Epoch of Reionization: 21-cm signal fluctuations from inhomogeneous Ly-α background

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21-cm signal: brightness temperature

The 21-cm brightness temperature depends on:

- T_S : Hydrogen spin temperature
- δ: Baryon overdensity
- **$1-x_i$** : Neutral fraction

$$\boxed{\delta T_B = T_B - T_{CMB} \propto (1+\delta)(1-x_i)\left(\frac{T_S - T_{CMB}}{T_S}\right)}$$

⇒ **If $T_S < T_{CMB}$, signal seen in absorption against the CMB**
If $T_S > T_{CMB}$ signal seen in emission.

Simulations required to predict T_b :

- δ: Dynamics (DM + hydro)
- **$1-x_i$** : Dynamics + Star formation + Radiative transfer (UV continuum)
- T_S : Dynamics + Star formation + Radiative transfer (UV continuum + **Ly-α**)

21-cm signal: physics of the emission

Value of the spin temperature T_S: 3 competing processes

- Scattering of CMB photons: $T_S \rightarrow T_{CMB}$ on a time scale 3. $10^5/(1+z)$ years.
- Collisions with e^- or other atoms: $T_S \rightarrow T_K$ in dense regions ($\delta\rho/\rho > 30$ at z=10).
- **Pumping by Ly-α photons (Wouthuysen-Field effect): $T_S \rightarrow T_c \approx T_K$.**

$$T_S^{-1} = \frac{T_{CMB}^{-1} + x_\alpha T_c^{-1} + x_{col} T_K^{-1}}{1 + x_\alpha + x_{col}} \quad \text{with} \quad x_\alpha = \frac{4 P_\alpha T_*}{27 A_{10} T_{CMB}}$$

$$\text{and} \quad T_c \approx T_K$$

P_α is the number of Ly-α scatterings per atom per second

Our goal: compute P_α with full radiative transfer.

$\Rightarrow$ New fluctuations in 21-cm e

Non-uniform Ly-α pumping

- Usual approach: uniform $P_\alpha(z)$ for 21-cm emission maps

Usually simple z threshold $\Rightarrow T_s(z > z_0) = T_K$

δT_b fluctuations from ρ_{HI} and T_K fluctuations only.

- Improved approach: non-uniform P_α (Barkana & Loeb 2005, Pritchard & Furlanetto 2006)

✓$P_\alpha \propto J(\nu_\alpha) \propto 1/r^2 \Leftrightarrow$ No wings in line profile
✓Contribution from upper Lyman series line.
✓Source distribution (clustering + Poisson)

Significant enhancement of δT_b fluctuations (up to ~ 10 mK)

Here P_α is independent of gas density (except for source position)

