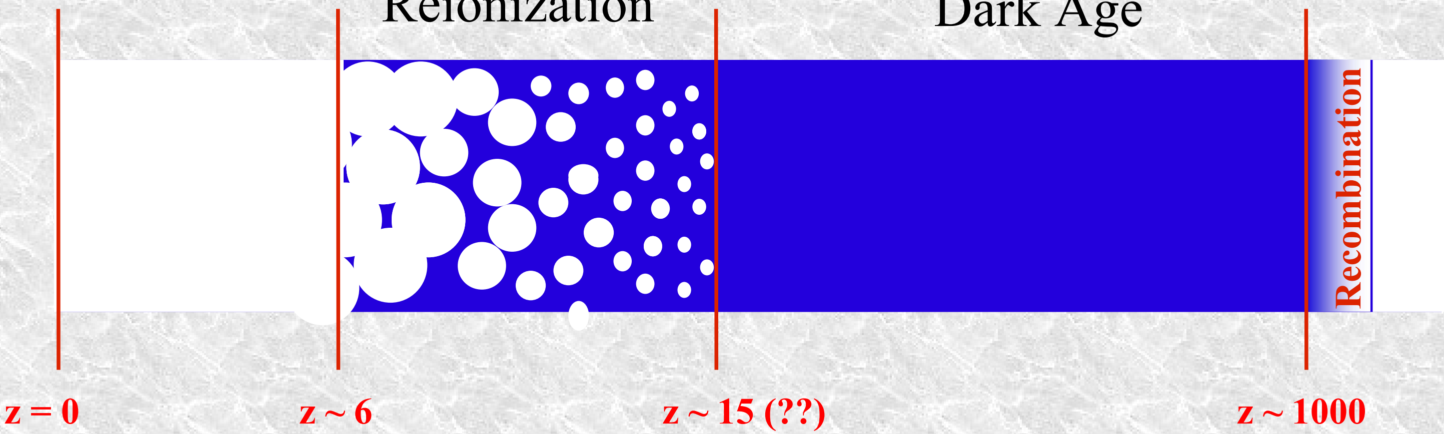
Epoch of Reionization: numerical simulations for LOFAR and SKA.

28 March 2006

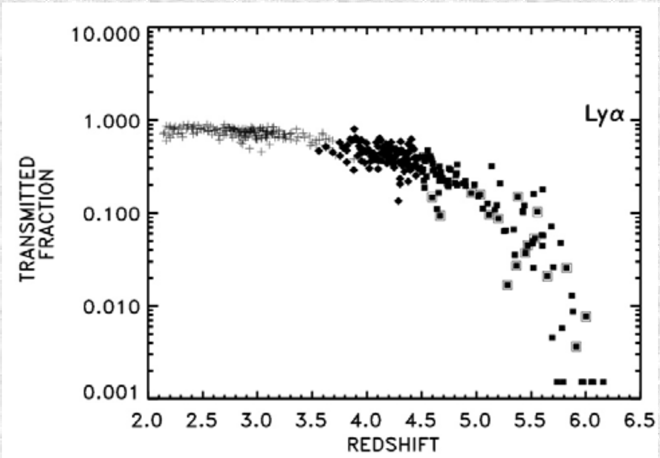
Benoît Semelin - LERMA

What we think we know about EoR



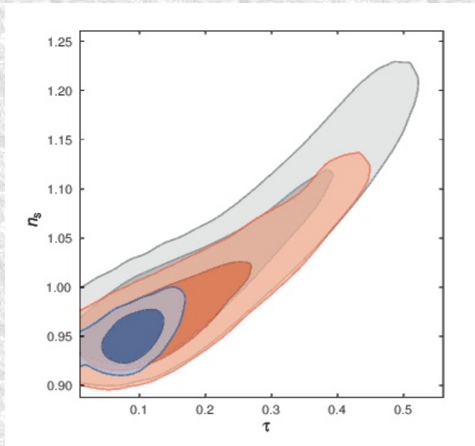
Example of constraints on reionization redshifts:

Gunn-Peterson effect in high *z* quasars



Fan et al. 2006

WMAP: optical depth to EoR



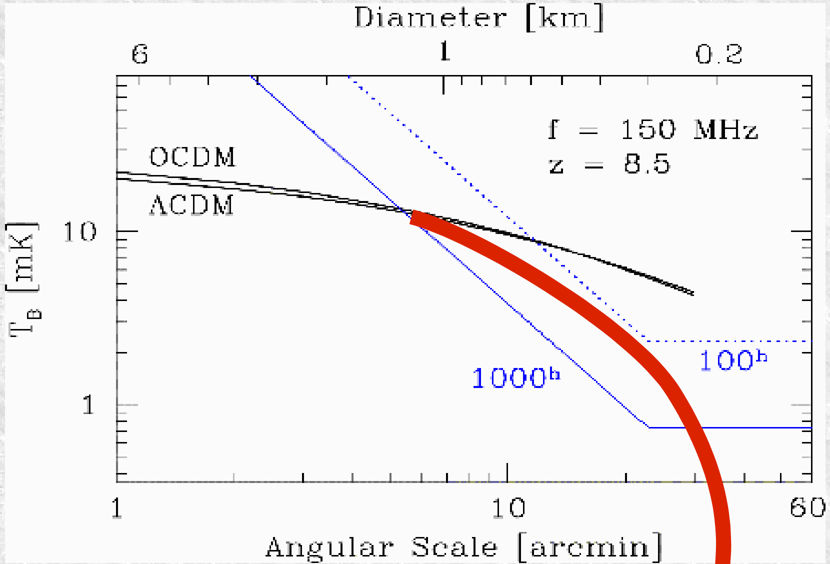
Spergel et al. 2006

1 year:
- $\tau \sim 0.17$
- $z_{ion} = 17 \pm 5$

3 years:
- **$\tau \sim 0.092$**
- **$z_{ion} \sim 10$**

What will we learn from LOFAR and SKA ?

LOFAR and SKA will produce a **tomography** (maps at different redshift) of the **neutral hydrogen 21 cm line**.



<u>Expected signal properties:</u>

- In absorption (against CMB) or emission
- ~ 20 mK average brightness temperature
- Structures from 1° down to 0.1 arcsec.

<u>Goals with LOFAR and SKA:</u>

Global signal detection

- LOFAR: $6 < z < 20$
- SKA: $z < 10$

Spatial structure analysis

- LOFAR: down to 6' i.e. cluster size (1000h intégration, 1.5 km baseline)
- SKA: down to 1' (?) (better sensitivity).

We need better predictions for the signal properties: homogenous or patchy reionization?

What can we learn from numerical simulations of EoR

Numerical simulations necessary ingredients:

- Dynamics (gravitation+hydro): N-body or grid-based
- Sub-grid physics: star formation, feedback, cooling.
- Radiative Transfert + ionization/recombination physics.
- HI emission modelization.

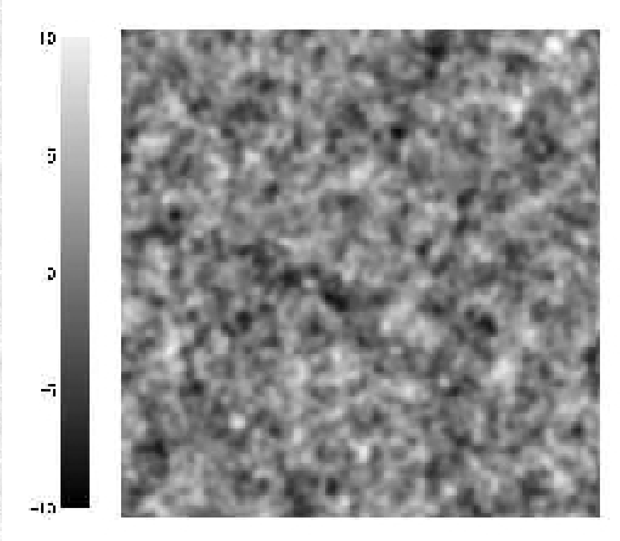
Predictions:

- Brightness temperature maps of HI 21cm emission at all redshifts.

