Durham University
Institute for Computational Cosmology

# An atomic model for hydrogen recombination line modelling

## With application in post-processing of radiation-hydrodynamic simulations


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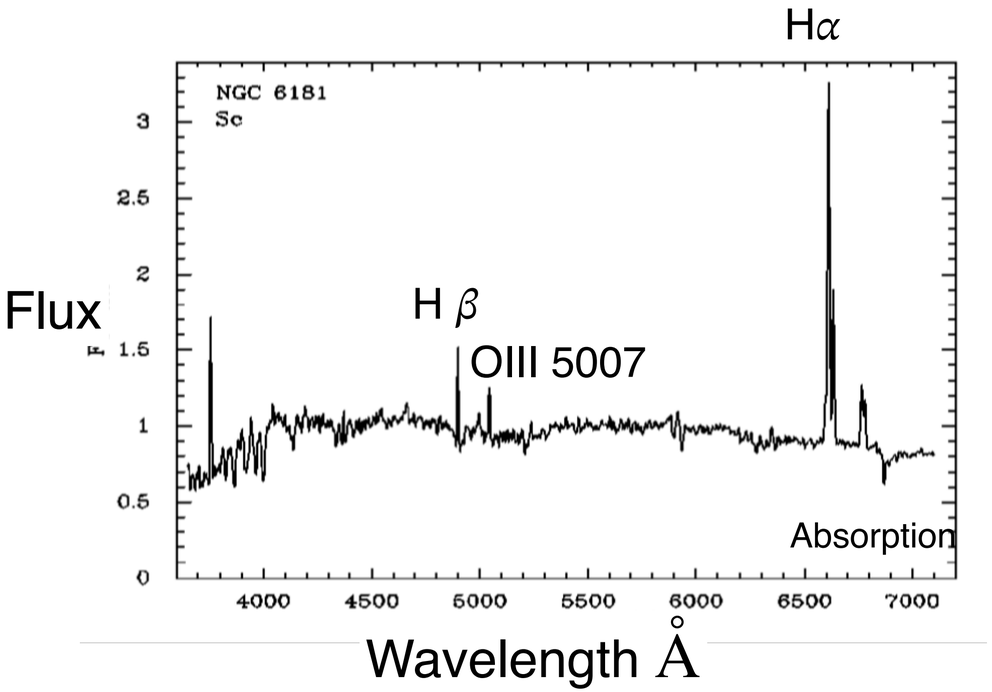
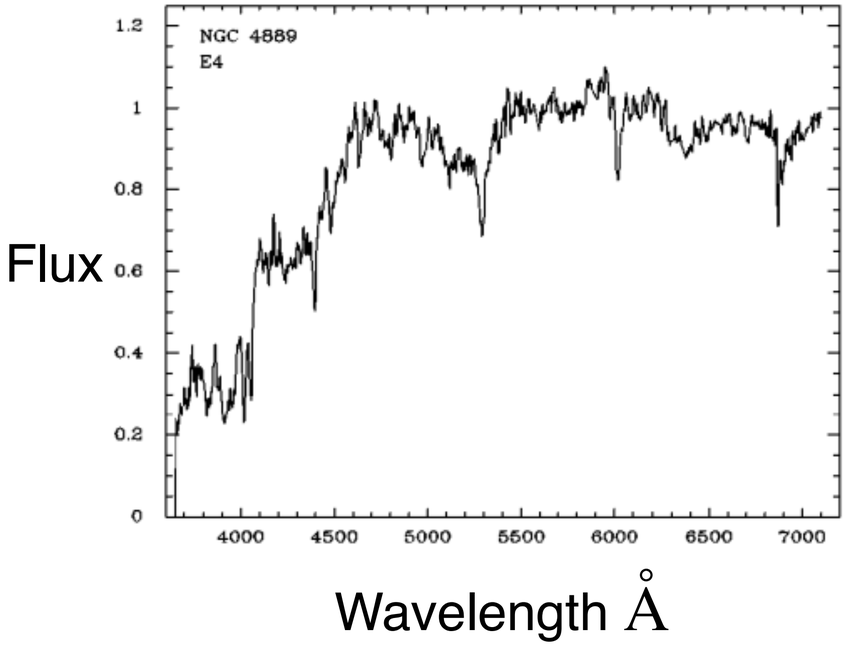
2. Centre for Extragalactic Astronomy, Durham University
3. Department of Physics, Chinese University of Hong Kong
4. E.A. Milne Centre for Astrophysics, University of Hull

# Motivation

## Line emission in galaxies




Kennicutt (1992)

# Motivation

McLeod19

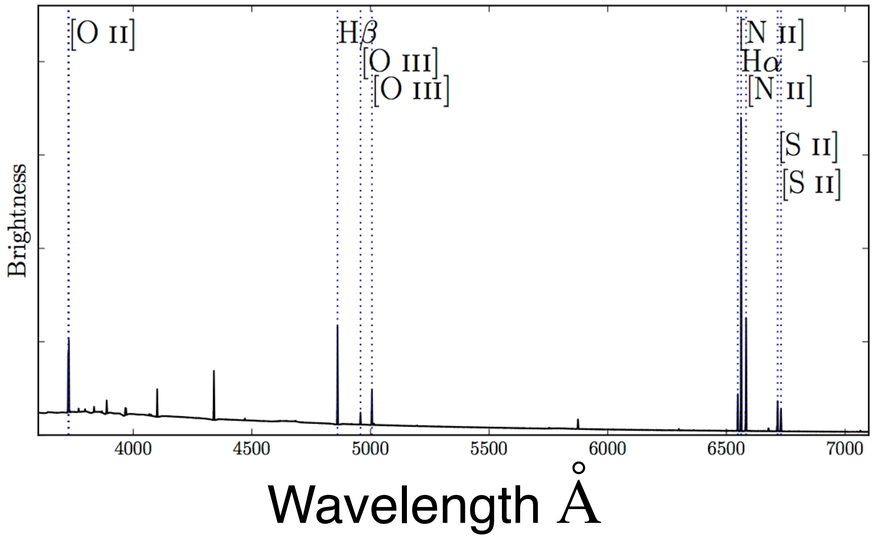
- Density
- Temperature
- Metallicity

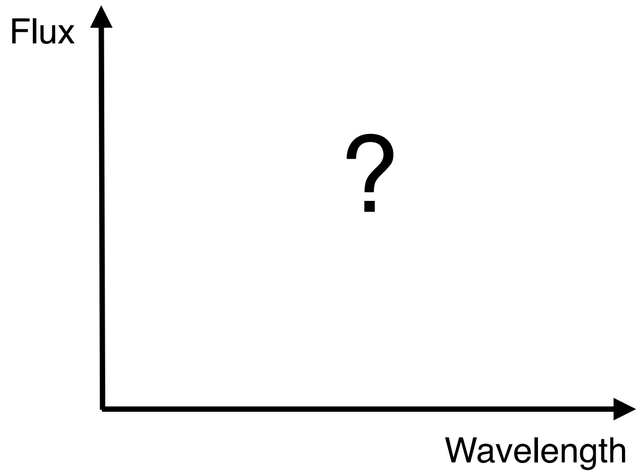
etc.

