Radiative Transfer in Highly Thick Media through Rayleigh and Raman Scattering with Atomic Hydrogen

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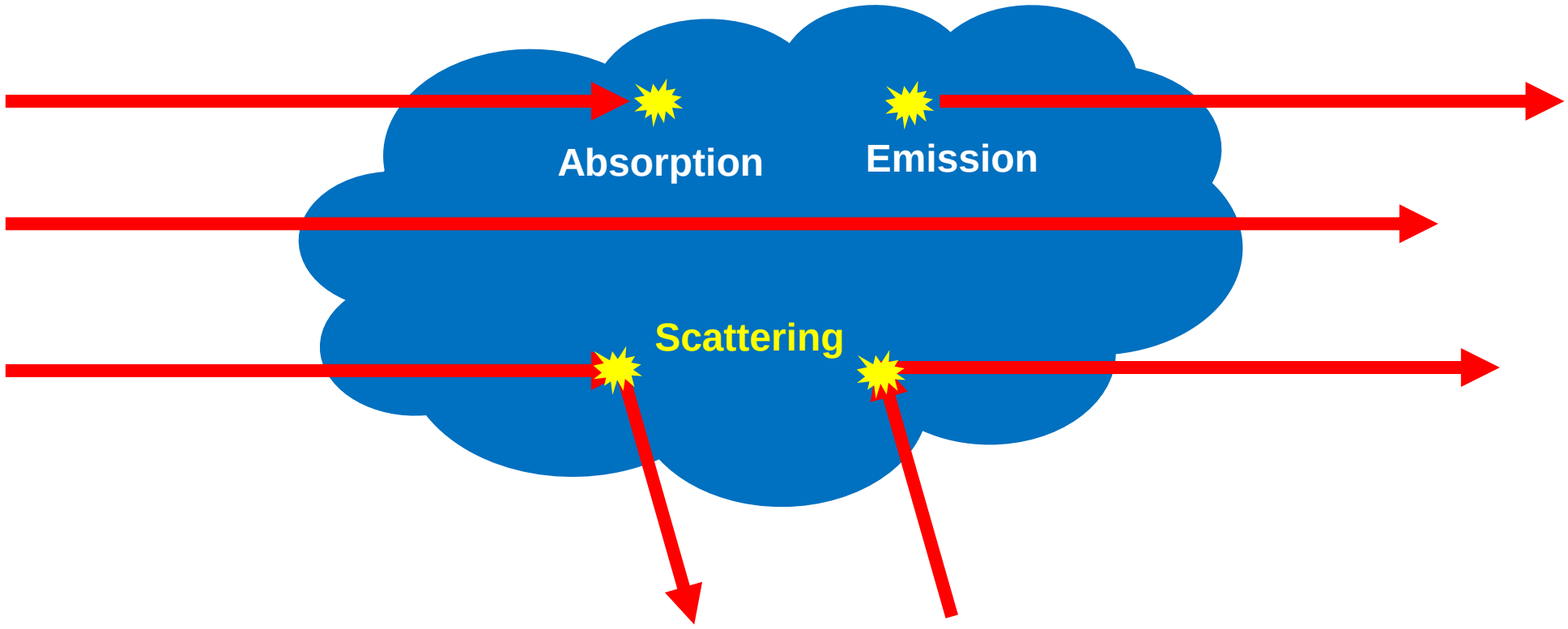
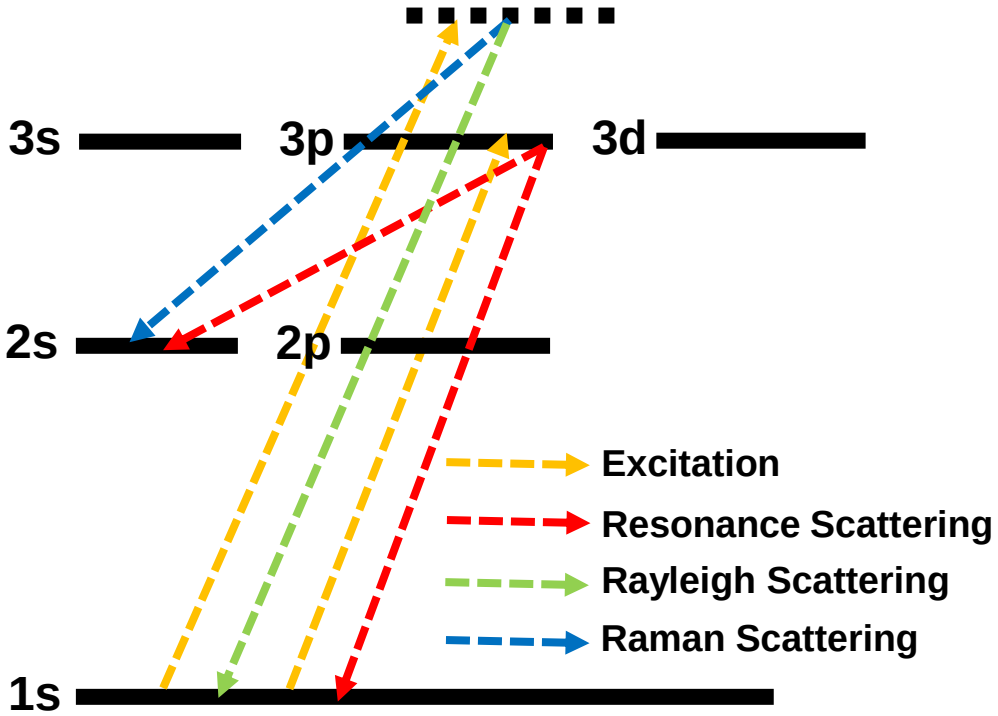
Contents

Radiative Transfer

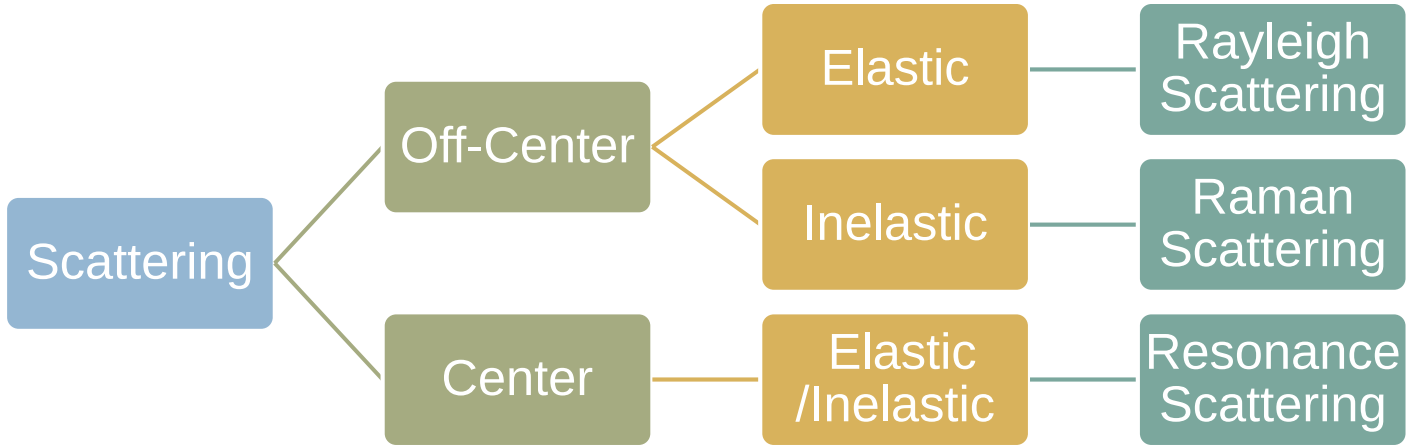
Radiative transfer is the physical phenomenon of energy transfer in the form of electromagnetic radiation.



Scattering with Atomic Hydrogen

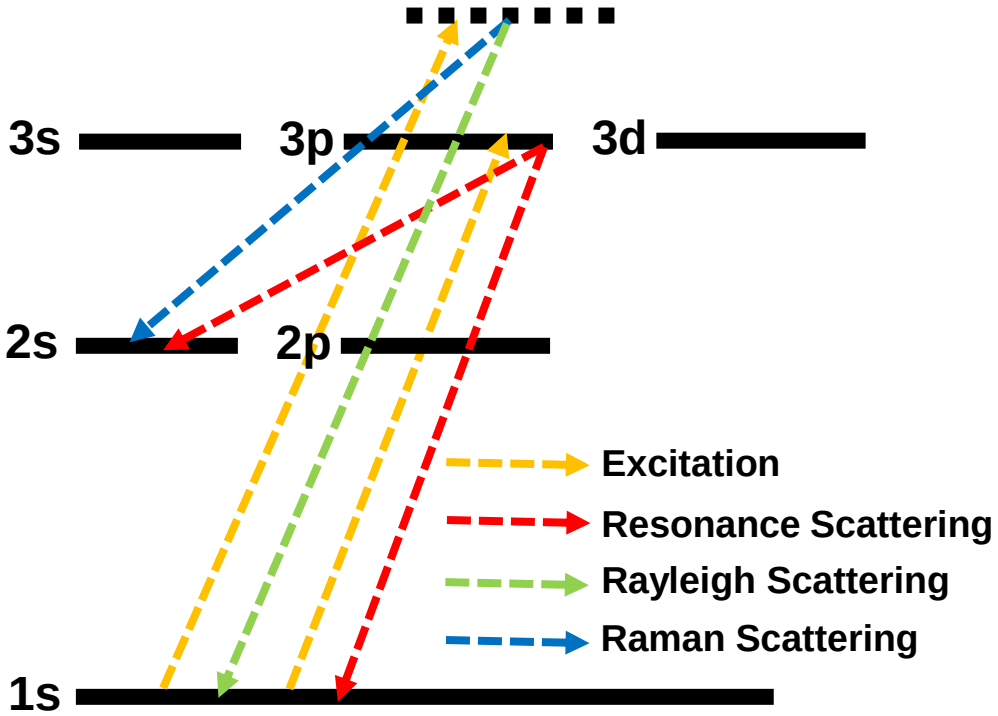


Type of Scattering with Atomic Hydrogen



- **Resonance scattering** is the transition between the states.
- **Rayleigh and Raman scattering** occur as the bounded electron excited to the energy level between the states.
- The excited hydrogen atom may de-excite into an excited state resulting in reemission of a lower energy photon, which is called ***Raman Scattering.*** If the de-excitation is made into the ground state, then result is an elastic scattering, which is also called ***Rayleigh scattering.***

Scattering with Atomic Hydrogen



Type of Scattering with Atomic Hydrogen

Literature	Subject	Type of Scattering	Object
Chang et al. 2015	Scattering Wing of Hα and Hβ	Raman Scattering	AGN
Lee et al. 2016	Raman Scattered O VI	Raman Scattering	Symbiotic Stars
Chang et al. 2017	Polarization of Lyα	Rayleigh scattering	AGN
Chang et al. 2018A	Resonantly Scattered Hα and Lyβ	Resonance Scattering	ISM
Chang et al. 2018B	Scattering Wing of Hα and Hβ	Raman Scattering Thomson Scattering	Symbiotic Stars
Choi et al. 2020	Raman scattered He II	Raman scattering	Planetary Nebulae
Chang et al. 2020	Grid-Based Simulation	Rayleigh scattering Raman scattering	STaRS
Chang et al. prep	Scattered Lyα in CGM and IGM	Resonance Scattering Rayleigh Scattering	Lyα Blobs

Radiative Transfer for Raman Scattering

Raman Scattering in Astrophysics – Schmid 1989

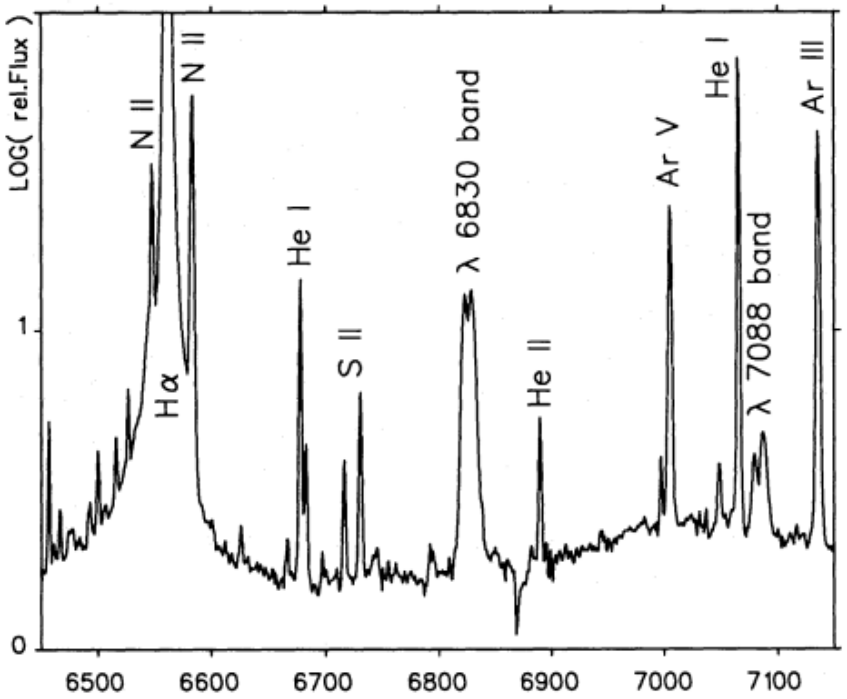
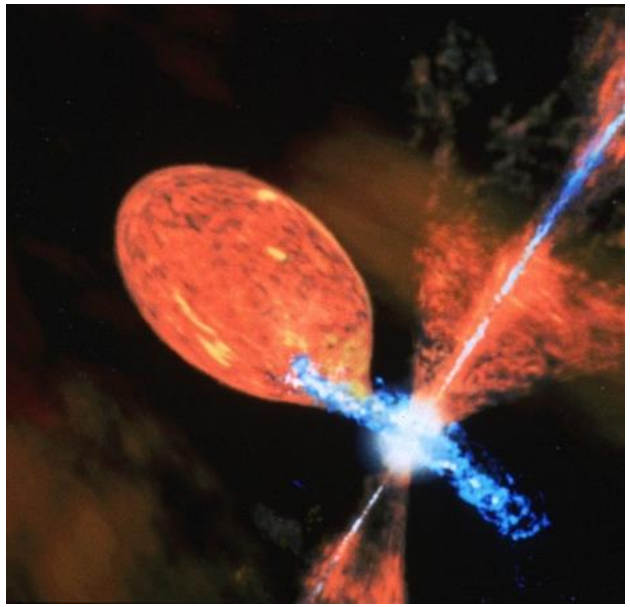


Fig.1. Raman scattered emission bands in the symbiotic star V1016 Cyg. The spectrum was obtained on the 1.93m telescope at the Observatoire de Haute Provence.

