Radiative Transfer in Lyα Nebulae:

Modeling Continuous or Clumpy Spherical Halo with Central Source

Seok-Jun Chang

MPA

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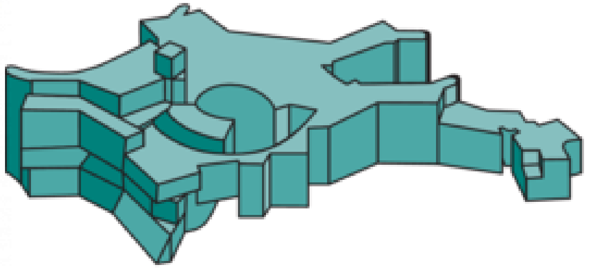
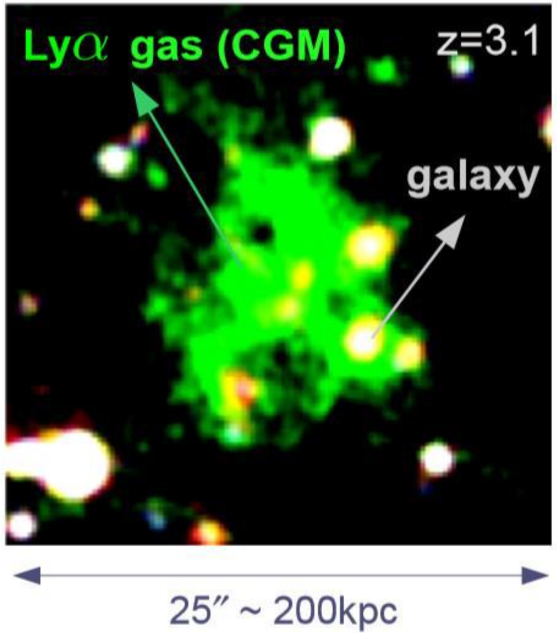
Astronomy for All

Busan 2022

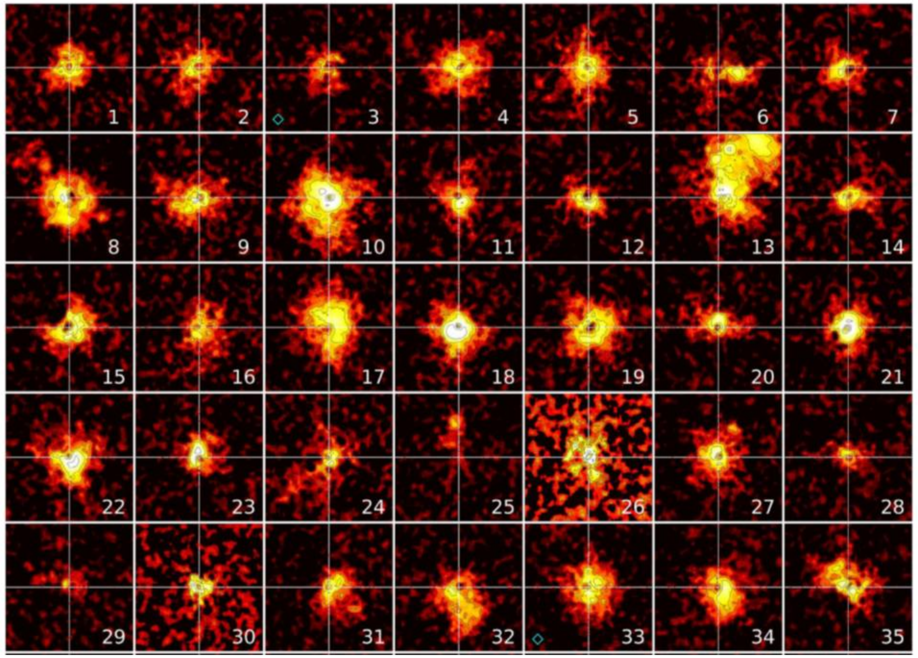


Contents

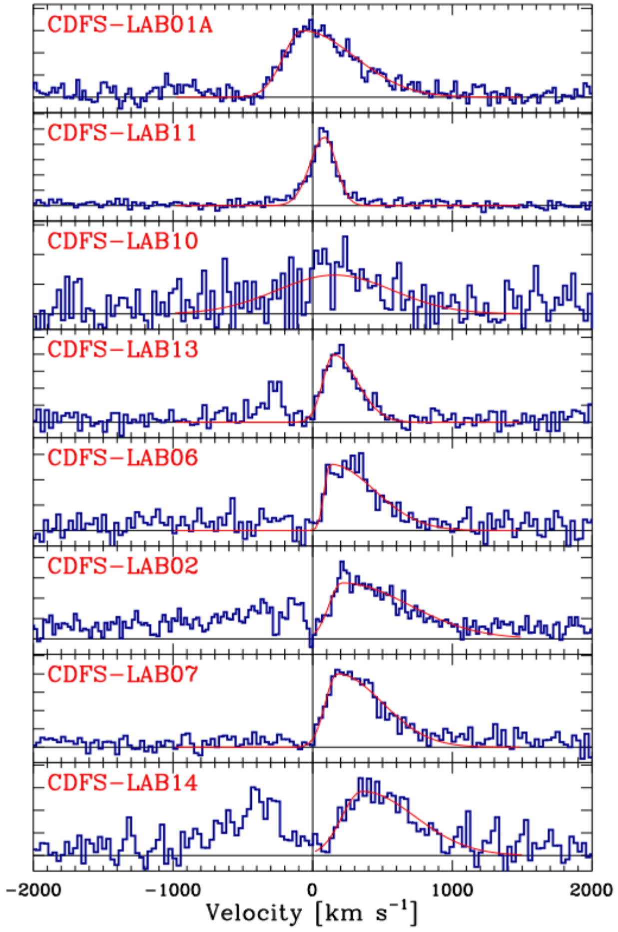
Lyα Nebulae



Subaru Image of
SSA22-LAB1
(Matsuda et al. 2004)

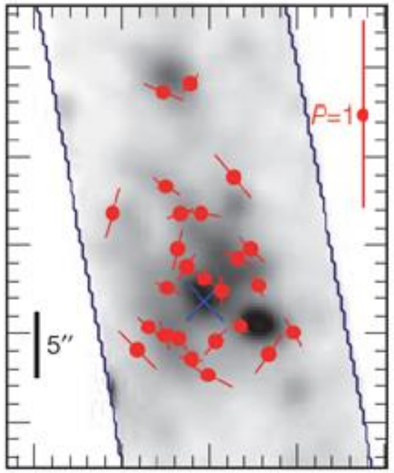


Lyα Nebulae around QSO
QSO Museum
(Arrigoni Battaia et al. 2019)



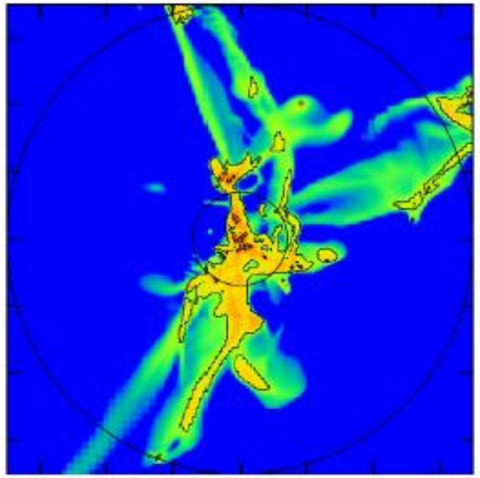
Lyα spectra of LAB
(Yang et al. 2014A)

Lyα Emission Mechanism

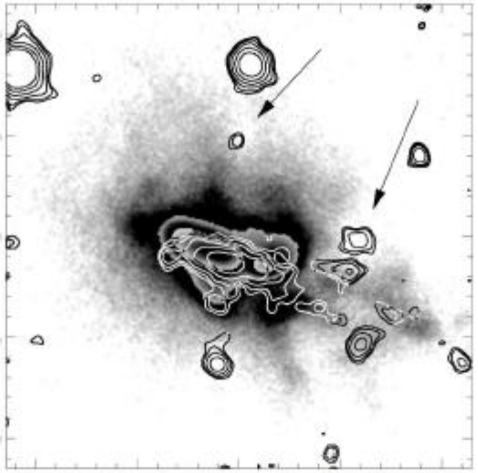


Resonant scattering
Polarization map
(Hayes+11)

Superwind
(Galactic wind in M82)



Cold accretion
(Goerdt+10)



Radio galaxy, AGN
(Reuland+03)

- Shock from Super Wind (Cabot et al. 2016, Travascio et al. 2020)
- Cold Accretion by Massive Dark Matter Halo (Trebitsch et al. 2016, Ao et al. 2020)
- Photoionization by the source (Steidel et al. 2010, Arrigoni Battaia et al. 2019)
- Scattering with Atomic Hydrogen (Hayes et al. 2011, Kim et al. 2020, Li et al. 2021)

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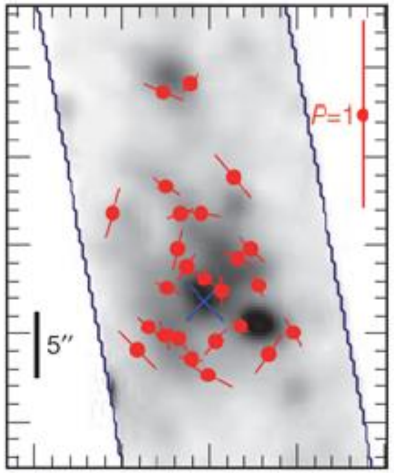

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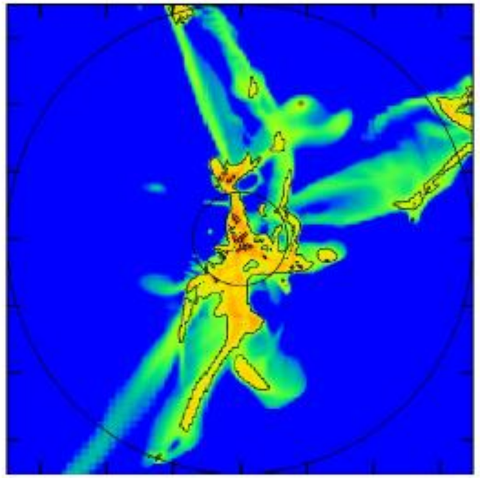
Cold accretion
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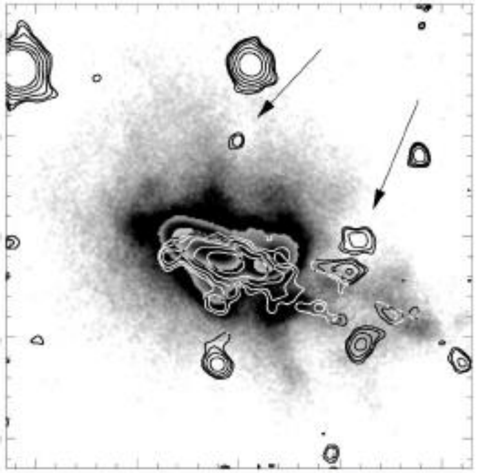
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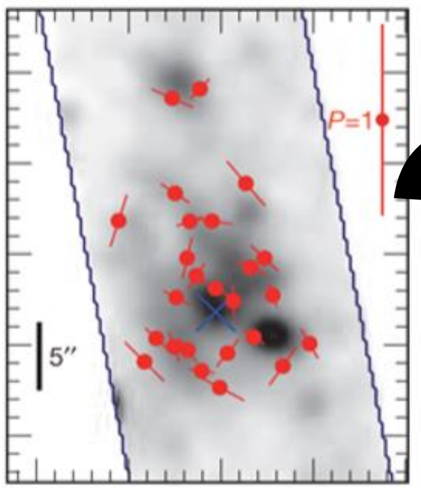
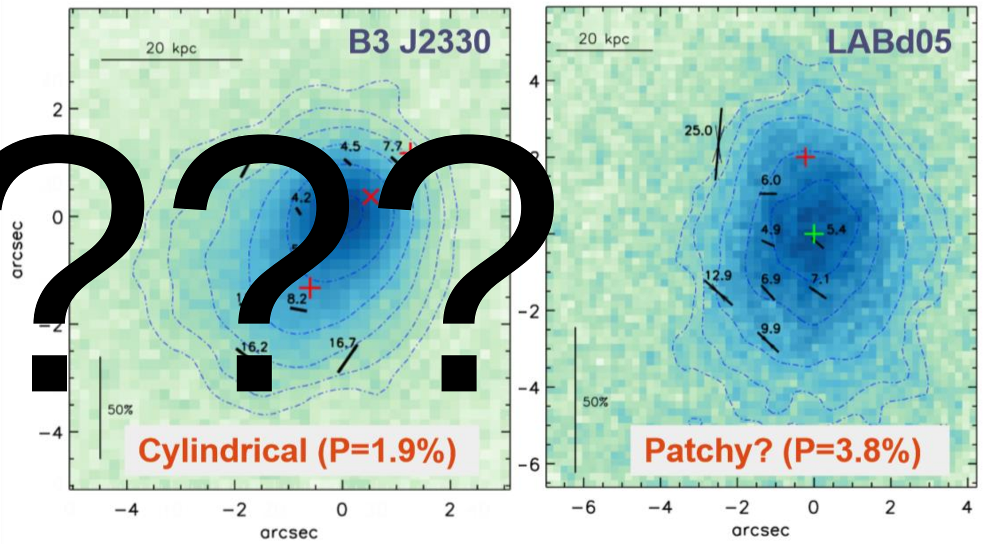
- **Scattering with Atomic Hydrogen (Hayes et al. 2011, Kim et al. 2020, Li et al. 2021)**

