Detection of interstellar radio recombination lines with NenuFAR

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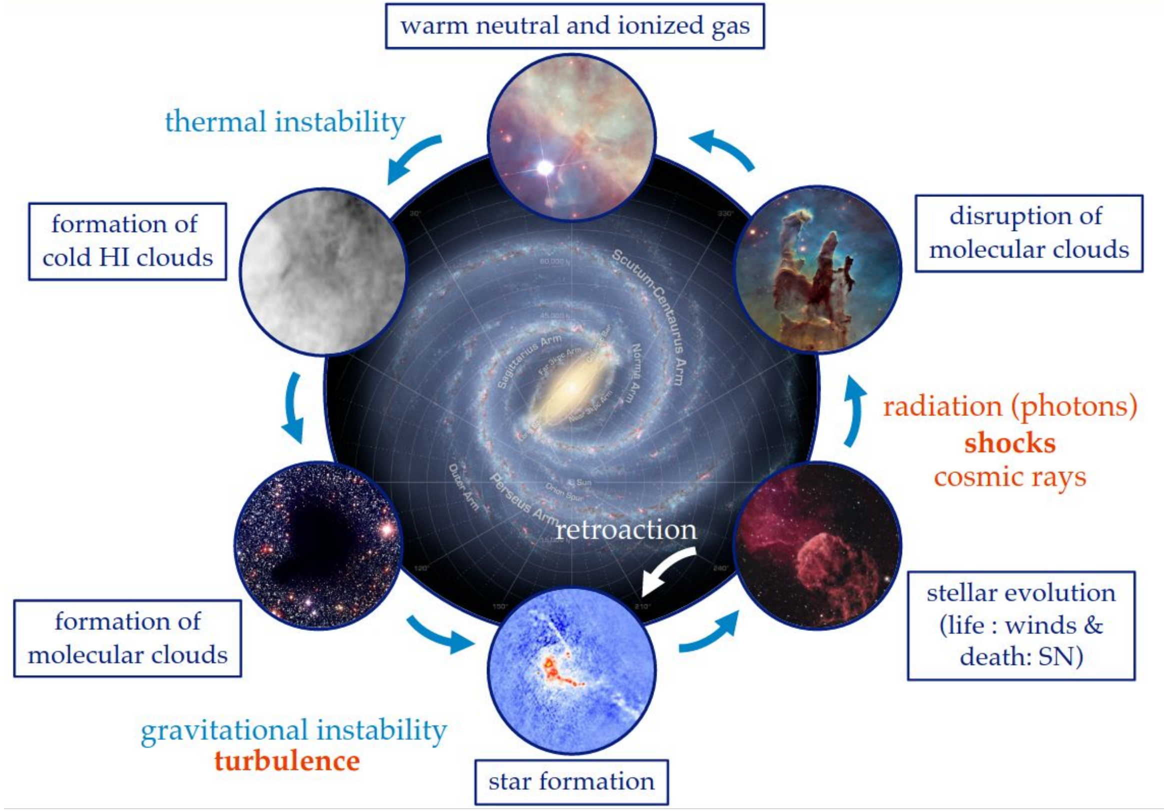
Goal

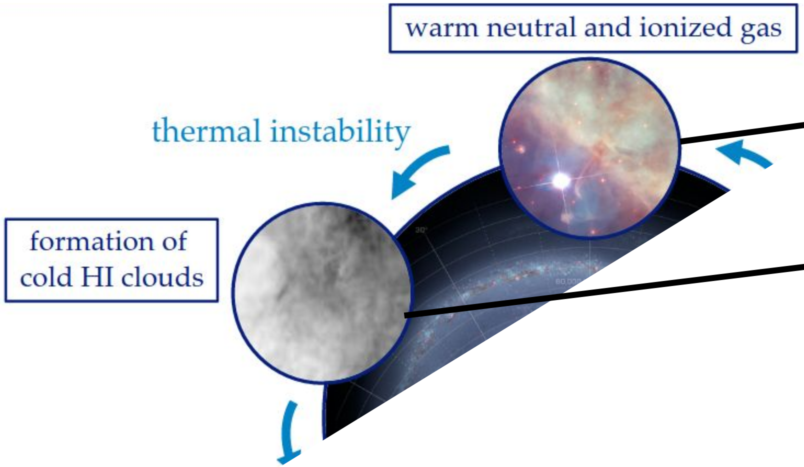
➔ Characterisation of the **diffuse ISM phase**.

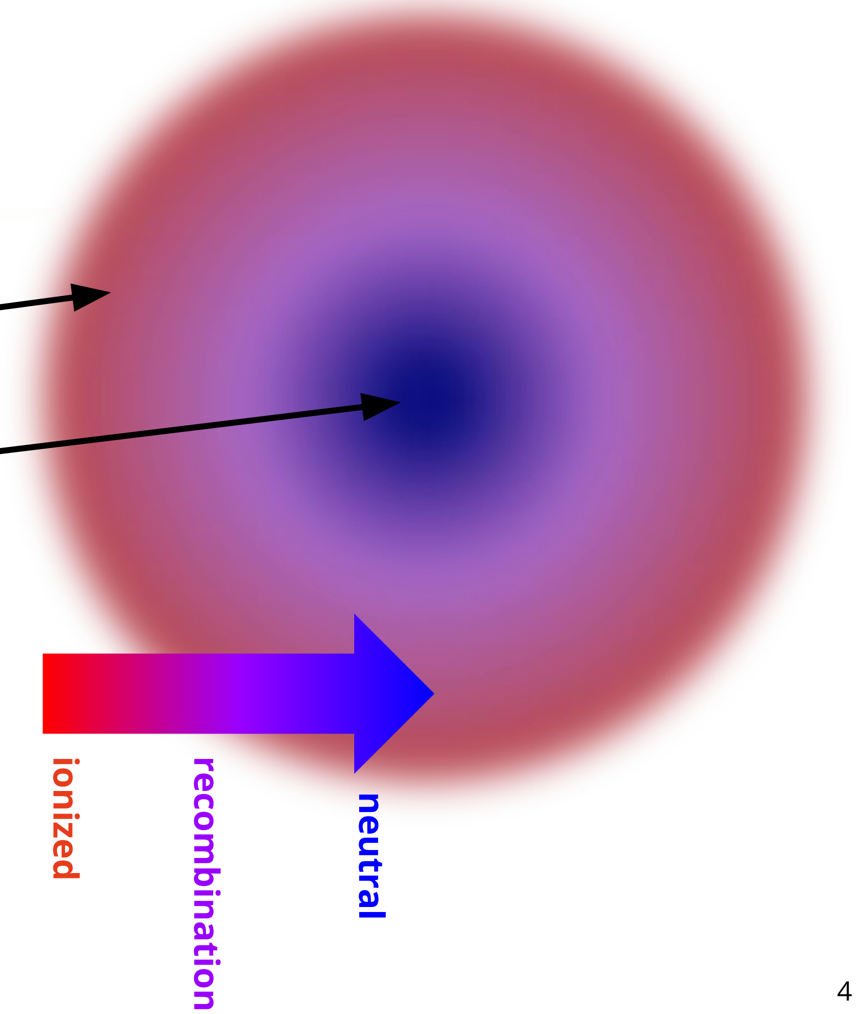
- **Scientific context**
  - The cycle of matter in the ISM
  - Advantages of Carbon RRLs
  - Sources
- **Data reduction**
  - NenuFAR, its obstacles, and how to tackle them
- **First results**
  - Line detection
  - From line fitting to physical constraints
- **Next ?**
  - Perspectives for the RRL team of NenuFAR