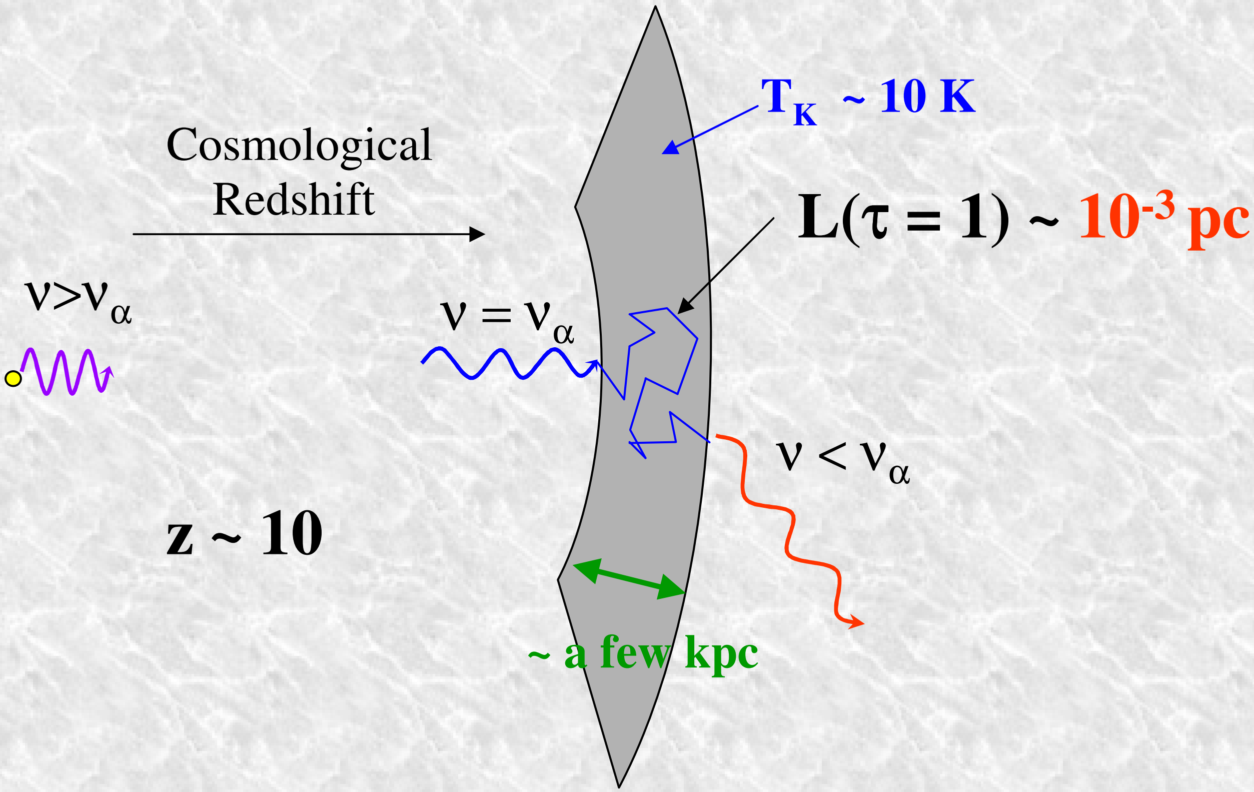
- Full radiative transfer approach: (Semelin, Combes and Baek 2007, submited to A&A)

✓Monte Carlo radiative transfer
✓Ly-α line only (for now)
✓Direct P_α evaluation

P_α is not $1/r^2$:
steeper and anisotropic
$\Rightarrow$ **Larger** δT_b fluctuations

Lyman-alpha simulations

Lyman-α cosmological radiative transfer:



Challenges:

- High τ fluctuations on small scales
- High τ values

Easy part:

-Almost no feedback on dynamics.

-No feedback on ionisatio

Ly-α transfer with LICORICE: algorithms and validation tests

Main features:

- Monte Carlo
  + Ray Tracing

- Adaptative grid

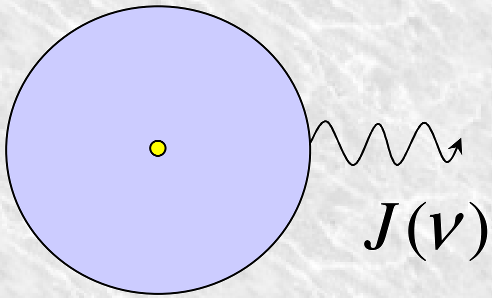
- Resonant scattering with Voigt line profile.

