Introduction to CLOUDY

Federico Esposito (OAN, Madrid)

Outline lectures

Outline (Dec 1)

- CLOUDY introduction
- CLOUDY installation
- a quick CLOUDY run: the input file
- exploration of CLOUDY output
- Q&A

Outline (Dec 2)

- exploration of CLOUDY output
- CLOUDY grid
- exercise
- your future: PhD, post-doc, etc
- Q&A

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My academic journey

- chose humanistic studies for high school
- started studying math at uni, left after 6 months
- worked in bakery and supermarket while playing in a band
- got bored
- moved to Bologna to study astronomy
- after my master degree (thesis with Prof. Pozzi) left for 3 years of travel and work abroad
- came back to Bologna to get a PhD in astrophysics (with Prof. Pozzi and Dr. Vallini)
- during my PhD spent 6 months in Madrid at Centro de Astrobiología, with Dr. Alonso-Herrero
- moved to Madrid for a post-doc at Observatorio Astronómico Nacional, with Dr. García-Burillo
- recently got a permanent position at Observatorio Astronómico Nacional (OAN)

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Introduction to CLOUDY

Cloudy is an *ab initio* spectral synthesis code designed to model a wide range of interstellar "clouds", from H II regions and planetary nebulae, to Active Galactic Nuclei, and the hot intracluster medium that permeates galaxy clusters.

Cloudy has been in continuous development since 1978, led by Gary Ferland

Useful links

CLOUDY wiki: https://gitlab.nublado.org/cloudy/cloudy/-/wikis/home

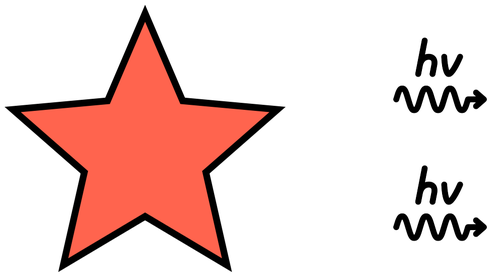
CLOUDY users forum: https://cloudyastrophysics.groups.io/g/Main

CLOUDY youtube page: https://www.youtube.com/@Cloudy-Astroph

Gary Ferland talking about CLOUDY: https://youtu.be/q3kKWFKnI8I?si=emp1AE5sGPC8DHxf

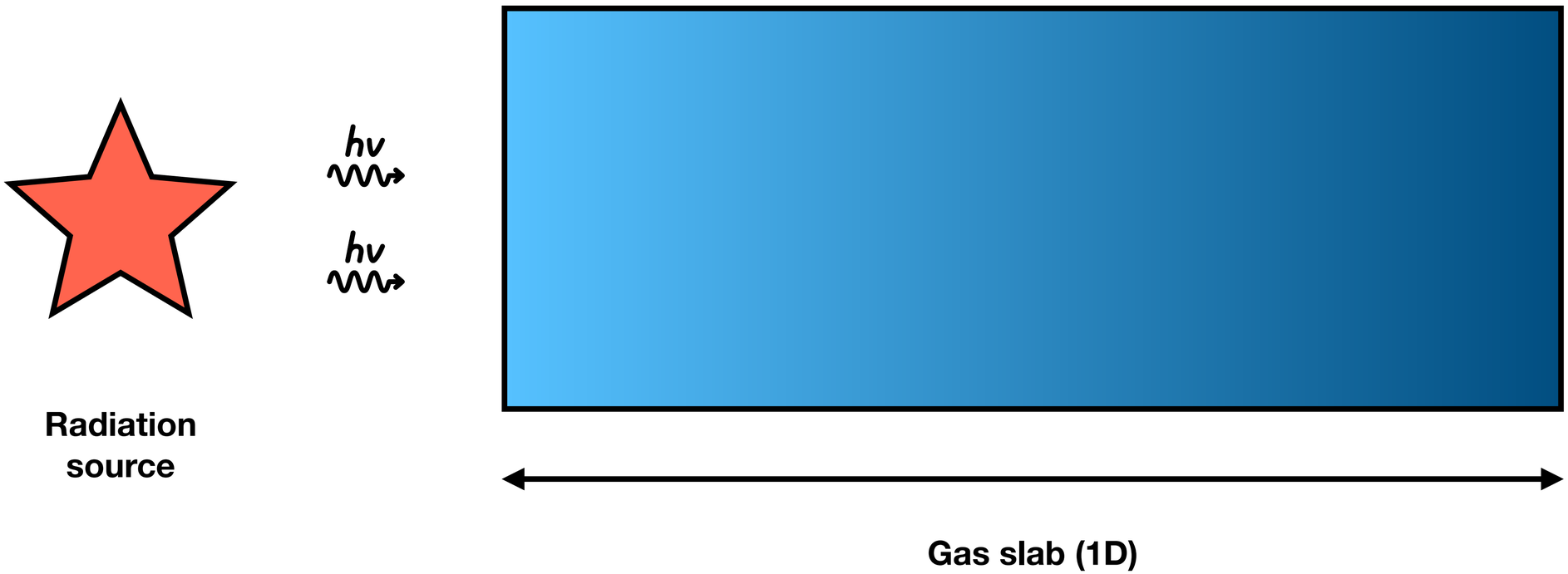
CLOUDY song: https://youtu.be/L-fIO7_HJBo?si=Cybj98m2ULEUheRU

