The CNM through low-frequency radio recombination lines

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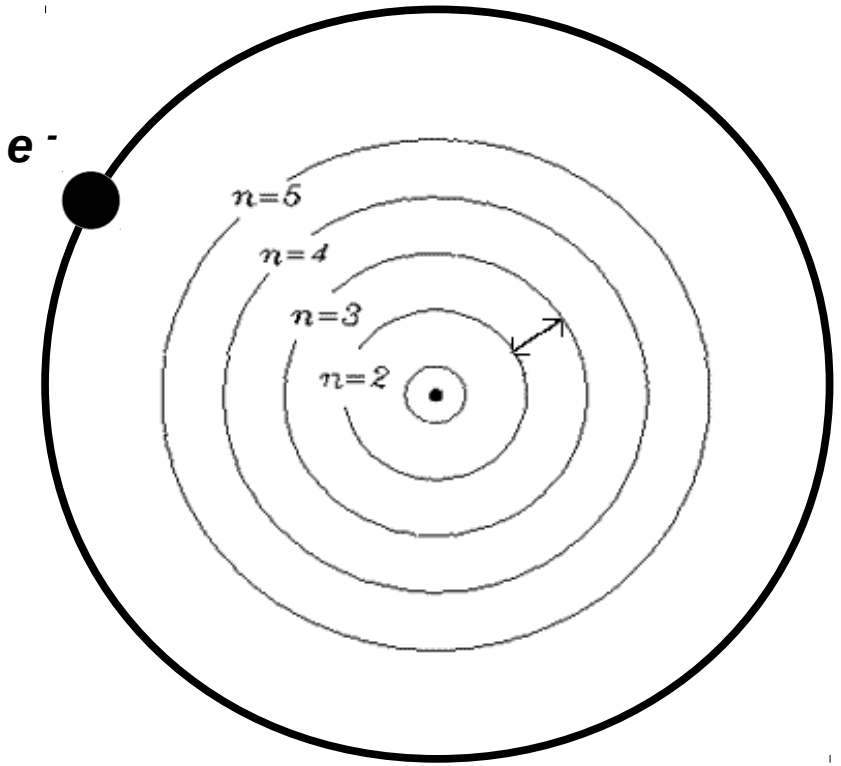
Outline

- **ISM & Low-frequency RRL**
- **LOFAR**
- **Cassiopeia A (1' survey)**
- **Cygnus (10' survey)**
- **Summary**

Rydberg atoms: almost dust ...



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

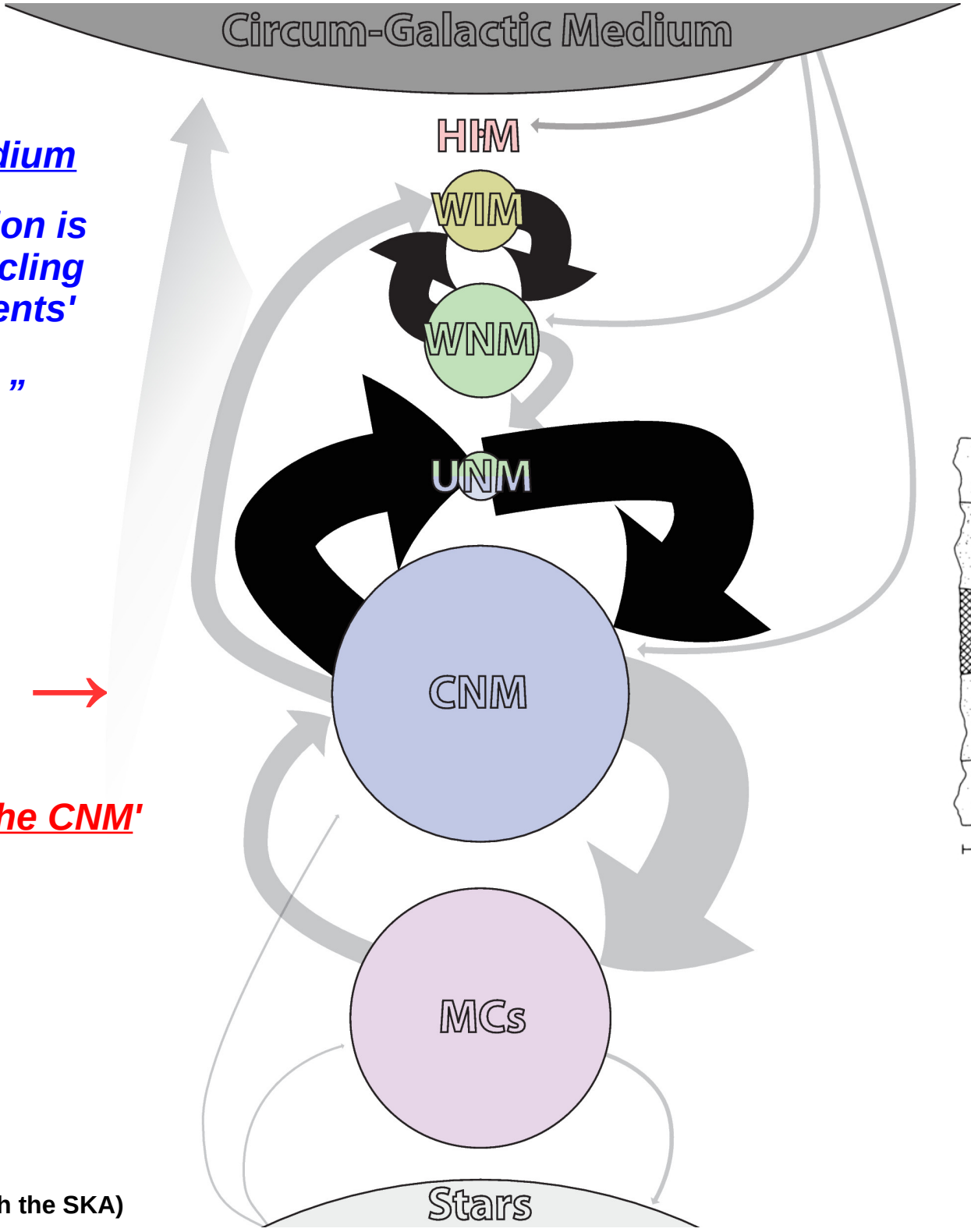
Interstellar Medium

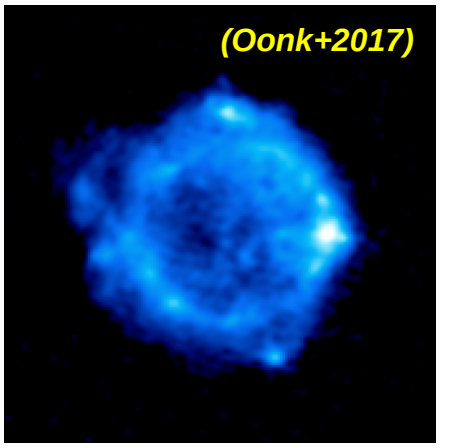
'Galaxy Evolution is driven by recycling of its constituents'

