Lyman-alpha emitting galaxies at high redshift

Semi-analytic modelling

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OUTLINE

- Introduction : theory and observations

- Role of radiative transfer

- Modelling of Lyα galaxies
(Garel+12a, MNRAS; Garel+12b, in prep)

    - Semi-analytic model of galaxy formation
    - Model of Lyα emission

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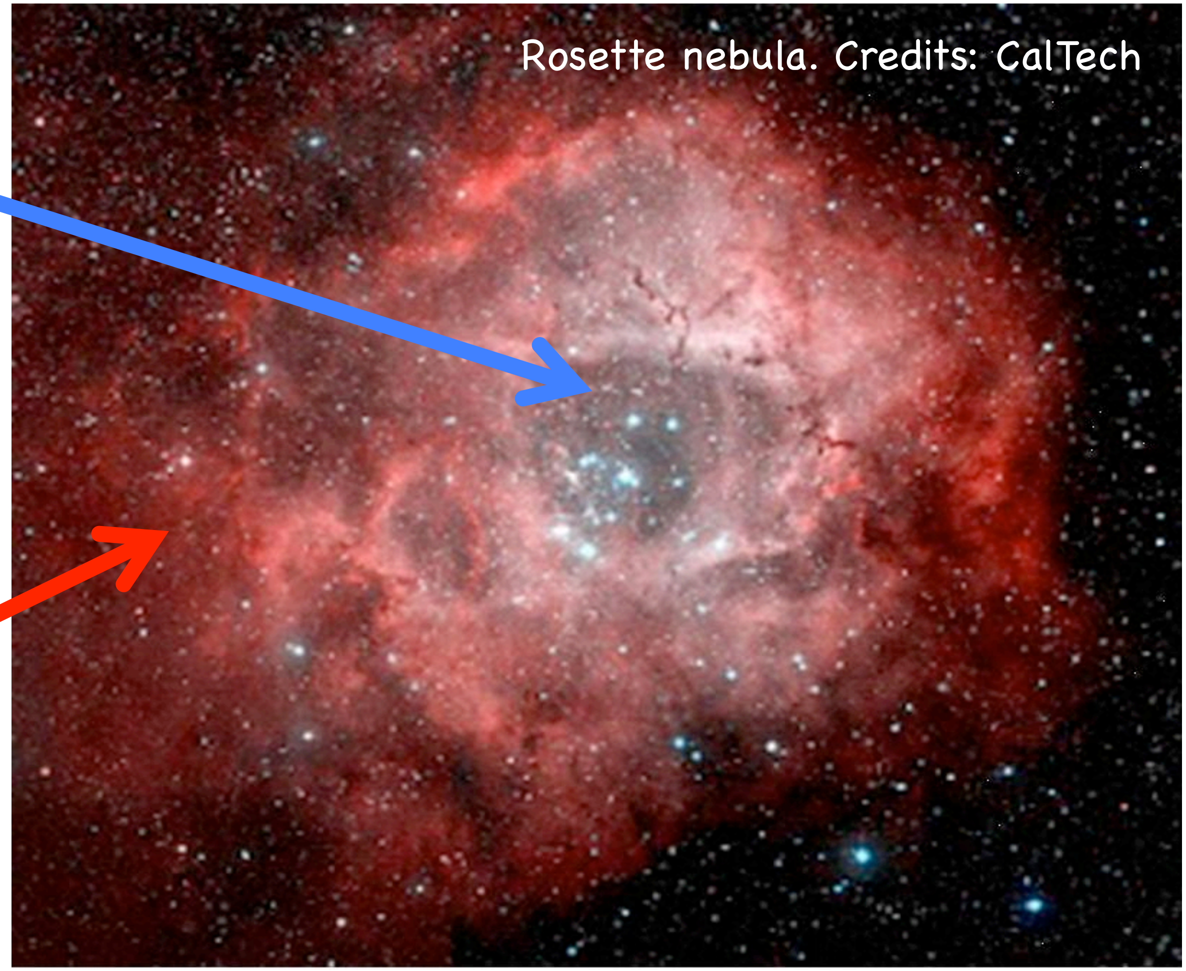
Lyman-alpha (Lyα) emission from HII regions

OB stars
Ionizing radiation

HII region
Hα, ***Lyα***



Recombination of HII regions

- **Probability(Lyα=1216 A) ≈ 2/3 per recombination**

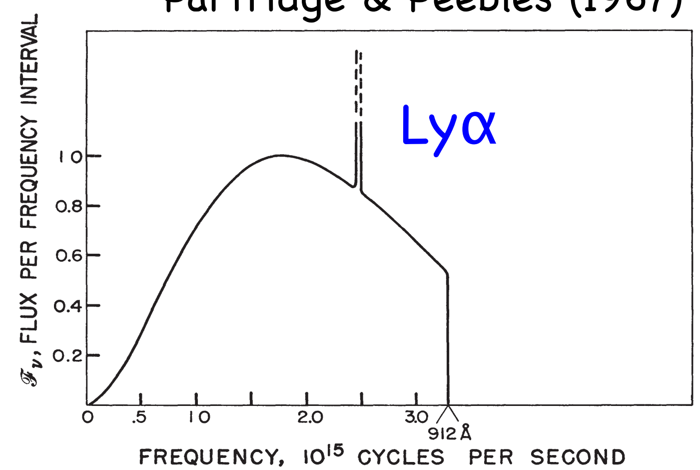
Intrinsic Lyα luminosity $\mathbf{L}^{\mathrm{intr}}_{\mathrm{Ly}\alpha} \propto \frac{\mathbf{2}}{\mathbf{3}}\dot{\mathcal{N}}^{\mathrm{OB}}_{\mathrm{ion}} \propto \mathrm{SFR}$

- **Intense line in star-forming galaxies**

$$\mathbf{L}^{\mathrm{intr}}_{\mathrm{Ly}\alpha} \approx 10\%\mathbf{L}_{\mathrm{bol}}$$

- **Easy to detect at high redshift !**

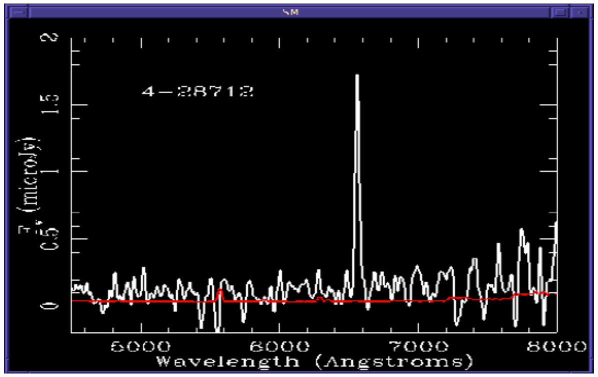
Partridge & Peebles (1967)



Lyα in the observational context

Lyα selected galaxies = Lyman-Alpha Emitters (LAE)

- Narrow band vs Broad band (Ouchi+08;Hu+10)
  => LAE candidate if $\mathbf{EW_{Ly\alpha} > EW_{threshold}}$



- Blind search with slit or IFU
  (e.g. Rauch+08, Blanc+10)

$\lambda_{obs} = (1+z) \times \lambda_{Ly\alpha}$: seen in optical-NIR at $3 < z < 7$

➡ Large samples (>3000) of LAEs at $3 < z < 7$ (e.g. Subaru, VLT) allow to derive statistical constraints on LAEs

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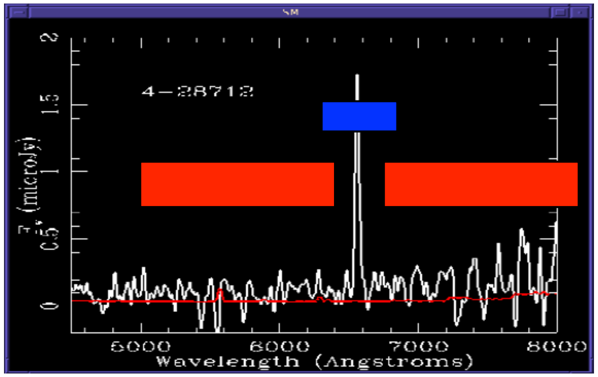

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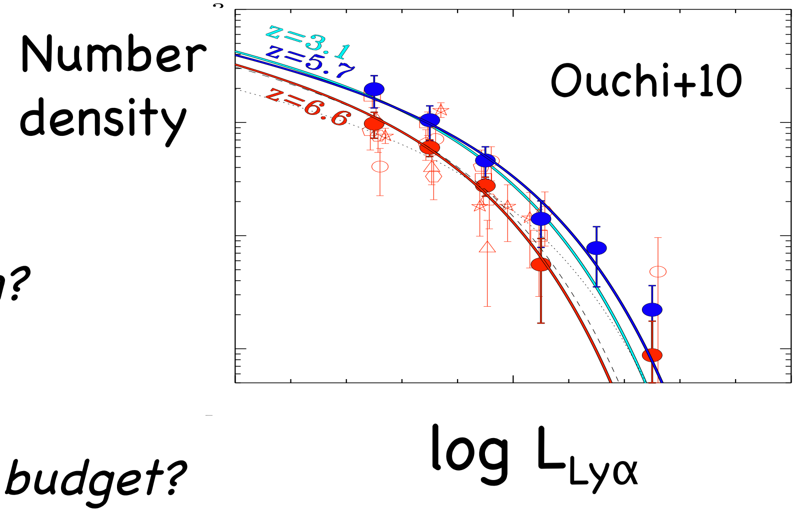
Lyα in the observational context

Lyα Luminosity Function



- evolution with z ?

