A New Grid-Based Monte Carlo Code for Raman Scattered He II

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In Collaboration with Seok-Jun Chang & Hee-Won Lee

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  - Raman Scattered He II
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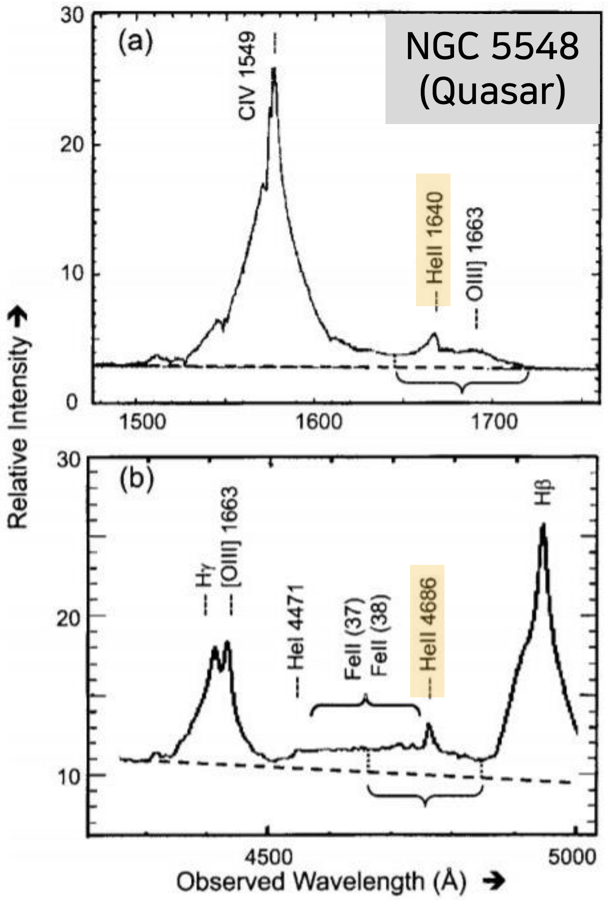
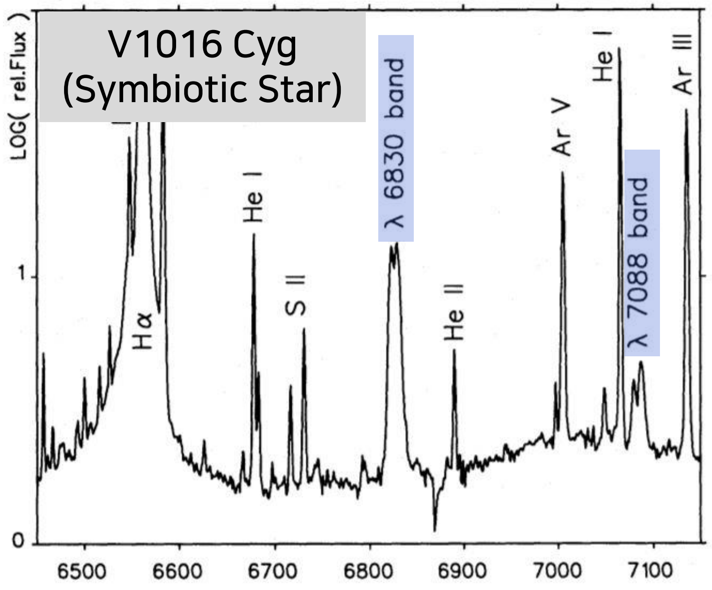
He II Emission

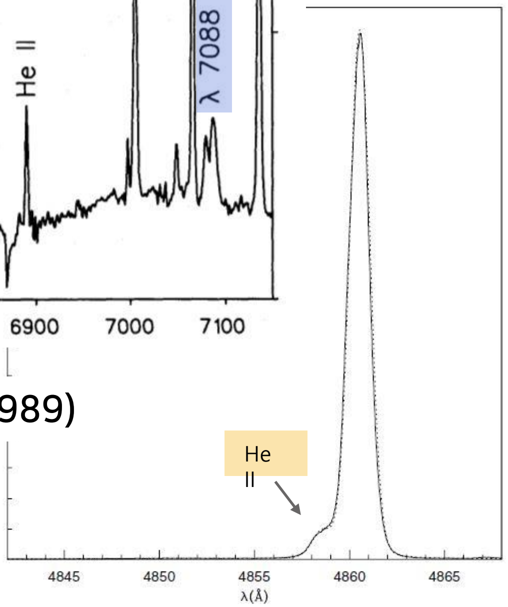
- At high temperature, He II, C IV, O VI, O VII ⋯ emission



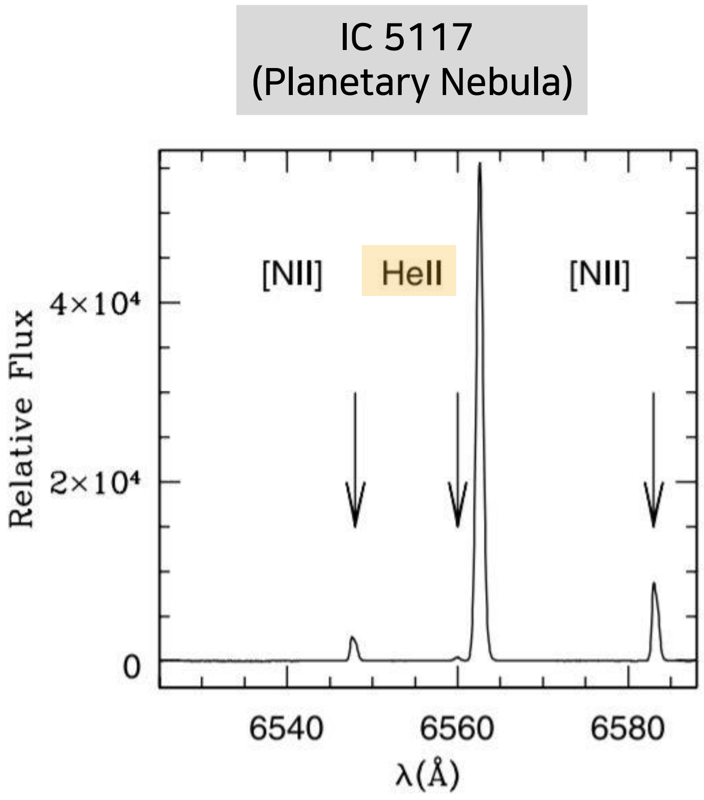
Bottorff et al. (2002)



Schmid (1989)

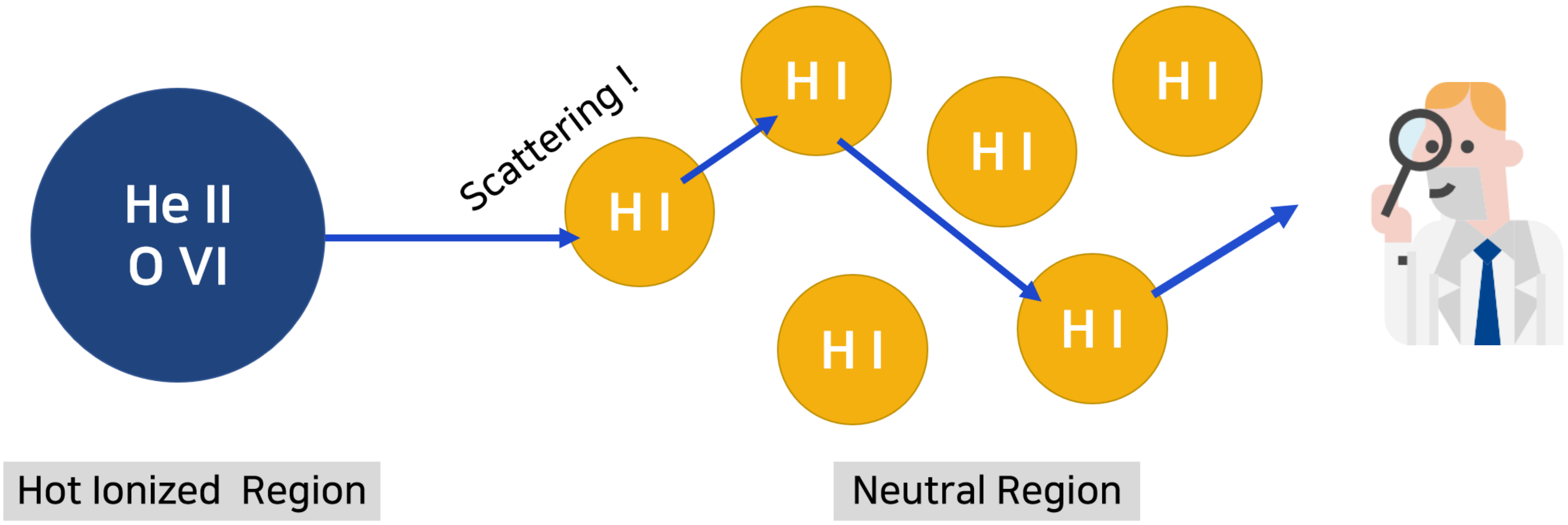


Jung & Lee (2004)



Lee et al. (2006)