Starforge

**Observation**

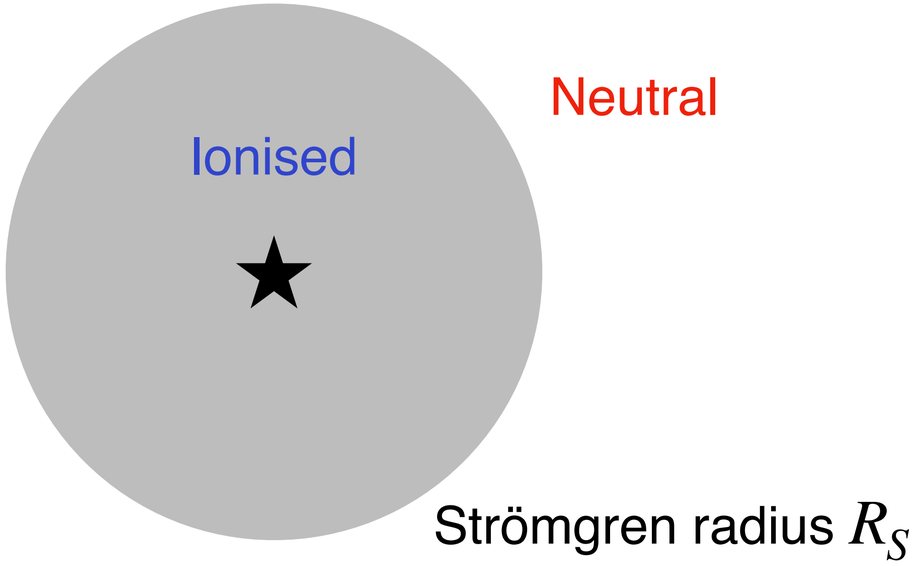
**Simulation**



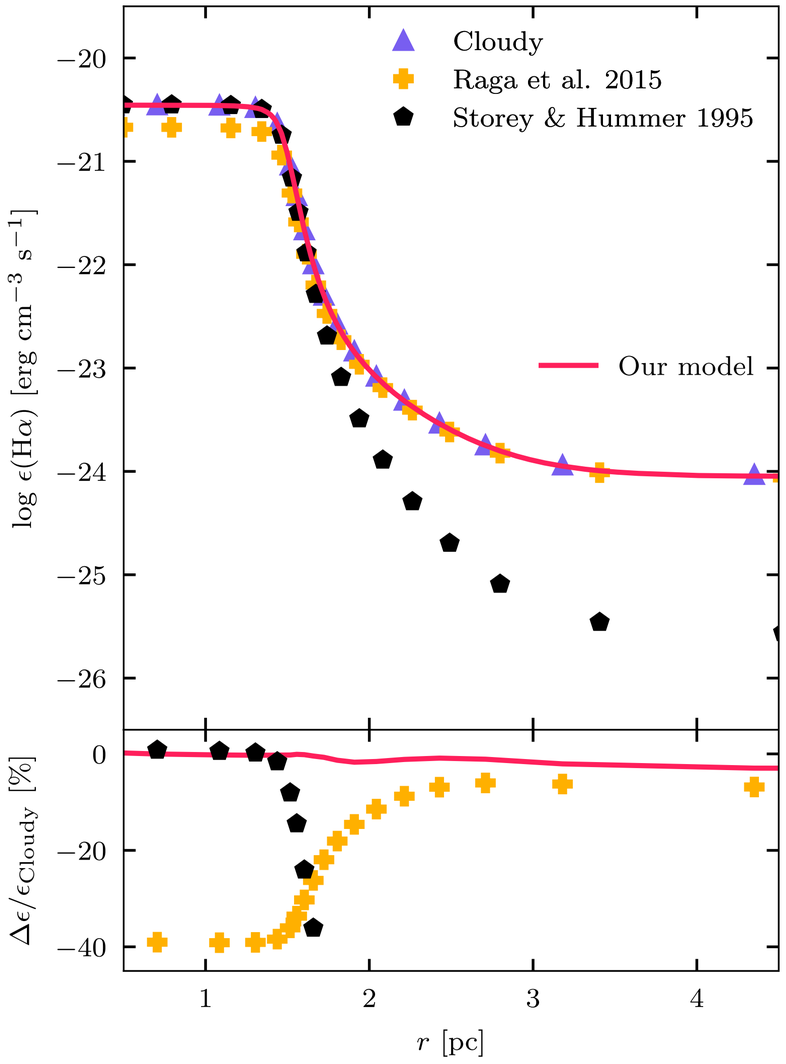




Credit: MOSFIRE Team

# H II region



# H$\alpha$ emissivity profile




**Cloudy**:

Cloudy & Associates

Photoionization simulations for the discriminating astrophysicist since 1978

A photo-ionisation code

**Storey & Hummer 1995**:

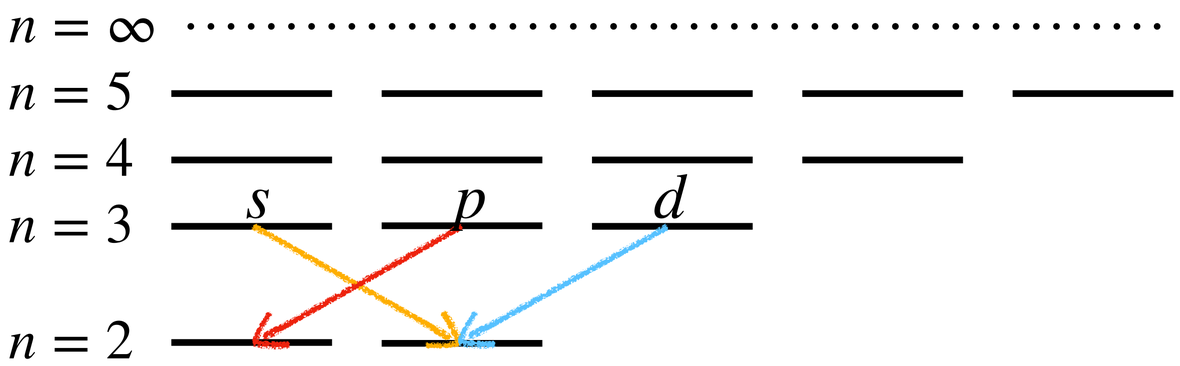
A tabulated table

**Raga et al. 2015**:

An analytical method

# Atomic model for hydrogen

## H$\alpha$ as an example

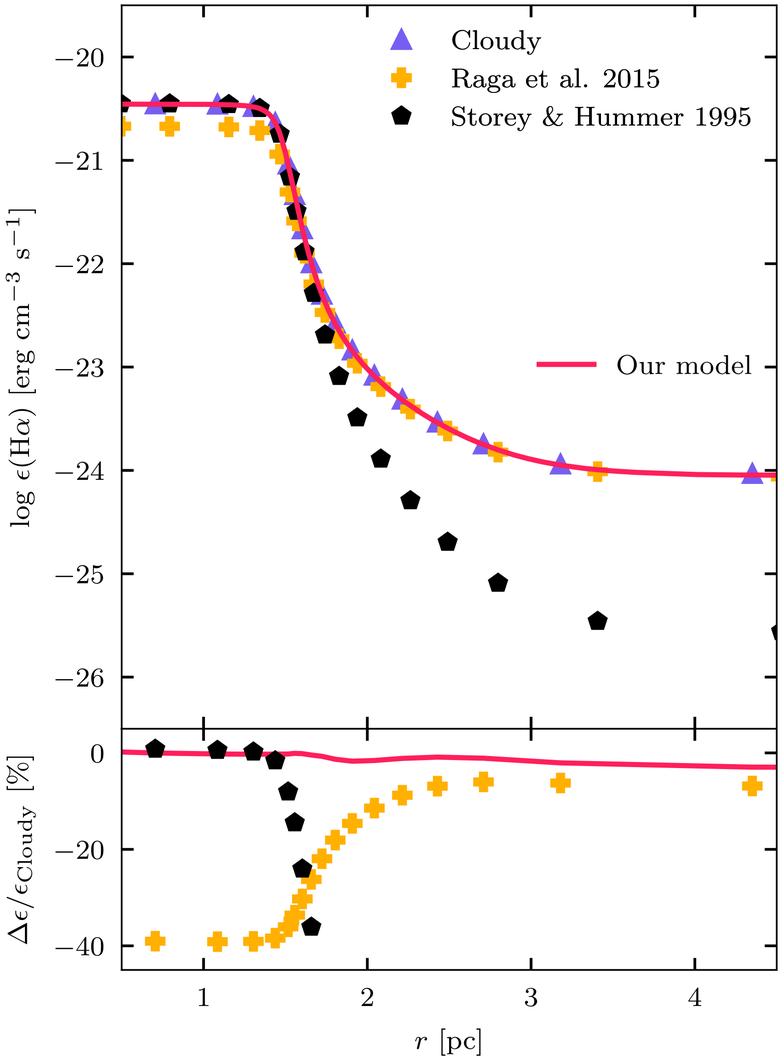



$$\Delta l = \pm 1$$

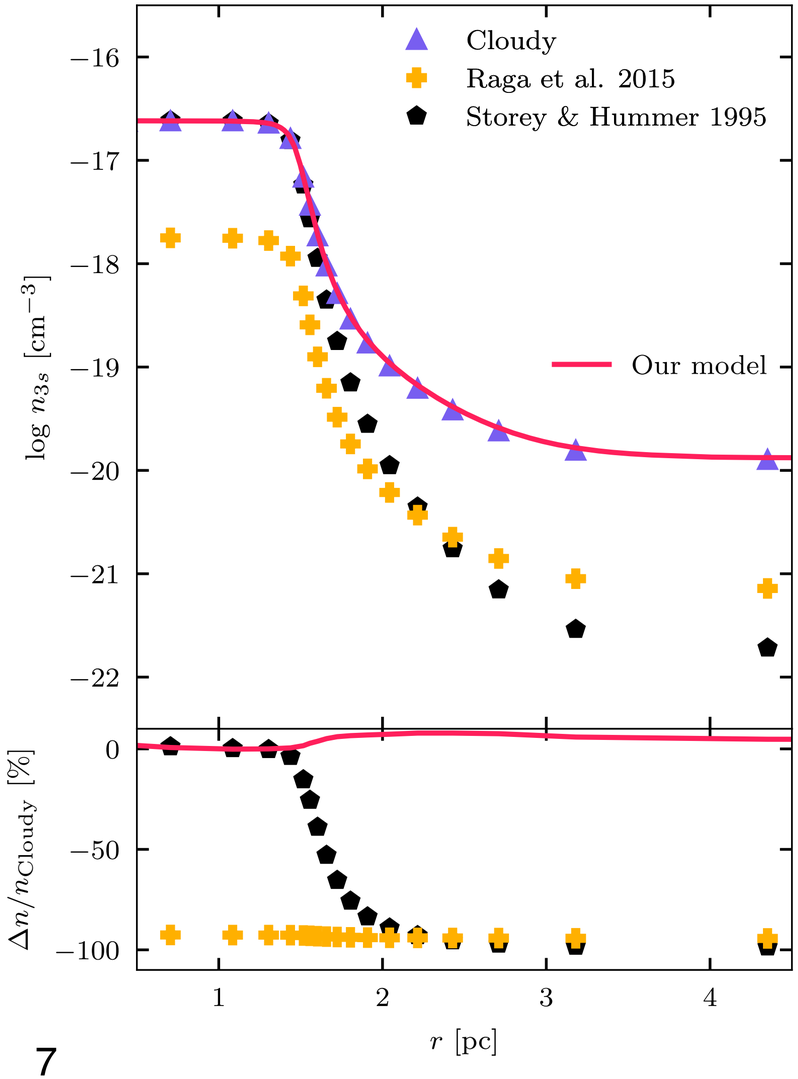
Line emissivity of H$\alpha$

$$\epsilon_{32} = (n_{3s}A_{3s,2p} + n_{3p}A_{3p,2s} + n_{3d}A_{3d,2p})h\nu_{3\to 2}$$