Some relevant parameters:

- Source type: Pop III stars vs quasars
- f_{esc} : photon escape fraction
- Source clustering (not a real parameter).

20°x 20°



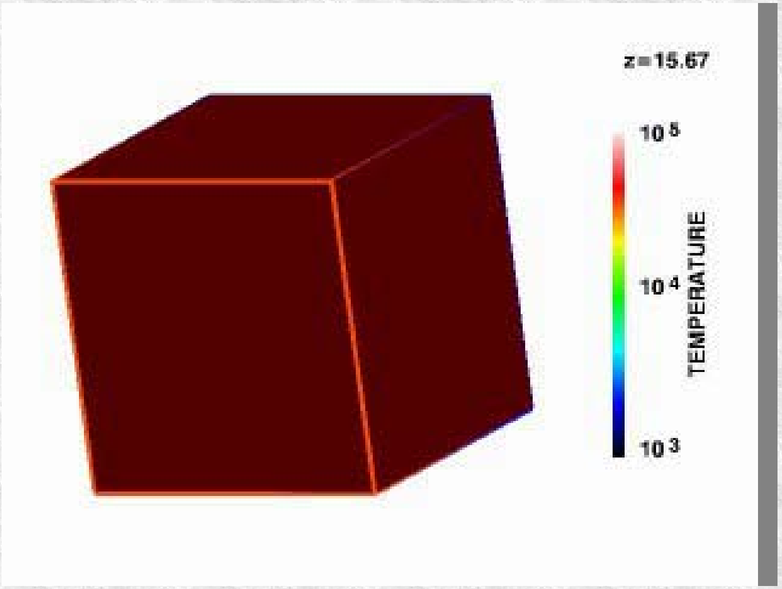
Brightness temperature fluctuations of redshifted HI 21cm line at z=9, using OTVET (Gnedin & Shaver 2004)

State of the art codes for simulations of EoR

Radiative transfer exact solution cost: $N^{5/3}$
Dynamics cost: N ln(N)

Clever radiative transfer scheme are needed !

Some comological radiative transfer codes:



(Gnedin)

- **OTVET** (Gnedin & Abel): use momentum equations for RT.
- **CRASH** (Maselli, Ferrara, Ciardi): Monte Carlo propagation on grid. (no dynamics)
- **FLASH-HC** (Rijkhorst et al.): Ray-tracing on AMR
- **C^2-RAY** (Mellena et al.)
- **ART** (Nakamoto et al.) (no dynamics)
- several other...

The HORIZON project

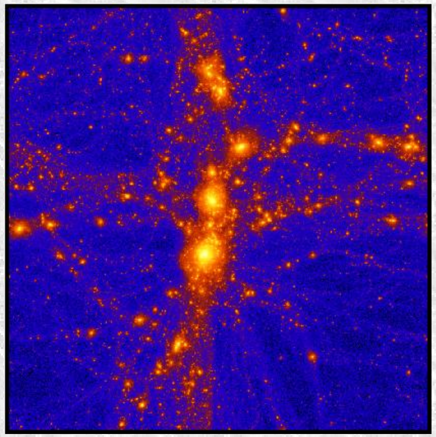
http://www.projet-horizon.fr

The HORIZON projet federates numerical simulations activities in france around Galaxy Formation. Main projects:

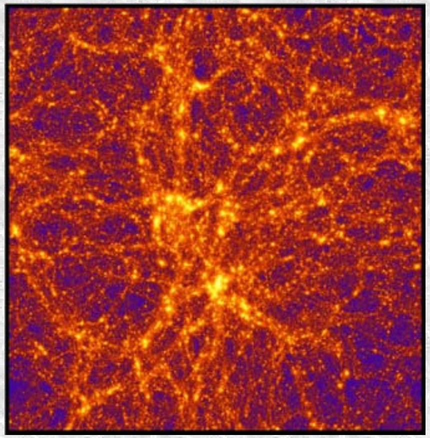
- **Large-scale simulations**
  - o Cosmological Horizon (Hubble volume) simulation
  - o Several simulations of Large-Scale Structures
  - o Several zoom-simulations of galaxy clusters
- **Galaxy-scale simulations**
  - o Several simulations of "Lyman-alpha" filament forest
  - o Several zoom-simulations of galaxies
- **Small-scale simulations**
  - o **Simulations of the re-ionization epoch**
  - o Several zoom-simulations of first stars formation

First results:

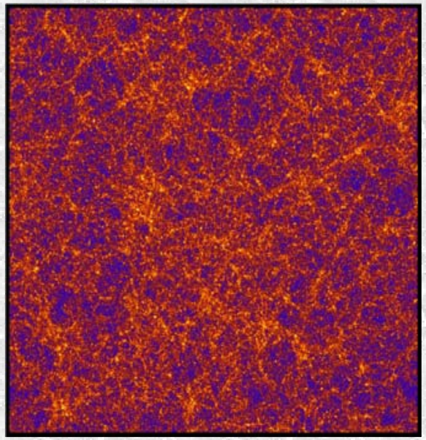
$20\ h^{-1}.Mpc\ 256^3$



$100\ h^{-1}.Mpc\ 512^3$



$500\ h^{-1}.Mpc\ 512^3$



EoR simulations activities in the HORIZON project

EoR is a new field of investigation for us.

The EoR team within Horizon:

- F. Combes
- B. Semelin
- S. Baek (Master + PhD)
- ?? (Post-Doc Sept 06, SKA-DS funding)

Our objectives:

- Compute 4-D (space+redshit) density + ionization fraction fields for gas with coupled **Dynamics and Radiative Transfer.**
- Derive 21cm line tomography, test models…

What will we do differently?

- ***Multizoom:*** A working parrallel Treesph, **multiphase**, dynamical code.
- **Radiative transfer code:** Monte Carlo on an **adaptative** grid.

Still under construction.

The *Multizoom* code

Multipurpose code including:

-Dynamics (gravitation + hydro)
- Multi-phase gas physics
- Cooling, star formation, feedback

