

# Cygnus in unprecedented detail at the lowest frequencies

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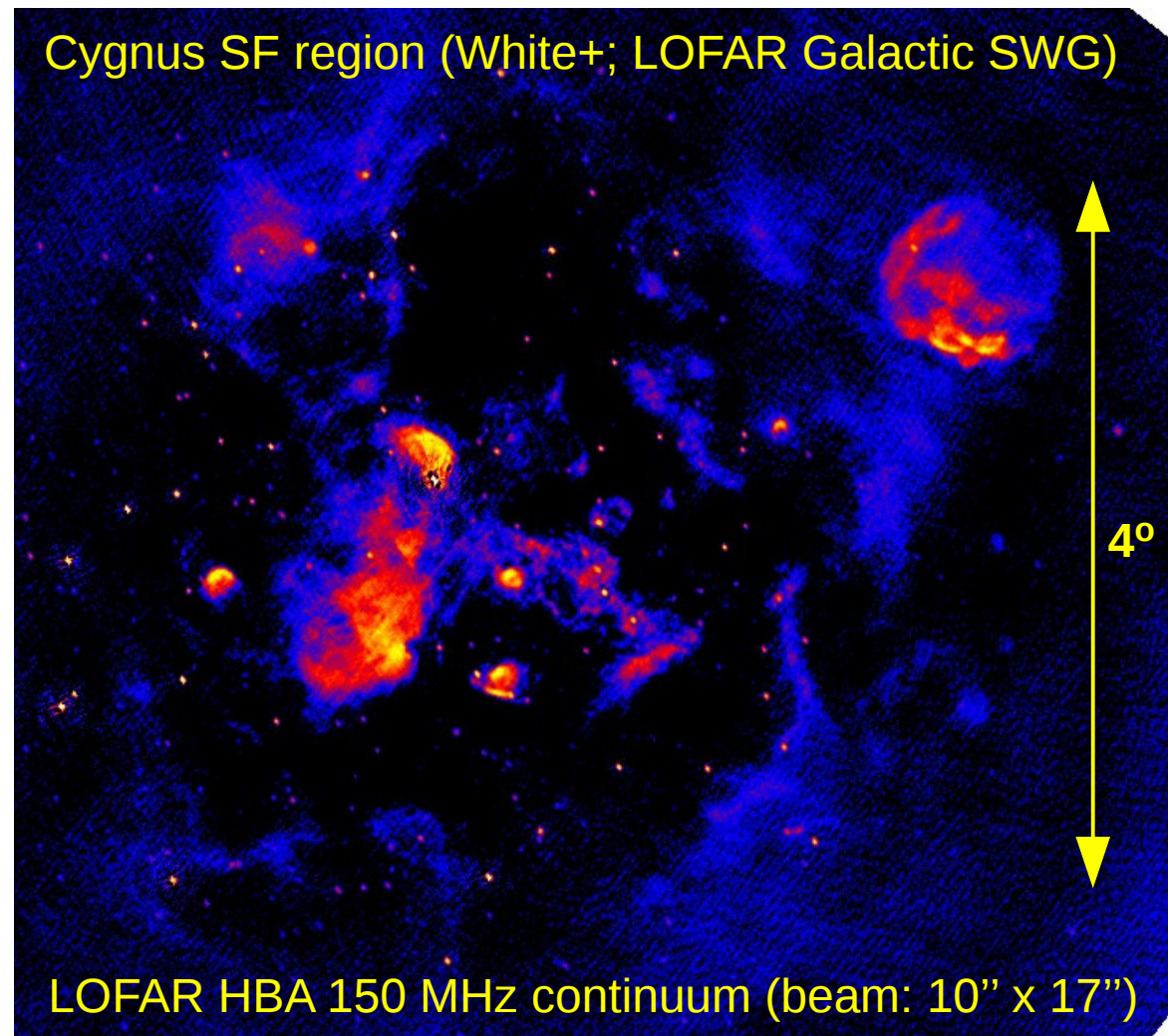
## Outline