# Hα emissivity profile

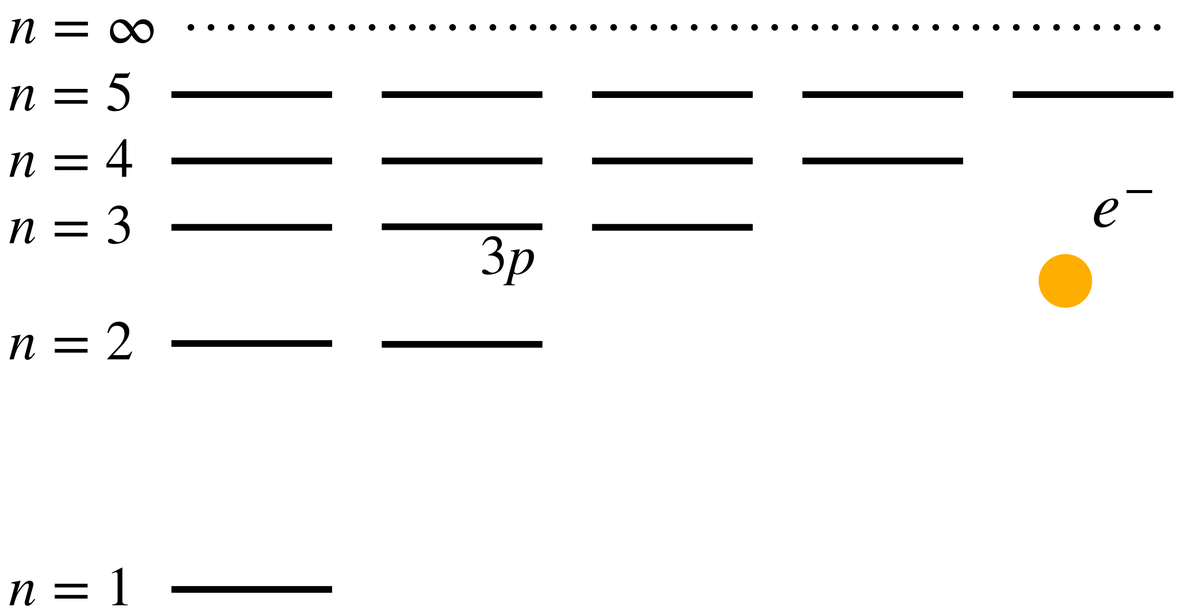



# $n_{3s}$ level population profile



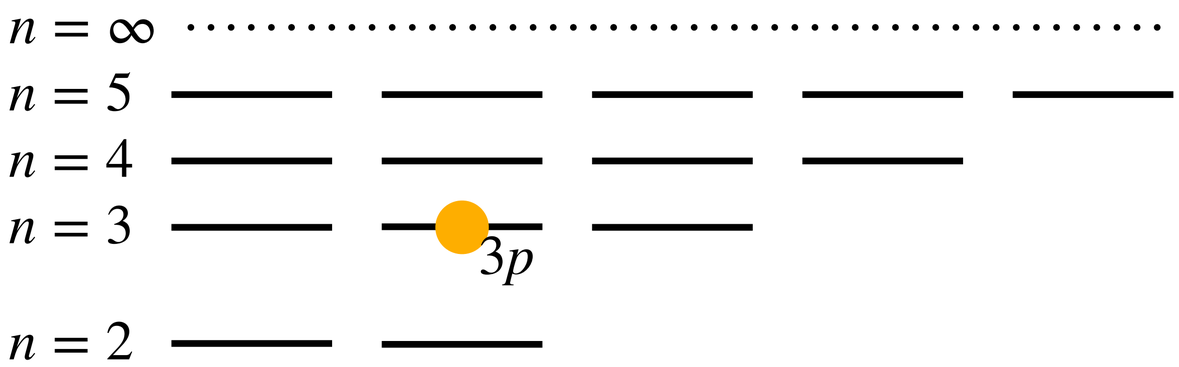
# Atomic model for hydrogen

## Rate equation



# Atomic model for hydrogen

## Rate equation



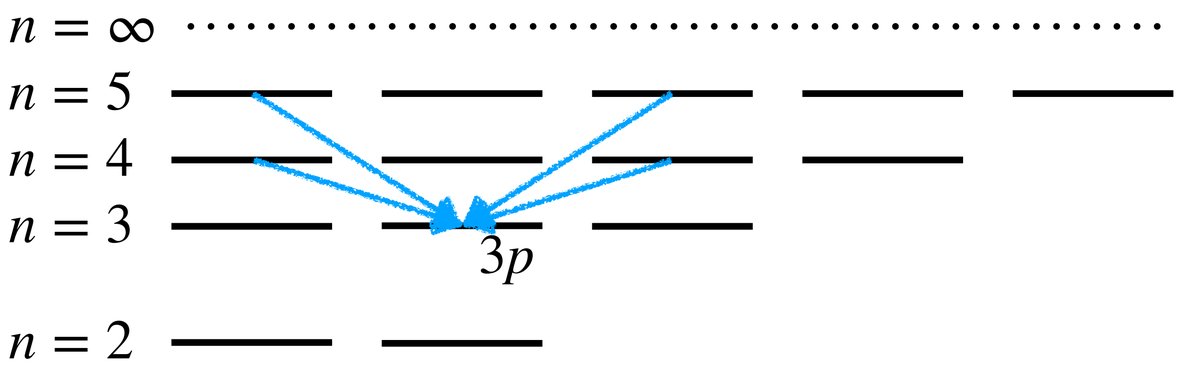

$$\alpha_{nl}(T) n_p n_e$$

$n = 1$ Direct radiative recombination

$$\Delta l = \pm 1$$

# Atomic model for hydrogen

## Rate equation




$\alpha_{nl}(T) n_p n_e$

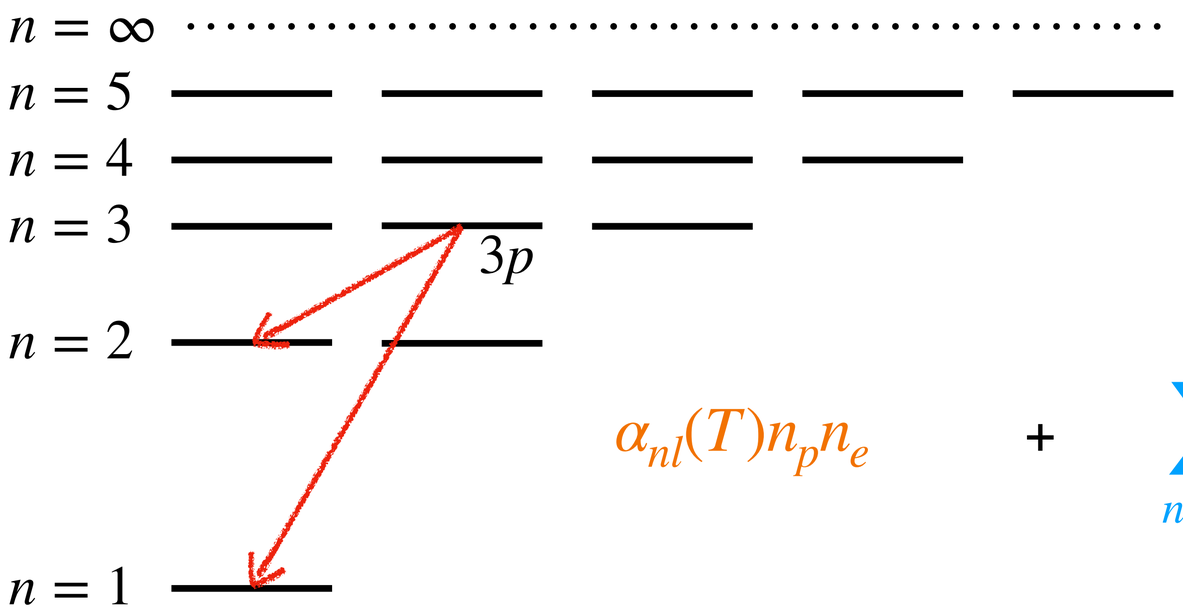
$$\sum_{n'>n}^{\infty} \sum_{L'=L\pm1} n_{n'L'} A_{n'L',nL}$$