  Variation of ISM or IGM absorption?

- faint end slope ?

  Contribution of faint galaxies to SF budget?

Mean physical properties of LAEs

- stellar mass: $\langle M_{star} \rangle \approx 5.10^8\ M_{sun}$
- dust extinction: $\langle A_V \rangle \approx 0.1$
- age of stellar pop. $\langle Age_{stars} \rangle \approx 200$ Myr

e.g. Gawiser+06; Finkelstein+07

Lyα in the observational context

UV selected = Lyman-Break Galaxies (LBG, Steidel+99, Bouwens+07)

- UV-continuum magnitude M_{UV} selection
  (= highly star-forming galaxies)

- LBG seem more massive, more dusty and older than LAE

- Spectroscopic follow-up "sometimes" shows Lyα !
(e.g. Shapley+03, Stark+10)

We want to understand the properties of Lyα Emitters, but also their link with the Lyman-Break Galaxies

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- **Role of radiative transfer**

- Modelling of Lyα galaxies
(Garel+12a, MNRAS; Garel+12b, in prep)

    - Semi-analytic model of galaxy formation
    - Model of Lyα emission

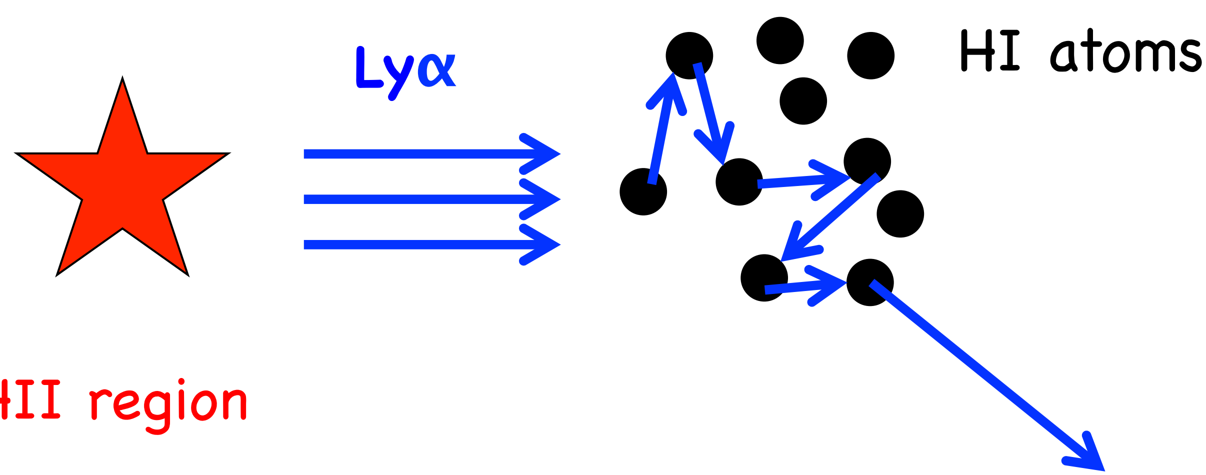
Radiative transfer - I

Lyα photons travel through the ISM : $N_H(\text{ISM}) \approx 10^{20}\ \text{cm}^{-2}$

Lyα scattering cross section is huge: $\sigma_{Ly\alpha} \approx 10^{-16}\ \text{cm}^2$

➡ Medium optically thick to Lyα photons: **resonant scattering**

Simplistic ISM scheme



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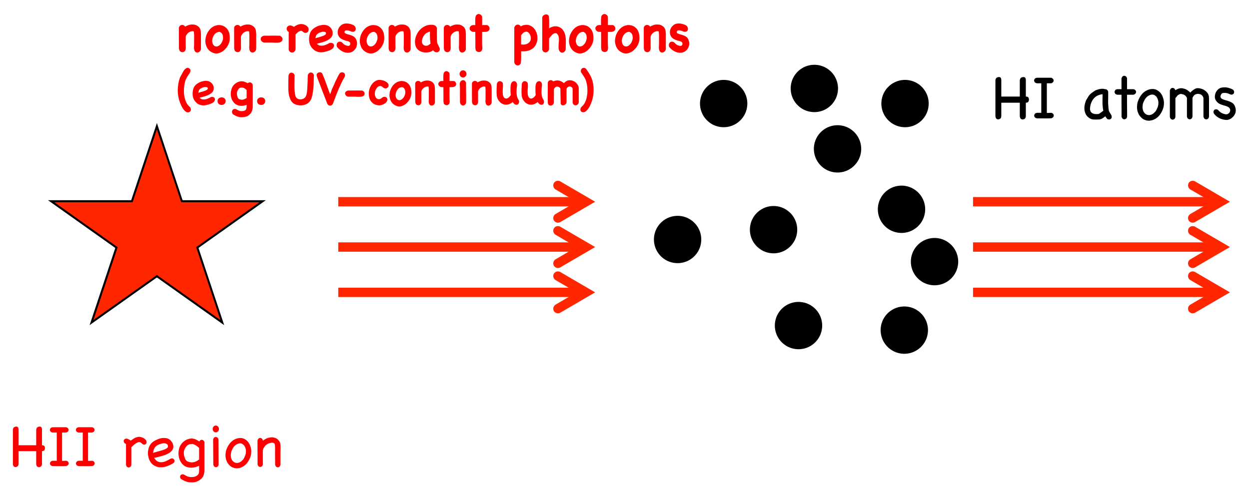


Radiative transfer - I

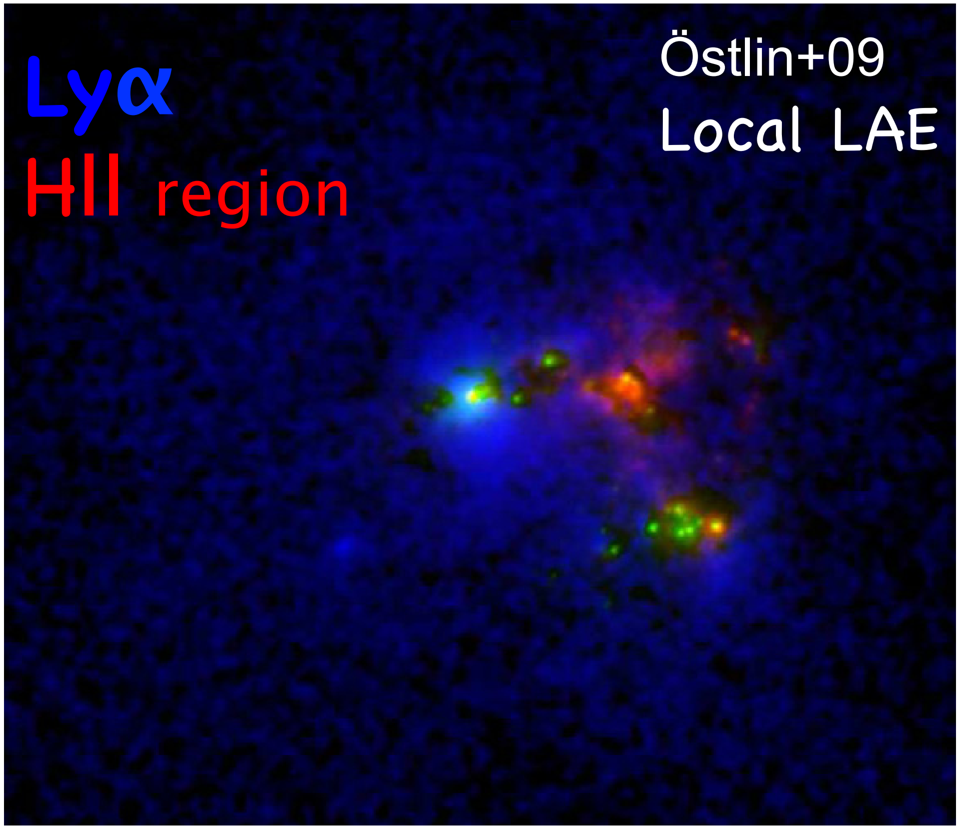
- This is actually observed

- Path(Lyα) greatly increased

=> Enhancement of dust extinction

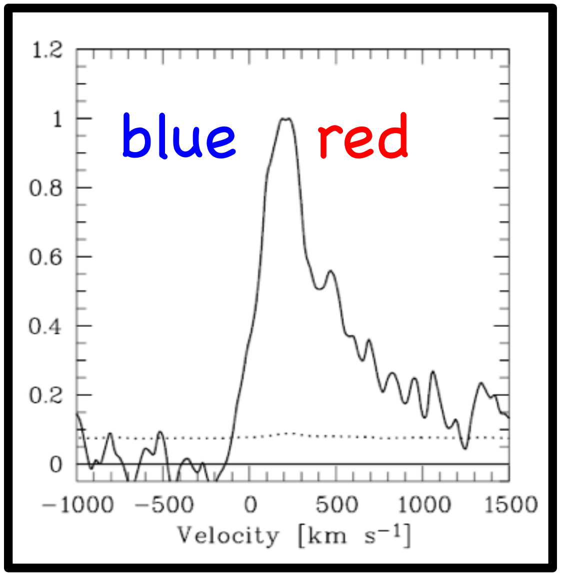
Escape fraction of Lyα photons f_{esc} hard to infer or predict !