He II Emission

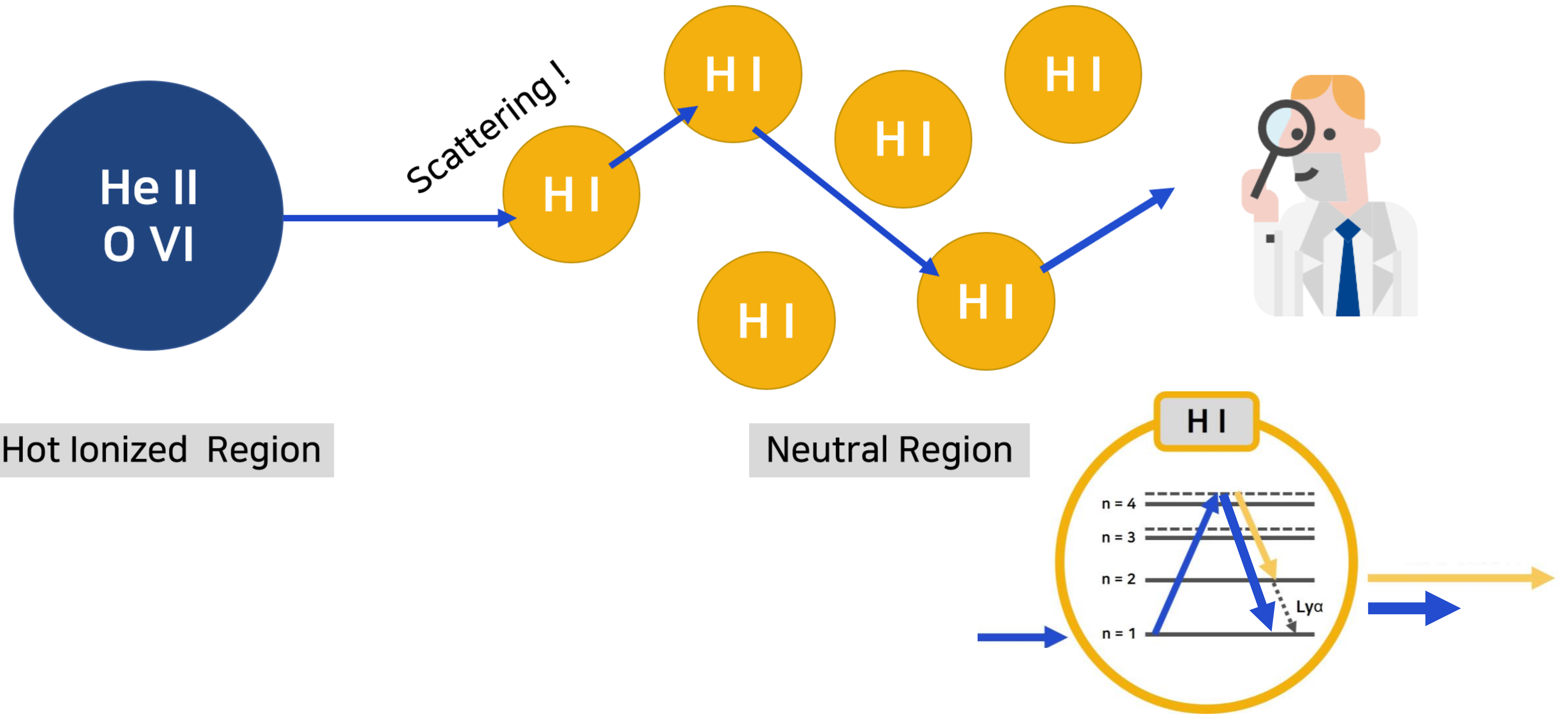


Symbiotic Stars & Planetary Nebulae

- Wide binary systems
  hot white dwarf + mass-losing giant

- Young planetary nebulae
- The heavy mass-loss at the giant stage

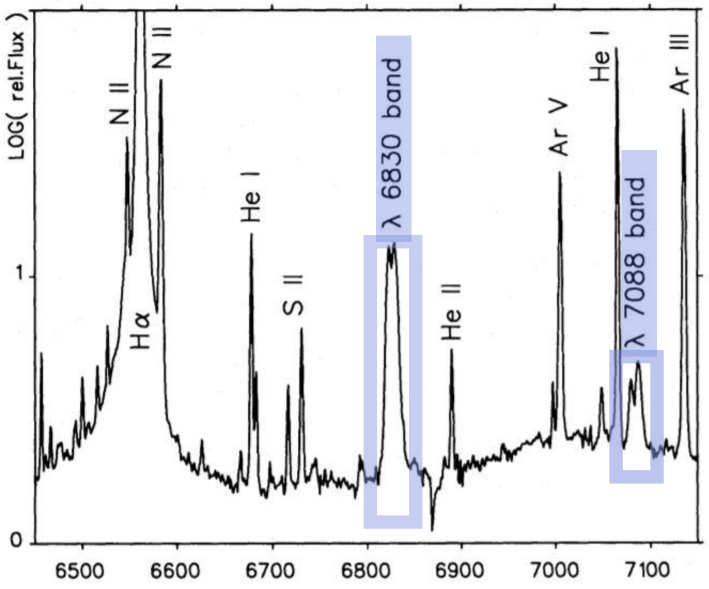
Symbiotic Stars & Planetary Nebulae



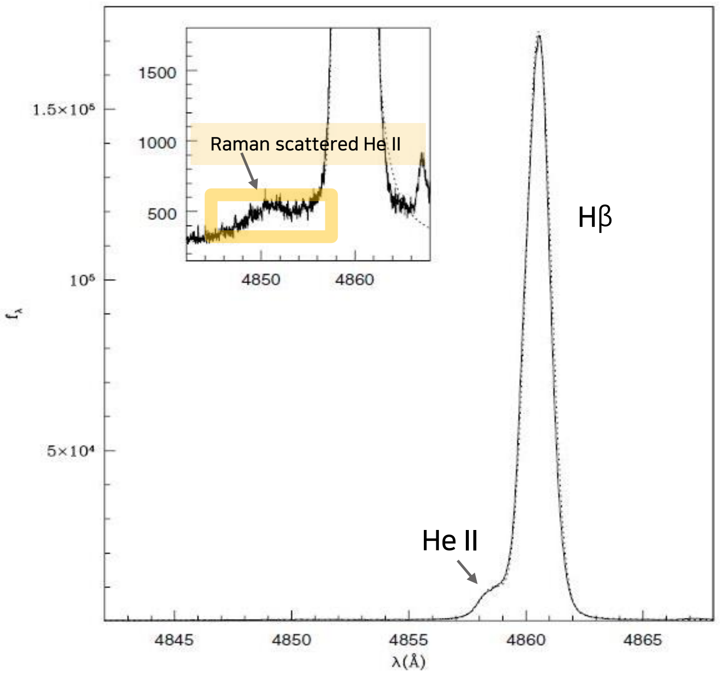
Symbiotic Stars & Planetary Nebulae

V1016 Cyg
(Symbiotic Star)

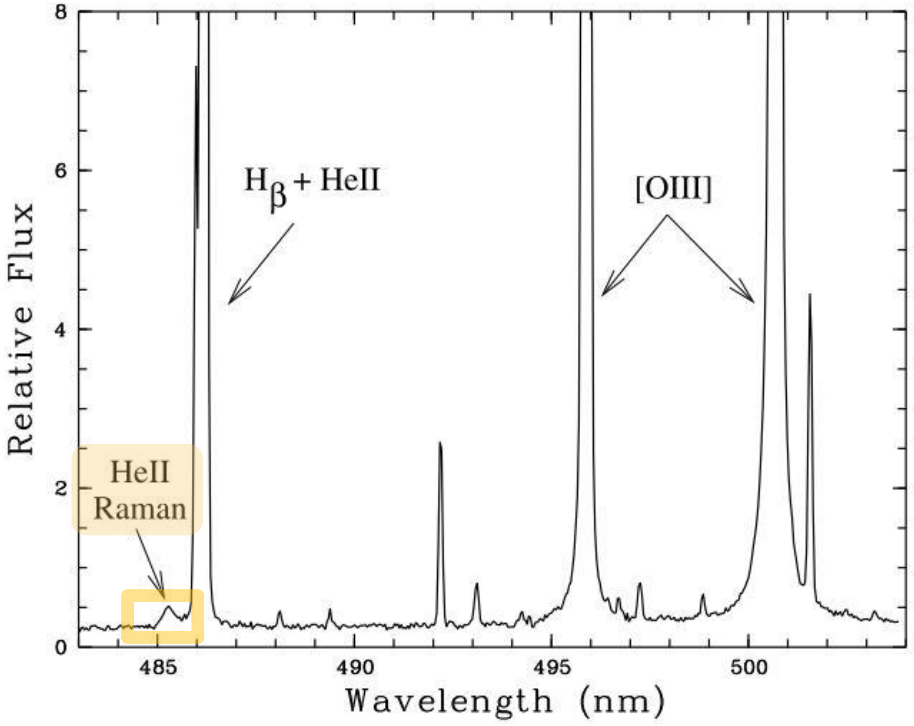
NGC 7027
(Planetary Nebula)



Schmid (1989)

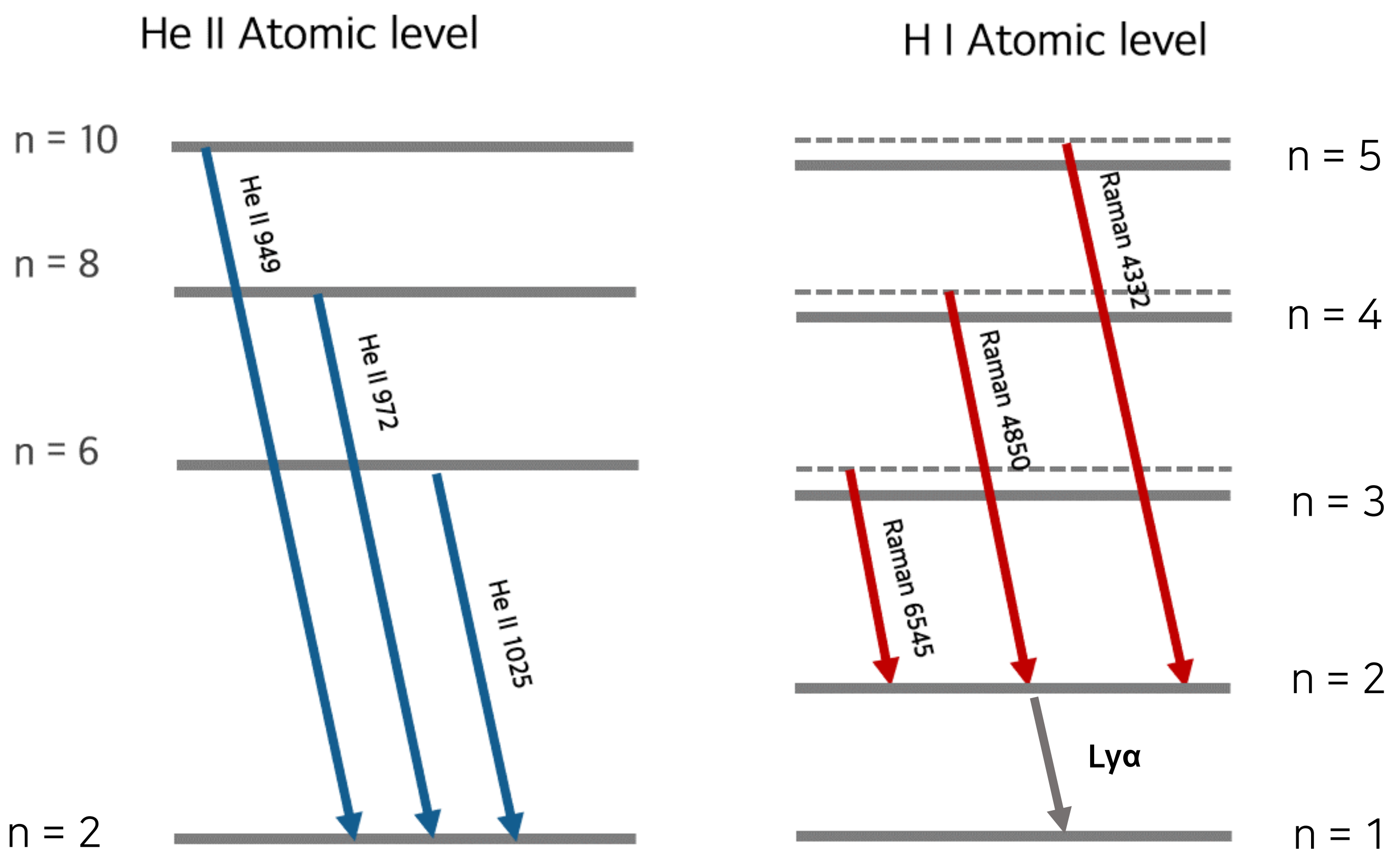


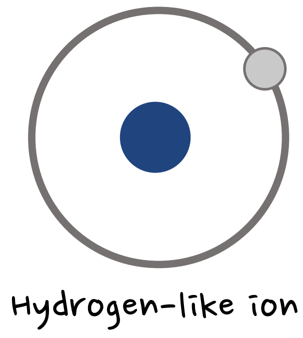
Jung & Lee (2004)



Pequignot et al. (1997)

