The role of cold, atomic gas in our Galaxy and beyond

RRL group:

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E-infra group: *(Leiden + SURFsara)*

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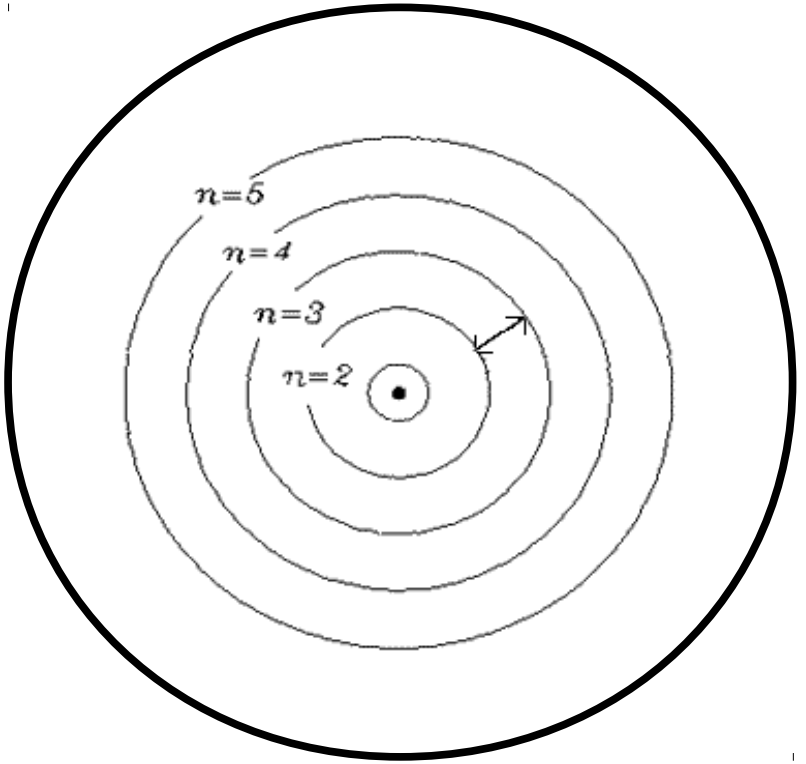
Rydberg atoms: cold, diffuse gas



11 MHz (n=843)

Outline

- CNM & Low-frequency RRL
- LOFAR
- < 1' survey : Cassiopeia A
- 10' survey : Cygnus
- Summary

Interstellar Medium

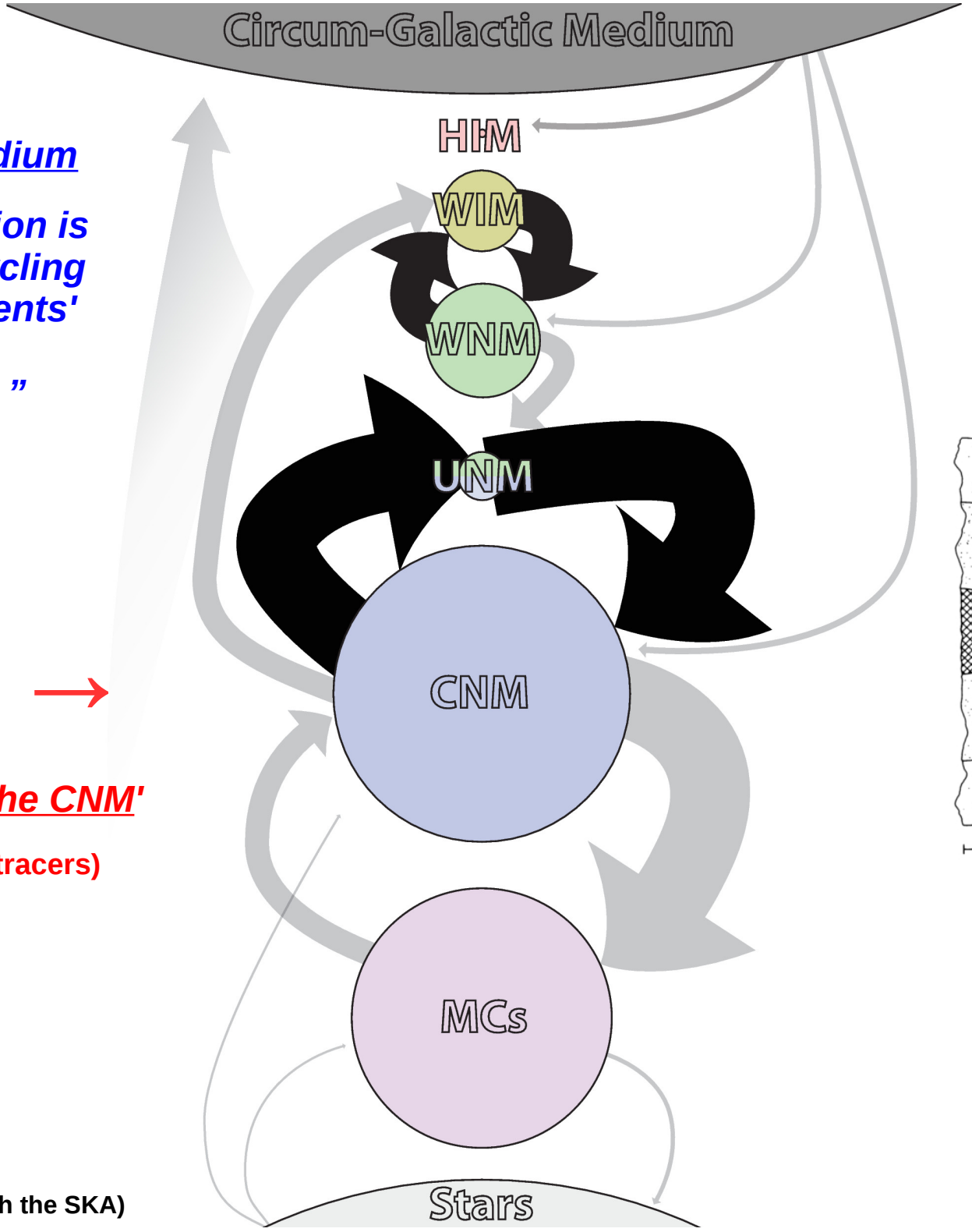
'Galaxy Evolution is driven by recycling of its constituents'

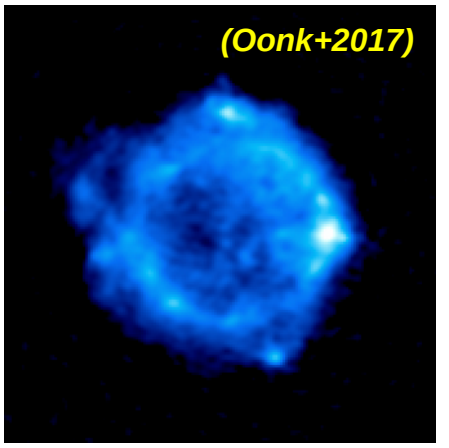
" mass flows "

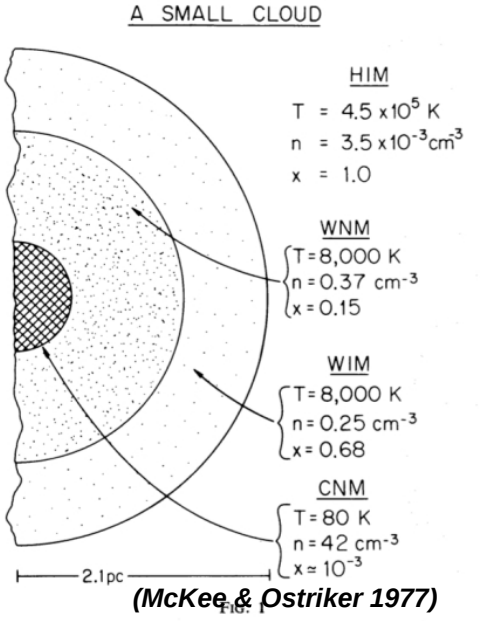
? →

'CRRLs trace the CNM'

