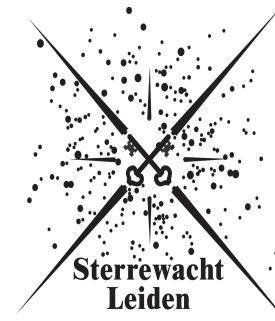
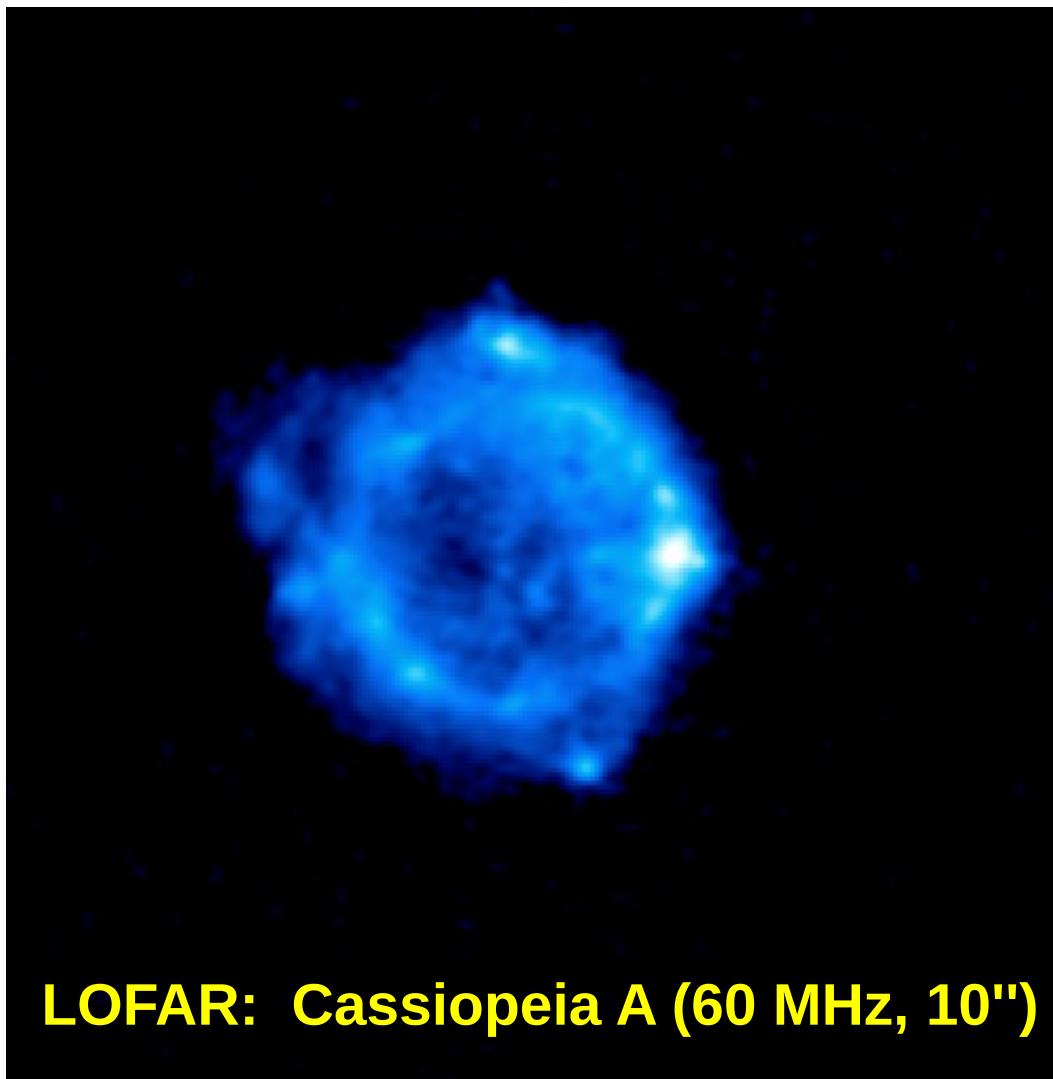


# LOFAR: Spectral Line Data Analysis.

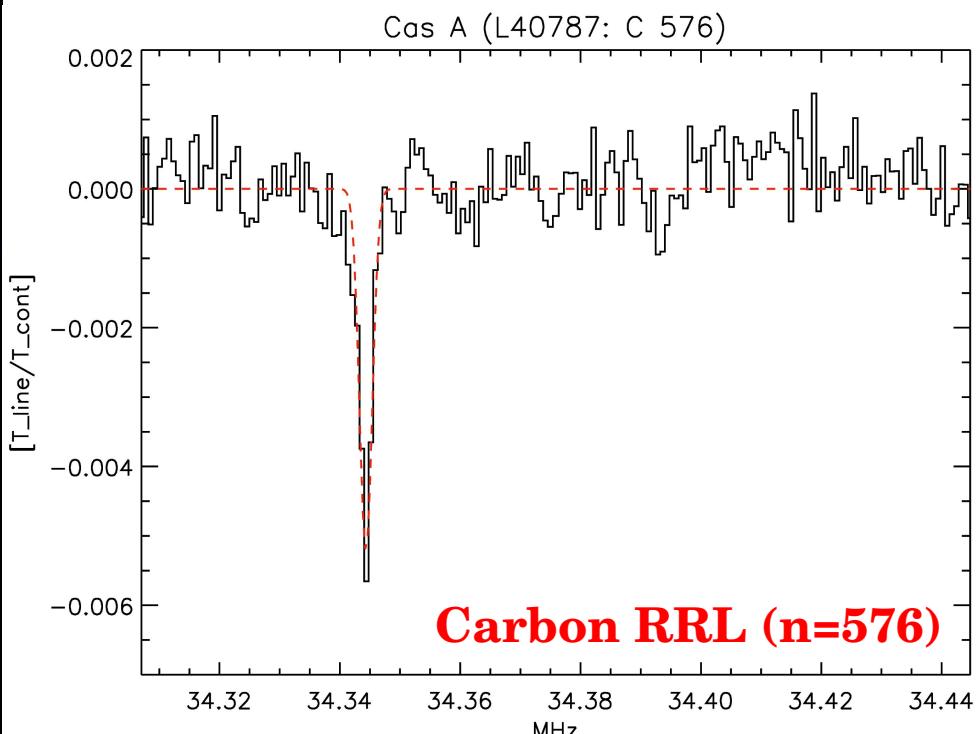
**ASTRON**

JBRO, R. van Weeren, F. Salgado, L. Morabito,  
M. C. Toribio, X. Tielens, H. Rottgering.

*John McKean, Richard Fallows, Jason Hessels*



**LOFAR**



# LOFAR: Spectral Line Data Analysis: [Outline](#)

## **1) Low-frequency Radio lines**

**- Radio Recombination Lines**

## **2) LOFAR's capabilities for spectroscopy**

## **3) LOFAR spectroscopy examples**

**- Interferometer (M82, 3C241)**

**- Beamformed (W3OH)**

## **4) Spectroscopy: bandpass (global, gaps, flagging)**

## **5) Spectroscopy: computing requirements**

# LOFAR: Spectral Line Data Analysis.

## Low-frequency lines:

- 1) Redshifted HI 21cm (  $z > 4.7 \Leftrightarrow f < 250$  MHz )
- 2) Molecules (OH, H<sub>2</sub>CO, NO etc.)
- 3) Radio Recombination Lines ( “Rydberg atoms” )

## Line lists:

\* splatalogue: <http://www.cv.nrao.edu/php/splat/>

# LOFAR: Spectral Line Data Analysis.

**ASTRON**

\* **splatatalogue:** <http://www.cv.nrao.edu/php/splat/>

The screenshot shows the Splatalogue search interface. At the top, there are three tabs: Basic (selected), Advanced, and Expert. On the left, a "Quick Picker" lists various molecular species with their transitions, such as CO v = 0, c<sup>17</sup>O, CH<sub>3</sub>OH v<sub>1</sub> = 0, HCN v = 0, H<sup>13</sup>CN v = 0, DCN v = 0, CS, NH<sub>3</sub>, C II, O III, H<sub>2</sub>O v = 0, and SiO v = 0. In the center, the "splatalogue database for astronomical spectroscopy" logo is displayed over a background of a spectrum. Below the logo is a search bar with fields for "Search:" (containing "ex: ammonia, carbon monoxide, methanol, water, CO, NH3 e"), "Any" (ALMA Band 3 (84-116 GHz)), "Telescope Bands:" (ALMA Band 4 (125-163 GHz)), "Redshift:" (0.0), "Energy Range:" (Min, Max), "Frequency Range:" (Min, Max), "Frequency Unit:" (GHz), and "Search" button. To the right, there is a section titled "Astronomical Filters" with a list of filters: Top 20 list, Planetary Atmosphere, Hot Cores, Dark Clouds, Diffuse Clouds, Comets, AGB/PPN/PN, and Extragalactic. A QR code is also present with the text "Scan to Mobile Splat".

**Welcome to the “New” Splatalogue!**

Over the past several years, there has been an active effort to improve the overall functionality and usability of Splatalogue. We are now offering new options to navigate the nearly 6 million spectral lines available via Splatalogue. The user community has suggested a simpler, more efficient way of searching for and obtaining the more common spectral line features from the radio to submillimeter wavelength.

This new **Splatalogue Basic** search page is now available and has several new and quick search features including:

**Redshift Converter:** Located in the center of the page, you can now enter your desired redshift and the appropriate frequency or wavelength conversion will be completed. Both the redshifted value and the rest frame value will be displayed under the Ordered column as labeled. If nothing is entered, the default redshift is set to 0.

**Wavelength or Frequency Search:** You can choose whether you would like to search by frequency or wavelength. The options range from Hz to THz for frequency and angstroms through meters for wavelength. Choose the best option from the drop down menu just beside the frequency search range.

**The Quick Picker:** Located on the far left. Popular species are included. Click on your favorite, hit search and the results will pop up. You can also limit the frequency by entering in your preferred frequency or wavelength range.

**Search Bar:** Located in the center of the page. Type in the name (or in some cases, the formula) of your favorite molecule and all species with that molecule name, including isotopologues of that species, will be displayed. Again, you can limit the frequency displayed by entering in your preferred frequency or wavelength range.

**Telescope Band Search:** Located at the center of the page. This feature allows users to search molecules by telescope bands of the GBT, Jansky VLA, and ALMA. Instead of limiting your search by typing in a specific frequency or wavelength range, you can choose your favorite telescope band of interest. NOTE: the current version only allows searching one band at a time!

**Astronomical Filters:** Located on the far right. This option allows you to limit your search to the species currently known within certain astronomical environments. Also available is the “Top 20 list” which is the same as in the ALMA OT. When selected, the Top 20 species will be displayed. You can also choose your own desired frequency or wavelength range here as well to limit the output.

**Any questions, comments, suggestions or concerns about Splatalogue?** We would love to hear from you! Please submit a Helpdesk ticket through the ALMA Science Portal. To reach the Helpdesk, head to the ALMA Science Portal at [www.alma-science.org](http://www.alma-science.org) and select your preferred ALMA Regional Center (ARC) on the ...

**Low-frequency**  
=   
**weak lines !!**

# **LOFAR SPECTROSCOPY**

**Why ? → a.o. RRLs**

# The Interstellar Medium (ISM)

Phase	T [K]	$n_H$ [cm $^{-3}$ ]	H-state	$X_e$	Obsv.
HIM	$10^6$	0.003	$H^+$	1	X-ray, UV
WIM	$10^4$	0.04	$H^+$	1	UV-IR
WNM	8000	0.1	$H^0$	0.1	HI (em)
CNM (HI)	100	50	$H^0$	$<10^{-3}$	HI (abs)
CNM ( $H_2$ )	30	>1000	$H_2$	$<10^{-7}$	CO

Galaxy evolution is driven by (SF) recycling of ISM

=> *What is the role of the atomic CNM ?*

=> *HI em (contaminated), HI abs (difficult)*

# Outstanding questions.

***“ Galaxy evolution is driven by recycling of the ISM ”***

**but,**

**what is the role of the cold atomic gas in galaxy evolution ?**

**In particular:**

- What is its morphology, dynamics and how does this compare to molecular, starforming & hot gas ?
- What is its thermal, pressure balance ?
- What is its ionization rate ?
- What is its chemical enrichment ?
- What is the CNM fraction of the HI 21 cm signal ?