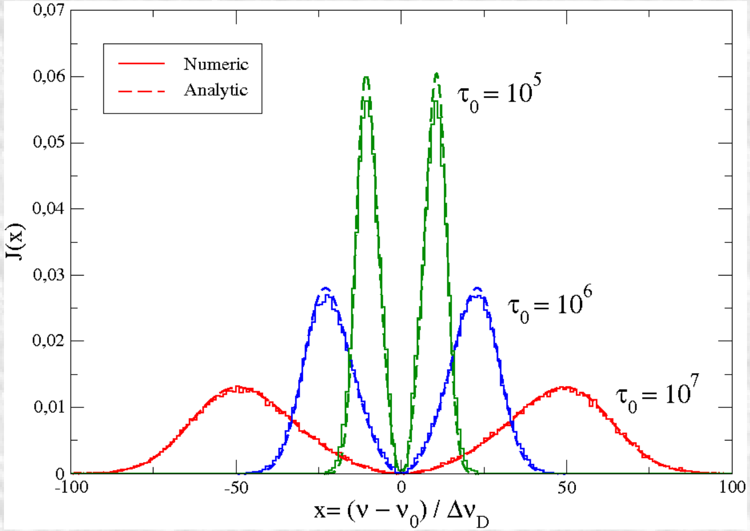
- Core-skipping acceleration scheme.

- Cosmological expansion included

Homogenous spherical cloud, central source: emerging spectrum

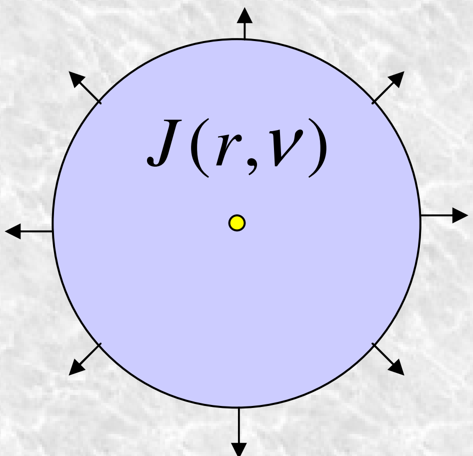
(Dijkstra et al. 2006)

