LOFAR: Spectral Line Data Analysis.

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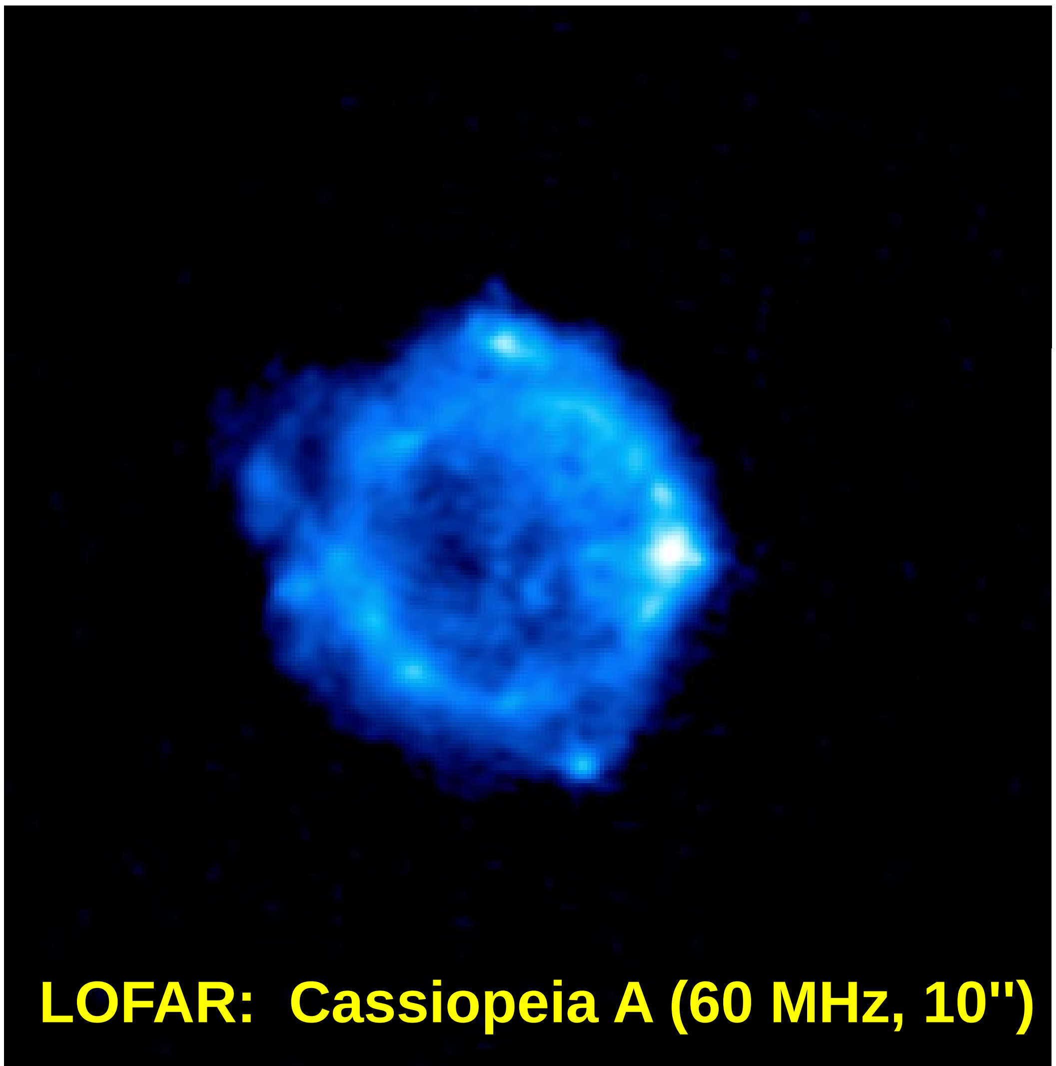
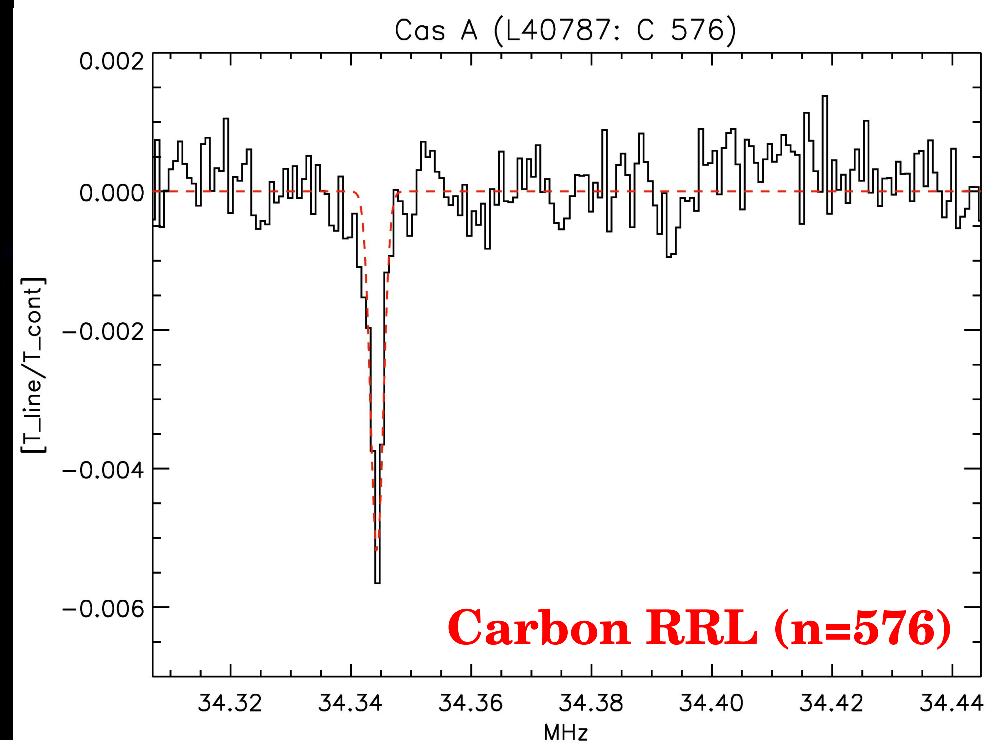




LOFAR: Spectral Line Data Analysis: Outline

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 ($z > 4.7$ <=> $f < 250$ MHz)

2) Molecules (OH, H_2CO, NO etc.)

3) Radio Recombination Lines (“Rydberg atoms”)

Line lists:

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

LOFAR: Spectral Line Data Analysis.

ASTRON

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

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 (≤ 1 GHz)

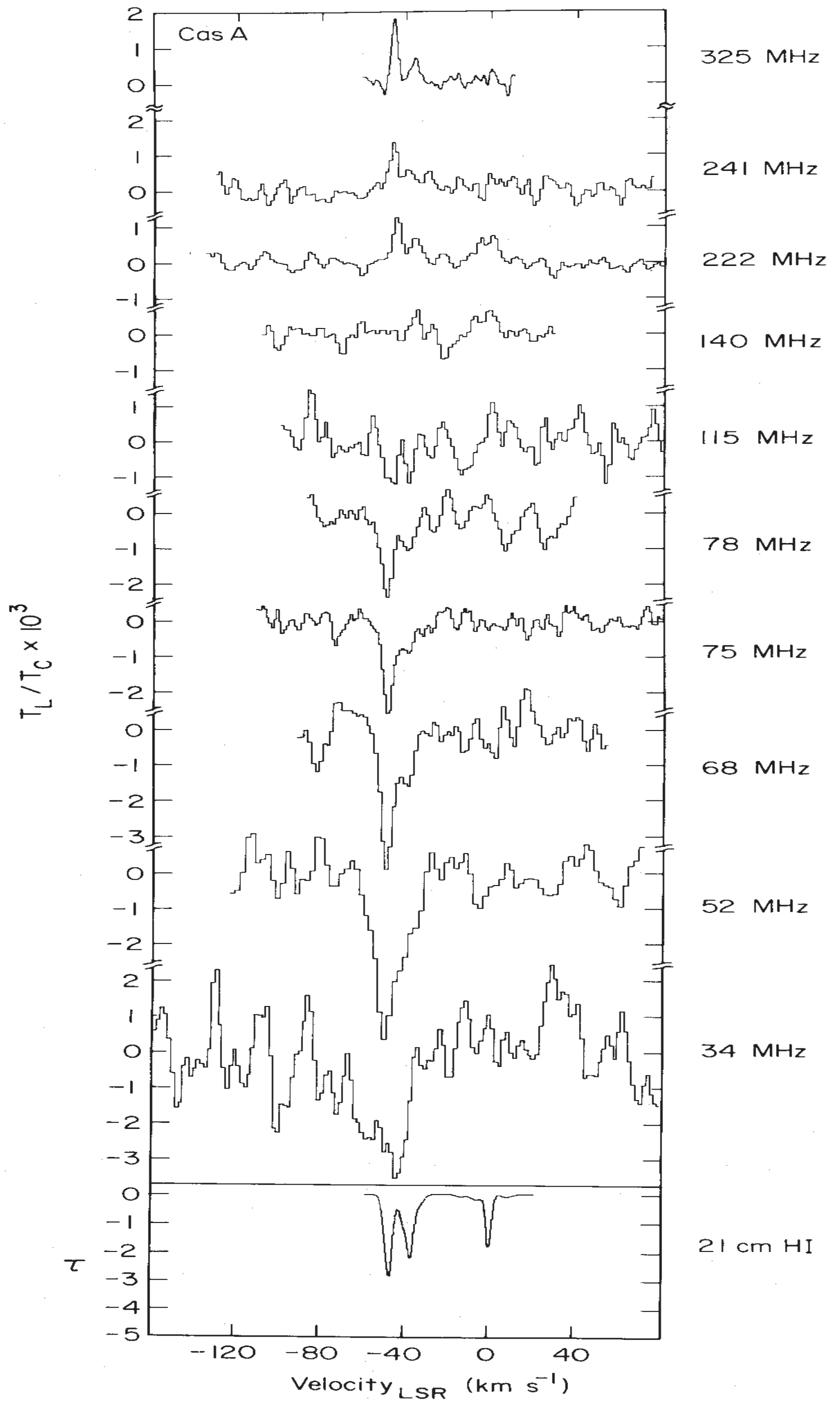
Cas A (Payne+1989)

- **RL: “ ions recombining with electrons ”**
- **Classical (*Palmer & Zuckerman 1966*)**
  - **ionised gas (WIM)**
- **Diffuse (*Konovalenko & Sodin 1981*)**
  - **Carbon, Hydrogen RRL's**

    C absorption ≤ 130 MHz ≥ C emission
  - **CNM / PDR's**

    T_e ~ 10-300 K, n_e ~ 0.01-1.0 cm^{-3}
  - **weak : τ_{peak} ~10^{-4} to 10^{-3} (MW)**
  - **many : 500 α lines (LOFAR)**
  - **Measure : τ , v , Δv**
  - **Derive : T_e , n_e , EM , ζ(H) , [C/H]**

(−) WNM : T ~ 10000 K



<u>RRL models</u>: Line width broadening

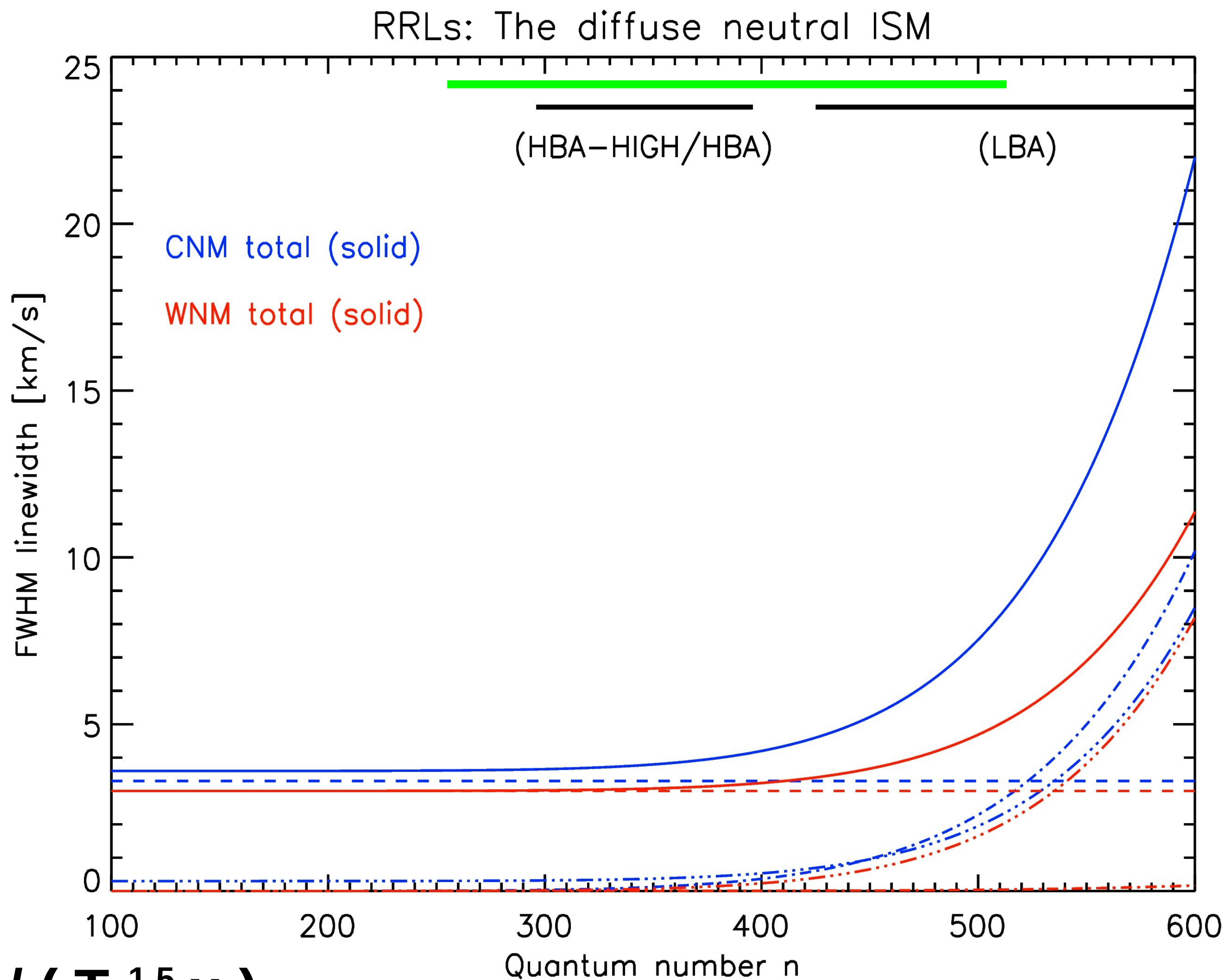
Total (solid) width

Contributions:

(1) Doppler
(dash)

(2) Pressure
(dash-dot)

(3) Radiation
(dash-dot-dot)



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

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

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

RRL models: Integrated Optical Depth (τ)

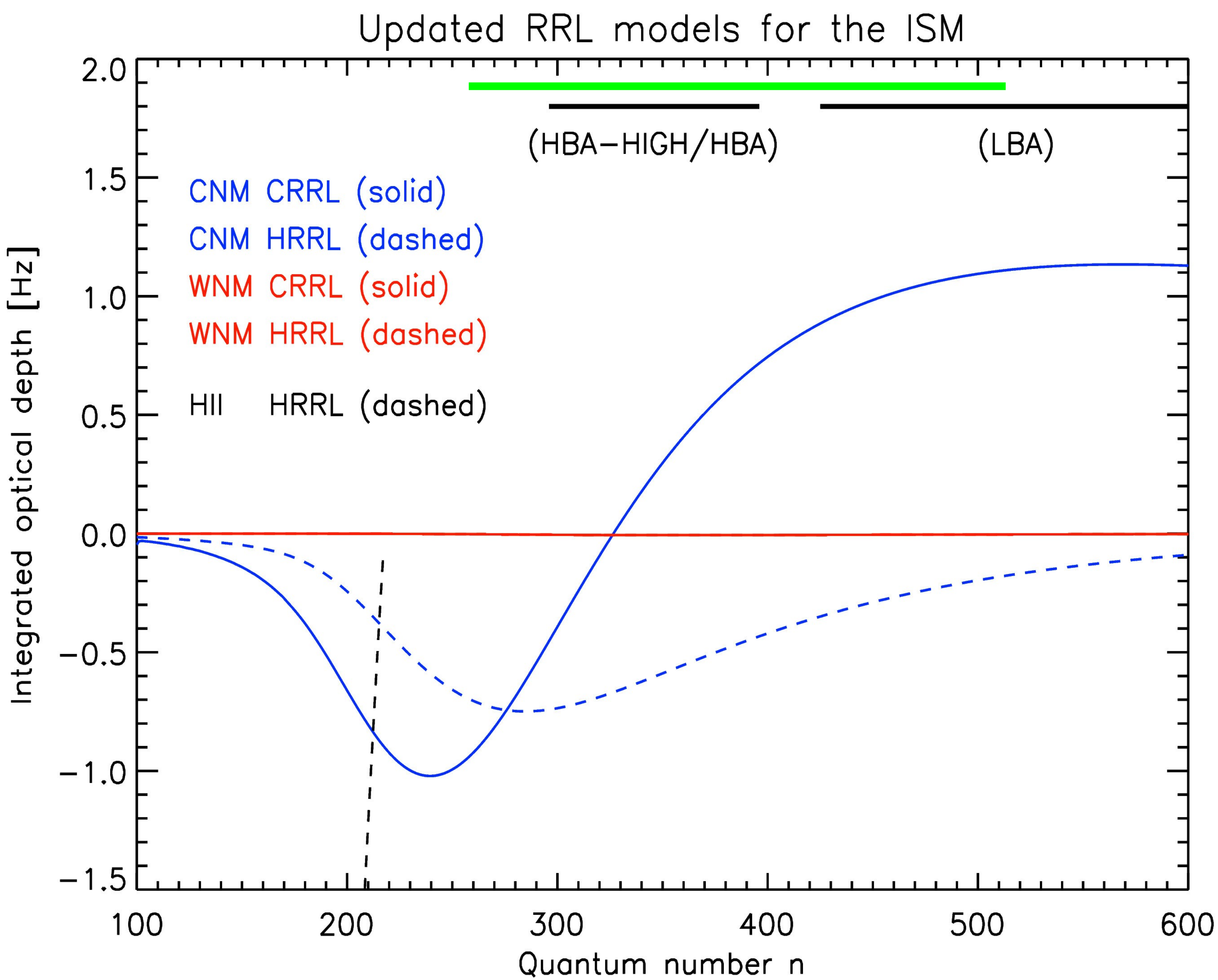
Phases:

CNM (atomic):
- $n_e = 0.05\ cm^{-3}$
- $T_e = 100\ K$

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

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

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



$$\tau_C \sim T_e^{-5/2}\, EM_C\, (b_n\, \beta_n)_C$$

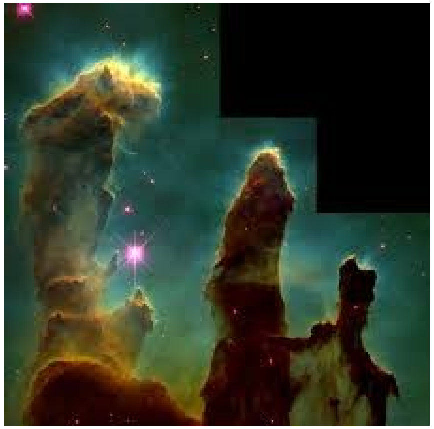
[N(HI)=10^{20} cm^{-2}]

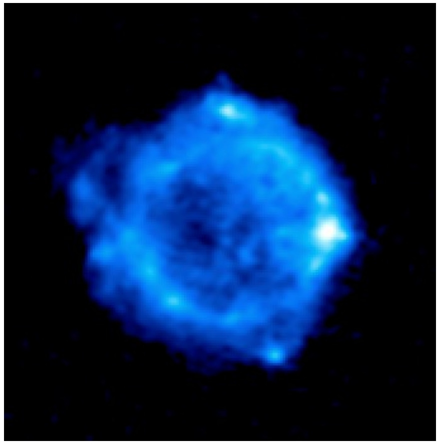
Returning to the BIG question.

" 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** ***(ζ_H)***
- **Carbon abundance** ***([C/H])***
- **Kinematics of the RRL gas** ***(v , Δv)***

RRL Surveys

The Power of LOFAR:

Sensitivity , Resolution , FoV , BW

=> "Survey speed" (α , δ , λ)

LBA 10 - 70 MHz : 400 RRL α-lines
HBA 105 - 250 MHz : 100 RRL α-lines

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

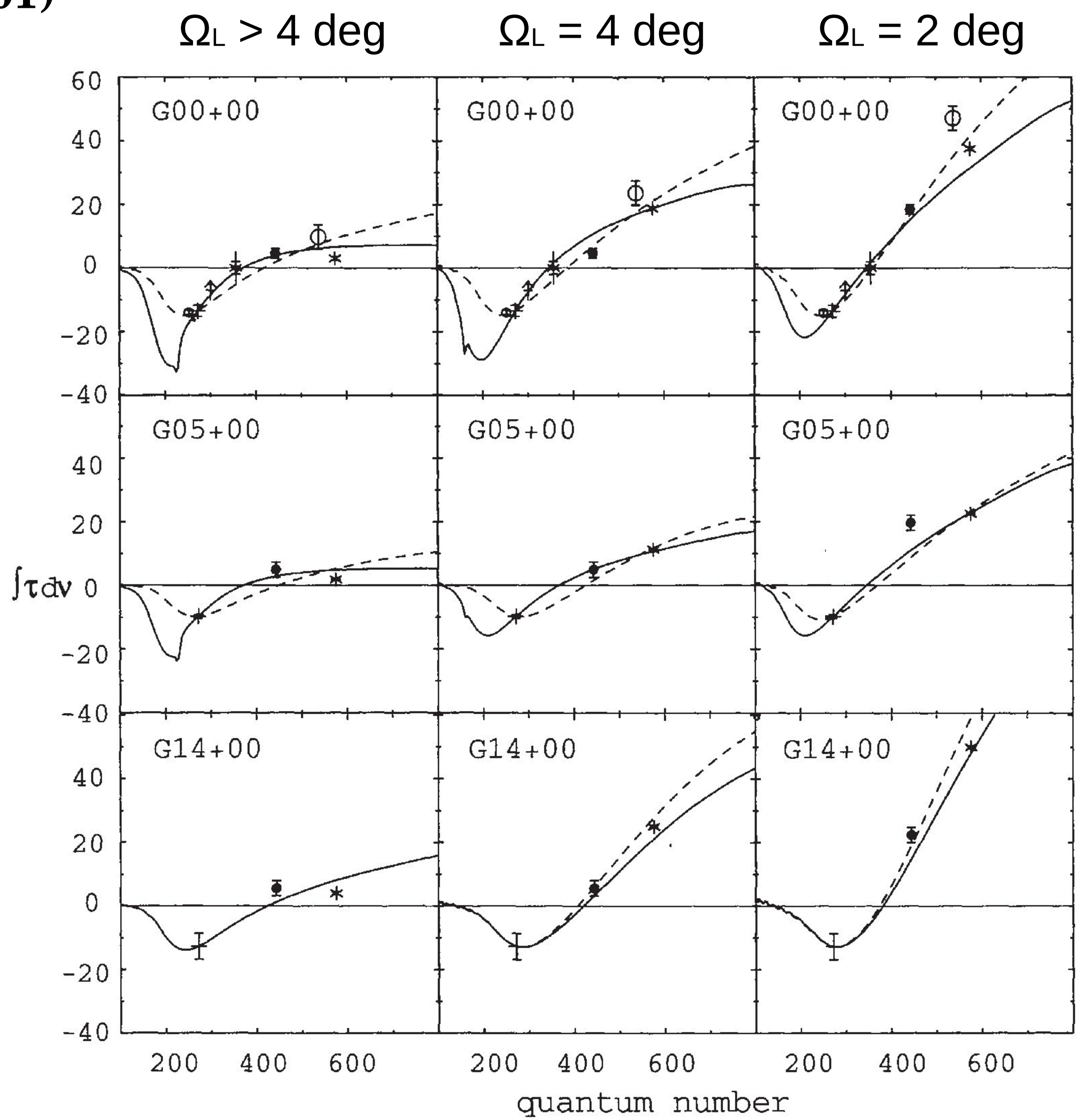
(Kantharia & Anantharamaiah 2001)

Major issues:

(1) Beam FWHM > 2 deg.
(unresolved cloud sizes)

(2) Resolution mismatch
(spatial & spectral)

