Polarization of Rayleigh Scattered Lyα in Active Galactic Nuclei

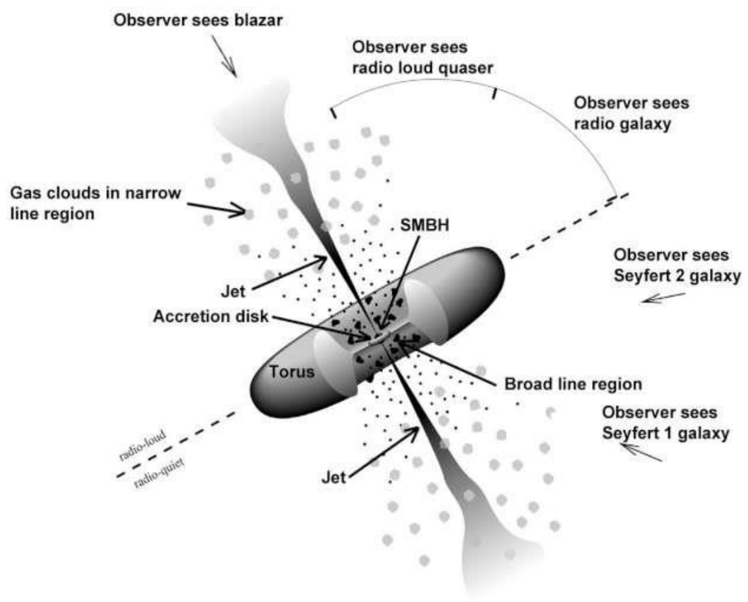
Seok-Jun Chang and Hee-Won Lee

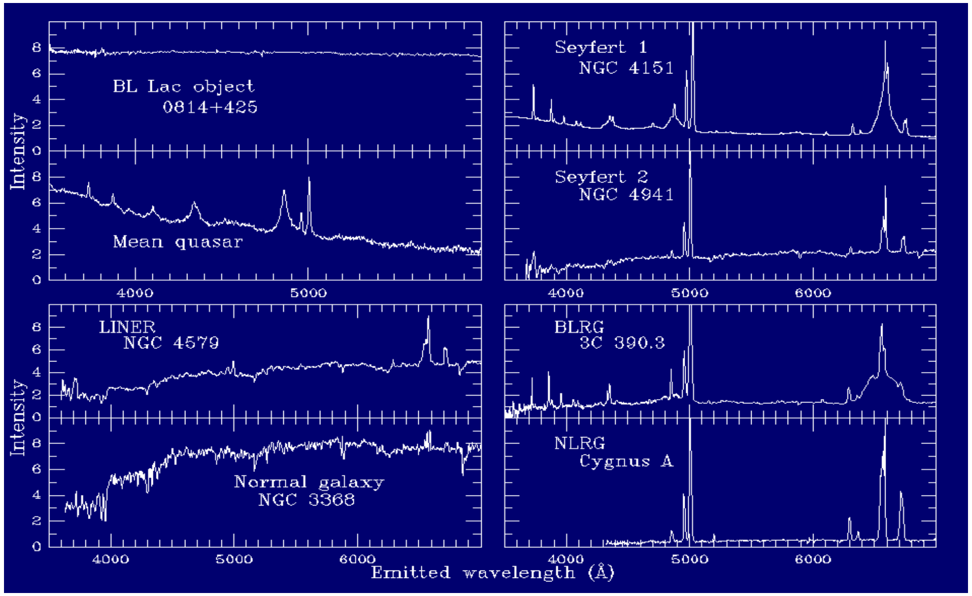
Sejong University

Contents

- Introduction
  - ➢ AGN Unification Model
  - ➢ Rayleigh and Raman Scattering
  - ➢ Polarization
- Results
  - ➢ Slab Model for Basic Study
  - ➢ Torus Model for Unification Scheme
- Summary and Future Work

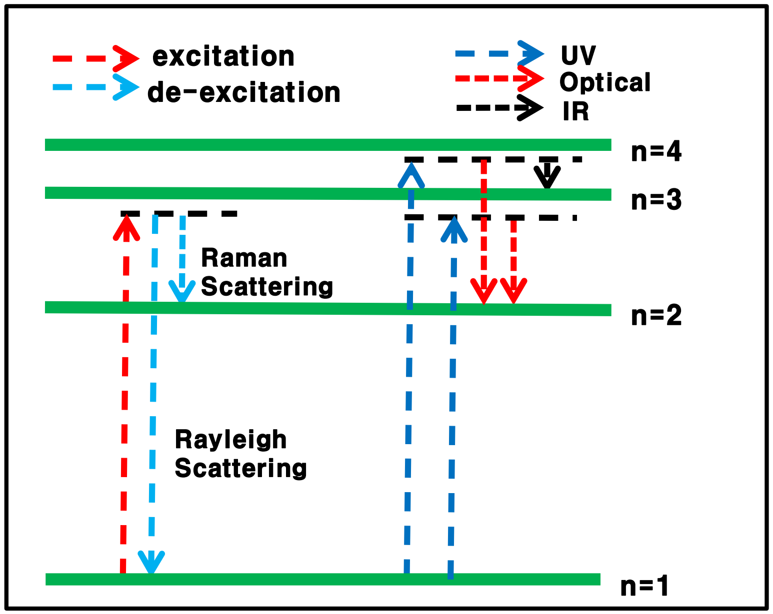
AGN Unification Model



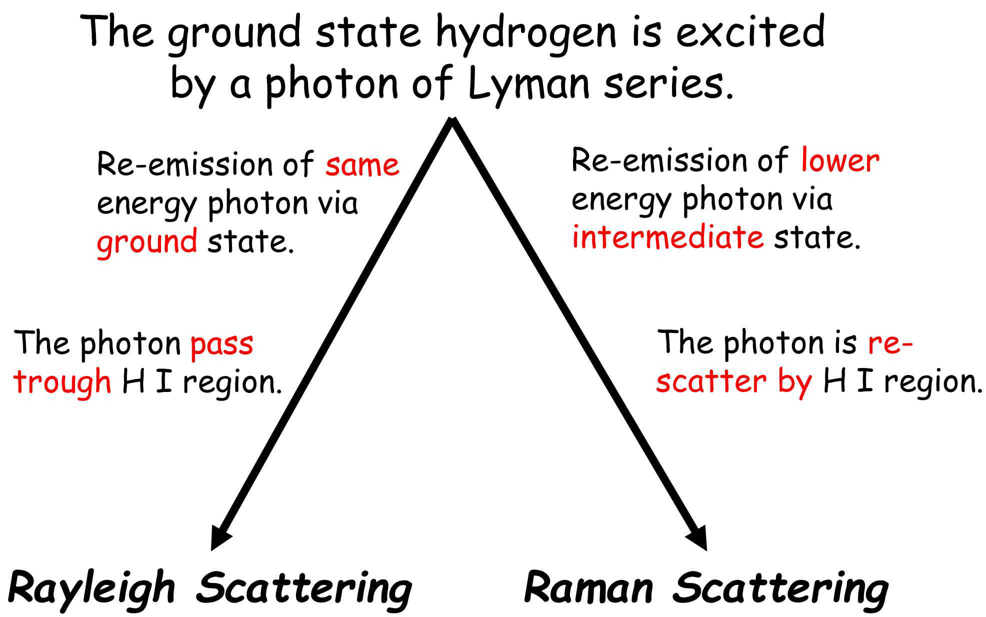


Components	Effect in Spectrum
Super Massive Black Hole	*→ Non-thermal continuum*
Broad Line Region (BLR)	*→ Broad emission line, width of ~5,000km/s*
Narrow Line Region (NLR)	*→ Narrow emission line, width of ~500km/s*
Optically Thick Molecular Torus	*→ Obscuring BLR, Rayleigh scattering of Lya*

Rayleigh and Raman Scattering



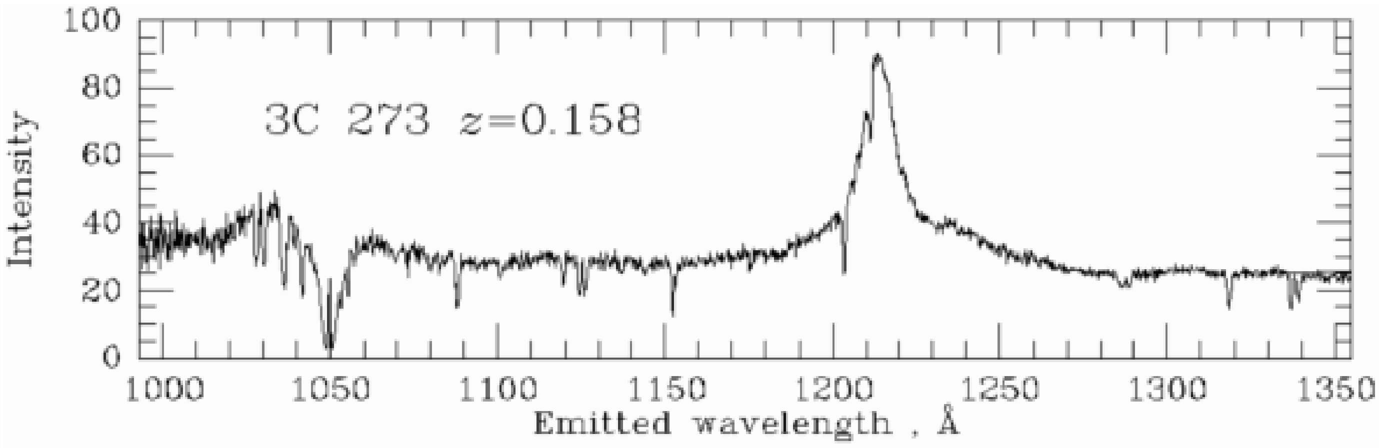
Hydrogen Atomic Level

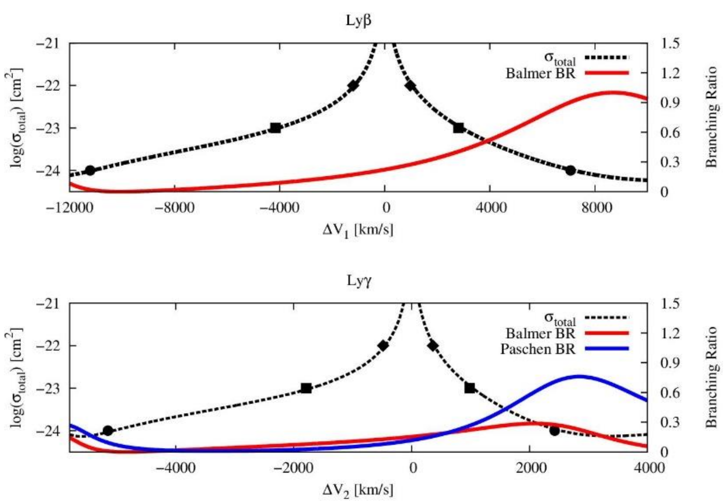


Scattering of Lyman Series by Atomic Hydrogen

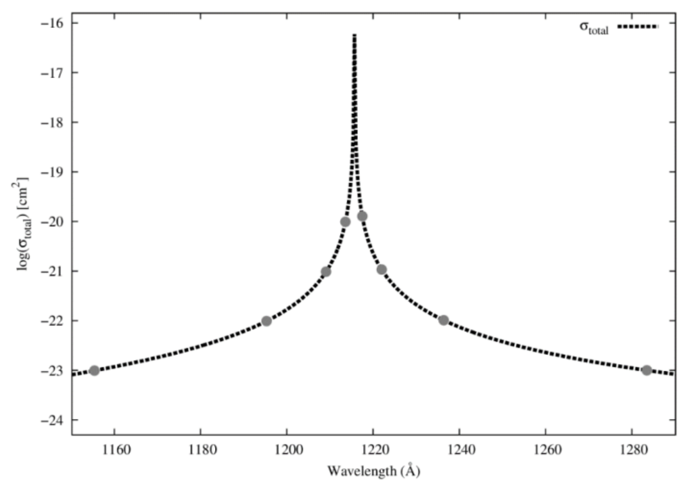
- The excited hydrogen atom may de-excite into an excited state resulting in reemission of a lower energy photon, which is called ***Raman Scattering***. If the de-excitation is made into the ground state, then result is an elastic scattering, which is also called ***Rayleigh scattering***.
- Lya can be dominantly Rayleigh scattered by atomic hydrogen and also optically thick. Therefore, Lya may show distinguished polarization compared with other hydrogen and metal lines.

