Low frequency RRL's as a probe of the CNM

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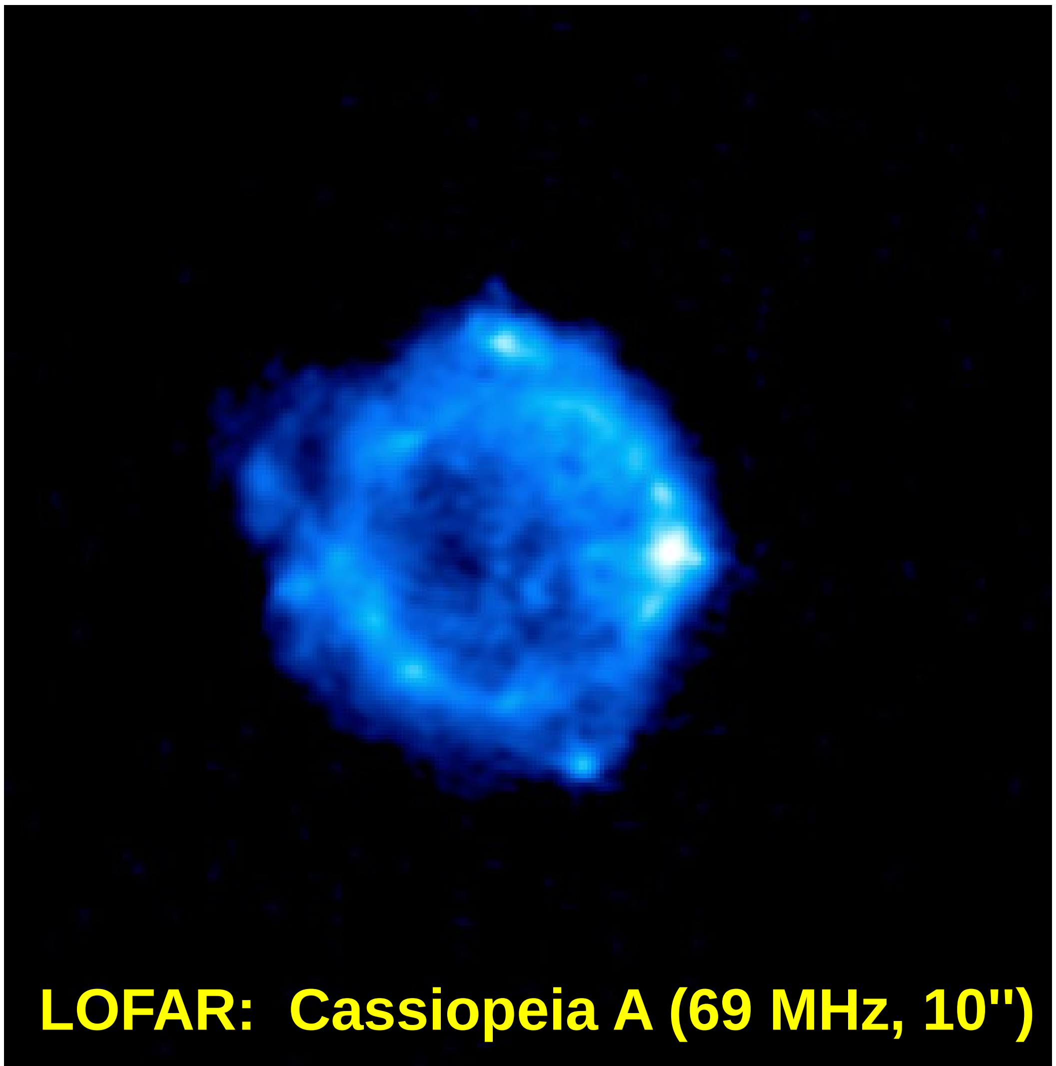
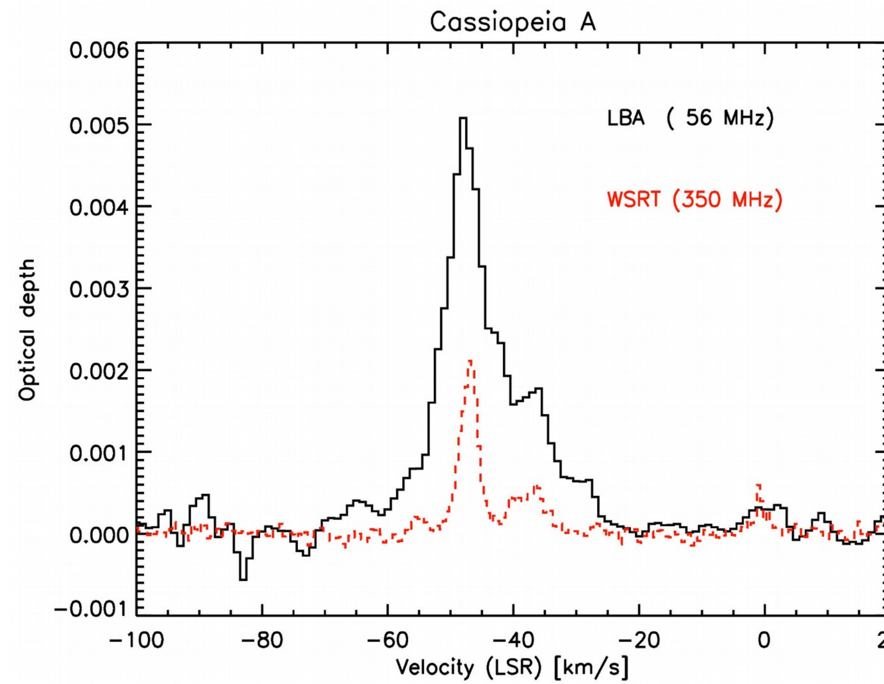
X. Tielens, H. Rottgering, *+ LOFAR SKSP/MKSP***



