Durham University
Institute for Computational Cosmology

Building H II regions from scratch

Understanding hydrogen recombination lines using a simple atomic model

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Yuankang Liu

Supervisors: Tom Theuns & Anna McLeod

In collaboration with Tsang Keung Chan (Hong Kong) and Alex Richings (Hull)

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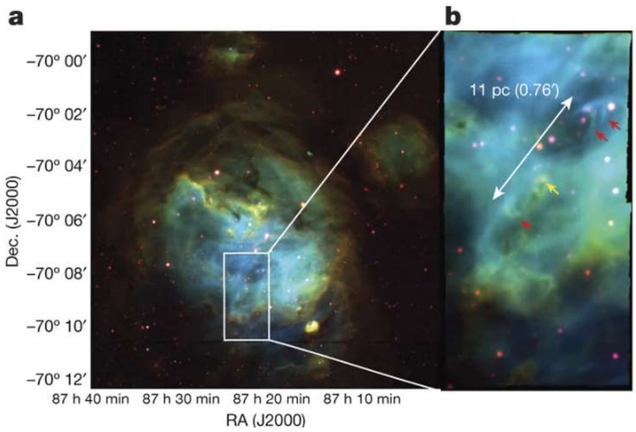
Observations meet simulations

H II region in LMC



McLeod et al., 2018

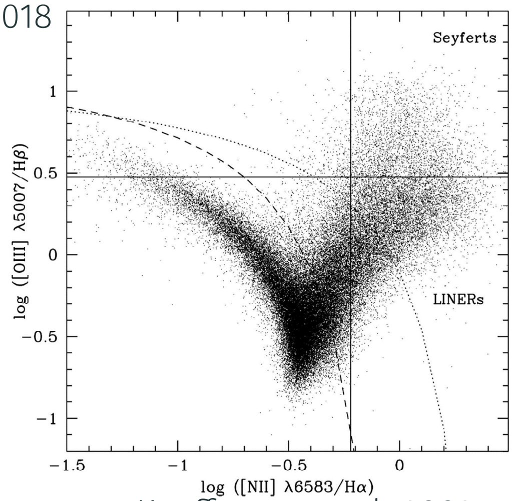
Starforge simulation

Guszejnov et al. 2021

red - [S II] 6731 Å

green - Hα

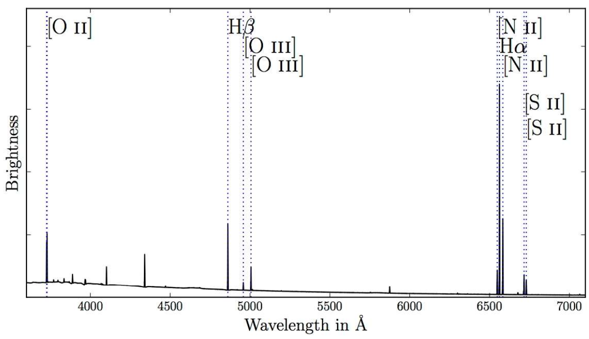
blue - [O III] 5007 Å



Kauffmann et al. 2003

HII region

Spectrum of an H II region



Observation

Density n

Temperature T

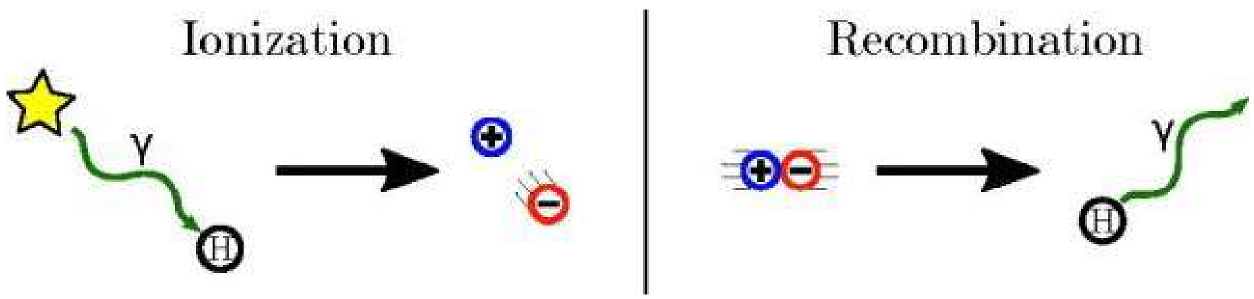
metallicity Z

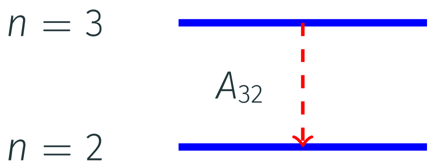
etc.