Why Rayleigh Scattering ?



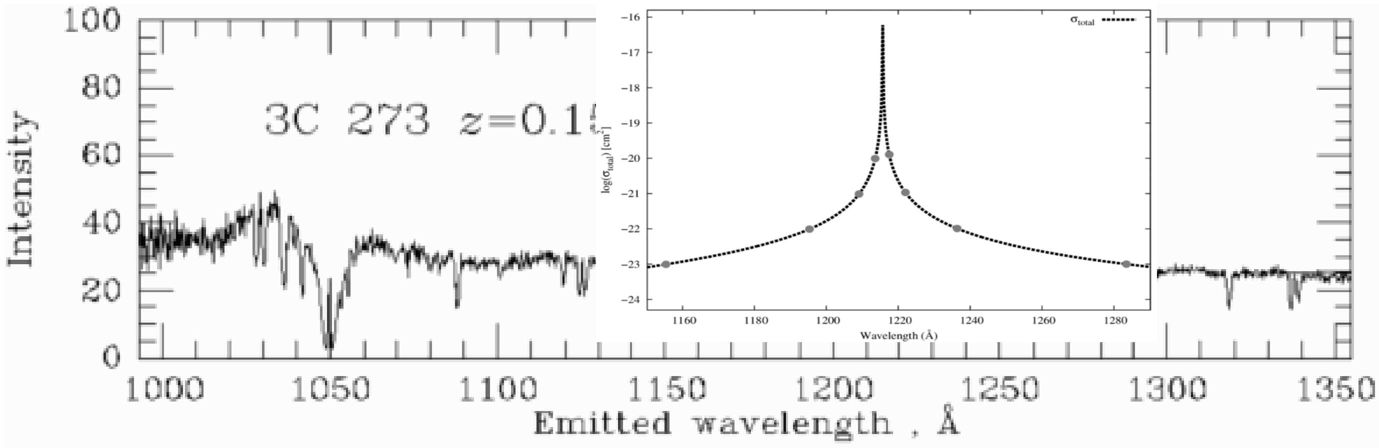


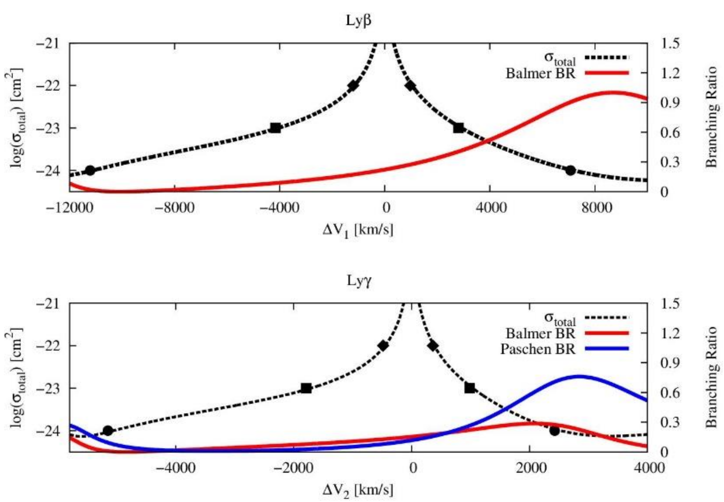
Cross section and branching ratio of Lyβ and Lyγ (Chang et al. 2015)



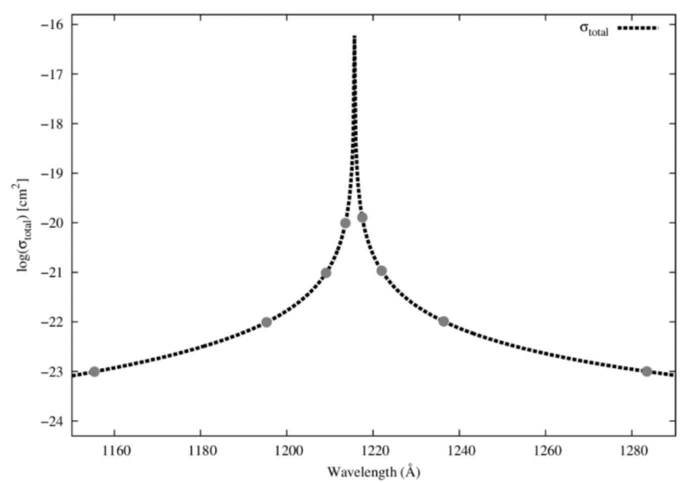
Cross section of Lyα

Why Rayleigh Scattering ?



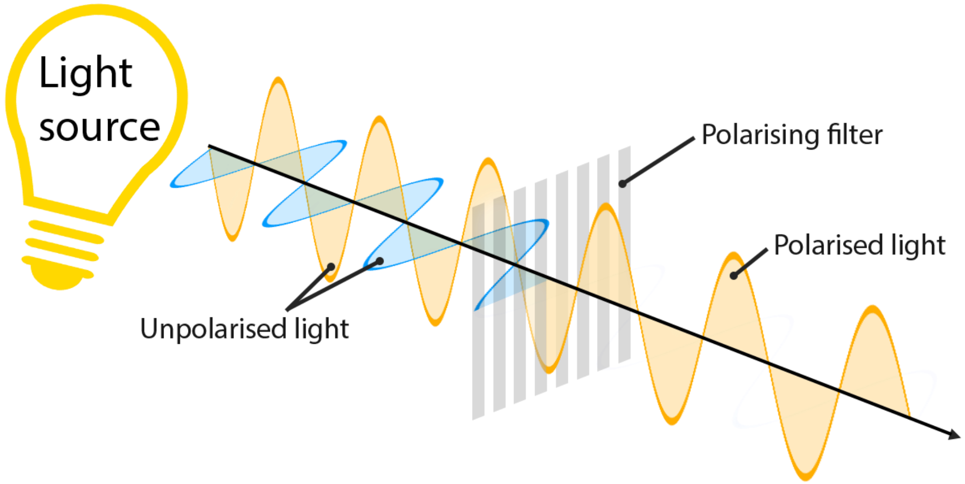


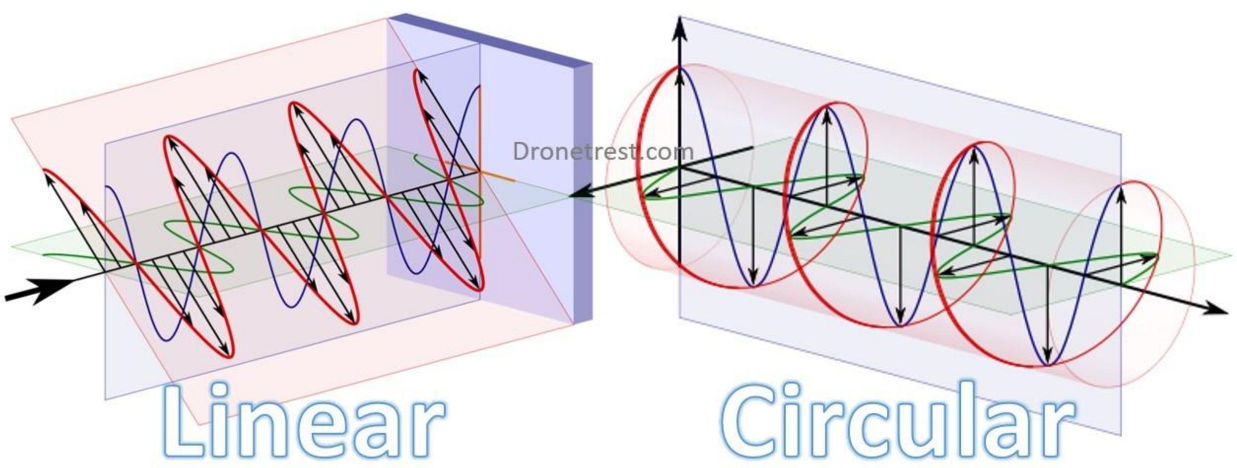
Cross section and branching ratio of Lyβ and Lyγ (Chang et al. 2015)



Cross section of Lyα

Polarization of Light





Stokes Parameters

$$I \quad Q \quad U \quad V$$

Stokes parameter are values to describe the polarization of electromagnetic wave.

$$I = |E_x|^2 + |E_y|^2$$

Total Intensity

$$Q = |E_x|^2 - |E_y|^2$$

Linear Polarization of Vertical Direction
$(0^o:\ +, 90^o: -)$

$$U = 2Re(E_x E_y^*)$$

Linear Polarization of Diagonal Direction
$(45^o:\ +, -45^o: -)$

$$V = -2Im(E_x E_y^*)$$

Circular Polarization
(Right-hand : +, Left- hand : -)

Stokes Parameters

$$I \quad Q \quad U \quad V$$

Stokes parameter are values to describe the polarization of electromagnetic wave.