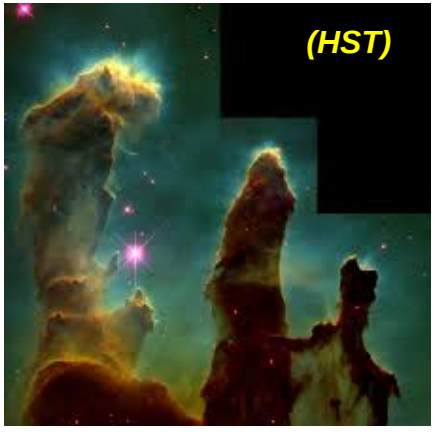
(dearth of good tracers)







(McKee & Ostriker 1977)

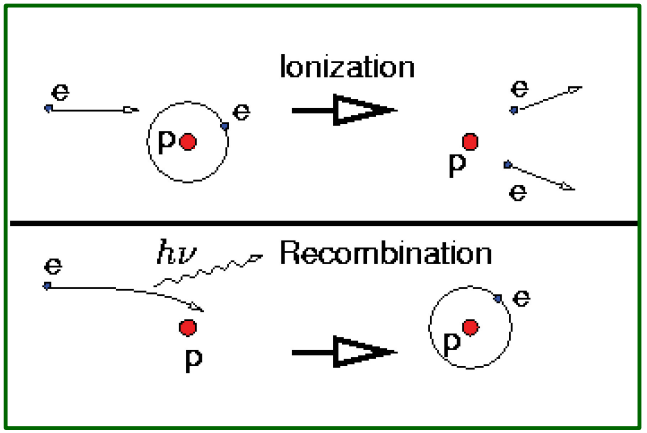


The physical conditions (T,n) of the CNM

Diffuse CNM: n_H ~ 10-1000 cm-3 , T ~ 50-500 K (C → C^+ ; 11 eV)

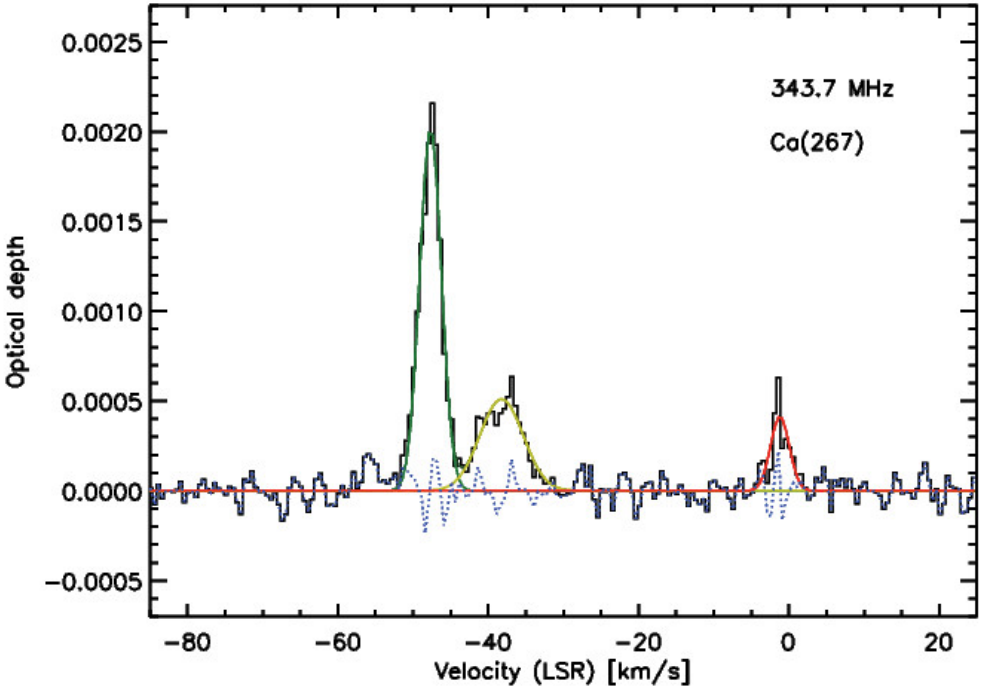
Atomic: HI 21 cm ***(e.g. Heiles & Troland 2003)***

Molecular: CO dark ***(e.g. Glover+2016)***

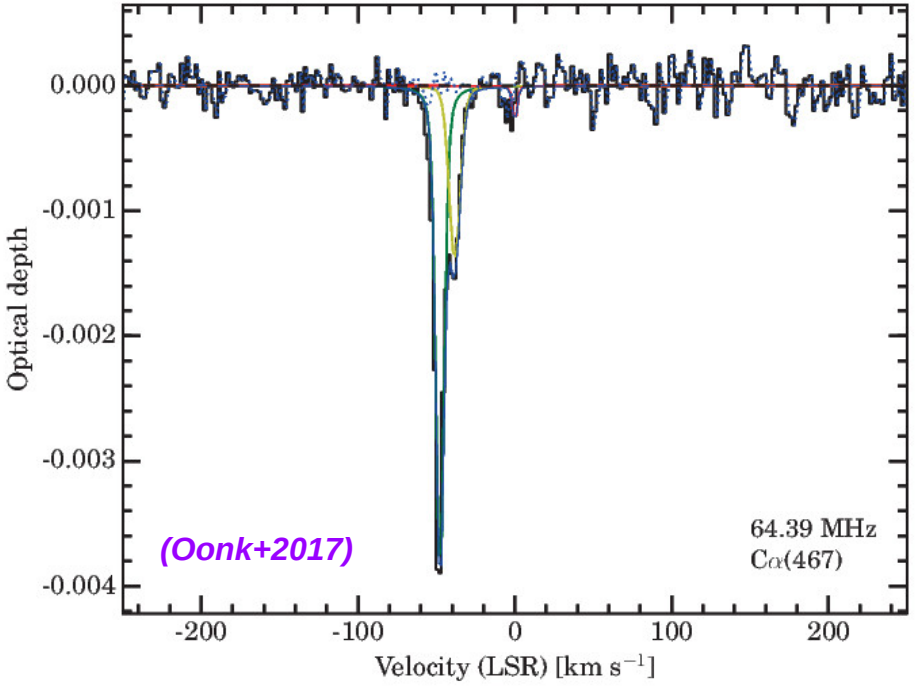


Alternative: low frequency Carbon RRLs

→ **" lines are weak τ_{peak} ~ 10^{-3} – 10^{-4} "**



Cas A (WSRT P-band)

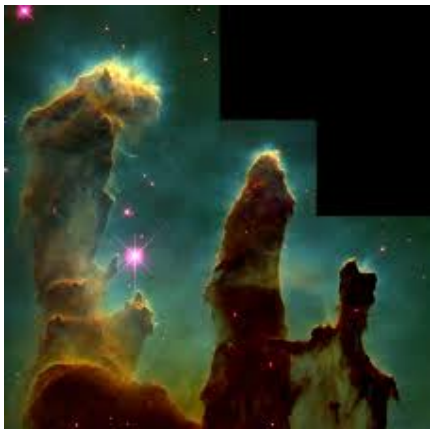


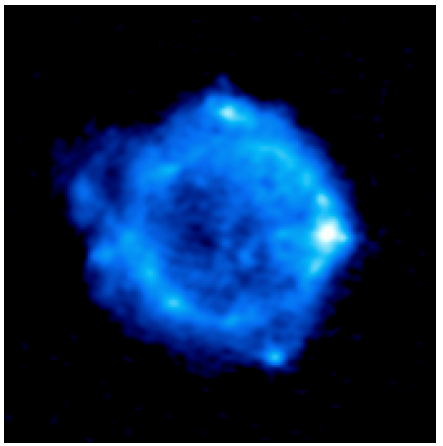
Cas A (LOFAR LBA)