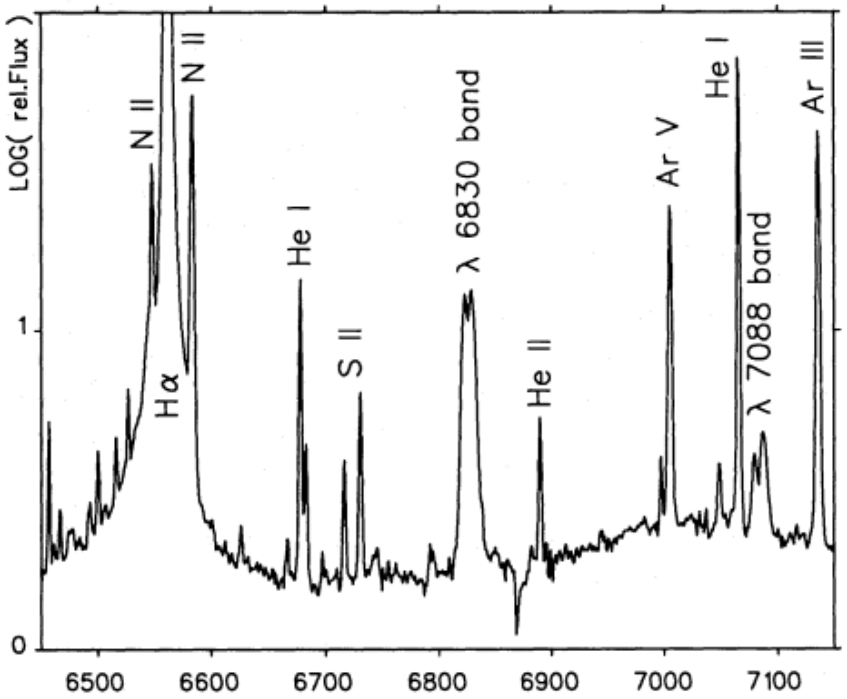


Symbiotic Stars

The binary stars composed of hot white dwarf and cool red giant

- Raman scattered lines are relatively broader than other emission lines.
- Schmid (1989) identify Raman Scattered O VI at 6825 Å and 7082 Å in V1016 Cyg.
- The incident photons are O VI λ1032 and λ1038.

Raman Scattering in Astrophysics – Schmid 1989



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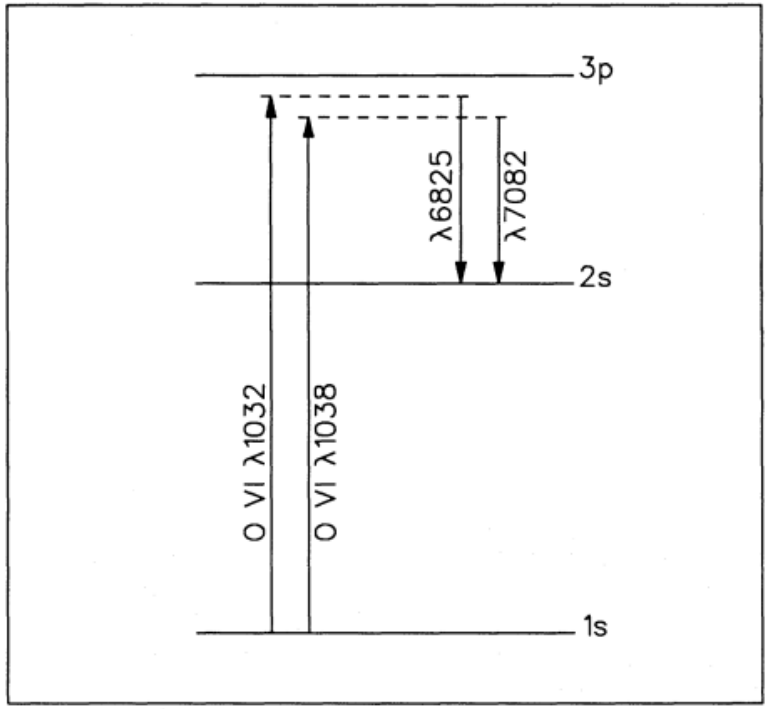


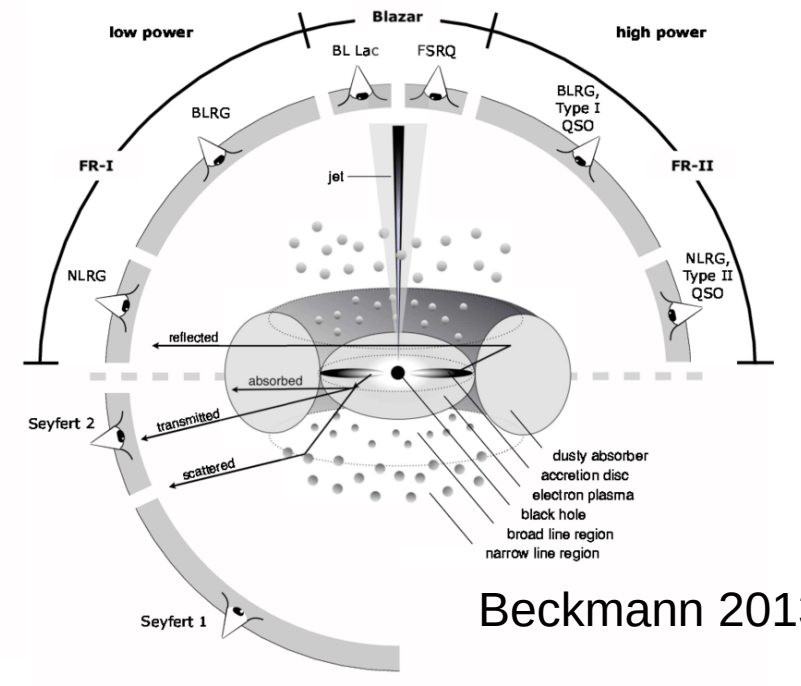
Fig.2. Schematic energy level diagram for Raman scattering of OVI photons by neutral hydrogen.

- Raman scattered lines are relatively broader than other emission lines.
- Schmid (1989) identify Raman Scattered O VI at 6825 Å and 7082 Å in V1016 Cyg.
- The incident photons are O VI λ1032 and λ1038.

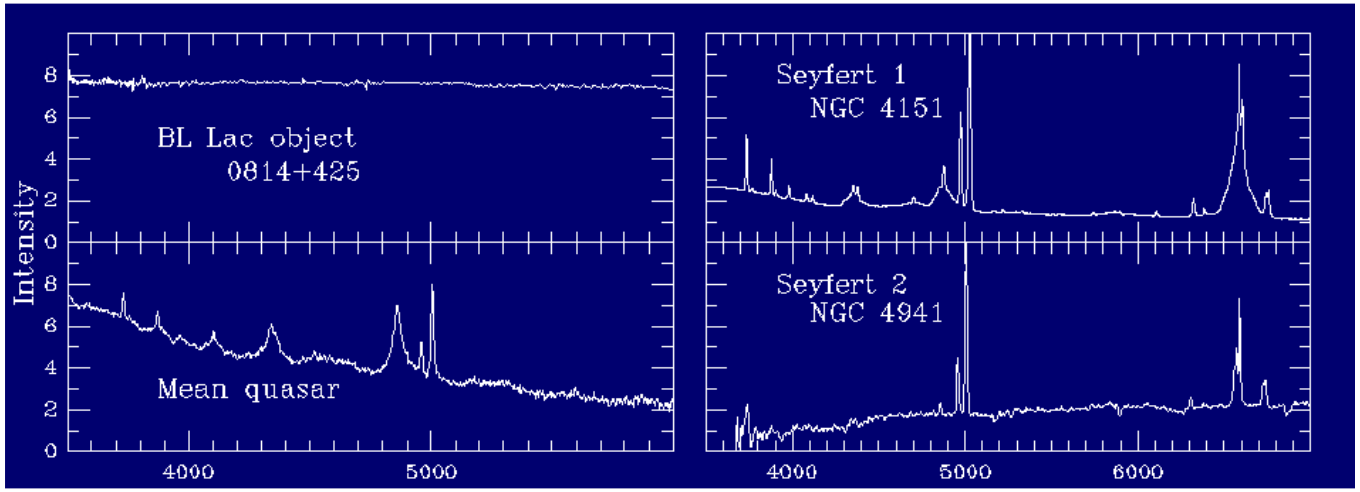
Raman Scattering in Previous Works

- Chang et al. 2015, Formation of Raman wings near Hα, Hβ, and Paα in AGN unification model
- Chang et al. 2018, Broad Balmer wing in Symbiotic Stars
- Chang & Lee 2020, 3D grid-based Monte Carlo code for Raman scattering

Formation of Raman wings in AGN Unification Model



Beckmann 2013



The spectra of AGN
(Bill Keel 2002)

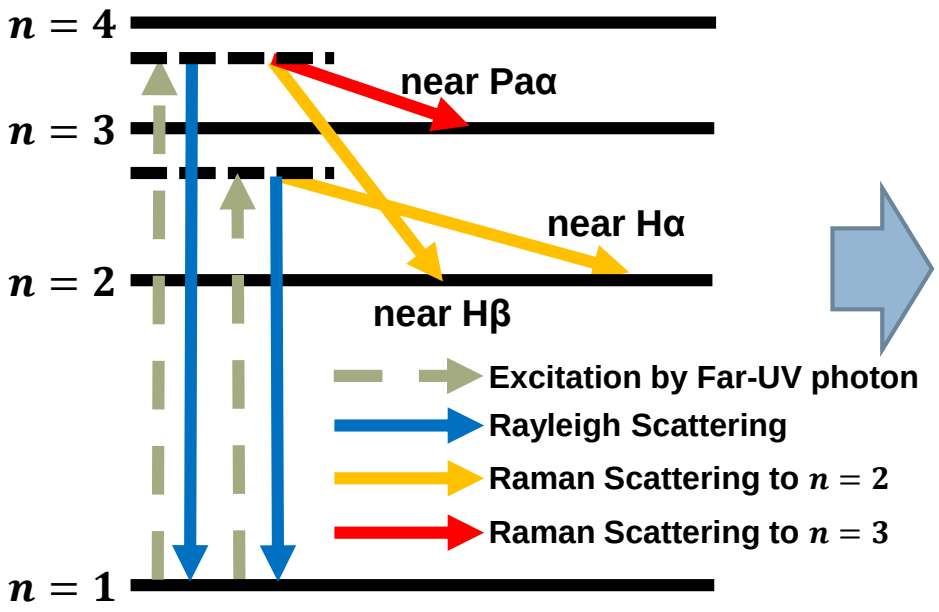
- In AGN unification model, the type of AGN is determine by the line of sight of one unification model.
- The torus obscure the super massive black hole and broad line region.
- The hydrogen column density of the torus is ~ $10^{23}\ cm^{-2}$ measured by the hardness of X-ray.

