Mg II & Lyα Radiative Transfer in the Cold CGM

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If you are interested in my talk,
feel free to contact me :D

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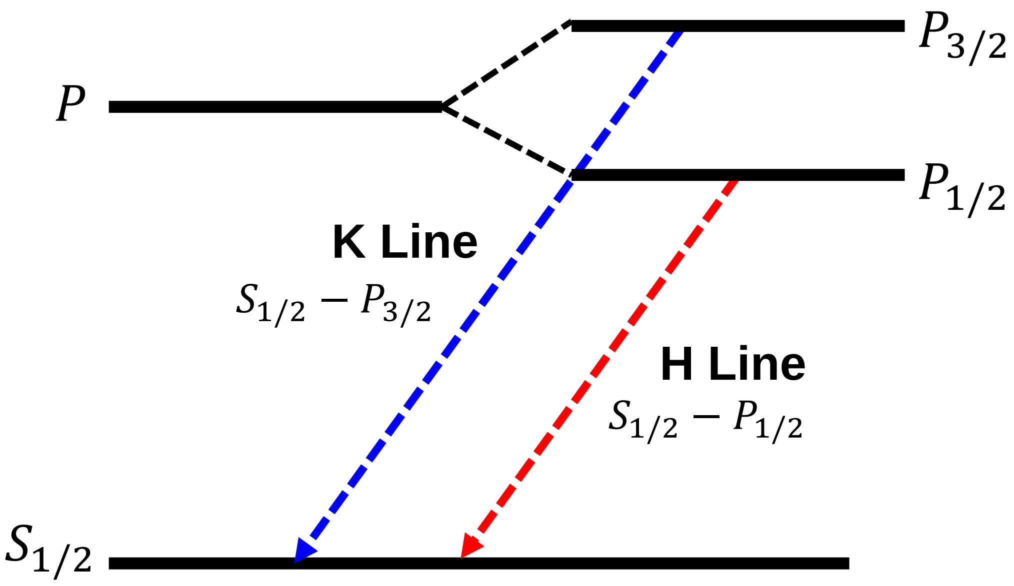
All simulated results in this presentation
are made by own my RT simulation.

The Multiphase CGM in Ringberg Castle

All simulated results in this presentation are made by own my RT simulation.

If you want to analyze observational data of resonance lines considering RT effect or adopt RT simulation in the hydrosimulation, please let me know.
I'm happy to discuss it with you!

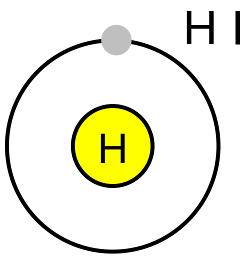
Resonance Doublets



Energy Level of Atom

Resonance doublets represent $S - P$ transitions in the atom having **one electron in the outer orbit.**

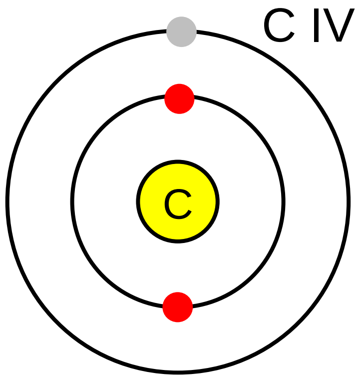
The doubles easily interact with the atom emitting the themselves.



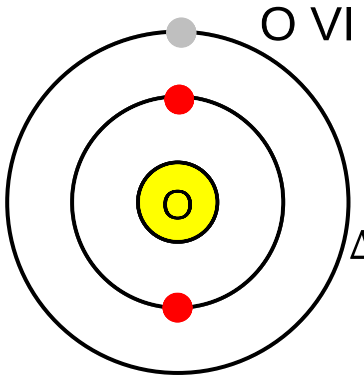
$1s - 2p$ transition $T \sim 10^4$ K

$\lambda_K \sim 1215.668$ Å
$\lambda_H \sim 1215.674$ Å
$\Delta V_{sep} \sim 1.5$ km s^{-2}

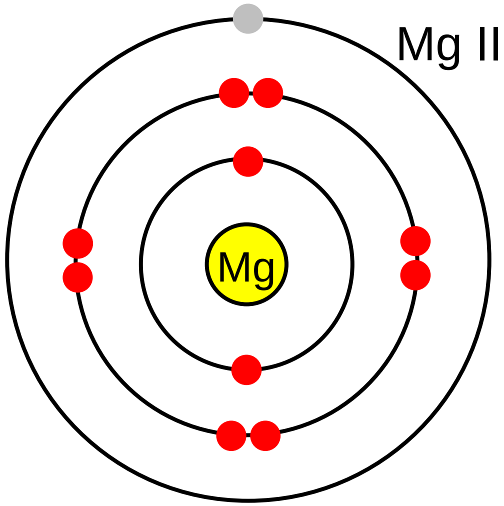
$2s - 2p$ transition $T > 10^5$ K



$\lambda_K \sim 1548.2$ Å
$\lambda_H \sim 1550.8$ Å
$\Delta V_{sep} \sim 500$ km s^{-2}



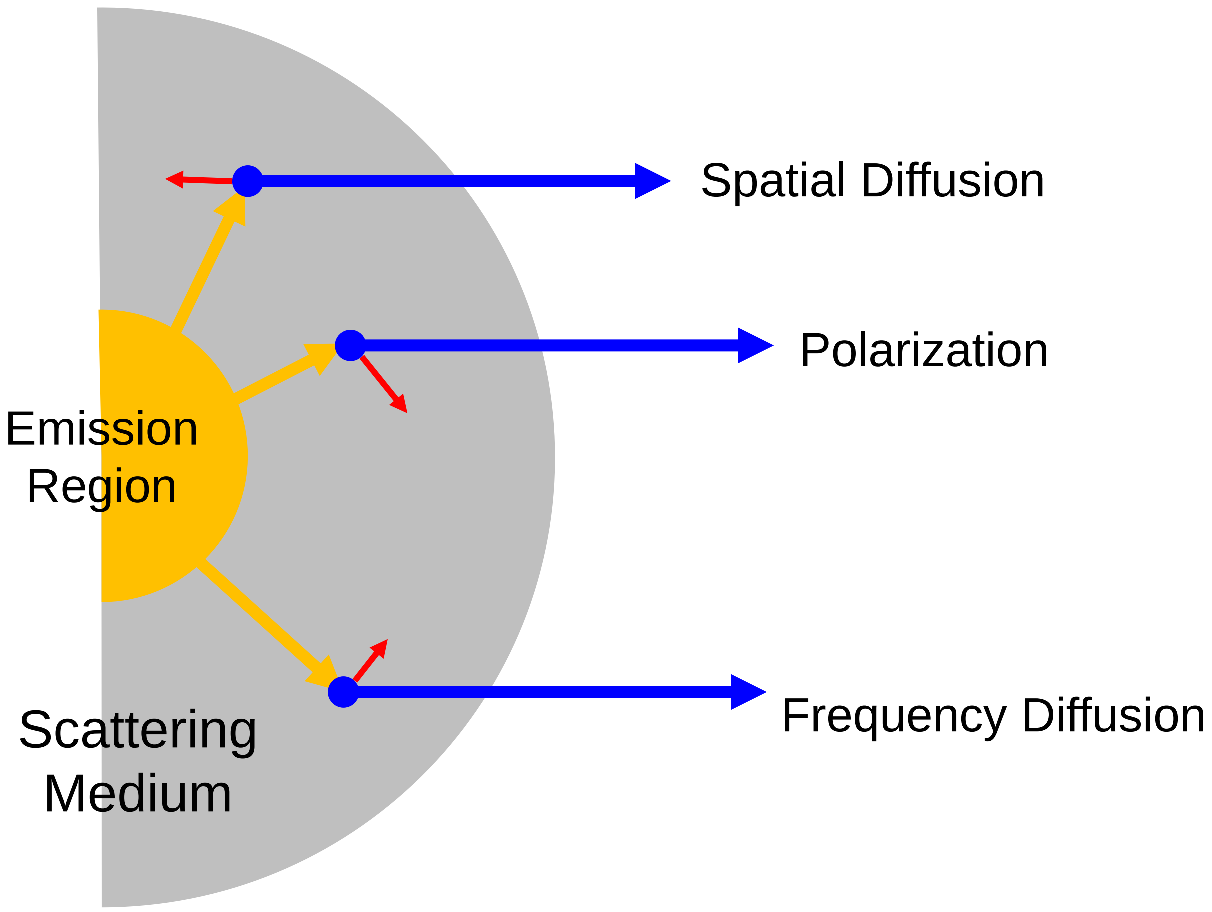
$\lambda_K \sim 1031.9$ Å
$\lambda_H \sim 1037.6$ Å
$\Delta V_{sep} \sim 1{,}600$ km s^{-2}



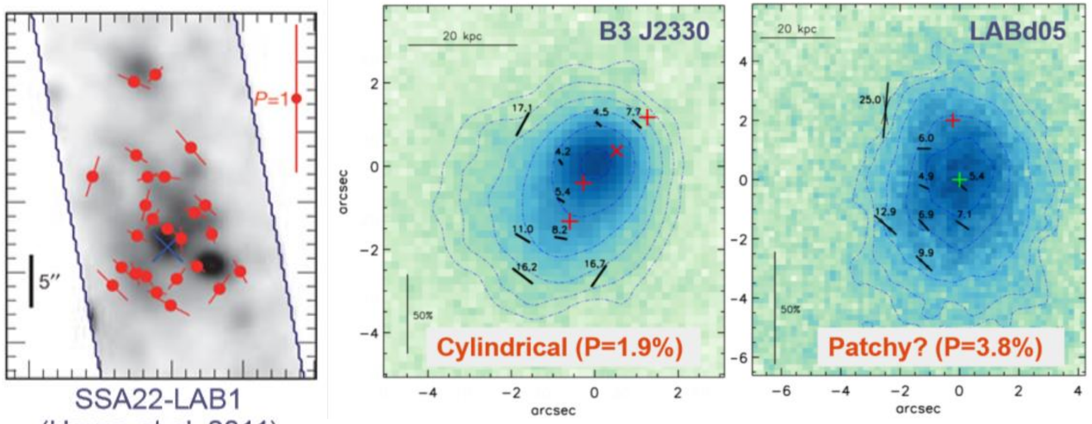
$3s - 3p$ transition $T \sim 10^4$ K

$\lambda_K \sim 2795.5$ Å
$\lambda_H \sim 2802.7$ Å
$\Delta V_{sep} \sim 750$ km s^{-2}

Lyα Scattering



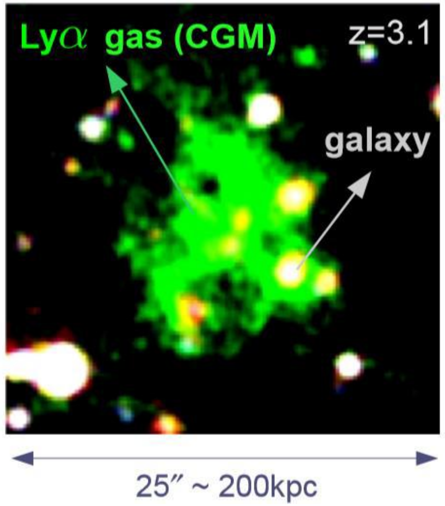
Lyα Polarimetry of LABs



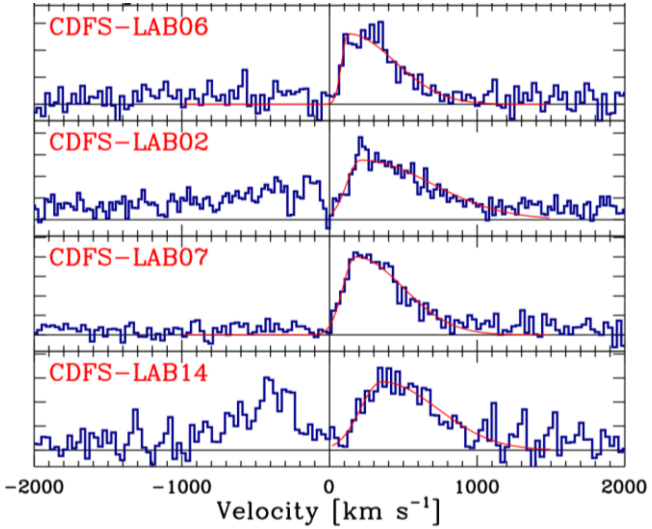
SSA22-LAB1 (Hayes et al. 2011)

You et al 2017

Kim et al 2020

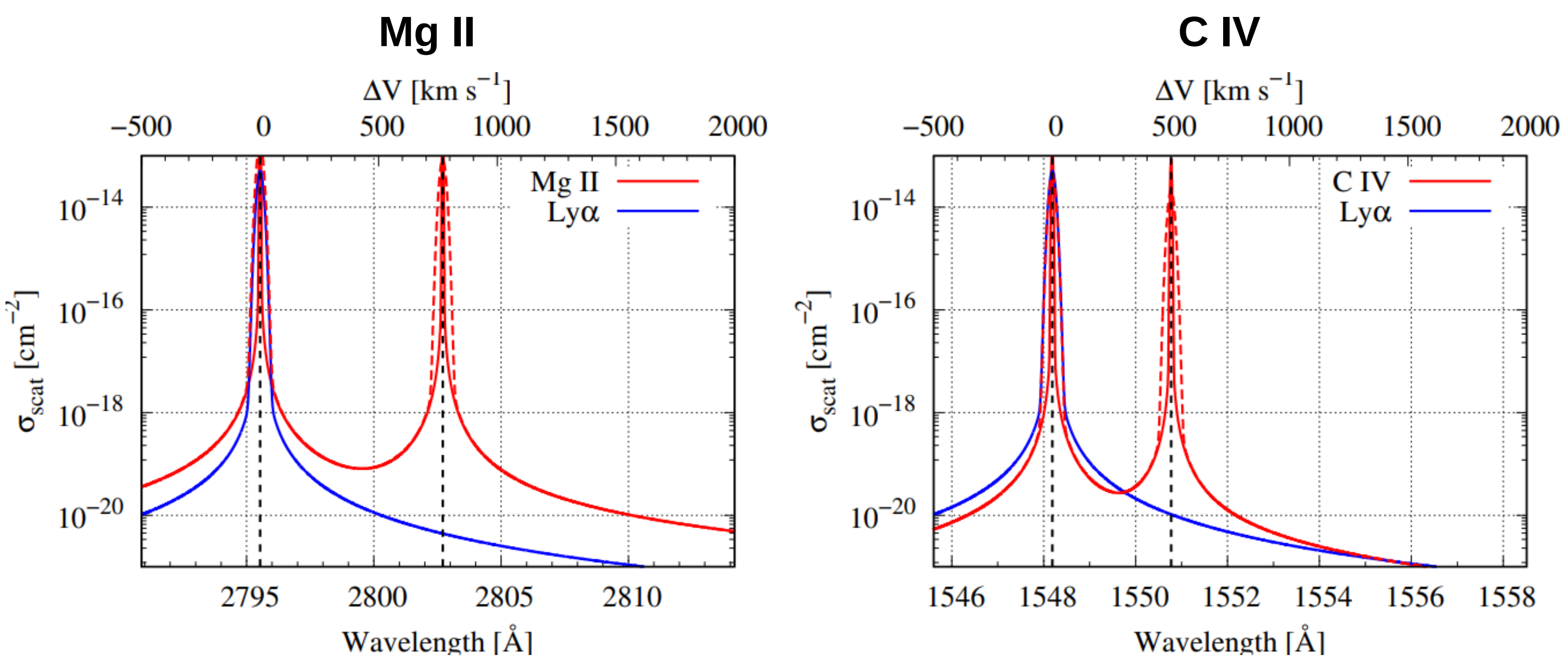


Subaru Image of SSA22-LAB1 (Matsuda et al. 2004)