“ Galaxy evolution is driven by recycling of the ISM ”

but,

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





<u>Method : Low-frequency (C)RRL's</u>

- **Localize RRL gas and compare w. CO, HI, HII**
- **Physical conditions of RRL gas** ***(T_e , n_e , L_C)***
- **Ionization rate of the RRL gas** ***(ζ_H)***
- **Carbon abundance** ***([C/H])***
- **Kinematics of the RRL gas** ***(v , FWHM)***

** enabled by our new models (Salgado+2017a,b)*

LOFAR & CRRL: NWO – TOP1 (Oonk / Tielens 2014)

Power of LOFAR:

Sensitivity, Resolution, FoV, BW

=> *"Survey speed"* (α , δ , λ)

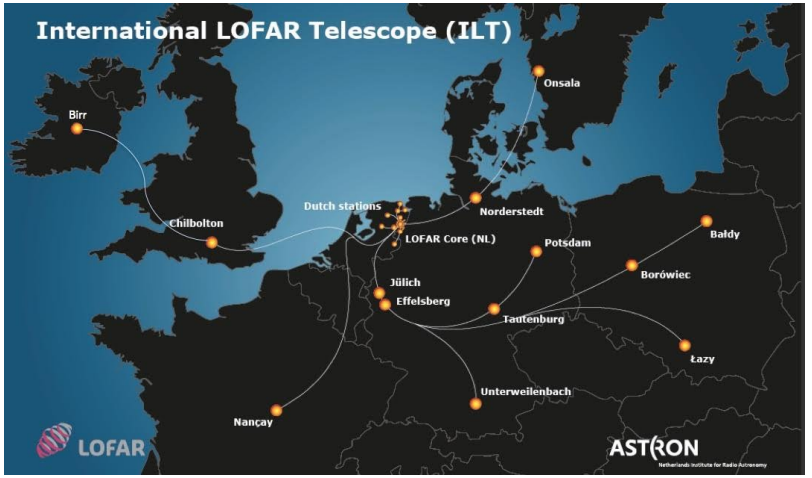
* **LBA 10 - 90 MHz : 450 RRL α-lines**
* **HBA 110 - 250 MHz : 100 RRL α-lines**

LOFAR CRRL surveys (PI: Oonk)