(3) Limited frequency coverage



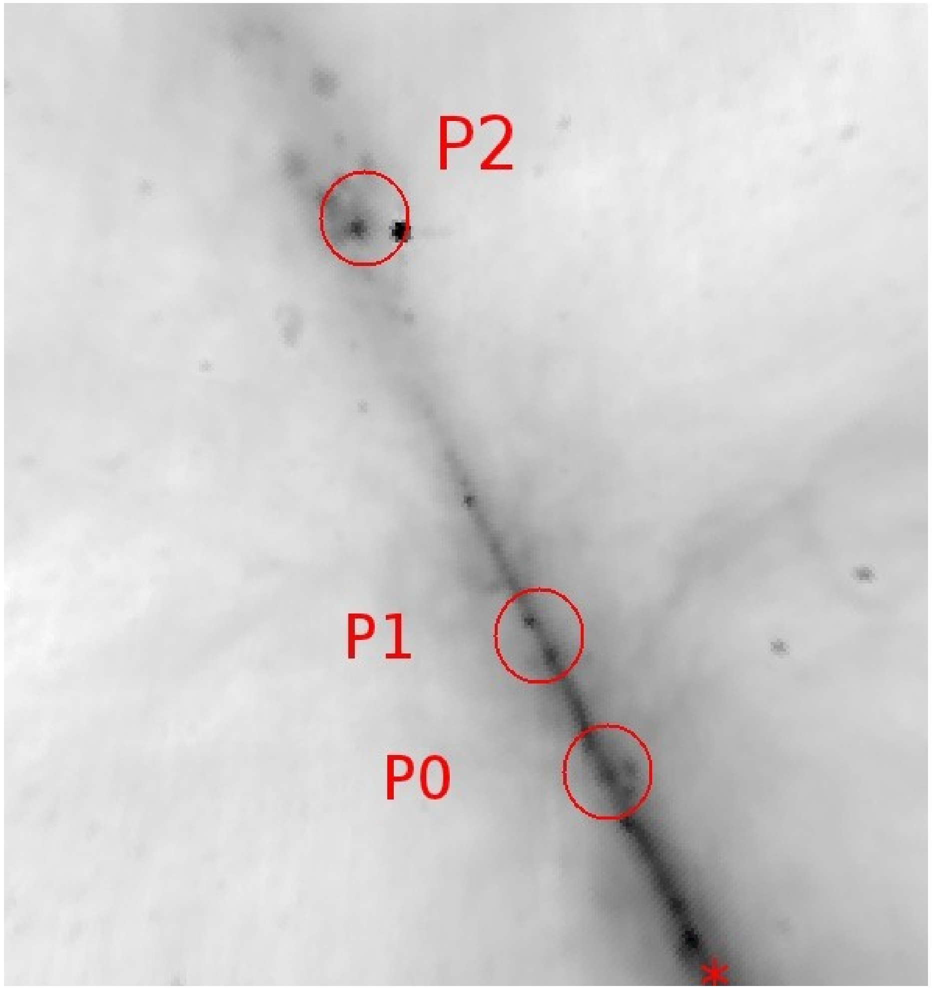
Data:

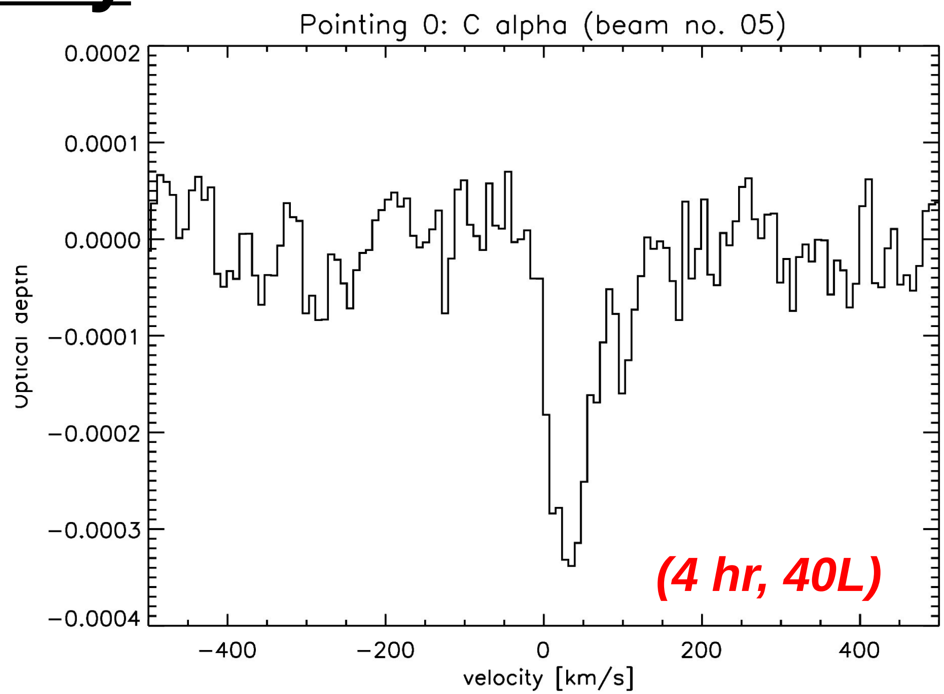
**** 328 MHz , Anantharamaiah (1985)***

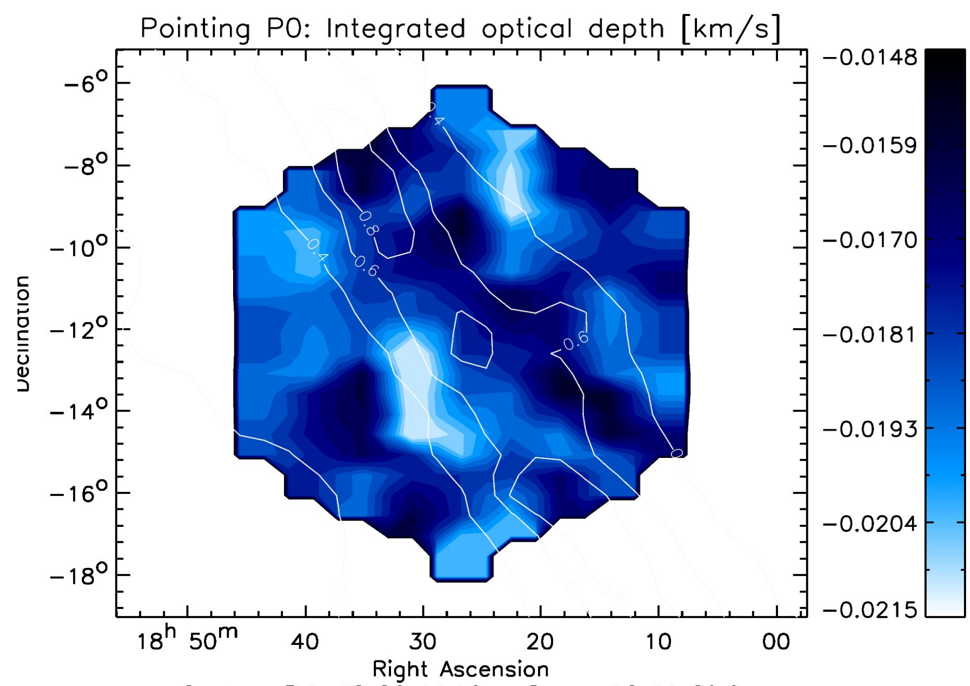
**** 76 MHz , Erickson et al. (1995)***

**** 34 MHz , Kantharia & Anantharamaiah (2***

A: LOFAR Galactic RRL Survey







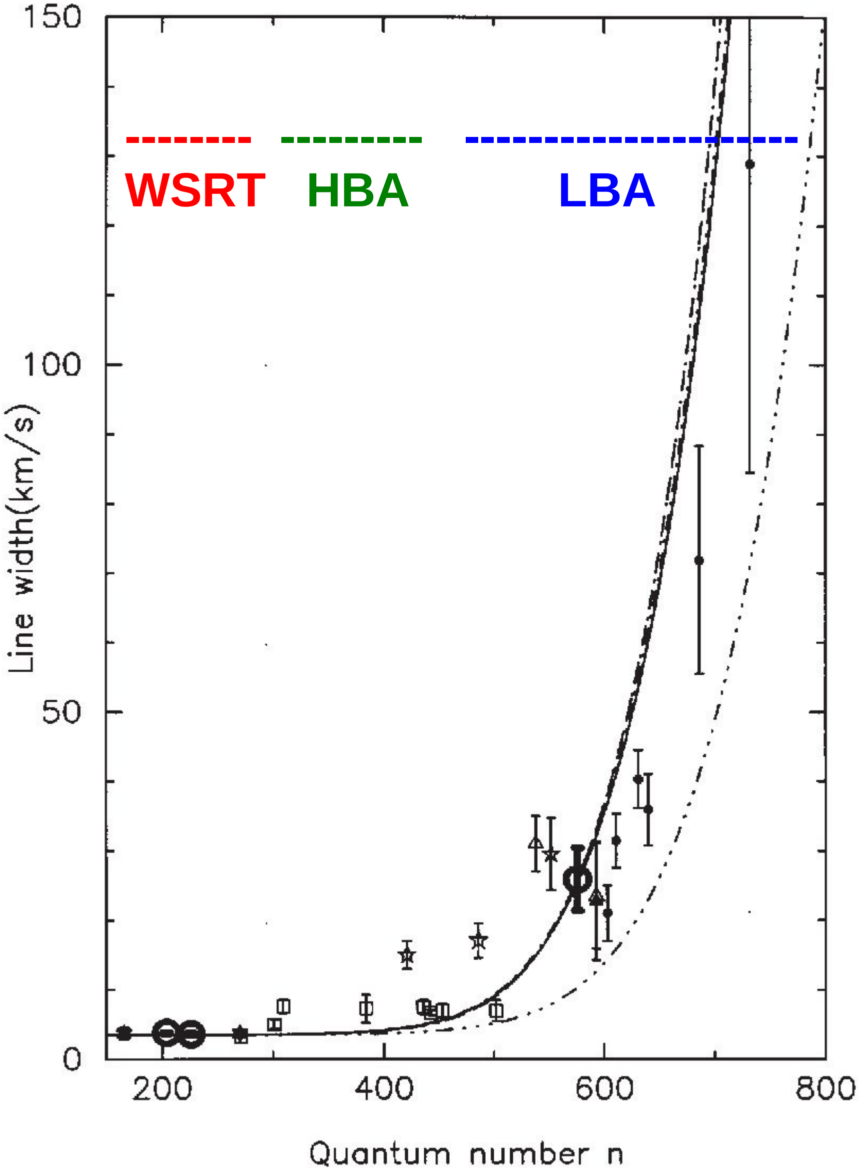
LOFAR:

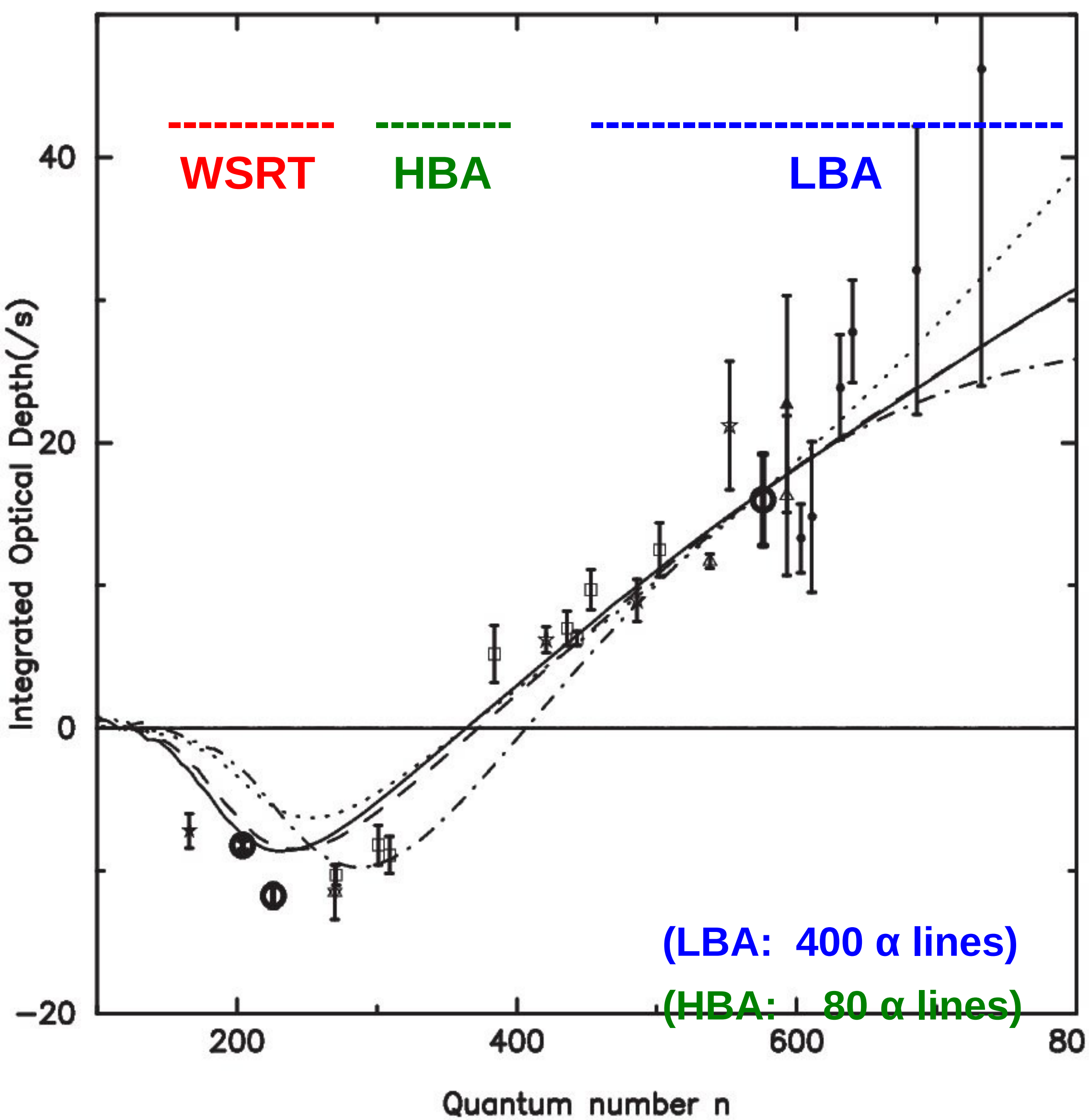
→ **CRRL wide spread in Galactic plane**