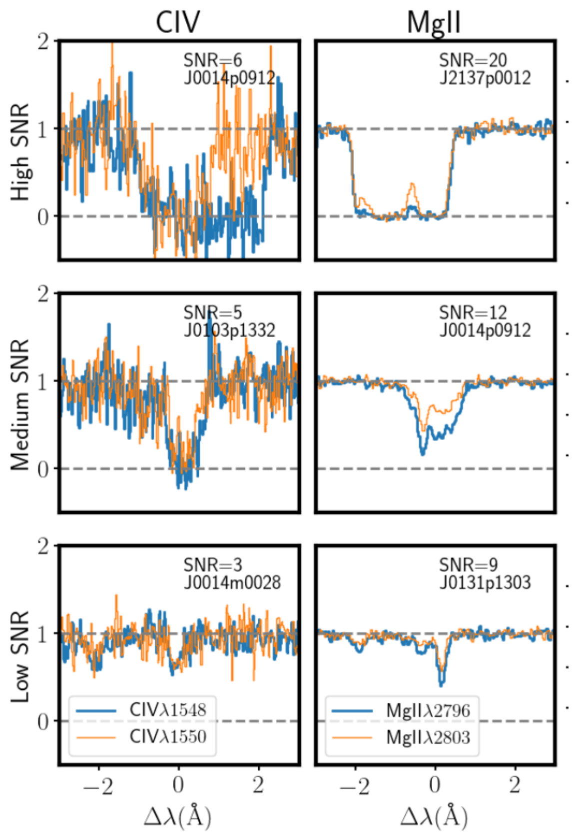


Lyα Spectra in LABs
Yang et al. 2014

Mg II and C IV doublets



Scattering cross section of Mg II, C IV and Lyα



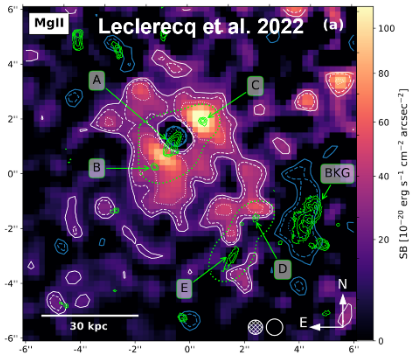
C IV and Mg II absorption in quasar spectra (MEGAFLOW)
Schroetter et al. 2021

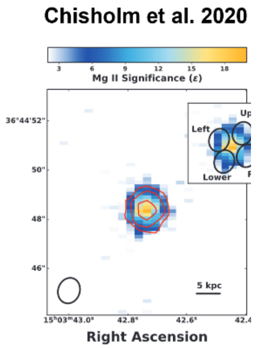
The scattering cross sections of metal doublets are comparable with that of Lyα.

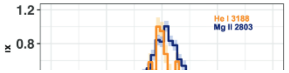
Due to the large cross section, Mg II and C IV have been mainly investigated as absorption line features.

Also, Mg II can become a tracer of cold gas in high redshift z > 6 by JWST.

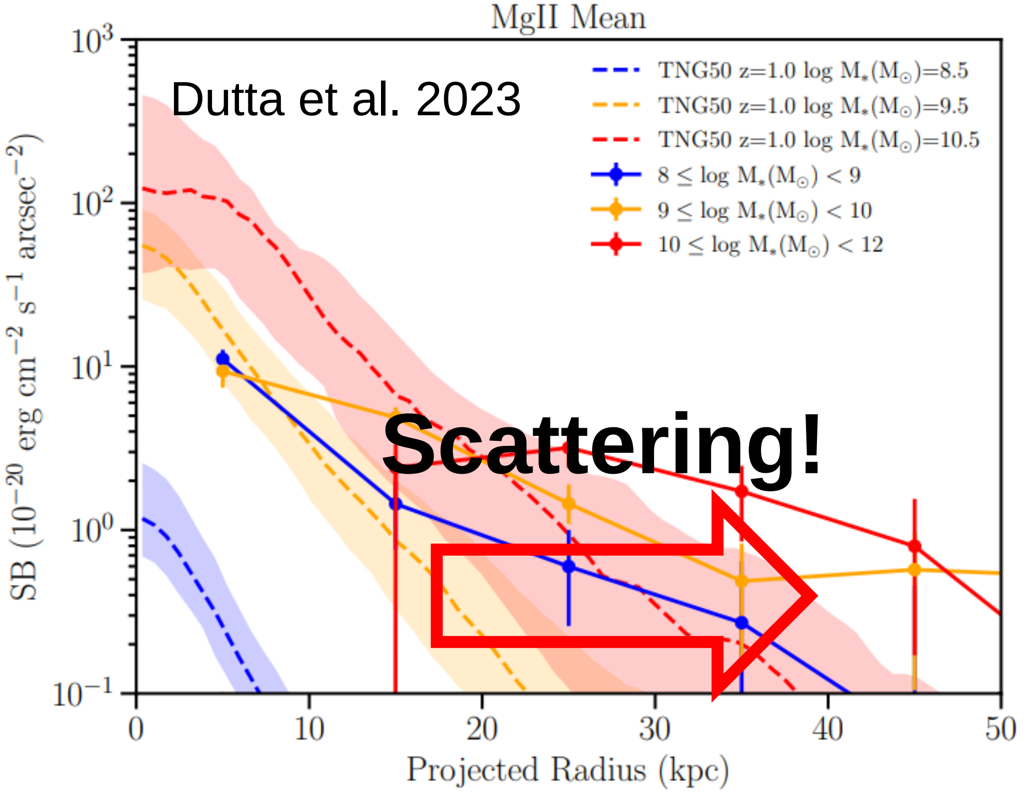
Metal Doublets Emission Nebulae

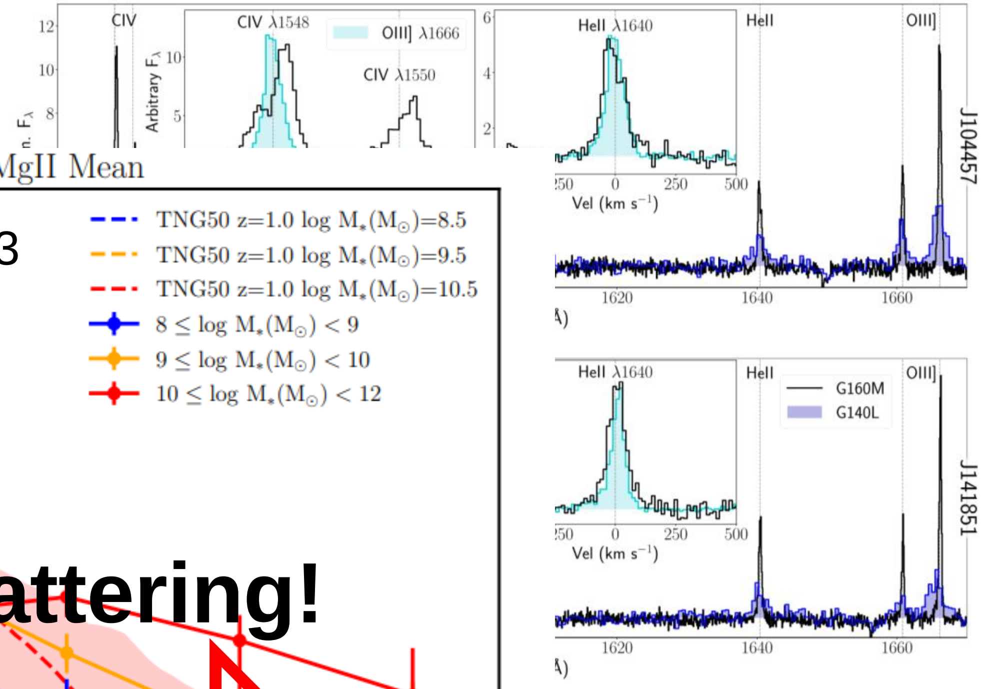






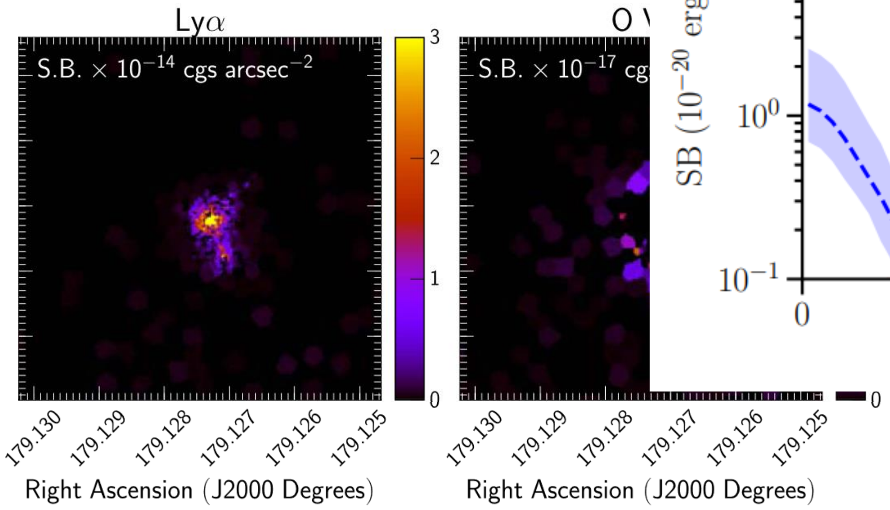
Mg II Nebulae





ission galaxies in z ~0
l. 2019

He II λ1640 are observed.

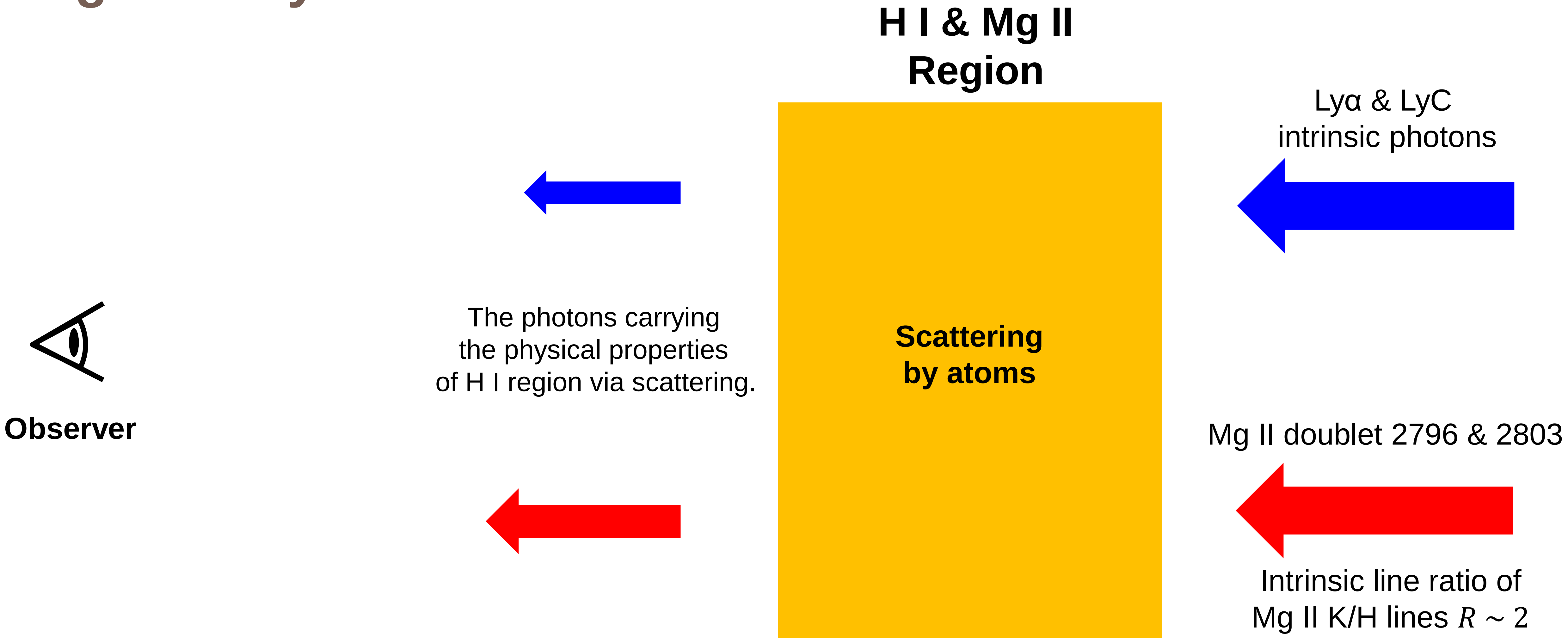


Lyα and O VI Nebula of SFG
Hayes et al. 2016

- Spatially extended Mg II & O VI nebulae are observed.

