First detections of Carbon Radio Recombination Lines using NenuFAR

Bright radio sources: Cassiopeia A, Cygnus A, Taurus A

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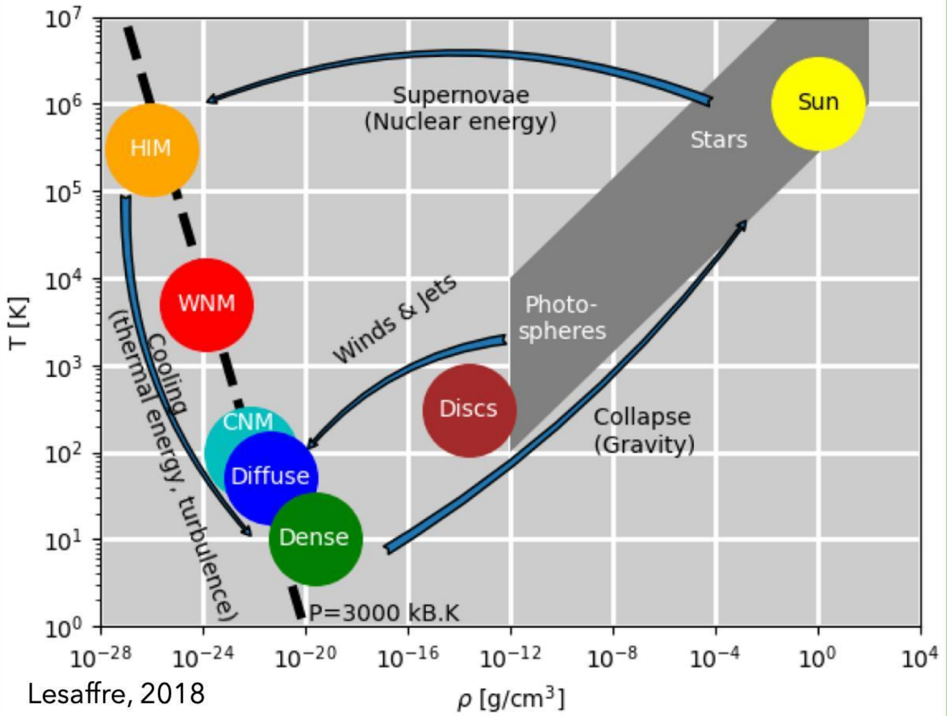
Outline

- Introduction
- Reduction pipeline
- Data Analysis
- First results
- Perspectives

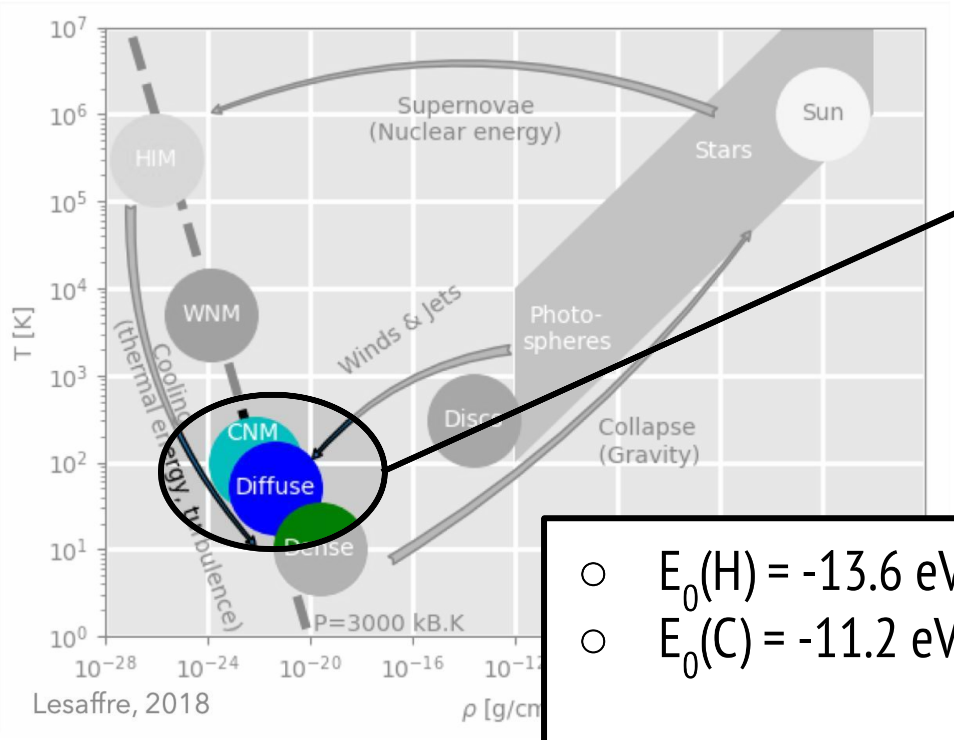
Introduction

Generalities on Carbon RRLs in the diffuse ISM



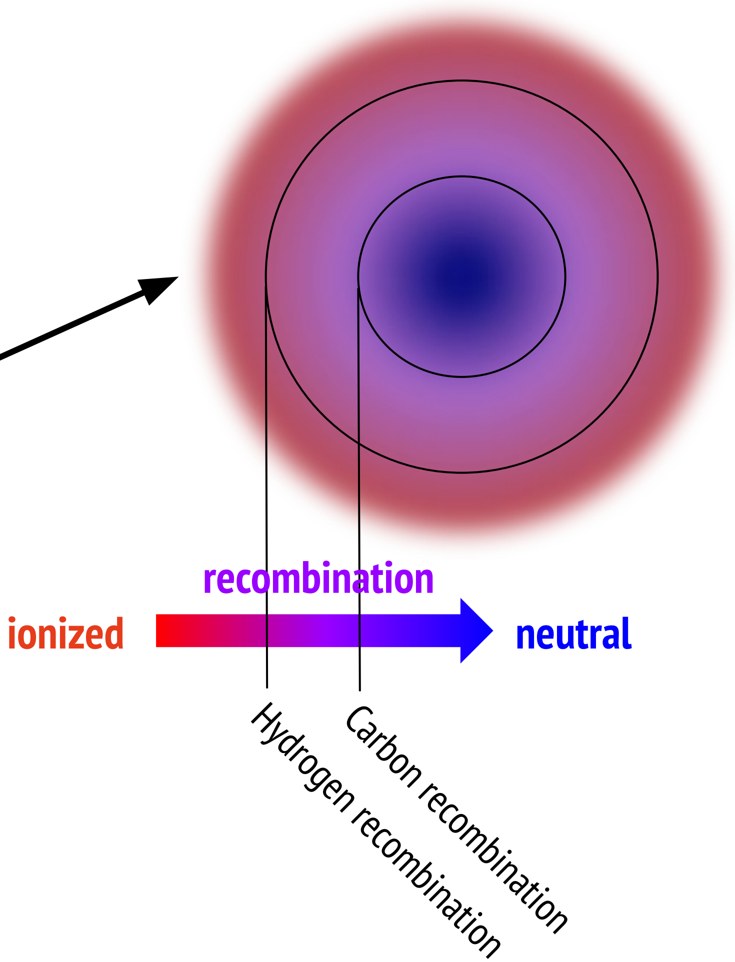
Lesaffre, 2018

Phase transition

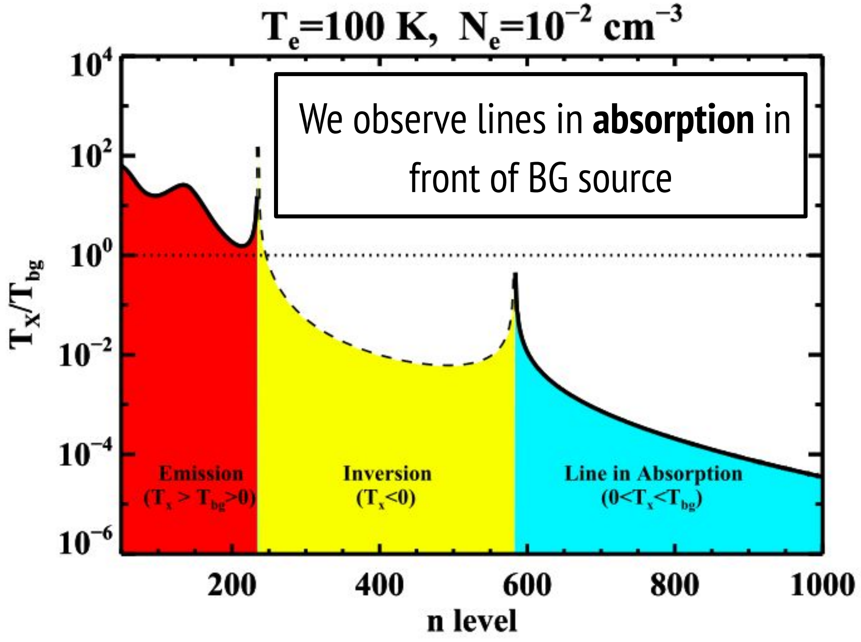


- $E_0(H) = -13.6$ eV
- $E_0(C) = -11.2$ eV

⇒ C^+ in HI region



CRRLs specificities at low frequencies

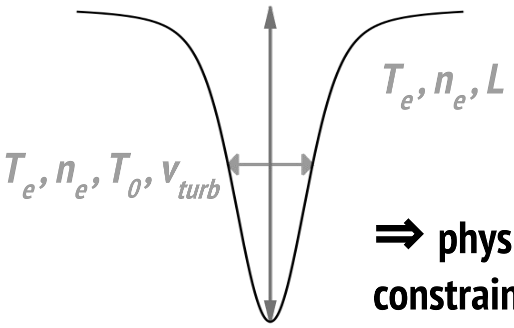


Salgado et. al 2017

Cnα transitions for n ∈ [400,850] (i.e [10,85] MHz):