Chang et al. 2015, ApJ, 814, 98C

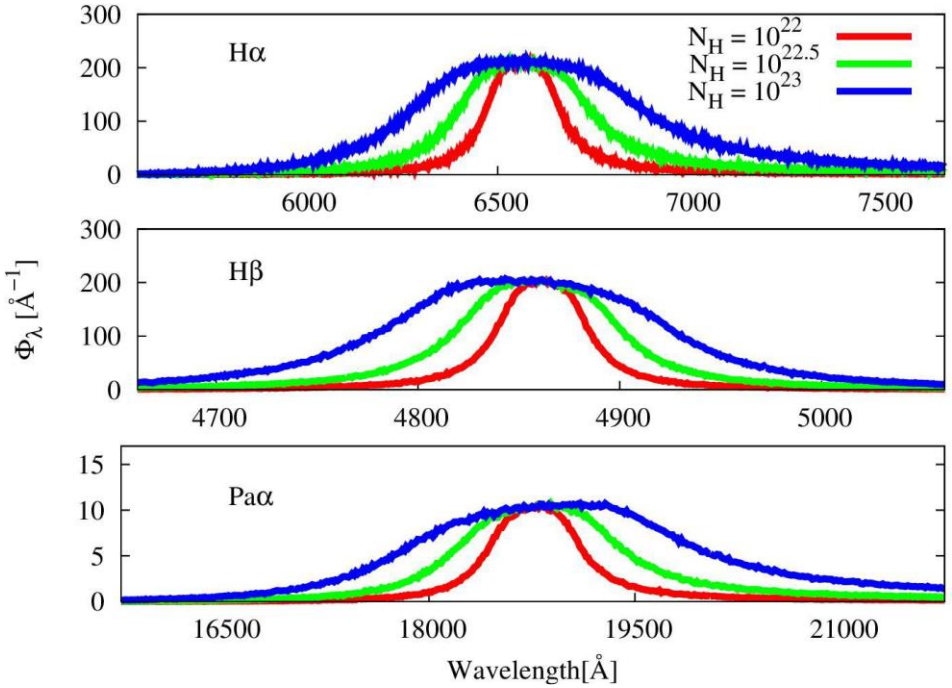
Formation of Raman wings in AGN Unification Model

Continuum emission near Lyβ and Lyγ

From the vicinity of SMBH



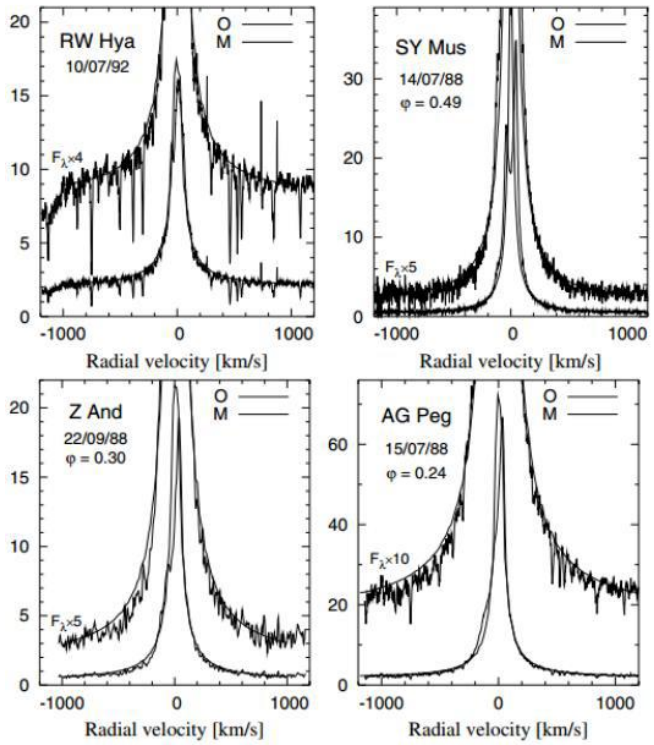
Chang et al. 2015



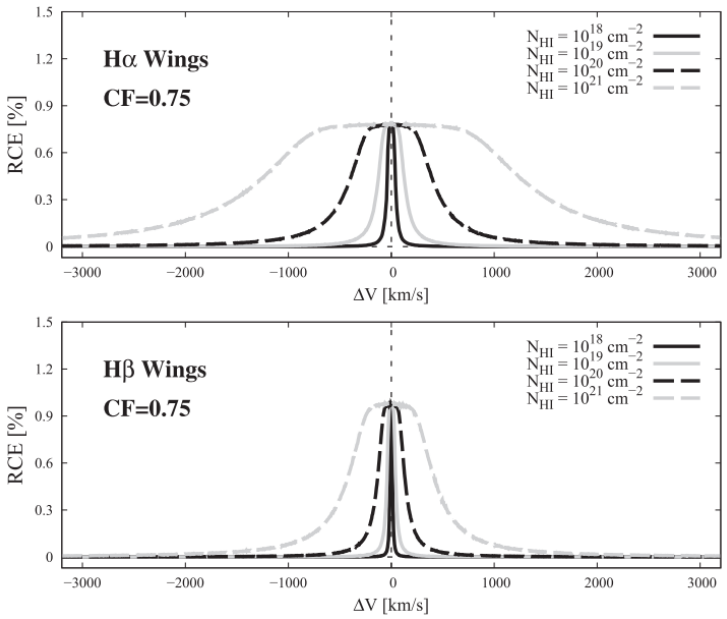
- The continuum near Lyβ and Lyγ convert to Raman wings near Hα and Hβ.
- The widths of Raman wings are proportional to $N_{HI}^{0.5}$.
- Raman wings show the asymmetry, when $N_{HI} \geq 10^{23} cm^{-2}$.

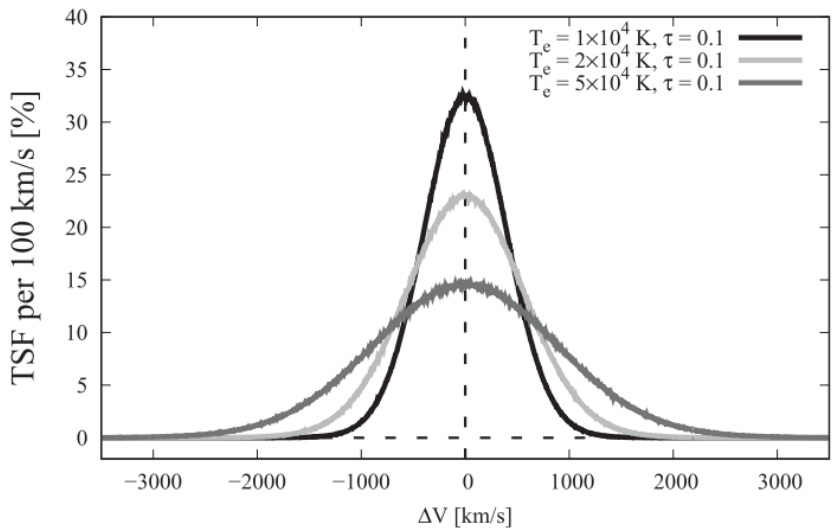
Chang et al. 2015, ApJ, 814, 98C

Broad Balmer Wings in Symbiotic Stars



Hα Wings in Symbiotic Stars
(Skopal et al. 2006)



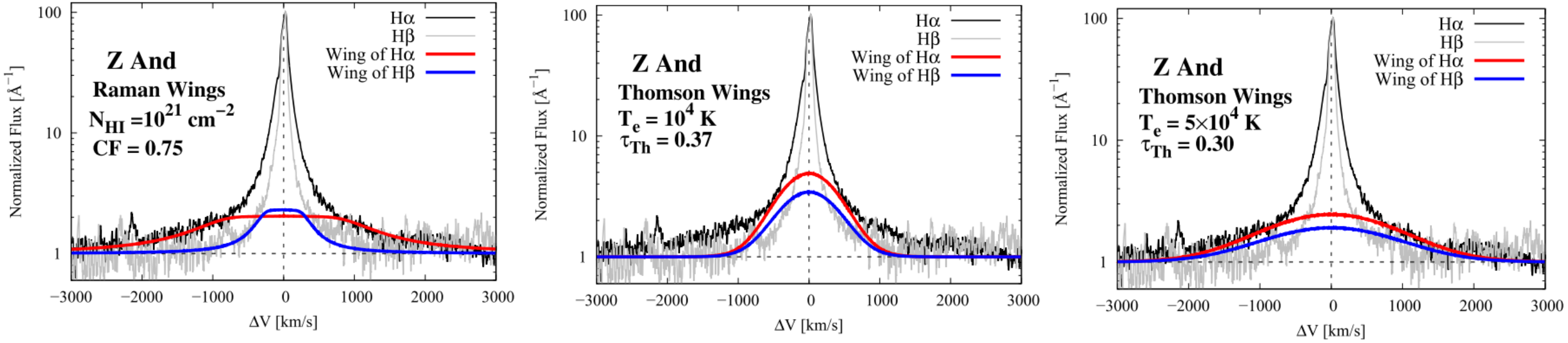


Raman and Thomson Wings
(Chang et al. 2018)

- Hα in symbiotic stars shows the broad wing over ~ 1000 km/s.
- Thomson scattering wings show the same width near Hα and Hβ.
- Raman scattering wing near Hα is 3 times broader than Hβ.

Chang et al. 2018, ApJ, 866, 129C

Broad Balmer Wings in Symbiotic Stars

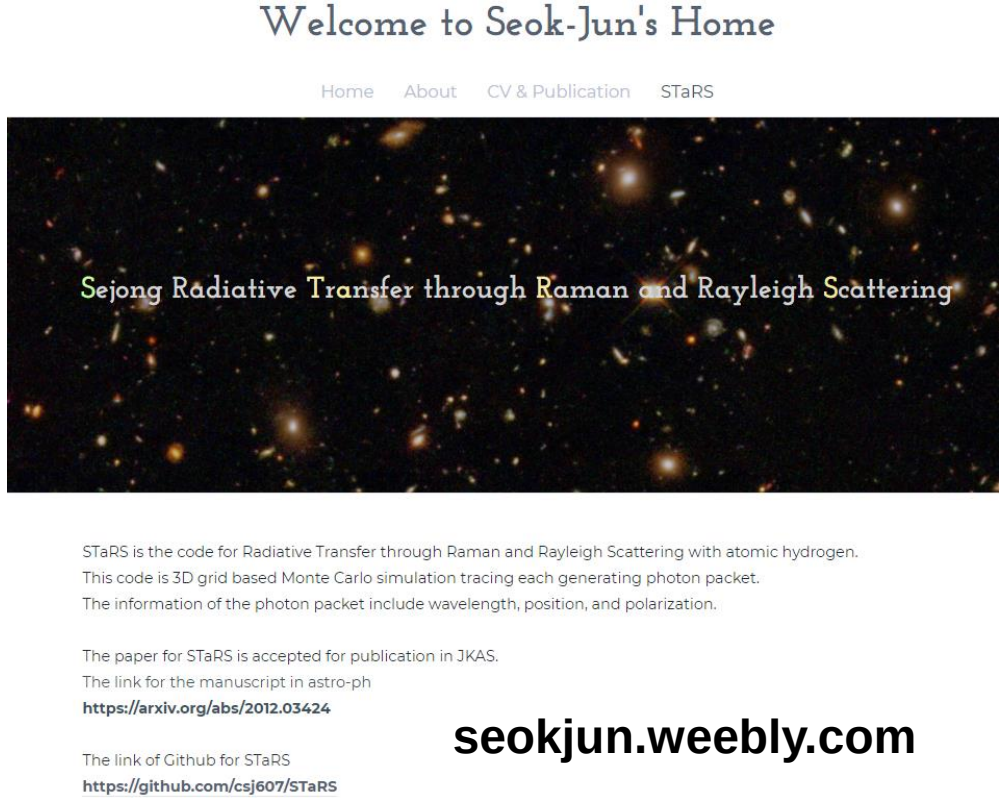


Hα and Hβ of S-type Symbiotic Stars, Z And
(Chang et al. 2018)

- We got the spectrum of symbiotic stars, Z And, by CFHT.
- We compare with the observation data and simulated wings.
- We conclude that Raman scattering largely contribute to the formation of broad wing in Z And, because Hα wing is broader than Hβ.

Chang et al. 2018, ApJ, 866, 129C

STaRS – Poster – PSA-05



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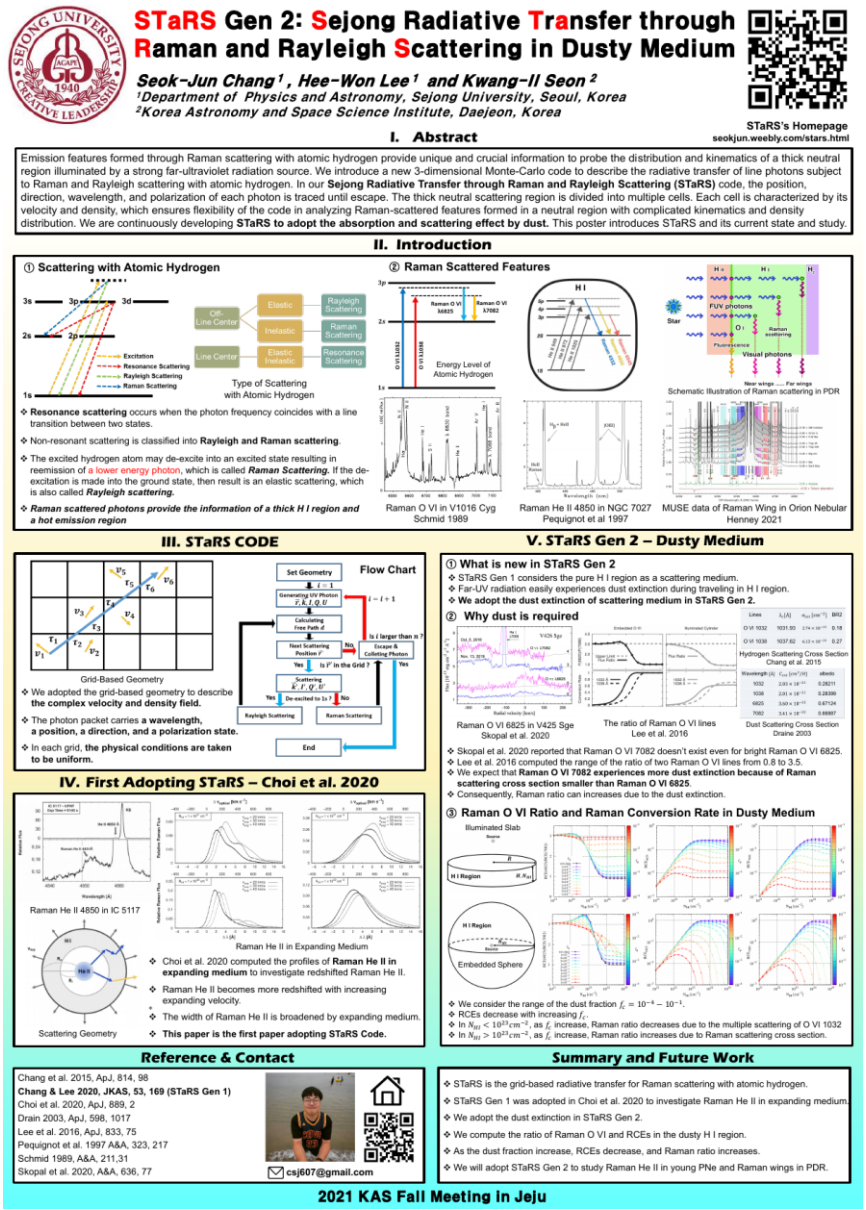
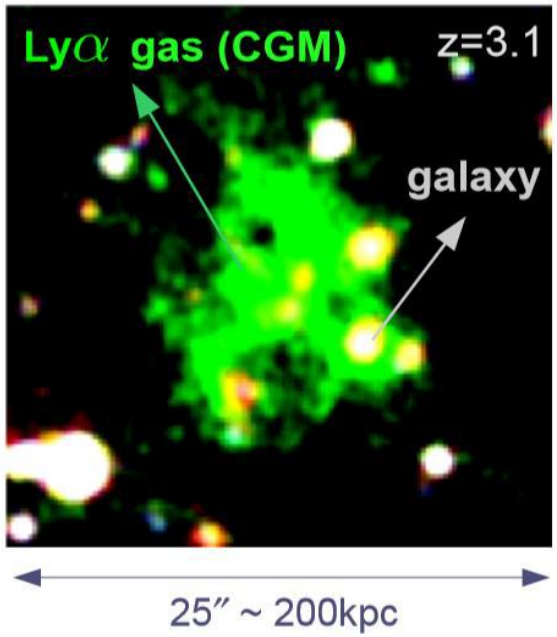