- **CNM & low-frequency RRL**
- **Continuum: Cygnus SF**
- **RRL 3' - 10' : Cygnus SF**
- **LOFAR & LTA processing**  
→ (*Mechev et al. 2017 ISGC*)

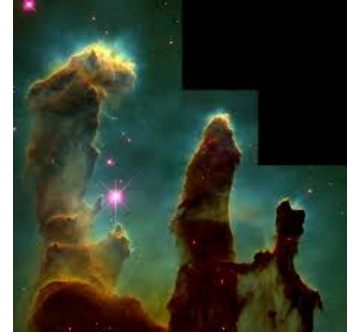
**ASTRON**



Universiteit Leiden



# The (diffuse) cold neutral medium: Questions



## The interstellar medium:

- a) *What is the life cycle of cool matter in the interstellar medium ?*
- b) *How do molecular clouds form, evolve and dissolve ?*
  - + *how does this relate to the star formation process and the presence of massive stars*
- c) *What are the kinematic characteristics of the ISM ?*
  - + *what does that tell us about the origin of large-scale turbulence in the ISM*

## LOFAR CRRL specific for the Milky Way:

- 1) *What is the morphology of CRRL emitting regions ?*
  - + *how does it relate to HI, H<sub>2</sub>, star-forming and hot gas, as well as the large-scale structure*
- 2) *What are the physical conditions in cool ISM clouds ?*
  - + *how does this vary with location (inner arm, intra arm and regions of massive star formation)*
- 3) *What is the ionization rate and carbon abundance in the cool ISM ?*
  - + *how does this vary with galacto-centric radius ?*

# Circum-Galactic Medium

## Interstellar Medium

“Galaxy Evolution is driven by recycling of its constituents”

## 'CRRLs trace the CNM'

\* cold atomic (HI)

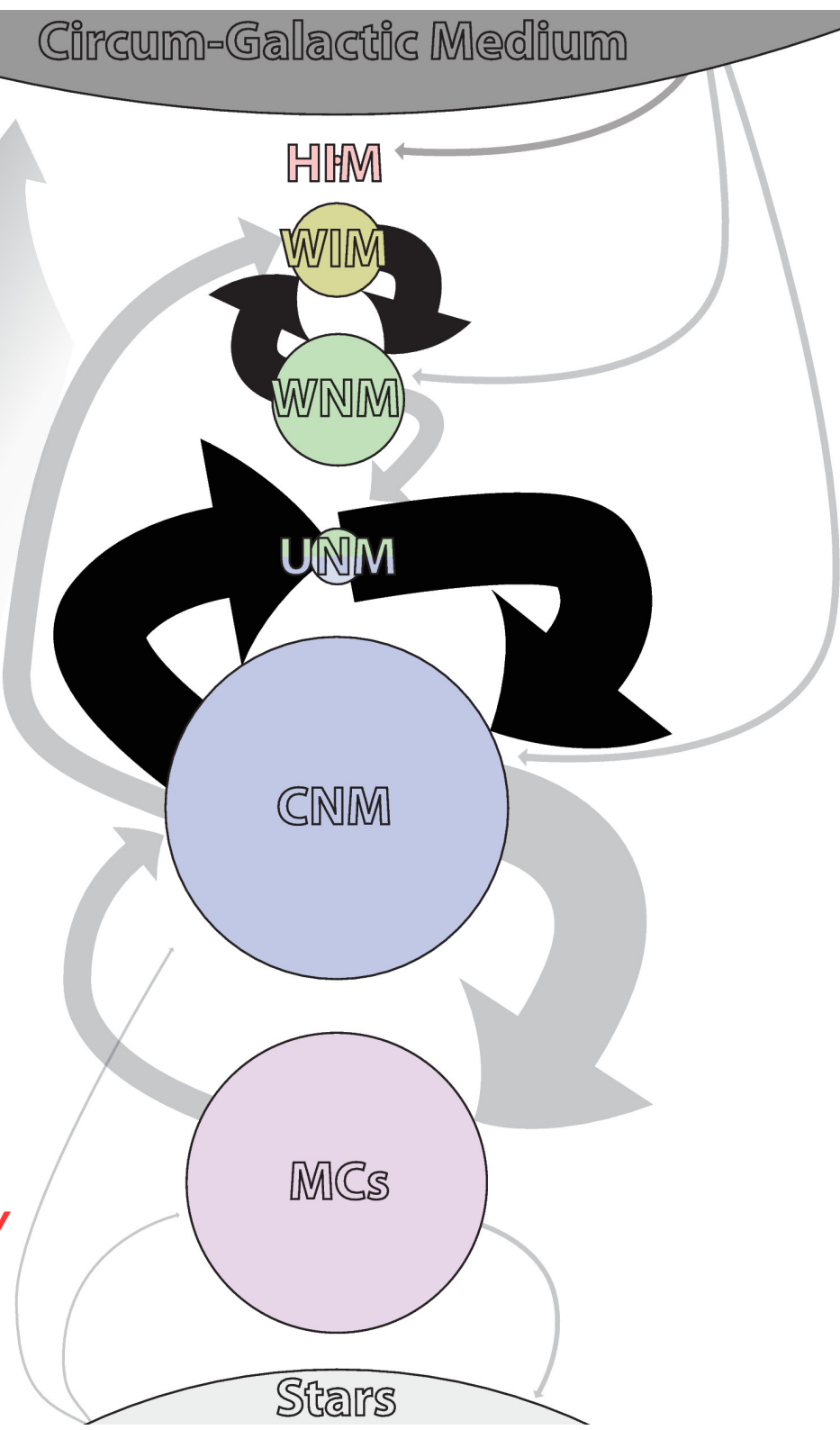
\* diffuse molecular (CO – dark H<sub>2</sub>)