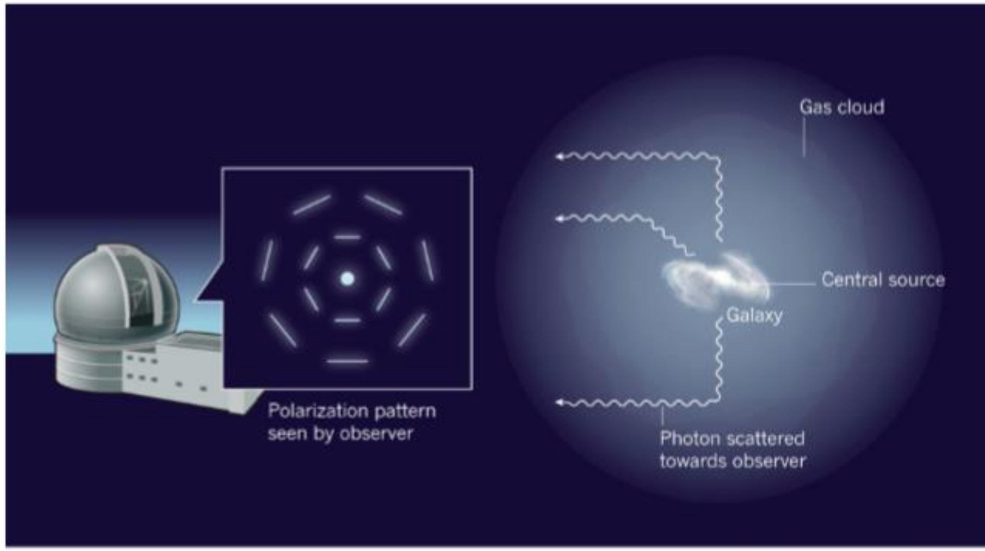
Polarization of Lyα



SSA22-LAB1
(Hayes et al. 2011)



You et al 2017 Kim et al 2020

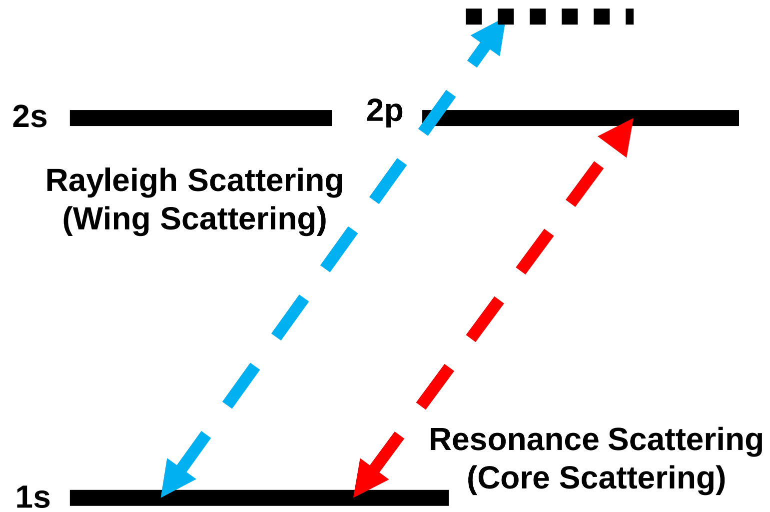


(R. Bower 2010)

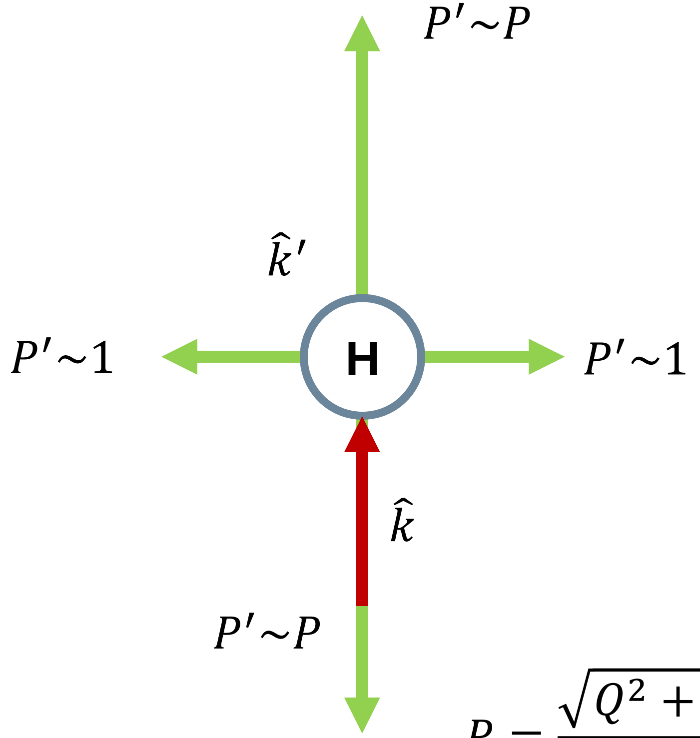
- Lyα emission photons are unpolarized.
- Scattering with Atomic hydrogen → linear polarization

- Polarized Lyα is observed in Lyα blobs
  (Prescott et al. 2011, Hayes et al. 2011, Beck et al. 2016, You et al. 2017, Kim et al. 2020)

Lyα Scattering with atomic Hydrogen

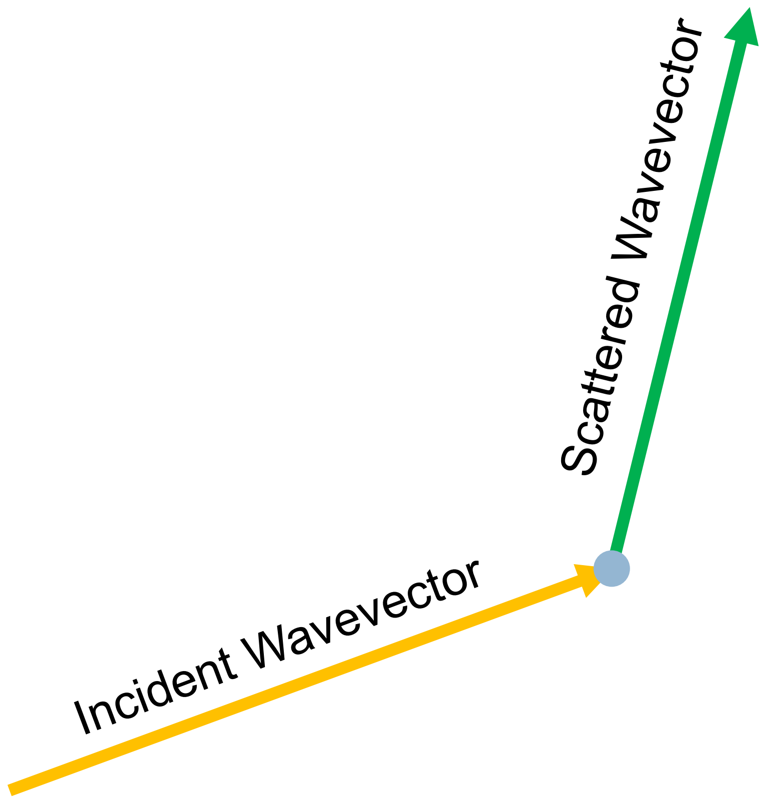


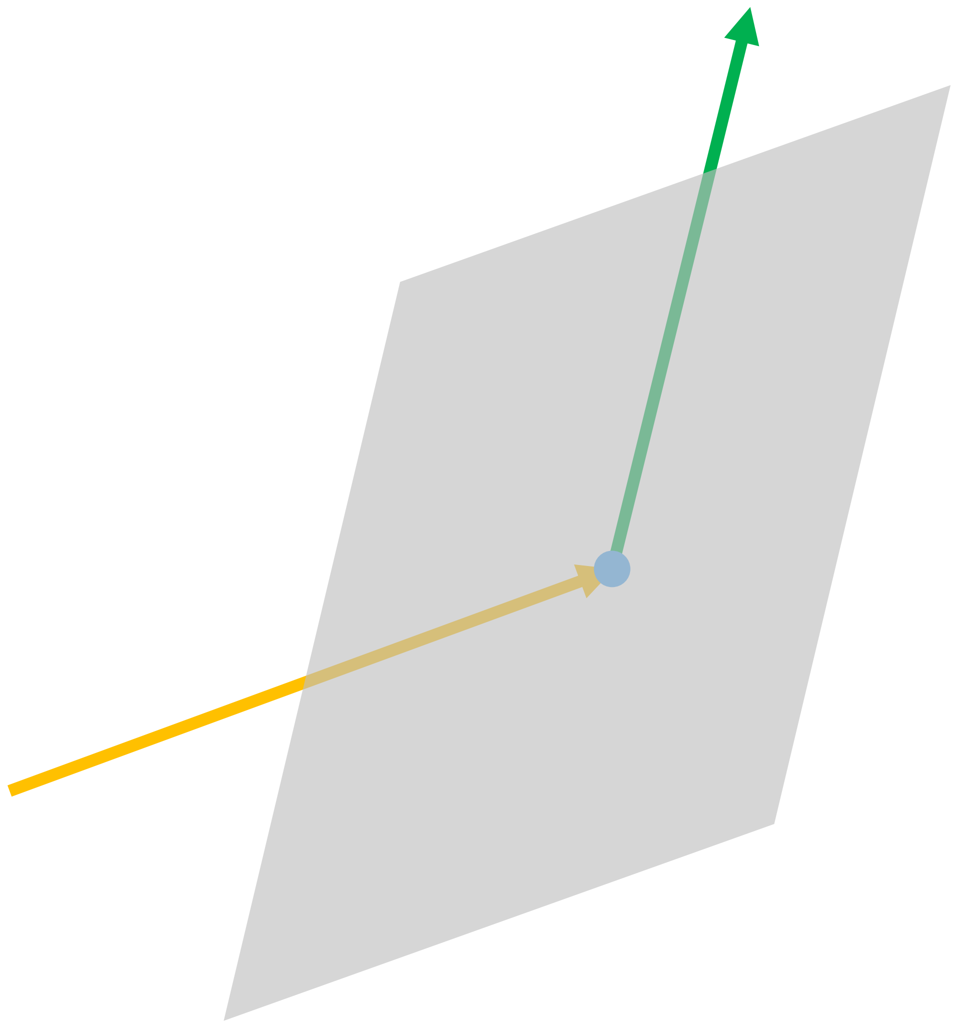
	Resonance	Rayleigh
Transition	$1s-2p$ (line center)	$1s-$ near $2p$ (off center)
Phase Function	Isotropic	Dipole Transition
Polarization	Un-polarized ($2p_{1/2}$) Weak ($2p_{3/2}$)	Strong
Free Path	short	long