→ **improve resolution from degree to arcmin scales**

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

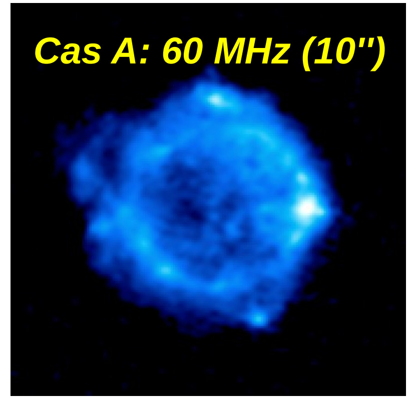
Cas A (Kantharia+1998)



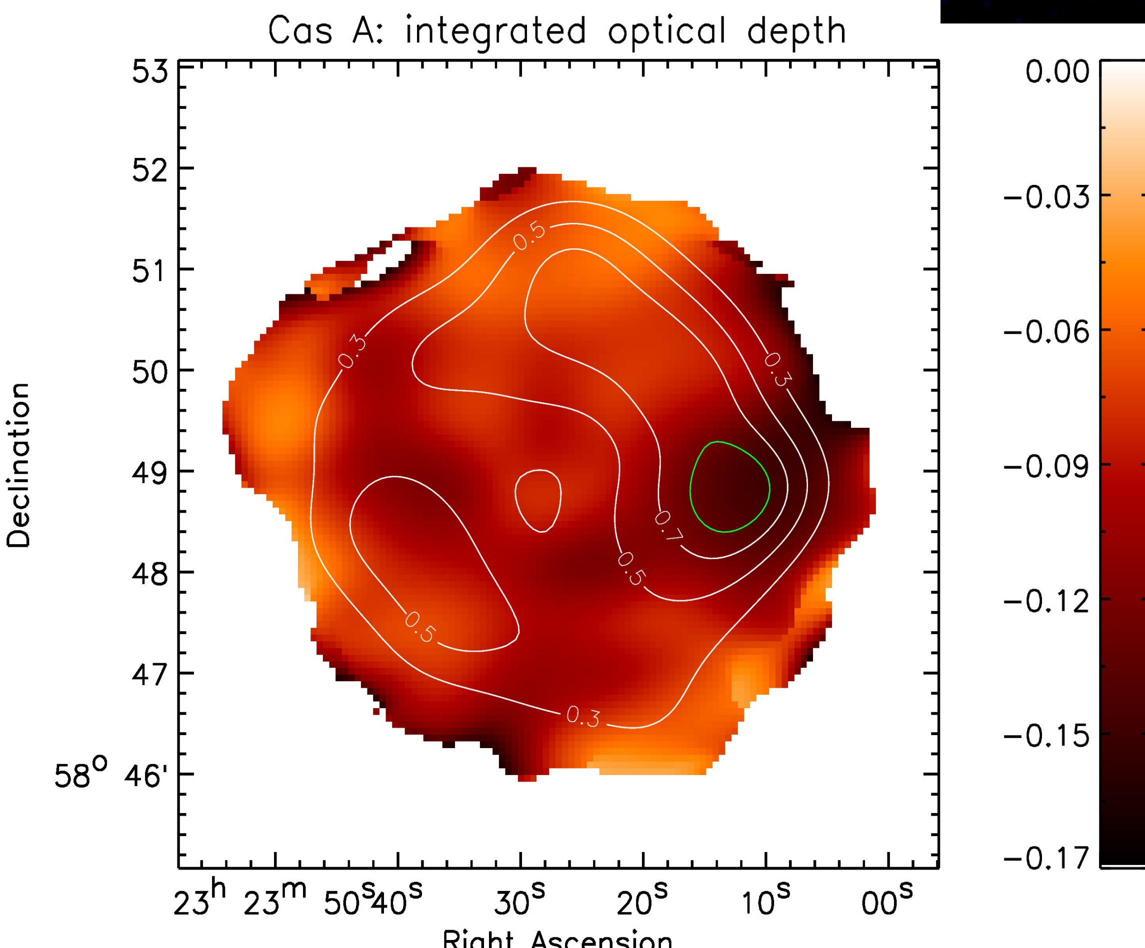


** LOFAR: will provide better measurements at low frequencies (high n), reduce the scatter !!*

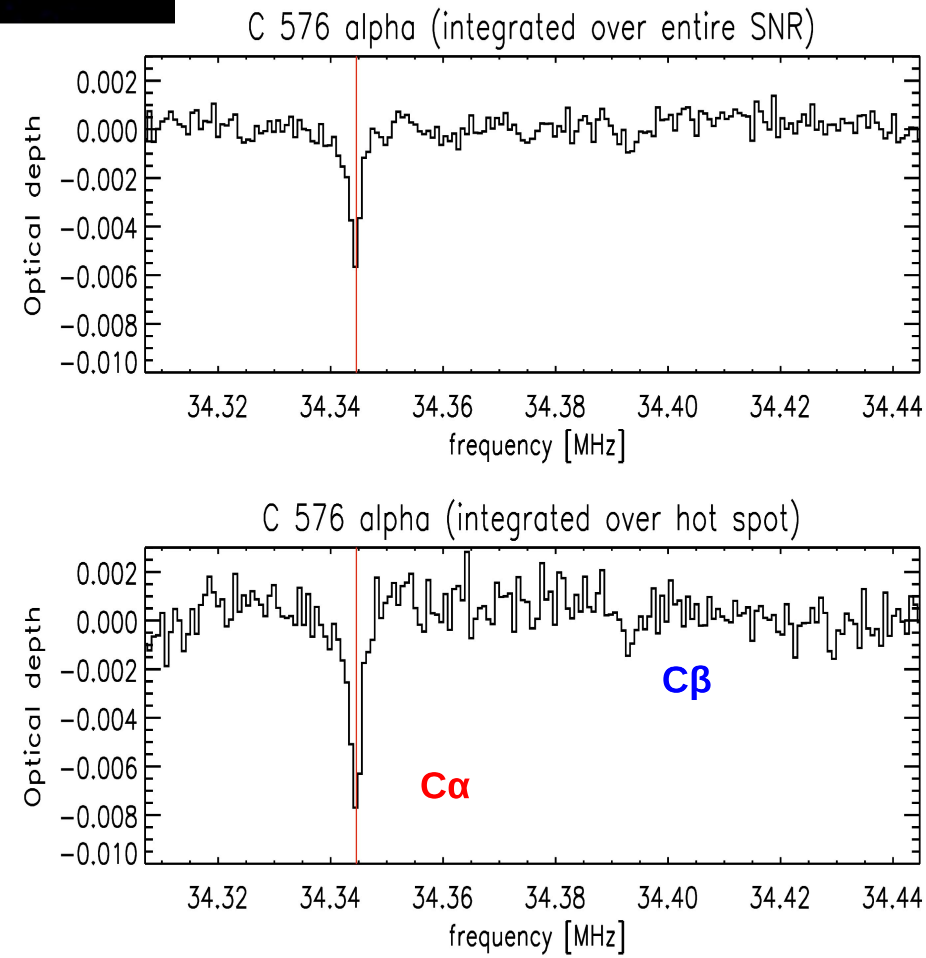
B: Cas A (33-56 MHz)



CRRL line stacking (47 L)



CRRL single line (n=576)

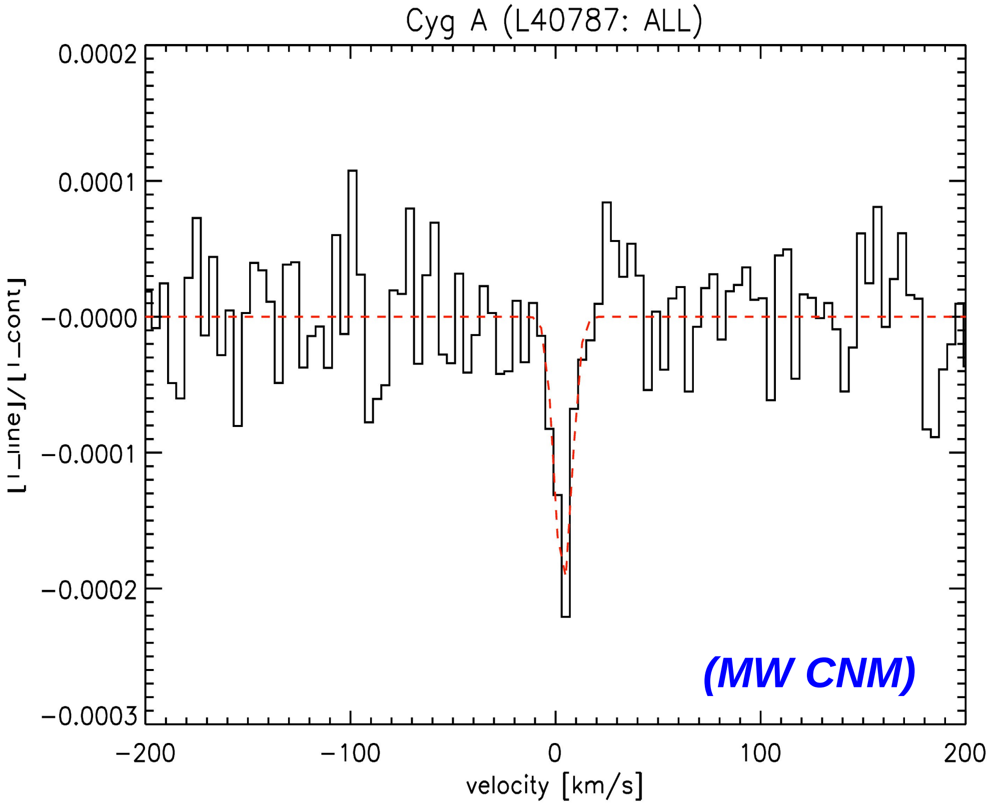


=> Integrated τ varies over the supernova remnant

(Oonk+)

B: LOFAR Galactic pinhole studies

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



LOFAR-LBA (10h)

BW = 33-57 MHz

Δf = 0.4 kHz

Δv = 2-4 km/s

Measurements:

τ_{PEAK} = 2 x 10^{-4}

v_{LSR} = +4 km/s

FWHM = 10 km/s

Derived properties:

T_e = 110 K

n_e = 0.06 cm^{-3}

EM_C = 0.001 cm^{-6} pc

[C/H] = 1.8×10^{-4}

ζ_H < 4×10^{-16} s^{-1}

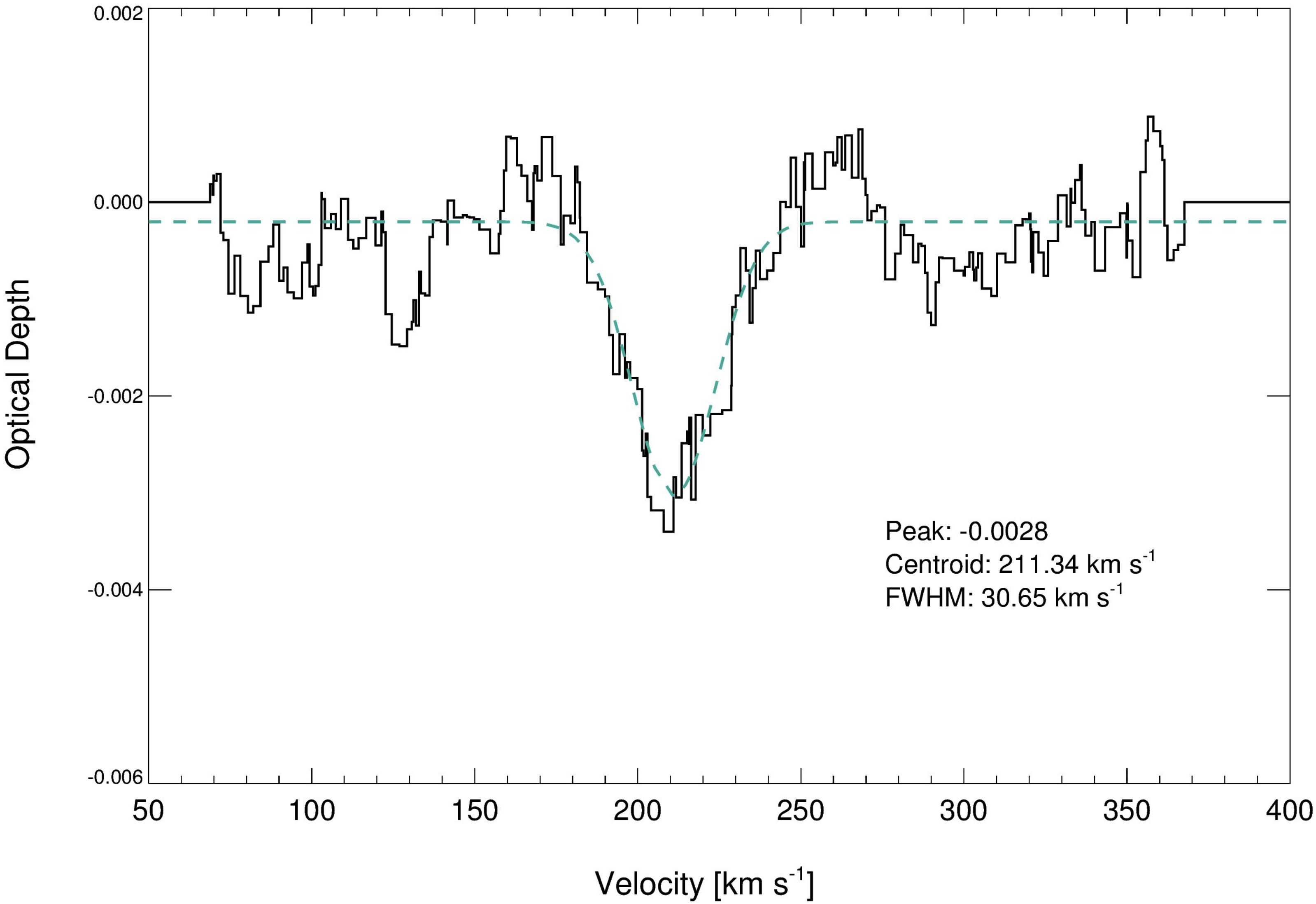
C: LOFAR Beyond the Milky Way

τ_{PEAK} = 3×10^{-3}

v_{LSR} = +211 km/s

FWHM = 30 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

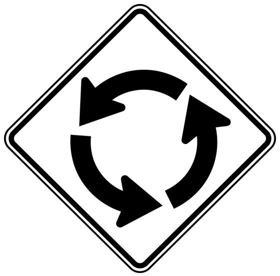
Example 1 "Simple" : M82 LBA observation