$T = 50 - 150 \text{ K}$

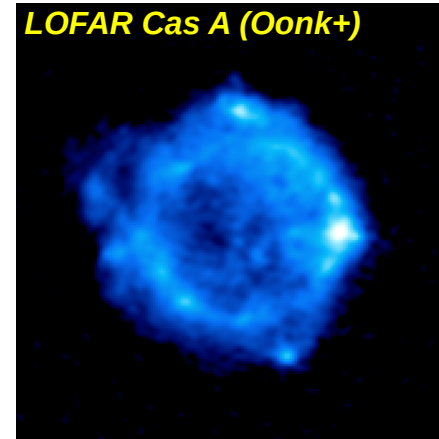
$n_H = 50 - 1000 \text{ cm}^{-3}$

→  $T, n, L, \zeta, [C/H], v, \Delta v$

(LC: Galactic science with the SKA)



LOFAR Cas A (Oonk+)



Pillars of Life (HST)



# The LOFAR (C)RRL surveys

(10-250 MHz → 600α lines)

## **A) Galactic pinhole survey ( $F_{150} > 3$ Jy/beam) [P. Salas]**

\* SKSP – Galactic SWG data for MW foreground (goal ~5-60'')

HBA (512 chn/SB @ 150 MHz):  $\Delta v = 0.7$  km/s

LBA (512 chn/SB @ 60 MHz):  $\Delta v = 1.9$  km/s

## **B) Medium resolution Galactic survey ( $b < |10|$ deg) [JBRO]**

\* RRL group (PI: 0onk) Galactic plane survey (goal ~ 3-10')