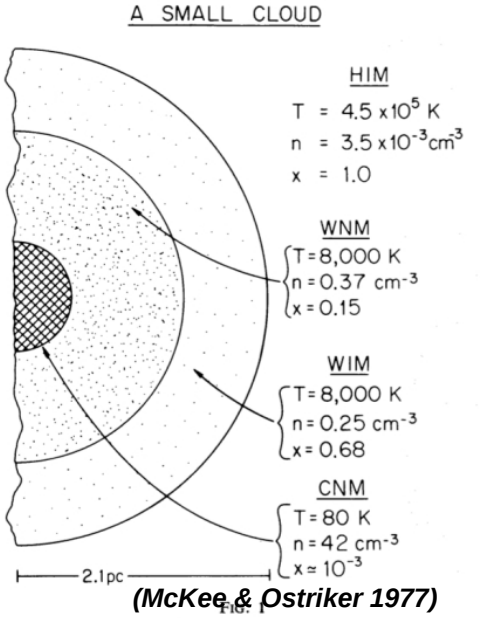
" mass flows "

? →

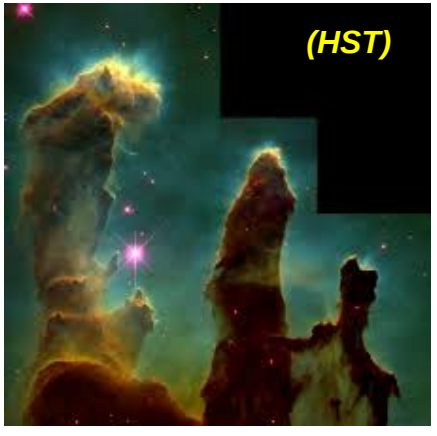
'CRRLs trace the CNM'







(McKee & Ostriker 1977)

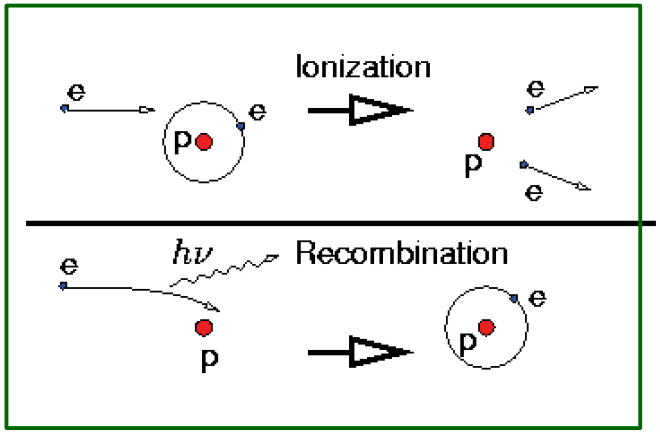


The physical conditions (T,n) of the CNM

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

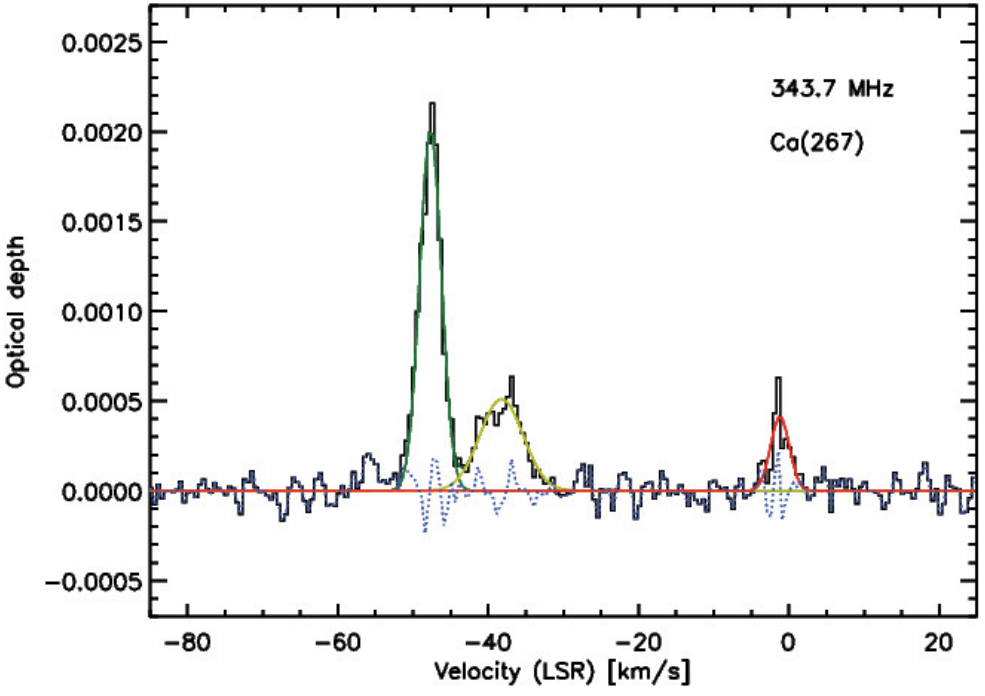
Atomic: HI 21 cm ***(e.g. Heiles & Troland 2003)***

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

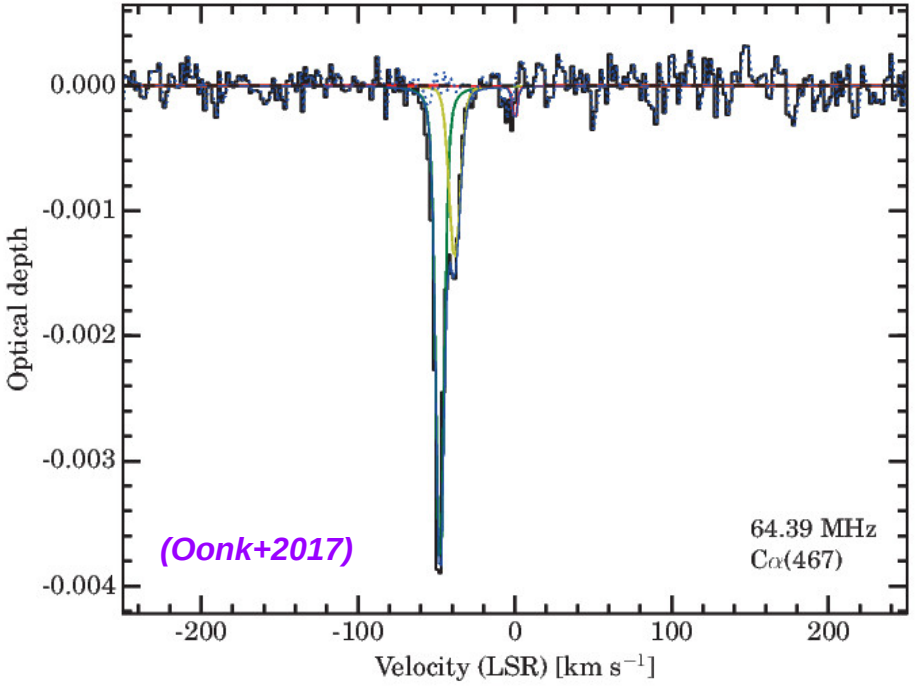


Alternative: low frequency Carbon RRLs

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



Cas A (WSRT P-band)