$$\mathbf{L}^{\rm obs}_{\rm Ly\alpha} = \mathbf{f}_{\rm esc}\mathbf{L}^{\rm intr}_{\rm Ly\alpha}$$



Radiative transfer - II

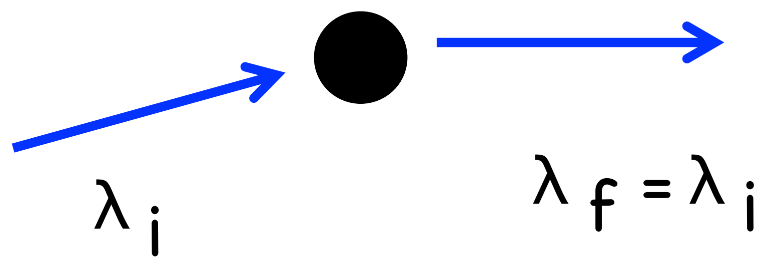
Tapken+07



Typical observed Lyα profile
- broad
- **redward asymetry**
- 0 < z < 7

(Kunth+98, Hu+10, Yamada+12)

Rest-frame

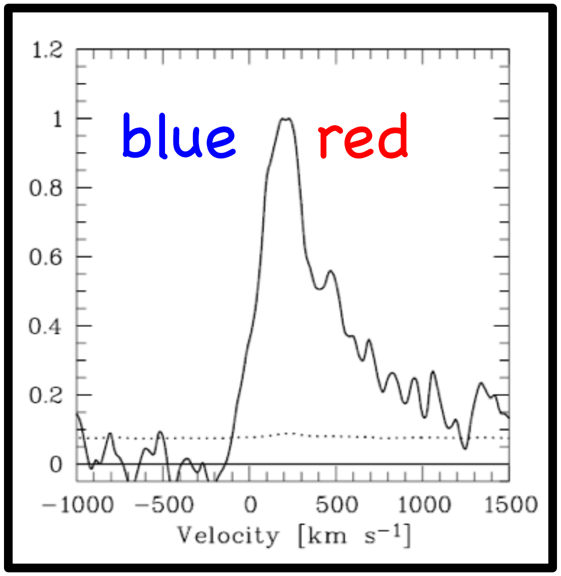


- Again, resonant scattering seem to be at play: Doppler shift

- Potential impact of gas motion (e.g. galactic winds)

Radiative transfer - II

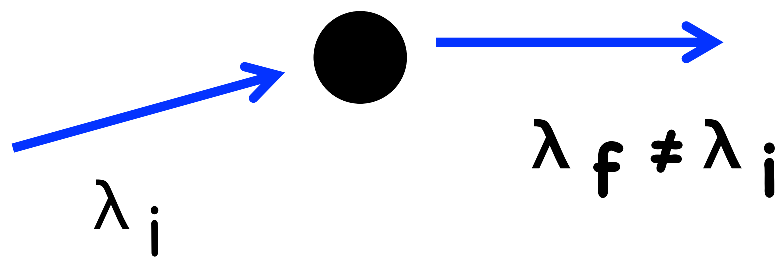
Tapken+07



Typical observed Lyα profile
- broad
- **redward asymetry**
- 0 < z < 7

(Kunth+98, Hu+10, Yamada+12)

External-frame
in which $\mathbf{V_{atom}} \neq 0$



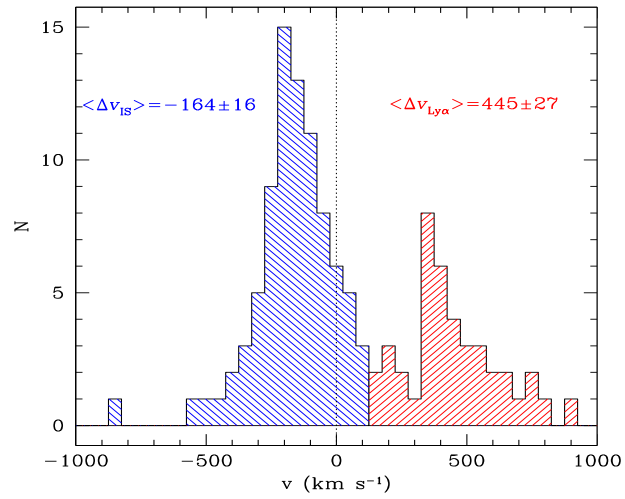
- Again, resonant scattering seem to be at play: Doppler shift

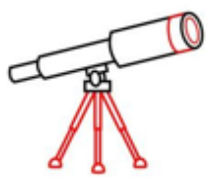
- Potential impact of gas motion (e.g. galactic winds)

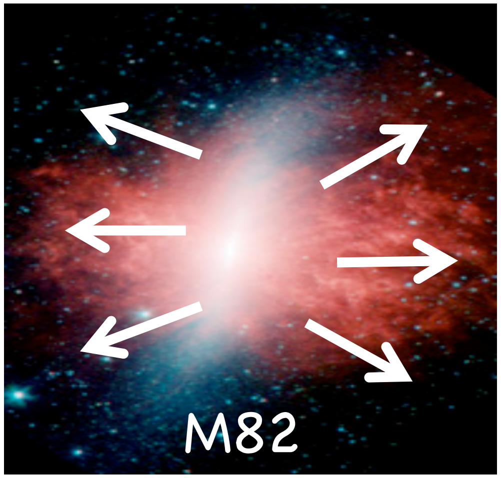
Radiative transfer - II

- Galactic outflows seem to be quite common at high redshift

(e.g. Shapley+03, McLinden+10)







Steidel+10

Model of Lyα transfer through spherical expanding shell has been proposed (Verhamme+06, Dijkstra+06)

Radiative transfer - II

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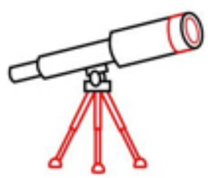
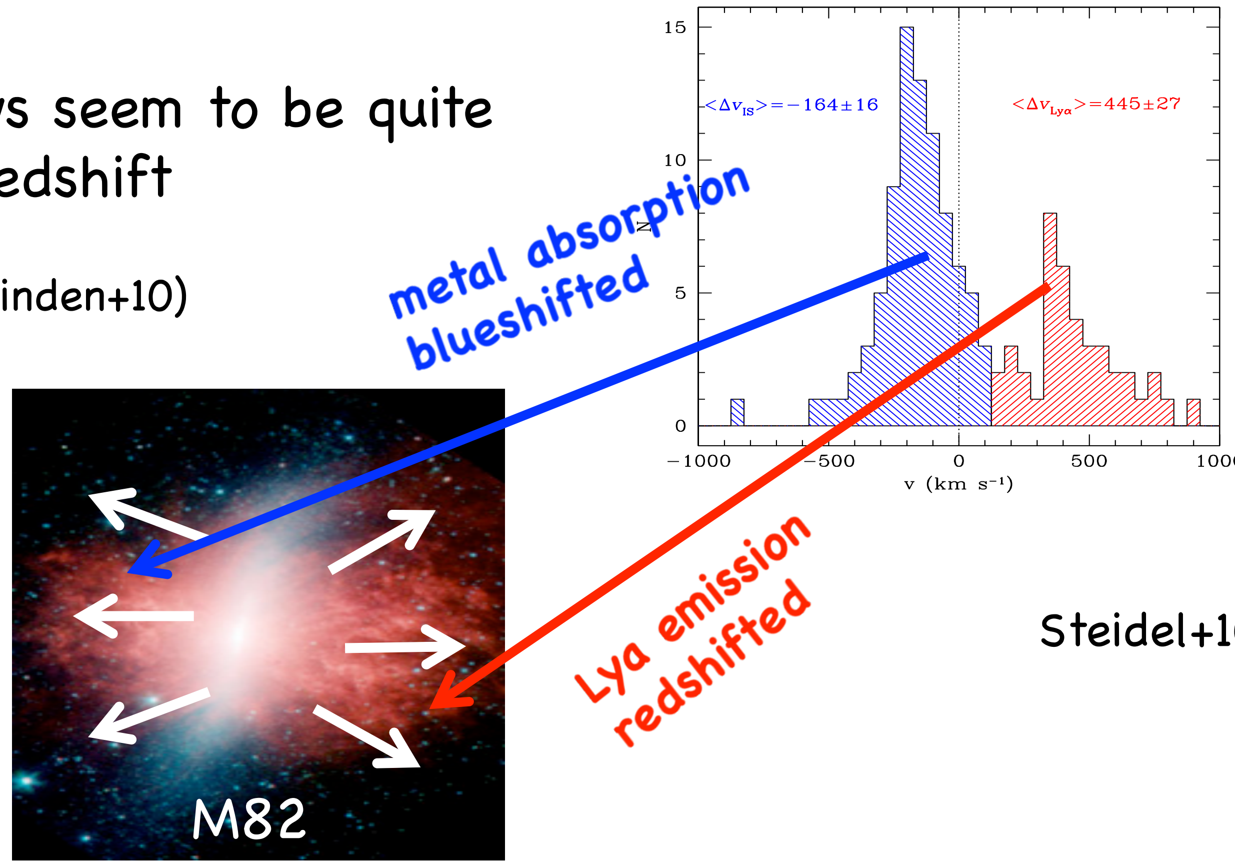