Raman Scattered He II



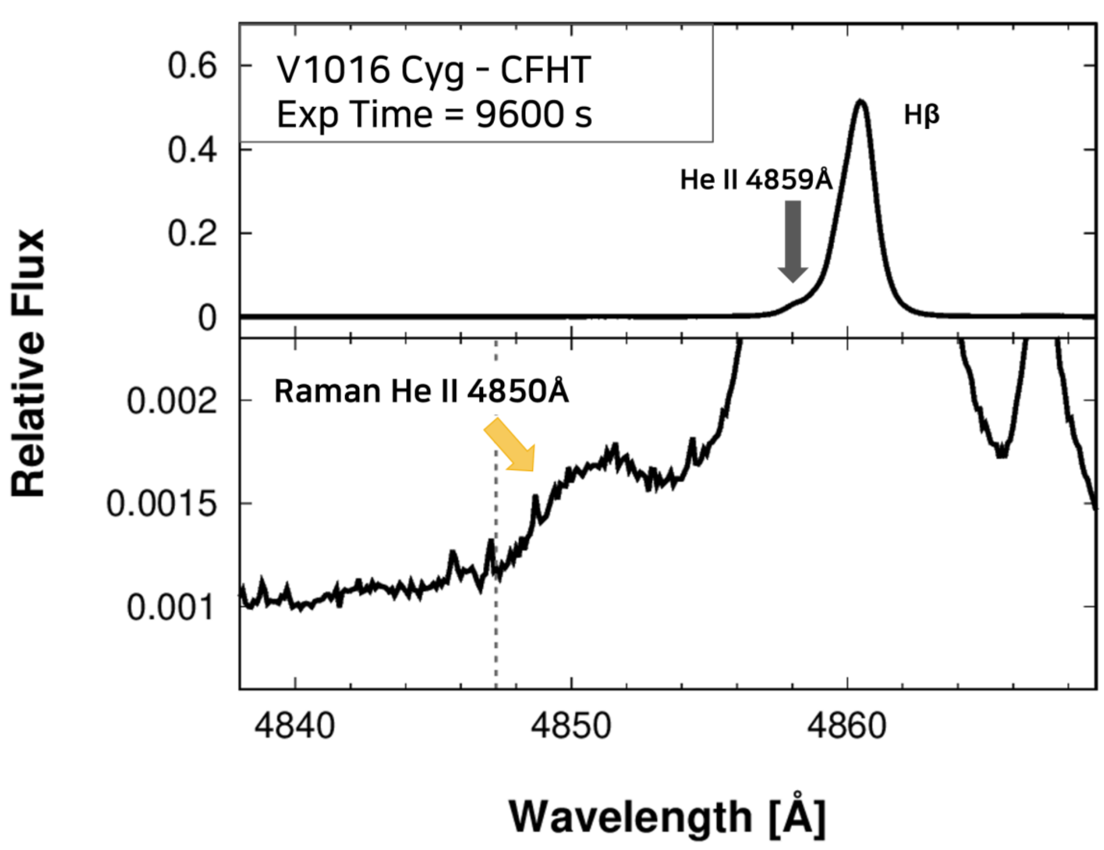


① He II 1025 → 6545 Å
blueward of Hα

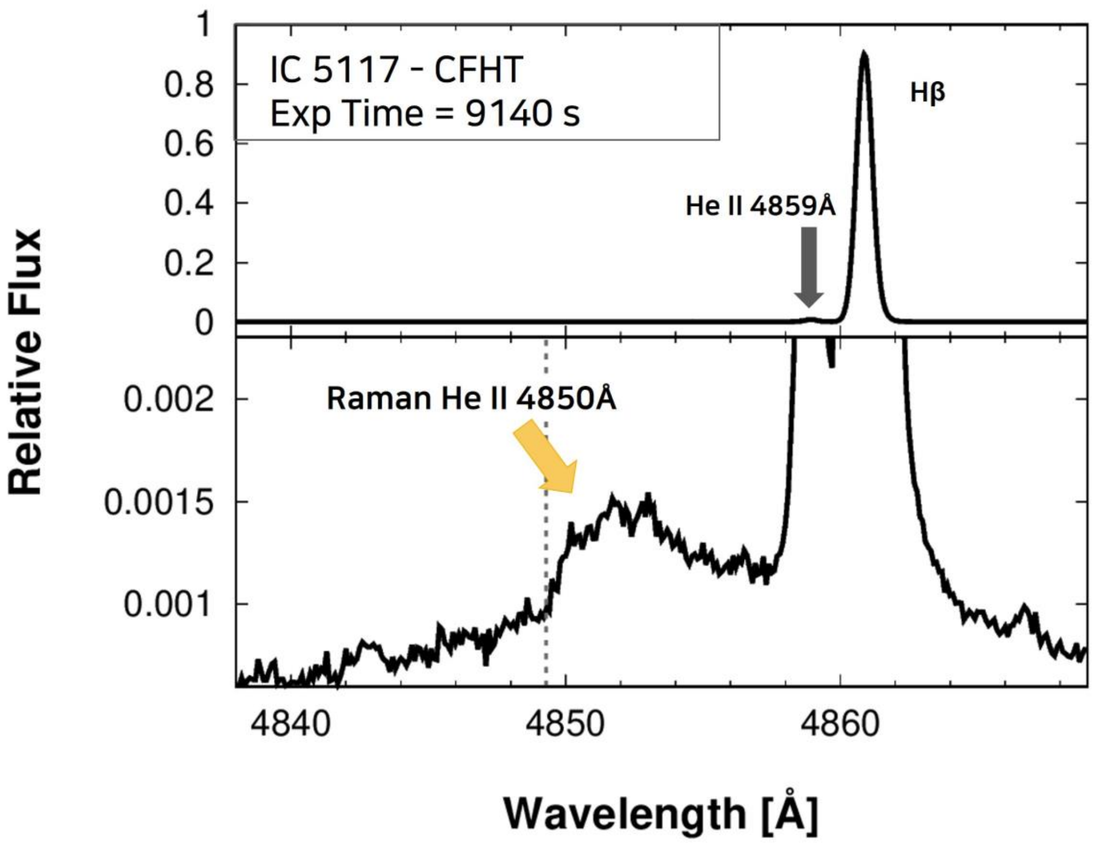
② He II 972 → 4850 Å
blueward of Hβ

③ He II 949 → 4332 Å
blueward of Hγ

Raman He II Features

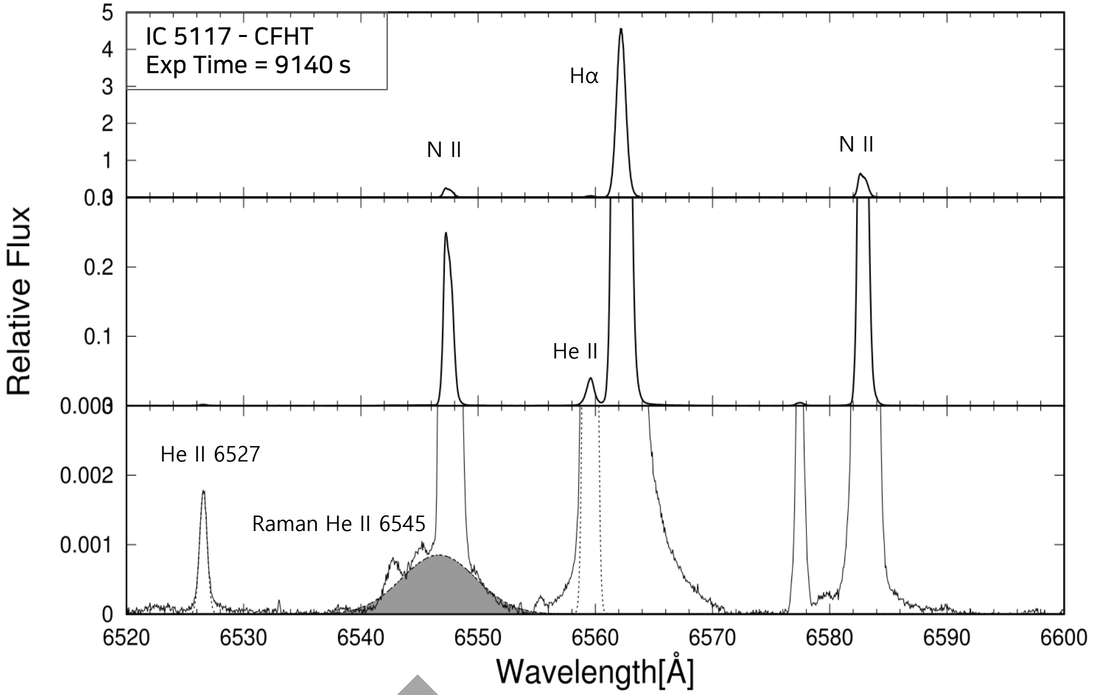


v_{shift} = 50 km/s

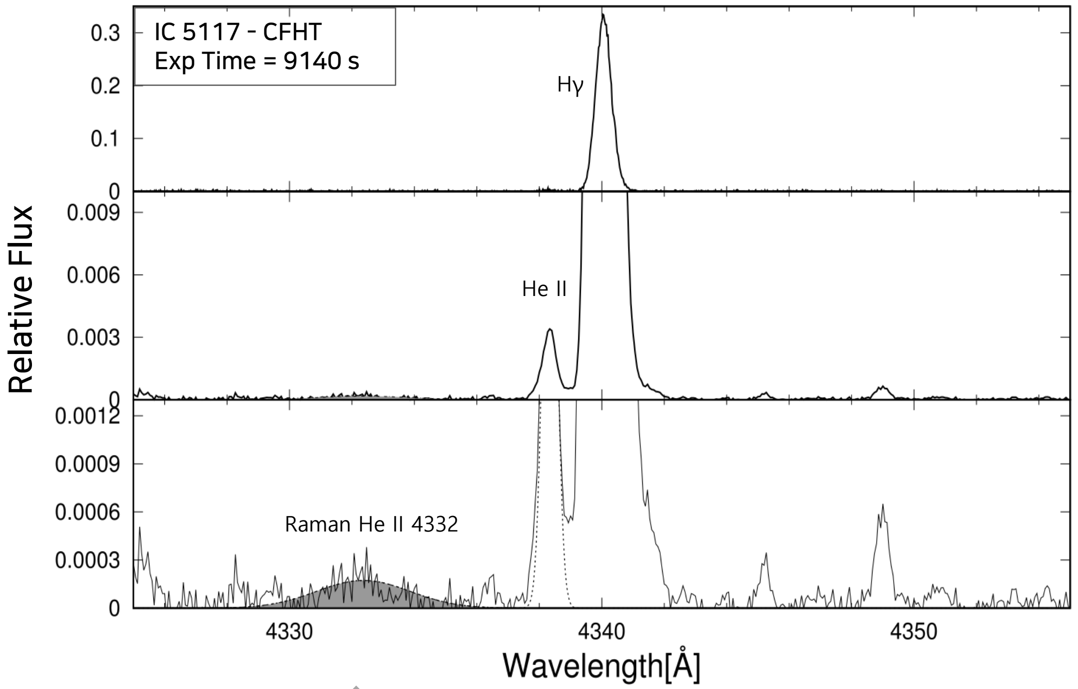


v_{shift} = 30 km/s

Raman He II Features

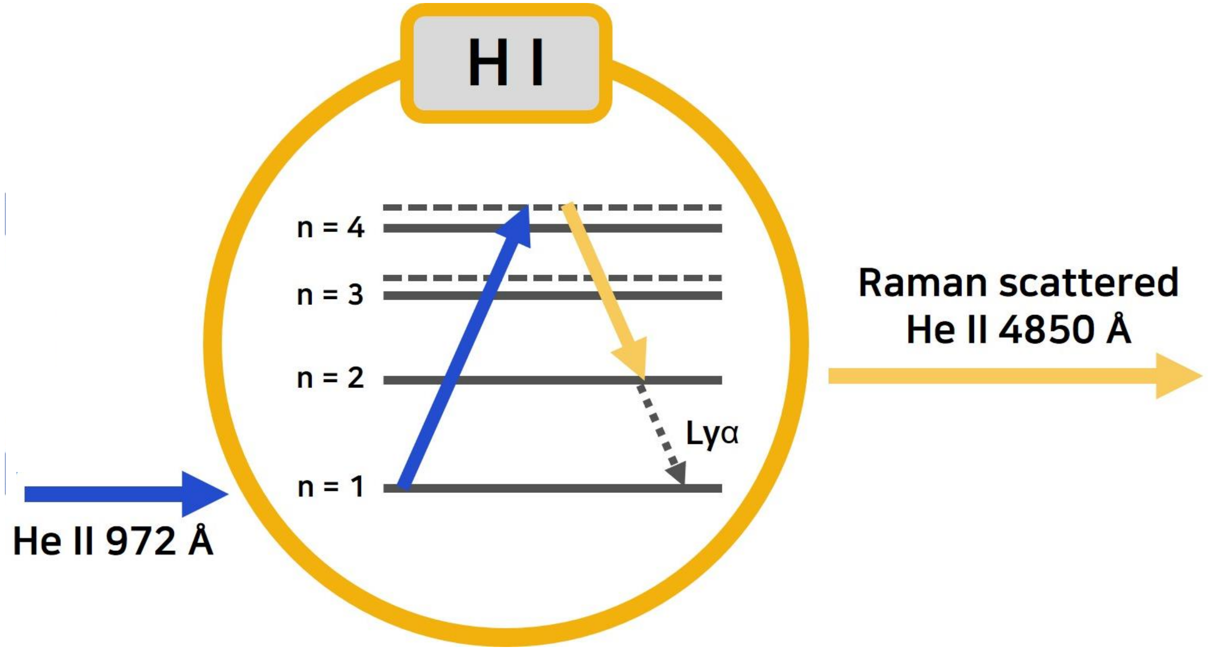


strong N II line



too weak feature
compared with noise

Raman Scattered He II