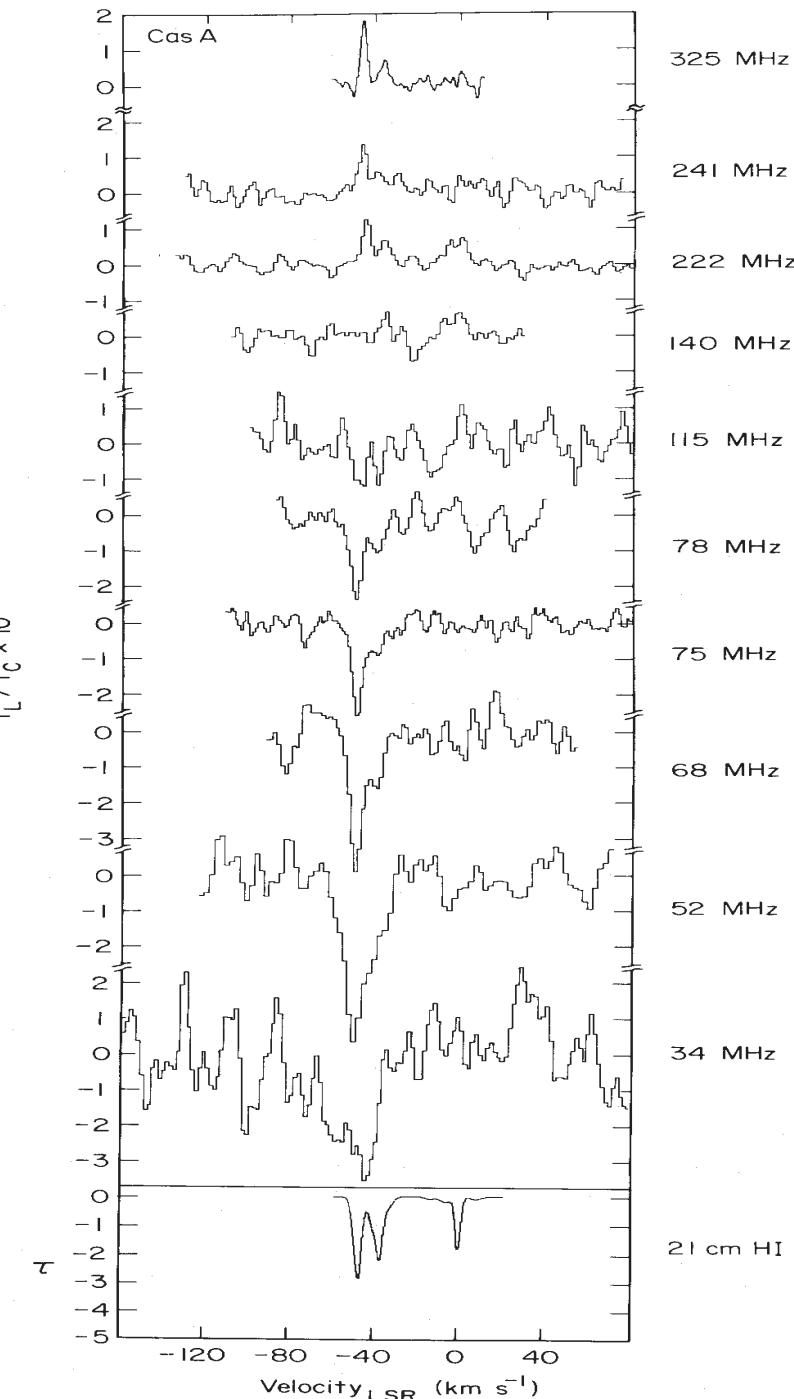
# Diffuse RRL's ( $\leq 1$ GHz)

Cas A (Payne+1989)

- RL: “ ions recombining with electrons ”
- Classical (Palmer & Zuckerman 1966)
  - ionised gas (WIM)
- Diffuse (Konovalenko & Sodin 1981)
  - Carbon, Hydrogen RRL's  
*C absorption  $\leq 130$  MHz  $\geq$  C emission*
  - CNM / PDR's
    - $T_e \sim 10\text{-}300 K, n_e \sim 0.01\text{-}1.0 cm^{-3}$
  - weak :  $\tau_{peak} \sim 10^{-4}$  to  $10^{-3}$  (MW)
  - many : 500  $\alpha$  lines (LOFAR)
  - Measure :  $\tau, v, \Delta v$
  - Derive :  $T_e, n_e, EM, \zeta(H), [C/H]$

---

(-) WNM :  $T \sim 10000$  K



# RRL models: Line width broadening

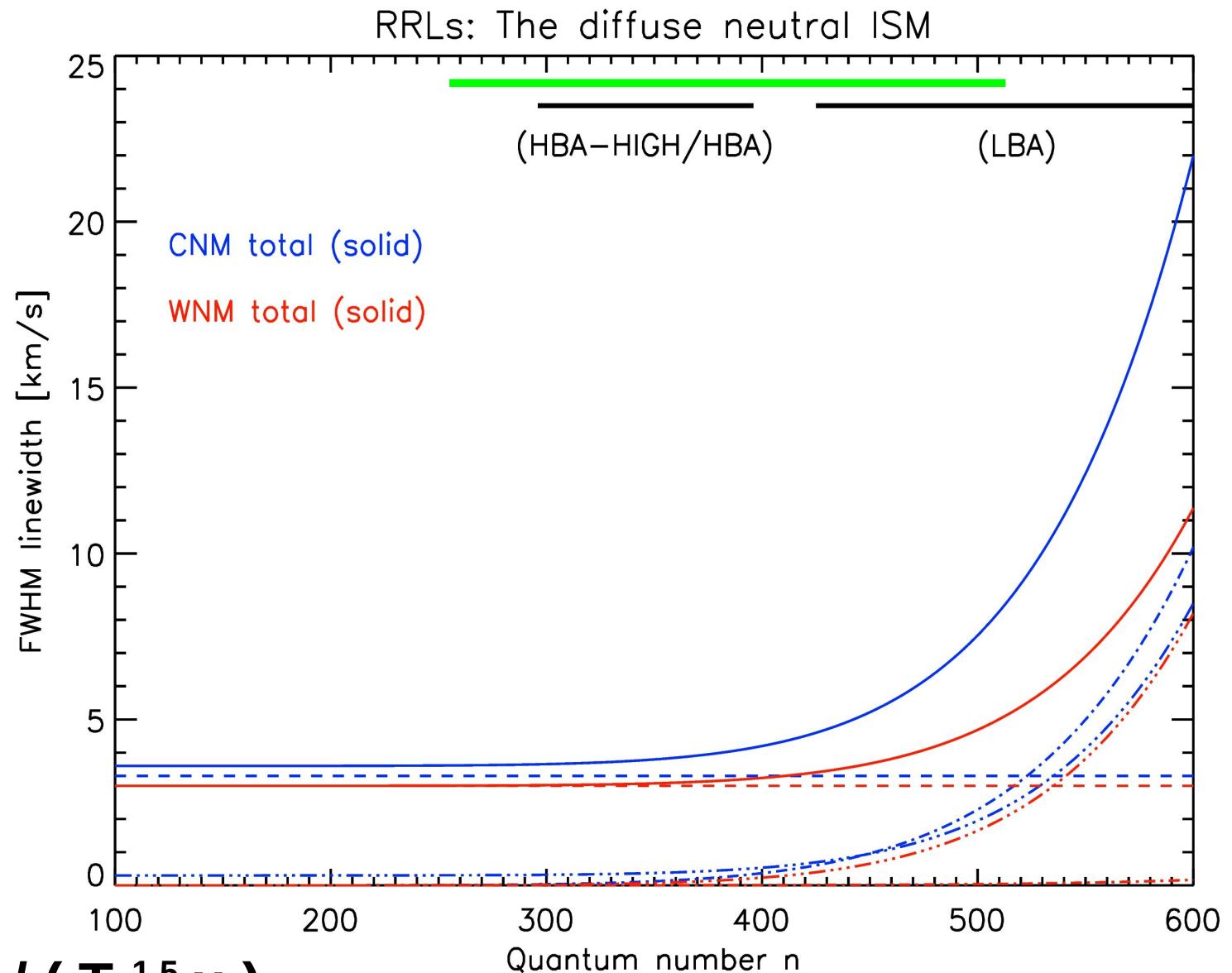
**Total (solid) width**

**Contributions:**

(1) Doppler  
(dash)

(2) Pressure  
(dash-dot)

(3) Radiation  
(dash-dot-dot)



$$\Delta V_P \sim (n_e n^{5.2}) / (T_e^{1.5} v)$$

$$\Delta V_R \sim (T_R n^{5.8}) / v$$

[N(HI)= $10^{20}$  cm $^{-2}$ ]

# RRL models: Integrated Optical Depth ( $\tau$ )

Phases:

**CNM (atomic):**

- $n_e = 0.05 \text{ cm}^{-3}$
- $T_e = 100 \text{ K}$

**WNM:**

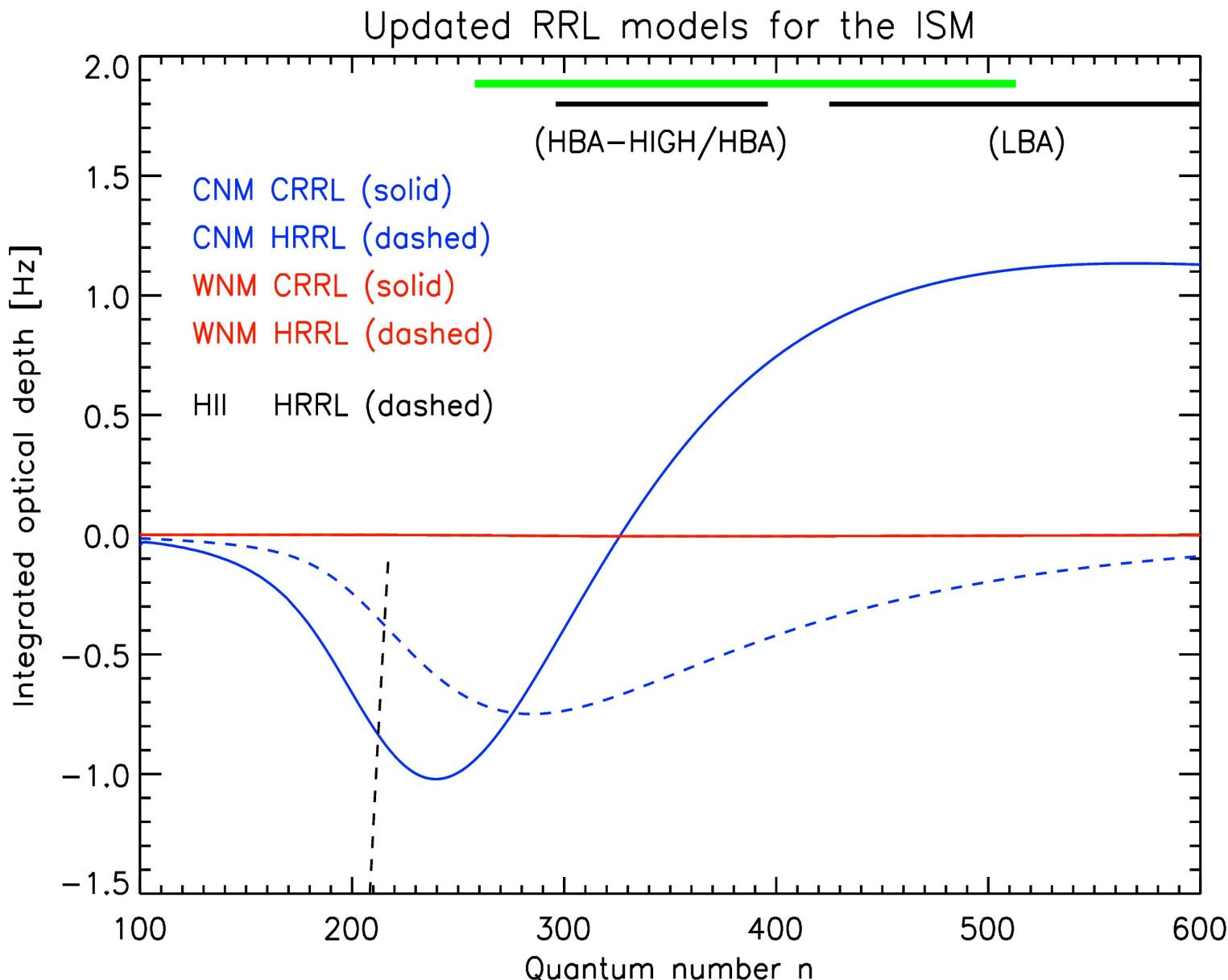
- $n_e = 0.01 \text{ cm}^{-3}$
- $T_e = 10^4 \text{ K}$

**HII:**

- $n_e = 300 \text{ cm}^{-3}$
- $T_e = 10^4 \text{ K}$

\* i.e. RRL can disentangle CNM, WNM in HI 21 cm

$$\tau_c \sim T_e^{-5/2} E M_c (b_n \beta_n)_c$$



[ $N(\text{HI}) = 10^{20} \text{ cm}^{-2}$ ]

# Returning to the BIG question.

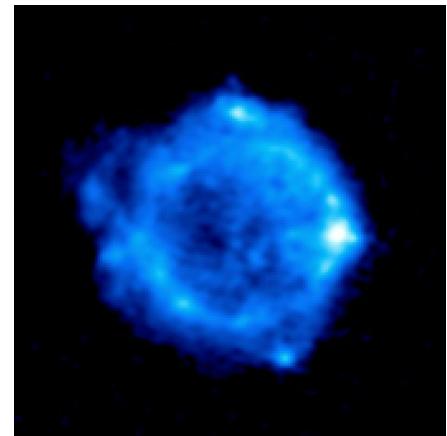
***“ Galaxy evolution is driven by recycling of the ISM ”***

but,

what is the role of the cold atomic gas in galaxy evolution ?

## Method : Low-frequency RRL's

- Localize RRL gas and compare w. CO, HI, HII
- Thermal properties of RRL gas      ( $T_e$ ,  $n_e$ , EM)
- Ionization rate of the RRL gas      ( $\zeta_H$ )
- Carbon abundance                        ([C/H])
- Kinematics of the RRL gas            ( $v$ ,  $\Delta v$ )



# RRL Surveys

The Power of LOFAR:

*Sensitivity , Resolution , FoV , BW*

=> “Survey speed” ( $\alpha$  ,  $\delta$  ,  $\lambda$ )

LBA 10 - 70 MHz : 400 RRL  $\alpha$ -lines

HBA 105 - 250 MHz : 100 RRL  $\alpha$ -lines

ASTRON



LOFAR

**A) Medium resolution Galactic survey**

*From degree-scales to >10'-scales*

**B) Galactic pinhole survey**

*Adding the <10'-scales*

**C) Extragalactic survey**

*The extragalactic (C)RRL universe*



# A: Galactic diffuse RRL's: All that was known sofar

(Kantharia & Anantharamaiah 2001)