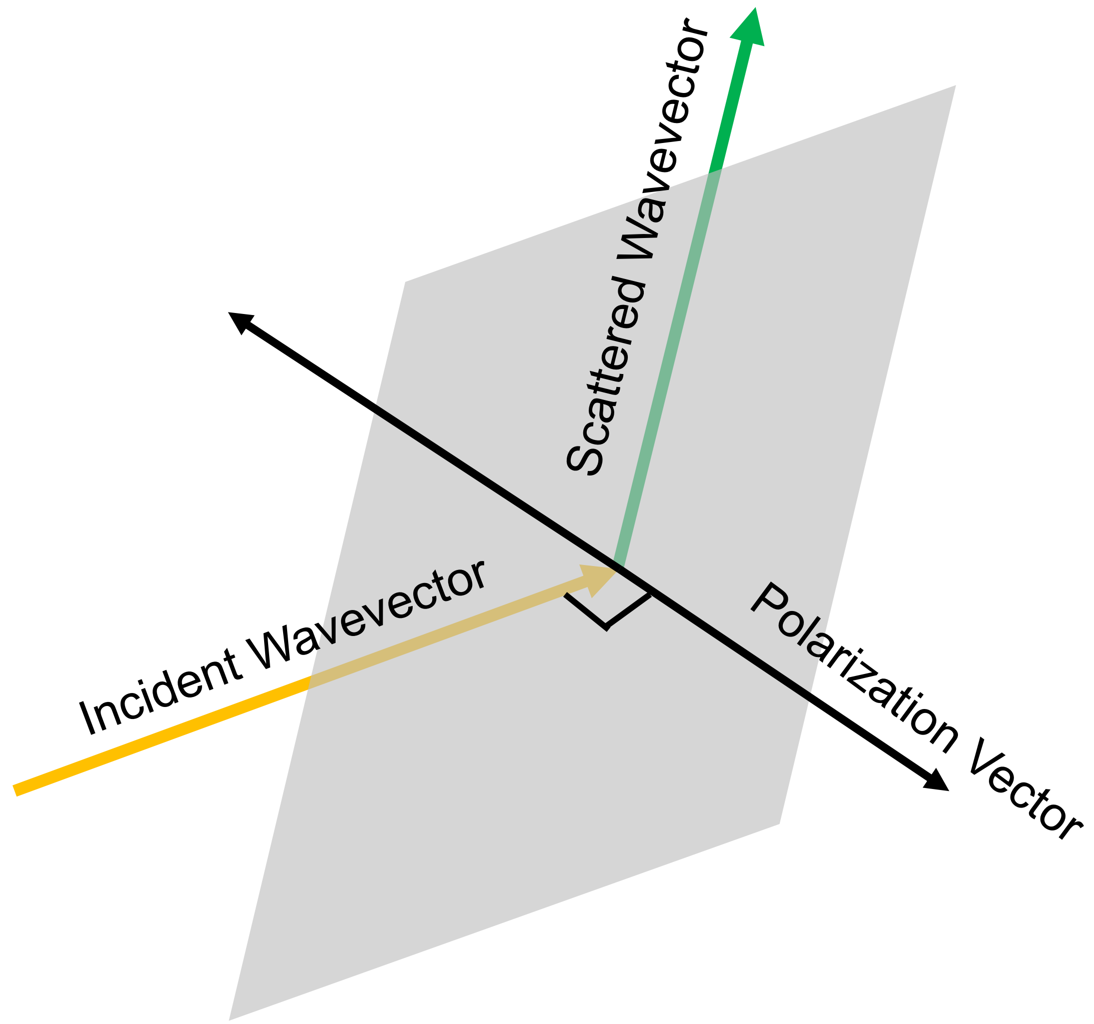


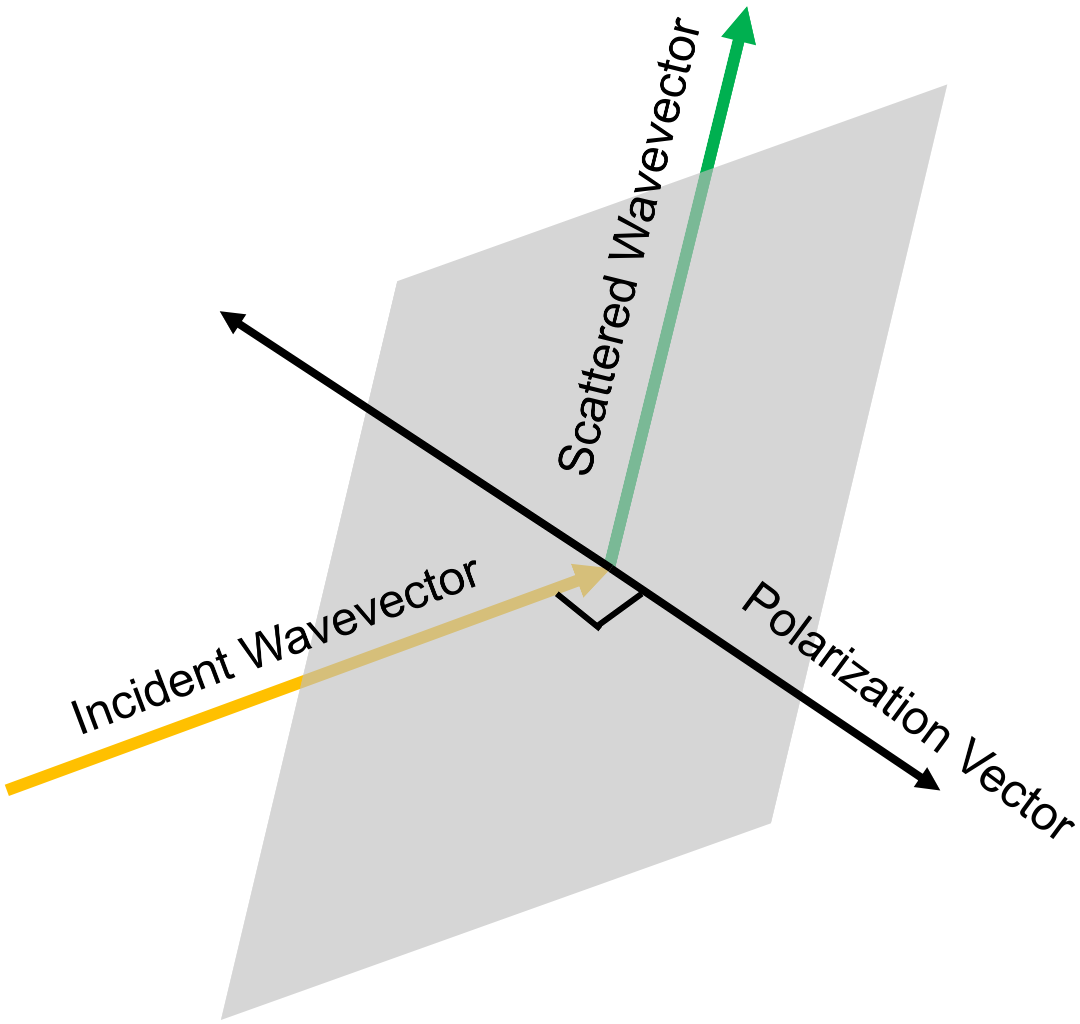
$$P = \frac{\sqrt{Q^2 + U^2}}{I}$$

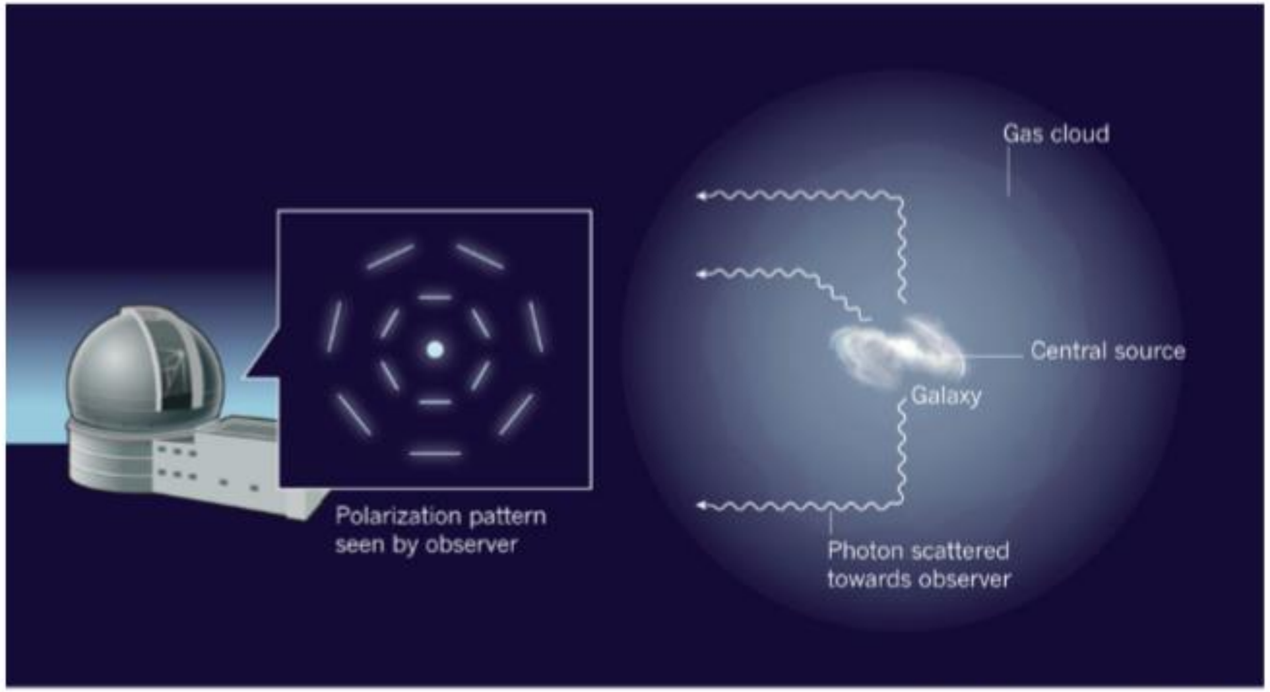
The degree of polarization of the photon after Rayleigh scattering maintain (forward and backward scattering) or increase (90^o scattering).


Scattered Wavevector
Incident Wavevector



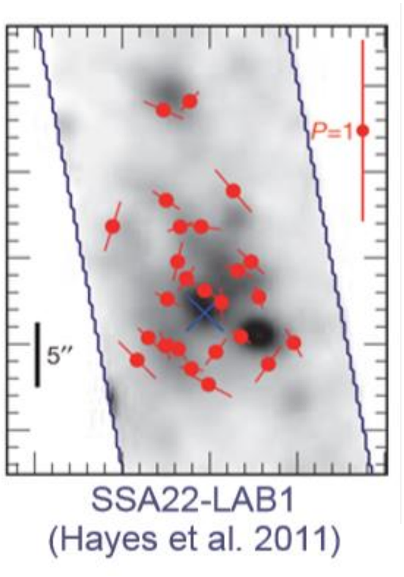

Scattered Wavevector
Incident Wavevector
Polarization Vector

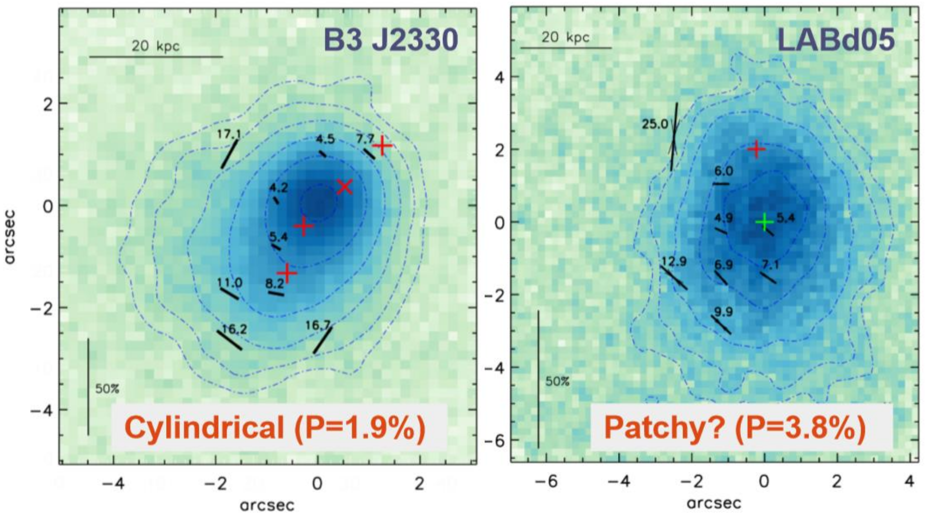

Scattered Wavevector
Incident Wavevector
Polarization Vector


Gas cloud
Central source
Galaxy
Polarization pattern
seen by observer
Photon scattered
towards observer

(R. Bower 2010)

Lyα Radiative Transfer for Lyα Nebulae





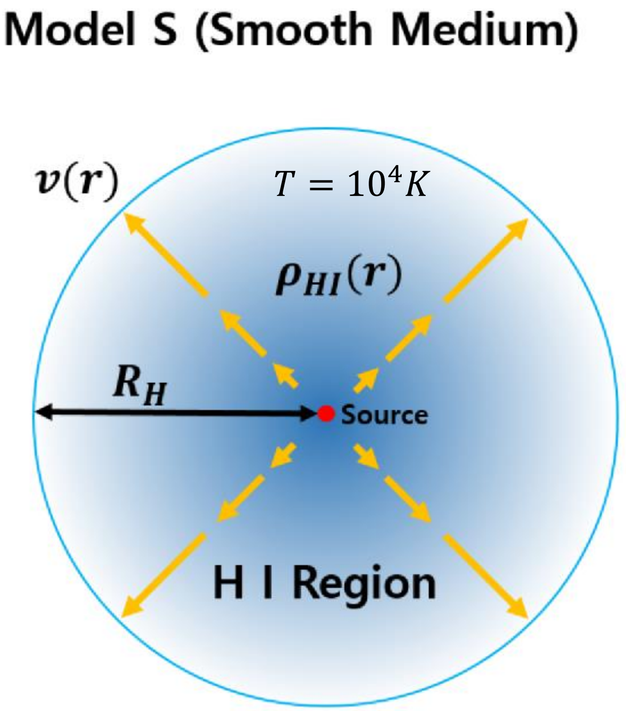
You et al 2017 **Kim et al 2020**

Can the Lyα point source become LAB through only scattering by an atomic hydrogen in H I halo ?

Essential Components for RT

- Polarization behavior by core and wing scattering
- Large scale halo ~ 100 kpc
- Broad intrinsic Lyα emission
- Clumpy Medium

Scattering Geometry



Lyα Source

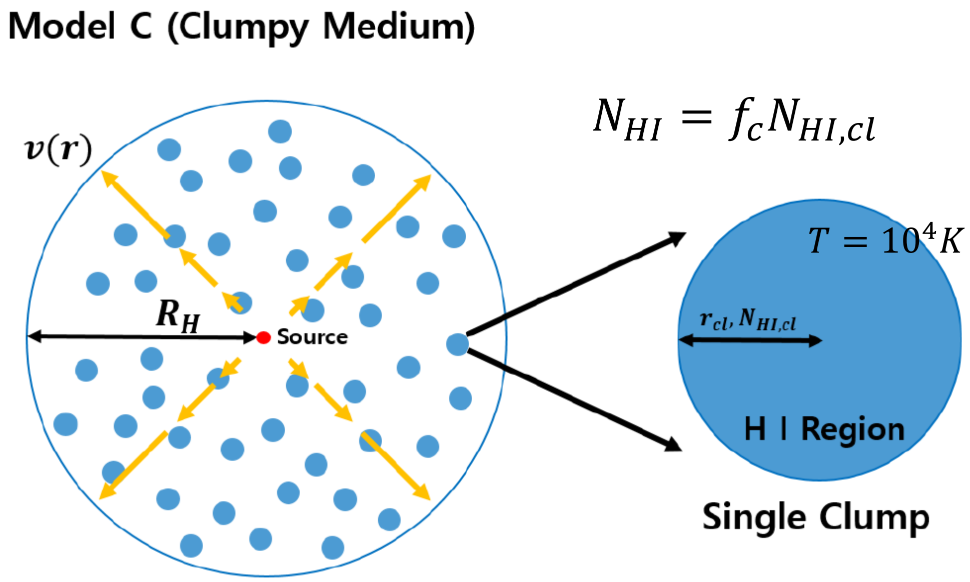
$z = 3$ (7.855 kpc/")

$L_{Ly\alpha} = 10^{44} erg/s$

$$v(r) = v_{exp}\frac{r}{R_H}$$

$$N_{HI} = \int^{R_H} \rho_{HI}(r)\,dr$$

$$\rho_{HI}(r) = n_0 e^{r/R_e}$$



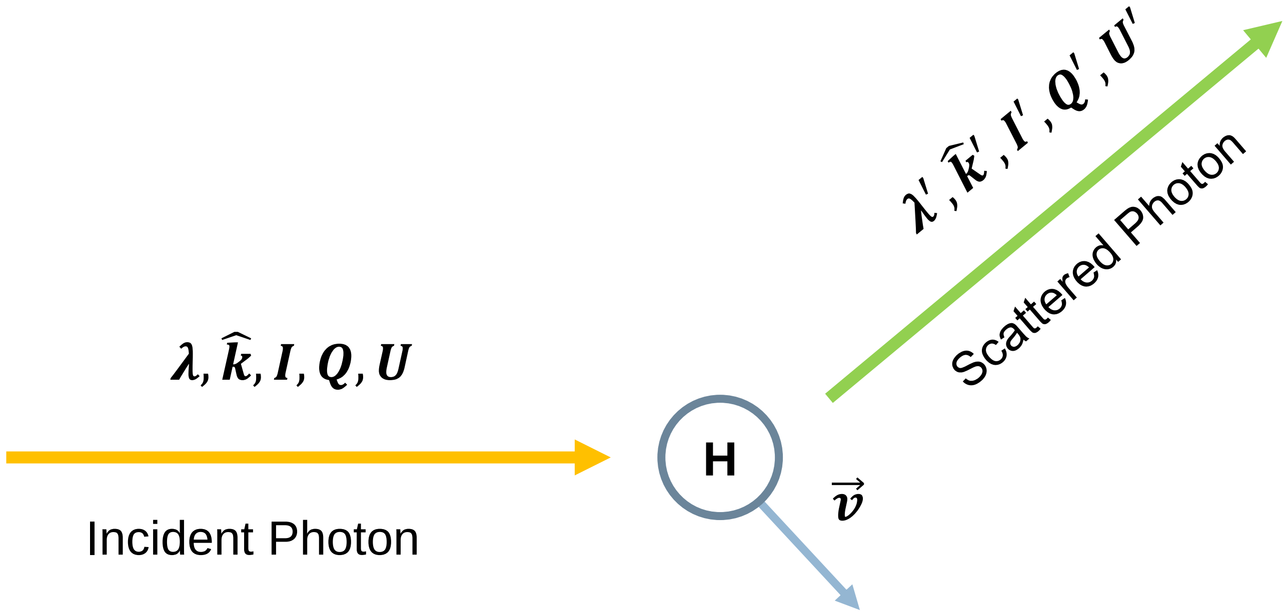
- The simulation is based on LaRT (Seon & Kim 2020, Seon et al. 2022).
- We consider Smooth and Clumpy H I spherical halo with $R_H = 100$ kpc surrounding Lyα point source.
- The range of (1) Lyα emission width from the source $\sigma_{src} = 100 - 400$ km s^{-1} (100 km s^{-1} : SFG, 400 km s^{-1} : AGN)