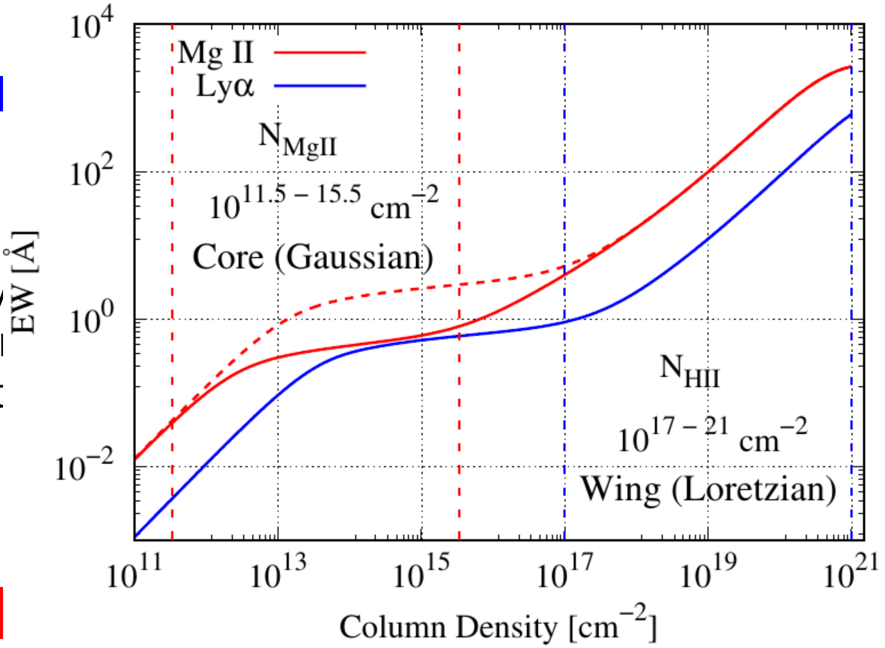
Scattering?

Mg II Study



This work try to find the correlation between Lyα and Mg II photons scattered in same H I region.

Mg II Study



H I & Mg II Region

Lyα & LyC intrinsic photons

doublet 2796 & 2803

Intrinsic line ratio of Mg II K/H lines $R \sim 2$

The photons carry the physical proper of H I region via scat

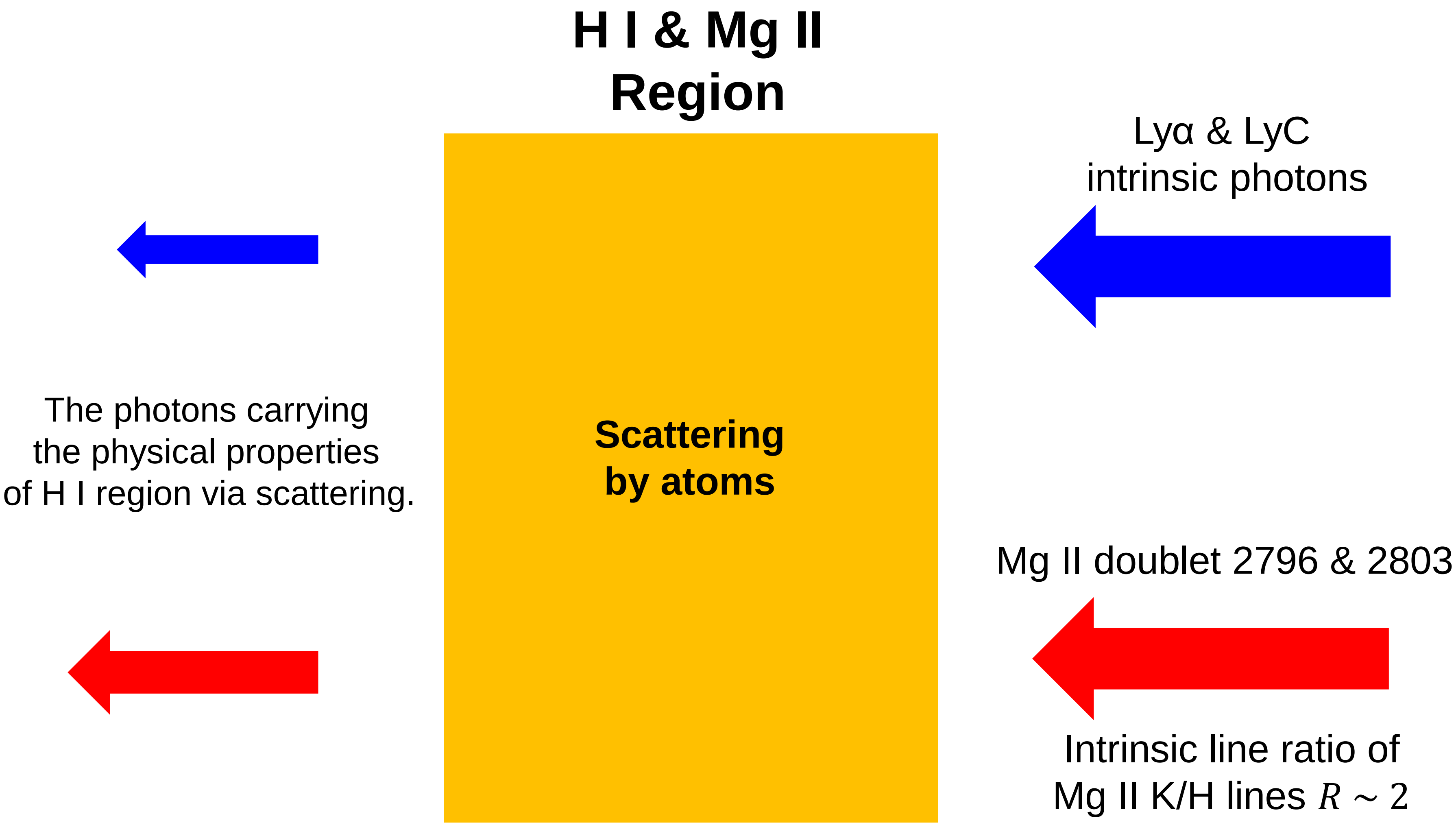
Observer

Because of small Mg fraction (~$10^{-5.5}$), Mg II and Lyα radiative transfer show different behaviors.

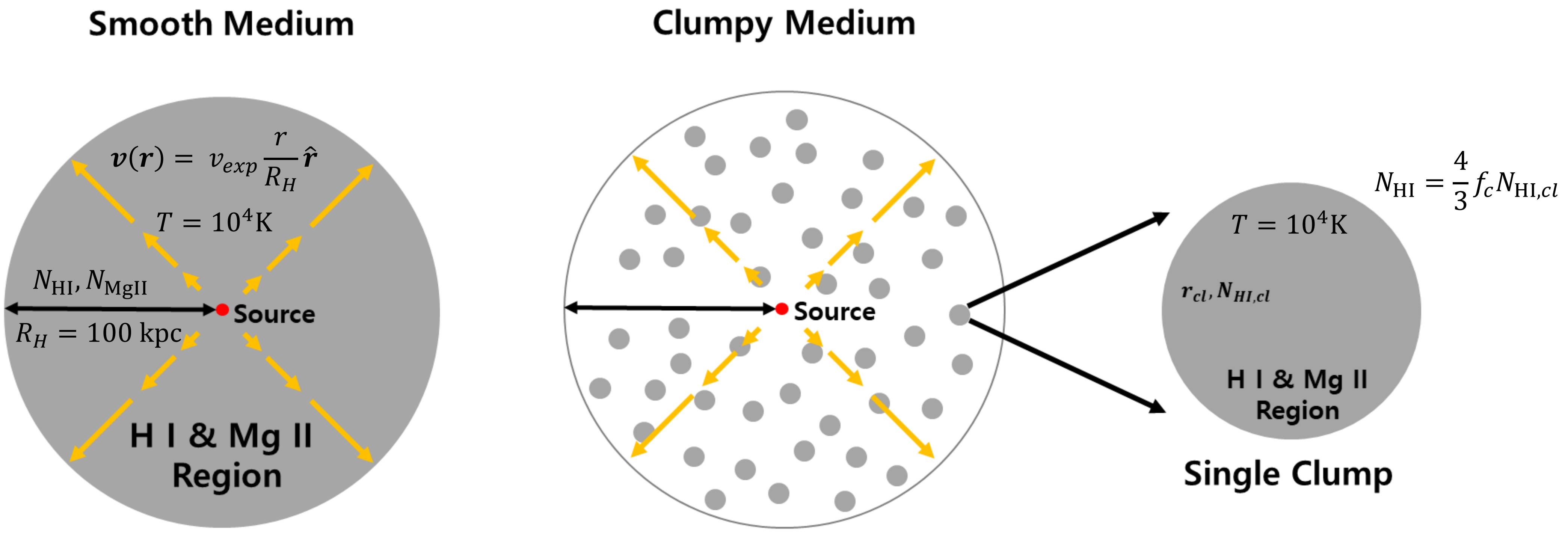
Mg II Study

- Escaping fraction & spectral profiles of Mg II and Lyα

- Line ratio of Mg II doublets



Model Geometry: Point Source and Sphere with Hubble-like Outflow



Range of parameters of scattering medium

$N_{\mathrm{HI}} = 10^{18-21}$ cm^{-2},

$N_{\mathrm{MgII}} = 10^{12.5-15.5}$ cm^{-2} ($\log(\mathrm{Mg/H}) \sim -5.5$)

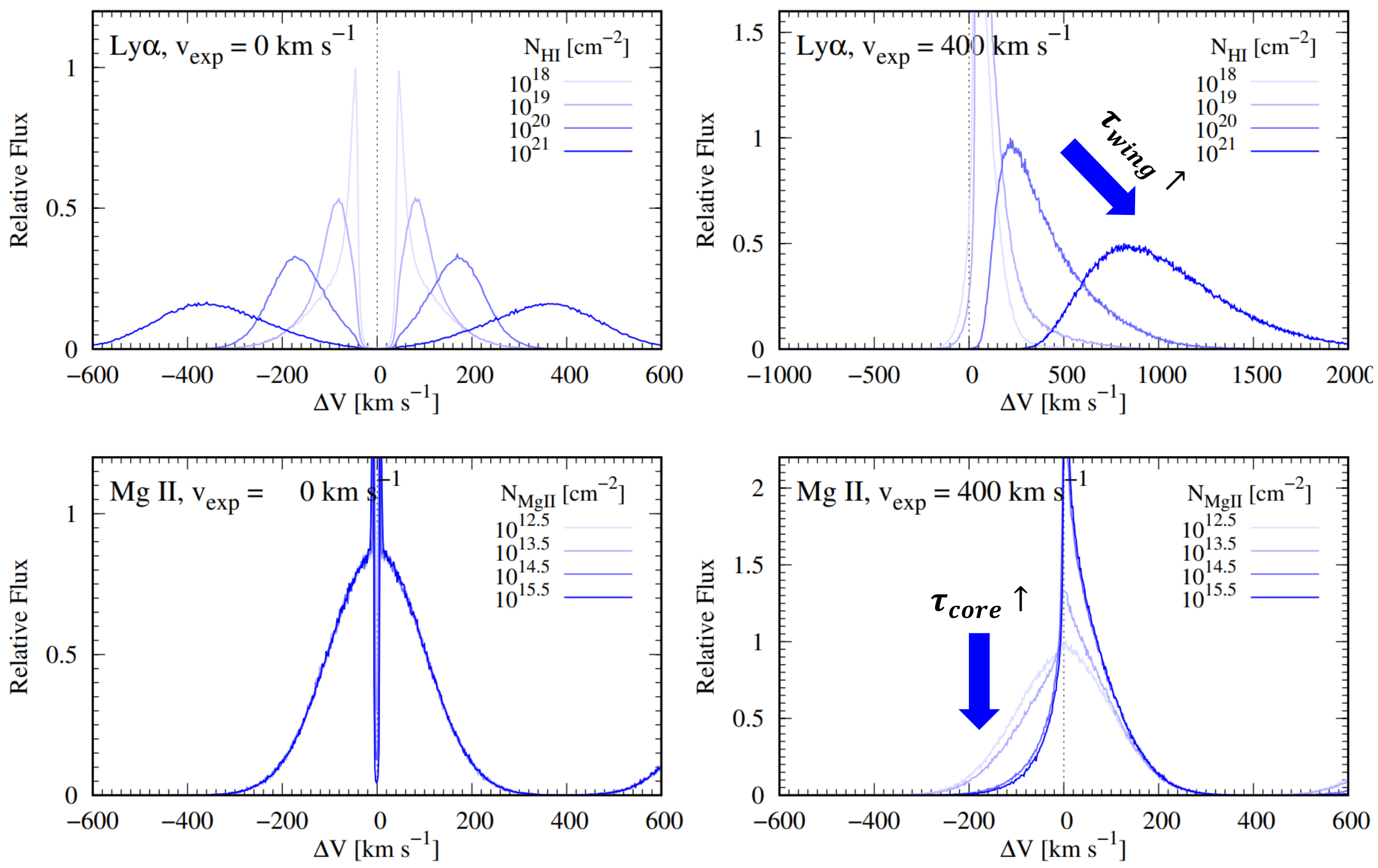
$|v_{exp}| = 0 - 1000$ km s^{-1}

$f_c = 1 - 100$ (Clumpy medium)

Type of Source

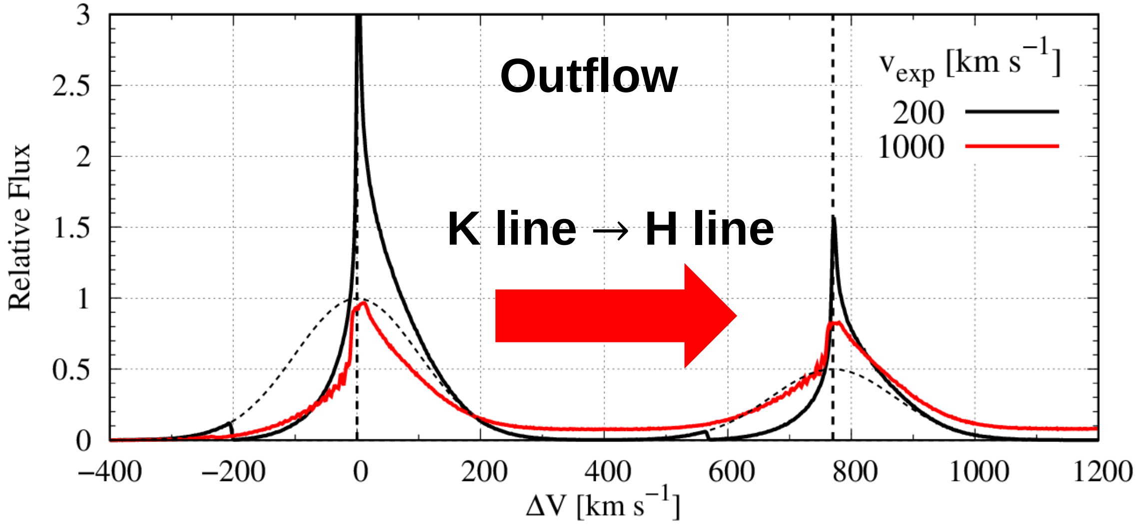
- Gaussian emission with $\sigma_{src} = 100$ km s^{-1}
- Flat Continuum (only for Mg II)