Spontaneous decay from higher levels

$$\Delta l = \pm 1$$

# Atomic model for hydrogen

## Rate equation



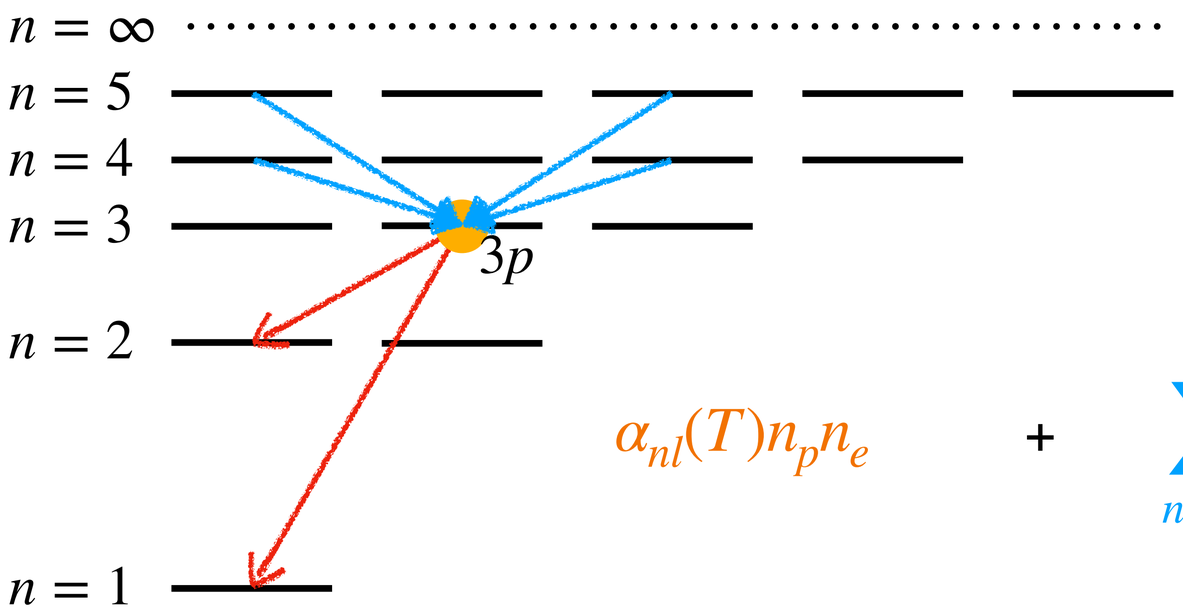

$$\alpha_{nl}(T) n_p n_e + \sum_{n'>n}^{\infty} \sum_{L'=L\pm1} n_{n'L'} A_{n'L',nL} = n_{nl} \sum_{n''=n_0}^{n-1} A_{nL,n''L''}$$

Spontaneous decay to lower levels

$$\Delta l = \pm 1$$

# Atomic model for hydrogen

## Rate equation



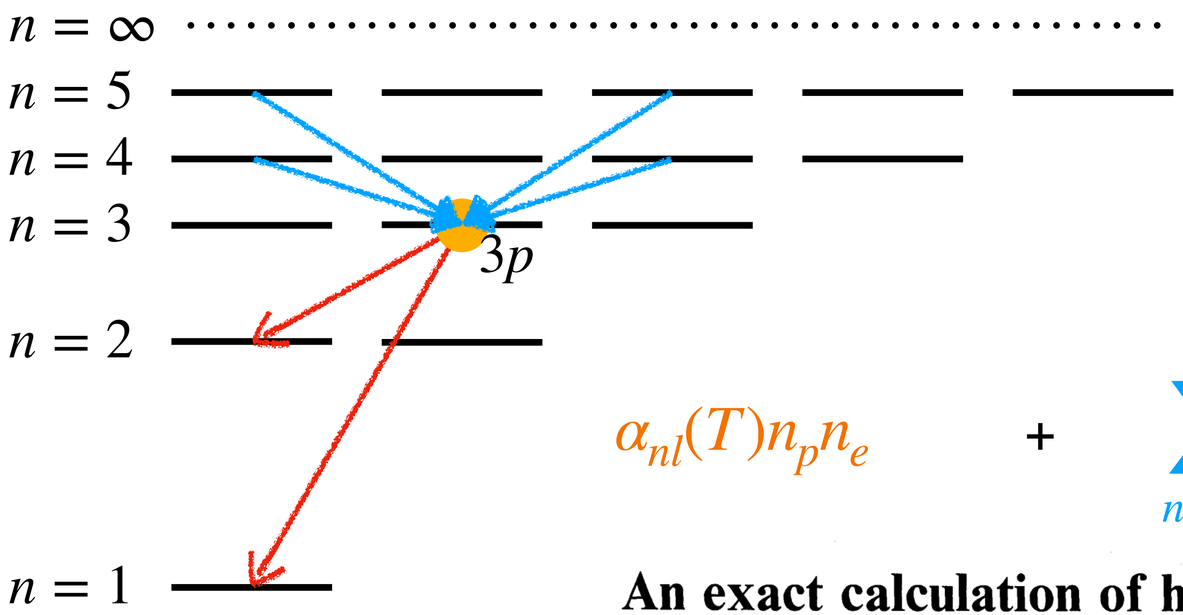

$$\alpha_{nl}(T) n_p n_e + \sum_{n'>n}^{\infty} \sum_{L'=L\pm1} n_{n'L'} A_{n'L',nL} = n_{nl} \sum_{n''=n_0}^{n-1} A_{nL,n''L''}$$

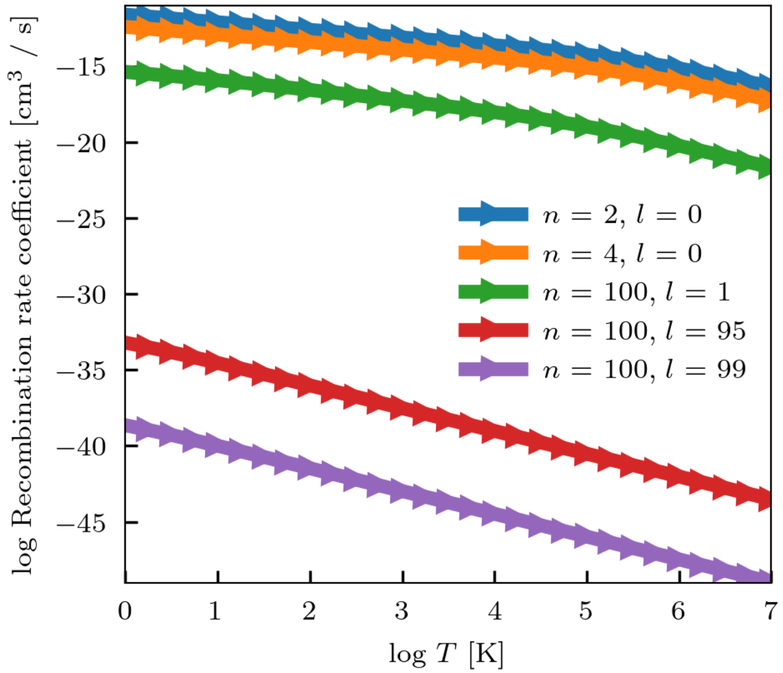
Population

De-population

# Atomic model for hydrogen

## Rate equation




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

**An exact calculation of hydrogenic radial integrals and oscillator strengths, for principal quantum numbers up to $n \approx 1000$**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LAM, Observatoire de Paris, F-92195 Meudon Cedex, France



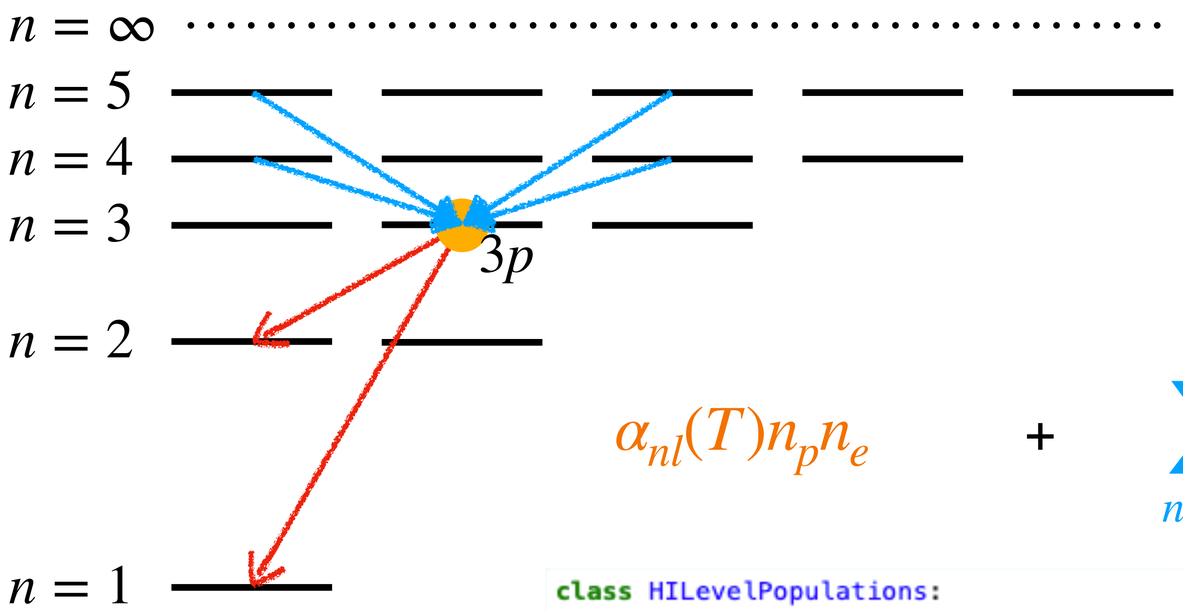
Received April 5, accepted April 25, 1990

