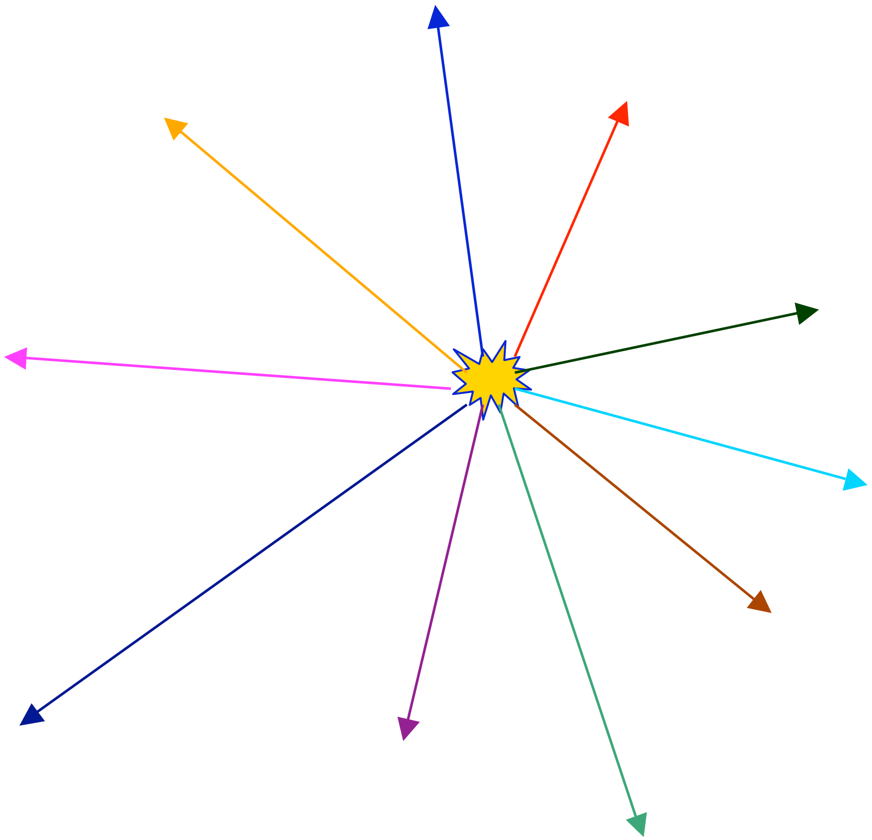
TIME EVOLUTION
of
TEMPERATURE
and
IONIZATION FRACTIONS