Simulation

Credit: MOSFIRE Team

Hydrogen recombination lines - a two-level system



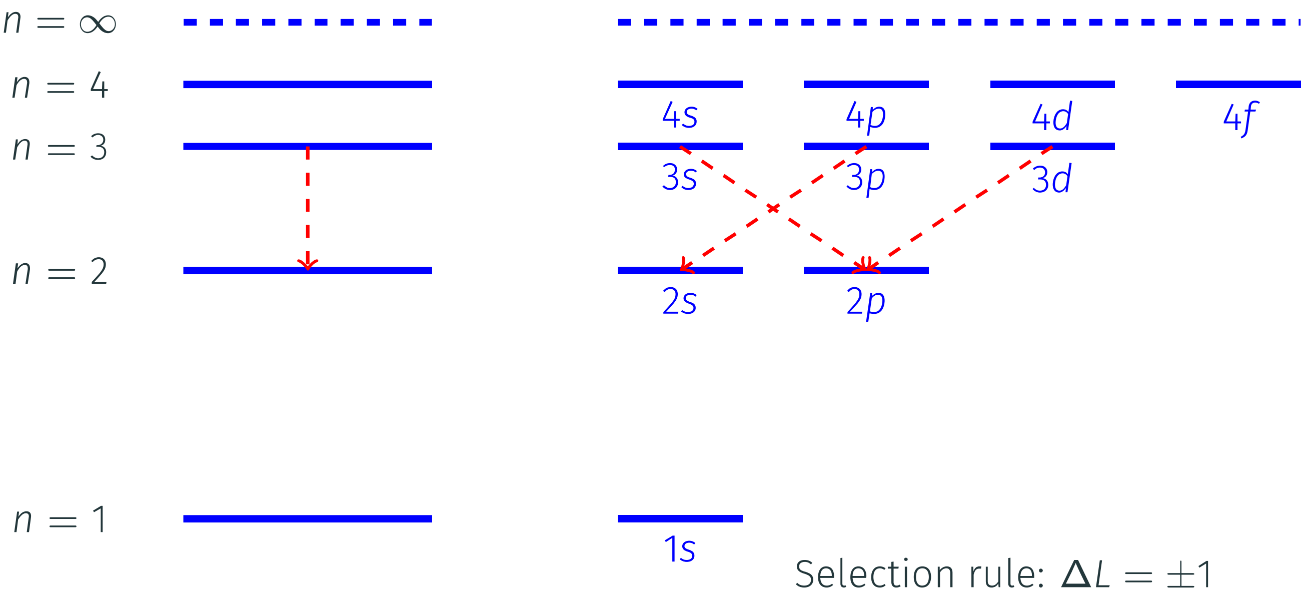


Line emissivity j_ν [erg s^{-1} cm^{-3}]:

$$4\pi j_\nu = n_3 A_{32} h\nu_{32}. \tag{1}$$

- Spontaneous decay

Hydrogen recombination lines - H α

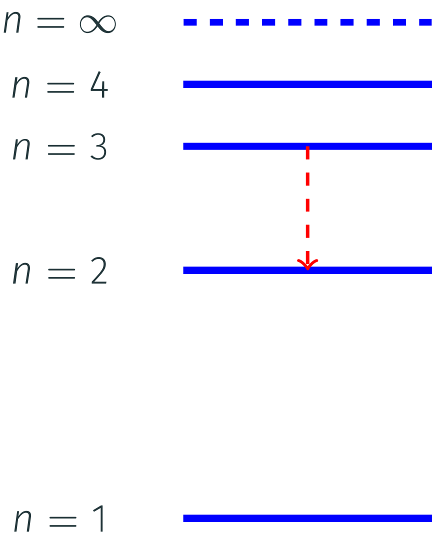


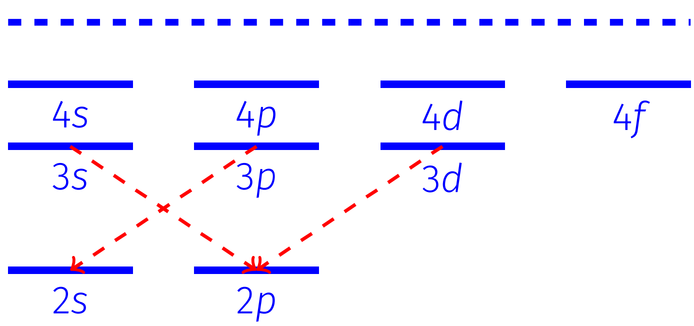
Selection rule: $\Delta L = \pm 1$

Line emissivity j_ν:

$$4\pi j_\nu = (n_{3s}A_{3s,2p} + n_{3p}A_{3p,2s} + n_{3d}A_{3d,2p})h\nu_{32}. \qquad (2)$$

Hydrogen recombination lines - H α





Einstein A values (NIST)