Cycle of matter in the Interstellar Medium



Diffuse phase

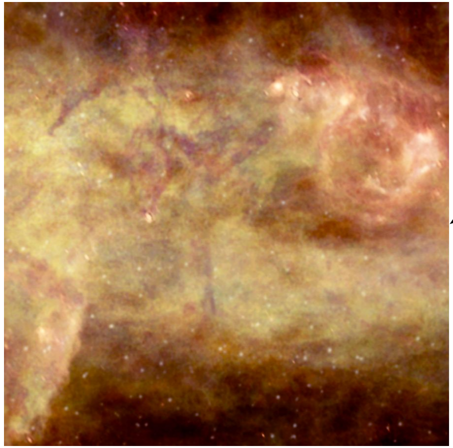




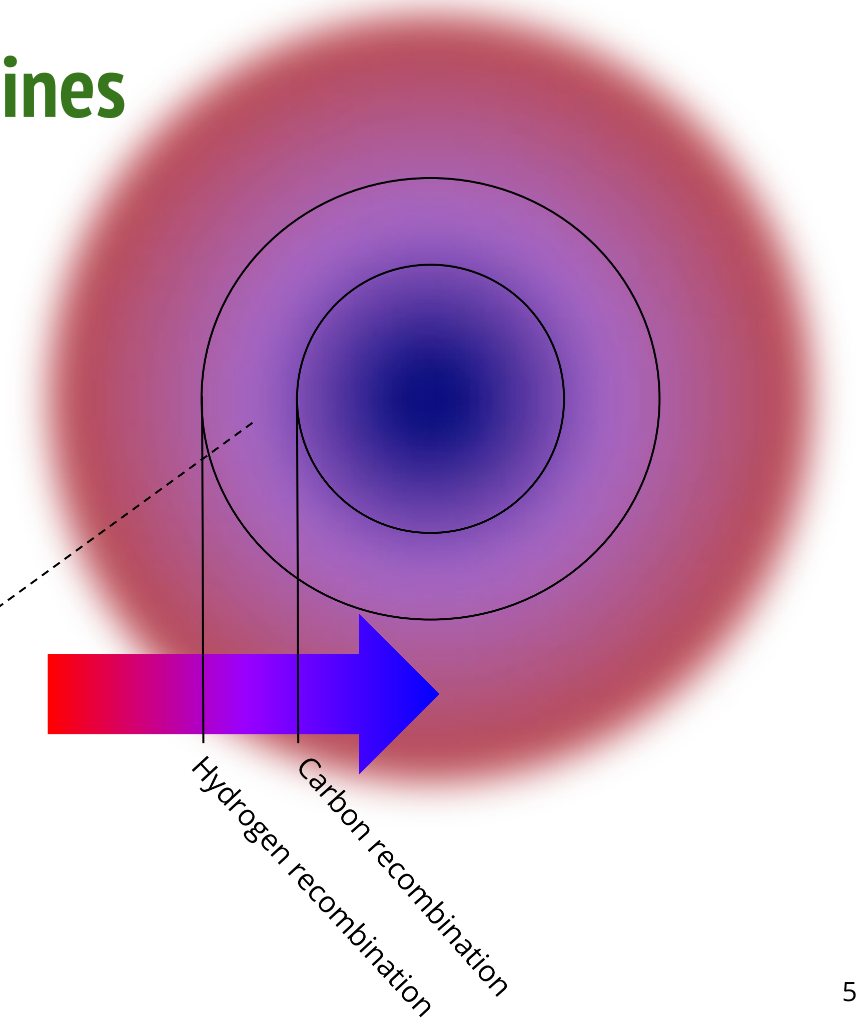
Carbon Radio Recombination Lines

- $E_0(H) = -13.6$ eV
- $E_0(C) = -11.2$ eV

⇒ C^+ in HI region



21-cm map of the Perseus arm
J. English : Canadian galactic plane survey



Carbon Radio Recombination Lines

- $E_0(H)$ = -13.6 eV
- $E_0(C)$ = -11.2 eV

⇒ C^+ in HI region

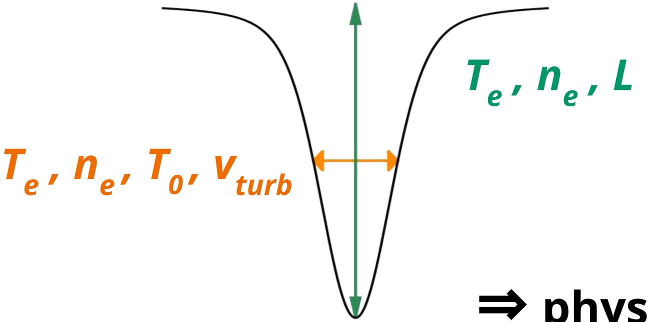
At high *n* : $0 < T_X < T_{bg}$
⇒ line in **absorption**

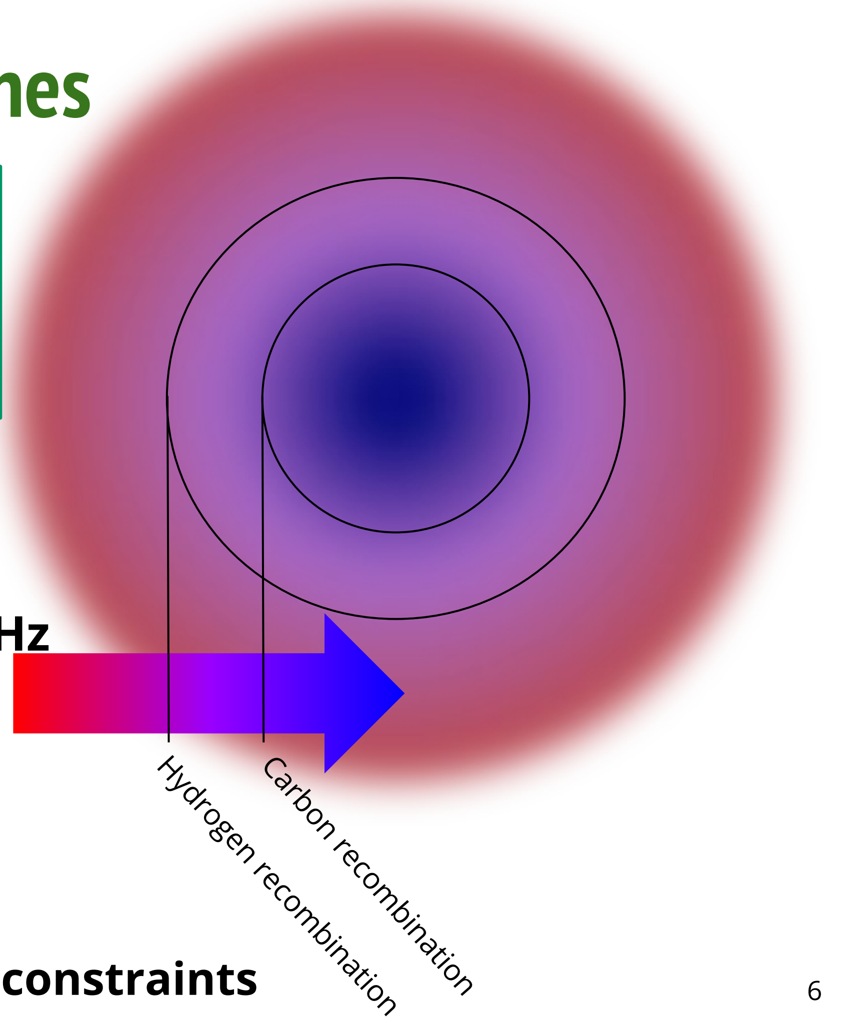
Salgado et. al 2017

$C\alpha(n)$ transition for $n \in [400, 850]$ ($\Longleftrightarrow$ $[10, 85]$ MHz) :

$$\nu_{n+1 \to n} \propto \left(\frac{1}{n^2} - \frac{1}{(n+1)^2} \right) \simeq \frac{2}{n^3}$$

⇒ **450 lines in 70 MHz**





⇒ **physical/chemical constraints**

Sources

Source	Type	Coordinates RA (J2000) Dec (J2000)	Flux density at 50 MHz [Jy]	Size arcmin [arcmin]	Velocity components [km/s]
Cassiopeia A	SNR	$23^h23^m27.94^s$ $+58°48'42.4''$	27 104	7.4	-47, -38, 0
Cygnus A	Radio galaxy	$19^h59^m28.35^s$ $+40°44'02.1''$	22 146	2.3	4
Taurus A	SNR	$05^h34^m31.97^s$ $+22°00'52.1''$	2 008	7.9	14

NenuFAR (Nancay Observatory)

Standalone radiotelescope + LOFAR extension + SKA pathfinder

EXPERIMENTAL SETUP

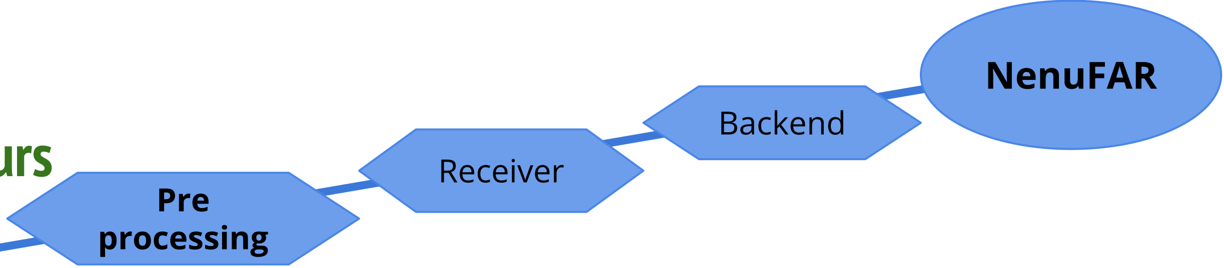
- ~80 mini-array of 19 antennas

- Frequency range : [10, 85] MHz
- spectral resolution **df ~ 95 Hz**
- spatial resolution ~ 1°