Introduction to CLOUDY

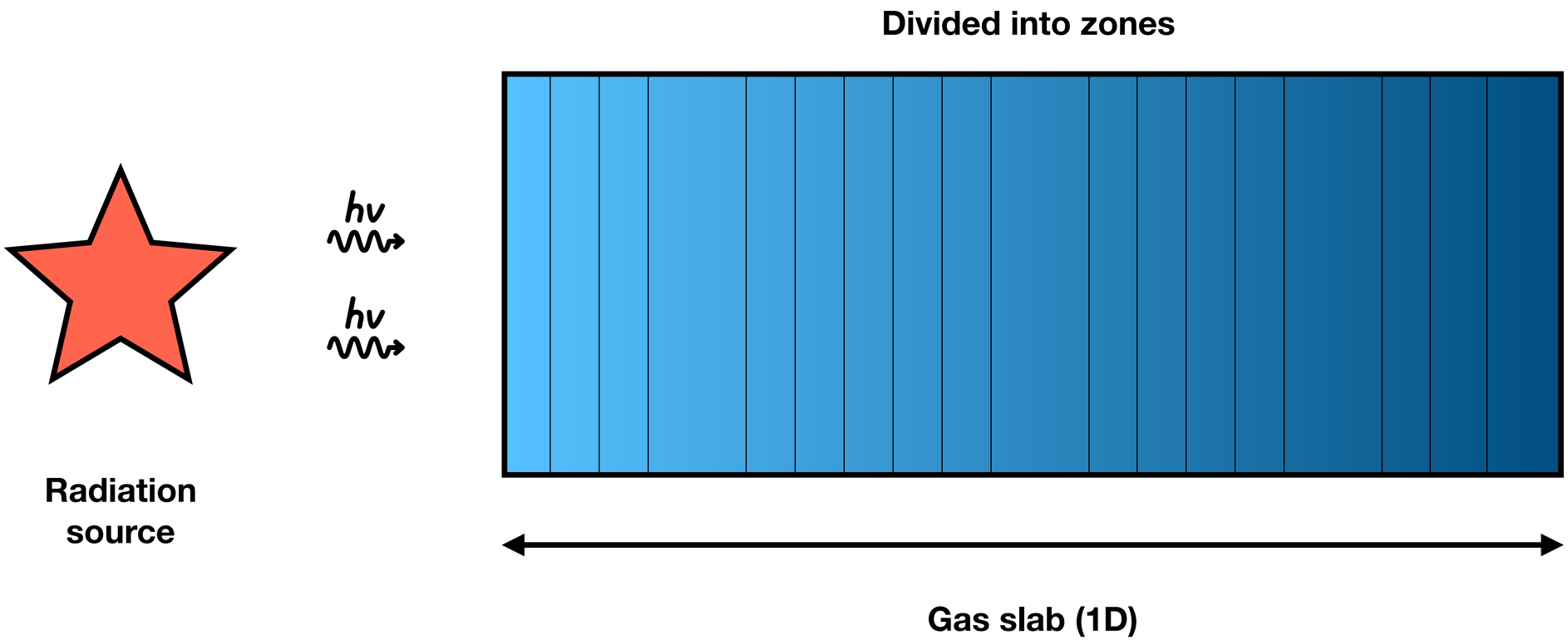


Radiation source

Introduction to CLOUDY



Introduction to CLOUDY



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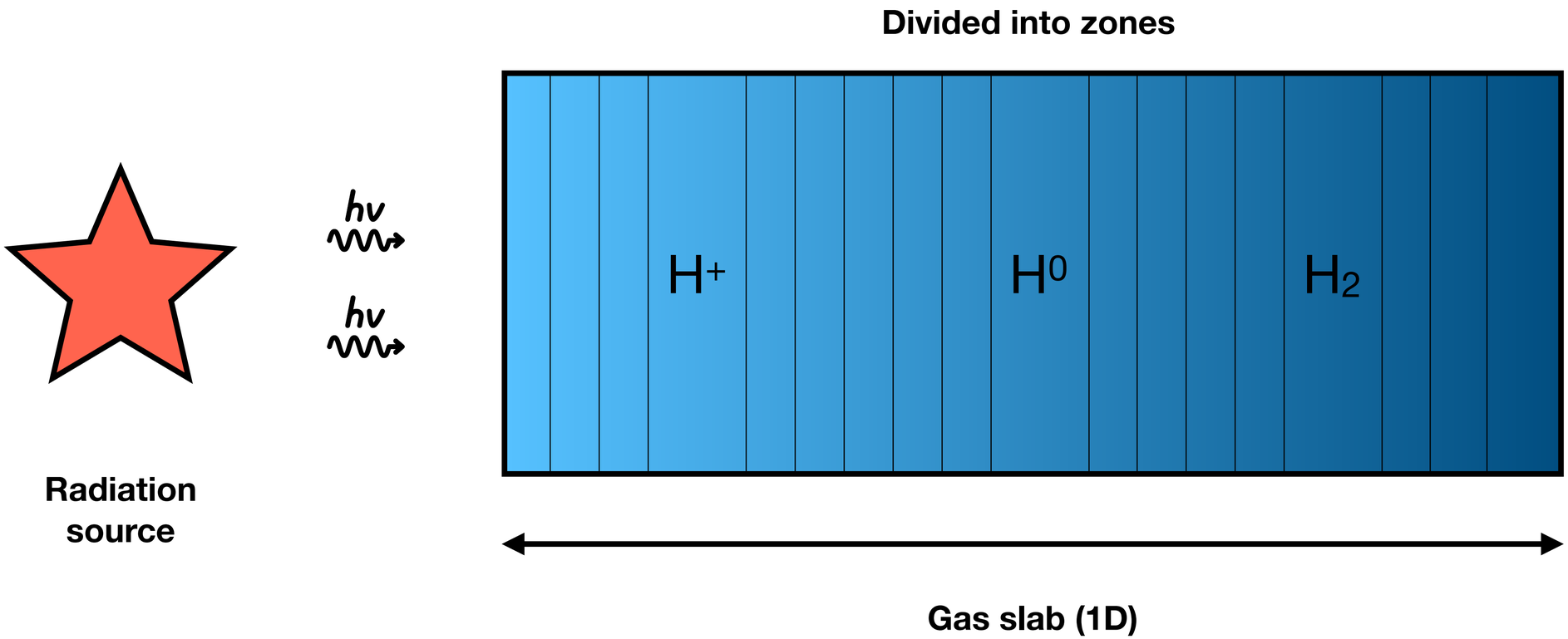