**Major issues:**

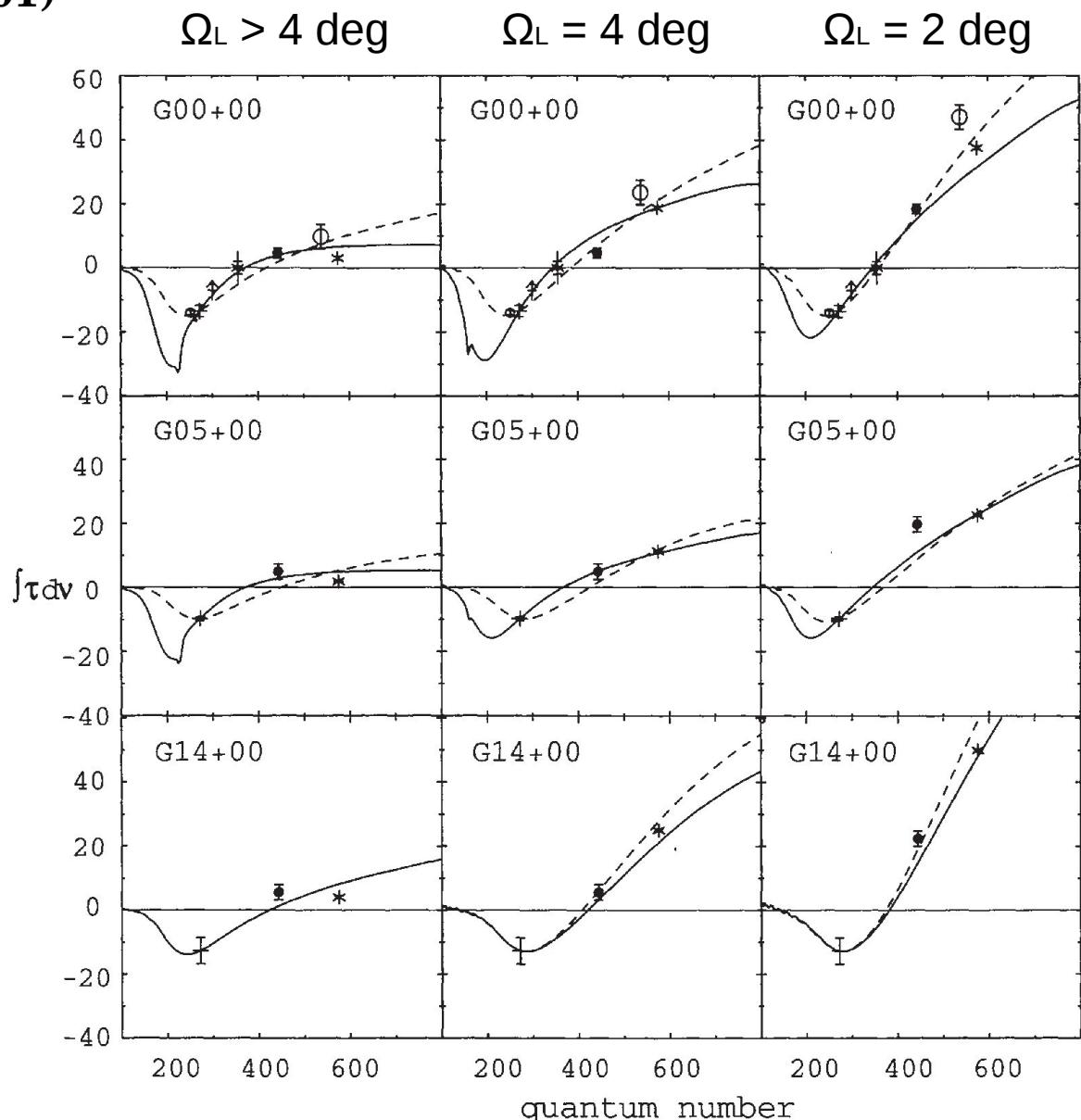
- (1) Beam FWHM > 2 deg.  
(unresolved cloud sizes)
- (2) Resolution mismatch  
(spatial & spectral)
- (3) Limited frequency coverage

**Data:**

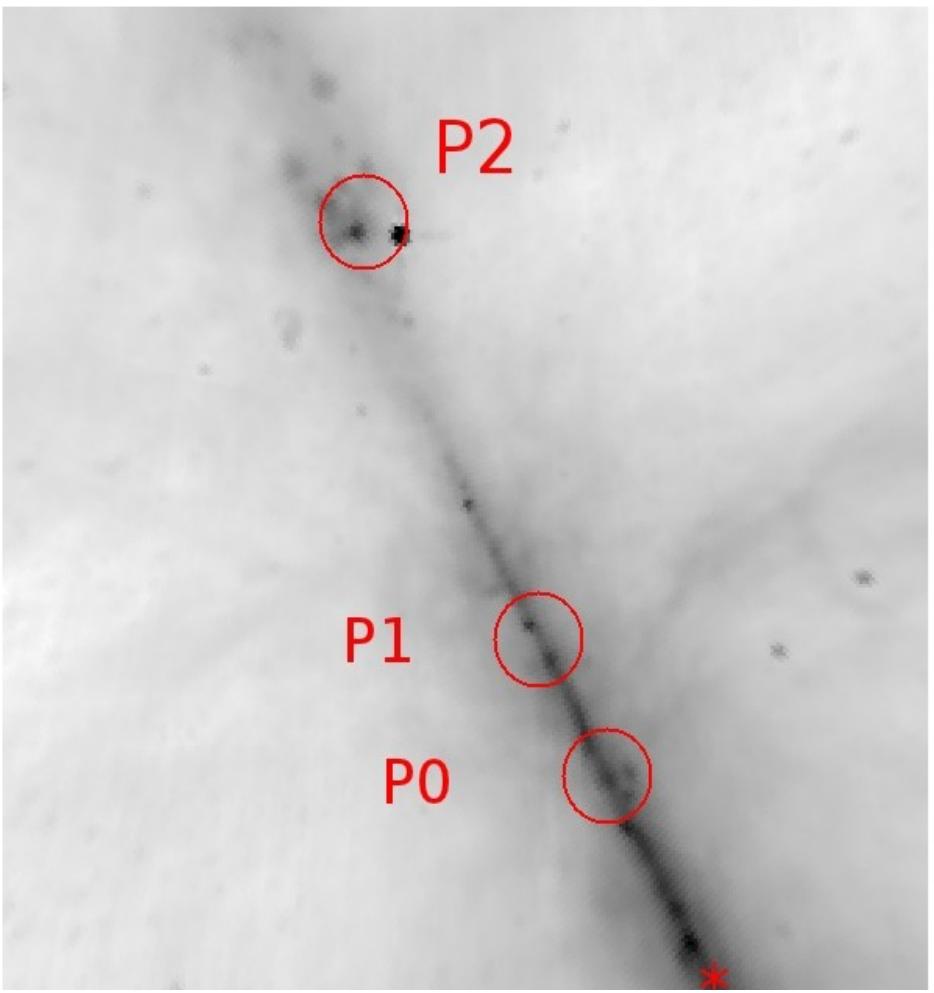
\* 328 MHz , Anantharamaiah (1985)

\* 76 MHz , Erickson et al. (1995)

\* 34 MHz , Kantharia & Anantharamaiah (2

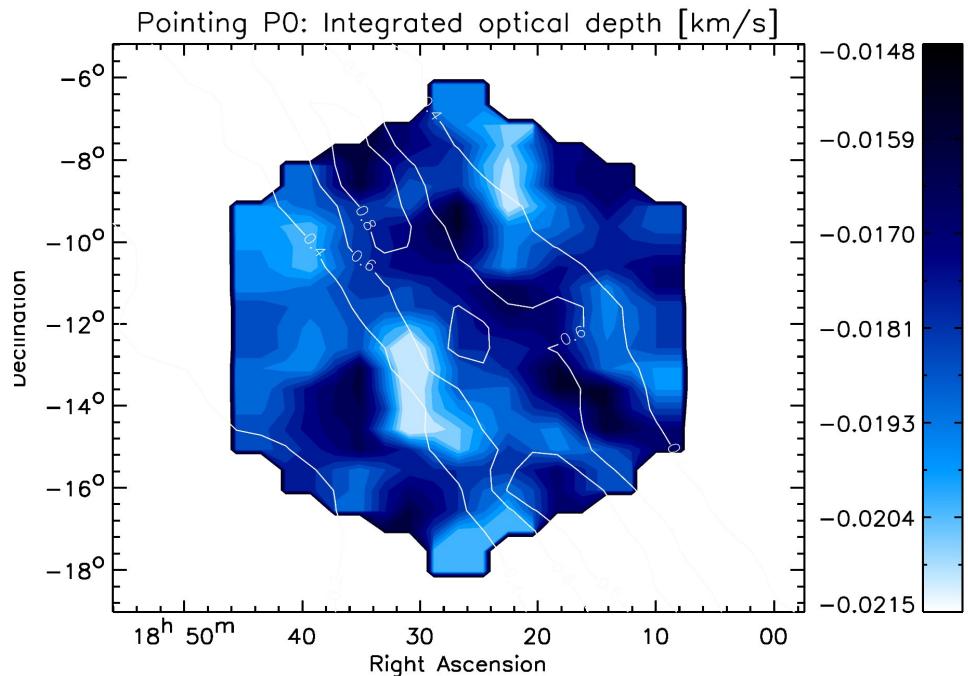
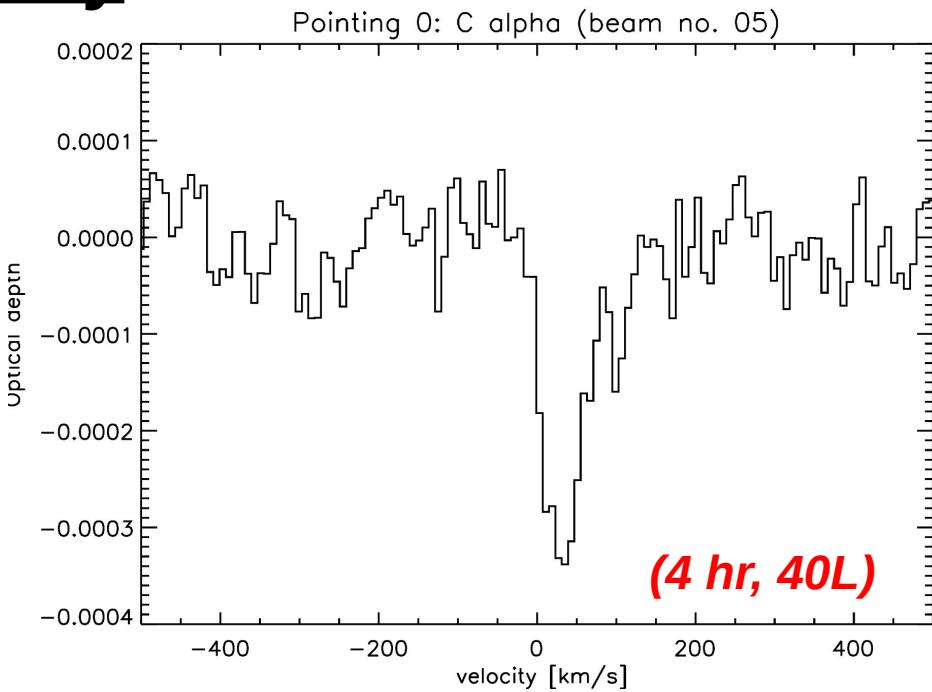


# A: LOFAR Galactic RRL Survey



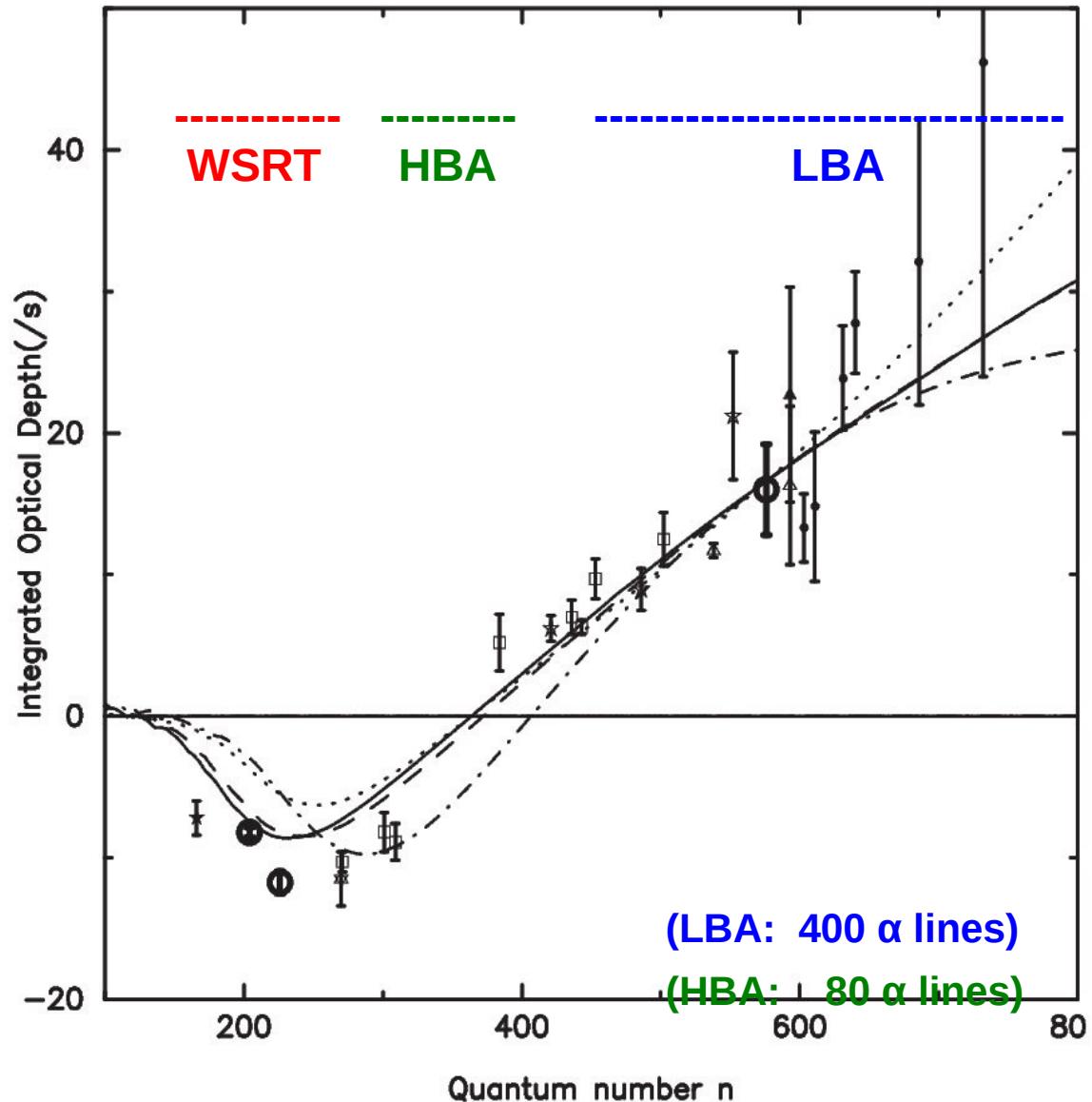
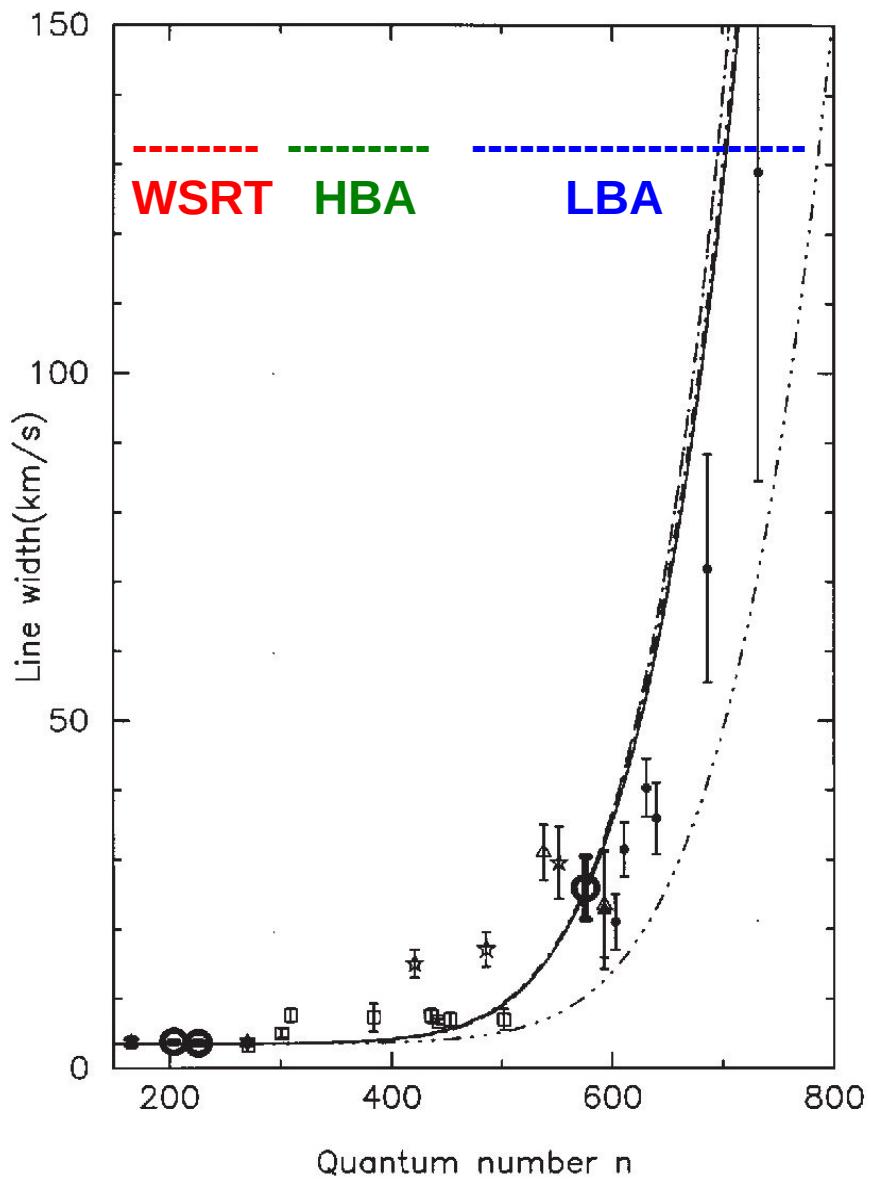
LOFAR:

- CRRL wide spread in Galactic plane
- improve resolution from degree to arcmin scales



## B: Galactic pinhole RRL's (all that was known sofar)

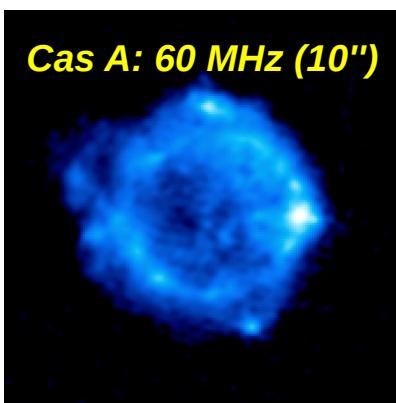
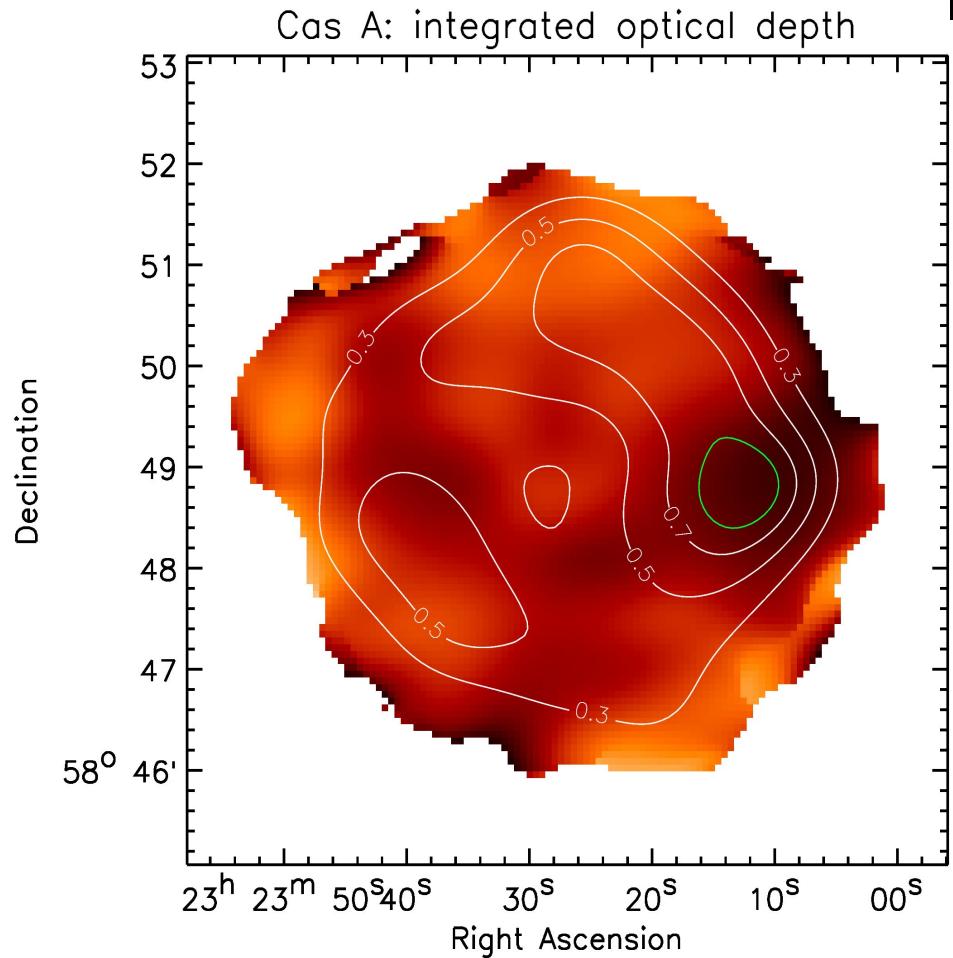
Cas A (Kantharia+1998)



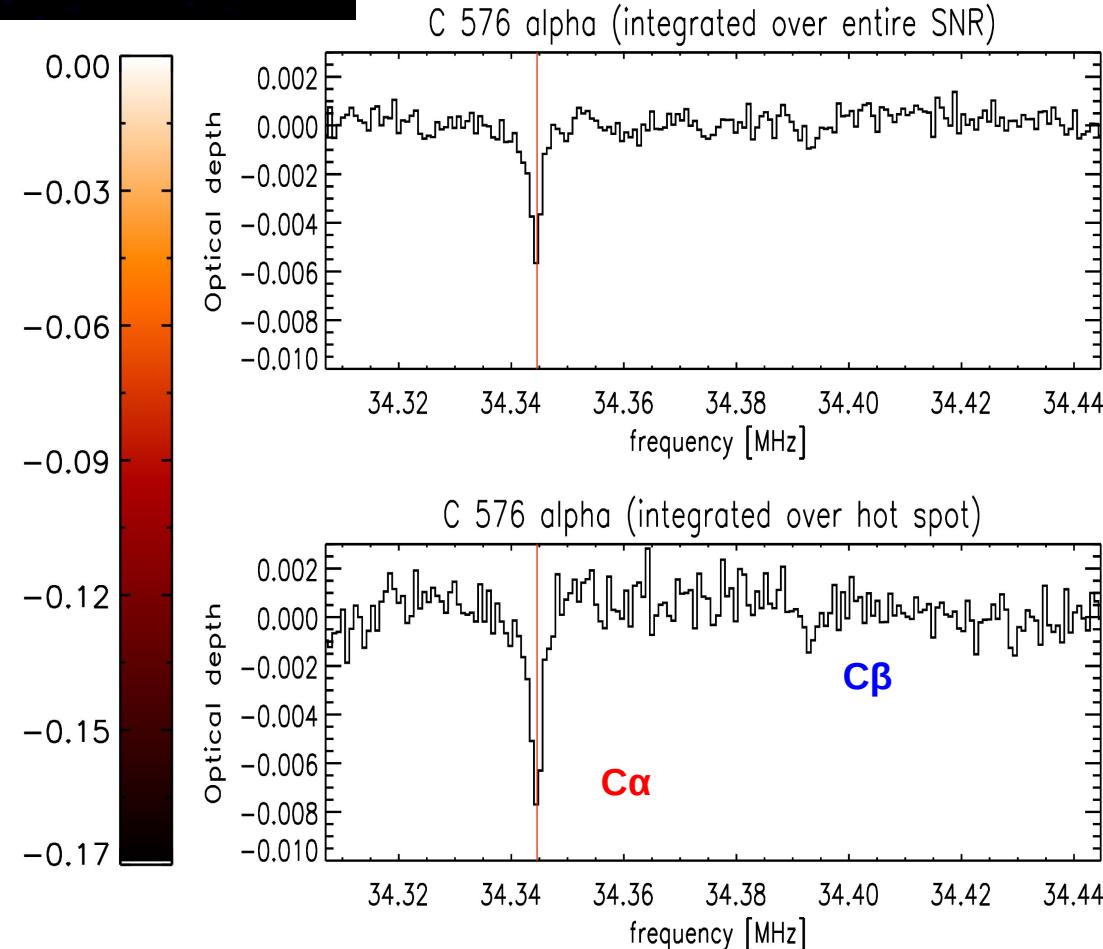
\* LOFAR: will provide better measurements at low frequencies (high  $n$ ), reduce the scatter !!

## B: Cas A (33-56 MHz)

CRRL line stacking (47 L)



CRRL single line (n=576)

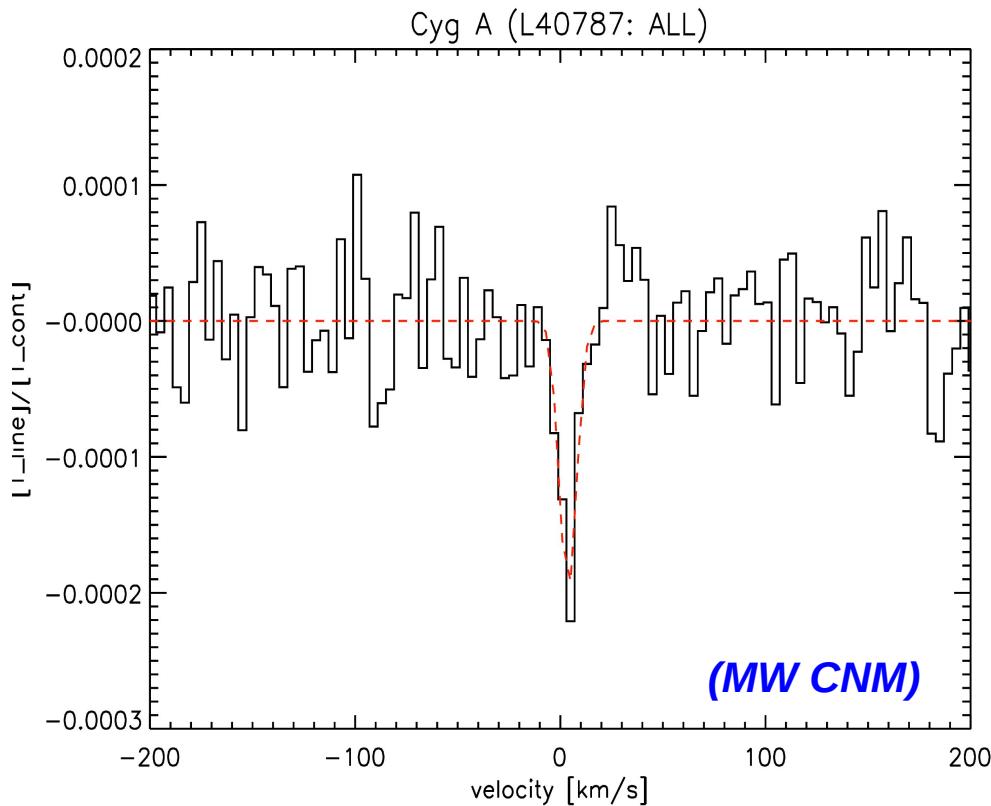


=> Integrated  $\tau$  varies over the supernova remnant

(Oonk+)

## B: LOFAR Galactic pinhole studies

Cygnus A (bright, extragalactic source; [Oonk et al. 2014](#))