$$I = |E_x|^2 + |E_y|^2$$

Total Intensity

$$Q = |E_x|^2 - |E_y|^2$$

Linear Polarization of Vertical Direction
$(0^o: +, 90^o: -)$

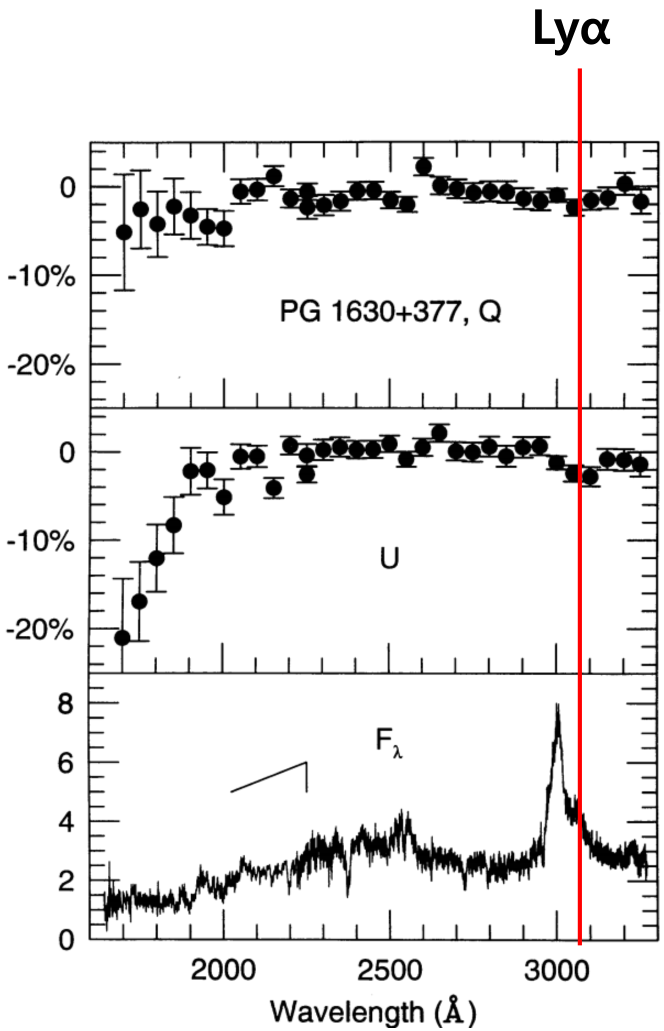
$$U = 2Re(E_x E_y^*)$$

Linear Polarization of Diagonal Direction
$(45^o: +, -45^o: -)$

$$V = -2Im(E_x E_y^*)$$

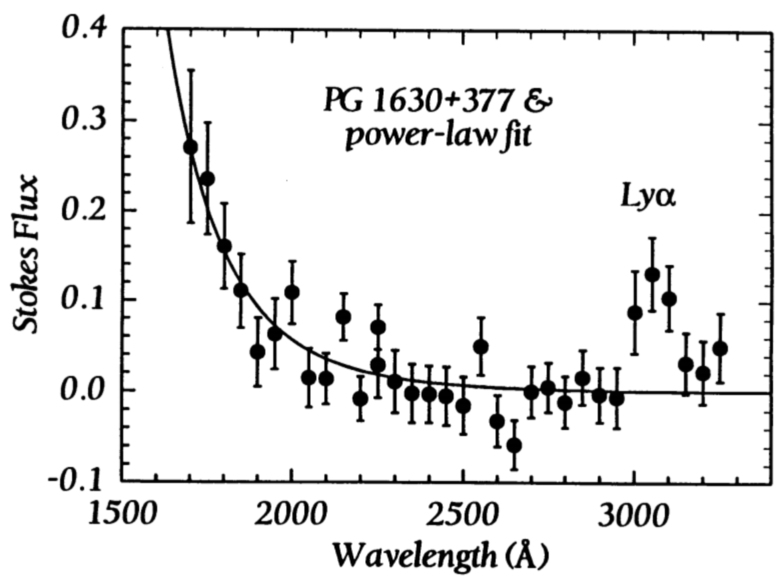
Circular Polarization
(Right-hand : +, Left- hand : -)

Polarized Lyα in Quasar



Spectropolarimetric Data of PG 1630+377
(Koratkar et al. 1995)

Quasar PG 1630+377 is one notable example observed by HST through spectropolarimtry.

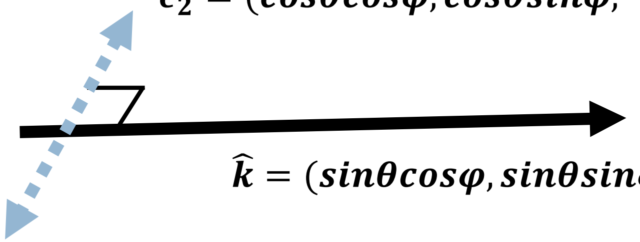


Stokes Flux of PG 1630+377
(Koratkar et al. 1995)

Density Matrix Transition for Scattering

$$\vec{\epsilon_1} = (-sin\varphi, cos\varphi, 0)$$

$$\vec{\epsilon_2} = (cos\theta cos\varphi, cos\theta sin\varphi, -sin\theta)$$



$$\hat{k} = (sin\theta cos\varphi, sin\theta sin\varphi, cos\theta)$$

Wavevector $\hat{k}$ and the Polarization Basis Vectors $\vec{\epsilon_1}$ and $\vec{\epsilon_2}$

$$\rho = \begin{pmatrix} \rho_{11} & \rho_{12} \\ \rho_{21} & \rho_{22} \end{pmatrix} = \begin{pmatrix} \frac{I+Q}{2} & \frac{U+iV}{2} \\ \frac{U-iV}{2} & \frac{I-Q}{2} \end{pmatrix}$$

Density Matrix of Light Polarization

A density Matrix is a quantum mixed state composed of Stokes Parameters.

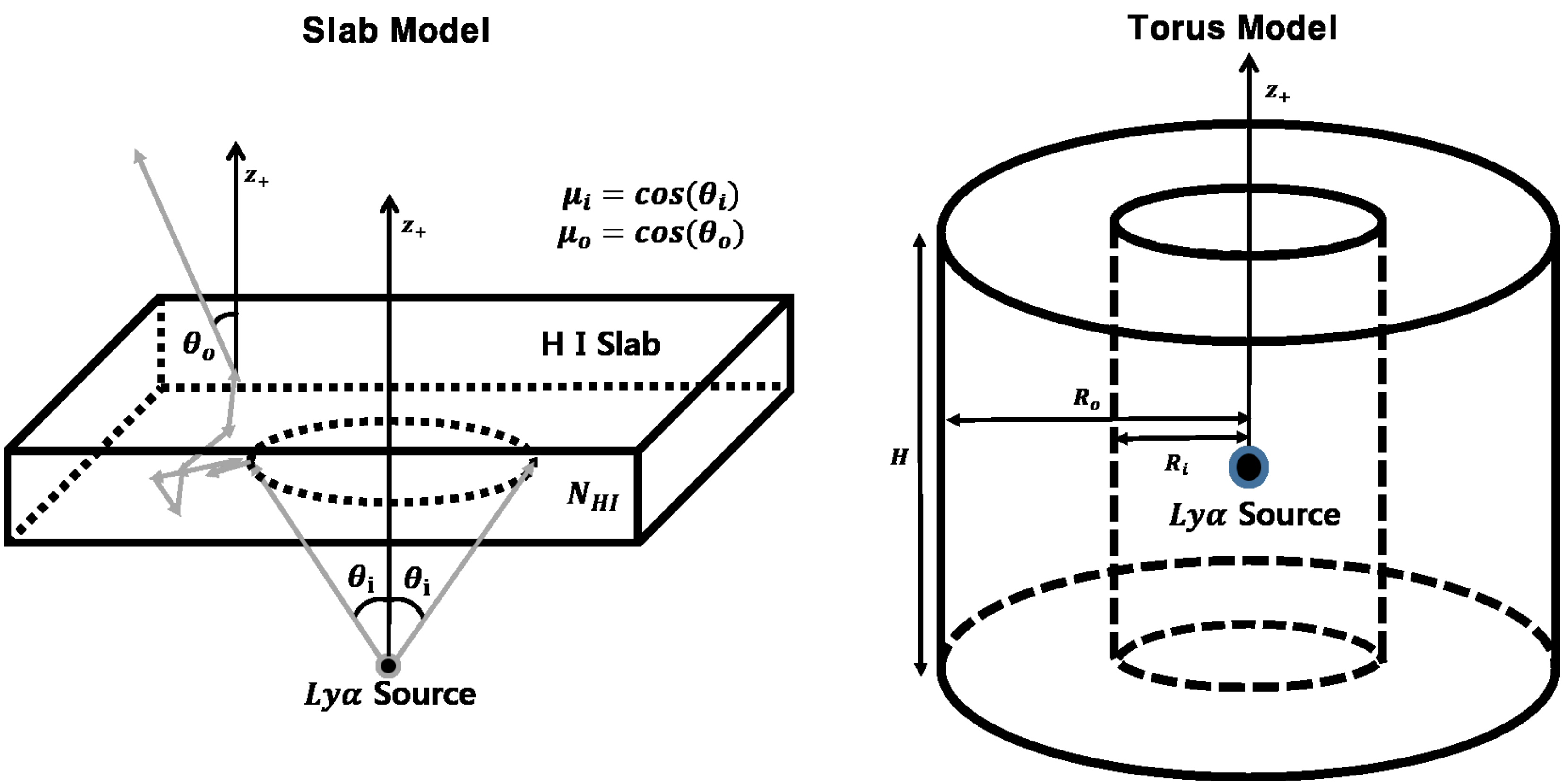
$$\rho'_{11} = (cos^2\Delta\varphi)\rho_{11}$$
$$-(cos\theta sin2\Delta\varphi)\rho_{12}$$
$$+(sin^2\Delta\varphi cos^2\theta)\rho_{22}$$

$$\rho'_{22} = (cos^2\theta' sin^2\Delta\varphi)\rho_{11}$$
$$+cos\theta'(2sin\theta sin\theta' sin\Delta\varphi$$

$$\rho'_{12} = (1/2cos\theta' sin2\Delta\varphi)\rho_{11}$$
$$+(cos\theta cos\theta' cos2\Delta\varphi$$

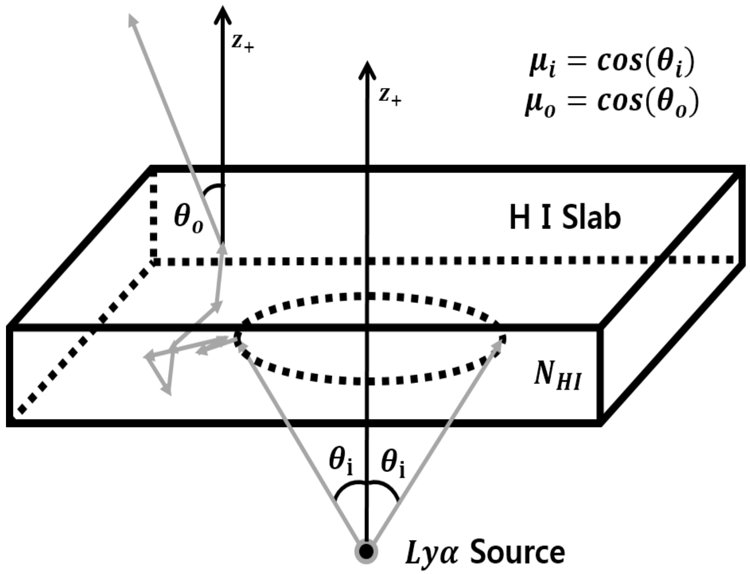
Density Matrix Formula for Scattered Photon
(Ahn and Lee 2015 and Chang et al. 2015)