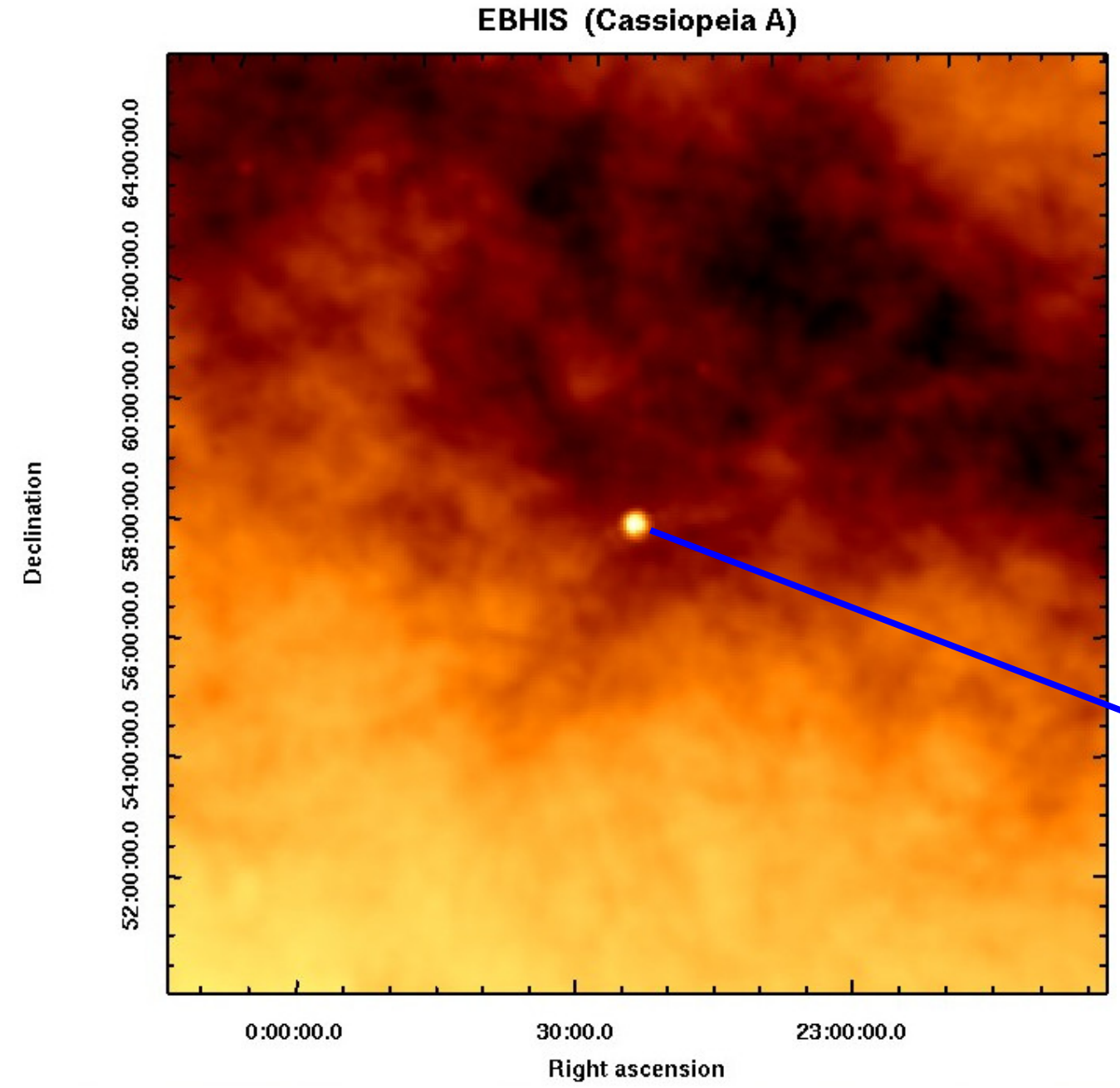
A) Galactic pinhole survey (< 1') *

B) Galactic 10' tied-array survey *

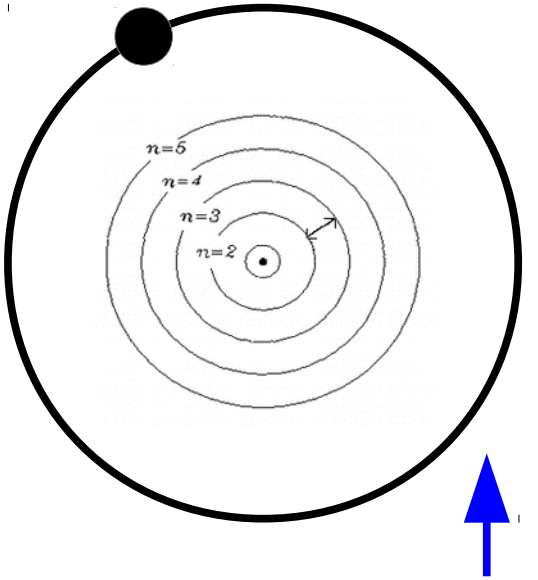
C) Extragalactic survey

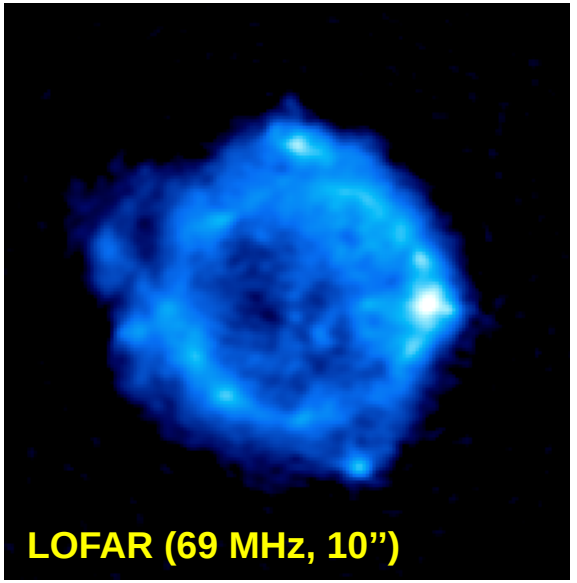


Cas A & Low-frequency radio recombination lines

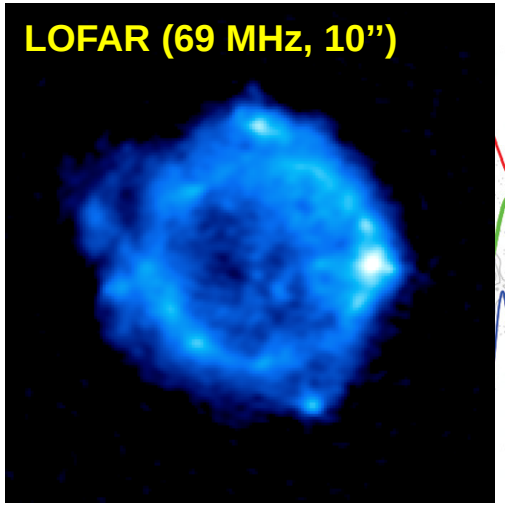


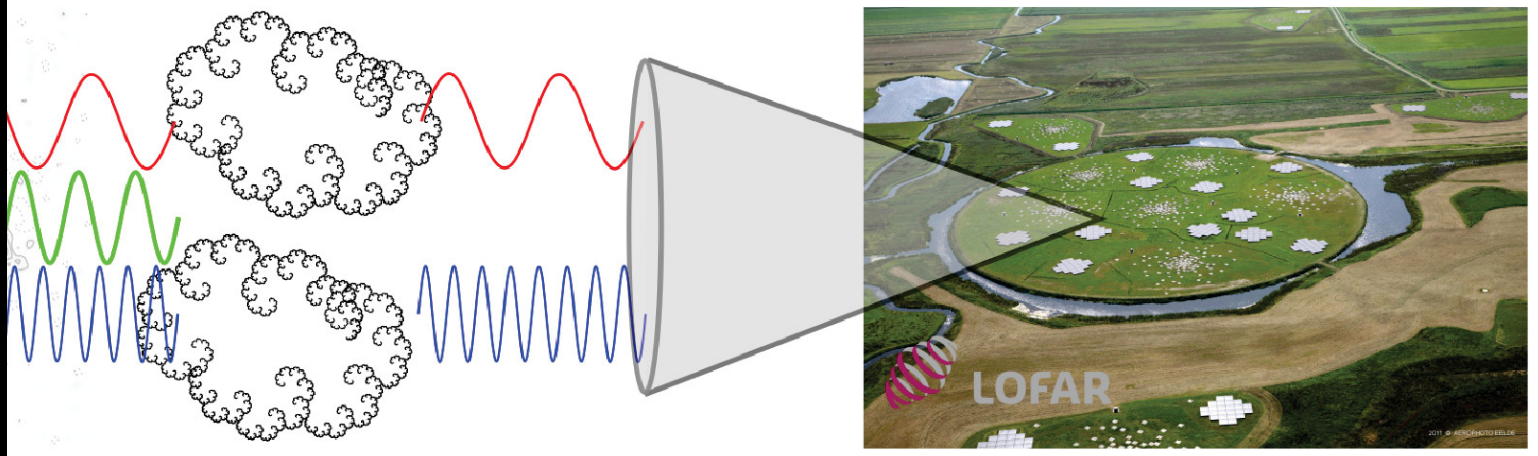
11 MHz (n=843): r ~ 1 micron





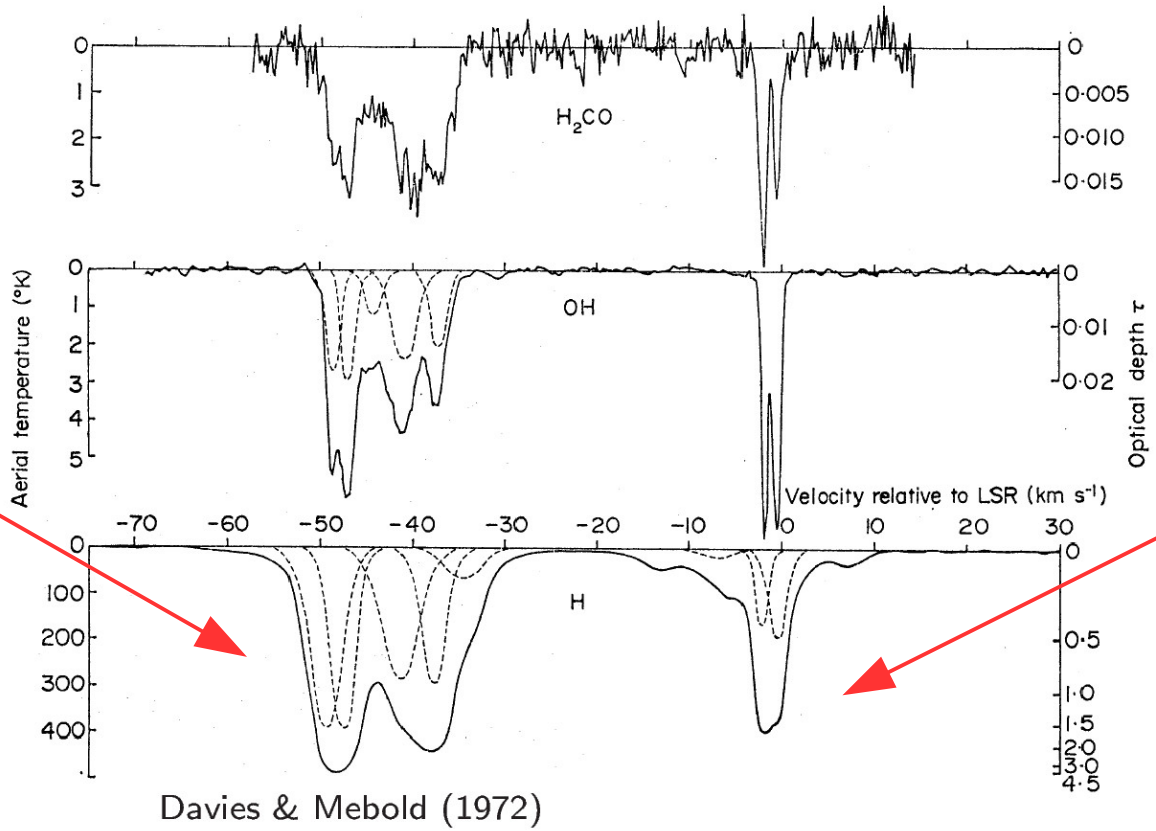
The line of sight towards Cassiopeia A (Oonk+, Salas+ 2017)





(Perseus arm)

(Orion spur)