HBA (256 chn/SB @ 150 MHz):  $\Delta v = 1.5$  km/s

LBA (256 chn/SB @ 60 MHz):  $\Delta v = 3.8$  km/s

## **C) Extragalactic survey ( $F_{150} > 3$ Jy/beam) [K. Emig]**

\* SKSP Tier1 survey in-situ and intermediate z absorption

HBA ( 16 chn/SB @ 150 MHz):  $\Delta v = 24$  km/s

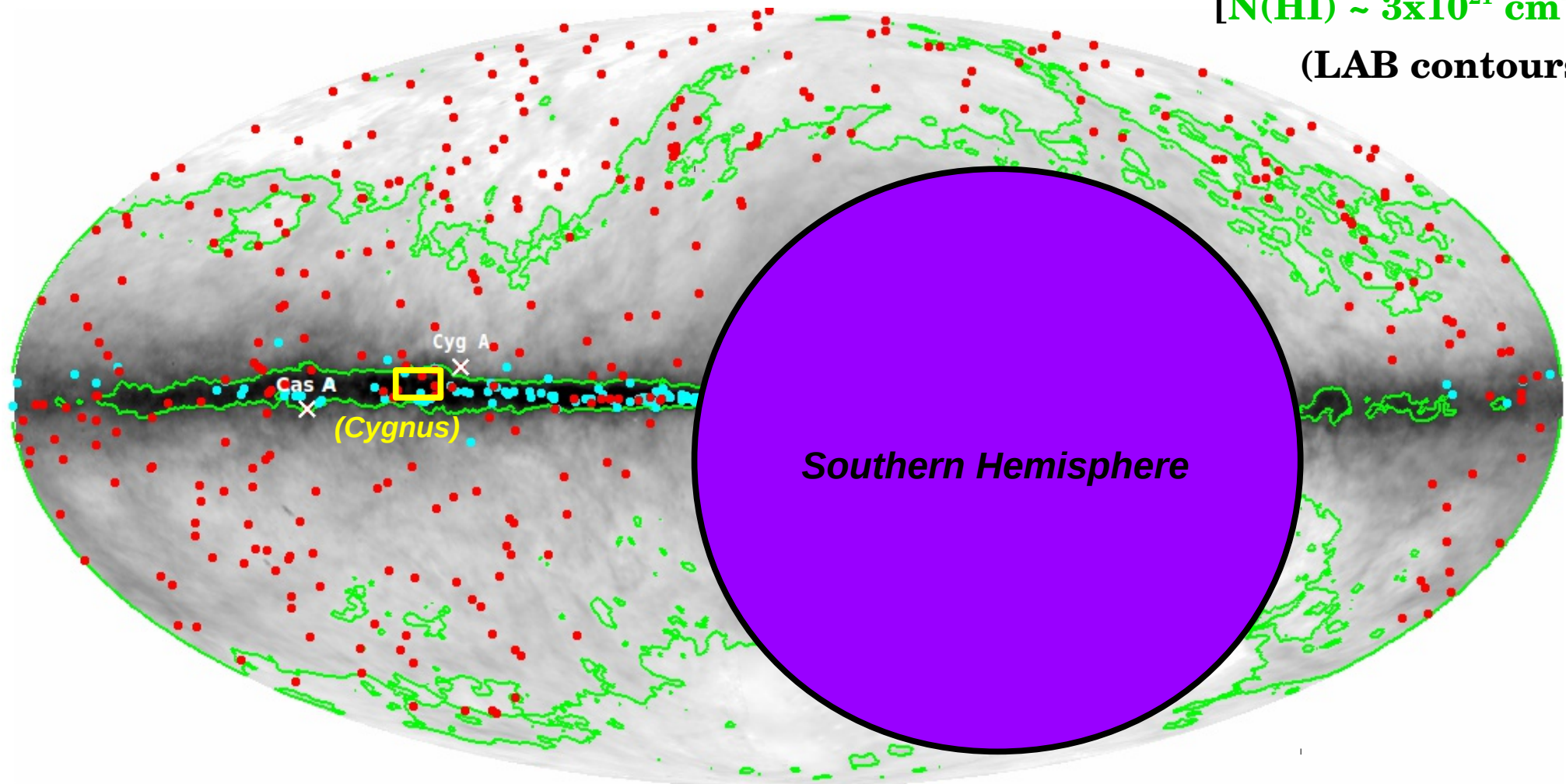
LBA ( 16 chn/SB @ 60 MHz):  $\Delta v = 60$  km/s

# LOFAR (C)RRL: ( HI 21 cm , 3C , SNR )

[N(HI) ~ 3x10<sup>20</sup> cm<sup>-2</sup>]

[N(HI) ~ 3x10<sup>21</sup> cm<sup>-2</sup>]

(LAB contours)