Slab and Torus Models



The z-axis is symmetric axis -> $U \approx 0$

Simple Slab Model for Basic Study



Geometry of Slab Model

θ_i : Incident Angle

θ_o : Esacpe Angle

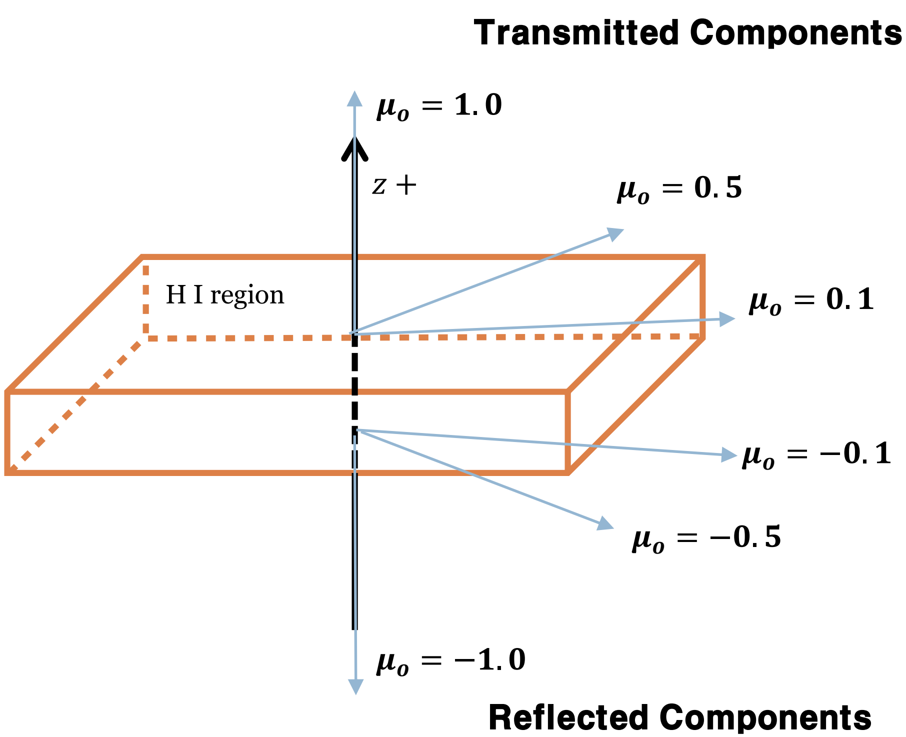
N_{HI} : Column Density

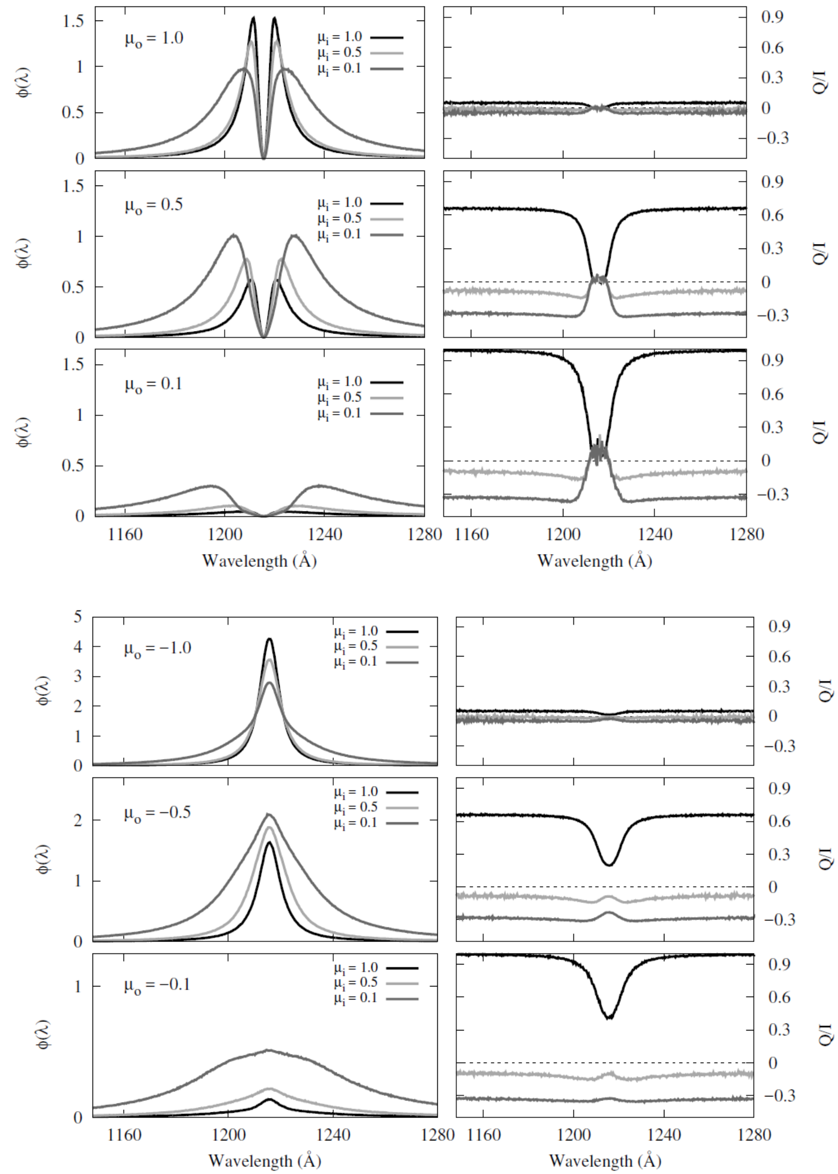
$f(\lambda) = const$: Flat Continuum

We select a slab model to assure properties of the polarization of scattered radiation by H I region.

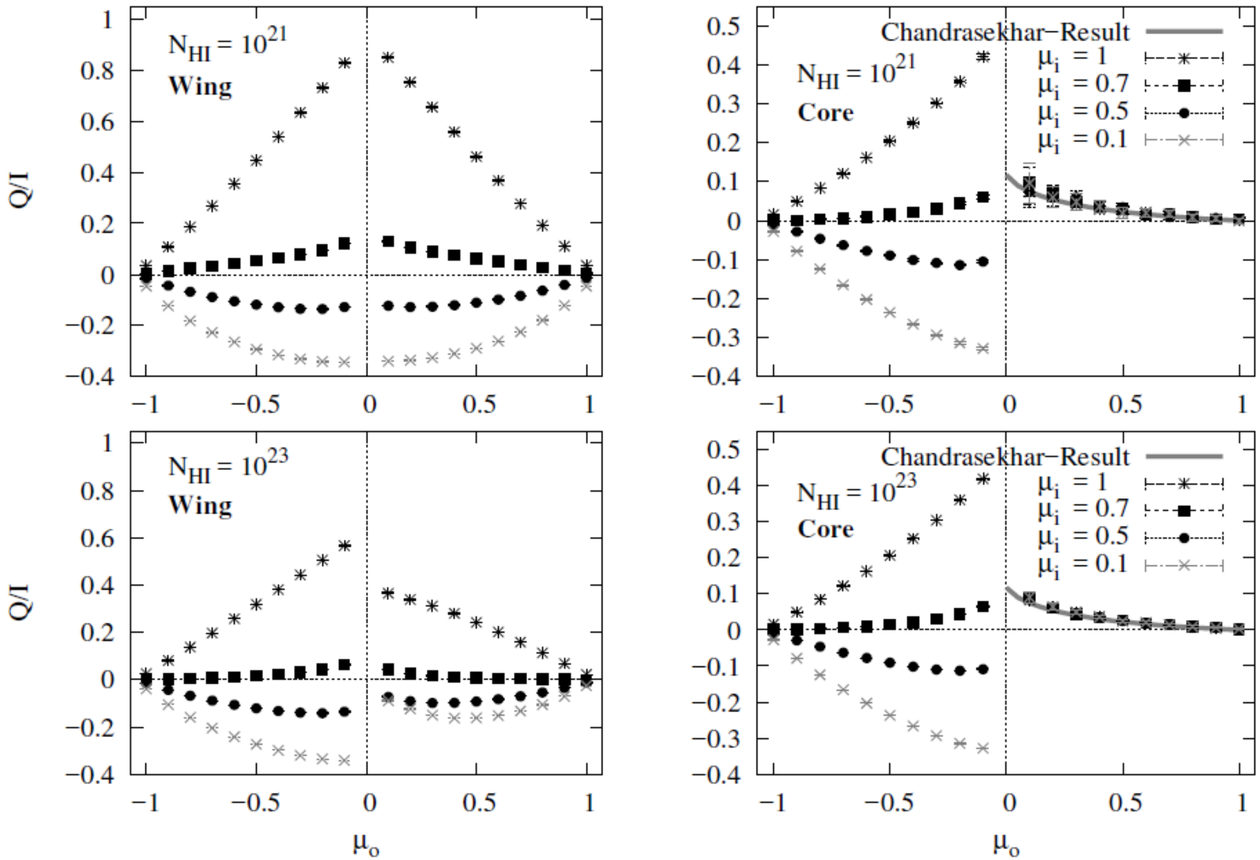
- Setting the fixed θ_i to compare between normal and grazing case. (not isotropic case)
- Colleting photons by μ_o to calculate polarization of the observer's position.
- Setting the various column densities $N_{HI} = 10^{20-23}$ for effect of the optical depth τ.
- Adopting the flat input $f(\lambda)$.