  (2) the total column density $N_{HI} = 10^{18-21}$ cm^{-2}

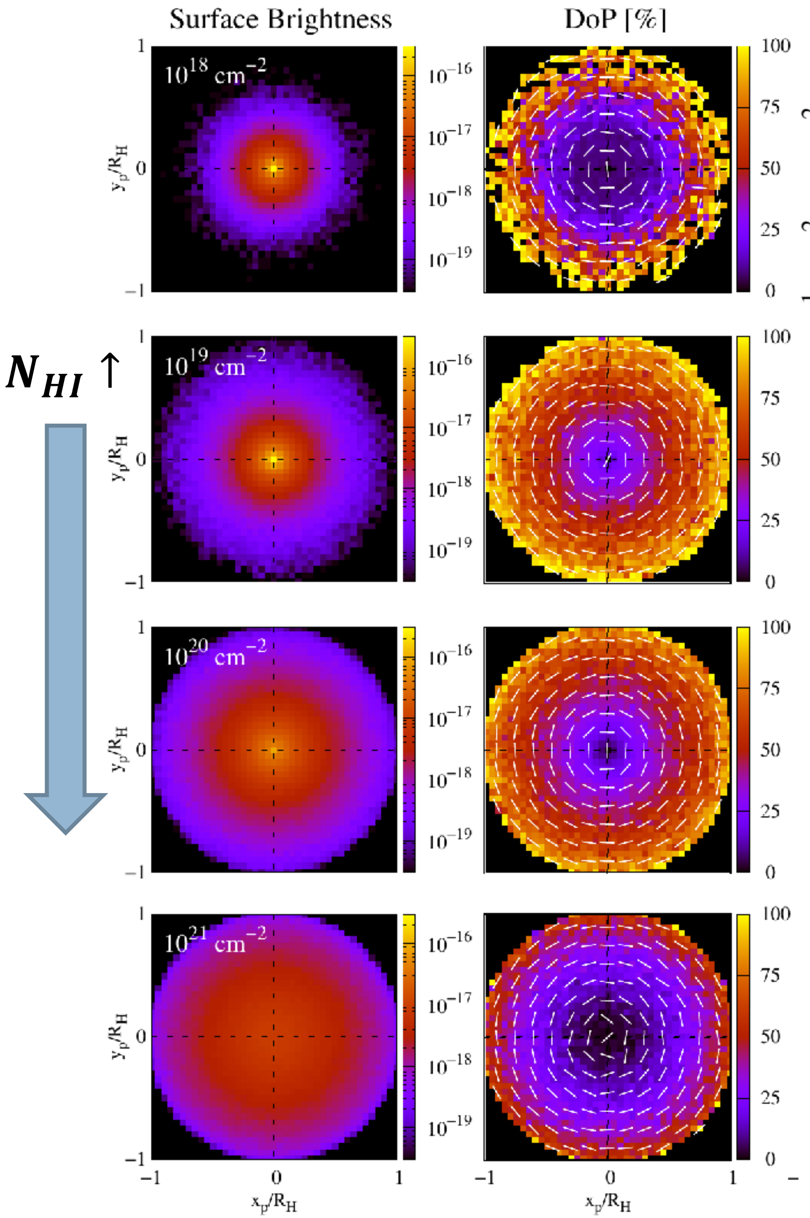
  (3) Outflow velocity $v_{exp} = 0 - 400$ km s^{-1}

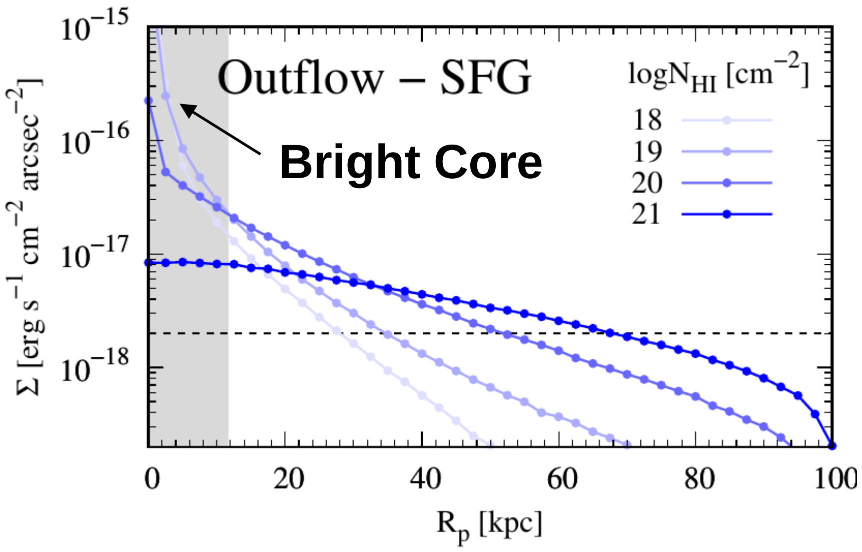
  (4) Covering factor $f_c = 1 - 100$

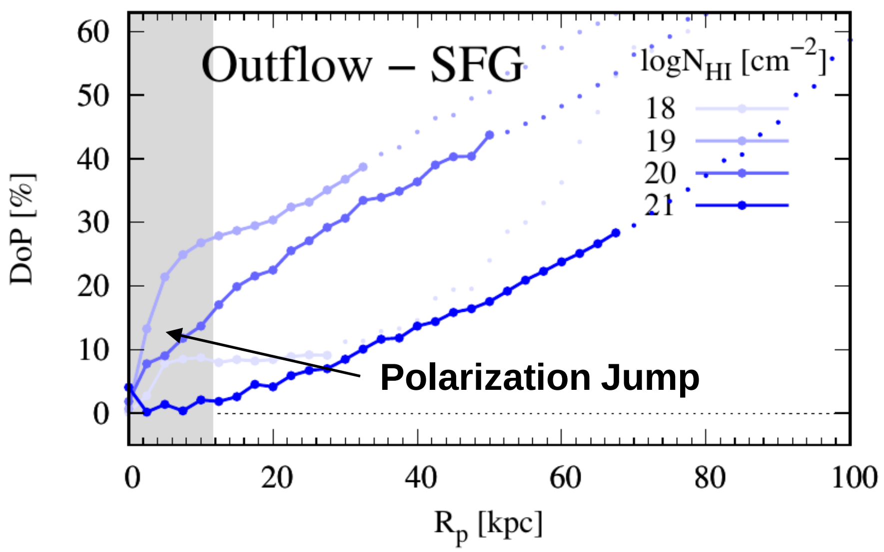
Photon Packets in Simulation



Lyα Projected Image of Model S



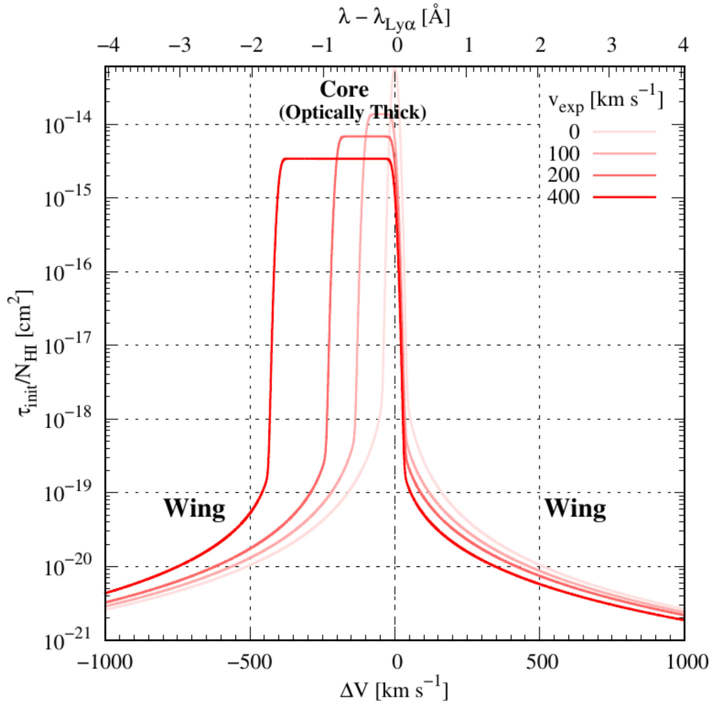




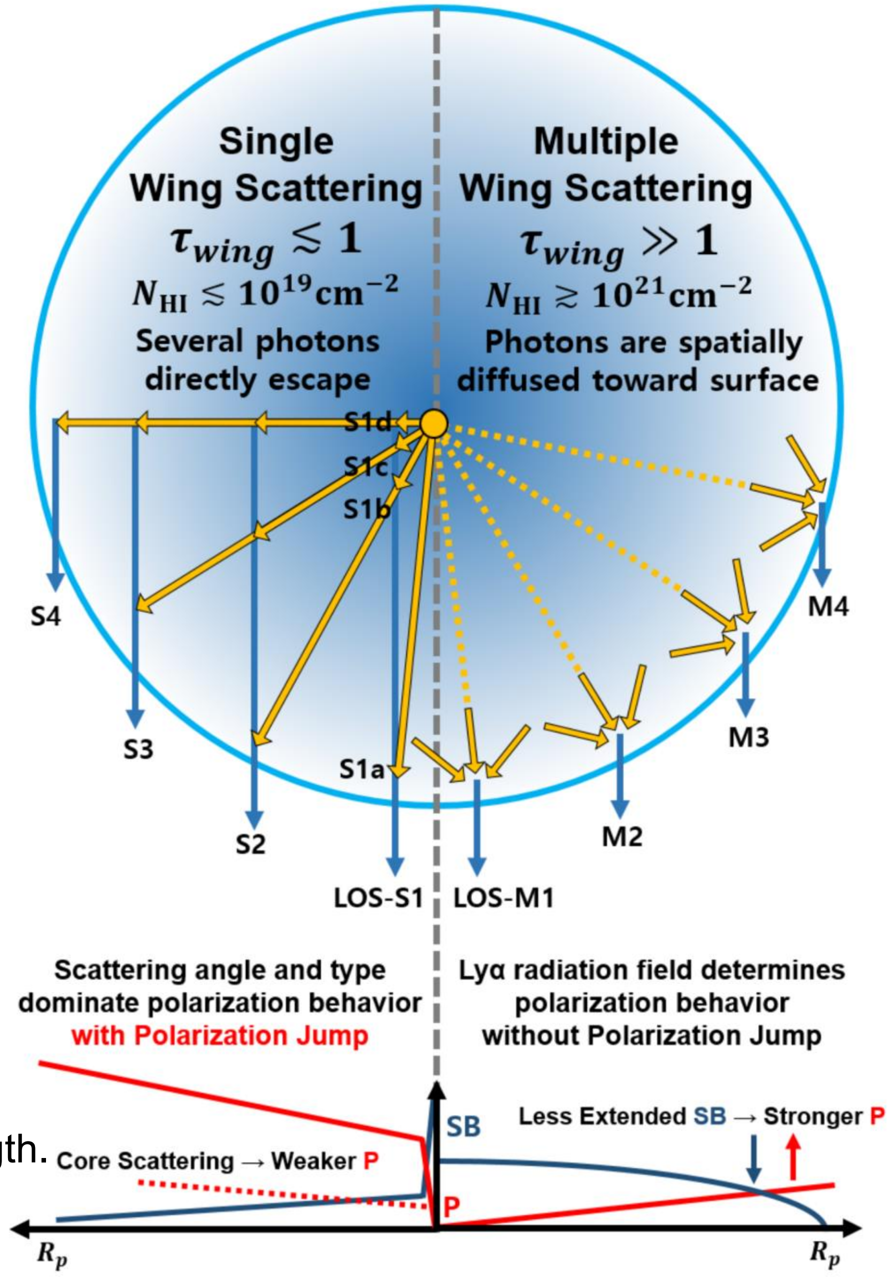
- The projected images are for various N_{HI}, at $\sigma_{src} = 100\ km\ s^{-1}$ and $v_{exp} = 400 km\ s^{-1}$.
- The surface brightness becomes more extended with increasing N_{HI}.
- The degree of polarization is not monotonic as N_{HI} increases.

- When $N_{HI} \leq 10^{19}\ \mathrm{cm}^{-2}$, the bright core and polarization jump coexist.
- When $N_{HI} = 10^{21}\ \mathrm{cm}^{-2}$, the polarization gradually increases without bright core.