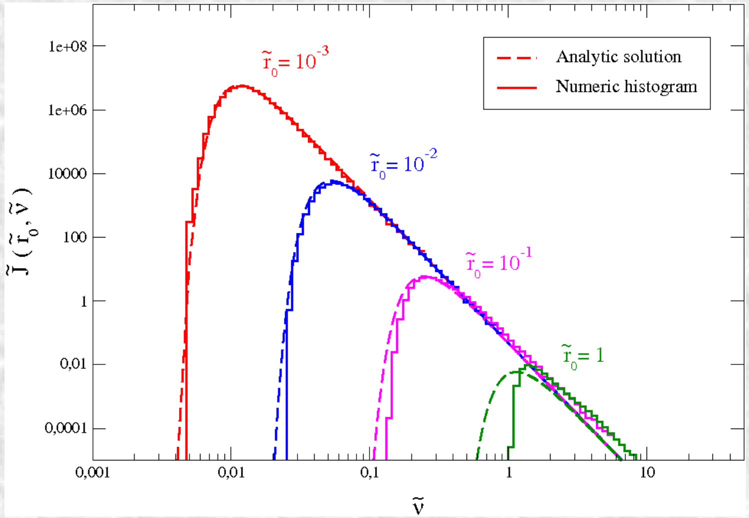




Expanding spherical cloud (T_K=0), central source: intensity map

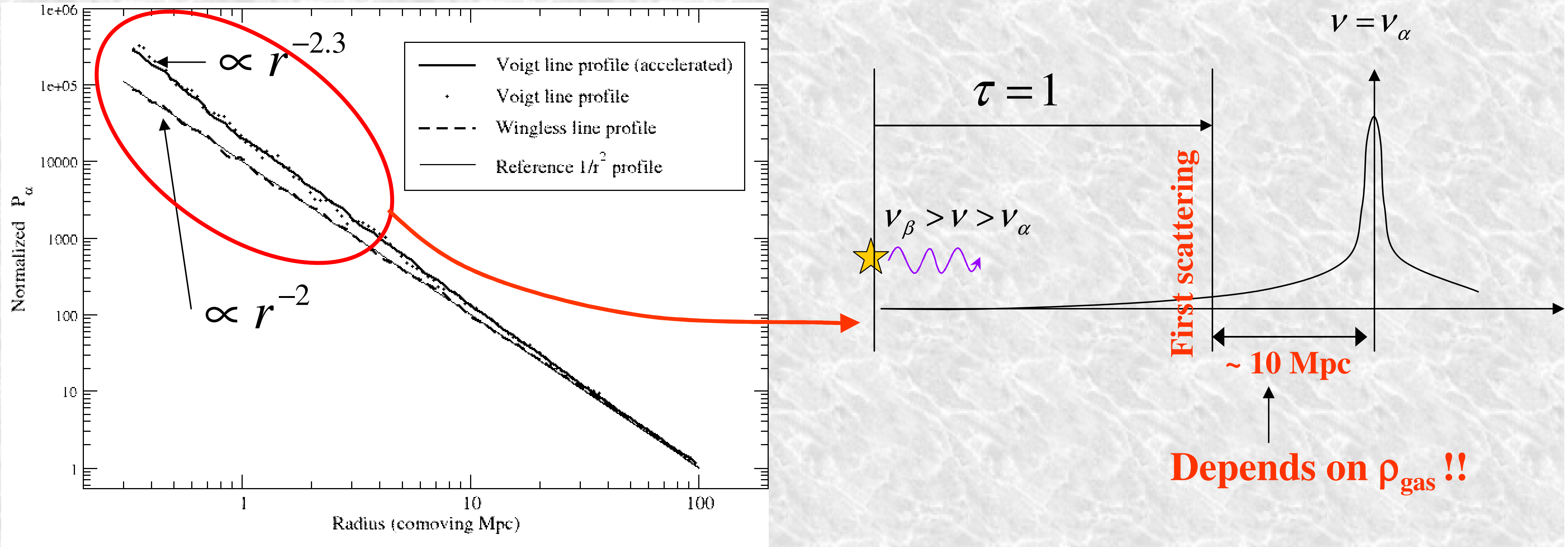
(Loeb & Rybicki, 1999)