Flux and Polarization



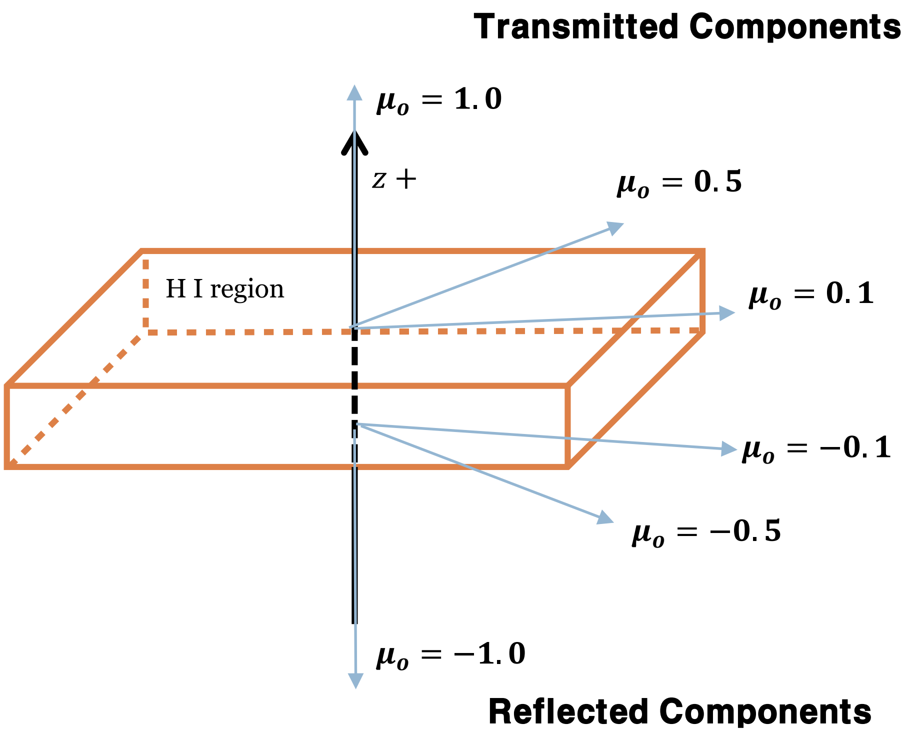


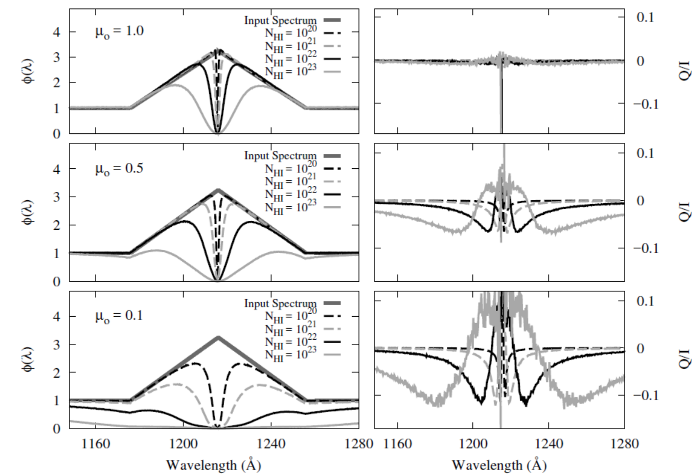
Total Degree of Polarization

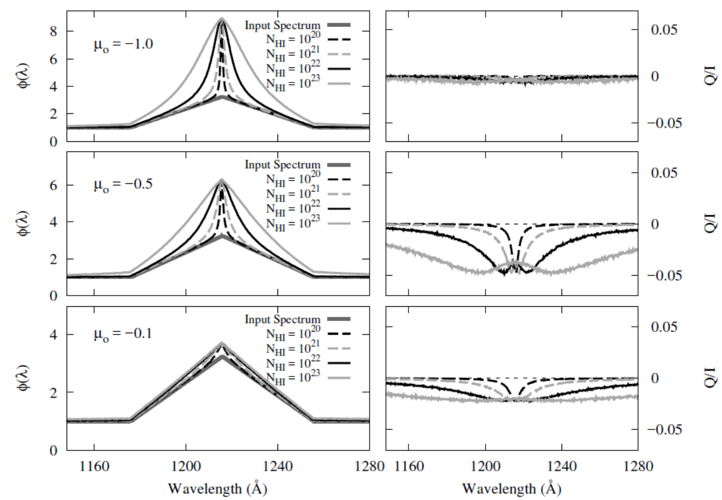


Optically Thick Case -> Chandrasekhar's Result

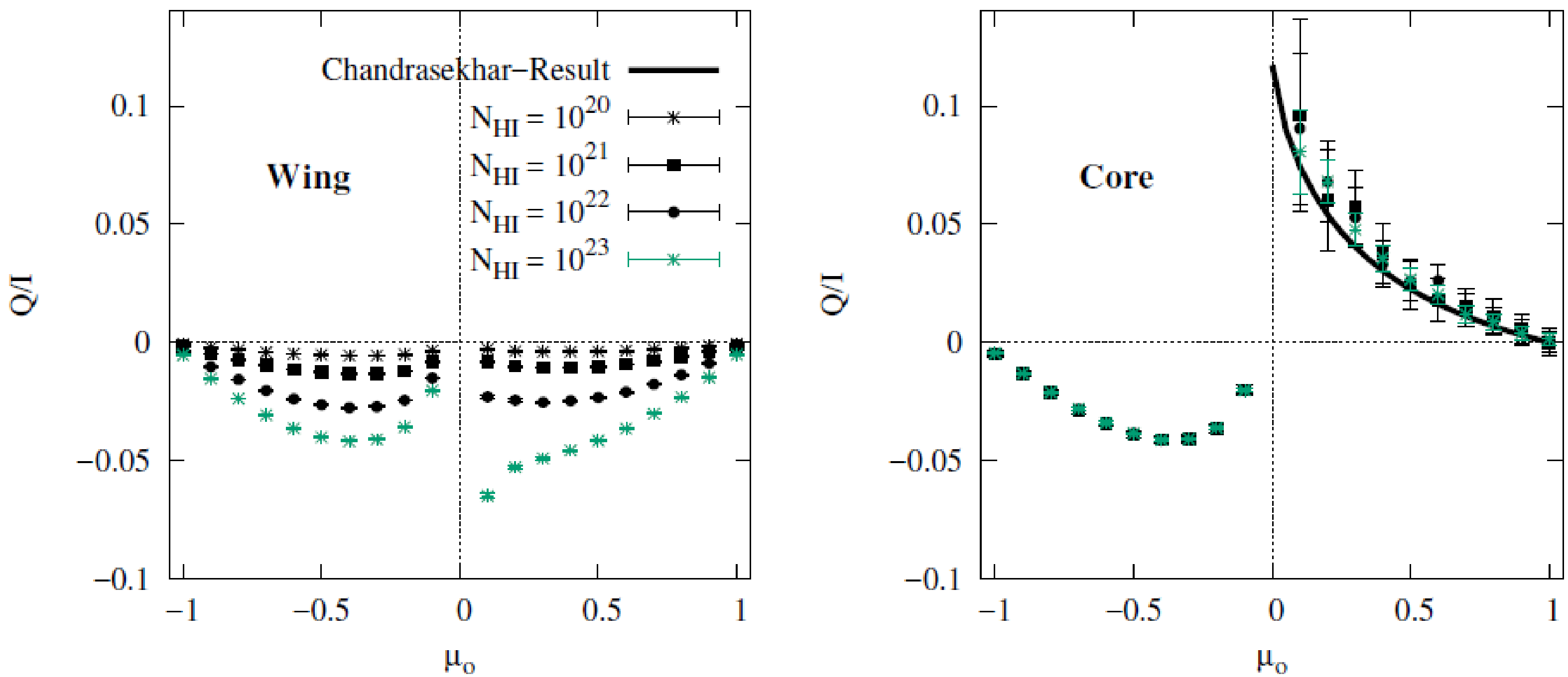
Slab Model Adopting Isotropic Source







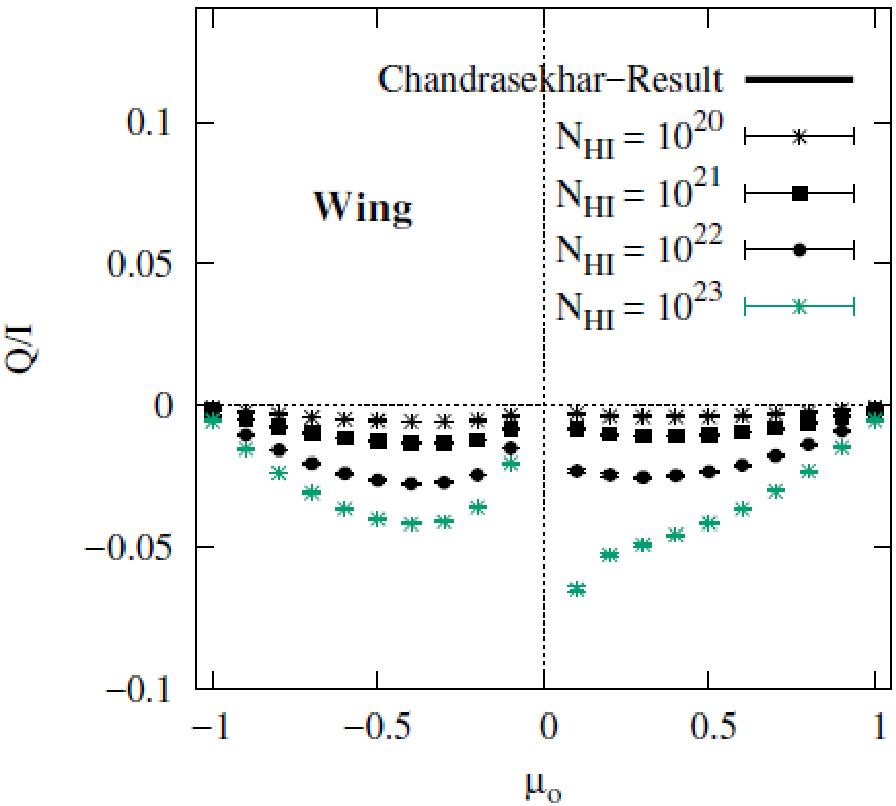
Slab Model Adopting Isotropic Source

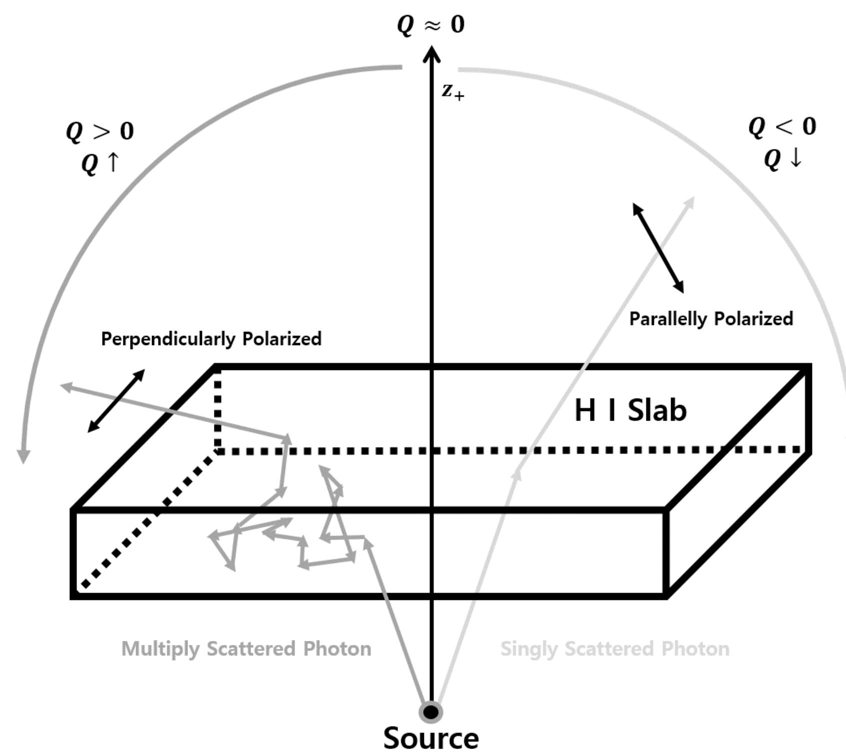


$\tau < 10$ $\tau > 10$

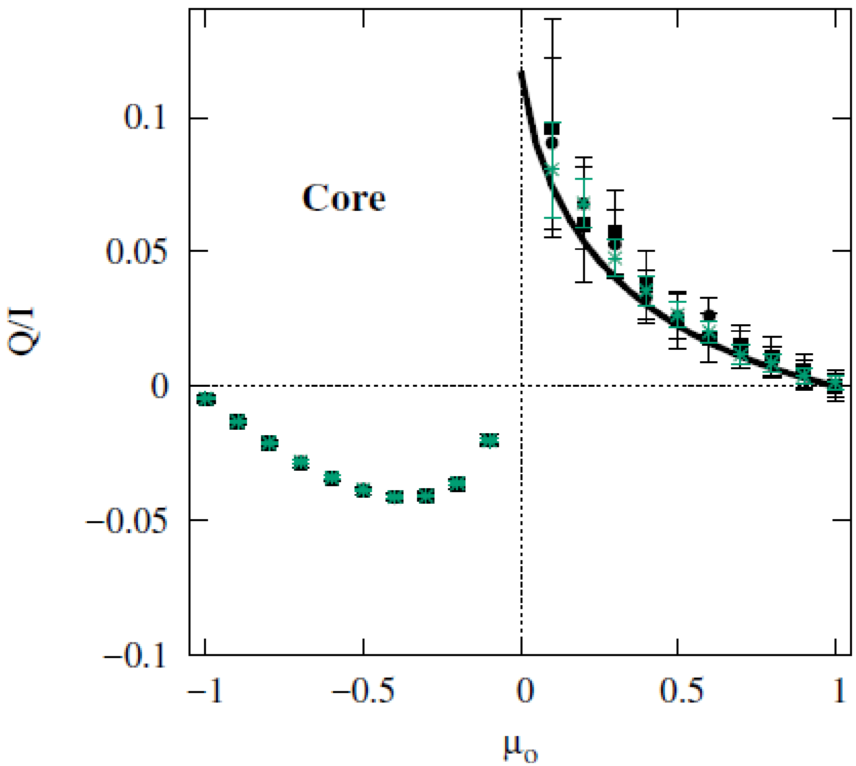
Optically Thick Case -> Chandrasekhar's Result

