Observing the cold ISM with LOFAR

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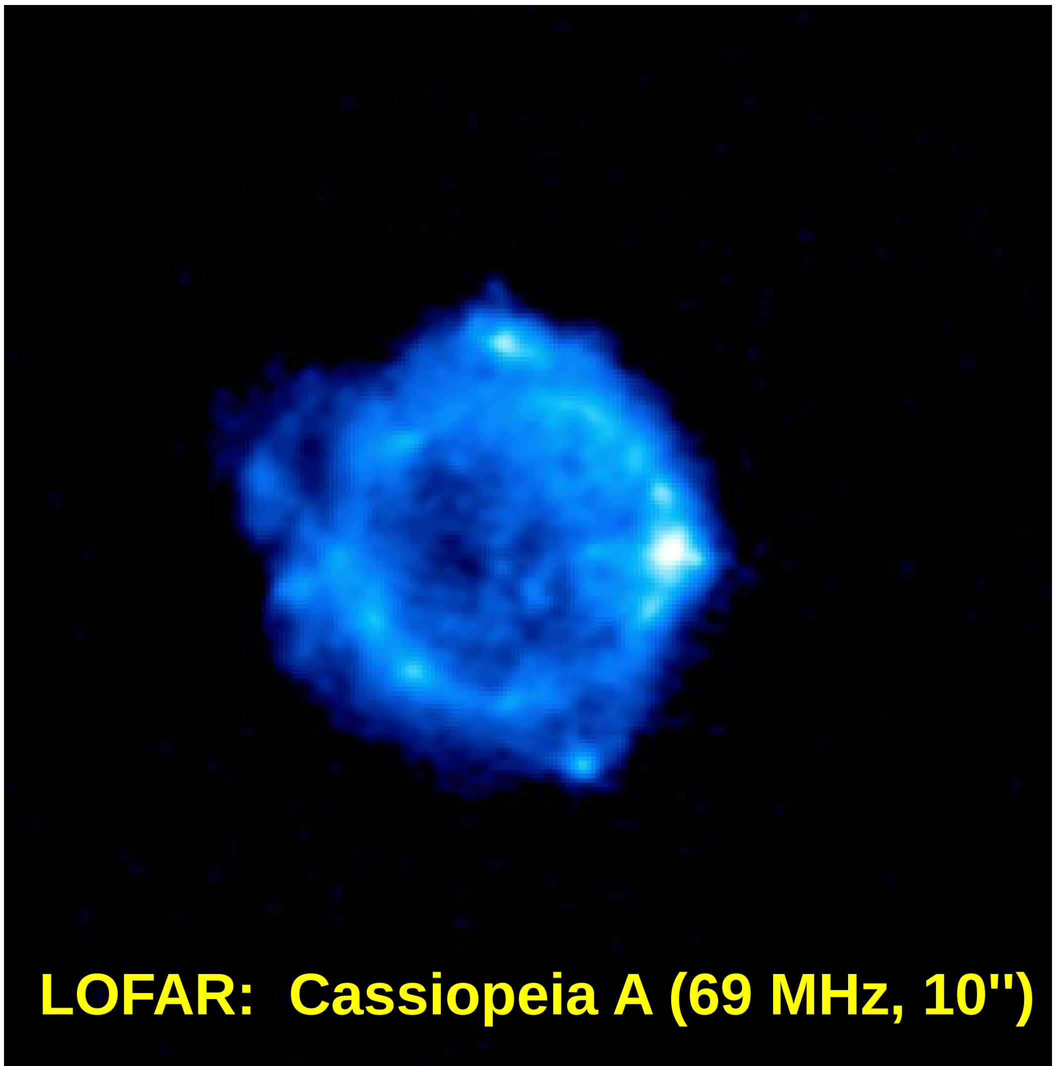
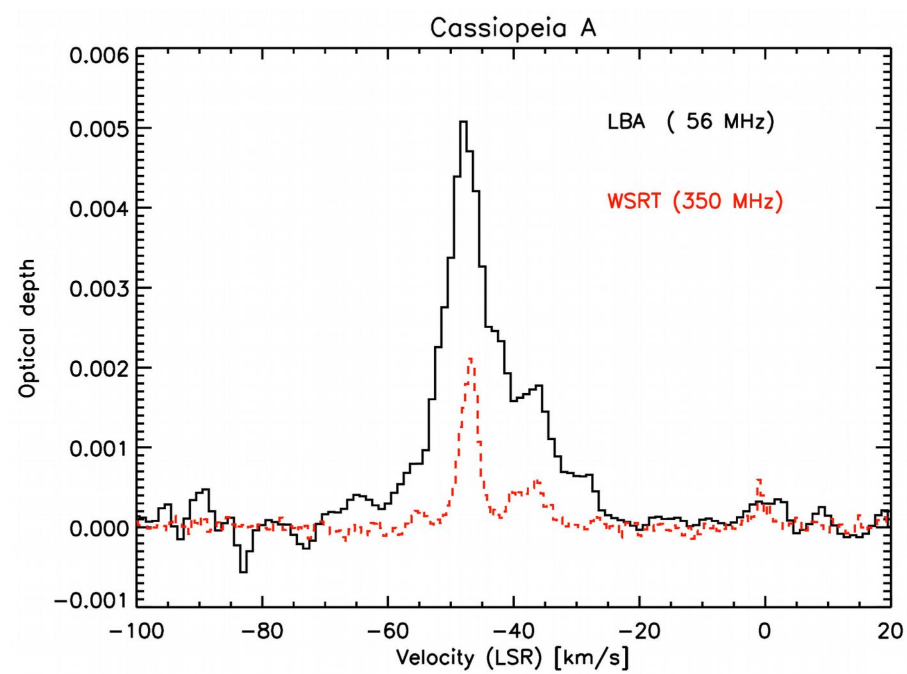
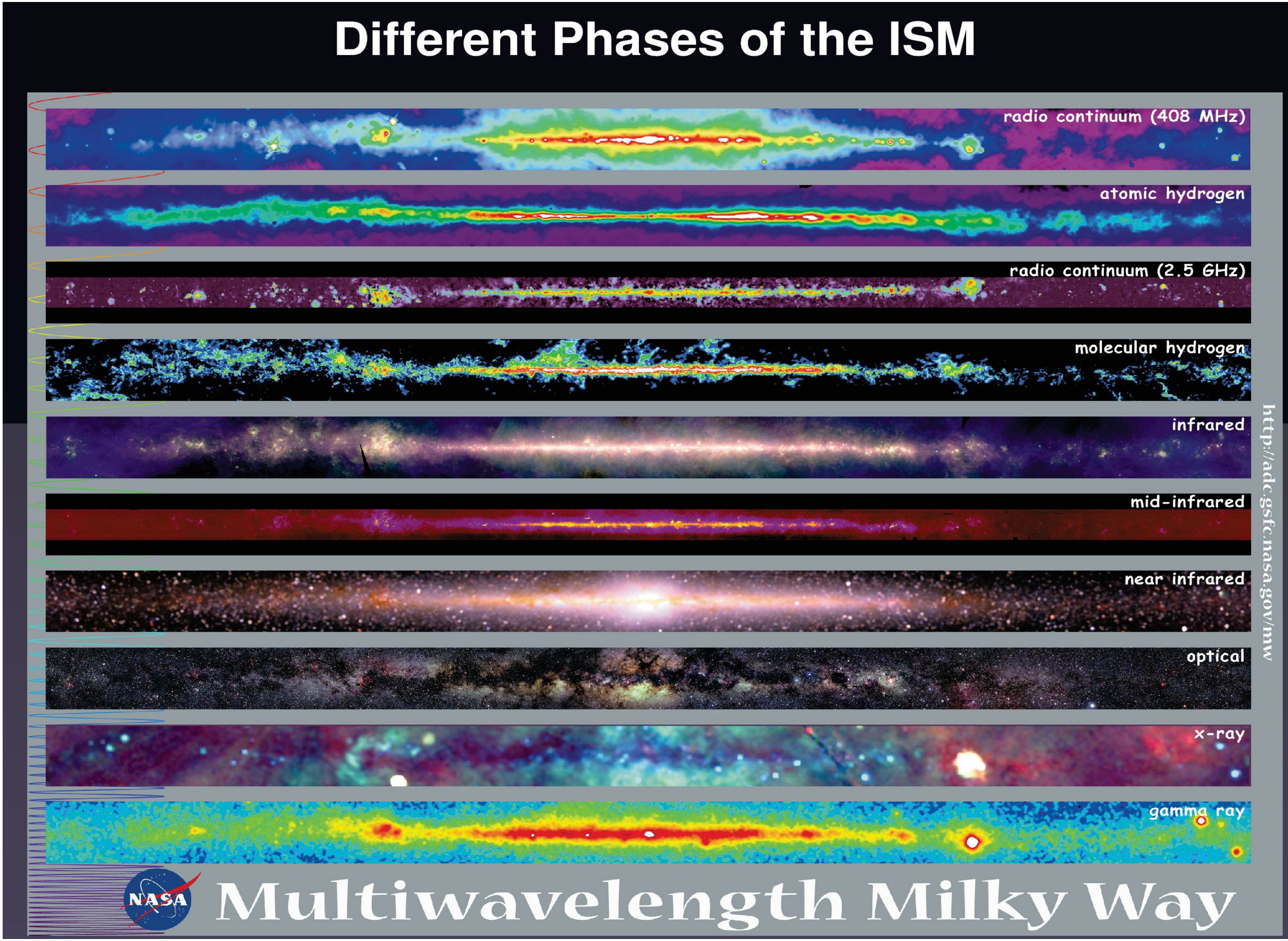