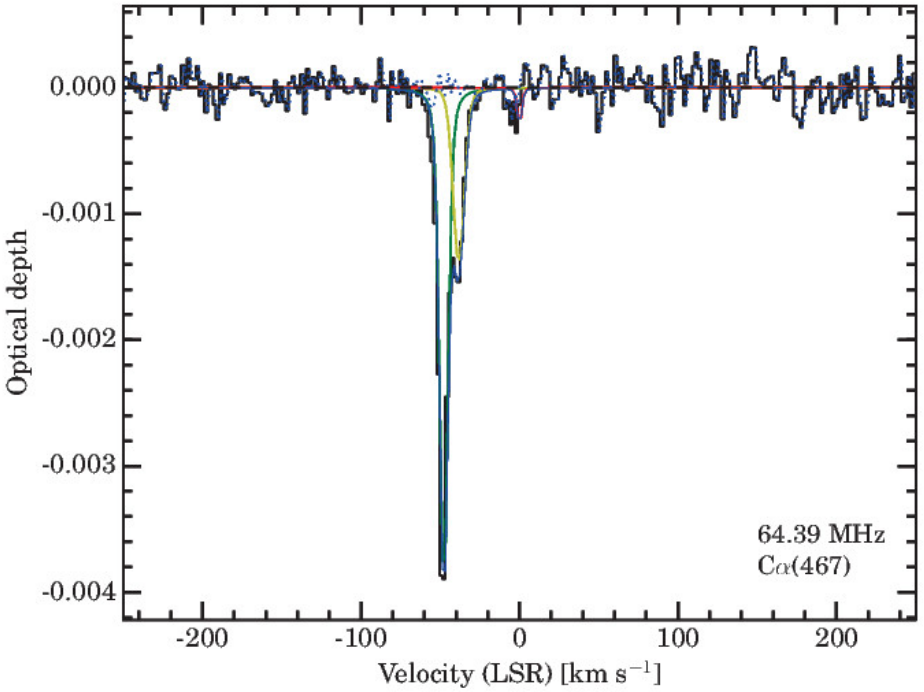
Davies & Mebold (1972)

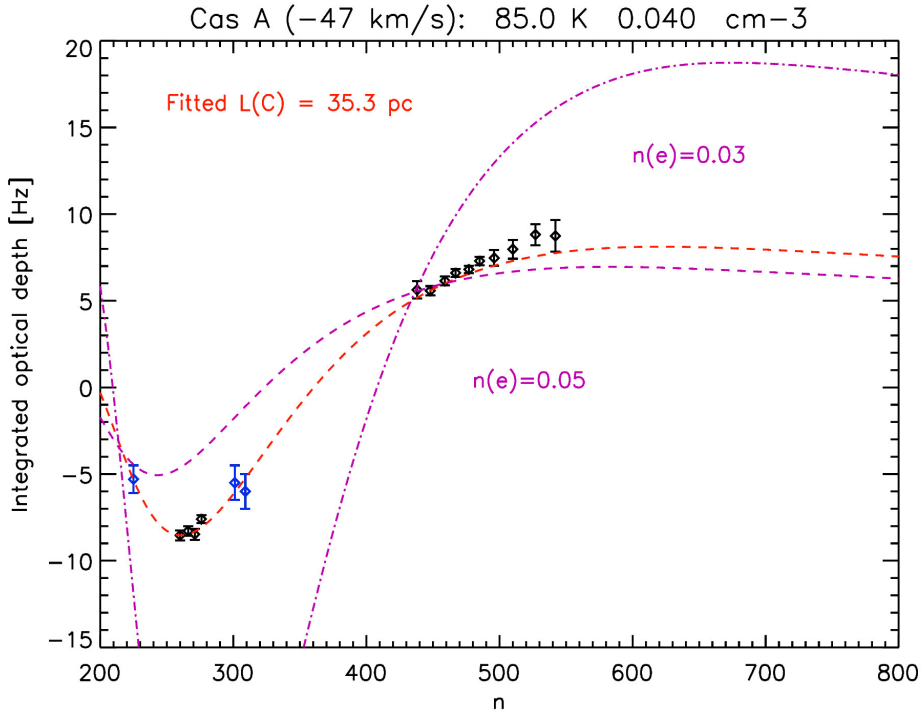
LOFAR LBA 3x10hr

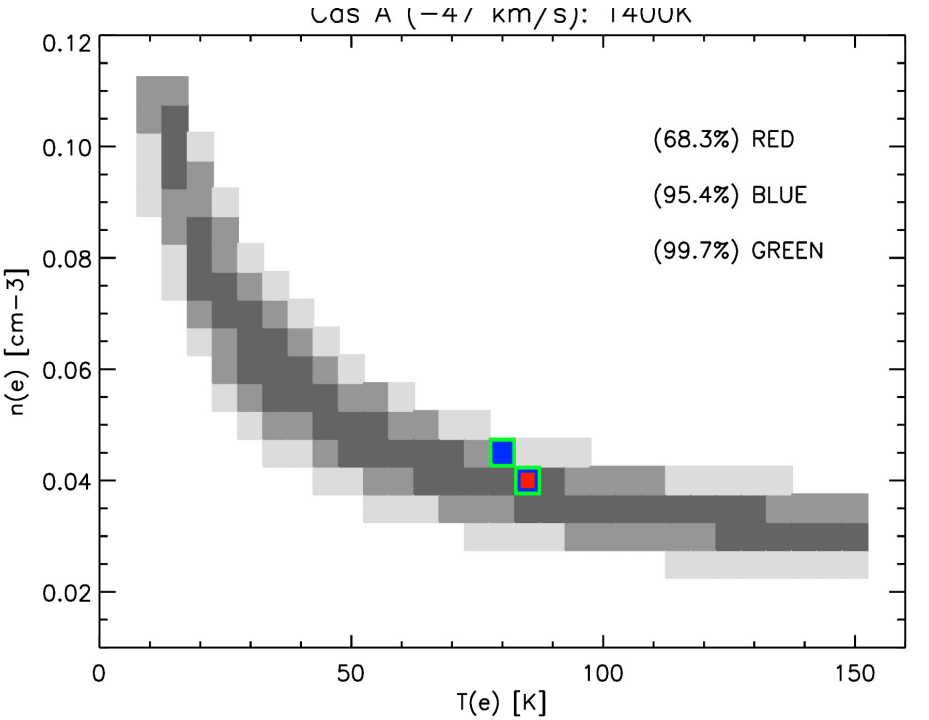
** LBA 10- 80 MHz*
** 0.4 kHz resolution*