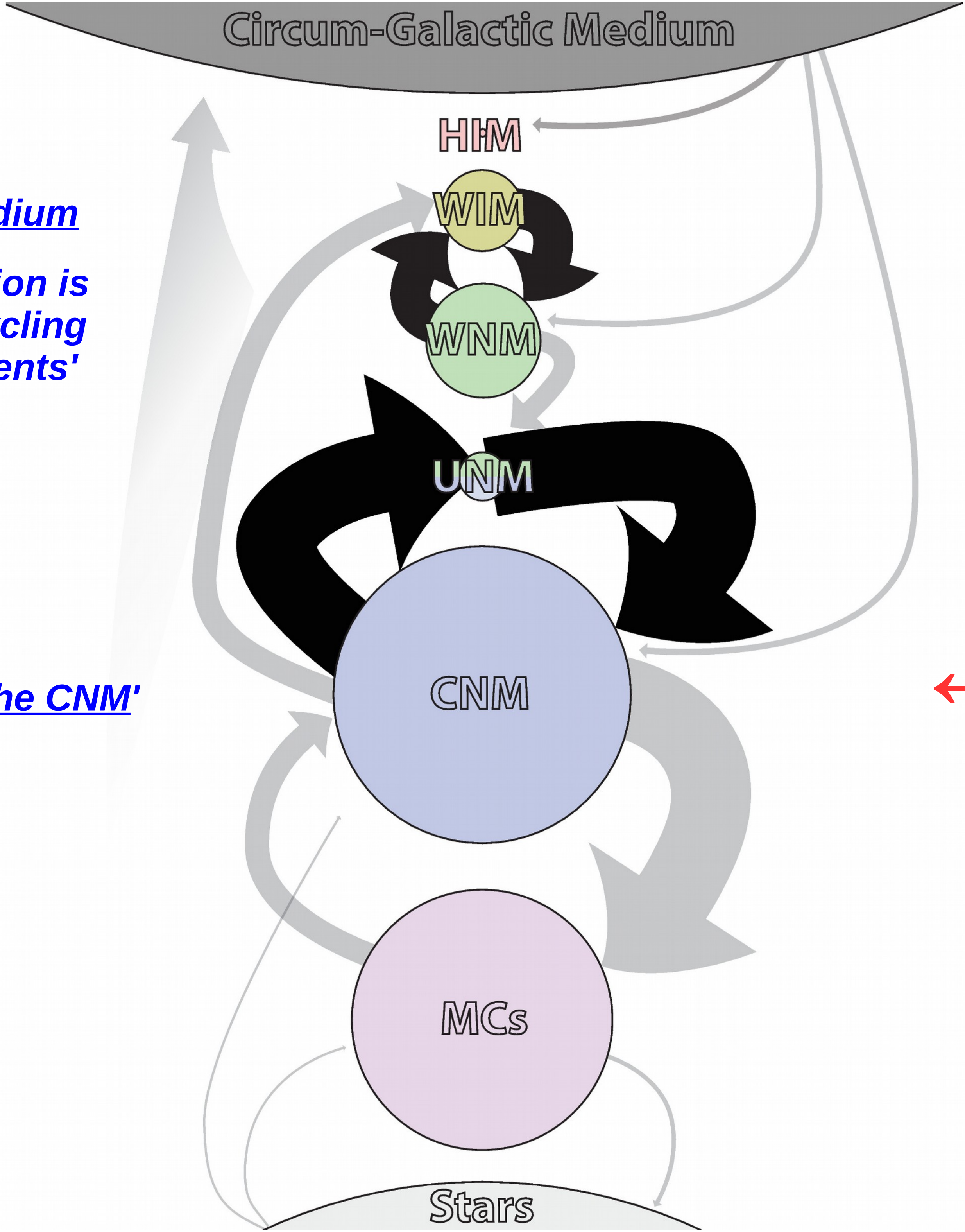


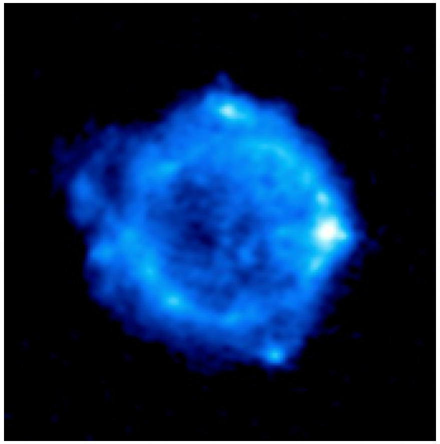
(1) ISM & low-frequency CRRL
→ full (n,l) non-LTE models

(2) Cas A & GP RRL surveys

Interstellar Medium

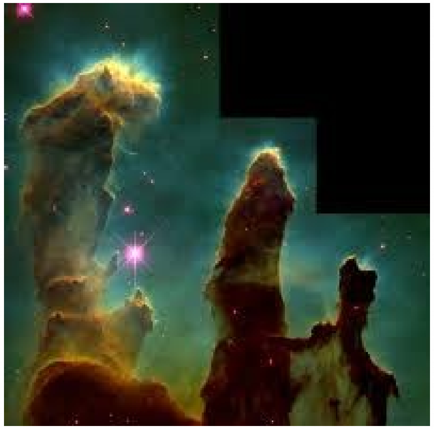
'Galaxy Evolution is driven by recycling of its constituents'





'CRRLs trace the CNM'

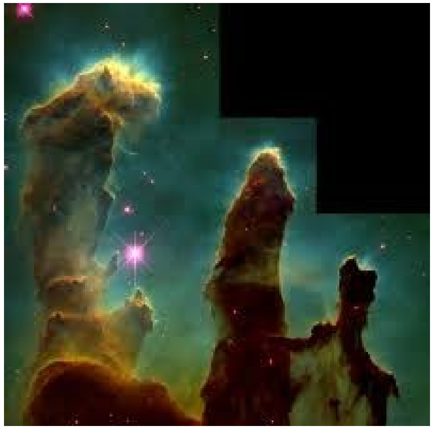
← ?

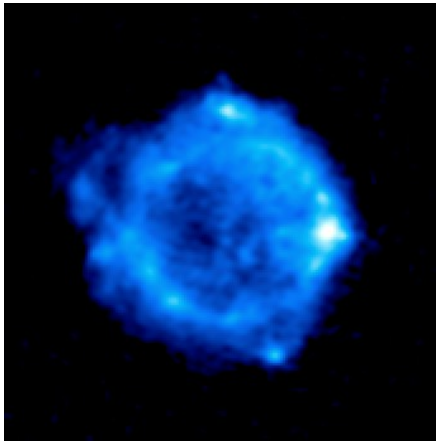


“ Galaxy evolution is driven by recycling of the ISM ”

but,

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





Method : Low-frequency (C)RRL's

- **Localize RRL gas and compare w. CO, HI, HII**
- **Thermal properties 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*)

(Salgado in prep.)

New RRL models: Optical Depth (τ)