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)

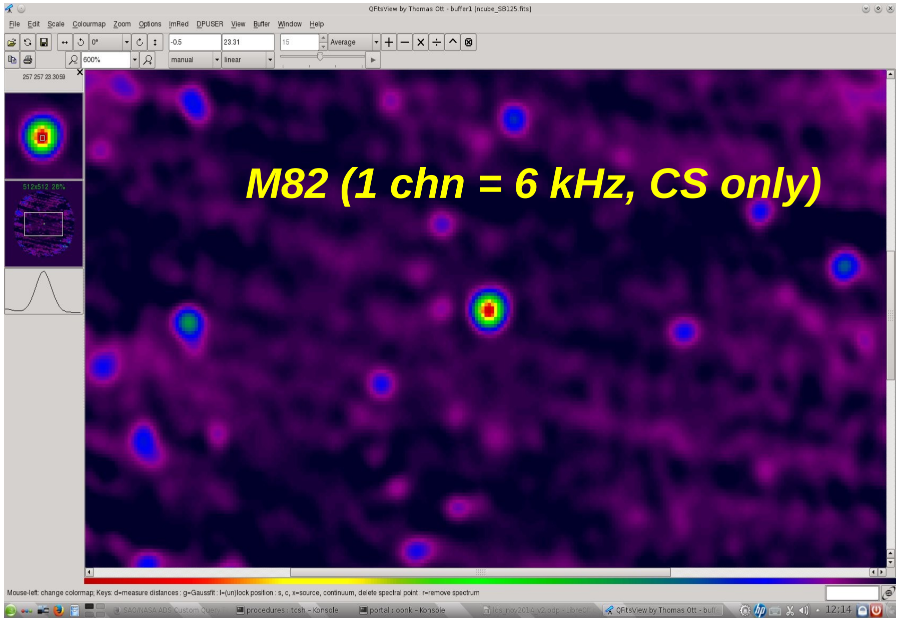
- BBS correct M82 using 3C196 solutions

Example 1 “Simple” : M82 LBA observation

Imaging: (limit memory)

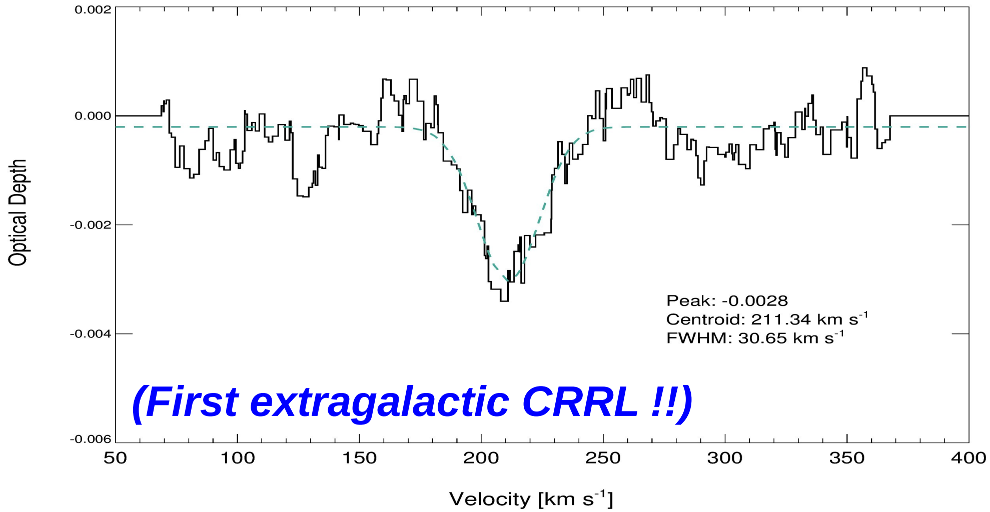
(Morabito+2014)

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



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)

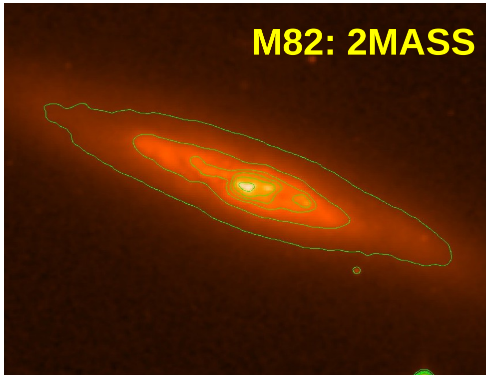
(Toribio+ in prep)

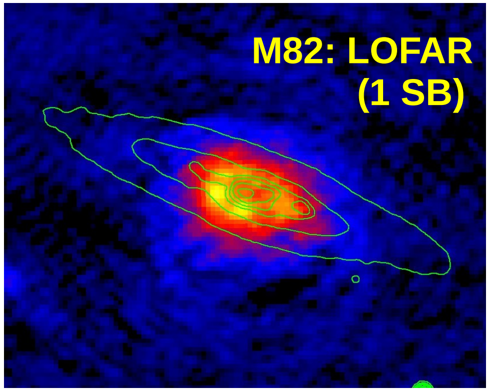
- 3C295, M82, 3C295 , M82, etc (single beam)
- HBA Dual inner 110-190 MHz (200 MHz clock)
- 64 Chn/SB, 1 SB = {35} GB (total 17 TB)

Reduction/Calibration:

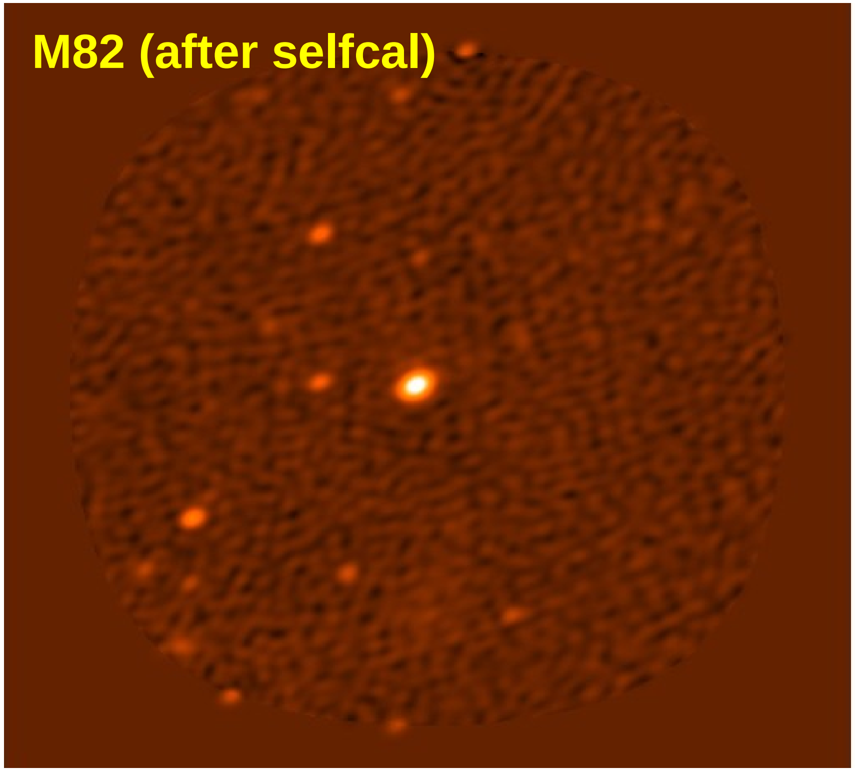
- Flag (aoflagger: std. settings)
- Avg (NDPPP Src/Cal: df = 1/64 , dt = 1/1)
- BBS calibrate 3C295 (1 ampl, phase per SB)
- Export solutions and make time indep.
- BBS correct M82 using 3C295 solutions
- Create cp of M82 corr. and avg to 1 chn
- Run selfcal on M82 corr., 1 chn set
- Apply selfcal solutions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

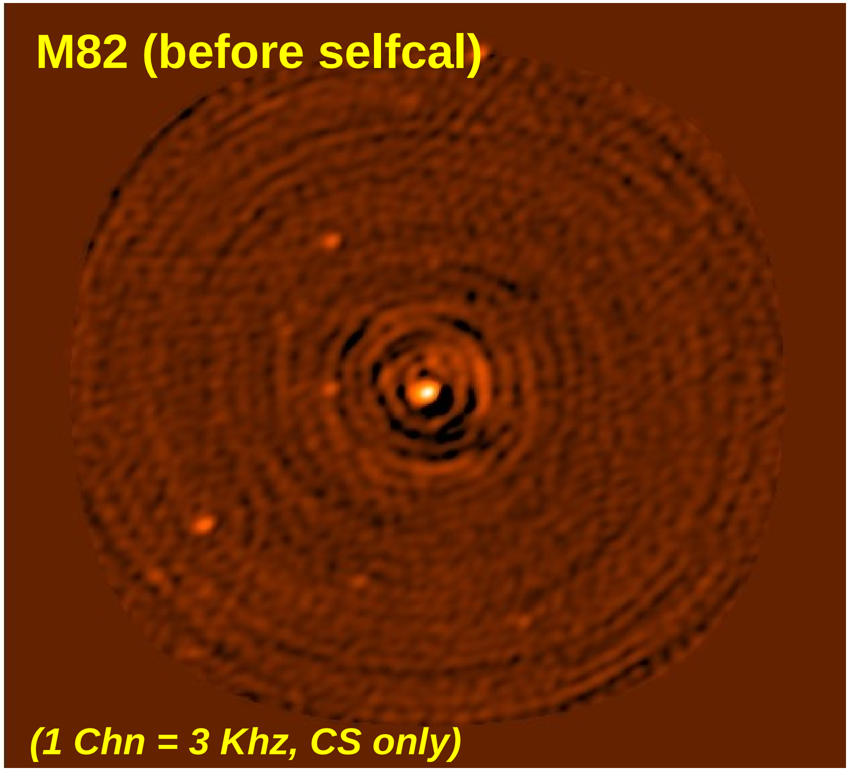
→ Imaging and Analysis as before ...