Sejong Radiative Transfer through Rayleigh and Raman Scattering

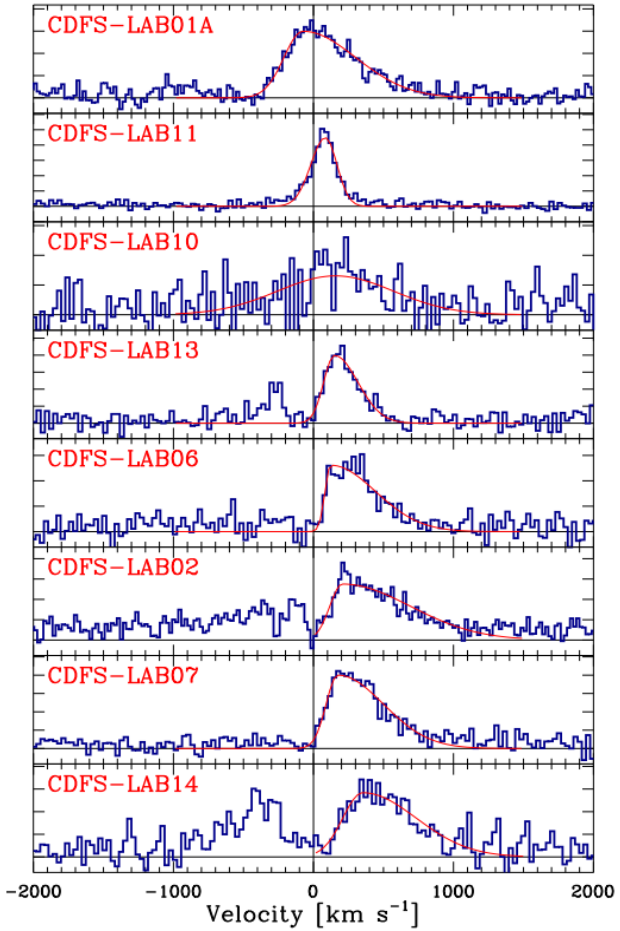
Chang et al. 2020, JKAS, 53, 169C

Lyα Radiative Transfer for Lyα Blobs

Lyα Blob



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

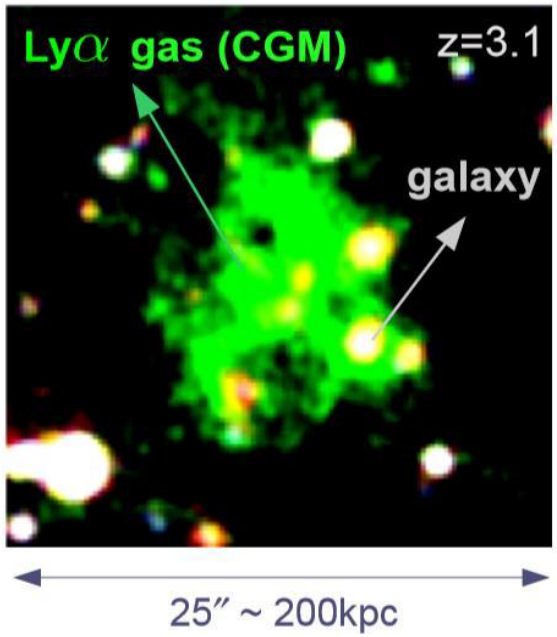


Lyα spectra of LAB
(Yang et al. 2014)

- High redshift z > 2
- Spatially Extended > 100 kpc
- Luminous Lyα 10^{43-44} erg/s
- Over-Dense Region
- Proto Galaxy Cluster
- Circumgalactic Medium in LAB →

  Intercluster Medium in Galaxy cluster

Lyα Blob



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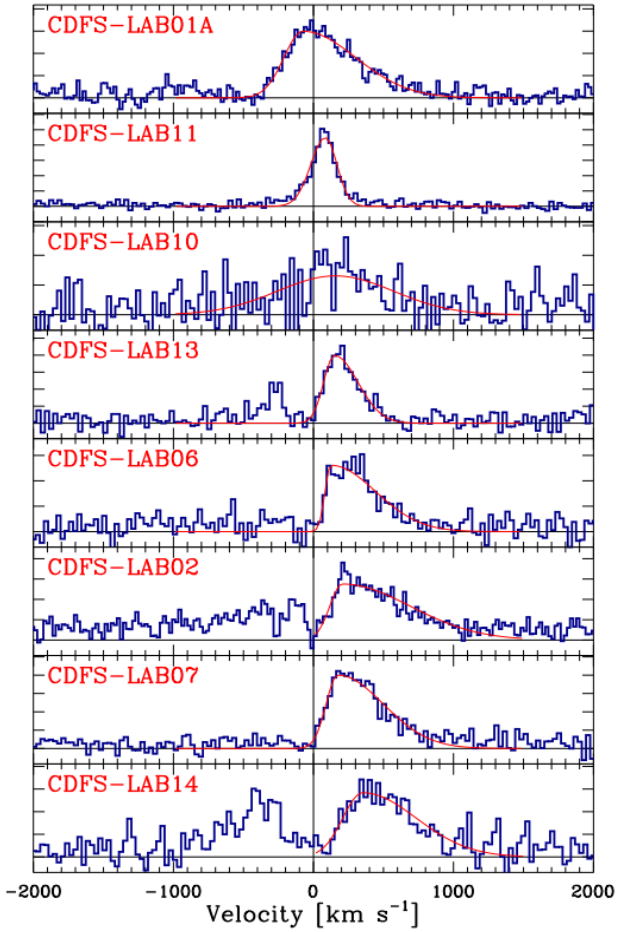
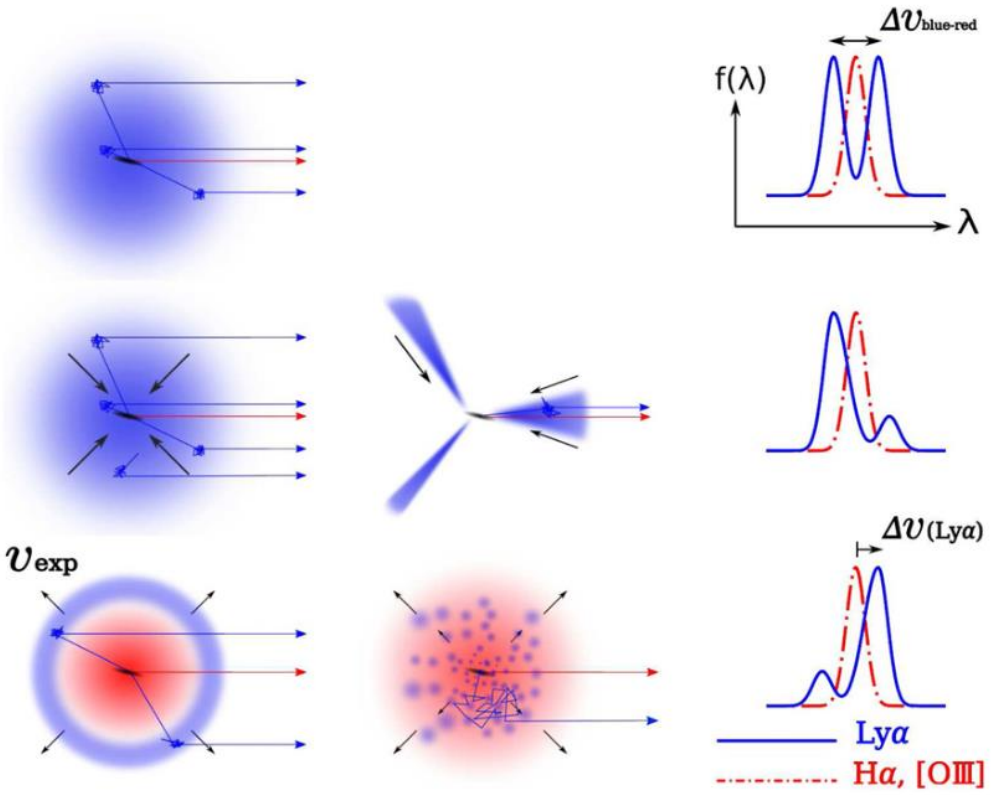
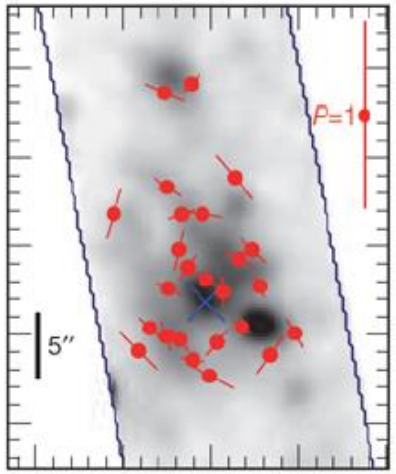


Lyα spectra of LAB
(Yang et al. 2014A)



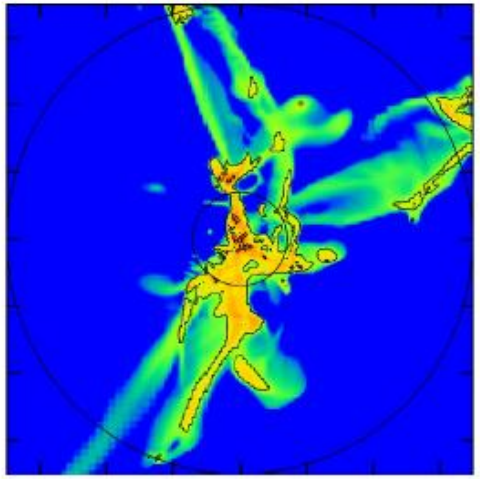
Lyα spectra by Gas kinematics
(Yang et al. 2014B)

Lyα Emission Mechanism

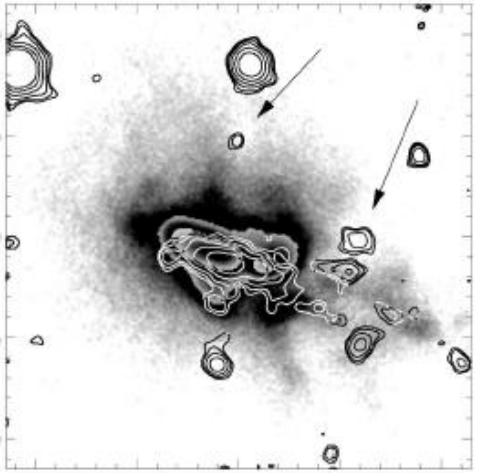


Resonant scattering
Polarization map
(Hayes+11)

Superwind
(Galactic wind in M82)



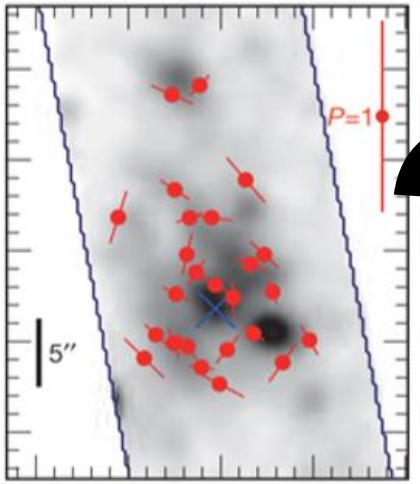
Cold accretion
(Goerdt+10)



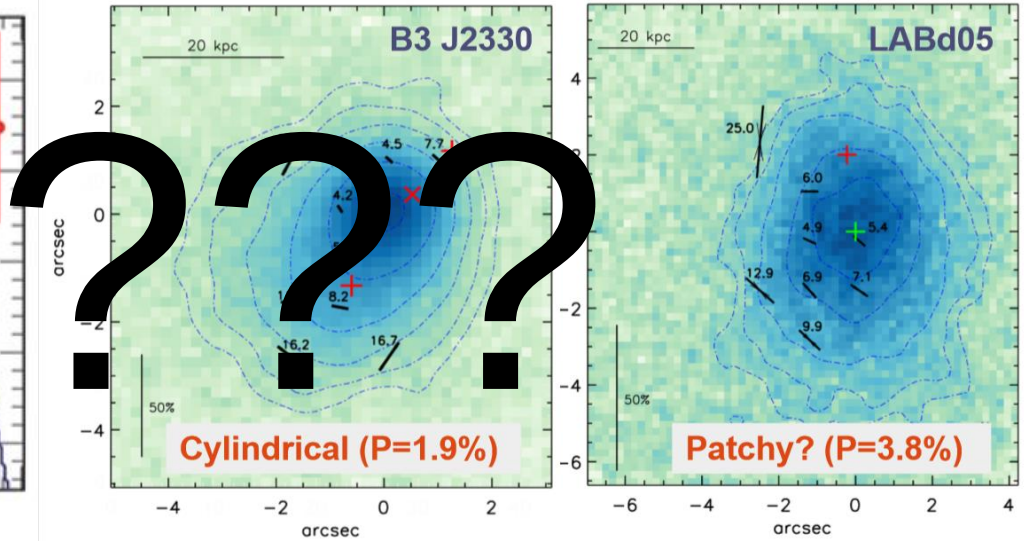
Radio galaxy, AGN
(Reuland+03)

