The Dynamic Duo: Lyα & Mg II as tracers of cold gas in CGM

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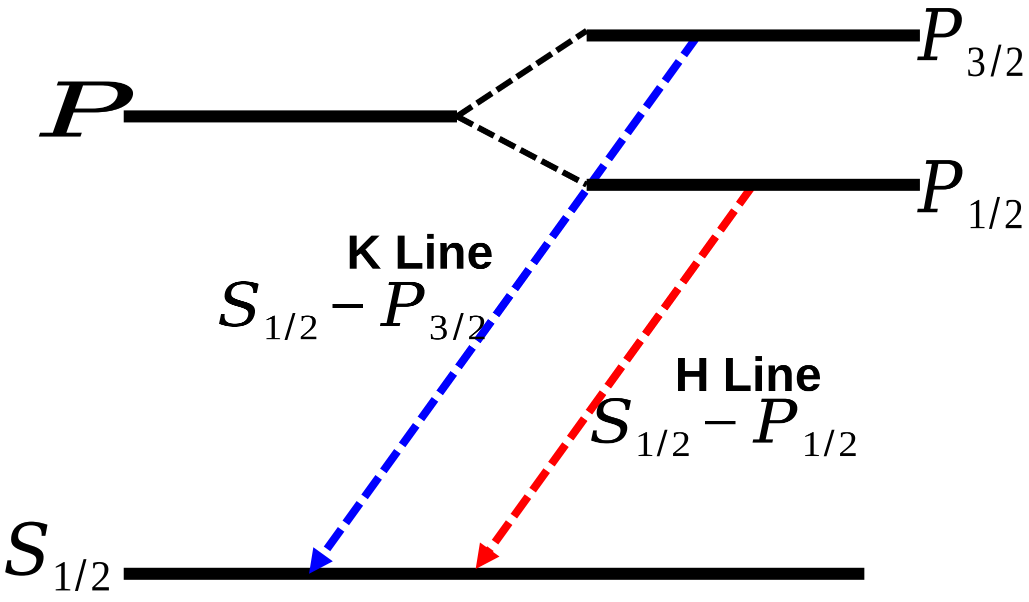
With Max Gronke

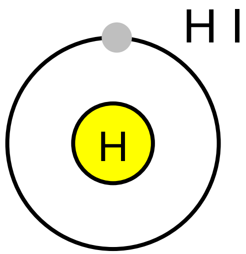
Escape of Lyman Radiation from Galactic Labyrinths
in Crete, April 18-21, 2023

Cold Dynamic Duo: Lyα & Mg II



Energy Level of Atom

Resonance doublet represent
transitions in the atom
having one electron in the outer orbit.



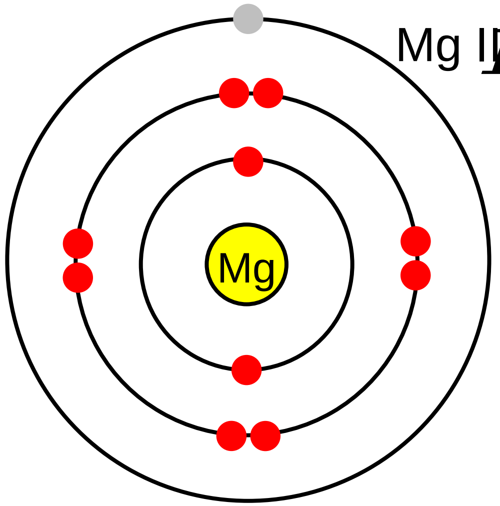
$E_i \quad 13.6\, eV \quad T \quad 10^4\, K$

$\lambda_K \quad 1215.668\, Å$

$\lambda_H \quad 1215.674\, Å$

Lyα

$\Delta V_{sep} \quad 1.5\, km\, s^{-1}$



$E_i \quad 15\, eV \quad T \quad 10^4\, K$

$\lambda_K \quad 2795.5\, Å$

$\lambda_H \quad 2802.7\, Å$

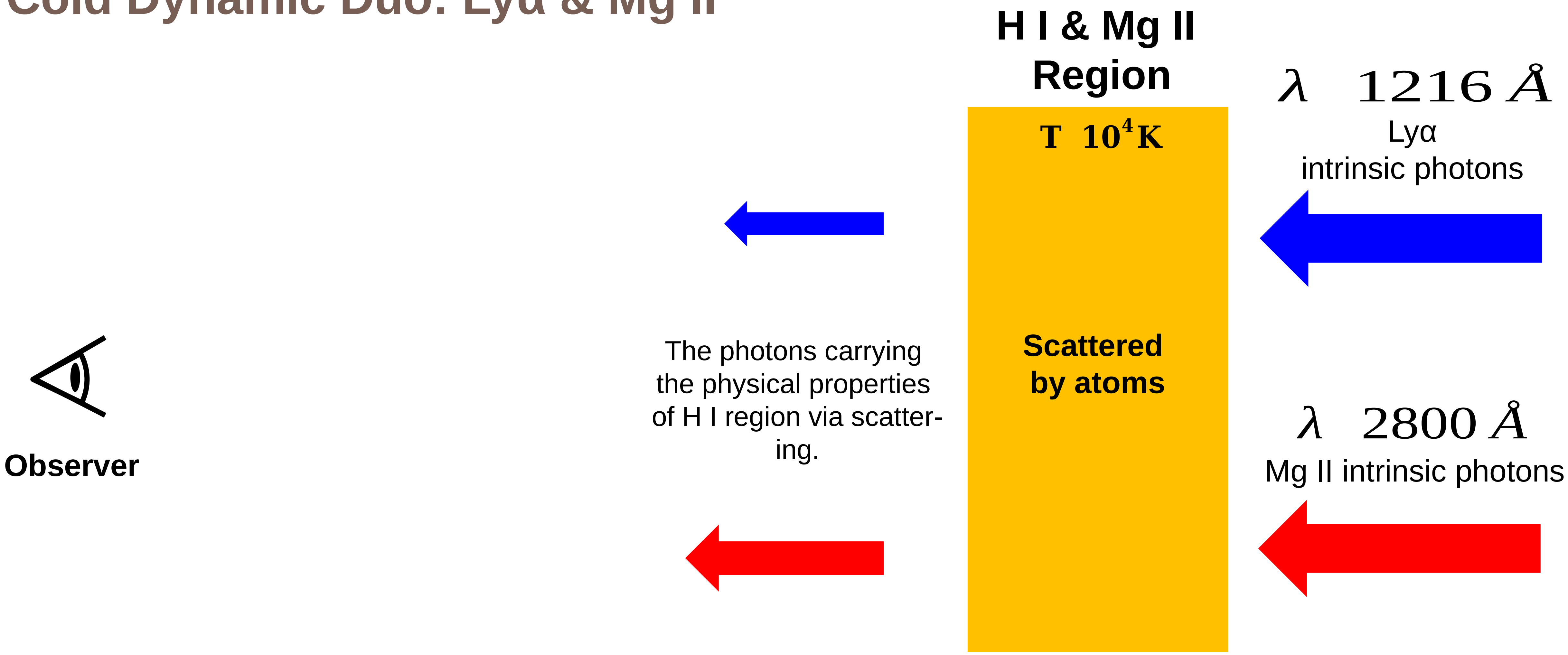
Mg II doublet

$\Delta V_{sep} \quad 750\, km\, s^{-1}$

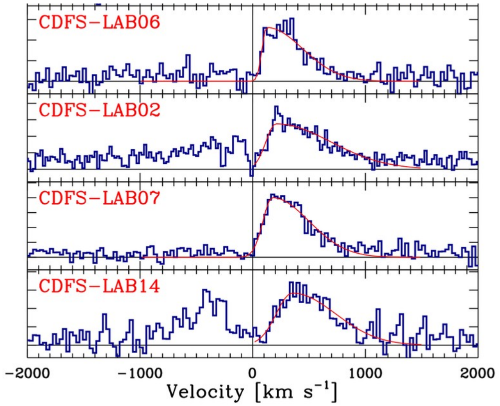
1. Intrinsic line ratio of K and H lines are ~ 2.

2. The cross section of the K line is 2 time higher than the H line.

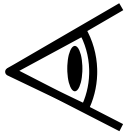
Cold Dynamic Duo: Lyα & Mg II



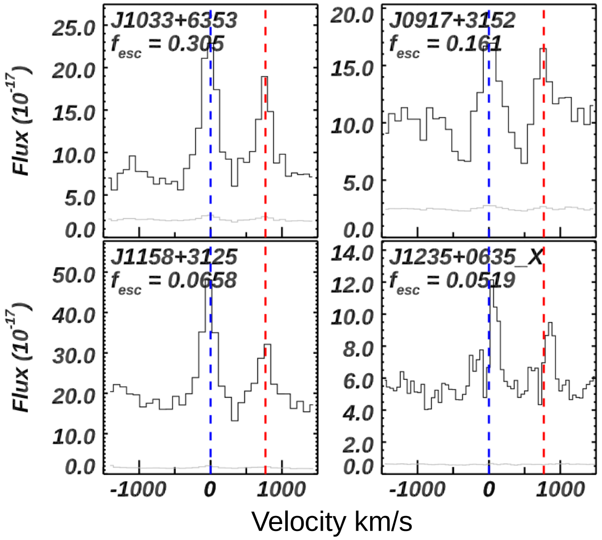
Cold Dynamic Duo: Lyα & Mg II



Lyα Spectra
Yang et al. 2014



Observer



Mg II Spectra
Xu et al. 2023

The photons carrying the physical properties of H I region via scattering.

H I & Mg II Region

$T \sim 10^4 K$

Scattered by atoms

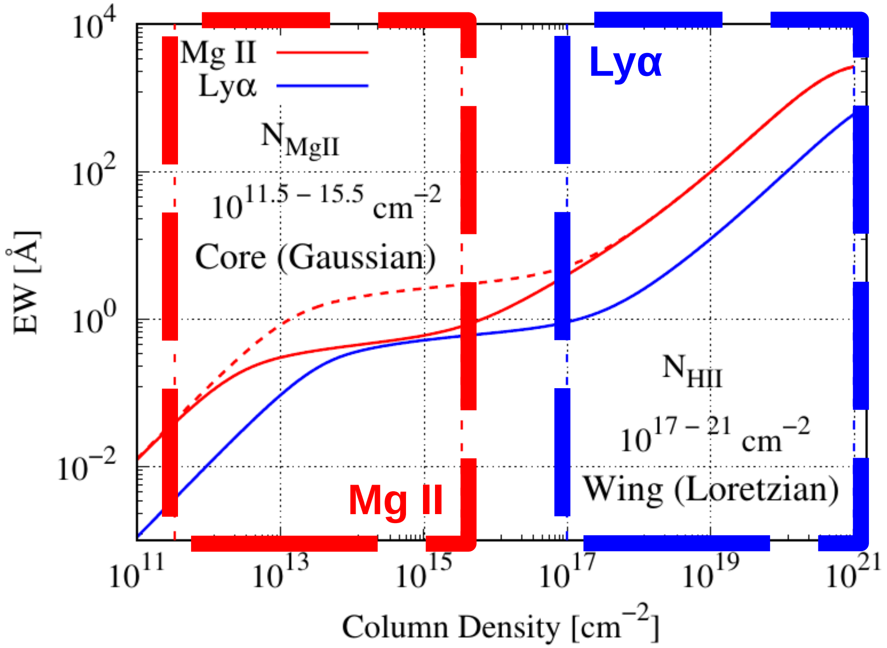
$\lambda \sim 1216 \AA$

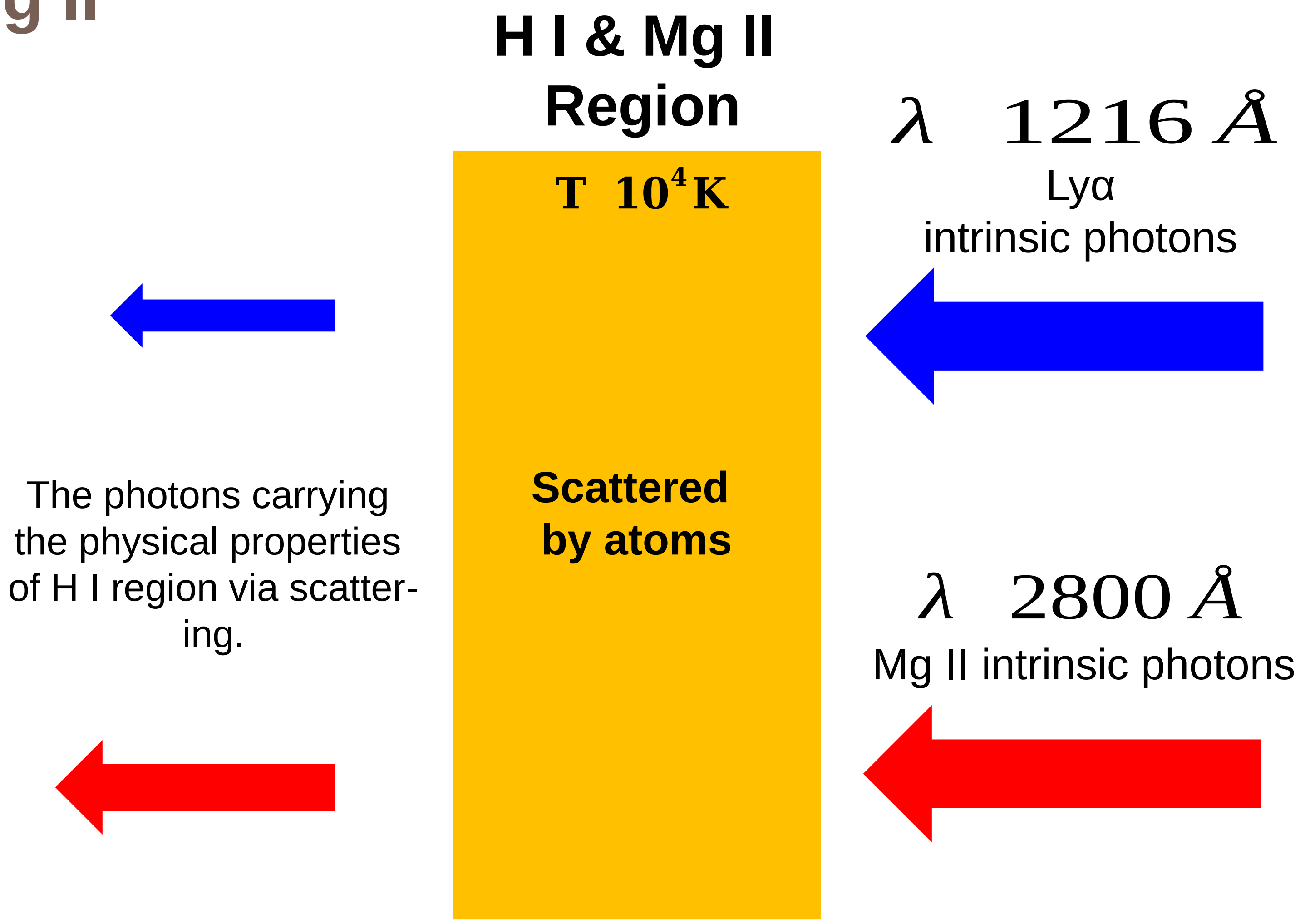
Lyα intrinsic photons

$\lambda \sim 2800 \AA$

Mg II intrinsic photons

Cold Dynamic Duo: Lyα & Mg II



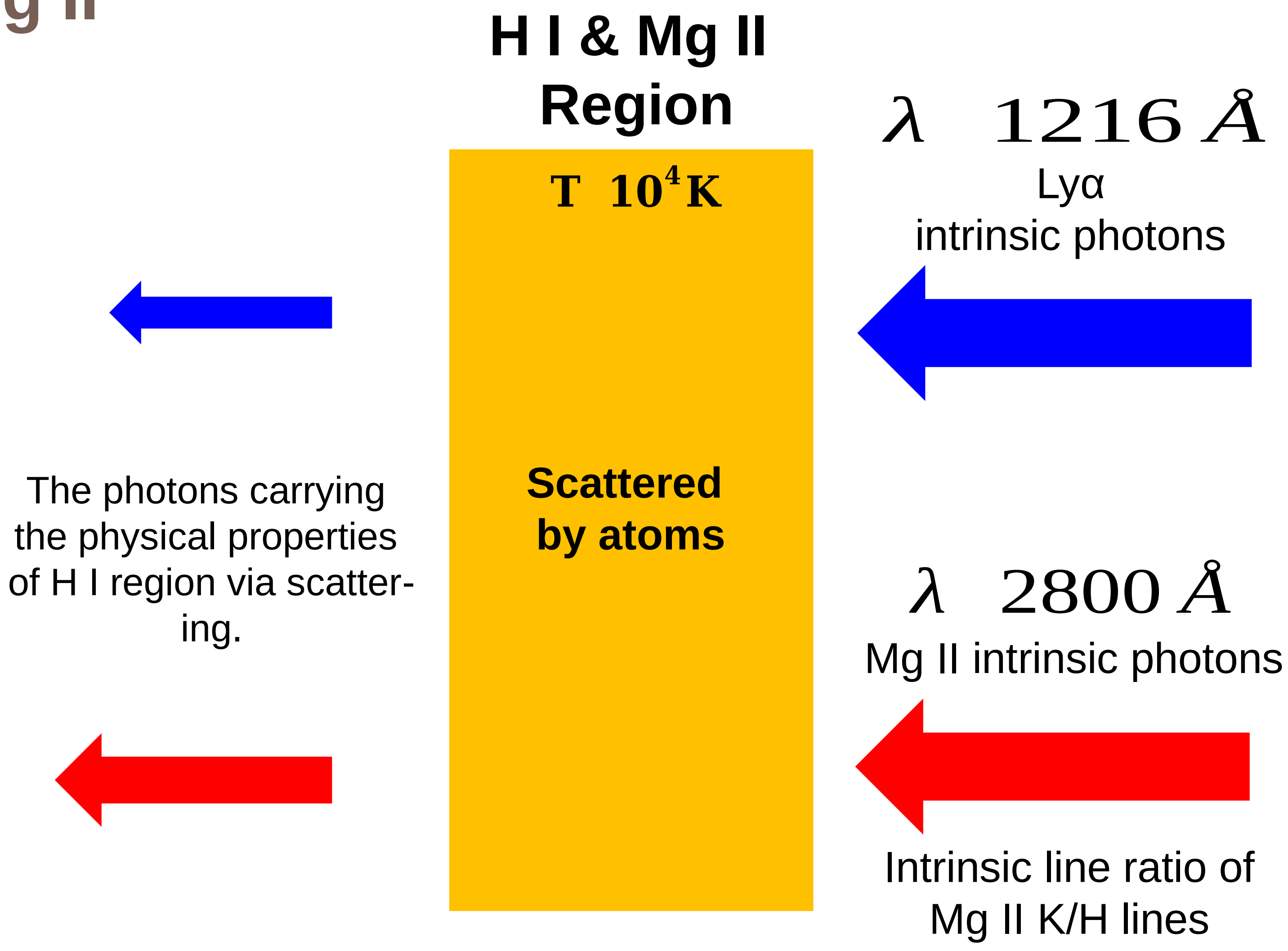


Because of small Mg fraction (~), Mg II and Lyα radiative transfer show different behaviors.