1.98e+20

4.94e+20

9.92e+20

1.68e+21

2.58e+21

3.67e+21

4.95e+21

6.45e+21

8.12e+21

LOFAR 8 hr, 5 $\sigma$  CRRL limits: Column densities

$N_H$  > 3x10<sup>20</sup> cm<sup>-2</sup>

Source fluxes

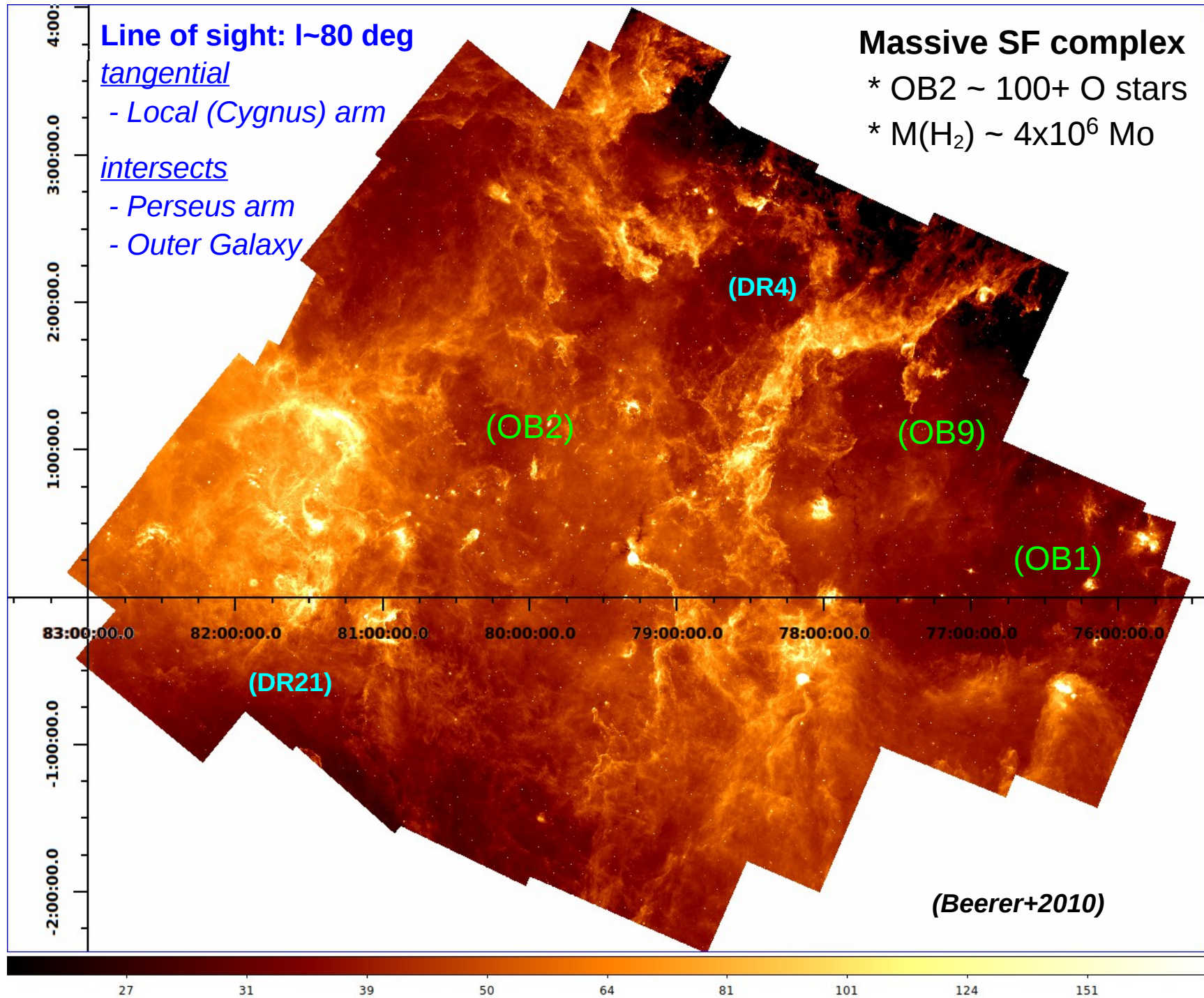
$S_v$  > 3 Jy/beam

Diffuse Milky Way

$T(408)$  > 40 K

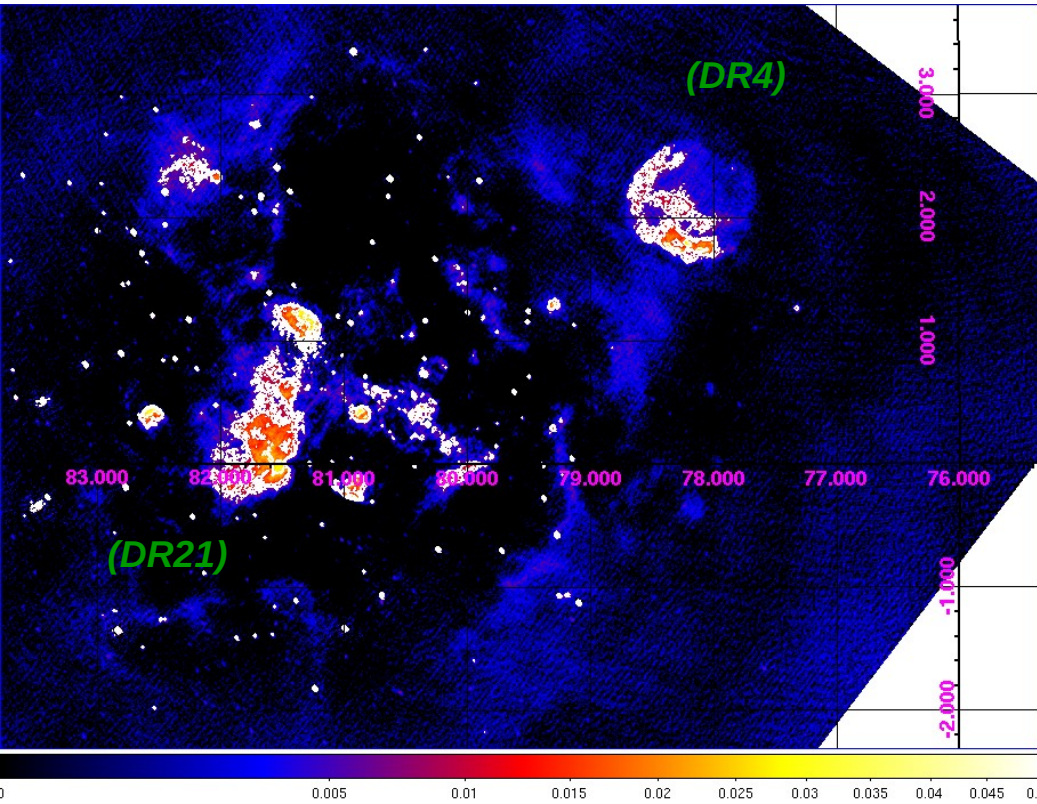
# Cygnus SF region (d=1.7 kpc)

(Spitzer 8  $\mu\text{m}$ : traces MC surfaces = PDR)