- Shock from Super Wind
- Cold Accretion by Massive Dark Matter Halo
- Photoionization by the source
- Star Formation
- **Scattering with Atomic Hydrogen**

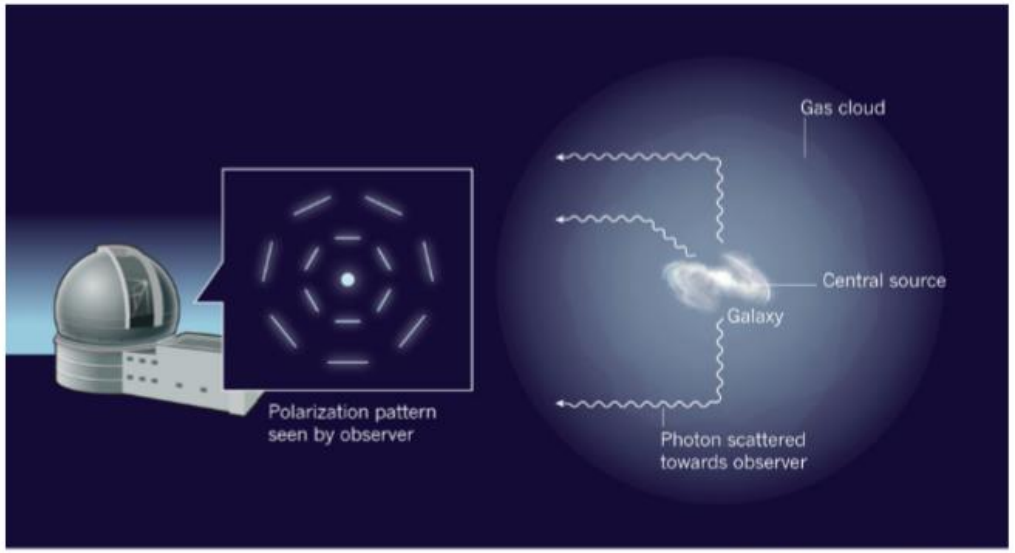
Polarization of Lyα Blob



SSA22-LAB1
(Hayes et al. 2011)



You et al 2017 Kim et al 2020

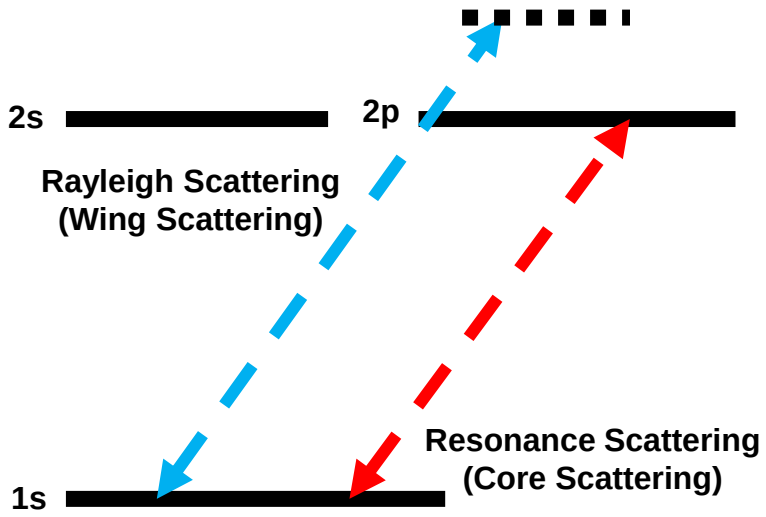


(R. Bower 2010)

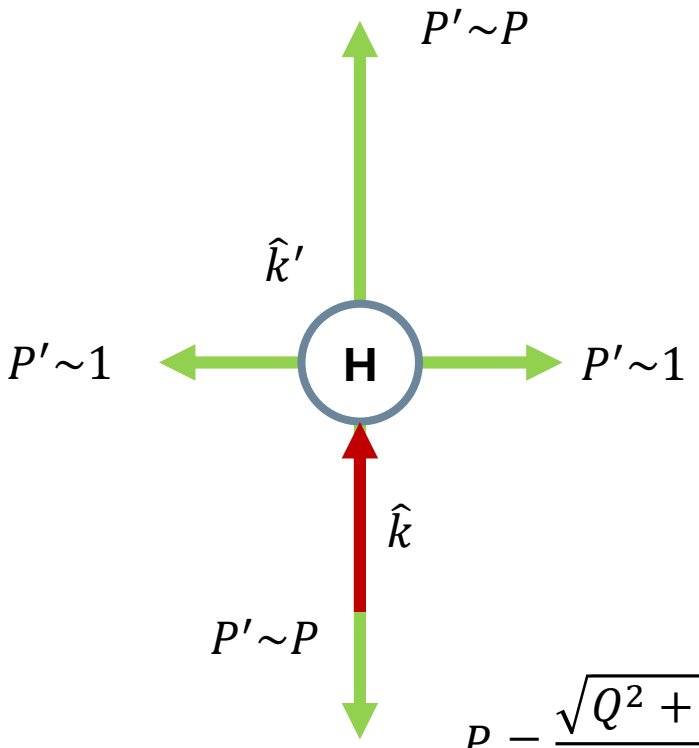
- Lyα emission photons are unpolarized.
- Scattering with Atomic hydrogen → linear polarization

- 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)

Polarization by Scattering



	Resonance	Rayleigh
Transition	1s-2p (line center)	1s- near 2p (off center)
Phase Function	Isotropic	Dipole Transition
Polarization	Un-polarized	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° scattering).

Lyα Radiative Transfer

1990

Neufeld 1990, 1991 – Analytic Solution

Ahn & Lee 1998, 2002 – First Numerical Method for polarization of scattered Lyα, No spatial distribution

2000

Zheng & Miralda-Escude 2002 – Spectrum & surface brightness

Verhamm et al. 2006 – Spectrum in dusty medium

Dijkstra & Loeb 2008 – Spatial distribution of Polarization, Only Rayleigh scattering

2010 - current

Gronke et al. 2016, 2017 – Spectrum in clumpy medium

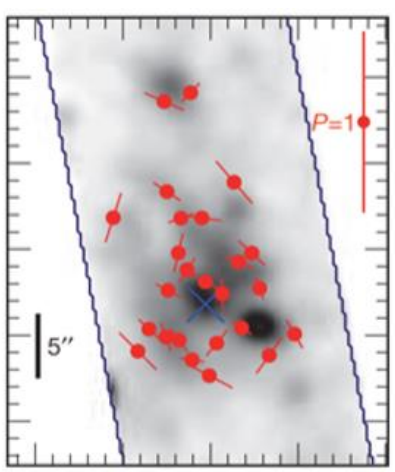
Chang et al. 2017 – Polarized Lyα in AGN unification model

Eide et al. 2018 – Polarization of Lyα for LAE, Small physical scale

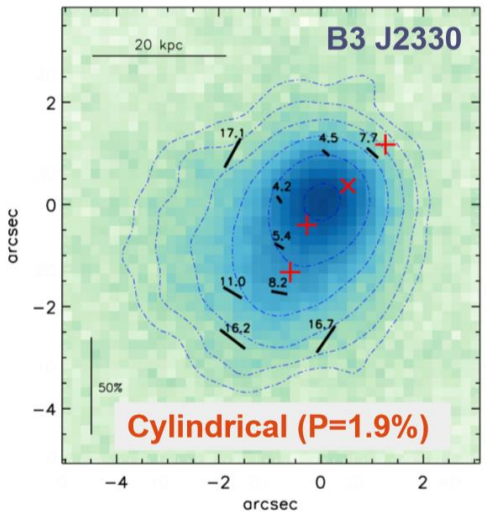
Seon & Kim 2020 – WF effect with hyper-find structure

Seon et al. in prep – Polarization adopting Stokes parameter, Narrow emission line width

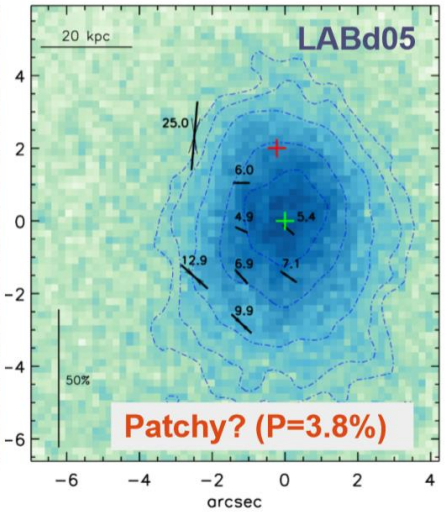
Radiative Transfer for LAB



SSA22-LAB1
(Hayes et al. 2011)



You et al 2017



Kim et al 2020

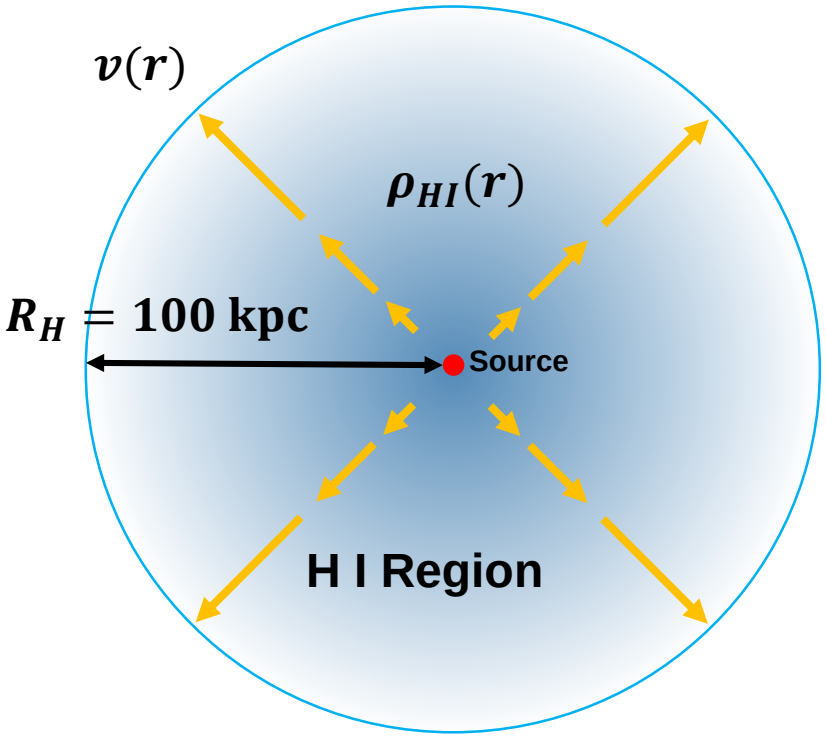
Can the Lyα point source become LAB through only scattering by an atomic hydrogen in H I halo ?

Essential Components for LAB

- Polarization behavior
  by core and wing scattering
- Large scale halo ~ 100 kpc
- Broad Lyα emission
- Kinematics of scattering medium

Lyα Radiative Transfer for Lyα Blobs, Chang et al. prep

Scattered-Only Lyα in Spherical H I halo



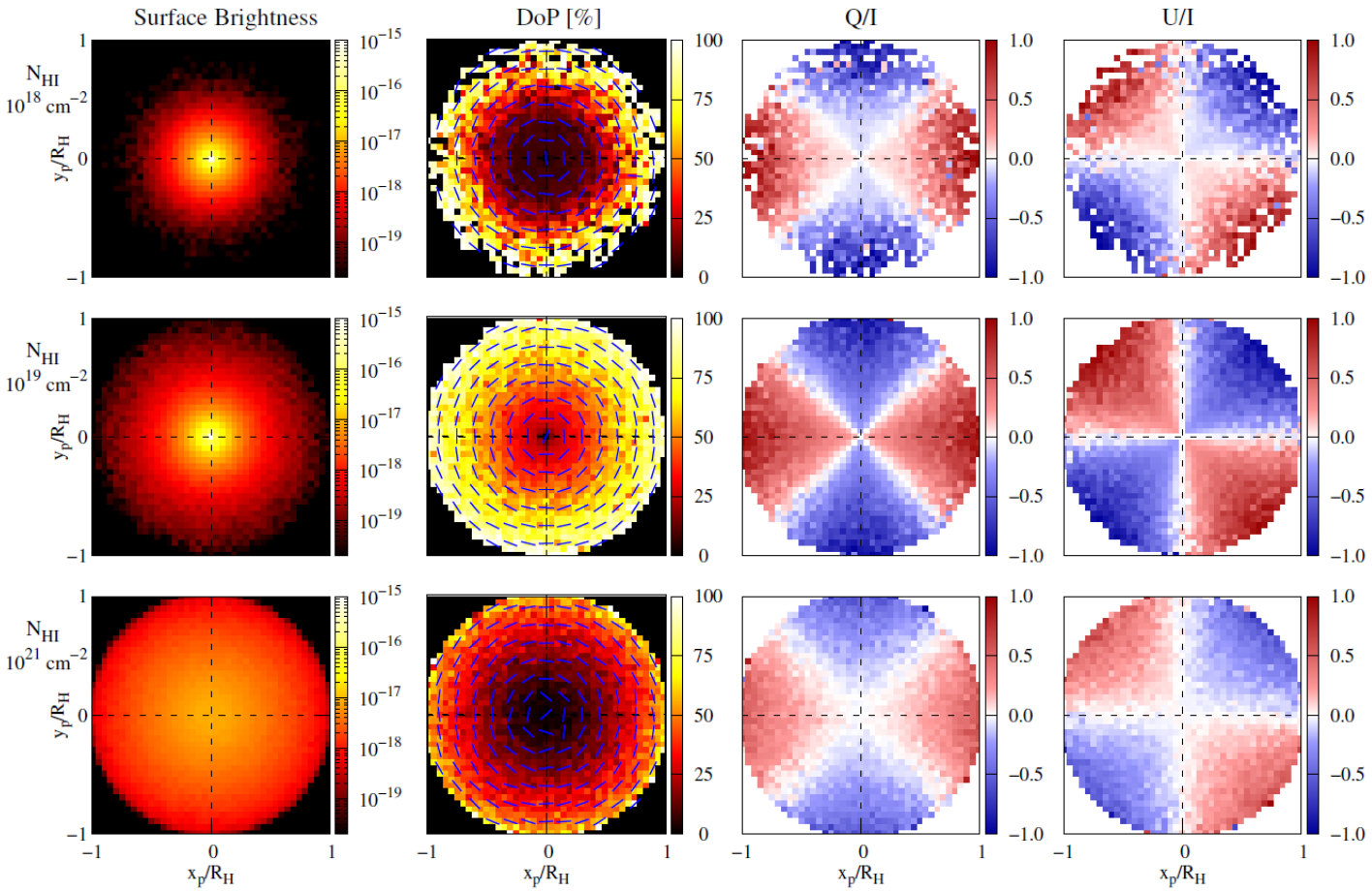
$$v(r) = v_{exp}\frac{r}{R_H} \qquad N_{HI} = \int^{R_H} \rho_{HI}(r)\,dr \qquad \rho_{HI}(r) = n_0 e^{r/R_e}$$