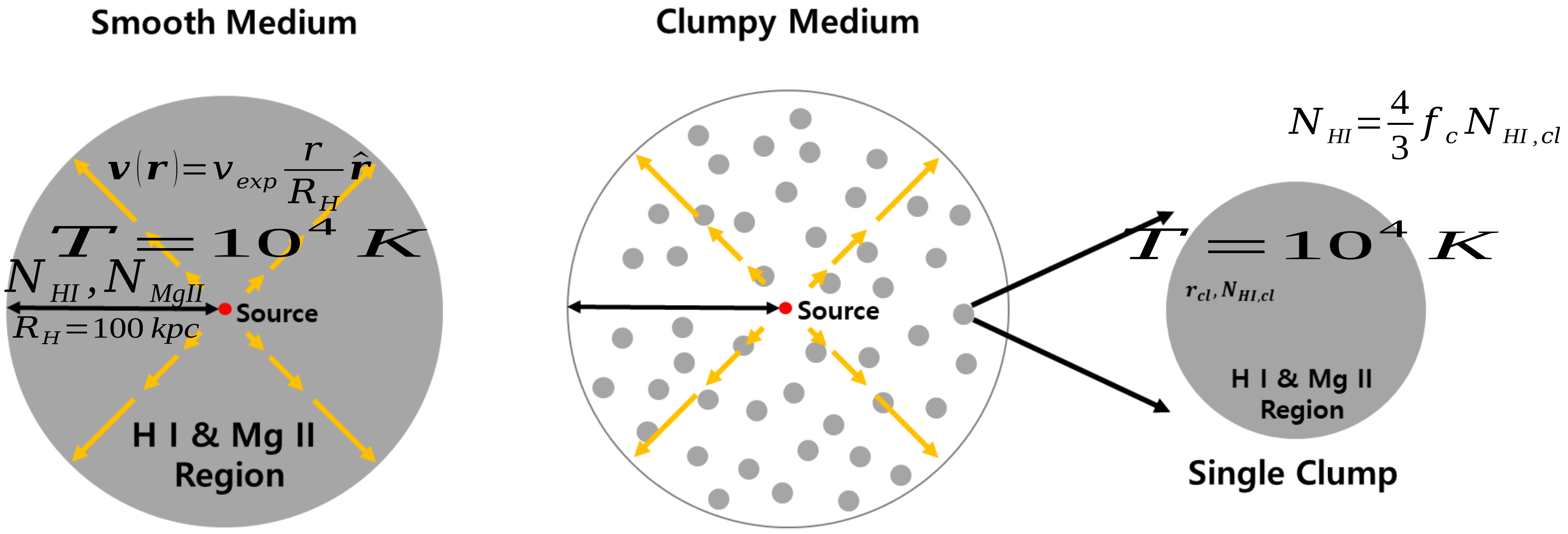
Cold Dynamic Duo: Lyα & Mg II

- Escaping fraction of Mg II and Lyα
- Spectrum of Mg II and Lyα
- Testing Mg II as a tracer of LyC escape

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



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



Range of parameters of scattering medium

,

()

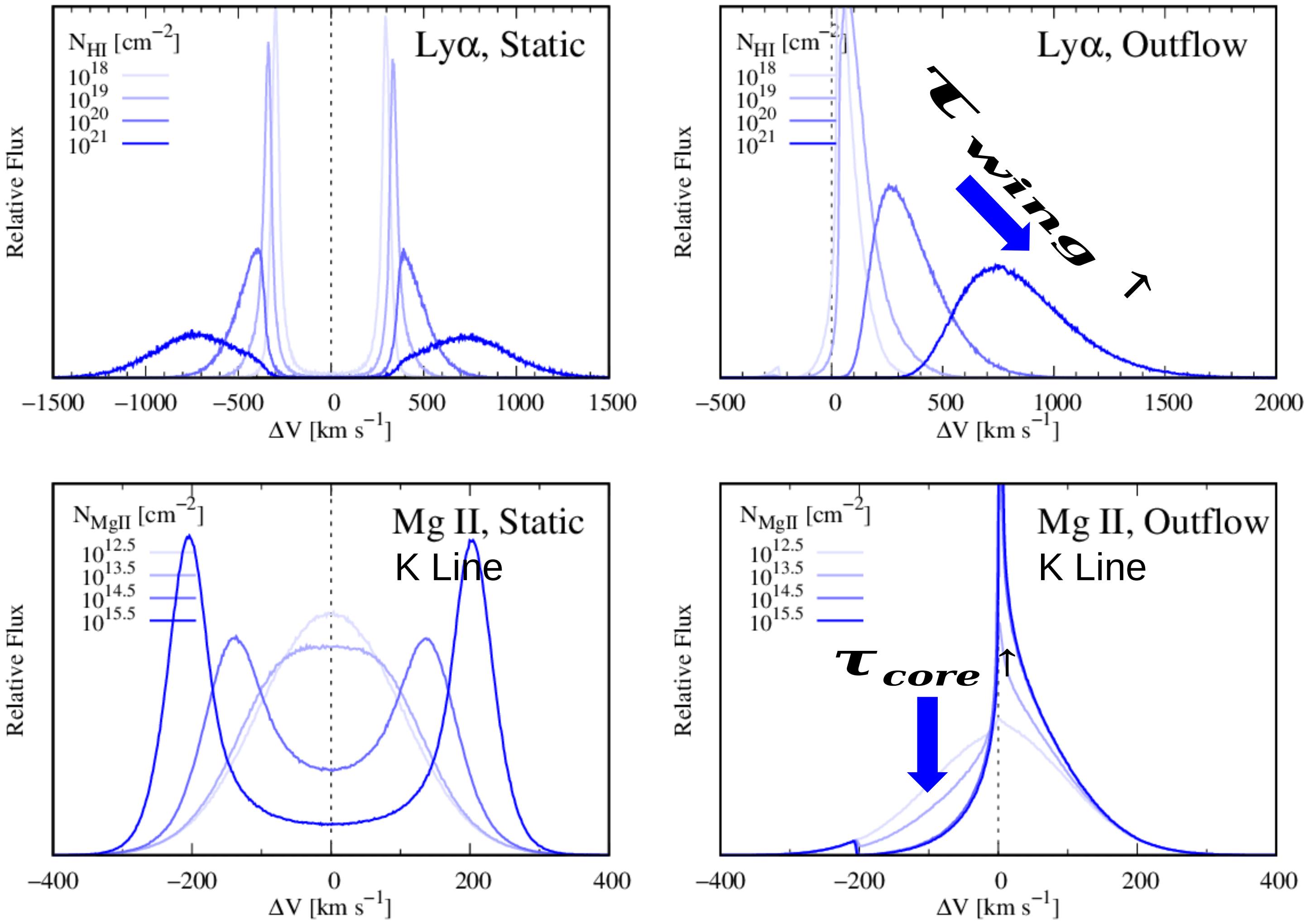
for clumpy medium
(Mean number of clumps in the line of sight)

Type of Source

- Gaussian emission with
- Flat Continuum (only for Mg II)

The simple model allows us to under-stand RT effects.

Mg II & Lyα Spectra for Various Column Densities

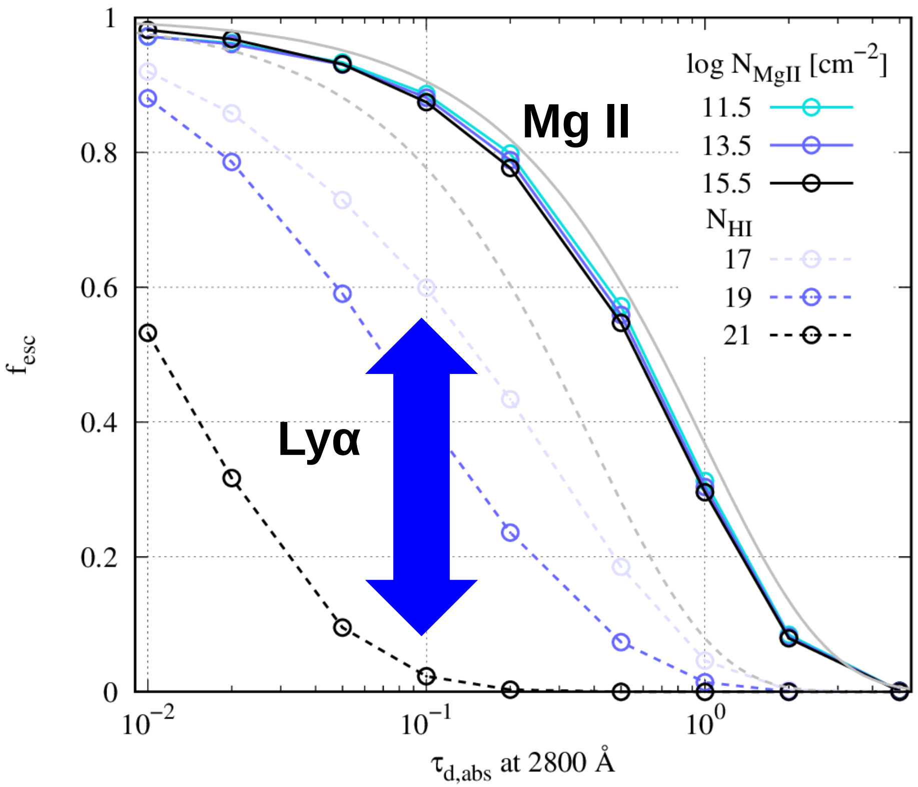


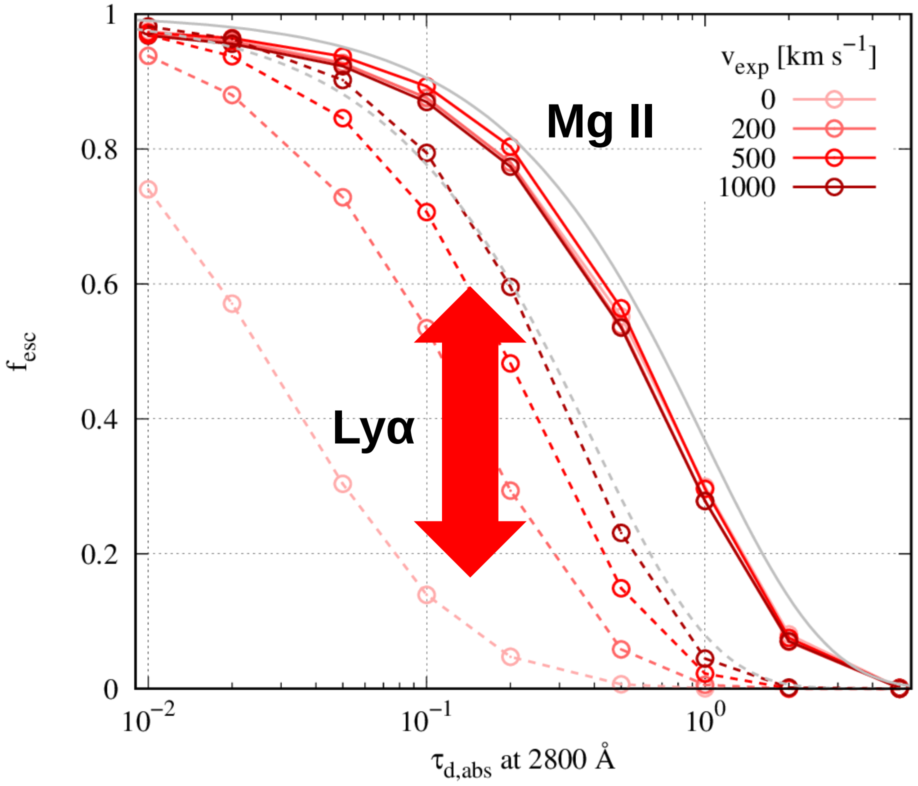
- In the static medium, Lyα and Mg II spectra becomes broaden with increasing column density.
- In the outflowing medium, unlike Lyα, the spectral peak of Mg II is close to the line center.

Mg II & Lyα escaping fraction

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

MW dust model
(Drain 2003a,b)





of Lyα < of Mg II because

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

Mg II & Lyα escaping fraction

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

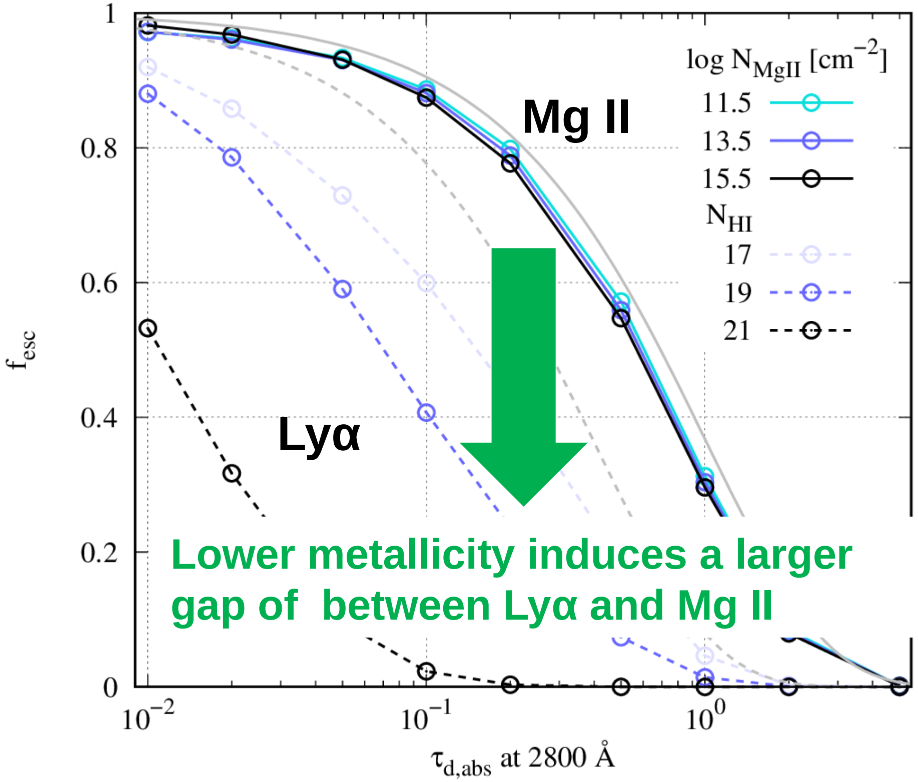
MW dust model
(Drain 2003a,b)

$\tau_{d,Ly\alpha}$ 3.79 $\tau_{d,MgII}$

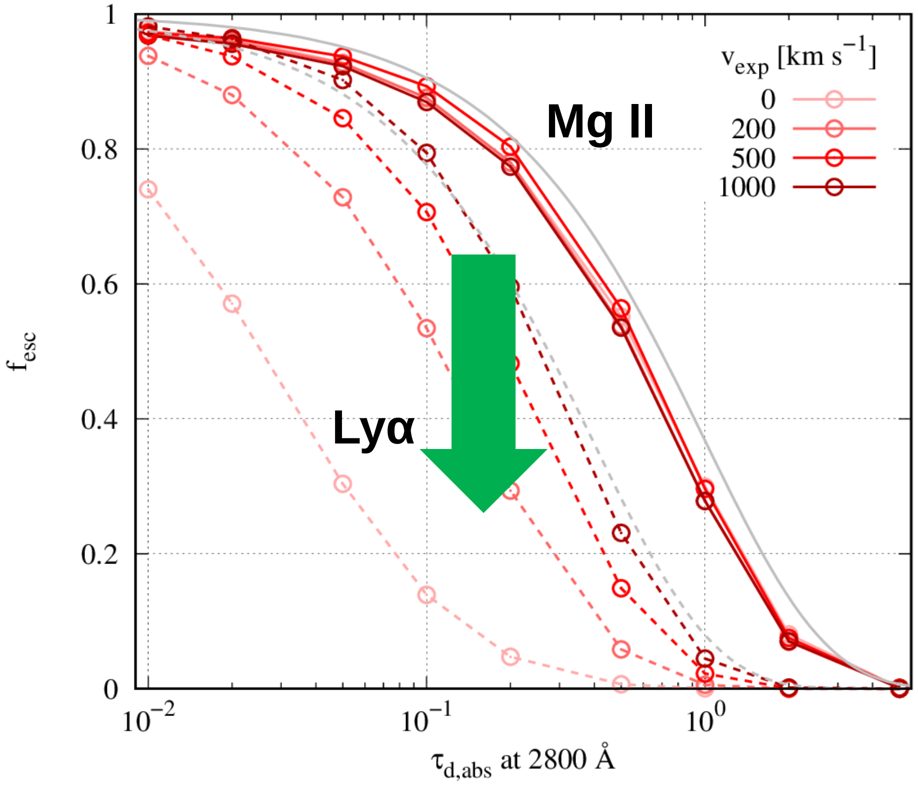
LMC dust model

$\tau_{d,Ly\alpha}$ 9.26 $\tau_{d,MgII}$

SMC dust model



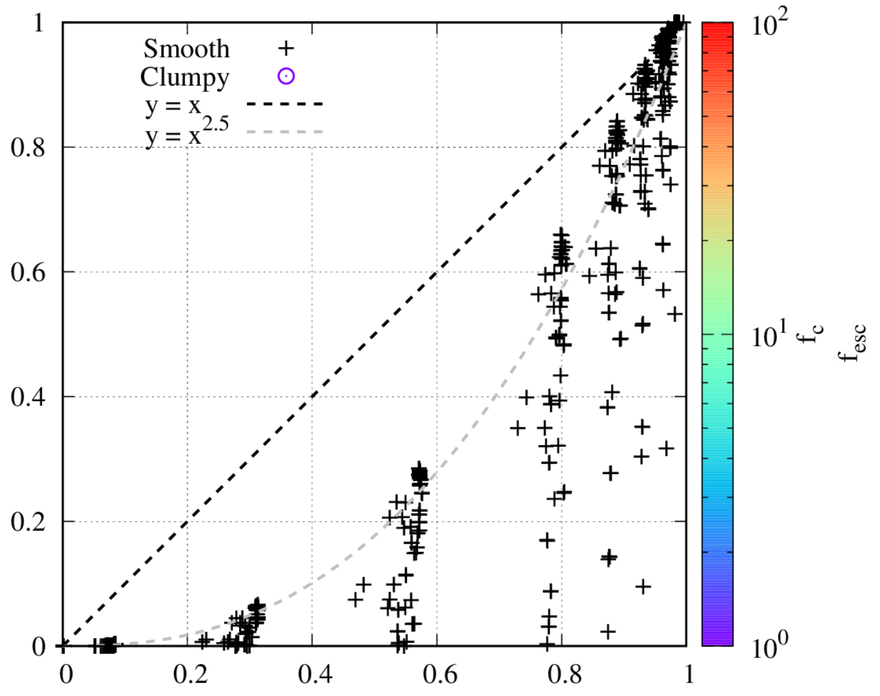
Lower metallicity induces a larger gap of between Lyα and Mg II