Cas A (LOFAR LBA)

HI 21cm absorption & (C)RRL

* **τ_{peak} (HI 21cm) / τ_{peak} (CRRL) ~ 10 , but (C)RRL many lines**

* **CRRL vs. HI morphology, if related then CRRL → (n, T)**

  - *CRRL widespread in GP on degree scales (e.g. Erickson+1995), beyond ?*

  - *CRRL modeling requires detailed non-LTE models (Salgado+2017a,b)*

* **CRRL can be mapped against diffuse background**

  - *HI 21cm absorption pinholes (tomography: GASKAP, SKA1)*

* **Need cold HI for carbon abundance [C/H] (convert n_e to n_H)**

  - *N(C)/N(H) ~ [C/H] ~ $1.5x10^{-4}$ – $3x10^{-4}$ (within ISM only ~2 uncertainty)*

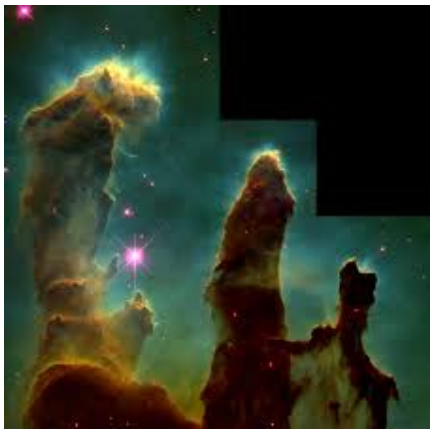
  - *Carbon enrichment of the ISM and its thermal balance*

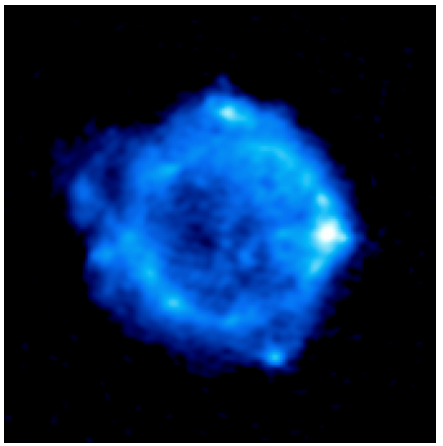
* ***Cosmic ray ionization rates*** *(HRRL/HI ; e.g. Oonk+2017, Payne+1989)*

“ 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)

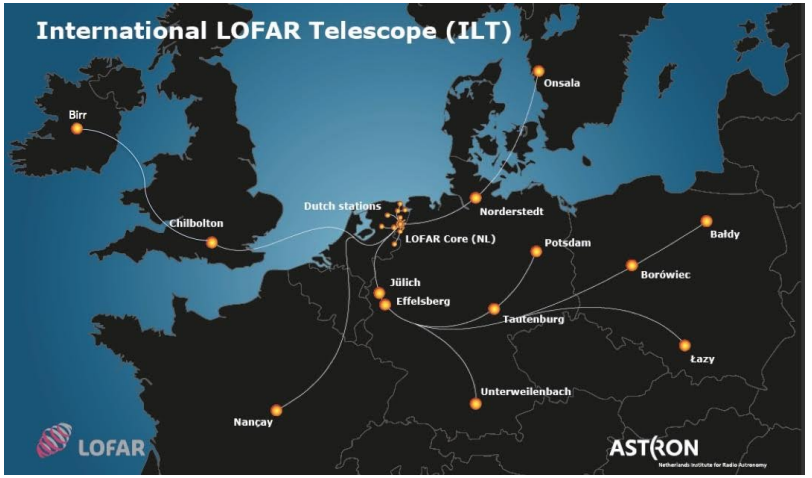
* **LBA 10 - 90 MHz : 450 RRL α-lines**
* **HBA 110 - 250 MHz : 100 RRL α-lines**

LOFAR CRRL surveys (PI: Oonk)