*LOFAR-LBA (10h)*

*BW= 33-57 MHz*

*$\Delta f = 0.4 \text{ kHz}$*

*$\Delta v = 2-4 \text{ km/s}$*

### Measurements:

$\tau_{\text{PEAK}}$  =  $2 \times 10^{-4}$

$v_{\text{LSR}}$  = +4 km/s

FWHM = 10 km/s

### Derived properties:

$T_e$  = 110 K

$n_e$  =  $0.06 \text{ cm}^{-3}$

$\text{EM}_c$  =  $0.001 \text{ cm}^{-6} \text{ pc}$

[C/H] =  $1.8 \times 10^{-4}$

$\zeta_H$  <  $4 \times 10^{-16} \text{ s}^{-1}$

## C: LOFAR Beyond the Milky Way

$$\tau_{\text{PEAK}}$$

$$= 3 \times 10^{-3}$$

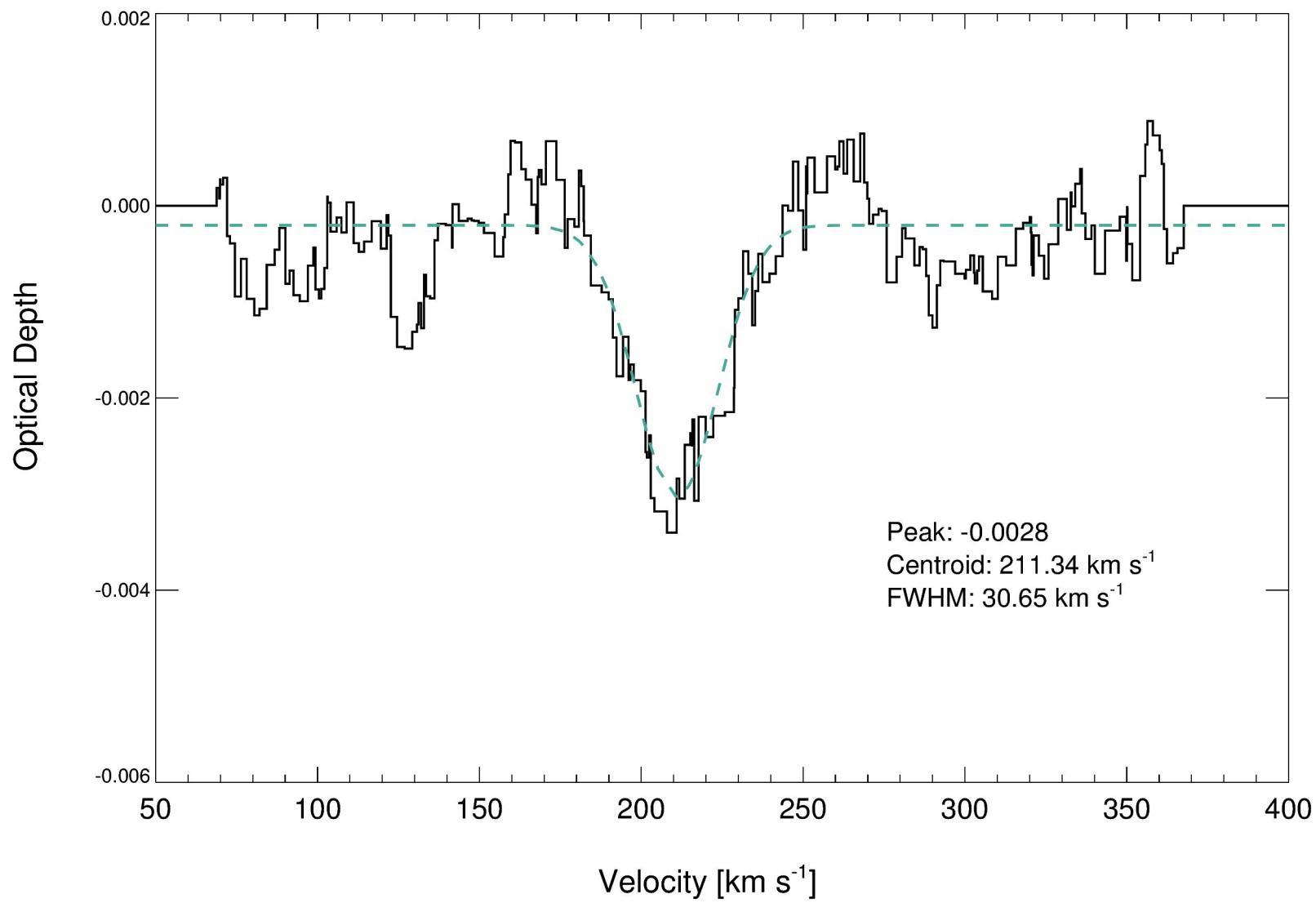
$$v_{\text{LSR}}$$

$$= +211 \text{ km/s}$$

$$\text{FWHM}$$

$$= 30 \text{ km/s}$$

M82 (LBA 60 MHz)



(Morabito+2014)

# **LOFAR SPECTROSCOPY**

## **capabilities**

## LOFAR: Capabilities for spectroscopy

**LBA 10-90 MHz , HBA 110-190 MHz , HGH 210-250 MHz**

**SB width is 0.1953125 MHz “fixed”**

**(→ 1000 km/s @ 60 MHz , 250 km/s @ 240 MHz)**

**SB central frequency “fixed (clock dependent)”**

**#SB per observation is max. 488 → 96 MHz**

**#Chn/SB**

**Interferometric : 64, 128, 256, 512, ... , 2048 (tested)**

**Beamformed : 64, 128, 256, ... , 2048 (tested)**

\* { beams, BW, freq. resolution } depends on data rate !!

\* LOFAR has no doppler tracking i.e. do this offline !!

# **LOFAR SPECTROSCOPY**

**Some examples**

# Example 1 “Simple” : M82 LBA observation

**Setup:** ( 2013, LC0, 5hr , 1s sampling)

(*Morabito+2014*)

- M82, 3C196 (dual beam)
- LBA outer 30-90 MHz (200 MHz clock)
- 128 Chn/SB, 1 SB = 52 GB (total 25 TB)

## Reduction/Calibration:

- Flag (aoflagger: std. settings)
- Avg (NDPPP Src/Cal: df = 4/128 , dt = 6/6)
- BBS calibrate 3C196 (1 ampl,phase p. SB)

\* check, check, check, check, check  
e.g. solutions (station, baseline)  
e.g. image cal (imag./spec.noise)

- BBS correct M82 using 3C196 solutions



# Example 1 “Simple” : M82 LBA observation

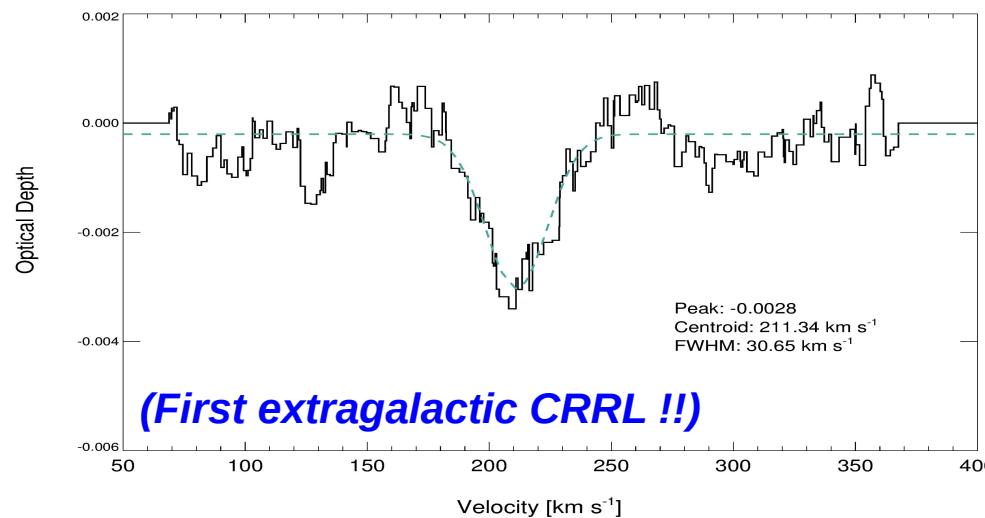
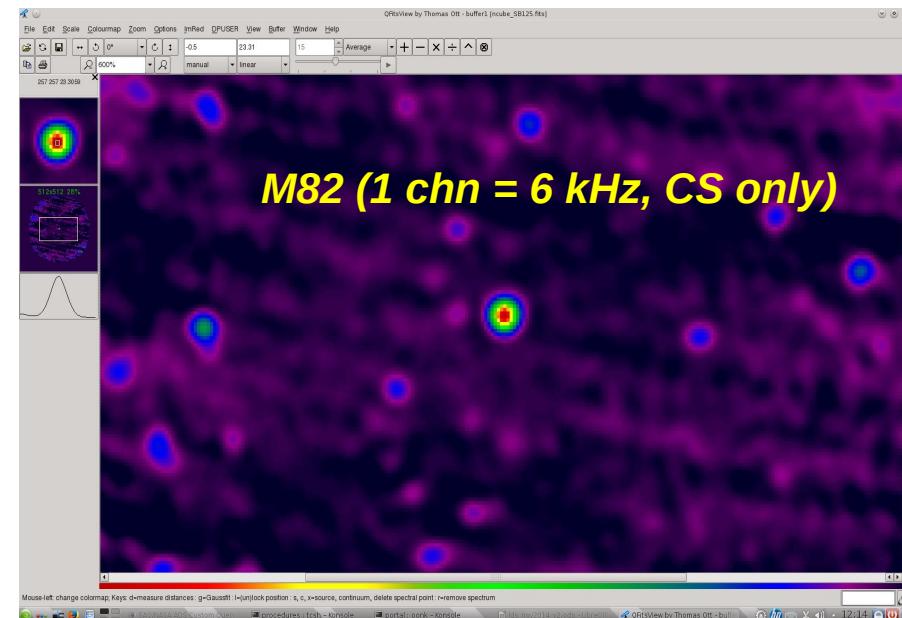
## Imaging: (limit memory)

- NDPPP (split SB in channels)
- AWimager (each channel)

(Morabito+2014)

## Analysis: (dedicated user scripts)

- CASA
  - \* convolve chn to same beam
- IDL (+ ds9 , qfitsview)
  - \* create 3D cubes
  - \* select spectra
  - \* bandpass (astro/poly)
  - \* continuum subtraction
  - \* spectral stacking
  - \* line fitting
  - \* map creation



## Example 2 “Interleaved”: M82 HBA observation

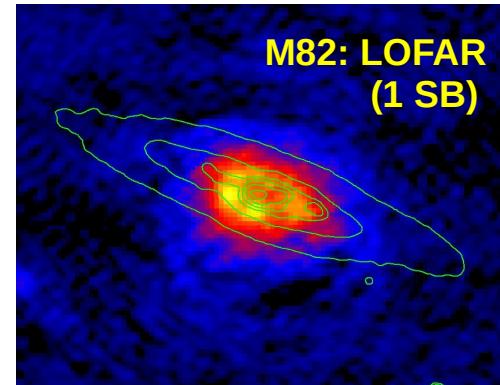
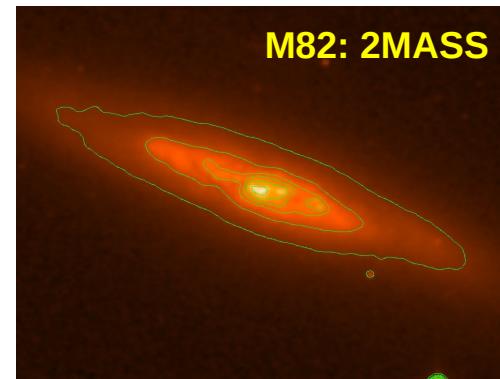
Setup: ( 2013, LC0, 5hr , 2s sampling )

(Toribio+ in prep)