$$\nu_{n+1\rightarrow n} \propto [n^{-2} - (n+1)^{-2}] \simeq 2\, n^{-3}$$

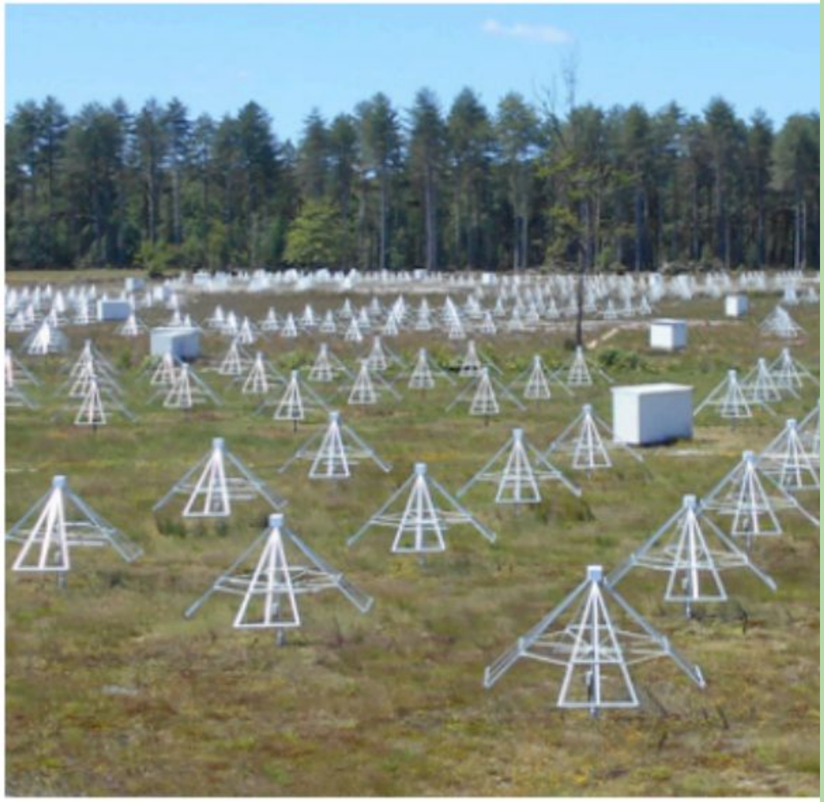
⇒ **450 lines in 70 MHz**



⇒ **physical/chemical constraints on the local ISM**

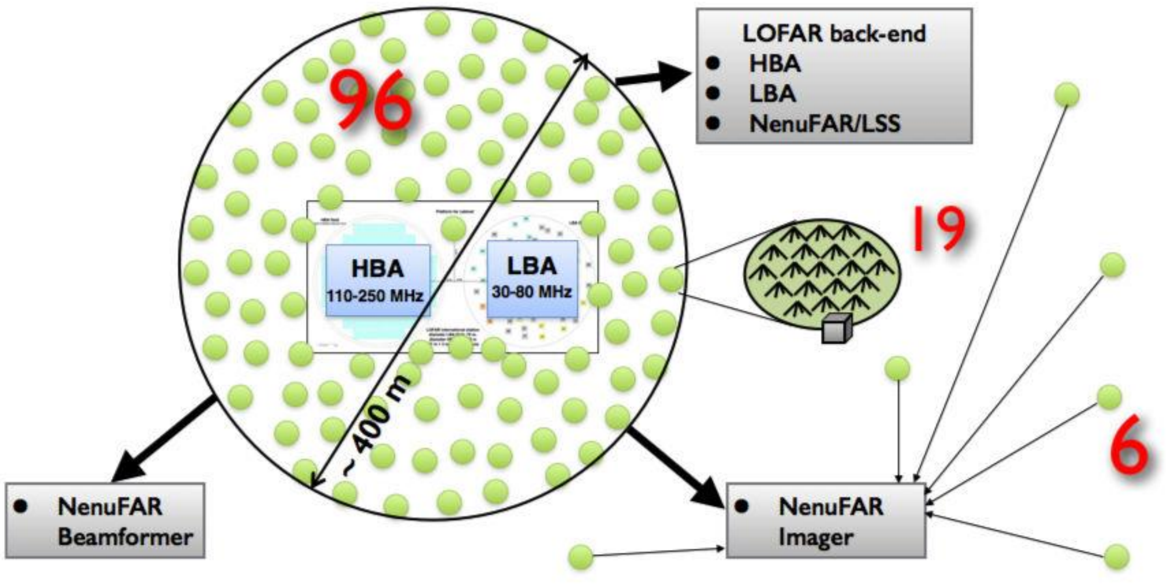
Reduction pipeline

NenuFAR data reduction



NenuFAR (Nancay Observatory)

Standalone radiotelescope + LOFAR extension + SKA pathfinder



EXPERIMENTAL SETUP

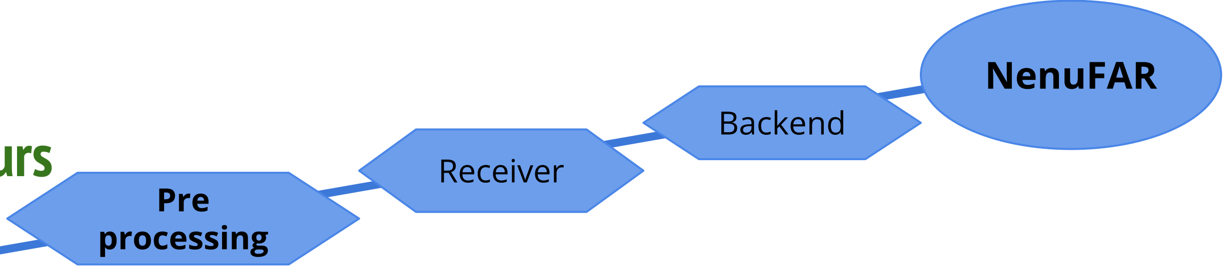
- ~80 mini-array of 19 antennas

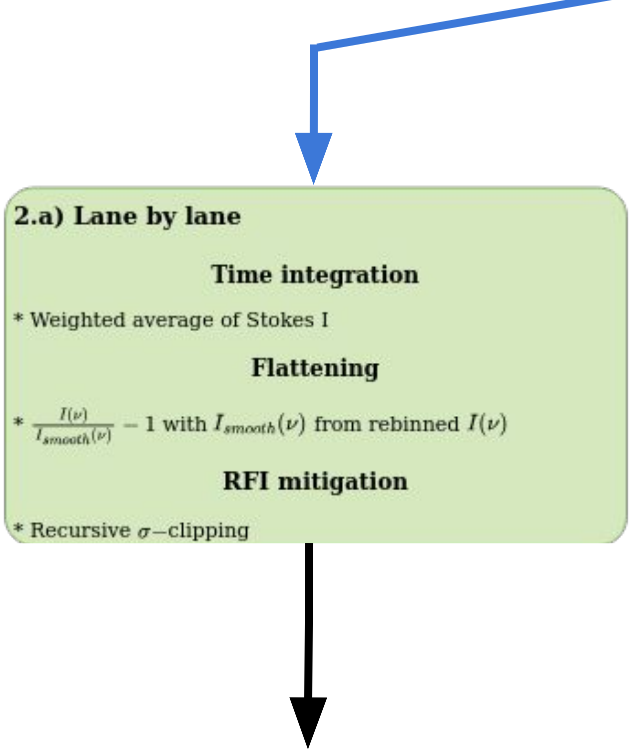
- Frequency range : [10, 85] MHz
- spectral resolution **df ~ 95 Hz**
- angular resolution ~ 1°
- temporal resolution ~ 30s

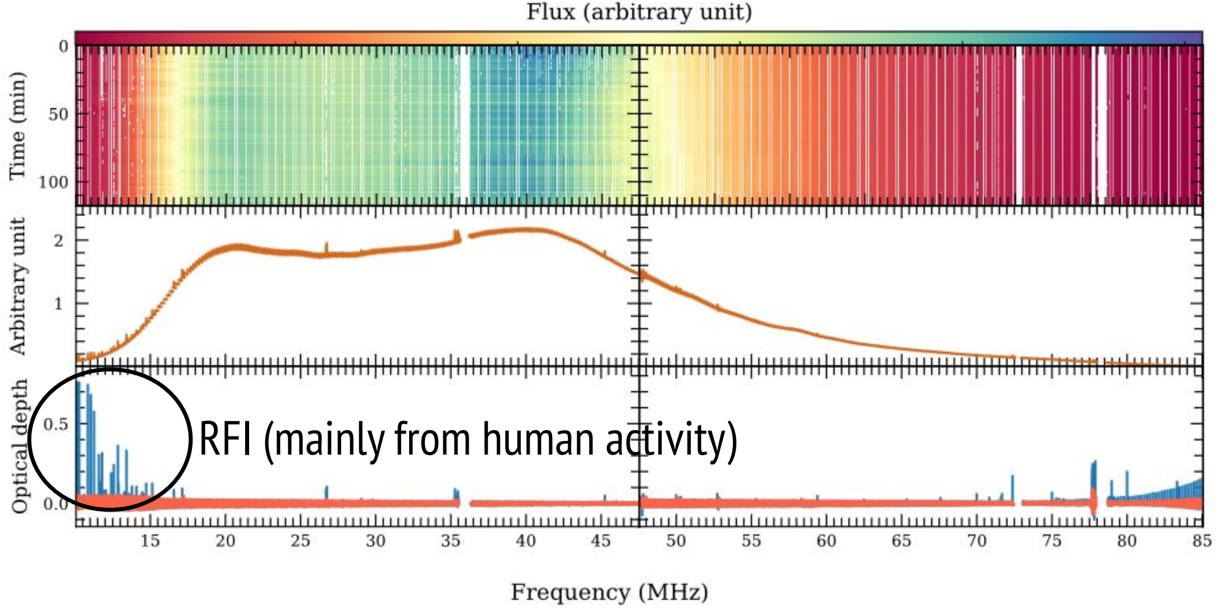
- LT10 : Radio Recombination Lines
  - ➢ Key Project since 2019, when NenuFAR was 1st commissionned
- Beamforming mode

Processing of data

example : Cassiopeia A, 2 hours







=> 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

* $\sigma-$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

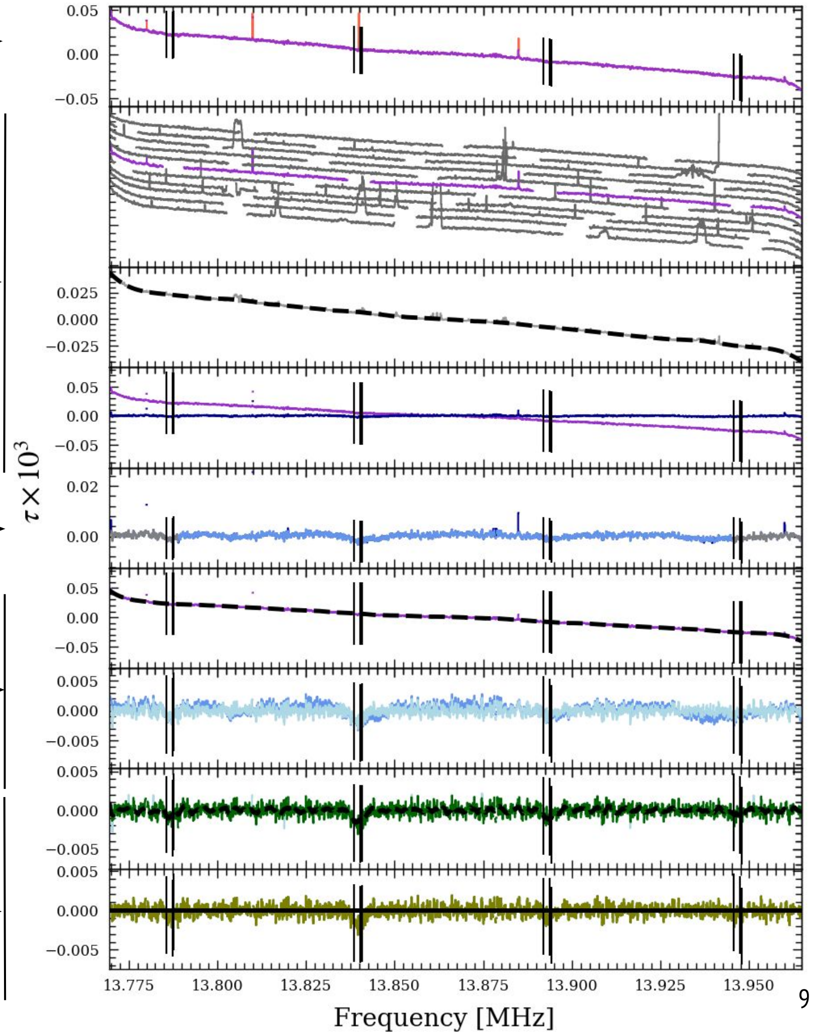
* Mask around expected lines
* recursive $\sigma-$clipping based on masked subband

