Stratospheric Observatory for Infrared Astronomy

The analysis of high spectral resolution observations in the far-infrared

With a focus on the interstellar medium (ISM)

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SOFIA Infrared School

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Outline

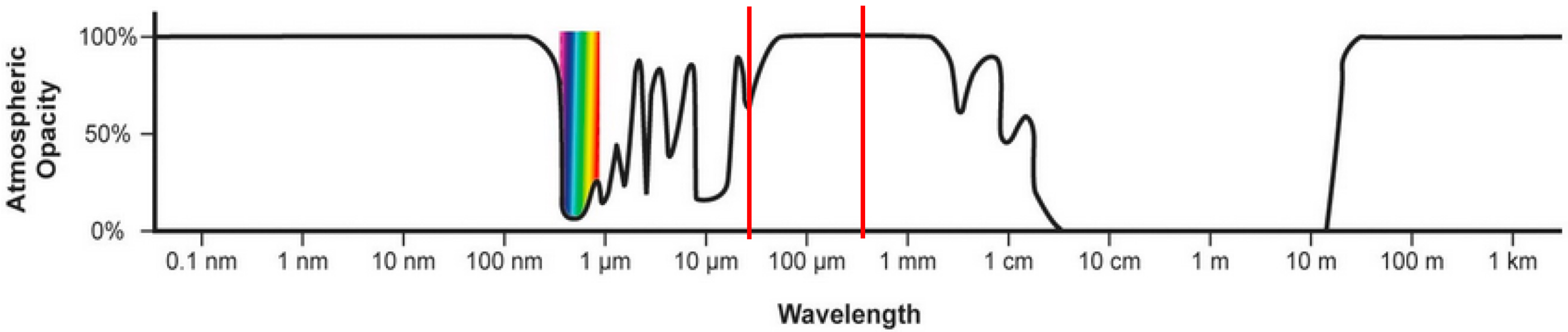
- Short overview: high-resolution spectroscopy in the far-infrared

- ISM studies: far-infrared spectra
  - Dynamics, chemical abundances and excitation conditions

- ISM studies: far-infrared spectral data cubes
  - Visualizing and quantifying the data
  - Segmenting the data for analysis

Far-infrared astronomy

- Far-infrared astronomy: 30 – 300 (or 450) µm
- Observe from space or at least in the stratosphere
  - Mostly water absorption in the atmosphere (also CO_2 contribution)

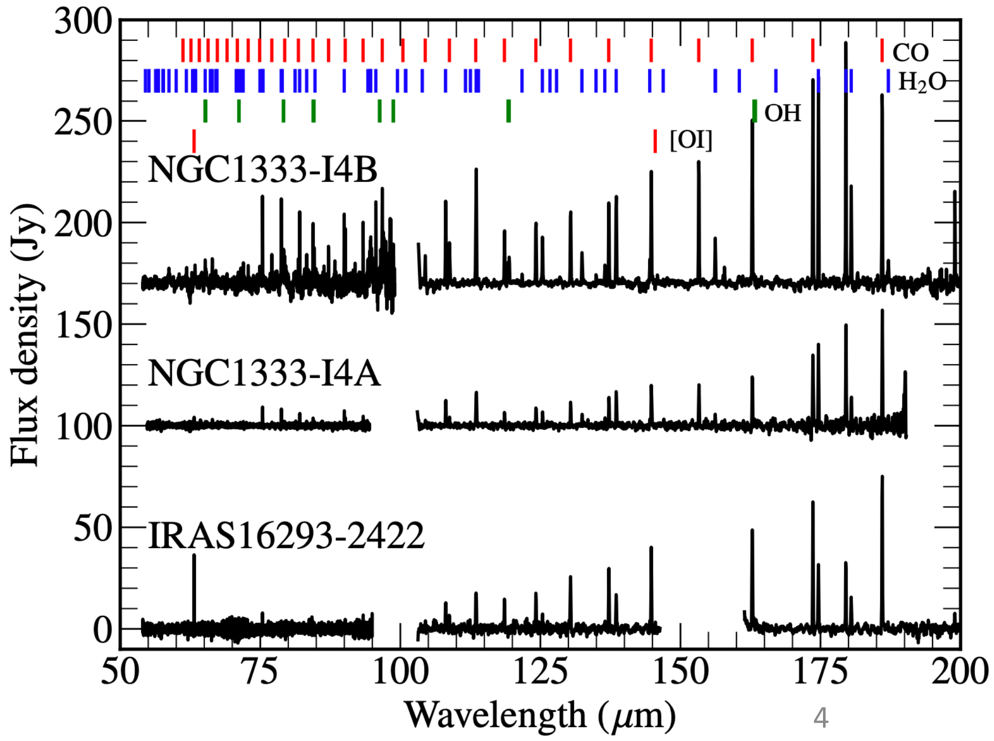


Spectral lines in the far-infrared

- Far-infrared spectral lines contain a lot of information
  - Dynamics, excitation conditions, chemical abundances,...

- Spectral lines:
  - H_2O (proto-planetary disks, atmospheres)
  - [CII] (galaxies, ISM)
  - HD (proto-planetary disks)
  - CO (shocks, galaxies, ISM)
  - [NII], [OI], [OIII], HeH^+, H_2D^+, OH, CH,...

Herschel WISH program (van Dishoeck et al. 2021)

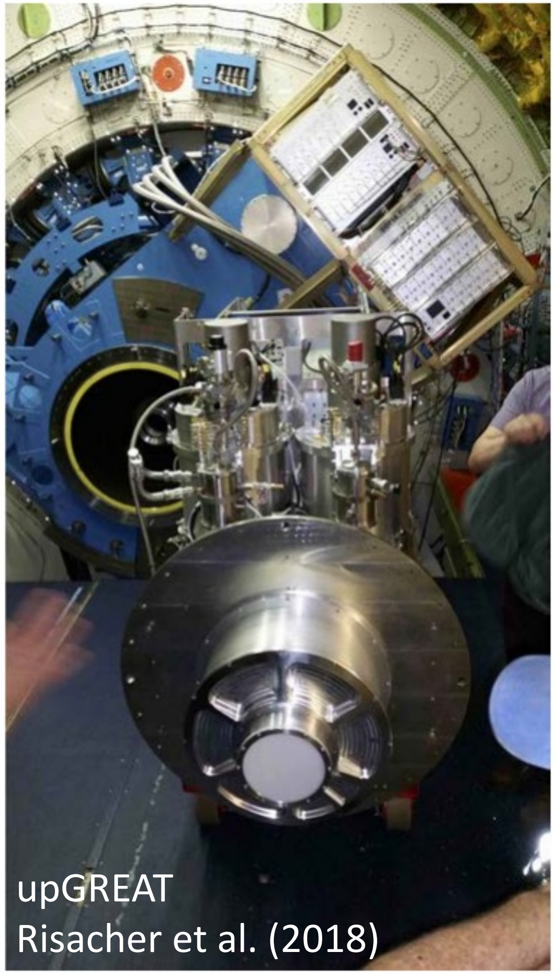


Far-infrared spectroscopy (history)

- ISO - LWS (1995-1998)
  - Spectral resolution: ~10 km s^{-1} (Swinyard et al. 1998)

- Herschel - HIFI (2009-2013)
  - Spectral resolution: ~0.1 km s^{-1} (de Graauw et al. 2010)

- SOFIA - (up)GREAT/4GREAT (2010-2022)
  - Spectral resolution: ~0.1 km s^{-1} (Heyminck et al. 2012; Risacher et al. 2016; Duran et al. 2021)


upGREAT
Risacher et al. (2018)

The up/4GREAT receiver

- Heterodyne far-infrared receivers
  - upGREAT: 2-band receiver, 7 pixels
  - 4GREAT: 4-band receiver, 1 pixel
- Data reduction
  - see talk R. Higgins (up next)

GREAT Configurations

Front-End	Frequencies (GHz)	Lines of Interest	DSB[6] Receiver Temperatures (K)	Main beam efficiencies
HFA [1]	4744.77749	[OI] 63 µm	1250	0.63
LFAH [2]	1835–2007	[CII] 158 µm, CO, OH, $^2\Pi_{1/2}$, ^{12}CH, ^{13}CH	1000	0.69
LFAV [2]	1835–2007 2060–2065	Same as LFAH, plus [OI] 145 µm		
4G4	2490–2590	OH $^2\Pi_{3/2}$, ^{18}OH $^2\Pi_{3/2}$	3300	0.57
4G3	1240–1395 1427–1525	[NII] 205 µm, CO, OD, HCN, SH, H_2D^+	1100	0.70
4G2 [3,4]	890–984 990–1092	CO, CS	> 600 300	0.59
4G1 [4]	491–555 560–635	NH_3, [CI] 609 µm, CO, CH	< 150	0.51

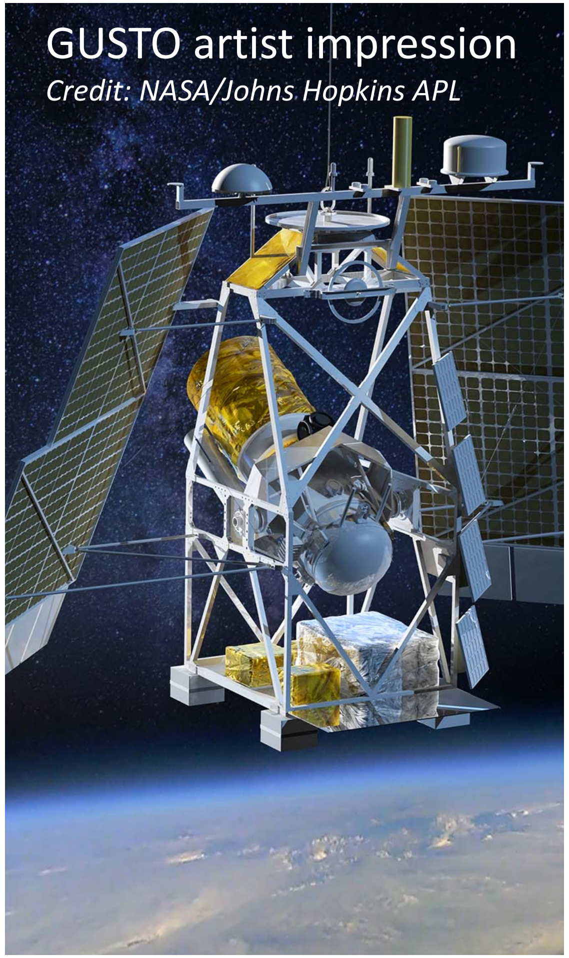
Far-infrared spectroscopy (the future)

- Stratospheric balloon missions
  - GUSTO (2023-2024: see e.g. Goldsmith et al. 2022)
    - [NII] @ 205 μm, [CII] @ 158 μm and [OI] @ 63 μm
  - ASTHROS (2024-2025: see e.g. Pineda et al. 2022)
    - Includes [NII] @ 205 μm and 122 μm, and HD @ 112 μm
  - Probe mission in 2030-2040?