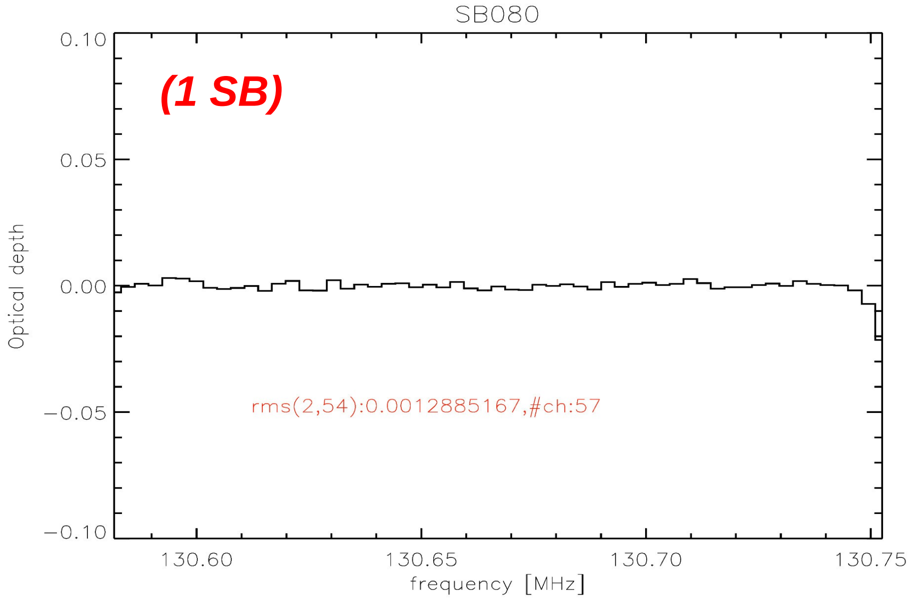


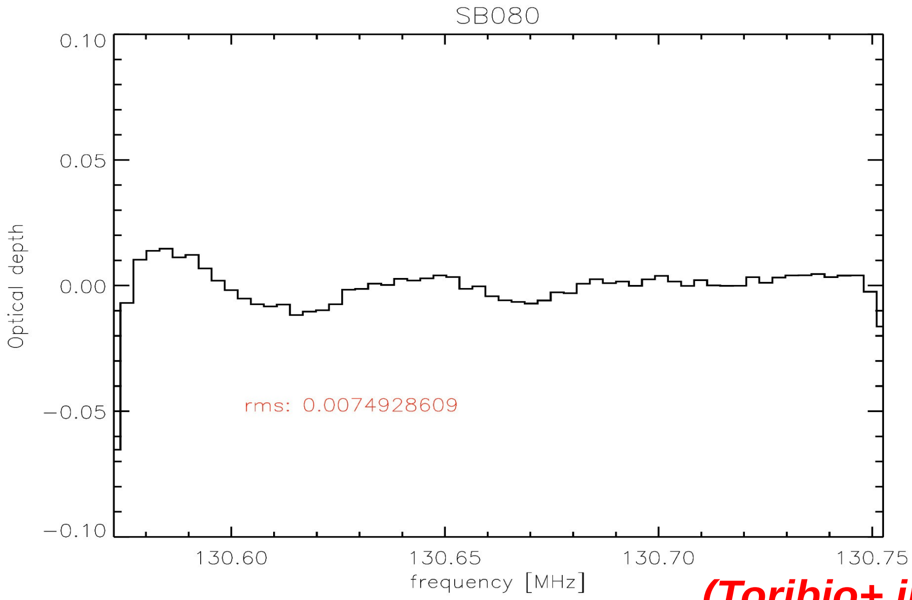


Example 2 “Interleaved”: M82 HBA observation









(Toribio+ in prep)

Example 3 "Simple+Stitch": 3C241 HBA-HIGH obsv

Setup: (2013, LC0, 4hr , 2s sampling) *(Oonk+ in prep)*

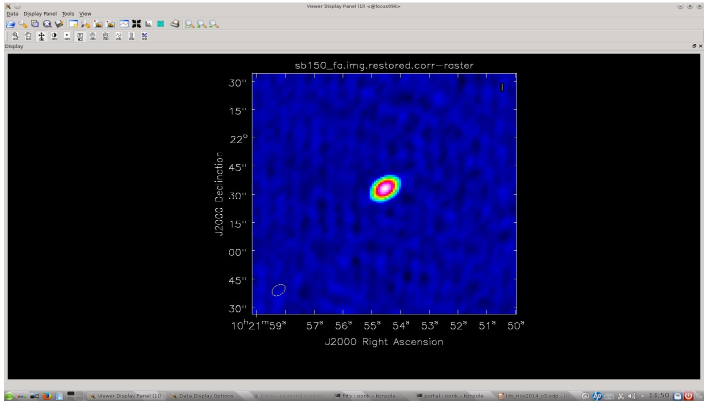
- 3C196, 3C241, 3C196 (single beam)
- HBA-HIGH joined 210-250 MHz (200 MHz clock)
- 64 Chn/SB, 1 SB = 20 GB (total 10 TB)

Reduction/Calibration:

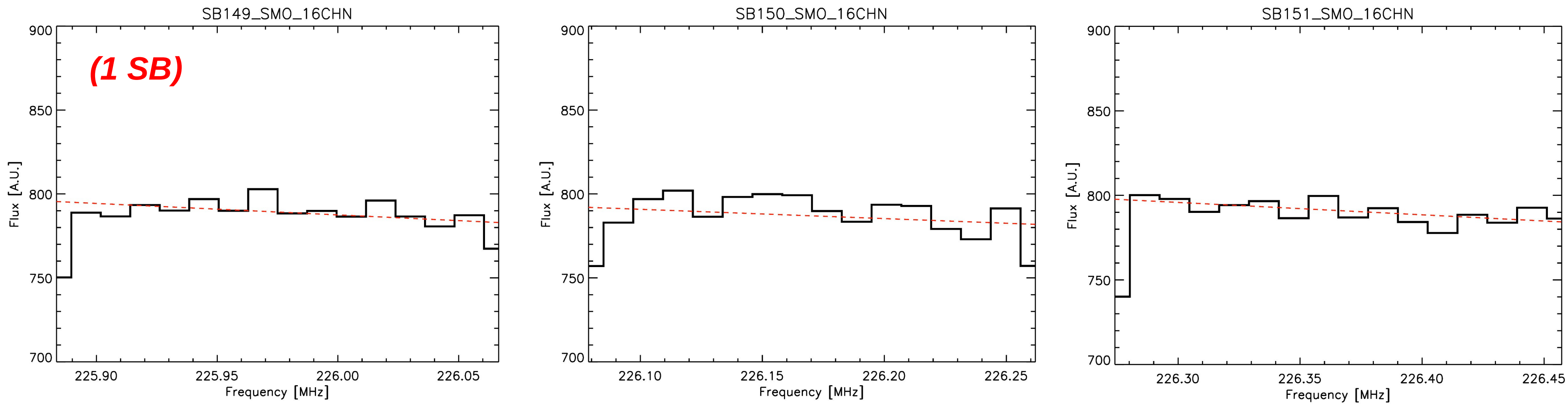
- Flag (aoflagger: std. settings)
- Avg (NDPPP Src: df = 4 , dt = 5)
- BBS calibrate 3C241 (1 ampl,phase p. SB)
- Smooth solutions in time (lowers noise)
- BBS correct 3C241

→ **Imaging** & **Analysis** as before ... ,

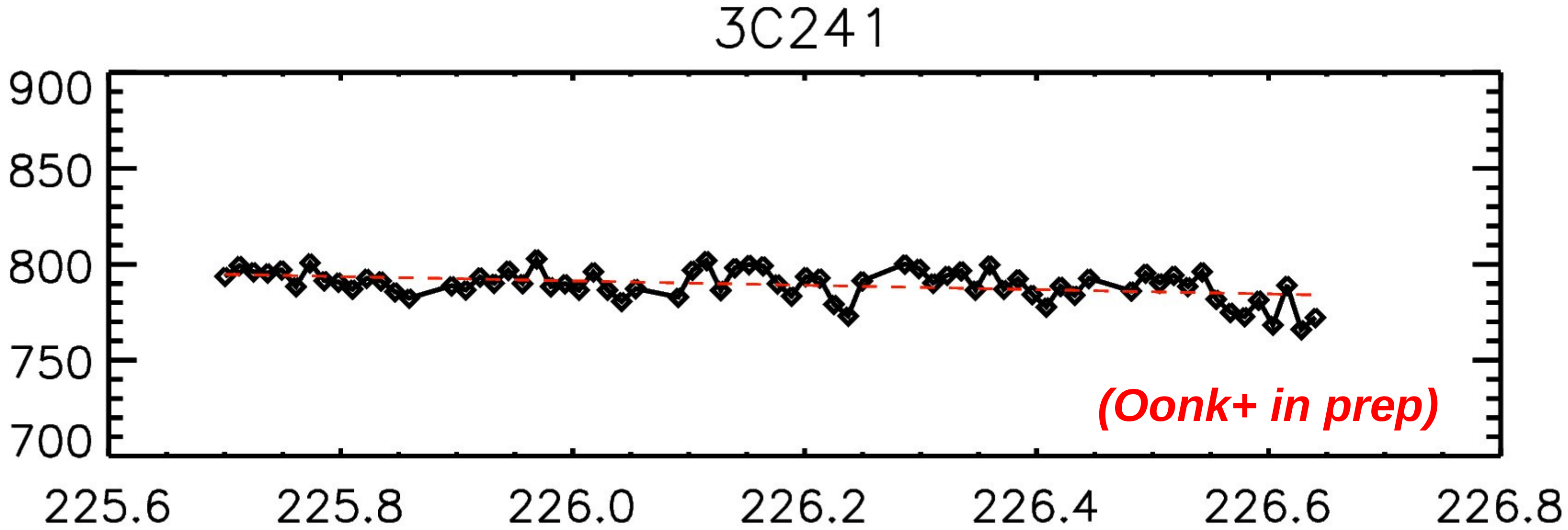
except for "stitching" of SB's



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



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



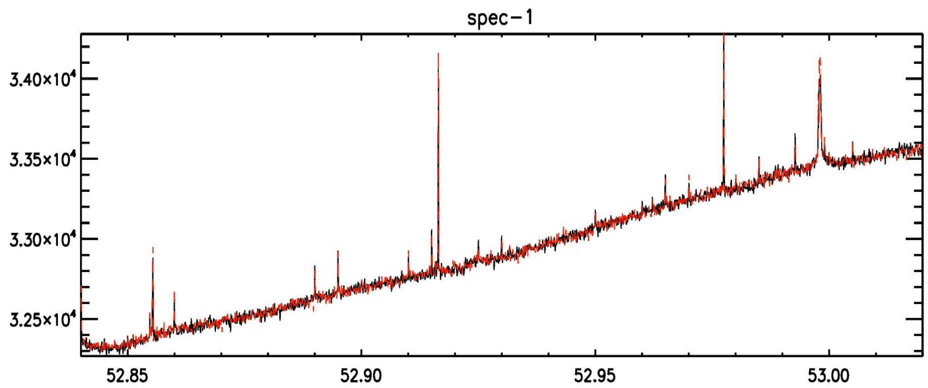
Example 4: Beamformed observations: W3OH

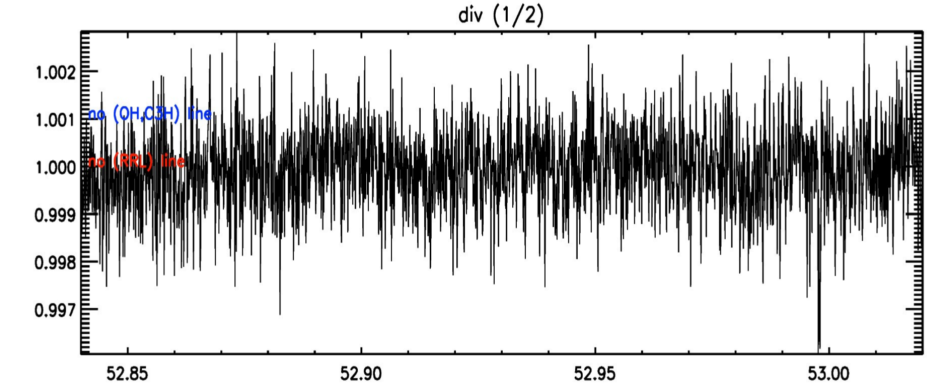
Setup: (2012, LC1, 8hr , 0.02s sampling)