of Lyα < of Mg II because

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

Mg II & Lyα escaping fraction

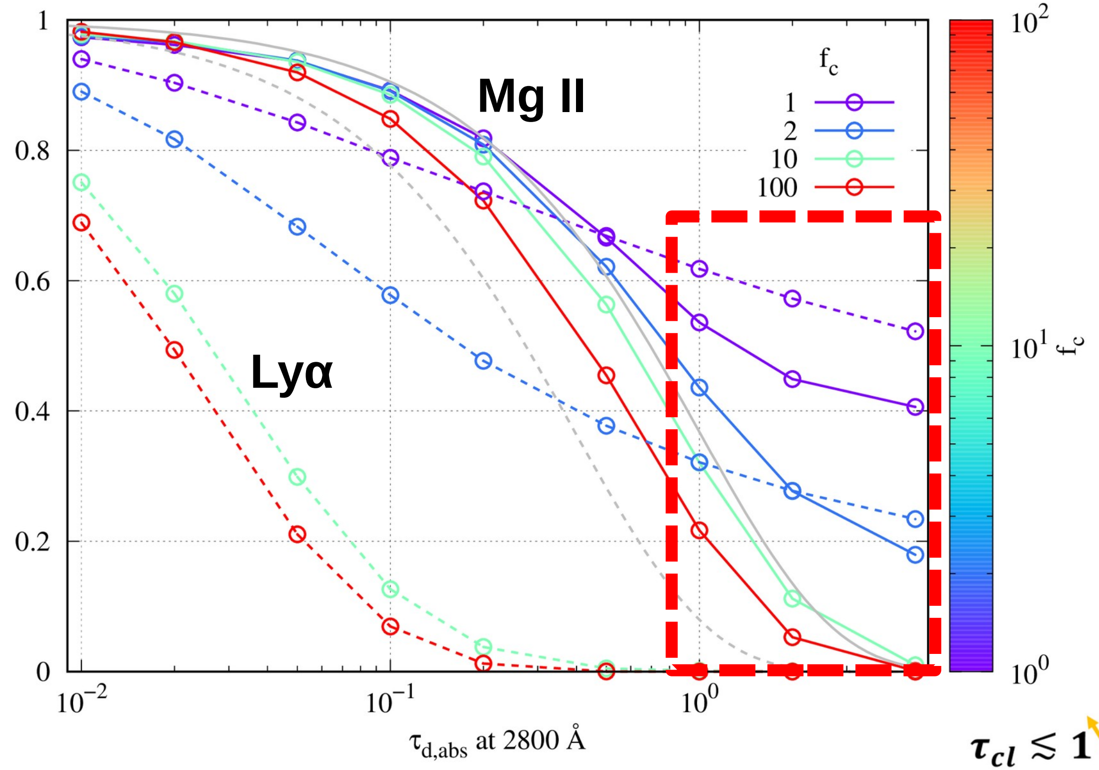


of Lyα

of Mg II

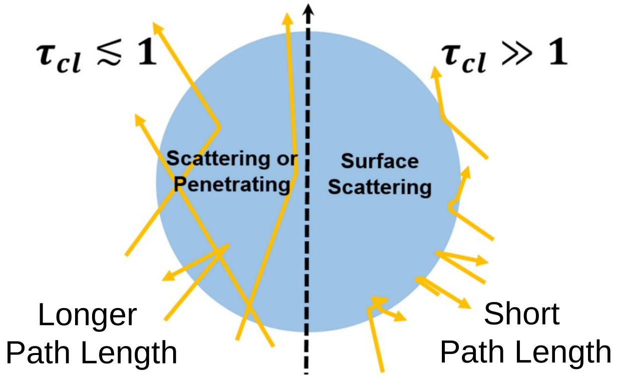
of Lyα < of Mg II

in smooth medium



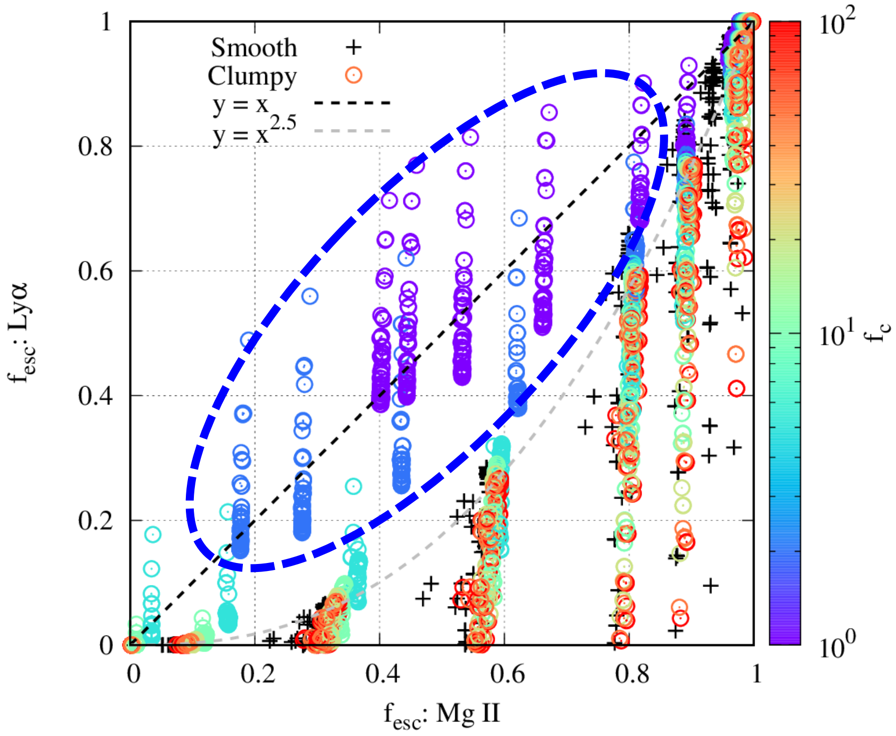
Covering factor

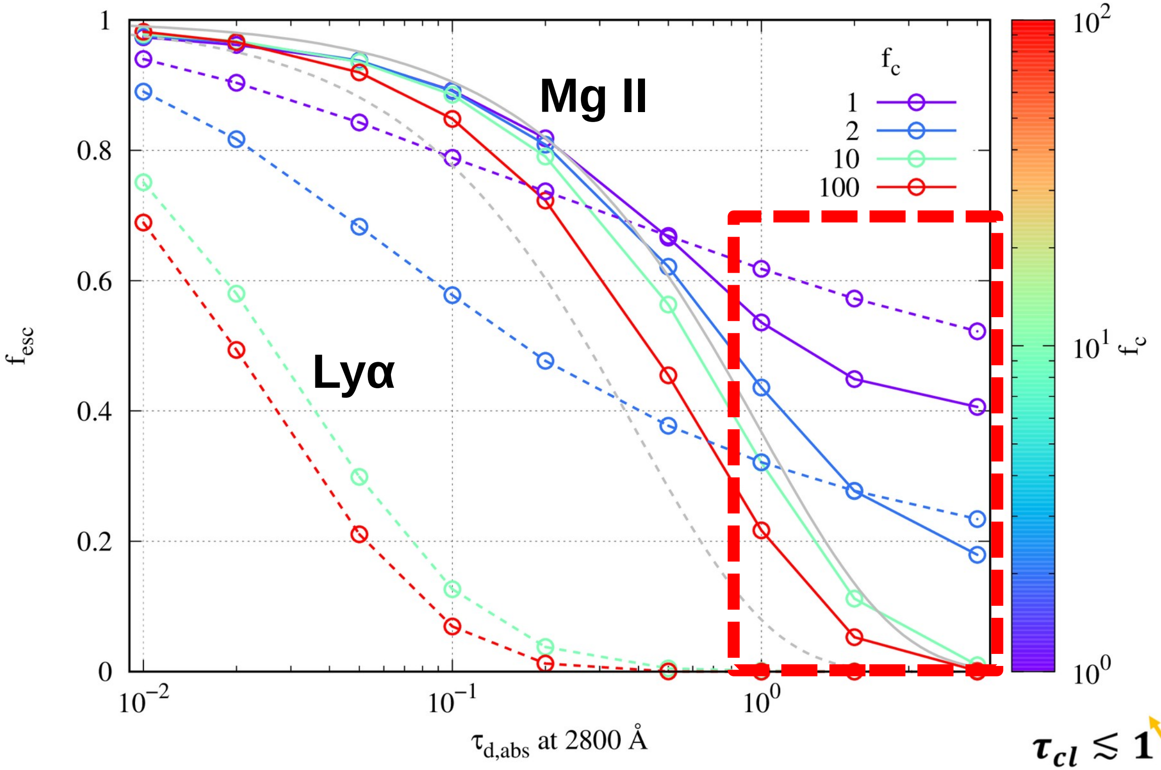
of Lyα > of Mg II when

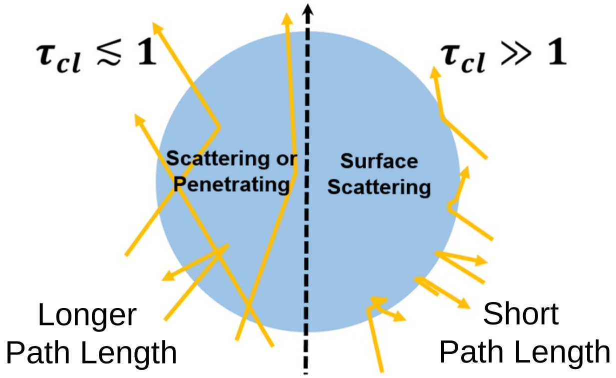


Surface Scattering
Neufeld 1991, Chang et al. 2023

Mg II & Lyα escaping fraction







Surface Scattering
Neufeld 1991, Chang et al. 2023

of Lyα < of Mg II

in smooth medium

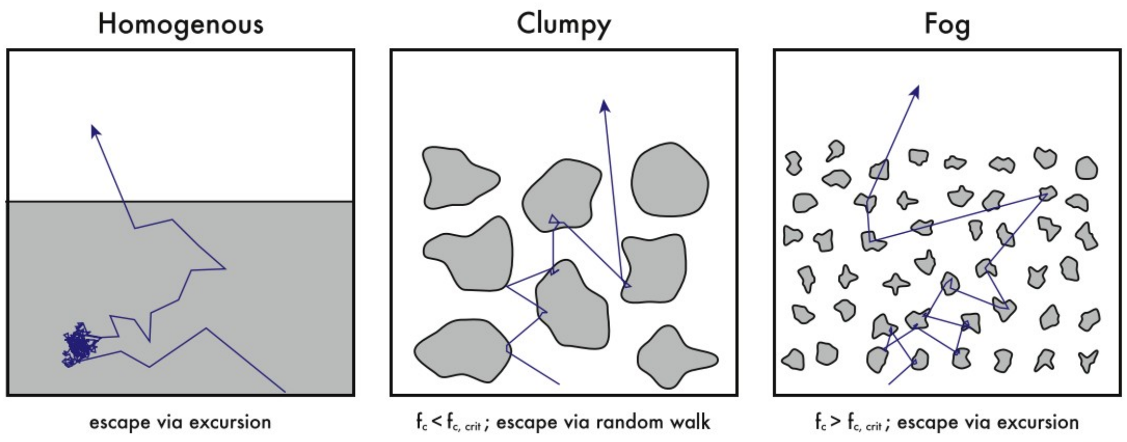
of Lyα ~ of Mg II

in clumpy medium at

Covering factor

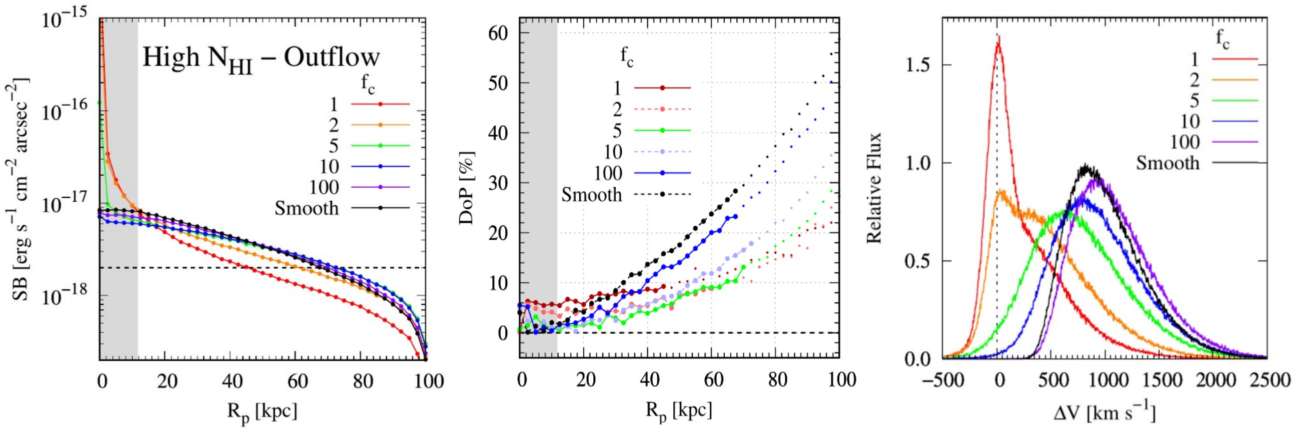
of Lyα > of Mg II when

Lyα & Mg II Spectra in Clumpy Medium



Gronke et al. 2016

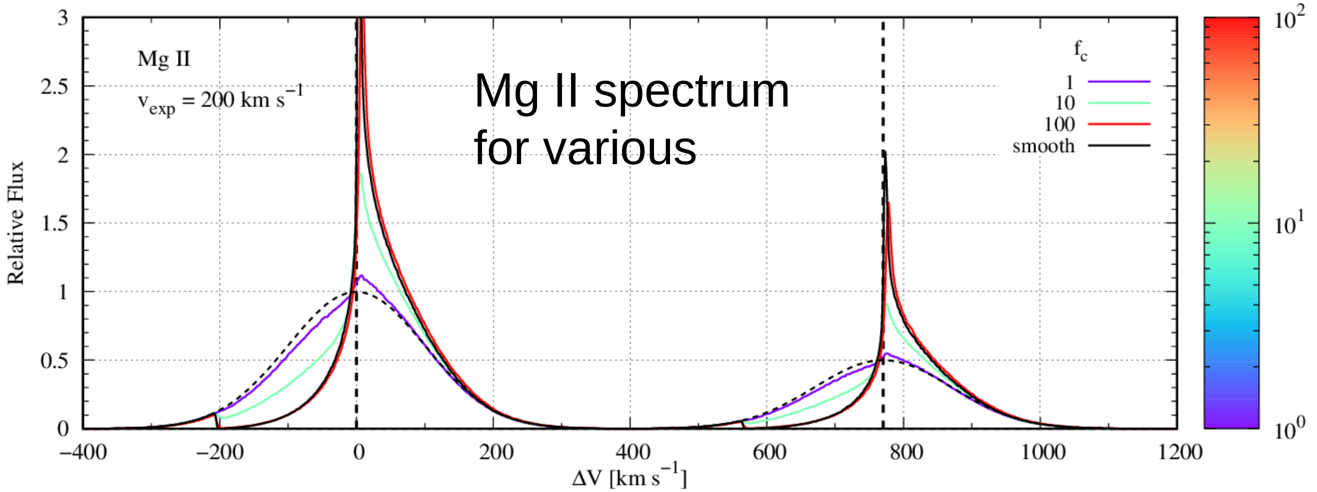
Gronke et al. 2017 noted that the Lyα spectrum at is comparable to that in smooth medium.



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

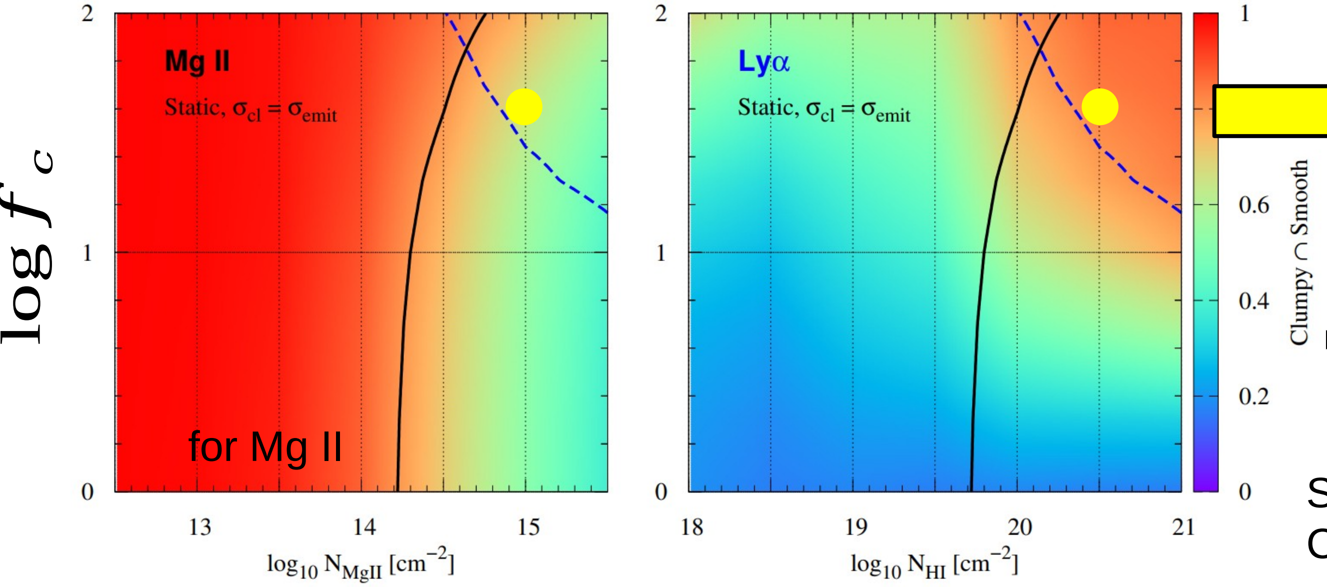
Chang et al. 2023 confirmed that high causes similar behavior for the surface brightness and polarization.

Lyα & Mg II Spectra in Clumpy Medium

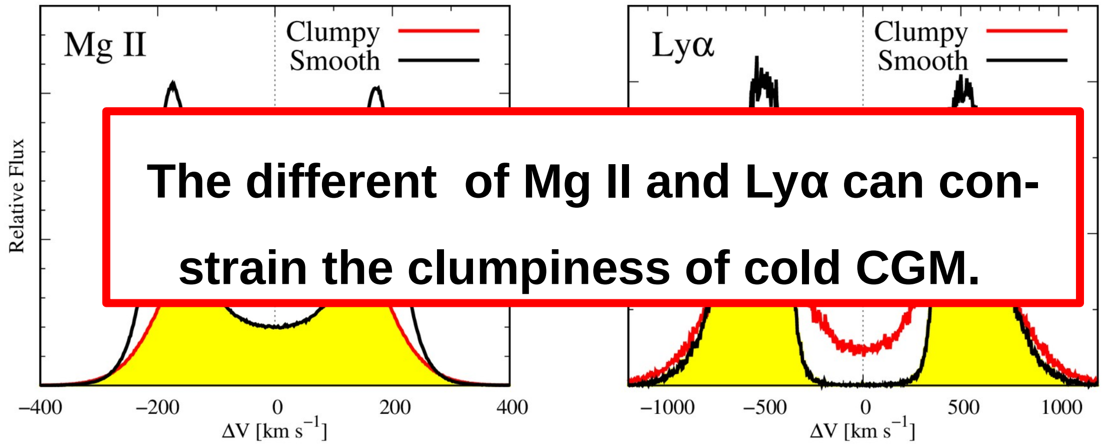


The Mg II spectrum at is identical to that of smooth medium.