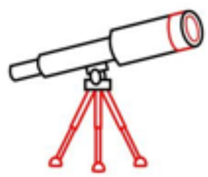
Steidel+10

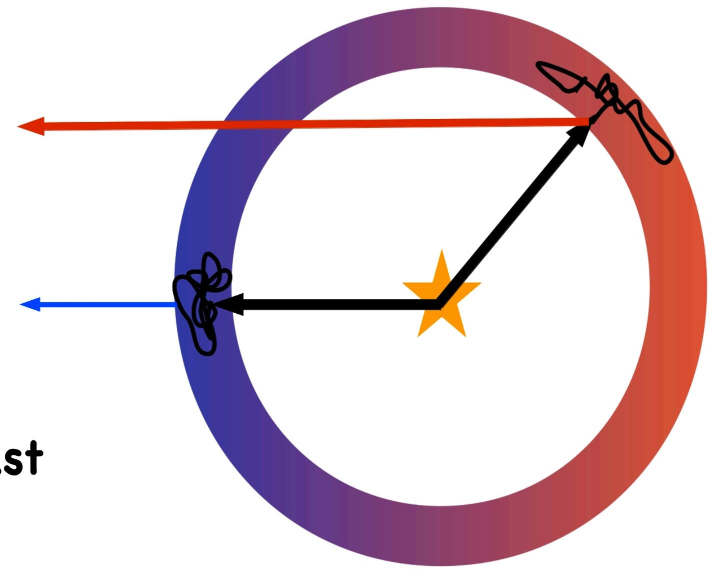
→ Model of Lyα transfer through **spherical expanding shell** has been proposed (Verhamme+06, Dijkstra+06)

MCLya: Numerical radiative transfer code

(Verhamme+06)

- Central isotropic emission of Lyα photons
- Solves **resonant scattering** in **expanding shell** (gas + dust)





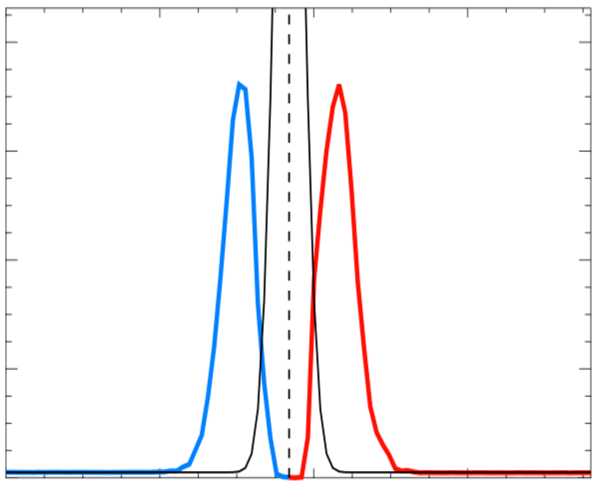
- 4 parameters: $\mathbf{V_{exp}}$, $\mathbf{N_H}$, $\mathbf{b}$, $\boldsymbol{\tau_{dust}}$

→ $\left\{ \begin{array}{l} f_{esc} \\ \text{profile} \end{array} \right.$

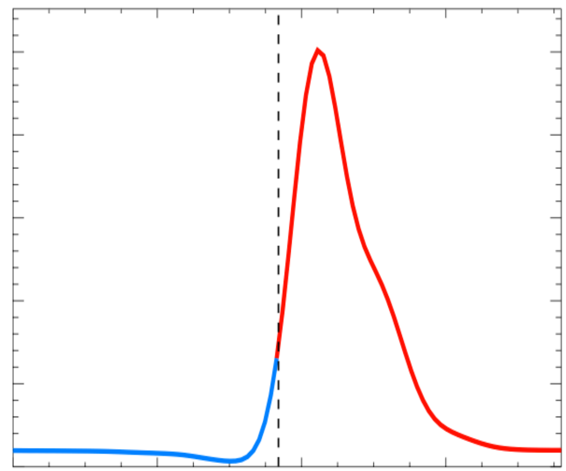
Backscattering redshifts Lya photons

MCLya: Line profiles

static



non-static



Lya photons escape mainly through backscattering

- Extension of MCLya by Schaerer+11: **Library of 6000 models**

i.e. 6000 sets of shell parameter values $\mathbf{V_{exp}}$, $\mathbf{N_H}$, $\mathbf{b}$, $\boldsymbol{\tau_{dust}}$

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- Modelling of Lyα galaxies: apply/test "shell picture" in cosmological model of galaxy formation

    - Semi-analytic model of galaxy formation
    - Model of Lyα emission

Semi-analytic model of galaxy formation

GALICS

(*GALaxies In Cosmological Simulations, Hatton+03*)

<u>Coupling of:</u>

- N-body simulation to describe the evolution of structures of dark matter in a cosmological volume

- Semi-analytic prescriptions to model galaxies

Cosmological N-body simulation

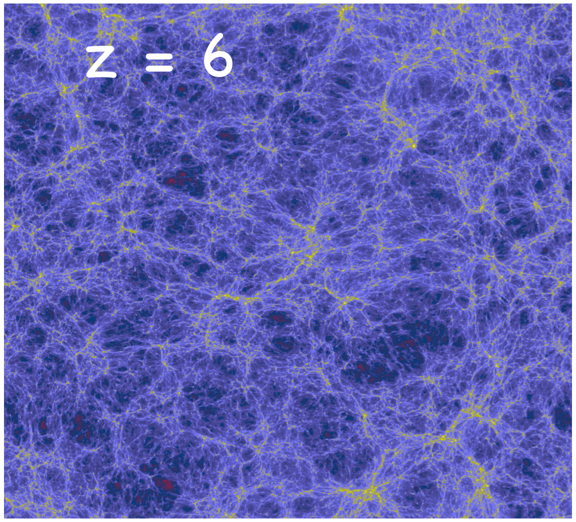
- Follow dynamics of dark matter particles in cosmological box

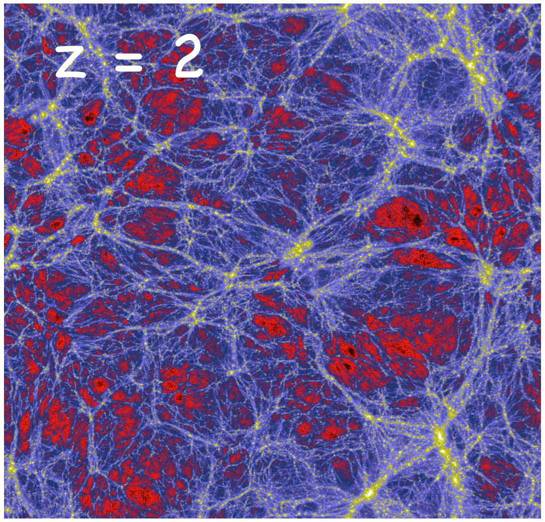
Initial conditions

Cosmological parameters (WMAP-5)