Transitions	Einstein A's [s^{-1}]
3s –> 2p	6.3E+06
3p –> 2s	2.2E+07
3d –> 2p	6.5E+07

Line emissivity j_ν:

$$4\pi j_\nu = (n_{3s}A_{3s,2p} + n_{3p}A_{3p,2s} + n_{3d}A_{3d,2p})h\nu_{32}. \quad (3)$$

Modelling recombination line intensity

Ways to calculate recombination line intensity:

- Look-up table (Storey & Hummer 1995)
  RAMSES-RTZ (Katz 2022)
- Solving statistical equilibrium equation for level populations (Raga et al. 2015, Osterbruck & Ferland 2006)
  FIRE simulations (Richings et al. 2022); Cloudy (Chatzikos et al. 2023)

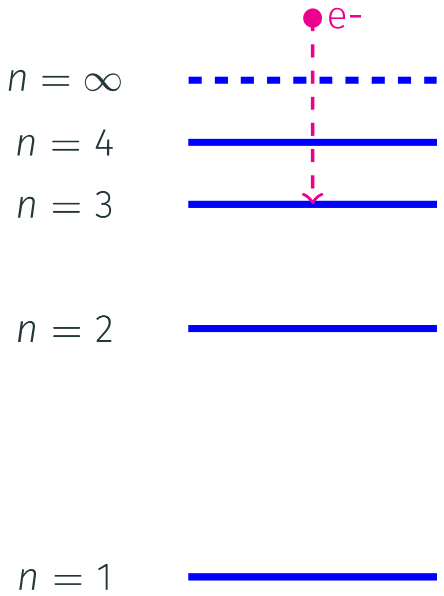
For a simple H II region model, level population of $n = 3$
Raga 2015: 8.09e-18 cm^{-3};
Osterbruck & Ferland 2006: 9.43e-17 cm^{-3};
Cloudy v22.01: 2.18e-16 cm^{-3}

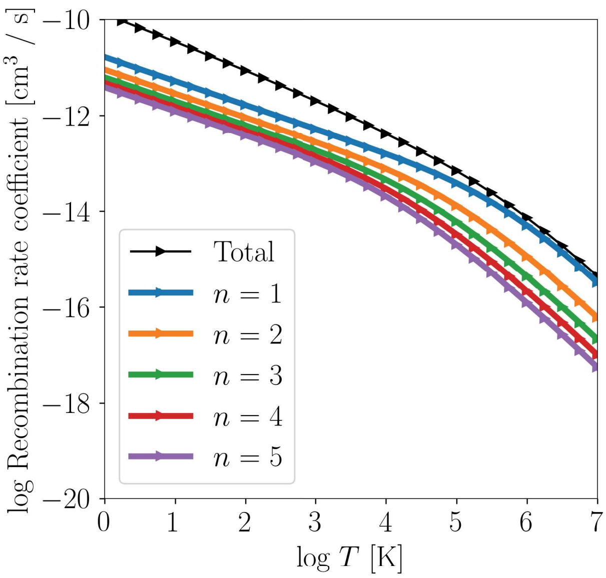
How do we calculate the level population of a specific state?

Rate equation

$$n_p n_e \alpha_{nL}(T) + \sum_{n'>n}^{\infty} \sum_{L'=L\pm1} n_{n'L'} A_{n'L',nL} = n_{nL} \sum_{n"=n_0}^{n-1} A_{nL,n"L"} \qquad (4)$$