OUTLINE

- ISM & Low-frequency RRLs
- New Carbon RRL models
- CRRL diagnostic power
- Resolving the Milky Way
- Total power spectroscopy
- Conclusions



The Interstellar medium



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

Galaxy evolution is driven by (SF) recycling of ISM

=> ***What is the role of the atomic CNM ?***

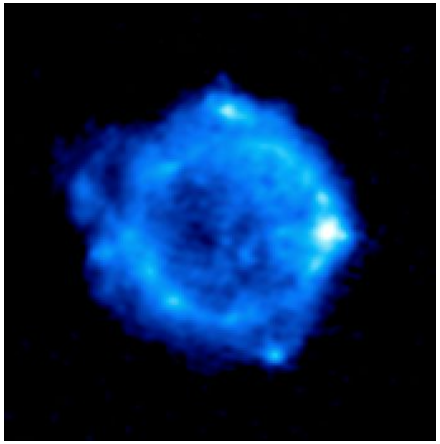
=> ***HI em*** *(contaminated)*, ***HI abs*** *(difficult)*

Outstanding questions

“ Galaxy evolution is driven by recycling of the ISM ”

but,

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



In particular:

- **Morphology, dynamics and how does this compare to molecular, SF and hot gas ?**
- **Thermal, pressure balance ?**
- **Ionization rate ?**
- **Chemical enrichment ?**
- **CNM fraction of the HI 21 cm signal ?**

Diffuse RRL's (≤ 1 GHz)

- Hydrogen RRL's
  always in Emission

- Carbon RRL's
  emission ≥ 130 MHz
  absorption ≤ 130 MHz

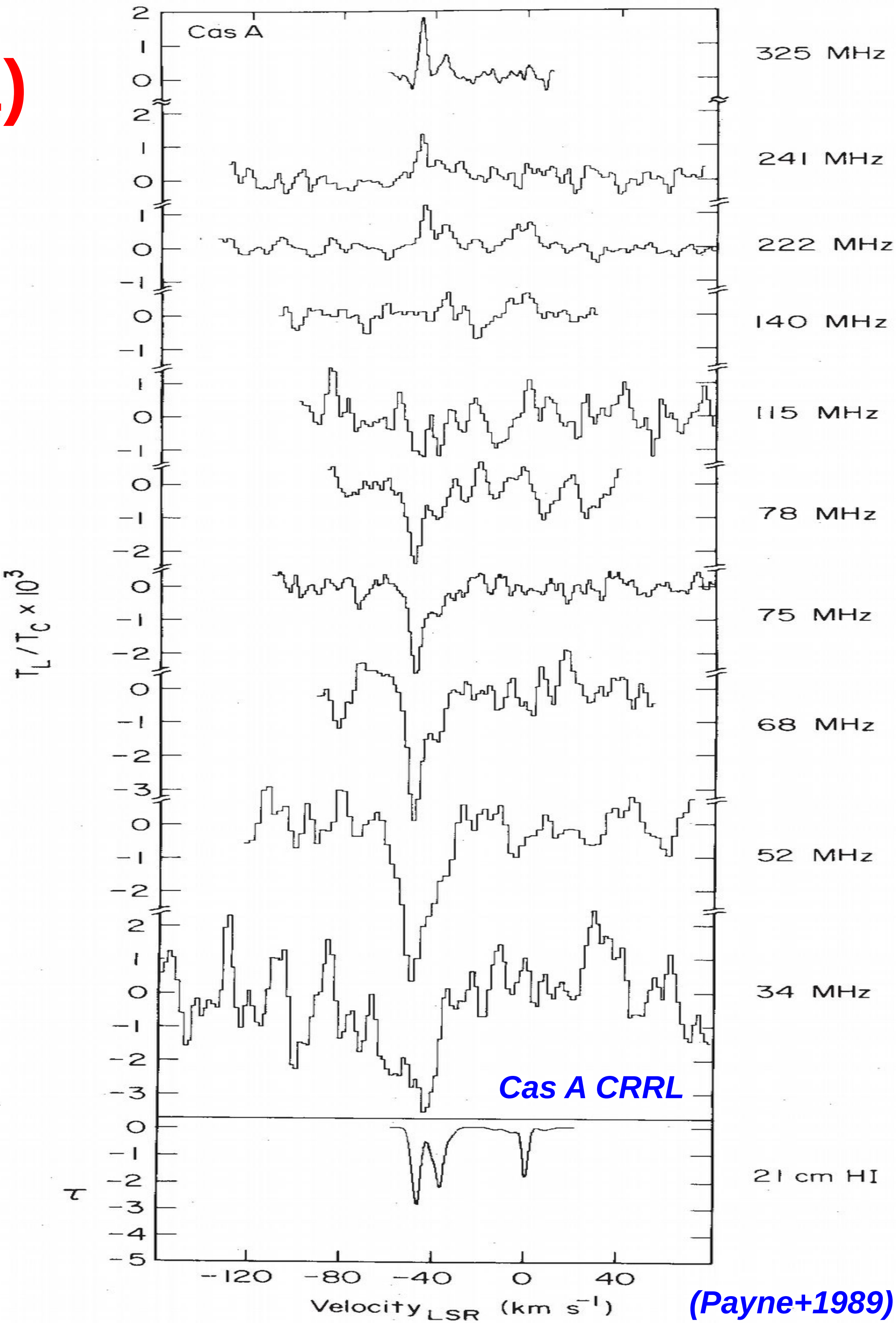
- Associated with CNM / PDR's
  T_e ~ 10-300 [K]
  n_e ~ 0.01-1.0 [cm^{-3}]