Flattening 3 : residual baseline variation

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

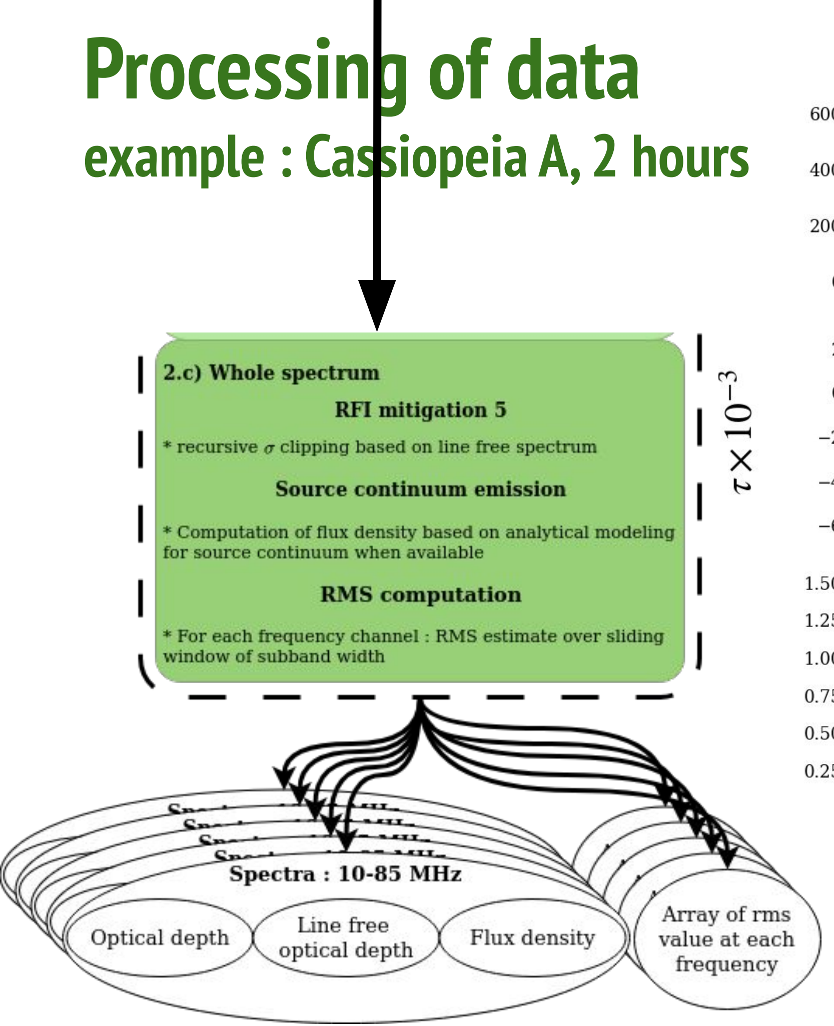
RFI mitigation 4 : inside masked lines

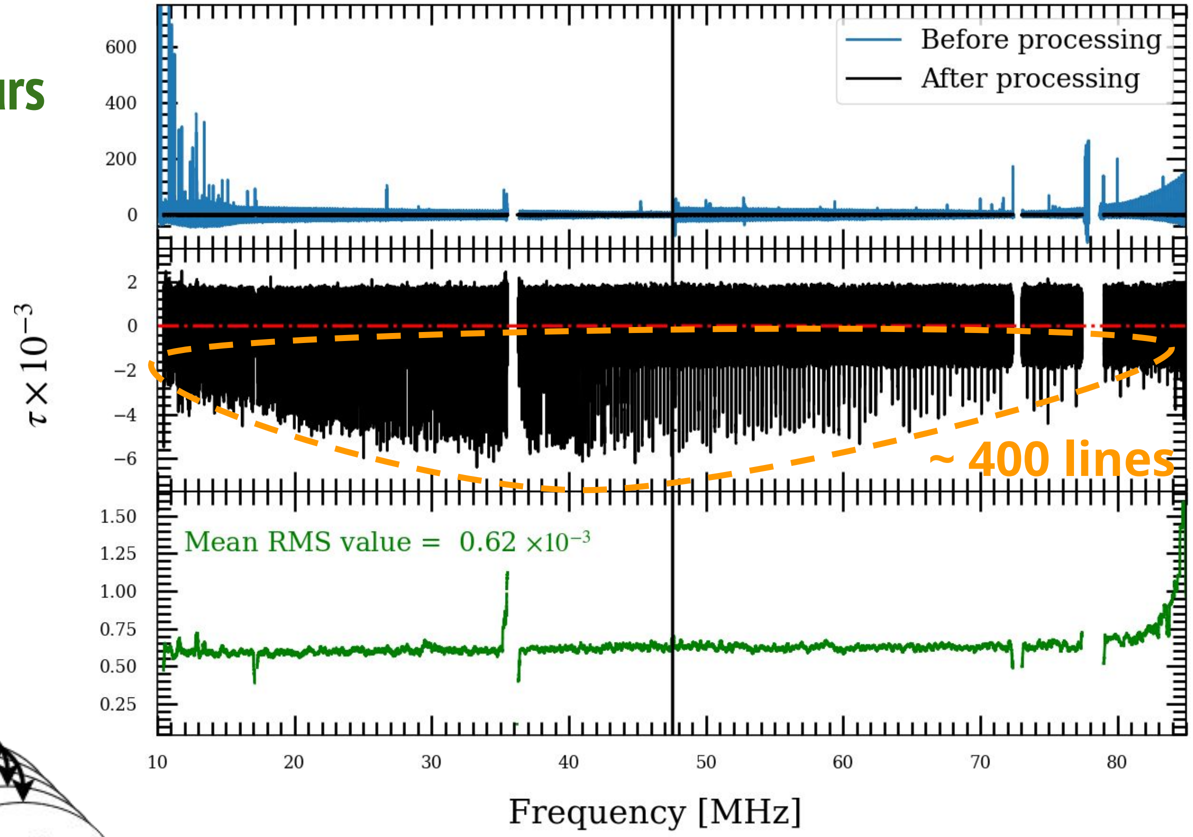
* Flattening of lines with a Savitzky-Golay filter
* recursive $\sigma-$clipping based on the flattened subband.