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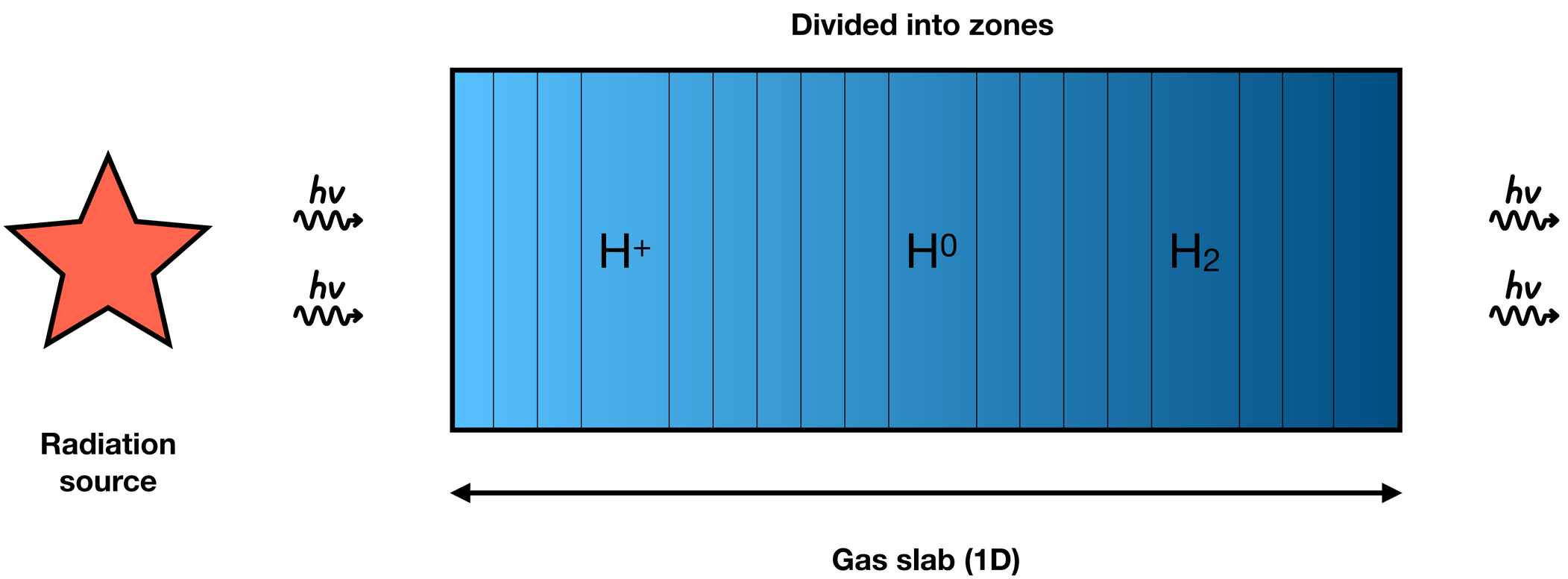