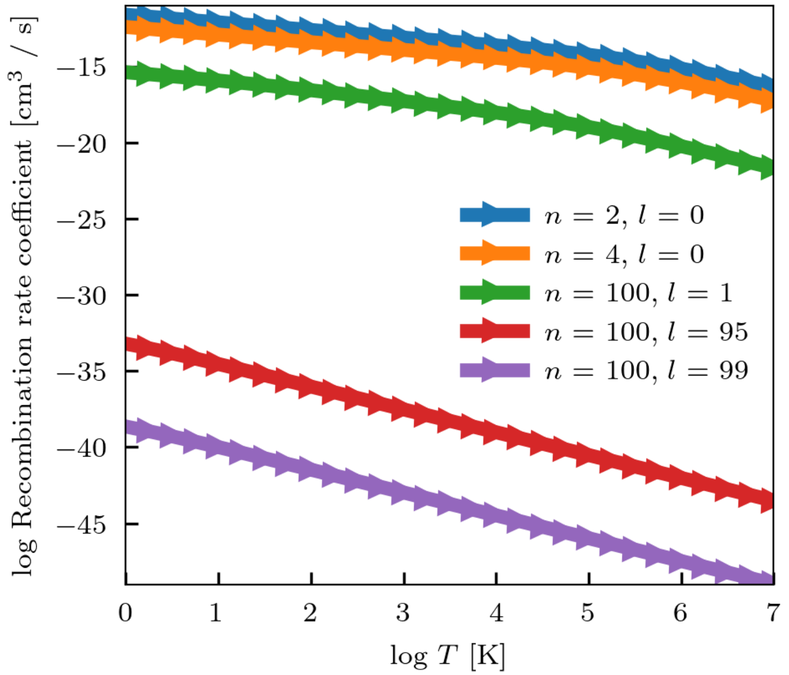

- Solved by Cascade Matrix Formalism (CMF)

https://github.com/YuankangLiu/hypop

# Atomic model for hydrogen

## Rate equation




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

```
class HILevelPopulations:
    '''
    Compute level population for HI using the cascade matrix formalism.
    See Osterbrock & Ferland 2006, section 4.2
    '''
    def __init__(self, nmax=60, TabulatedEinsteinAs = '/cosma/home/dphlss/tt/Codes/EinsteinAs/EinsteinA.dat',
                 TabulatedRecombinationRates = '/cosma/home/dphlss/tt/Data/Recomb/h_iso_recomb.dat',
                 caseB = True, caseBnmax=5, verbose=False):
```

- Solved by Cascade Matrix Formalism (CMF)

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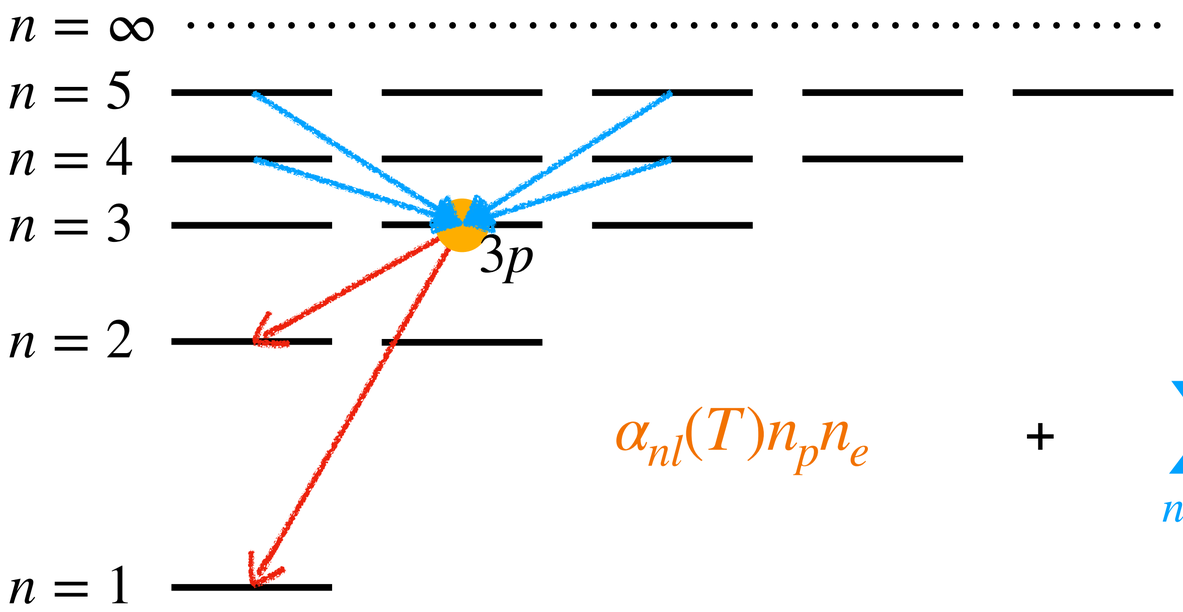
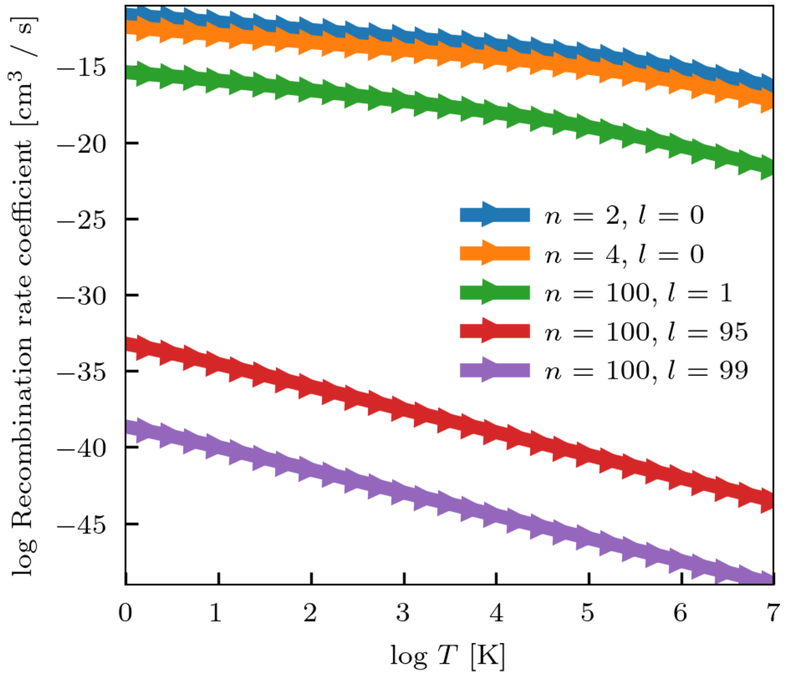
# Atomic model for hydrogen