for Lyα



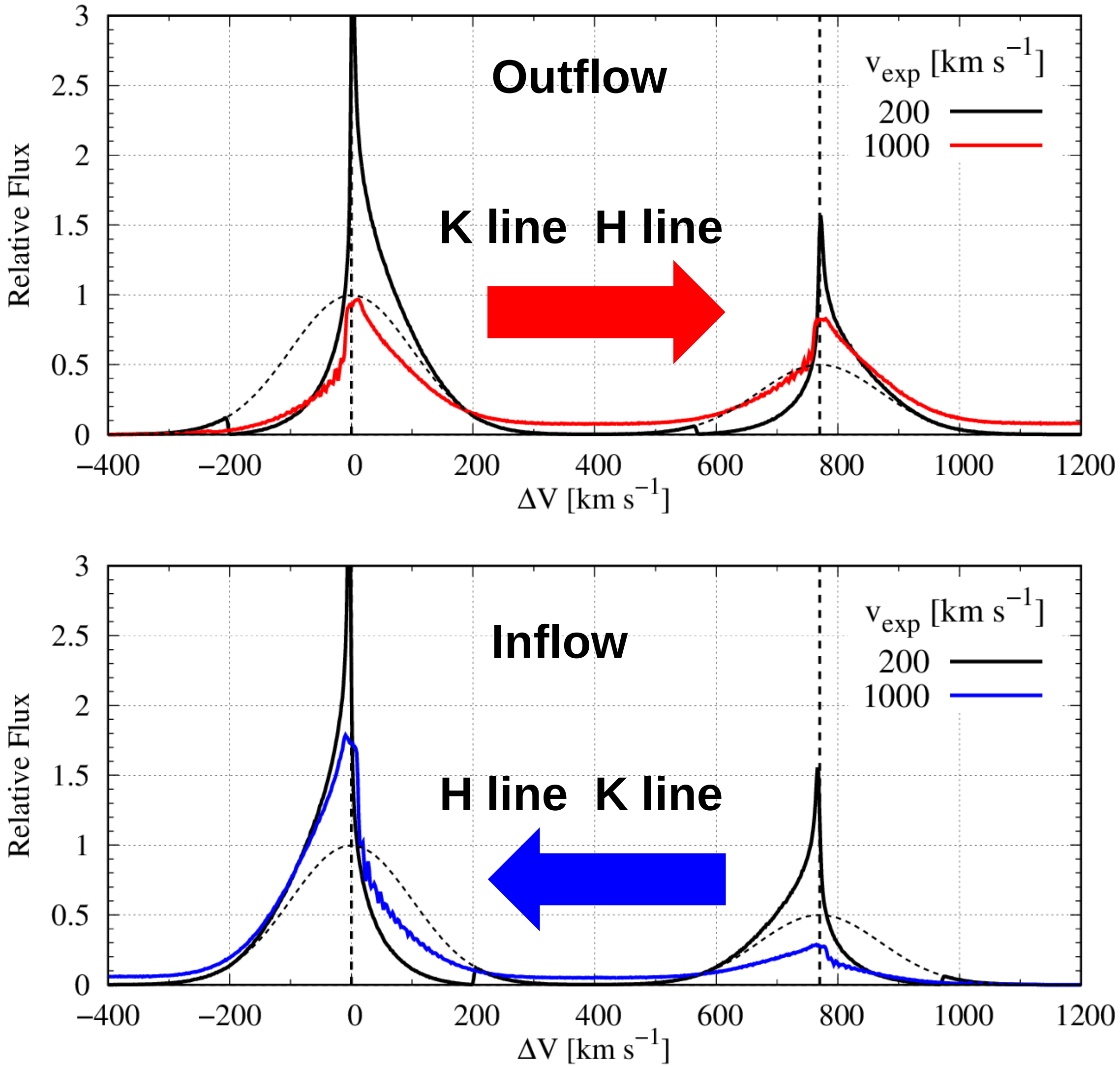
$f_c = 50$

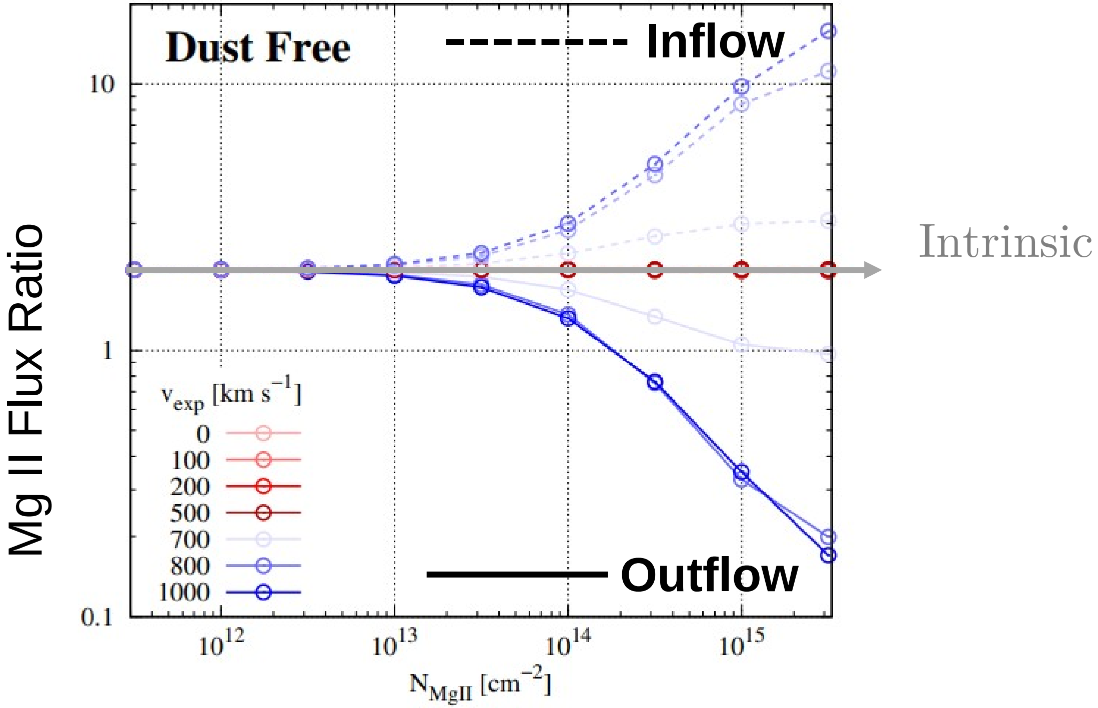


The different of Mg II and Lyα can constrain the clumpiness of cold CGM.

Similarity of Spectra from Clumpy and Smooth Medium

Mg II Flux Ratio by Kinematics

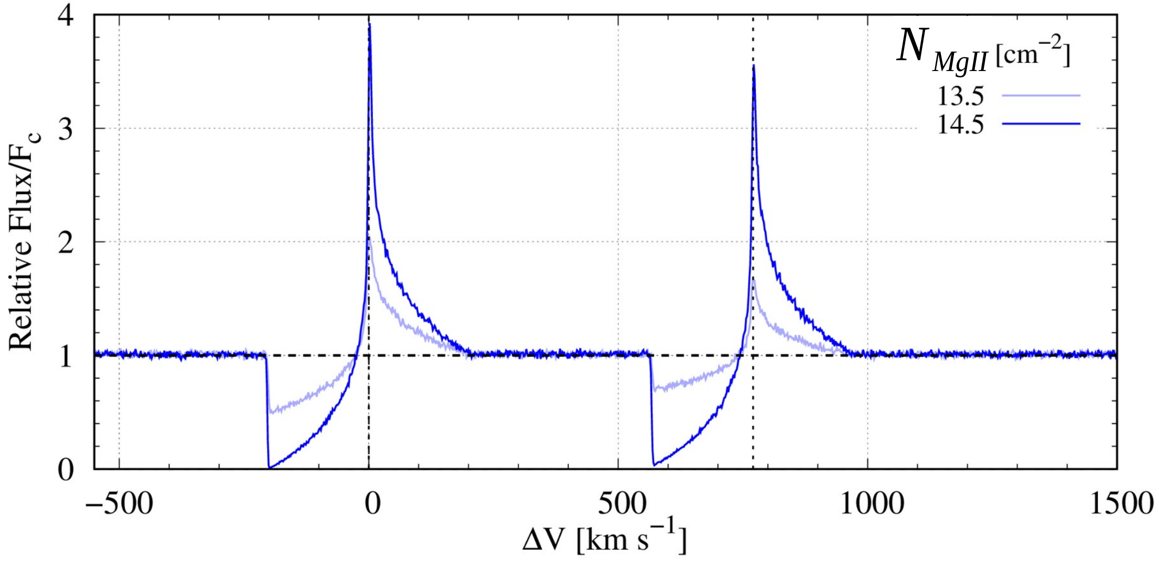


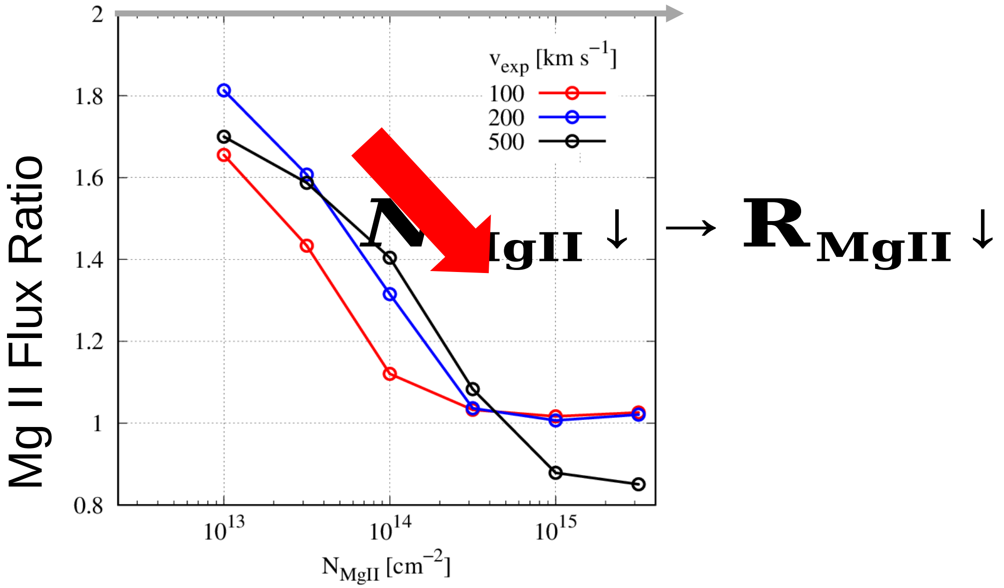


increases (decreases) with the increasing out-flow (inflow) velocity when **and .**

Mg II Flux Ratio from Scattering of Stellar Continuum

Intrinsic flux ratio of
in situ emission,

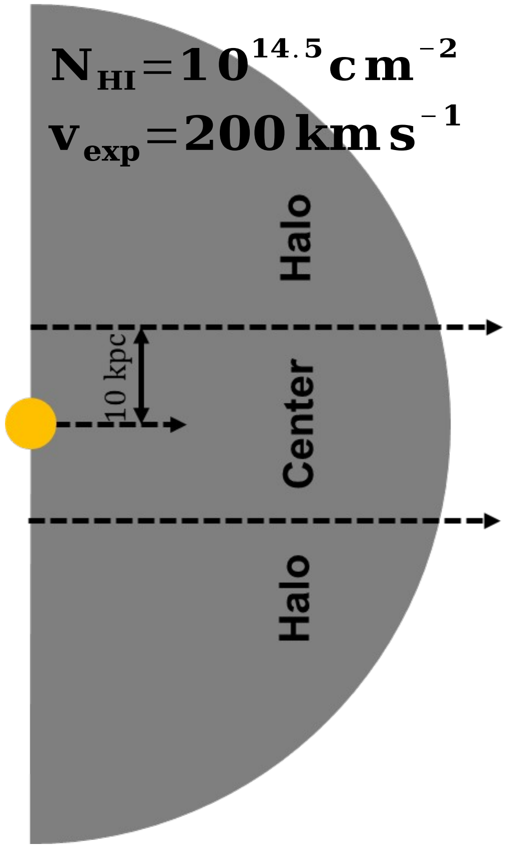


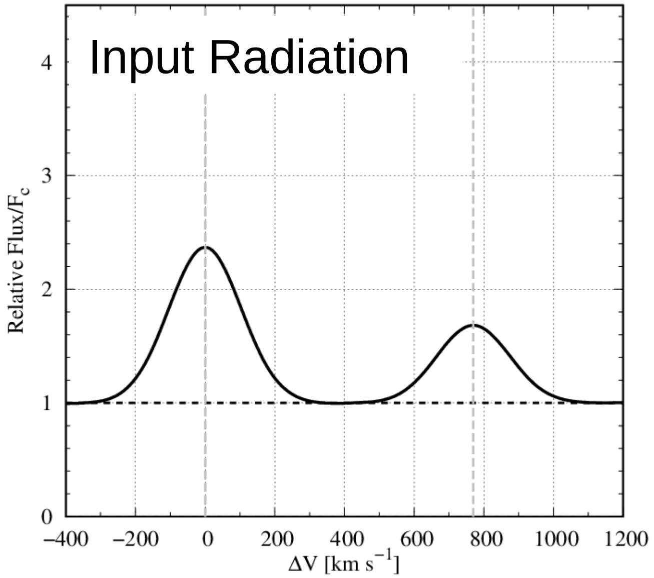


- At , the emission and absorption features of the K line are stronger than of H line.
- At , the profile of K line and H line are similar.

Mg II flux ratio < 2

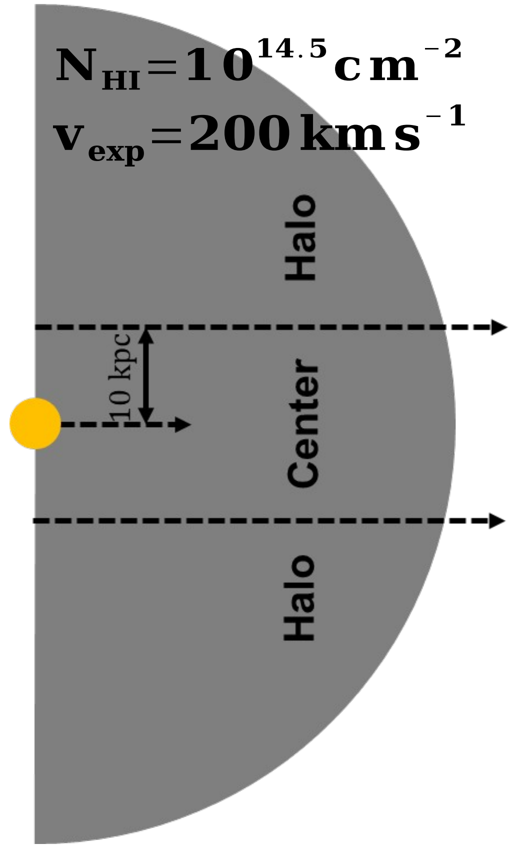
Mg II Emission in Galaxy vs CGM

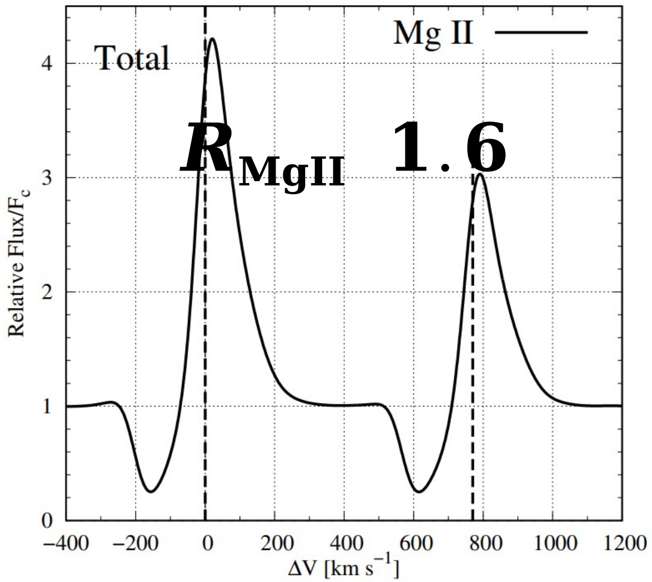




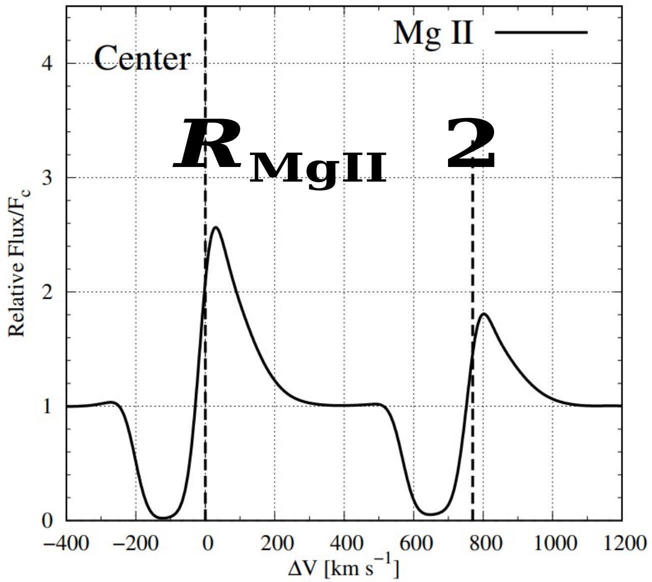
- Flat continuum + Gaussian emission with |EW| = 5 Å
- Convolution with Gaussian function for the width