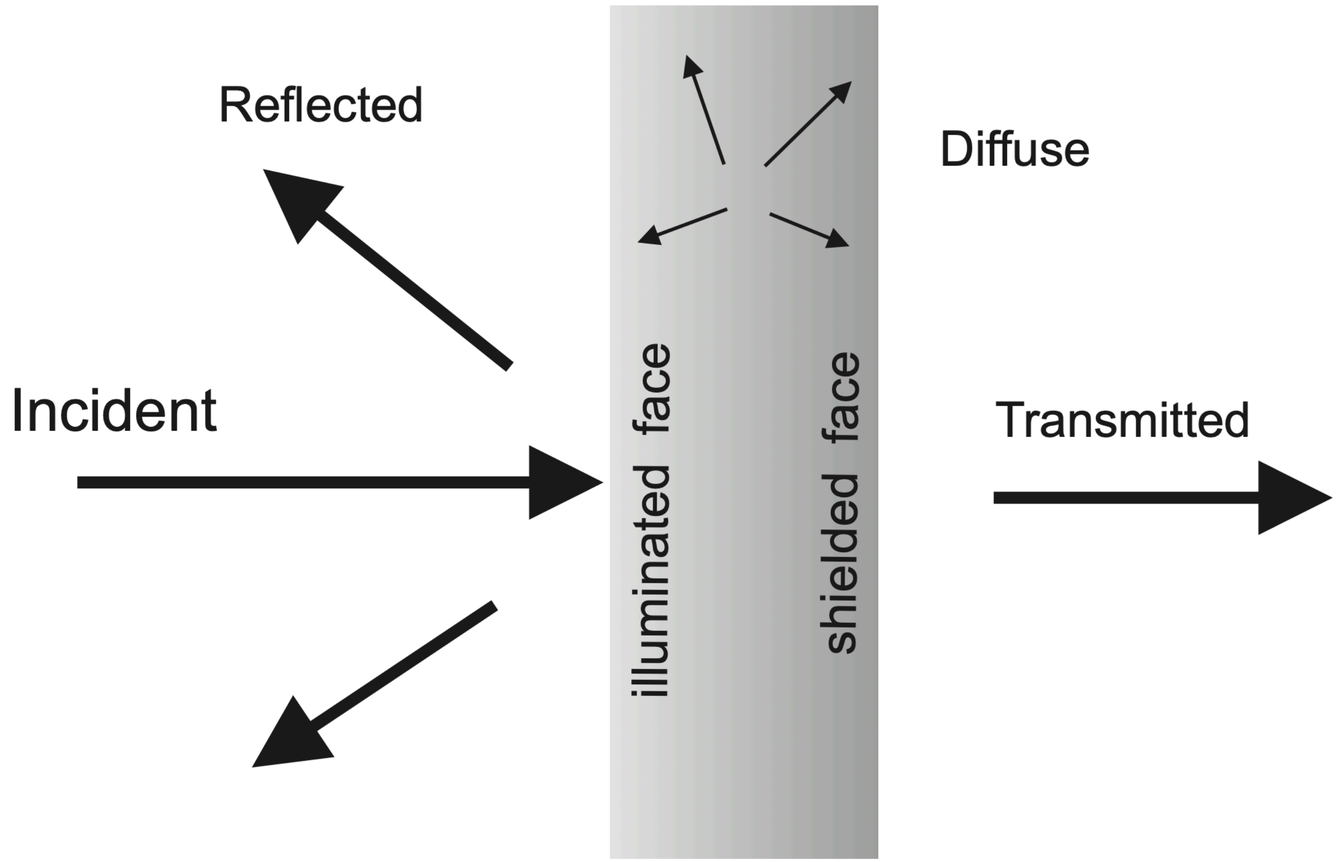
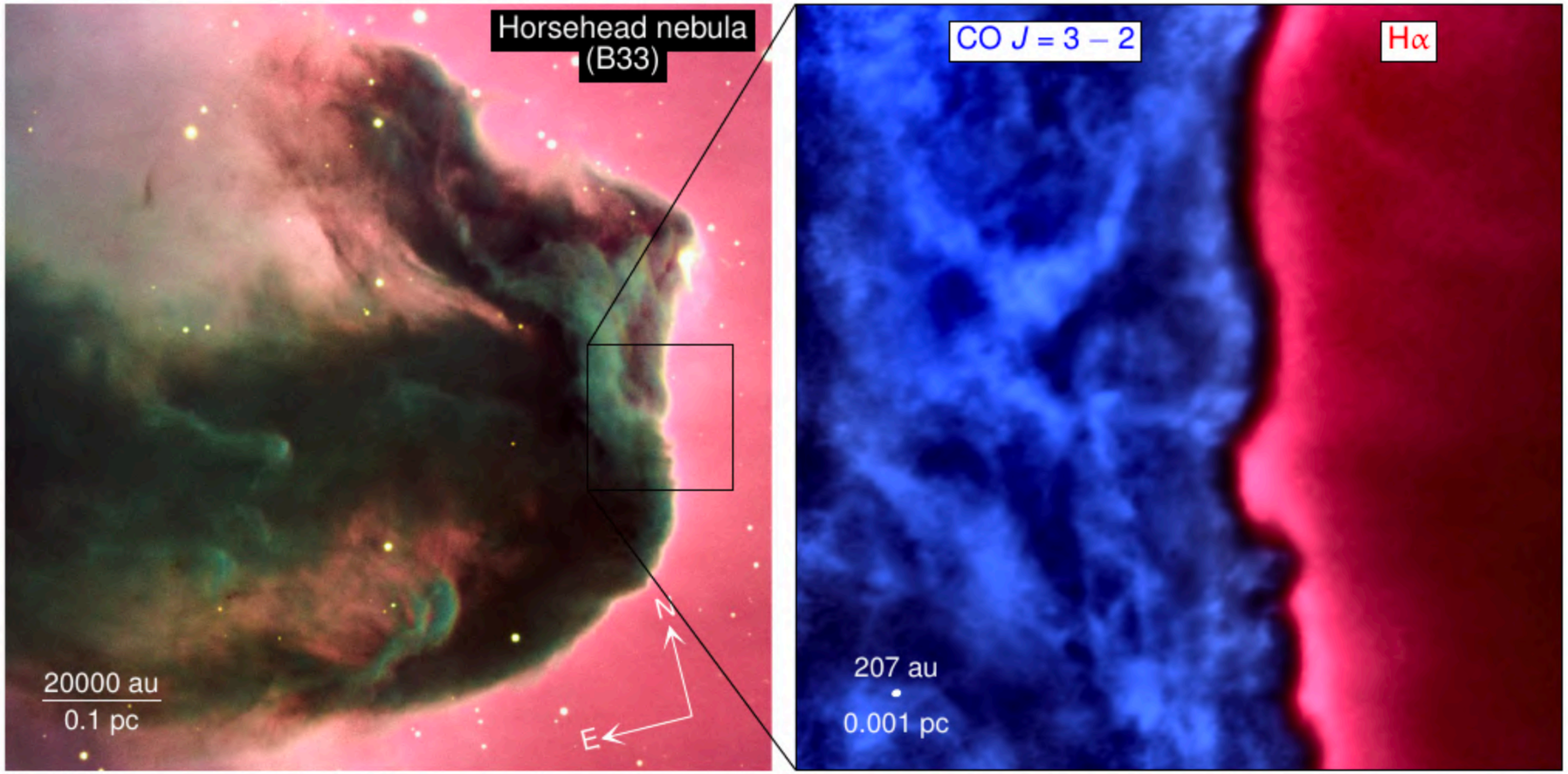