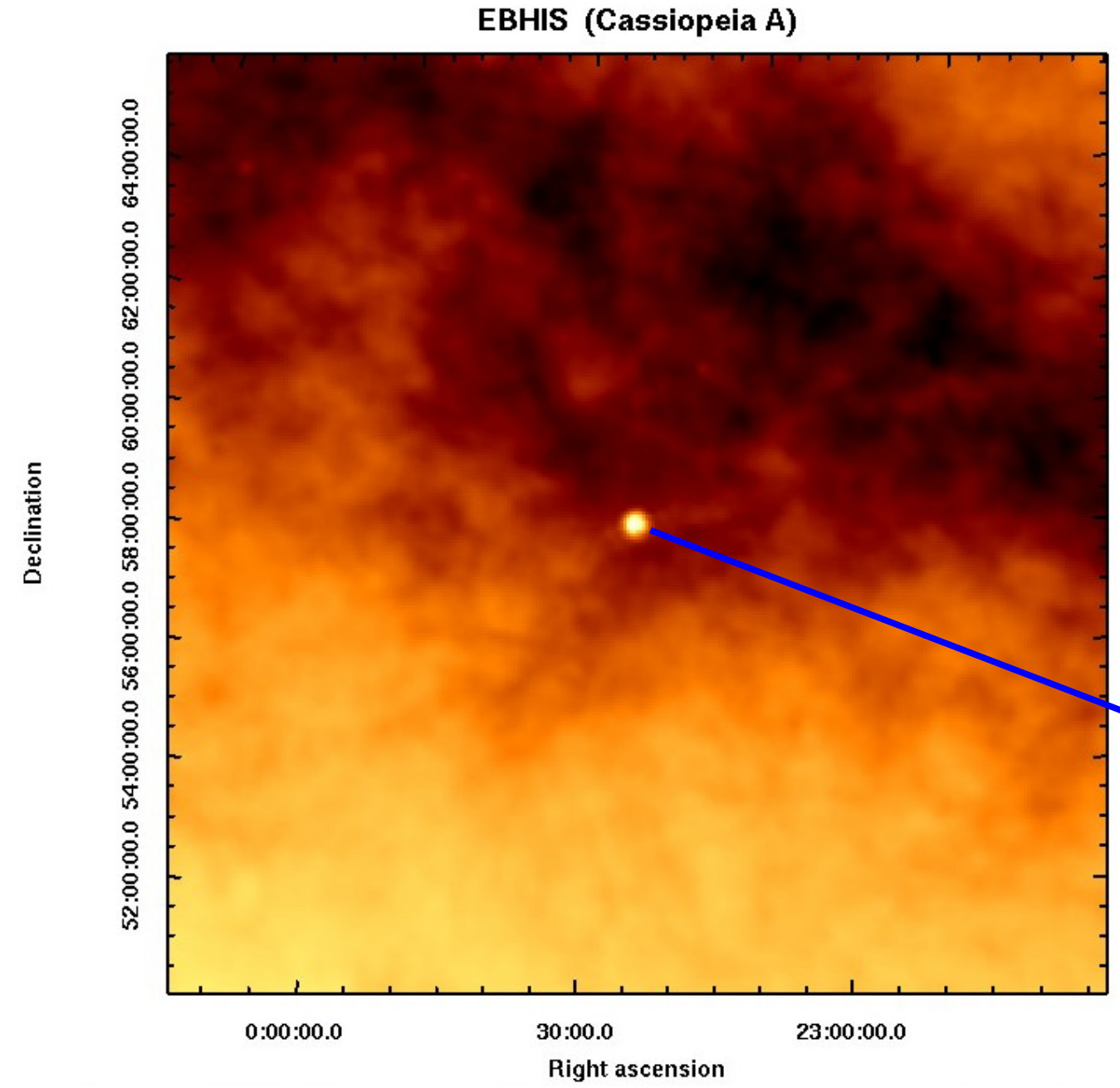
A) Galactic pinhole survey (<10') *

B) Galactic 10' tied-array survey

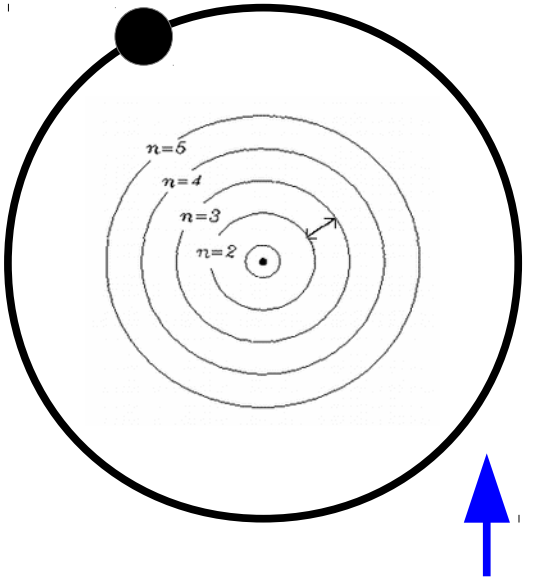
C) Extragalactic survey

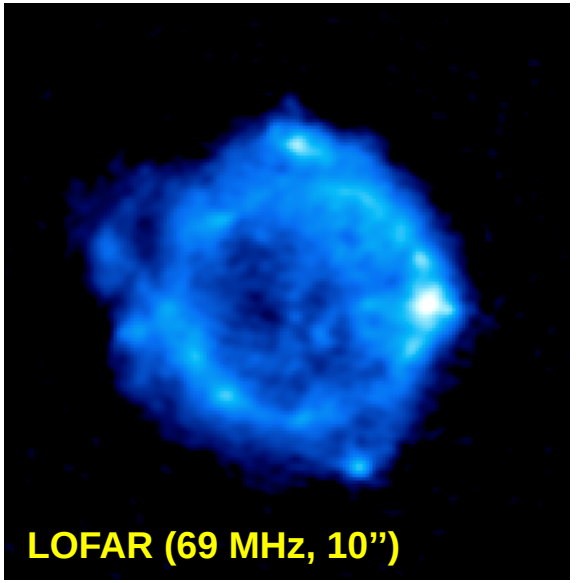


Cas A & Low-frequency radio recombination lines