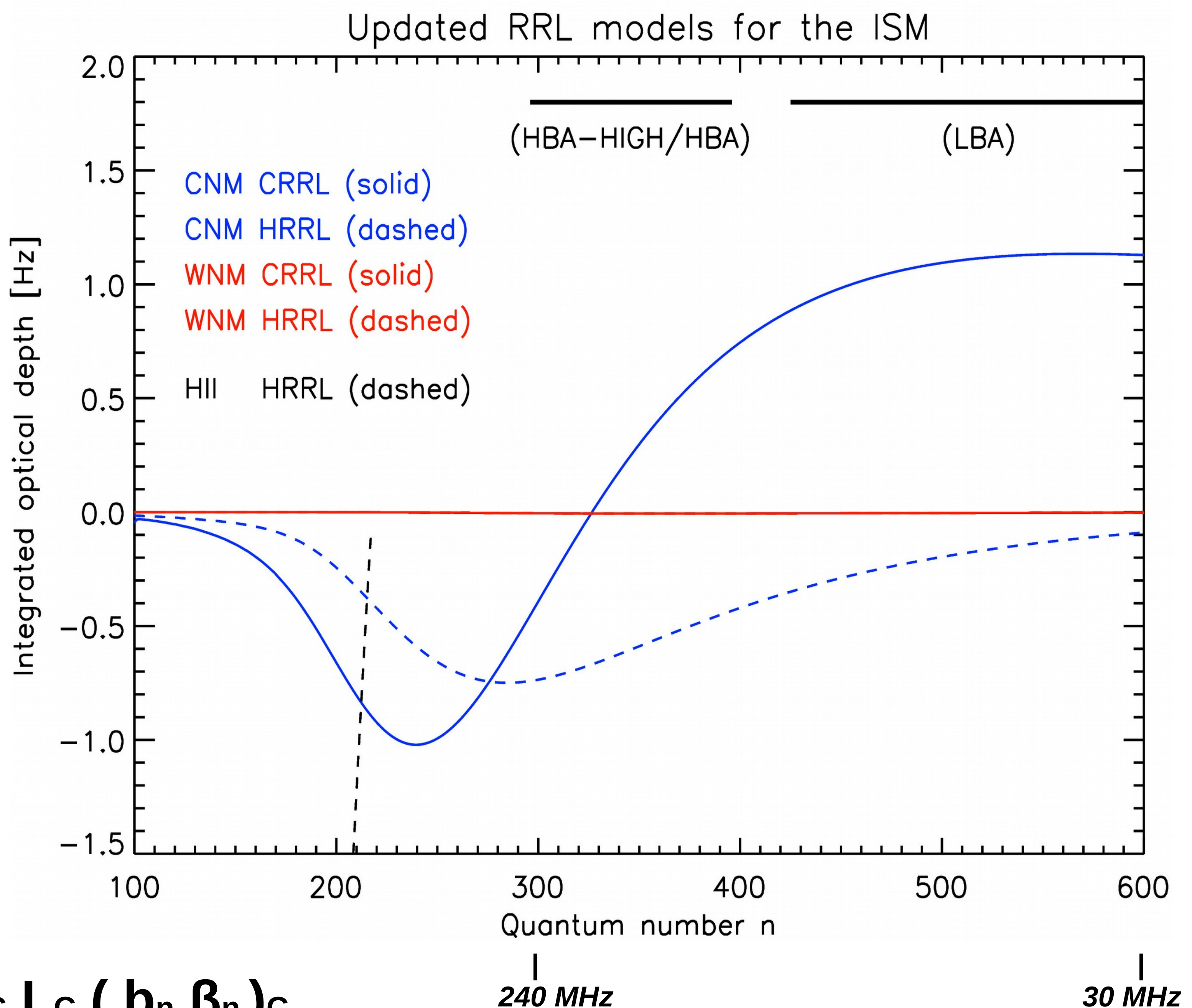
[N(HI)=10^{20} cm^{-2}]

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*



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

New RRL models: Line broadening

(Salgado in prep.)

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

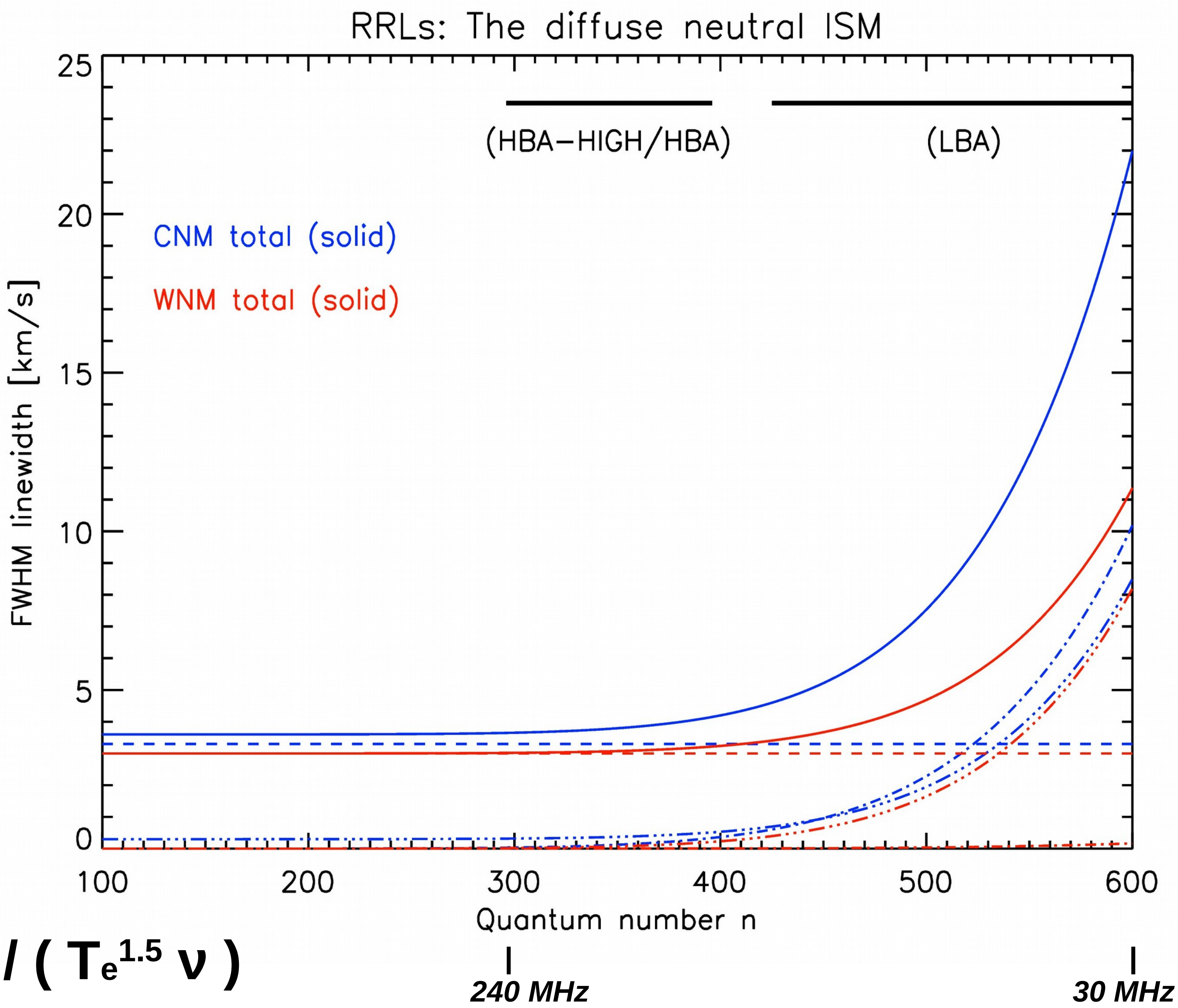
Total (solid) width:

(1) Doppler (dash)

(2) Pressure (dash-dot)

(3) Radiation (dash-dot-dot)

**** new formulation reduces width ~30% at high n***



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

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

The LOFAR (C)RRL Surveys

A) Galactic pinhole survey (F_{150} > 5 Jy/beam)

** Dedicated and SKSP data for MW foreground*
HBA (512 chn/SB @ 150 MHz): dv = 0.7 km/s
LBA (512 chn/SB @ 60 MHz): dv = 1.9 km/s