Mg II Emission in Galaxy vs CGM

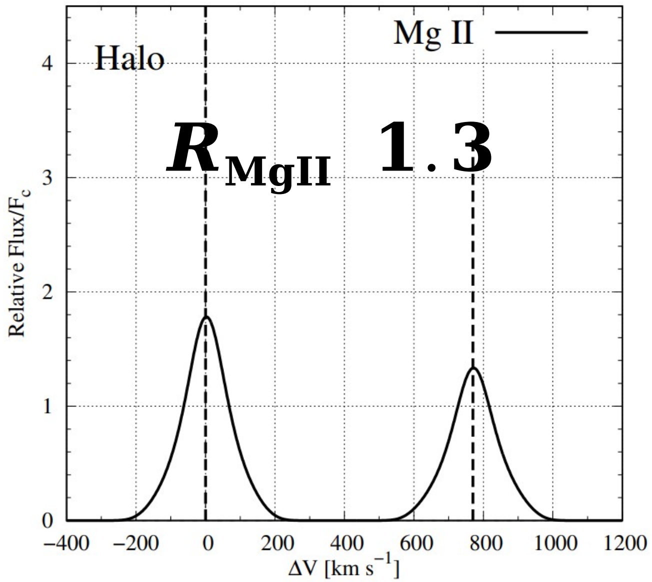




Total integrated spectrum

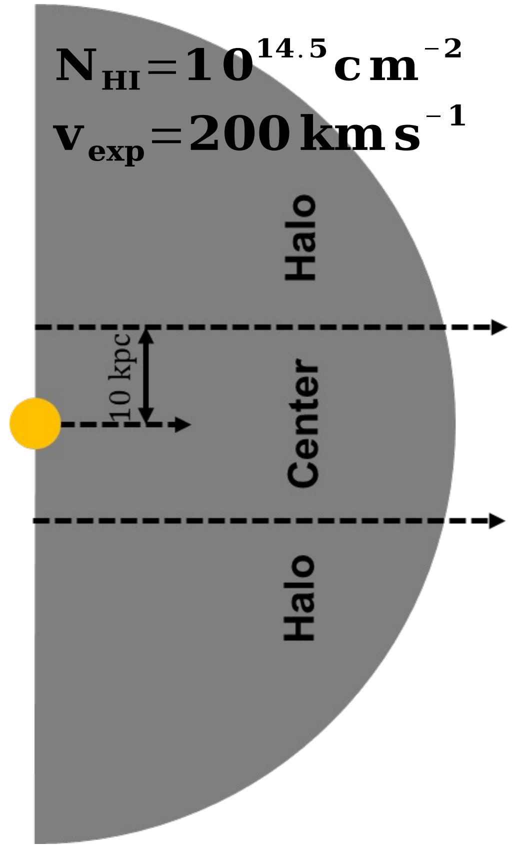


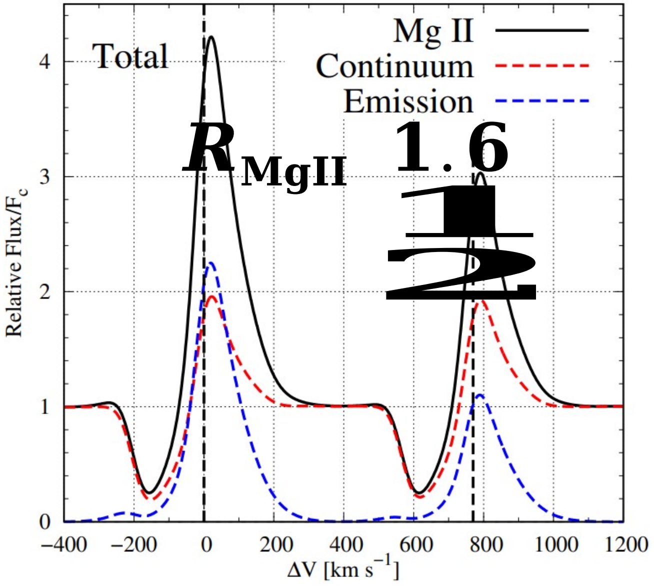
projected radius



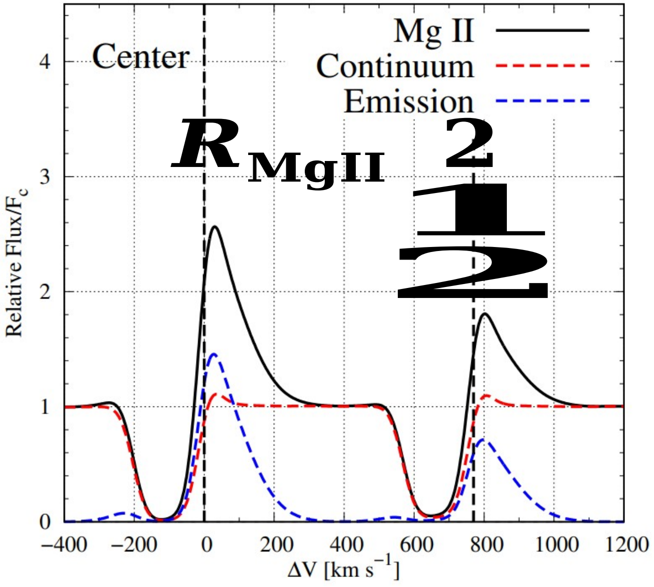
projected radius

Mg II Emission in Galaxy vs CGM

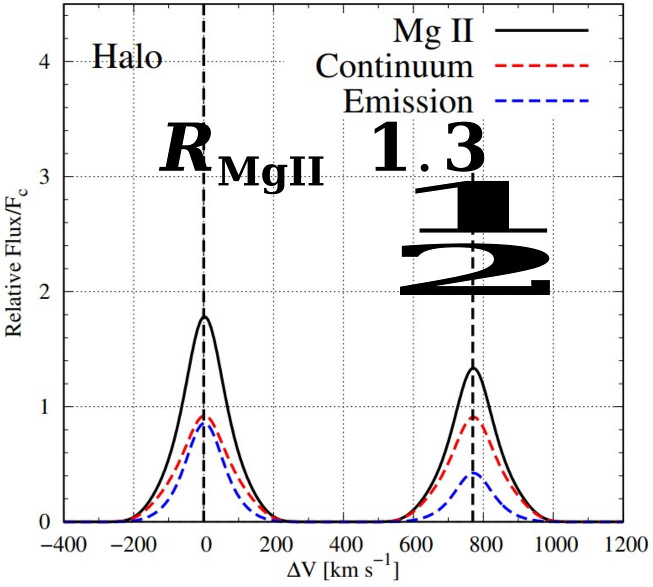




Total integrated spectrum



projected radius

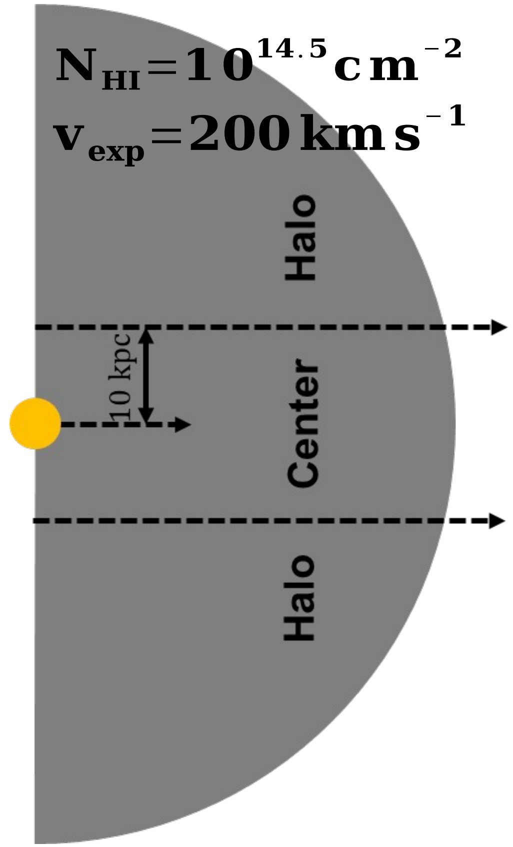


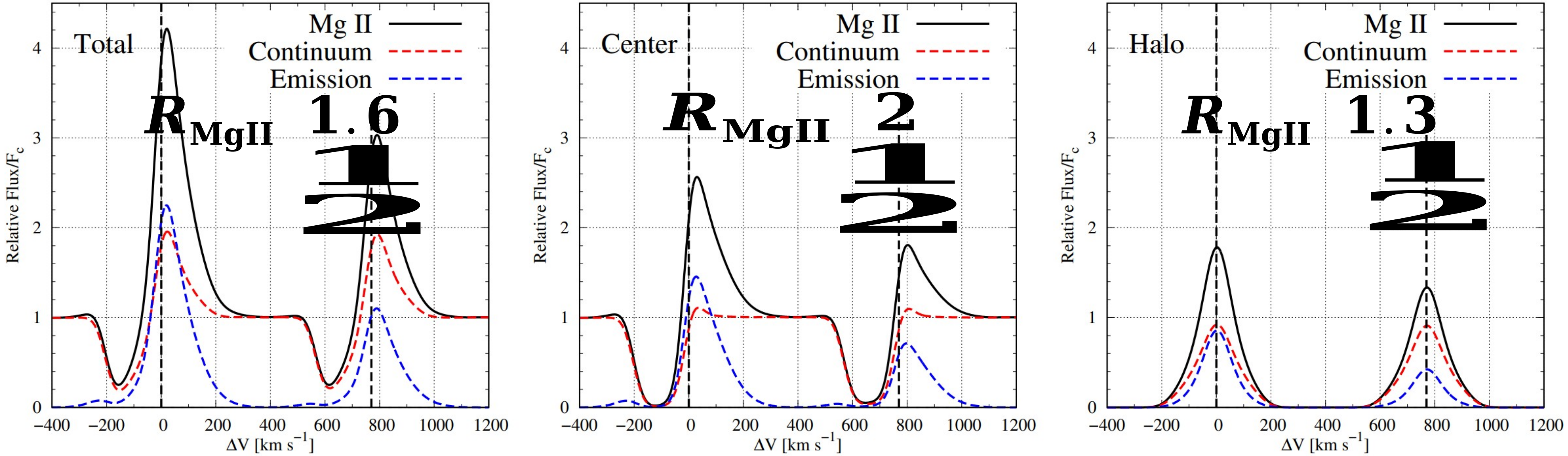
projected radius

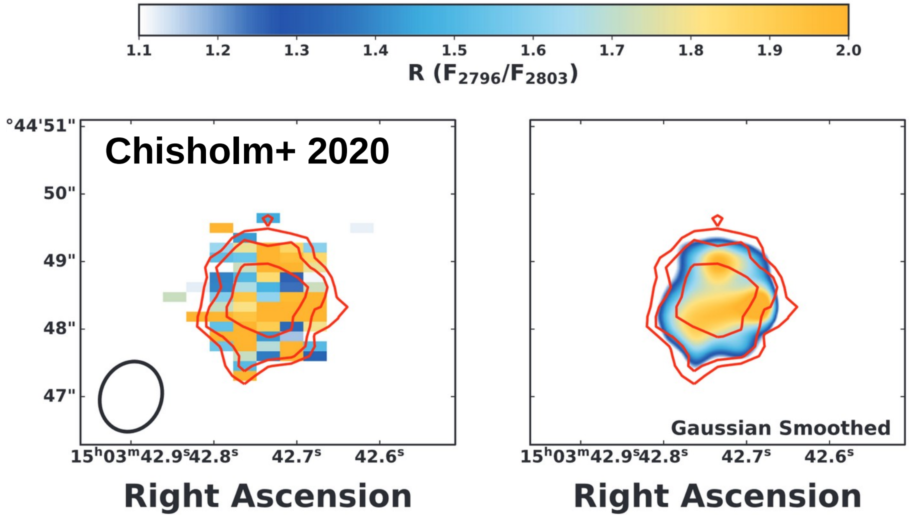
The contribution of Mg II from the continuum and emission determines

Mg II flux ratio

Mg II Emission in Galaxy vs CGM



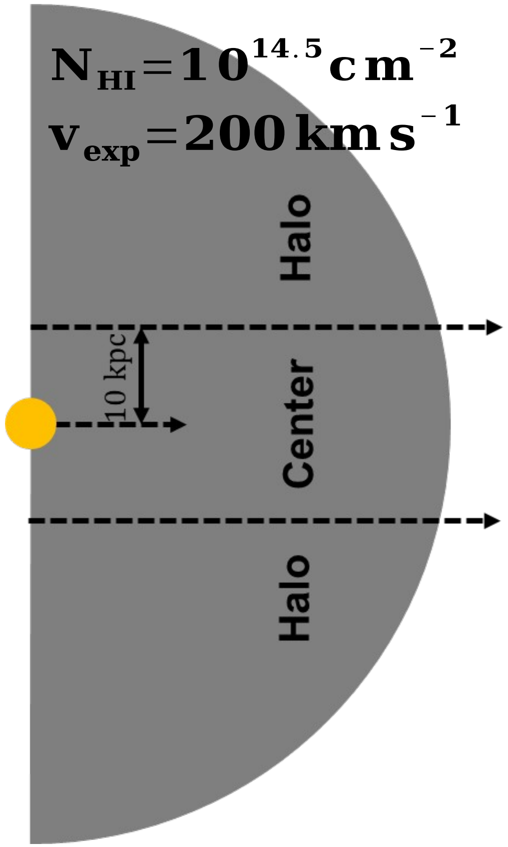


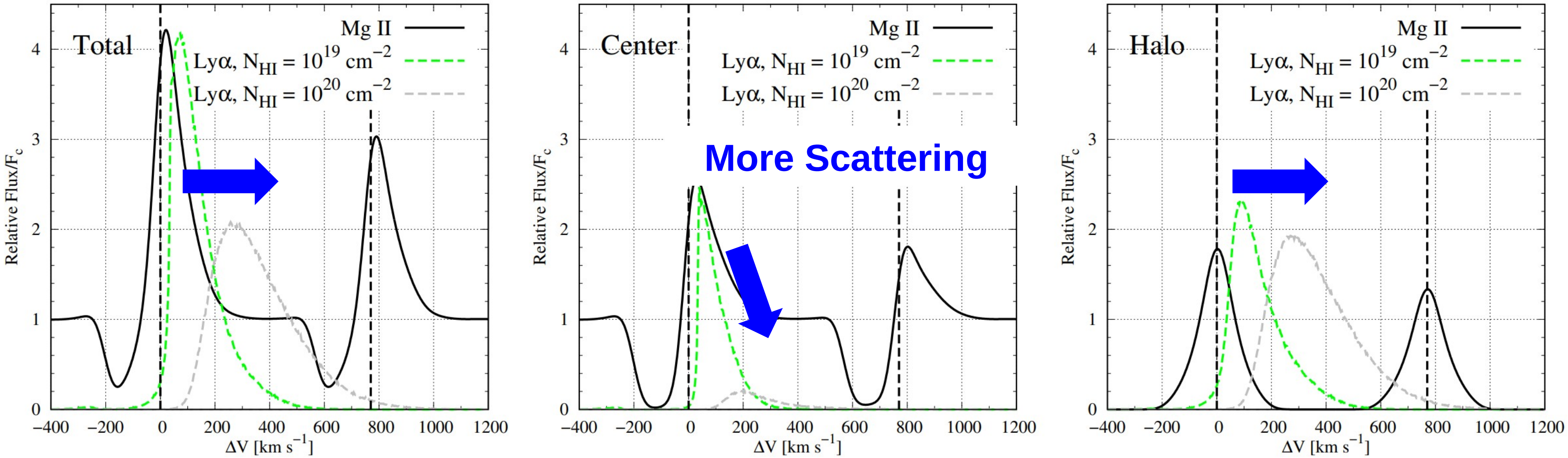


Chisholm et al. 2020 reported Mg II ratio **~ 2 at the center** and **~1.3 in the halo**

The Mg II emission from a continuum can explain

Mg II Emission in Galaxy vs CGM

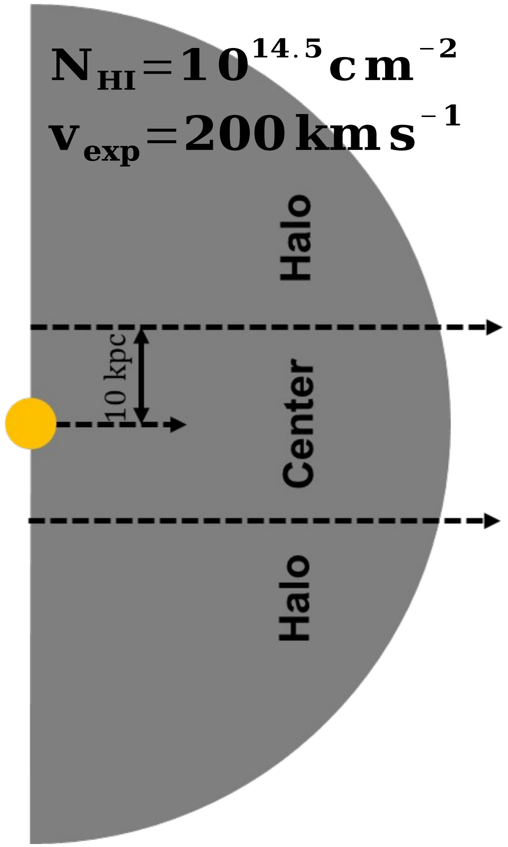


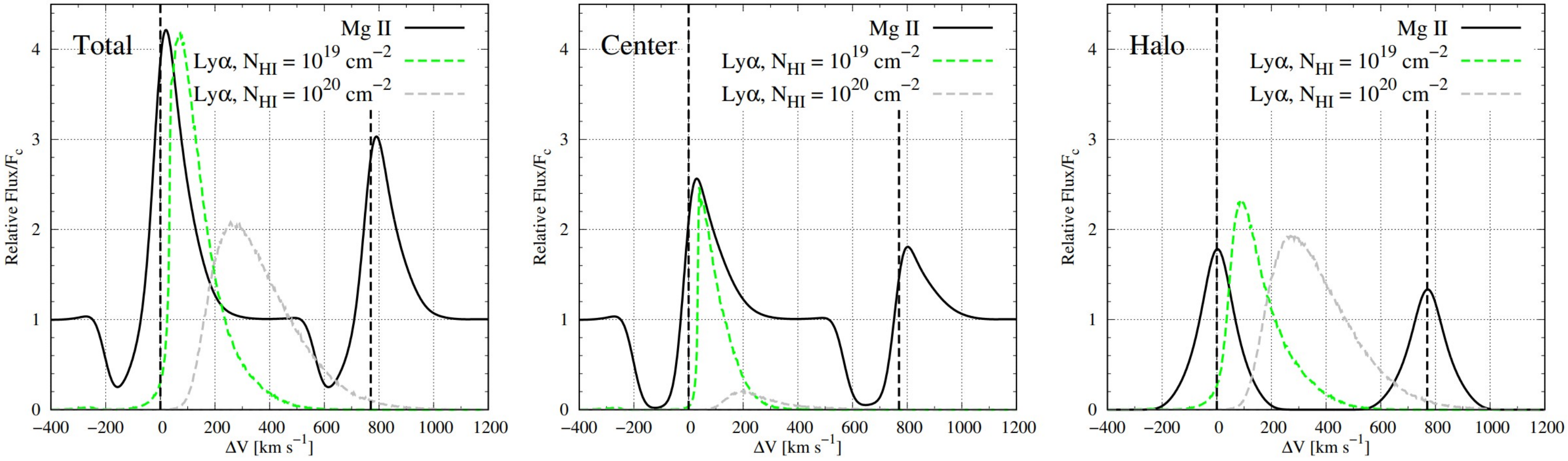


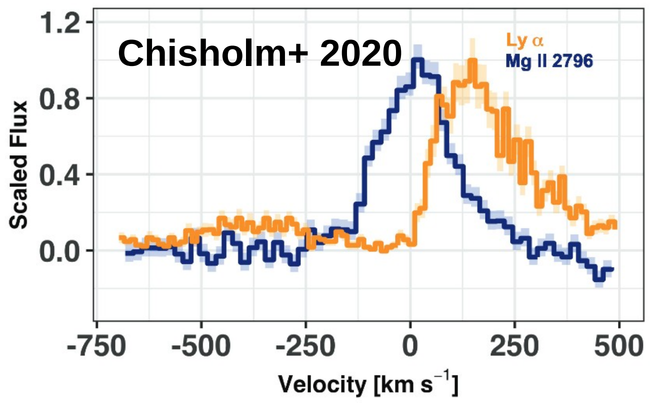
Lyα spectrum is more redshifted and broader than Mg II

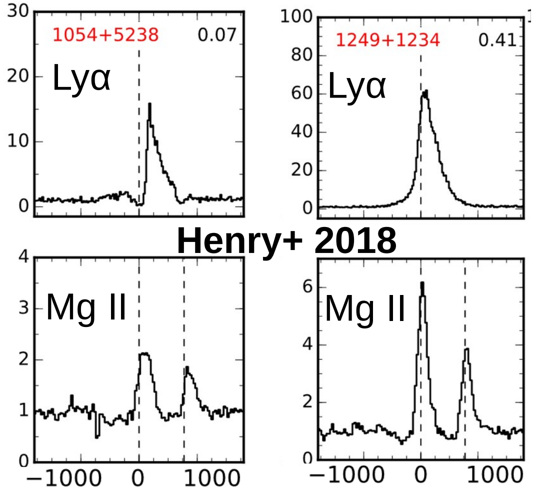
because of .