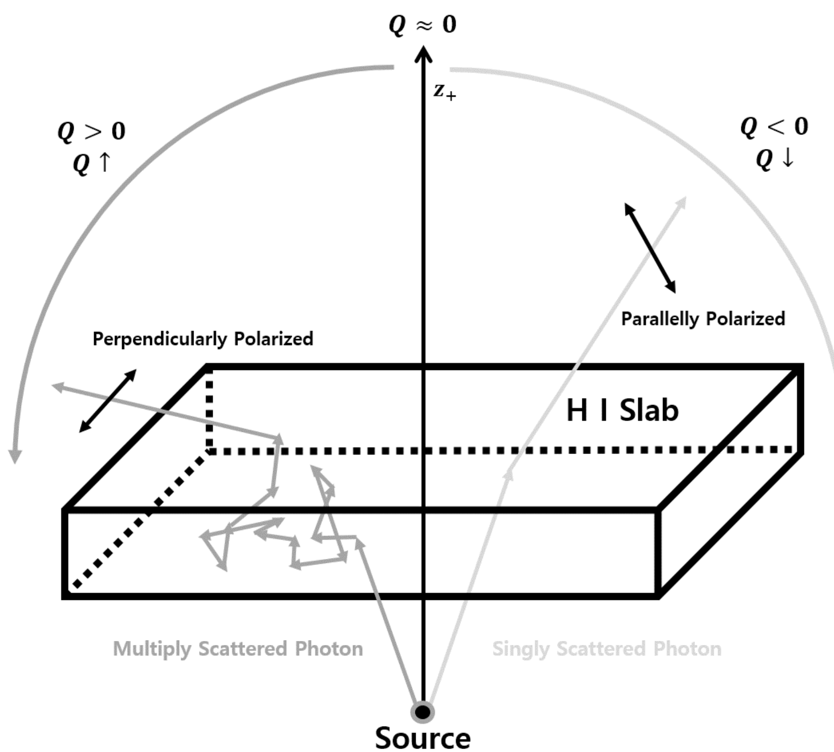
Polarization Behavior in Slab Geometry



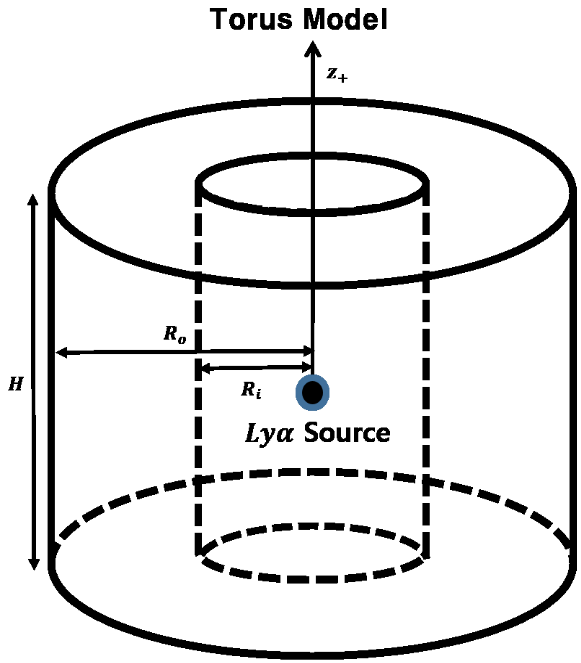


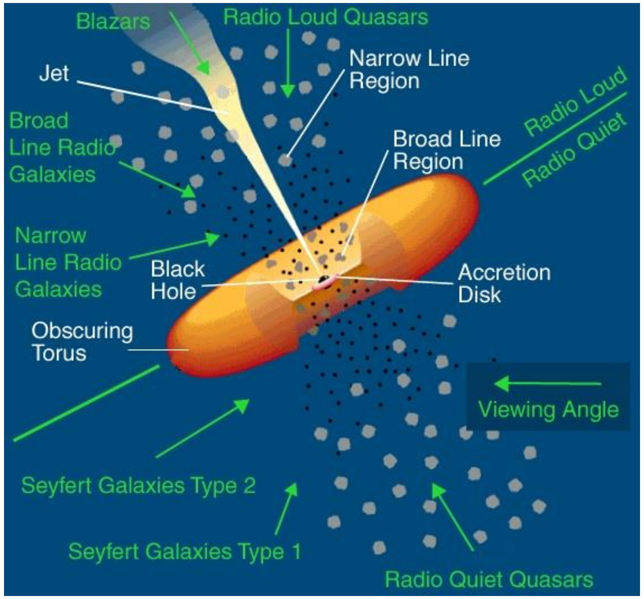
Polarization Behavior in Slab Geometry





Torus Model for Unification Model



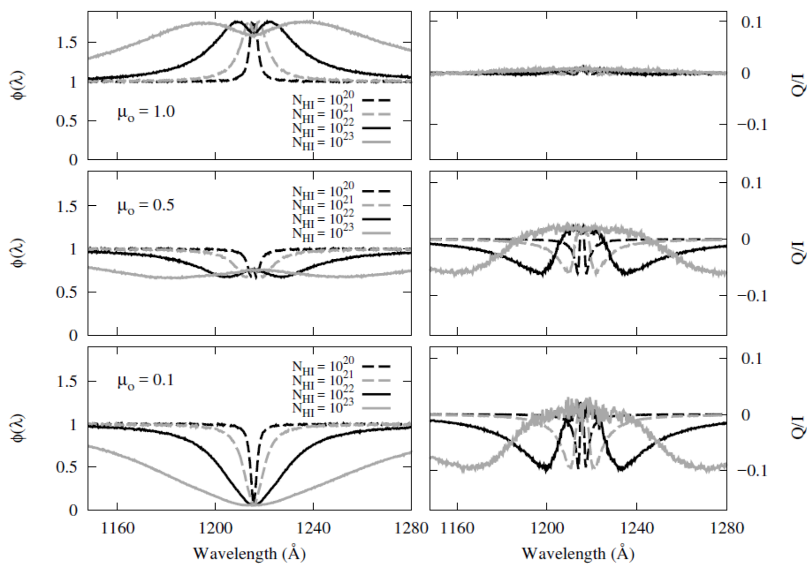


$$R_i, \qquad R_o = 2R_i$$

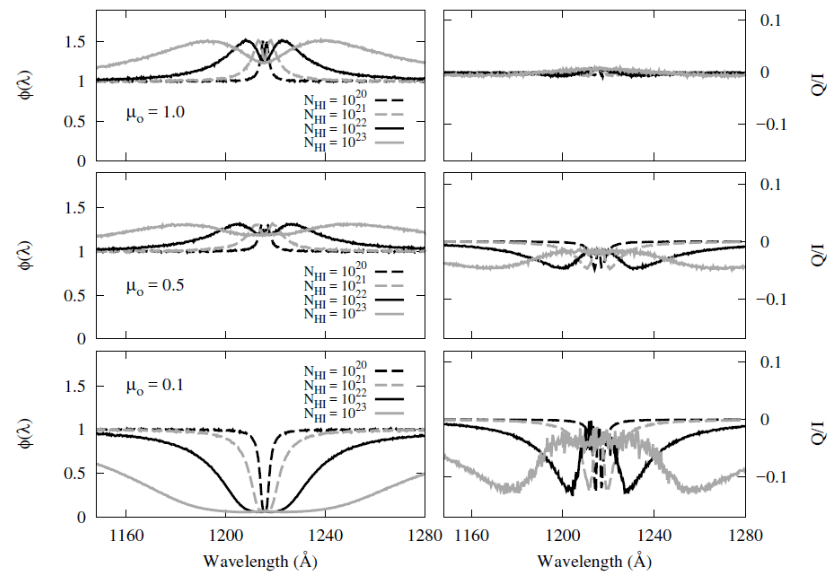
$$H = AR_i, \qquad A = 1, 2$$

$$N_{HI} = n_{HI}(R_o - R_i), \qquad N_{HI} = 10^{20-23}$$

Flux and polarization in Torus Model



Flux and Polarization in a Tall Torus, $H = 2R_i$

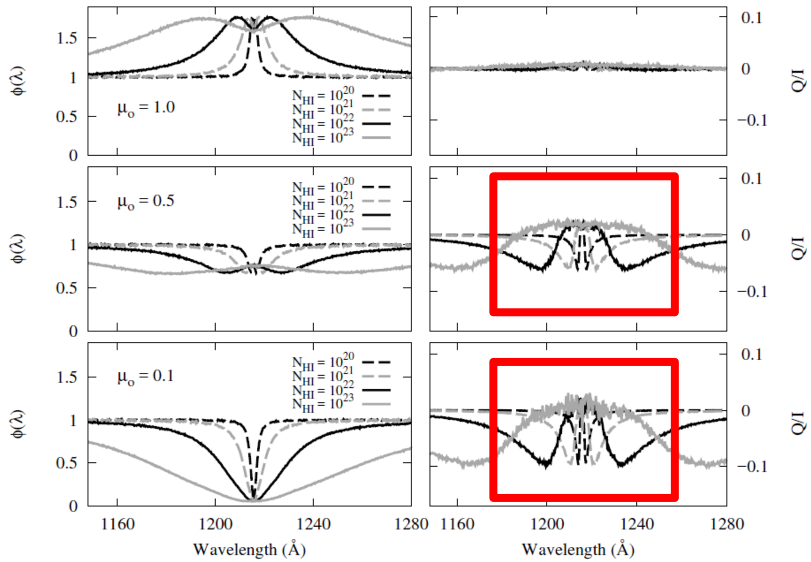


Flux and Polarization in a Short Torus, $H = R_i$

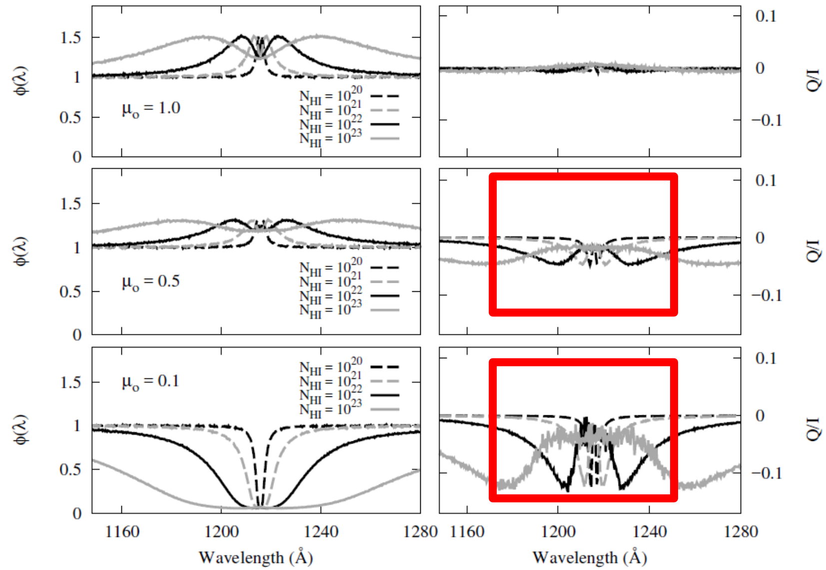
- We consider two torus models with differing H and overplot flux and degree of polarization for various values of N_{HI}.
- An interesting feature is positively polarized (polarized along the equatorial plane) central part in the case of the tall torus ($A = 2$). They escape the tall torus through repeated scattering on the inner wall resulting in electric field relaxed in the direction perpendicular to the z-axis.

Flux and polarization in Torus Model

Polarization Flip !



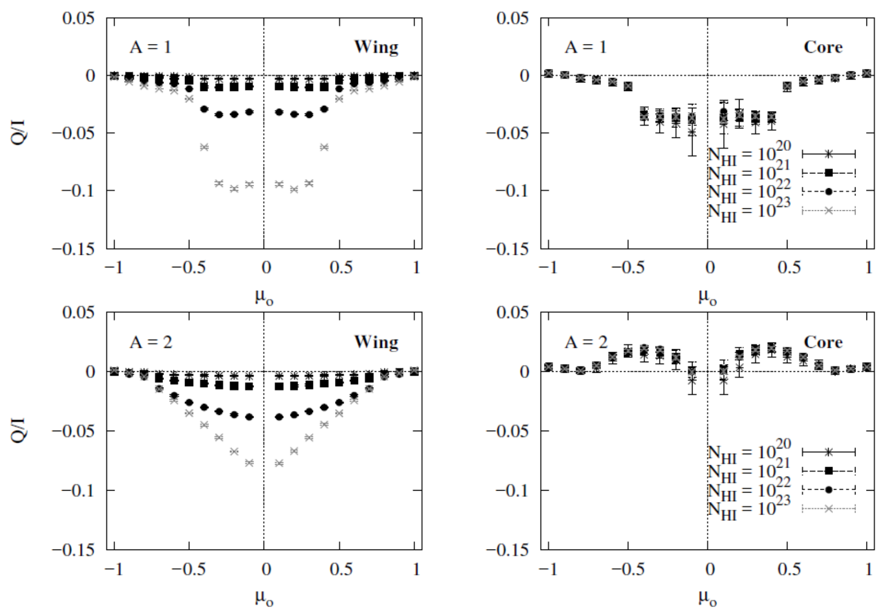
Flux and Polarization in a Tall Torus, $H = 2R_i$

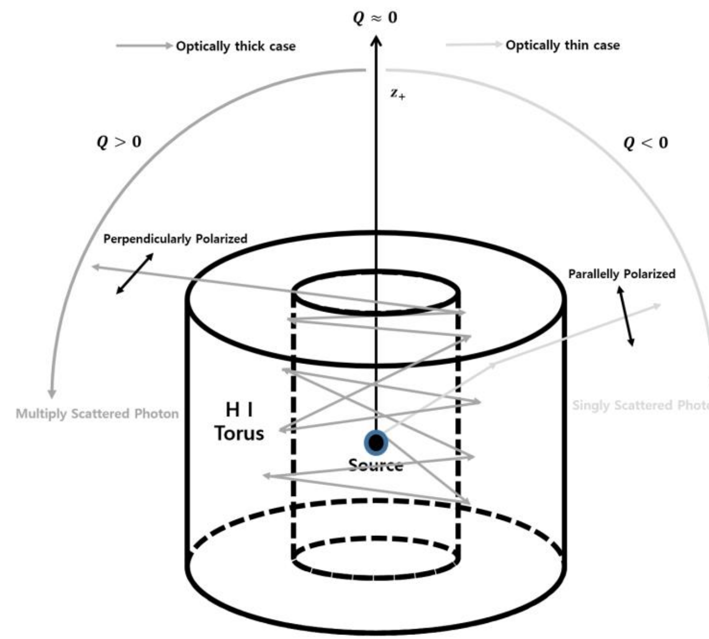