1024^3 dark matter particles

$L_{box} = 100\ h^{-1}$ Mpc



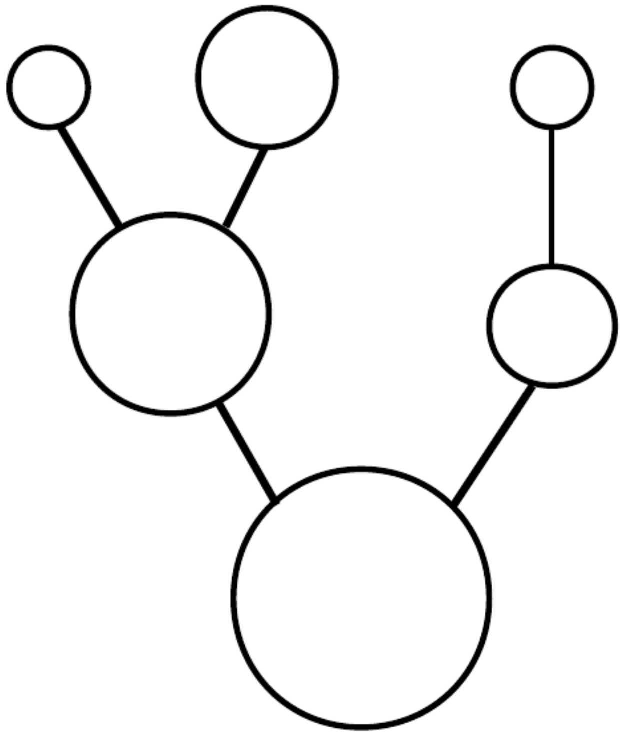


1- find **halos** = "bound groups" of > 20 particles

2- Track growth of halos = merging history

Cosmological N-body simulation

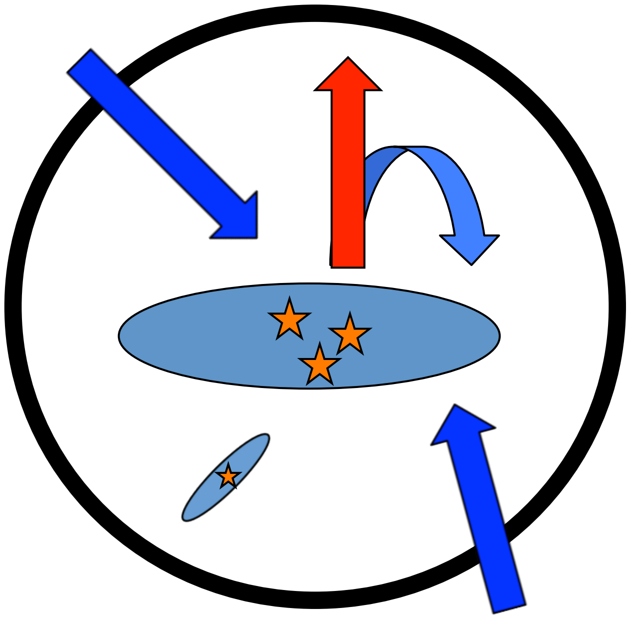
Example of halo **merger tree**



Add baryons to DM halos in post-processing to model galaxies

Semi-analytic models for galaxies

- Compute complex galaxy physics…



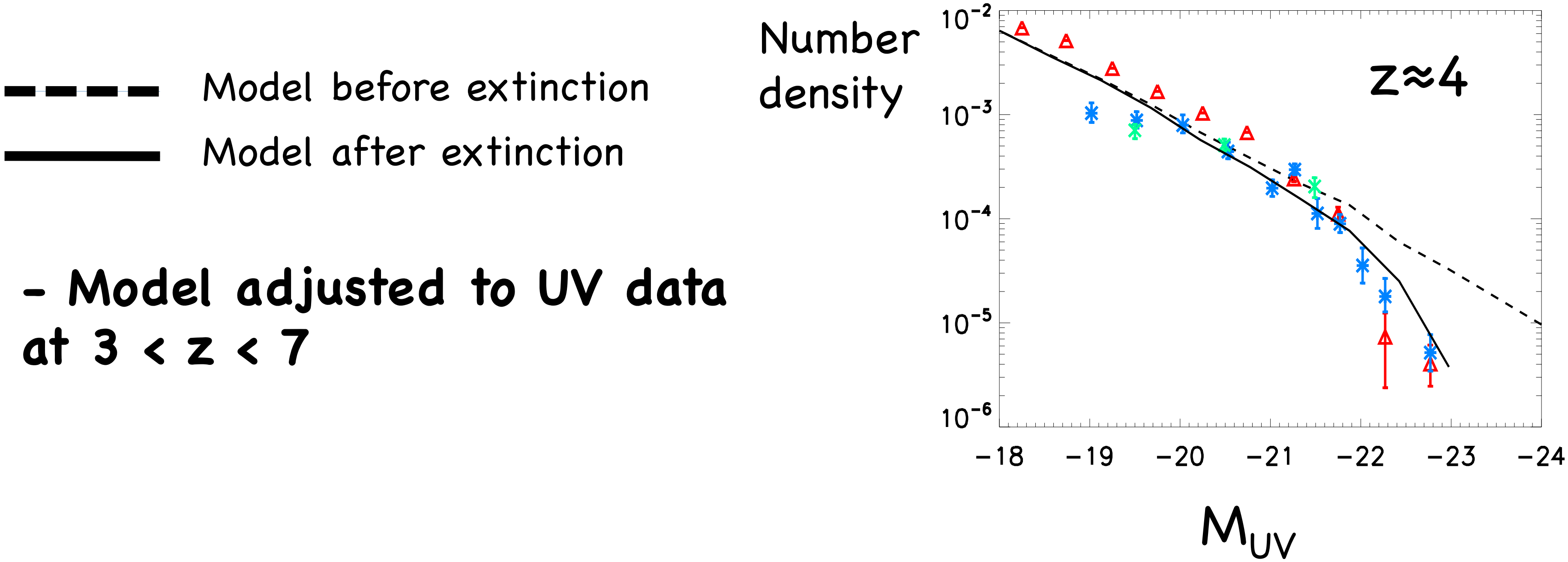
- Gas accretion
- Star formation
- SN Feedback
- Galactic fountain
- ISM chemical enrichment
- Mergers…

… with simple analytic recipes:
e.g. star formation (Kennicutt law)

$$\log\Sigma_{SFR} = 1.4\log\Sigma_{gas} + \alpha_{SF}$$

UV luminosity functions of LBGs

- GALICS predicts properties of > 1 million galaxies at high z.
  SFR, gas & stellar mass, dust… + UV-continuum magnitude