- Herschel & SOFIA archive

http://archives.esac.esa.int/hsa/whsa/

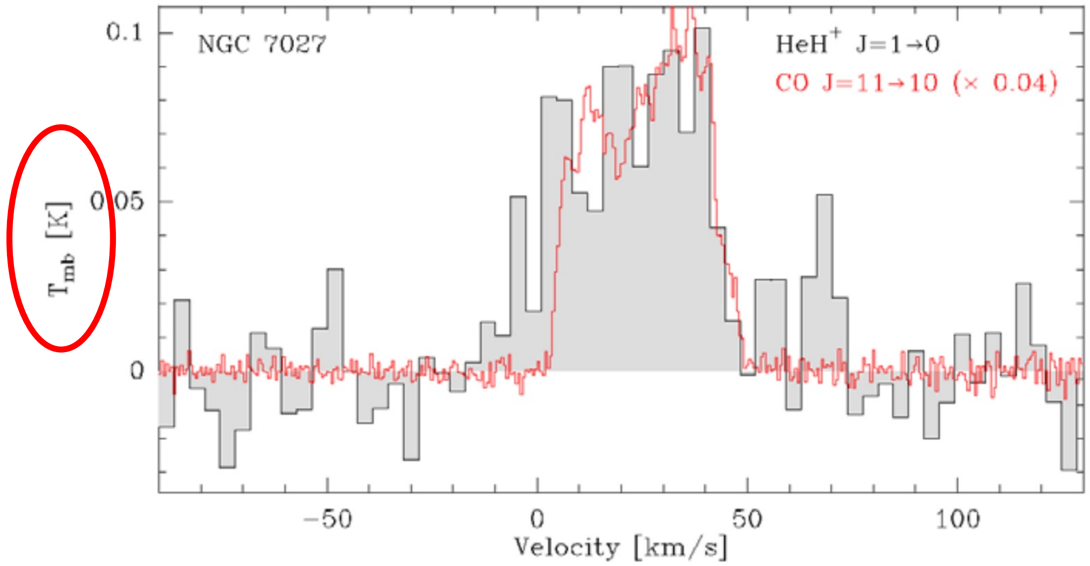
https://irsa.ipac.caltech.edu/applications/sofia/?__action=layout.showDropDown&



Units

- ‘Brightness temperature – T (K)’ or ‘(milli/mega-)Jansky – (m/M)Jy’
  - As in submillimeter and radio astronomy

Guesten et al. (2019)



- Flux density (S): 1 Jy = 10^{-26} W m^{-2} Hz^{-1}

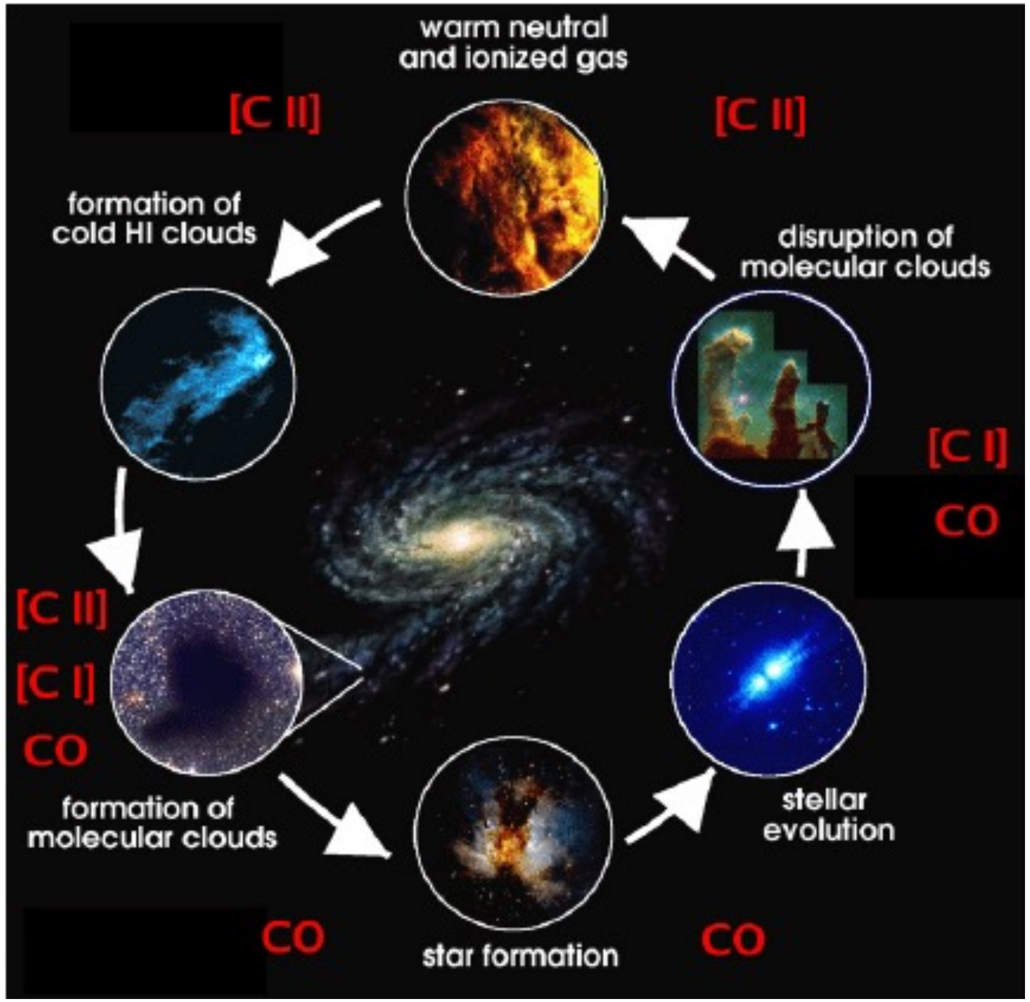
- Brightness temperature: $T = \frac{\lambda^2}{2\,k\Omega} S$
  - Rayleigh-Jeans law

https://science.nrao.edu/facilities/vla/proposing/TBconv

https://www.atnf.csiro.au/research/radio-school/2011/talks/Parkes-school-Fundamental-II.pdf

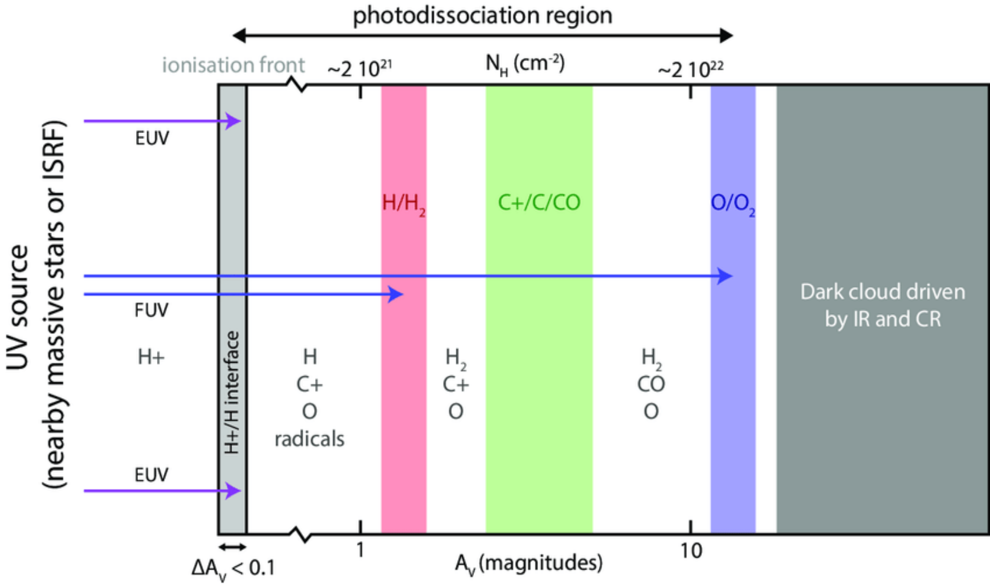
The cycle of matter in galaxies

Kulesa et al. (2013)



The [CII] fine structure line

- The ionization potential of carbon is 11.3 eV
  - Can trace neutral regions in the ISM (< 13.6 eV)
  - Fine-structure line emits at 158 µm ([CII])
- Dominant cooling line in the neutral ISM
  - [CII] mostly originates from photodissociation regions (PDRs) (e.g. Pineda et al. 2013; Tarantino et al. 2021)
  - PDRs: see talks M. Wolfire, J. Sutter



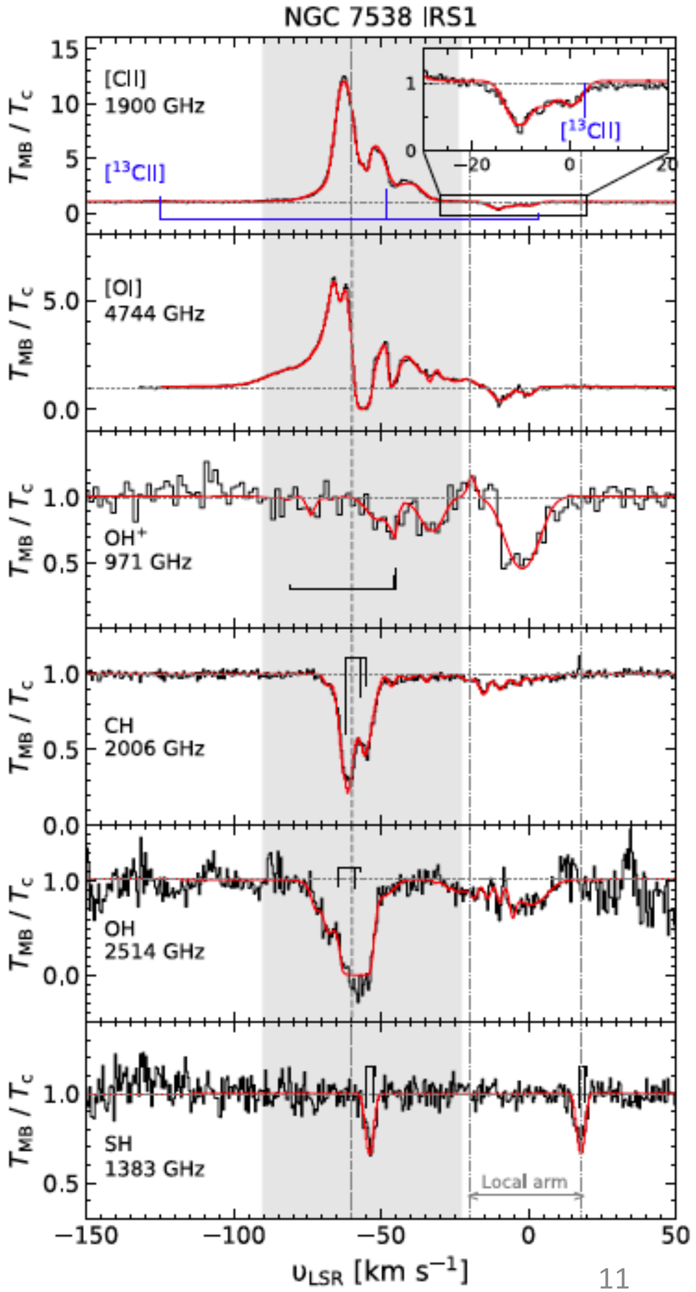
- FEEDBACK Legacy survey: large [CII] maps (Schneider et al. 2020)

Spectral features

- (Self/foreground-)absorption + emission
  - Spectra modelled with XCLASS (Möller et al. 2017)
  - Automated fitting routine: MAGIX (Möller et al. 2013)