Single and Multiple Wing Scattering Behavior

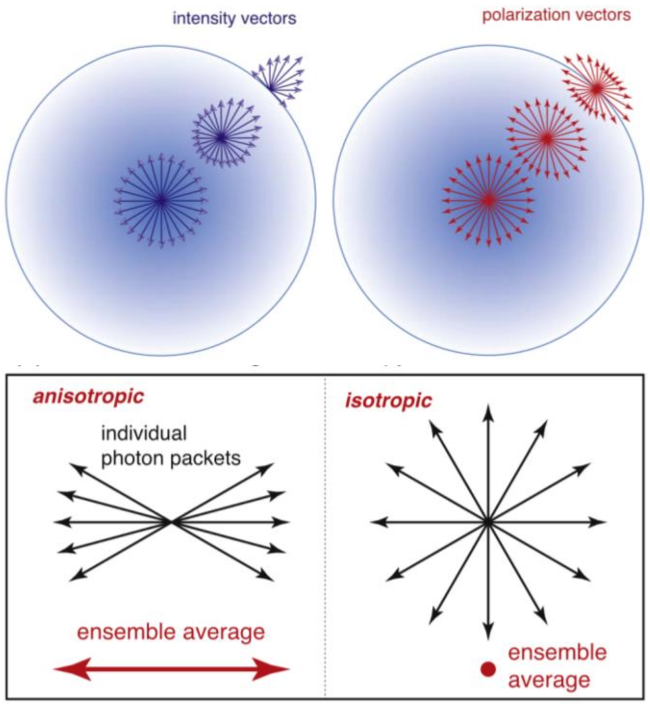


Optical depth of initial photon as a function of ΔV

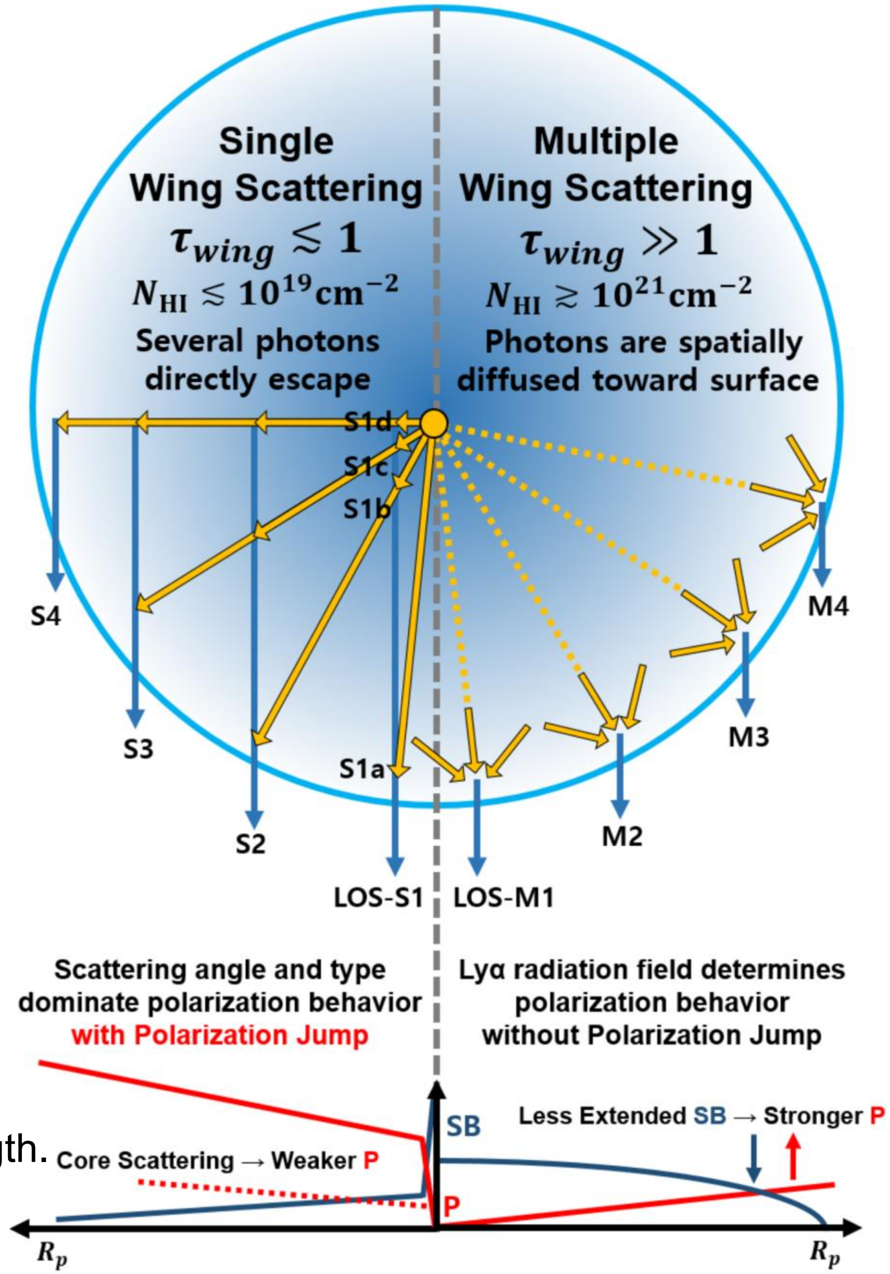


- At $N_{HI}{\sim}10^{19} cm^{-2}$, the photon easily escape through several wing scattering.
- At $N_{HI}{\sim}10^{21} cm^{-2}$, the photon must go through multiple wing scattering.
- The photon’s journey in Single wing scattering case strongly depends on initial wavelength.
- The photons in Multiple wing scattering case are continuously optically thick.

Single and Multiple Wing Scattering Behavior



Polarization Behavior of
multiply scattered Lyα photons
Seon et al. 2022



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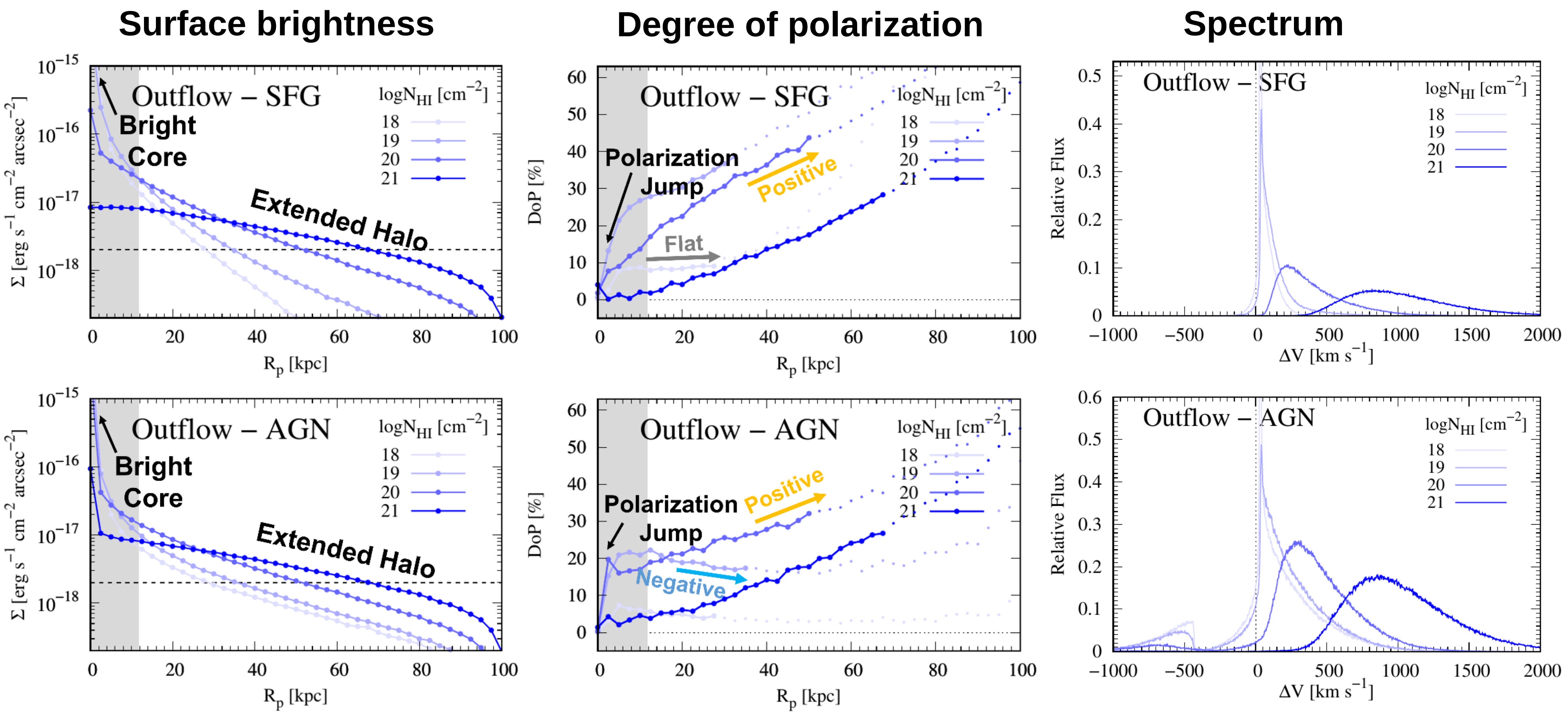
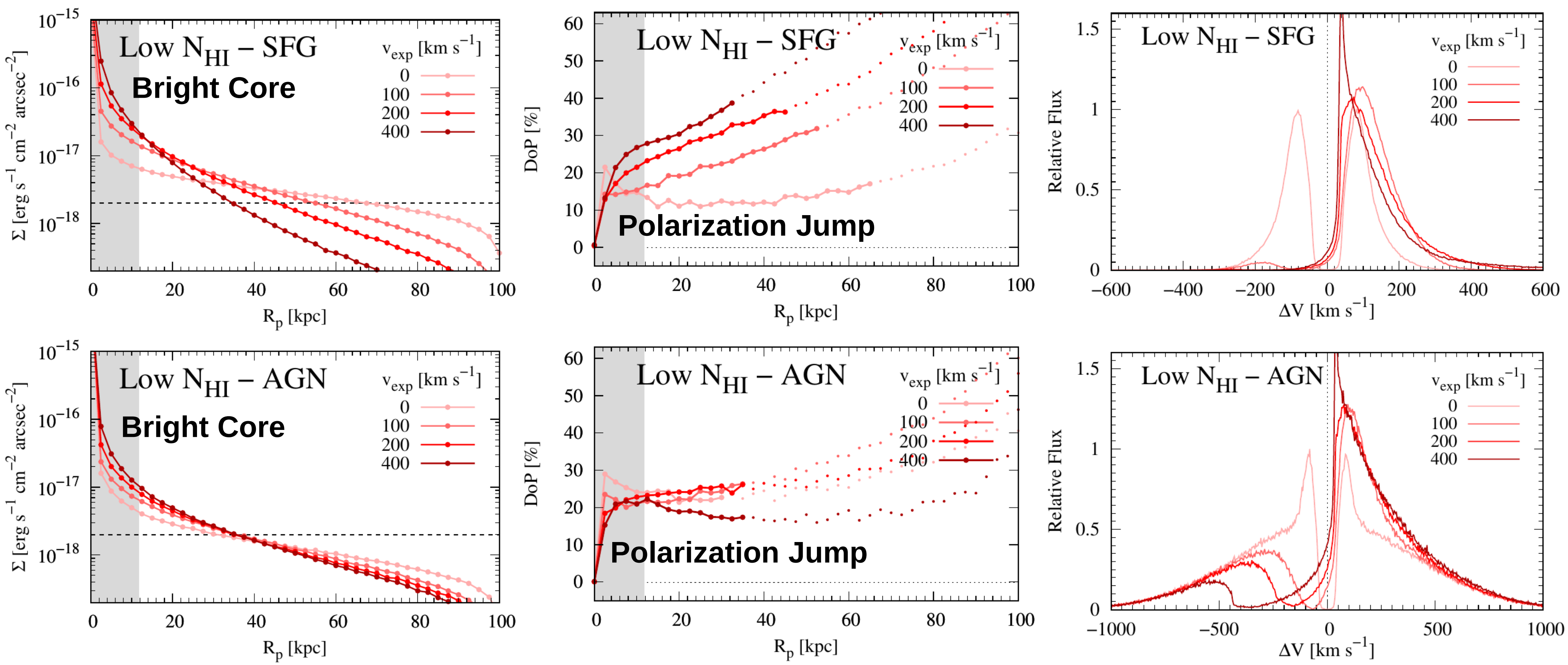
Dependence on N_{HI}



$N_{HI} \uparrow \rightarrow$ SB is more extended
Polarization…. ☹… Strange..
Spectrum is more broadened

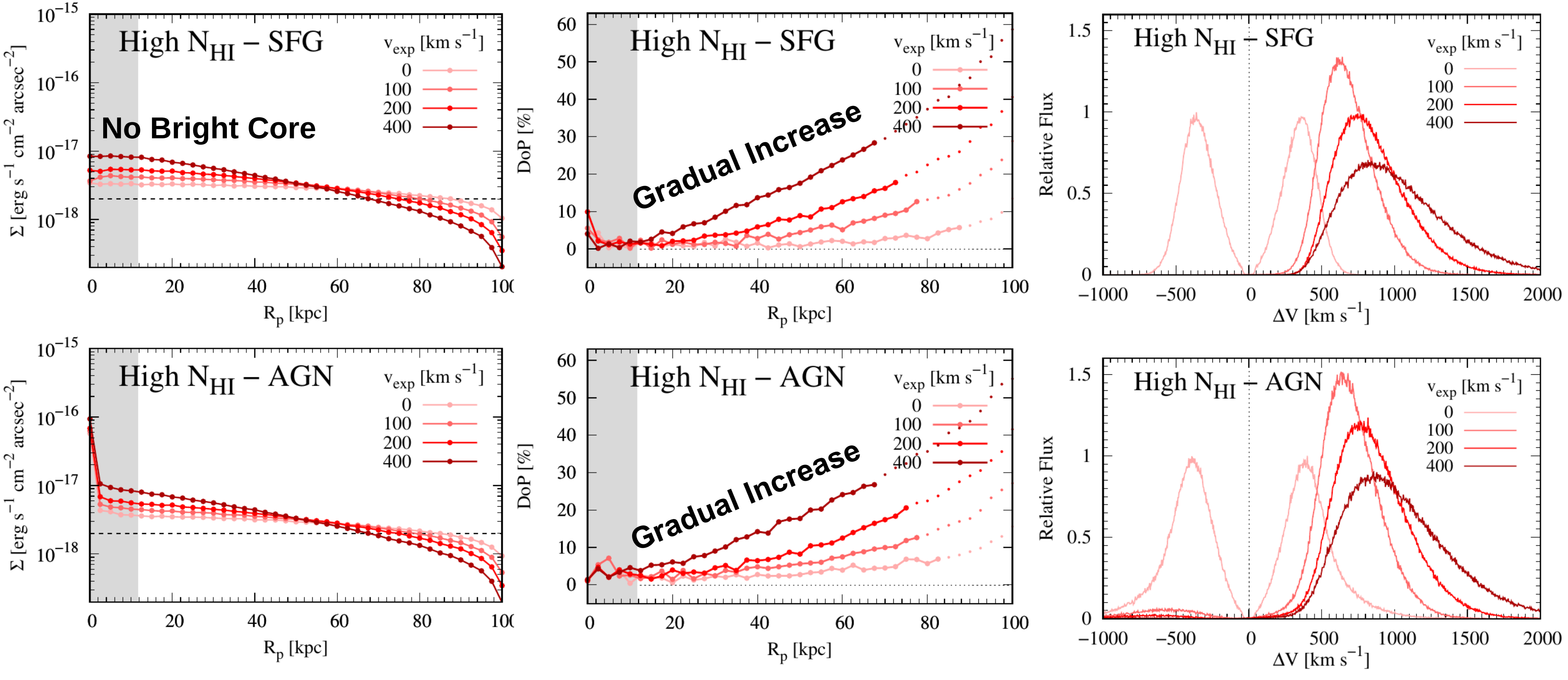
Dependence on v_{exp} at Low N_{HI} $(10^{19} cm^{-2})$