- **Model adjusted to UV data at 3 < z < 7**

- One more step: model Lyα properties of galaxies

Use "MCLya shell" model for GALICS

Shell parameters derived for each galaxy using scaling arguments

$V_{exp} \sim SFR^{1/6}$ SNII analytic model by Bertone+05

$N_H \sim M_{ISM} / 4 \pi R_{disc}^2$

$\tau_{dust} \sim Z_{metal} N_H (1+z)^{-1/2}$ Guiderdoni+87, Reddy+06

$b = 20$ km/s $T \approx 10^4$ K

Lyα properties (f_{esc}, profile) from MCLya library

Lyα escape fraction

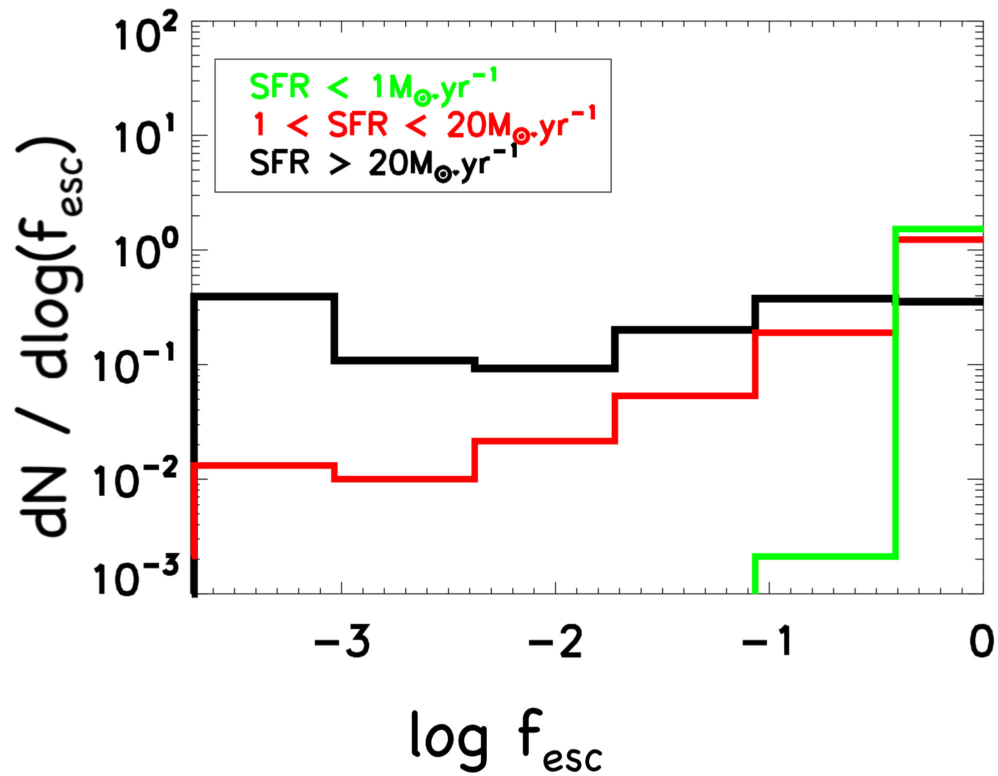
f_{esc} distribution vs SFR

- Low SFR galaxies

  $f_{esc} \approx 1$
  Lyα can trace SFR

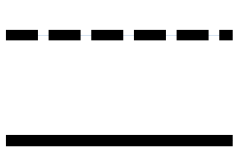
- High SFR galaxies

  $0 < f_{esc} < 1$
  Lyα uncorrelated with SFR

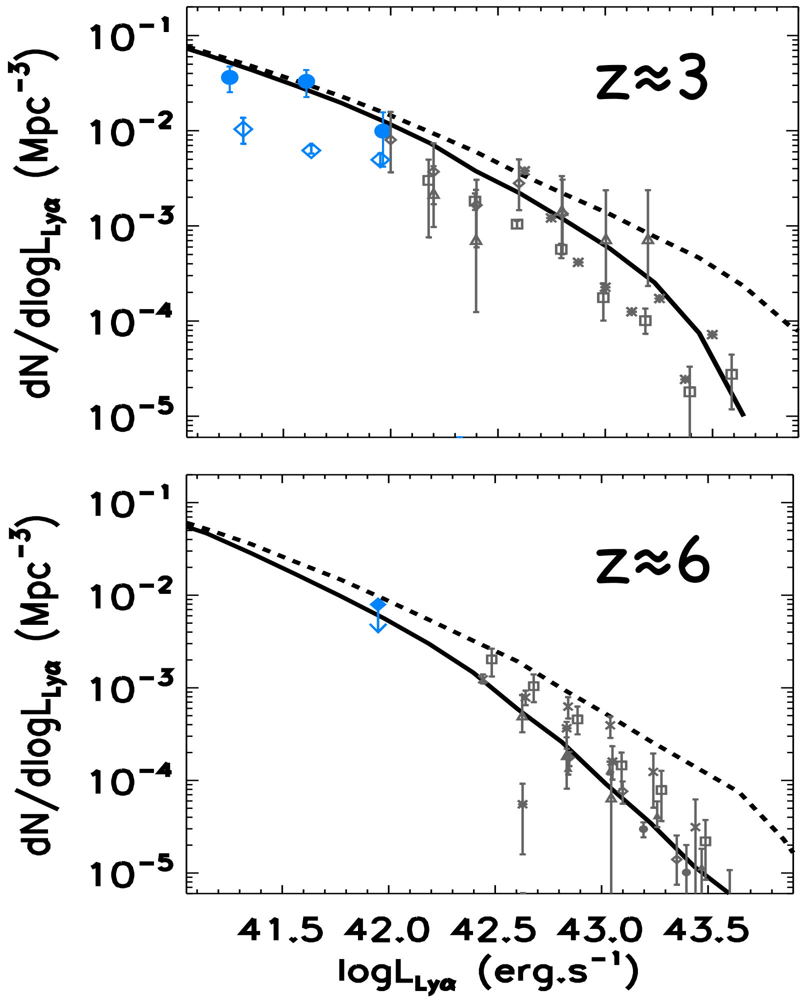


Lyα luminosity functions

$$\mathbf{L}^{\rm obs}_{\rm Ly\alpha} = \mathbf{f}_{\rm esc}\mathbf{L}^{\rm intr}_{\rm Ly\alpha}$$

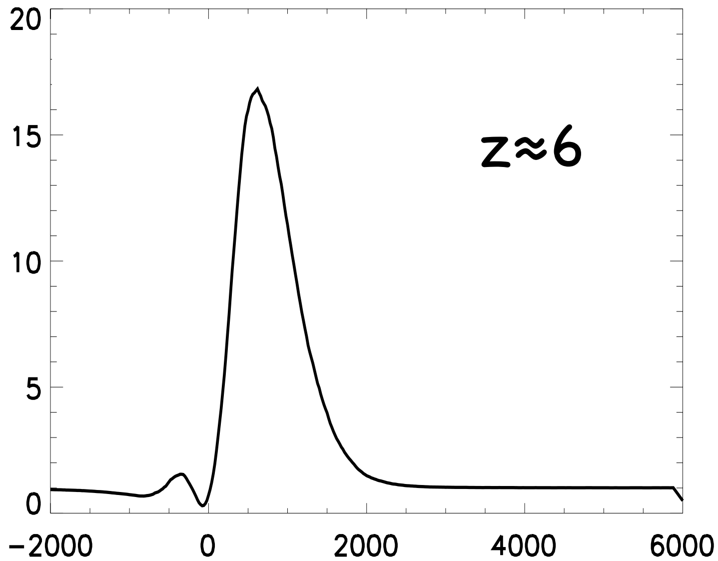


- OK with obs. data @ 3 < z < 7
- High abundance of faint LAEs
- *Data still inhomogeneous*

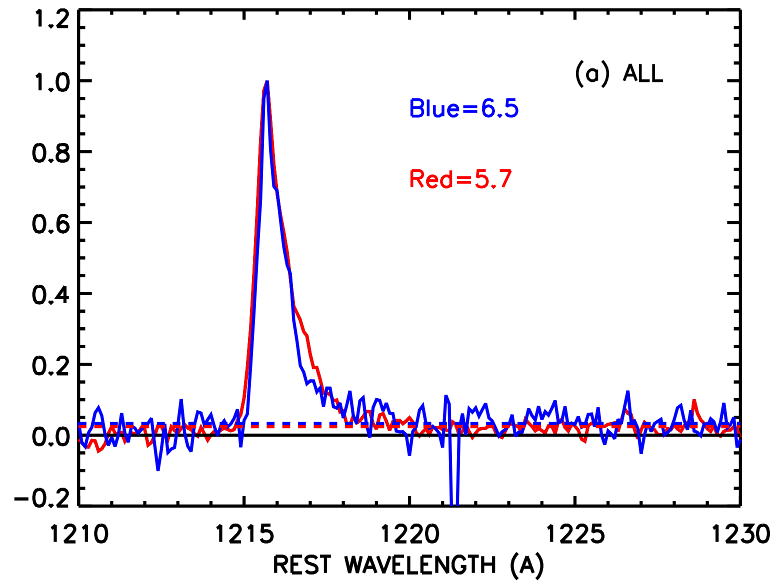


Line profile – *stacked spectra*

Model



Obs



- Asymetric shape well reproduced

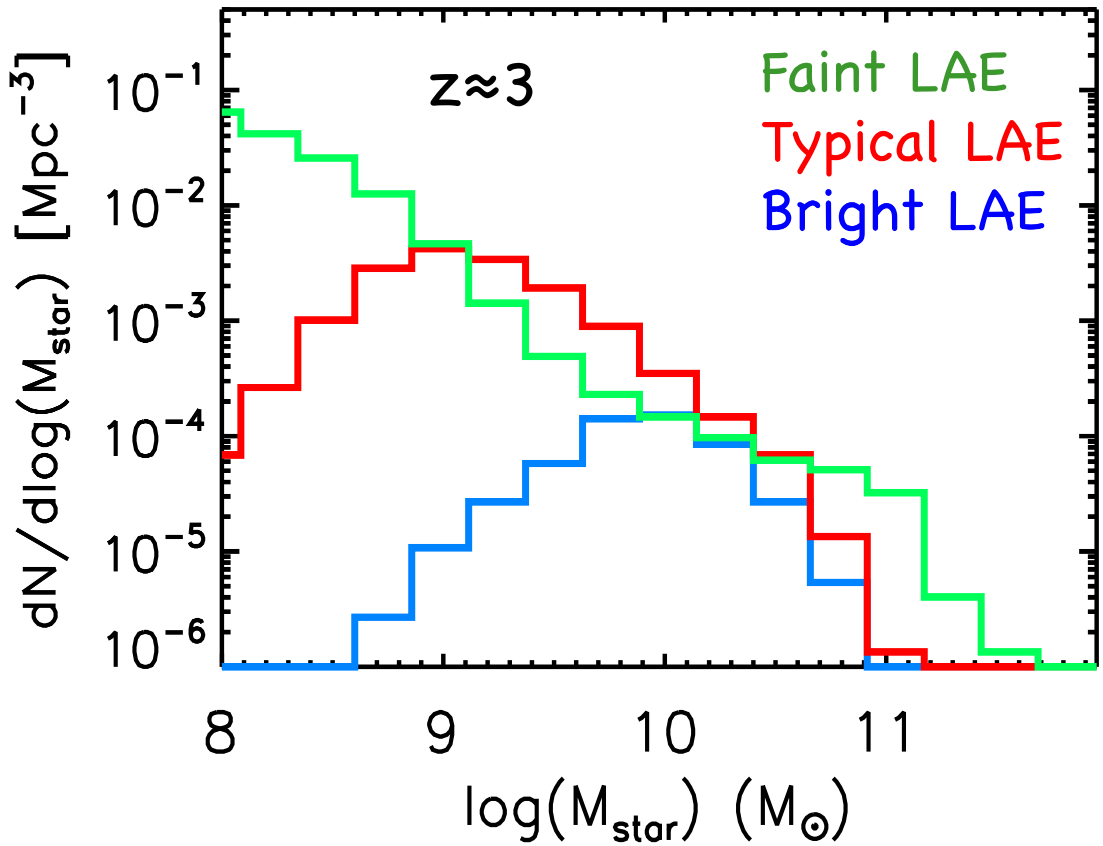
- $\text{FWHM}_{\text{model}}$ slightly higher than FWHM_{obs}

Stellar masses of LAEs

- Most massive galaxies (LBG) ≠ brightest LAE

- Typical LAE:
  $\langle M_{star} \rangle \approx 10^9\ M_{sun}$

OK with observations



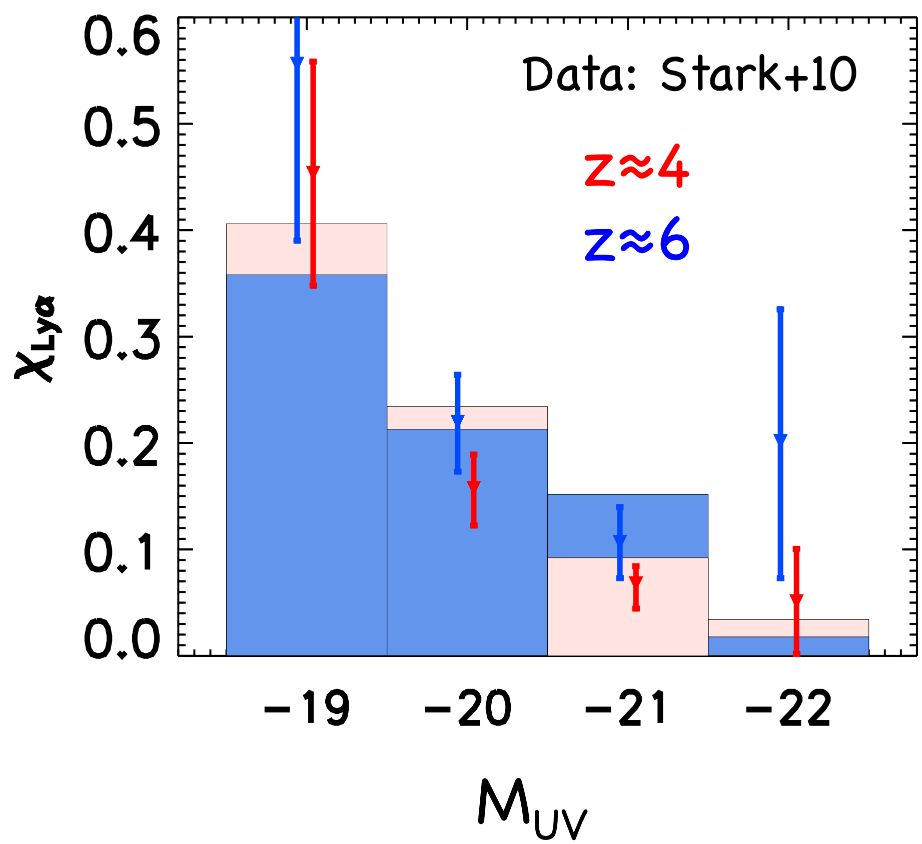
Link LAE-LBG

Fraction of Lyα emitters in LBG

- Observations show that fraction X_{Lya} increases at fainter M_{UV} (points + bars)