- KP10 : Radio Recombination Lines
- Beamforming mode

Processing of data

example : Cassiopeia A, 2 hours



Baseline flattening and RFI mitigation

2.a) Lane by lane

Time integration

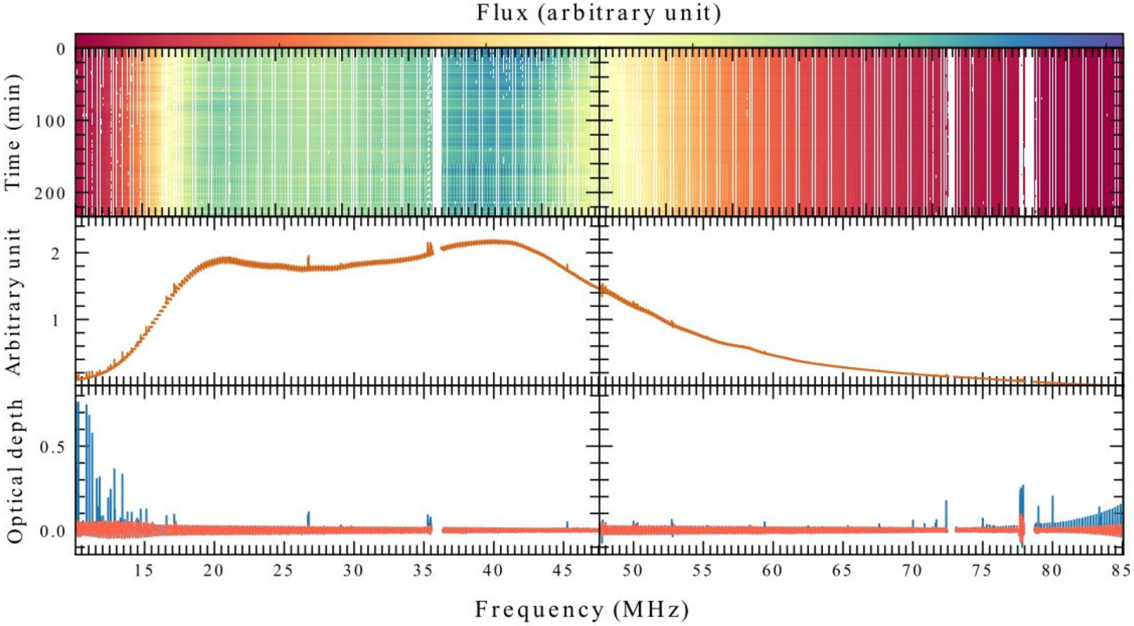
* Weighted average of Stokes I

Flattening

* $\frac{I}{I_{smooth}} - 1$ with I_{smooth} from rebinned I

RFI mitigation

* recursive σ clipping



=> 2 lanes, 384 subbands, 786432 frequency channels

Processing of data

example : Cassiopeia A, 2 hours

2.b) Subband by subband

RFI mitigation 2 : narrow spikes

* σ clipping based on subband gradient

Flattening 2 : baseline S-shape

* Individual subband shape inferred from the median of k neighboring subbands

Mitigation 3 : broad spikes, outside lines

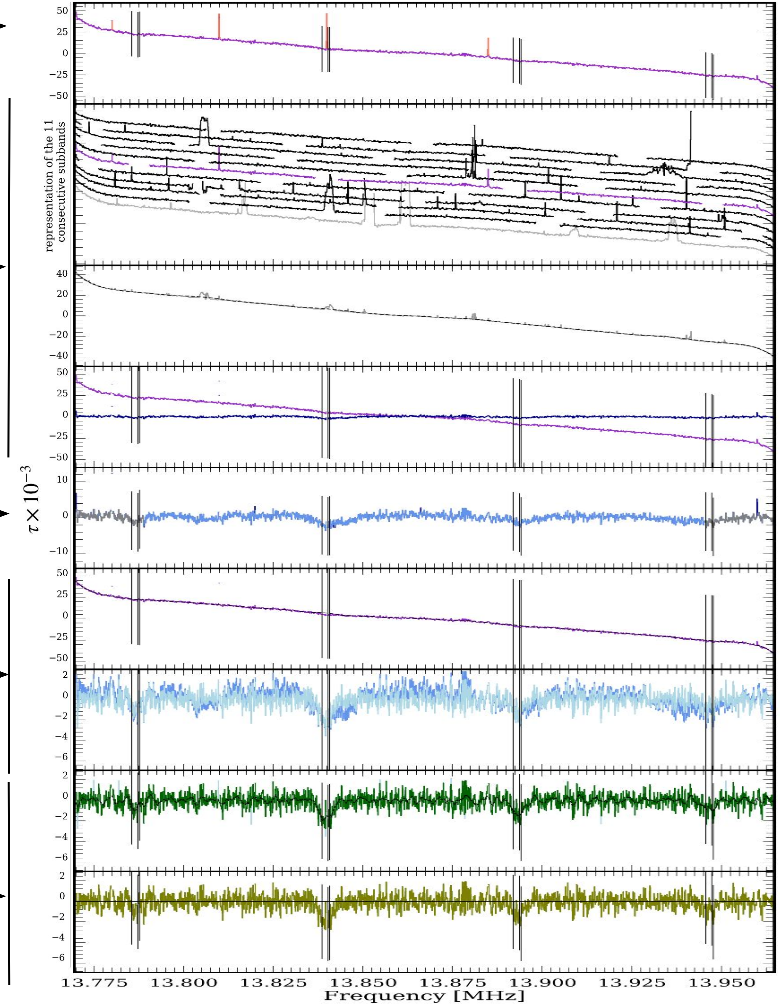
* Mask around expected lines
* recursive σ clipping based on masked subband

Flattening 3 : residual baseline variation

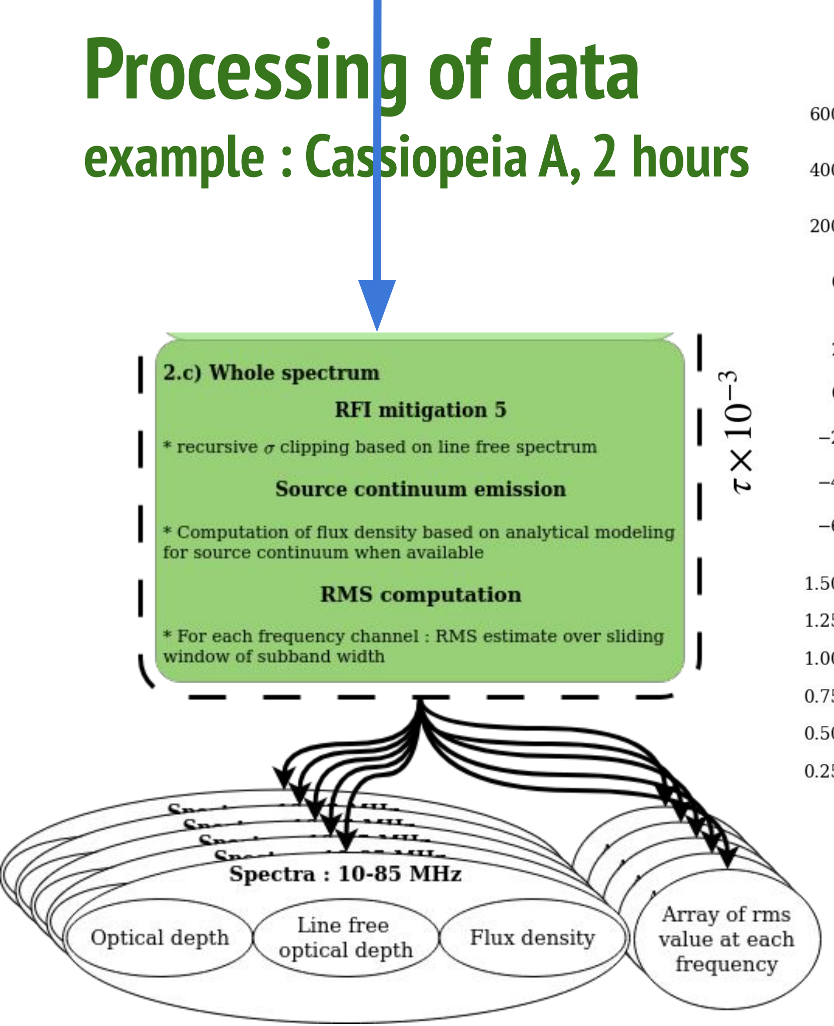
* Smoothing with a SavGol filter of the masked subband to find and remove residual variation.

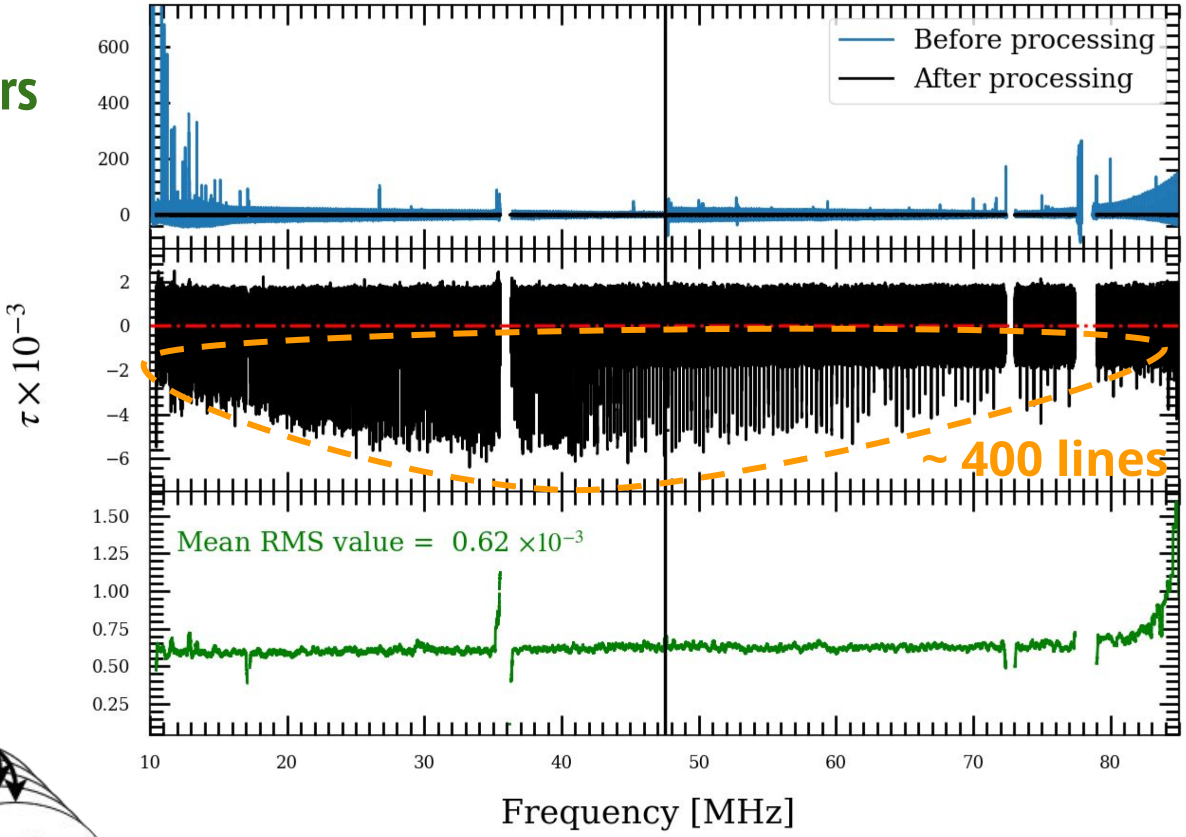
RFI mitigation 4 : inside masked lines

* Flattening of lines with a SavGol filter
* recursive σ clipping based on the flattened subband.