- Properties : T_e , n_e , EM

- Ionisation : ζ(H)

- Metallicity : [C/H]

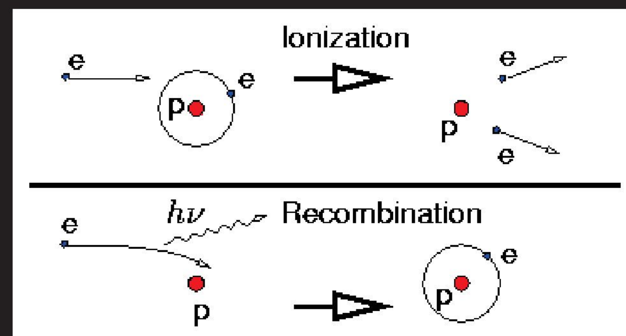
- Kinematics: vel , FWHM



(Payne+1989)

New Carbon RRL models

Recombination Lines



http://silas.psfc.mit.edu/introplasma/chap1.html

All quantum numbers, n

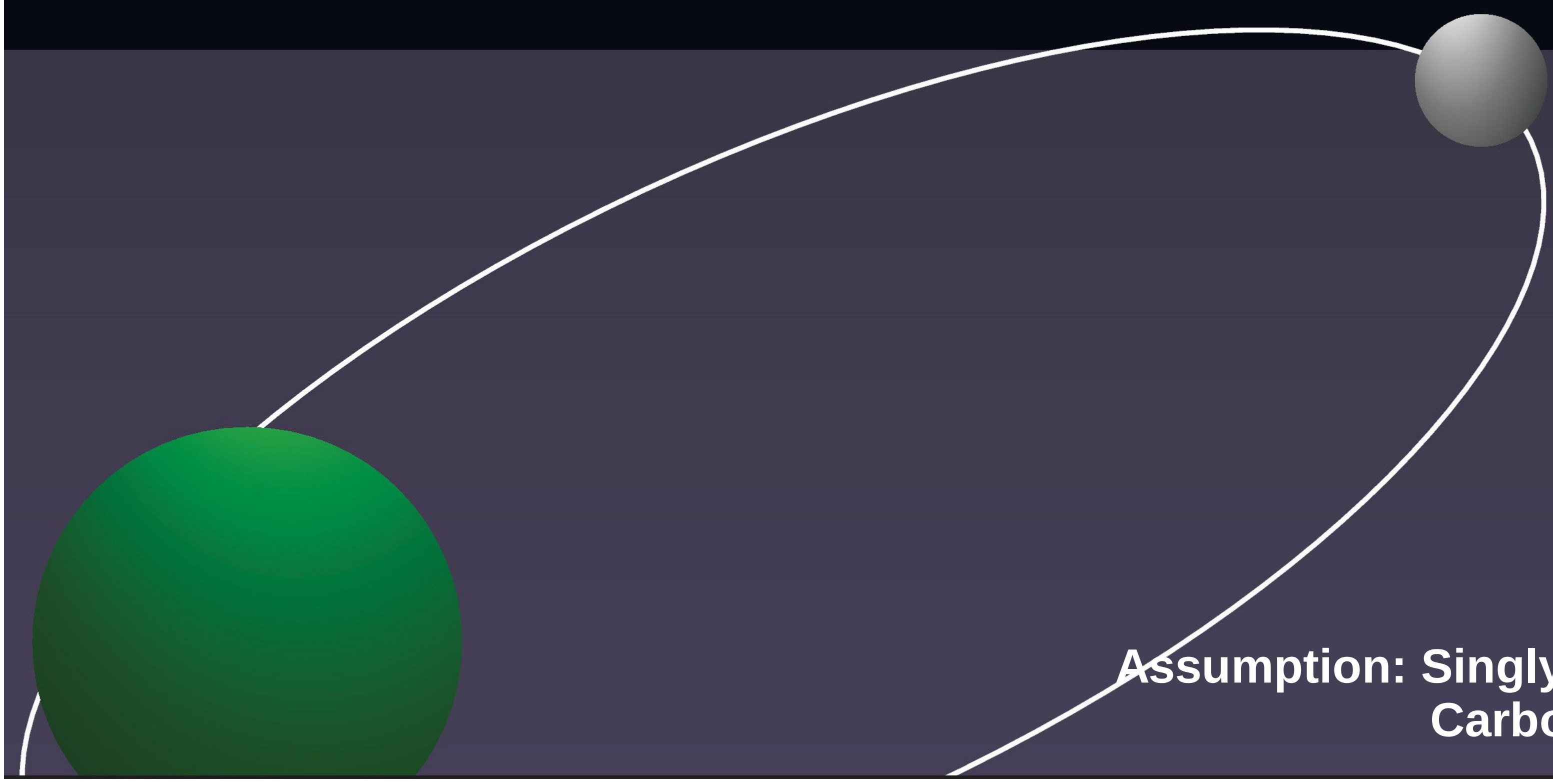
- UV-IR: $n < 50$
- Radio: $n > 50$

http://www.astro.rug.nl/~ndouglas/teaching/ObservingTechniques/spectroscopy.html

Rydberg Atom

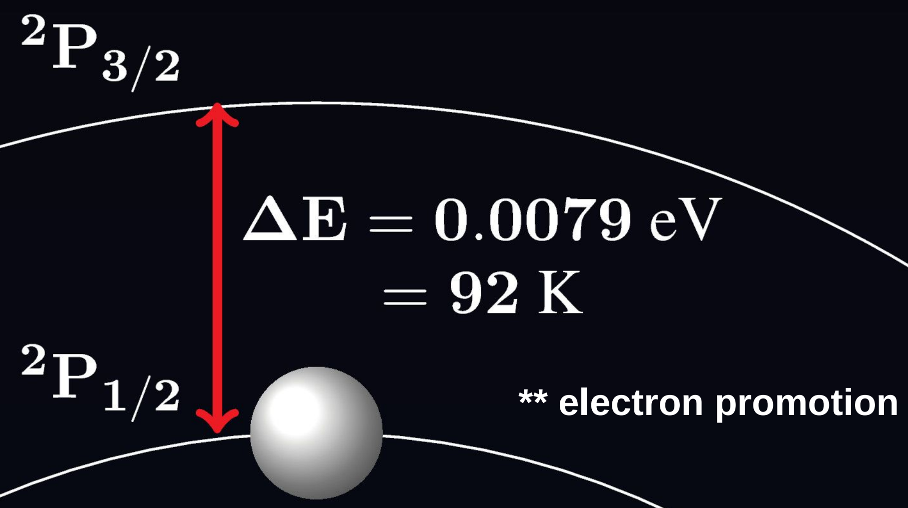
- Outermost electron in high-n state
- Sees nucleus with $+1$ charge
- "Hydrogenic"

Regular (radiative) recombination: e- + A (q+) → A (q-1) + photon



Assumption: Singly ionized, recombining Carbon (i.e. " hydrogenic ")

Dielectronic-like Recombination



Dielectronic recombination: e- + A (q+) → A (q-1) → A (q-1) + photon**

- free e- can give ΔE=0.0079 eV to $^2P_{1/2}$ and still recombine with neglible binding energy

- <u>Optical depth</u> ∫ τ ~ b_n * β_n (LTE departure coefficients 'stimulation')

=> build a non-LTE model (<u>Salgado et al. 2016 subm/acc.</u>)

New RRL models: Optical Depth (τ)

(Salgado+ subm/acc.)

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

CNM (atomic):