INSIDE THE
SIMULATION VOLUME

LARGE APPLICATION RANGE

Implementation: Basic Description

Radiation described in its particle-like nature



Source radiation field

|||

N_p photons packets

Frequency and propagation direction determined by Monte Carlo sampling of

- Spectral Energy Distribution
- Angular Emissivity

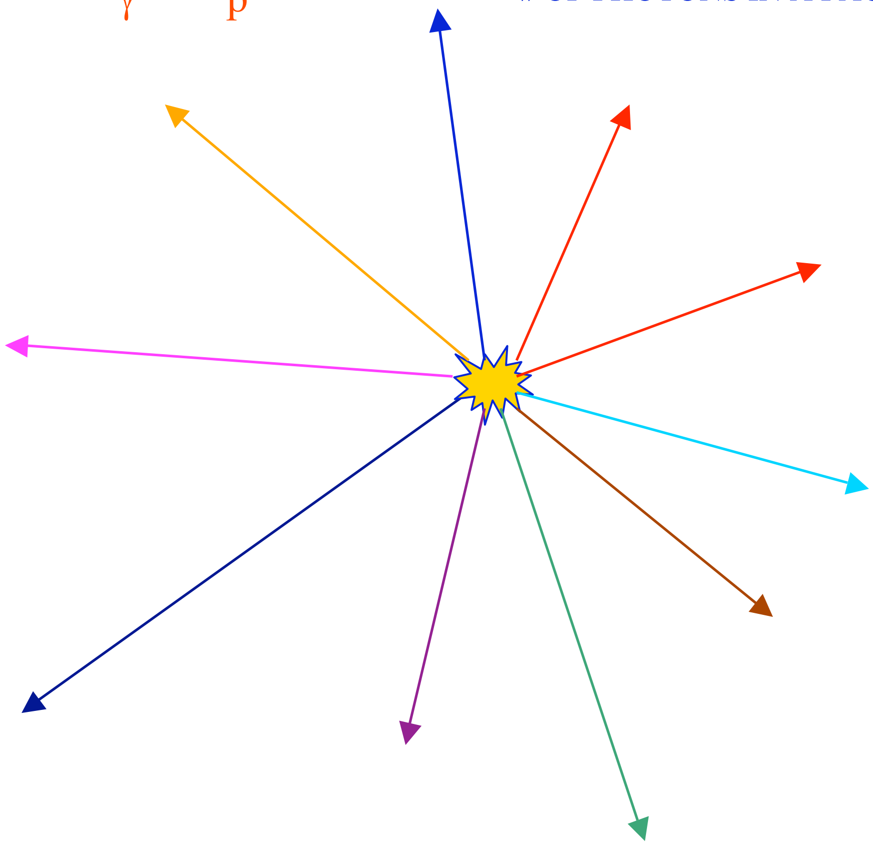
Implementation: Point sources

(x_s, y_s, z_s), $L_s(t)$, $S(\nu)$, $A(\theta,\varphi)$

$E_{tot} = \int_0^{t_s} L_s(t)\, dt$ TOTAL ENERGY EMITTED BY A SINGLE SOURCE

$E_p = E_{tot} / N_p$ ENERGY IN A SINGLE PACKET

$N_\gamma = E_p / h\nu$ # OF PHOTONS IN A PACKET



TIME EVOLUTION ⇔ Emission time step $dt = t_s/N_p$

PACKET ⇒ MC

- ✓ frequency
- ✓ propagation direction

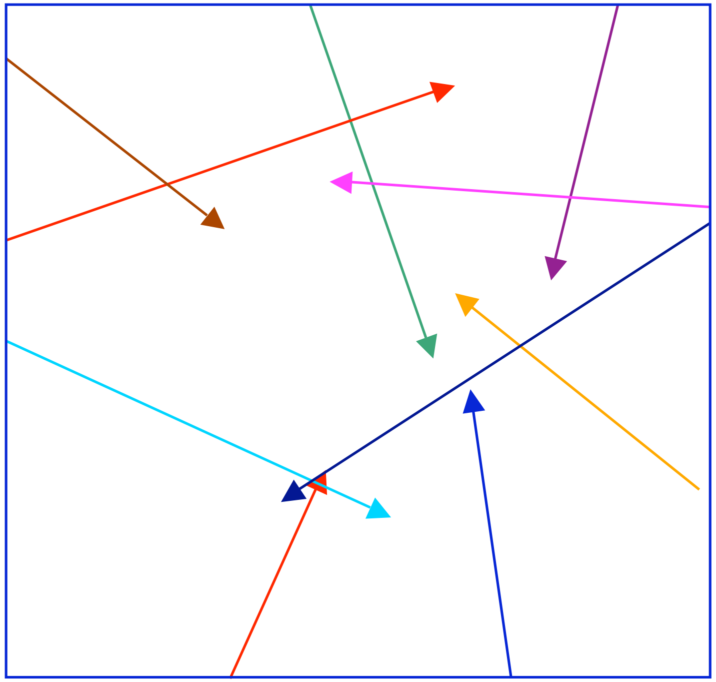
Implementation: Background

(x_s, y_s, z_s), $L_s(t)$, $S(\nu)$, $A(\theta,\varphi)$

E_{tot} TOTAL BACKGROUND ENERGY EMITTED BY BOUNDARY CELLS

$E_p = E_{tot} / N_p$ ENERGY IN A SINGLE PACKET

$N_\gamma = E_p / h\nu$ # OF PHOTONS IN A PACKET



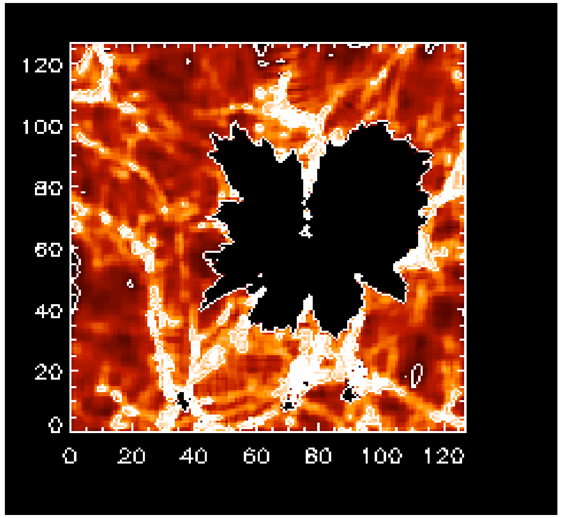
TIME EVOLUTION ⟺ Emission time step $dt = t_s / N_p$

PACKET —MC→
- ✓ frequency
- ✓ propagation direction
- ✓ emission cell

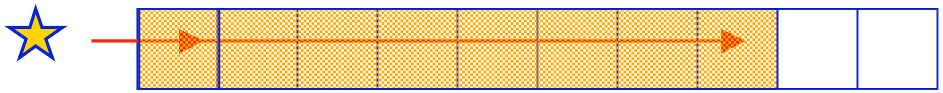
Propagation: matter-radiation interaction

Absorption Probability

$$P(\tau)=1-e^{-\tau}$$



A packet with N_γ photons is emitted



Optical Depth

$$\tau = \tau_{HI} + \tau_{HeI} + \tau_{HeII}$$

\# absorbed photons

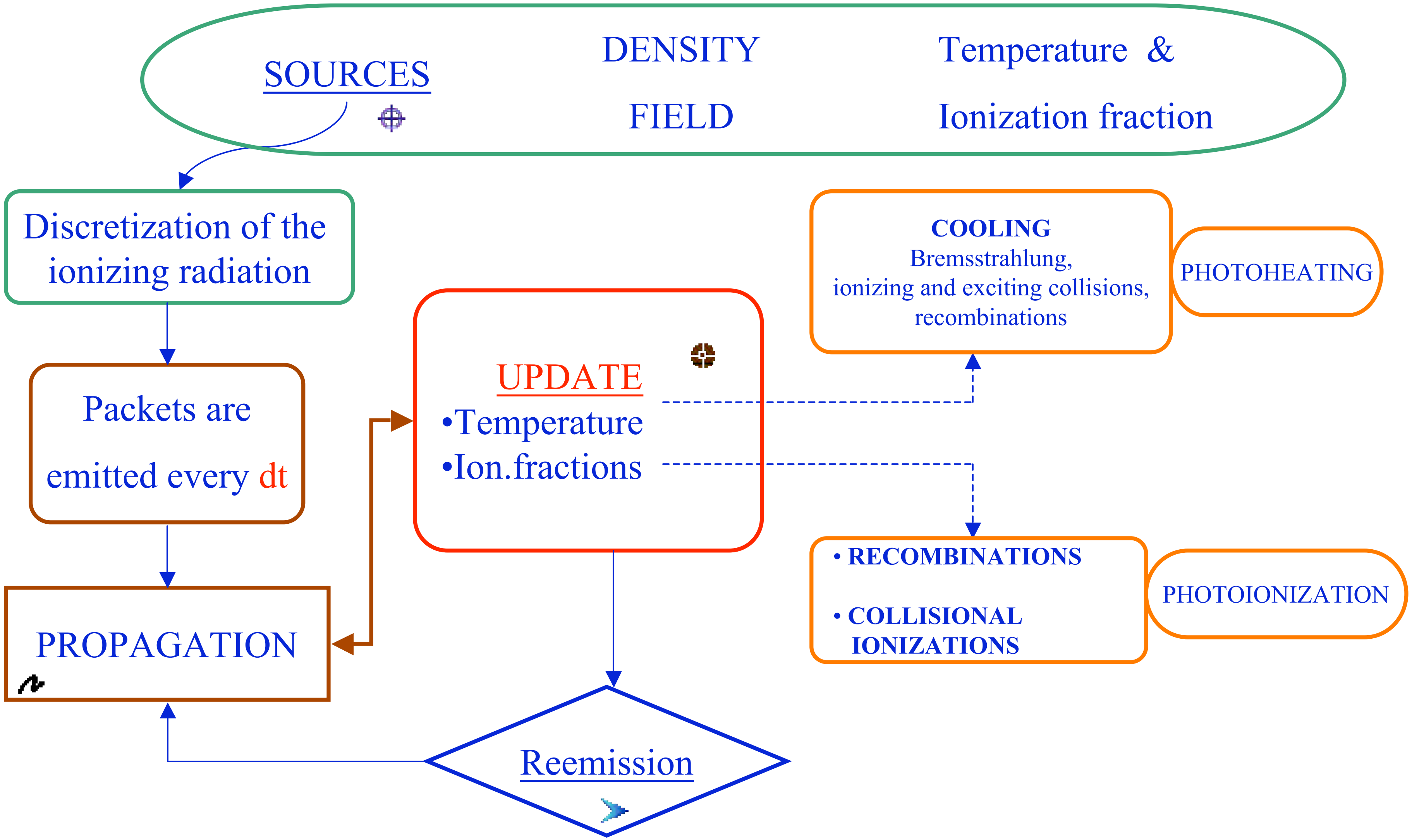
$$N_A = N_\gamma (1-e^{-\tau}) = N_\gamma^{HI} + N_\gamma^{HeI} + N_\gamma^{HeII}$$