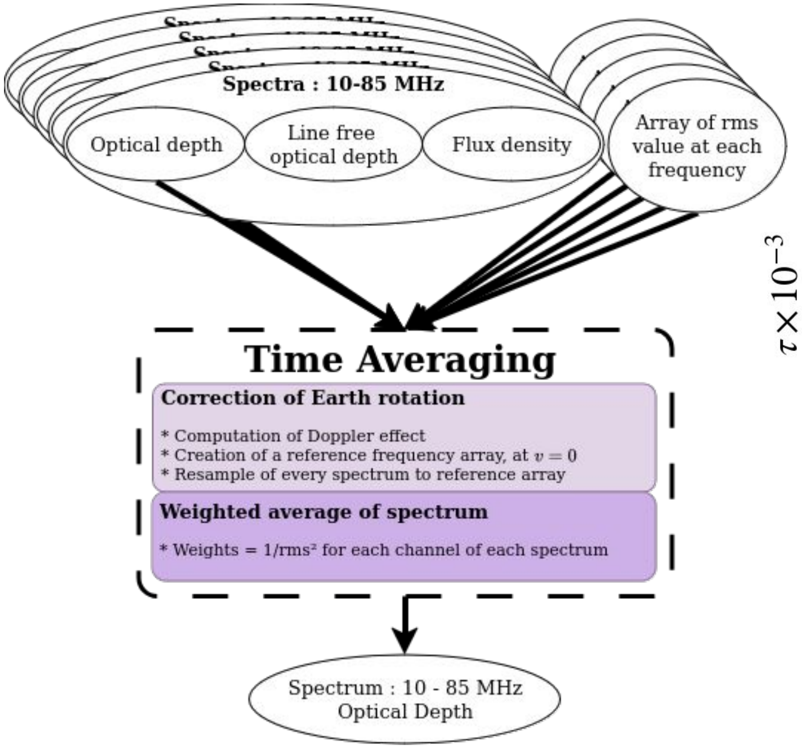


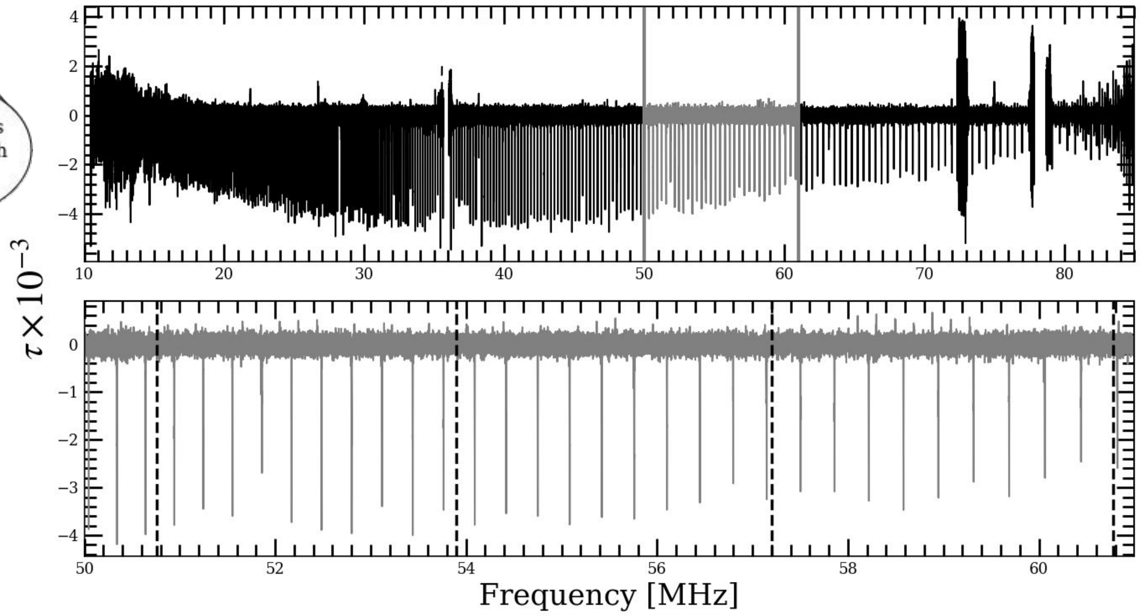
Processing of data
example : Cassiopeia A, 2 hours





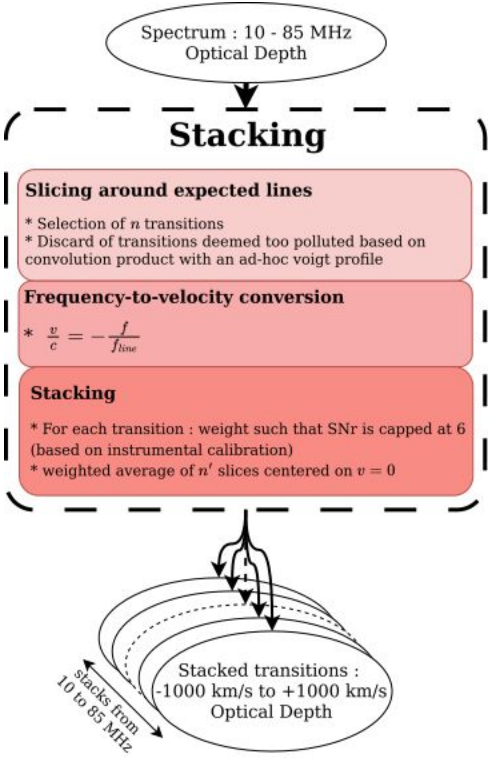
Processing of data
example : Cassiopeia A, 71 hours