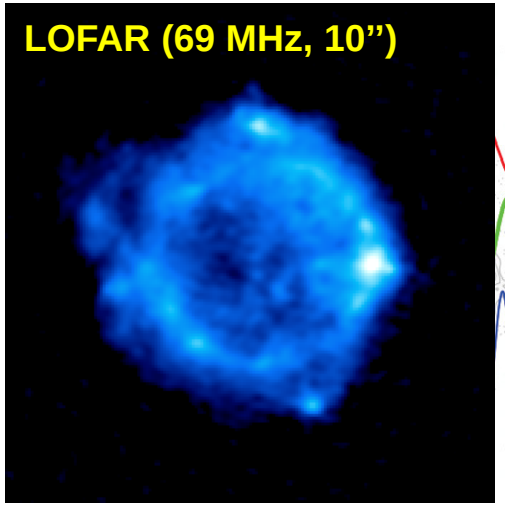


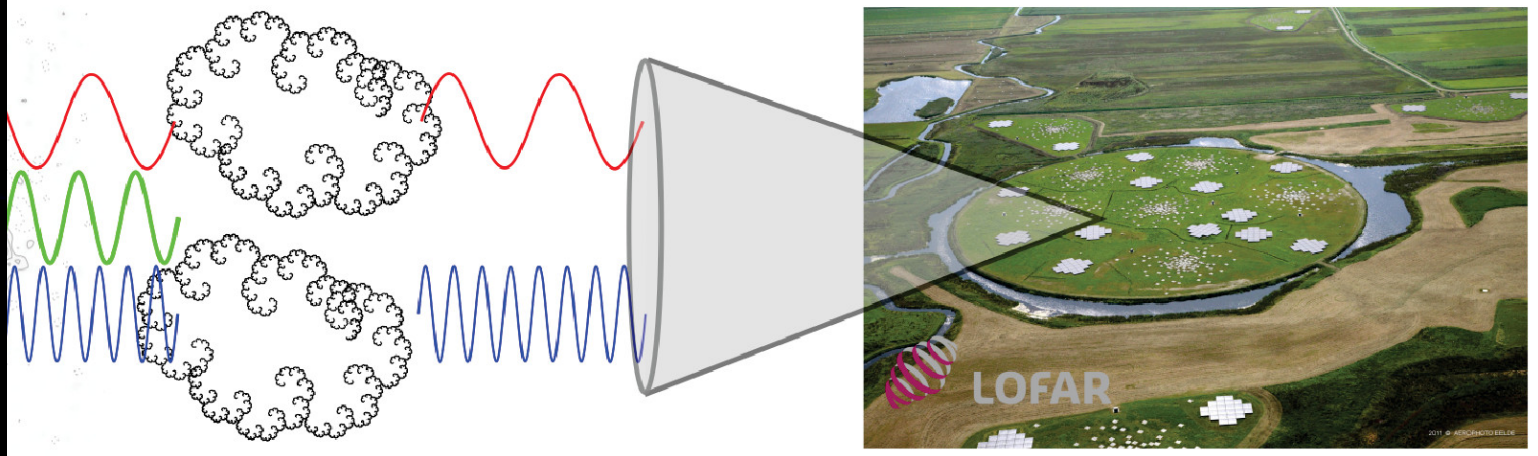
11 MHz (n=843): r ~ 1 micron

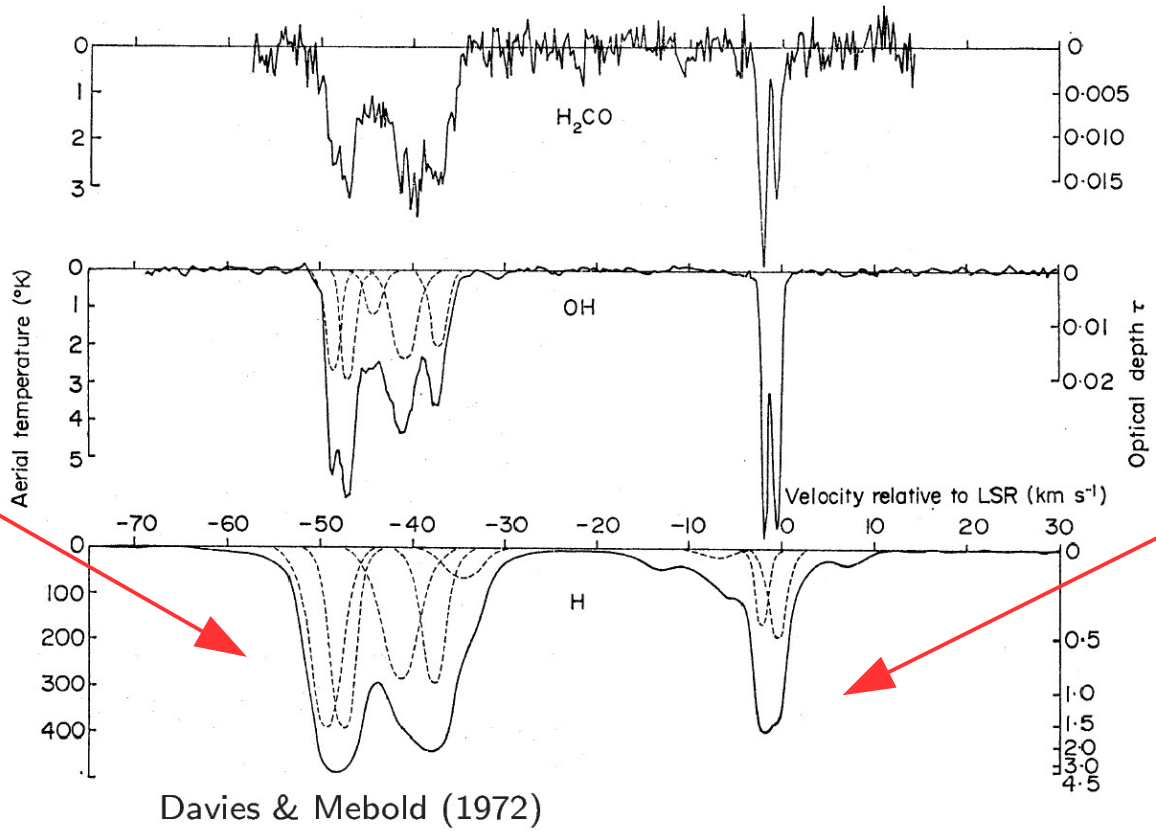




The line of sight towards Cassiopeia A (Oonk+2017)







Davies & Mebold (1972)

(Perseus arm)

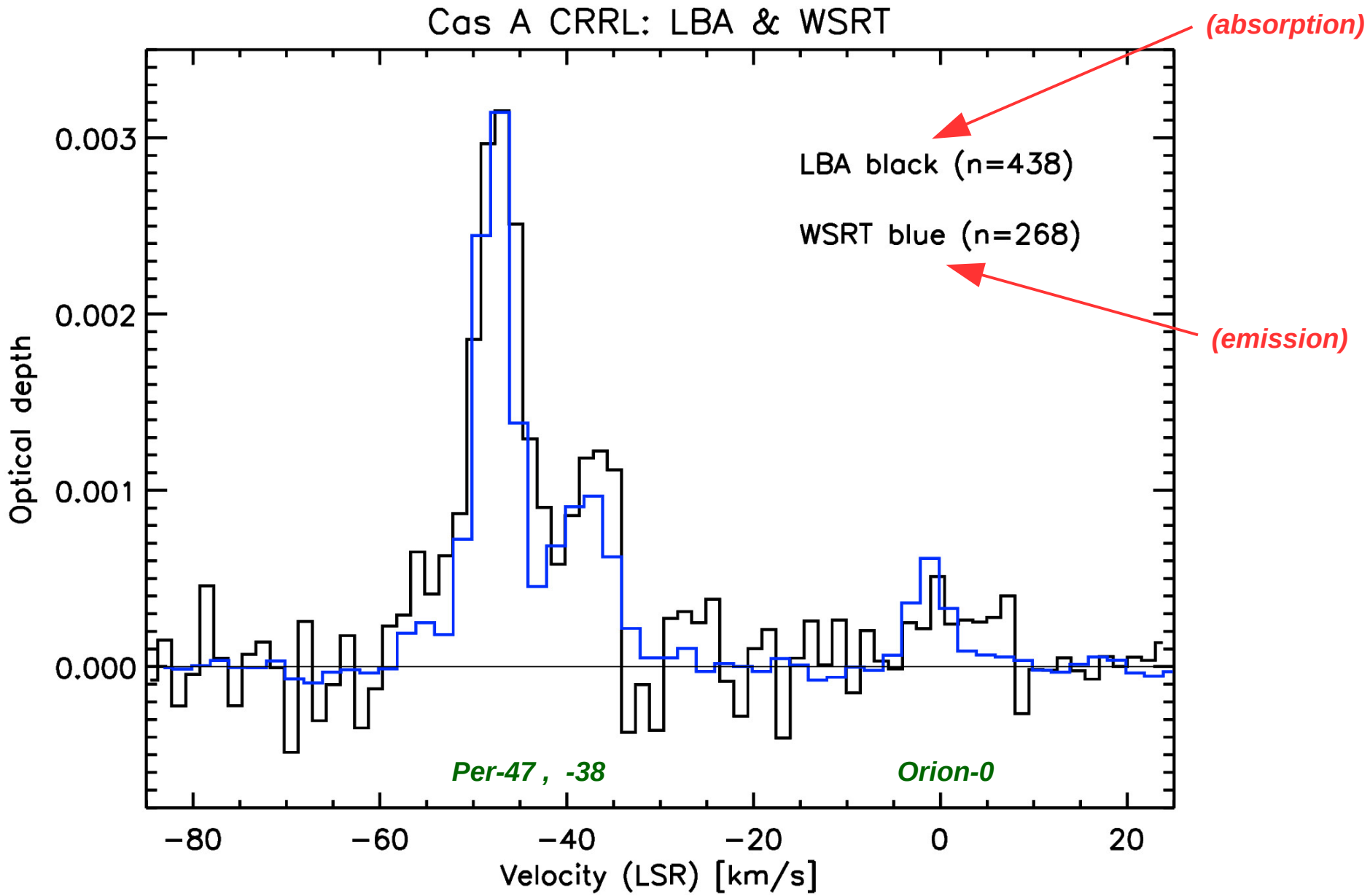
(Orion spur)