Radiative recombination

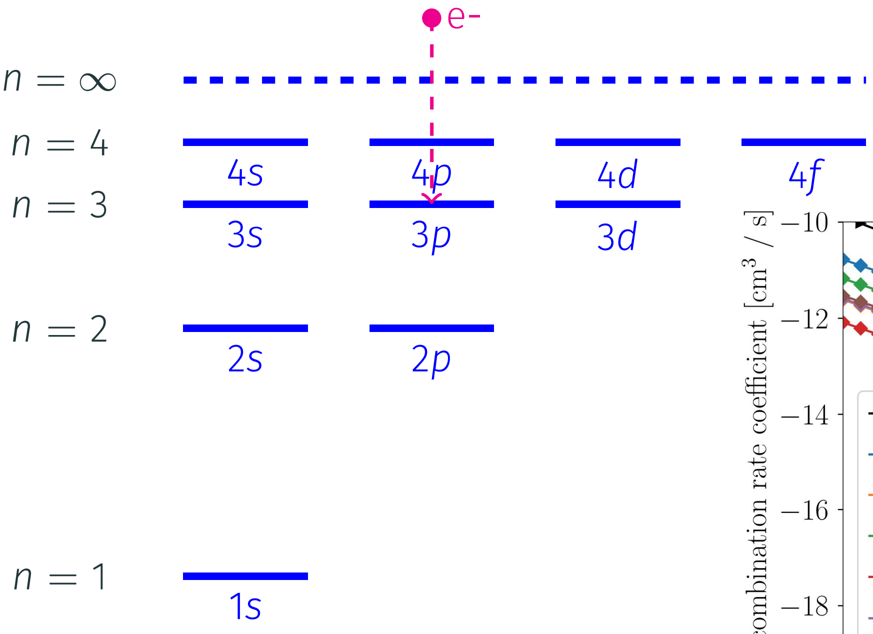


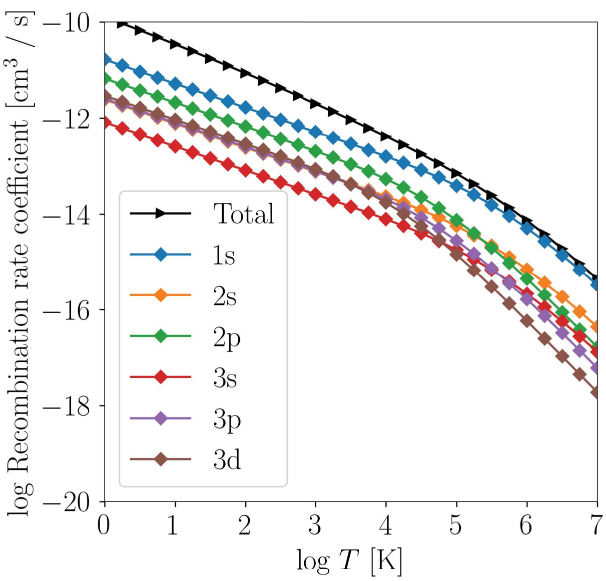


Rate equation

$$n_p n_e \alpha_{nL}(T) + \sum_{n'>n}^{\infty} \sum_{L'=L\pm1} n_{n'L'} A_{n'L',nL} = n_{nL} \sum_{n''=n_0}^{n-1} A_{nL,n''L''} \qquad (5)$$

Radiative recombination

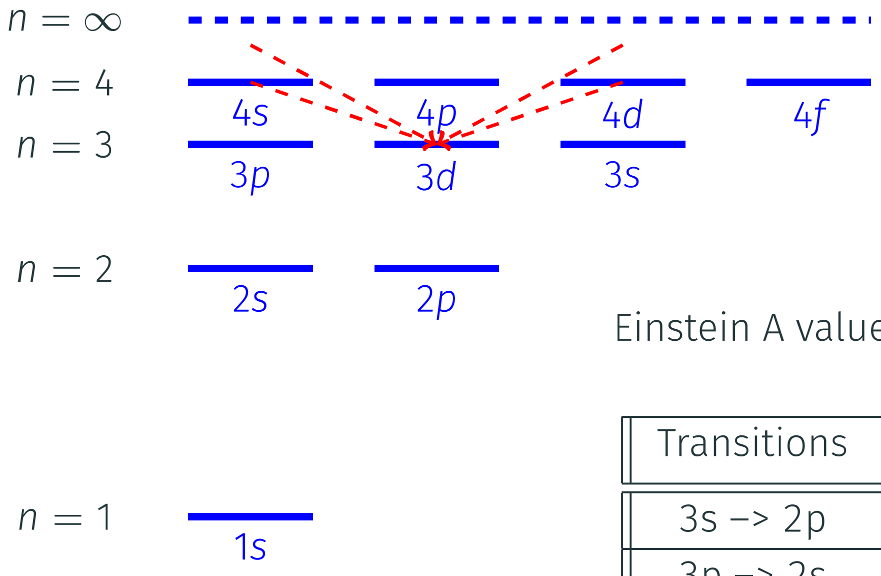




Rate equation

$$n_p n_e \alpha_{nL}(T) + \sum_{n'>n}^{\infty} \sum_{L'=L\pm1} n_{n'L'} A_{n'L',nL} = n_{nL} \sum_{n''=n_0}^{n-1} A_{nL,n''L''} \quad (6)$$

Spontaneous decay from upper levels



Einstein A values (Hoang-Binh 2005)