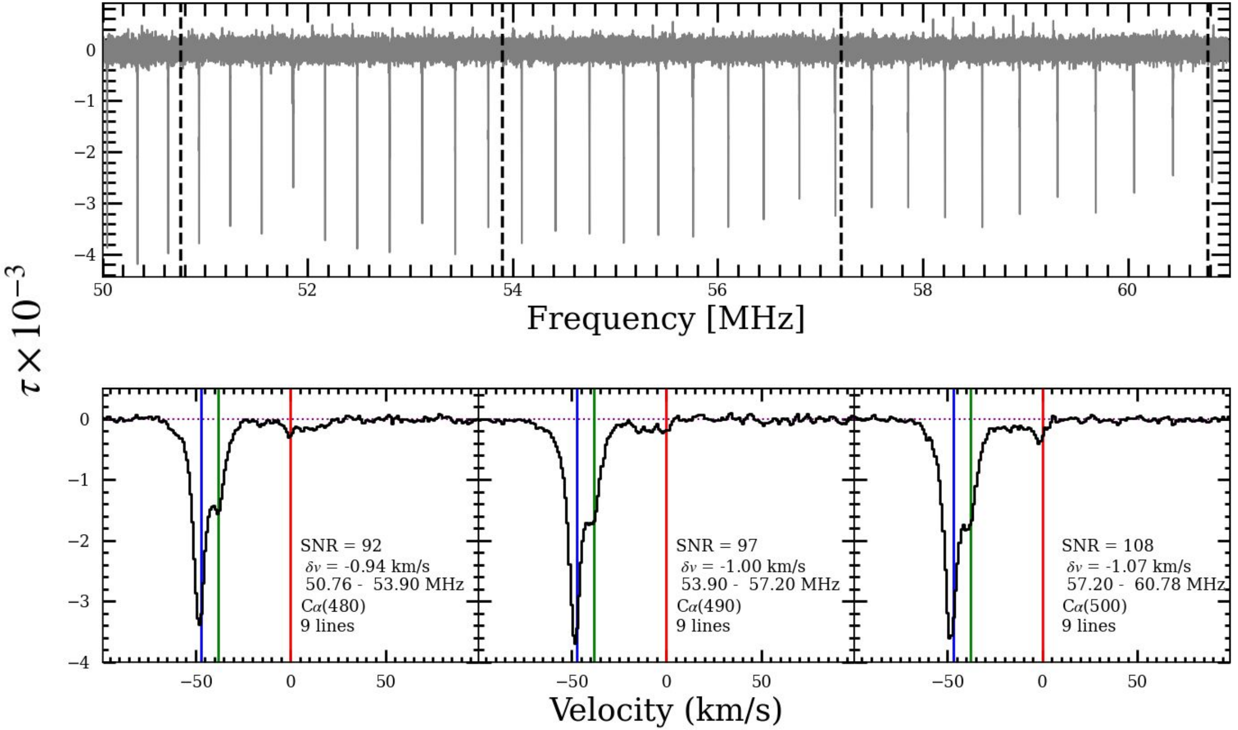




Processing of data

example : Cassiopeia A, 71 hours

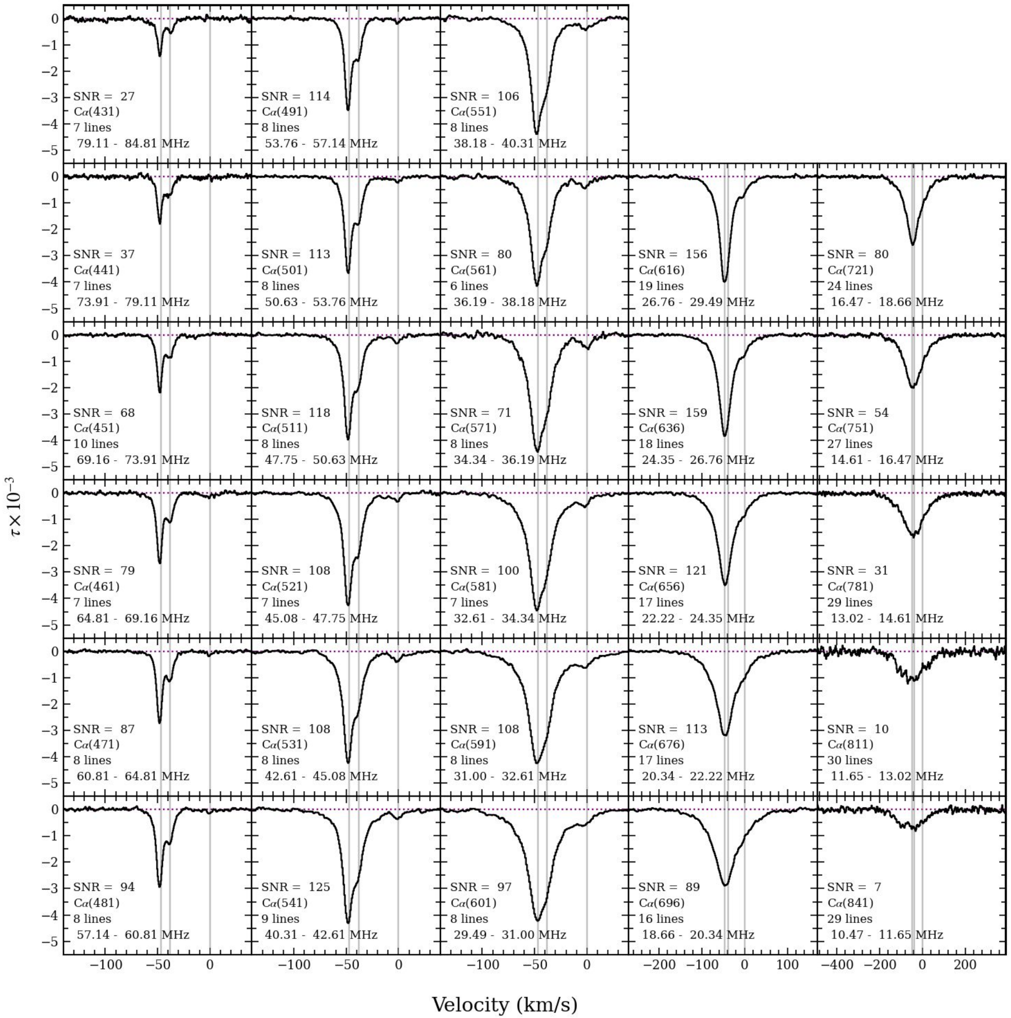




=> 3 velocity components : -47, -38 and 0 km/s

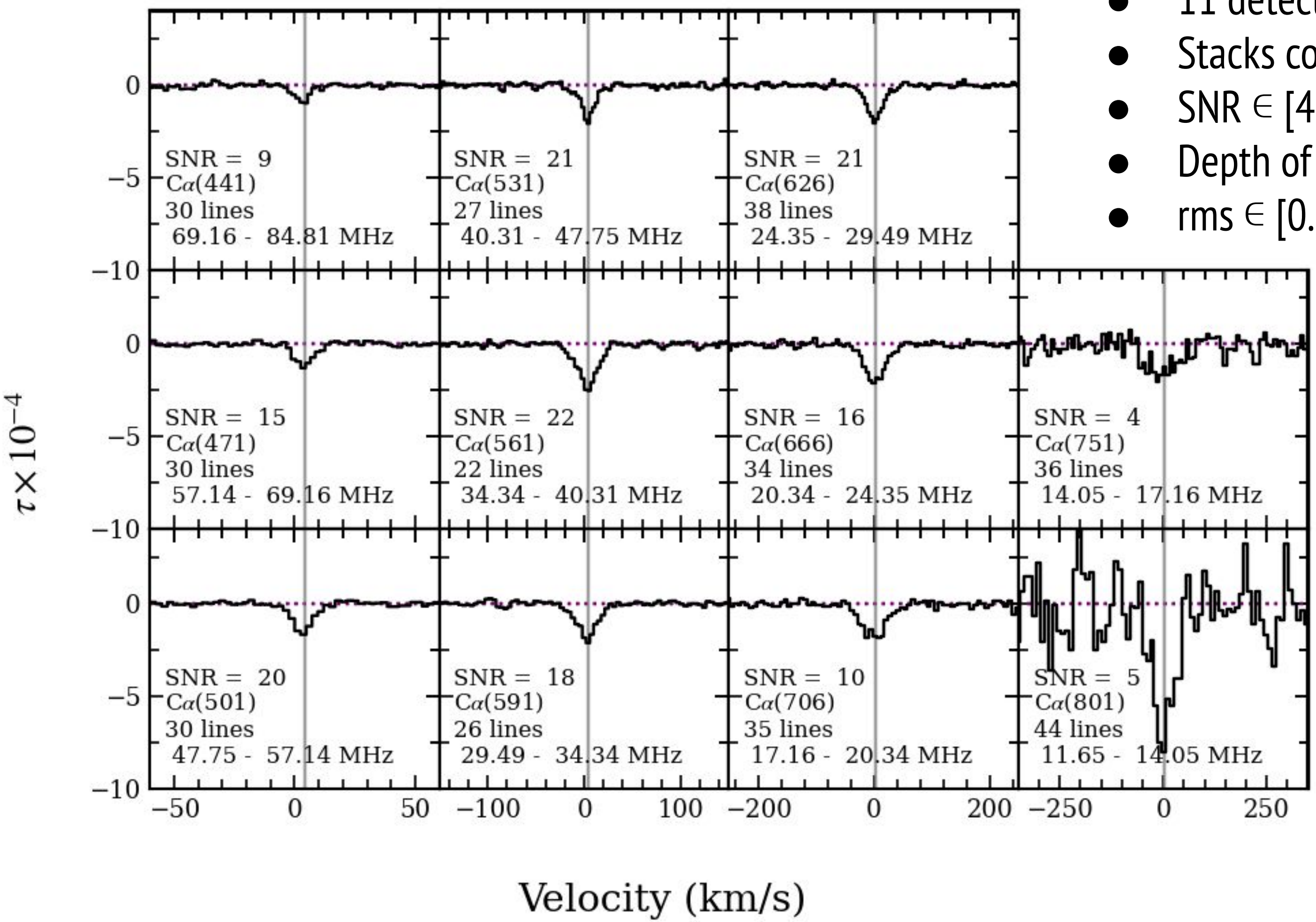
Detections

Source	On-source time (hours)	Expected velocity components (km/s)	Number of detection	Typical value of optical depth	Mean value of SNr
Cas A	71.5	-47, -38, 0	28	10^{-3}	88
Cyg A	157.5	4	11	10^{-4}	15
Tau A	104	14	17	10^{-4}	13



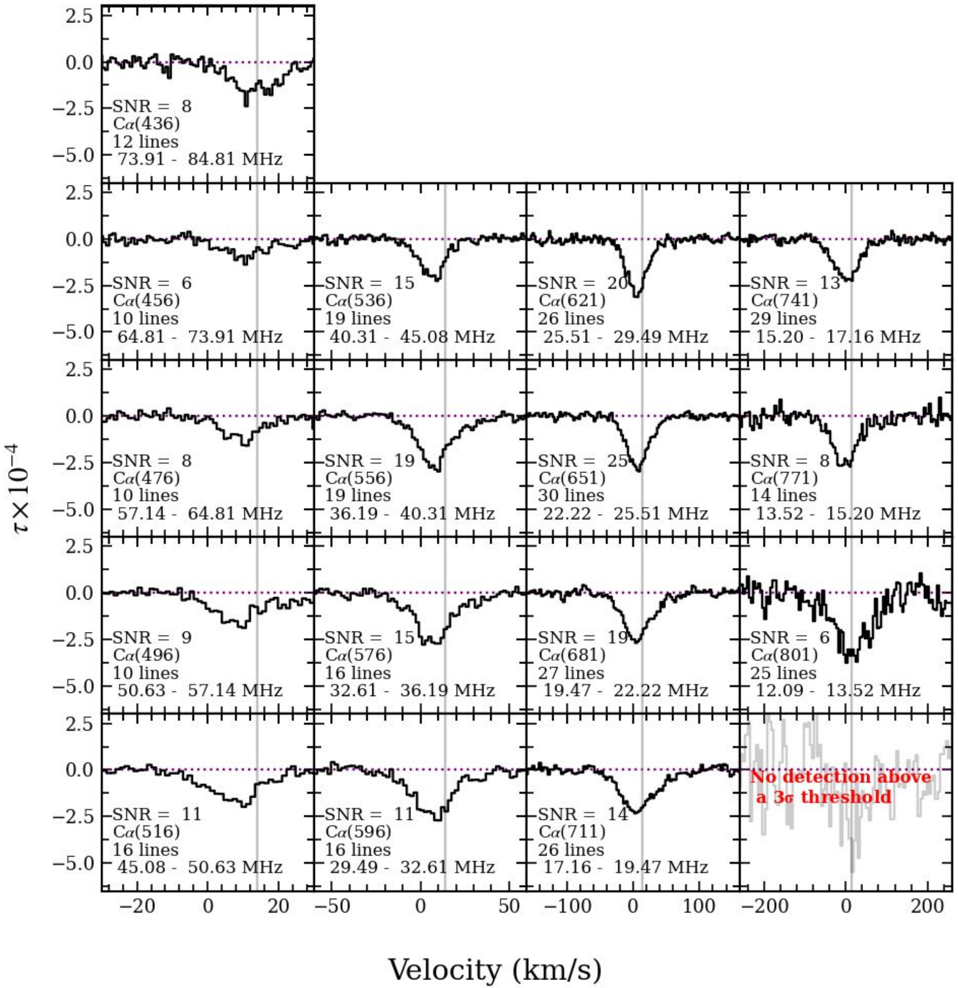
CASSIOPEIA A

- 28 detections at 3σ threshold
- Stacks contains 7 to 30 lines
- SNR ∈ [7, 159]
- Depth of line ∈ [0.8, 4.4] × 10^{-3}
- rms ∈ [2.4, 12.2] × 10^{-5}



- 11 detections at 3σ threshold
- Stacks contains 22 to 44 lines
- SNR ∈ [4, 22]
- Depth of line ∈ $[0.9, 8.8] \times 10^{-4}$
- rms ∈ $[0.8, 1.6] \times 10^{-5}$

CYGNUS A



TAURUS A

- 16 detections at 3σ threshold
- Stacks contains 10 to 30 lines
- SNR ∈ [6, 25]
- Depth of line ∈ $[1.3, 5.4] \times 10^{-4}$
- rms ∈ $[1.2, 17.3] \times 10^{-5}$

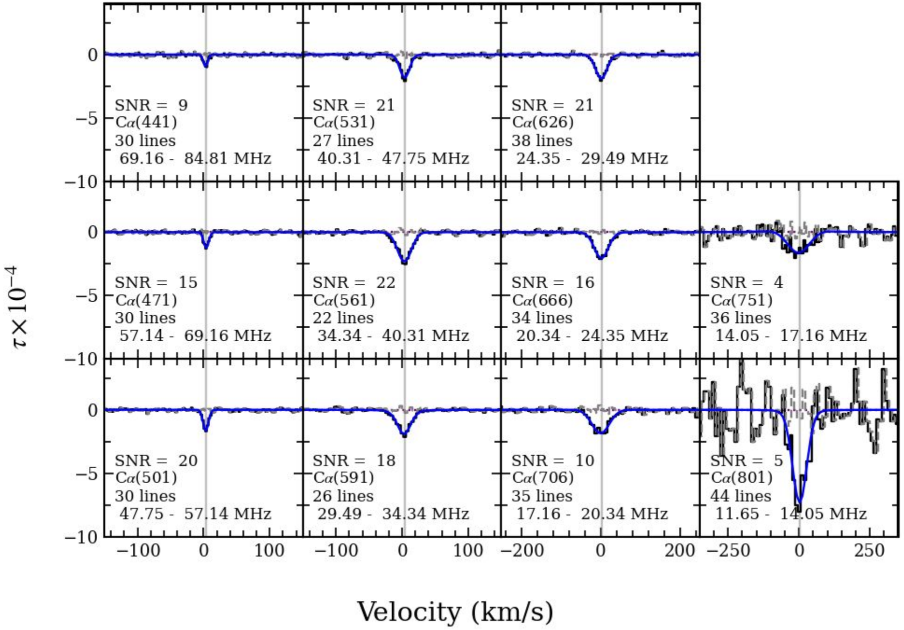
Inferring physical parameters of the local ISM => Methodology