The results depend on Lyα intrinsic width (SFG vs AGN)

$v_{exp} \uparrow \rightarrow$ **SB is more contracted**
Polarization ☹… in AGN case
Spectra in the redward are similar

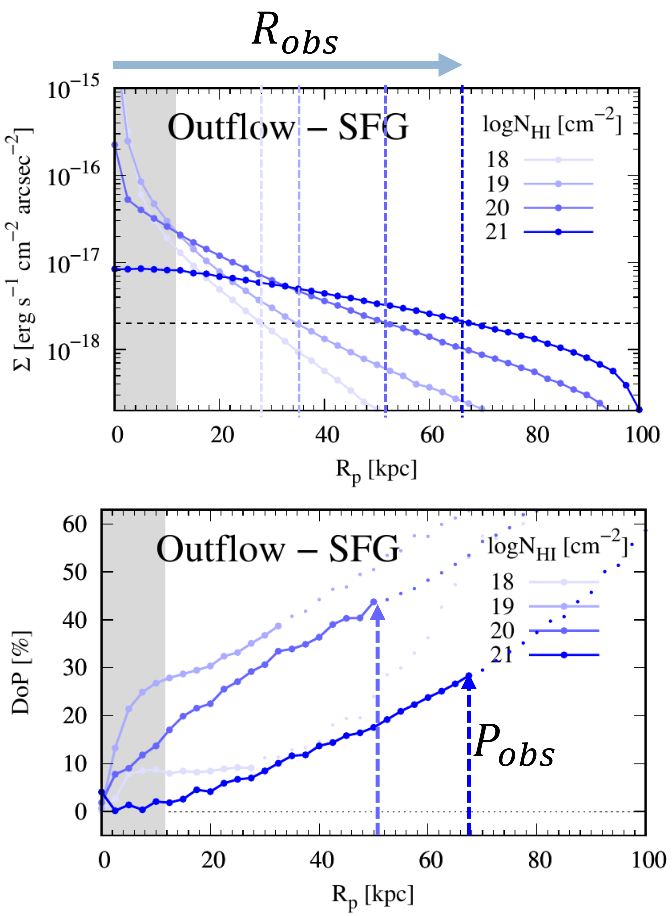
Dependence on v_{exp} at High N_{HI} $(10^{21} cm^{-2})$

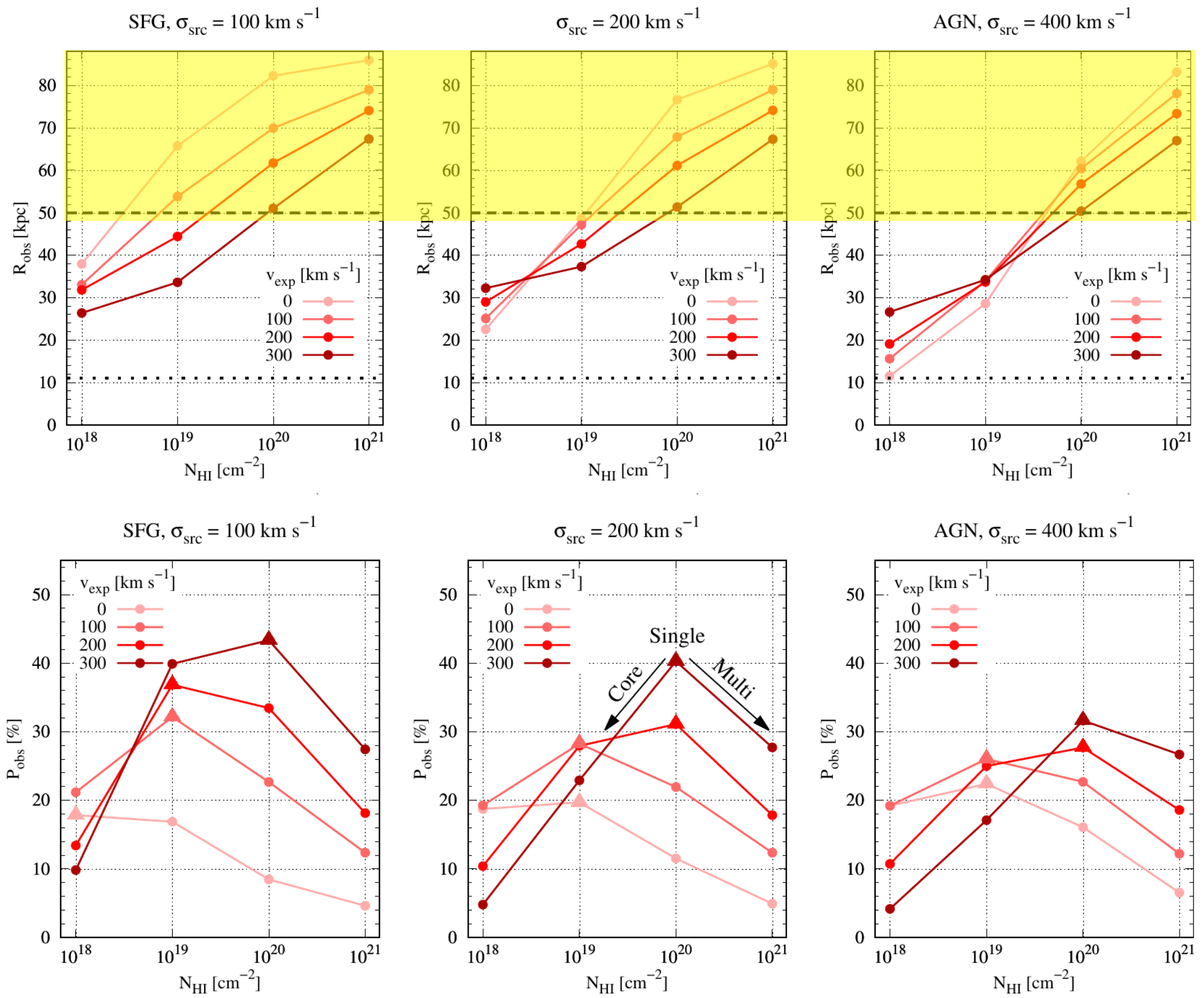


The results does on depend on Lyα intrinsic width
(SFG vs AGN)

$v_{exp} \uparrow \rightarrow$ **SB is more contracted**
Polarization ↑
Spectrum is more redshifted

Observable Values





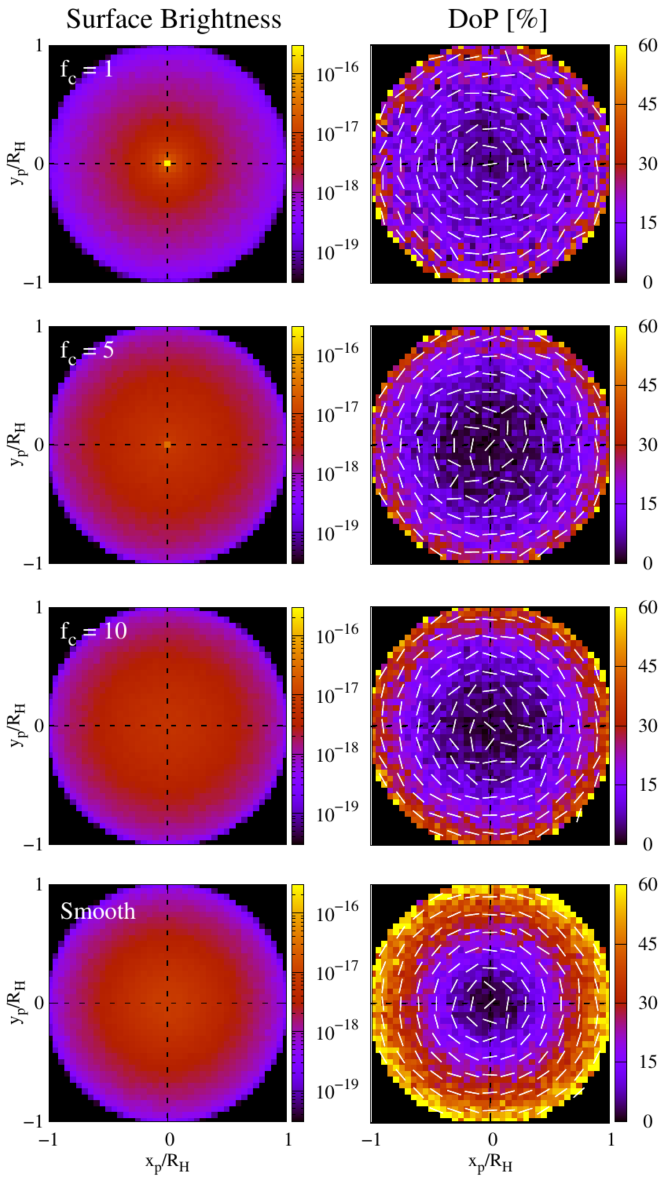
$N_{HI} \geq 10^{20} cm^{-2}$, $R_{obs} > 50$ kpc

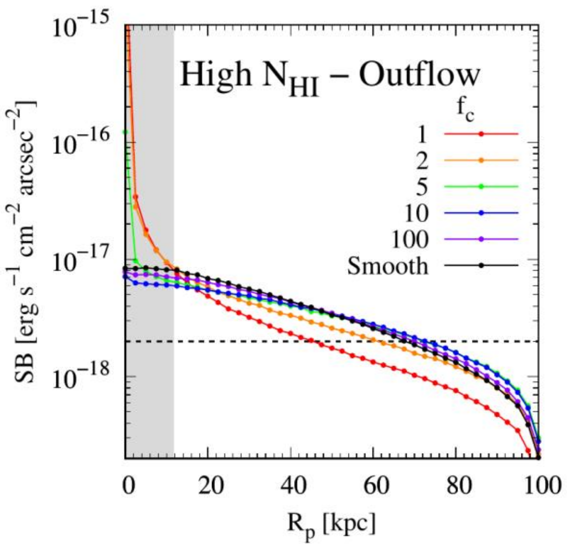
Summary of Model S

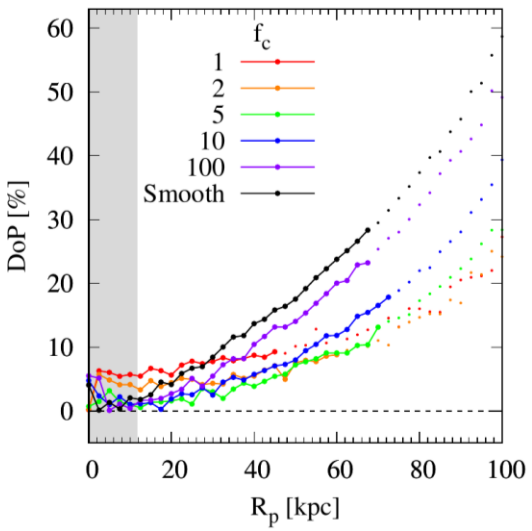
- In this work, the simulation for Lyα radiative transfer is based on LaRT in Seon et al. 2022.
- The surface brightness profiles become more extended with increasing N_{HI} and v_{exp}.
- The polarization behavior is more complex and does not monotonically vary as a function of N_{HI}
- Core scattering must be considered for accurate polarization of scattered Lyα.
- When $N_{HI} \geq 10^{20} cm^{-2}$, Lyα halo is extended over 100 kpc.