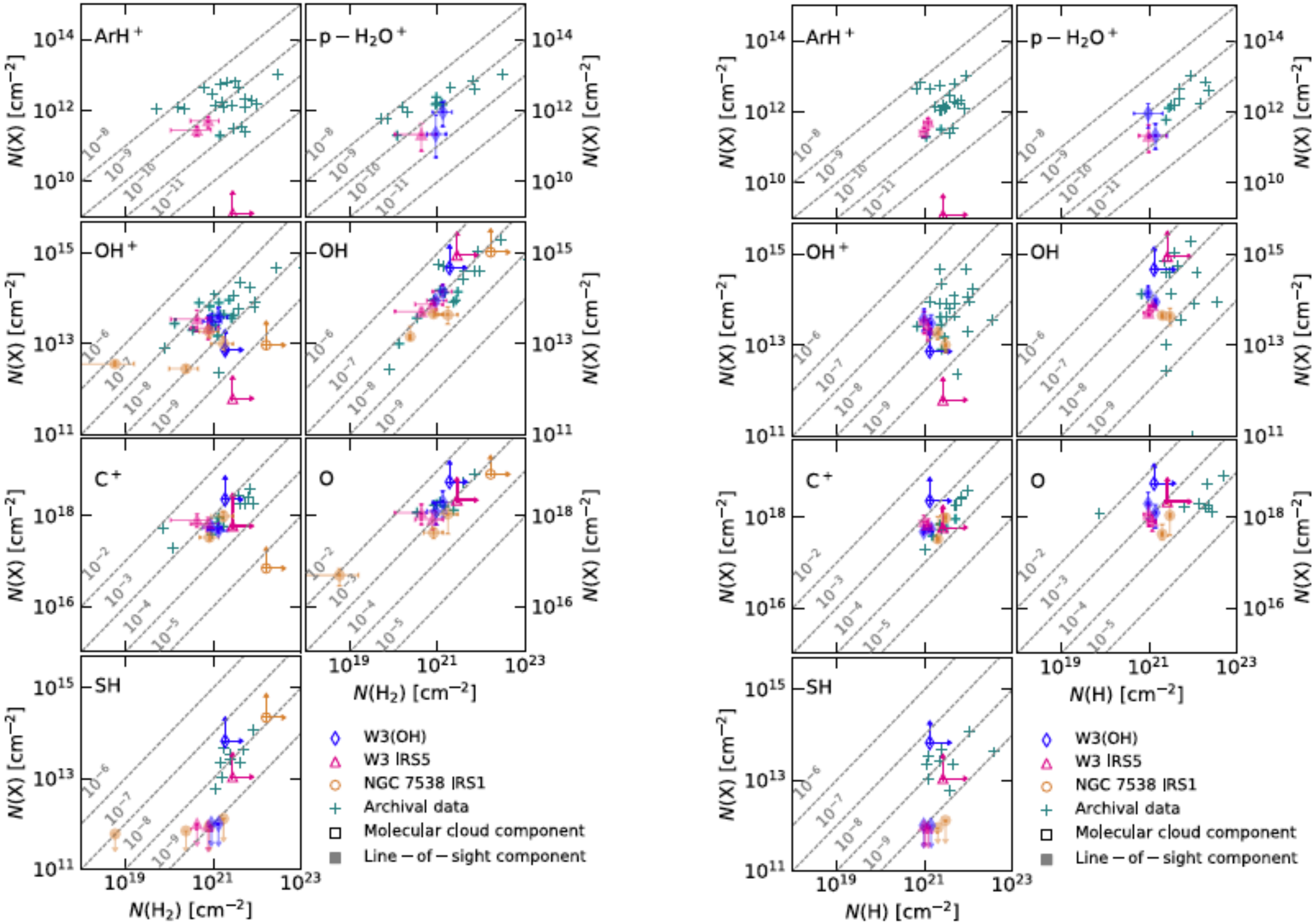
- XCLASS: A tool for CASA https://casa.nrao.edu/
  - Models spectral lines by solving the radiative transfer equation assuming LTE
  - Spectroscopic data from CDMS & JPL

Hygal legacy program: Jacob et al. (2022)



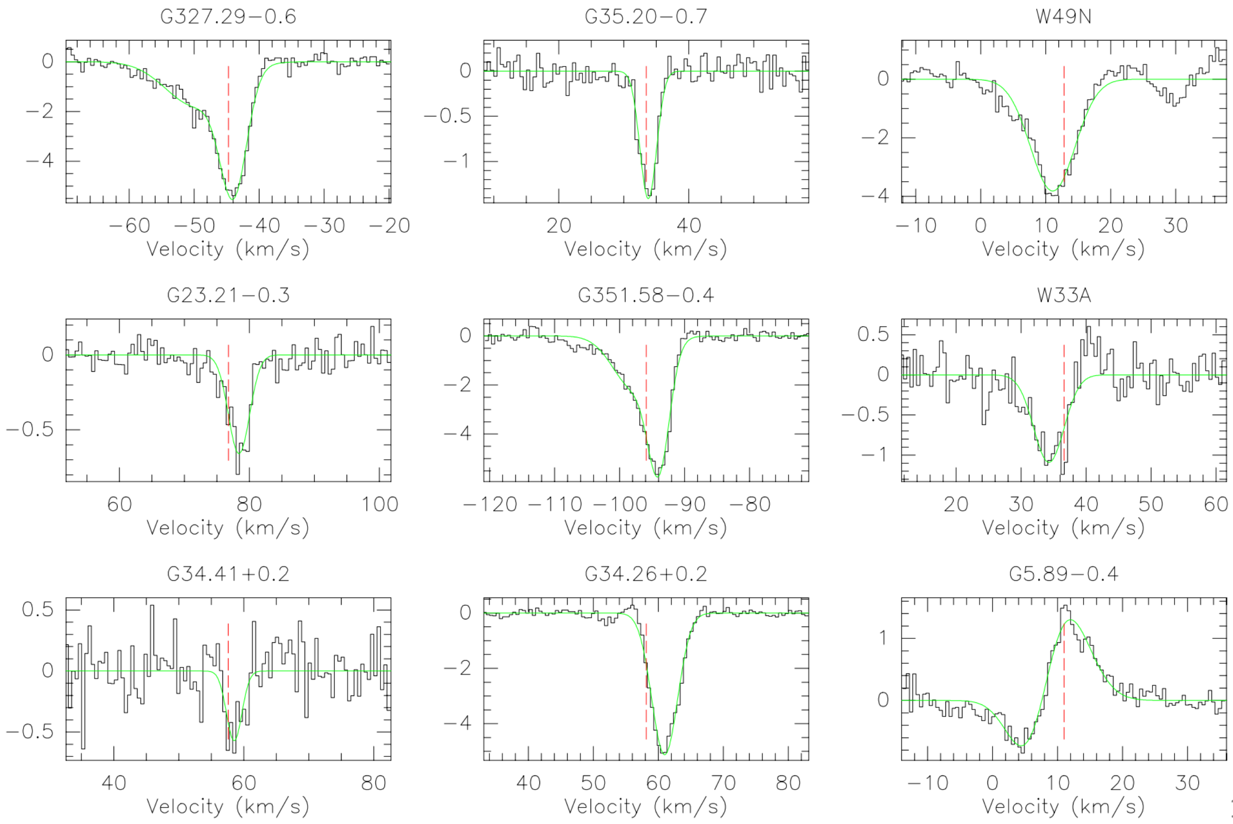
Abundances in the ISM

Jacob et al. (2022): Hygal Legacy program



Dynamics in the ISM

- Expansion and infall in massive star forming clumps (Wyrowski et al. 2012; 2016)
  - NH_3 absorption shift relative to the centroid velocity of $C^{17}O(3\text{-}2)$



- Fitting with CLASS
  - A GILDAS package
  - Can be coupled to Python

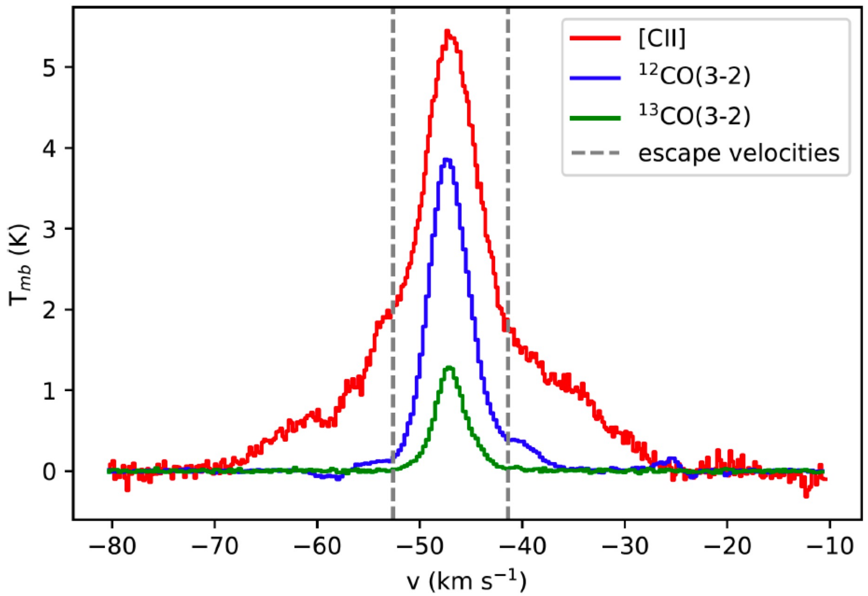
- GILDAS: see talk R. Higgins

https://www.iram.fr/IRAMFR/GILDAS/doc/html/class-html/class.html

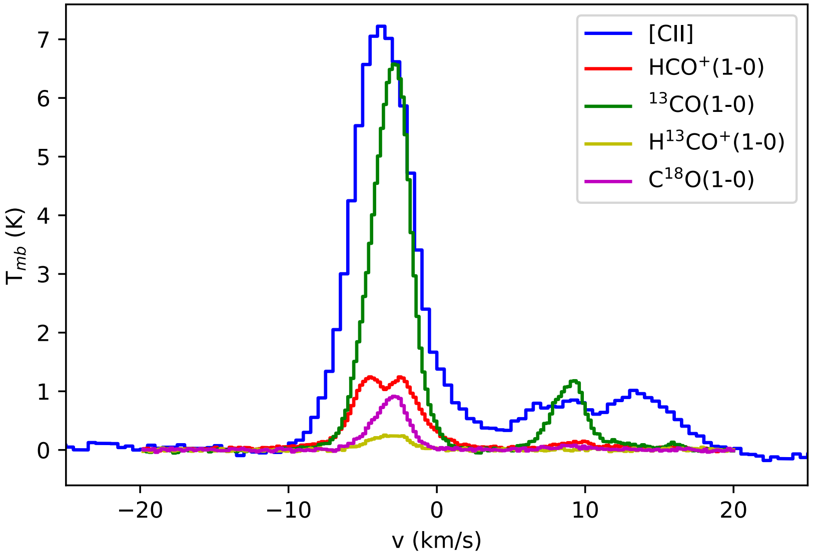
Dynamics in the ISM

- Emission: unveils previously unseen dynamics
  - Which gas phase does it trace?
  - Implications for ISM evolution?

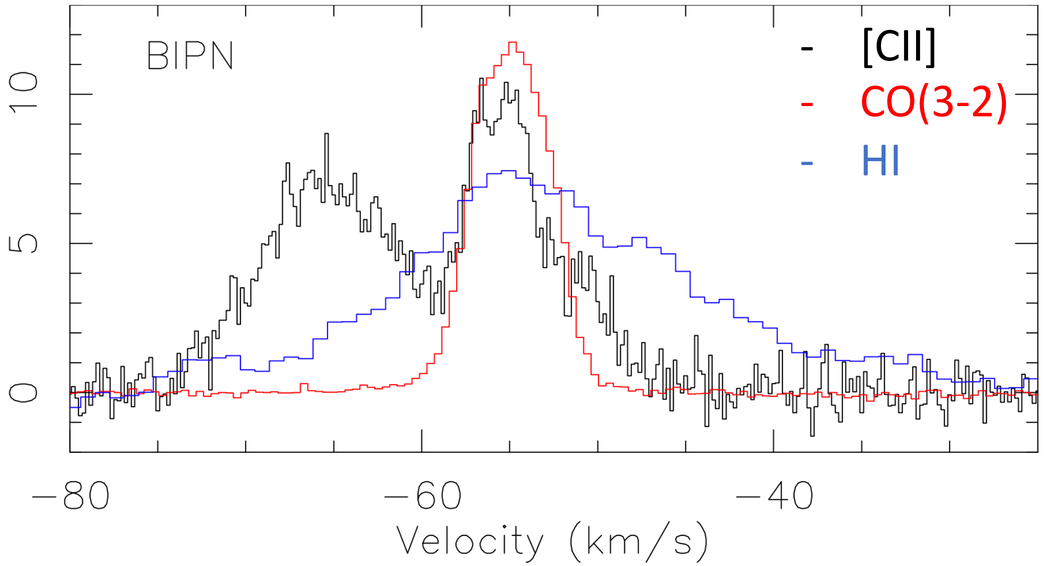
RCW 79: Bonne et al. in prep.