Transitions	Einstein A's [s^{-1}]
3s –> 2p	6.3E+06
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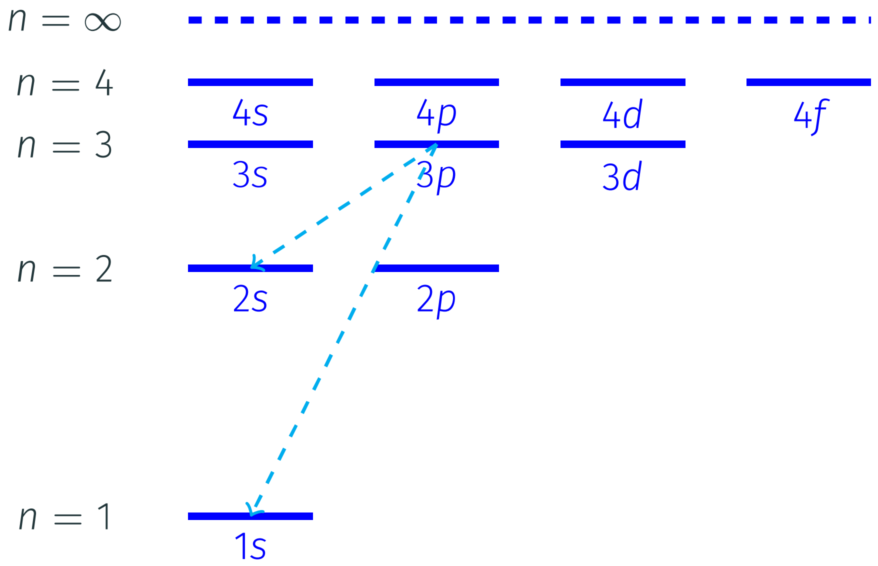
3d –> 2p	6.5E+07

Rate equation

$$n_p n_e \alpha_{nL}(T) + \sum_{n'>n}^{\infty} \sum_{L'=L\pm1} n_{n'L'} A_{n'L',nL} = n_{nL} \sum_{n"=n_0}^{n-1} A_{nL,n"L"} \quad (7)$$

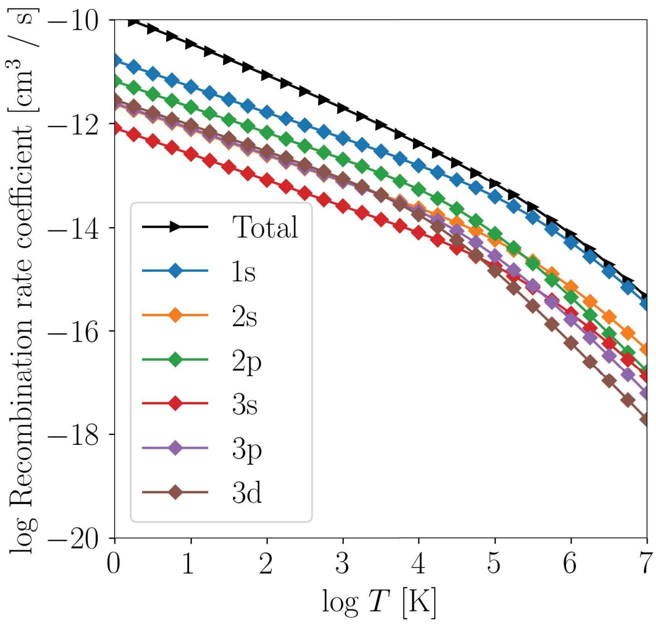
Spontaneous decay to lower levels



Our model

$$n_p n_e \alpha_{nL}(T) + \sum_{n'>n}^{\infty} \sum_{L'=L\pm1} n_{n'L'} A_{n'L',nL} = n_{nL} \sum_{n''=n_0}^{n-1} A_{nL,n''L''} \quad (8)$$

- Recombination coefficients extracted from Cloudy database
- Einstein A values calculated using a recursive method (Hoang-Binh 2005)



recombination coefficients

Comparison to Cloudy

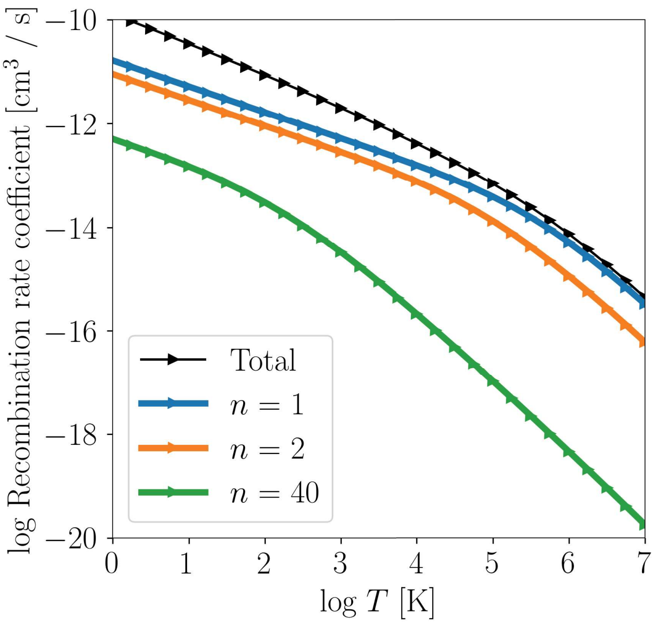
Our model:

- Direct radiative recombination
- Spontaneous decay
- Sufficient number of levels to reach convergence

Cloudy model:

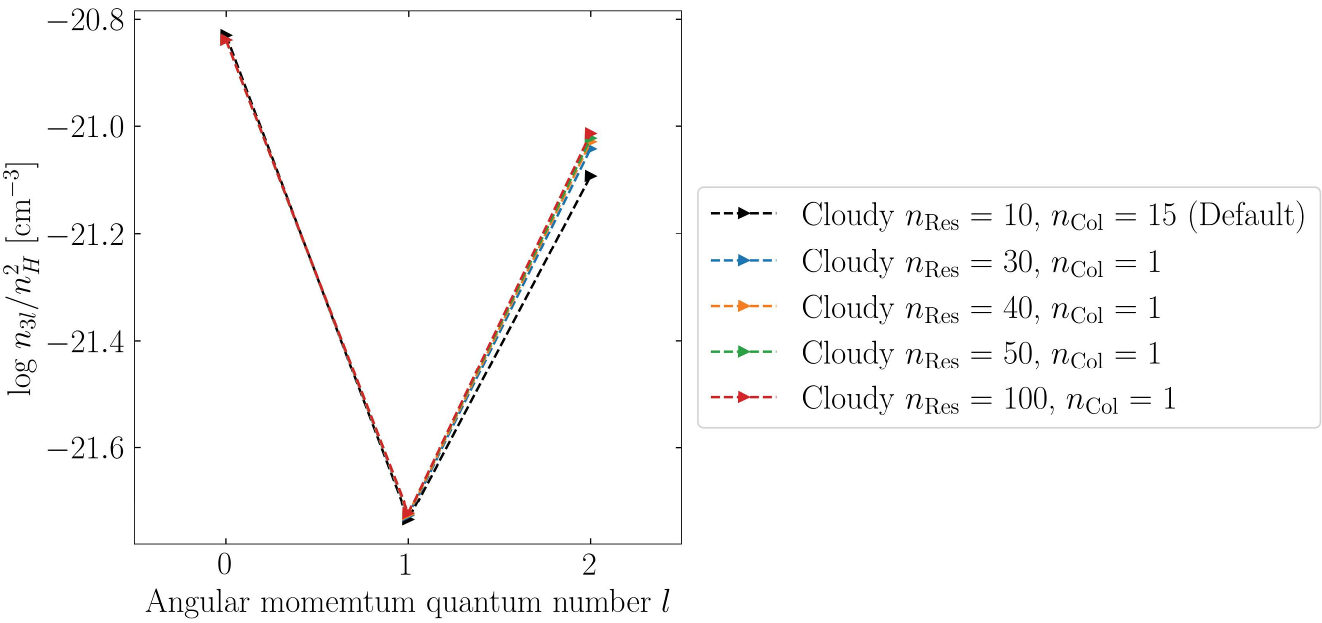
- Direct radiative recombination
- Spontaneous decay
- Adjustable number of levels
- Collisional processes
- etc.