Mg II Emission in Galaxy vs CGM



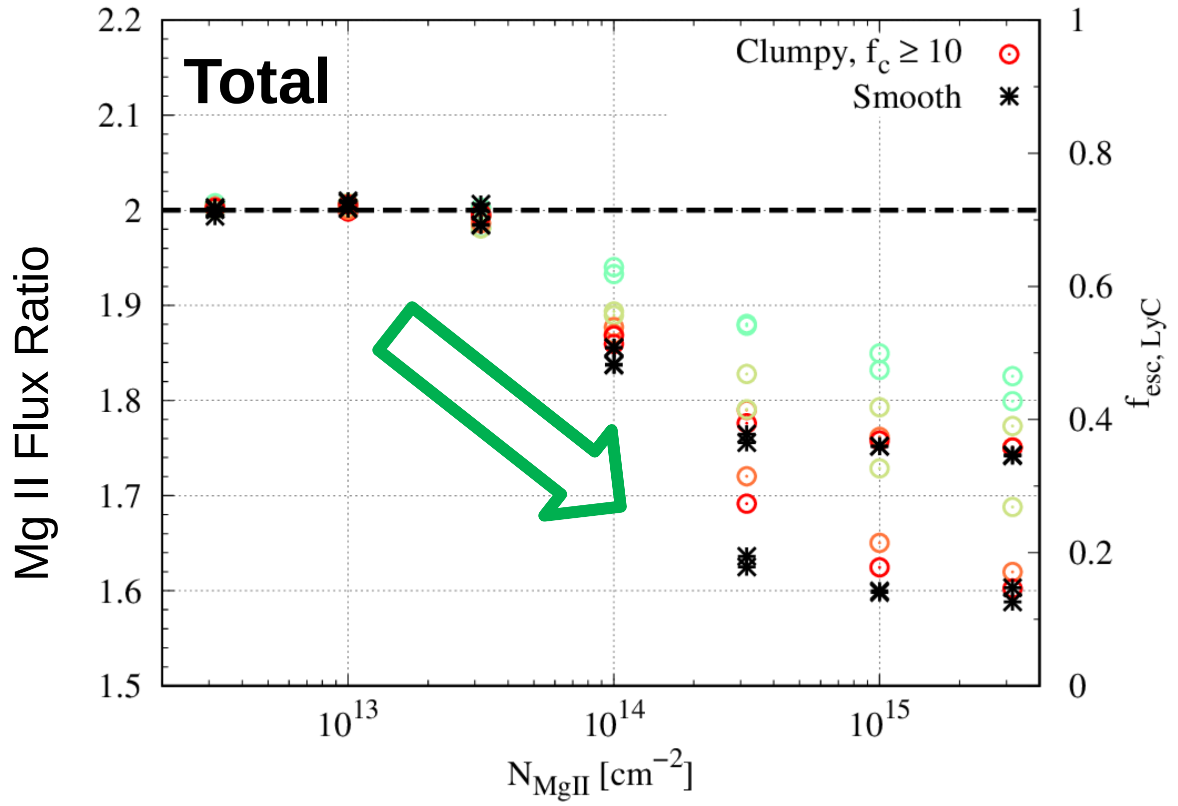






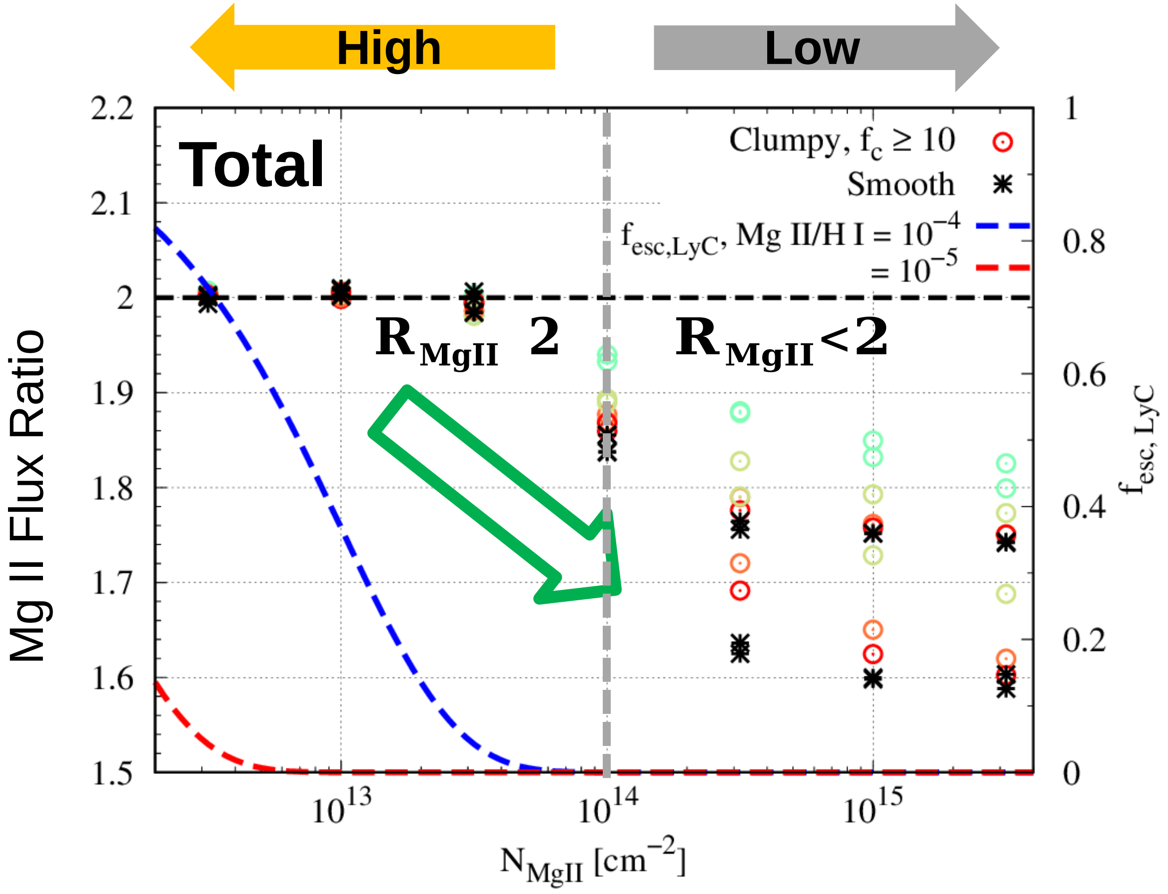
The simulated spectra are comparable to observational spectra of Mg II and Lyα.

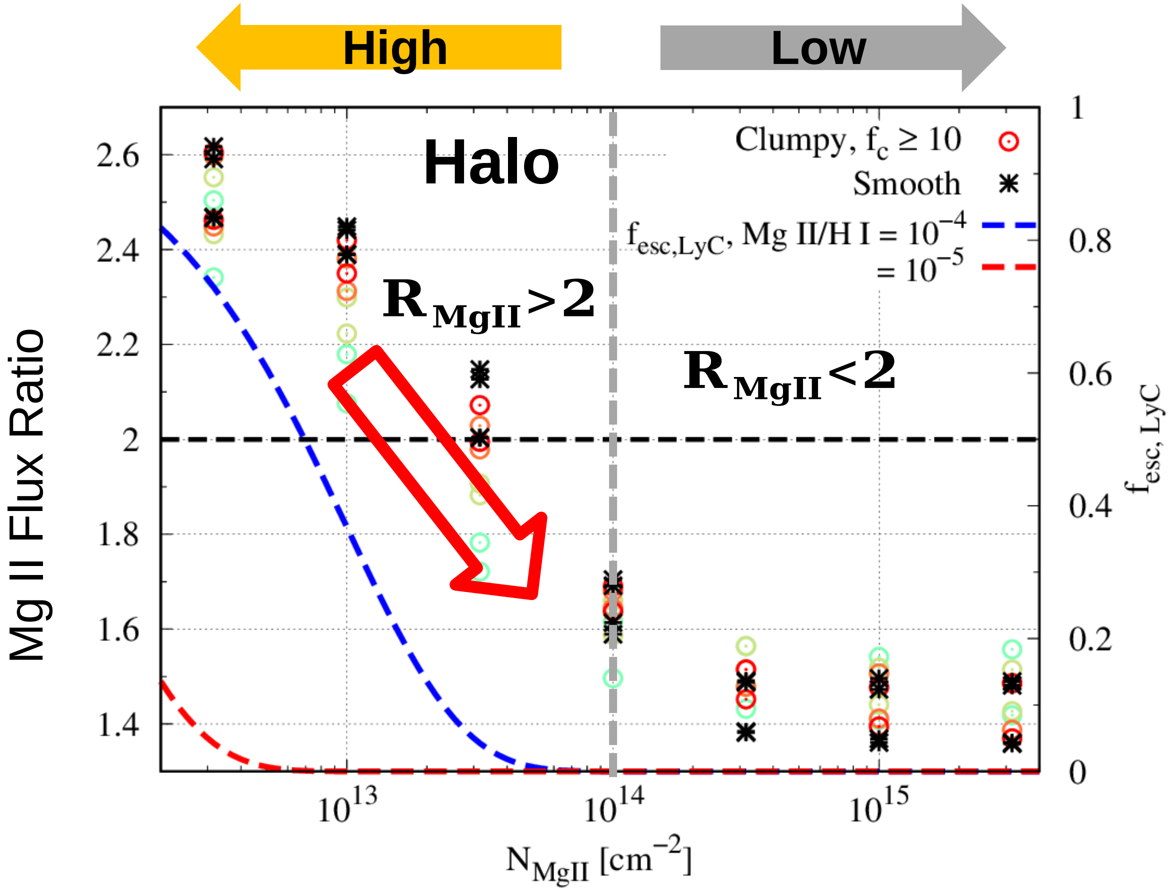
Flux Ratio of Mg II Emission & LyC Escaping Fraction



Because of contribution of the continuum

Flux Ratio of Mg II Emission & LyC Escaping Fraction



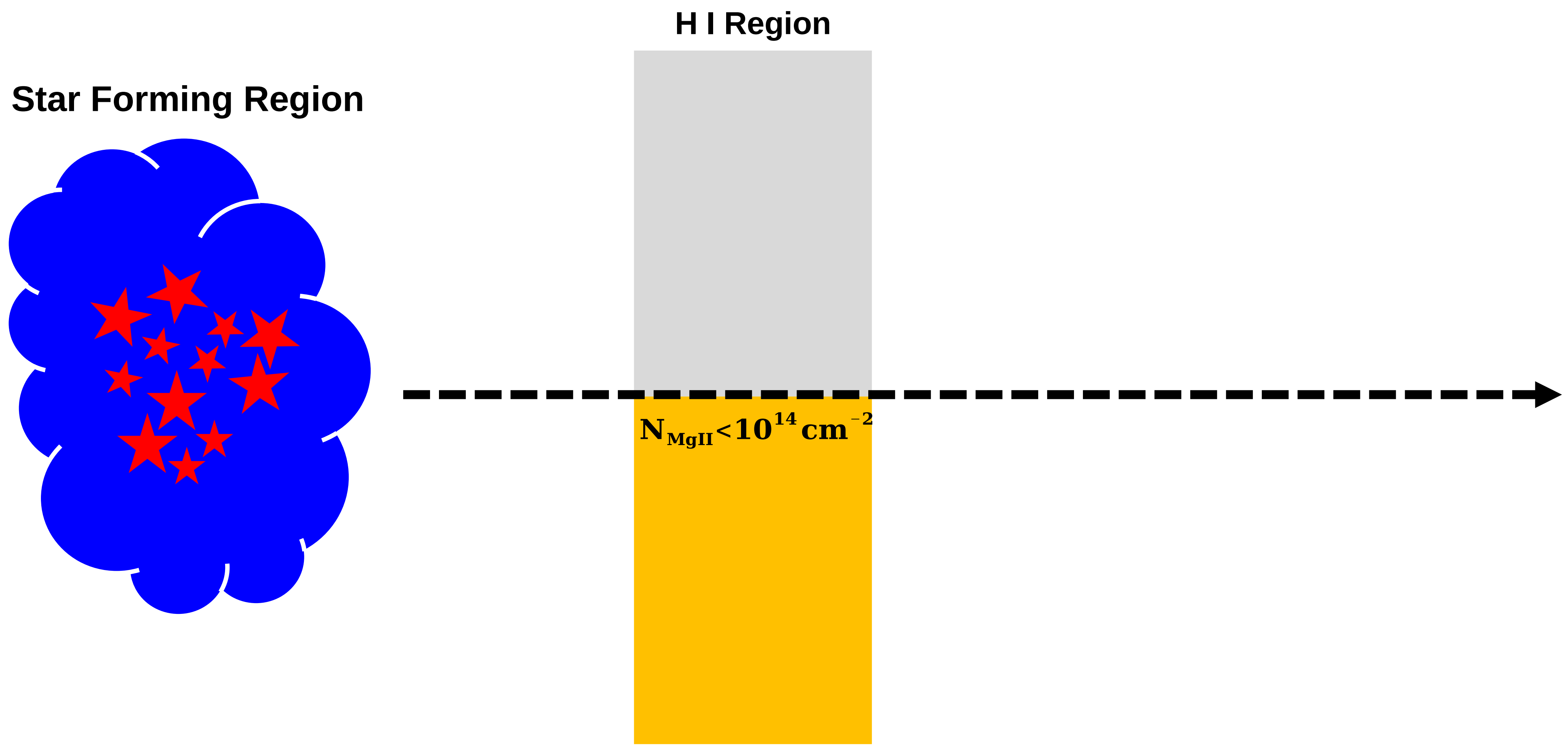


Because of contribution of the continuum

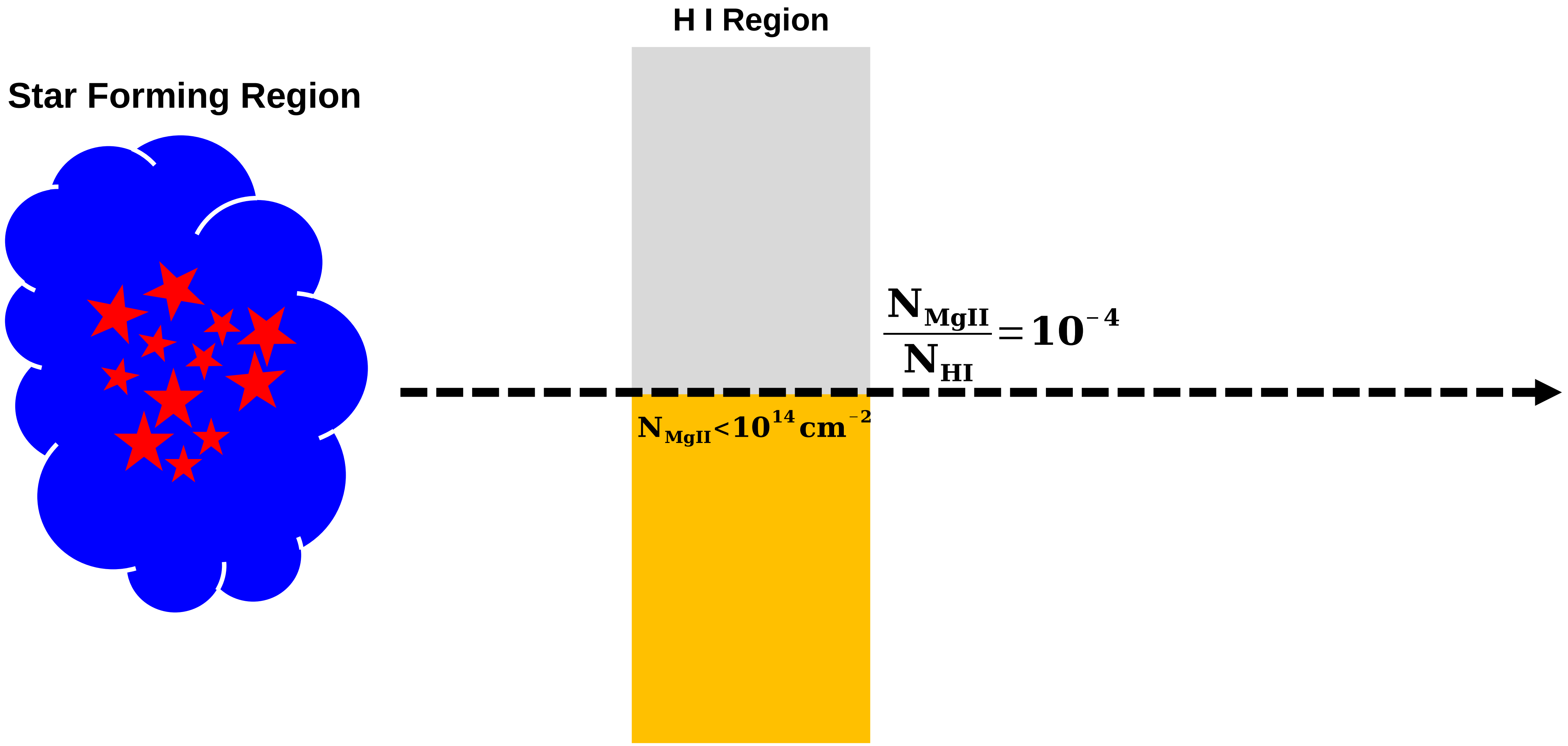
In Halo, **LyC escaping fraction**

Low

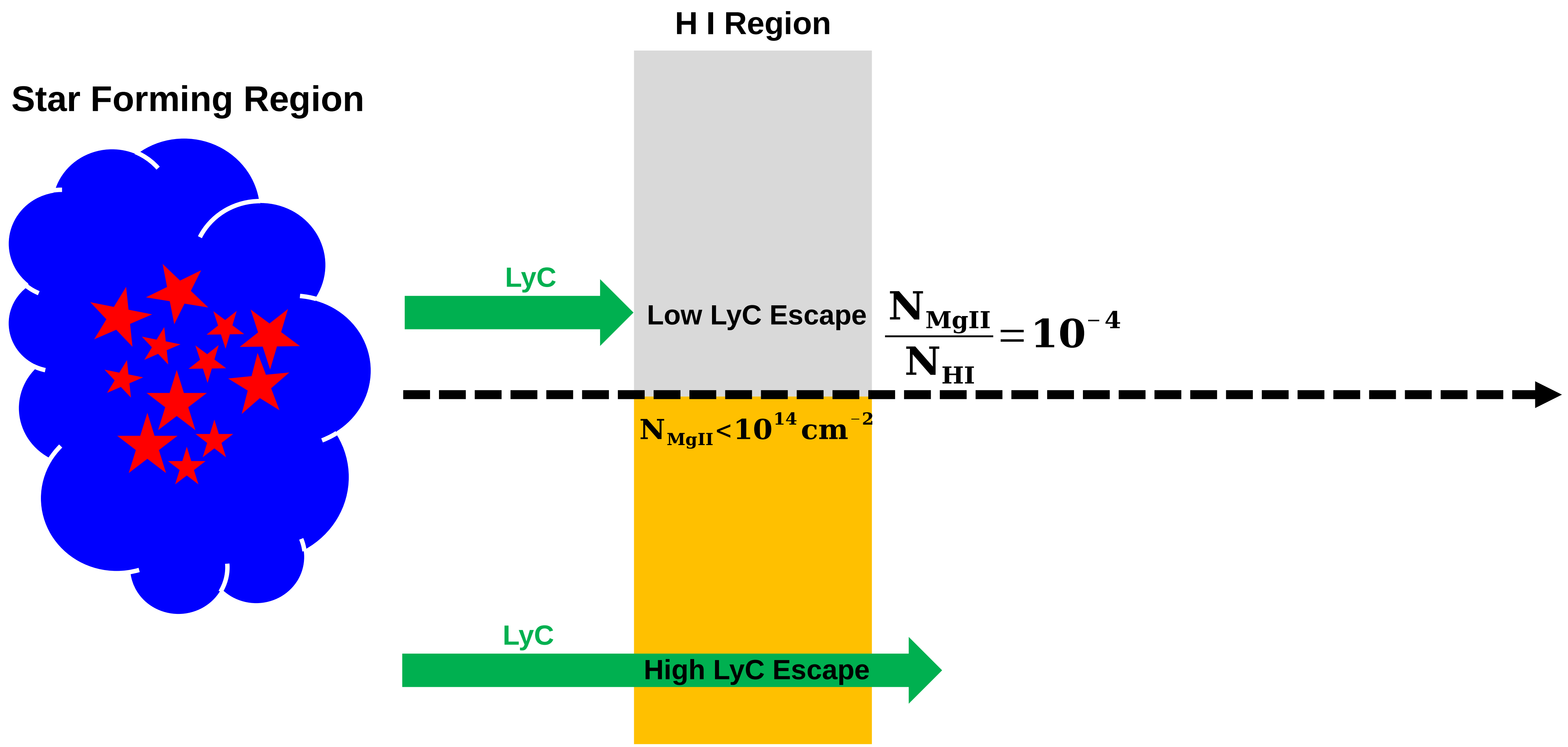
Flux Ratio of Mg II Emission & LyC Escaping Fraction