DR21: Bonne et al. in review; Schneider et al. (2023)

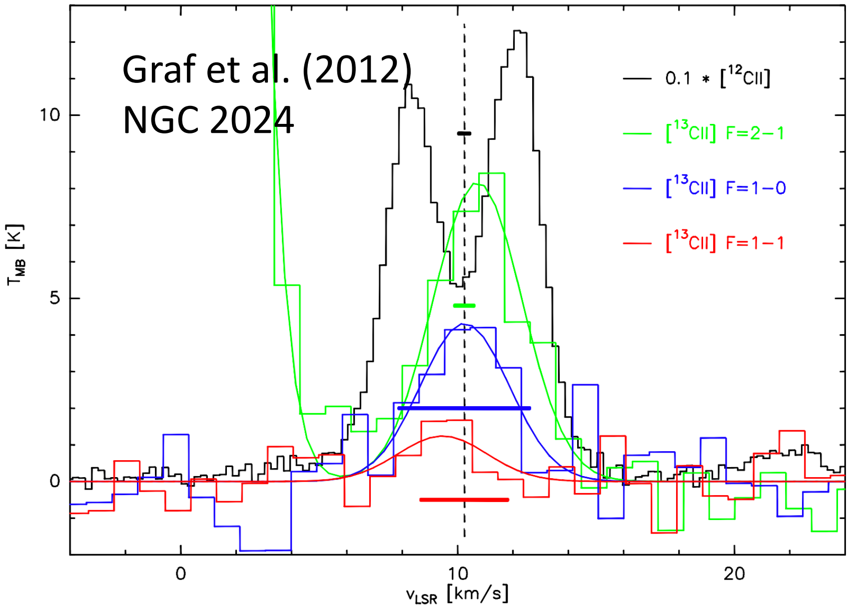


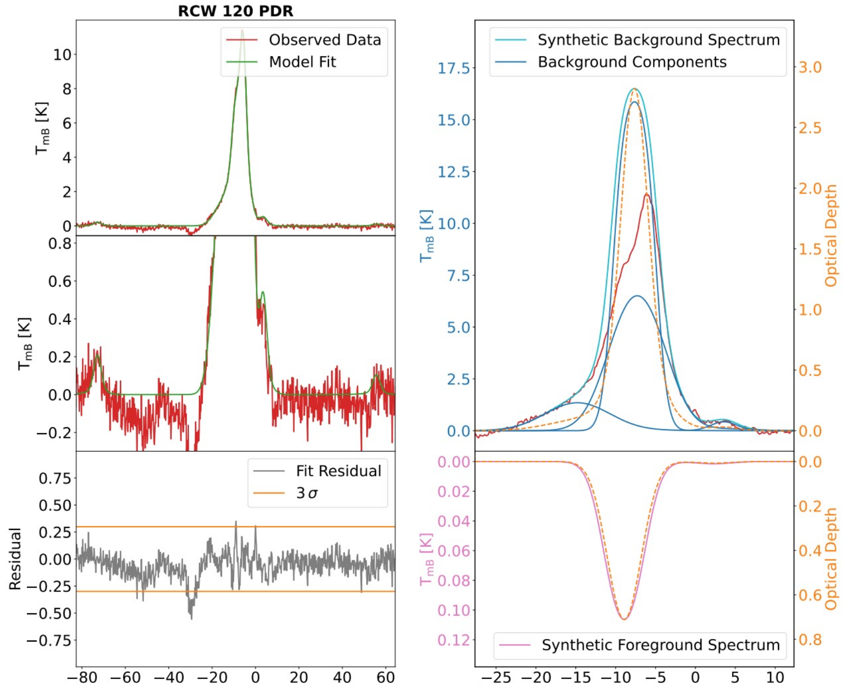
NGC 7538: Beuther et al. (2022)



Self-absorption

- ➢ Self-absorption in [CII]
  - Identified with [^{13}CII]
  - Origin of this self-absorption?
- ➢ Fit with a multi-layer model (see Guevara et al. 2020; Kabanovic et al. 2022)
  - Warm & cold layers of gas at different velocities
  - Also applicable to CO observations (Bonne et al. 2020)
- ➢ Also seen in [OI] @ 63 µm (e.g. Goldsmith et al. 2021)
  - Best identified with [OI] @ 145 µm

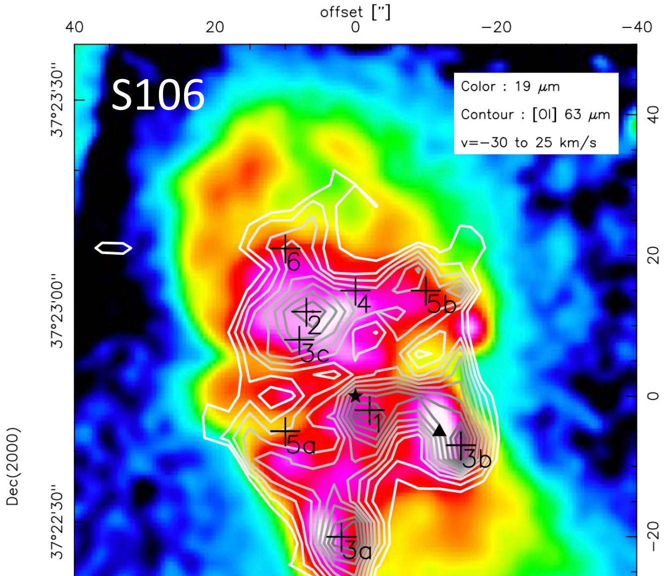


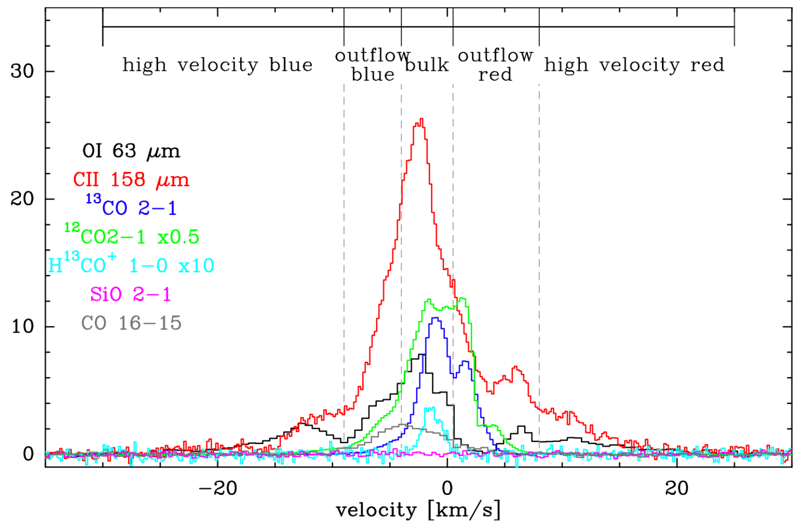


PDR modeling

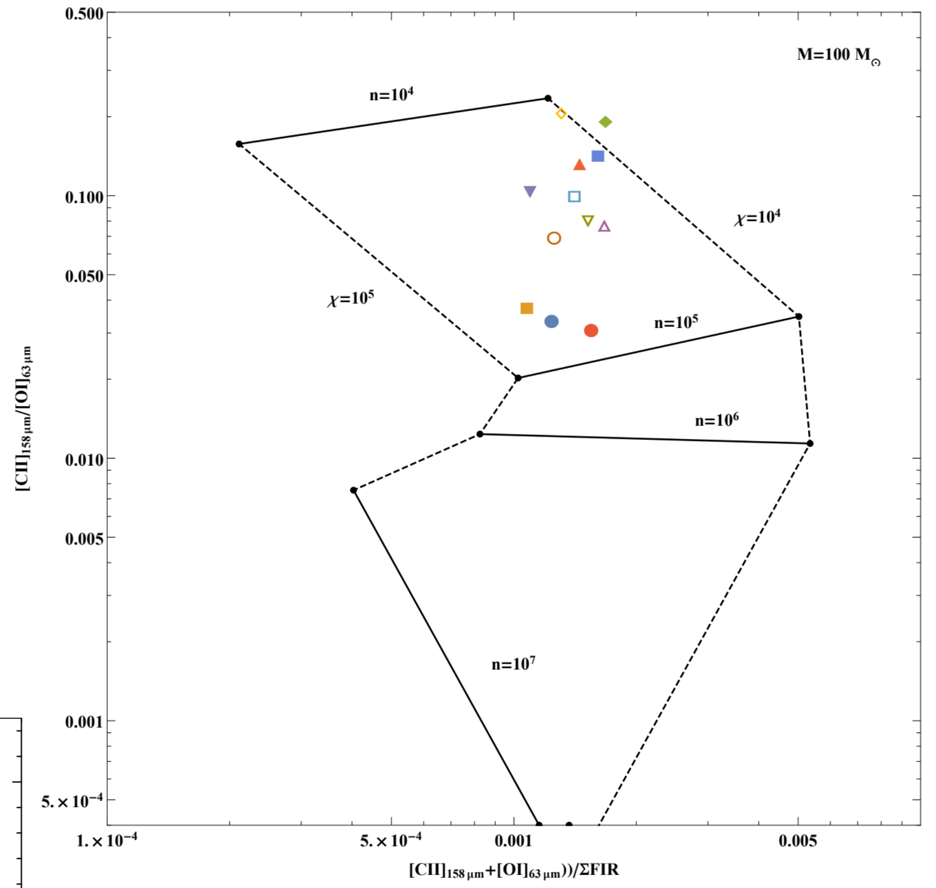
- PDR analysis at high spectral resolution
  - Can provide 3D information

- KOSMA-tau models (Stoerzer et al. 1996; Roellig et al. 2006)
  - Available in the PDR Toolbox (see talk M. Pound)



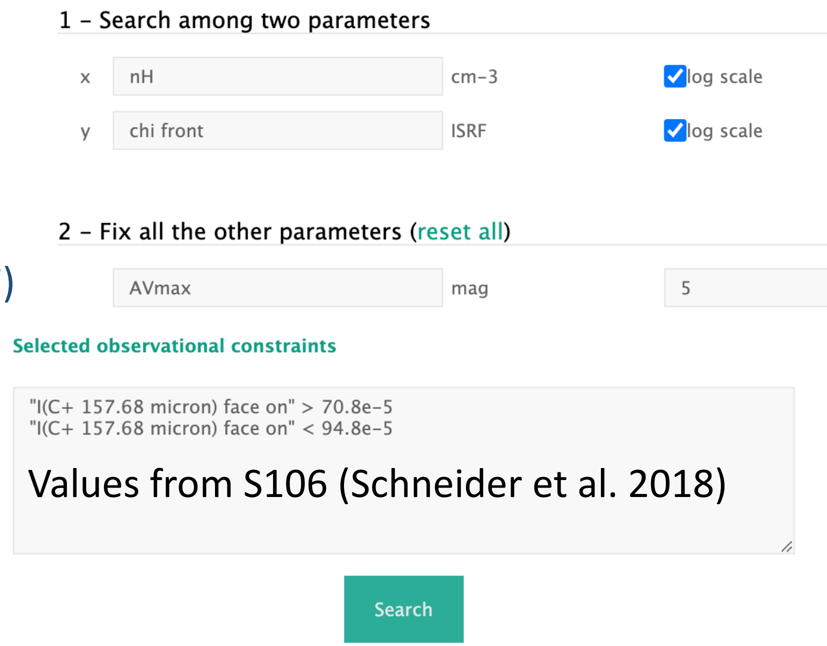


S106: Schneider et al. (2018)