LOFAR LBA 3x10hr

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

WSRT P-band 12hr

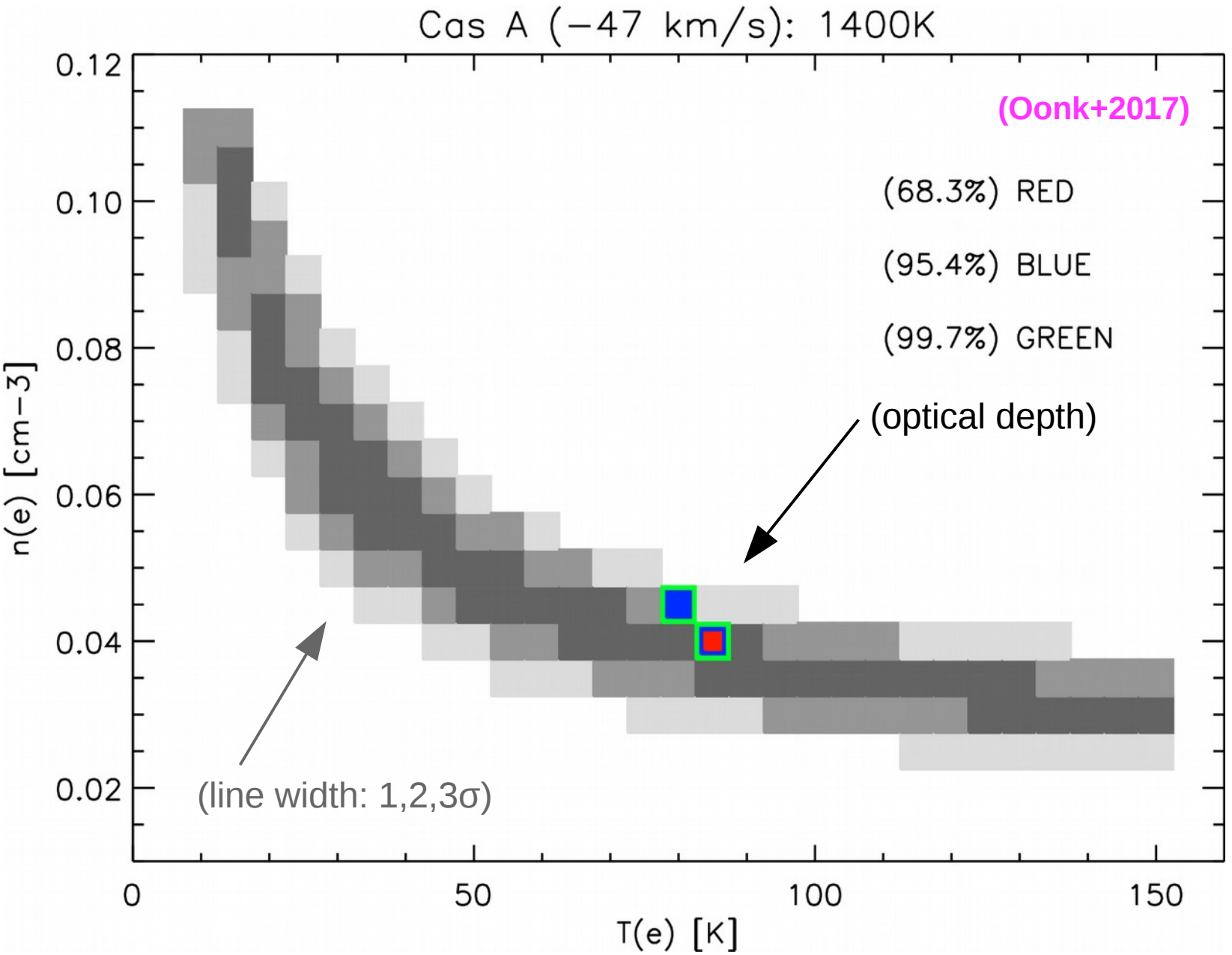
CRRL absorption and emission trace the same gas



* → in our CRRL model we set: N(CII, absorption) = N(CII, emission)

* → n-level (emission to absorption) traces the gas pressure (Oonk+2017)

Combining the CRRL line width and optical depth



*** Single set of physical parameters can explain both the line width and optical depth**

*** Optical depths tracing emission and absorption important (50 - 350 MHz)**

Cas A clouds, unresolved (1D slab model with f=1)

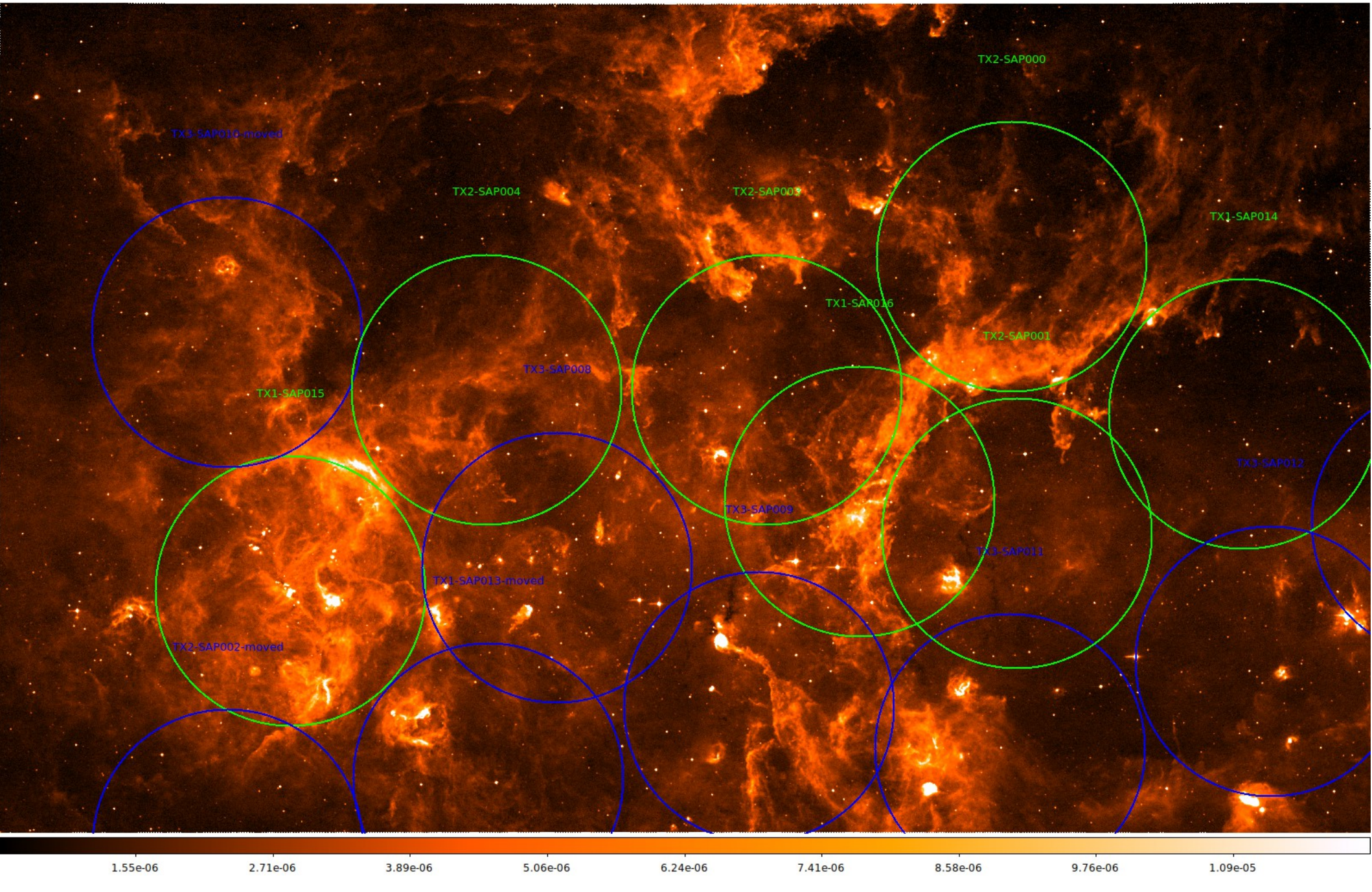
Parameter	unit	-47 km s^{-1}	-38 km s^{-1}
$T_{R,100}$	[K]	1400 (1351 ± 83)	1600 (1507 ± 128)
T_e	[K]	85 ± 5	85 ± 10
n_e	[cm^{-3}]	0.040 ± 0.005	0.040 ± 0.005
L_{CII}	[pc]	35.3 ± 1.2	18.6 ± 1.6
EM_{CII}	[cm^{-6} pc]	0.056 ± 0.014	0.030 ± 0.008
N_{CII}	[cm^{-2}]	$(4.4 \pm 0.6)\times10^{18}$	$(2.3 \pm 0.3)\times10^{18}$
N_H	[cm^{-2}]	$(3.1 \pm 0.4)\times10^{22}$	$(1.6 \pm 0.2)\times10^{22}$
n_H	[cm^{-3}]	286 ± 36	286 ± 36
$p_{thermal}/k$	[K cm^{-3}]	$(2.4 \pm 0.5)\times10^{4}$	$(2.4 \pm 0.5)\times10^{4}$
$p_{turbulent}/k$	[K cm^{-3}]	$(1.9 \pm 0.1)\times10^{5}$	$(7.6 \pm 1.0)\times10^{5}$
$p_{magnetic}/k$	[K cm^{-3}]	$(1.8\text{-}4.5)\times10^{4}$	—
ζ_H	[s^{-1}]	$(0.3 \pm 0.05)\times10^{-17}$	—