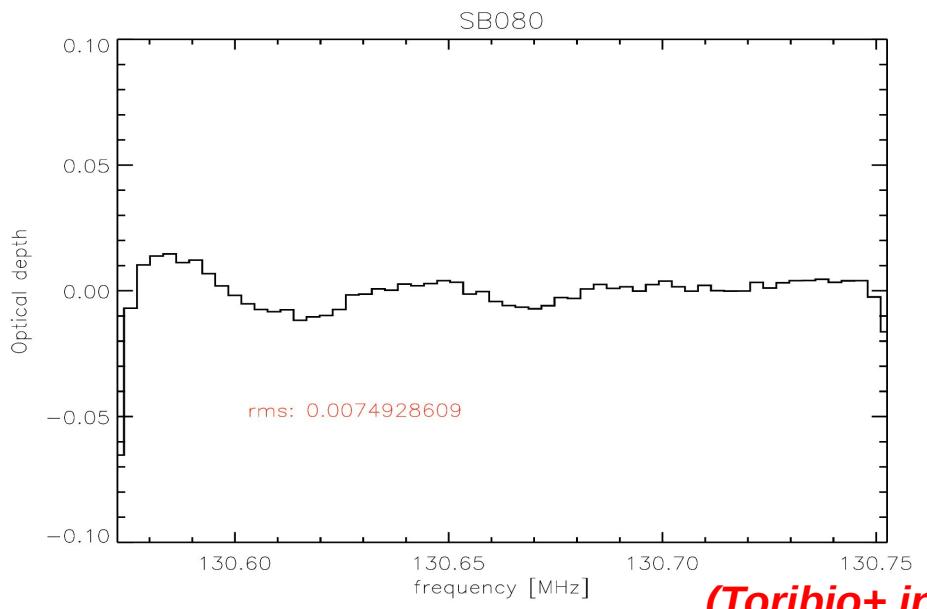
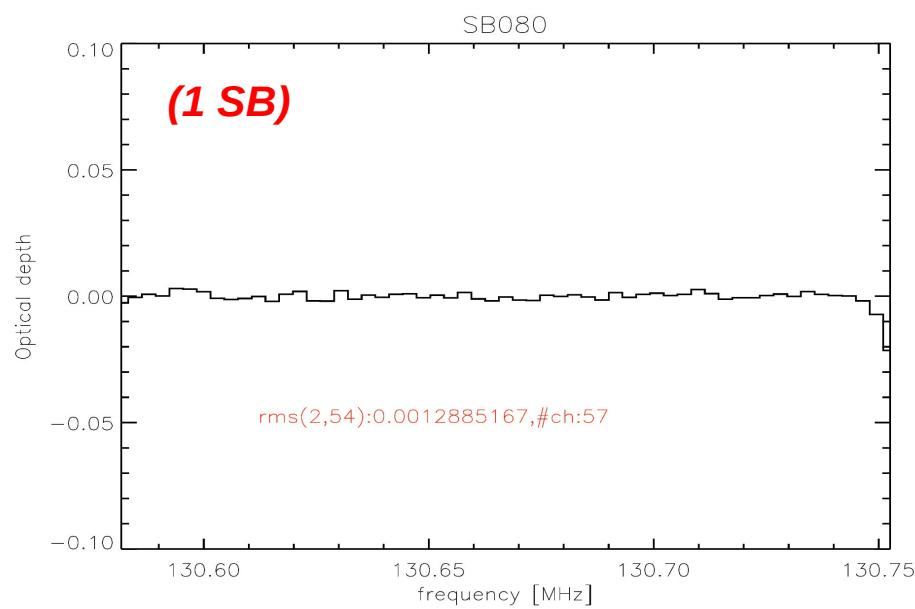
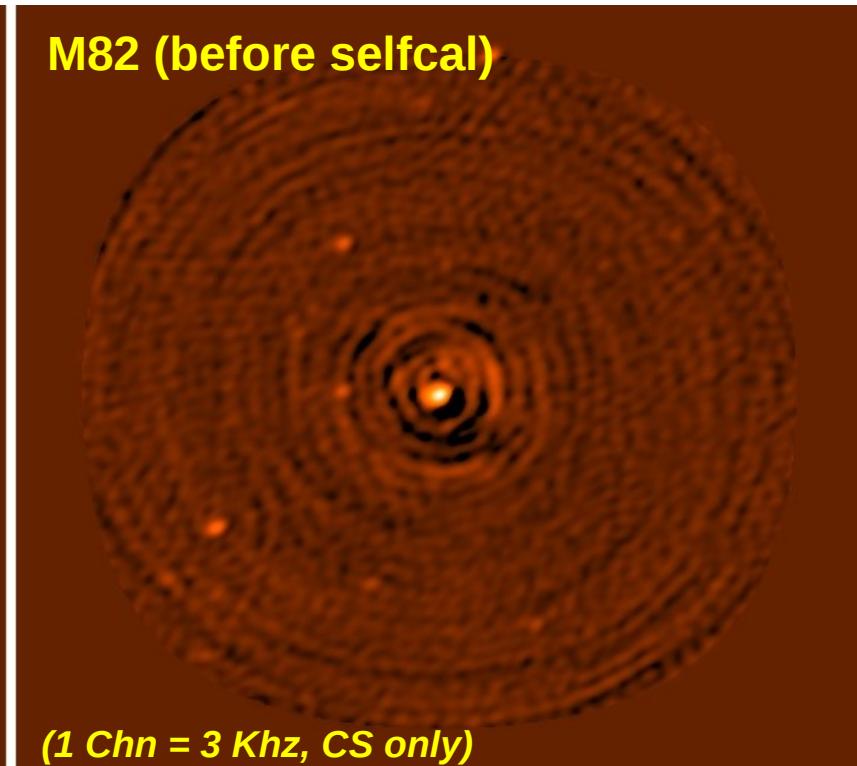
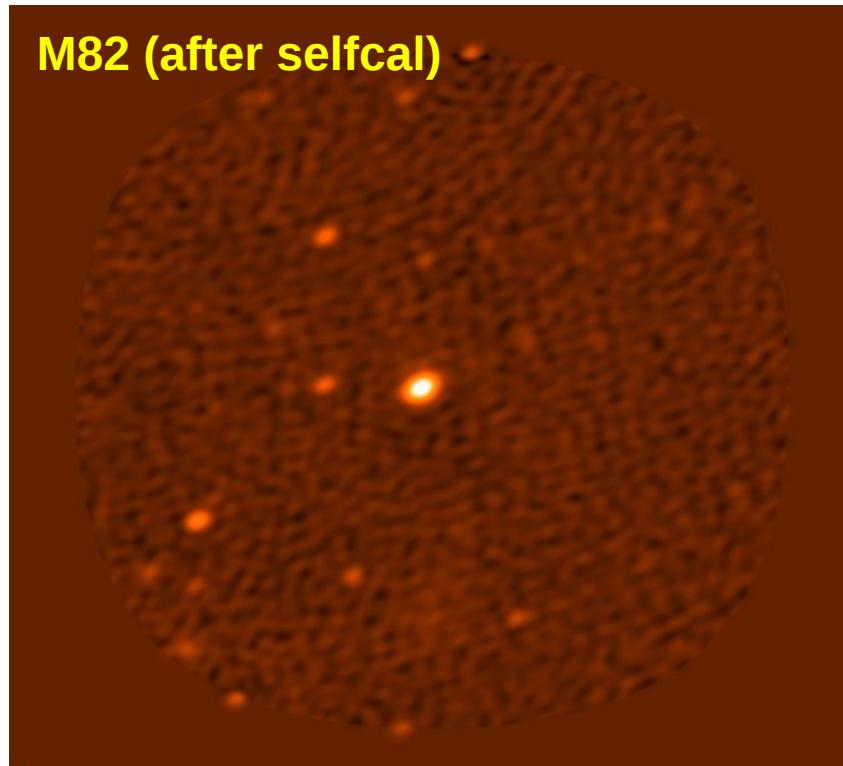
- 3C295, M82, 3C295 , M82, etc (single beam)
- HBA Dual inner 110-190 MHz (200 MHz clock)
- 64 Chn/SB, 1 SB = {35} GB (total 17 TB)

### Reduction/Calibration:

- Flag (aoflagger: std. settings)
  - Avg (NDPPP Src/Cal:  $df = 1/64$  ,  $dt = 1/1$ )
  - BBS calibrate 3C295 (1 ampl, phase per SB)
  - Export solutions and make time indep.
  - BBS correct M82 using 3C295 solutions
  - Create cp of M82 corr. and avg to 1 chn
  - Run selfcal on M82 corr., 1 chn set
  - Apply selfcal solutions to M82-corr 64 chn
- Imaging and Analysis as before ...



## Example 2 “Interleaved”: M82 HBA observation



(Toribio+ in prep)

## Example 3 “Simple+Stitch”: 3C241 HBA-HIGH obsv

Setup: ( 2013, LC0, 4hr , 2s sampling )

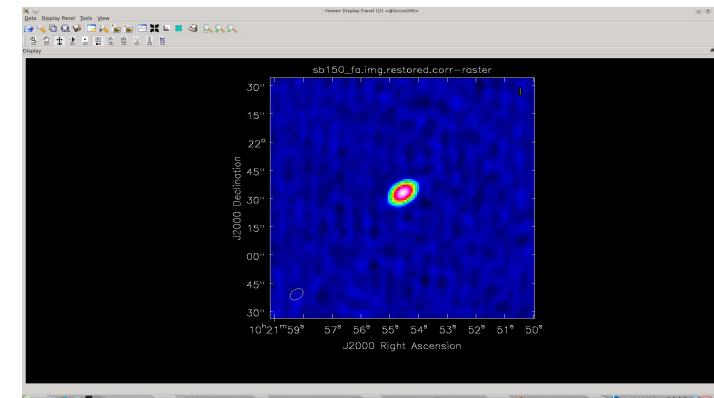
(Oonk+ in prep)

- 3C196, 3C241, 3C196 (single beam)
- HBA-HIGH joined 210-250 MHz (200 MHz clock)
- 64 Chn/SB, 1 SB = 20 GB (total 10 TB)

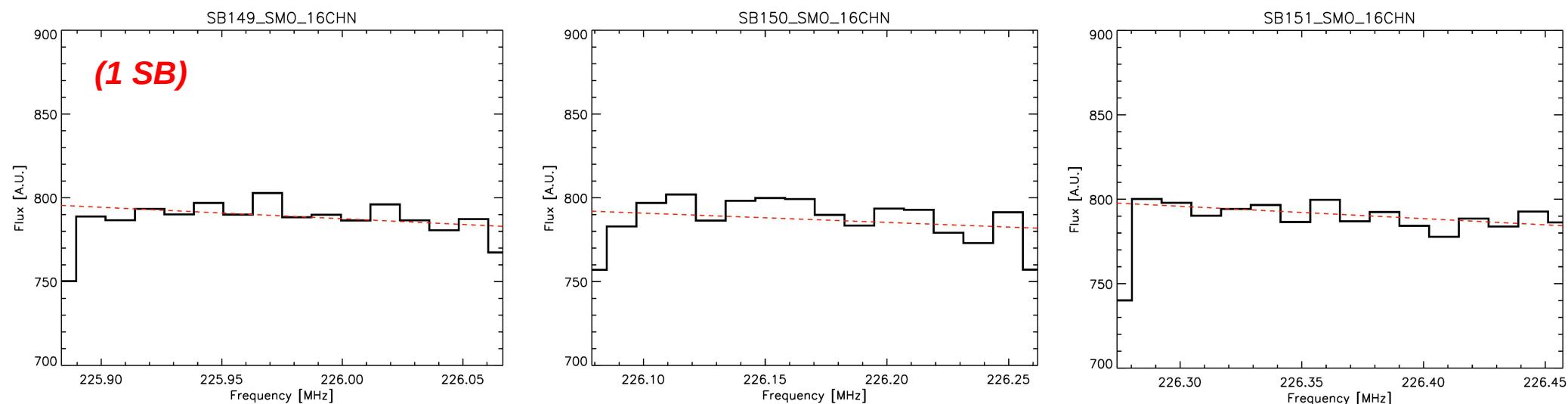
### Reduction/Calibration:

- Flag (aoflagger: std. settings)
- Avg (NDPPP Src: df = 4 , dt = 5)
- BBS calibrate 3C241 (1 ampl,phase p. SB)
- Smooth solutions in time (lowers noise)
- BBS correct 3C241

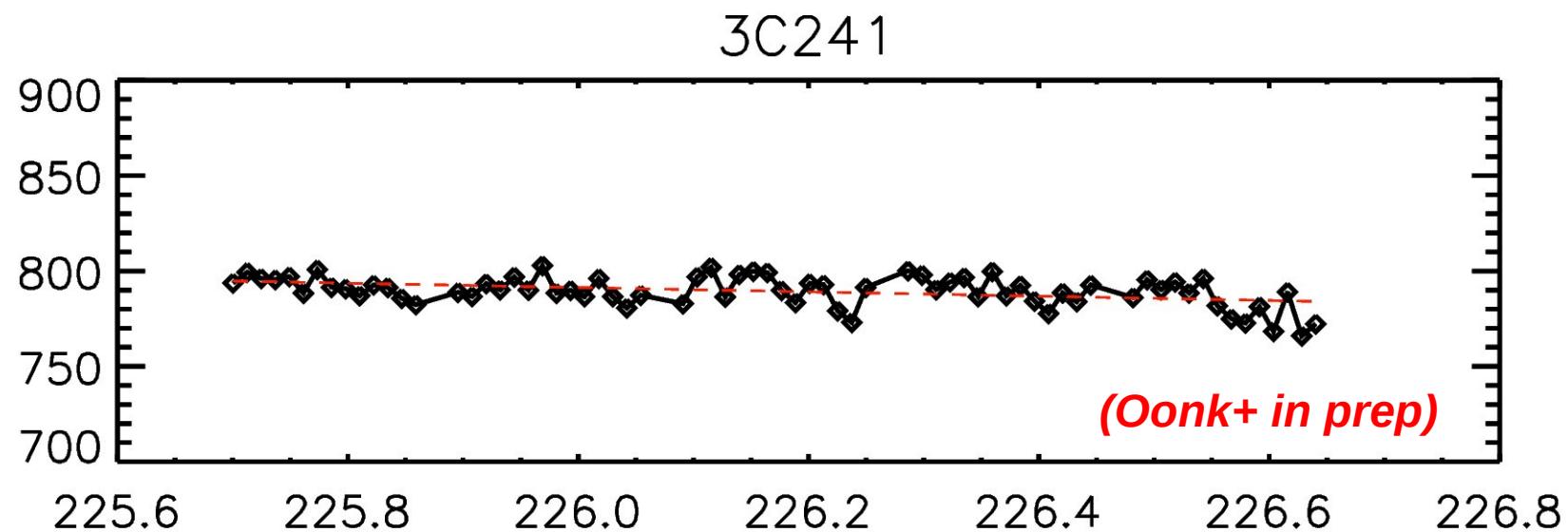
→ Imaging & Analysis as before ... ,  
except for “stitching” of SB's



# Example 3 “Simple+Stitch”: 3C241 HBA-HIGH obsv



\* blank edges and stitch: 5 SB = 1 MHz = 1300 km/s



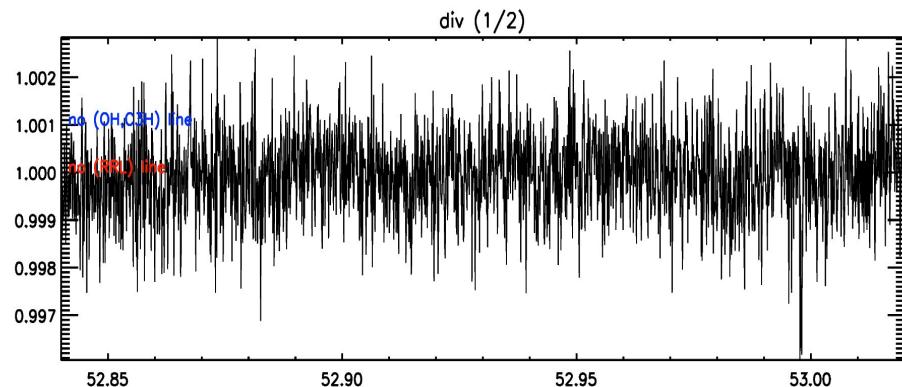
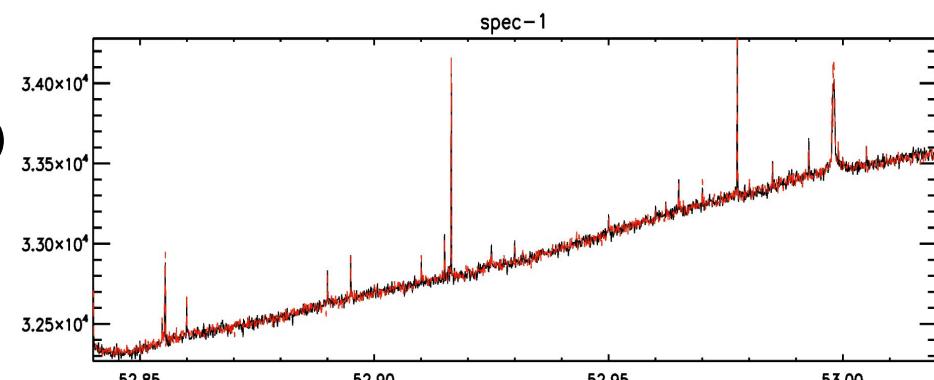
## Example 4: Beamformed observations: W3OH

**Setup:** ( 2012, LC1, 8hr , 0.02s sampling)

- W3OH ON/OFF (2 beams)
- LBA outer 30-90 MHz (200 MHz clock)
- 2048 Chn/SB, 1 beam = 111 GB (7 SB) (total 0.2 TB)

**Reduction/Calibration:**

- Convert HDF5 to MS (python)
  - \* → dynamic spectrum
- Flag (aoflagger: upd strategy)
  - \* → check flagging
- Avg + Filter (python)
  - \* → 1 spectrum per SB