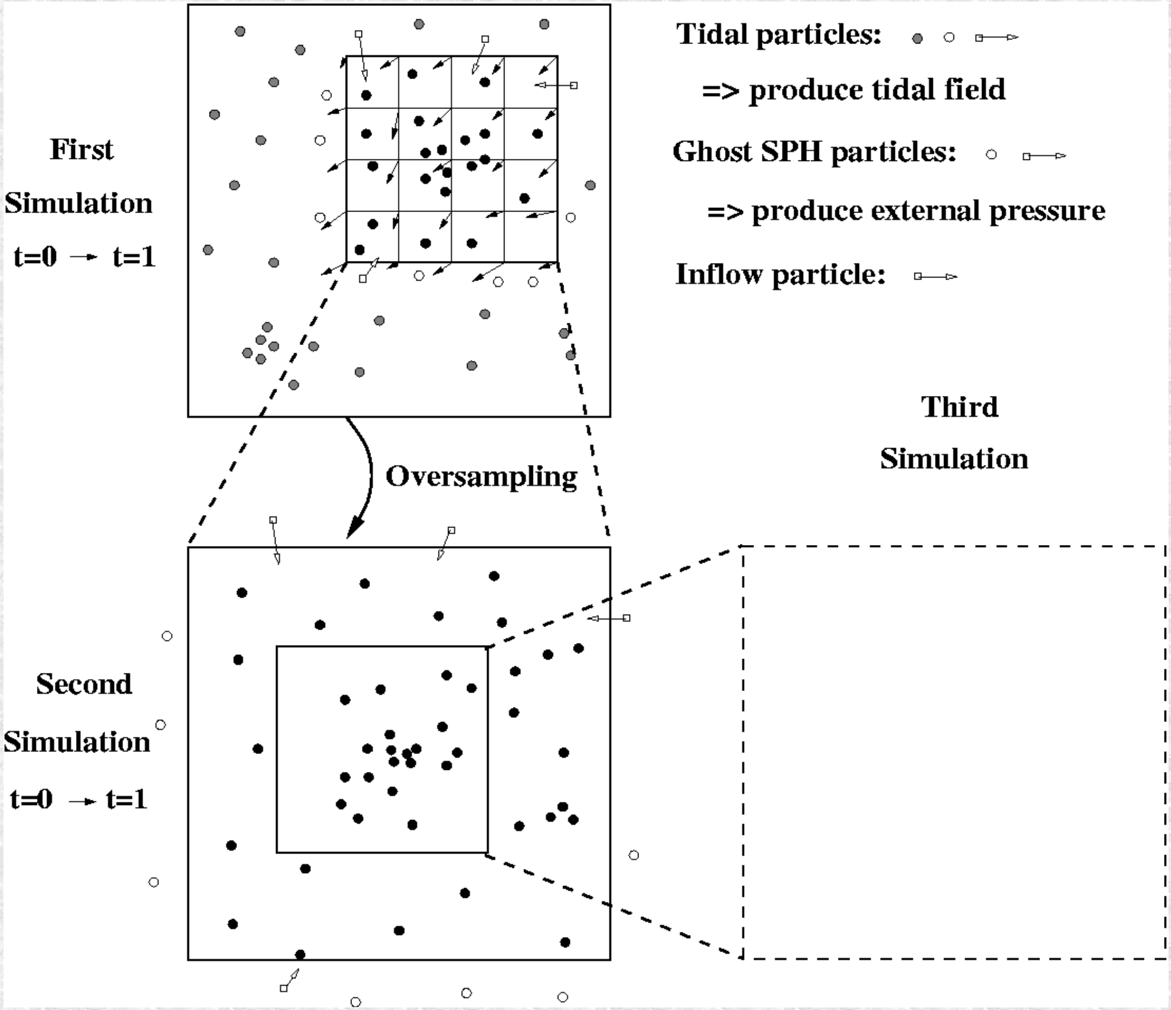
Special ability:

- Multi-step zooming procedure:
  => Very high mass resolution at moderate computational cost
  => Lower statistics

Present usage:

Galaxy formation in 20 Mpc box with

8. 10^5 $M_\odot$ baryonic mass resolution at last zoom level

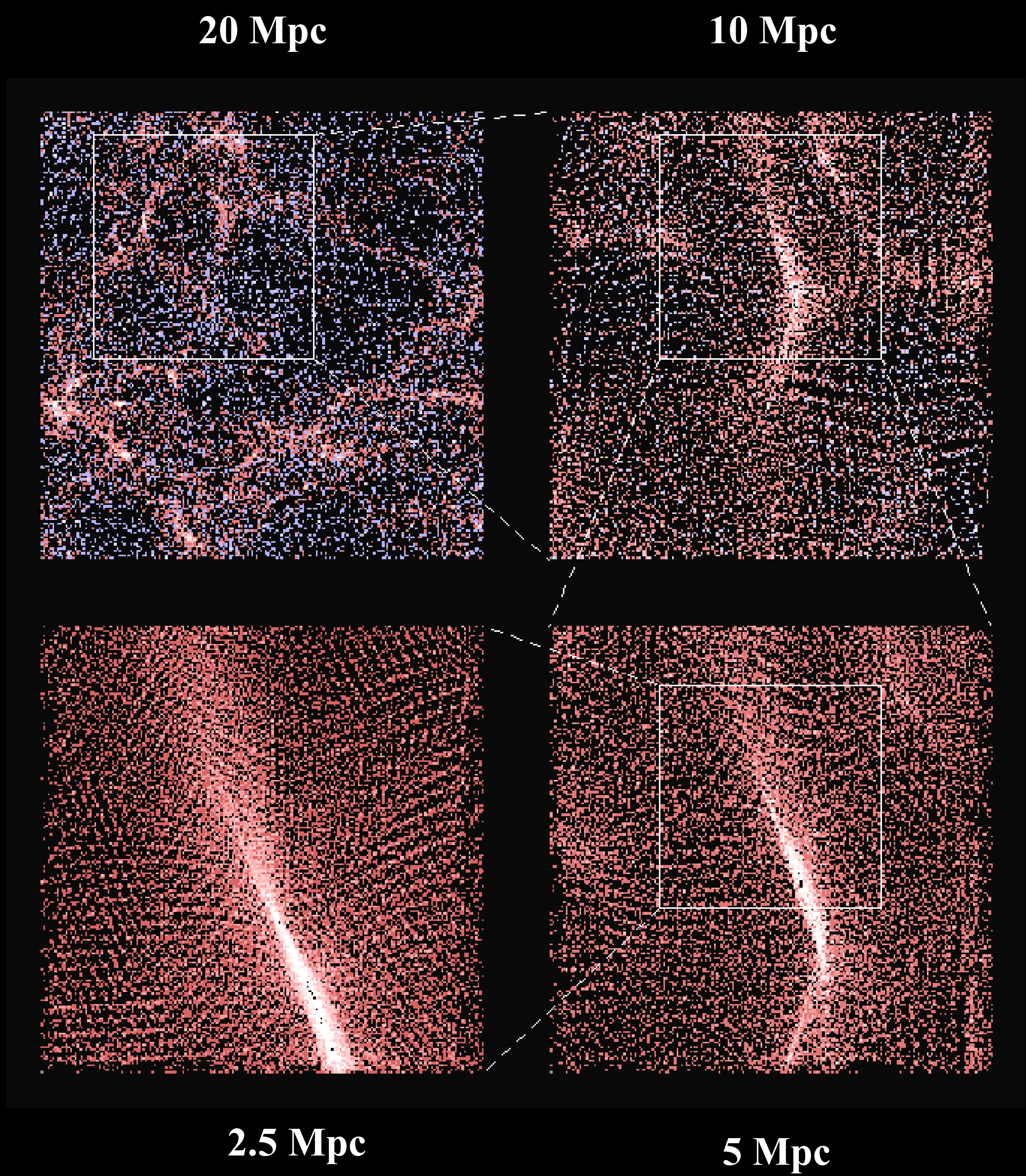


« Old » ΛCDM simulation
(Λ=0.7, h=0.7, Ω_m = 0.3)

4 « phases »

32^3 -> 256^3 particles.

z = 45. -> z=0.



Radiative transfer module

Algorithm: Monte-Carlo.

- Cast ray with random optical depth before absorption, τ_0.
- Follow ray on a grid.
- Compute current optical depth using cell properties (gas density, etc...)
- Absorption or diffusion at τ_0