- $E_f = E_i - E_{Ly\alpha}$

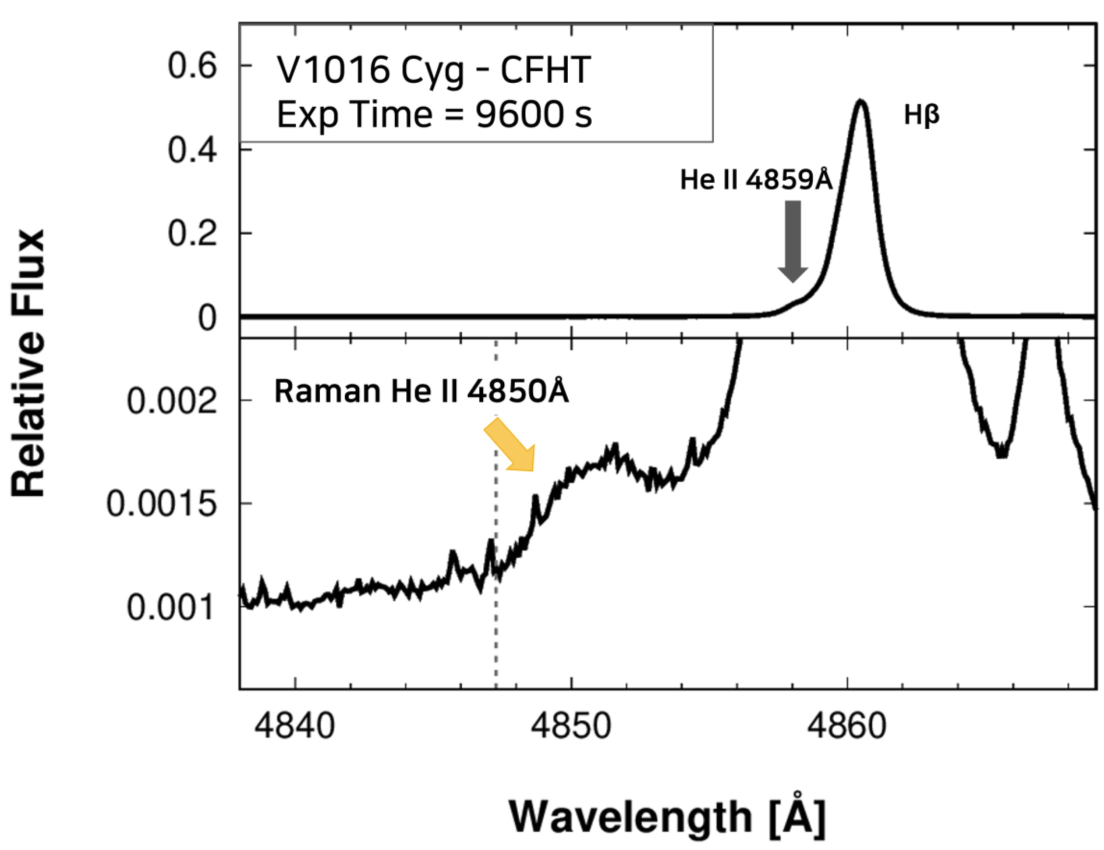
- $\frac{1}{\lambda_f} = \frac{1}{\lambda_i} - \frac{1}{Ly\alpha} \Rightarrow \frac{\Delta\lambda_f}{\lambda_f} = \left(\frac{\lambda_f}{\lambda_i}\right) \frac{\Delta\lambda_i}{\lambda_i}$

In the case of Raman He II 4850 Å,

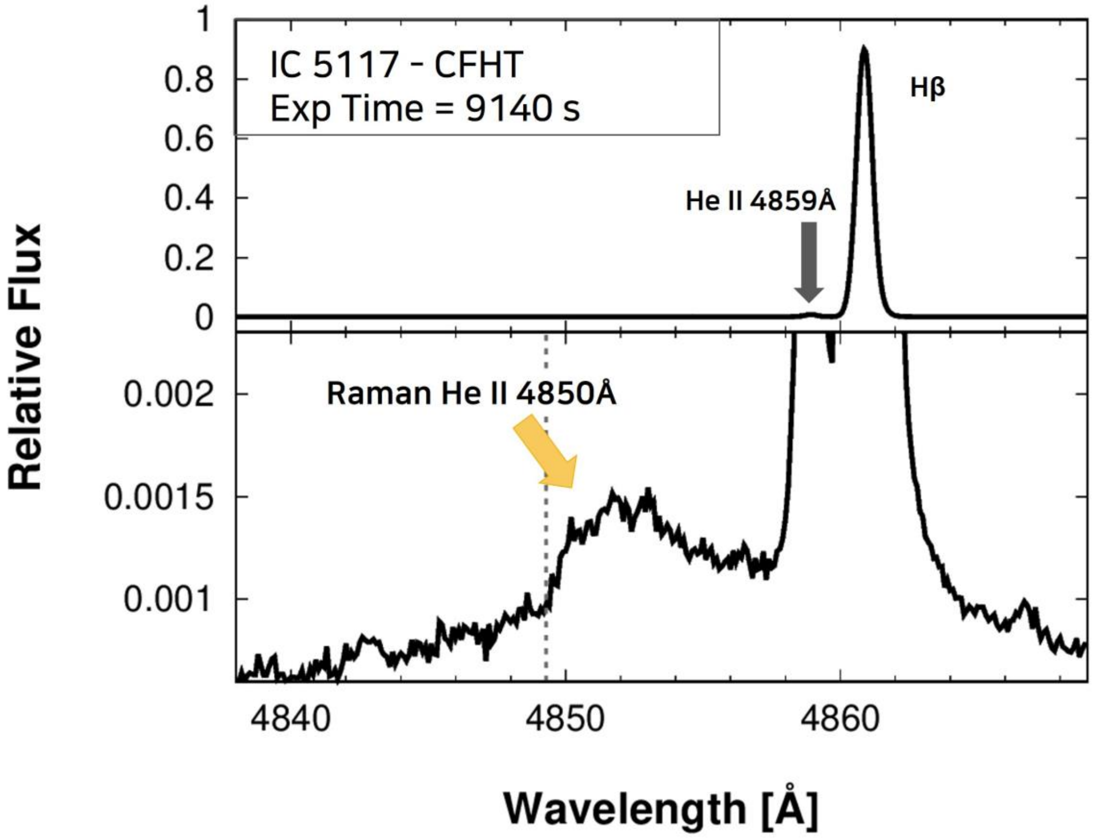
$$\left(\frac{\lambda_f}{\lambda_i}\right) = \left(\frac{4850}{972}\right) \approx 5$$

Raman scattered He II lines are a few times broader than He II emission lines !