- 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



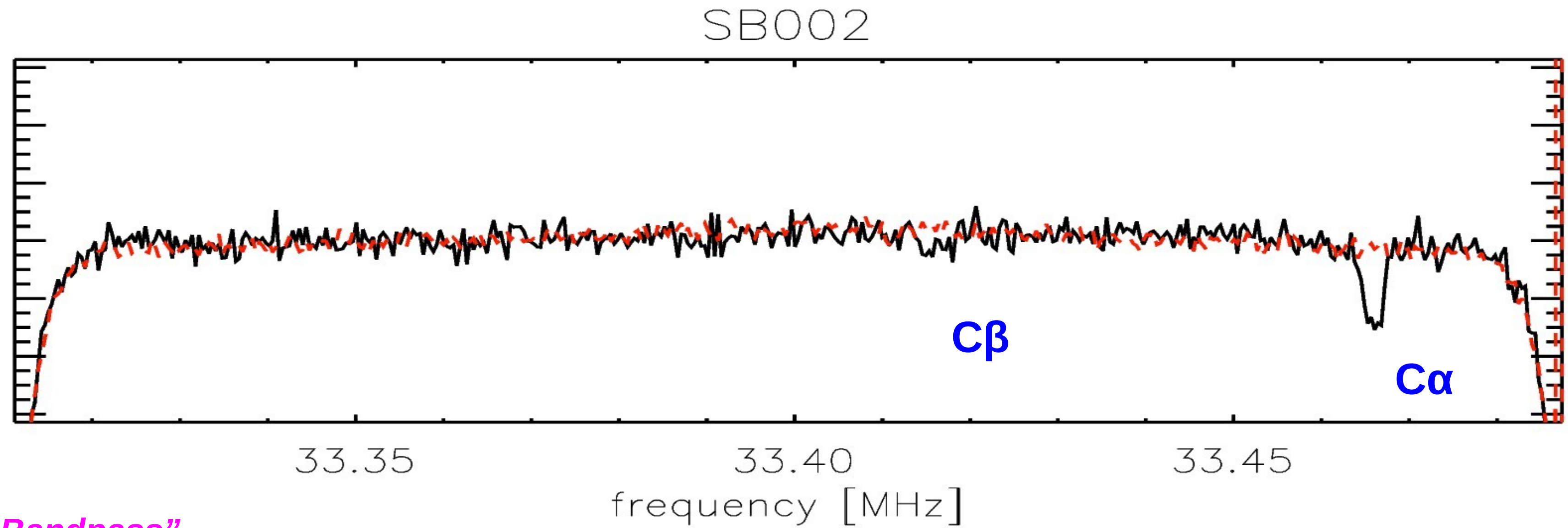


LOFAR SPECTROSCOPY

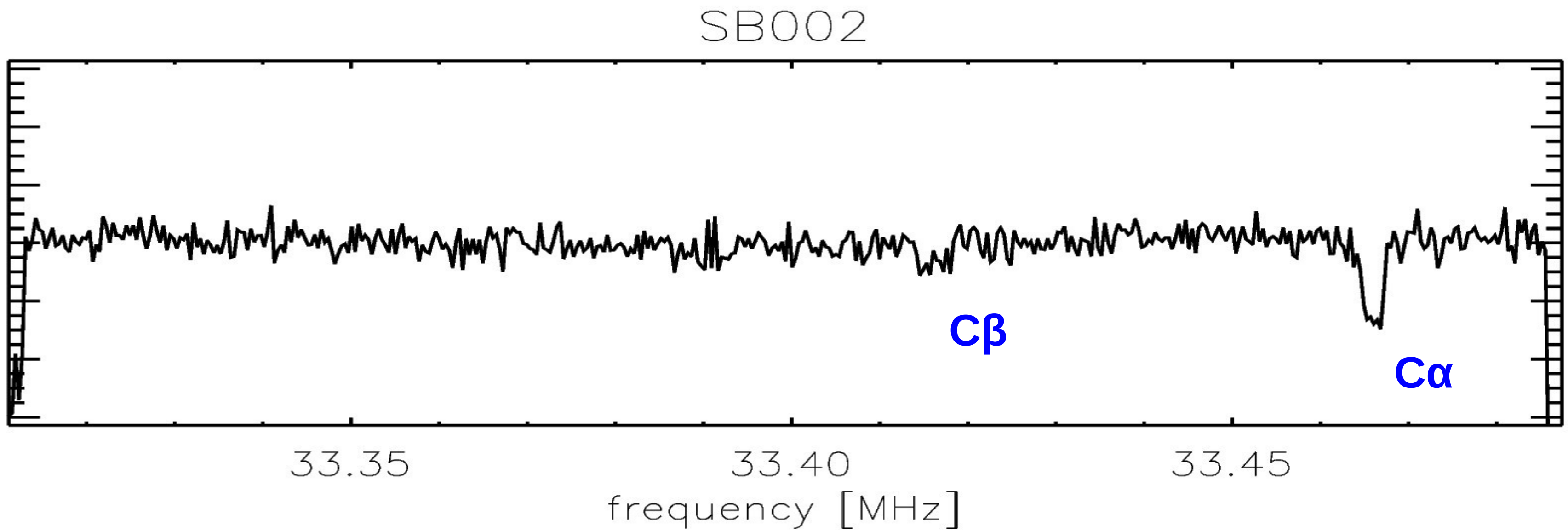
bandpass, bandpass, ...

Single SB: Astronomical Bandpass I

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

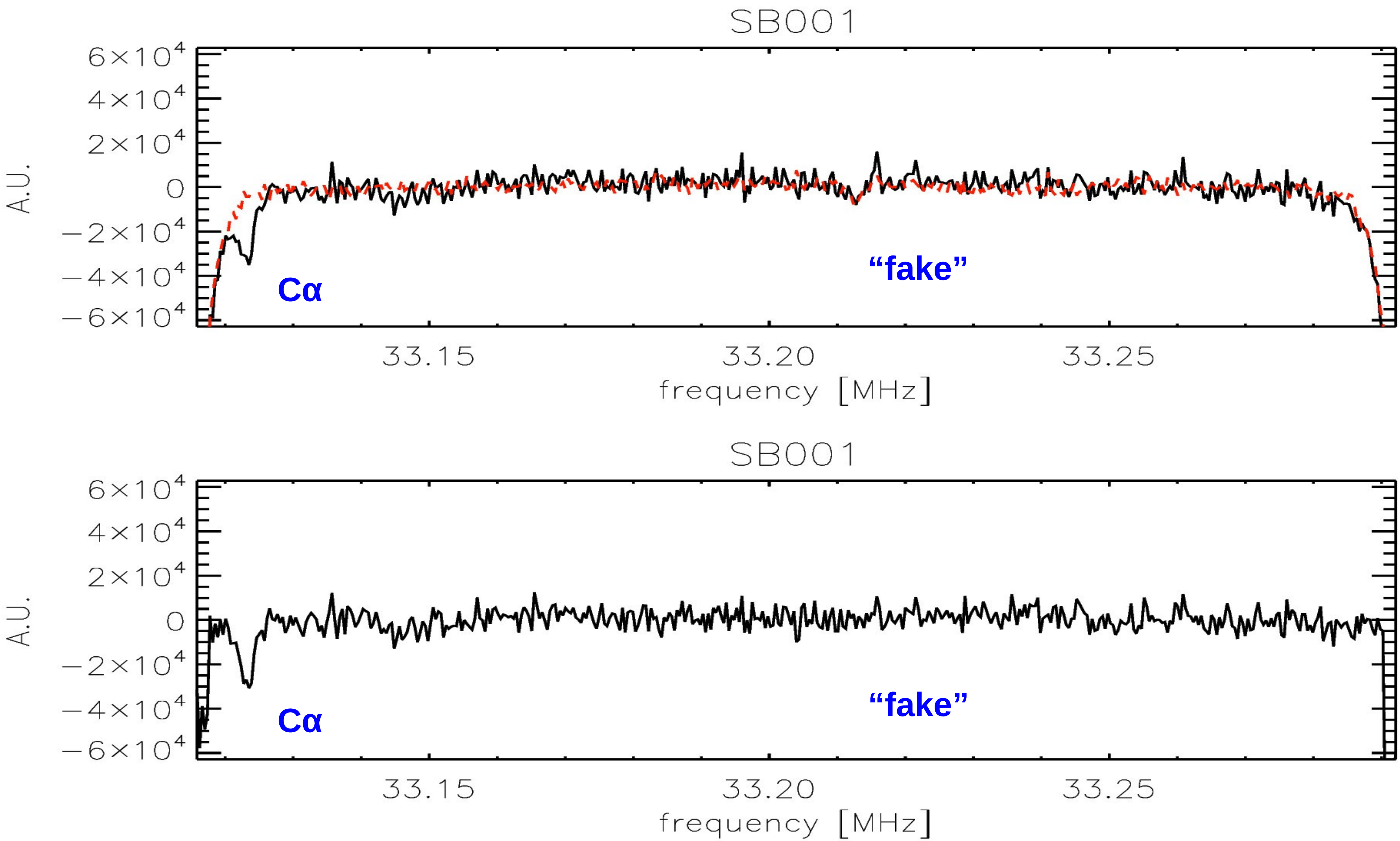


"Good Bandpass"



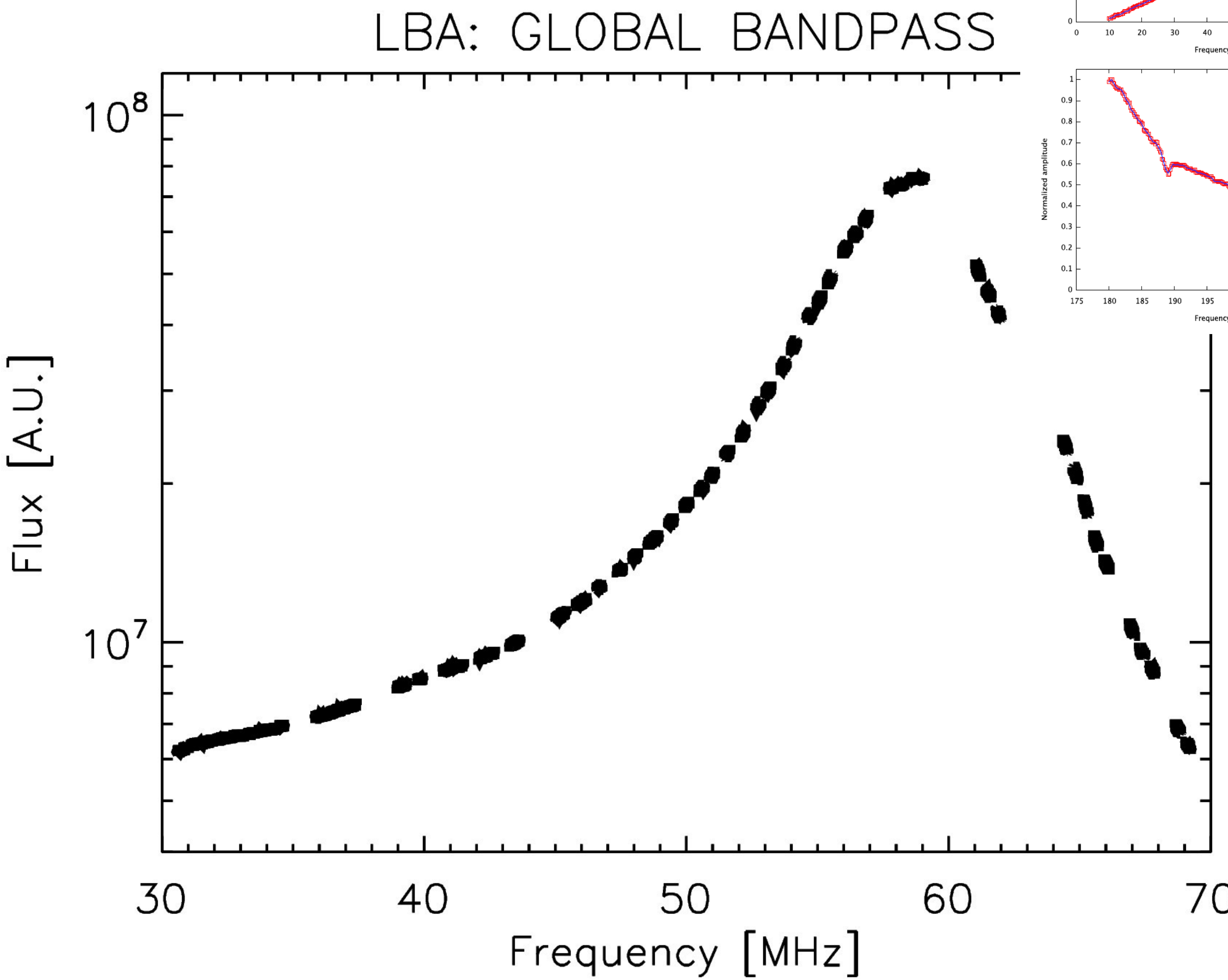
Astronomical Bandpass II

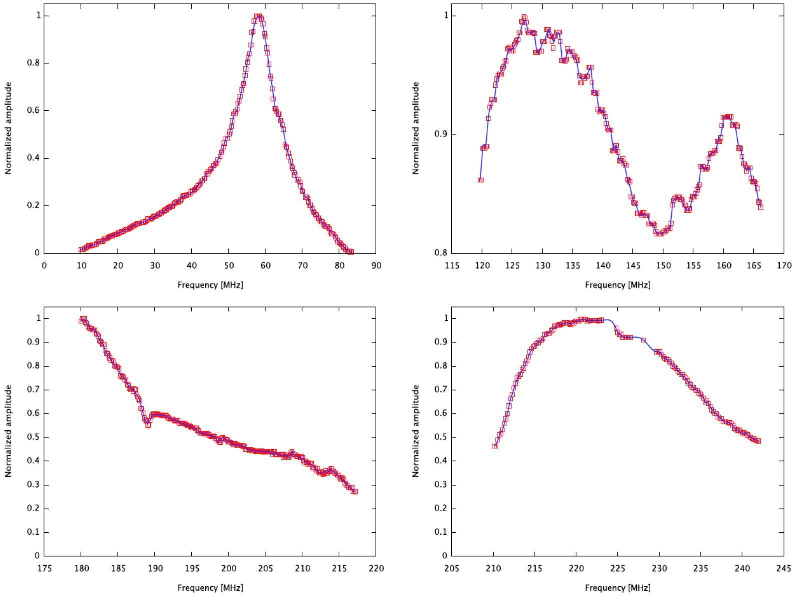
Bandpass: Cas A (black), Cyg A (red): fake and real detections