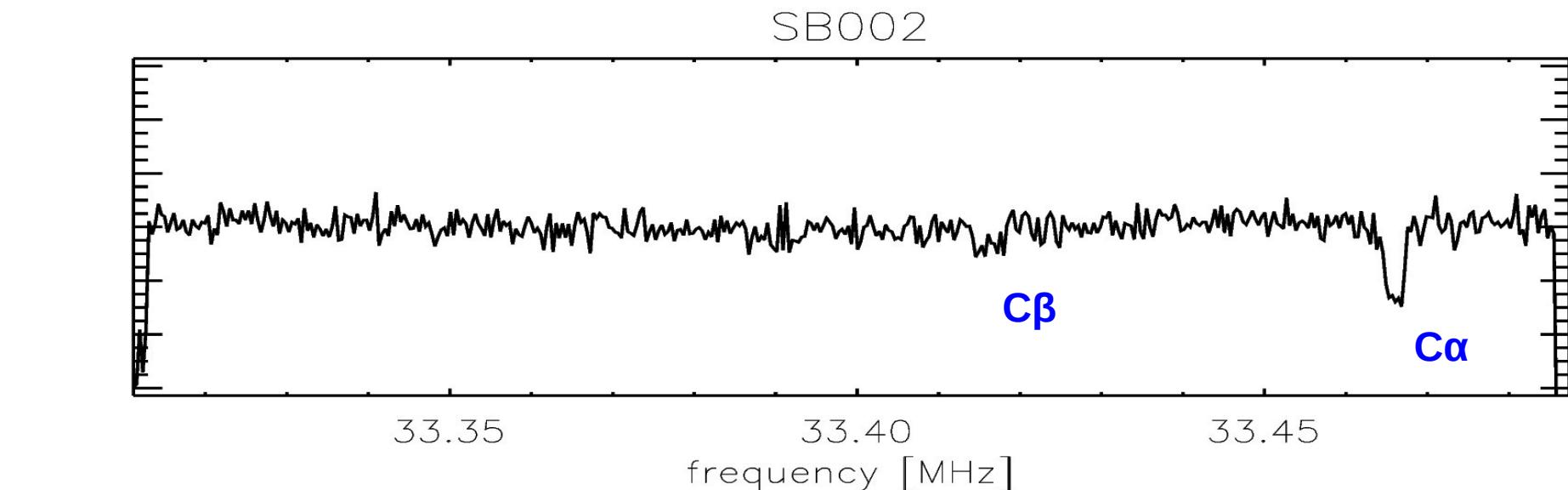
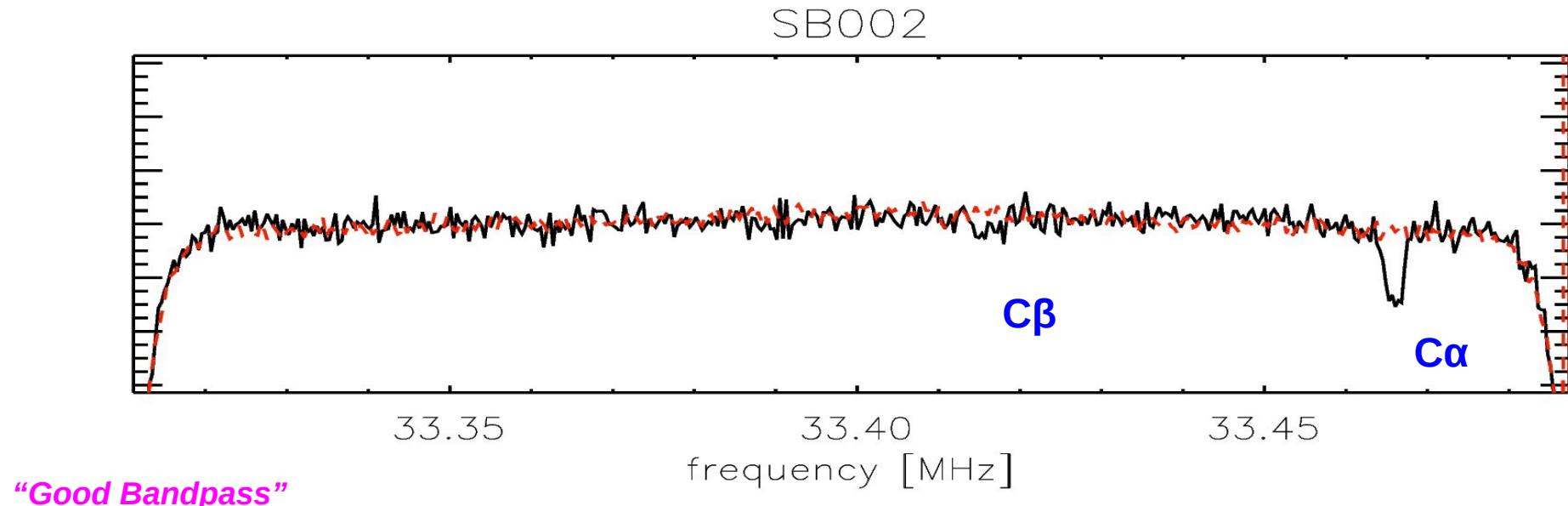


# **LOFAR SPECTROSCOPY**

**bandpass, bandpass, ...**

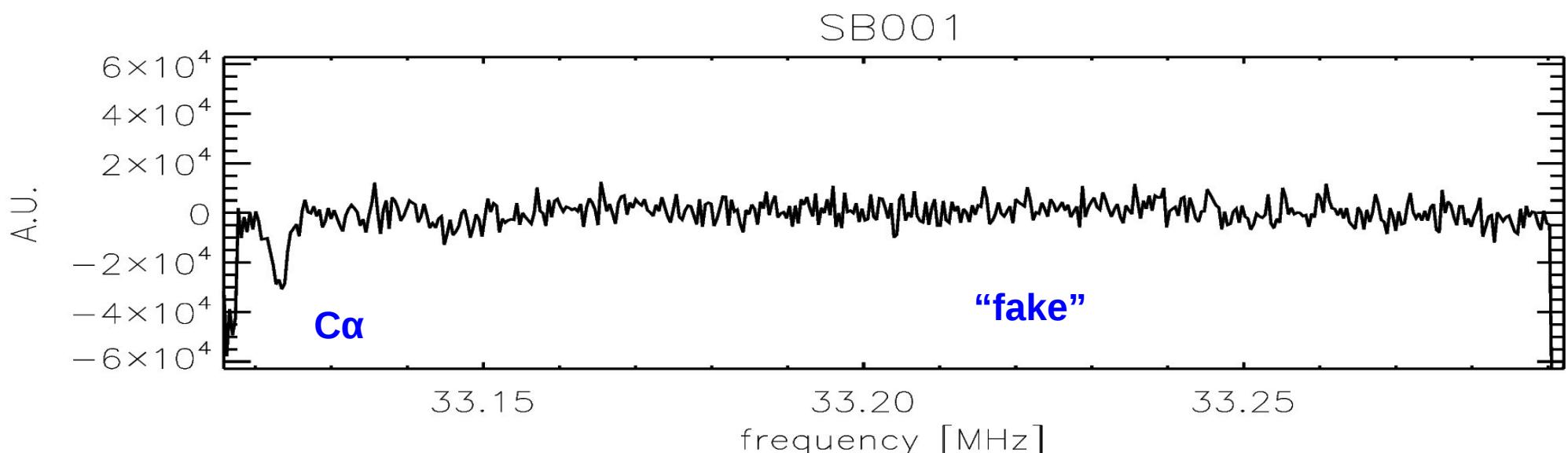
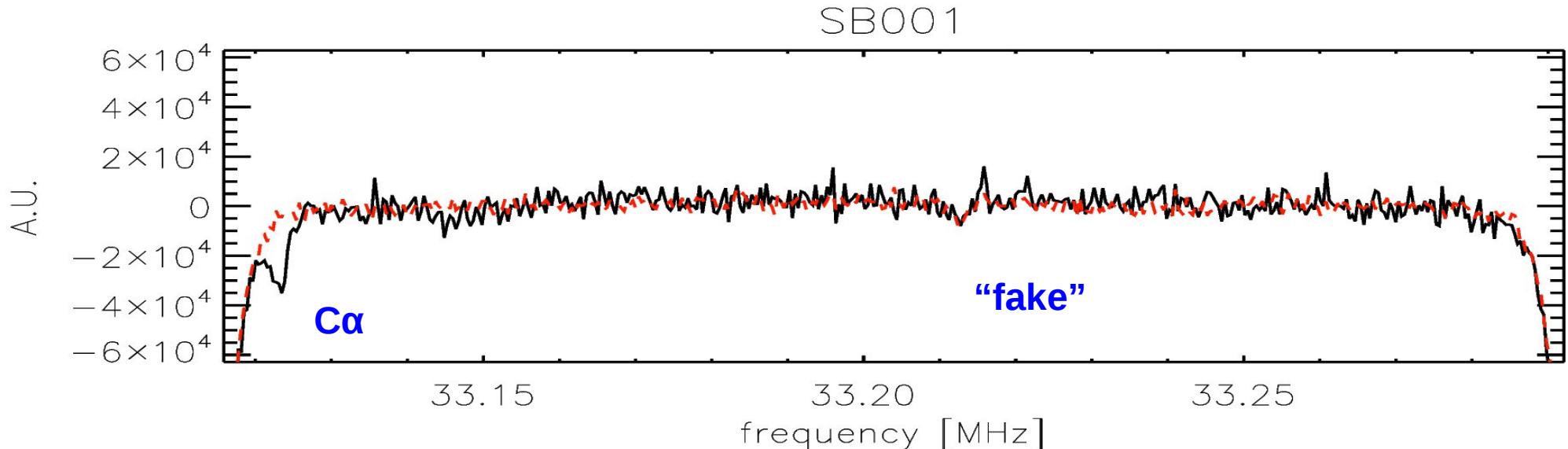
# Single SB: Astronomical Bandpass I