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

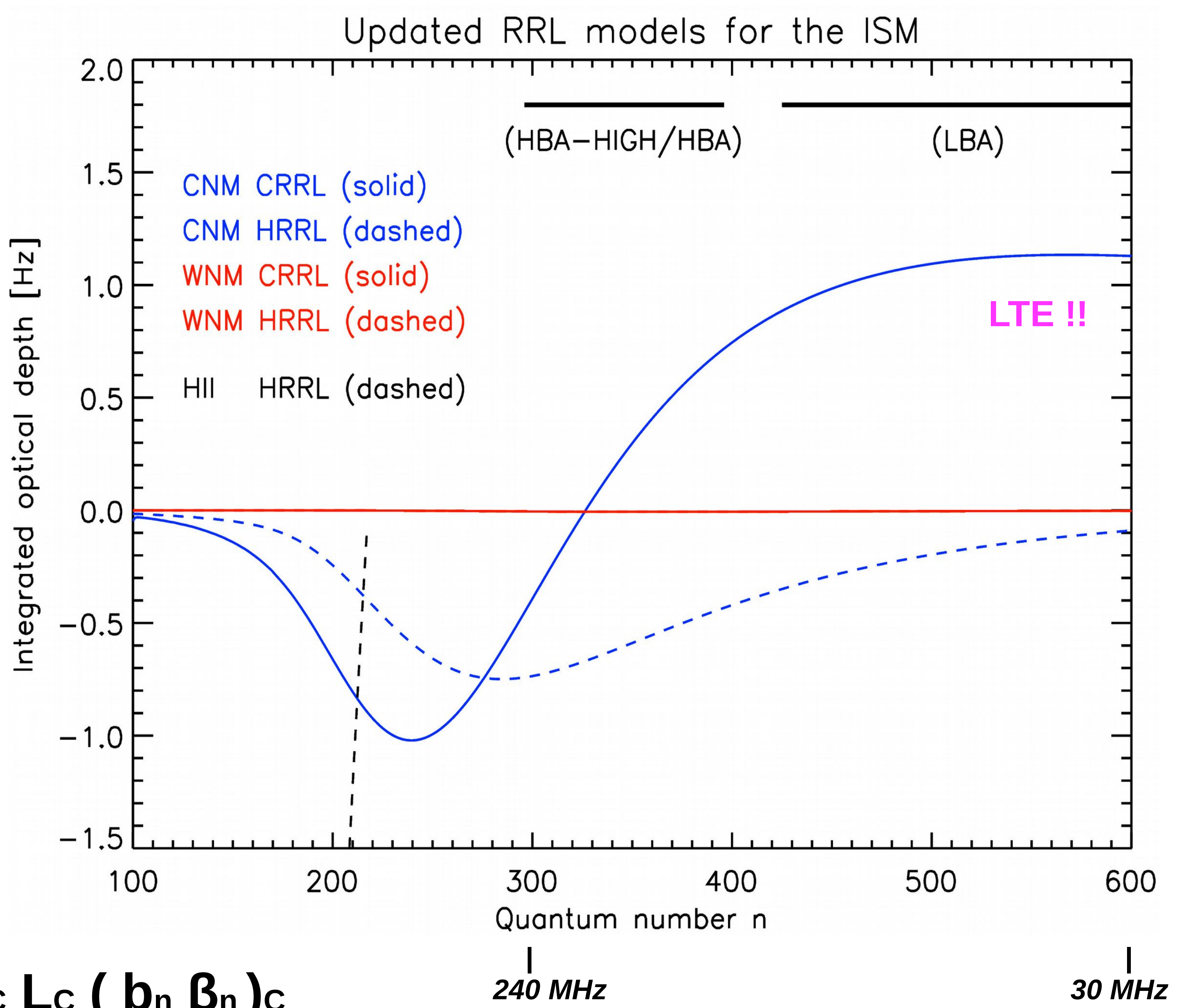
WNM:

- $n_e = 0.01$ 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*



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