WSRT P-band 12hr

Low-frequency CRRL → the physical conditions of CNM





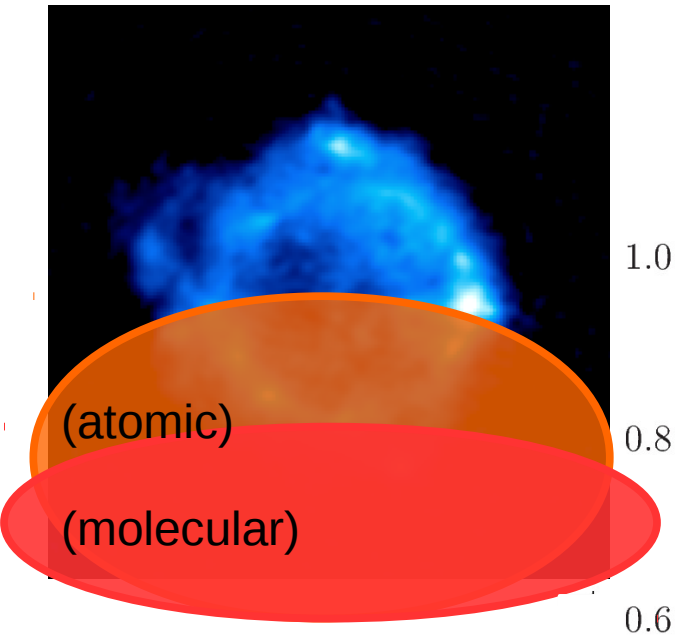


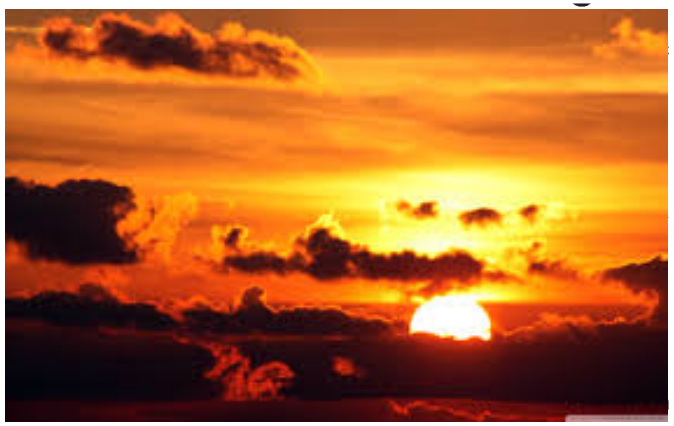
Cassiopeia A (-47 km/s) : (Oonk+2017)

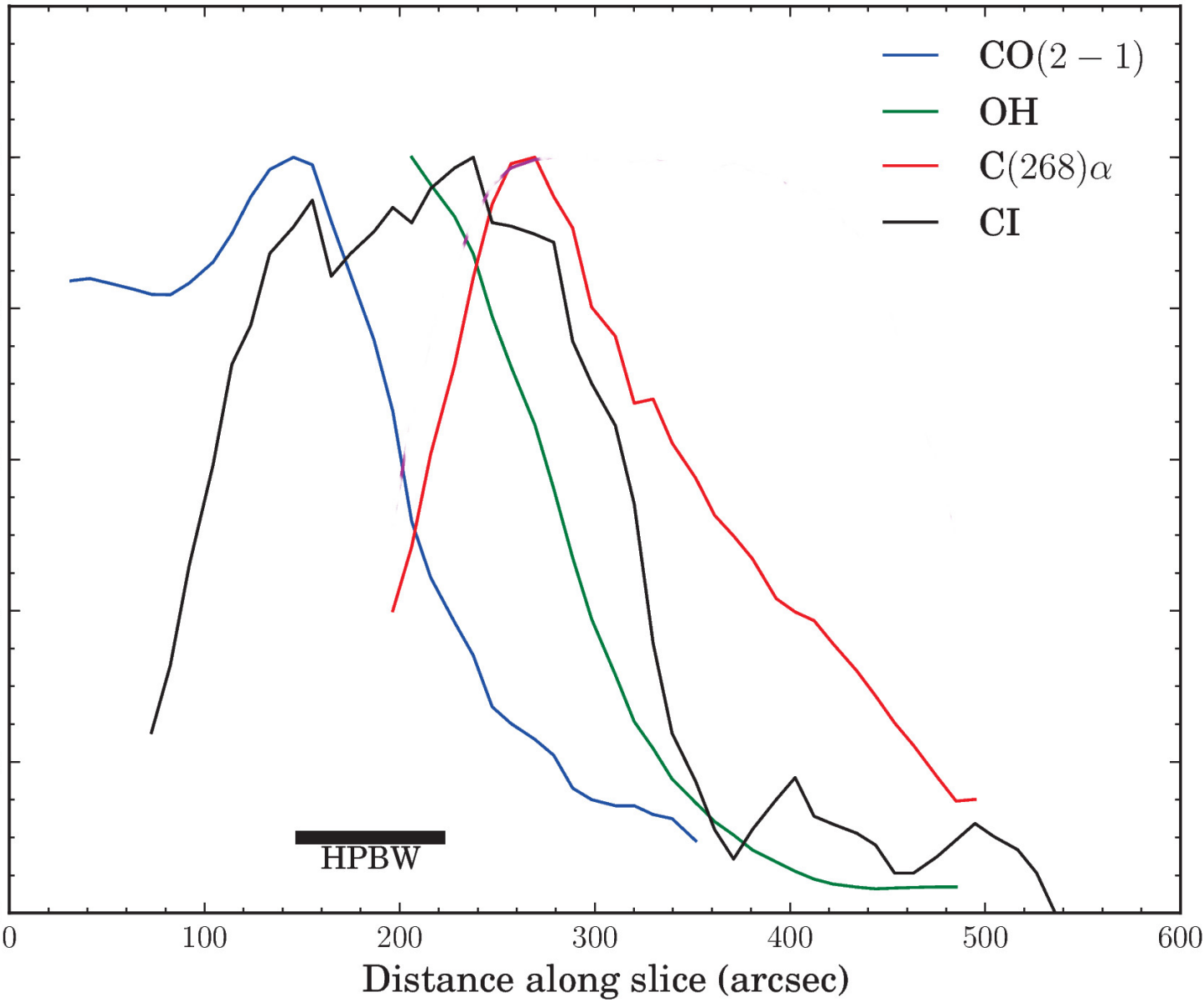
T_e = 85 +- 5 K
n_e = 0.04 +- 0.005 cm^{-3}
L_{CII} = 35 +- 1 pc
N_{CII} = (4.4 +- 0.6) x 10^{18} cm^{-2}
N_H = (3.1 +- 0.4) x 10^{22} cm^{-2}
n_H = 286 +- 36 cm^{-3}
P_{th} = (2.4 +- 0.5) x 10^4 K cm^{-3}

→ diffuse cloud edge/sheet (HI – H_2 interface)

Cas A clouds, a diffuse PDR (CRRL CO-dark/poor gas)