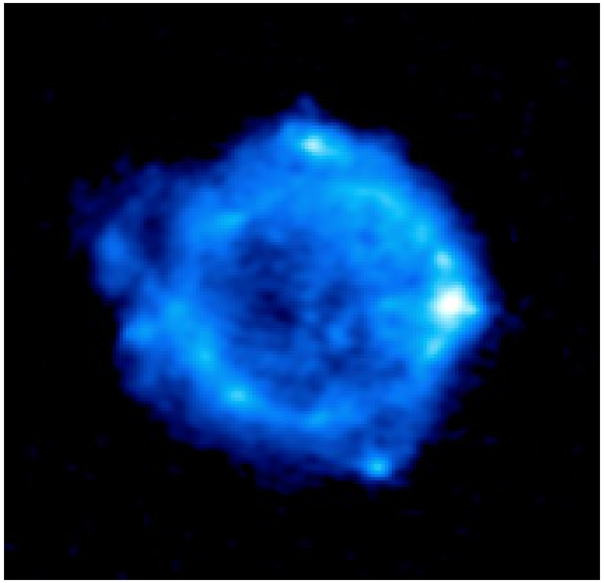
B) Medium resolution Galactic survey (b < |10| deg)

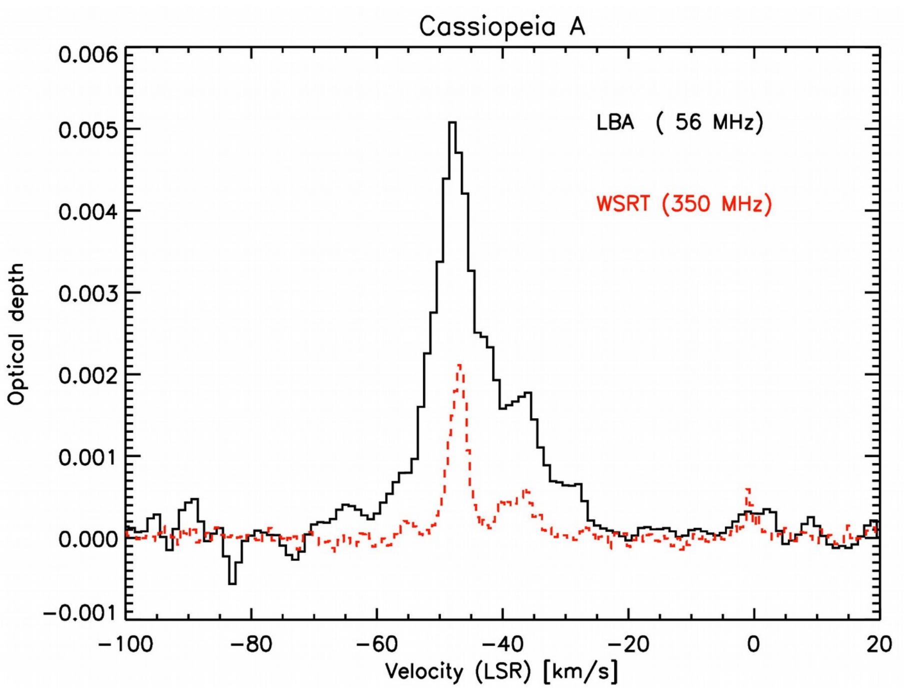
** SKSP Galactic plane survey (goal ~10')*
HBA (256 chn/SB @ 150 MHz): dv = 1.5 km/s
LBA (256 chn/SB @ 60 MHz): dv = 3.8 km/s

C) Extragalactic survey (F_{150} > 5 Jy/beam)

** SKSP in-situ and intermediate z absorption*
HBA (16 chn/SB @ 150 MHz): dv = 24 km/s
LBA (16 chn/SB @ 60 MHz): dv = 60 km/s

A) Cas A: A bright velocity resolved study II





3 Cloud Components (-47,-38, 0 km/s)

→ fit : FWHM and optical depth

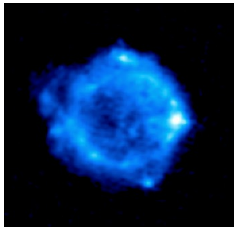
Perseus arm results (dense clouds)

Parameter	-47 km/s	-38 km/s
T_e [K]	90	90
n_e [cm^{-3}]	0.04	0.04
L_C [pc]	46	21
EM_C [pc cm^{-6}]	0.073	0.033
p [K cm^{-2}]	$1.2x10^4$	$1.2x10^4$
N_C [cm^{-2}]	$5.6x10^{18}$	$2.5x10^{18}$
N_H [cm^{-2}]	$1.9x10^{22}$	$8.5x10^{21}$

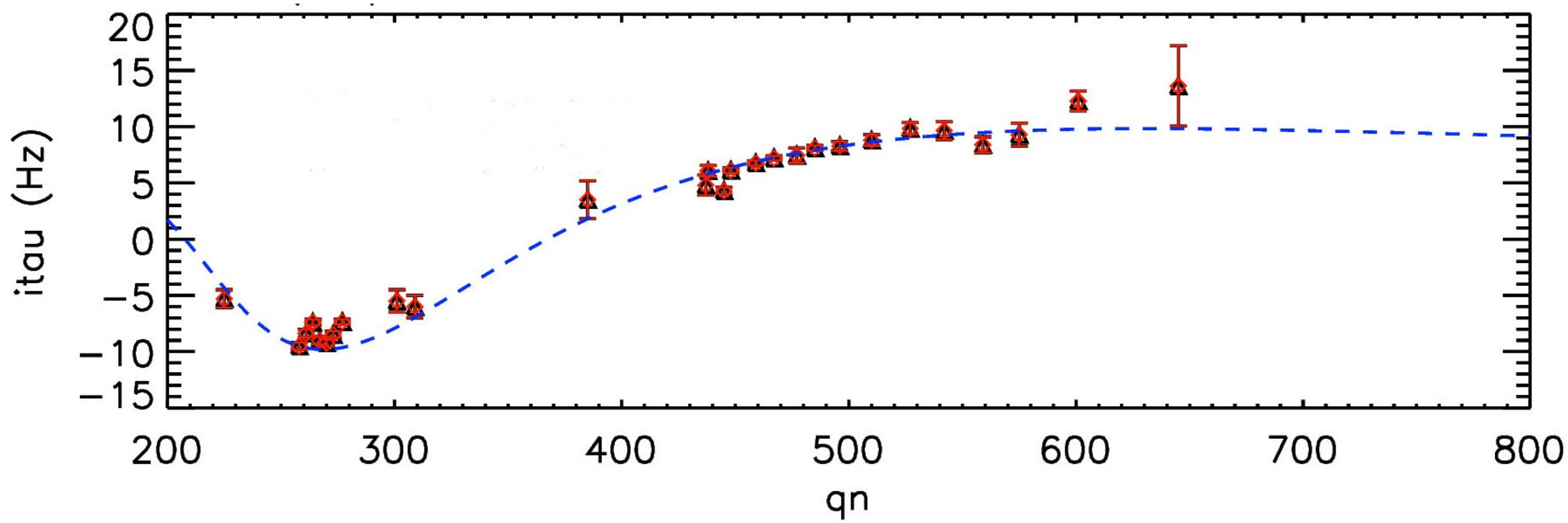
** uncertainty on T_e , n_e , L_C is about 15%*

(Oonk et al. In prep.)