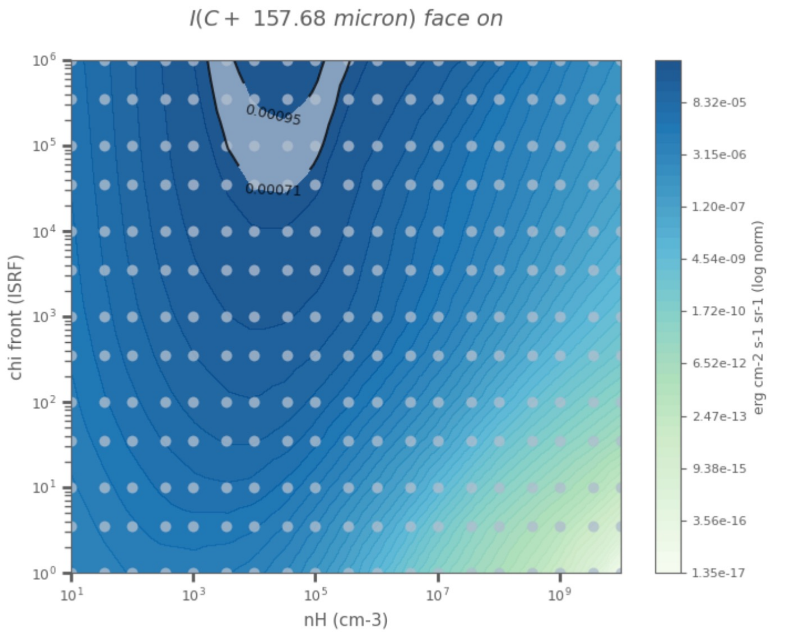
PDR modeling

- There are a wide variety of PDR codes (Roellig et al. 2007)
  - PDR Toolbox (Pound & Wolfire 2008; 2023)
  - Meudon PDR (Le Petit et al. 2006; Le Bourlot et al 2012)
  - CLOUDY (Ferland et al. 1998; 2017)
  - …



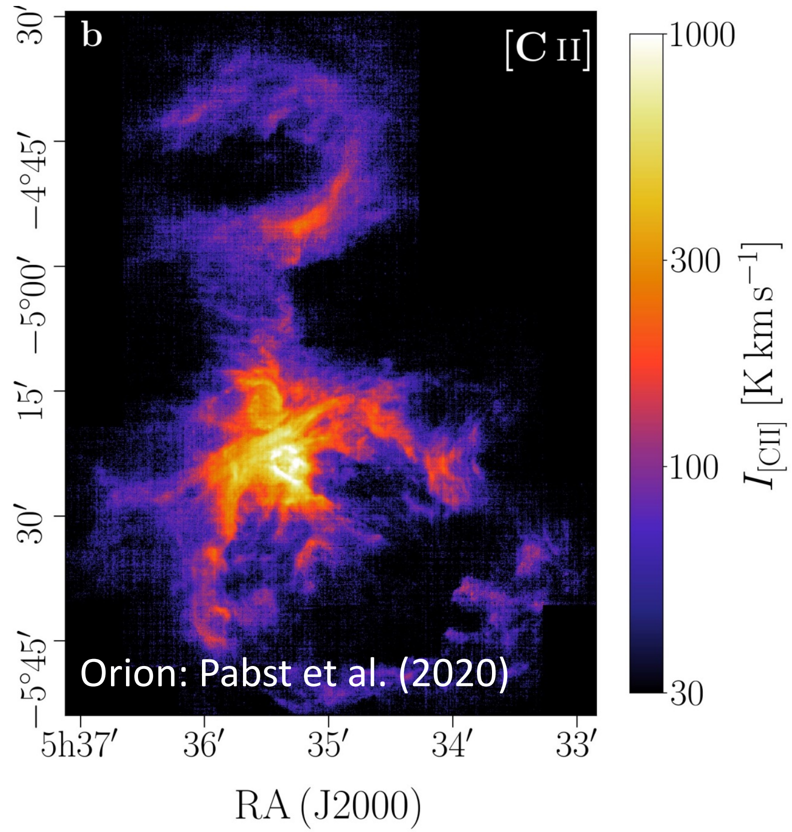
- Meudon code
  - Online model fitting (on the ISMDB)
  - ISMDB: also hosts shock code

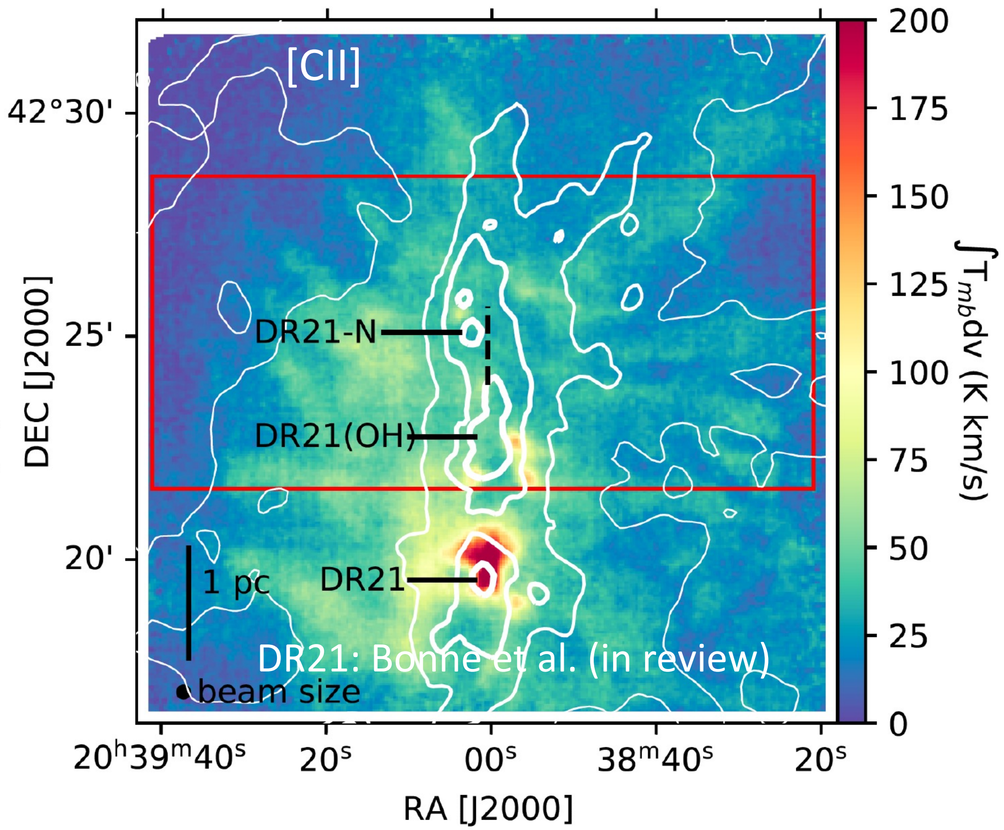
https://pdr.obspm.fr/



Spectral data cubes

- A lot of information in a single spectrum
  - Spectral cubes: up to millions of ([CII]) spectra

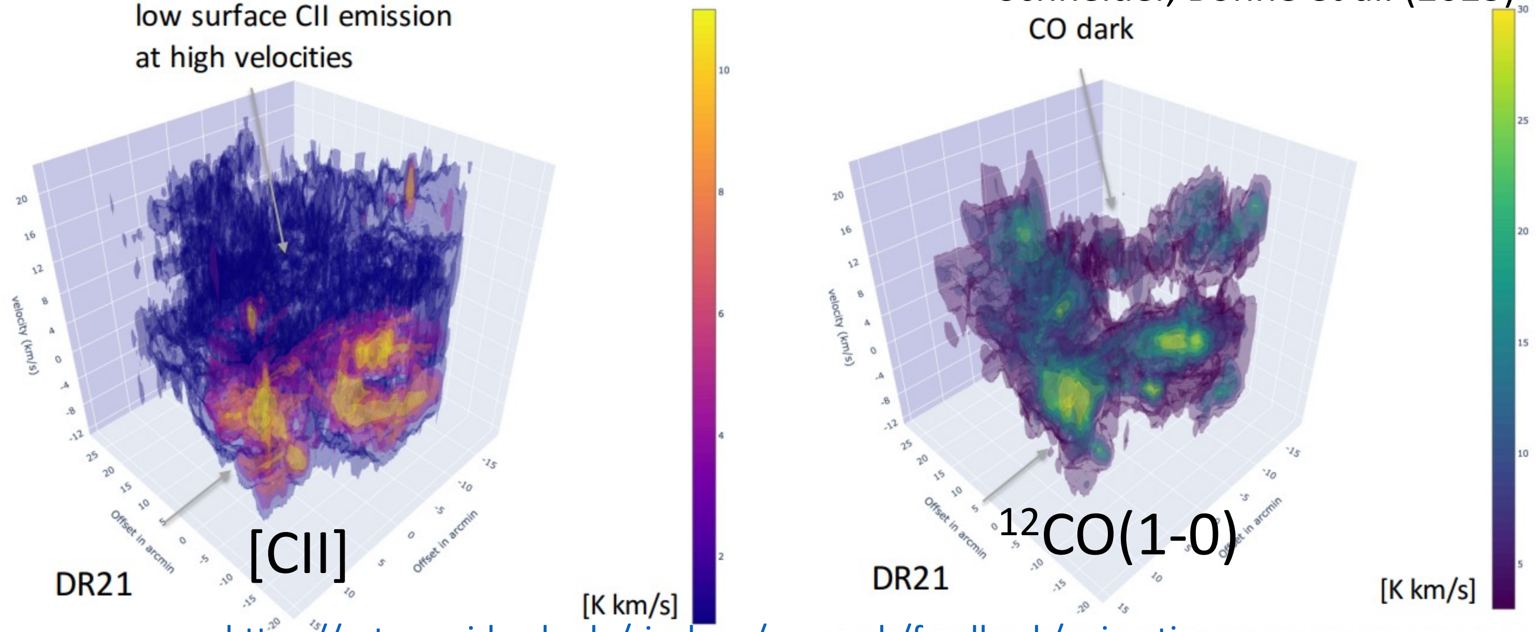




A 3D view of the spectral cube

- Isosurface plots with plotly in Python https://plotly.com/python/3d-isosurface-plots/
  - A relatively simple way to visualize the 3D cube
  - In Cygnus-X/DR21: unveils colliding flows forming molecular clouds

Schneider, Bonne et al. (2023)



https://astro.uni-koeln.de/riechers/research/feedback/animations

Position-velocity (PV) diagrams

- Extract velocity information along one axis
  - Function in astropy: pvextractor
  - X-ray & radio/optical data: stellar wind driven?