\# escaping photons

$$N'_\gamma = N_\gamma - N_A$$

THE SCHEME ENSURES BY CONSTRUCTION ENERGY AND PHOTON CONSERVATION

Flow Chart



SOURCES
DENSITY FIELD
Temperature & Ionization fraction
Discretization of the ionizing radiation
Packets are emitted every dt
PROPAGATION
UPDATE
•Temperature
•Ion.fractions
Reemission
COOLING
Bremsstrahlung, ionizing and exciting collisions, recombinations
PHOTOHEATING
• RECOMBINATIONS
• COLLISIONAL IONIZATIONS
PHOTOIONIZATION

TESTS

[details in Maselli et al. 2003, MNRAS, 345, 48]

1. **ANALYTICAL solution** ⟺
   - Pure H, homogeneous gas
   - Monochromatic source
   - Constant temperature

2. **General case including TEMPERATURE & He** ⟺ ***CRASH / CLOUDY*** comparison

3. **TWO POINT SOURCES**

4. **BACKGROUND RADIATION & INHOMOGENEOUS DENSITY FIELD**

Temperature & Helium

CLOUDY —— *comparison* —— CRASH

CLOUDY
- 1-D
- Equilibrium solution
- Multilevel atoms & ions

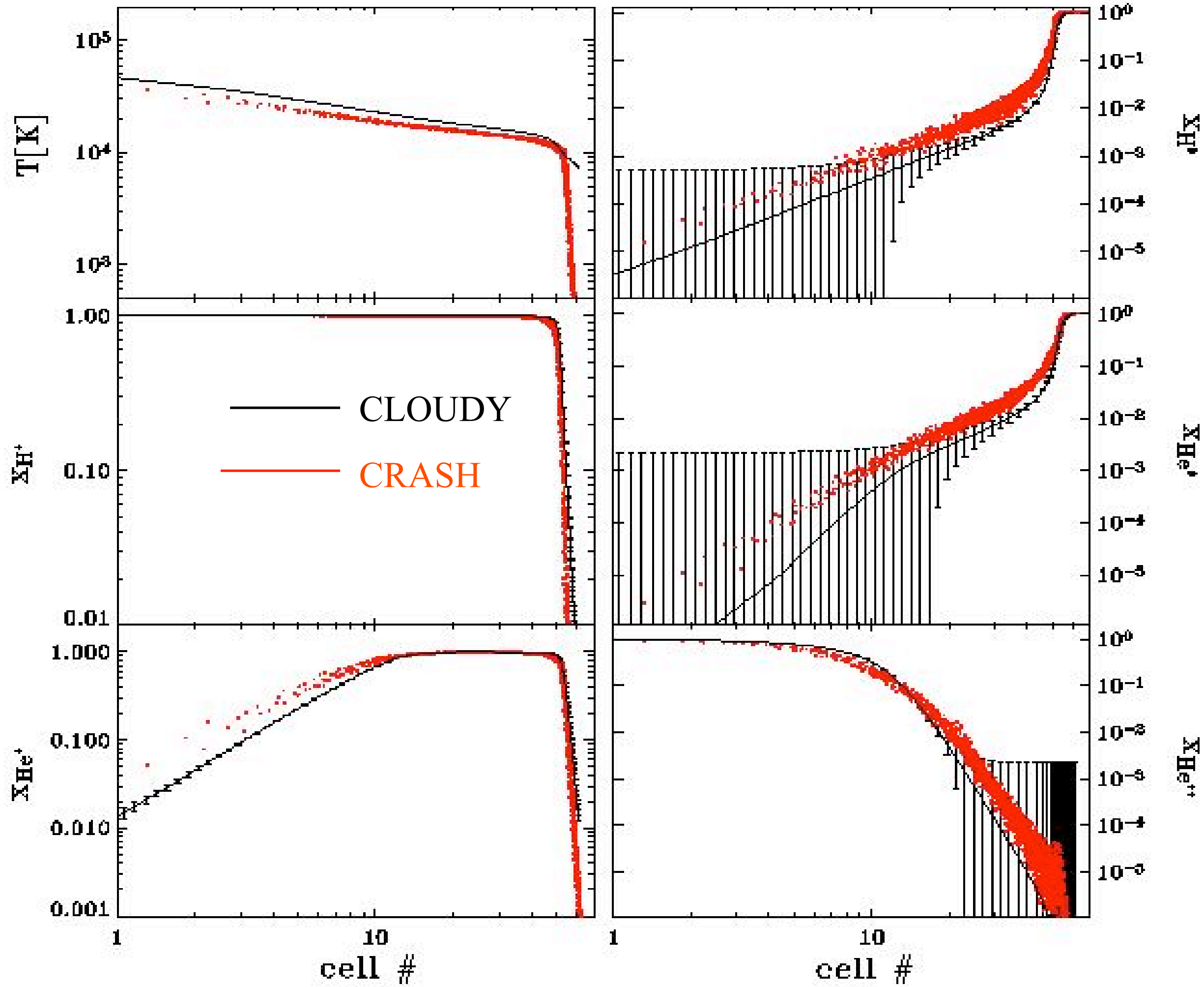
CRASH
- 3-D
- Time evolution
- One-level atoms & ions

- Homogeneous H/He density field

  $n = 1 cm^{-3}$, $f_H = 0.9$ & $f_{He} = 0.1$
- Point source: Blackbody, T= 6_10^4 K