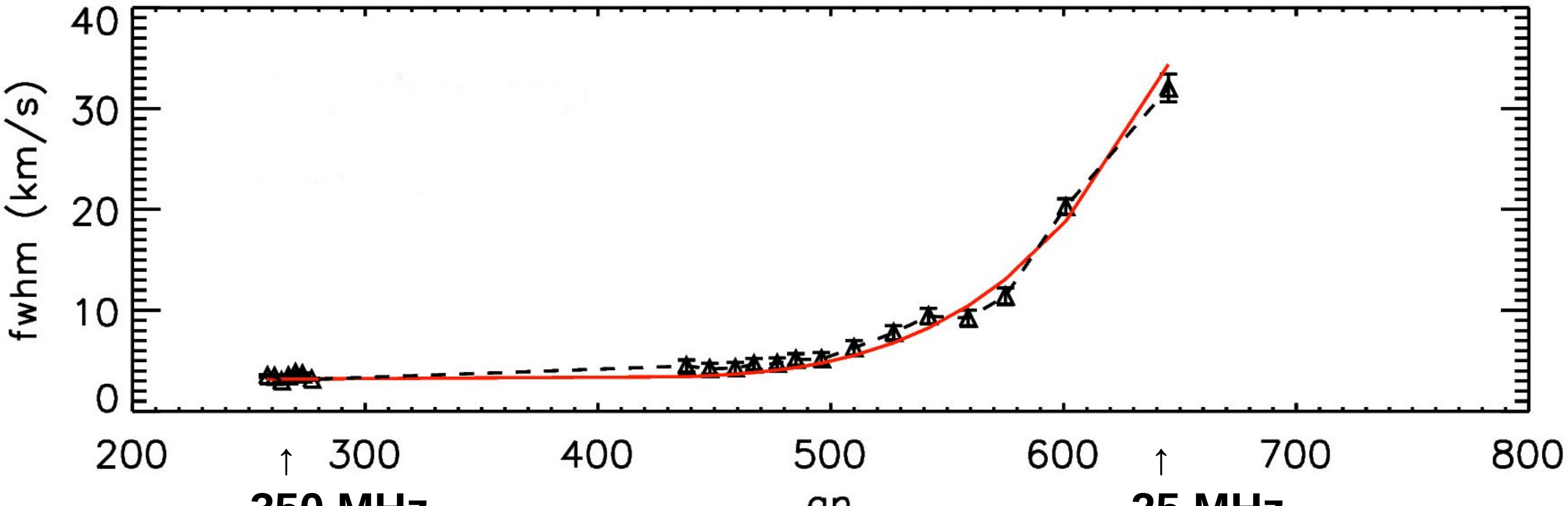
A) Cas A: A bright velocity resolved study II



Optical depth: T(e) = 90 K , n(e) = 0.04 cm-3 , L(c) = 46 pc



Line width: doppler = 3.4 km/s , T(R) = 1600 K , pressure (90;0.04)