Flux and Polarization in a Short Torus, $H = R_i$

- We consider two torus models with differing H and overplot flux and degree of polarization for various values of N_{HI}.
- An interesting feature is positively polarized (polarized along the equatorial plane) central part in the case of the tall torus ($A = 2$). They escape the tall torus through repeated scattering on the inner wall resulting in electric field relaxed in the direction perpendicular to the z-axis.

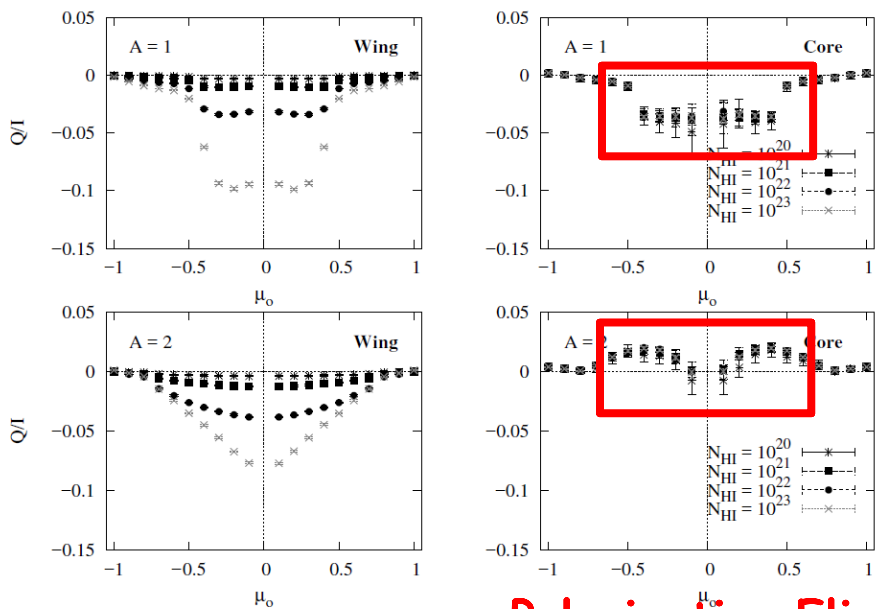
Total Degree of Polarization in Slab Model





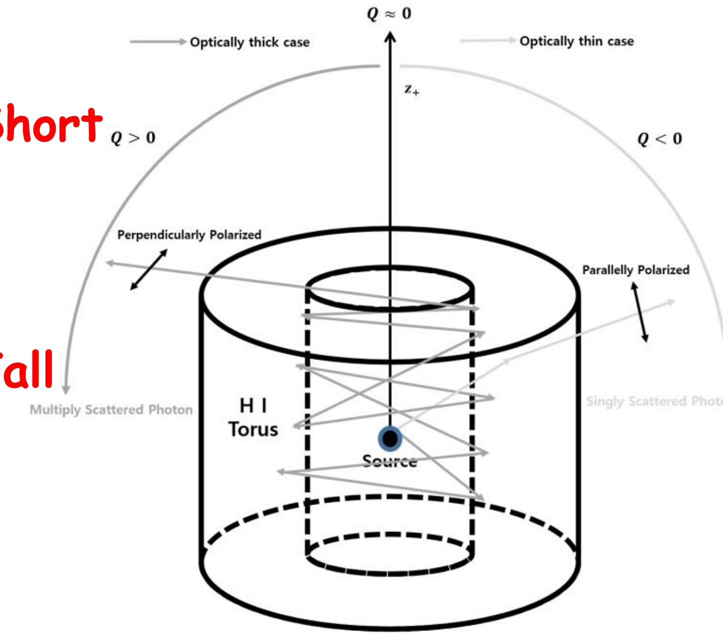
- This figure shows the angular distribution of polarization. Top panels are for a short torus ($A = 1$) and bottom panels are for a tall torus ($A = 2$)
- The left panels show polarization of photons with low Rayleigh scattering optical depths. They are mainly polarized in the direction parallel to the symmetry axis due to a small number of scatterings occurring in the equatorial plane.
- For optically thick photons to escape the tall torus, they need to climb up along the inner wall through many scatterings leading to eventual relaxation of the electric field parallel to the equatorial plane.

Total Degree of Polarization in Slab Model



Short

Tall



Polarization Flip !