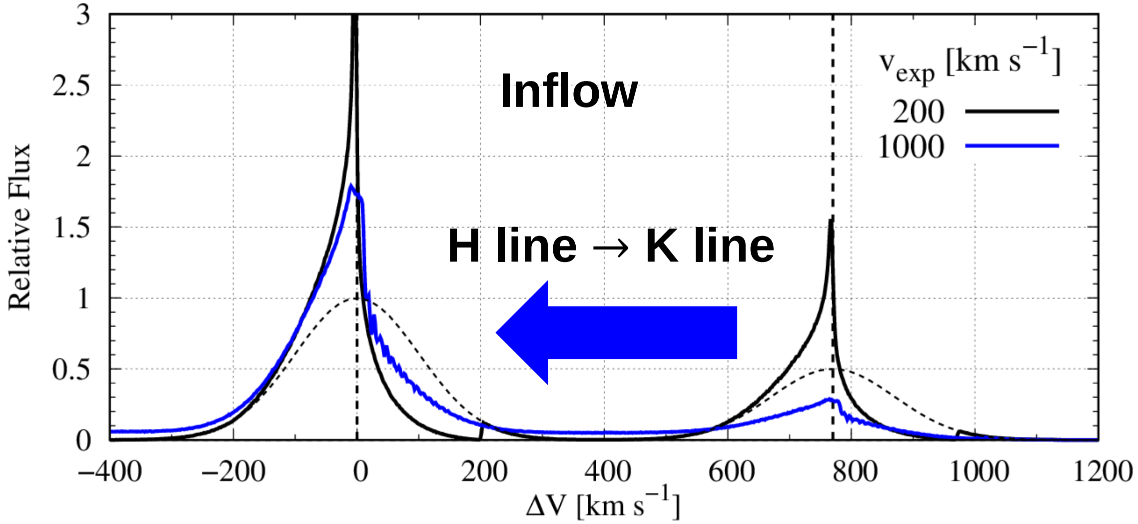
Mg II & Lyα spectra for various column densities

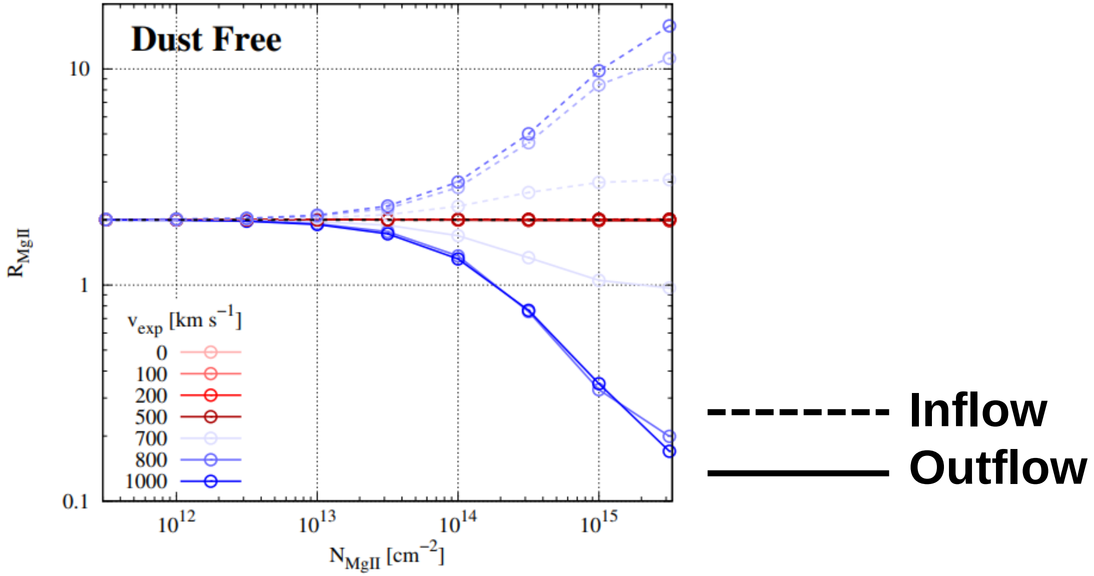


- Lyα spectrum becomes broaden with increasing the column densities.
- But, Mg II lines has narrow deep at the line center because of small Mg II fraction.
- In the outflowing medium, unlike Lyα, the spectral peak of Mg II is close to the line center.

Mg II spectra of strong outflow and inflow







- The intrinsic line ratio of Mg II R_{MgII} is fixed at 2.
- R_{MgII} increases (decreases) with the increasing outflow (inflow) velocity when $N_{\mathrm{MgII}} \geq 10^{14}\mathrm{cm}^{-2}$ ($N_{\mathrm{H}} \geq 10^{19.5}\mathrm{cm}^{-2}$) and $|v_{exp}| \geq 700\ \mathrm{km\ s}^{-1}$.

Mg II & Lyα escaping fraction f_{esc}

$\tau_{d,\mathrm{Ly\alpha}} \sim 2.53\tau_{d,\mathrm{MgII}}$

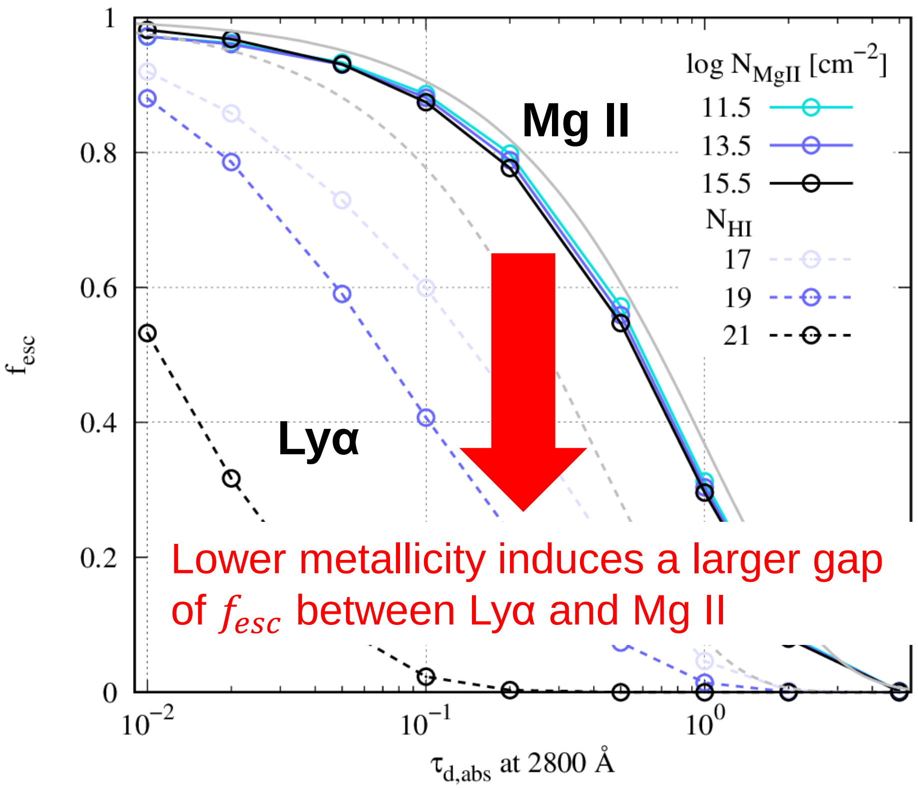
MW model

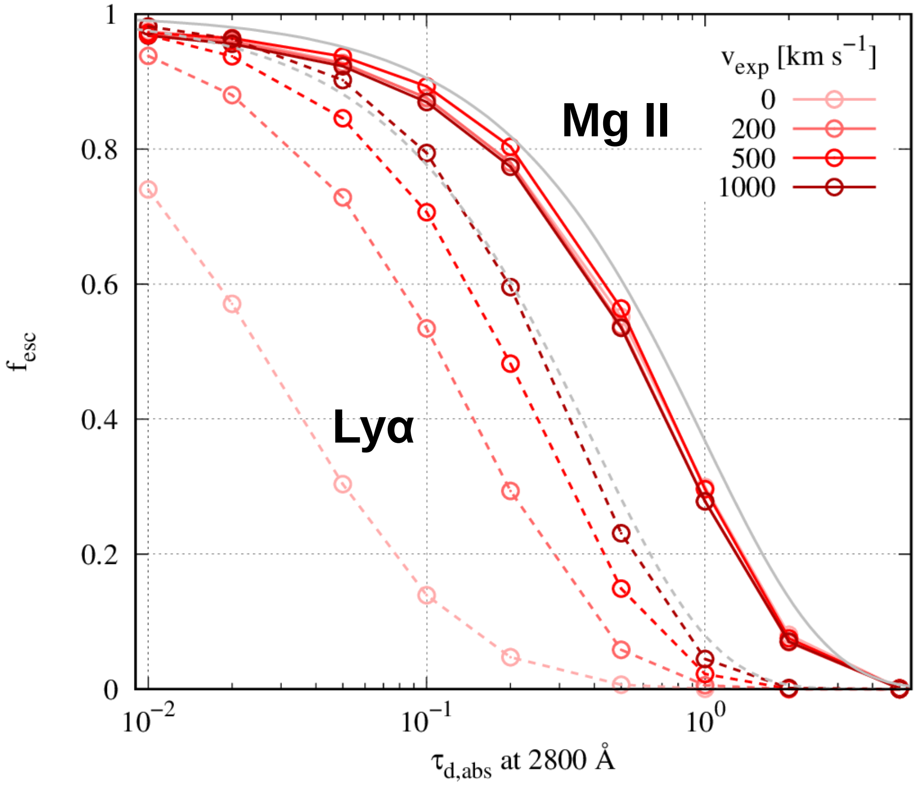
$\boldsymbol{\tau_{d,\mathrm{Ly\alpha}} \sim 3.79\tau_{d,\mathrm{MgII}}}$

LMC model

$\boldsymbol{\tau_{d,\mathrm{Ly\alpha}} \sim 9.26\tau_{d,\mathrm{MgII}}}$

SMC model



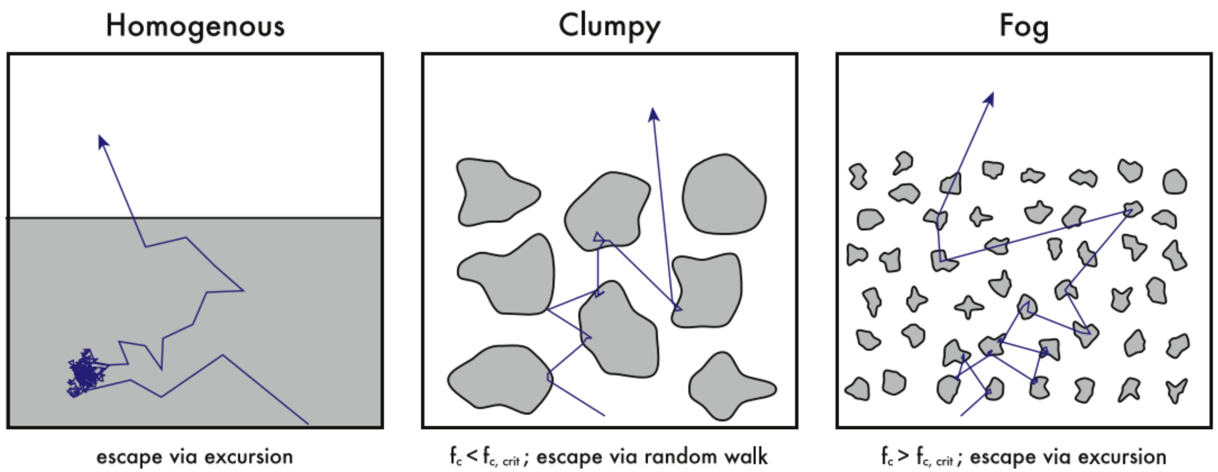


Lyα escaping fraction strongly depends on column density and gas kinematics.

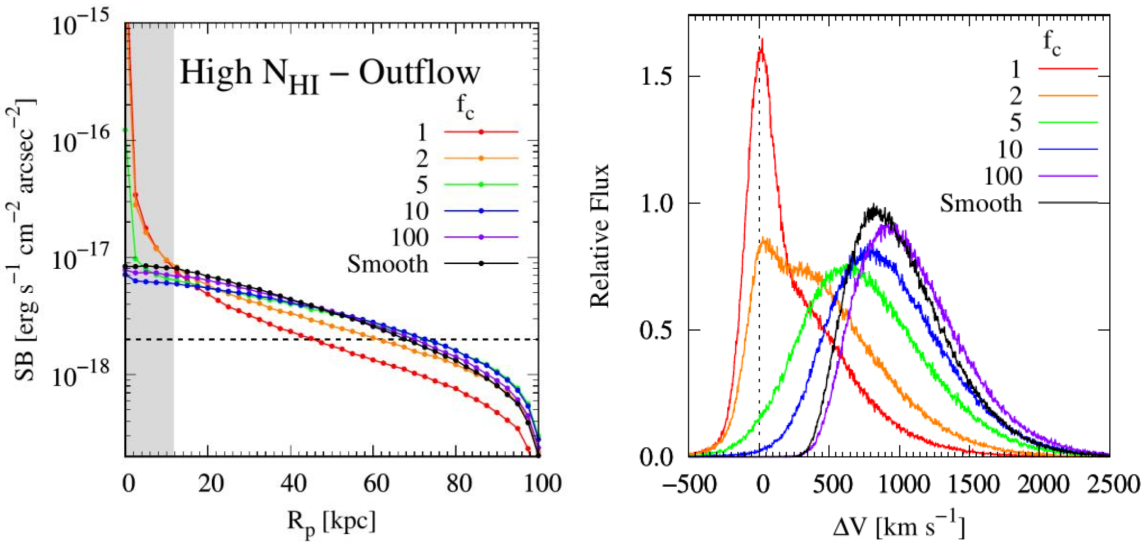
The dependence on column density and gas kinematics of Mg II escaping fraction is negligible.