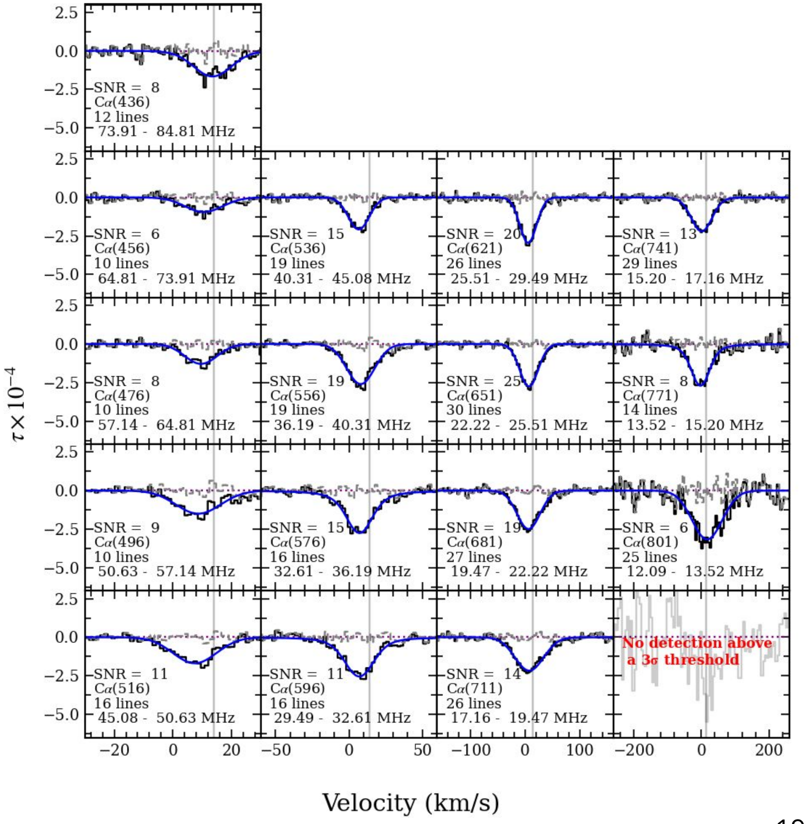
1. Fitting a voigt profile on each line
   - ➢ inferring the **FWHM (*w*)** and the **integrated intensity (*I*)** for each transition: we get a set of *w(n)* and *I(n)*.

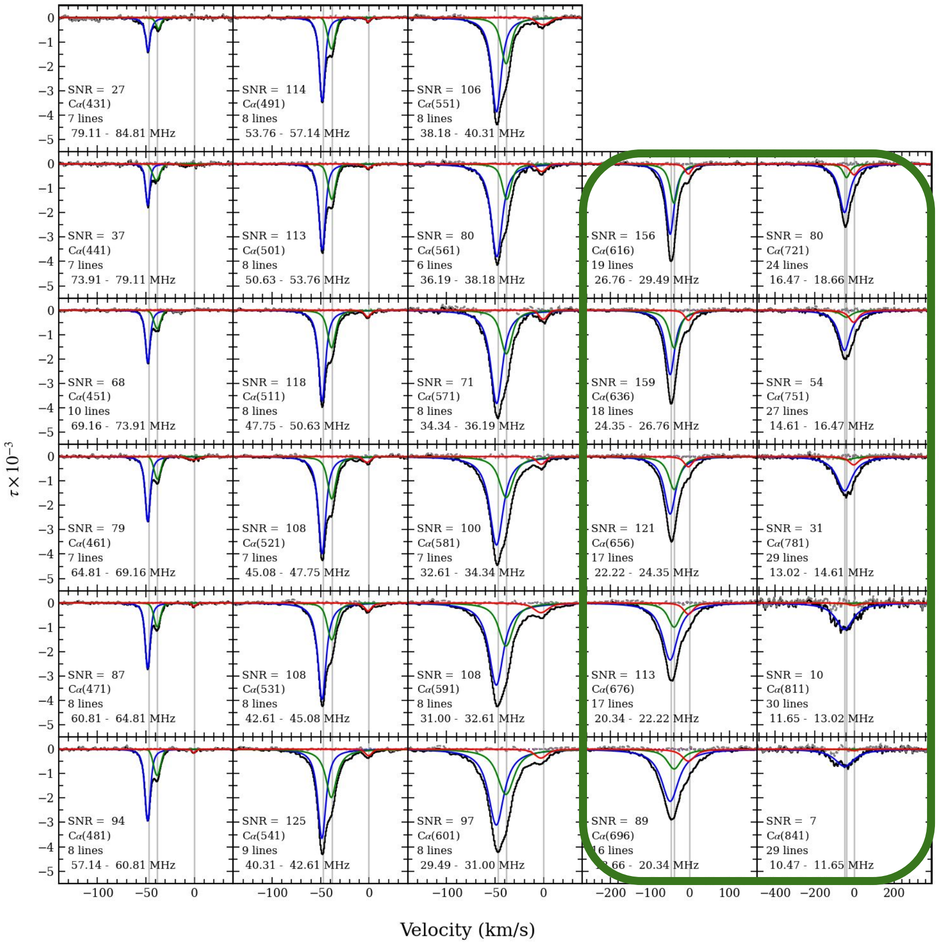
2. Modeling the **variation** of *w* and *I* as a function the principal quantum number of each transitions *n*.

3. Fitting the observed *w(n)* and *I(n)* with the **theoretical modelings** $w_{th}(n)$ $\int I$, Δv_L and Δv_G.
   - ➢ inferring constraints on the physical parameters T_e, n_e, T_0, v_t, L.

1. Fitting the lines
-> Method : *curve fit, scipy*

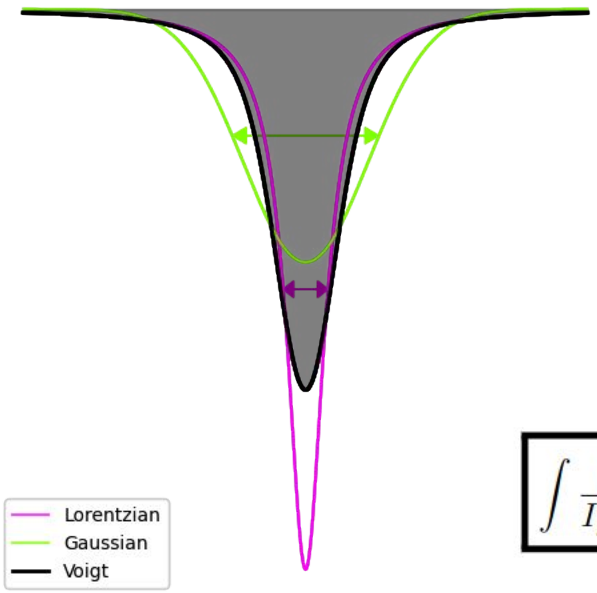






Blending of components => less confidence in the results of the fits

2. Modeling the transitions



$$\Delta\nu_G = \frac{\nu_{n\rightarrow n+1}}{c}\sqrt{\frac{2k_B T_e}{m_C} + \langle v_{turb}\rangle^2}$$

$$\Delta\nu_{natural} = \frac{1.2\,10^{-6}\,\ln n}{n^2}\nu_{n\rightarrow n+1}$$

$$\Delta\nu_{pressure} = \frac{1}{2\pi} n_e 10^{a(T_e)} n^{\gamma(T_e)}\ \mathrm{Hz}$$

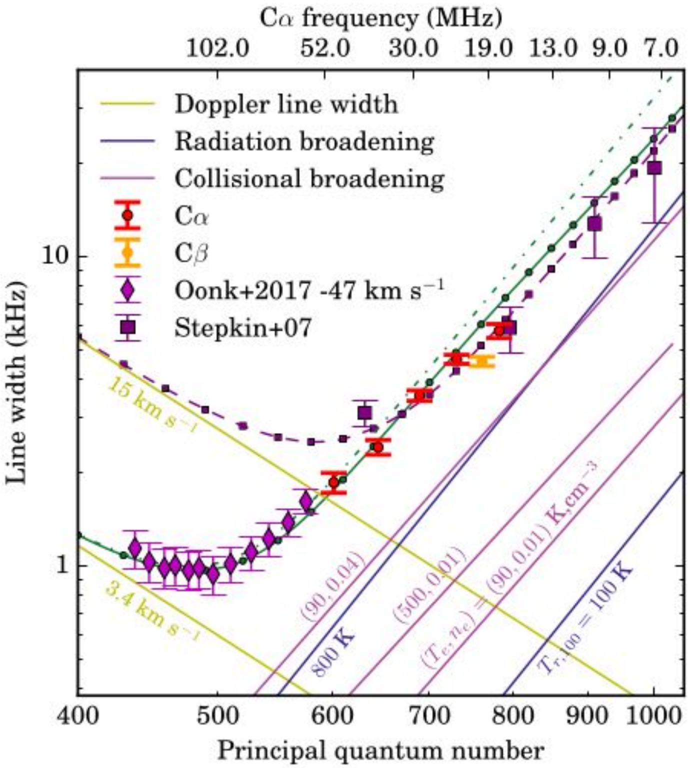
$$\Delta\nu_{radiation} = \frac{6.096\times10^{-17}}{2\pi} T_0 n^{5.8}\ \mathrm{Hz}$$