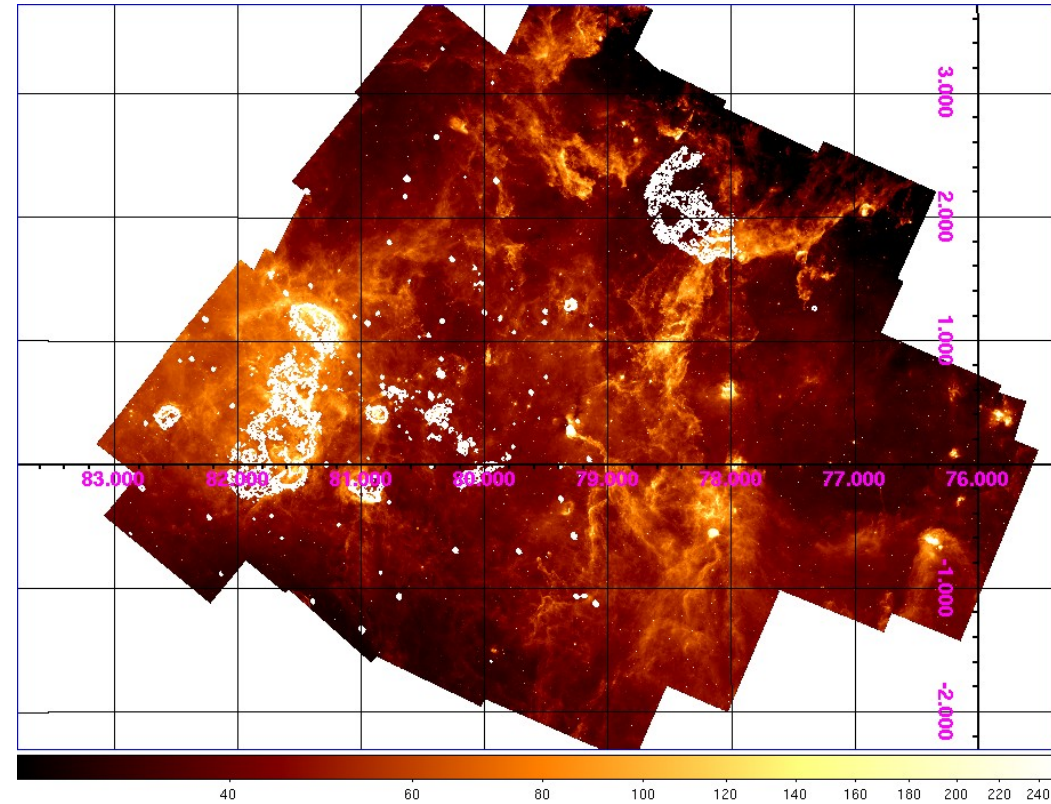


# Cygnus SF region – Continuum:

# 150 MHz vs. 8 um



LOFAR HBA (White+; Galactic SWG)



Spitzer 8um (Cygnus X team, Beerer+2010)

\* HBA 150 MHz continuum: *(note: Cygnus A is ~4 degrees away !)*

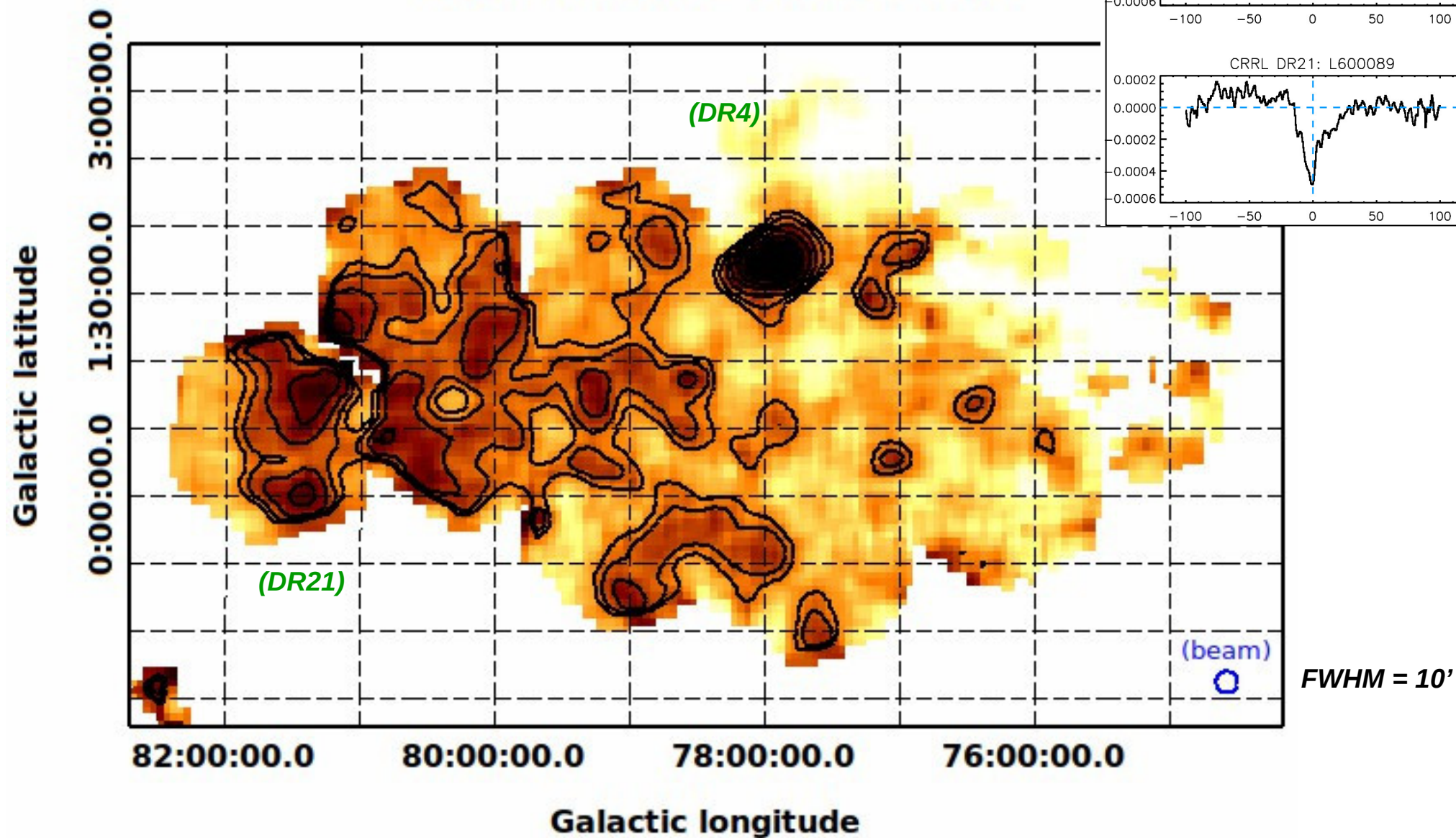
- clumpy & filamentary structures, but largest scales resolved out
- SF (HII regions, e.g. DR21) and also shocks (SNR, e.g. DR4)