Introduction to CLOUDY

in CLOUDY words (from Hazy 1):

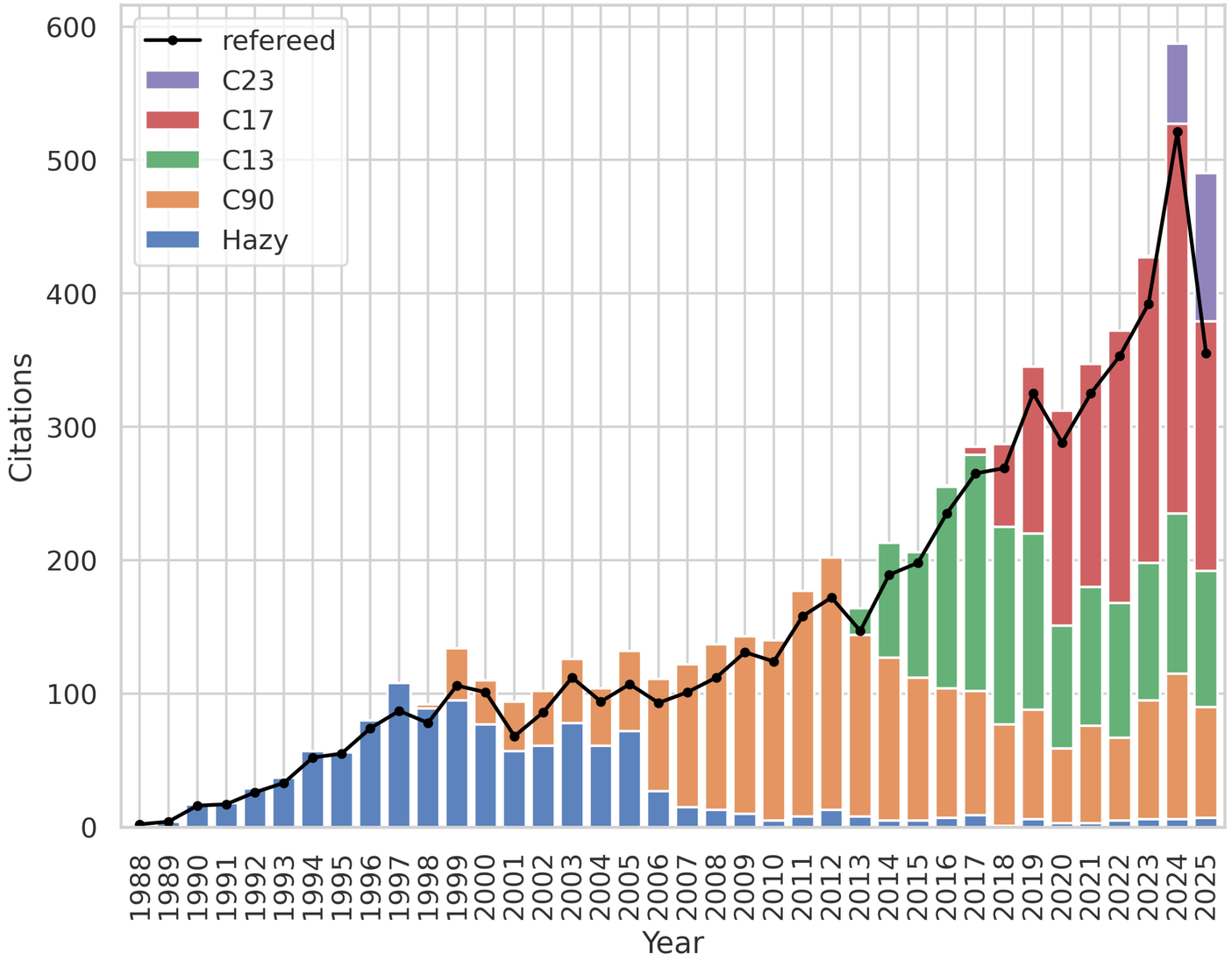


Introduction to CLOUDY



Hernández-Vera et al. (2023)