- f_{esc} of Lyα is always lower than of Mg I due to different dust optical depth.

Lyα Radiative Transfer in Clumpy Medium



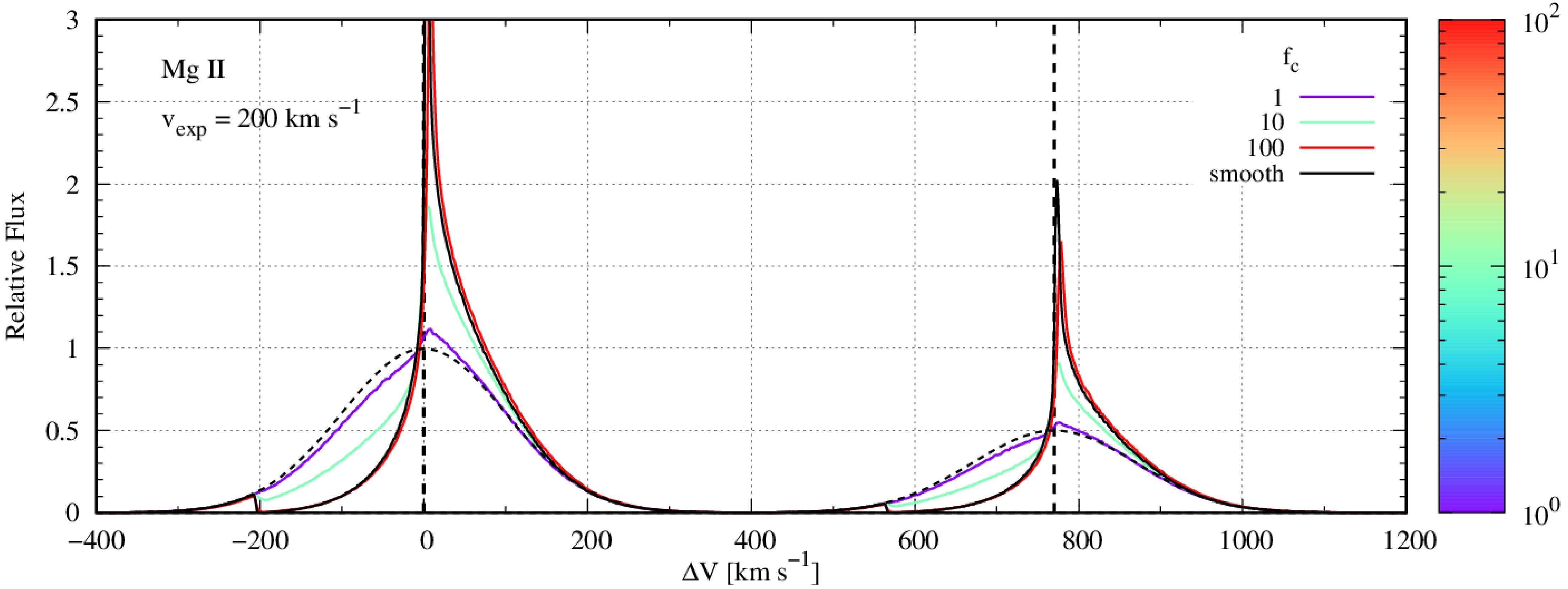
Gronke et al. 2016



Surface Brightness and Spectrum of Lyα
(Chang et al. 2023)

- The covering factor is a crucial parameter of Lyα radiative transfer in clumpy medium.
- When f_c increases, the simulated results of clumpy medium become like those of smooth medium at the same total column density.

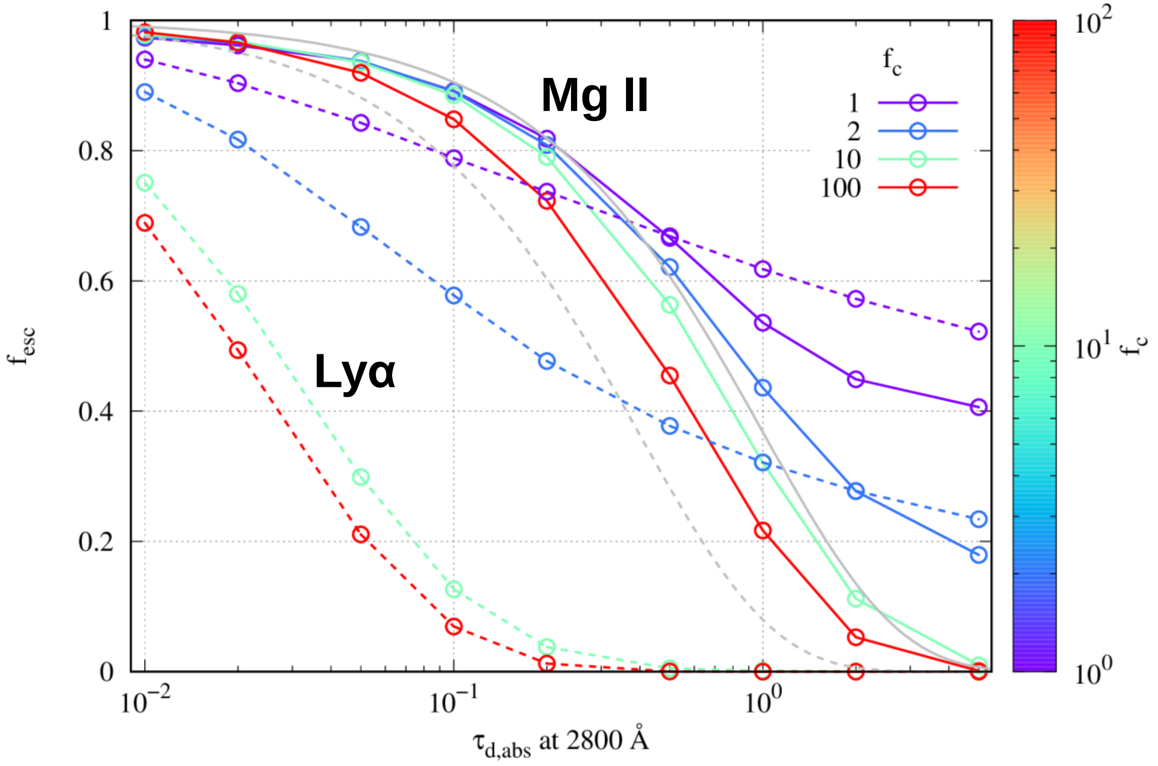
Mg II spectra in clumpy medium

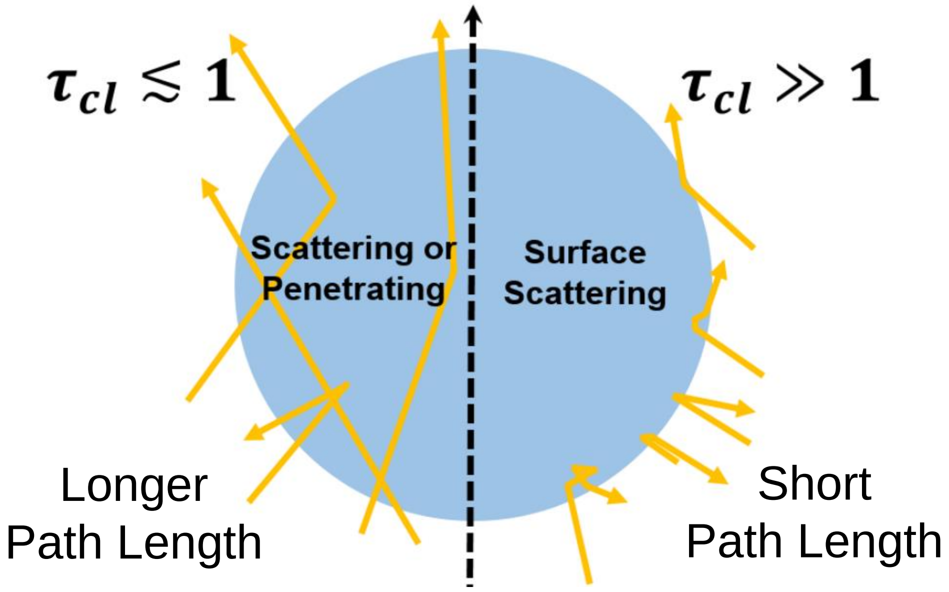


Mg II spectrum for various f_c

- The Mg II spectra from clumpy medium become identical to those of smooth medium with increasing f_c.
- At $f_c > 20$ Mg II, spectrum is identical to that of smooth medium case.

Escaping fraction in clumpy medium

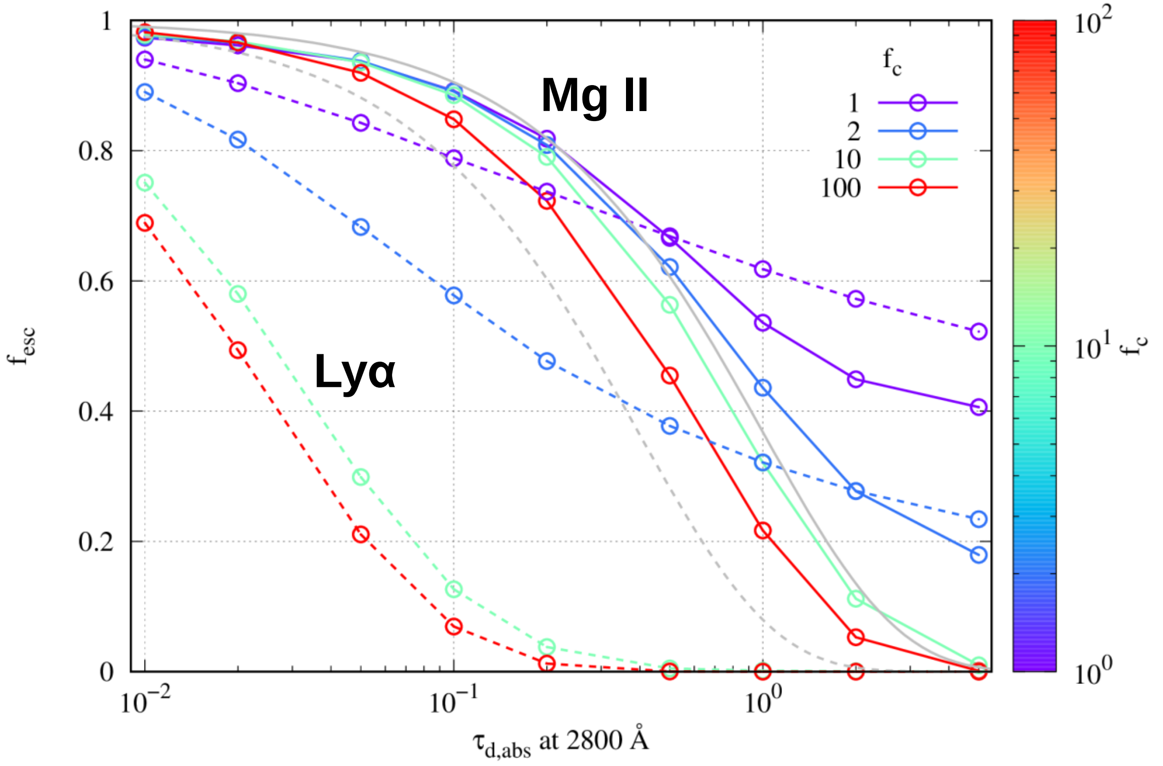


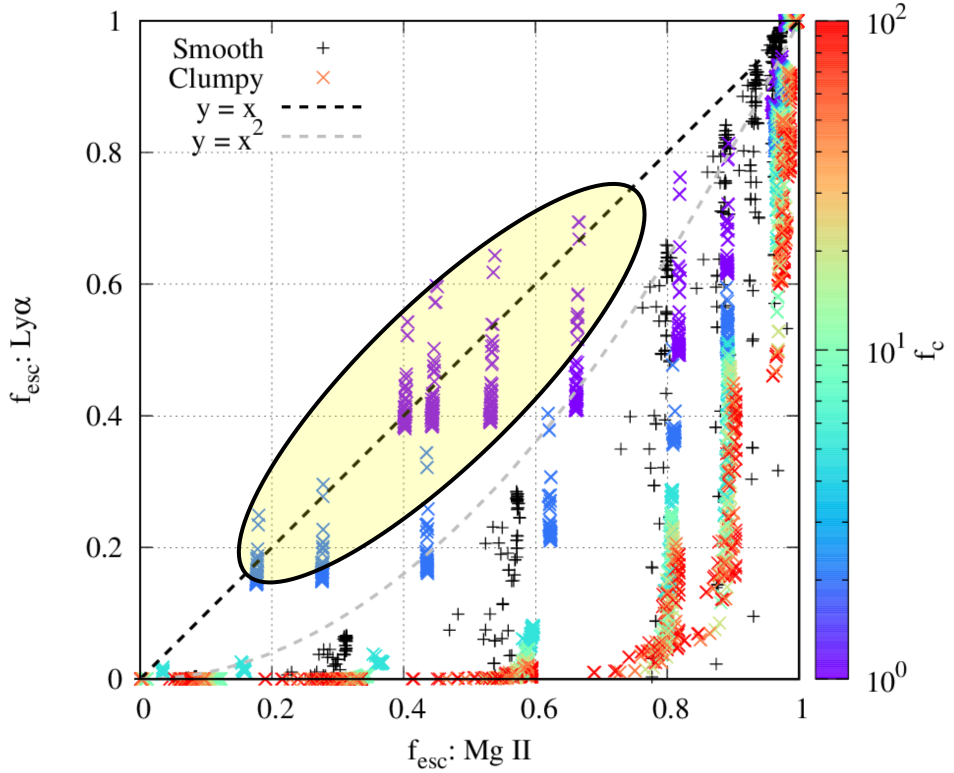


Surface Scattering
Chang et al. 2023

- The escaping fraction f_{esc} increases with decreasing f_c because of the surface scattering.