  $L = 10^{38}$ erg / s

Temperature & Helium



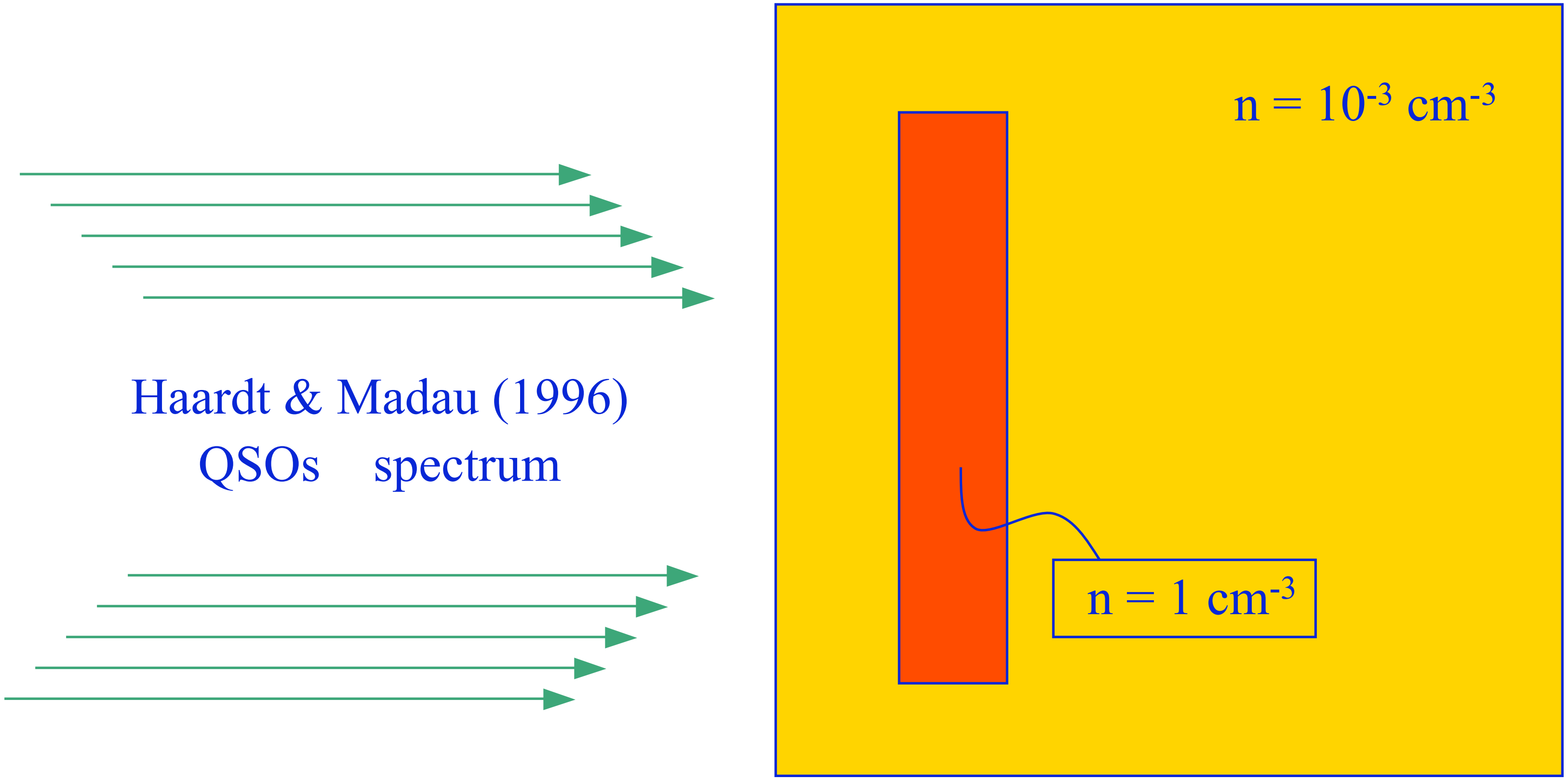
CLOUDY

CRASH:

Output at $t_s = 6 \times 10^5$ yr

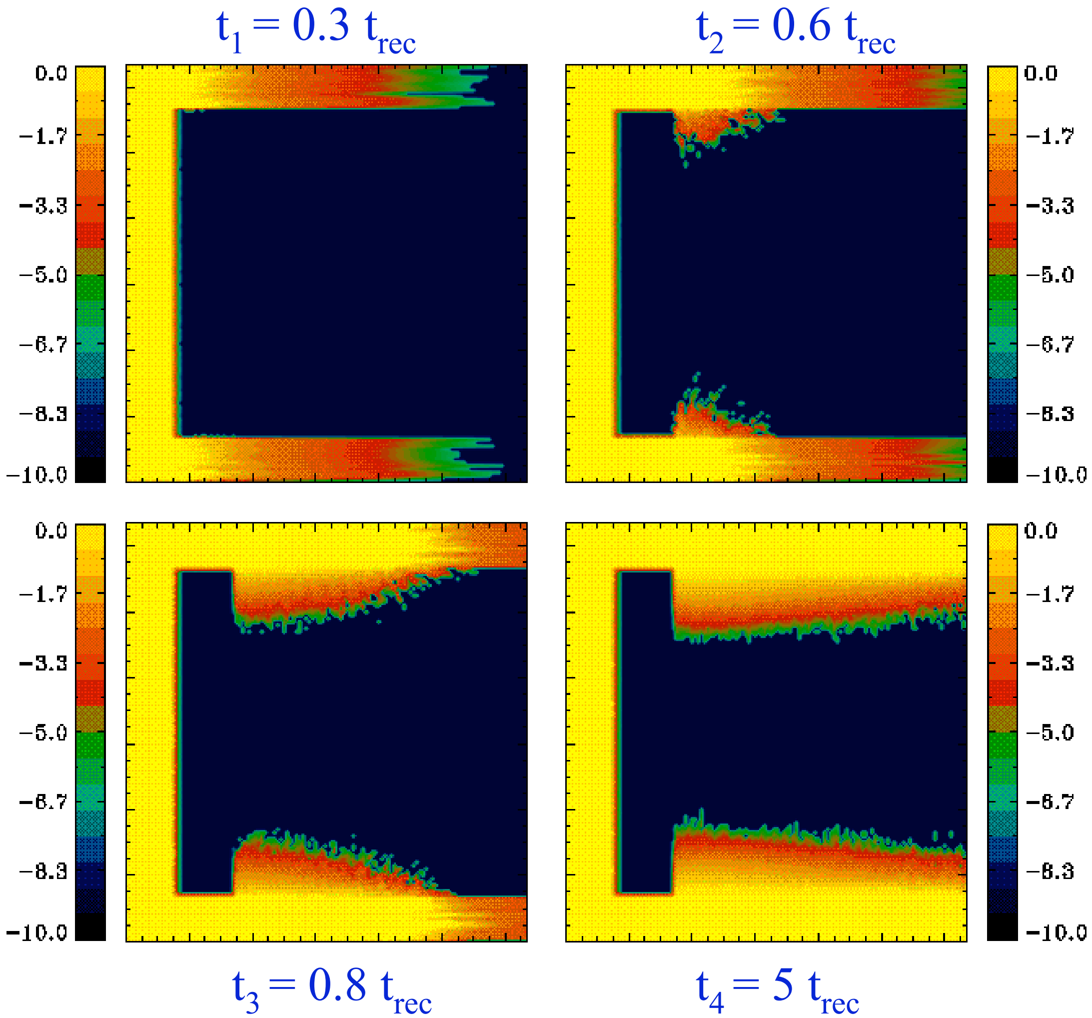
H/He gas, n = 1 cm^{-3}, Point source Black Body spectrum (T=60000 K), $T_i = 100$ K