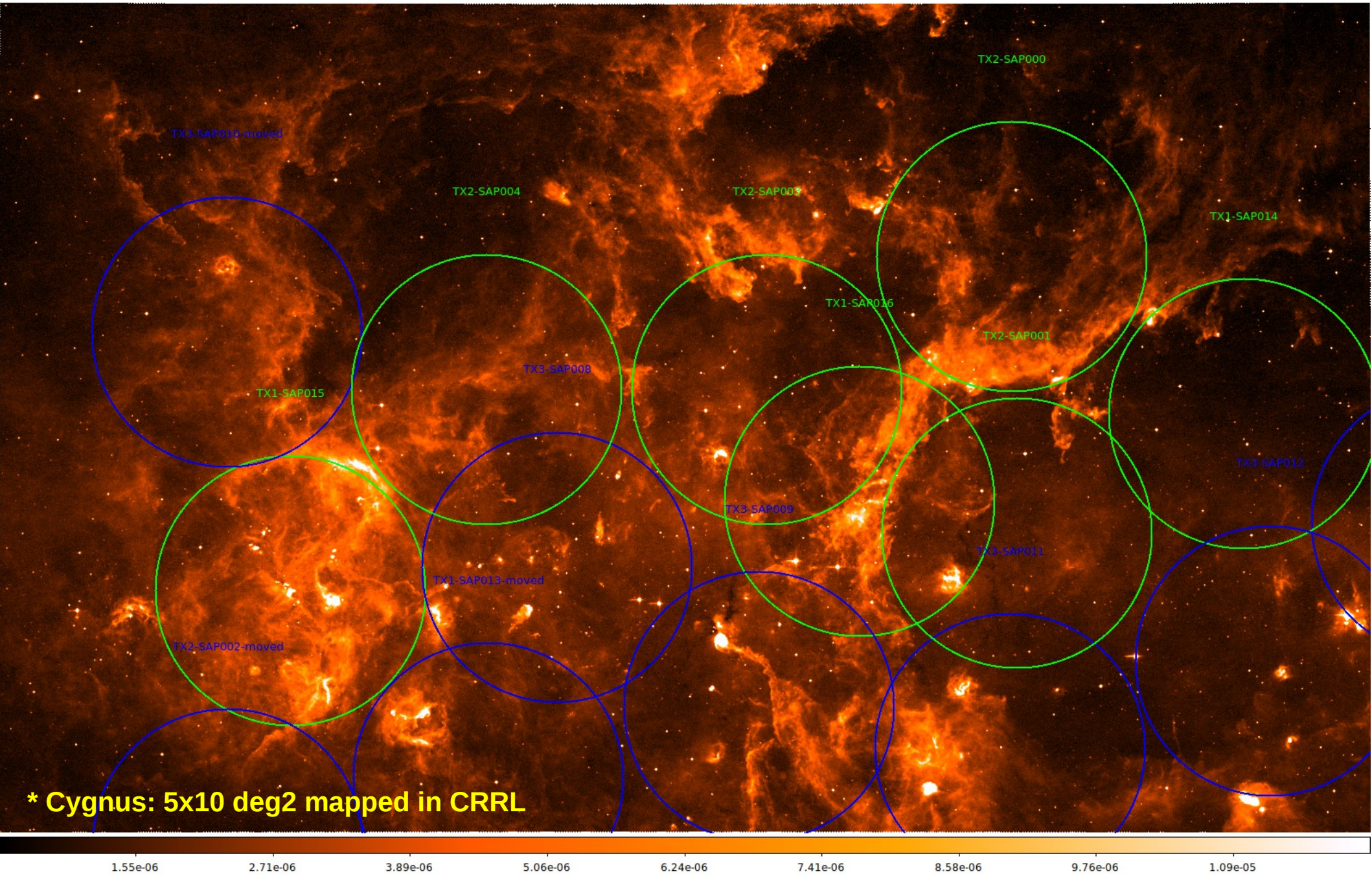




→ **P. Salas+ in prep: CRRL trace the envelope/sheet of the molecular complex (PDR)**

Cynus region (LOFAR 10’ CRRL survey)

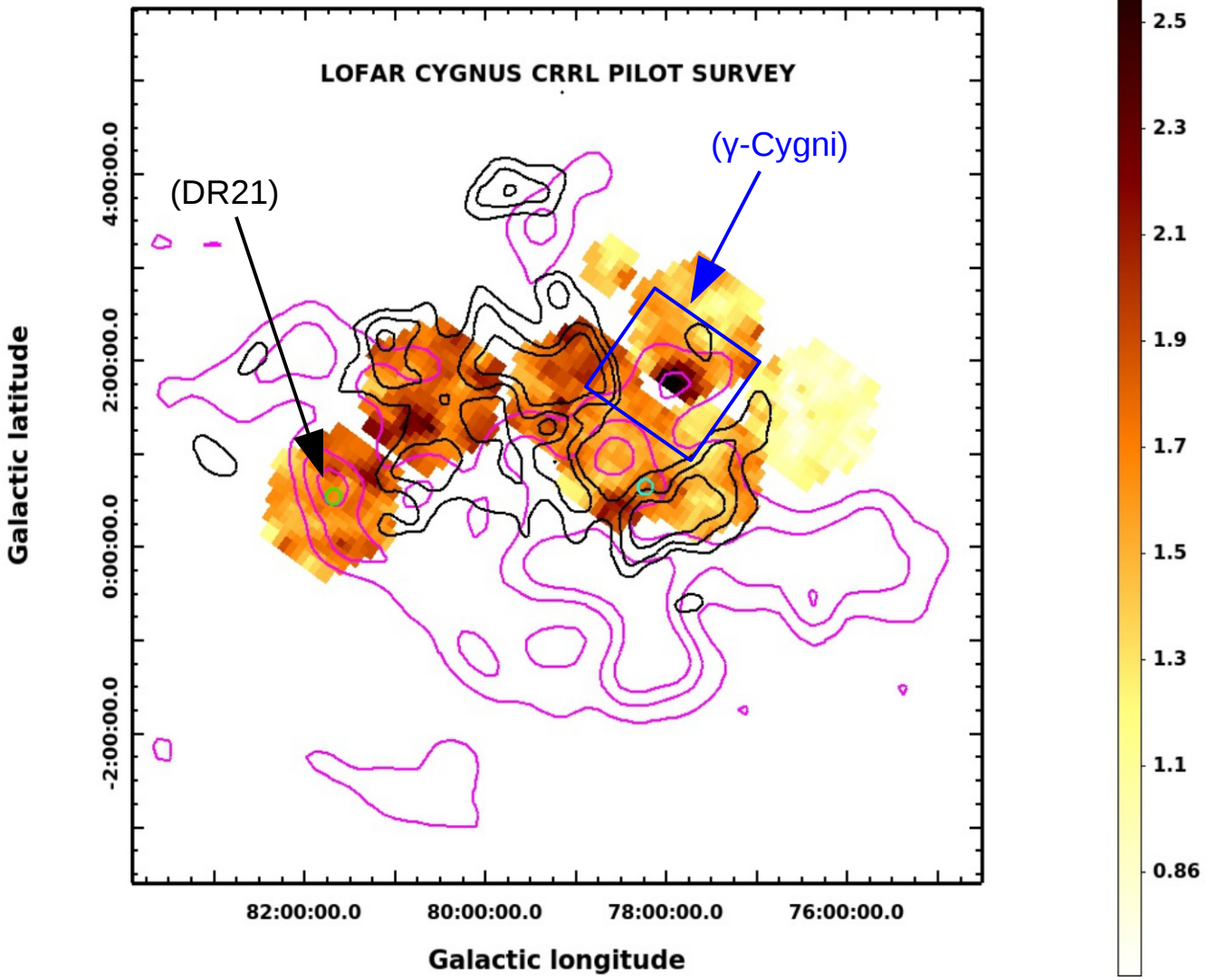
(MSX 8 μm)