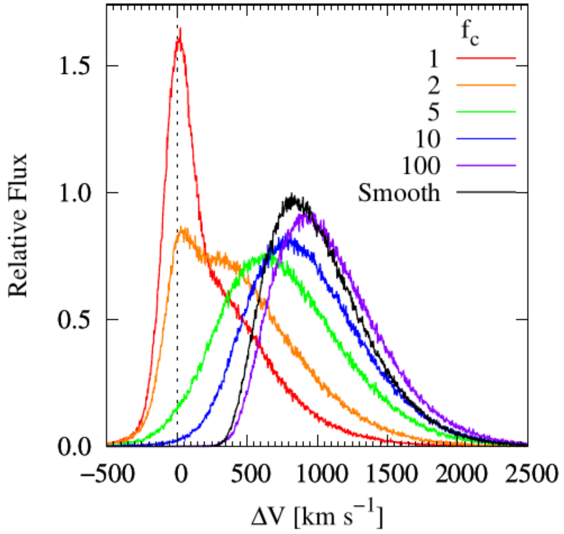
Lyα Projected Image of Model C

$f_c \uparrow$



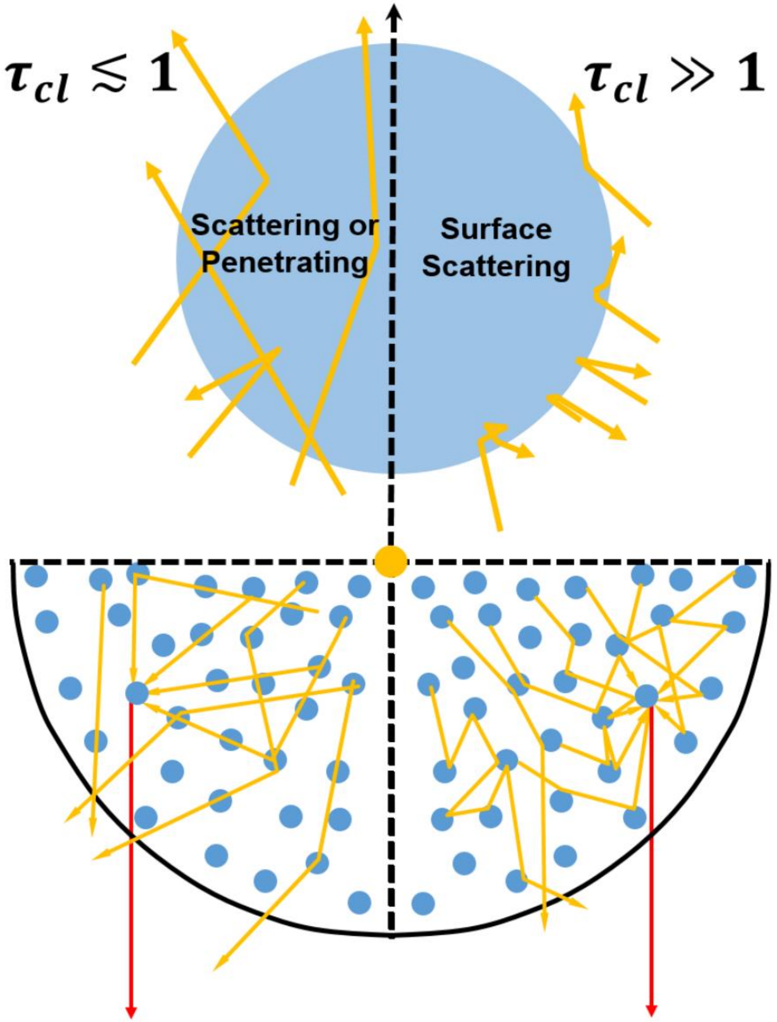


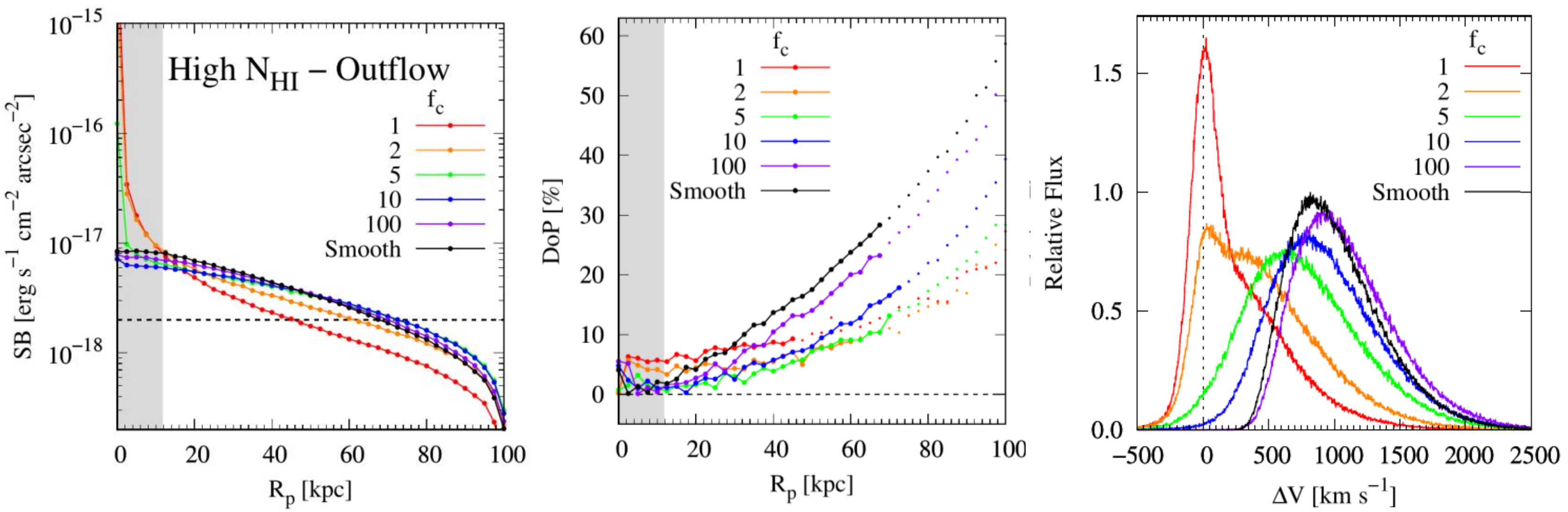




- The projected images are for various f_c, at $\sigma_{src} = 100\ km\ s^{-1}$, $v_{exp} = 400 km\ s^{-1}$, $N_{HI} = 10^{21} cm^{-2}$.
- The surface brightness becomes more contracted with decreasing f_c.
- But, at $f_c \geq 5$, the surface brightness profile is similar to the profile of Model S.
- The polarization of Model C is smaller than of Model S because of the surface scattering.
- The spectral profile shows more photons near the systematic velocity when f_c decreases.
- The simulated results with $f_c = 1$ and 2 are completely different from the results of Model S.

Surface Scattering at Clump





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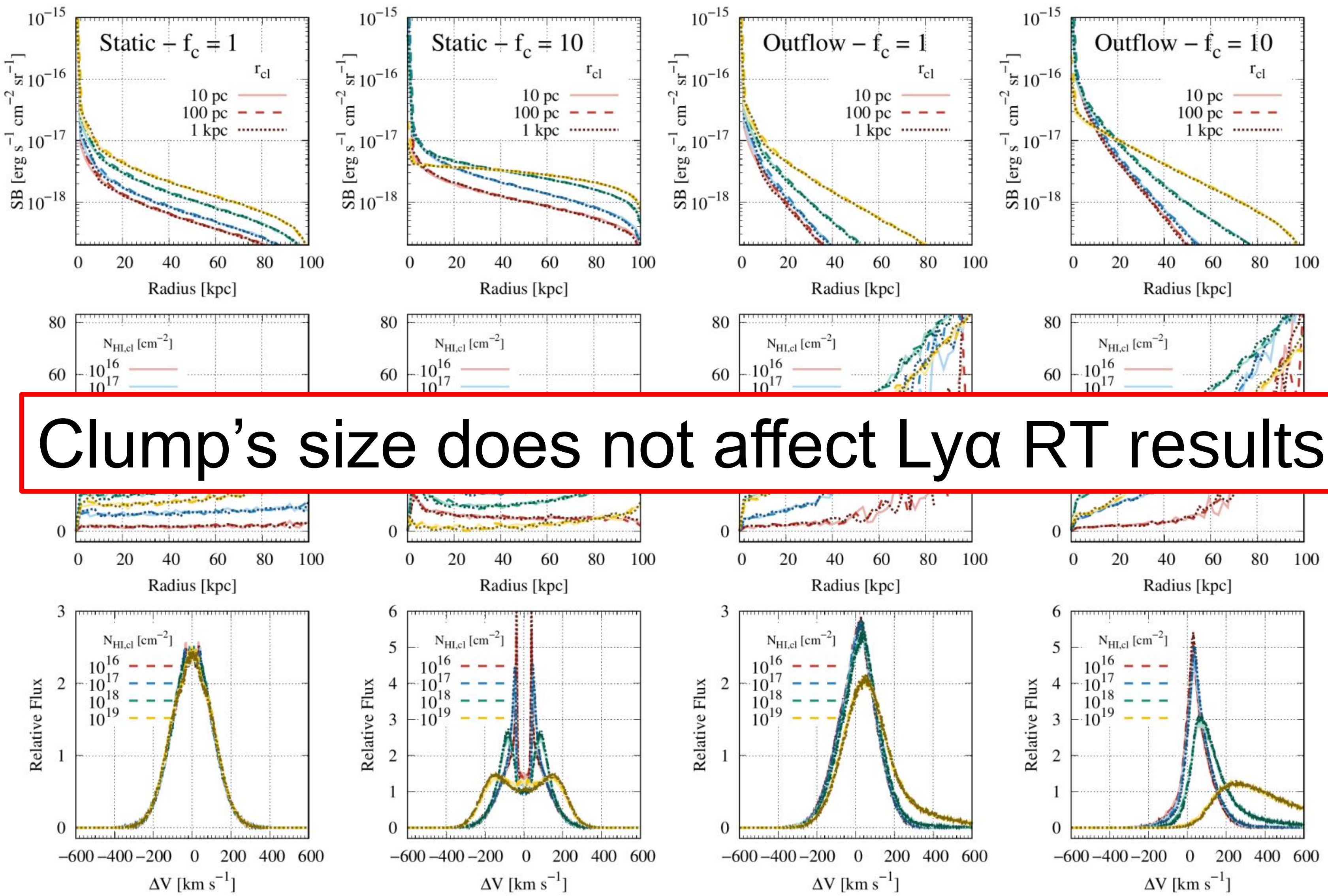
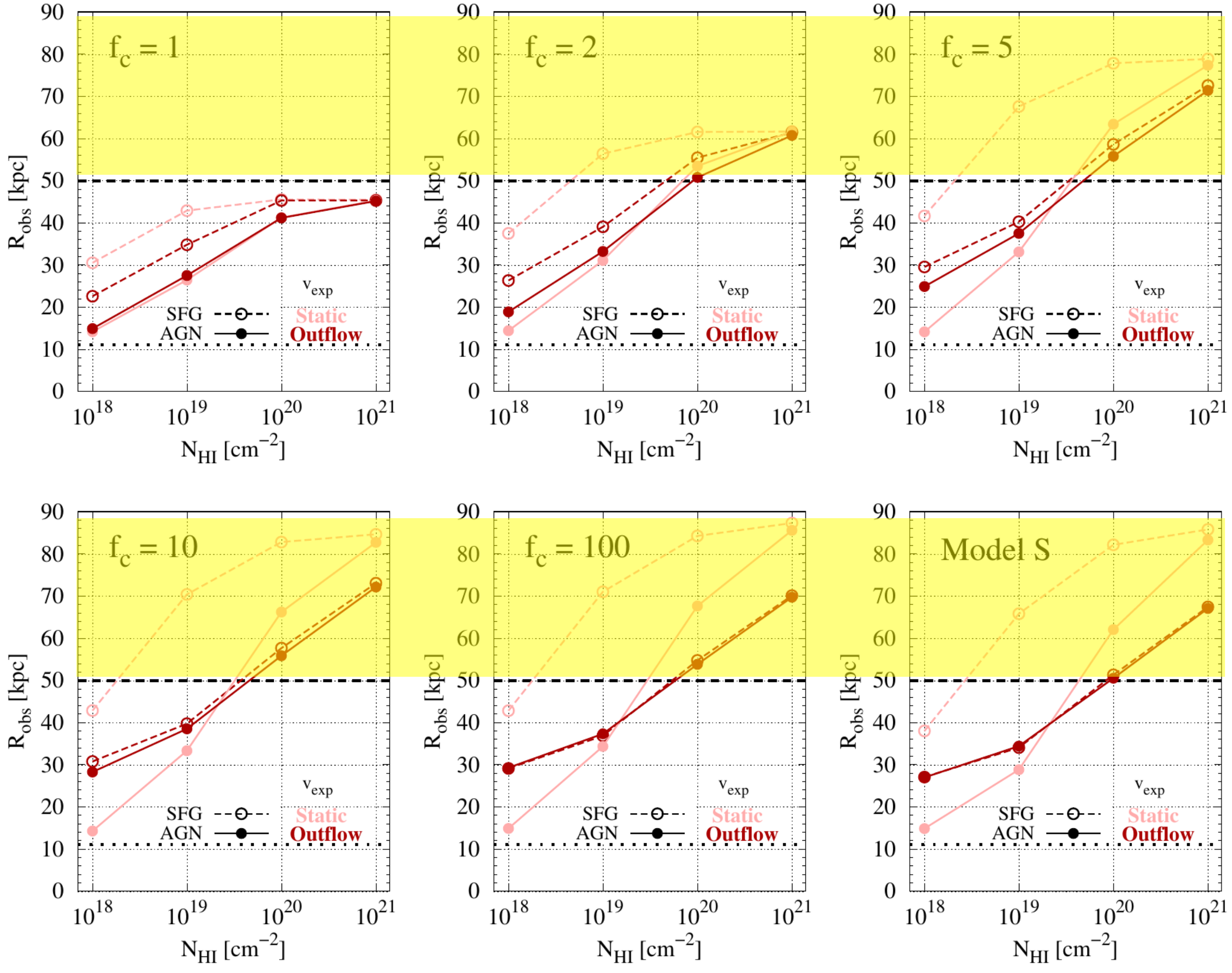
Dependence on Clump's size



Clump's size does not affect Lyα RT results.

Size of Lyα Halo in Clumpy Medium



$N_{HI} \geq 10^{20} cm^{-2}$ and $f_c \geq 2$,

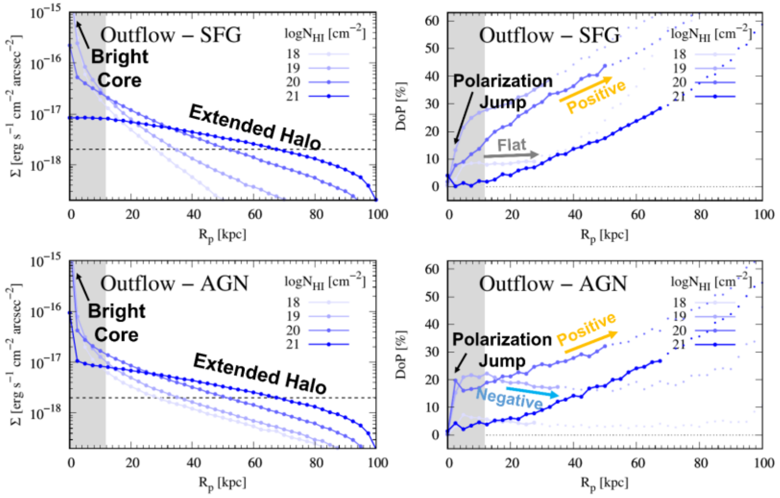
$R_{obs} > 50$ kpc

Summary of Model C

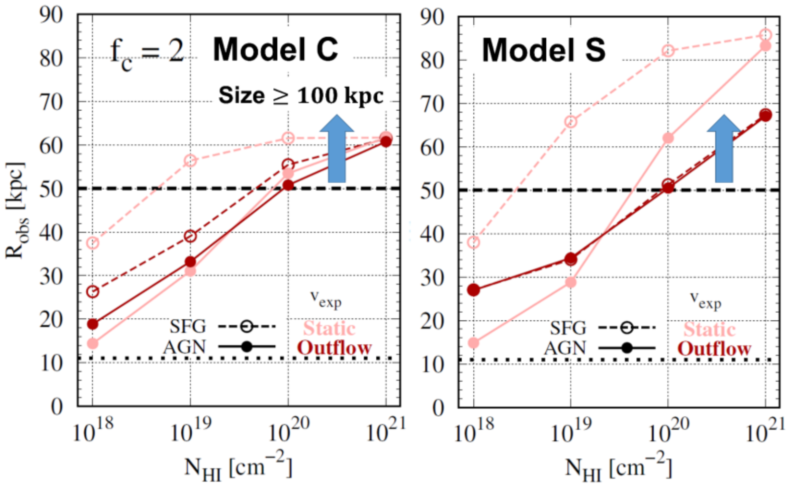
- The surface brightness profile of Model C with $f_c \geq 5$ is identical to the profile of Model S at the same NHI
- The surface scatterings decrease the overall polarization and the spectral line broadening.
- The size of clumps much smaller than the halo size does not affect the results of Lyα radiative transfer.
- The spectra of Model C with $f_c = 1 - 2$ are entirely different from those of Model S.
- When $N_{HI} \geq 10^{20} cm^{-2}$ and $f_c \geq 2$, Lyα halo is extended over 100 kpc.