Introduction to CLOUDY



How to run CLOUDY

1. Prepare a clean folder “`cloudytest`”
2. Within it, create a “`cloudytest.in`” text file
3. Edit “`cloudytest.in`” (next slide)
4. Run with `path/to/source/cloudy.exe cloudytest.in`
5. Wait…
6. Check the output files (within the same “`cloudytest`” directory)

CLOUDY input file 101

Input file	It is a text file with extension `.in`
Incident radiation	We need to specify intensity/luminosity + shape (i.e. SED)
Intensity case	Specify intensity [erg /s / cm^2]
Luminosity case	Specify luminosity [erg / s] + specify cloud distance [cm]
Cloud density	We will see constant density (in cm^{-3}) simulations
Cloud composition	How much C/O? Which metallicity? Do we want dust?
Stopping criteria	When should the simulation stop?

PDR input file (1/2)

```
set save prefix “pdr_test”
```

every saved file (except `.out`) will have this prefix

```
table star "sfr1_kroupa.ascii" age=1e6 years
```

this is the incident SED of a stellar population
(obtained with the starburst99 code)

```
intensity -2.8, range 0.44 to 1 Ryd
```

intensity G_0=1, since G_0 = 1.6 x 10^{-3} erg / s / cm^2
normalized between 6 and 13.6 eV

```
hden 4
abundances ISM no grains
grains ISM
metals and grains linear 1
```

gas+dust density, composition, and metallicity
`hden 4` means constant 10^4 cm^{-3}
`abundances` and `grains` are better split
`metals and grains` scale the abundances

PDR input file (2/2)

```
turbulence 1 km/s
cosmic rays background
no grain molecules
```

turbulence affects the shielding and pumping of lines
cosmic rays are important for molecular chemistry
`no grain molecules` avoid condensation onto grains

```
stop temperature off
stop column 23
set nend 5000
iterate to convergence
```

`stop temperature` default is 4000K
column density NH=10^{23} cm^{-2} to see CO lines
`nend` = number of zones (default 1400)
`iterate to convergence` sets max=7 iterations

```
save last overview ".ovr"
save last continuum ".cont"
save last pdr ".pdr"
save last lines zone cumulative emergent ".emis"
CO   2600.05m      # CO(1-0)
CO   1300.05m      # CO(2-1)
...
```

`last` means last iteration
files will be named with the `save prefix`
after `save lines` we need to list lines

XDR input file

```
table xdr
```

AGN SED truncated between 1-100 keV
to isolate the effect of X-rays

```
intensity 0.0, range 147 to 735 Ryd
```

intensity is $F_X = 10^0$ erg / s / cm^2
normalized between 2 and 10 keV

```
hden 4
abundances ISM no grains
grains ISM
metals and grains linear 1
turbulence 1 km/s
cosmic rays background
no grain molecules
stop temperature off
stop column 23
set nend 5000
iterate to convergence
save last overview ".ovr"
save last continuum ".cont"
save last pdr ".pdr"
save last lines zone cumulative emergent ".emis"
```

all subsequent commands are same as PDR

CLOUDY output files

main output (.out)

- the only default output file
- gives a lot of informations about the run
- lists warnings, failures, cautions, notes

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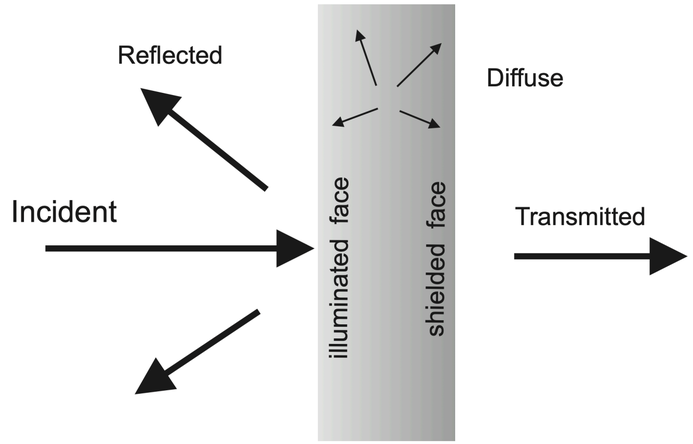
continuum (.cont)

- intrinsic continuum: to check the input SED
- total continuum: transmitted + reflected
- default units: Rydberg



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overview and PDR (.ovr .pdr)

- first column of both: cloud depth [cm]
- `ovr` contains temperature and ion. fractions
- `pdr` contains column density and G0

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lines cumulative emergent (.emis)

- first column: cloud depth [cm]
- every other column: line flux [erg/s/cm^2]

Explore CLOUDY results with Python

First, we create a **python virtual environment**.

