Radio Recombination Line studies on M82 from LOFAR observations

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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 (H2)	30	>1000	H_2	$<10^{-7}$	CO

Galaxy evolution is driven by (SF) recycling of the ISM

--> What is the role of the atomic CNM ?

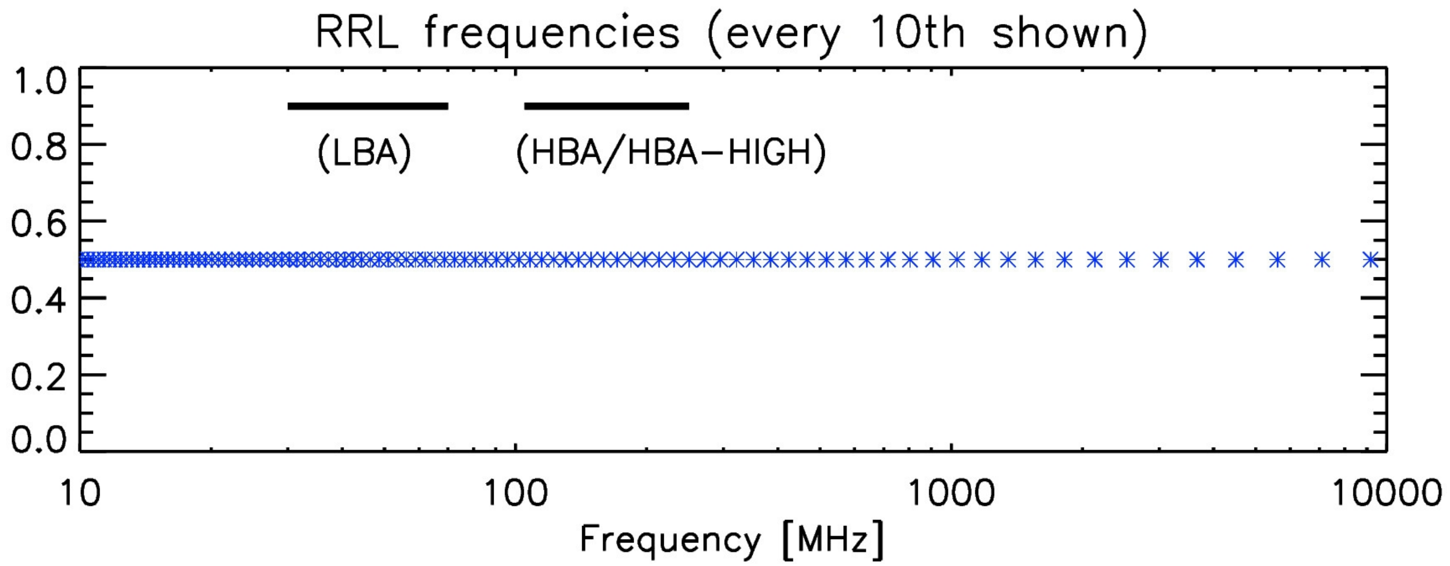
--> HI emission (contaminated), HI absorption (difficult)

Radio Recombination Lines (RRL)

" Spectral lines from ions recombining with electrons in a diffuse ionized plasma are called recombination lines "

Occur at all quantum levels (n): $\nu = Rc\,[\,1/n^2 - 1/(n+\Delta n)^2\,]$

- ***n < 50:*** **UV-IR (RL)**
- ***n > 50:*** **Radio (RRL):**
  - *Classical RRLs (>1 Ghz)*
    - H, He, C, S
    - HII Regions
    - Extragalactic detections
  - *Diffuse RRLs (<1 Ghz)*
    - Low ionization, C only
    - Cold neutral medium (CNM): $T_e \sim$ 10-300 K, $n_e \sim$ 0.01-1.0 cm^{-3}
    - No previous extragalactic detections (>>>LOFAR detection of M82)



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Diffuse Radio Recombination Lines (<1GHz)

The line profiles are determined by the

- **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)

>> Method: Localize the (C)RRL gas & compare with CO, HI and HII in order to probe the properties of the CNM.

RRL models: Integrated Optical Depth (τ)

Salgado+ (in prep)

Phases:

CNM (atomic):

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

WNM:

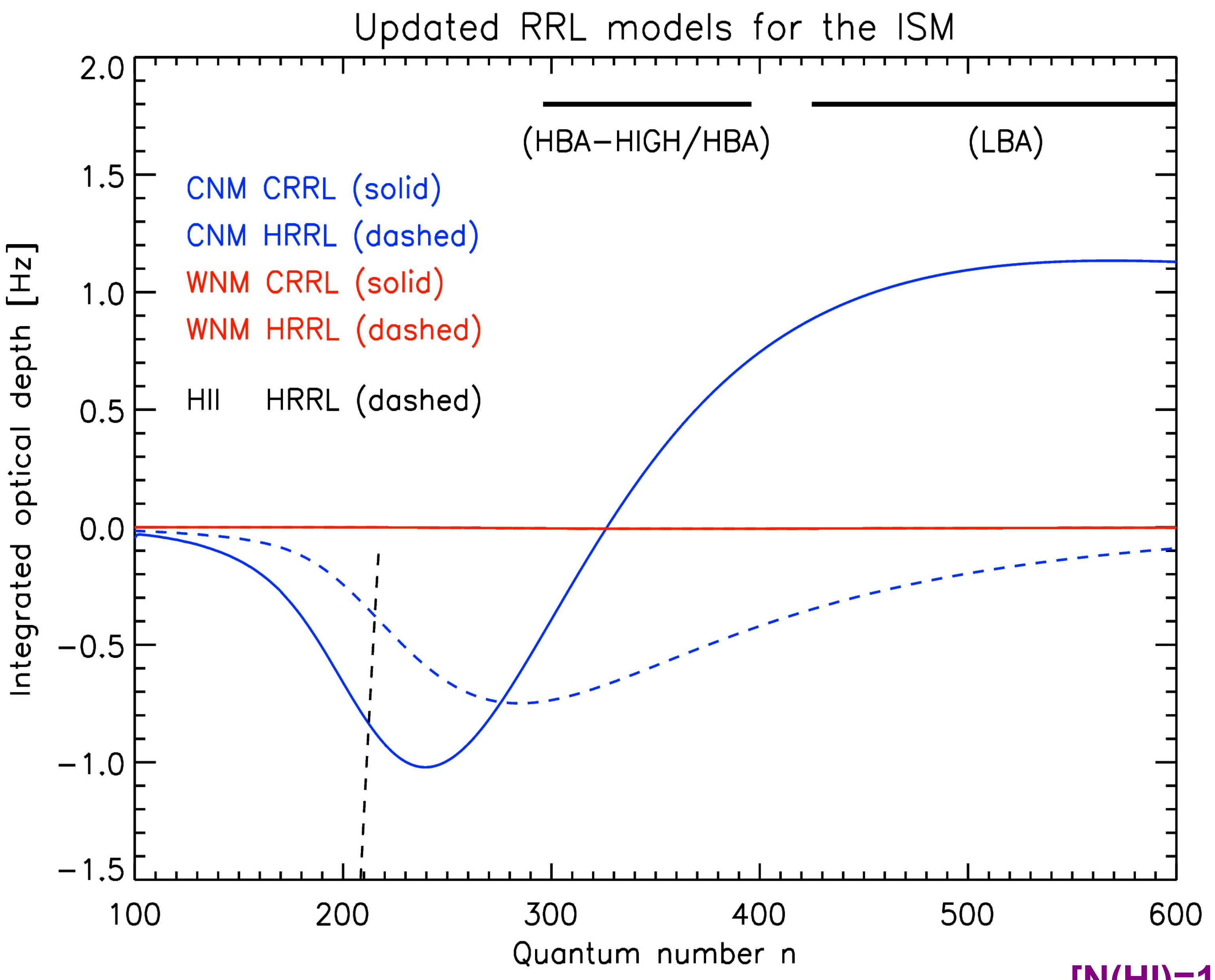
- $n_e = 0.01\ cm^{-3}$
- $T_e = 10^4$ K

HII:

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

*** i.e. RRL can disentangle CNM-WNM in the HI 21 cm line***

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



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

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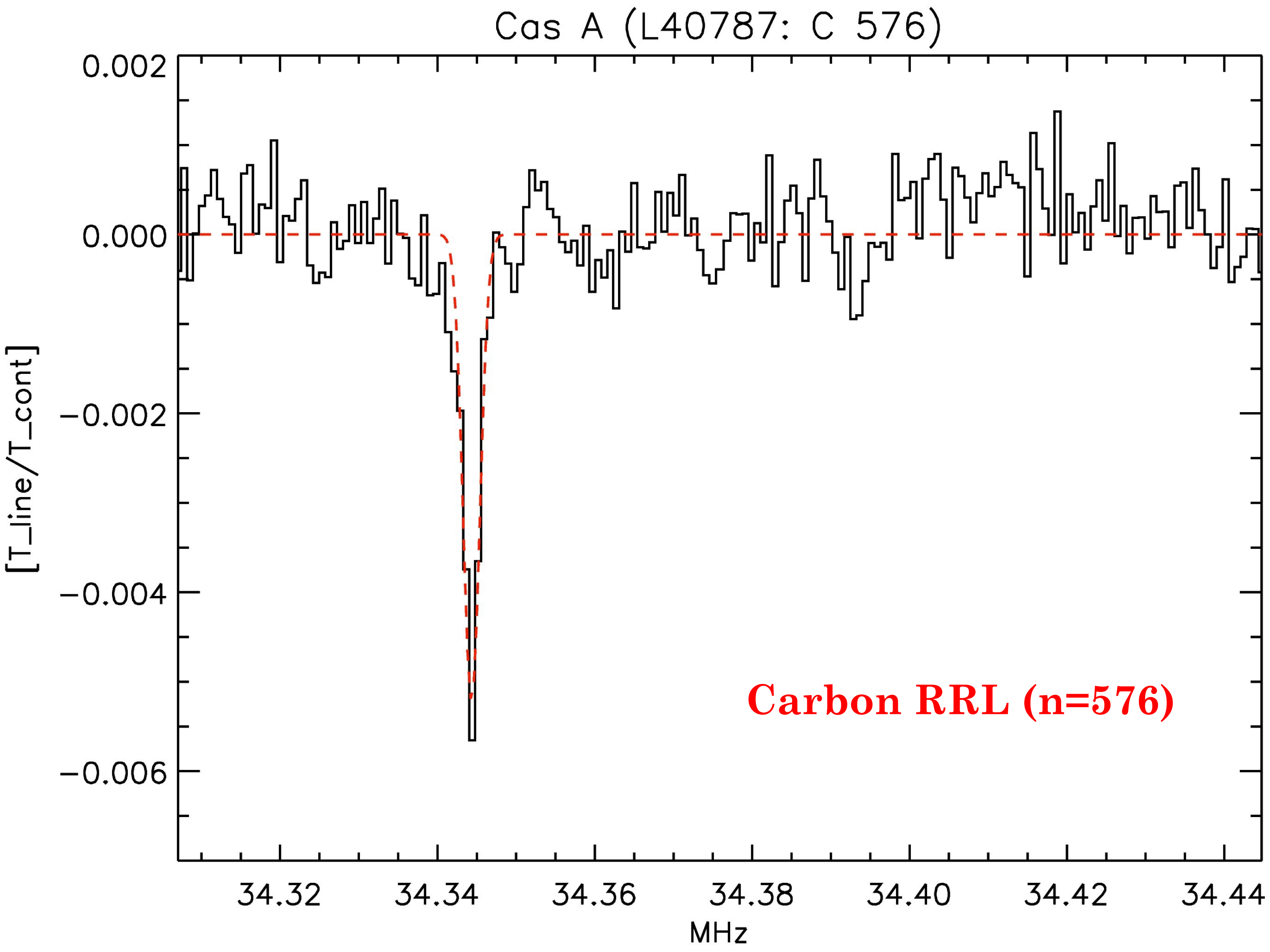
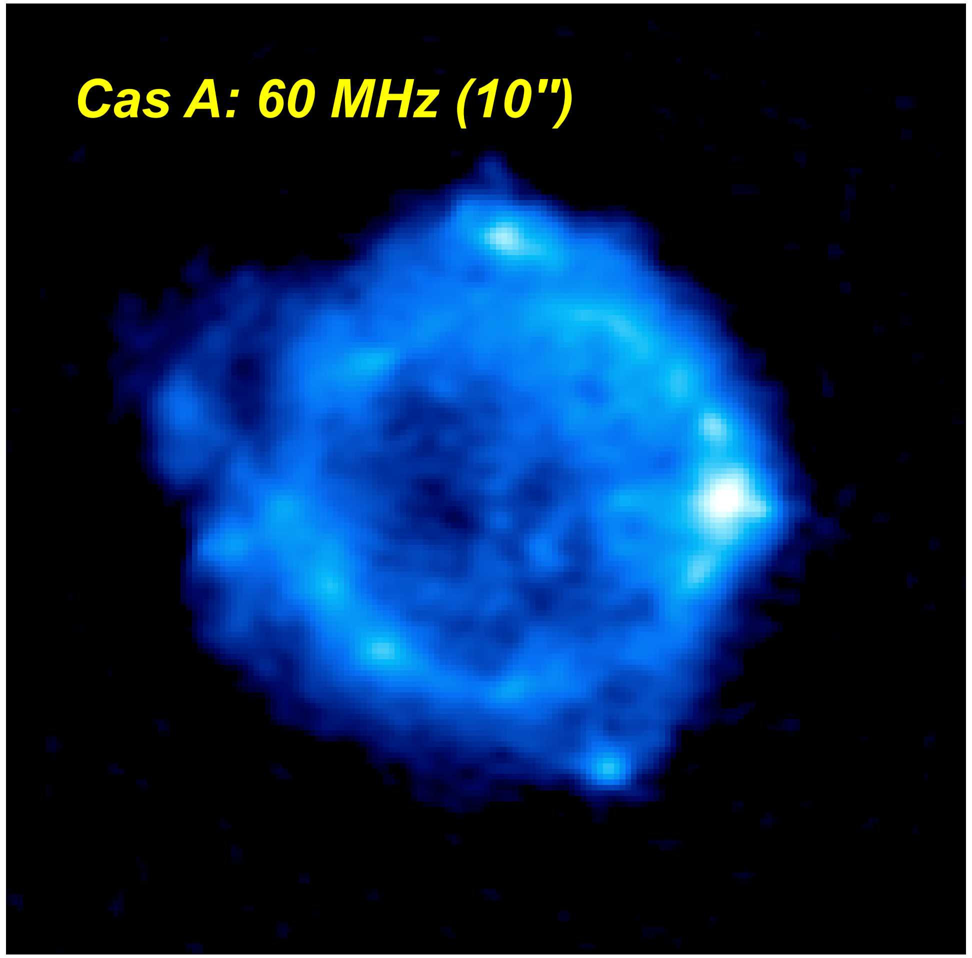
Constraining the CNM with LOFAR

LOFAR Cassiopeia A Spectral Survey (Oonk+)