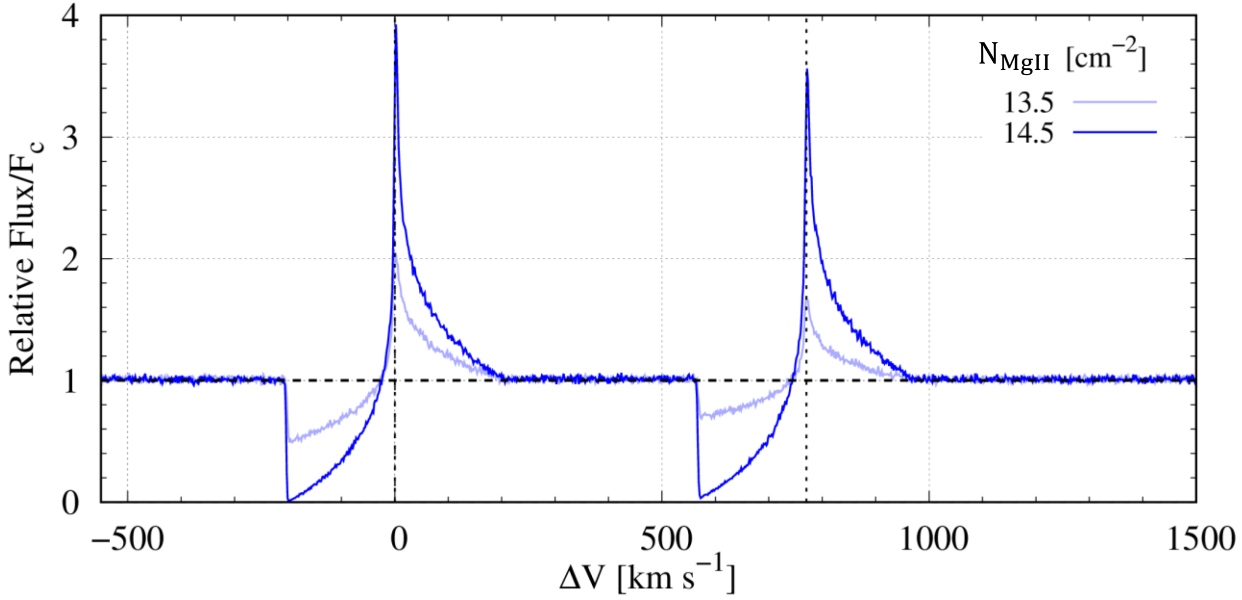
Escaping fraction in clumpy medium

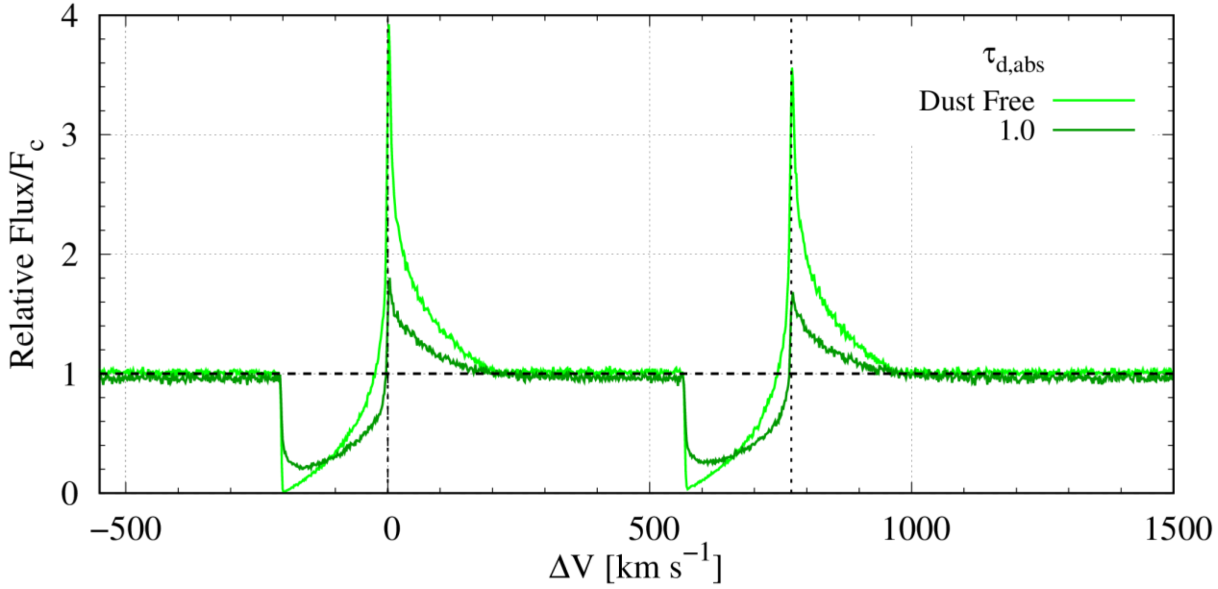




- The escaping fraction f_{esc} increases with decreasing f_c because of the surface scattering.
- In the smooth medium, f_{esc} of Lyα is always smaller than that of Mg II.
- In the clumpy medium, f_{esc} of Lyα is higher than that of Mg II as $f_c < 10$ because of strong effect of surface scattering in Lyα RT.

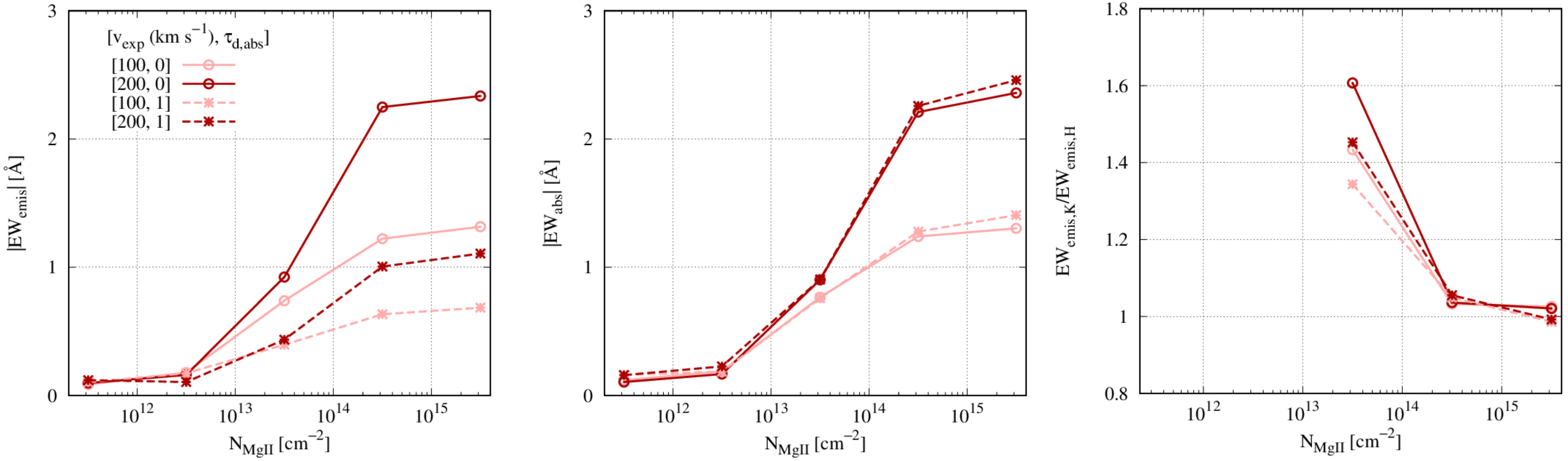
Mg II Scattering of Stellar Continuum





- At $N_{\mathrm{MgII}} < 10^{14}\ \mathrm{cm}^{-2}$, the emission and absorption features of K line are 2 times stronger than of H line.
- At $N_{\mathrm{MgII}} > 10^{14}\ \mathrm{cm}^{-2}$, the profile of K line is similar to H line because of high optical depth at the line center.
- In dust medium, the emission feature is suppressed by dust extinction because the feature has longer path length.

Equivalent Width of Emission and Absorption



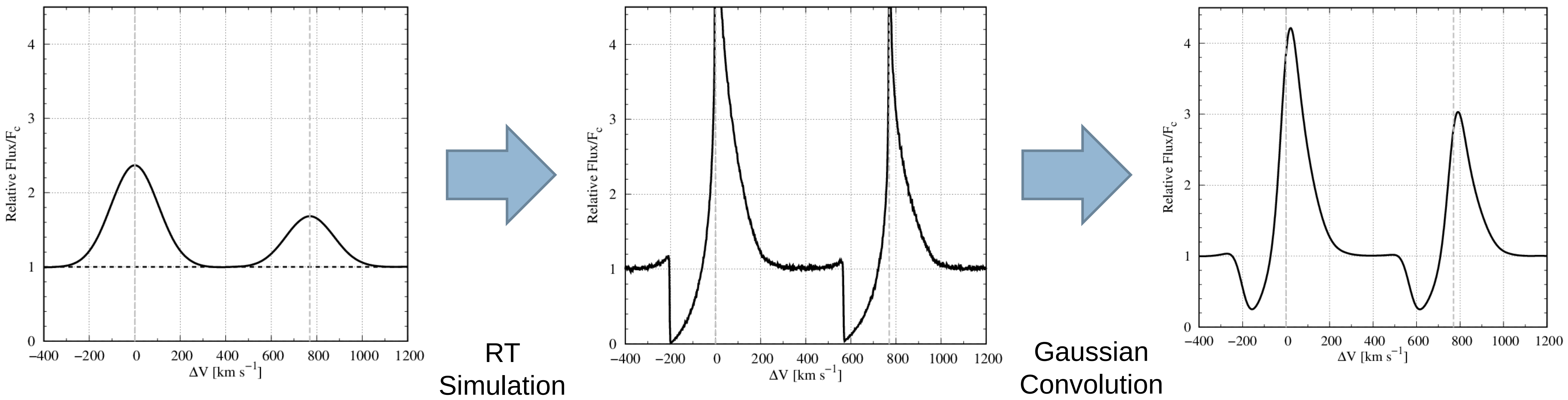
- The EW of emission feature increases with increasing N_{MgII}.
- The EW of emission is akin to that of absorption.

- In dusty medium, EW of emission decreases.
- EW of absorption is almost identical to in dust free result.

- **The emission EW ratio of Mg II K and H lines < 2.**

Incident Radiation: Continuum + Emission

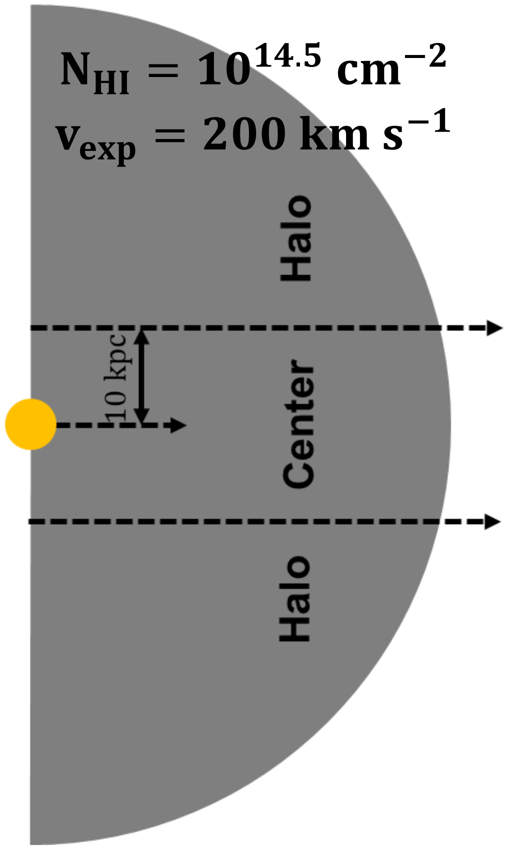
Incident Radiation | Escaping Spectrum | Observational Spectrum

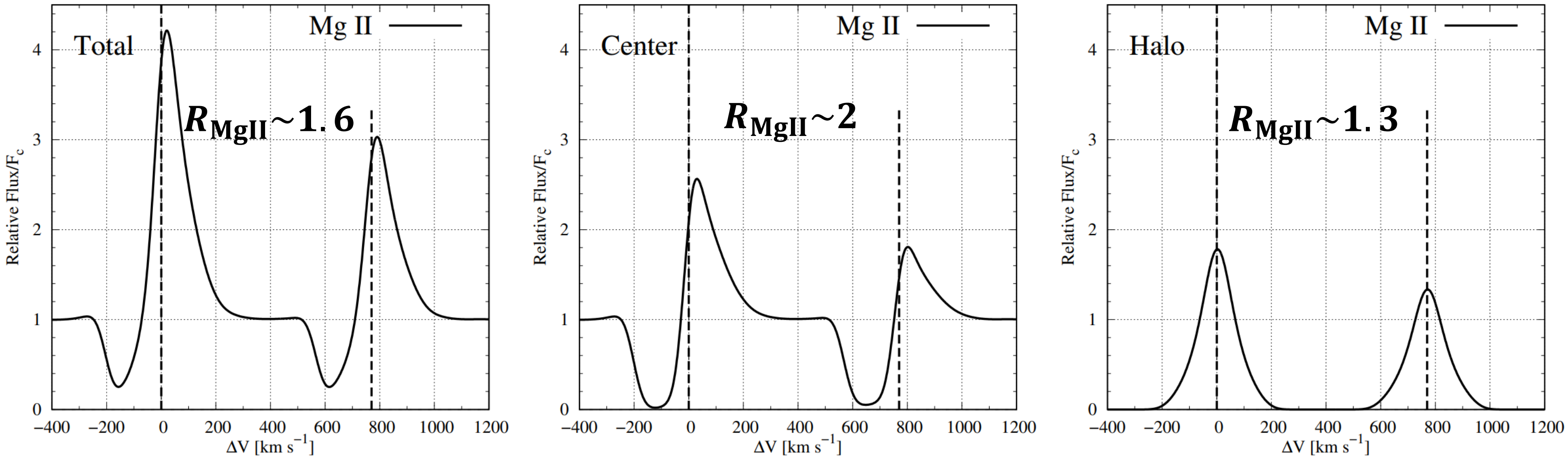


For the realistic spectrum, the incident radiation includes a flat continuum and Gaussian emission with EW = - 5 Å