P_α profiles in EoR-like situations

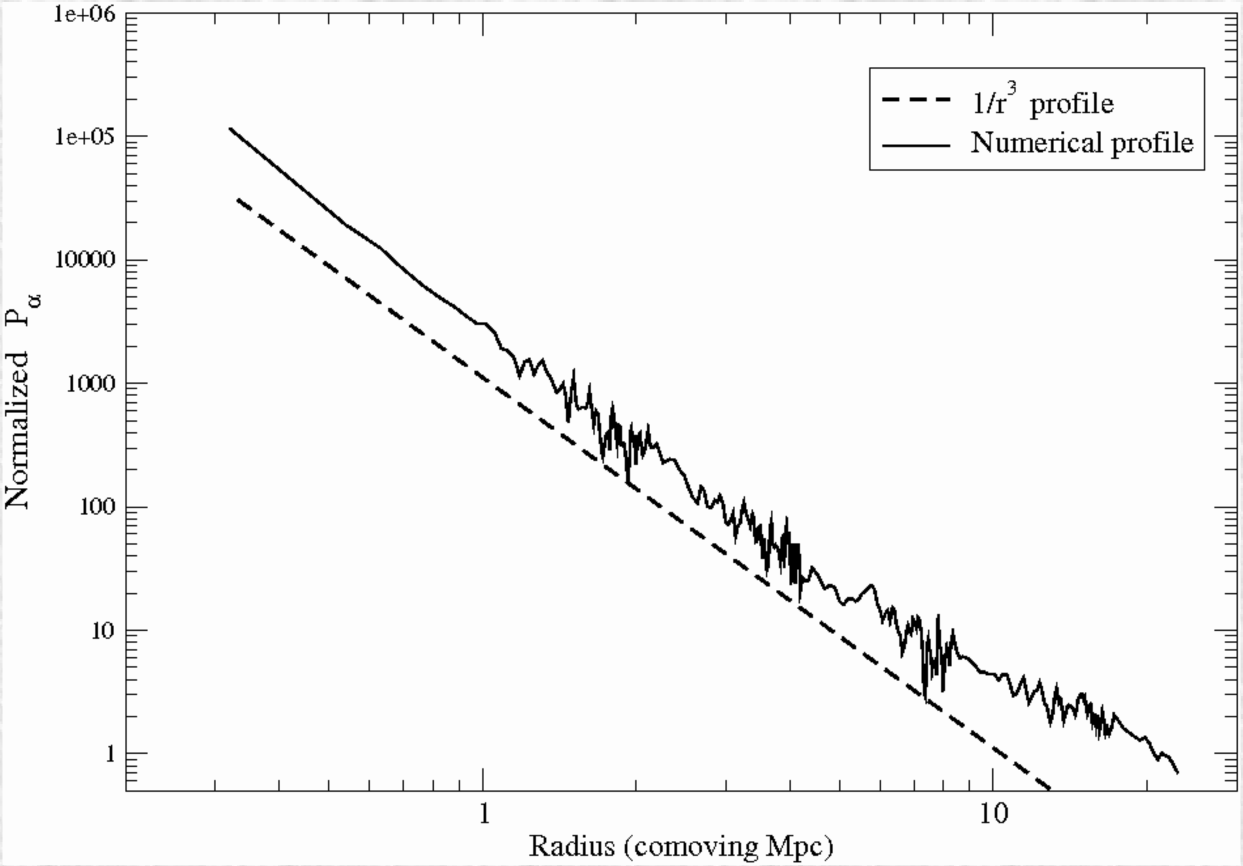
- Central source, **flat** spectrum
- Uniform gas medium (T_K=30K, ρ_{gas}= ρ_{crit}, z~10)