recombination coefficients at high-*n* levels



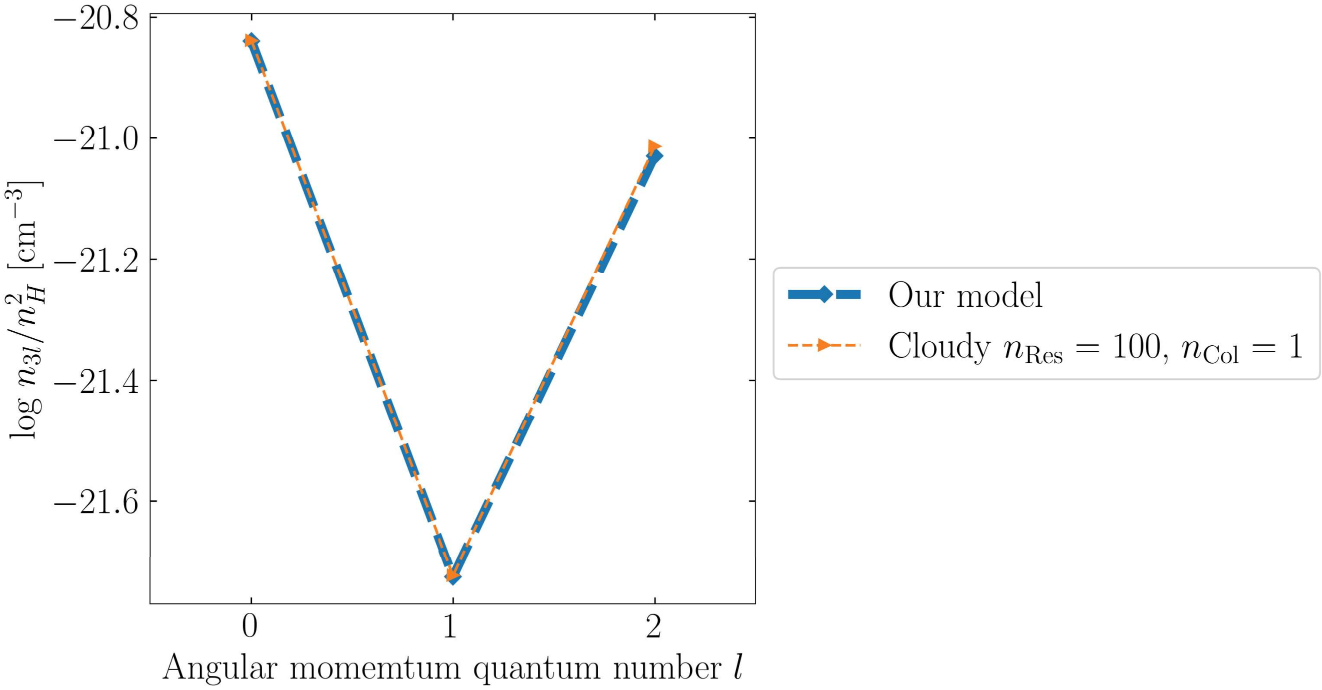
Convergence study - Cloudy

At 10^4 K, $n_H = 100\,\mathrm{cm}^{-3}$, level population at n = 3



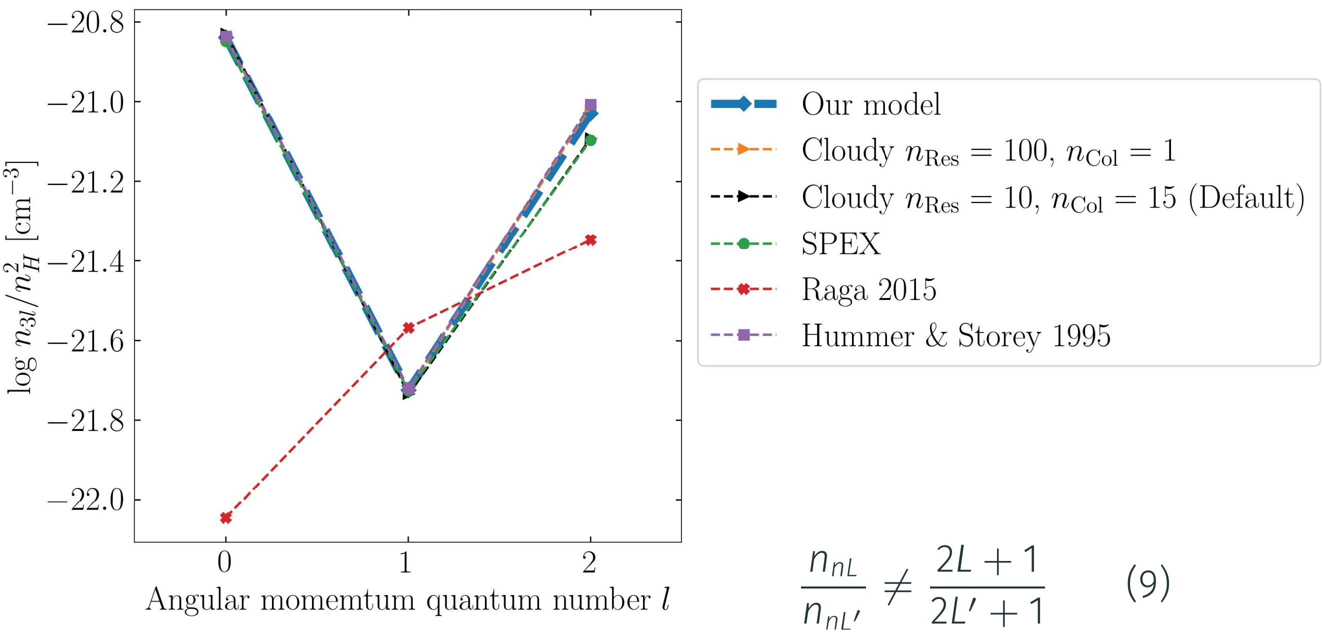
Convergence study

At 10^4 K, $n_H = 100\,\mathrm{cm}^{-3}$, level population at $n = 3$



Comparison to other codes

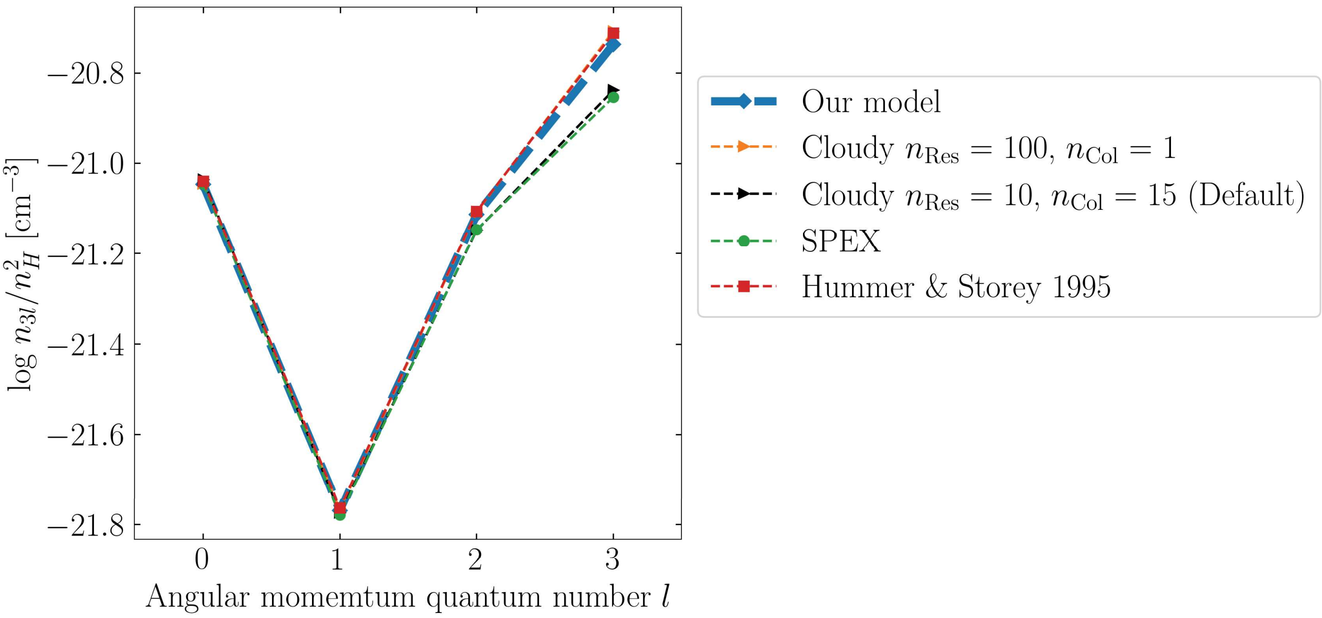
At 10^4 K, $n_H = 100\,\mathrm{cm}^{-3}$, level population at n = 3



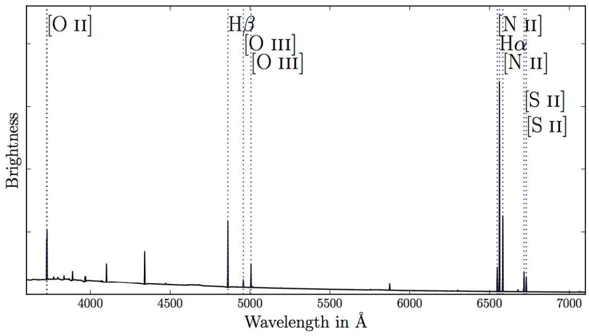
$$\frac{n_{nL}}{n_{nL'}} \neq \frac{2L+1}{2L'+1} \tag{9}$$

Comparison to other codes

At 10^4 K, $n_H = 100\,\mathrm{cm}^{-3}$, level population at $n = 4$