- Model catches this trend (histograms)

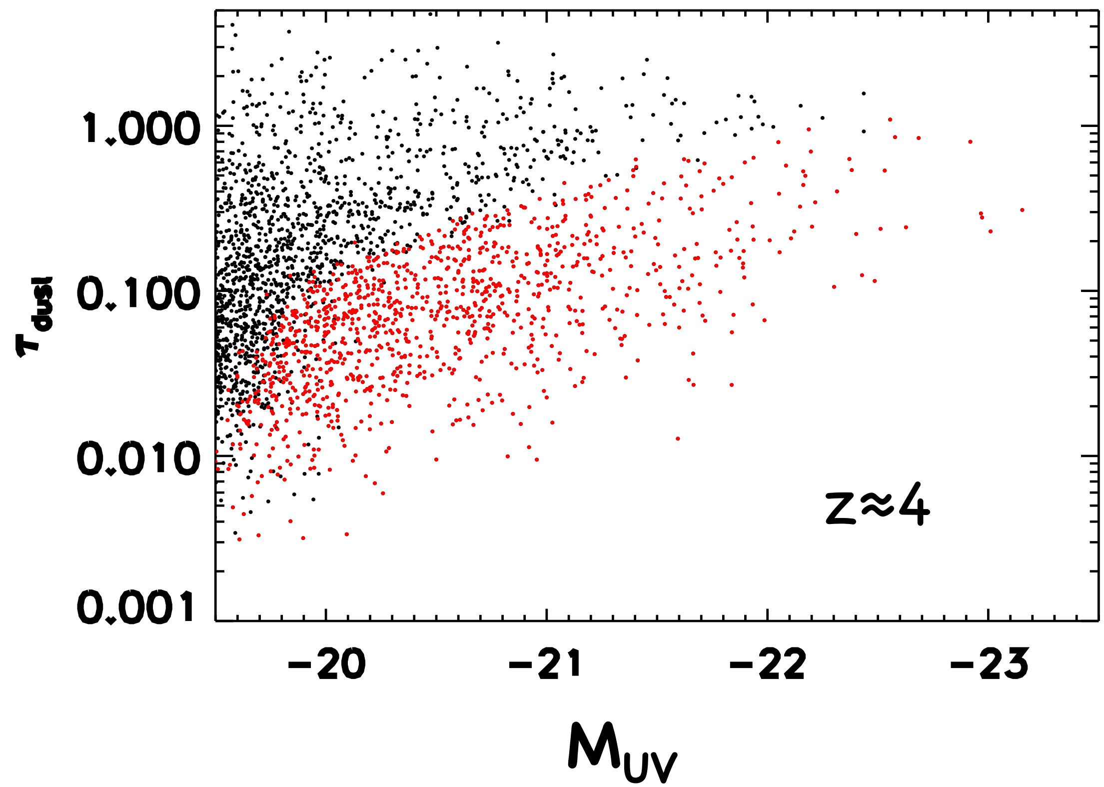
=> LAE-LBG picture seems coherent !



Link LAE-LBG

Dust opacity vs M_{UV}

- All galaxies
- Typical LAEs ($L_{Ly\alpha} > 10^{42}$ erg/s)



Less dusty UV-bright galaxies can appear as LAE

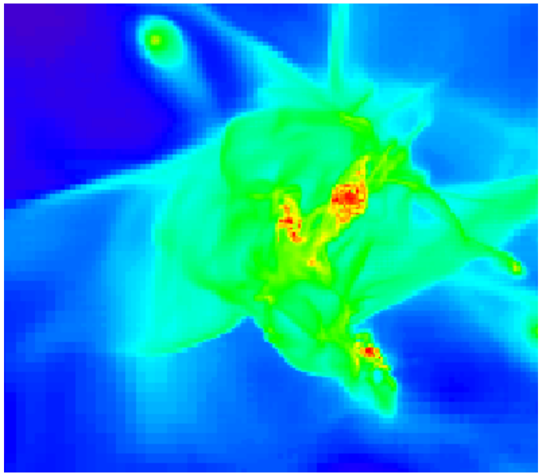
Conclusion

- Inclusion of resonant Lyα transfer through galactic outflows in cosmological model of galaxy formation

- Most of data of high-z LAE matched despite simplistic shell picture

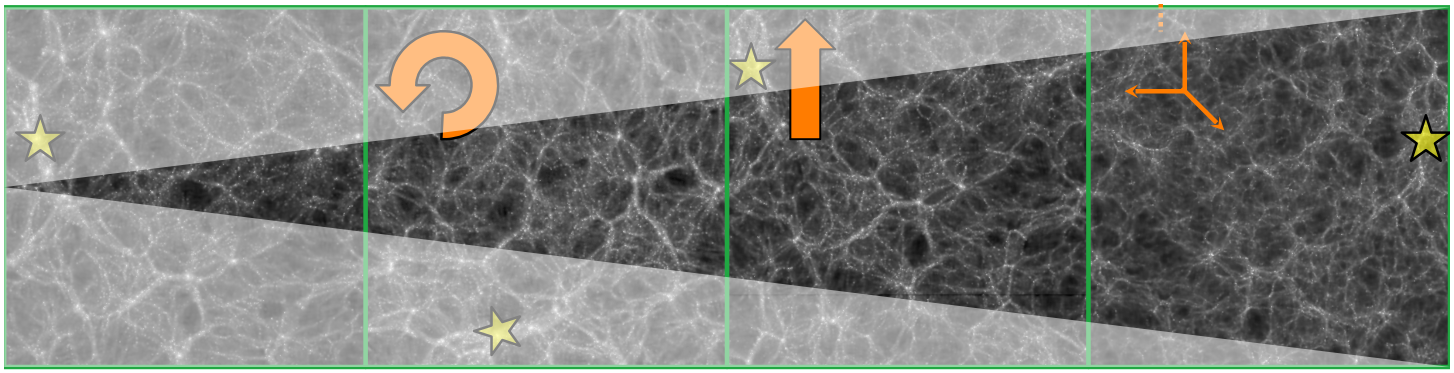
- **Lyα and UV** properties of galaxies are both well reproduced

In addition, studies in more "realistic" hydrodynamic simulations are important... but quite time-consuming



Mock LAE fields

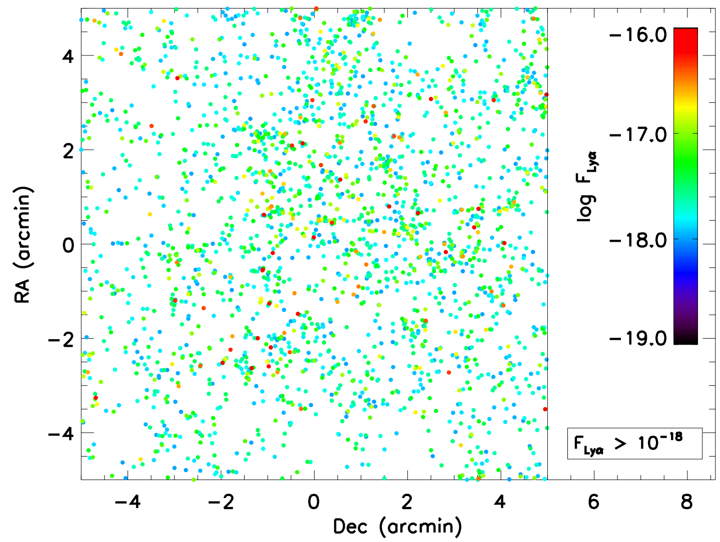
Generate light cones (MOMAF, Blaizot+06)



<u>Example:</u>

- 10 x 10 sq. arcmin
- $3 < z < 3.1$
- $F_{Ly\alpha} > 10^{-18}$ erg/s/cm^2

Typical VLT-MUSE field (2013)



Clustering of LAEs
Are LAEs in the right halos?