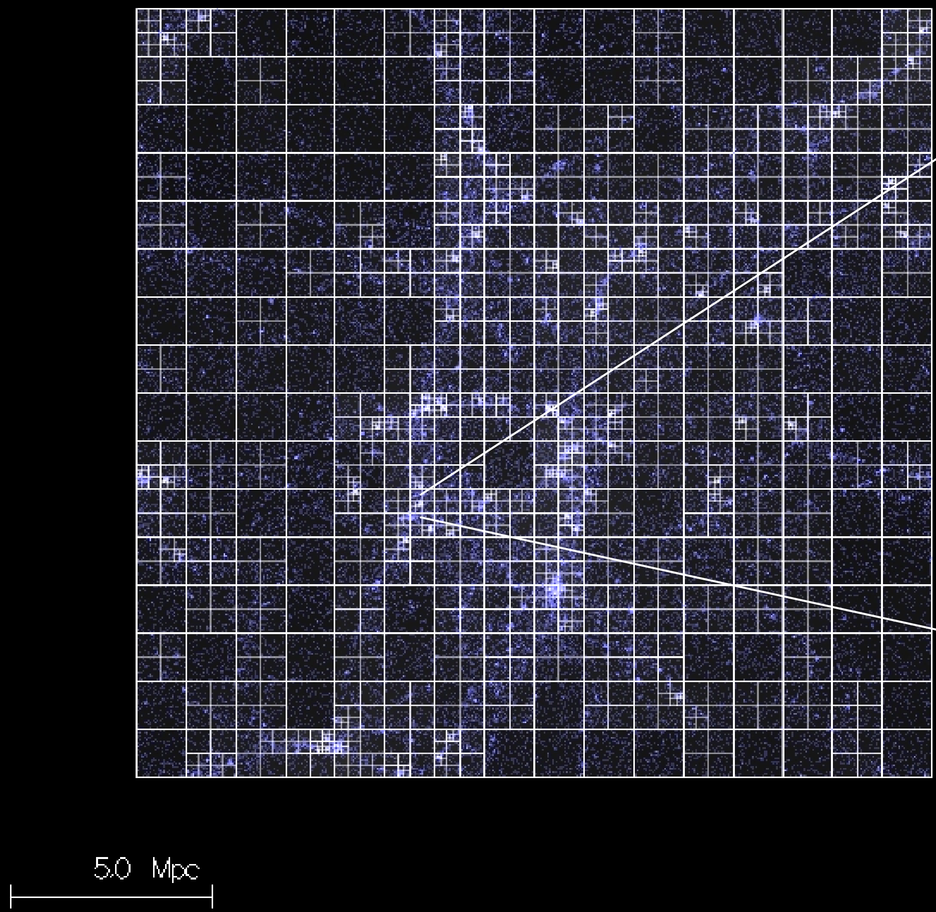
Pros and cons:

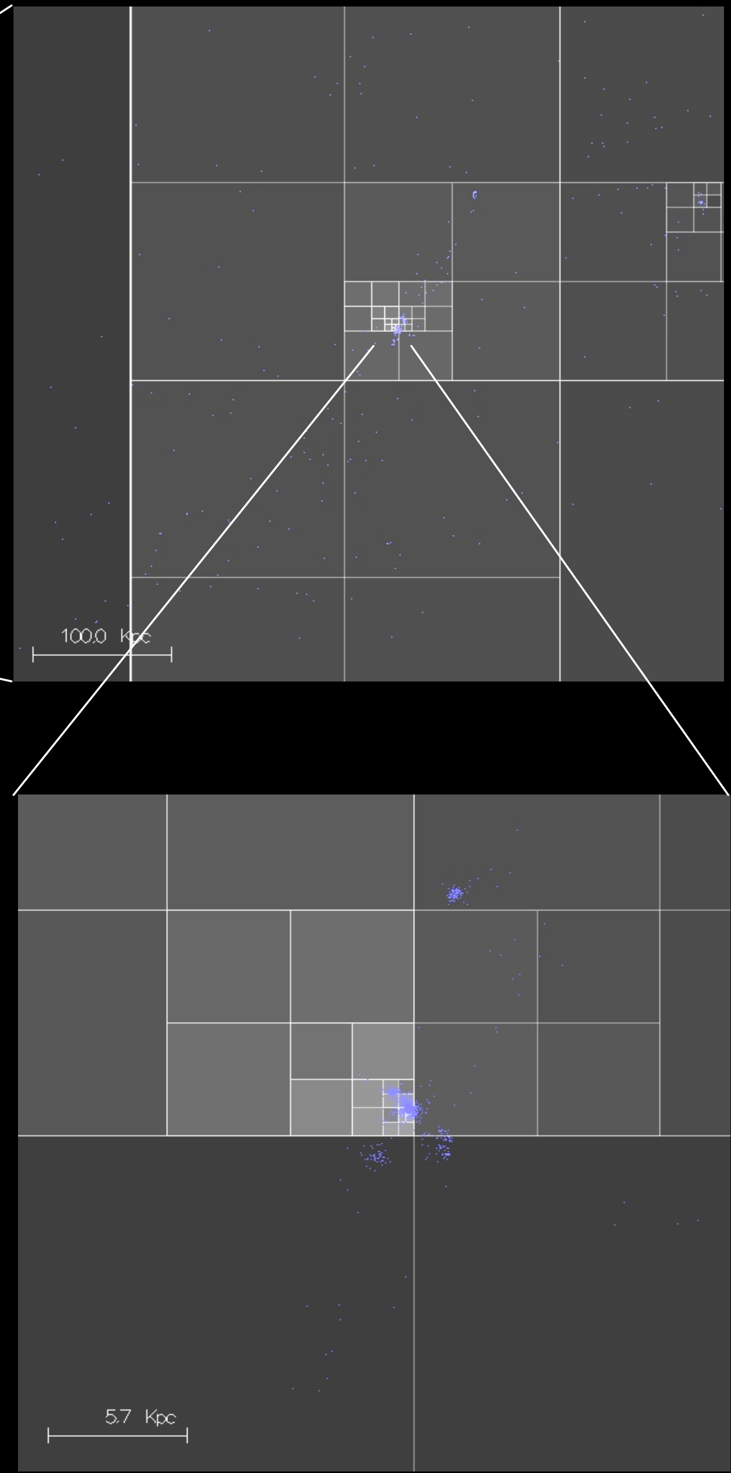
- **Valid in all opacity regimes.**
- **Handles arbitrary diffusion parameter.**