Spectrum of an H II region



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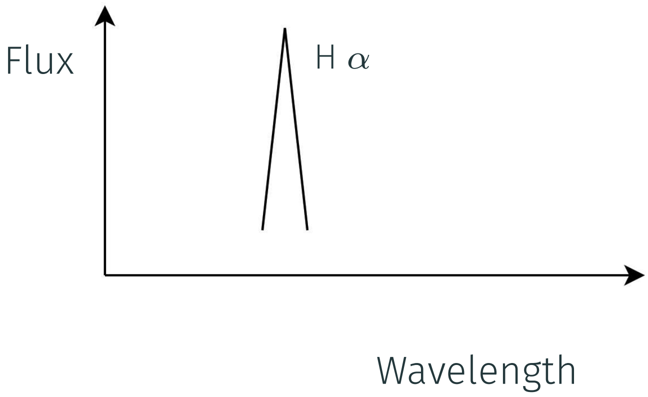
etc.

Simulation



Credit: MOSFIRE Team

Summary & future work

Summary:

- Implementation of a simple hydrogen atomic model for prediction of recombination line emissivity
- Our model in good agreement with Cloudy in low-density regime

Future:

- Integration of atomic model into postprocessing of RHD simulation snapshots run by SWIFT-RT coupled to CHIMES
- Implementation of more physical processes, e.g., collisional processes
- Possible application in radio recombination lines and low-density IGM