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

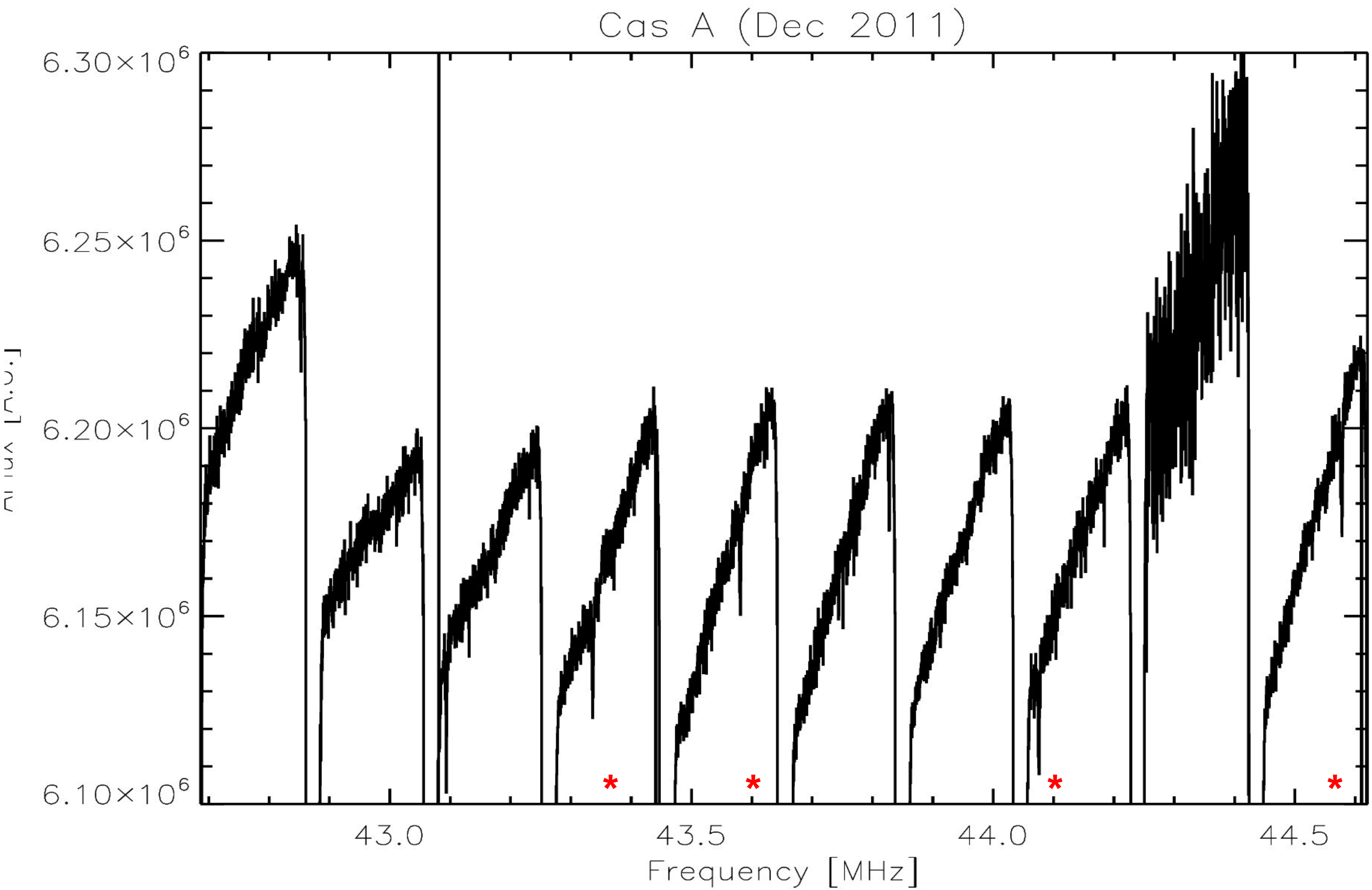
Global bandpass





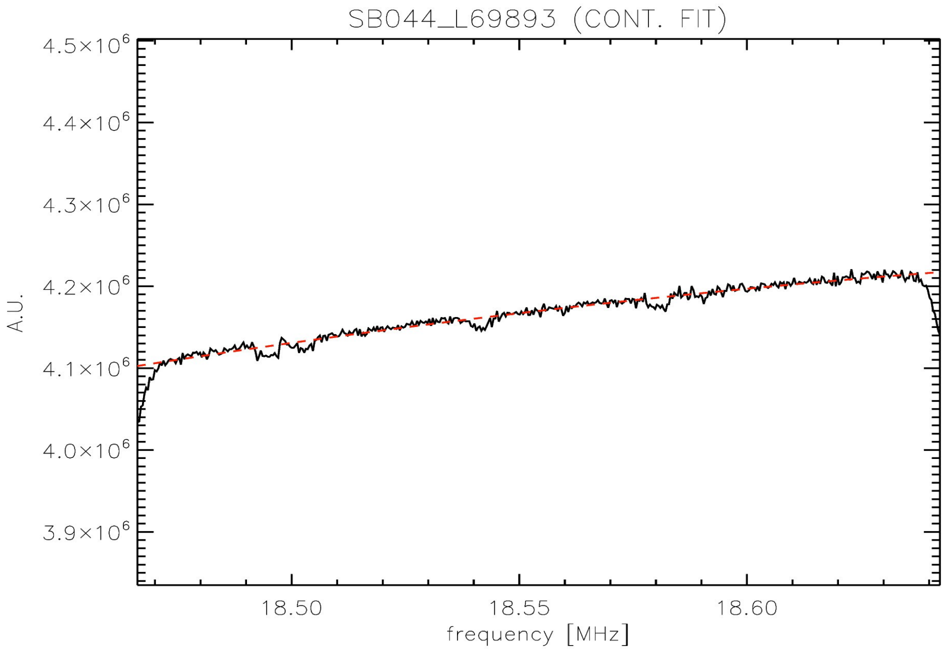
*** LOFAR system response convolved with source spectrum**

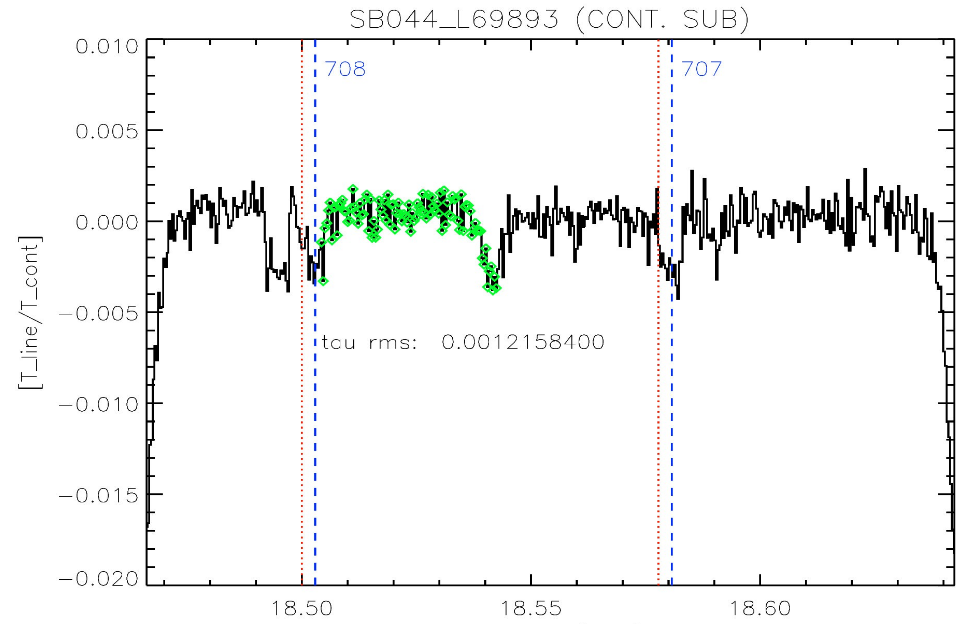
Spectral gaps & global calibration per SB

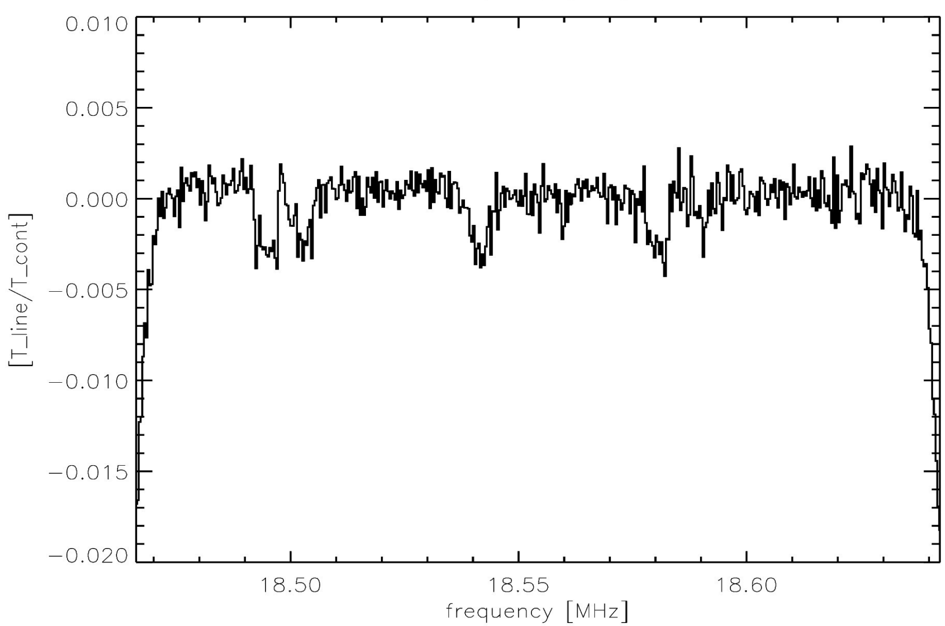


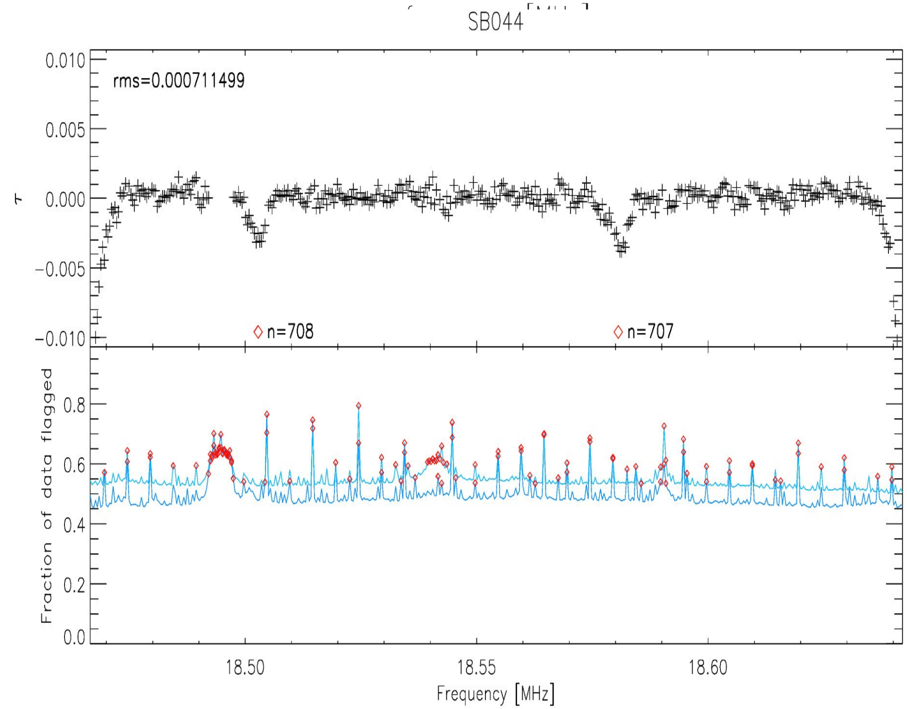
*** poly-bandpass is ok for narrow line (<< 1 SB), but not for broad lines !!**

bandpass & flagging statistics









(van Weeren+)

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)**

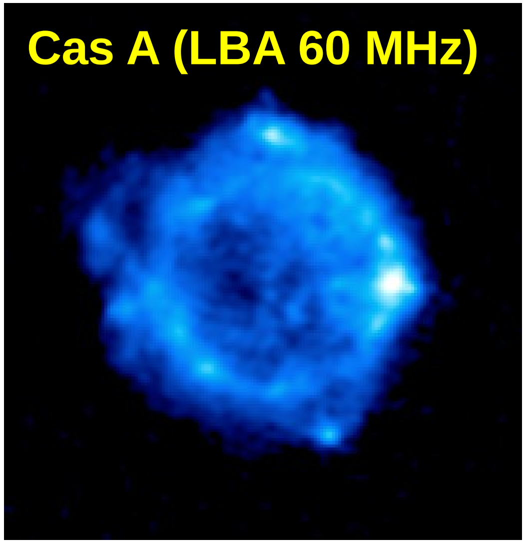
- raw data storage **20 GB/SB**
- processing ca. **~6 Hr per SB** (64 ram, 1 core)

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: √(time) , √(chan) , √(#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***