## Rate equation




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

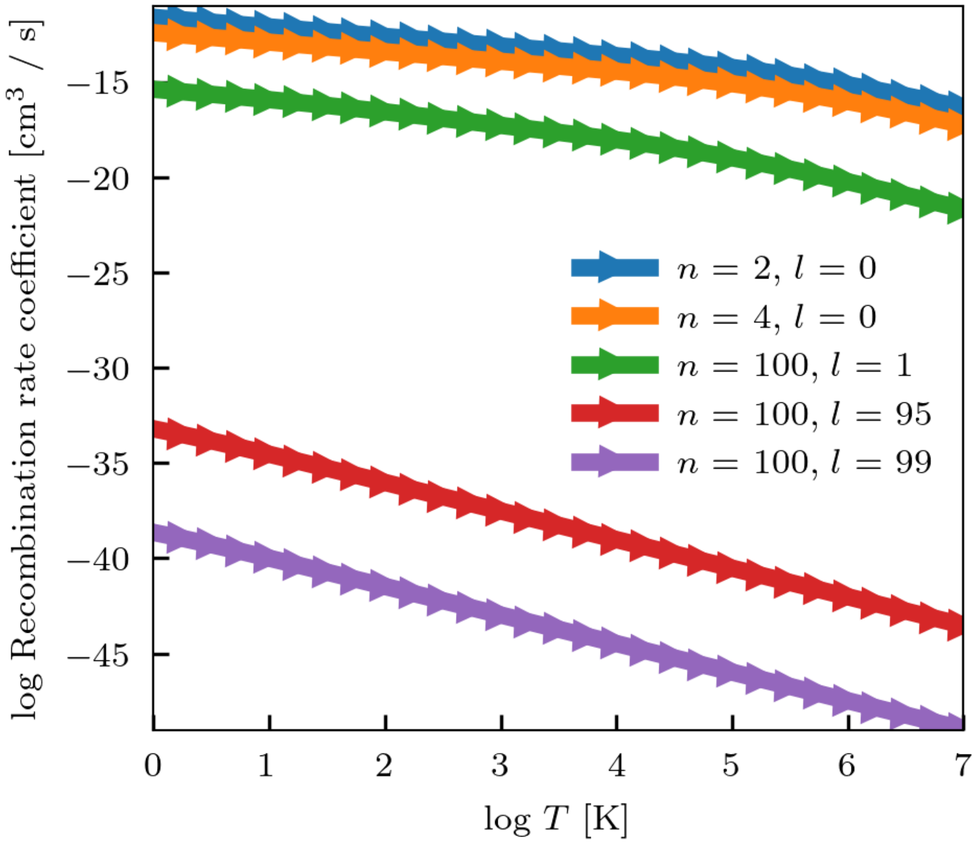
**HyPop** or **HyLight**

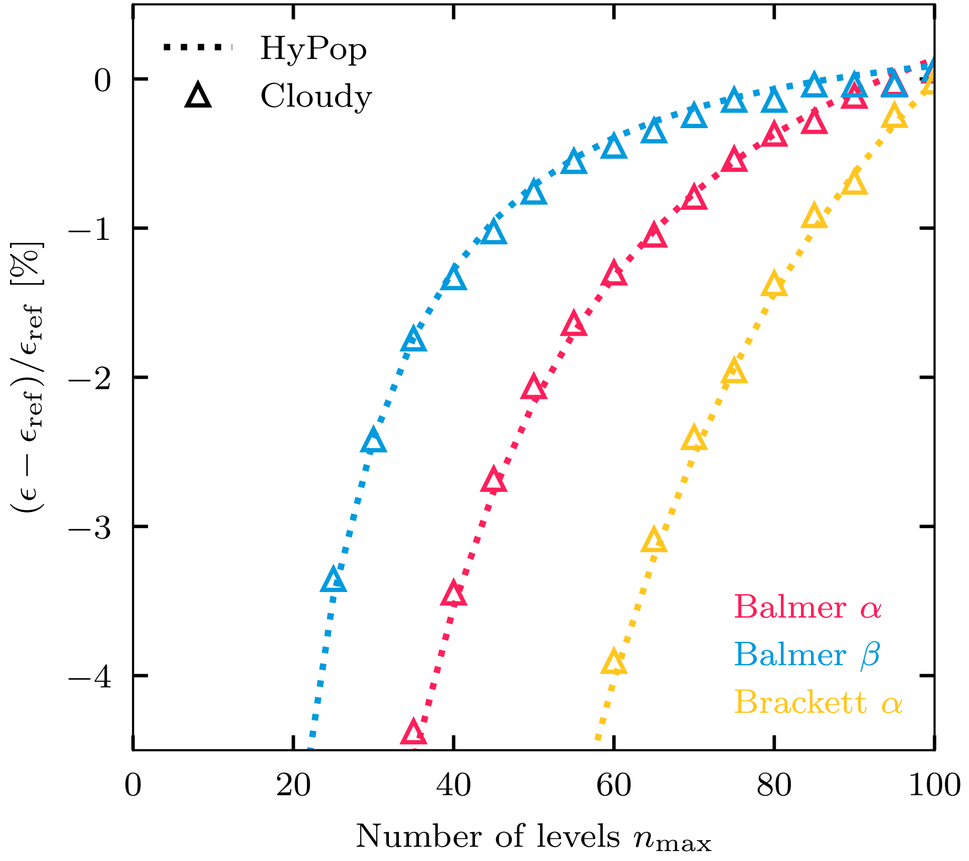
- Solved by Cascade Matrix Formalism (CMF)

https://github.com/YuankangLiu/hypop

# Convergence

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



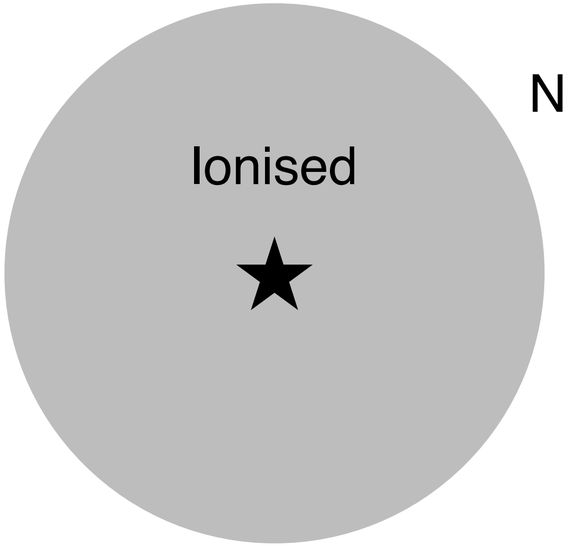
# Application - Mock observables

3D H II region simulation with radiative transfer

CHIMES + SPHM1RT


$n_{\mathrm{H}} = 10$ cm$^{-3}$

$Q(\mathrm{H}) = 5e47$ s$^{-1}$



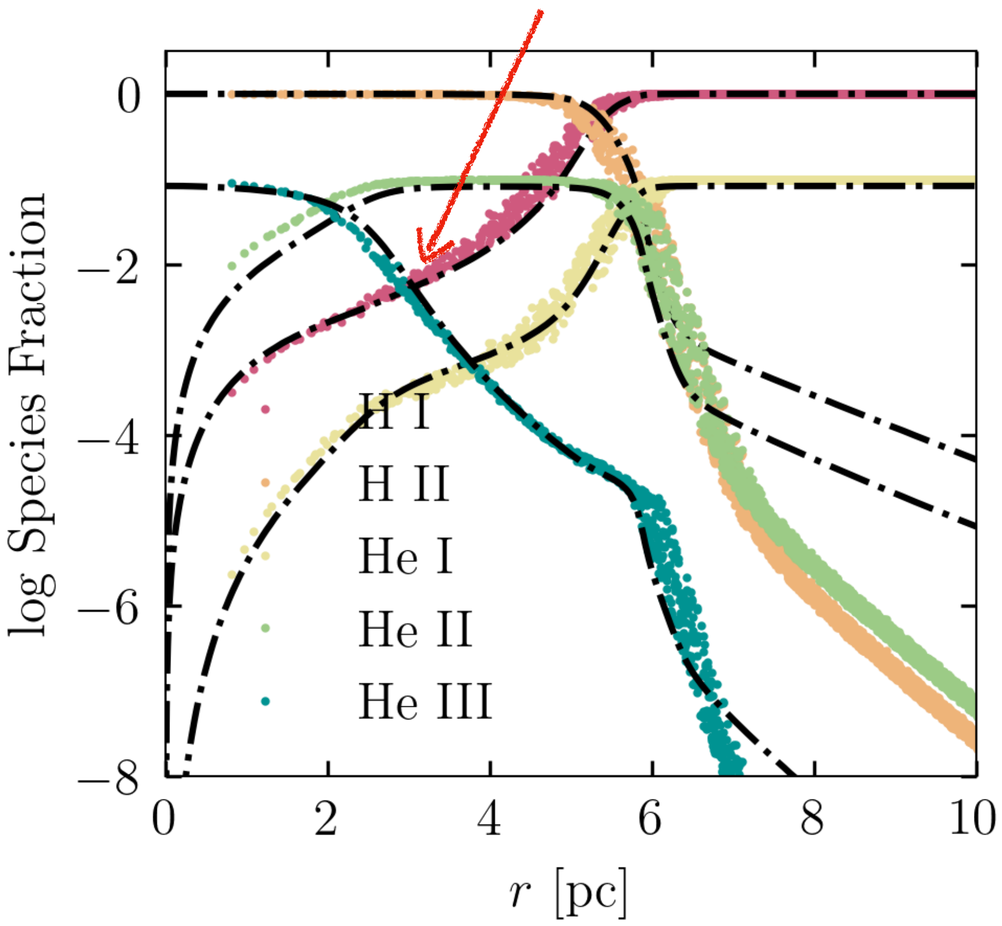
# Application - Mock observables

3D H II region simulation with radiative transfer

CHIMES + SPHM1RT

Ionisation structure

e.g., How many H atoms are in $n = 3$?




CHIMES-RT vs. Cloudy

# Application - Mock observables

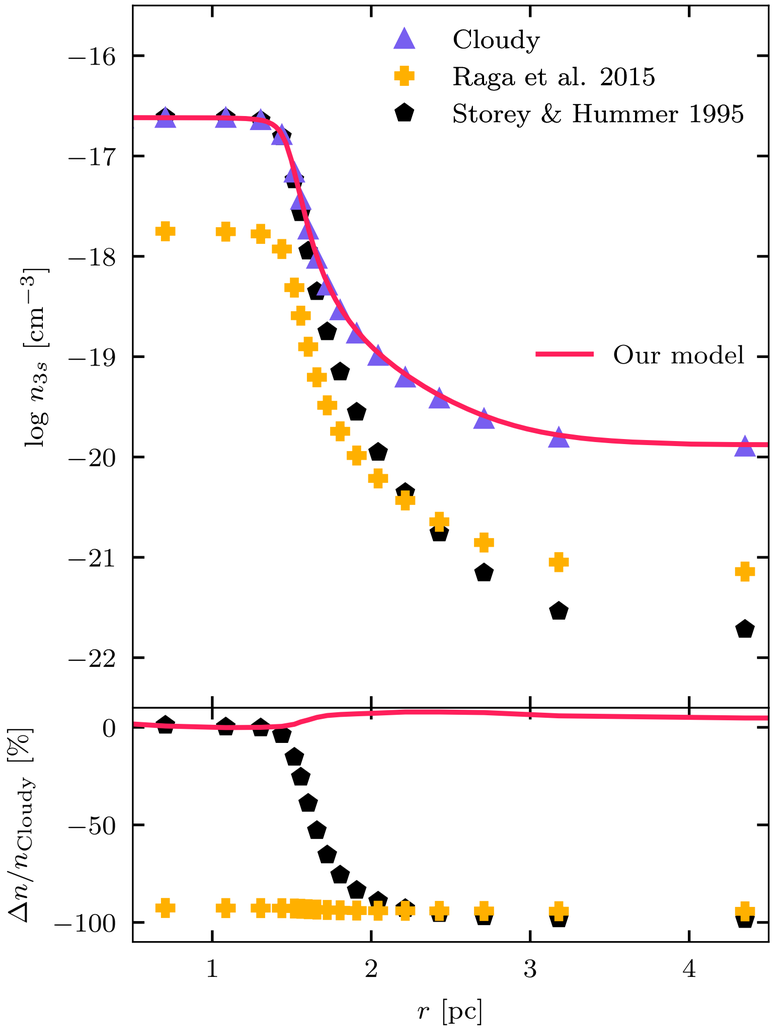
3D H II region simulation with radiative transfer