*** Gas conditions: Carbon = C^+ and n_H (HI → H2) => CO dark sheets ?**

*** Derived conditions are model dependent (Oonk+2017; Salgado+2017a,b)**

Cynus region (LOFAR 10’ CRRL survey)

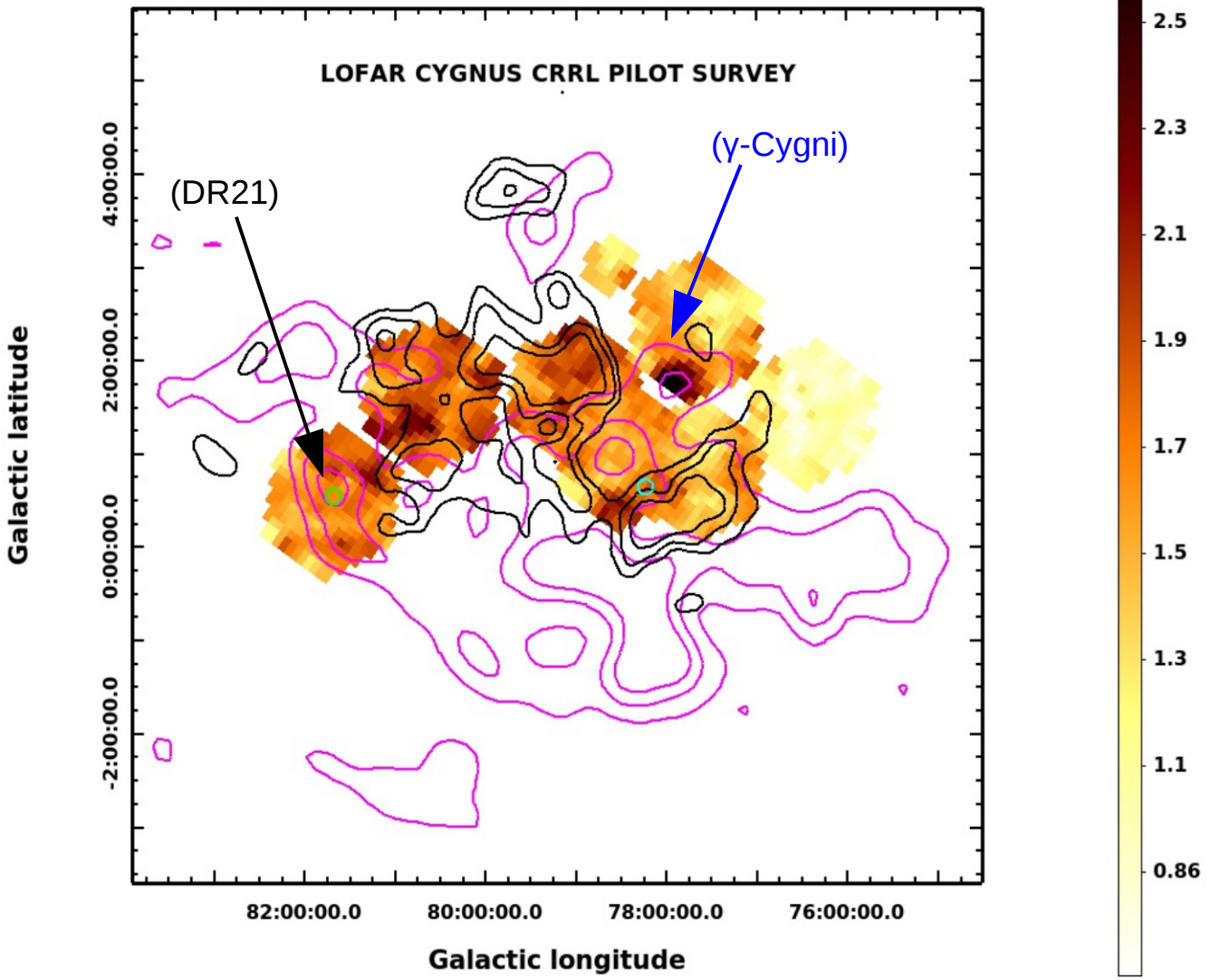
(MSX 8 μm)