P_α profile is **not $1/r^2$ at r < 10 Mpc**
because of **wing scattering.**

P_α profiles in EoR-like situations

- Central source, flat spectrum
- $1/r^2$ gas density profile out to 10 Mpc (T_K=30K, z~10)

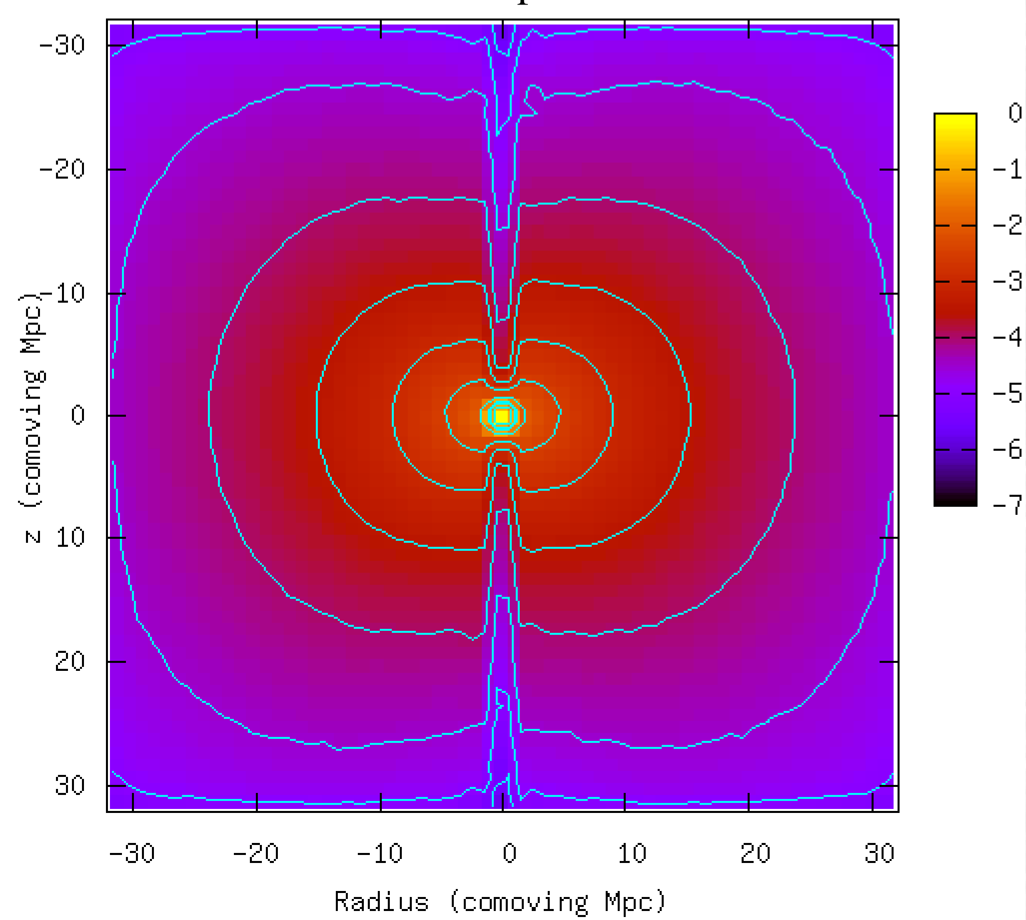


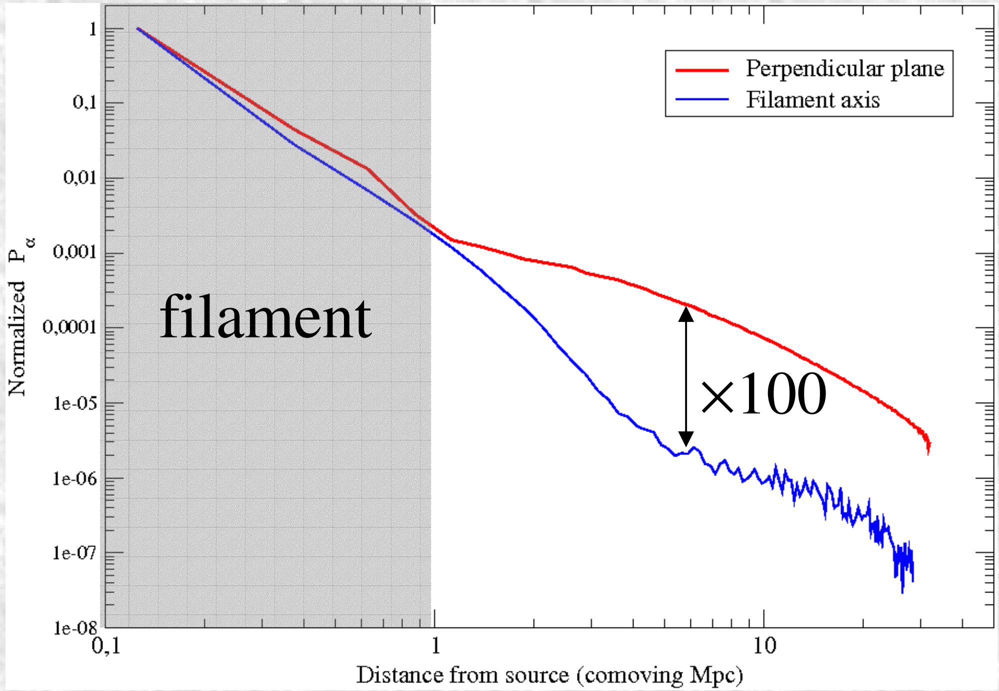
P_α **~ $1/r^3$**

where ρ_{gas}~ $1/r^2$

P_α map around a filament

~ 5×10^7 photons





Filament overdensity: $\delta\rho/\rho=63$
Filament radius: R= 1 Mpc

- ✓ Strong P_α depletion in the filament (shielding effect).
- ✓ Oblate contours up to large scales (axis ratio ~2 at 10 Mpc)

Conclusions & prospects

- Full radiative transfer affects P_α
- Surounding gas density affects P_α

What next?

Apply to an EoR simulations => produce 21-cm map
- For a static output.
- For the evolving density/ionization-fraction/source fie

Include upper Lyman series lines.