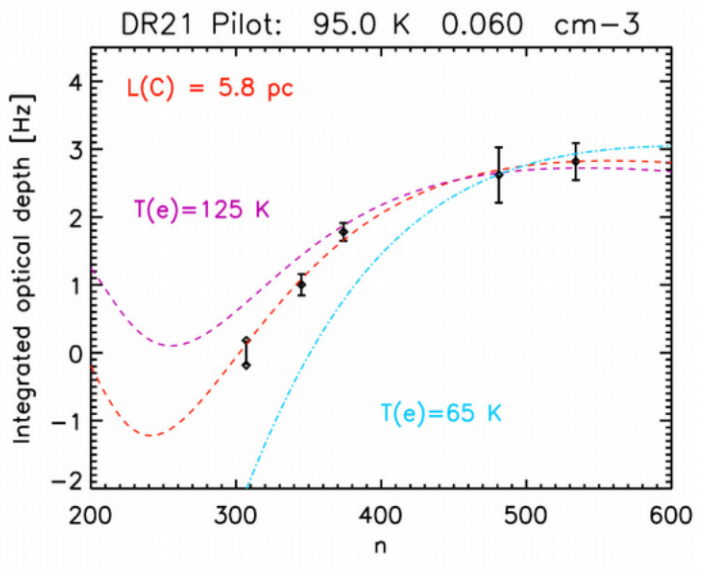


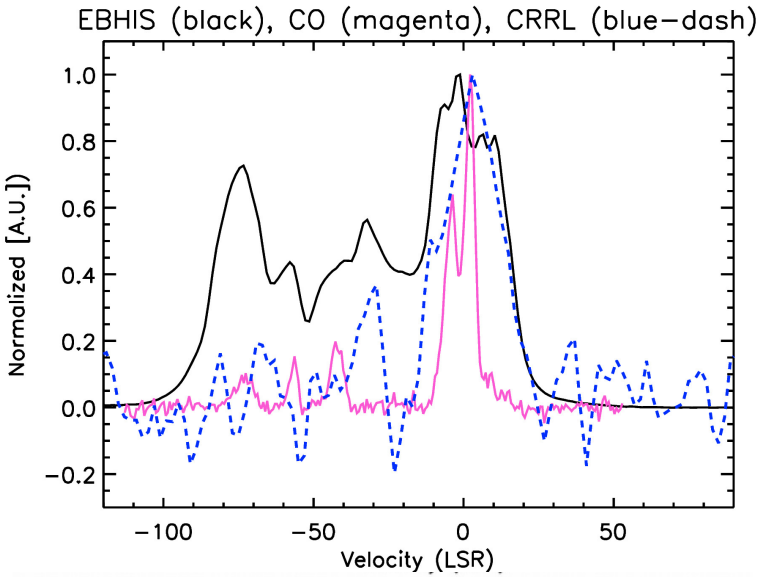
Cynus region (LOFAR 10' CRRL survey)

(Oonk+ in prep.)

HBA Cygnus CRRL map *(preliminary!)*



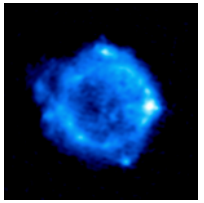




→ **CRRLs resolved on 10' scales: models show regions with increased T_e and n_e**

→ **matching HI-EBHIS (10'), CO-DHT10 (10'), radio continuum, dust and [CII]**

Summary:



1) Cas A clouds show the potential of low-frequency CRRLs & CNM

- A low temperature, low density electron plasma exists in the ISM *(e.g. Payne+1989; Oonk+2017)*

- simple 1D model : ***$T \sim 85$ K, $n \sim 300$ cm-3 , $p_{th} \sim 2e4$ K cm-3 "diffuse CNM"*** *(Oonk+2017)*

- CO, CI, OH, CRRL: ***diffuse PDR, CO – dark/poor gas envelope of MC complex*** *(Salas+)*

- CRRL + { HI absorption, [CII] 158 μm, HRRL } → provides: [C/H] , T , ionization rate *(Oonk+2017)*

**** RRL non-LTE, stimulated emission → detailed models (l-changing collision rates)*** *(Salgado+2017)*

2) LOFAR Cygnus data shows that large-scale 10' maps of CRRL can be made

- Cynus 5x10 deg2 has been mapped in CRRL with HBA and LBA

- LOFAR CRRL data matches HI 21cm (EBHIS) and CO (DHT10)

3) Extragalactic CRRL detections (also useful for Galactic Pinhole studies) *(Oonk+2014)*

*- M82 has been robustly detected at 50 MHz and at 160 MHz (Morabito+2014, **TORIBIO+ POSTER !**)*

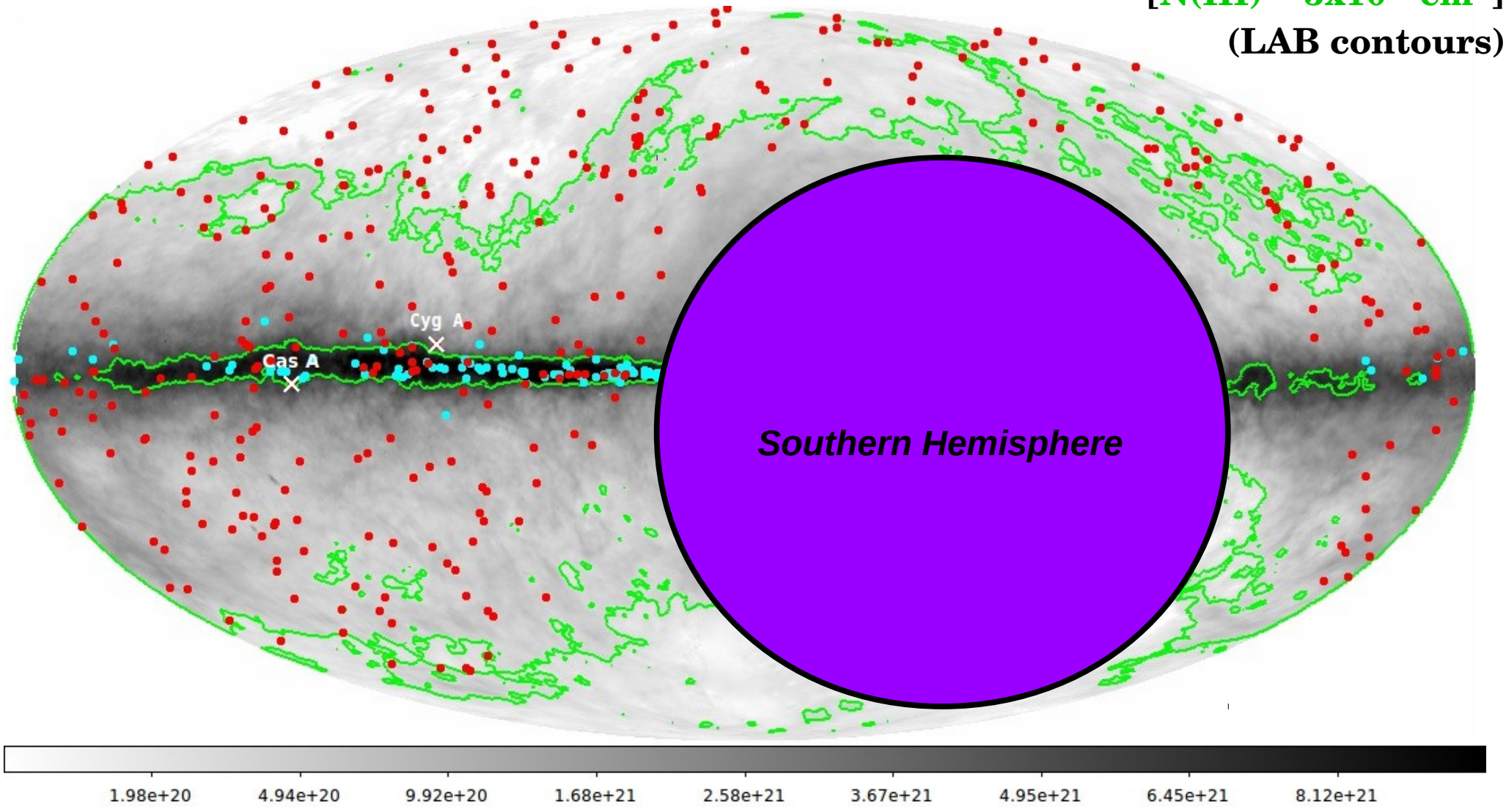
*- 3C radio galaxy sample is ongoing (**EMIG+ TALK ON THURSDAY !**)*

=> " LOFAR is starting to scratch the CRRL surface, but the SKA will transform it ! "

***** LOFAR e-infra data processing Leiden+SURFsara:*** ***MECHEV+ POSTER ! ****

LOFAR CRRL MW: (HI 21 cm , 3C , SNR)

[N(HI) ~ $3x10^{20}$ cm^{-2}]
[N(HI) ~ $3x10^{21}$ cm^{-2}]
(LAB contours)



LOFAR 8 hr, 5σ CRRL limits:

Column densities	N(H)	> 3e20 cm^{-2}
Source fluxes	S_ν	> 5 Jy/beam
Diffuse Milky Way	T(408)	> 40 K

J.B.R. Oonk (ASTRON/LEIDEN)