UVB & Inhomogeneous density field



H/He gas, Diffuse radiation field, $T_i = 100$ K

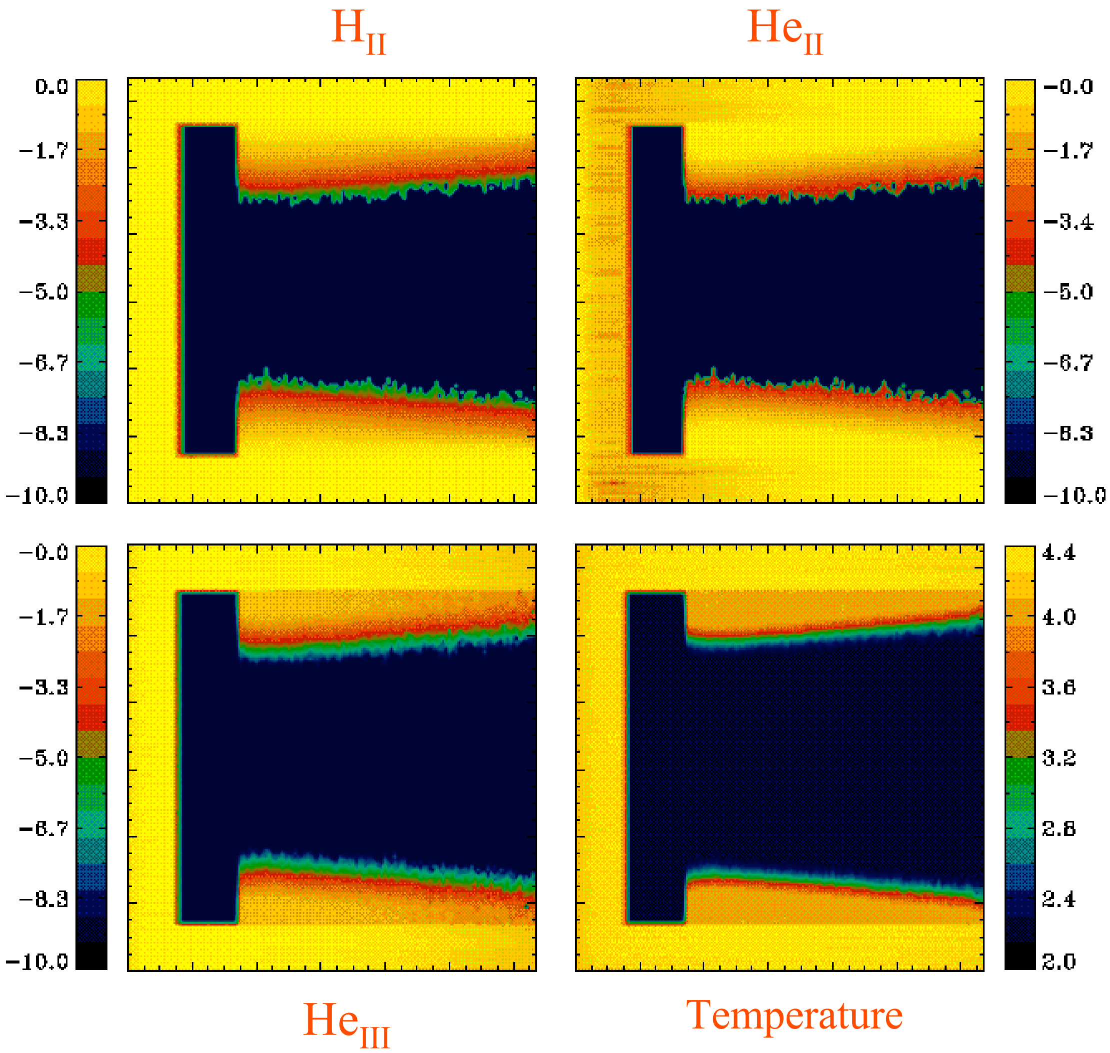
UVB & Inhomogeneous density field



H_{II} fraction evolution

H/He gas, Diffuse radiation field, $T_i = 100$ K

UVB & Inhomogeneous density field



$t = 5\ t_{rec}$

H/He gas, Diffuse radiation field, $T_i = 100$ K

Cosmological Applications

Ciardi, AF & White 2003

Reionization after WMAP

A Conservative Model: No "exotica"

- Maximum H_2/UV feedback: no stars in minihalos
- Smallest star-forming halos $M = 5\_10^8 M_O$
- Moderately heavy IMF: Larson, $M_c = 5 M_O$
- No Very Massive Stars, but metal-free
- Maximum Escape Fraction, $f_{esc} = 20\%$