Parameter	Range	Note
$N_{\rm HI}$	$10^{18-21}\,{\rm cm}^{-2}$	H I column density
R_e	$0.1R_H - R_H, \infty$	Effective radius
$v_{\rm exp}$	$0 - 400\,{\rm km\,s}^{-1}$	Expanding velocity
$\sigma_{\rm src}$	$100 - 400\,{\rm km\,s}^{-1}$	Lyα source width

$z = 3$ (7.855 kpc/”) $\quad L_{Ly\alpha} = 10^{44} erg/s$

- We develop the simulation to study scattered-only Lyα.
- The simulation is based on LaRT (Seon & Kim 2020, Seon et al. prep).
- We consider H I spherical halo with $R_H = 100$ kpc surrounding Lyα point source.
- The width of Lyα emission from the source is 100 – 400 km/s.

Lyα Projected Image



$N_{HI} = 10^{18} cm^{-2}$

$N_{HI} = 10^{19} cm^{-2}$

$N_{HI} = 10^{21} cm^{-2}$

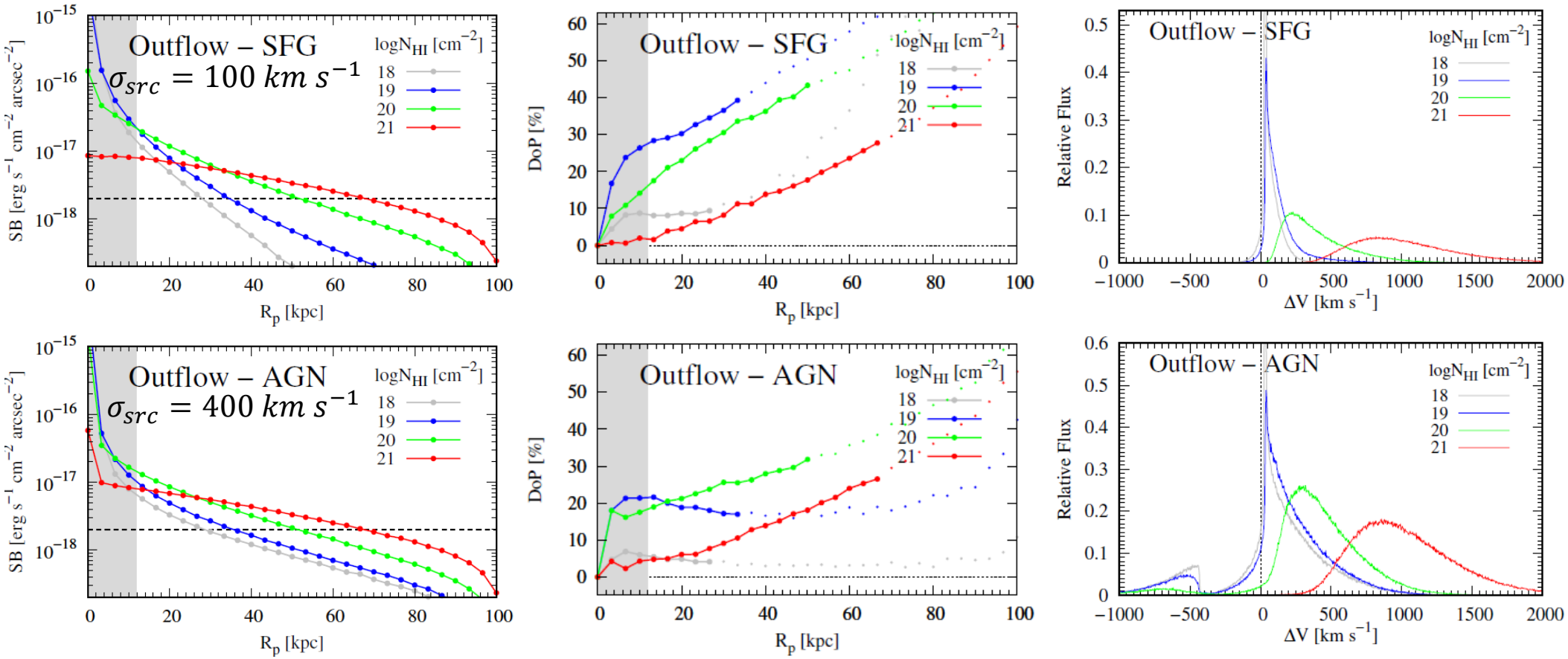
$N_{HI} \uparrow$

- 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.

Lyα Radiative Transfer for Lyα Blobs, Chang et al. prep

Dependence on N_{HI}

Surface brightness | **Degree of polarization** | **Spectrum**



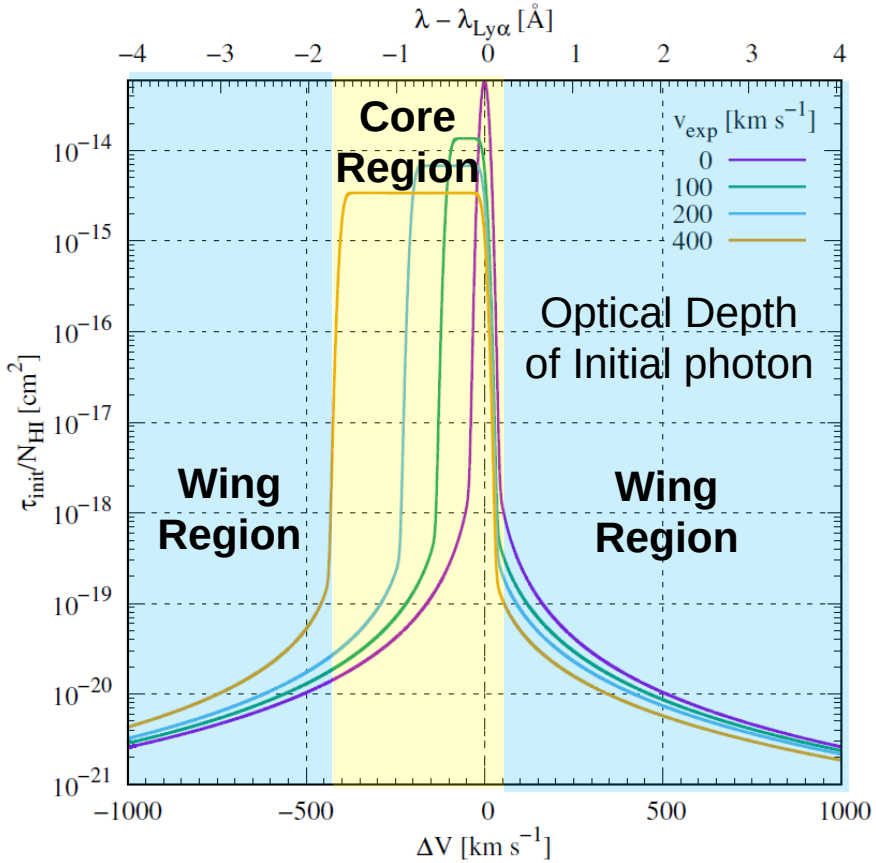
SB is more extended

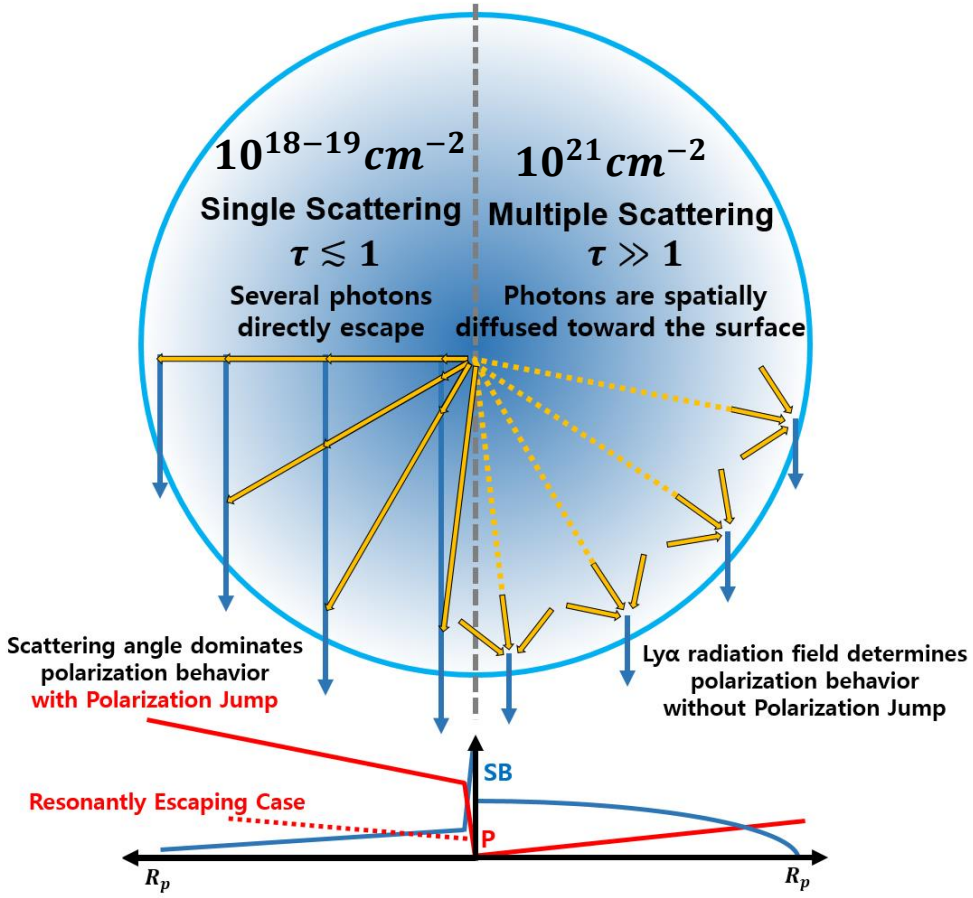
$N_{HI} \uparrow \rightarrow$ **Complex polarization behavior**

Spectrum is more broadened

Lyα Radiative Transfer for Lyα Blobs, Chang et al. prep

Single and Multiple Scattering

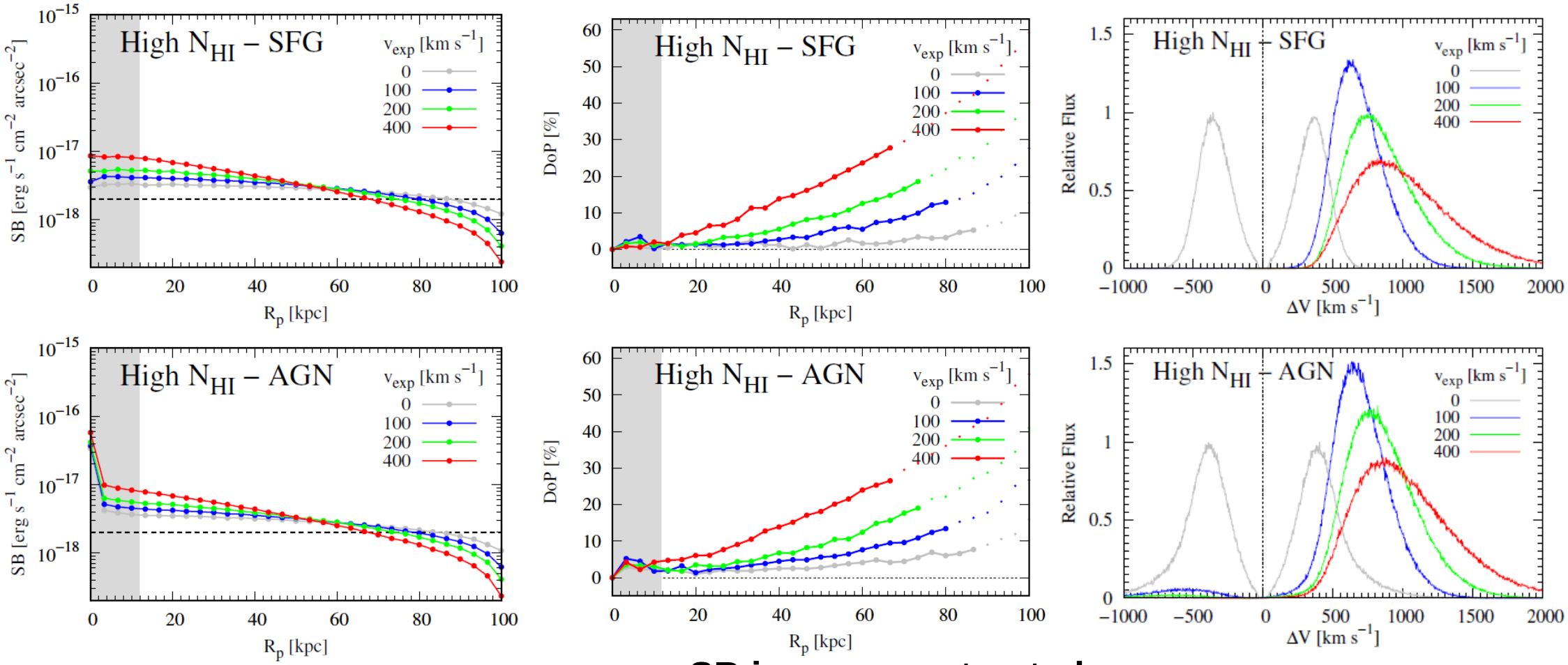




- At $N_{HI} = 10^{18-19} cm^{-2}$, the photon easily escape through several wing scattering.
- At $N_{HI} = 10^{18} cm^{-2}$, the degree of polarization decrease due to resonance scattering.
- At $N_{HI} = 10^{21} cm^{-2}$, the photon must go through multiple wing scattering.