Processing of data

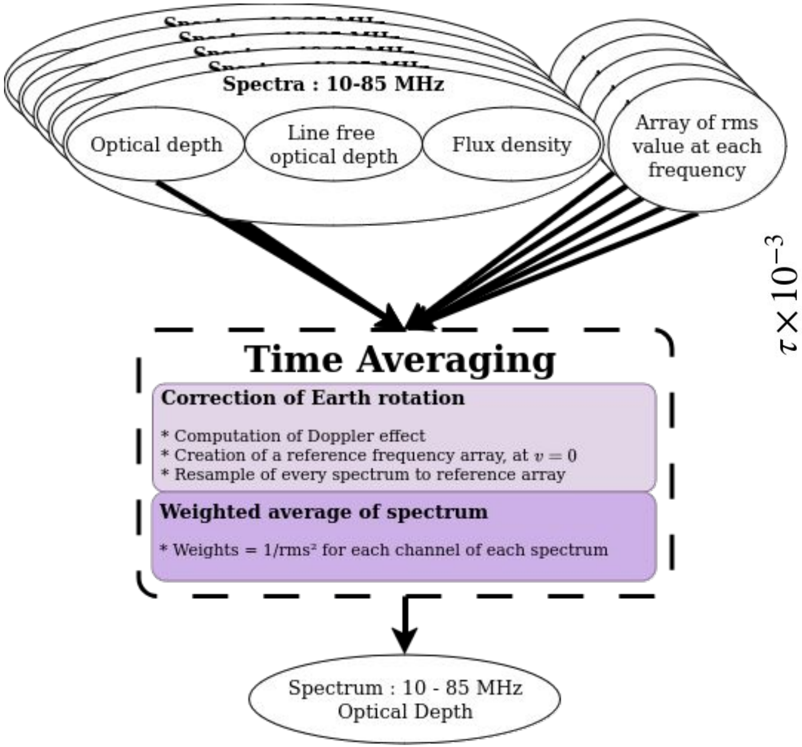
example : Cassiopeia A, 2 hours

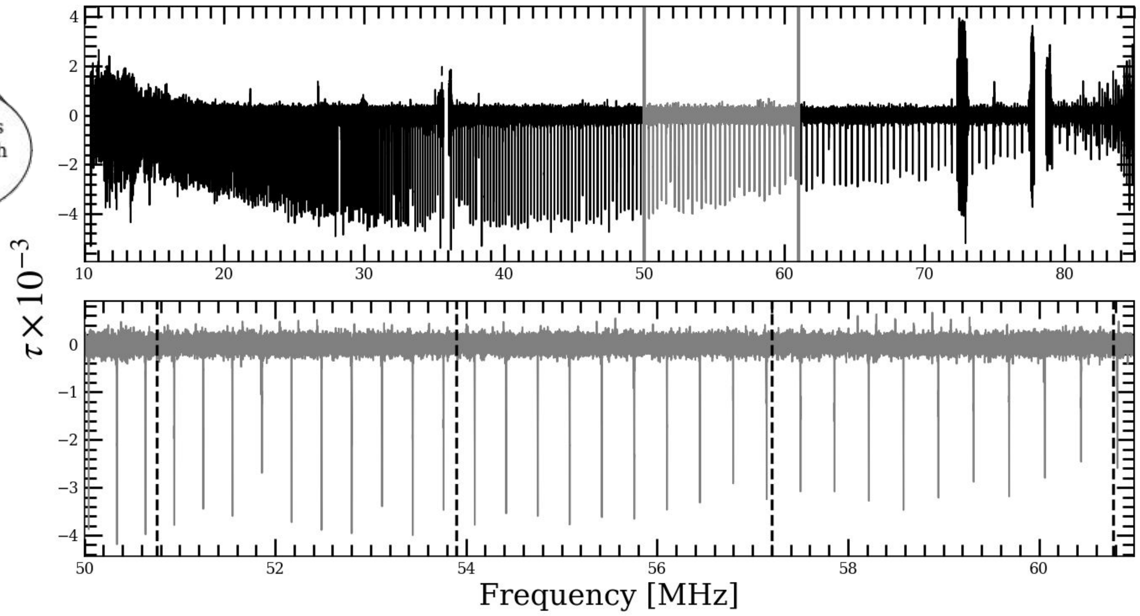




Processing of data

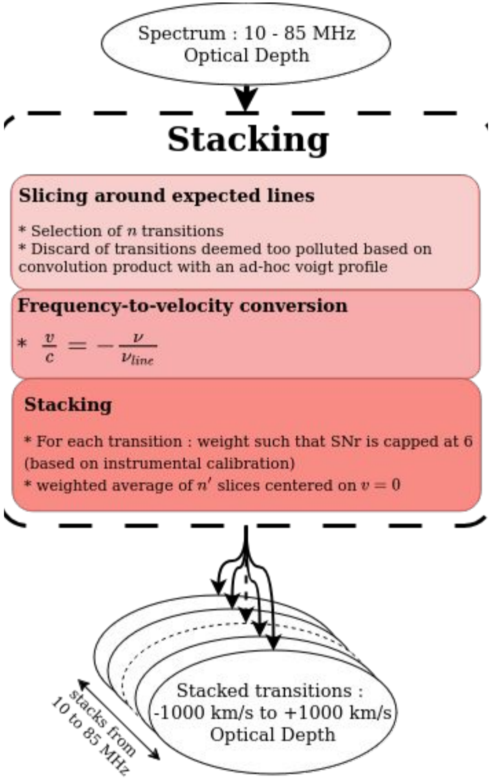
example : Cassiopeia A, 71 hours

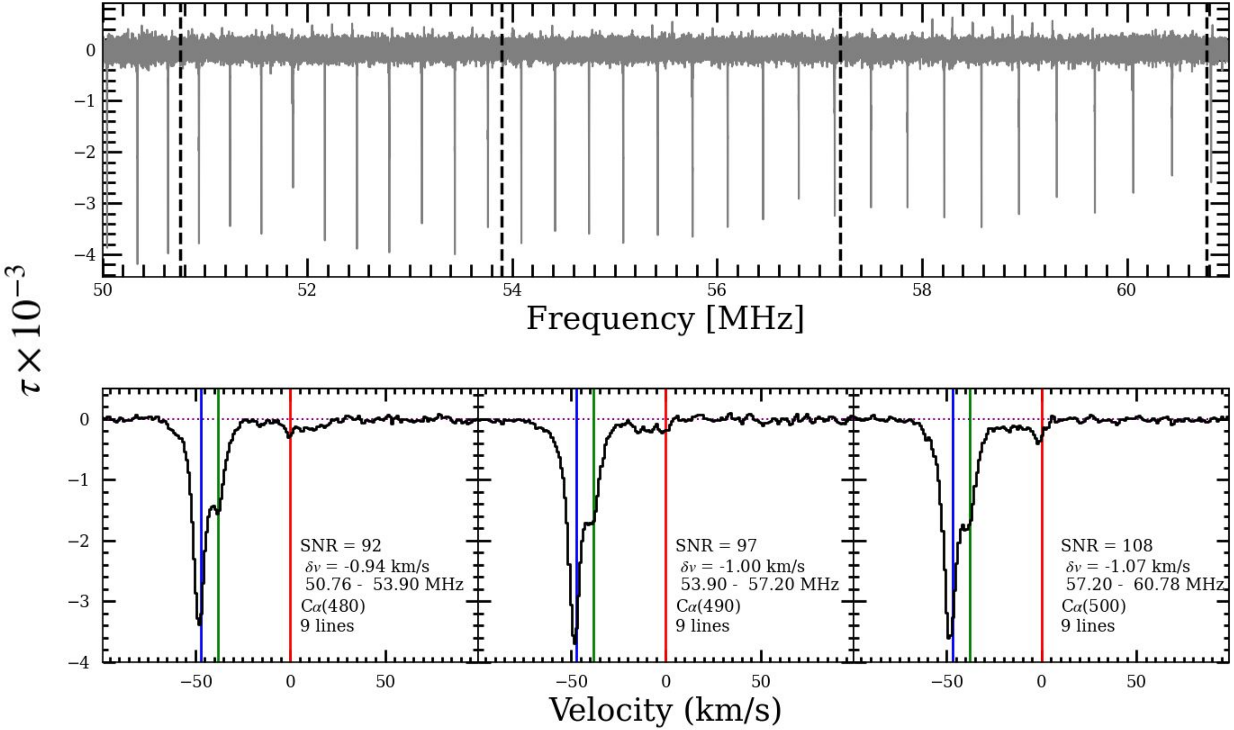




Processing of data

example : Cassiopeia A, 71 hours

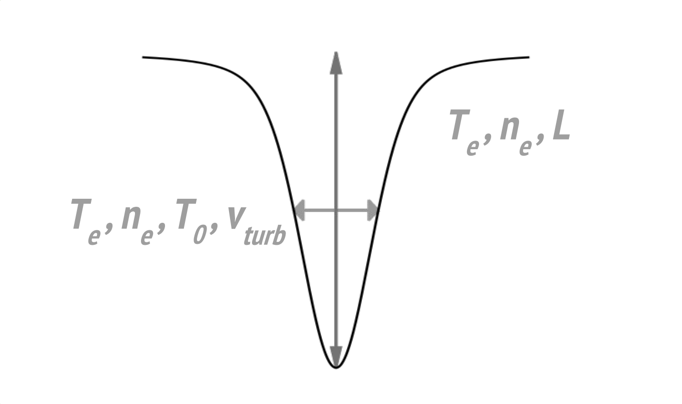




=> 3 clouds detected at velocities : -47, -38 and 0 km/s

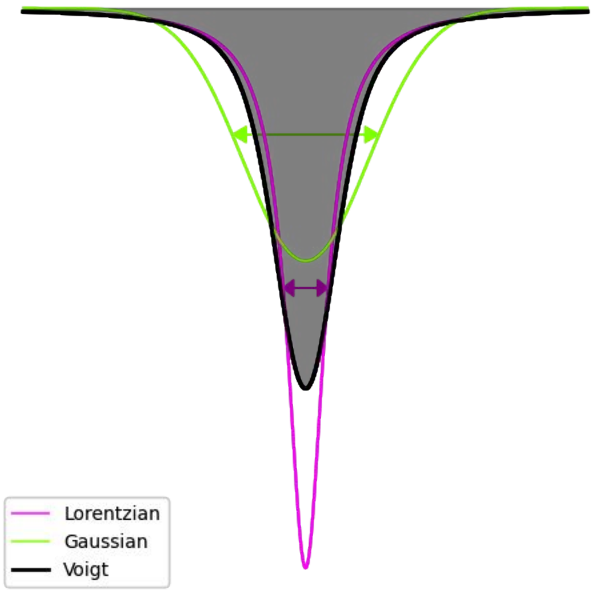
Data Analysis

From RRLs detection to physical constraints



Modeling the line profile

Voigt Profile



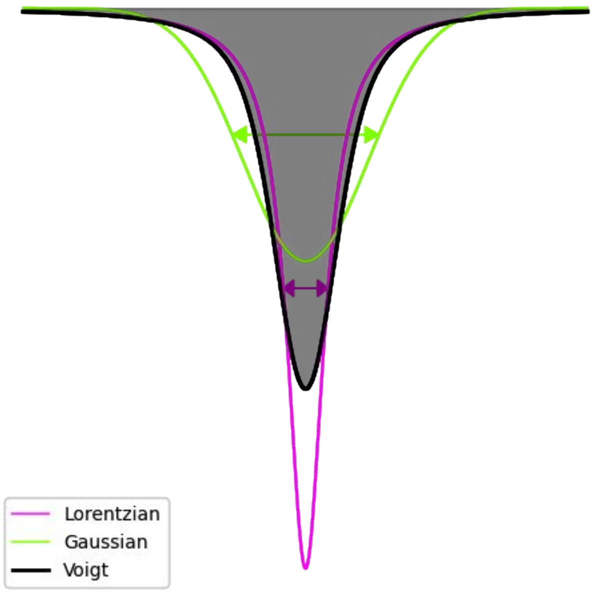
Gordon & Sorochenko, 2009
Salgado et al, 2017

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

Modeling the line profile

- $\Delta\nu_{\mathcal{G}} = \frac{\nu_{\mathrm{n}\rightarrow\mathrm{n}+1}}{c}\sqrt{\frac{2k_B T_{\mathrm{e}}}{m_{\mathrm{C}}} + {v_{\mathrm{t}}}^2}$

Voigt Profile



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

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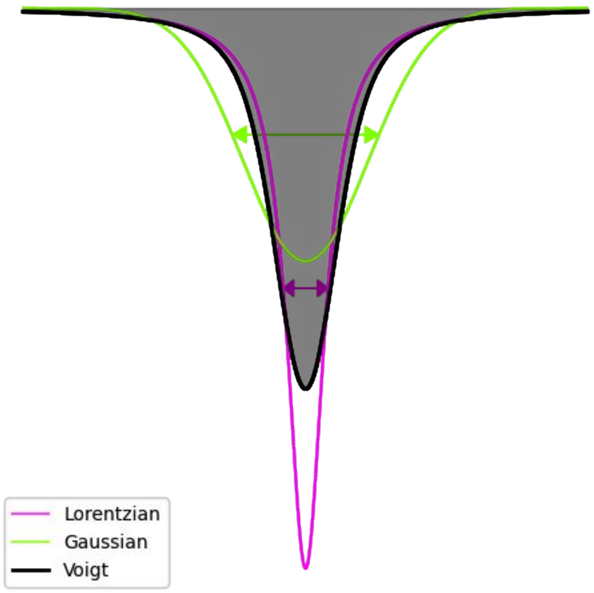
Voigt Profile



Gordon & Sorochenko, 2009
Salgado et al, 2017

- $\Delta\nu_{\mathcal{L}} = \Delta\nu_{\rm rad}(T_0, n) + \Delta\nu_{\rm col}(n_{\rm e}, T_{\rm e}, n) + \Delta\nu_{\rm nat}(n)$

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

- $\Delta\nu_{\rm rad} = \frac{4.274 \times 10^{-4}}{\pi}\left(\frac{2R_\infty c}{\nu_{0,\alpha}}\right)^{\alpha+1} k_{\rm B} T_0\, \nu_{0,\alpha} n^{-3\alpha-2}\sum_{\Delta n=1}^{\infty}(\Delta n)^{\alpha-2}$