<u>New RRL models</u>:   Line broadening

(Salgado+ subm/acc.)

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

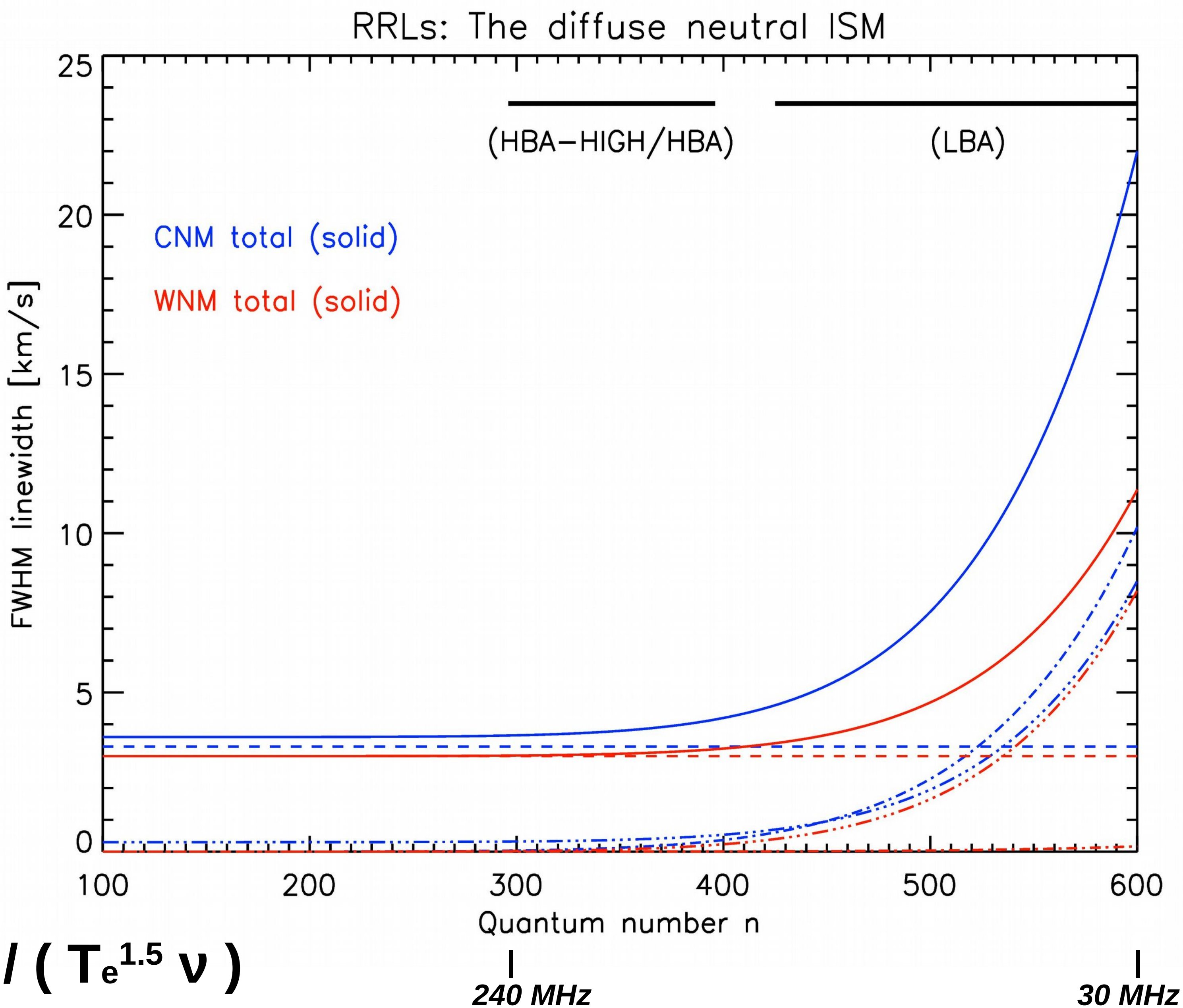
Total (solid) width:

(1) Doppler (dash)

(2) Pressure (dash-dot)

(3) Radiation (dash-dot-dot)

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



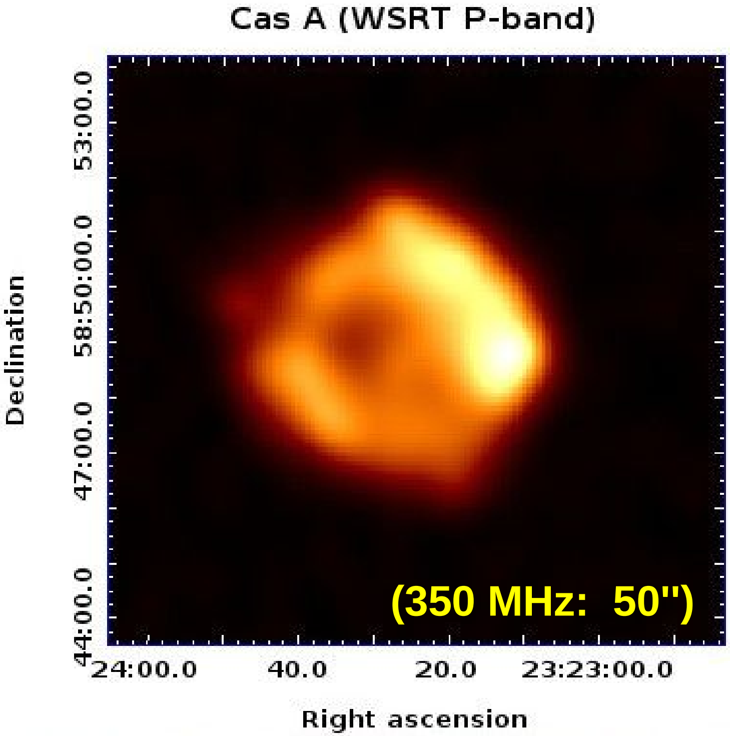
$$\Delta V_P \sim (n_e \, n^{5.2}) / (T_e^{1.5} \, \nu)$$