Raman He II Features

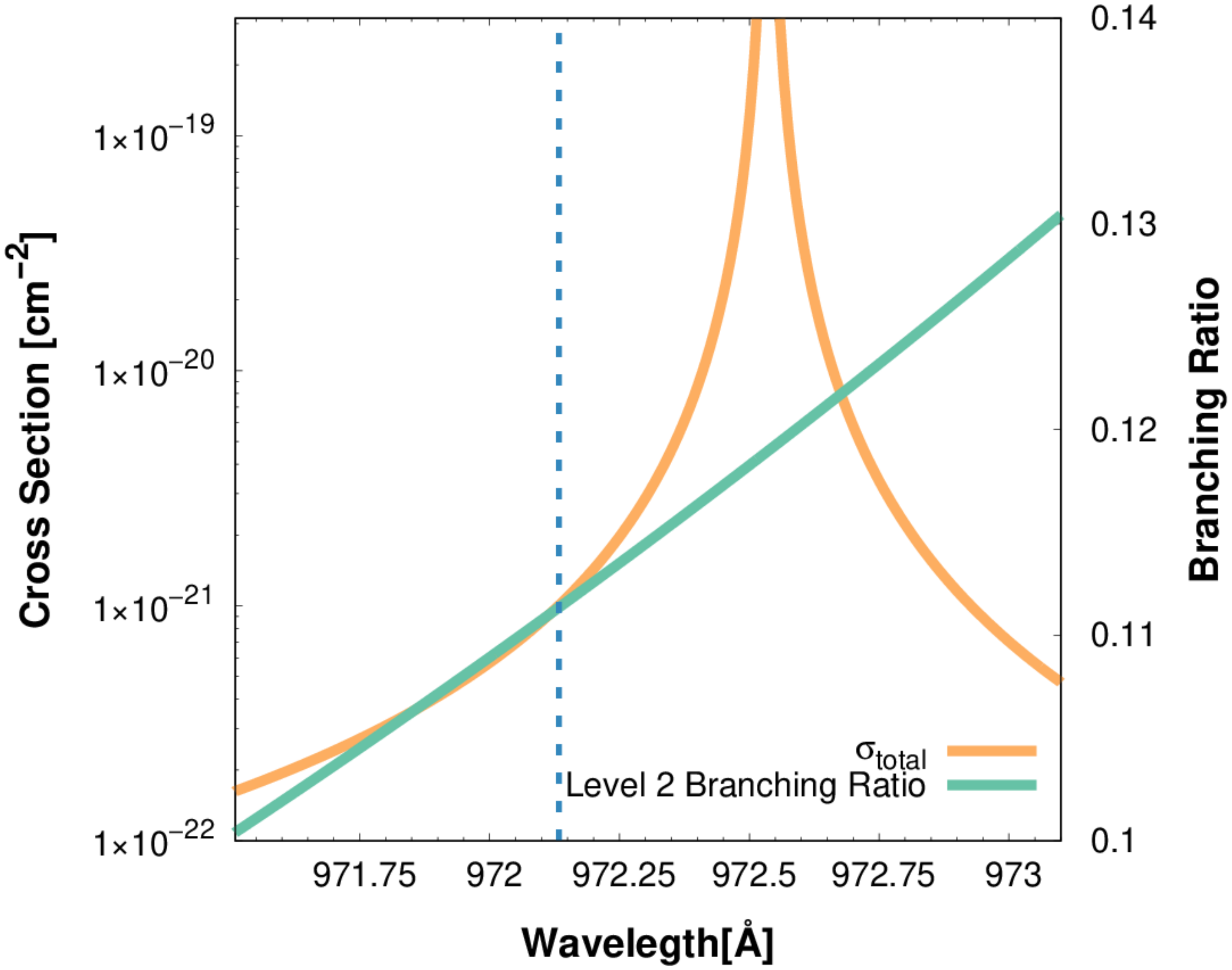


v_{shift} = 50 km/s



v_{shift} = 30 km/s

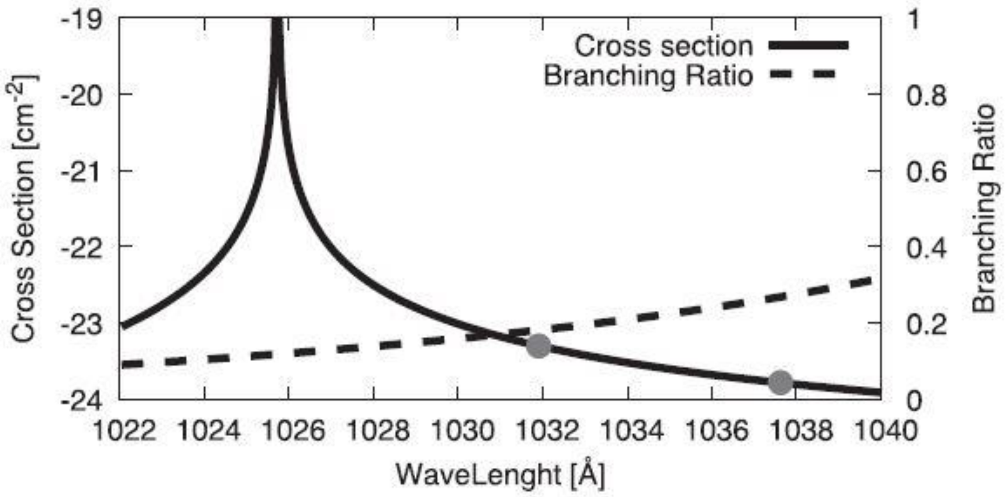
Raman Scattered He II



Raman scattered He II 4850 Å

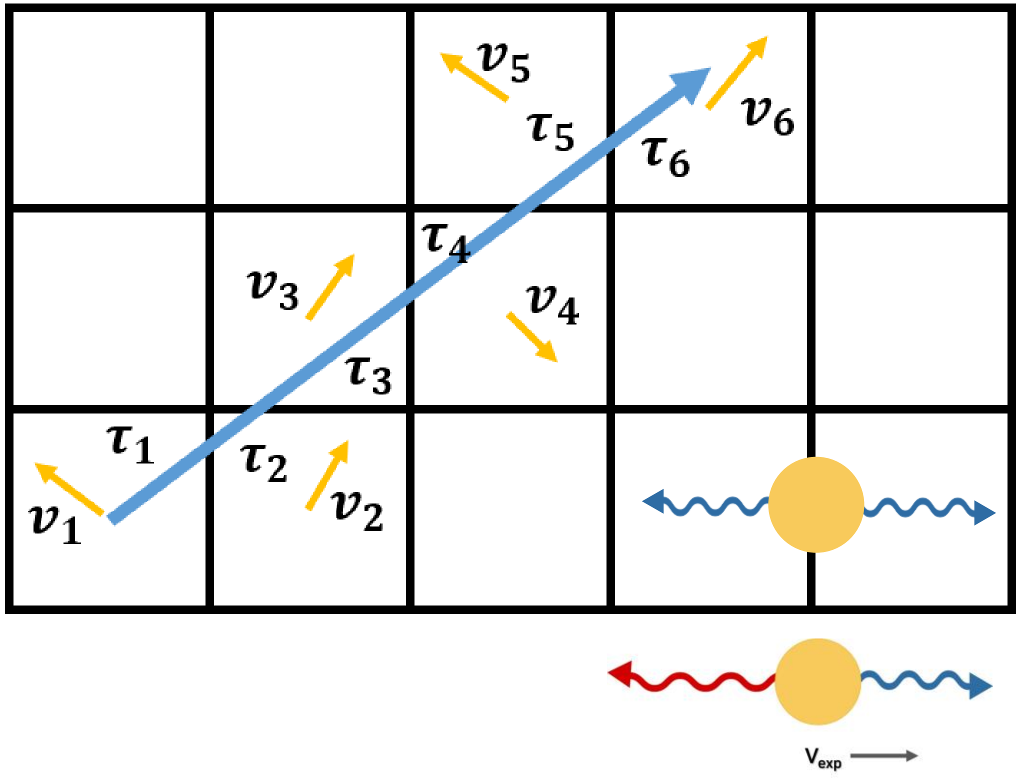
- Branching ratio ≈ 0.11
- $\sigma_{972} \approx 10^{-21}$ cm^2

For Raman scattering,
Thick neutral region with column density $N_{HI} \approx 10^{21}$ cm^{-2} is required



Lee et al. (2016)

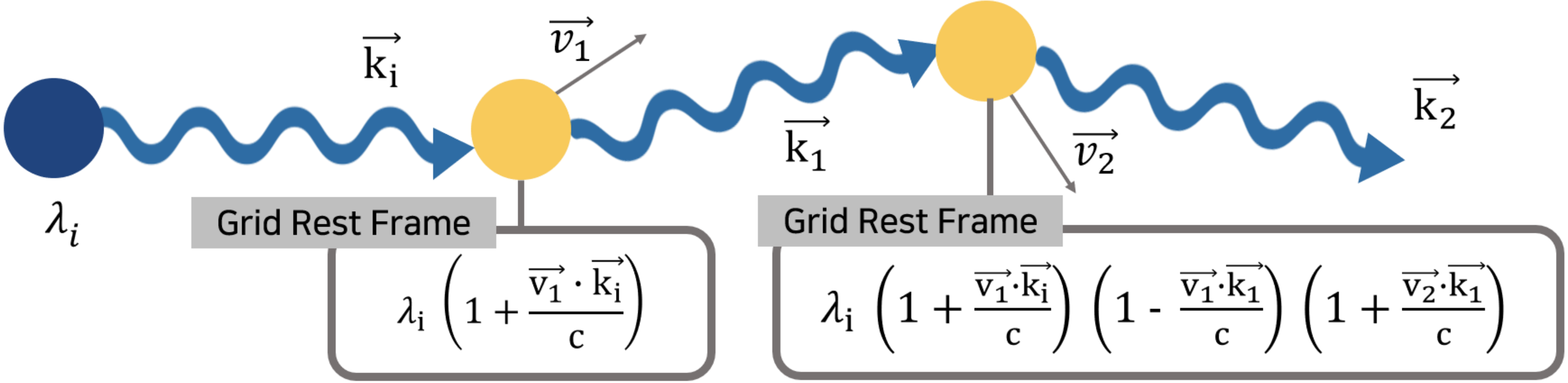
Grid-Based Radiative Transfer



$$\tau = \tau_1 + \tau_2 + \tau_3 + \tau_4 + \tau_5 + \tau_6$$

- In each grid, the physical conditions are taken to be uniform.
- A velocity vector and density are assigned to each grid.
- The optical depth τ_i for grid 'i' is computed by multiplying the cross section, density and the path length.
- By adding τ_i through the photon path, we determine the next scattering site.

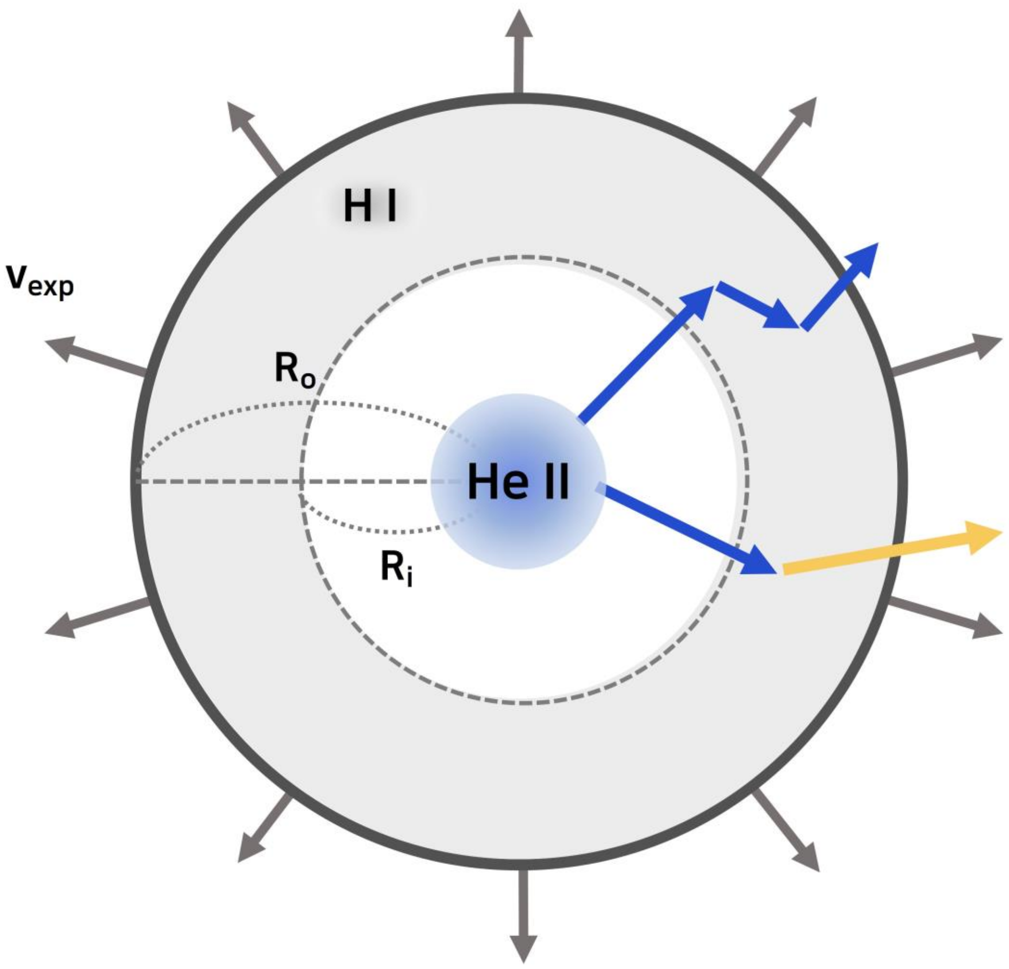
Grid-Based Radiative Transfer



$$\lambda_i \left(1 + \frac{\vec{v_1} \cdot \vec{k_i}}{c}\right) \left(1 - \frac{\vec{v_1} \cdot \vec{k_1}}{c}\right)$$

$$\lambda_i \left(1 + \frac{\vec{v_1} \cdot \vec{k_i}}{c}\right) \left(1 - \frac{\vec{v_1} \cdot \vec{k_1}}{c}\right) \left(1 + \frac{\vec{v_2} \cdot \vec{k_1}}{c}\right) \left(1 - \frac{\vec{v_2} \cdot \vec{k_2}}{c}\right)$$