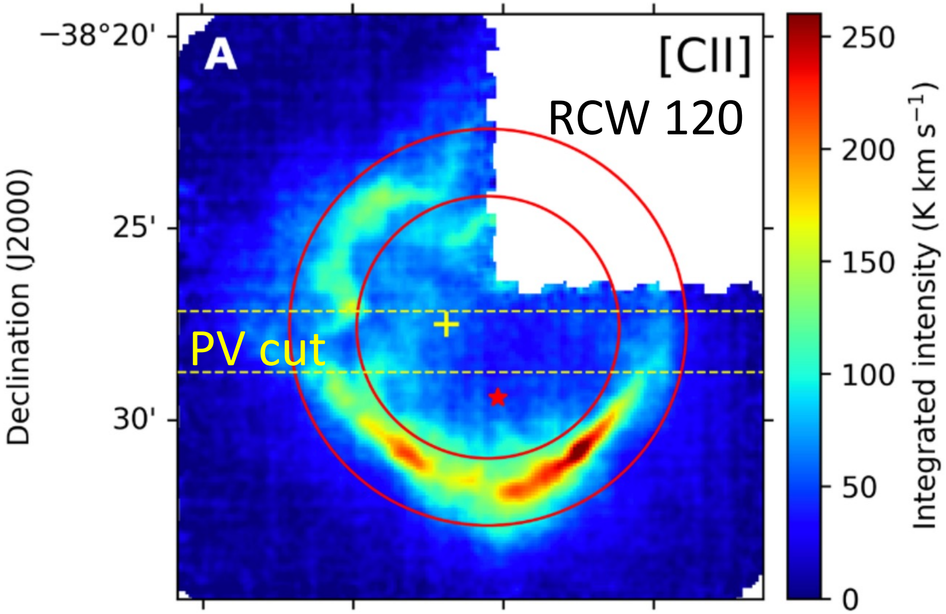
https://pvextractor.readthedocs.io/en/latest/
https://github.com/radio-astro-tools/pvextractor

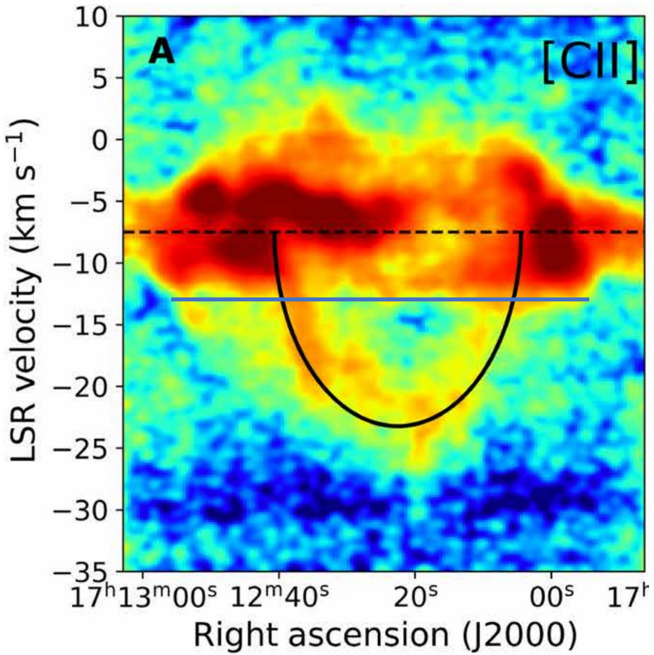
$v_{LSR} = V_{cloud} + V_{exp} * \cos(bx)$

Mass: Goldsmith et al. (2012) + Sofia et al. (2004)

N(C^+) [C^+]/[H]

Luisi et al. (2021)





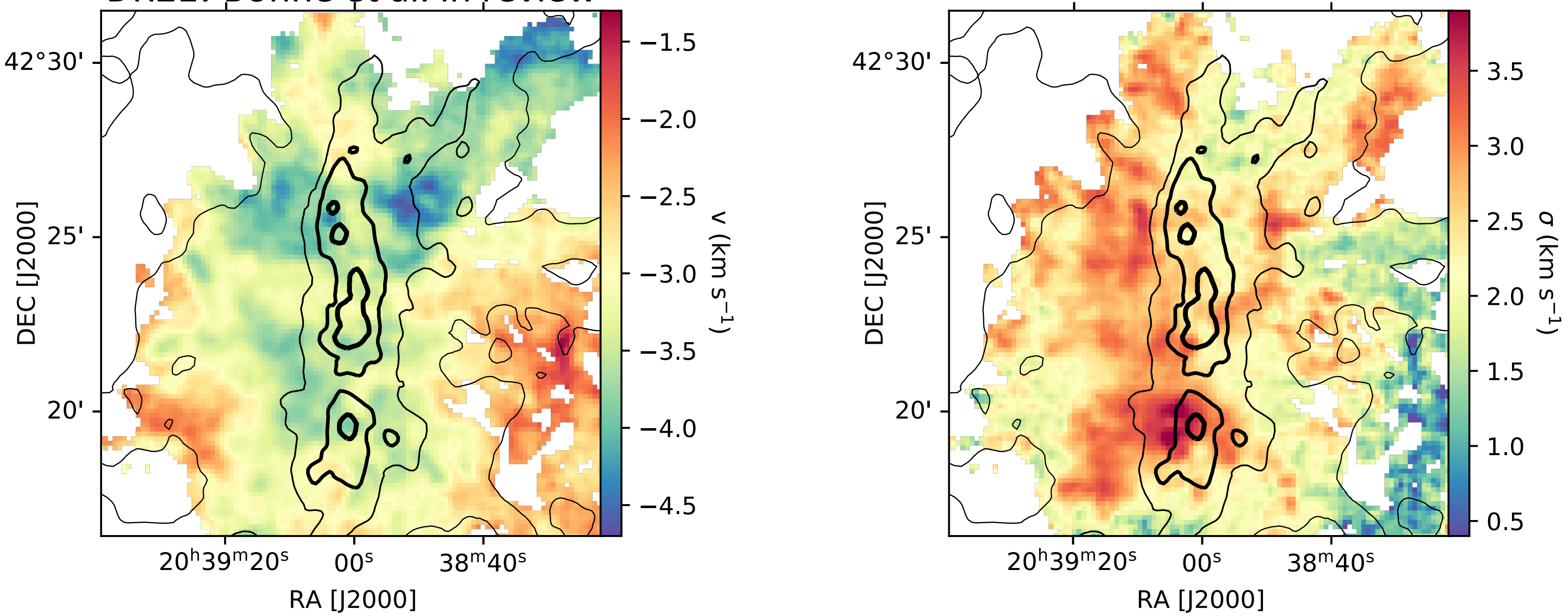
Moment maps

- Gives a perspective on the global velocity field and linewidth
  - Remarkable change in linewidth across the DR21 ridge
  - Use 'SpectralCube' package in Astropy
  - Be aware of S/N (see e.g. Teague et al. 2019)

```
>>> moment_0 = cube.moment(order=0)
>>> moment_1 = cube.moment(order=1)
>>> moment_2 = cube.moment(order=2)
```

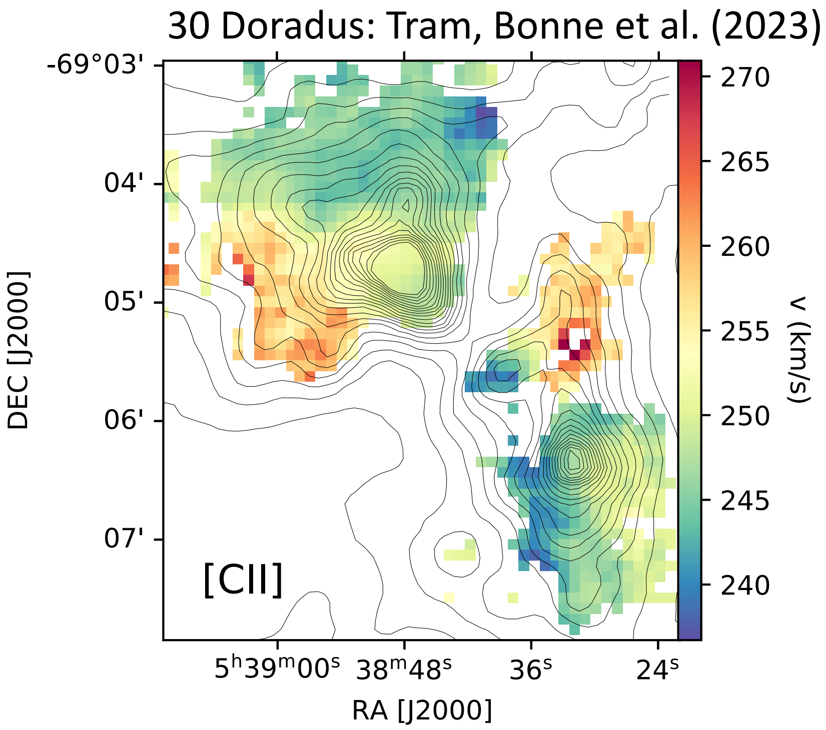
https://spectral-cube.readthedocs.io/en/latest/moments.html

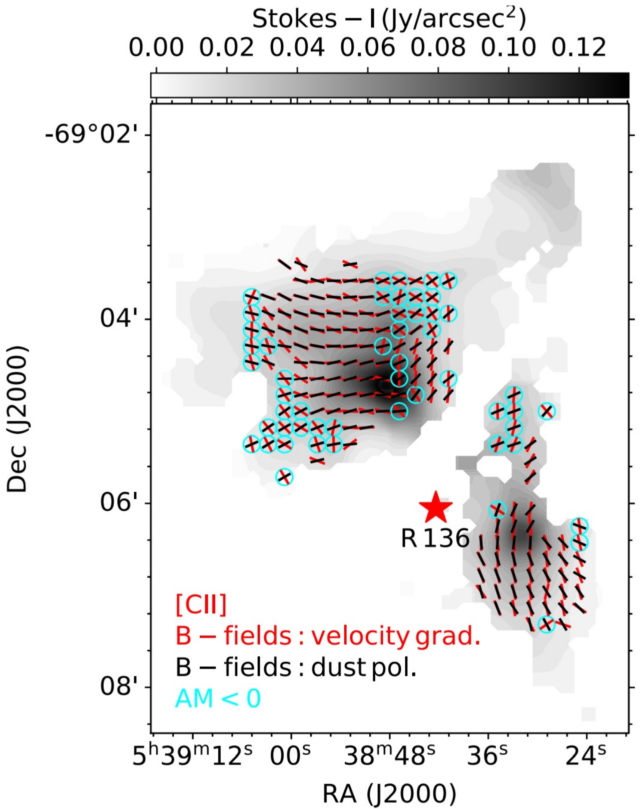
DR21: Bonne et al. in review



Synergy with the magnetic field observations

- Provides more comprehensive view of the ISM evolution
  - Determine the magnetic field strength (see talk V. Le Gouellec)
  - Velocity gradient technique (see Gonzalez-Casanova & Lazarian 2017)