Lyα Radiative Transfer for Lyα Blobs, Chang et al. prep

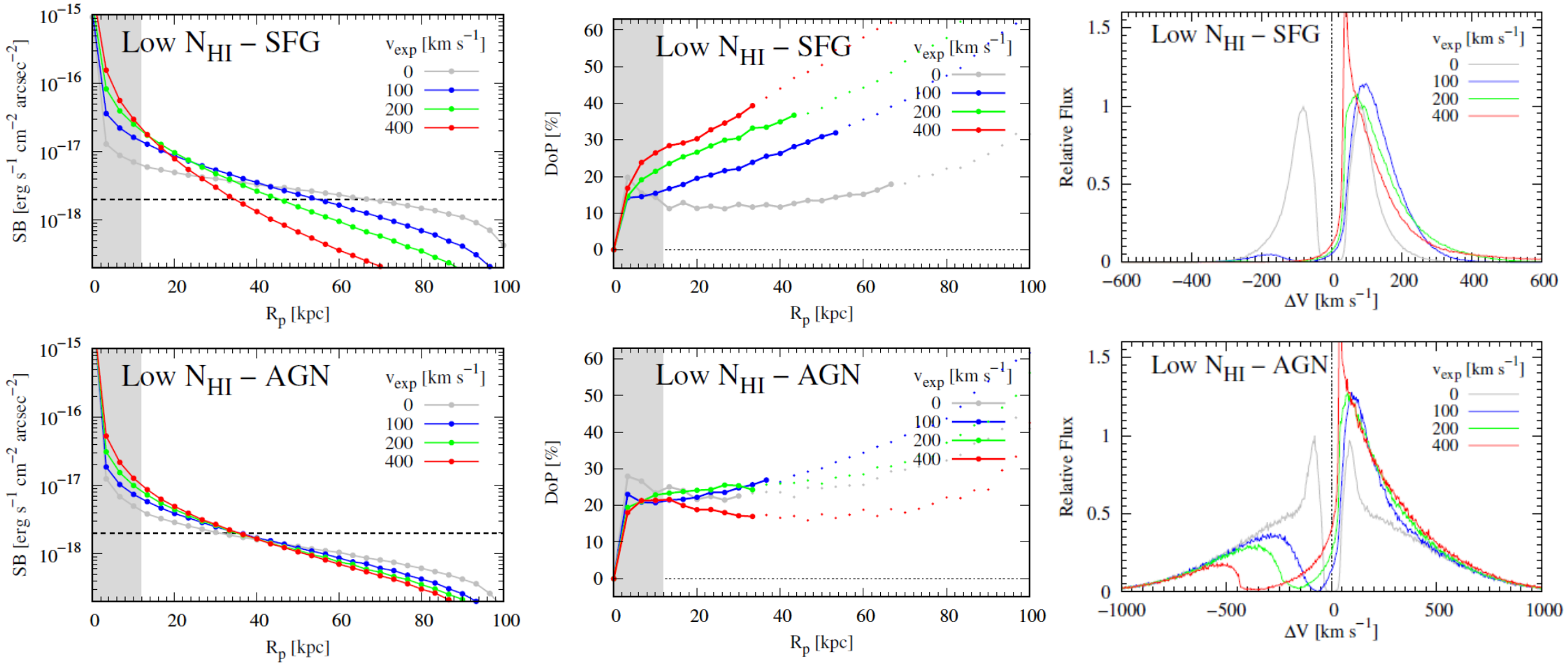
Dependence on v_{exp} in High N_{HI} $(10^{21} cm^{-2})$ Halo



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

Lyα Radiative Transfer for Lyα Blobs, Chang et al. prep

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



SB is more contracted

$v_{exp} \uparrow \rightarrow$ **Complex polarization behavior in AGN case**

Spectral peak is slightly more closed to the line center.

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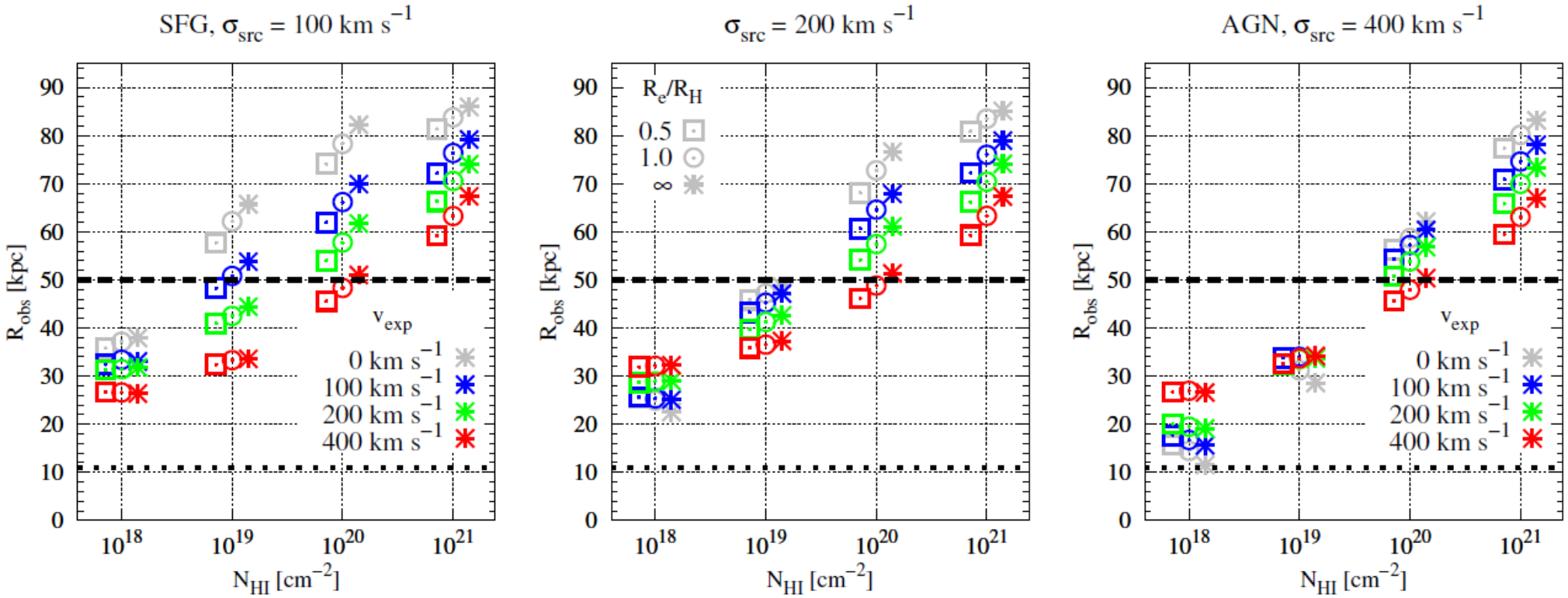
Size of Lyα Halo



$$N_{HI} \uparrow \rightarrow R_{obs} \uparrow$$

$$v_{exp} \uparrow \rightarrow R_{obs} \downarrow$$

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

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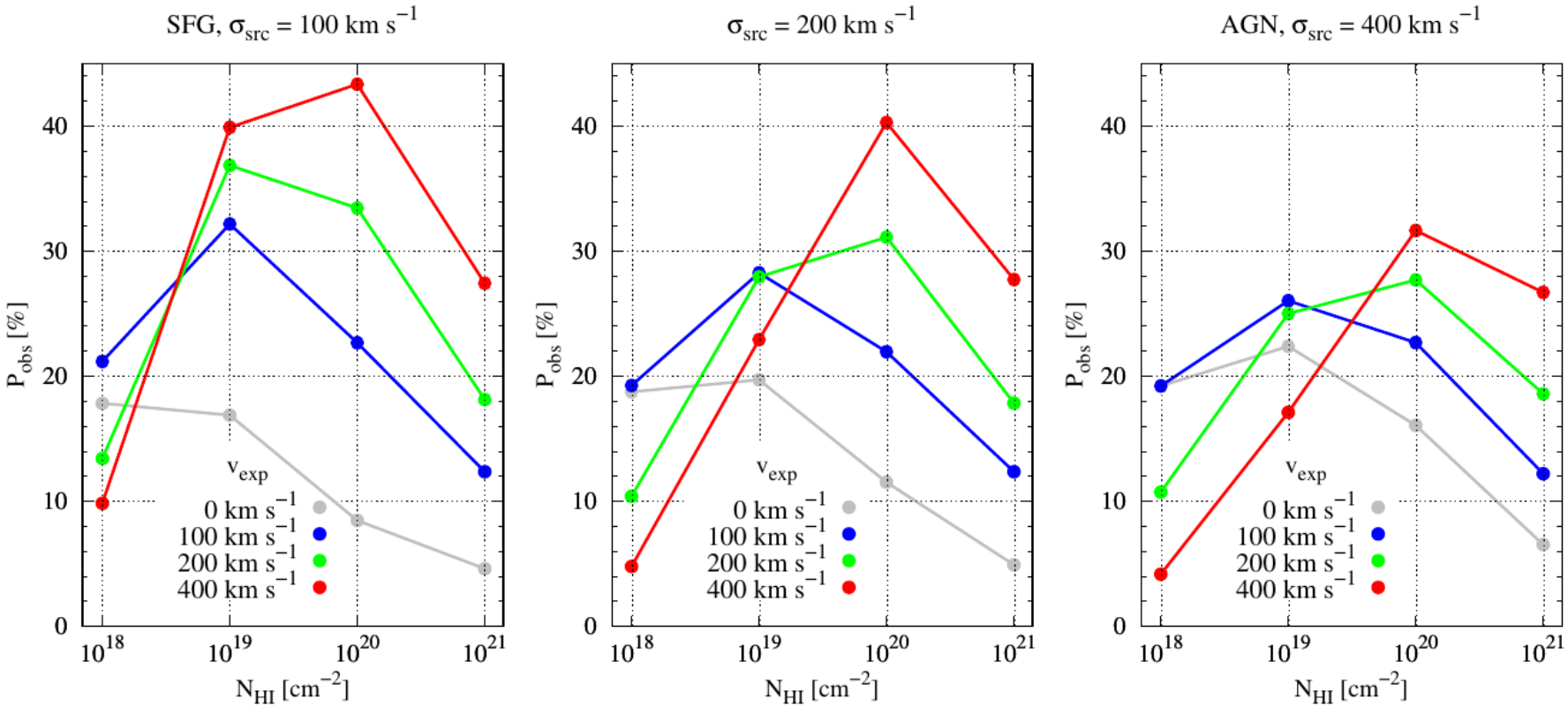
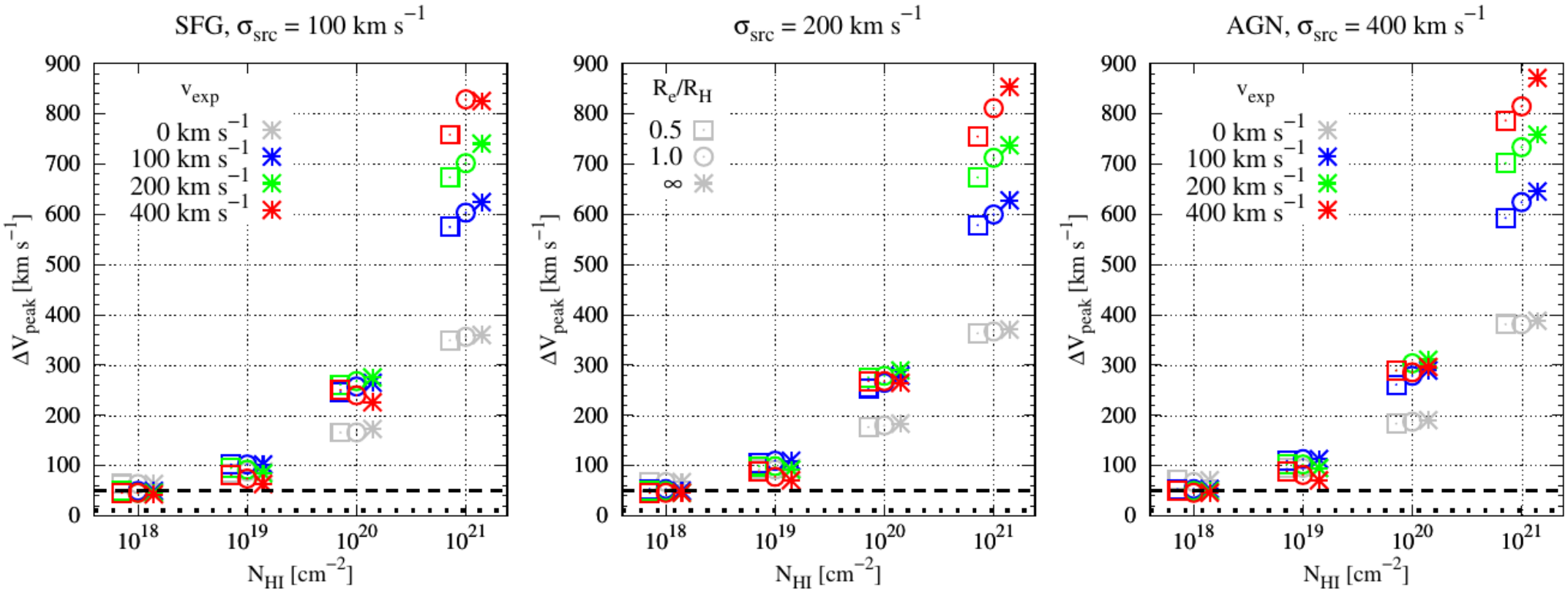
Polarization at R_{obs}



- When the polarization is maximum, the effect of the single wing scattering is strongest.
- At $N_{HI} = 10^{18}\ cm^{-2}$, the polarization decrease with increasing $v_{\exp}$.
- At $N_{HI} = 10^{21}\ cm^{-2}$, the polarization behavior does not depend on σ_{src}.