\* HBA resolution (10" x 17") matches Spitzer MIPS / Herschel PACS (FWHM~6-40")

\* Future: DDF → 5" and LB → 0.5" ('multi-array' reduction approach needed for all scales)

# Cygnus – RRL: Carbon alpha map (150 MHz)

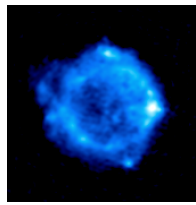
## Cygnus X CRRL - LOFAR HBA



\* CRRL peaks in filamentary structures on top of a very extended and diffuse component



# Summary:



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

- A low temperature, low density electron plasma exists in the ISM (Oonk+2017, Salas+2017, Asgekar+2013)
- **simple 1D model** :  $T \sim 85 \text{ K}$ ,  $n \sim 250 \text{ cm}^{-3}$ ,  $p_{\text{th}} \sim 2e4 \text{ K cm}^{-3}$  “diffuse CNM” (Oonk+2017,2015)
- **CO, CI, OH, CRRL**: diffuse PDR, CO – dark/poor gas envelope of MC complex (Salas+ subm.)
- **RRL non-LTE, stimulated emission** → detailed models (l-changing collisions) (Salgado+2017a,b)

## 2) LOFAR Cygnus data shows that large-scale 10' and 3' maps of CRRL can be made

- Cygnus  $3 \times 8 \text{ deg}^2$  has been mapped in CRRL with HBA/HGH and LBA (Oonk+2017 in prep)
- CRRL resolution matches HI 21cm (EBHIS: Winkel+2016), CO (DHT10), FIR (Planck/IRAS)
- **CRRL peaks in filaments (corr. w. FIR) on top of a very diffuse and extended component**
- **DR 21 region** :  $T \sim 95 \text{ K}$ ,  $n \sim 300 \text{ cm}^{-3}$ ,  $p_{\text{th}} \sim 3e4 \text{ K cm}^{-3}$  “diffuse CNM / CO – dark”

## 3) Extragalactic CRRL detections (also useful for Galactic Pinhole studies) (Oonk+2014,2015)

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

\*\*\* LOFAR (C)RRL project: 9 published papers (+1 submitted and +3 in preparation) \*\*\*

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