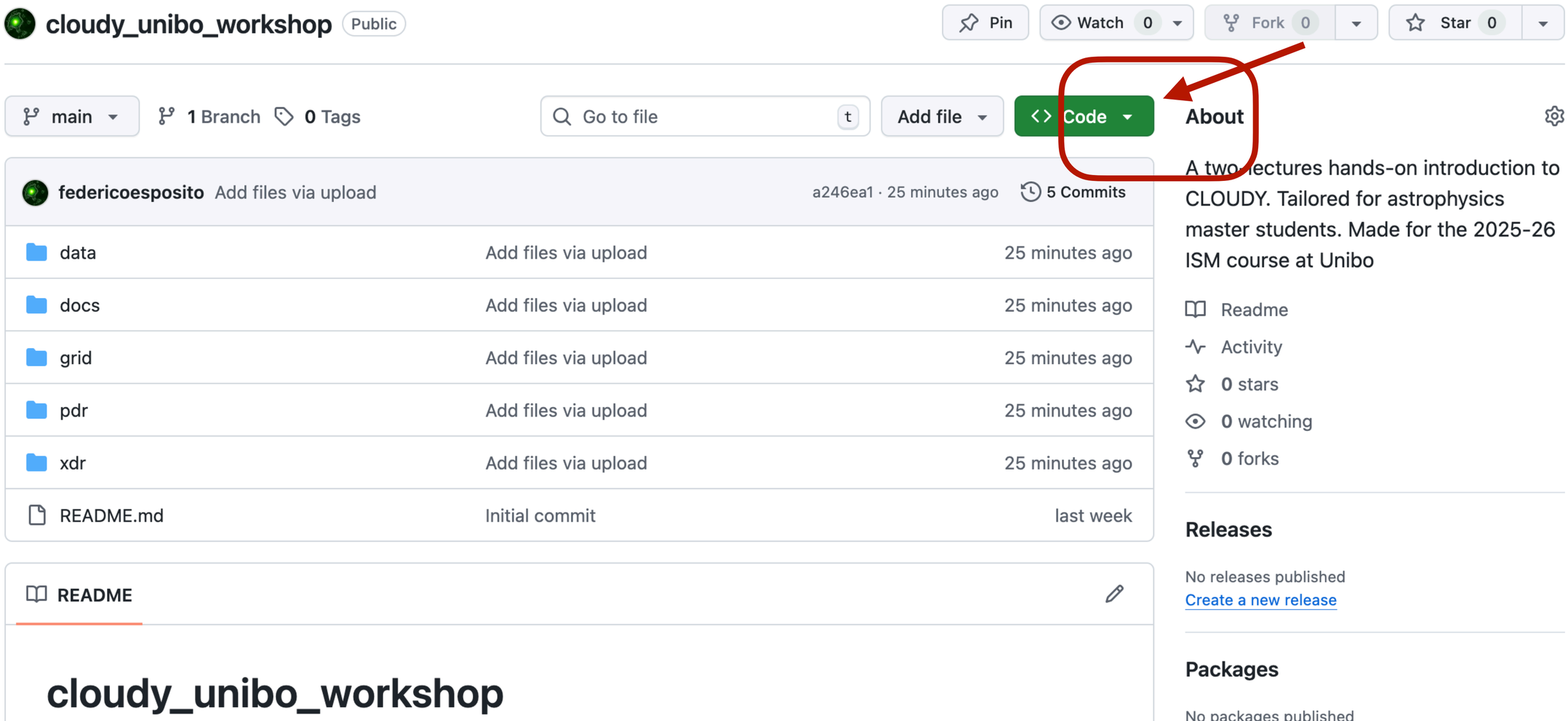
Choose a directory

Open terminal in that directory and execute line by line:

```
python3 -m venv cloudy_day
source cloudy_day/bin/activate
which pip  ### output should be path/to/cloudy_day/bin/pip
pip install –upgrade pip
pip install jupyter ipython ipykernel
python -m ipykernel install –user –name=cloudy_day
pip install numpy pandas matplotlib seaborn scipy
```