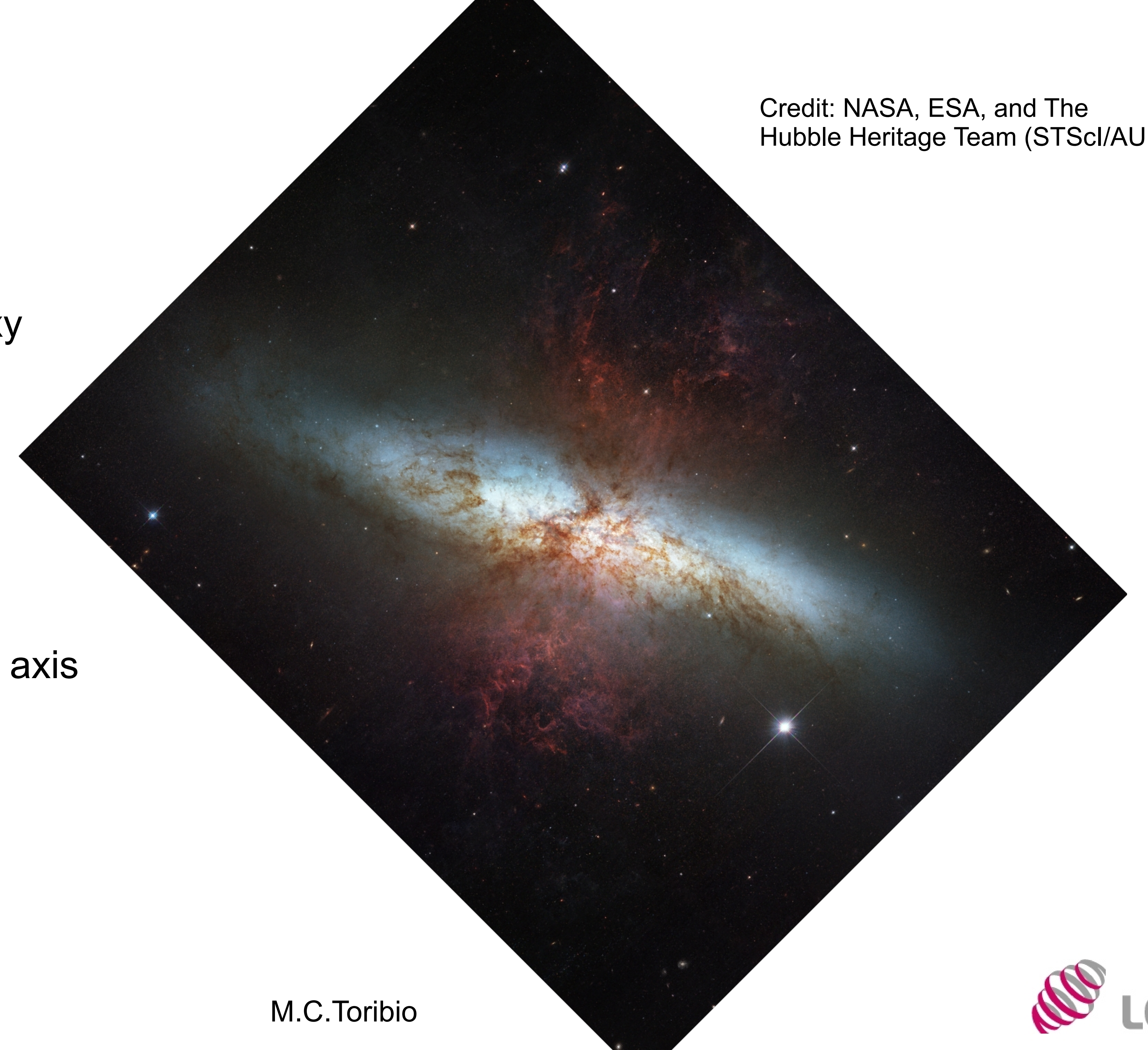




see also Cas A (Asgekar+13) and CygA (Oonk+14)

M82

- Nuclear starburst galaxy
- Distance 3.7 Mpc
- Velocity 203 ± 4 km/s
- Strong filamentary Hα-streamers in the direction of the rotation axis
- Interacting with M81



Credit: NASA, ESA, and The Hubble Heritage Team (STScI/AURA)

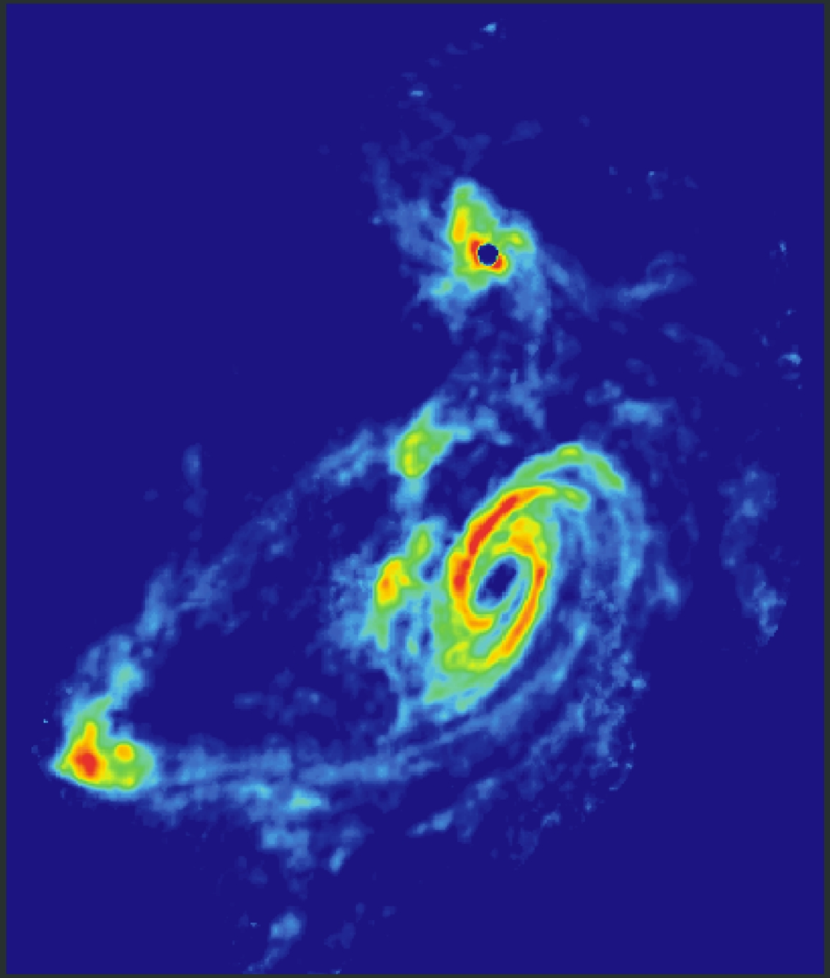
M82

Credit: Yun, Ho and Lo. Image courtesy of NRAO/AUI

TIDAL INTERACTIONS IN M81 GROUP

Stellar Light Distribution

21 cm HI Distribution



Credit: Johannes Schedler (Panther Observatory)