Flux Ratio of Mg II Emission & LyC Escaping Fraction



Flux Ratio of Mg II Emission & LyC Escaping Fraction



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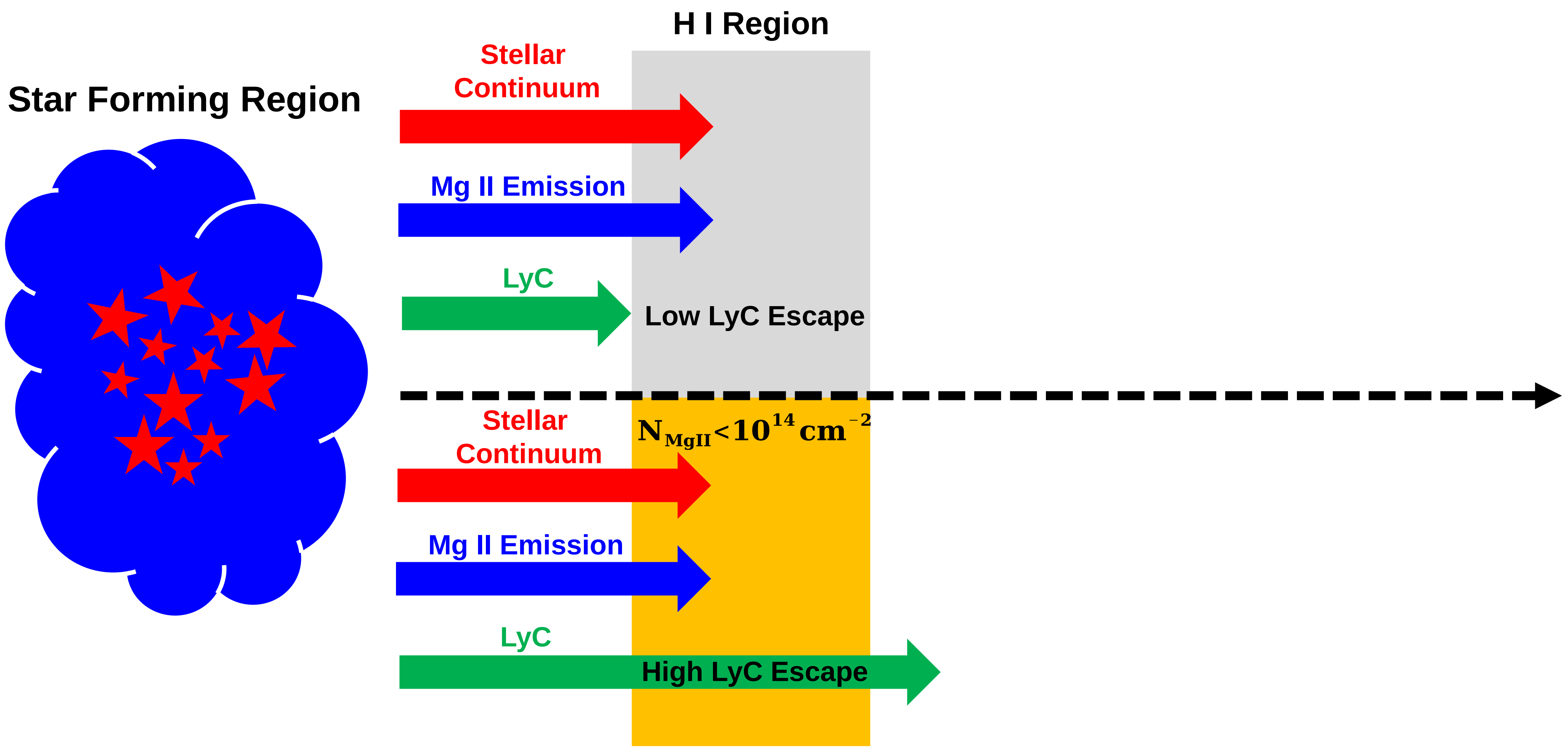
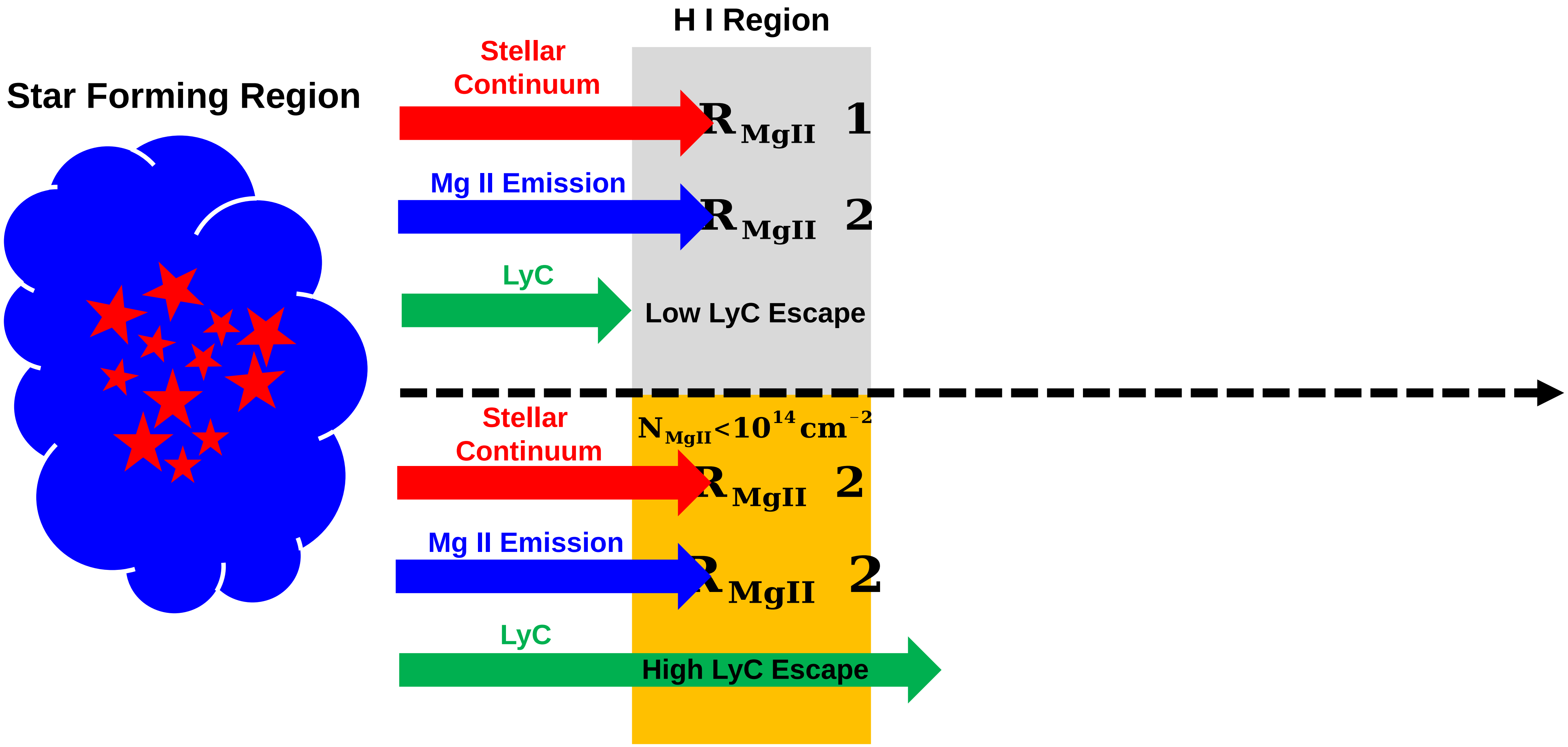
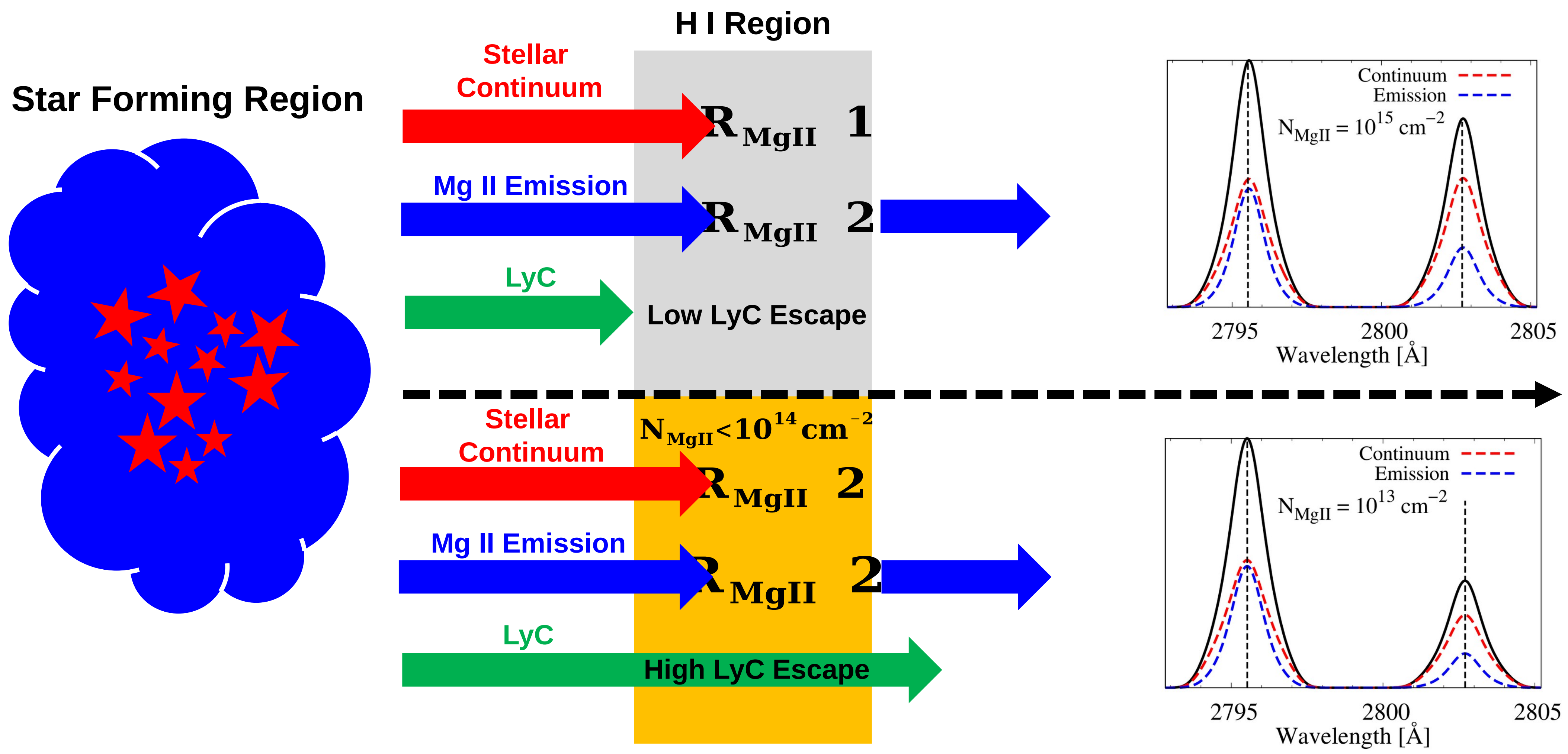


Flux Ratio of Mg II Emission & LyC Escaping Fraction

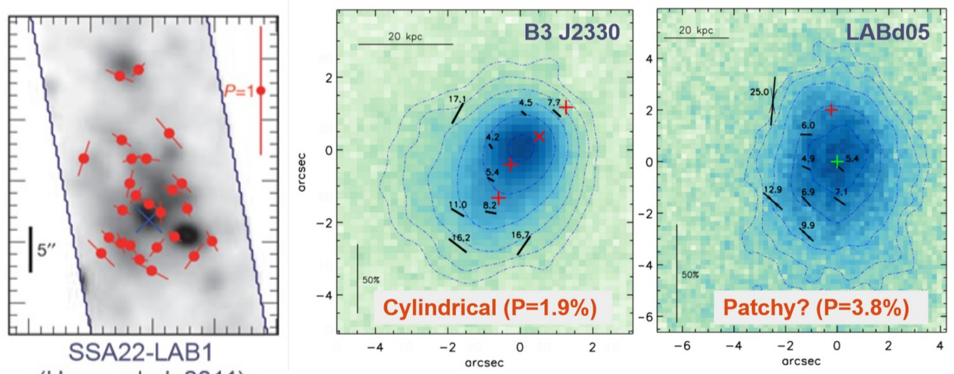


Flux Ratio of Mg II Emission & LyC Escaping Fraction

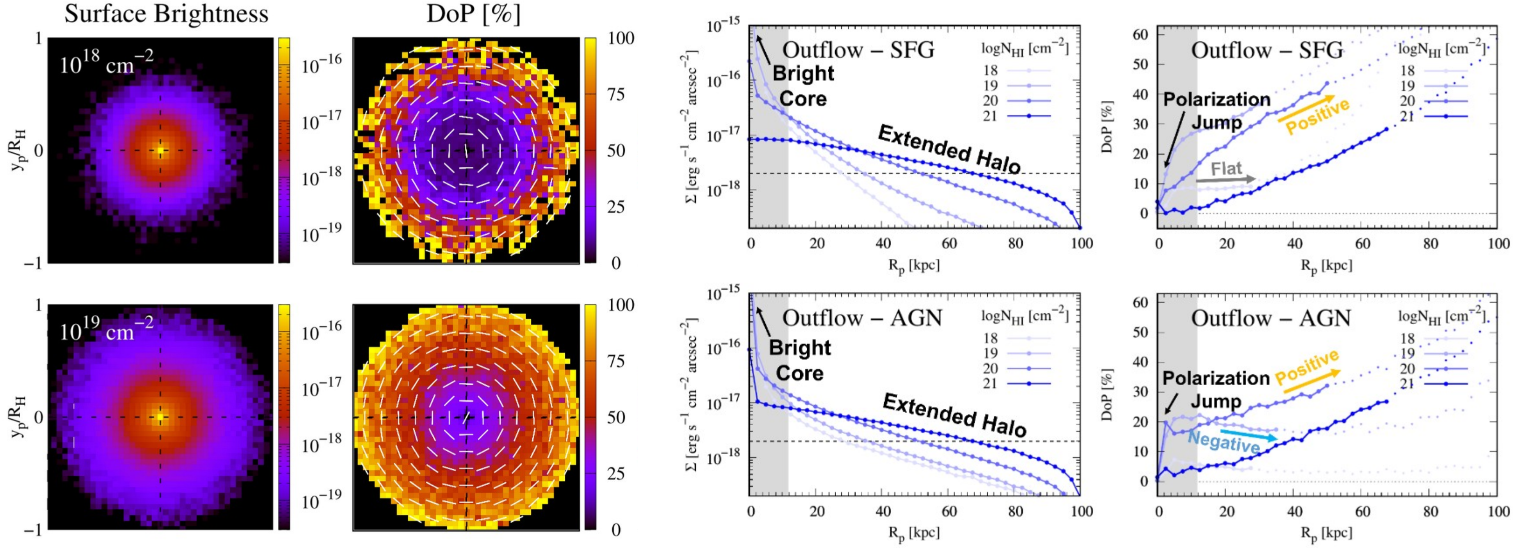


Other Interesting RT effect

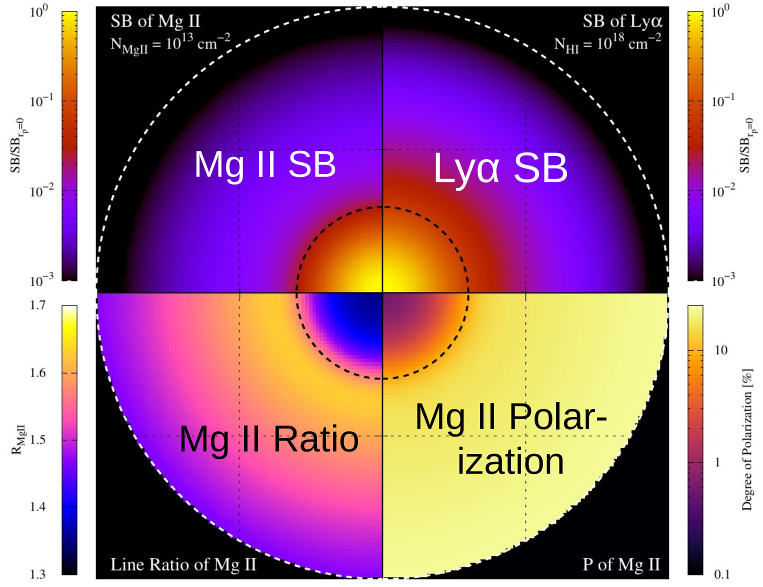
Lyα Polarimetry of LABs



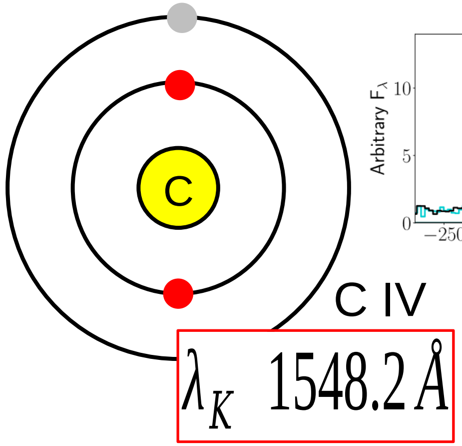
SSA22-LAB1 (Hayes et al. 2011)   You et al 2017   Kim et al 2020

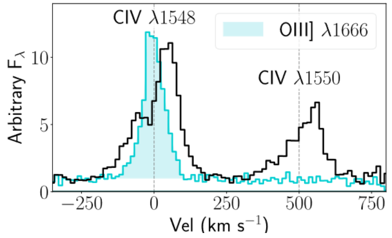


Lyα SB and Polarization
Chang et al. 2023

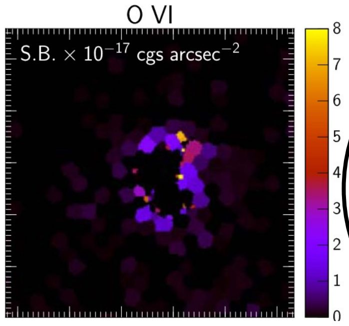


Hot Dynamic Dou ?

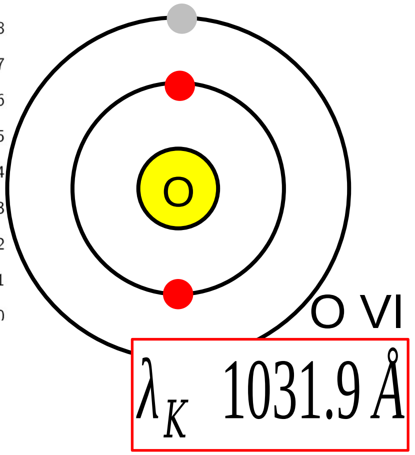




C IV and He II
Berg et al. 2019

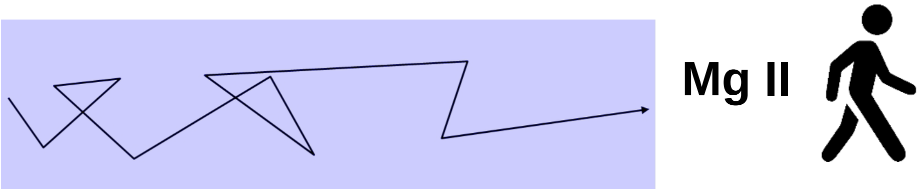


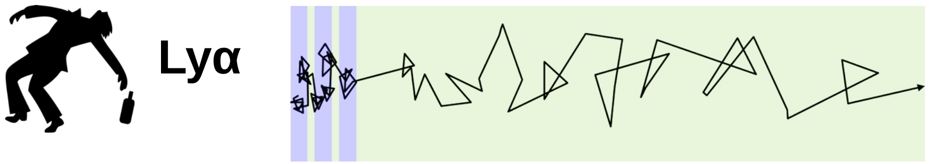
O VI Nebula of SFG
Hayes et al. 2016



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.

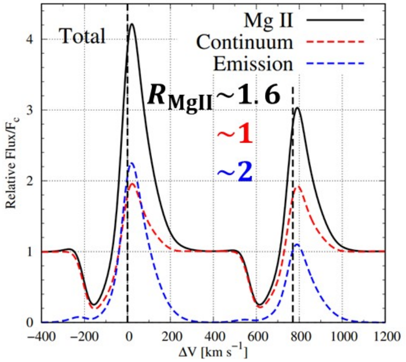


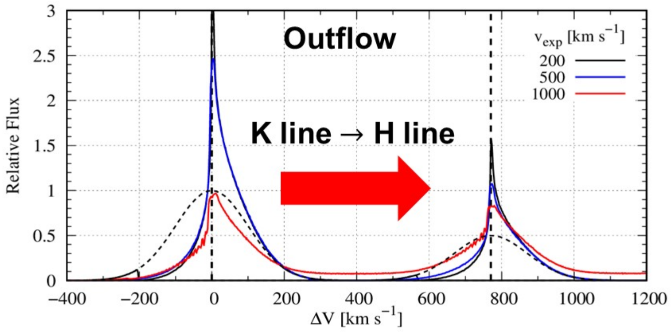


Strong outflow/inflow (> 700 km/s) change the line ratio.