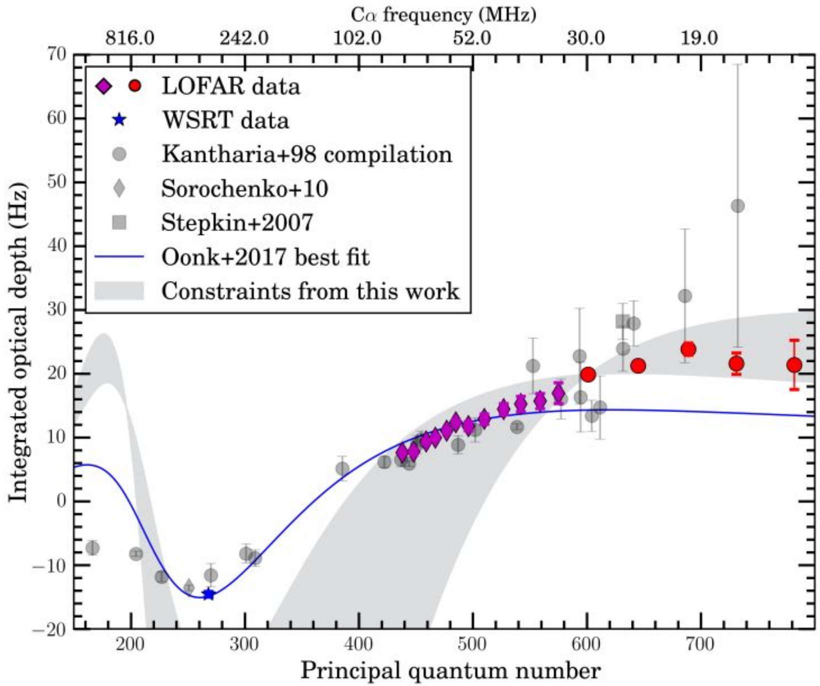
$$\int \frac{I_\nu}{I_\nu^{cont}} = -0.2 b_n(n_e, T_e)\ \beta_{n,n+\Delta n}(n_e, T_e)\left(\frac{T_e}{100\ \mathrm{K}}\right)^{-2.5}\left(\frac{n_e}{0.1\ \mathrm{cm}^{-3}}\right)^2\left(\frac{L}{\mathrm{pc}}\right)\ \mathrm{Hz}$$

$$T_e,\ n_e,\ v_{turb},\ T_0,\ L$$

Gordon & Sorochenko, 2009
Salgado et al, 2017

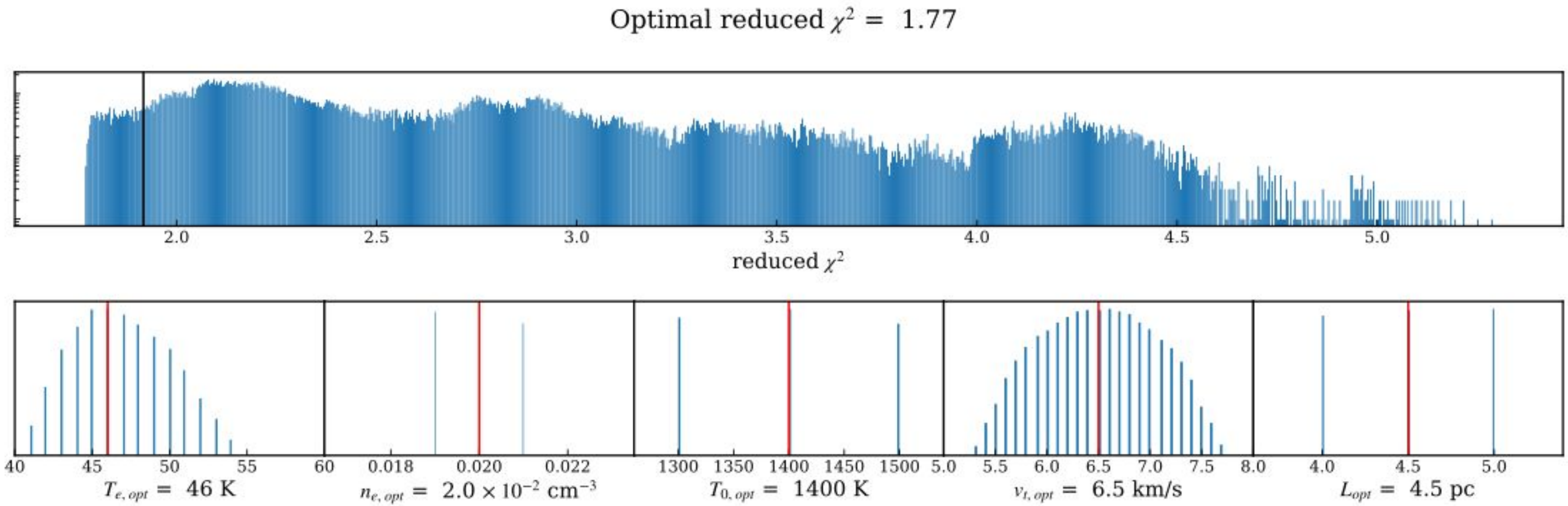
2. Broadening and intensity as a function of quantum number





Salas et al, 2017

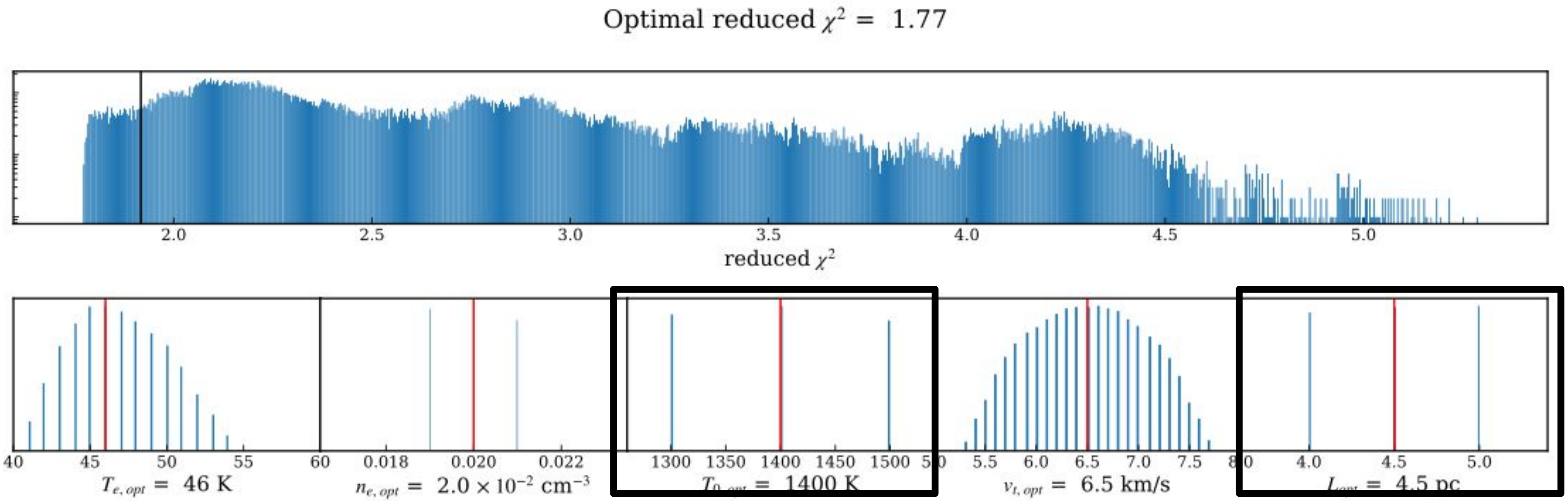
3. Fitting the variation of *w* and *I* as a function of *n*
-> Method : minimisation of reduced χ^2 on a 5D grid



Example for *Cygnus A*. Uncertainties are evaluated as the fifth percentile of the reduced χ^2 on the grid

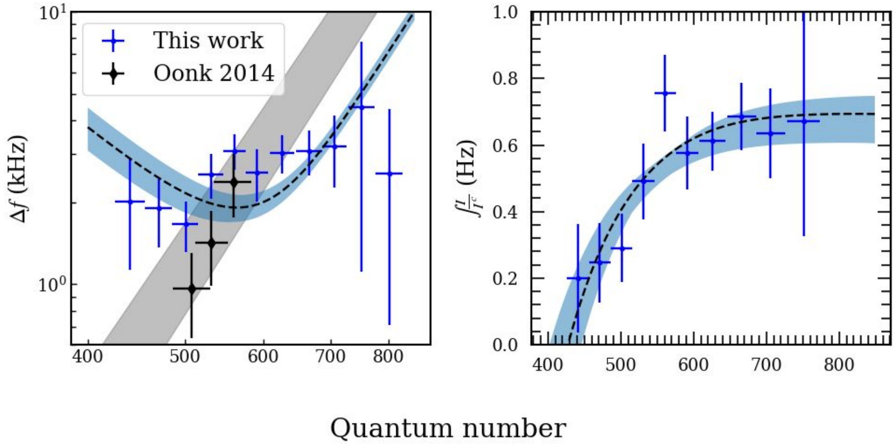
3. Fitting the variation of *w* and *I* as a function of *n*

-> Method : minimisation of reduced χ^2 on a 5D grid

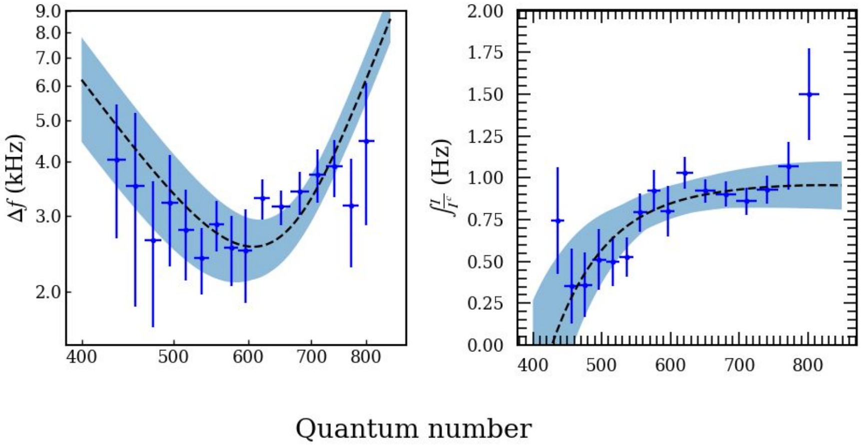


Example for *Cygnus A*. Uncertainties are evaluated as the first percentile of the reduced χ^2 on the grid