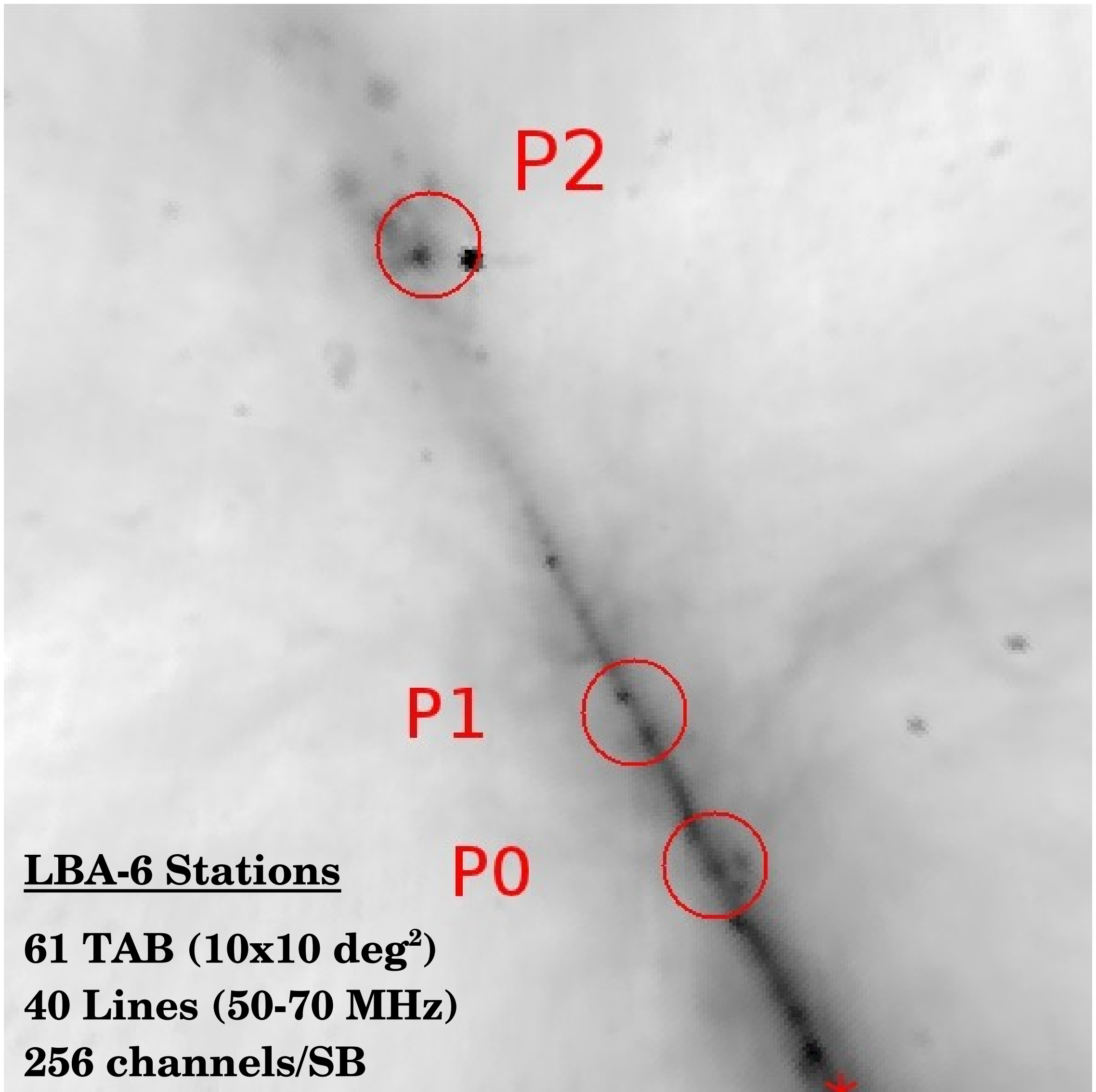


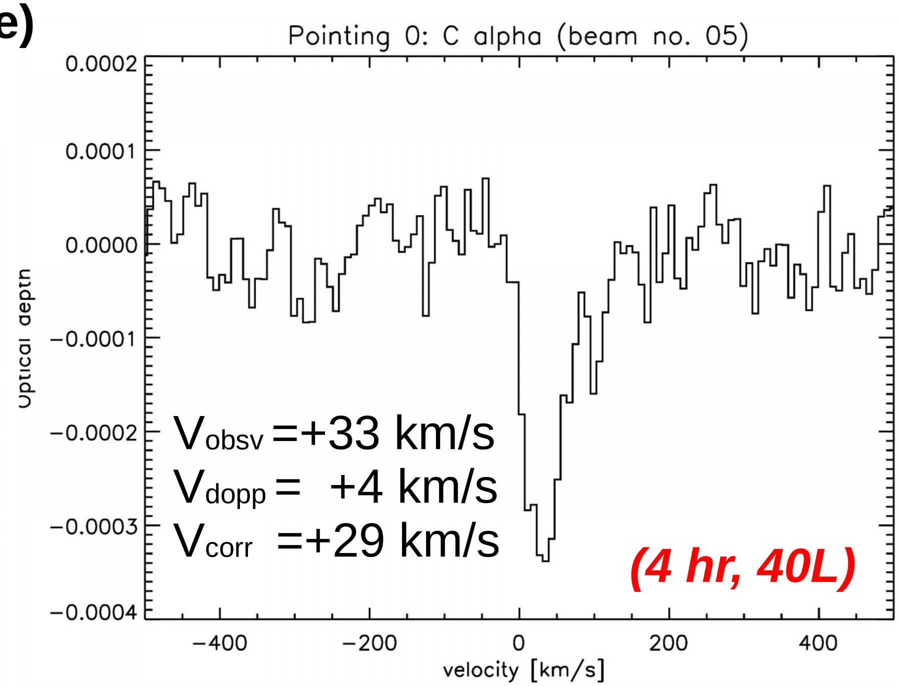
(Oonk et al. In prep.)

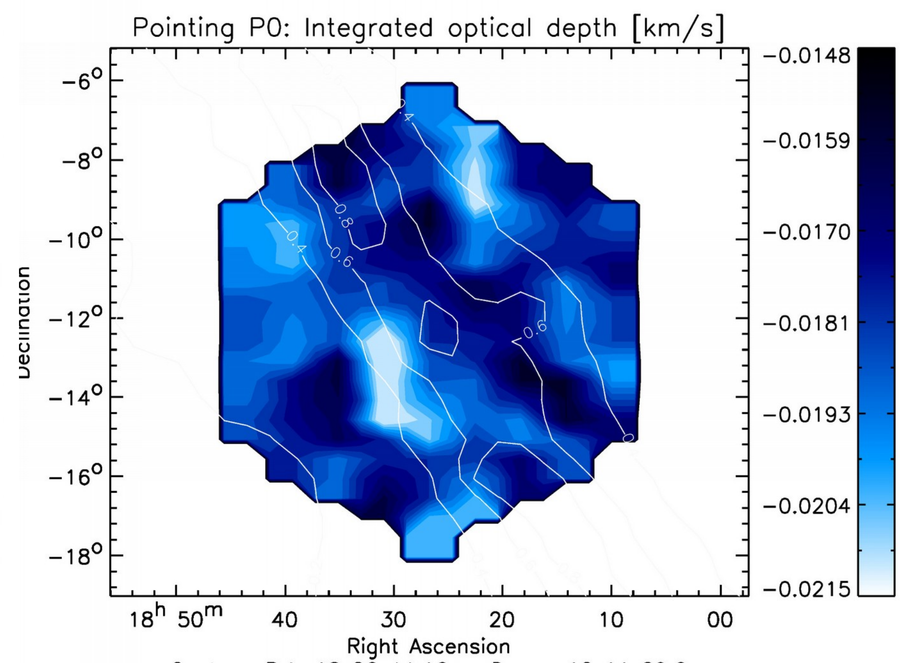
B) Galactic Tied Array observations (1 degree TAB's)

6 core stations; 1 degree resolution (early science)