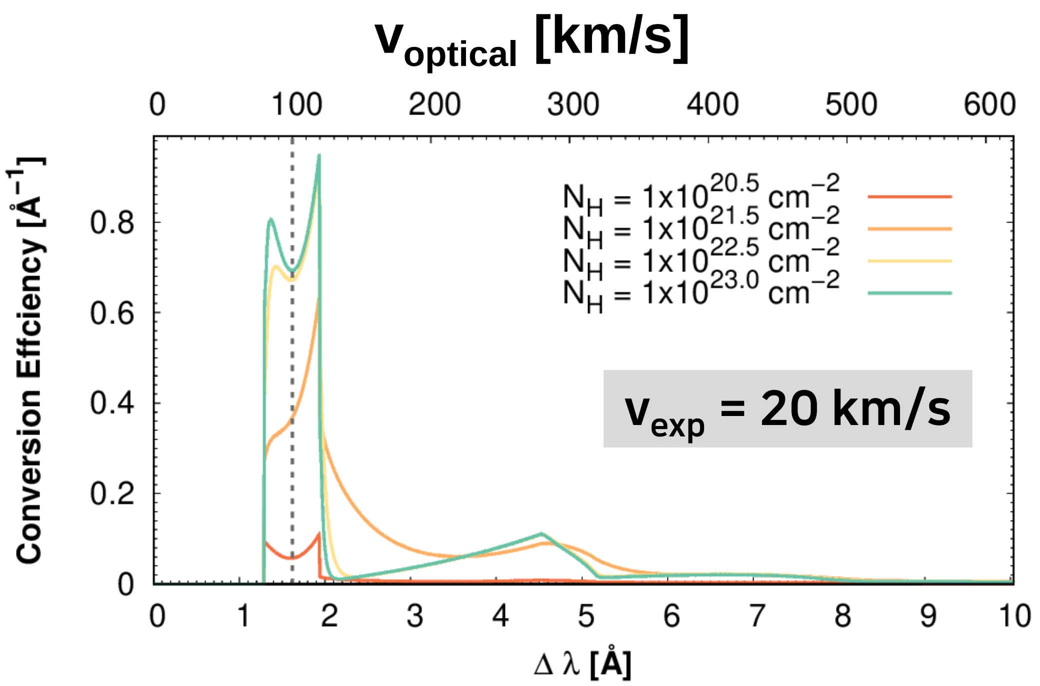
Geometry of Radiative Transfer

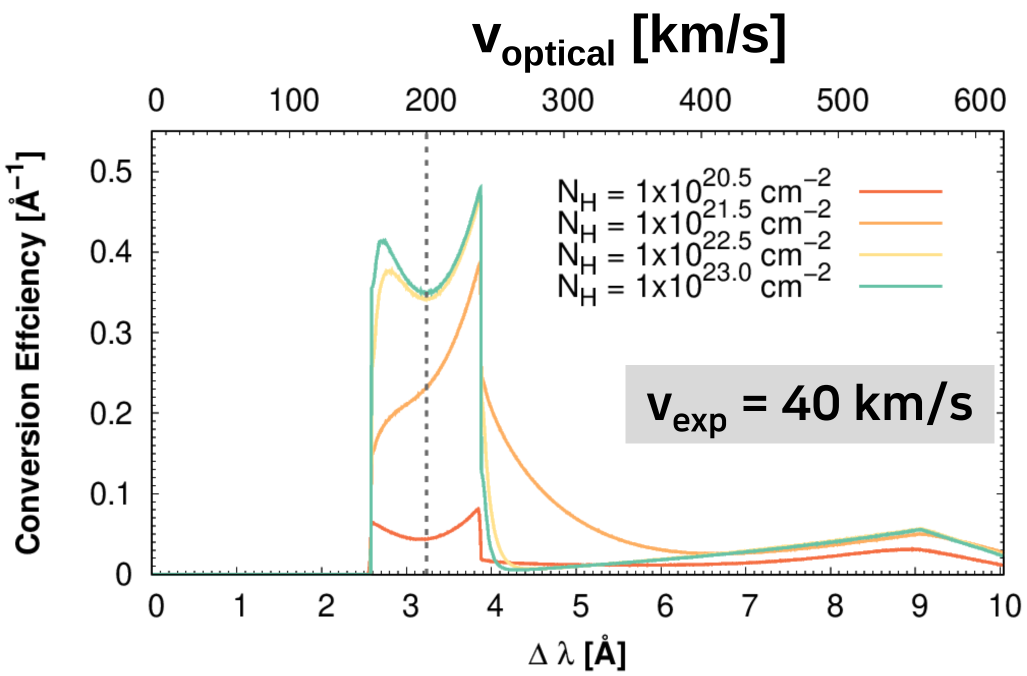


- Assume a monochromatic / Gaussian He II emission source is surrounded by a spherical shell-like H I region.
- He II UV photons can escape the scattering region by Rayleigh and Raman scattering.
- The H I region is moving away from the He II source with constant velocity v_{exp}.

- Parameters
  - $\mathbf{N_{HI}}$ (column density)
  - $\mathbf{v_{exp}}$ (expansion velocity of the HI region)

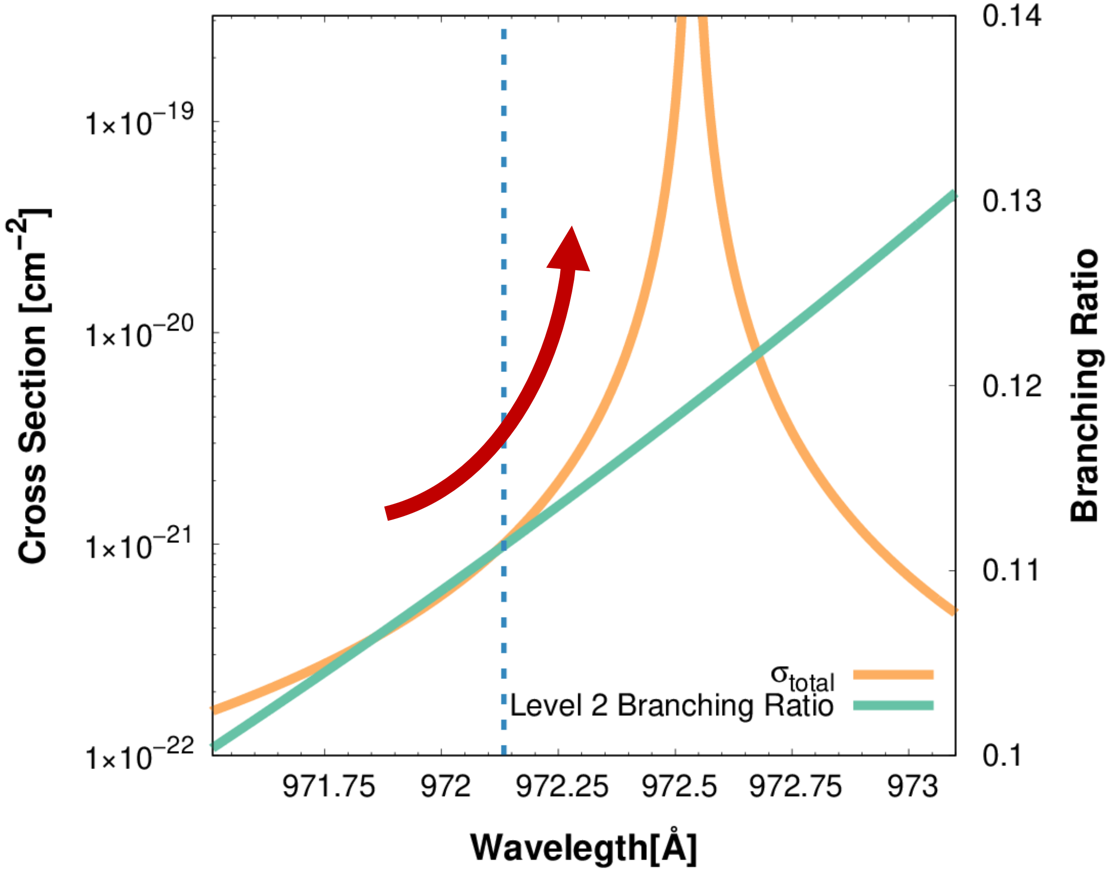
Result ① : Monochromatic Source

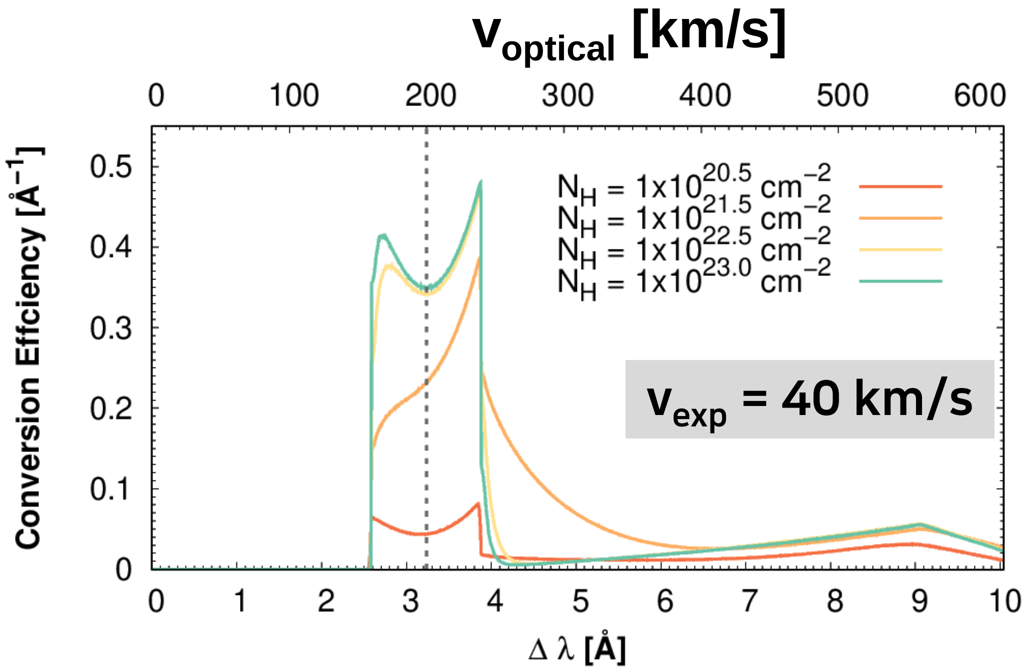




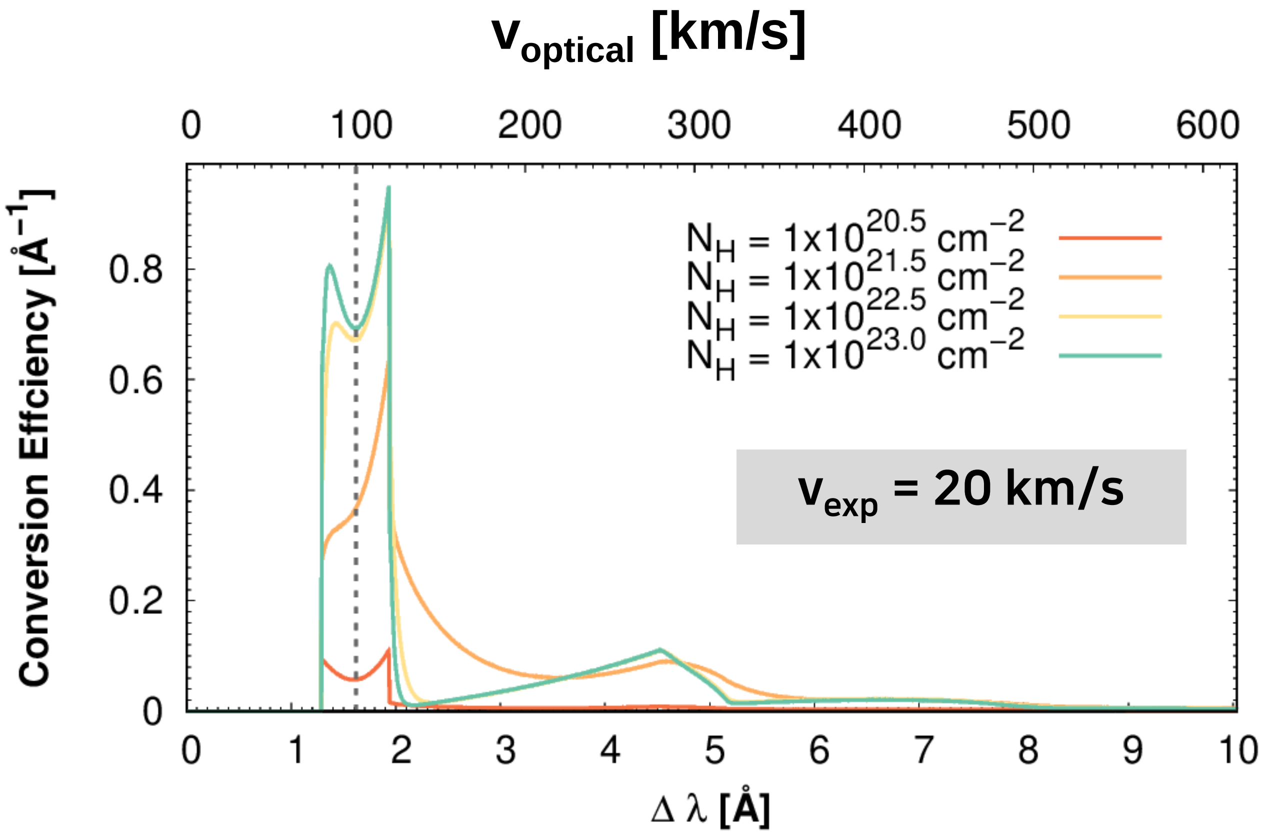
① Double peak structure varying with column densities
② Appearance of a secondary peak – reentry effect
③ The width of primary peak ≈ 2 v_{exp}