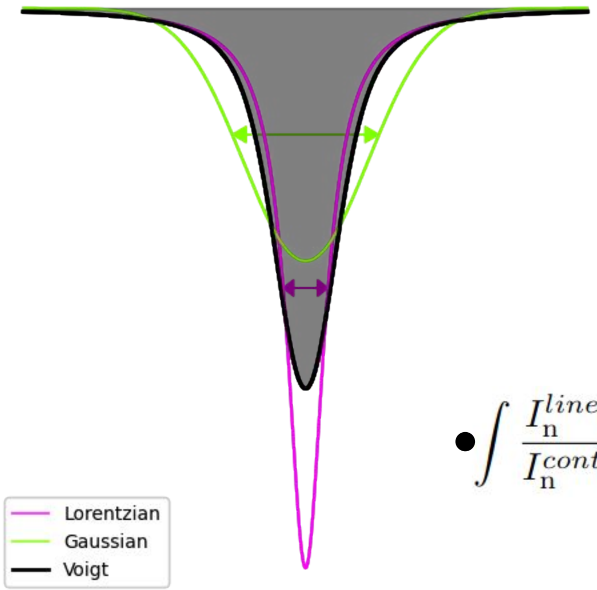
we assume α = -2.6 at ν = 100 MHz (Salas et al 2017)

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

Modeling the line profile

- $$\Delta\nu_{\mathcal{G}} = \frac{\nu_{\mathrm{n}\to\mathrm{n}+1}}{c}\sqrt{\frac{2k_B T_{\mathrm{e}}}{m_{\mathrm{C}}} + v_{\mathrm{t}}^2}$$

Voigt Profile



Gordon & Sorochenko, 2009
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- $$\Delta\nu_{\mathcal{L}} = \Delta\nu_{\mathrm{rad}}(T_0, n) + \Delta\nu_{\mathrm{col}}(n_{\mathrm{e}}, T_{\mathrm{e}}, n) + \Delta\nu_{\mathrm{nat}}(n)$$

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- $$\int \frac{I_{\mathrm{n}}^{line}(\nu)}{I_{\mathrm{n}}^{cont}(\nu)} d\nu = -0.2\, b_{\mathrm{n}}(T_{\mathrm{e}}, n_{\mathrm{e}})\, \beta_{\mathrm{n,n'}}(T_{\mathrm{e}}, n_{\mathrm{e}}) \left(\frac{T_{\mathrm{e}}}{100\,\mathrm{K}}\right)^{-2.5} \left(\frac{n_{\mathrm{e}}}{0.1\,\mathrm{cm}^{-3}}\right)^2 \left(\frac{L}{\mathrm{pc}}\right) \mathrm{Hz.}$$

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

Methodology

- 5D Grid exploration: (n_e, T_e, T_0, v_t, L) + minimisation of χ^2
- 3 statistical parameters (Lorentzian width, Doppler width, Line area) / 5 physical parameters => **degenerate** modeling
- First: wide grid, then refined until finest grid

wide grid

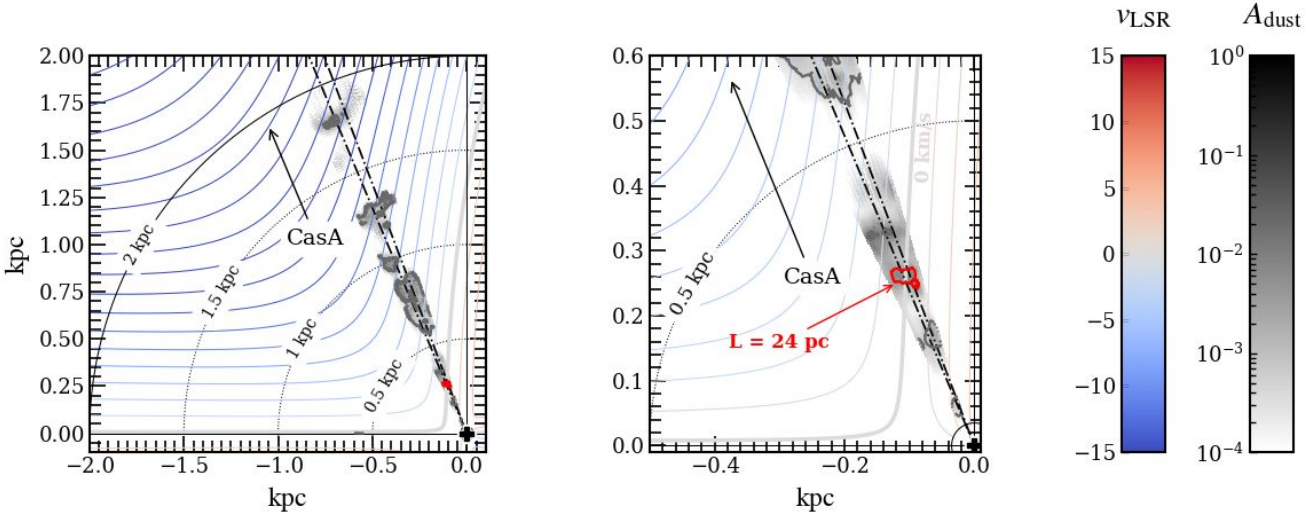
Parameter		Min	Max	Step
T_e	[K]	10	5000	10
n_e	[cm^{-3}]	10^{-2}	1	10^{-2}
T_0	[K]	100	5000	500
v_t	[km/s]	1	20	2
L	[pc]	1	30	2

fine grid

Parameter	Precision
T_e	1 K
n_e	1×10^{-3} cm^{-3}
T_0	100 K
v_t	0.1 km/s
L	0.5 pc

Methodology

➔ Prior on L by comparing with dust (Edenhofer 2023) :



=>

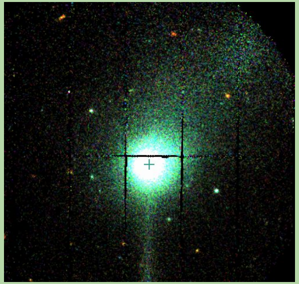
L [pc]	L_{opt} - 10	L_{opt} + 10	2

➔ We look around the value of T_0 where we find the global minimum of the wide grid