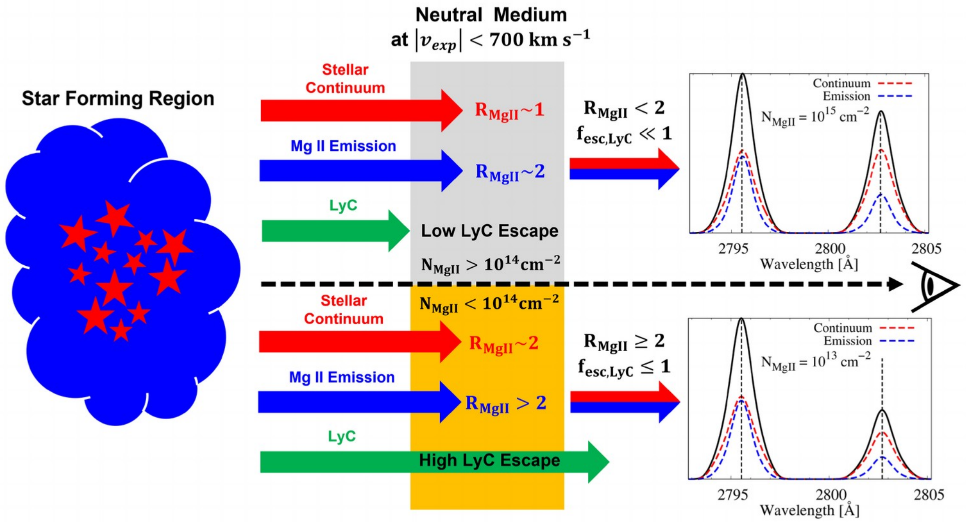
Mg II scattering from the continuum cause .

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

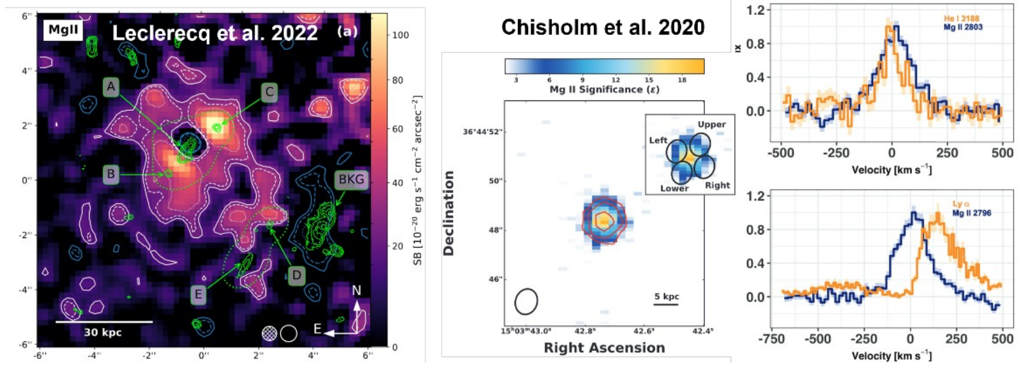




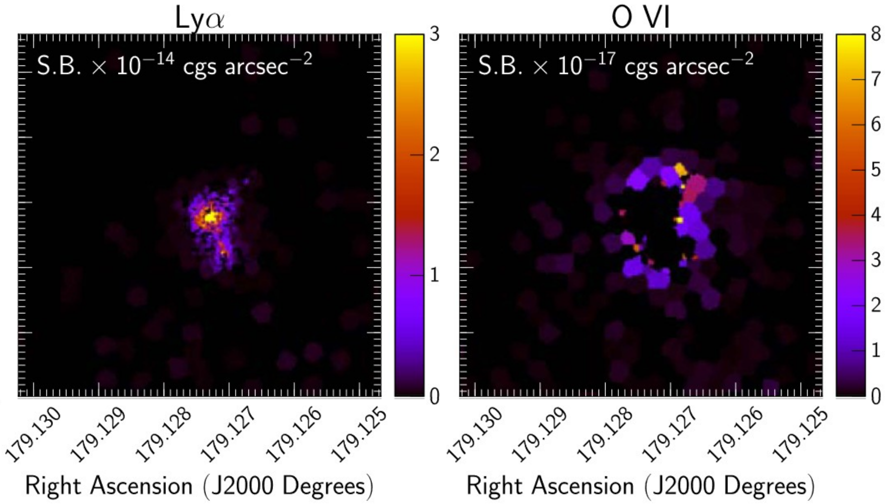
- Mg II flux ratio can be a tracer of LyC escape when st
lar continuum contribute the formation of Mg II emissi



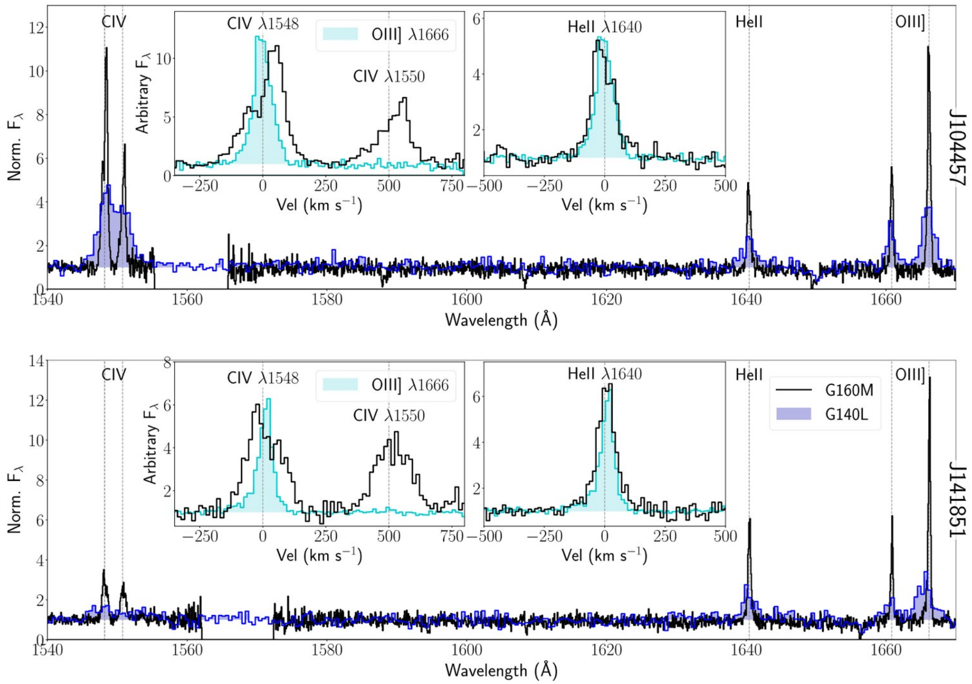
Metal Doublets Emission Nebulae



Mg II Nebulae



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

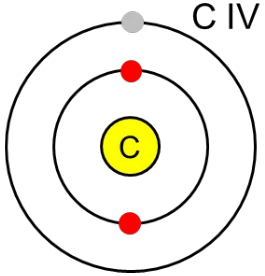


C IV and He II in UV emission galaxies in z ~0
Berg et al. 2019

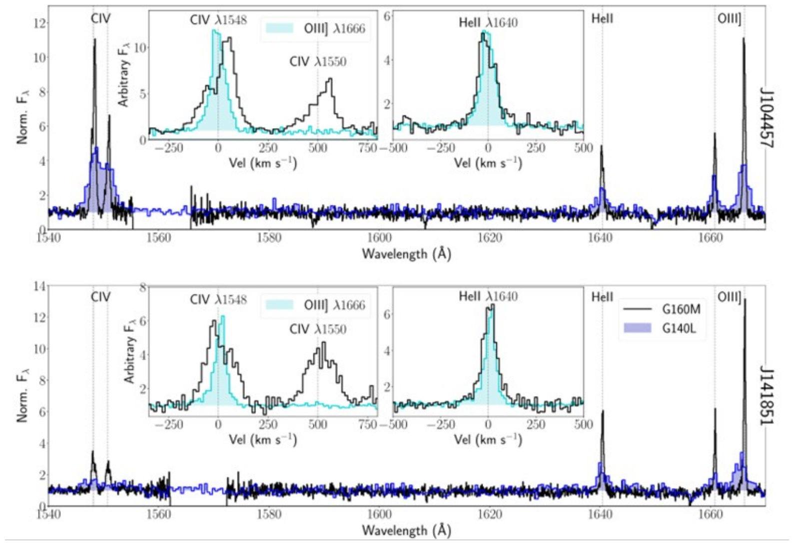
- C IV doublets broader than He II λ1640 are observed.
- Spatially extended Mg II & O VI nebulae are observed.

Scattering?

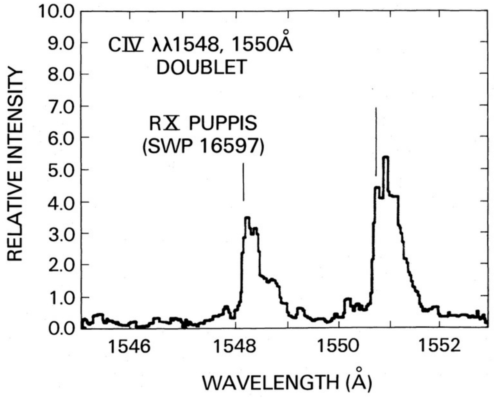
C IV Doublets



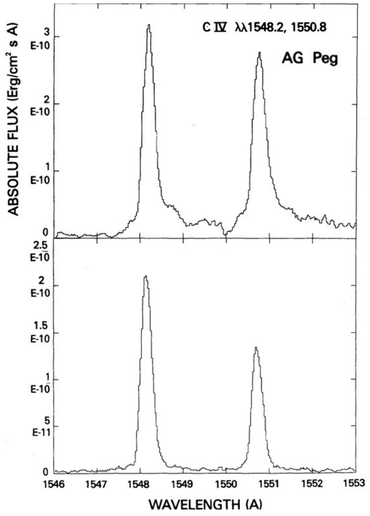
$\lambda_K \sim 1548.2$ Å
$\lambda_H \sim 1550.8$ Å
$\Delta V_{sep} \sim \mathbf{500\ km\ s^{-2}}$



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



Michalitsianos et al. 1988

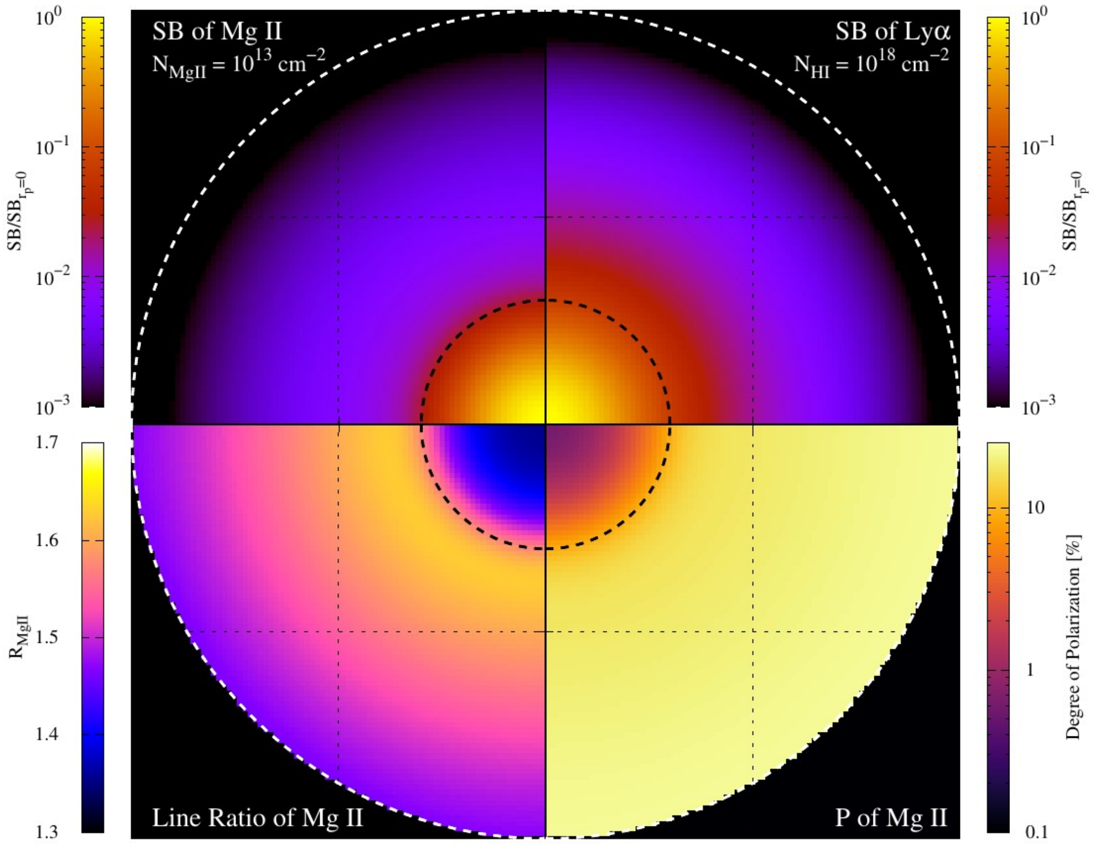


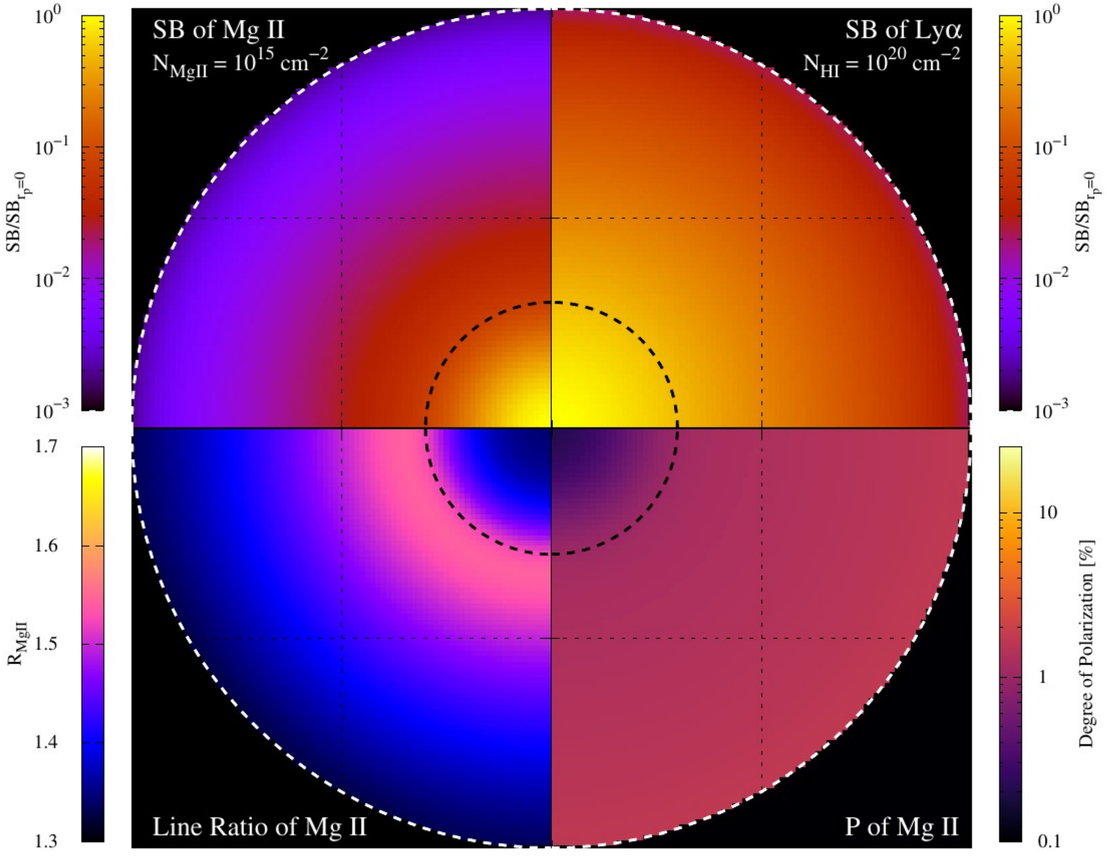
Michalitsianos et al. 1992

C IV in Symbiotic Stars

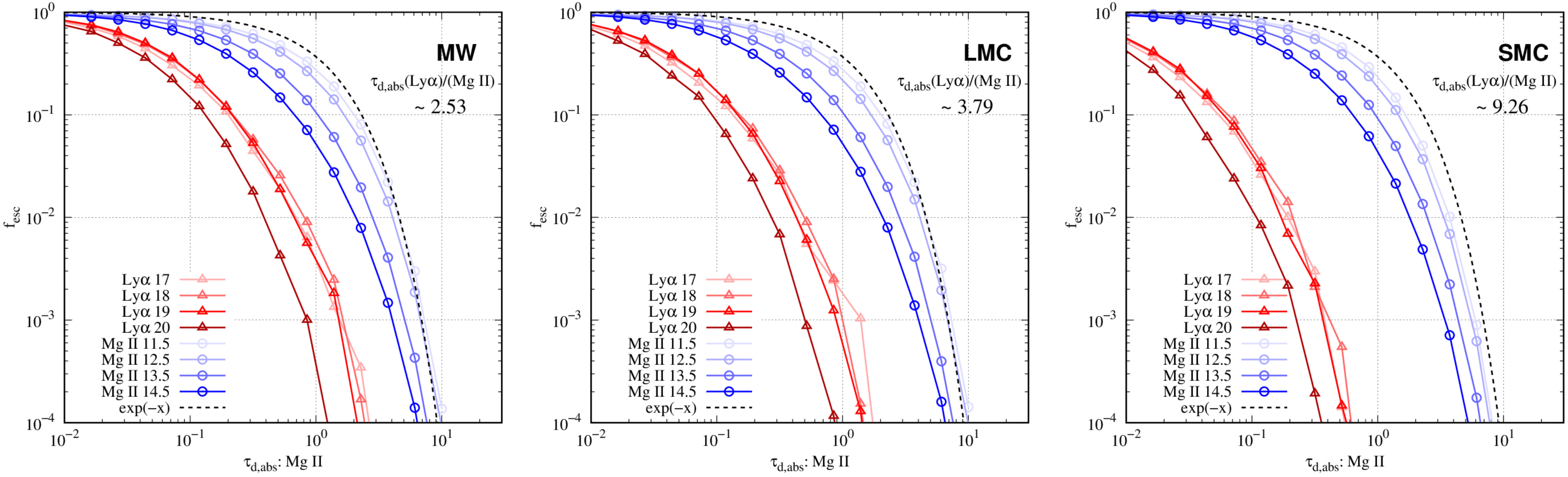
- Separation of C IV doublet (~ 500 km/s) is smaller than that of Mg II doublet (~ 750 km/s).
- For this reason, C IV lines are more easily mixed each other in outflow with speed > 400-500 km/s
- The ratio of C IV emission can be a tracer of fast hot wind components from galaxy.
- In 1980-1990, C IV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

Spatial Extended Mg II





Mg II & Lyα escaping fraction of monochromatic source



- In the dust model of LMC and SMC, the ratio of Lyα and Mg II dust optical depth is higher than that of MW.
- When the dust optical depth of Mg II > 1, the escaping fraction of Lyα is ten times lower than that of Mg II.