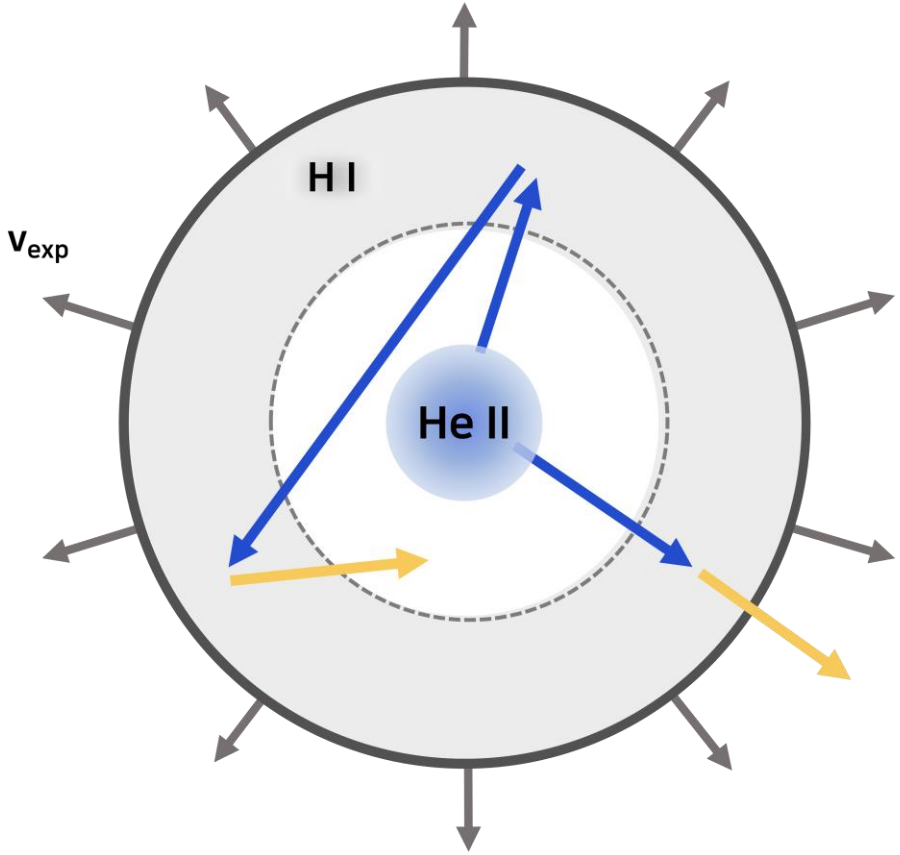
Result ① : Monochromatic Source



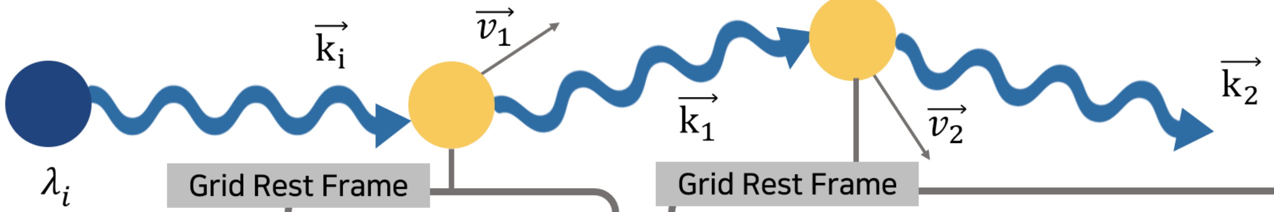


Result ① : Monochromatic Source





Result ① : Monochromatic Source

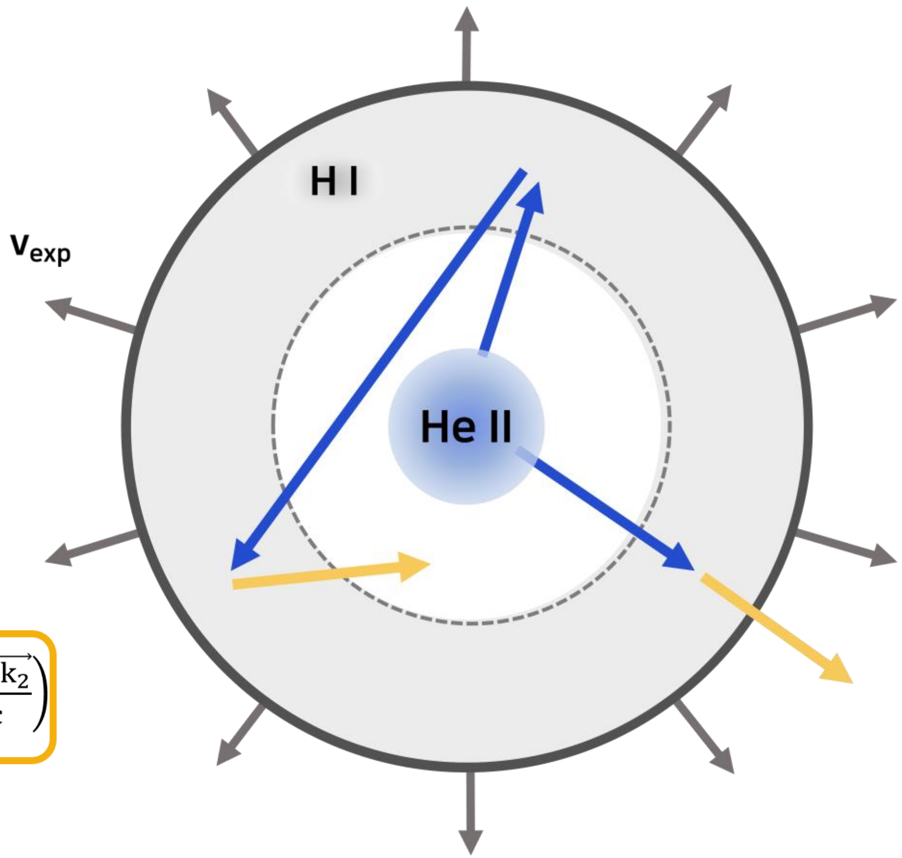


$$\lambda_i\left(1+\frac{\vec{v_1}\cdot\vec{k_i}}{c}\right)$$

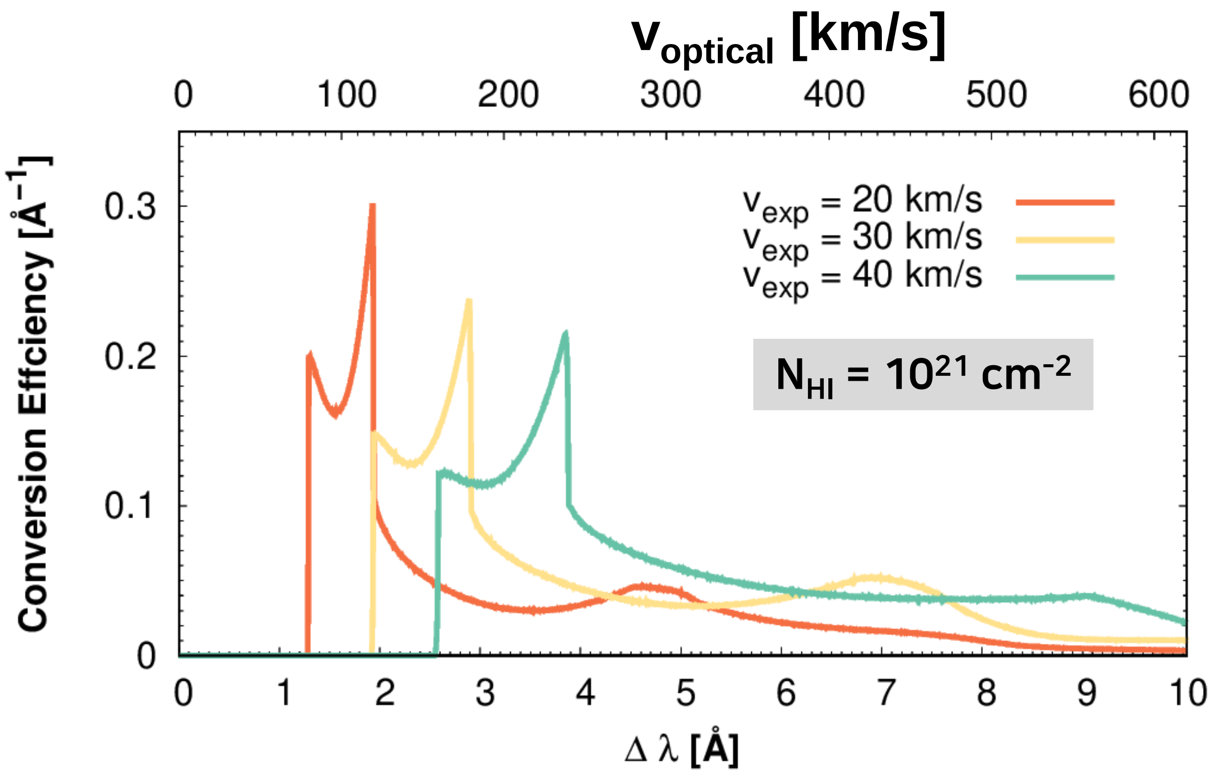
$$\lambda_i\left(1+\frac{\vec{v_1}\cdot\vec{k_i}}{c}\right)\left(1-\frac{\vec{v_1}\cdot\vec{k_1}}{c}\right)\left(1+\frac{\vec{v_2}\cdot\vec{k_1}}{c}\right)$$

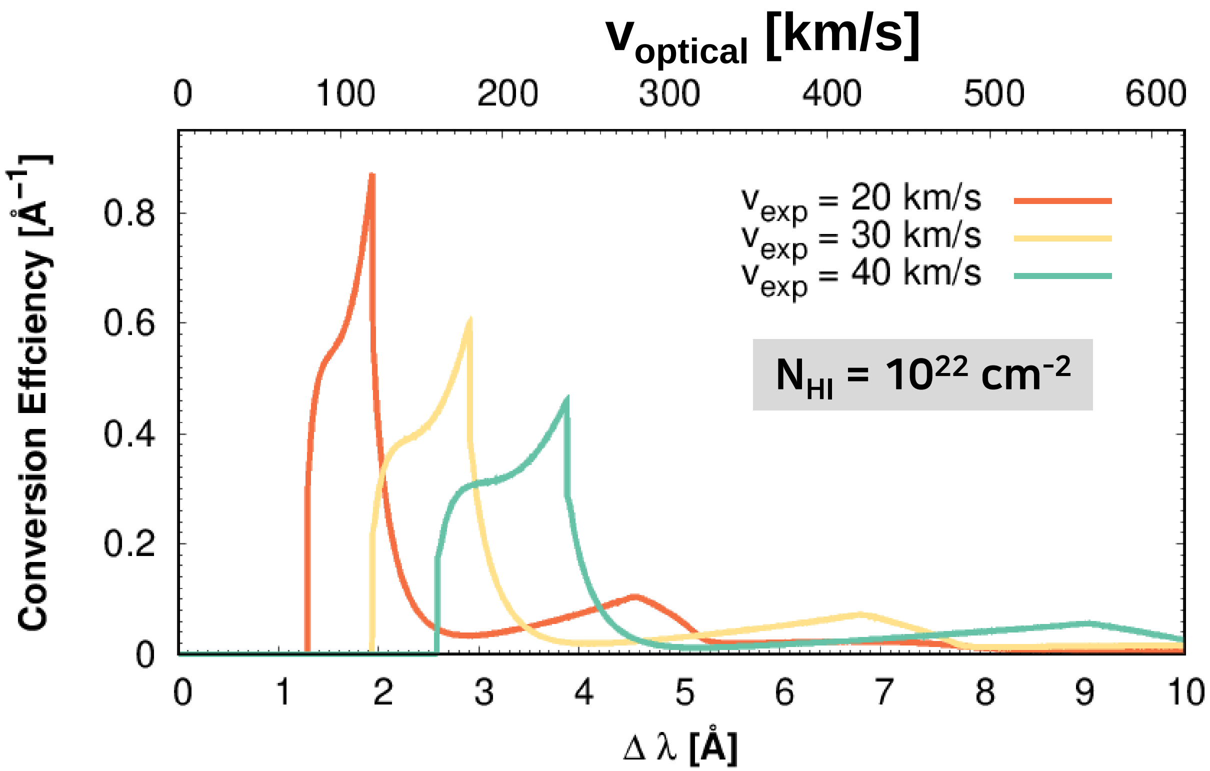
$$\lambda_i\left(1+\frac{\vec{v_1}\cdot\vec{k_i}}{c}\right)\left(1-\frac{\vec{v_1}\cdot\vec{k_1}}{c}\right)$$

$$\lambda_i\left(1+\frac{\vec{v_1}\cdot\vec{k_i}}{c}\right)\left(1-\frac{\vec{v_1}\cdot\vec{k_1}}{c}\right)\left(1+\frac{\vec{v_2}\cdot\vec{k_1}}{c}\right)\left(1-\frac{\vec{v_2}\cdot\vec{k_2}}{c}\right)$$