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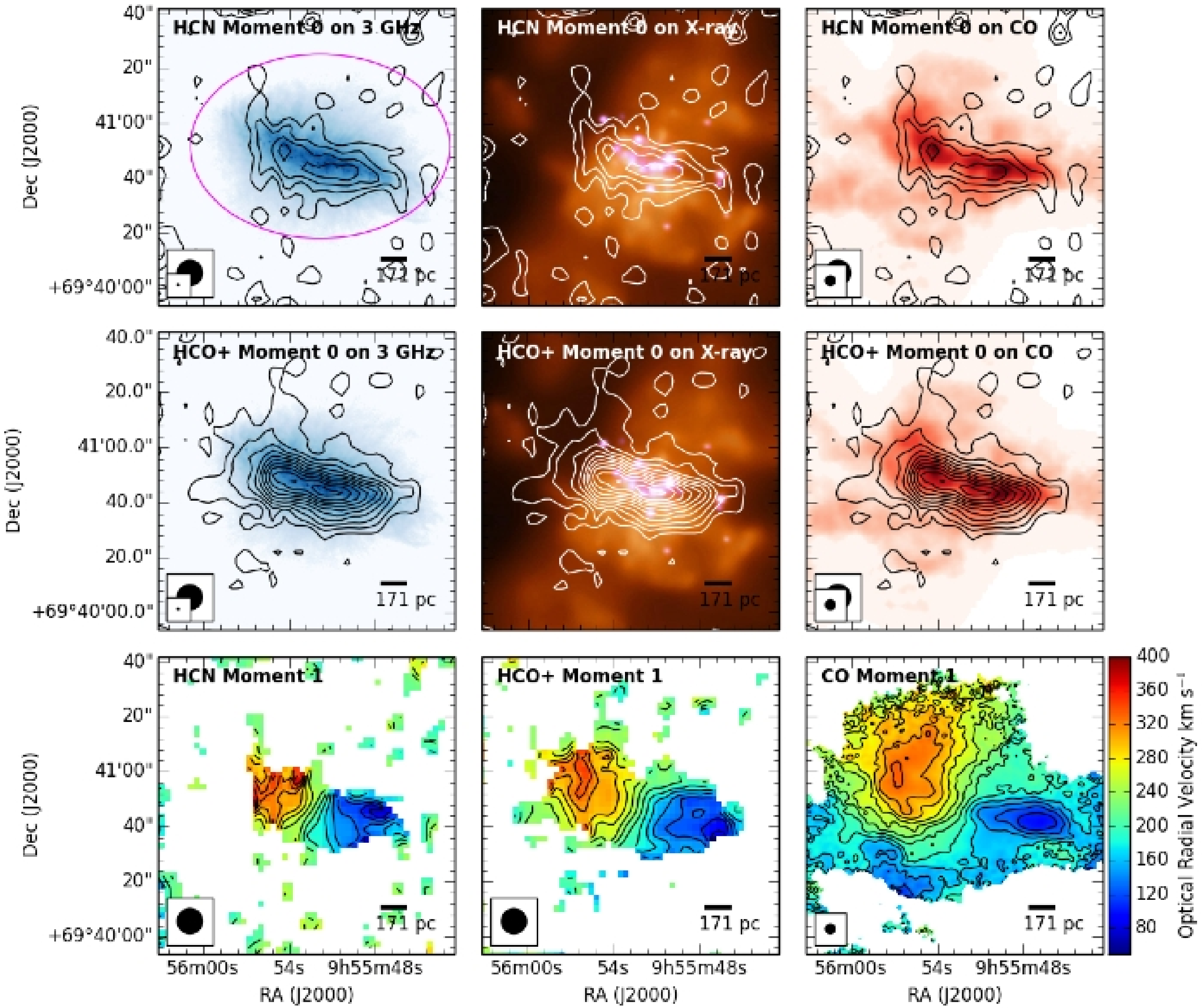
M82

Dense gas tracing
SF rotating torus
(Kepley+2014)



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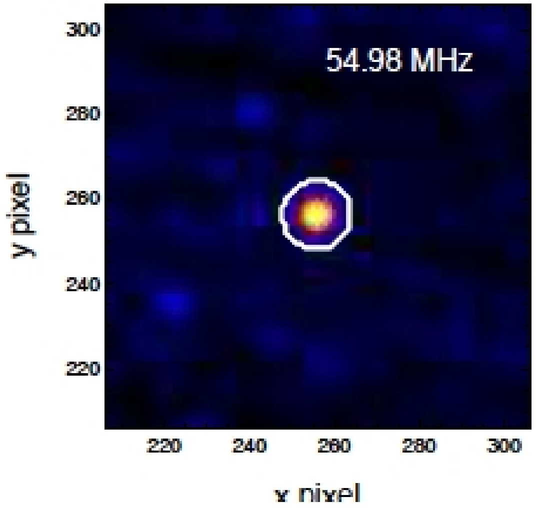
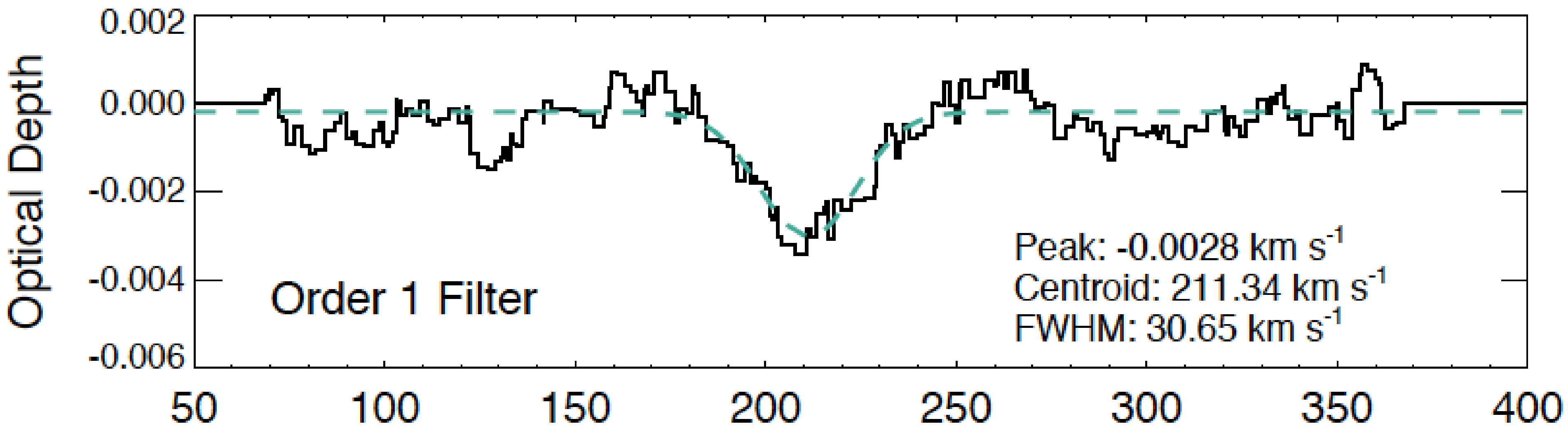
LBA measurements (30-78 MHz)