Owing to peaky Mg II escaping spectrum, the spectrum is convoluted with Gaussian function with $\sigma = 30\ \mathrm{km\ s^{-1}}$

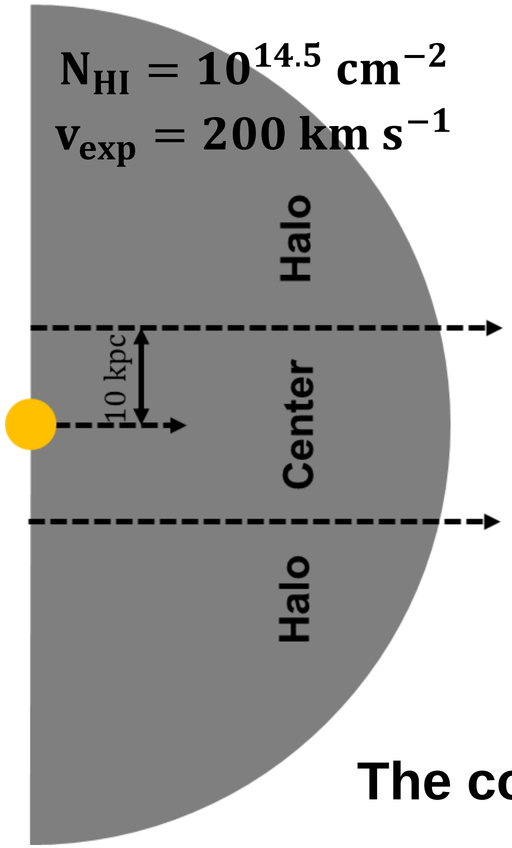
Mg II Emission in Galaxy vs CGM

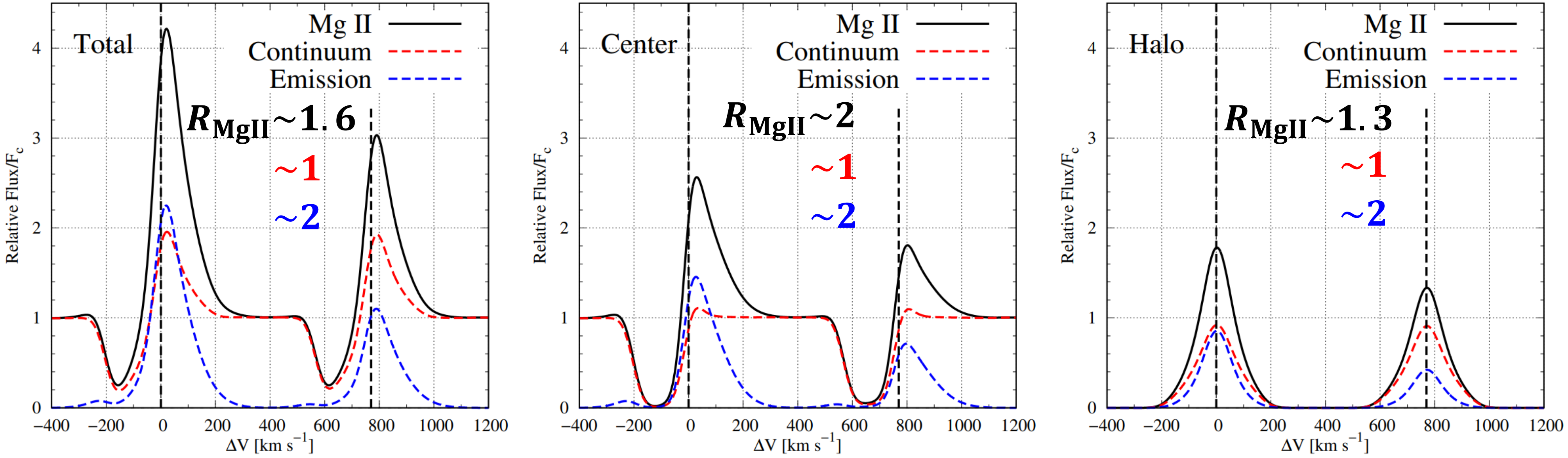




To show Mg II features in CGM, the center and halo spectra are composed of photons with projected radius < 10 kpc and > 10 kpc, respectively.

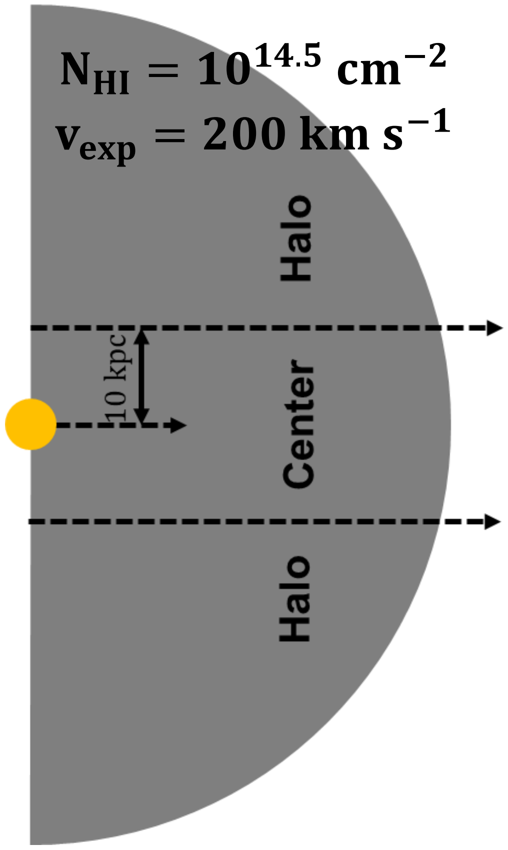
Mg II Emission in Galaxy vs CGM

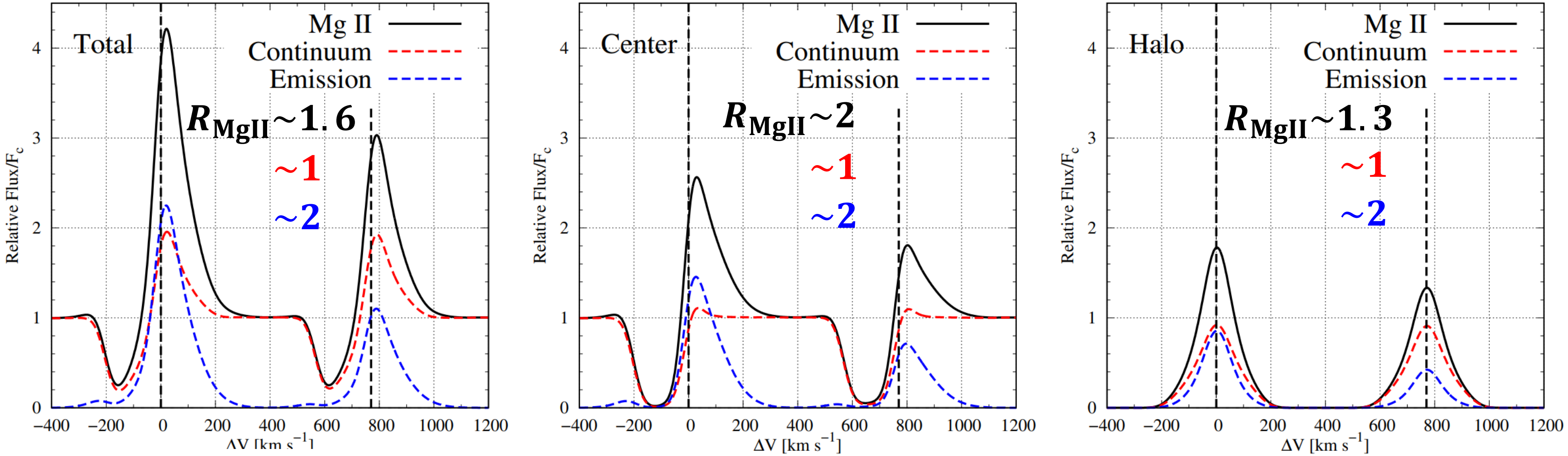


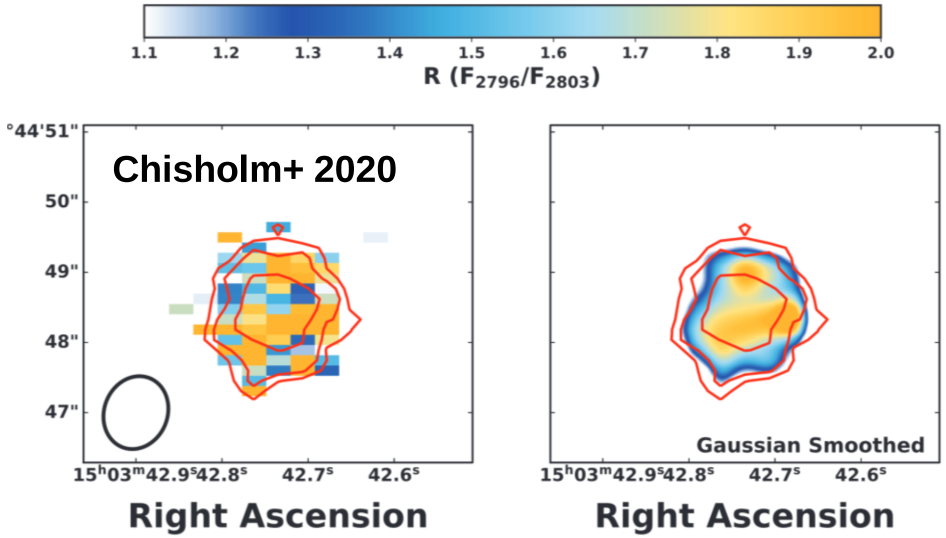


The contribution of Mg II from the emission and continuum determines Mg II line ratio.

Mg II Emission in Galaxy vs CGM



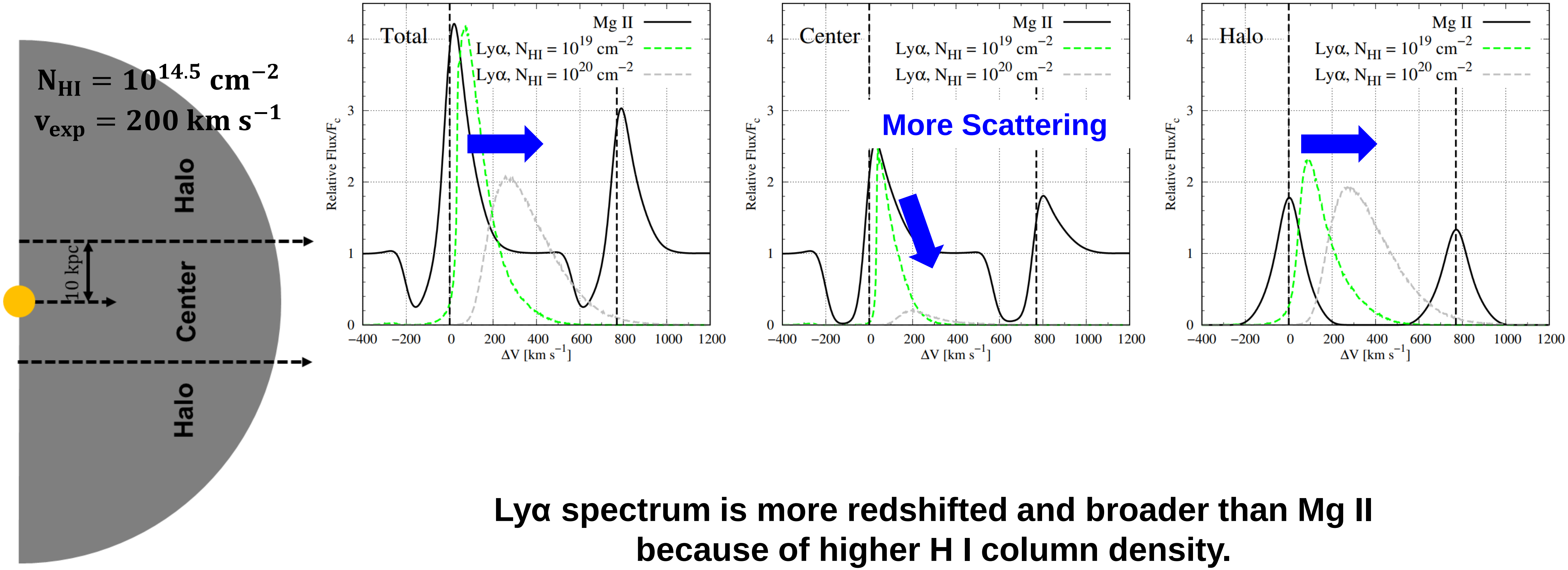




Chisholm et al. 2020 reported Mg II ratio **~ 2 at the center** and **~1.3 in the halo**

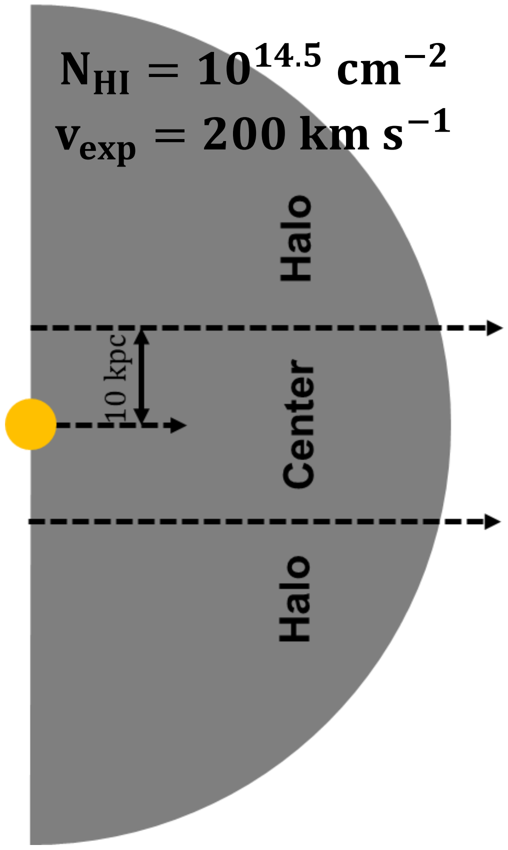
The Mg II emission from a continuum can explain $R_{MgII} < 2$