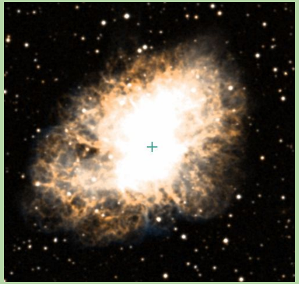
A Team results

Cassiopeia A, Cygnus A, Taurus A

Cassiopeia A - supernova remnant
27 104 Jy at 50 MHz



Cygnus A - radio galaxy
22 146 Jy at 50 MHz

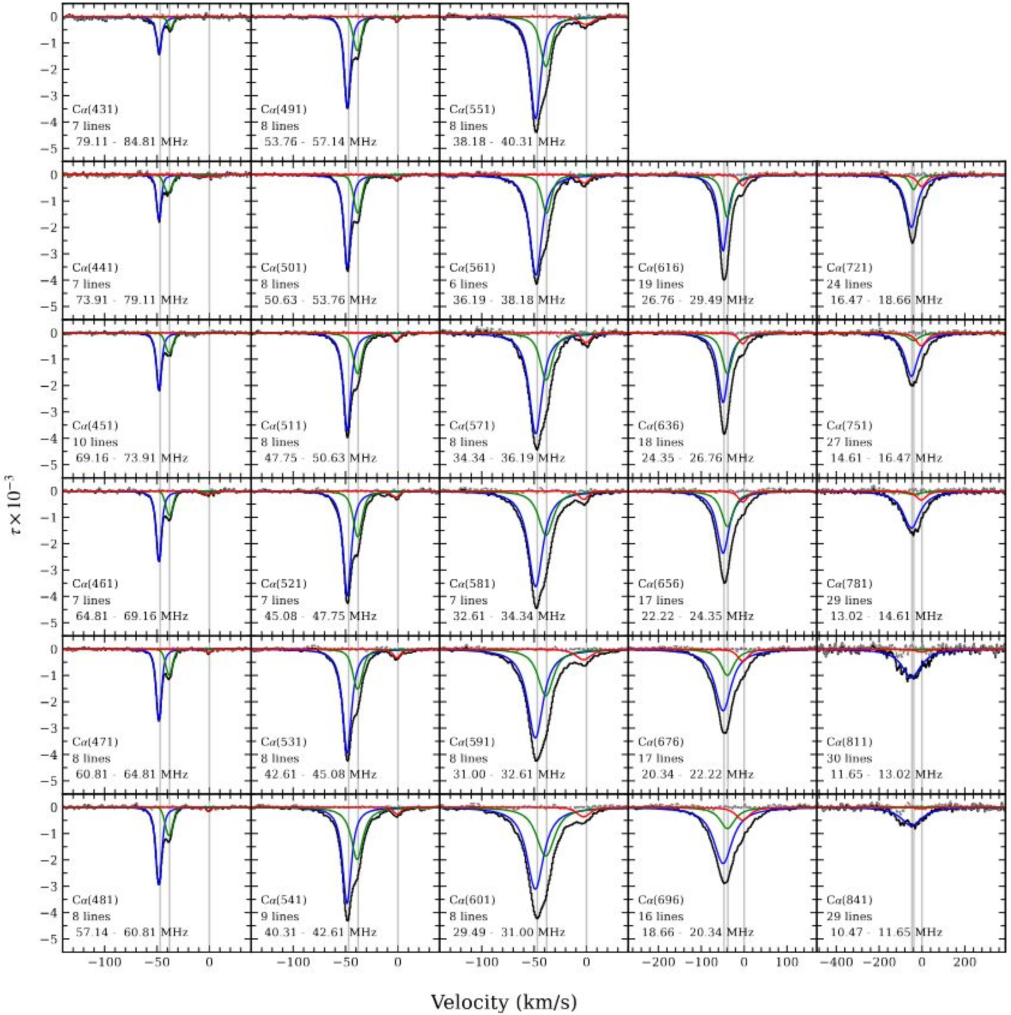


Taurus A - supernova remnant
2 008 Jy at 50 MHz

de Gasperin et al, 2020

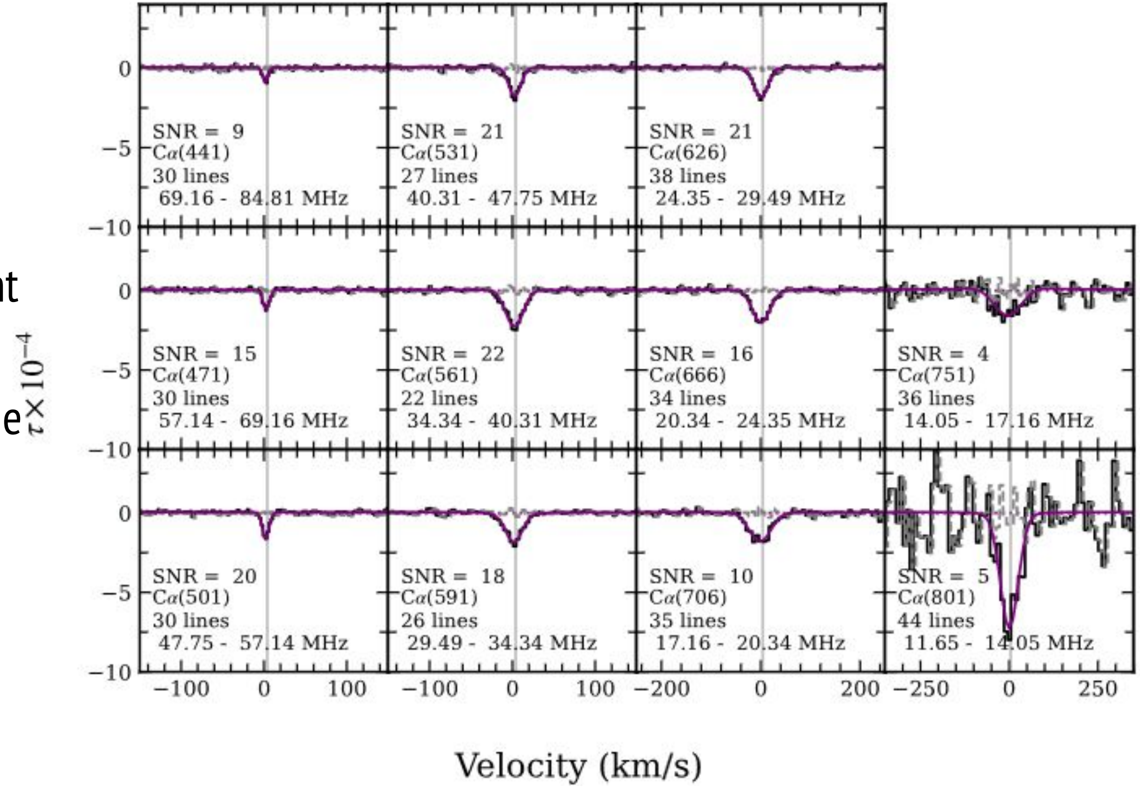
Line detection - Cas A

- Blending of components for n>600
- Deviation from LOFAR, probably due to beam effects
- Constraints for the three clouds



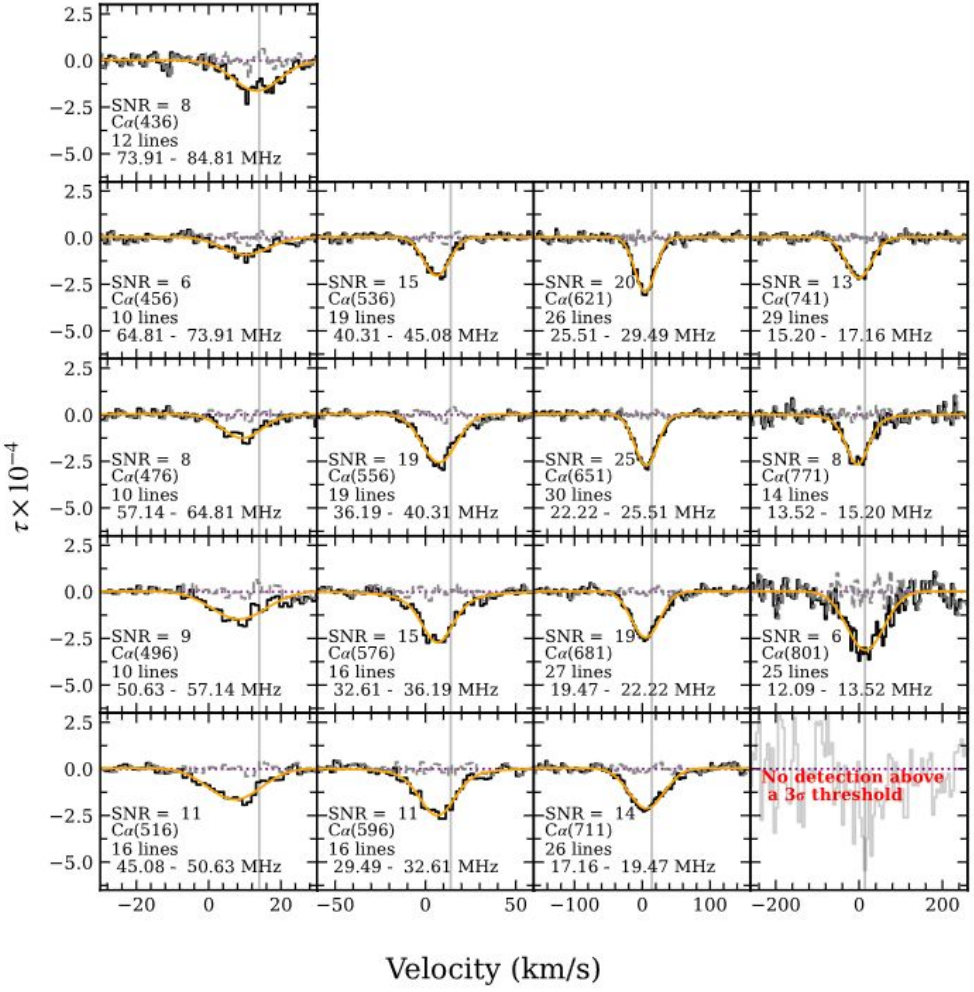
Line detection - Cyg A

- Need for more stacking
- Deviation from LOFAR less important than for Cas A
  - ➢ Cyg A is farther from Galactic Plane



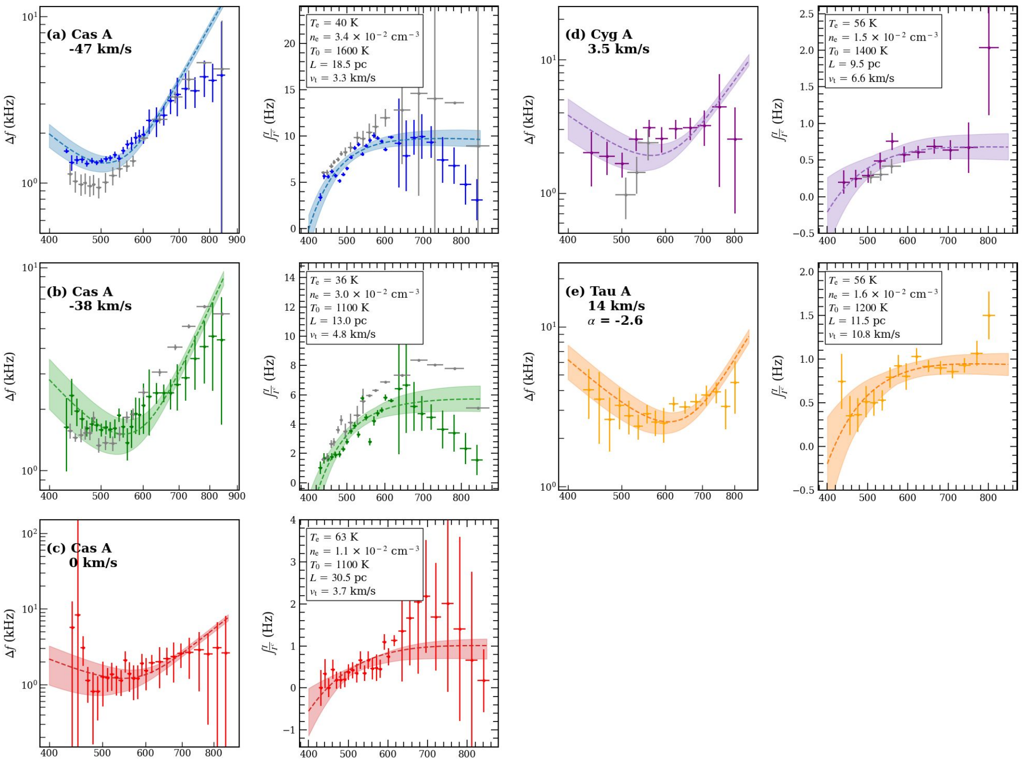
Line detection - Tau A

- New detections !
- Shift of the line center: indication of complex structure within the cloud (shocks ?)



Results

- Correlation with dust for Cas A 0 km/s and Cyg A
- General compatibility with LOFAR results for physical parameters
- T_e and n_e consistent with CNM for every cloud
- High value of turbulence in Tau A may indicate complex structure

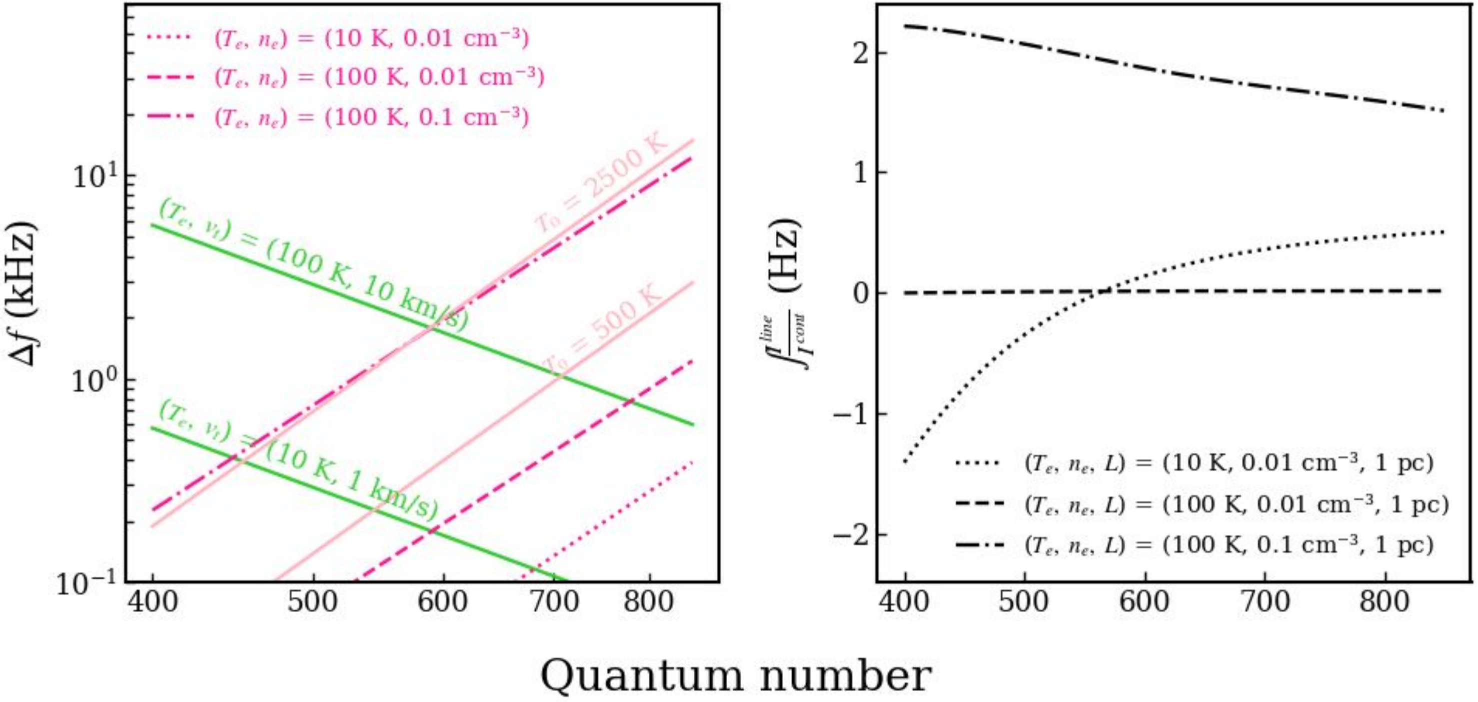


Perspectives

- Apply methods to:
  - Other transitions: β, γ, δ...
  - Other species: H, He, S...
- Observe new environments: more evolved supernova remnants and the diffuse ISM against Galactic background, extragalactic
  - Already started: HD210839, HD219188, NRAO150
  - In the future: IC443, Orion bar
  - Possible detection at Cyg A systemic velocity
- Prepare ourselves for SKA !