Haslam+1982 (408 MHz) map

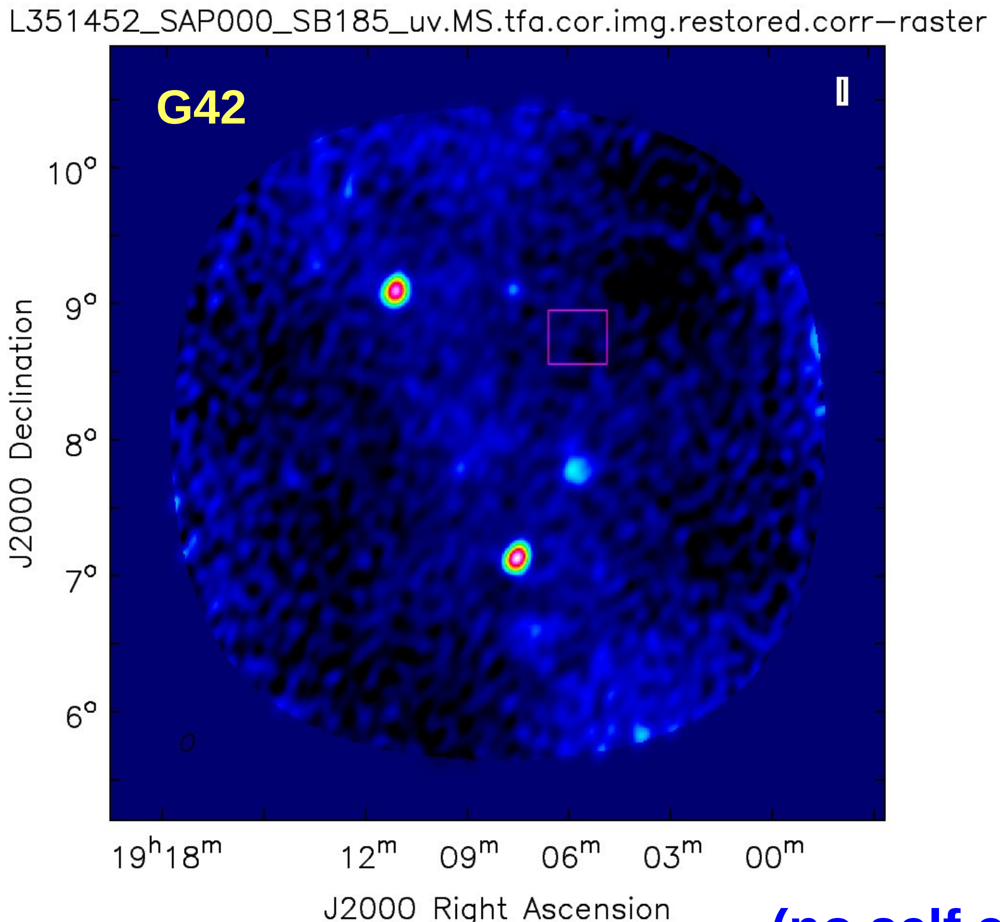




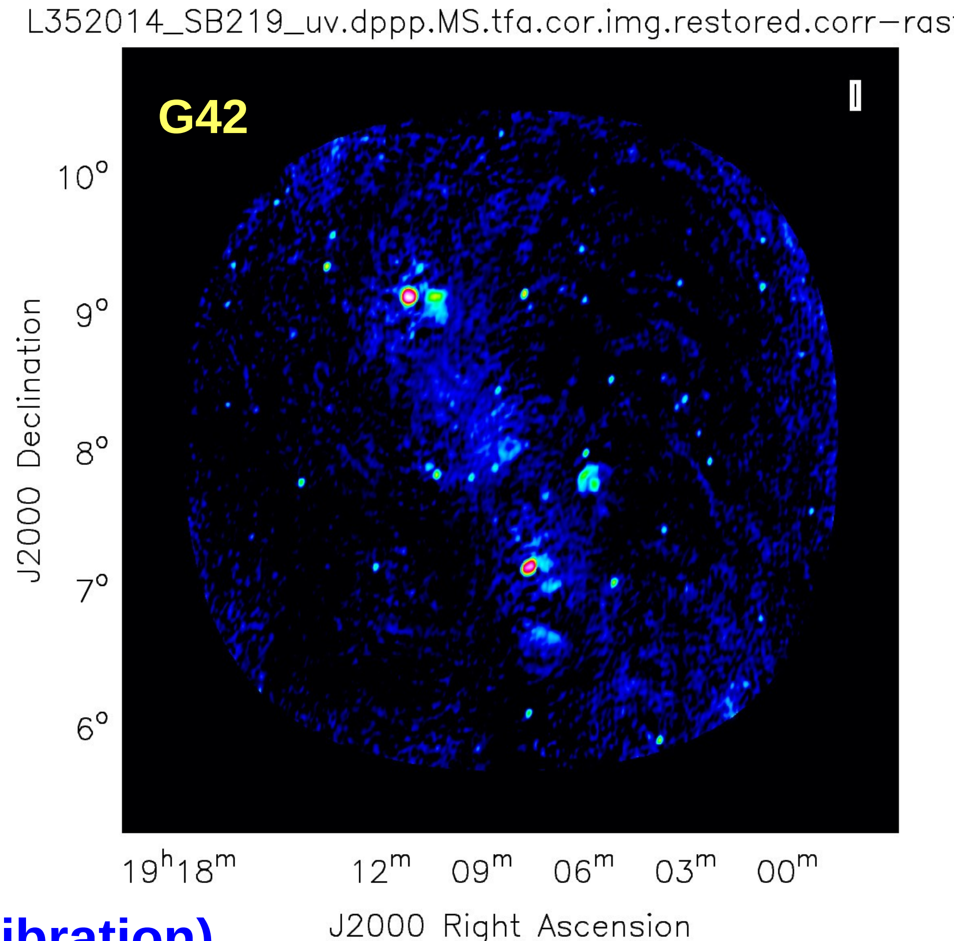


B) Galactic Interferometric observations (goal 10' beam)

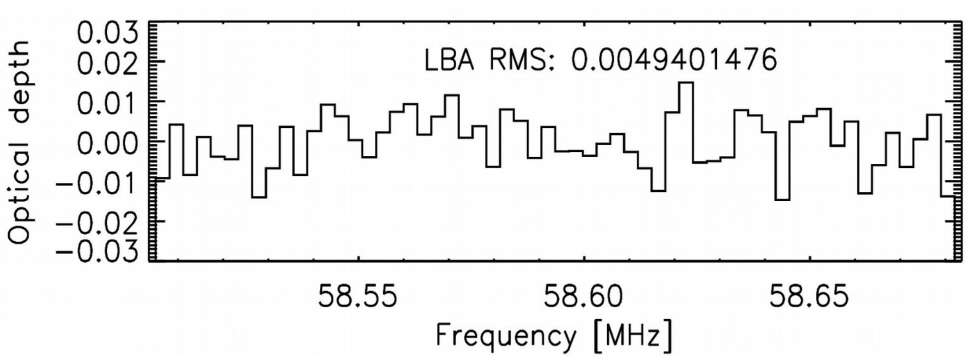
(LOFAR CORE LBA: 0.2 MHz)

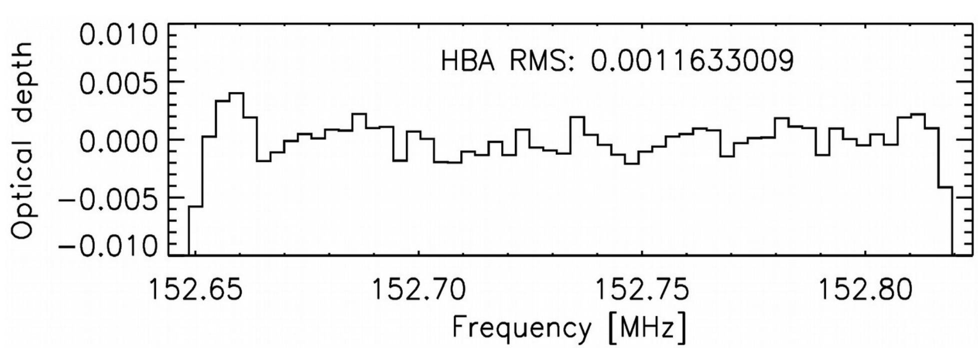


(LOFAR CORE HBA: 0.2 MHz)