CHIMES + SPHM1RT ↓

Ionisation structure

Atomic model ↓ $n_{nl}$ for given $n_p, n_e, T$

Level population



# Application - Mock observables

3D H II region simulation with radiative transfer

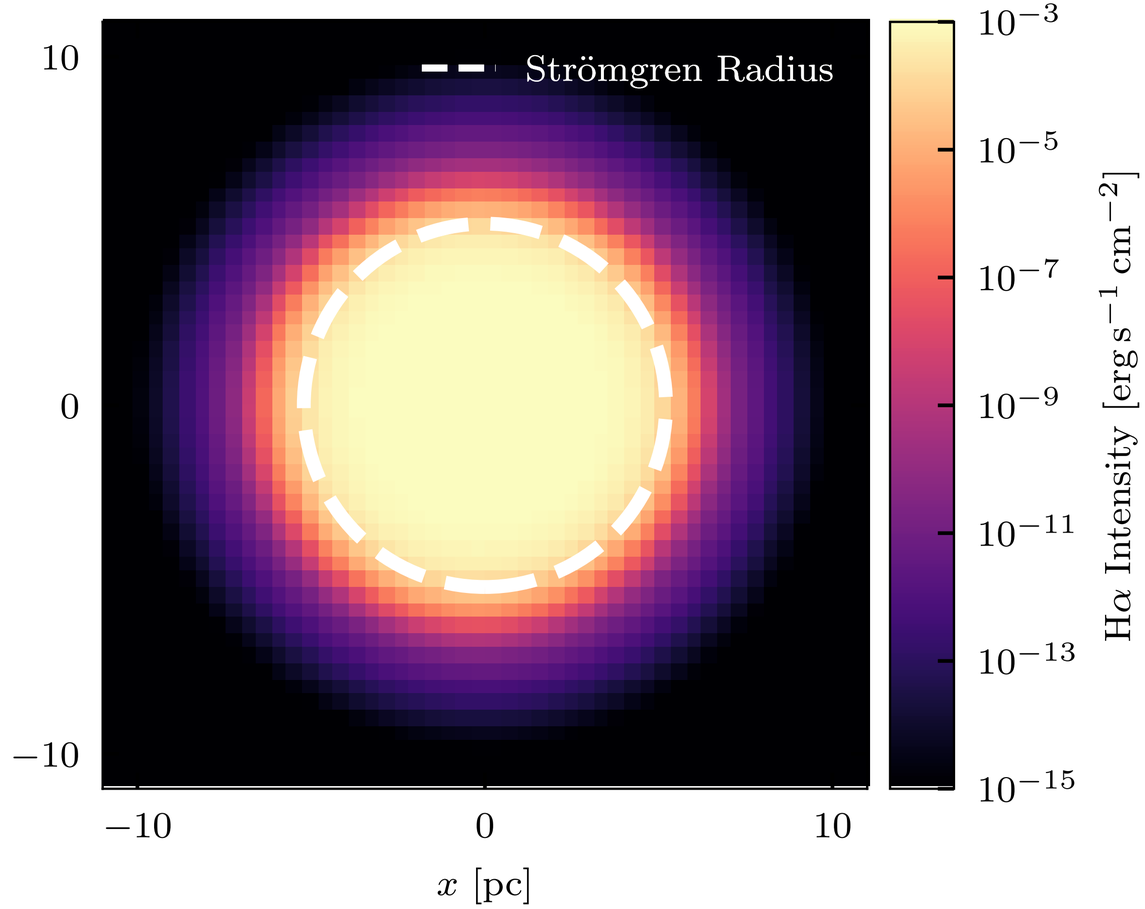
CHIMES + SPHM1RT

Ionisation structure

Atomic model $n_{nl}$ for given $n_p, n_e, T$

Level population


Spectrum & Image



# Application - Mock observables

3D H II region simulation with radiative transfer

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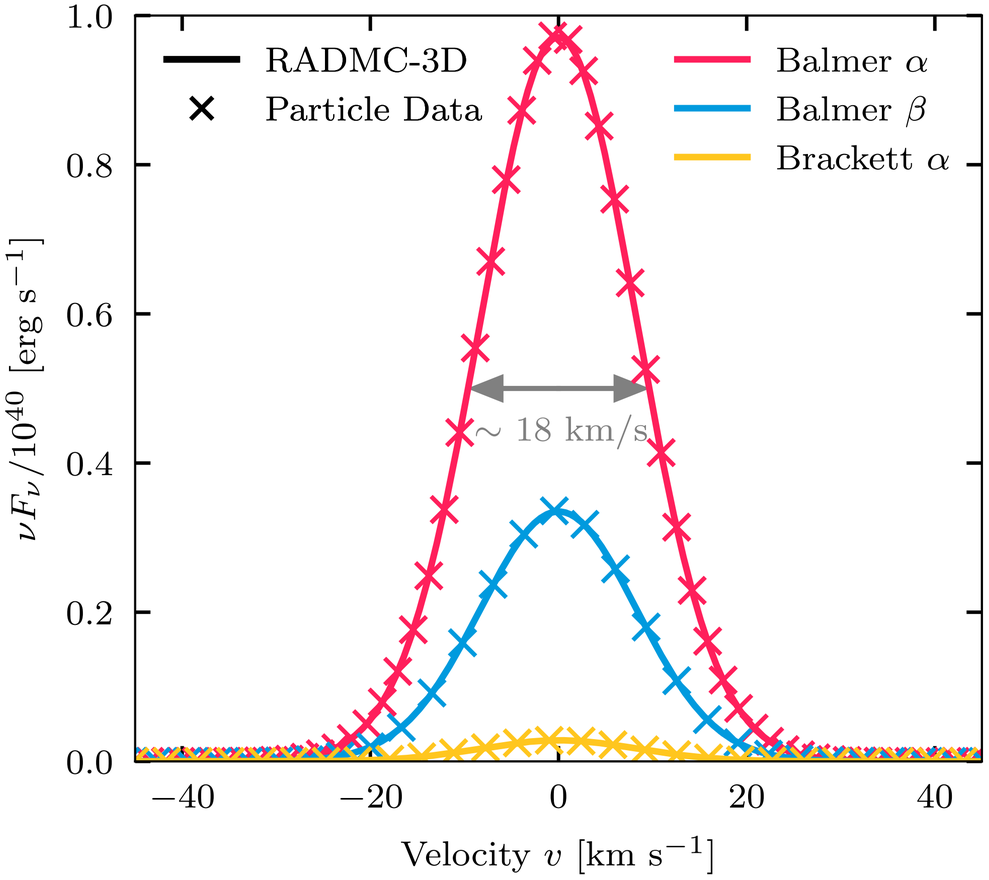
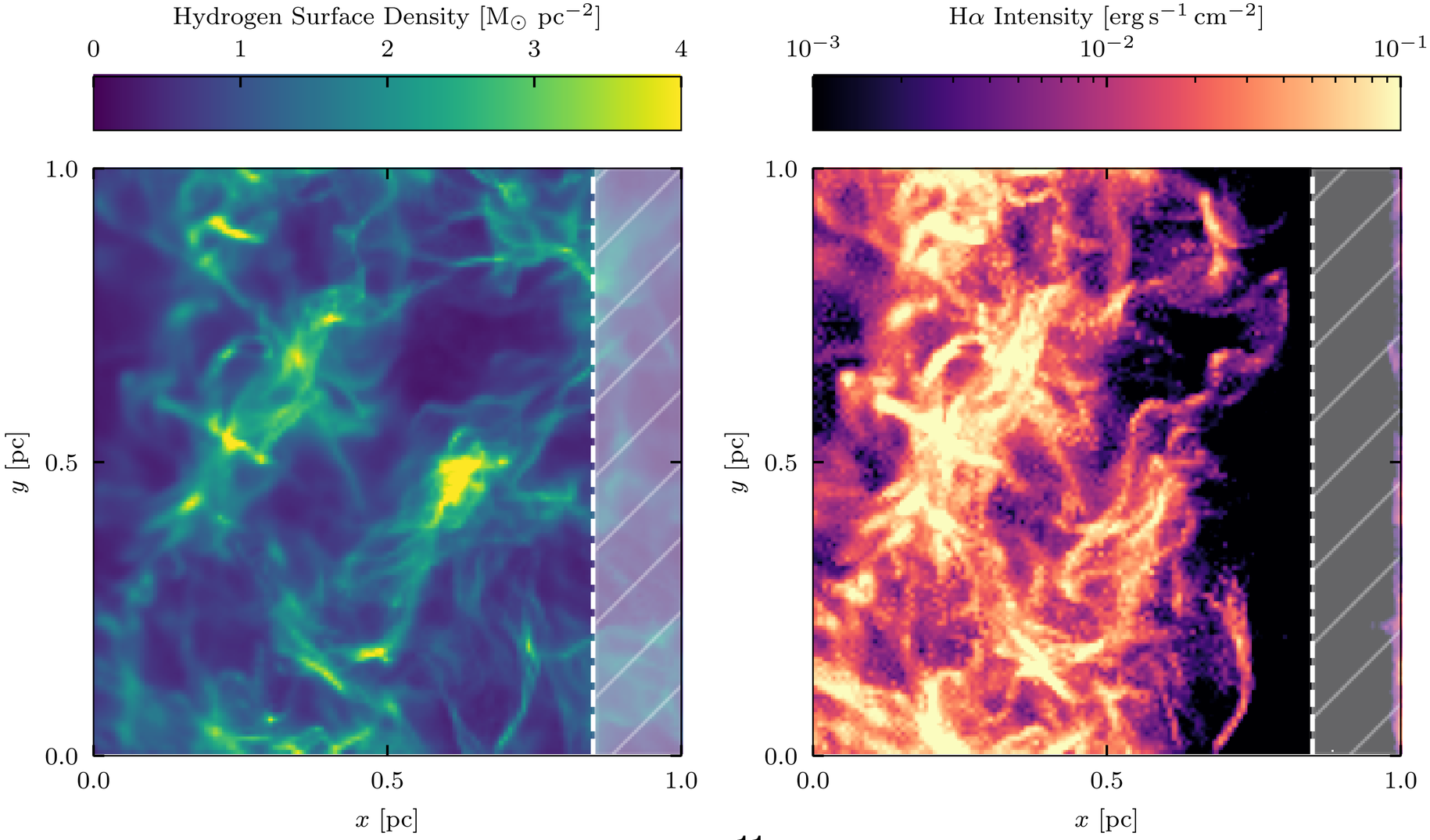
Spectrum & Image