Four Key Results

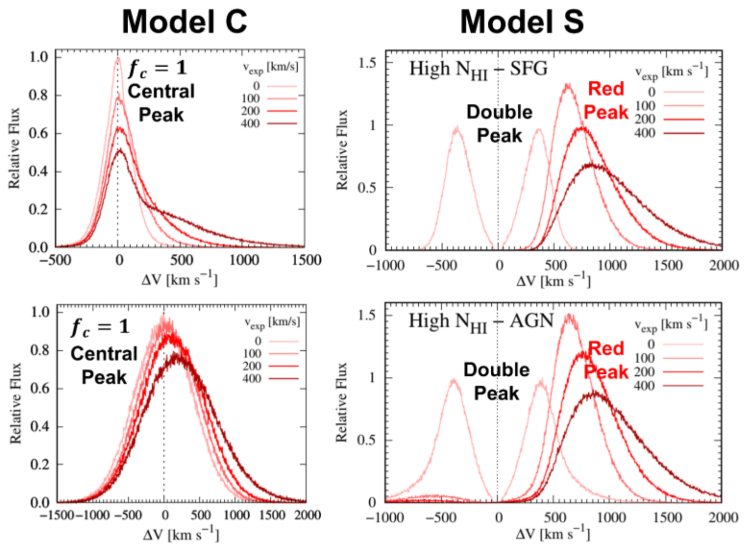
I & II



III



IV



I. Lyα halo with or without the bright core/polarization jump.

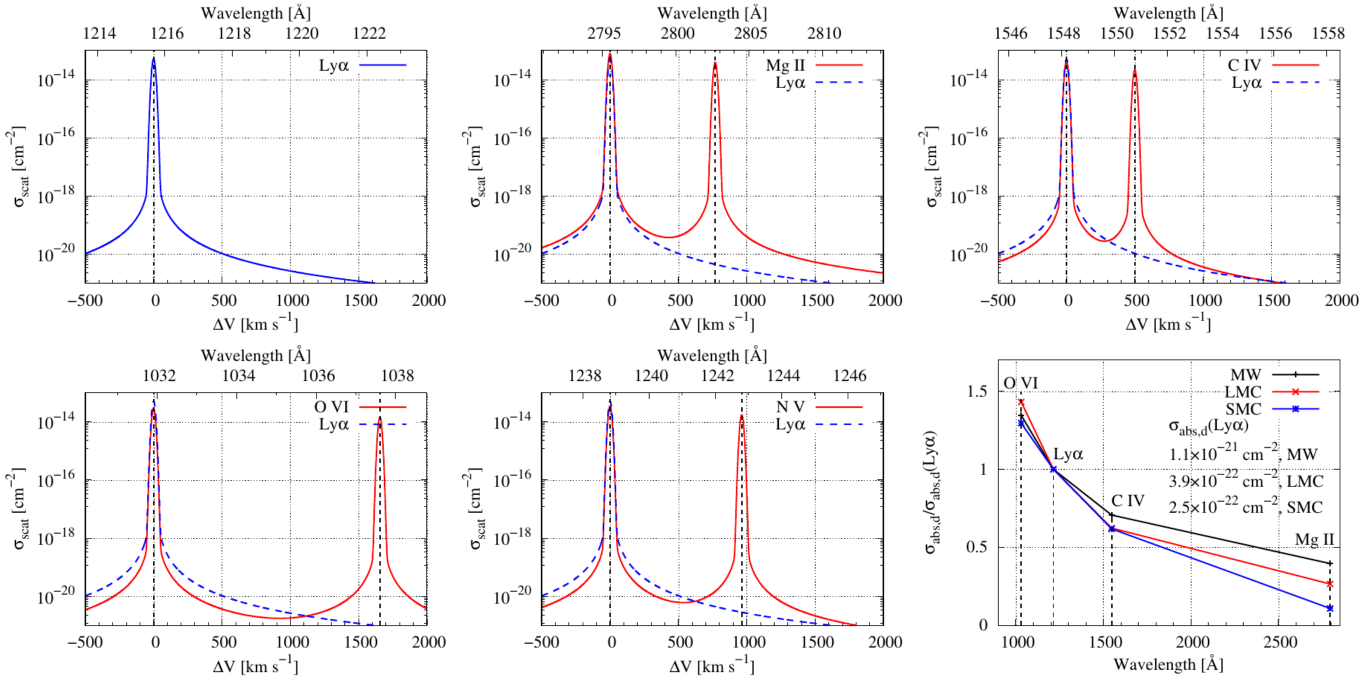
II. Positive, Flat, and Negative gradient of polarization.

III. Size of Lyα halo > 100 kpc when $f_c \geq 2$ and $N_{HI} \geq 10^{20}\ \mathrm{cm}^{-2}$.

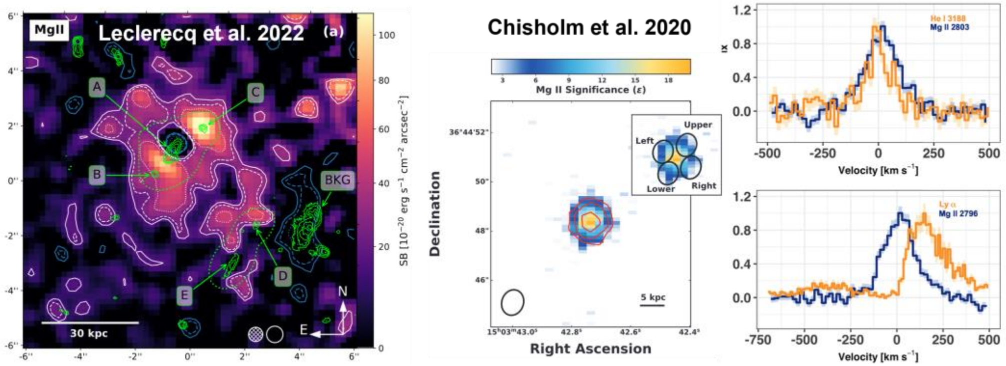
IV. Lyα spectra of low f_c and high N_{HI} Model C showing the profiles impossible to be explained by Model S.

Future Work

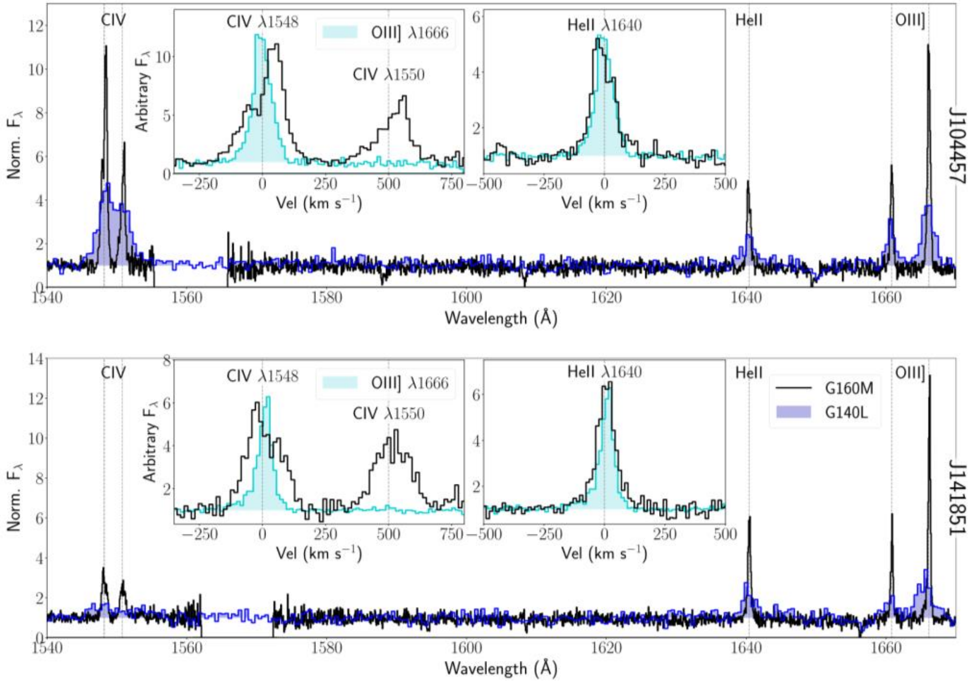
Future Work – Metal Resonance Doublets Transfer



Scattering Cross Section of Resonance Doublets

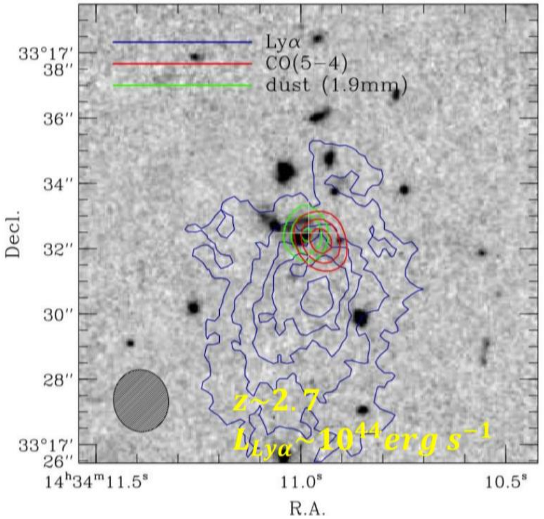


Mg II Nebulae

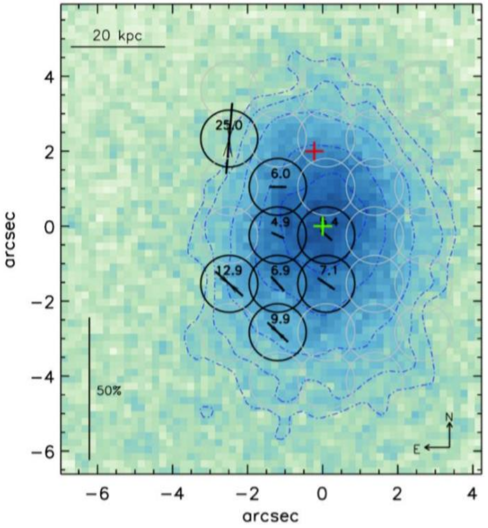


C IV and He II in UV emission galaxies in z ~0
Berg et al. 2019

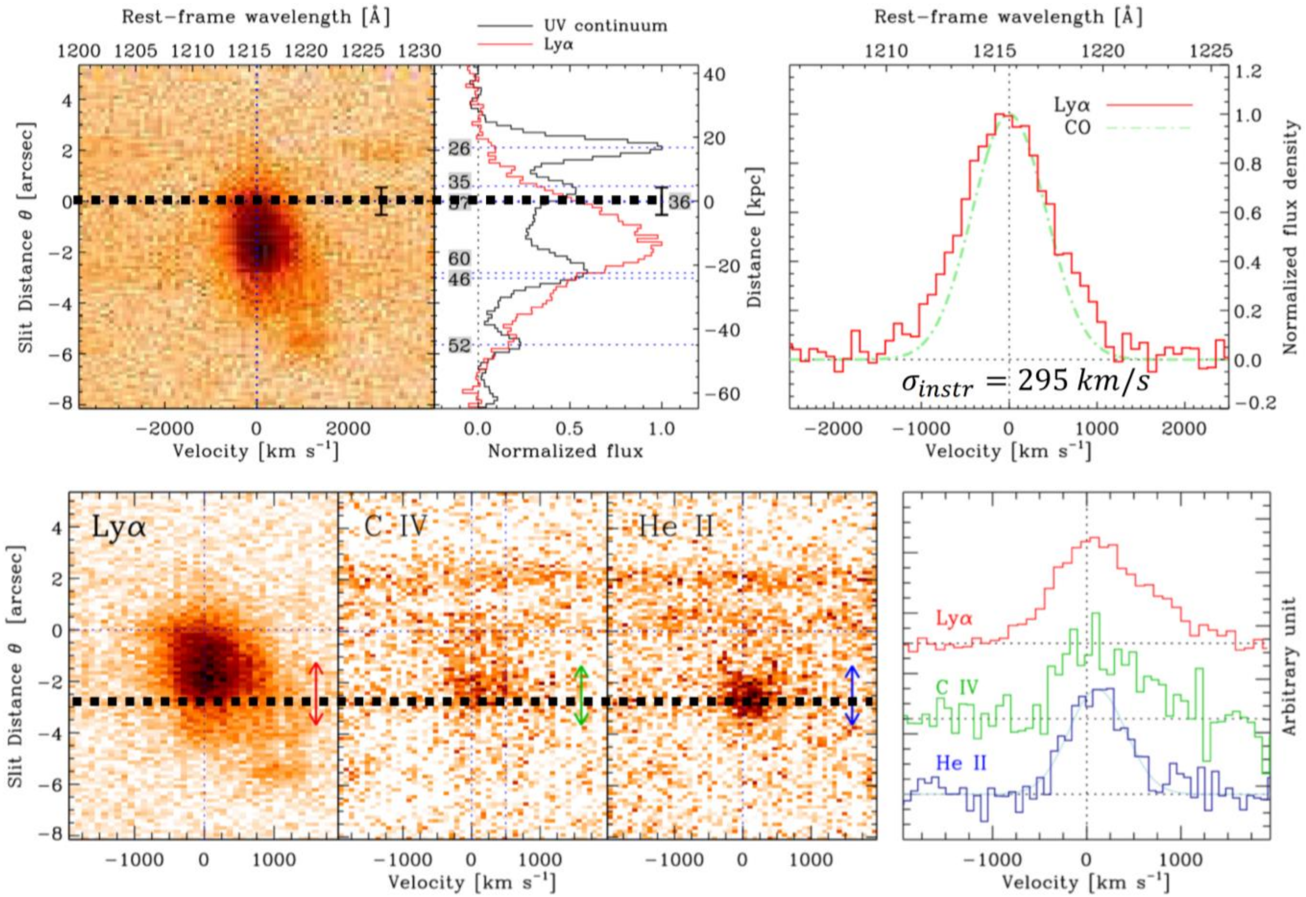
Future Work – Investigating LABd05 using clumpy model



Photometric data
Yang et al. 2014



Polarimetric data
Kim et al. 2020



Spectroscopic data
Yang et al. 2014

Thanks