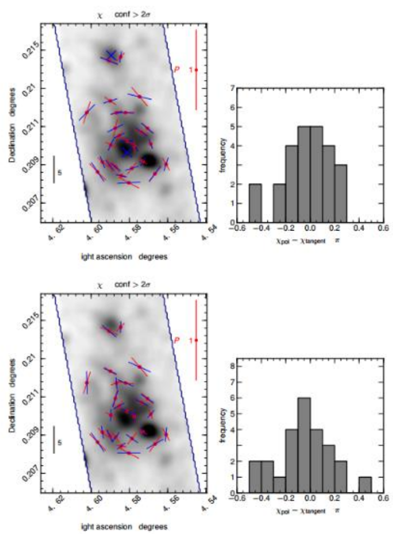
- This figure shows the angular distribution of polarization. Top panels are for a short torus ($A = 1$) and bottom panels are for a tall torus ($A = 2$)
- The left panels show polarization of photons with low Rayleigh scattering optical depths. They are mainly polarized in the direction parallel to the symmetry axis due to a small number of scatterings occurring in the equatorial plane.
- For optically thick photons to escape the tall torus, they need to climb up along the inner wall through many scatterings leading to eventual relaxation of the electric field parallel to the equatorial plane.

Summary

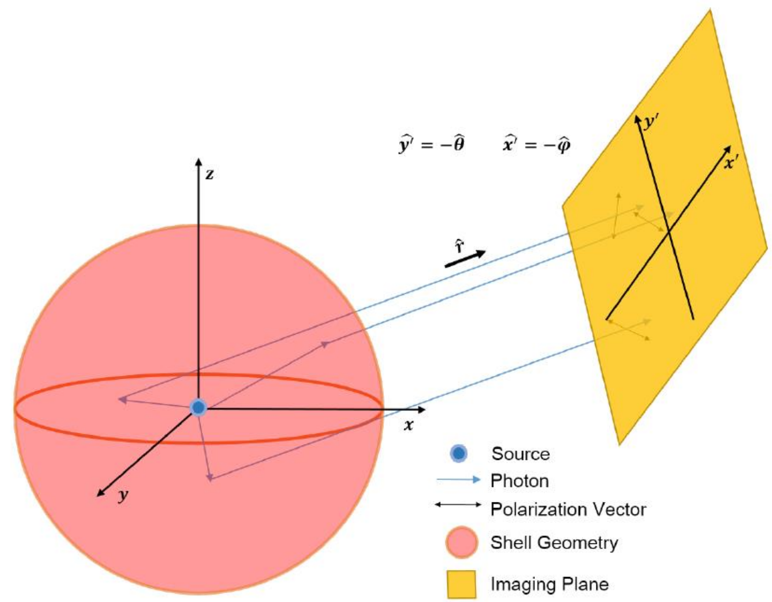
- Lyman alpha are more strongly polarized than other emission lines.
- In the case of optically thick H I region, we adopt Rayleigh scattering to describe polarization behaviors of Lya photons.
- The Rayleigh scattered polarization of transmitted components in optically thick case follow to Chandrasekhar result (1960).
- In the Torus Model, we find the polarization flip depended on a height.
- The detection of polarized Lya exhibiting the polarization flip indicate the presence of a tall molecular torus implying a population of Type 2 AGN.

Future Work

- Investigating polarization behaviors of other hydrogen lines.
- Comping the cross sections of high Lyman series.
- Developing Monte-Carlo technique for polarization imaging.

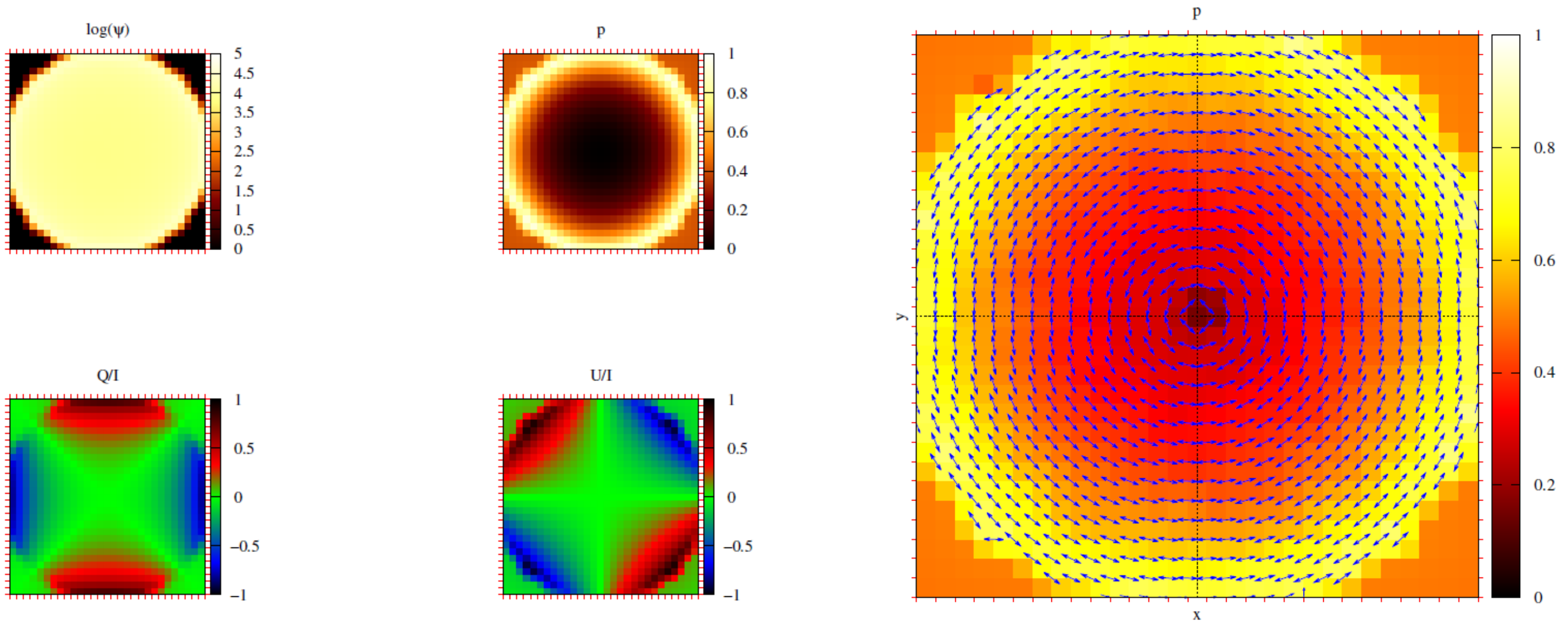


Polarization of Lyα Blobs (Hayes et al. 2011)



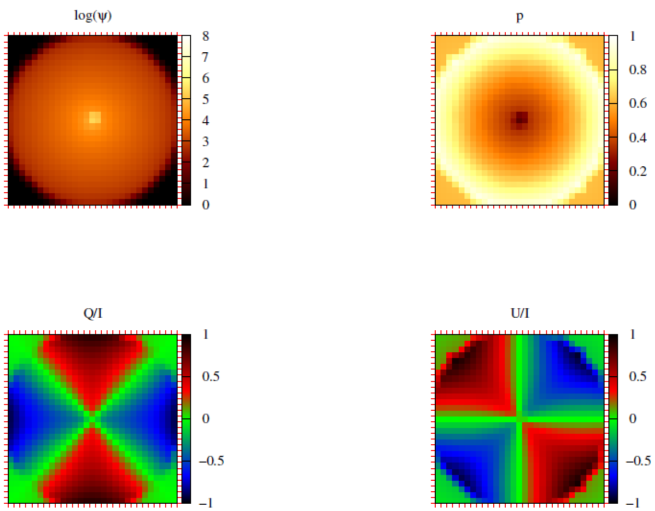
Geometry of Shell Model

Polarization Imaging in Shell Model

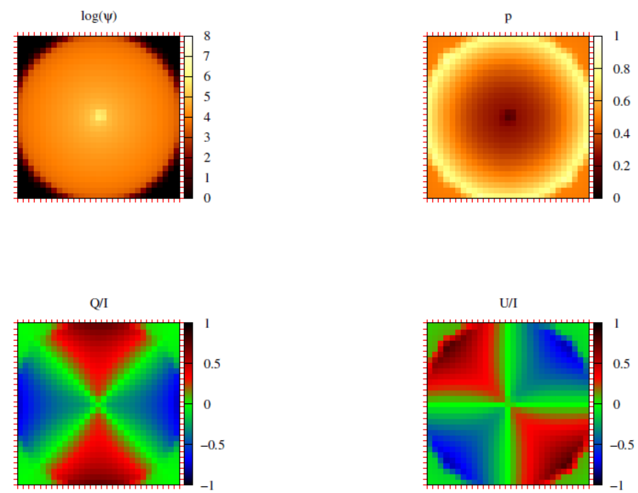


Polarization of Single Scattering

Polarization Imaging in Optically Thin Case

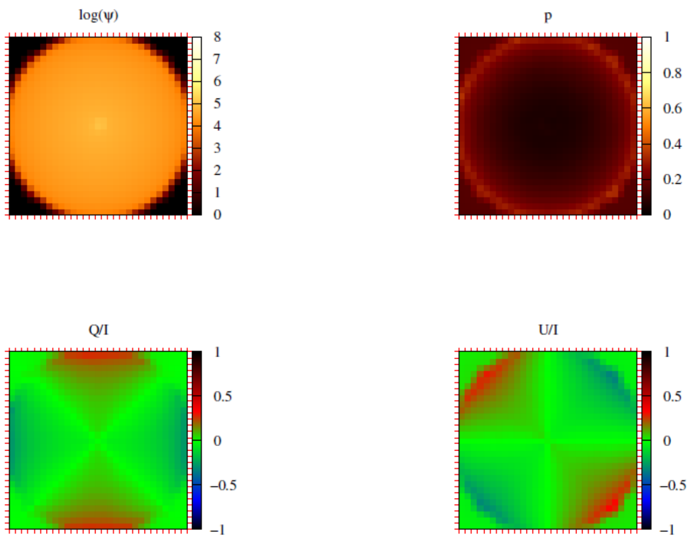


Polarization, at $\tau = 0.1$

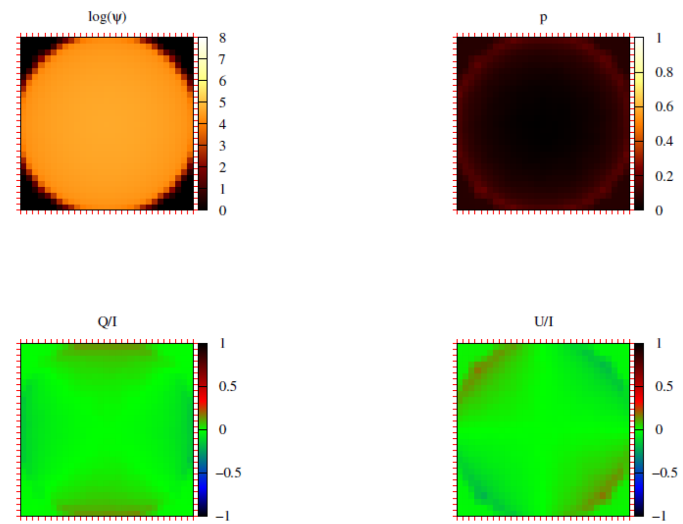


Polarization, at $\tau = 1$

Polarization Imaging in Optically Thick Case



Polarization, at $\tau = 5$



Polarization, at $\tau = 10$