Spectral Peak at ΔV_{peak}



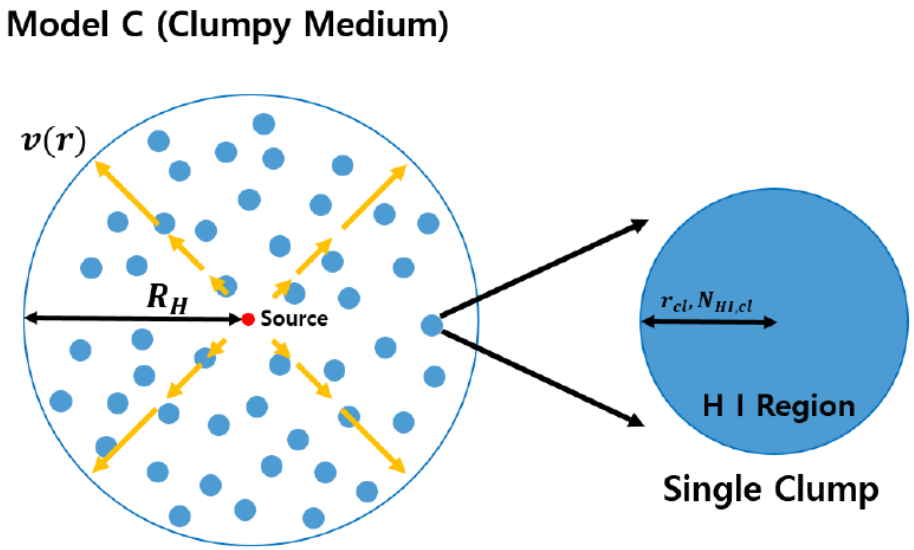
- $\Delta \boldsymbol{V_{peak}}$ does not depend on v_{exp} in $\mathrm{N_{HI}} < 10^{20}\ cm^{-2}$.
- $\Delta \boldsymbol{V_{peak}}$ does not depend on σ_{src}.
- The multiple wing scattering causes the variation of $\Delta \boldsymbol{V_{peak}}$ as v_{exp} increases.

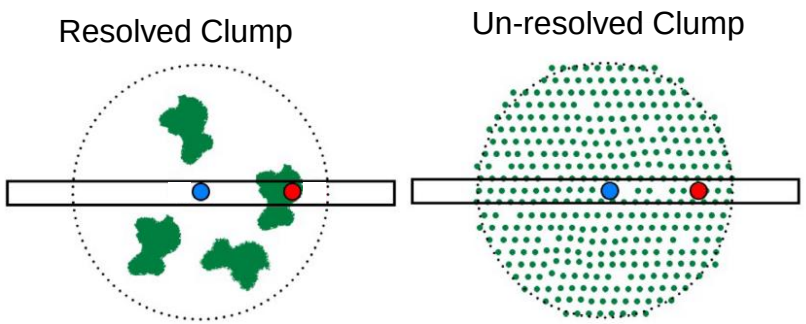
Summary

- In this work, the simulation for Lyα radiative transfer is based on LaRT.
- We test that scattered-only Lyα becomes LAB in spherical H I halo.
- The surface brightness profiles become more extended with increasing N_{HI} and v_{exp}.
- The polarization pattern is always concentric because of spherical scattering region.
- The degree of polarization is not monotonic due to resonance scattering in low N_{HI} regime.
- When $N_{HI} \geq 10^{20} cm^{-2}$, Lyα halo is extended over 100 kpc.

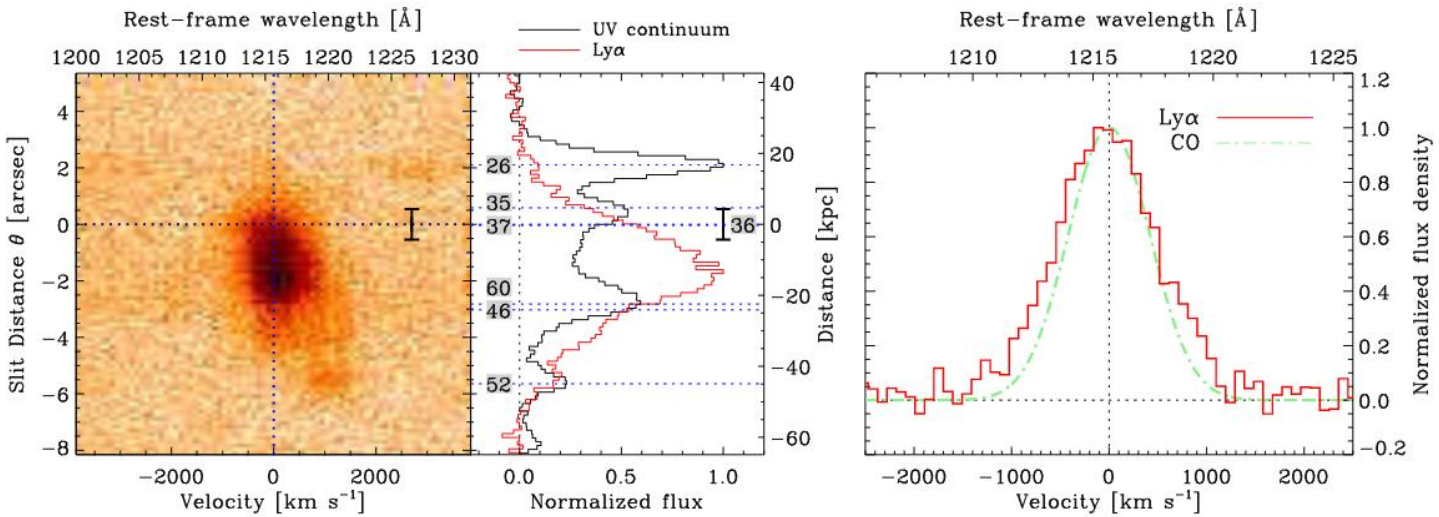
Future Work

Lyα Radiative Transfer in Clumpy Medium

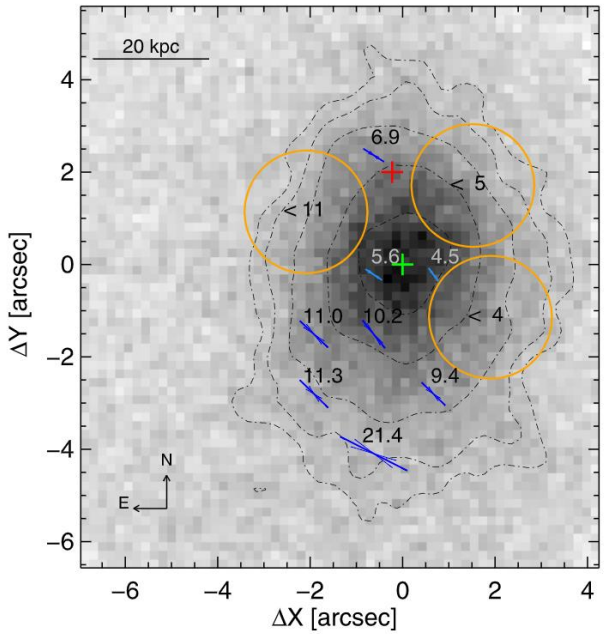




Schematic Illustration
Hennawi & Prochaskhar 2013



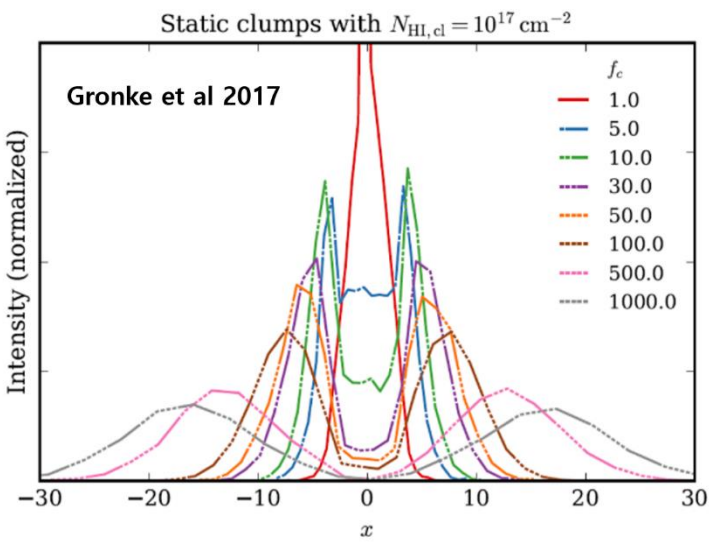
Lya Spectrum of LABd05, Yang et al. 2014

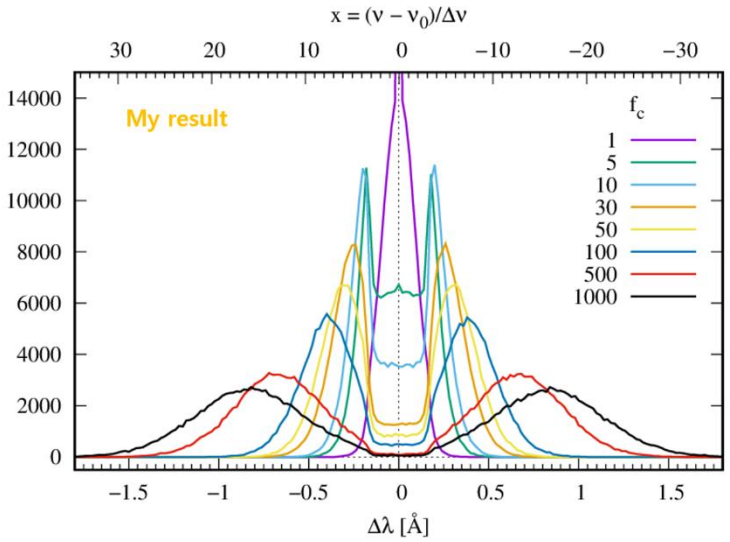


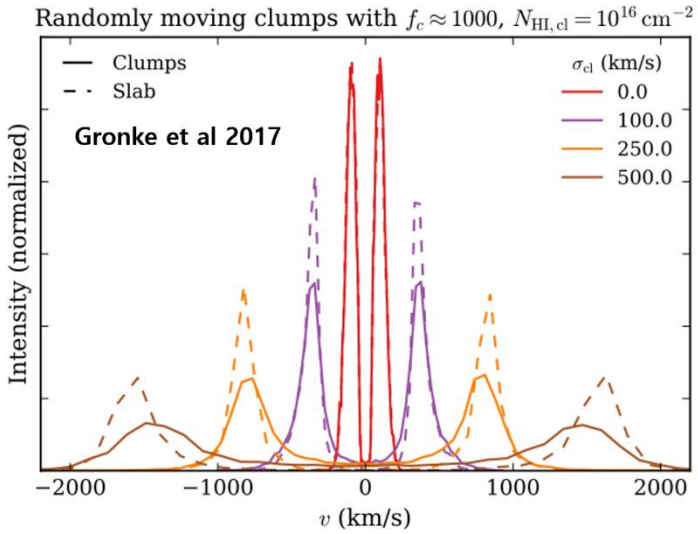
Lya Polarimetry of LABd05, Kim et al. 2020

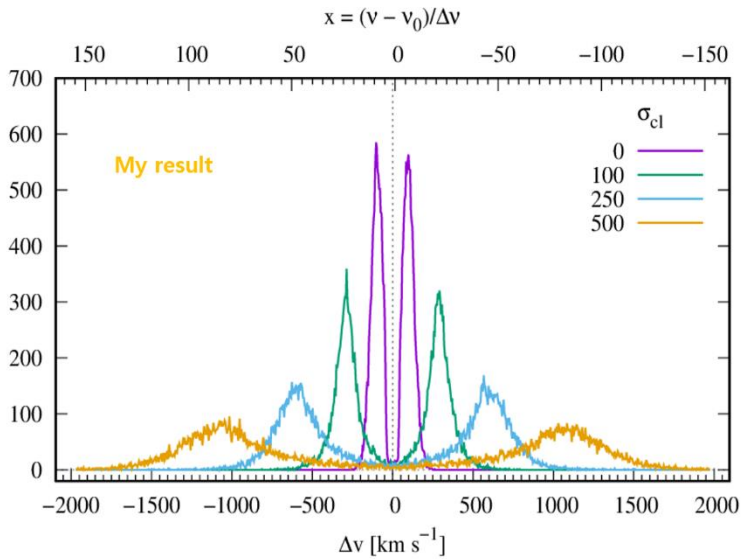
Clumpy Medium

- Gronke et al. 2017 studied the Lya spectrum profile in clumpy medium.
- They find that Lya spectrum in a clumpy medium becomes similar to the spectra of a continuous medium.
- We revisits the results in Gronke et al. 2017 using our simulation.









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Thanks