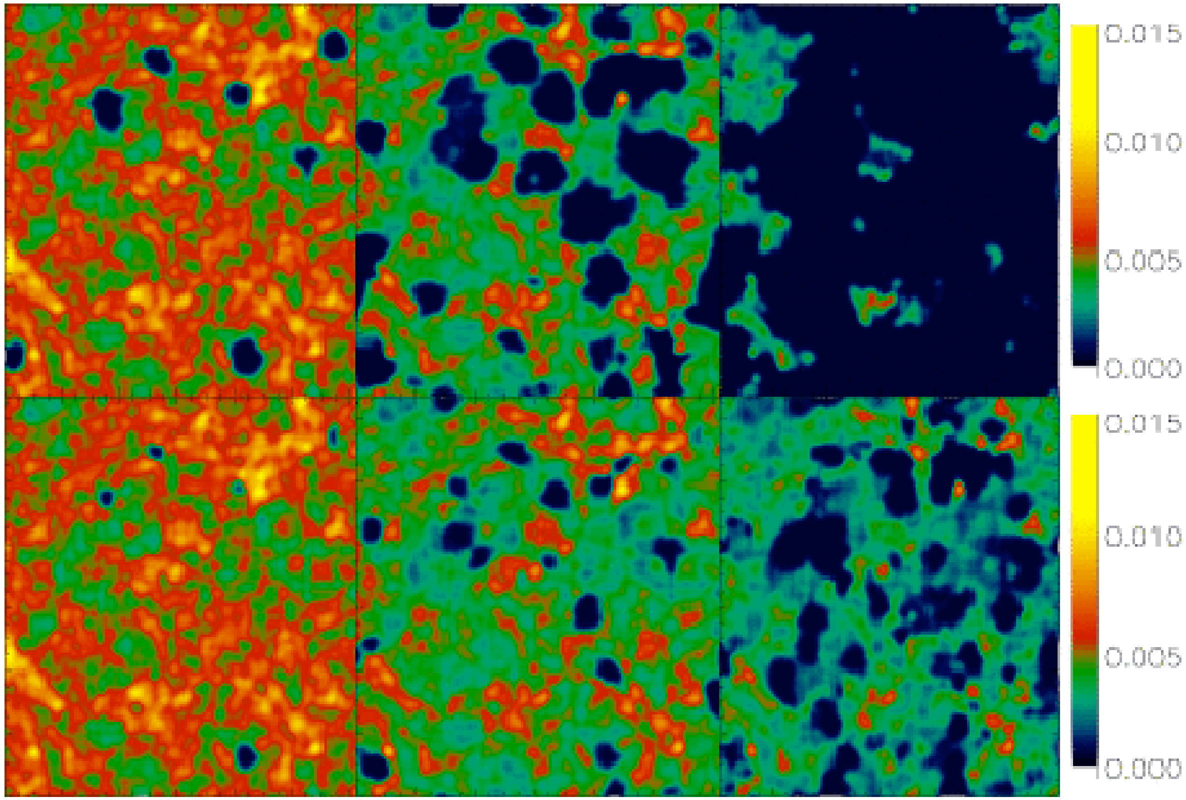
Ciardi, AF & White 2003

Reionization & the IMF

z = 17.6 *z=15.5* *z=13.7*

Larson IMF

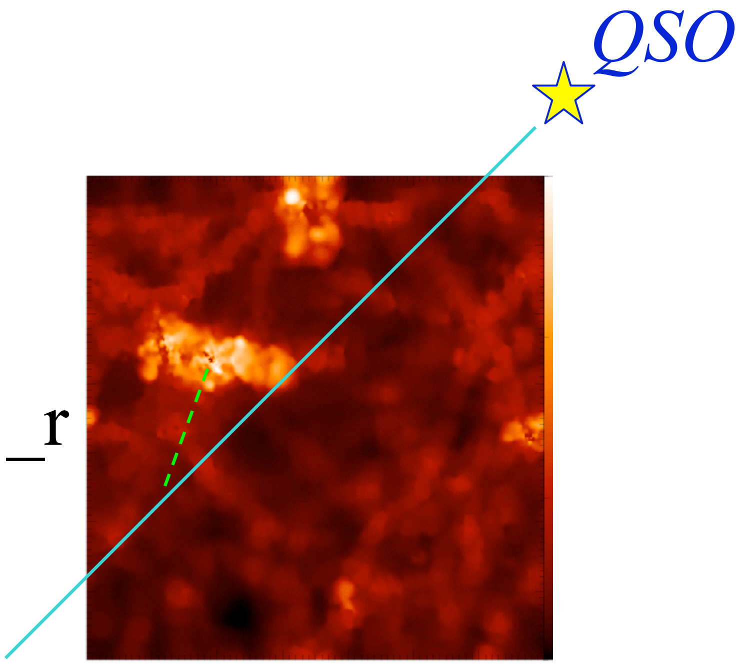
Salpeter IMF

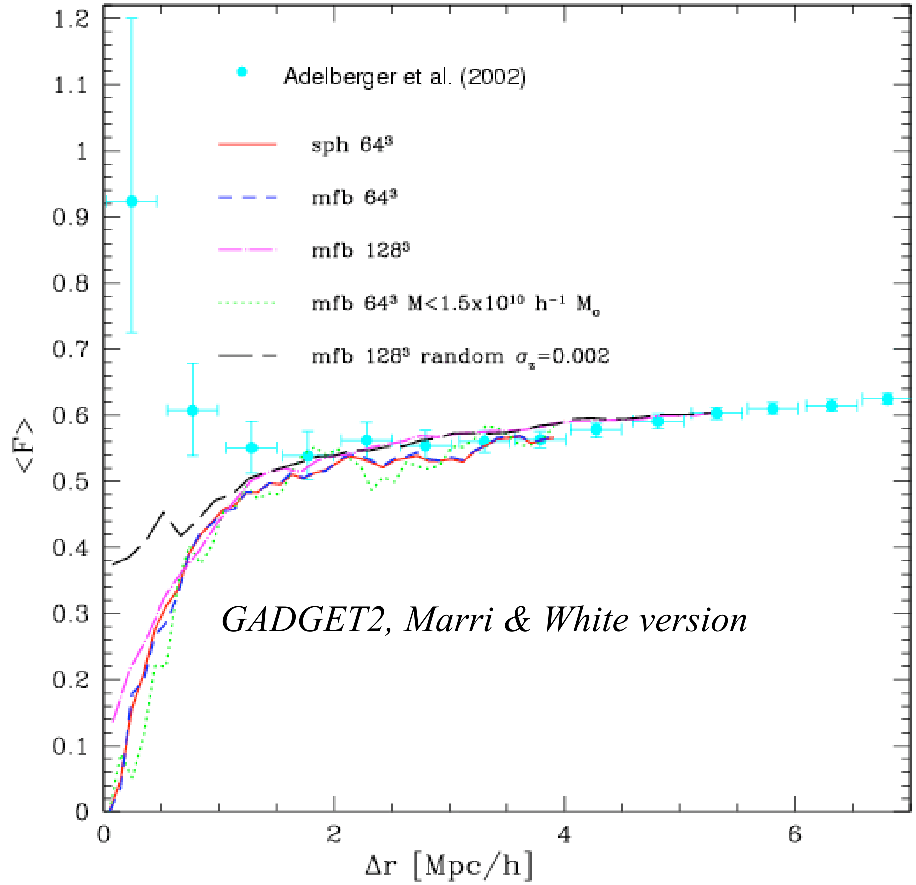


Radiative Transfer Effects on the Lyα Forest

Bruscoli et al 2003

Galaxy Proximity Effect @ *z = 3*



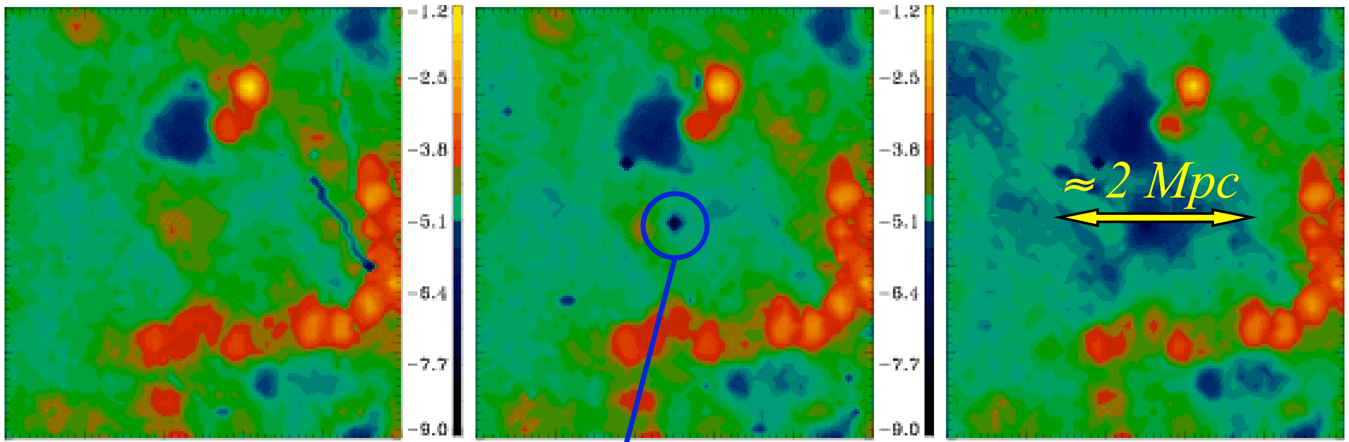


Maselli & AF, in prep