- **High CPU cost (in difficult situations).**

Difference with CRASH:

- Adaptative grid based on octal tree from treesph code.





« First light » for the RT module.

- Gray scale codes photon density.
- Blue points are gas particles.
- Sources in dense region (not plotted)

Challenges in 21 cm line observations and simulations

Foregrounds removal:

- Foreground 100 to 1000 brighter than 21 cm line signal:
  - -Radio halos (synchrotron)
  - -Radio relics (synchrotron)
  - -Radio galaxies
  - -Interstellar medium emission.

=> Combine data analysis, source modeling and simulations to remove foregrounds.

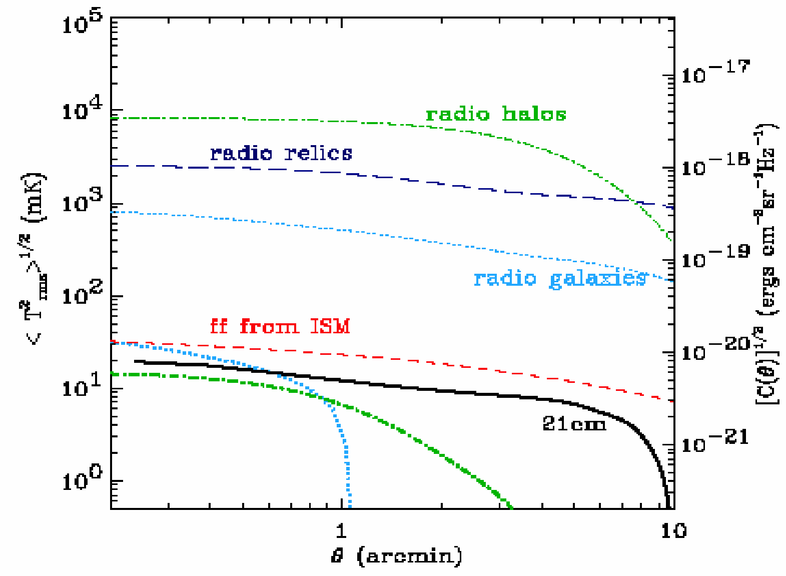


Figure 7. Prediction for the correlation signal owing to intensity fluctuations of radio galaxies (dotted lines), ISM free-free emission (short dashed), radio relics (dashed dotted), radio halos (long dashed) at $\nu = 115$ MHz. The thicker lines show the signal when sources above a flux $S_c = 0.1$ mJy are removed. The solid line shows the primary correlation signal due to the redshifted 21cm emission (CM)

Di matteo *et al.*, 2004

Predict reionization geometry:

- Early or late overlap ? Change signal properties.