Thanks for listening !

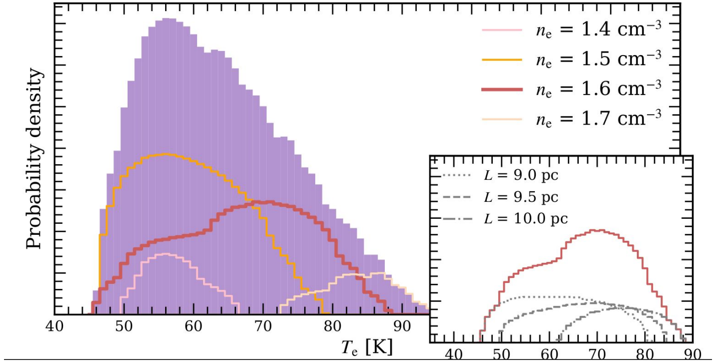
Modeling the line profiles



Methodology

- 5D Grid exploration: (n_e, T_e, T_0, v_t, L) + minimisation of χ^2
- 3 statistical parameters (Lorentzian width, Doppler width, Line area) / 5 physical parameters => degenerate modeling
- First: wide grid, then refined until finest grid

illustration of degeneracy



wide grid

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n_e	[cm^{-3}]	10^{-2}	1	10^{-2}
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fine grid

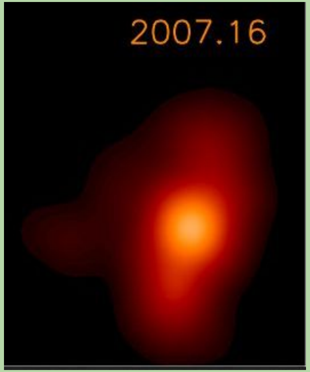
Parameter	Precision
T_e	1 K
n_e	1×10^{-3} cm^{-3}
T_0	100 K
v_t	0.1 km/s
L	0.5 pc

Diffuse ISM results

HD210839, HD219188, NRAO150

HD210189 - Blue supergiant

HD219839 - Star

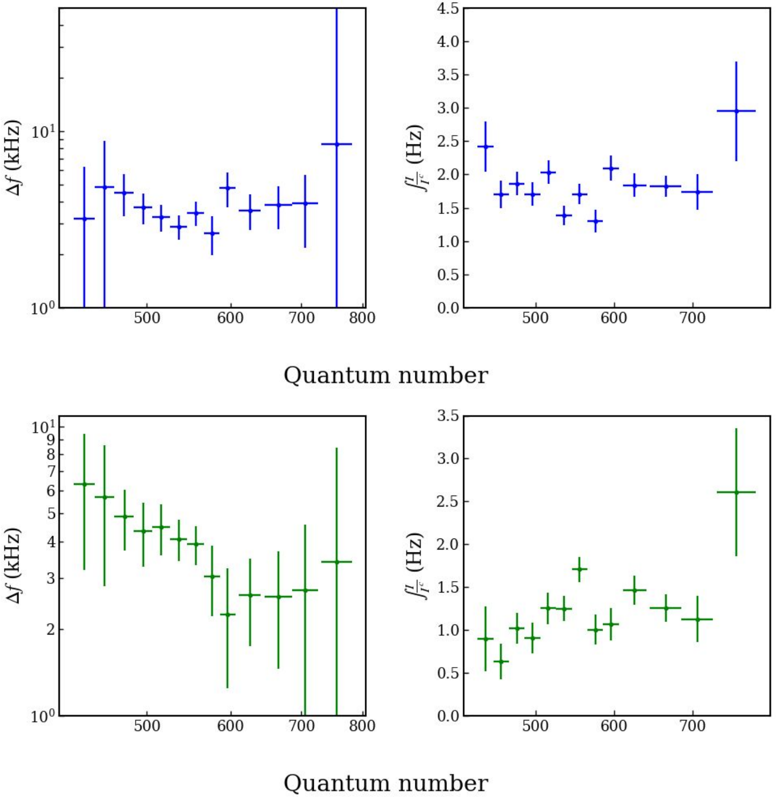


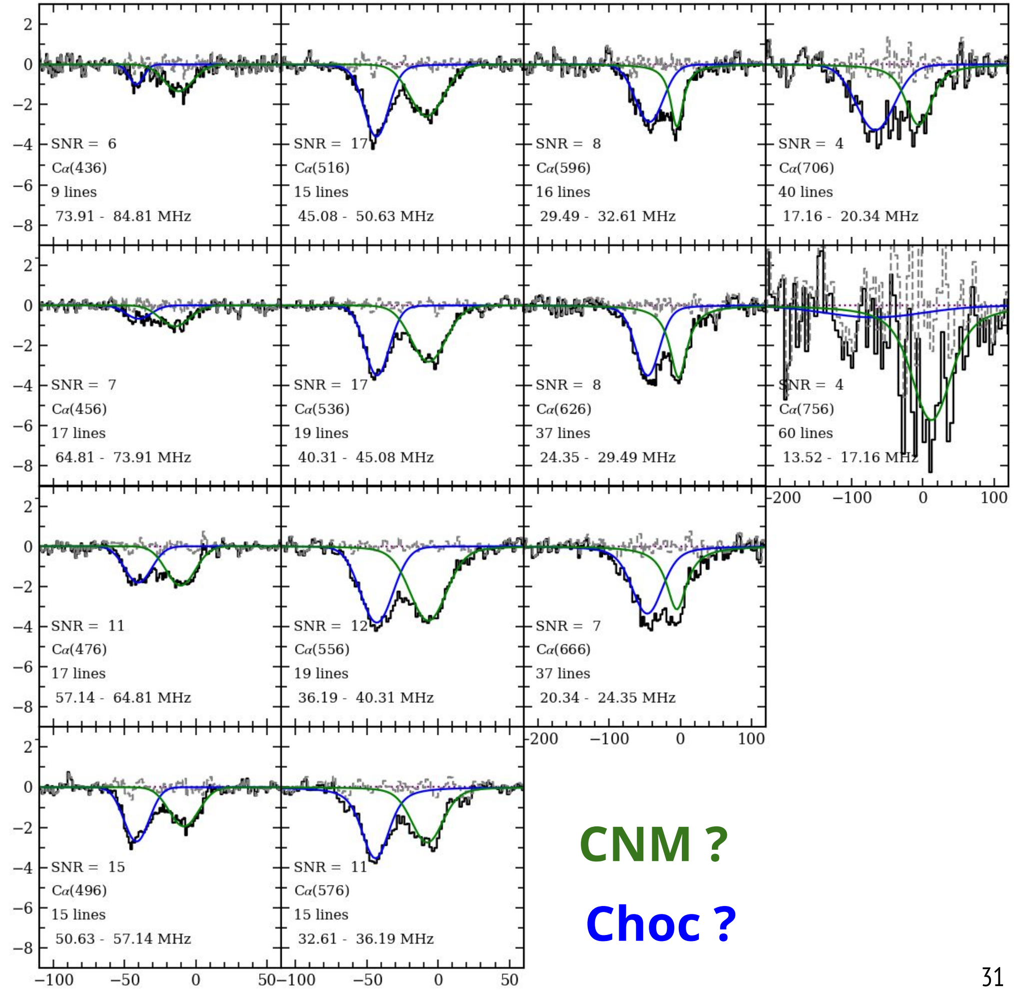
NRAO150 - Blazar

Detections

Source	On-source time (hours)	Expected velocity components (km/s)	Number of detection	Typical value of optical depth	Mean value of SNR
HD210839	89.25	-14, -34	13	10^{-4}	15
HD219188	14	-9, -39	4 - 6	10^{-4}	5
NRAO150	22	-4, -8.5, -10, -14, -17	7	10^{-4}	10