Download shared folder

https://github.com/federicoesposito/cloudy_unibo_workshop



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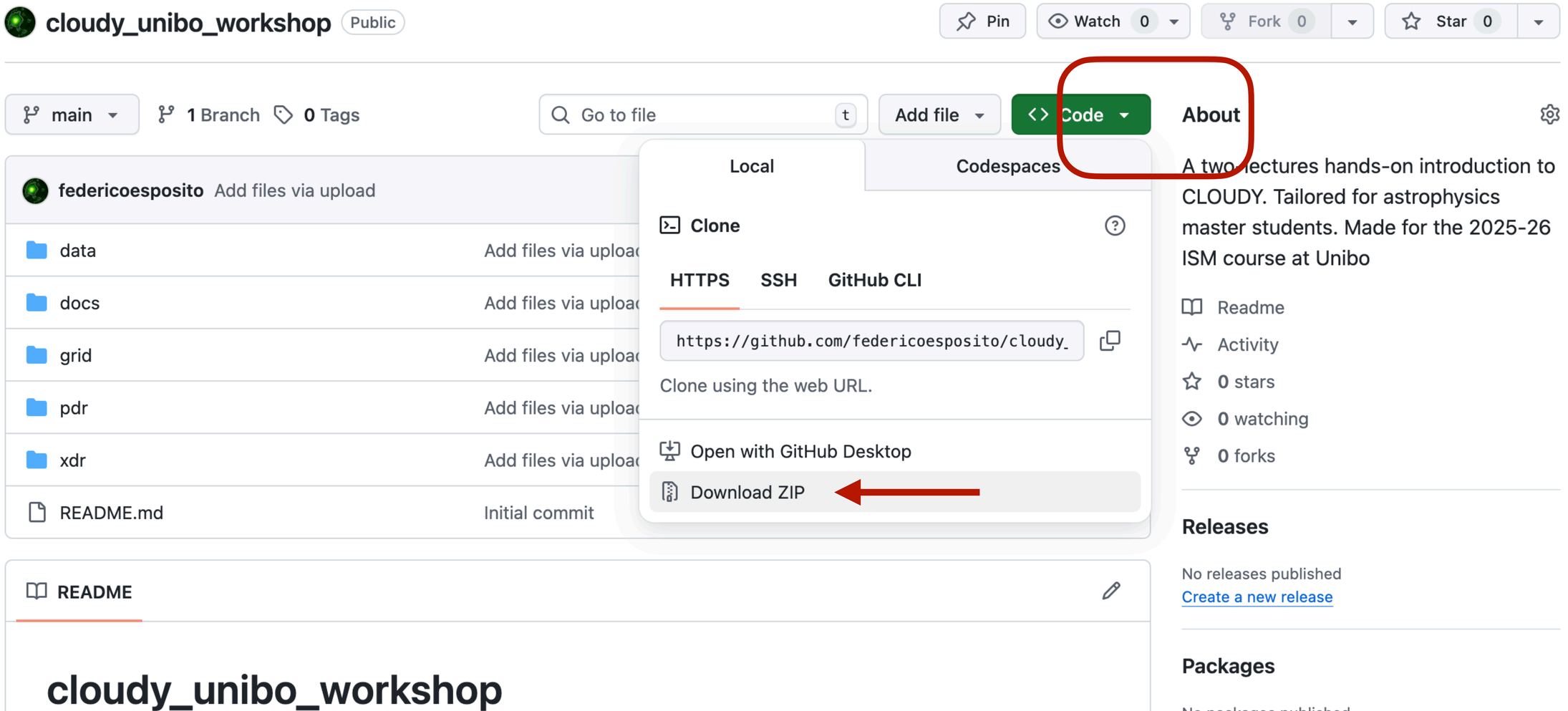

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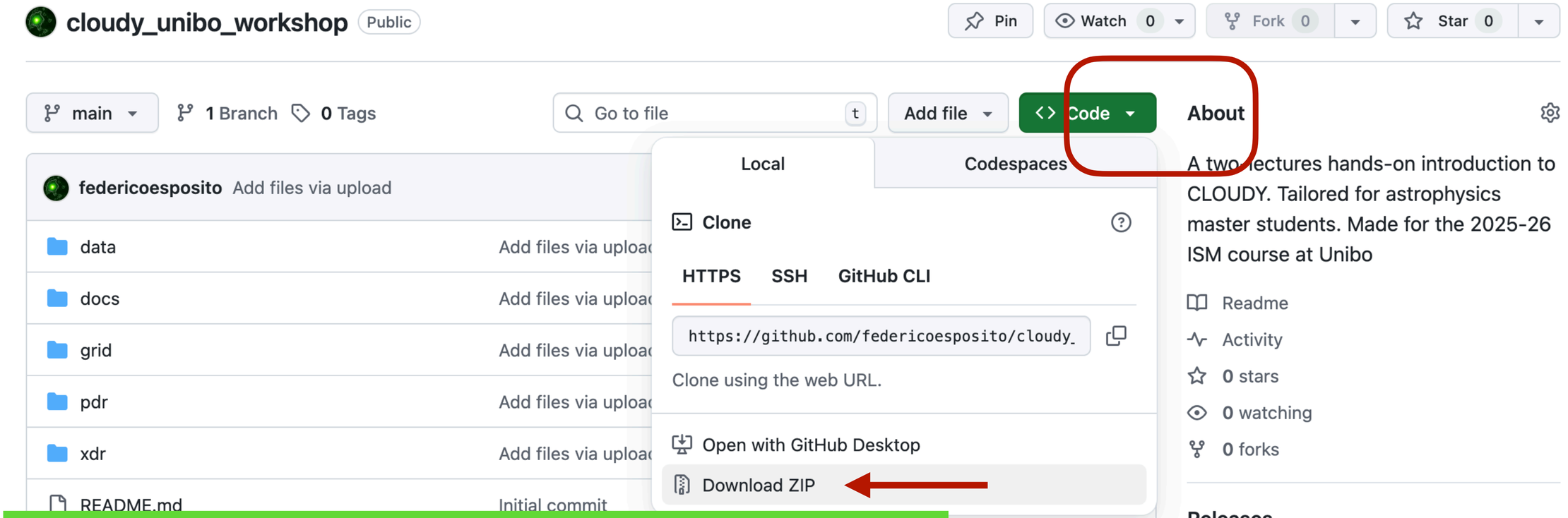

1. Download ZIP
2. Extract the ZIP
3. Move it to your favourite location
4. Rename the main folder ‘cloudy_unibo_workshop’

Anonymous questions

Fully anonymous, we will review the questions later / tomorrow

https://app.sli.do/event/35xx4R47zVRrTUaJQcbxeb

For direct messages:

f.esposito@oan.es