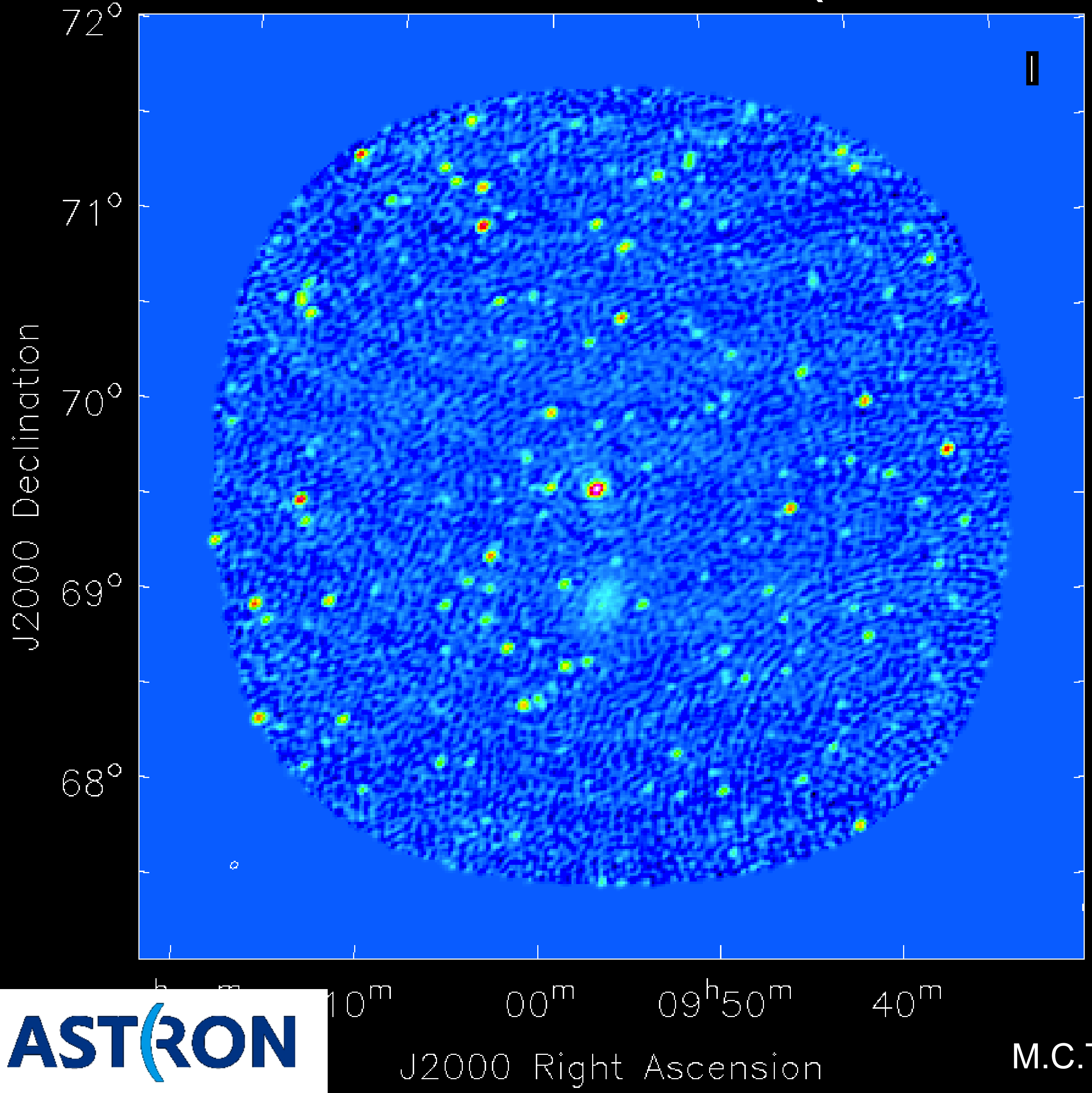
Morabito et al. (in prep):