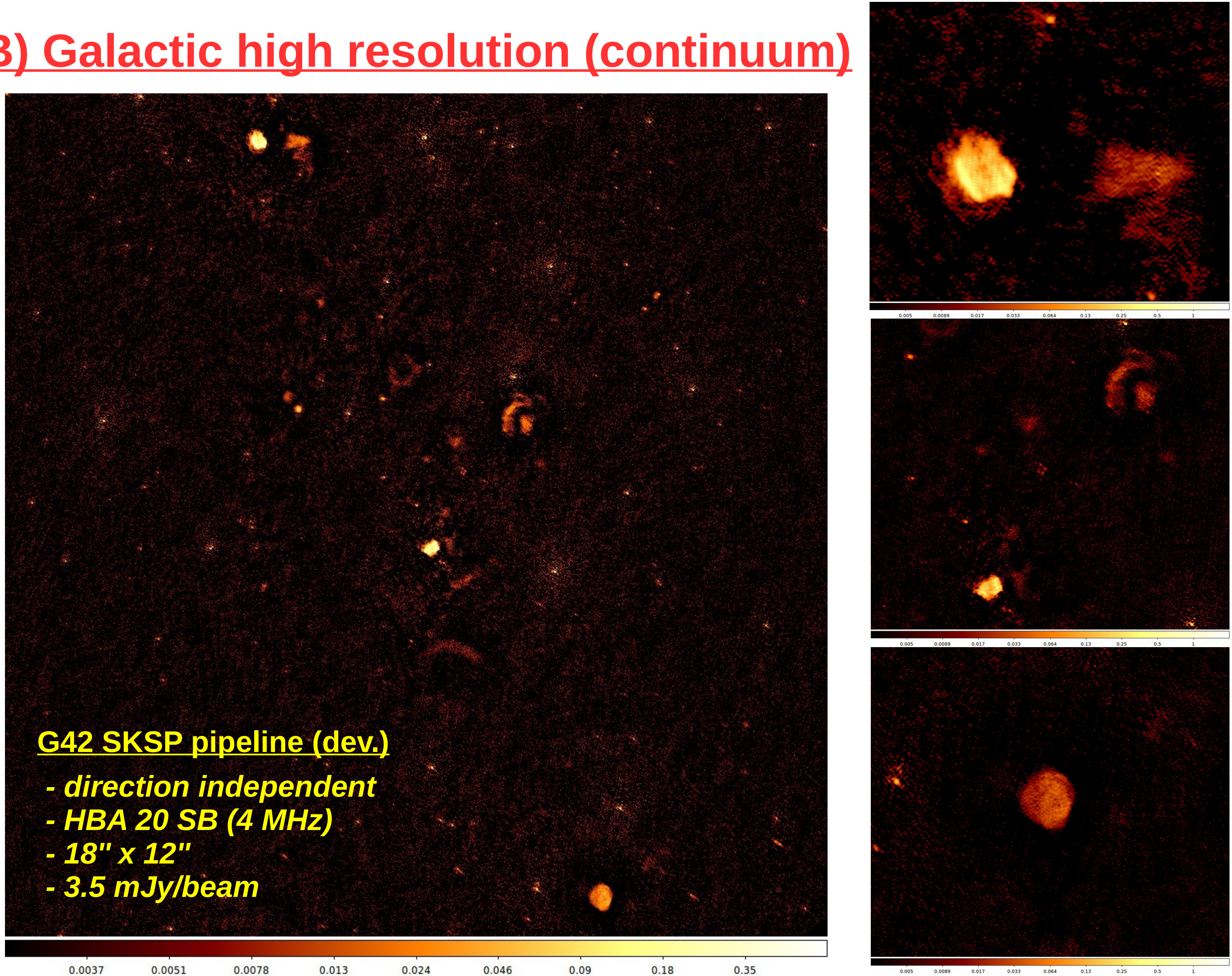


(no self calibration)





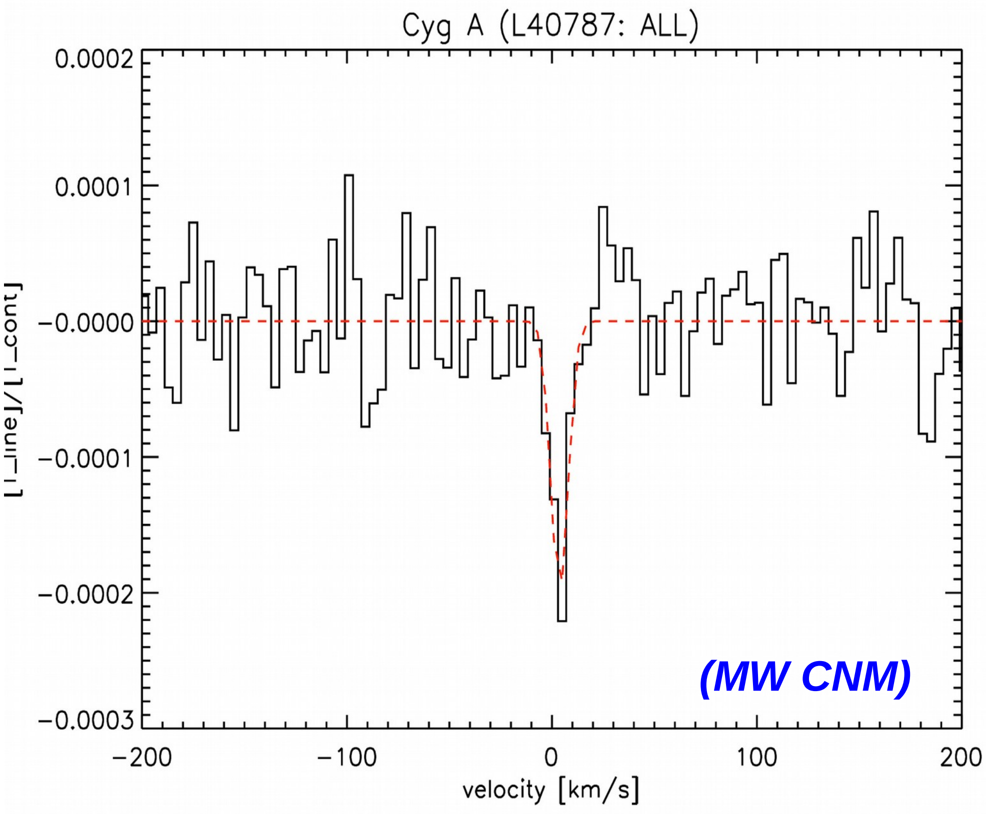
B) Galactic high resolution (continuum)



A) Galactic pinhole studies: Cygnus A)

(Oonk+2014)

Cygnus A (bright, FRII radio galaxy at z = 0.056)



LOFAR-LBA (10h)

BW = 33-57 MHz

Δf = 0.4 kHz

Δv = 2-4 km/s

Measurements:

τ_{PEAK} = 2×10^{-4}

v_{LSR} = +4 km/s

FWHM = 10 km/s

Derived properties:

T_e = 110 K

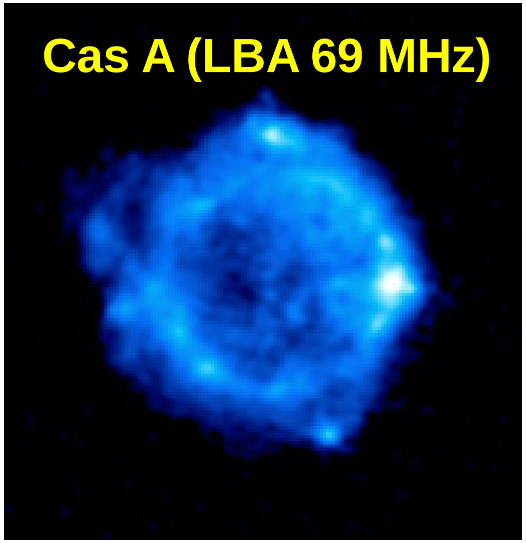
n_e = 0.06 cm^{-3}

EM_C = 0.001 cm^{-6} pc

[C/H] = 1.8×10^{-4}

ζ_H < 4×10^{-16} s^{-1}

LOFAR-RRL: Results & Outlook



CNM → (T_e , n_e , L_C , ζ_H , [C/H])

(a) new CRRL models and Cas A observations

- *New atomic data and full n,l treatment*
  LTE reached at lower n for optical depth
  Line width broadening is lower by ~30%
- *Cas A clouds are dense and not diffuse*

(b) LOFAR can map the large-scale CNM in the MW

- *Milky Way* ~ 10' [$N_H > 3x10^{20}$ cm^{-2}]
- *Galactic* SNR and HII regions
- *Extragalactic* ~ 300 galaxies

(c) Spectral RMS ~ [√(time) , √(chan) , √(lines)]