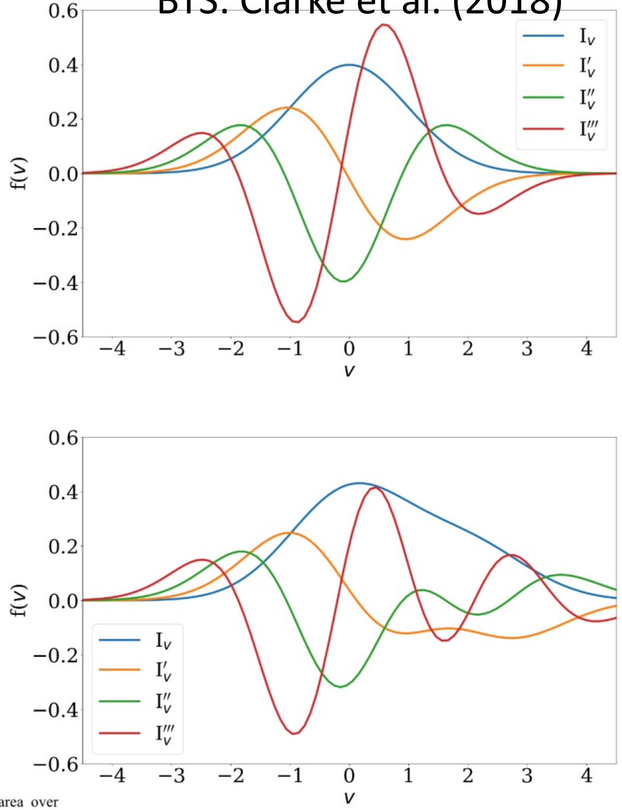


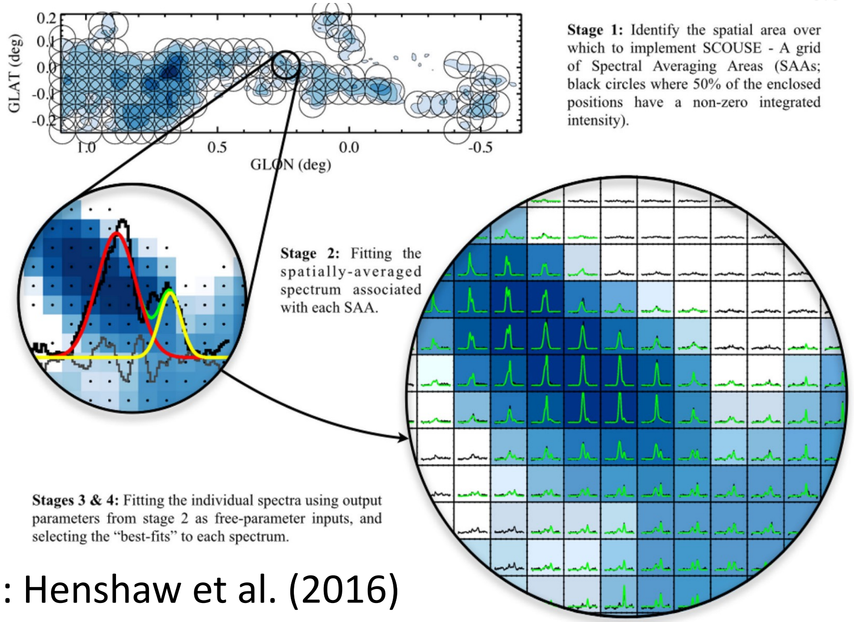


Multi-Gaussian fitting

- Extract more information from the spectra
- Don’t reinvent the wheel
  - Beyond The Spectrum (BTS) (Clarke et al. 2018)
    - Fully automated
  - Scouse(Py) (Henshaw et al. 2016; 2019)
    - Semi-automated
    - Hierarchical approach
    - Also exists in IDL
  - …

BTS: Clarke et al. (2018)





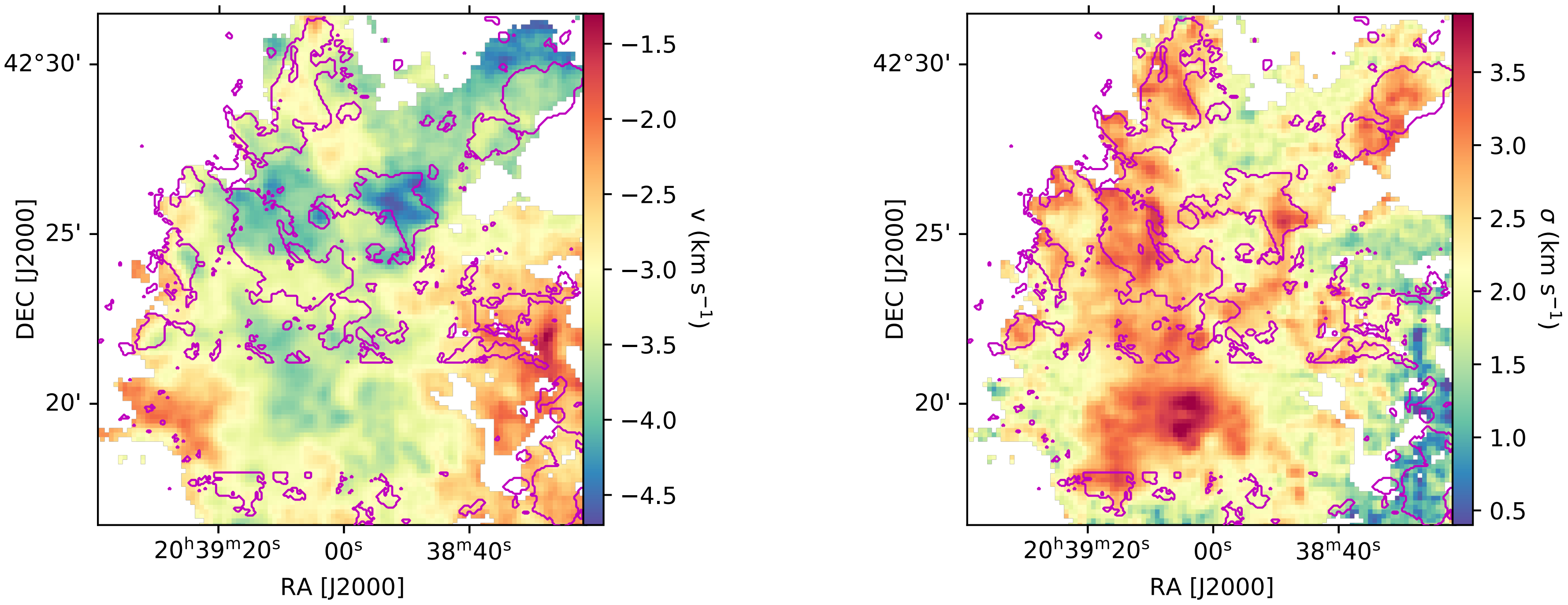
Scouse: Henshaw et al. (2016)

Multi-Gaussian fitting

- Dynamic features associated with multiple components
  - Need to be careful: self-absorption

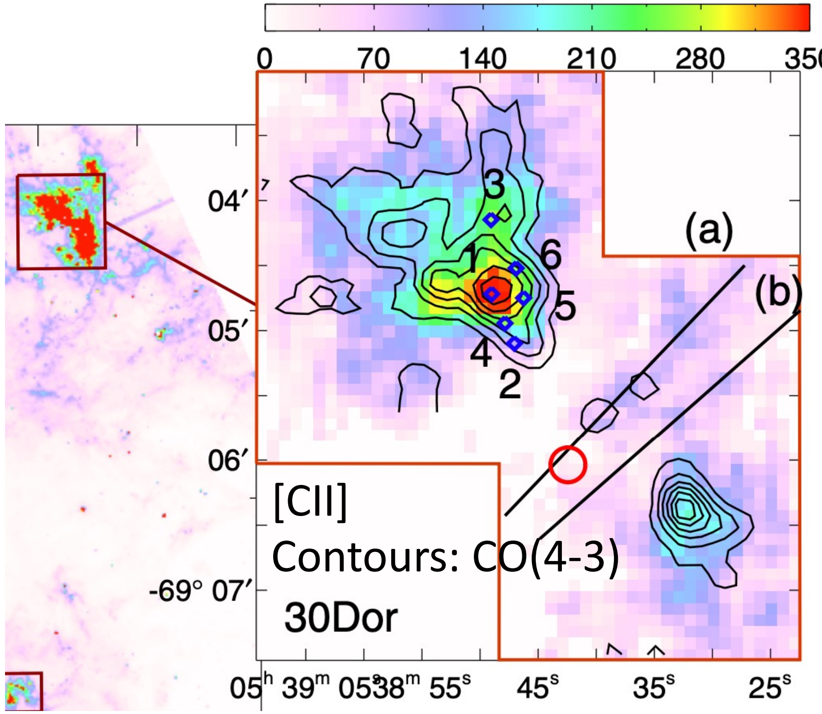
Results from BTS (Bonne et al. in review)

Magenta: regions with two velocity components

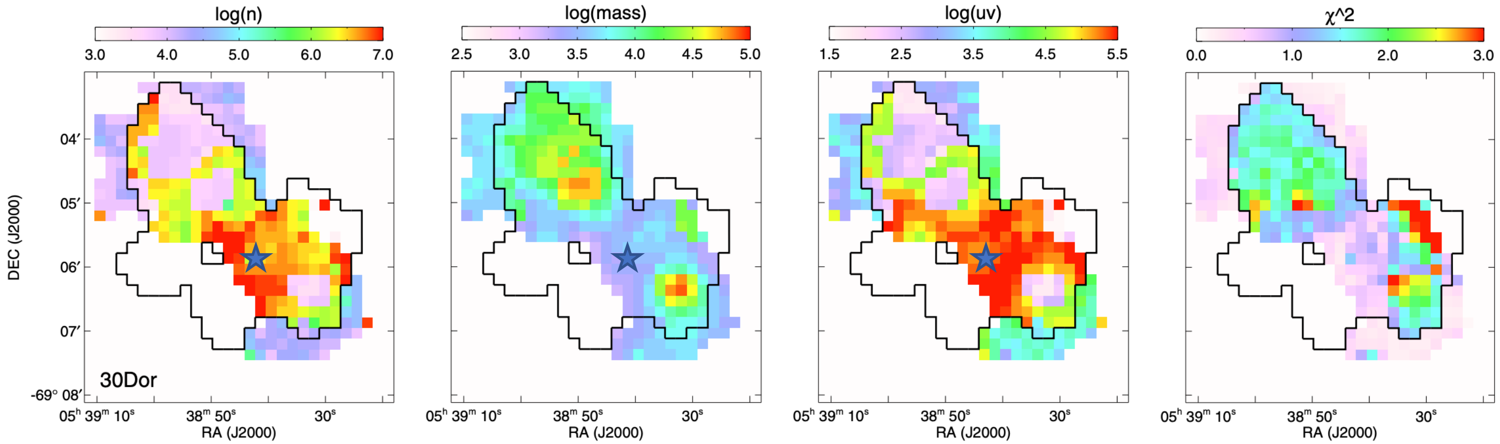


PDR analysis of far-infrared maps

- Fit pixel-by-pixel fitting
  - Kosma-tau (e.g. Okada et al. 2019)
  - PDR Toolbox (see talk M. Pound)

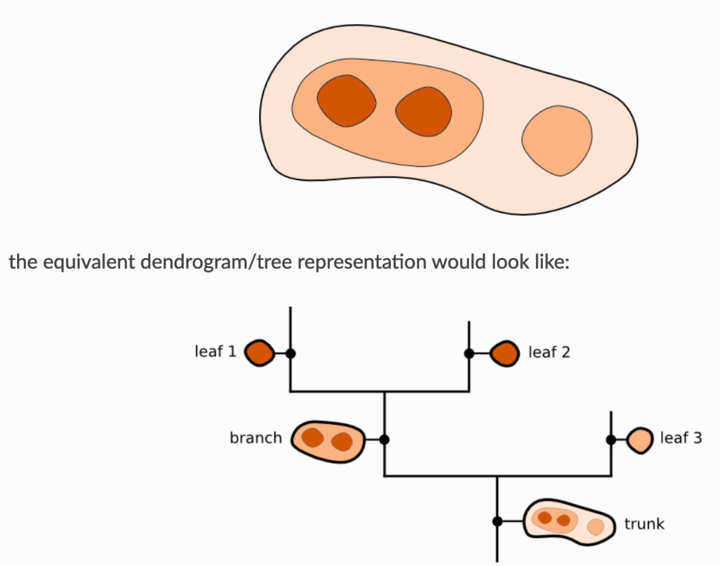


- Maps the (best fitting) excitation conditions
  - Using: [CII], [OI], [CI] & CO lines