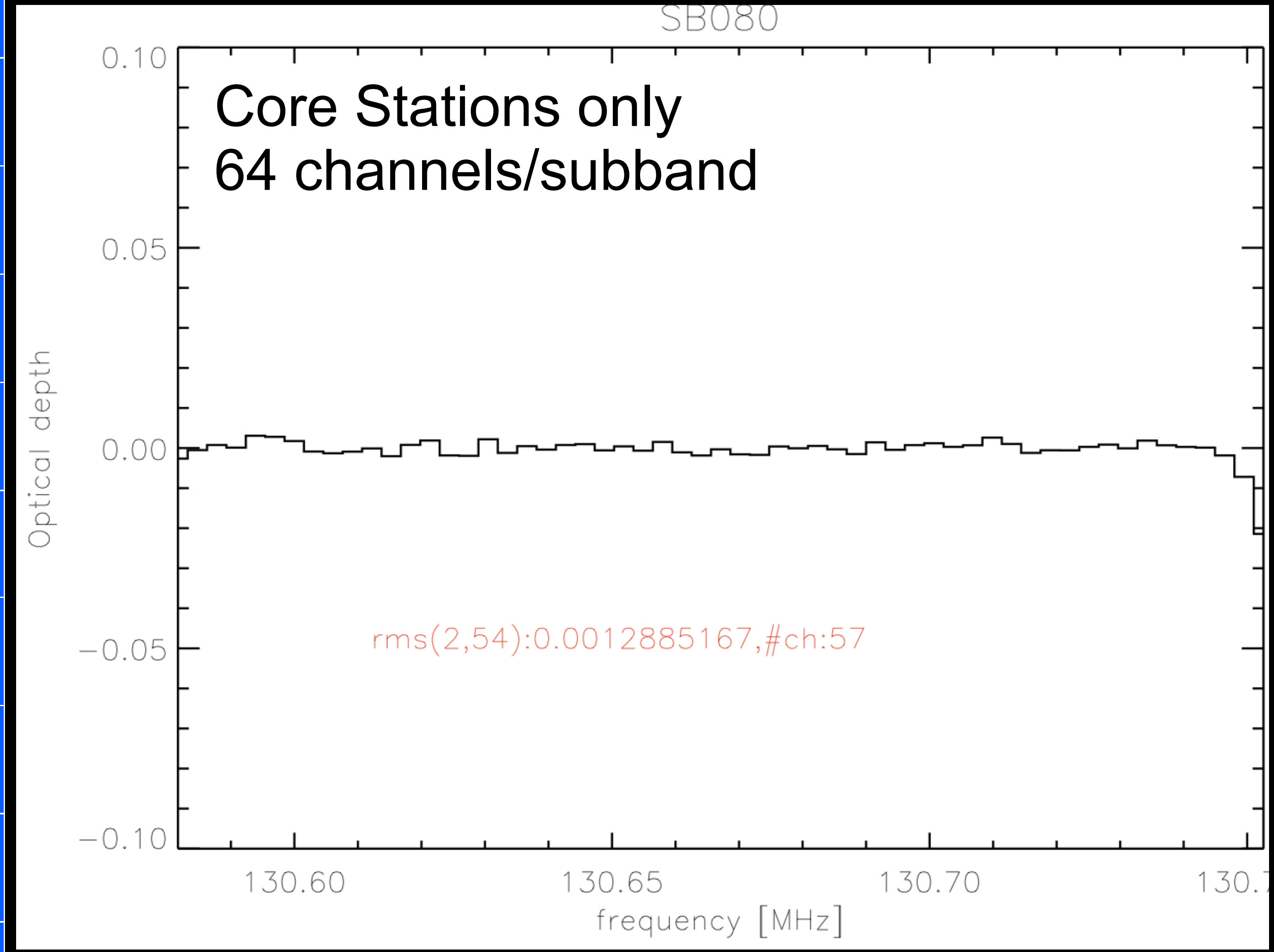
First detection of CRRLs from an extragalactic source



(32channels/subband, stacking 22 subbands)

HBA measurements (110-190 MHz)





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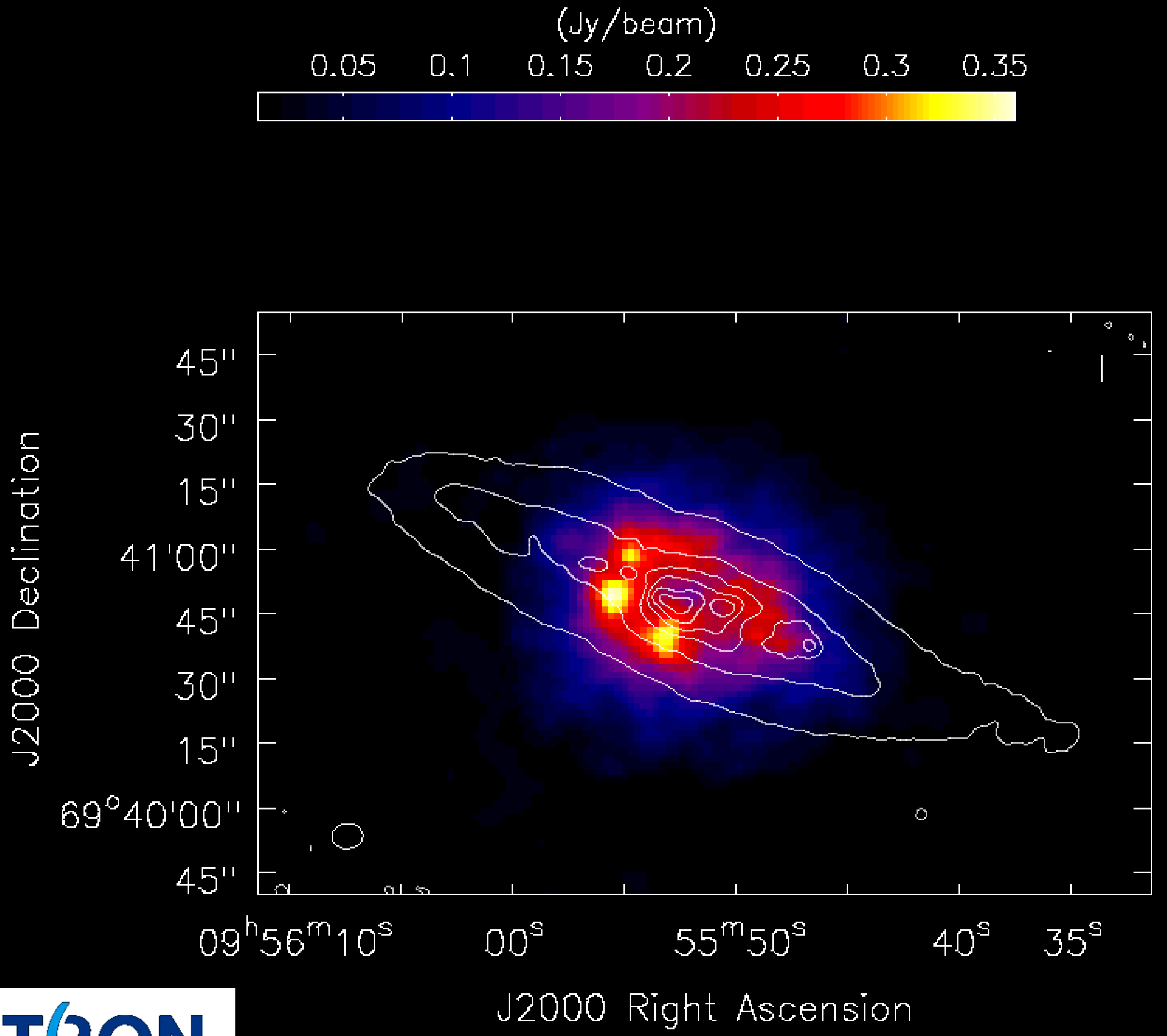