Line detection
HD210839

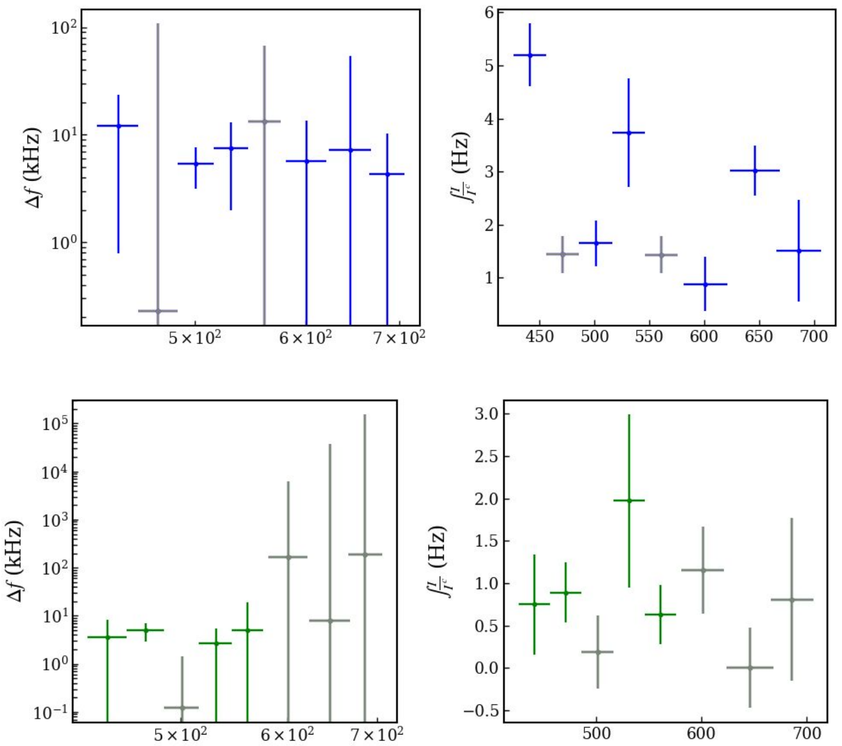


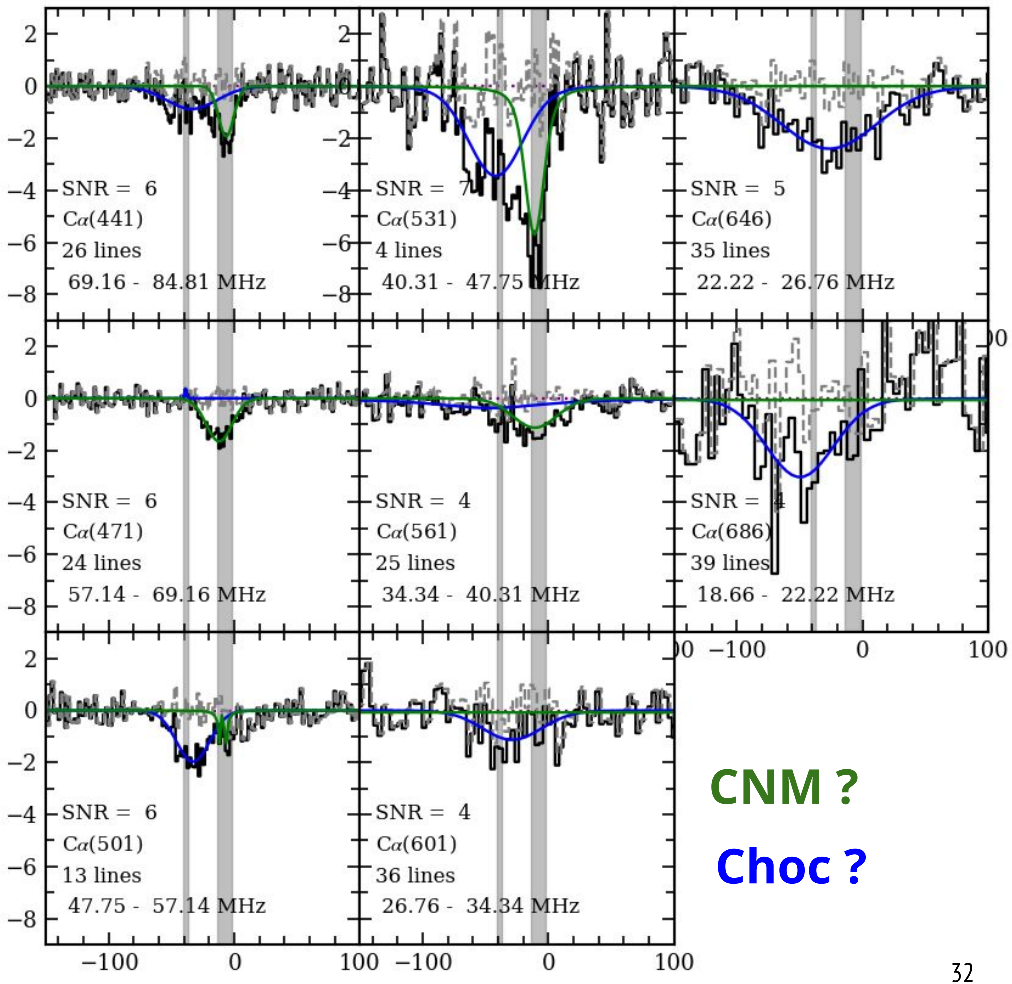


CNM ?

Choc ?

Line detection
HD219188



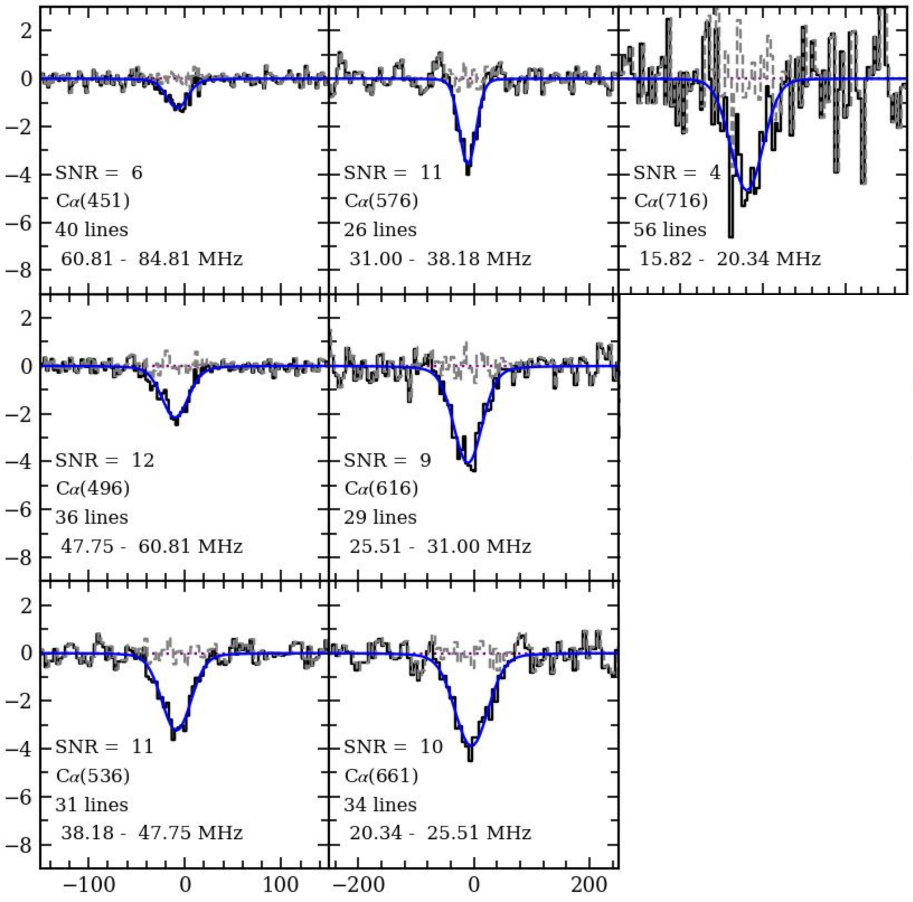


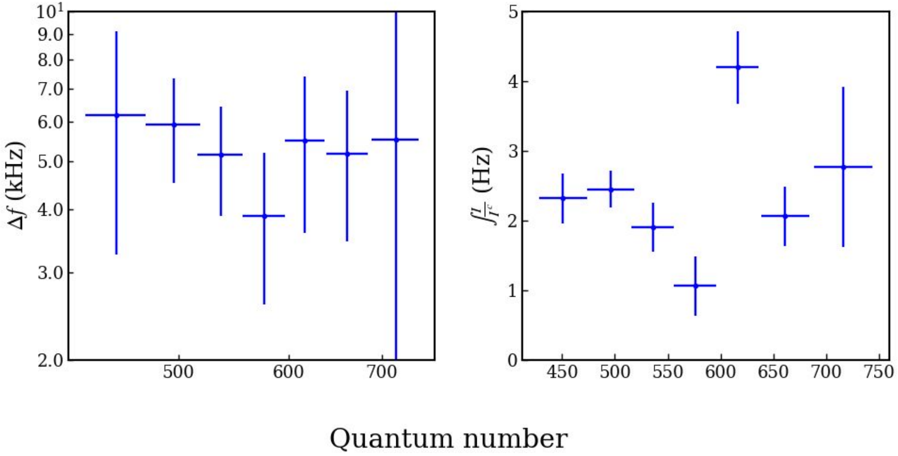
CNM ?

Choc ?

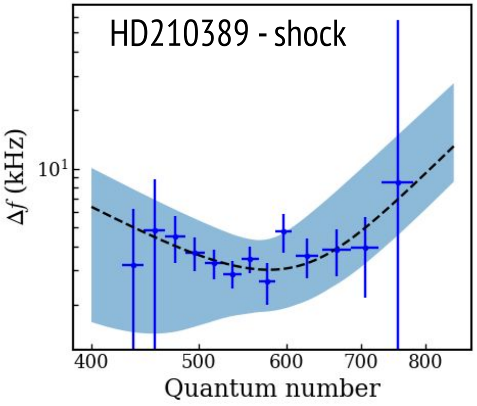
Line detection NRAO150

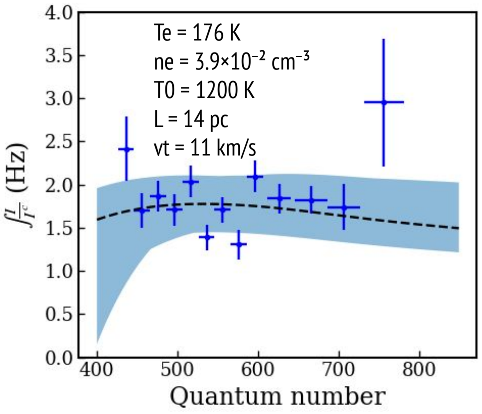
We detect one line => blended components

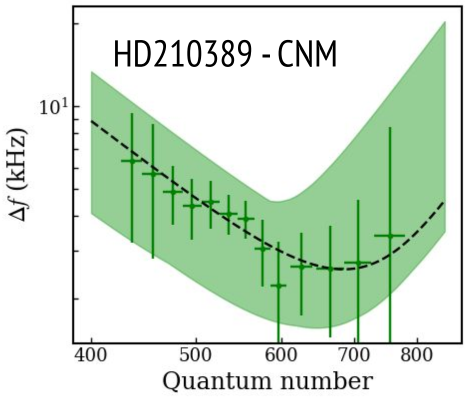


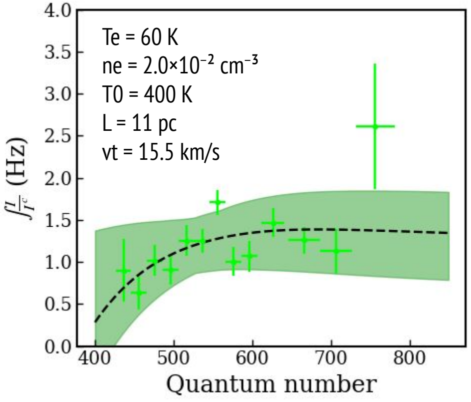


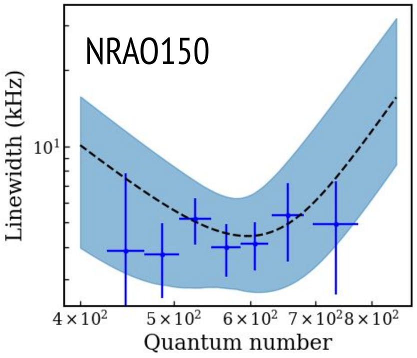
Results

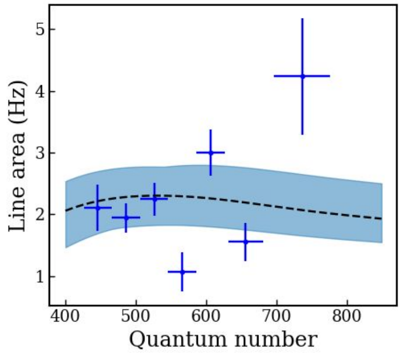












=> not satisfactory

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

Cyg A extragalactic ?