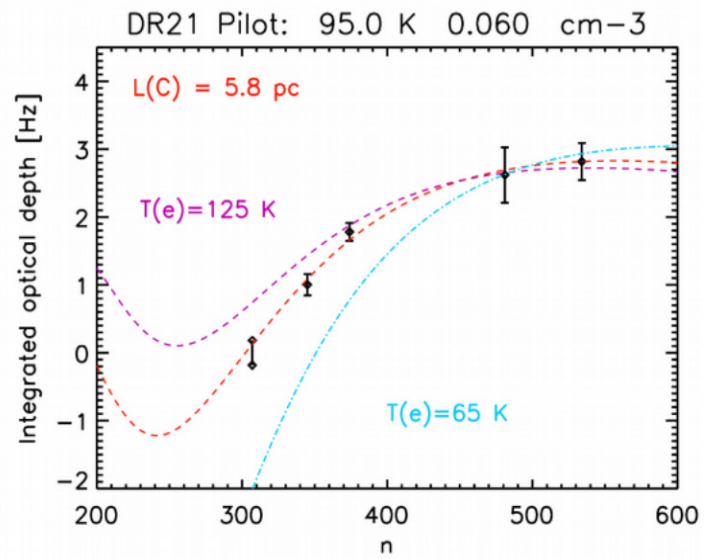


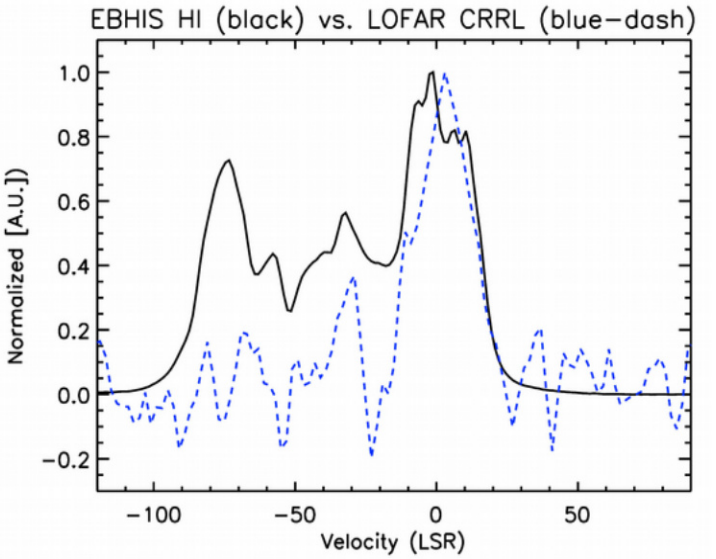
Cynus region (LOFAR 10' CRRL survey)

(Oonk+ in prep.)

HBA Cygnus CRRL map *(preliminary!)*



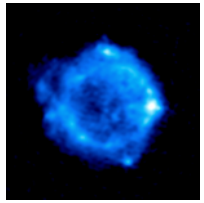




→ **CRRLs resolved on 10' scales: models show regions with increased T_e and n_e**

→ **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 → can provide the carbon abundance [C/H] of the CNM*
- *CRRL + [CII] 158 μm → possible T diagnostic for CNM, but do they trace the same gas ?*
- *CRRL + HRRL → ionization rates, but do they trace the same gas ?* *(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, resolution matches EBHIS (Winkel+2016) and CO (DHT10)*
- *Relation between CRRL, HI 21cm and CO is not yet clear (more data is coming)*

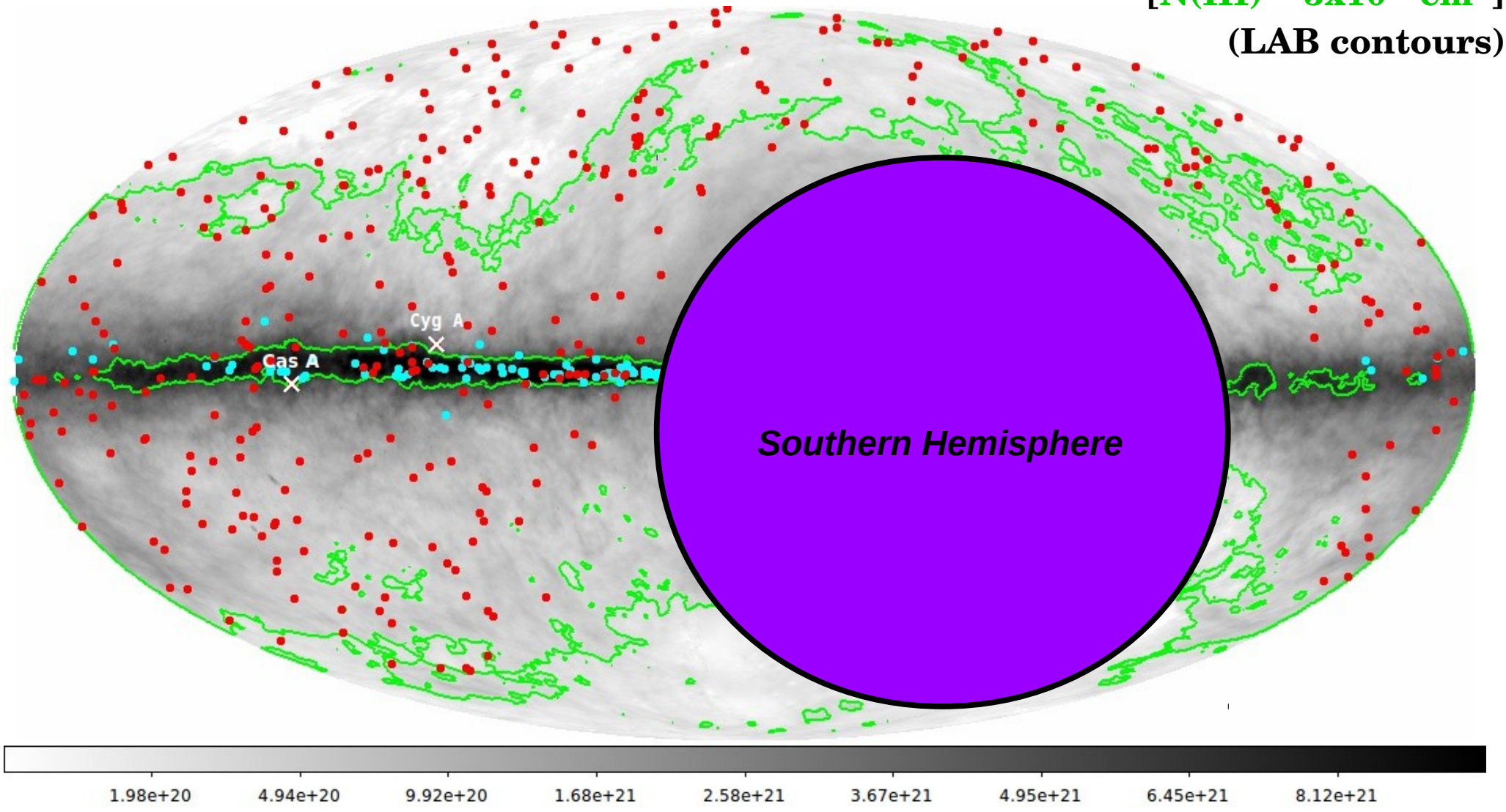
3) Extragalactic CRRL detections (also useful for Galactic Pinhole studies) *(Oonk+2014)*

- *M82 has been robustly detected at 50 MHz and at 160 MHz* *(Morabito+2014, Toribio+ in prep.)*
- *3C radio galaxy sample is ongoing* *(Emig+ in prep.)*

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

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

HI absorption 2017 16/06/2017

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