•Core and Remote Stations

LOFAR HBA: linear colorscale

2MASS J-band: contours (1,sqrt(2),4, 4*sqrt(2),8,8*sqrt(2)) x sky level

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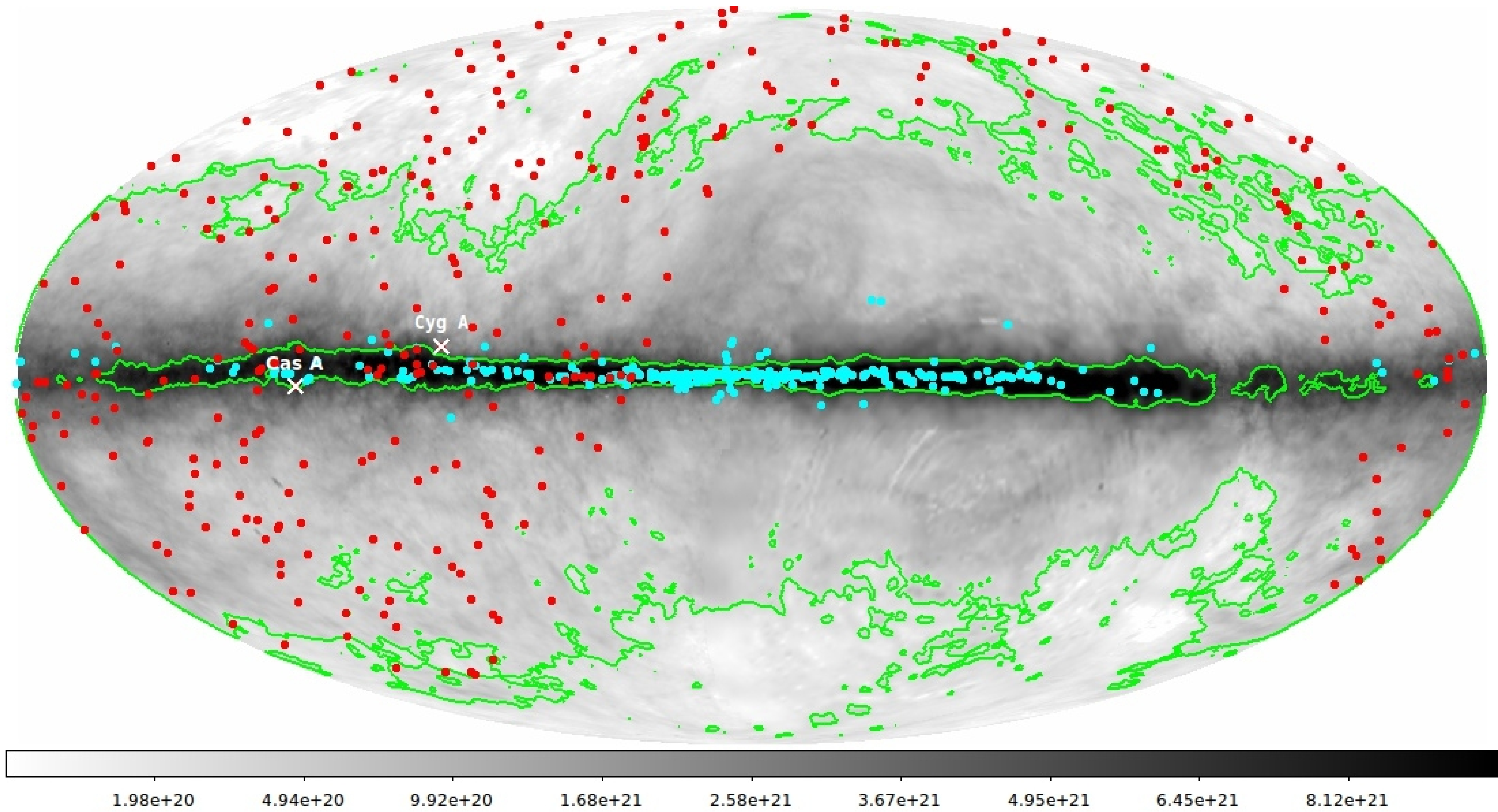
Summary

- **LOFAR LBA**: detection! (Morabito+, in prep)
- **LOFAR HBA**: work in progress
  - Better SNR than for the LBA >> feasible detection
  - CS spectra: no individual detections so far >> stacking
  - CS+RS spectra: disentangle the contribution from different clumps.

Future perspectives



HI 21cm
3C sources
SNR

- LOFAR Surveys of RRLs:
  - *Galactic* >= 10' , N(HI) > 3×10^{20} cm^{-2}
  - *Extragalactic* <= 300 sources

- SKA1-LOW sensitivities should allow to sharpen our focus by an order of magnitude (>10xLOFAR):
  - *Galactic* >= 3' , N(HI) > 5×10^{19} cm^{-2}
  - *Extragalactic* >= 100000 sources