Cygnus A

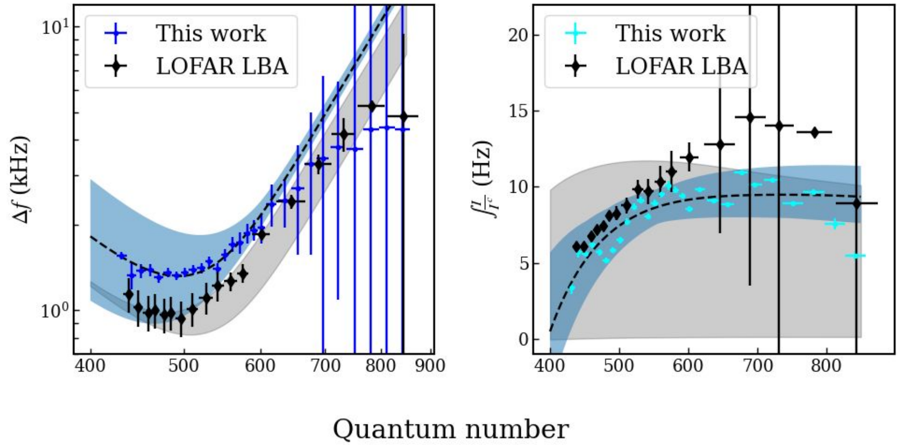


Taurus A

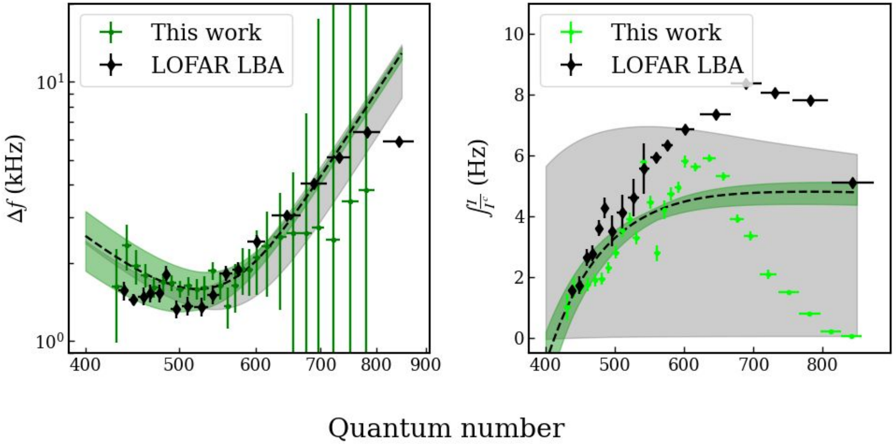


	T_e (K)	n_e (cm^{-3})	T_0 (K)	v_t (km/s)	L (pc)
Cyg A NenuFAR	46^{+8}_{-5}	$0.020^{+0.001}_{-0.001}$	1400 ± 100	$6.5^{+1.2}_{-1.2}$	4 ± 0.5
Cyg A LOFAR	50 - 500	0.005 - 0.070	(2700)	–	–
Tau A NenuFAR	34^{+13}_{-7}	$0.035^{+0.009}_{-0.005}$	1000 ± 100	$10.8^{+2.8}_{-3.1}$	1 ± 0.5

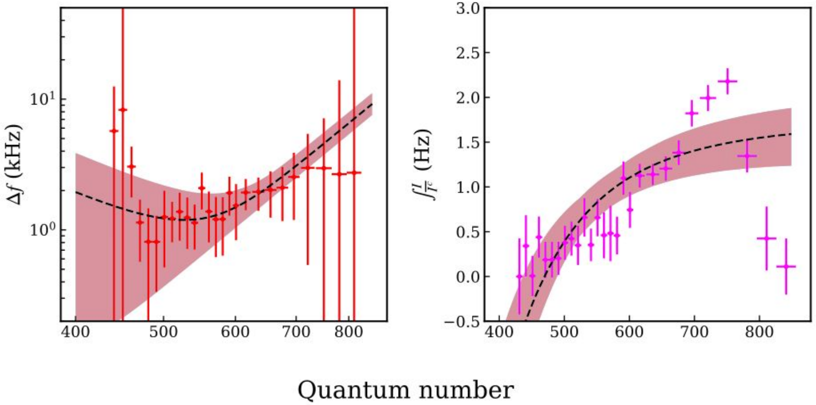
Cas A : -47 km/s



Cas A : -38 km/s



Cas A : 0 km/s



	T_e (K)	n_e (cm^{-3})	T_0 (K)	v_t (km/s)	L (pc)
-47 km/s NenuFAR	39^{+7}_{-4}	$0.036^{+0.001}_{-0.001}$	2000 ± 100	$3.0^{+1.2}_{-1.1}$	16 ± 0.5
-47 km/s LOFAR	85 ± 10	0.040 ± 0.005	1351 ± 83	2.013 ± 0.002	35.3 ± 1.2
-38 km/s NenuFAR	43^{+4}_{-3}	$0.026^{+0.000}_{-0.001}$	1800 ± 100	$4.3^{+1.1}_{-1.2}$	17 ± 0.5
-38 km/s LOFAR	85 ± 10	0.040 ± 0.005	1507 ± 128	4.069 ± 0.002	18.6 ± 1.6
0 km/s	16^{+11}_{-5}	$0.042^{+0.015}_{-0.016}$	1200 ± 100	$3.0^{+1.2}_{-1.1}$	0.5 ± 0.5

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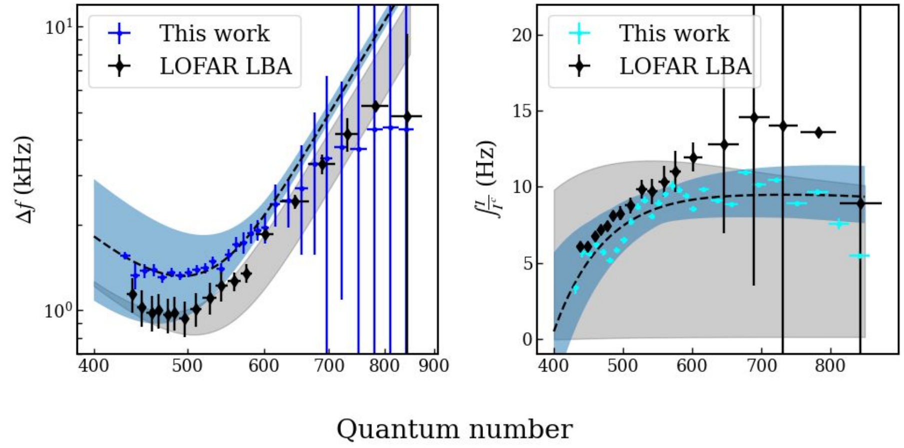

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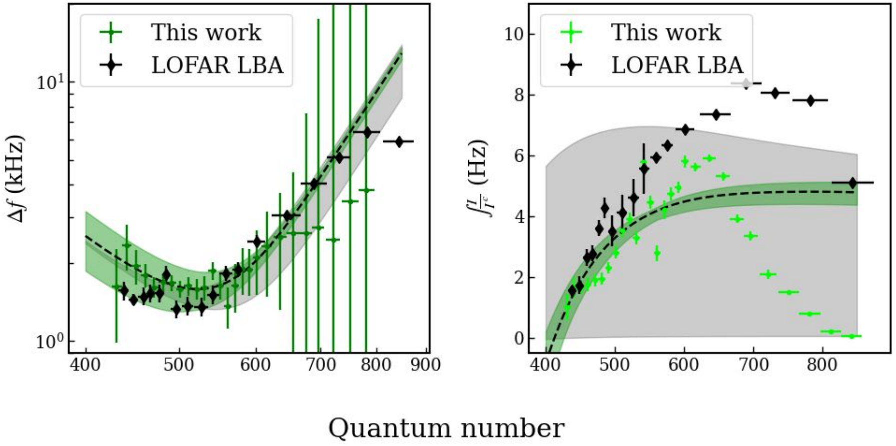
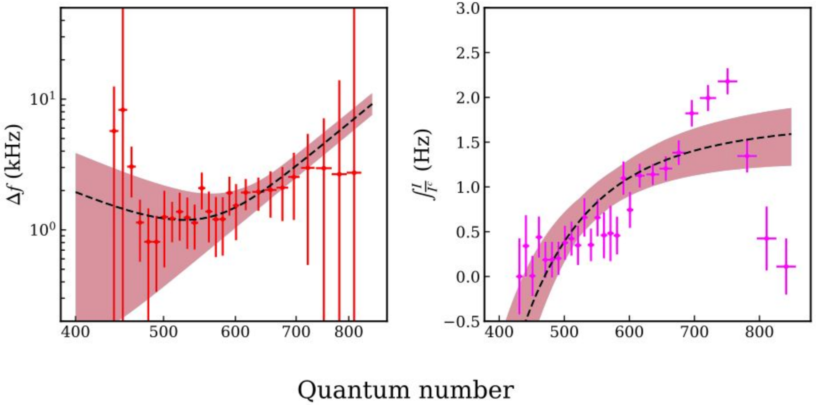


Cas A : 0 km/s



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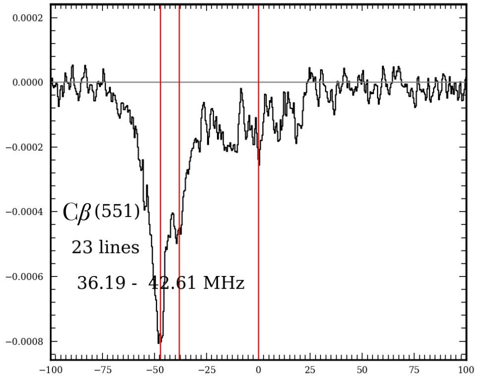
Perspectives

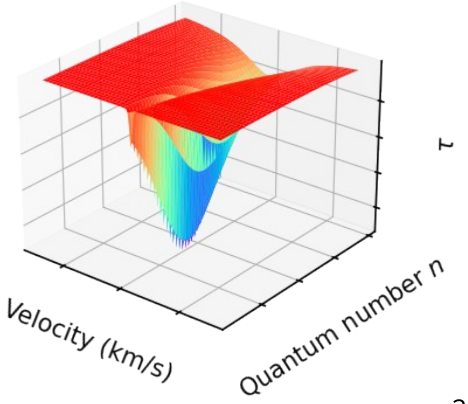
➢ Other transitions : C, H, He, S for α, β, γ, δ, ε

➢ 2D fitting : fitting directly the physics
  - Resolution using machine learning

➢ Paper in prep. : *First detections of Carbon Radio Recombination Lines with the NenuFAR telescope*

Cβ towards Cas A





Thank you for your attention !

*Nenufar means waterlily in French