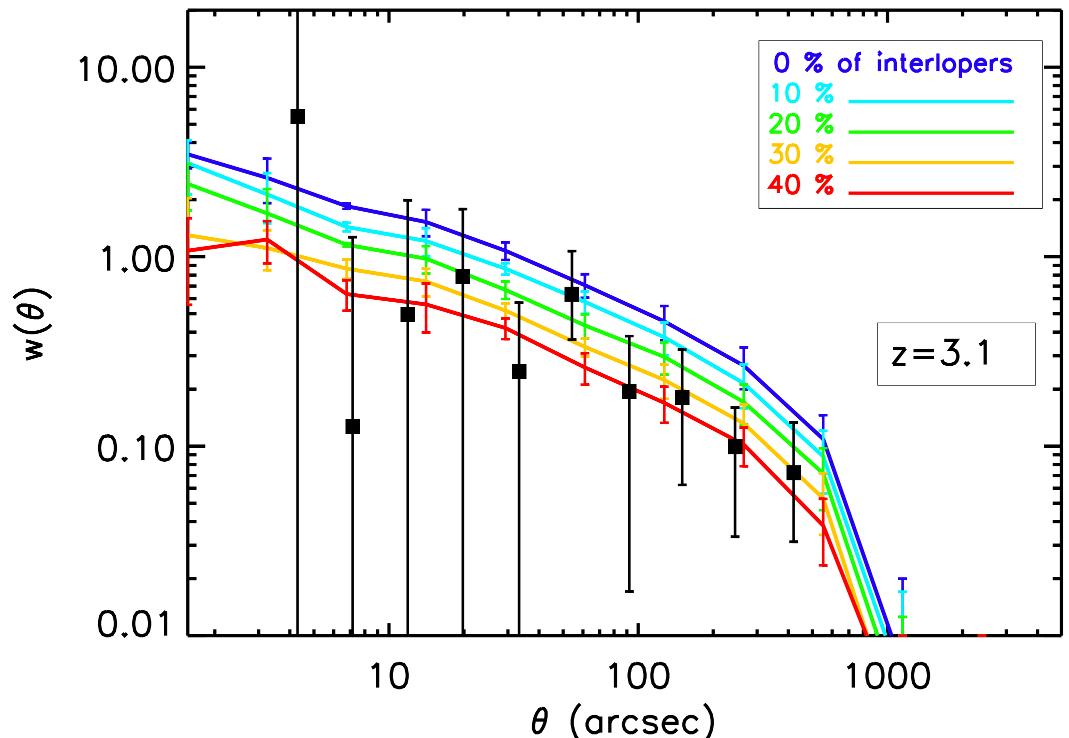
Angular correlation function w(θ)

- Measures excess of galaxy pairs at a given scale

- Low-z interlopers in Narrow-band surveys

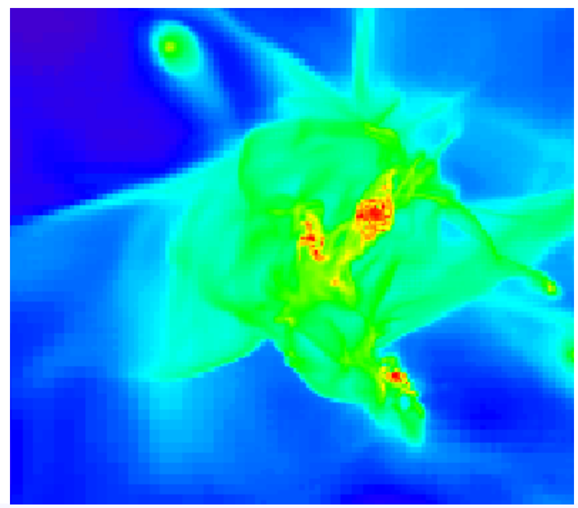
- Good match if f = 20-30%

Data: Ouchi+10

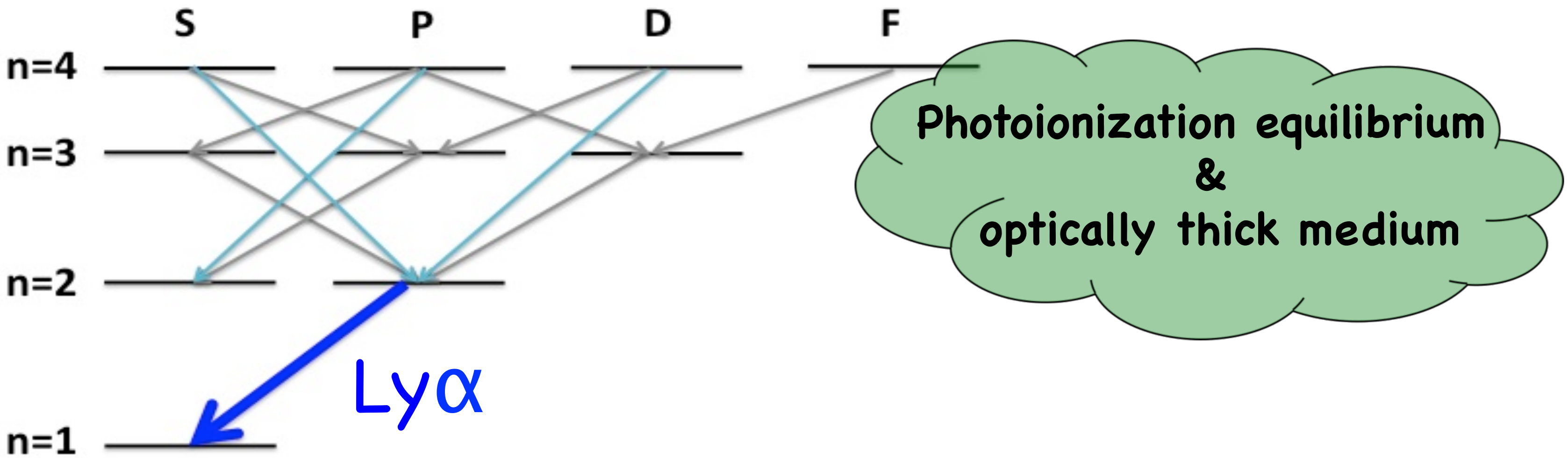


Conclusion

- Inclusion of Lyα transfer through galactic outflows in SAM
- Dispersion of f_{esc}-SFR relation => Lyα (non-)emission in LBG
- Most of LAE data matched despite simplistic shell picture
- Some disagreements persist (FWHM, equivalent widths)
- Need for complementary study in hydro. simulations



Recombination of HII regions - *radiative cascade*

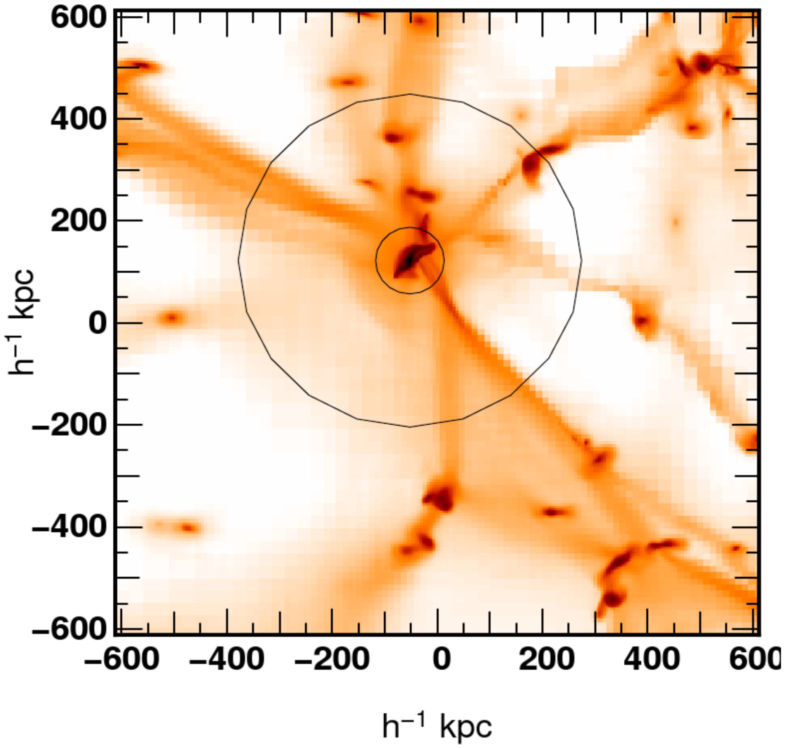


Probability(Lyα=1216 A) ≈ 2/3 per recombination

➡ Intrinsic Lyα luminosity $\mathbf{L}^{\rm intr}_{\rm Ly\alpha} \propto \frac{\mathbf{2}}{\mathbf{3}} \dot{\mathcal{N}}^{\rm OB}_{\rm ion} \propto \rm SFR$

Intense line in star-forming galaxies: $\mathbf{L}^{\rm intr}_{\rm Ly\alpha} \approx 10\% \mathbf{L}_{\rm bol}$

GALICS – *A hybrid model of galaxy formation* (Hatton+03)



$$M_{acc,\ gas} = F \times \Omega_b/\Omega_m\ M_{acc,\ DM}$$

$$F = \begin{cases} 1 & \text{if } M_h < M_{min} \\ (M_{max}-M_h)/(M_{max}-M_{min}) & \text{if } M_{min} < M_h < M_{max} \\ 0 & \text{if } M_h > M_{max} \end{cases}$$

11-04-2012 GEM - Swinburne

Link LAE-LBG

UV luminosity function of LAE