Adding Radiation from Local Sources

Neutral hydrogen maps

UVB only | Local Ionization | 10× Boosted SFR

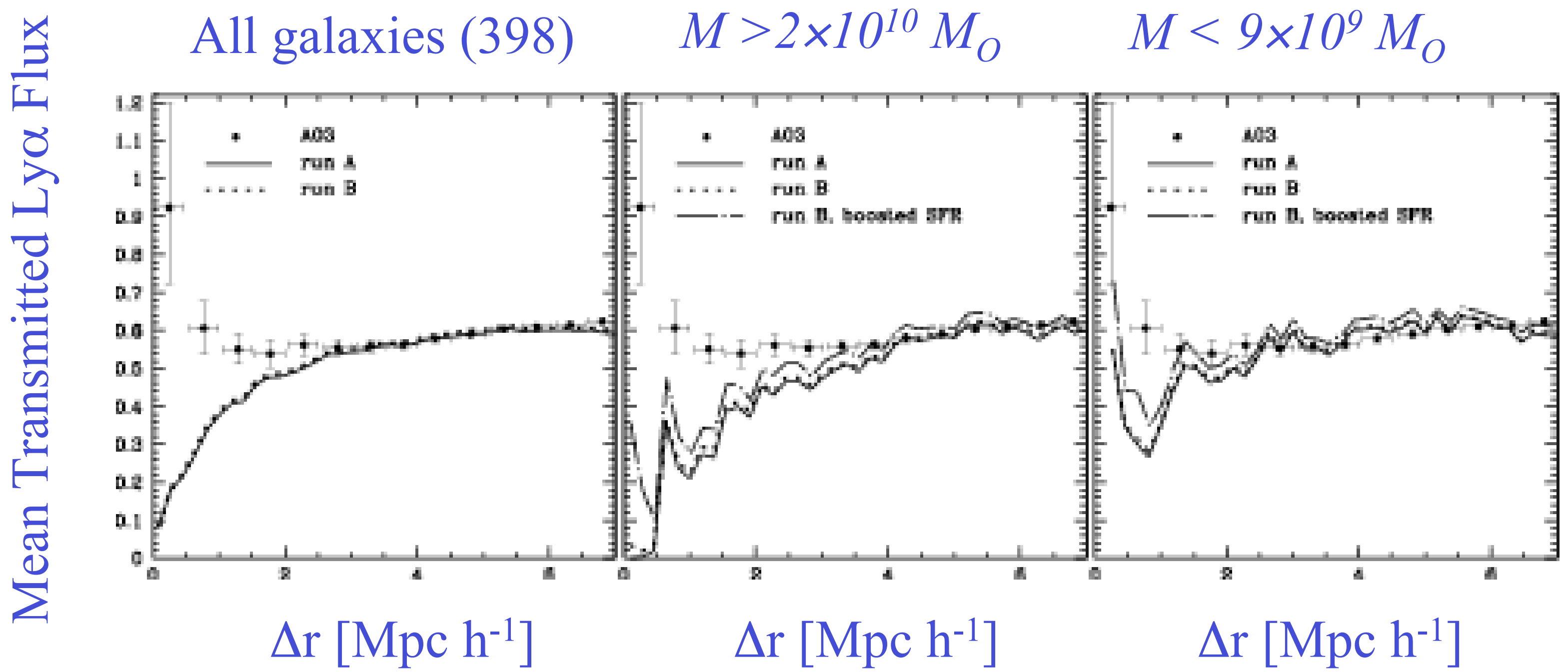


LBG-analog galaxy @ z=3.27

$M = 1.5\times10^{11}\ M_O$, $SFR = 30\ M_O\ yr^{-1}$

Maselli & AF, in prep

Adding Radiation from Local Sources



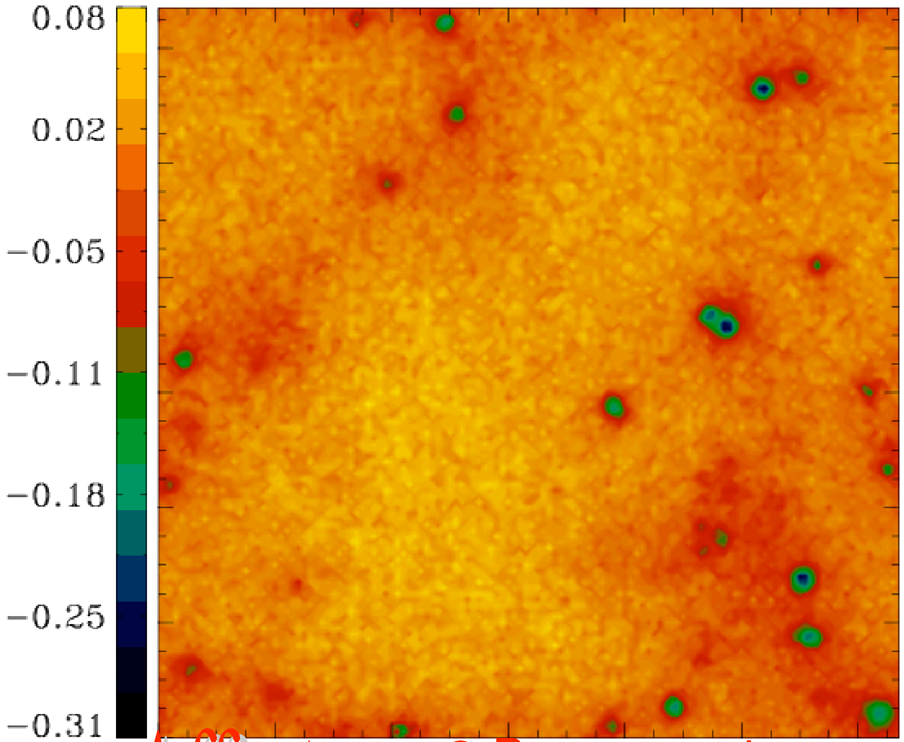
Proximity effect stronger around dwarf galaxies