Bandpass: Cas A (black), Cyg A (red): Real detections of C-alpha, C-beta



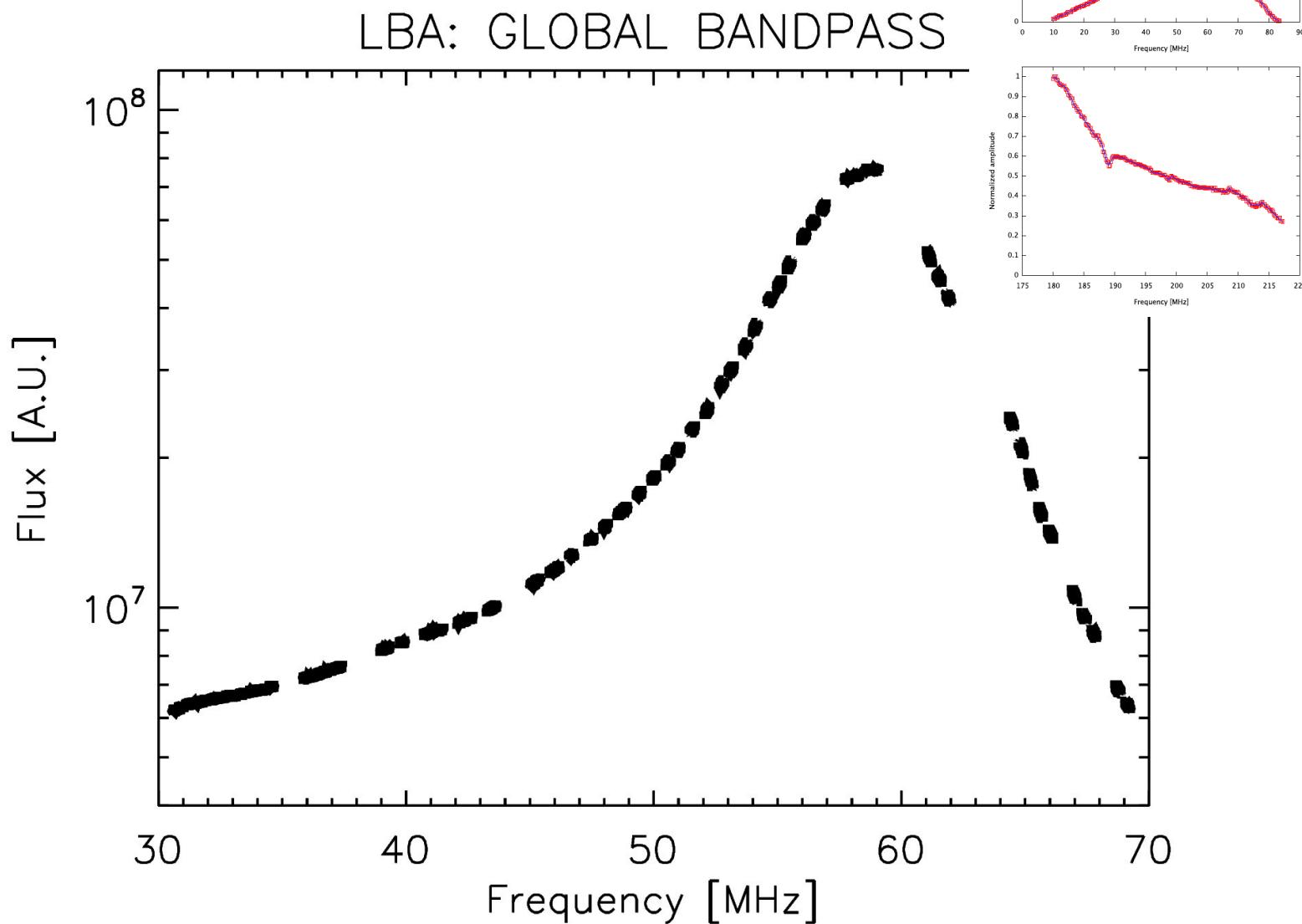
# Astronomical Bandpass II

**Bandpass: Cas A (black), Cyg A (red): fake and real detections**



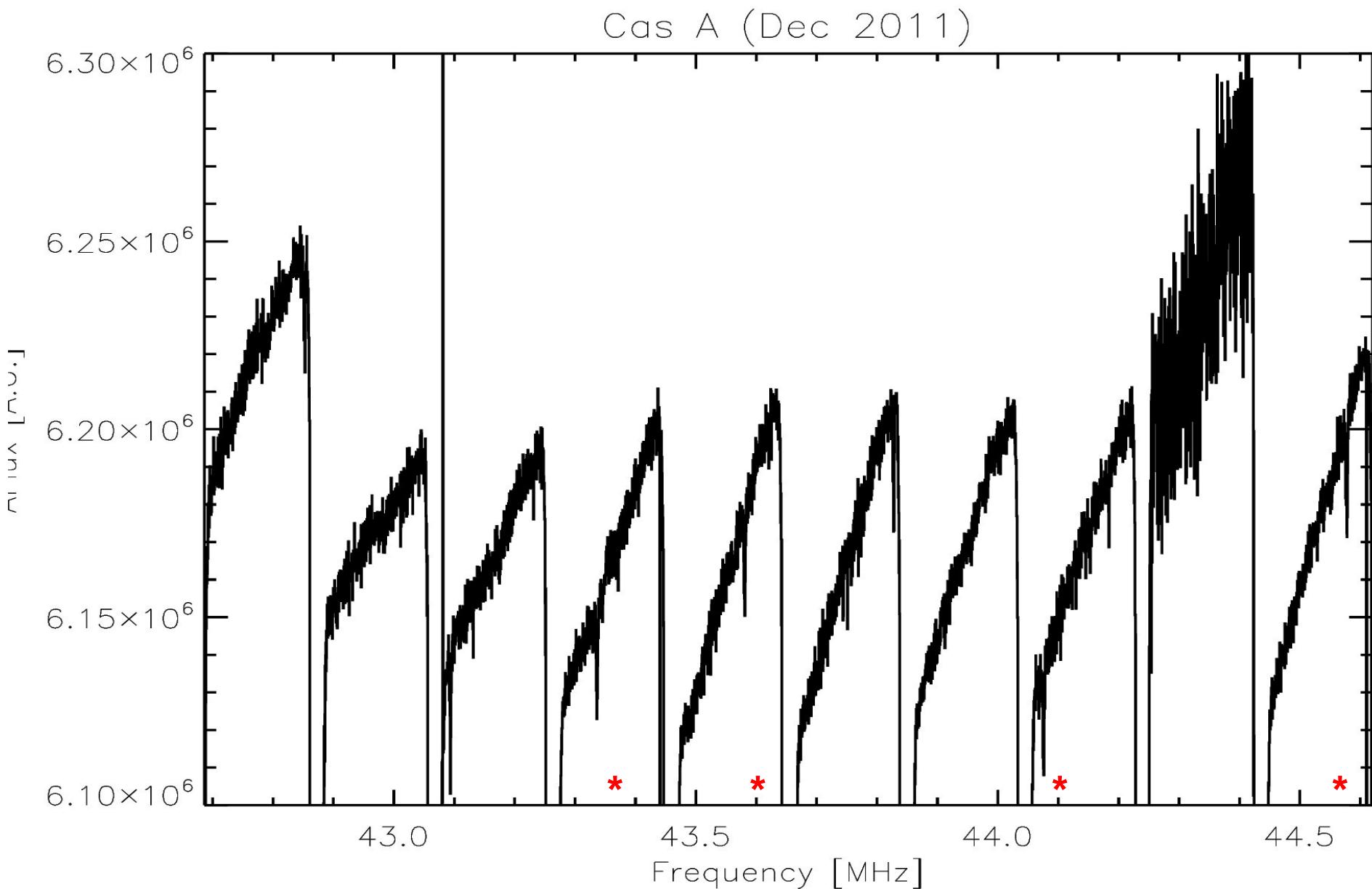
\* for narrow lines often a low-order polynomial is sufficient

# Global bandpass



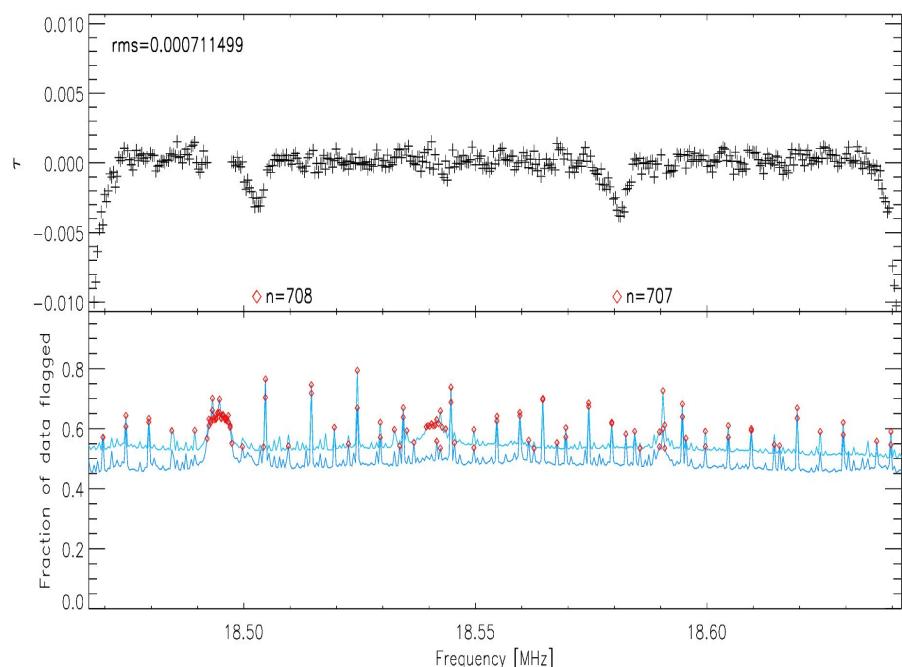
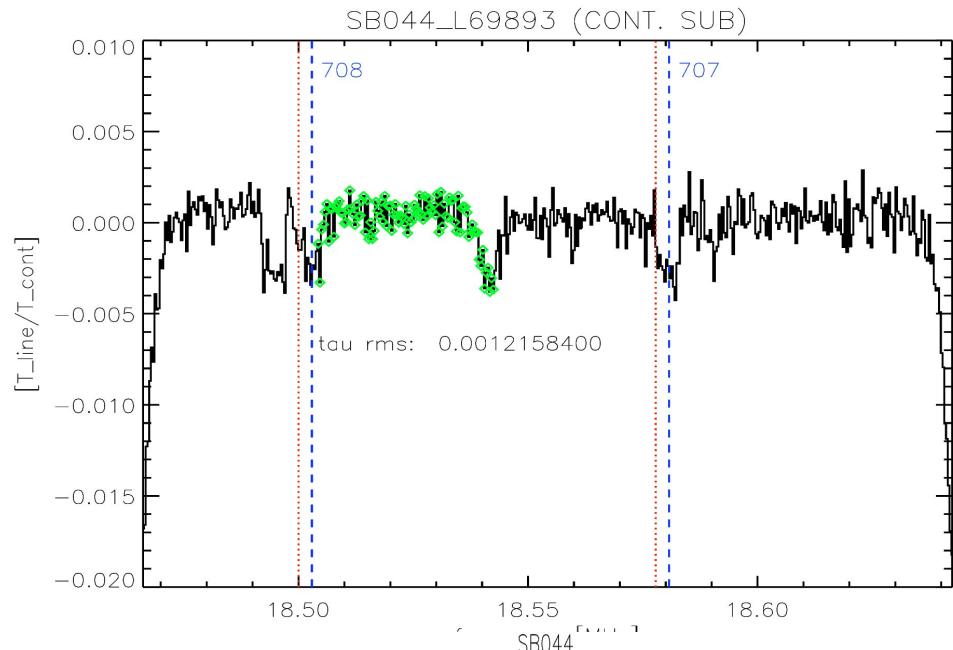
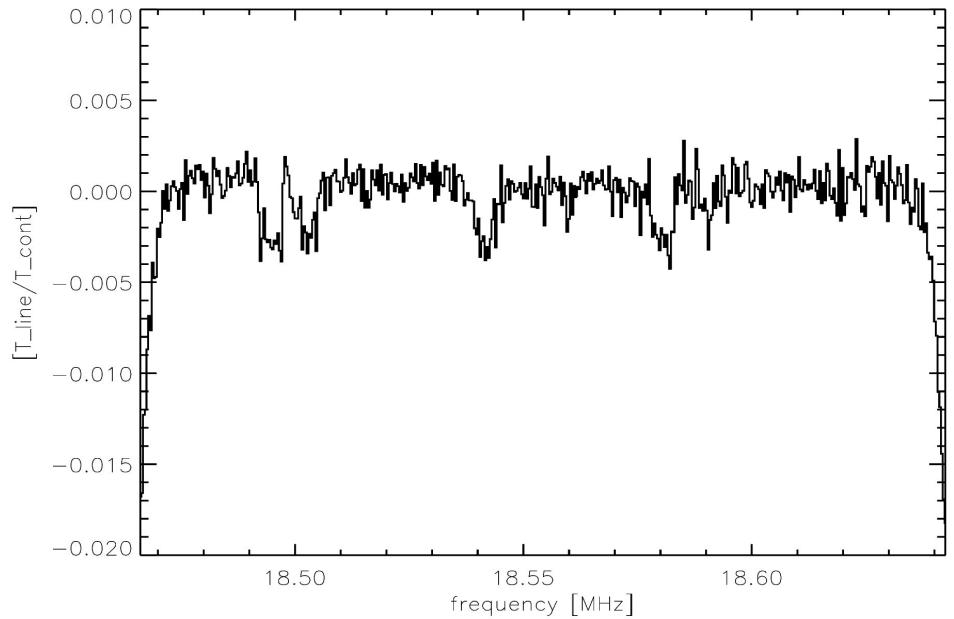
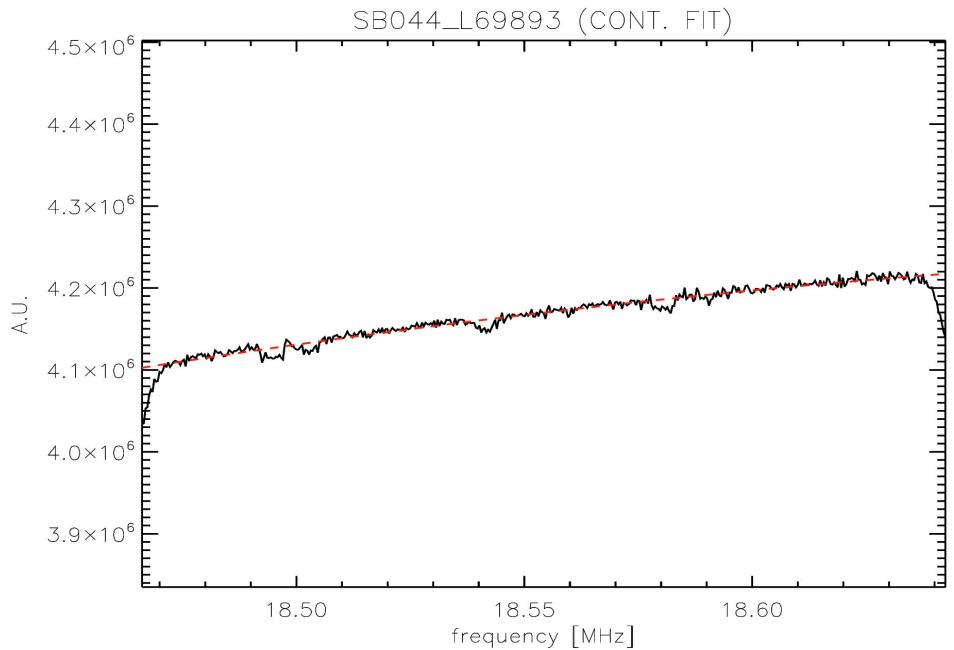
\* LOFAR system response convolved with source spectrum

# Spectral gaps & global calibration per SB



\* poly-bandpass is ok for narrow line ( $\ll 1$  SB), but not for broad lines !!

# bandpass & flagging statistics



# **LOFAR SPECTROSCOPY**

## **Computing**

- there is no spectroscopy pipeline ... yet ...**

# Computing requirements.

## **Ex. 1. M82 LBA (128 chn/SB)**

- raw data storage **52 GB/SB**
- processing ca. **~12 Hr per SB**

**(64 GB ram, 1 core)**

## **Ex. 2. M82 HBA (64 chn/SB)**

- raw data storage **35 GB/SB**
- processing ca. **~48 Hr per SB**

**(256 GB ram, 1 core)**

## **Ex. 3. 3C241 HGH (64 chn/SB)**

- raw data storage **20 GB/SB**
- processing ca. **~6 Hr per SB**

**(64 ram, 1 core)**

## **Ex. 4. W3OH (2048 chn/SB)**

- raw data storage **111 GB/beam**
- processing ca. **~48 Hr per beam**

**(64 GB ram, 1 core)**

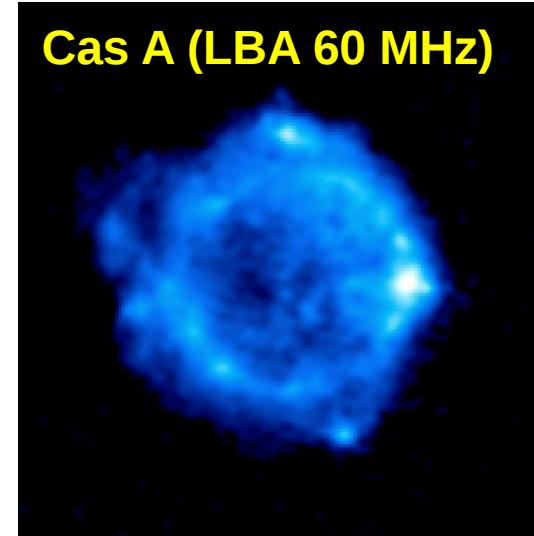
**\* software: LOFAR tools , CASA , IDL/python (ds9/qfitsview)**

# Conclusions

## Scientific

**LOFAR & low-frequency spectroscopy: YES !**

- Spectroscopic results stable (>2 years)
- Spectral RMS:  $\sqrt{(\text{time})}$  ,  $\sqrt{(\text{chan})}$  ,  $\sqrt{(\#SB)}$



## How-to ?

**Spectroscopy is still an 'export mode' , but can be reduced to 'do your best continuum calibration and then image all channels'**

***LOFAR/CASA tools with minor additions:***

***IF : aoflagger NDPPP, BBS, AWimager***

***BF : HDF5 → MS , (python, idl)***



***Help ? contact : oonk@astron.nl***

**\* Observatory processing for >64 chn/SB not supported**