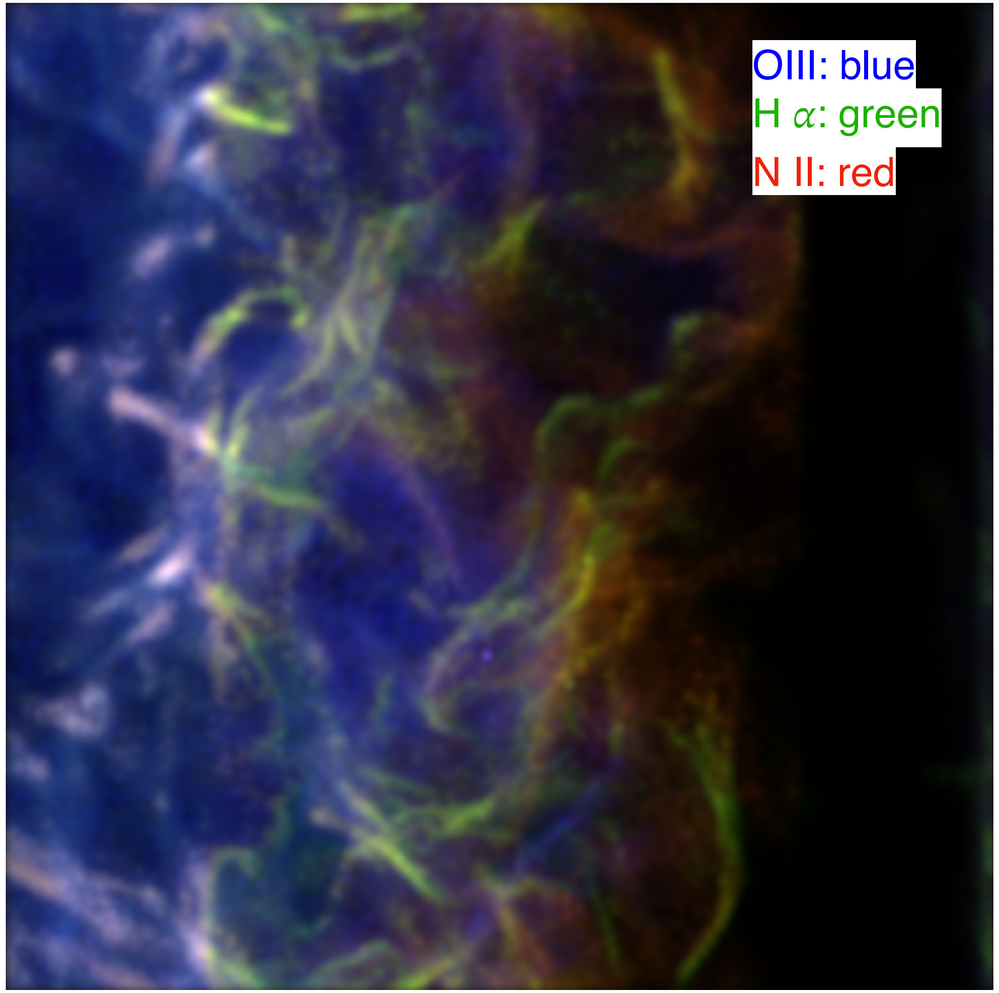


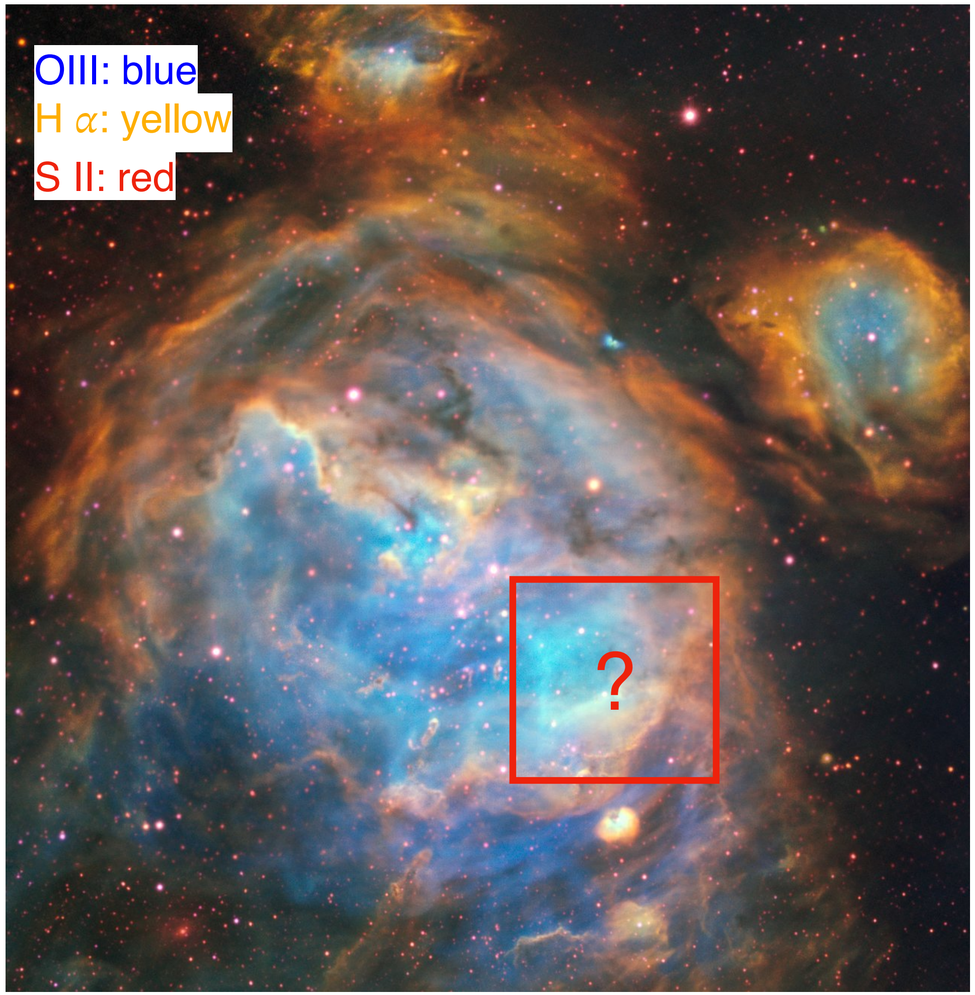
# Turbulent Density Field

**Not possible with Cloudy!**



# Example



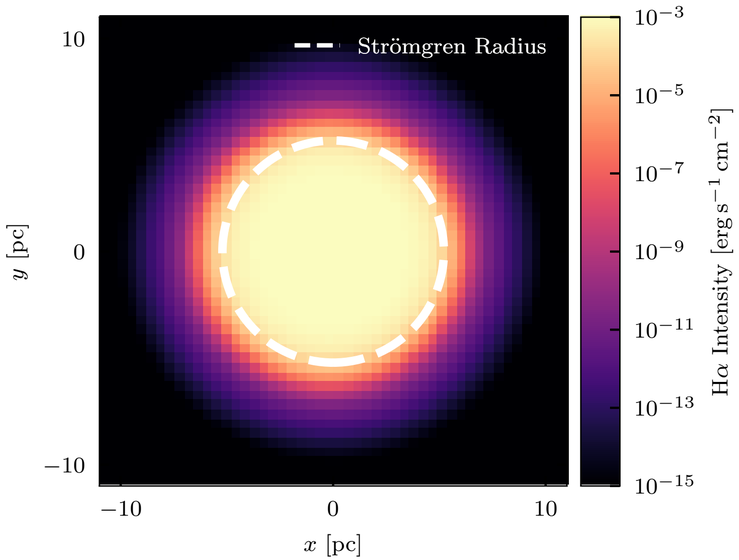




McLeod 2019

# Future works & Summary

- Simulations of H II regions and comparison with spatially-resolved observations

- Probing subgrid physics for stellar feedback & non-equilibrium evolution of ISM




- An atomic model for hydrogen recombination line (HyPop)

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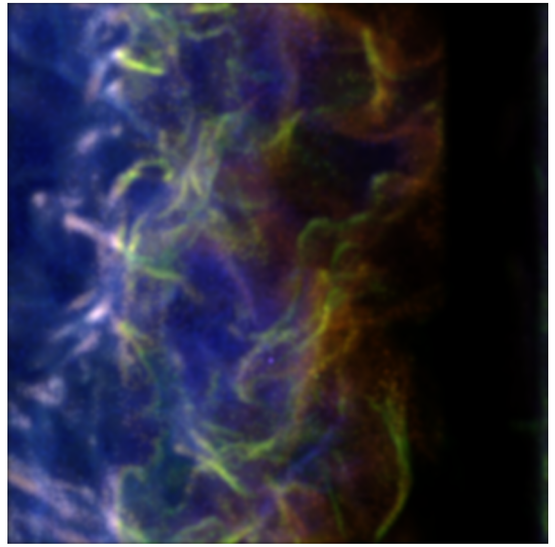

- Applicable for post-processing of radiation-hydrodynamic simulations