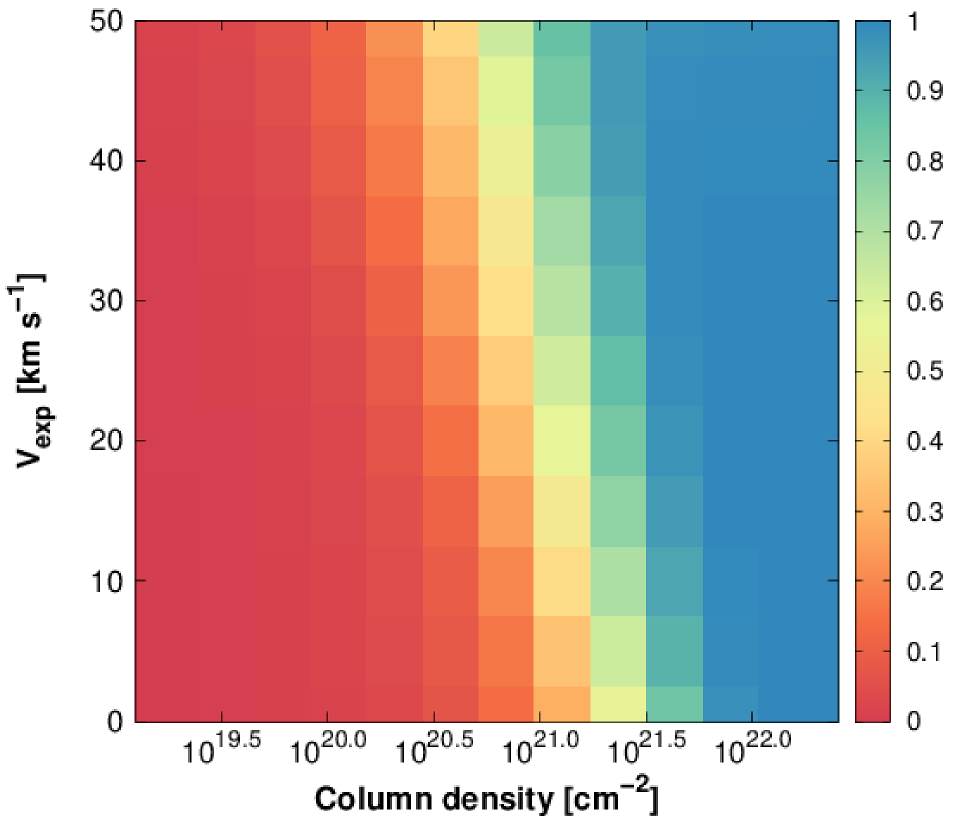
Result ① : Monochromatic Source



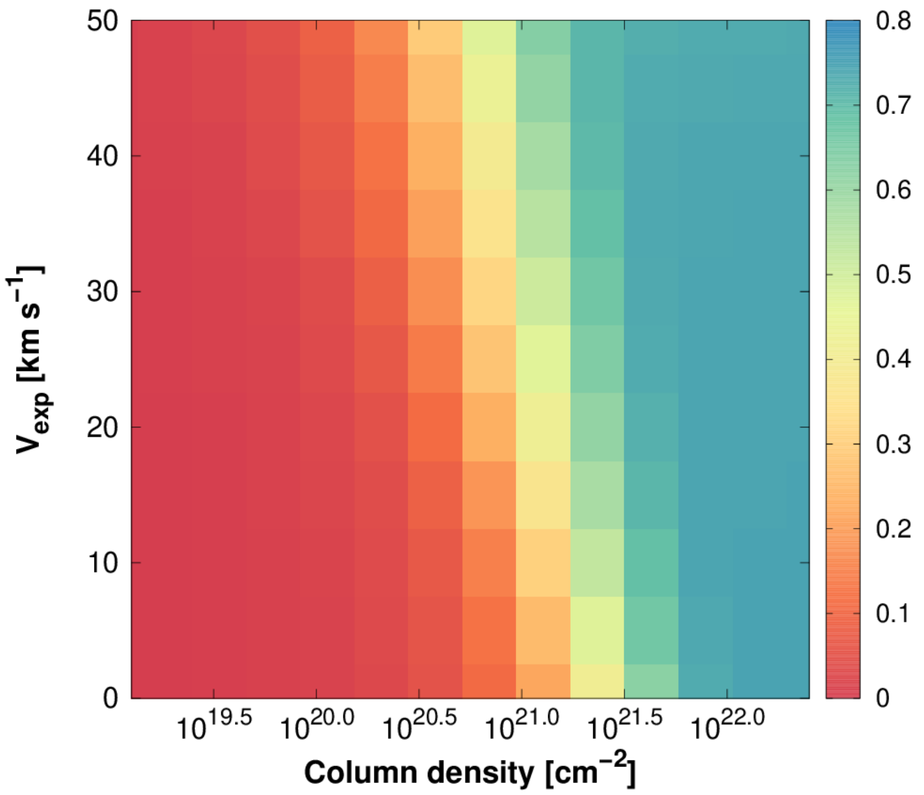


Result ① : Monochromatic Source

Total Raman conversion efficiency

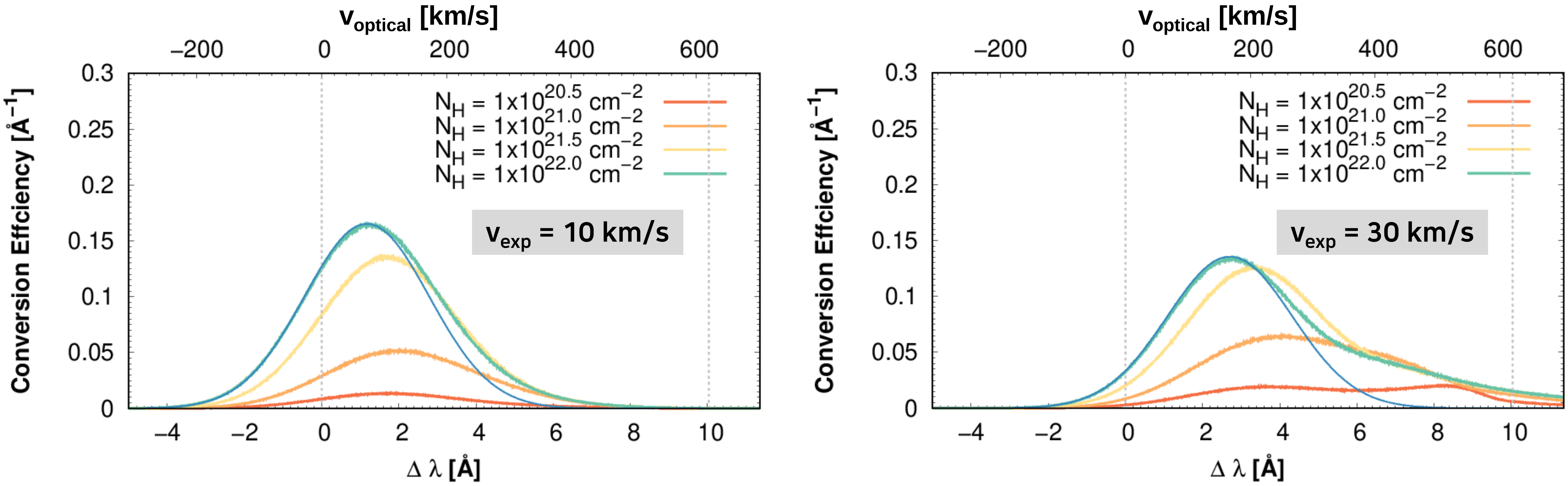


4850 Å conversion efficiency



Result ② :Gaussian Source

- v_{cir} = 20 km/s

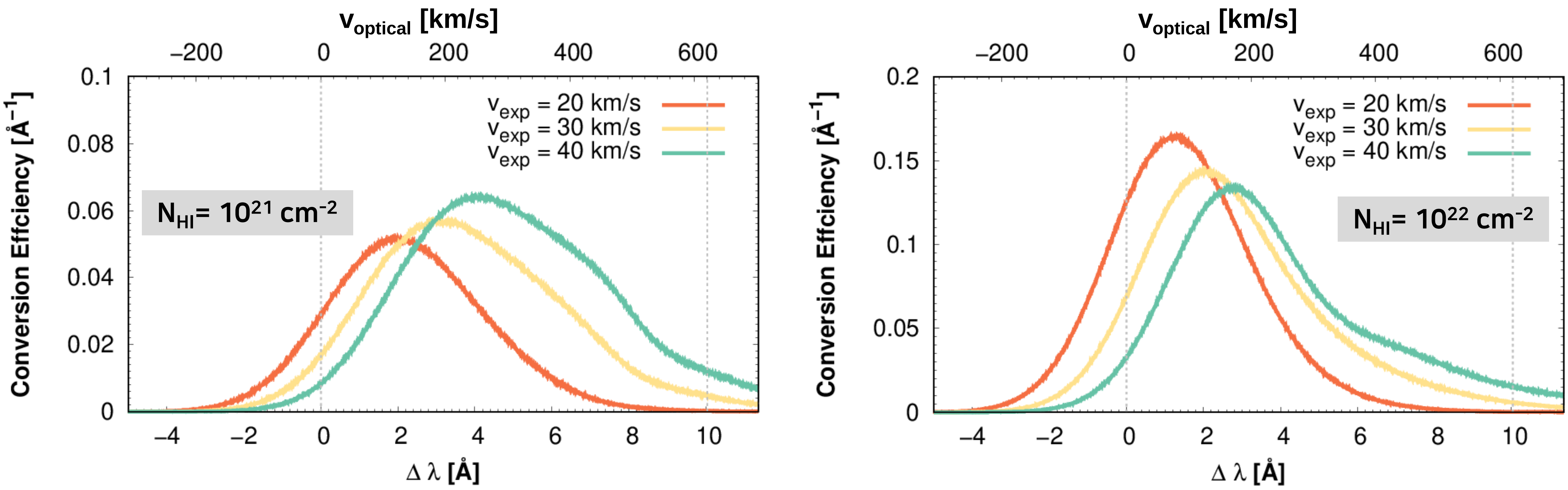


$v_{Gaussian}$ = 14.5 km/s

$v_{Gaussian}$ = 33.5 km/s

Result ② :Gaussian Source

- v_{cir} = 20 km/s



Future Work

- We will conduct statistical analyses for profile distortion – line center, width and skewness
- We will extend our analysis to the case of open geometry, which will yield additional information including inclination.
- Profile fitting should be carried out using observational data with excellent signal to noise ratio allowing reliable continuum subtraction.