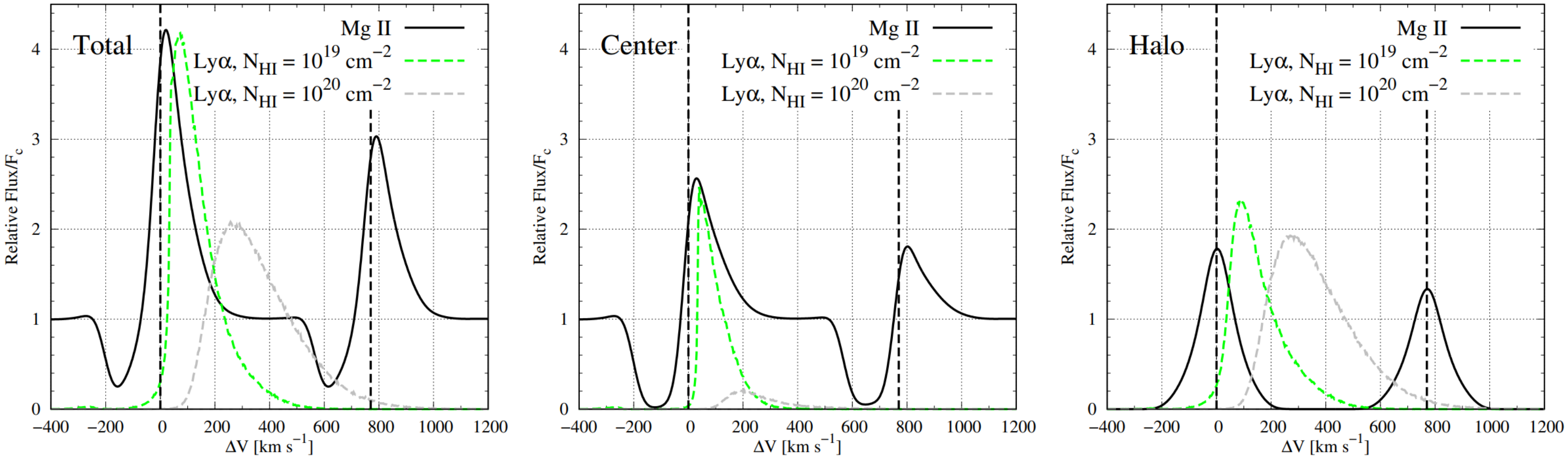
Mg II Emission in Galaxy vs CGM

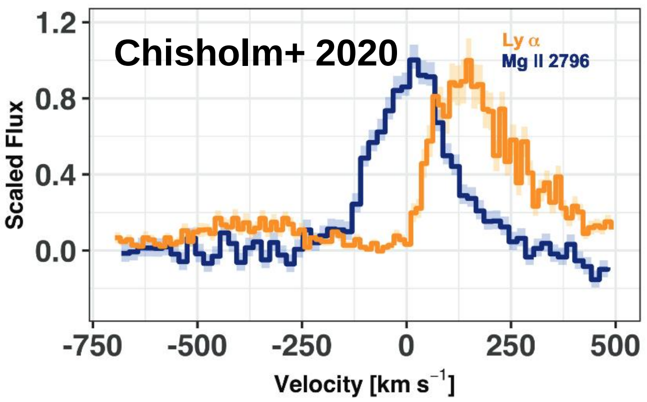


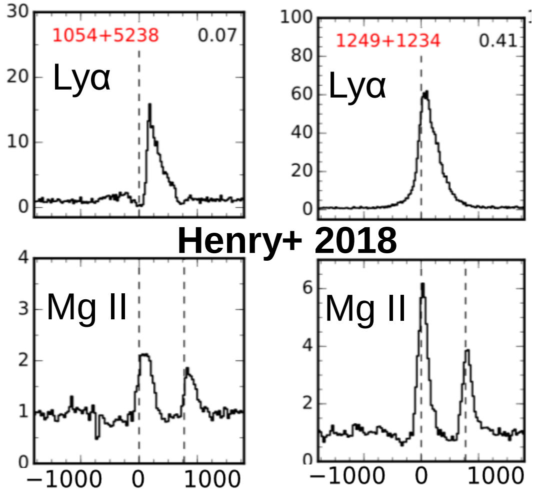
Lyα spectrum is more redshifted and broader than Mg II because of higher H I column density.

Mg II Emission in Galaxy vs CGM





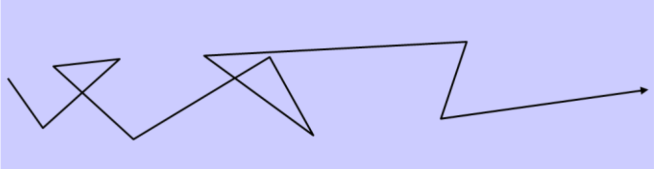




The simulated spectra are comparable to observational spectra of Mg II and Lyα.

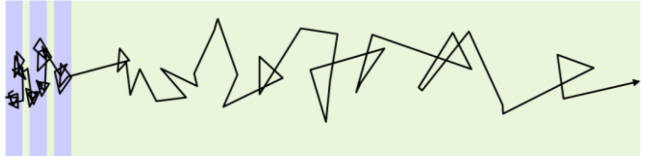
Summary

- Mg II & Lyα lines carry the physical properties of neutral hydrogen in ISM & CGM.
- Mg II & Lyα transfer traces the properties by different way because of different column density.



Mg II

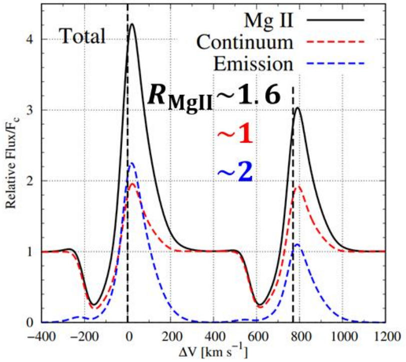
Lyα

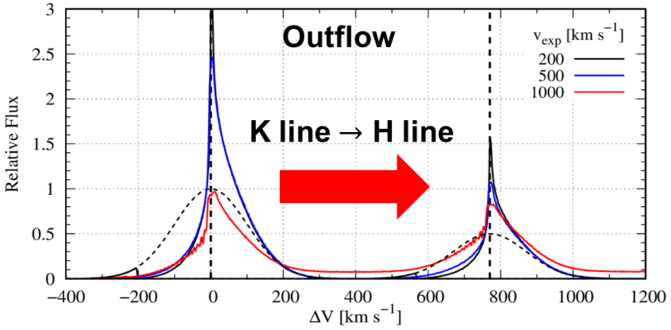


Strong outflow/inflow (> 700 km/s) change the line ratio.

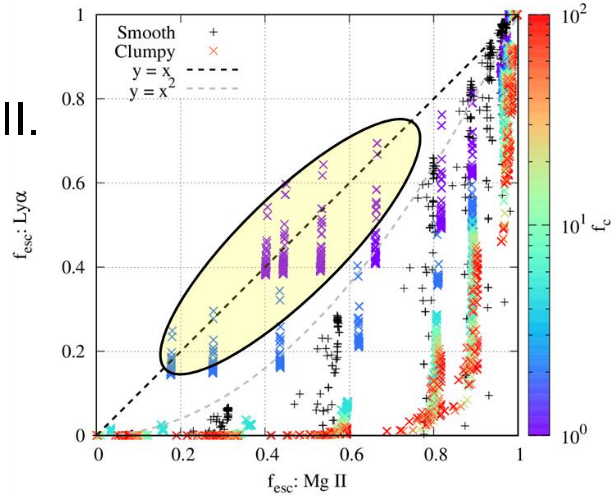
Mg II scattering from the continuum cause $R_{\rm MgII} < 2$.

- Mg II line ratio is determined by the contribution of continuum and emission.



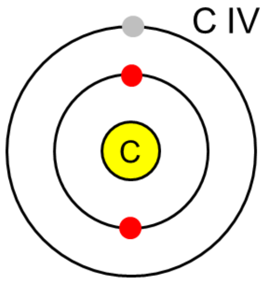


Mg II escaping fraction is always higher than that of Lyα in smooth medium but in clumpy medium Lyα escaping fraction can be higher than Mg II.

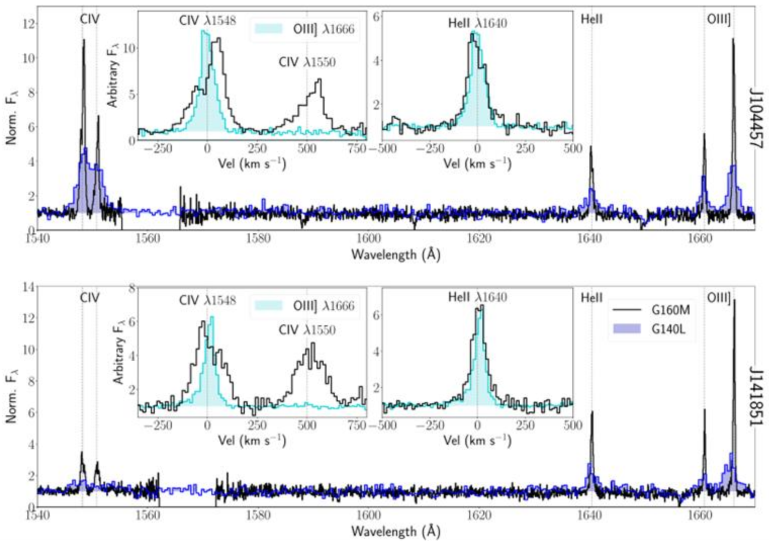


C IV Doublets

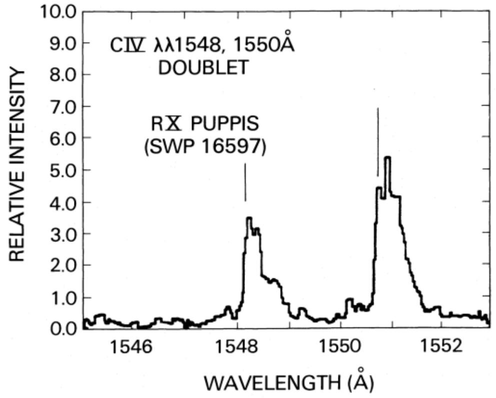
$2s-2p$ transition $T > 10^5$ K



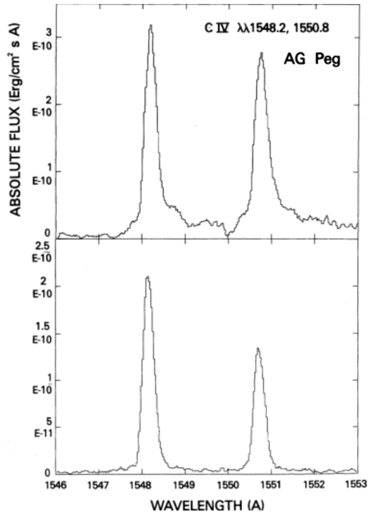
$\lambda_K \sim 1548.2$ Å
$\lambda_H \sim 1550.8$ Å
$\Delta V_{sep} \sim \mathbf{500\ km\ s^{-2}}$



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



Michalitsianos et al. 1988

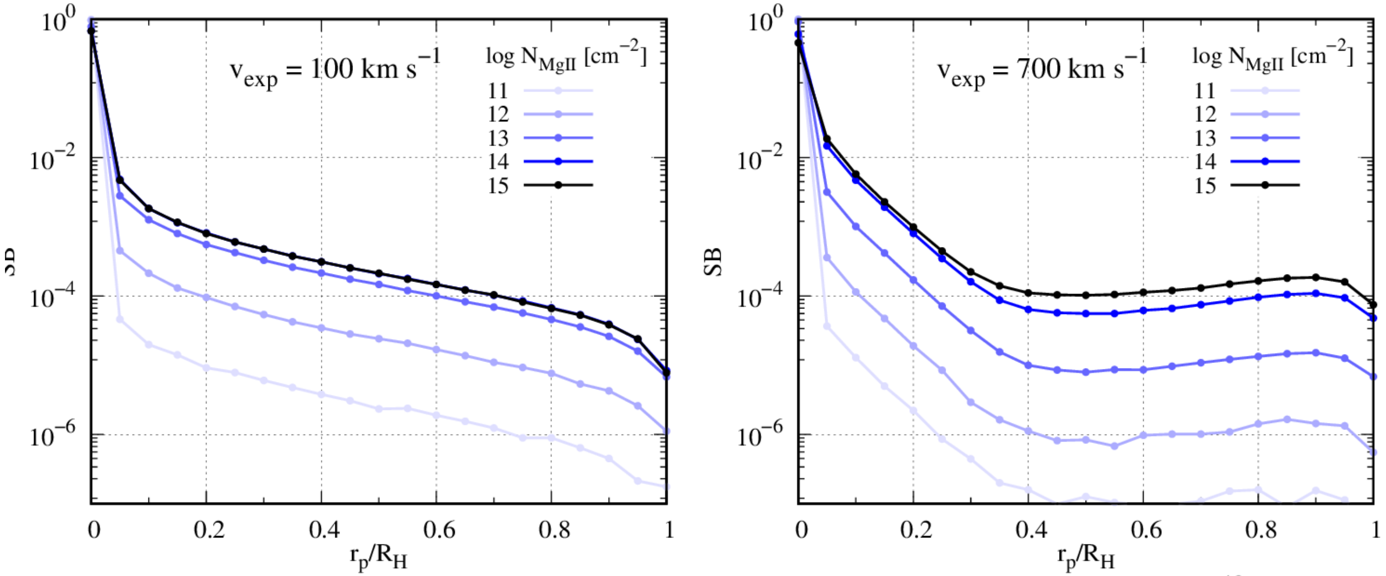


Michalitsianos et al. 1992

C IV in Symbiotic Stars

- Separation of C IV doublet (~ 500 km/s) is smaller than that of Mg II doublet (~ 750 km/s).
- For this reason, C IV lines are more easily mixed each other in outflow with speed > 400-500 km/s
- The ratio of C IV emission can be a tracer of fast hot wind components from galaxy.
- In 1980-1990, C IV doublets in FUSE spectrum of symbiotic stars shows various line ratio

Spatial Extended Mg II



Mg II surface brightness profile

Mg II degree of polarization profile