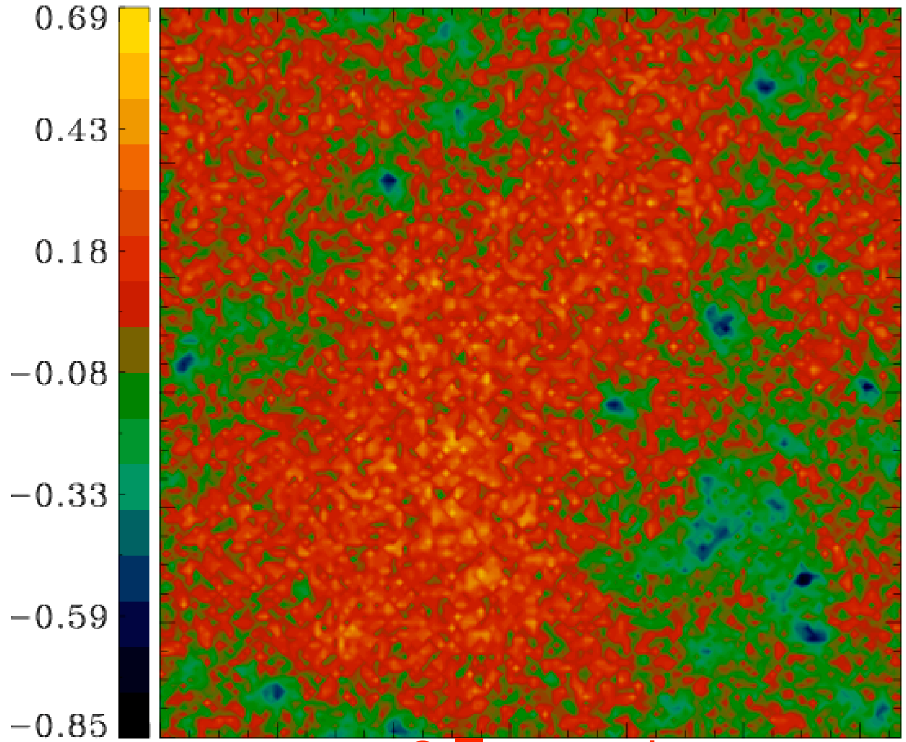
Radiative Transfer Effects on the Lyα Forest

Maselli & AF 2005

UVB fluctuations

$\delta\Gamma_{HI}$ $\delta\Gamma_{HeII}$





Photoionization rates fluctuations through a box at z=3.27

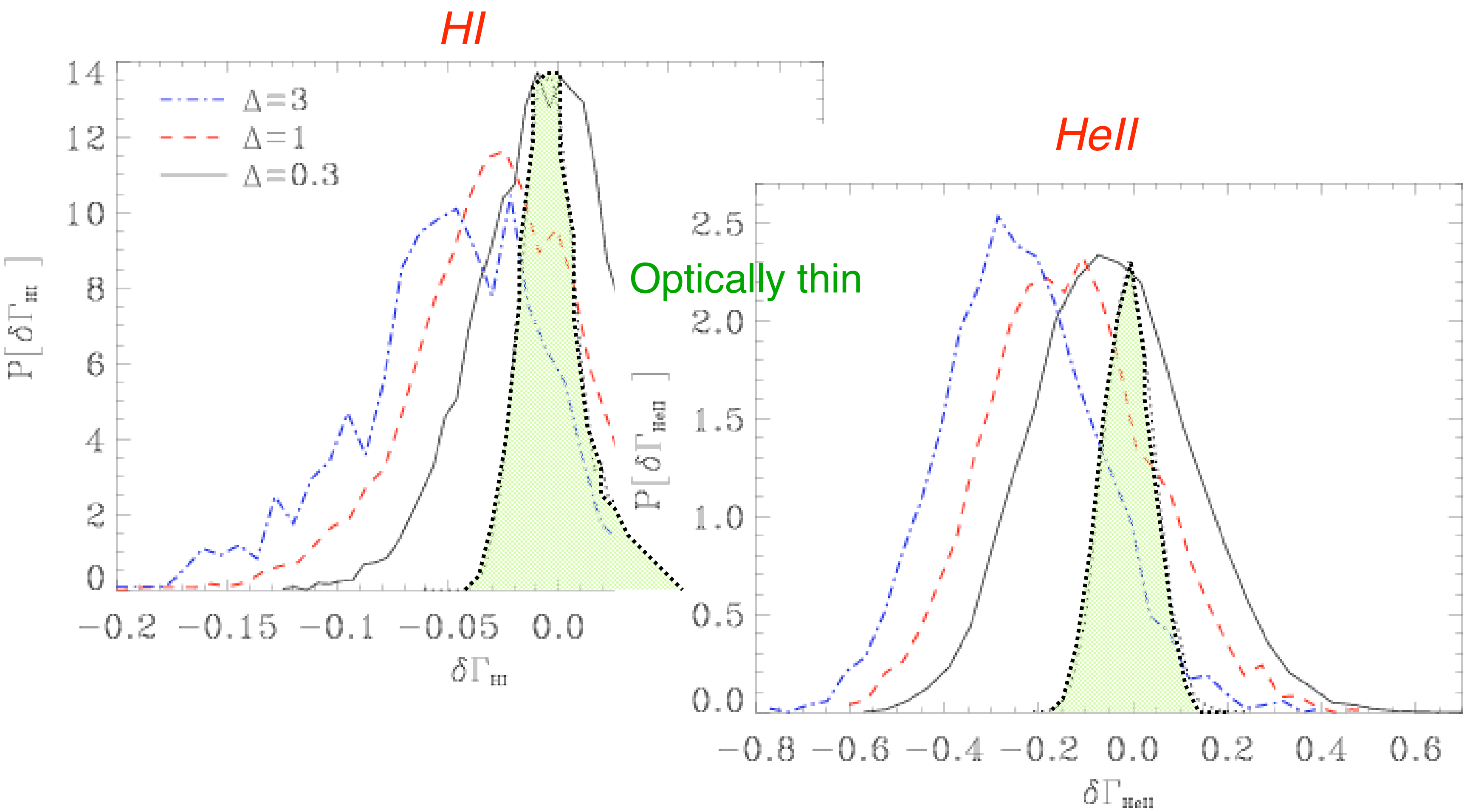
Affects:

- ⊗ Power spectrum
- ⊗ Elemental abundances
- ⊗ Temperature
- ⊗ Eta parameter

Radiative Transfer Effects on the Lyα Forest

Maselli & AF 2005

UVB fluctuations



Want to know more ?