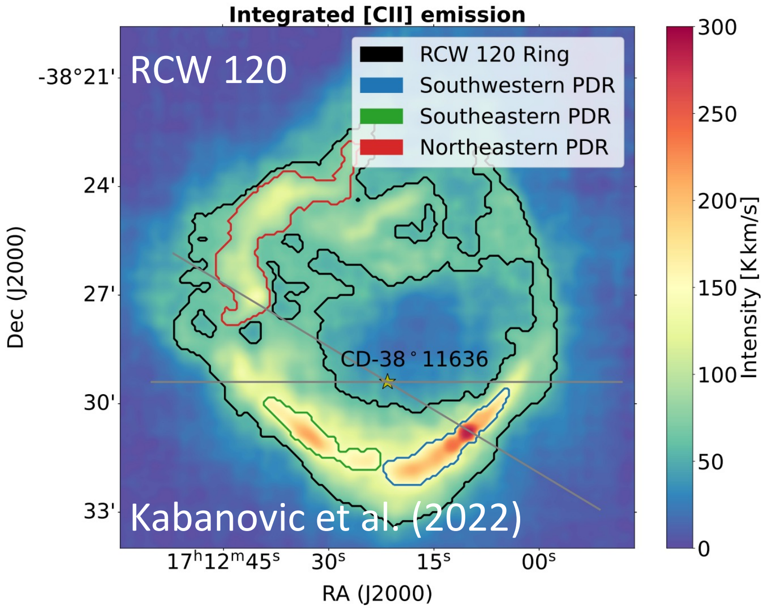


Segmenting data cubes: spatially

- Dendrograms: hierarchical structure (Rosolowsky et al. 2008)
  - Astrodendro package in Python https://dendrograms.readthedocs.io/en/stable/
  - Also applicable to PPV
  - Basis for: e.g. SCIMES (Colombo et al. 2015), Acorns (Henshaw et al. 2019)

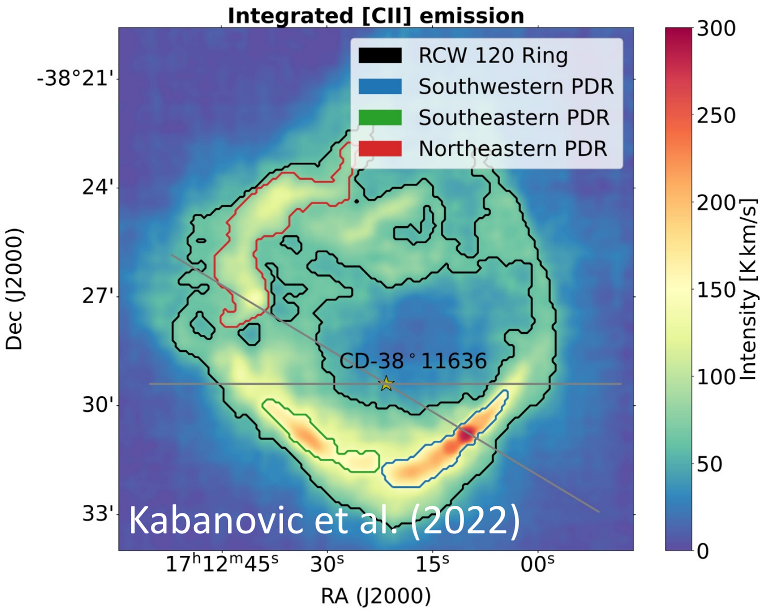


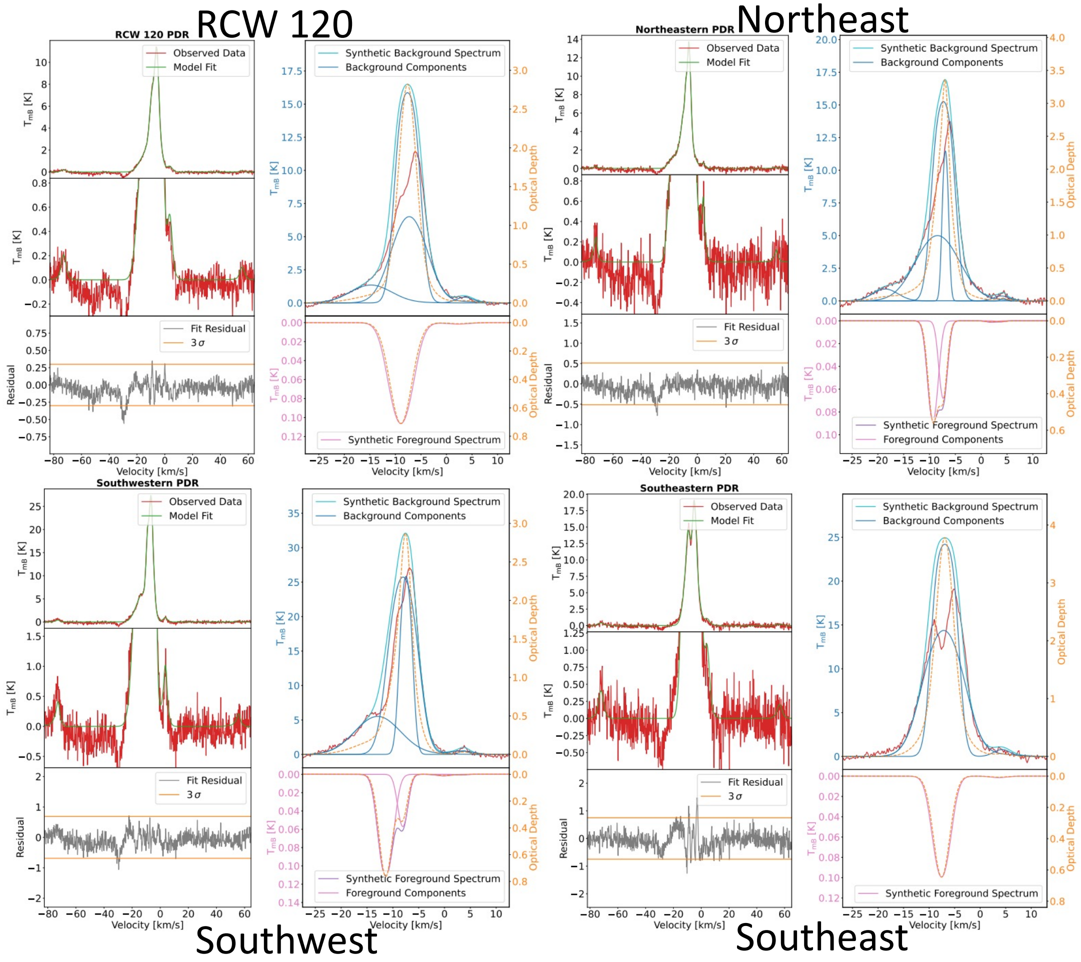
Adapted from: https://dendrograms.readthedocs.io/en/stable/



Segmenting data cubes: spatially

- Can analyze the different structures
  - [CII] self-absorption
  - Due to the cold atomic halo?

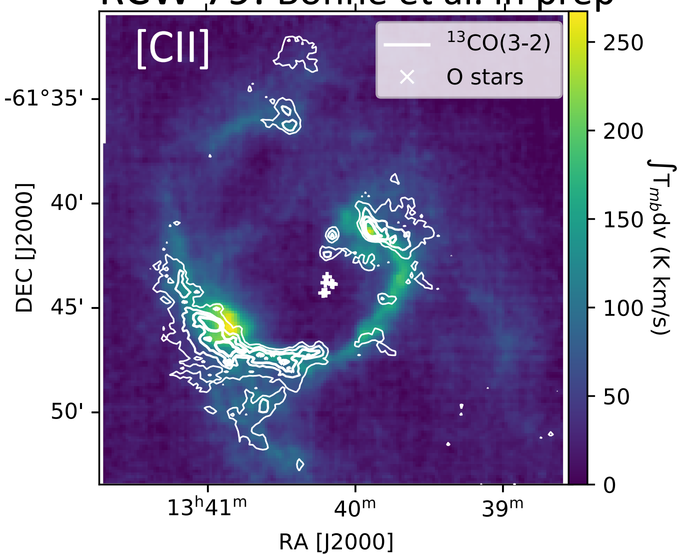


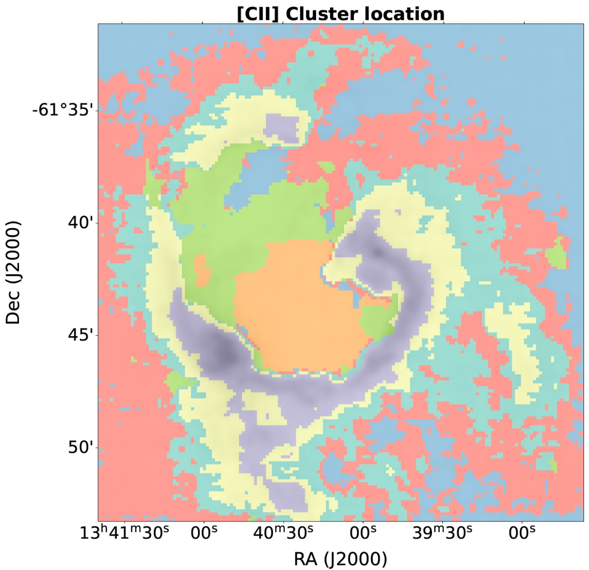


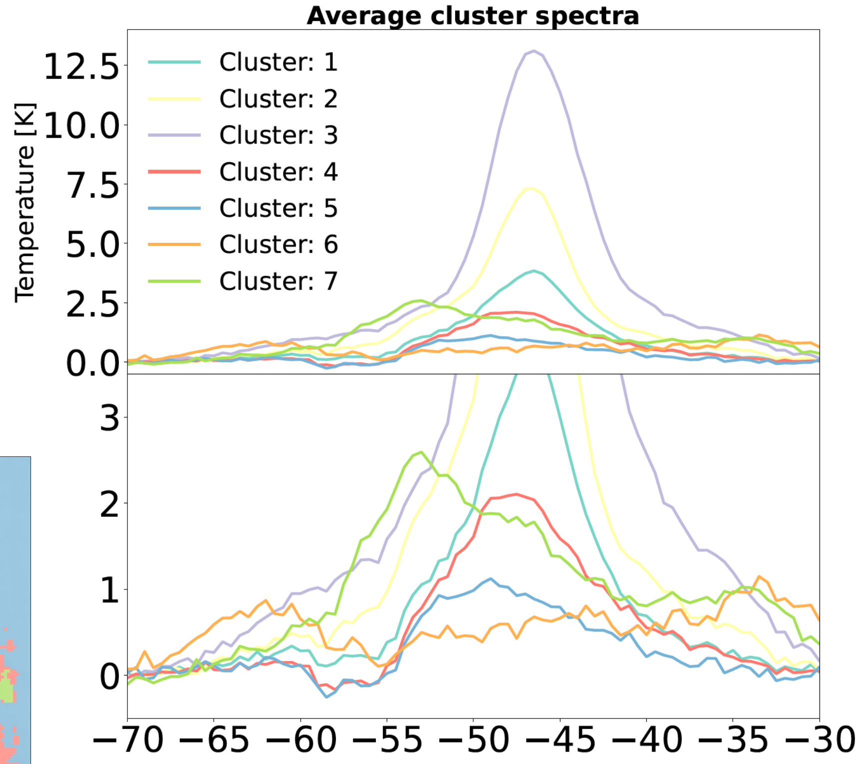
Segmenting data cubes: spectrally

- Segment map based on the spectra
- Gaussian Mixture Model (GMM)
  - Unsupervised machine learning (see Kabanovic et al. 2022)

RCW 79: Bonne et al. in prep







Conclusion

- ➢ Provides a unique view (on the ISM)
  - Work is only starting

- ➢ High spectral resolution provides detailed information
  - Dynamics
  - Chemical abundances
  - Excitation conditions

- ➢ Several analysis tools are already available