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

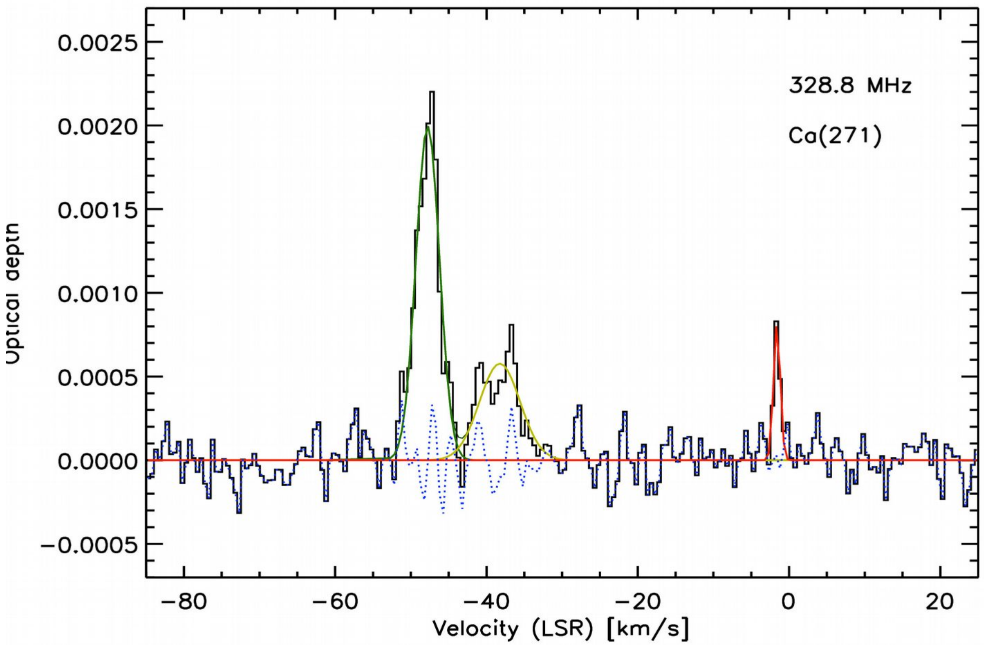
Diagnostic power of CRRL's

* Cas A as a case study *

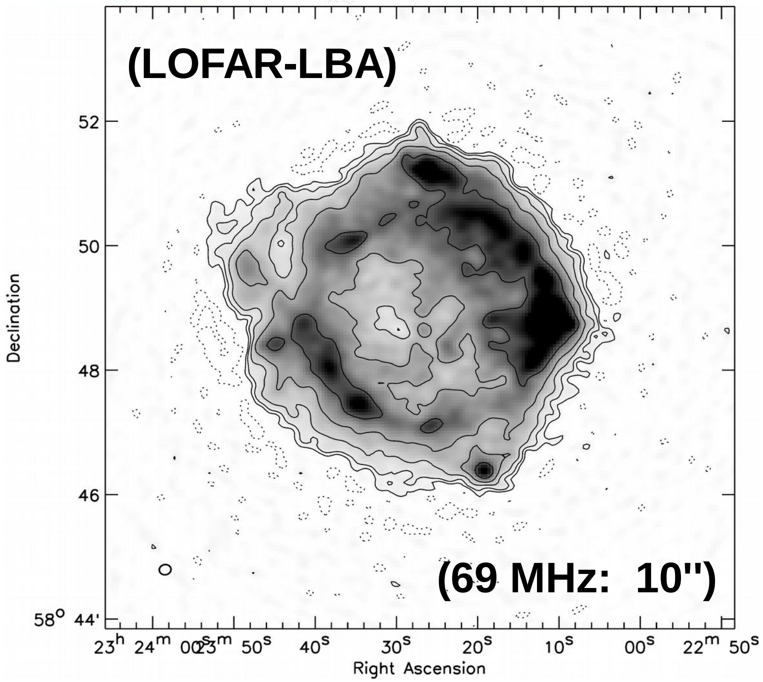
Cas A (data)



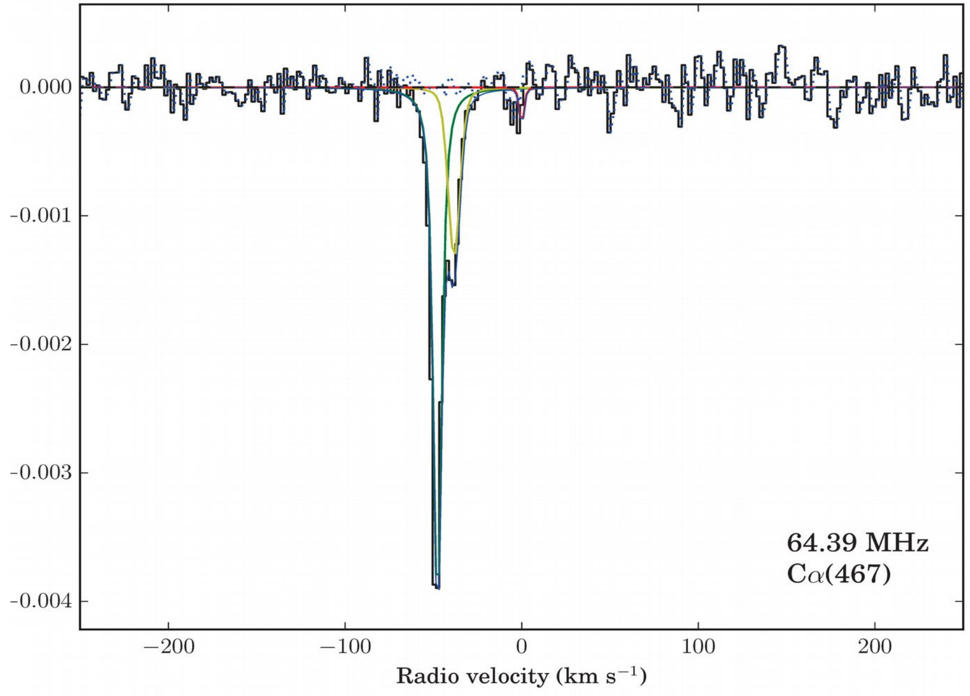
Cas A (WSRT P-band)
Declination
53:00.0
58:50:00.0
47:00.0
44:00.0
24:00.0
40.0
20.0
23:23:00.0
Right ascension
(350 MHz: 50")



0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
−0.0005
Optical depth
328.8 MHz
Cα(271)
−80
−60
−40
−20
0
20
Velocity (LSR) [km/s]

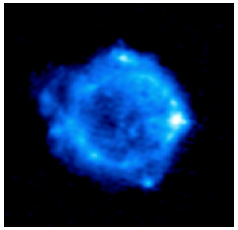


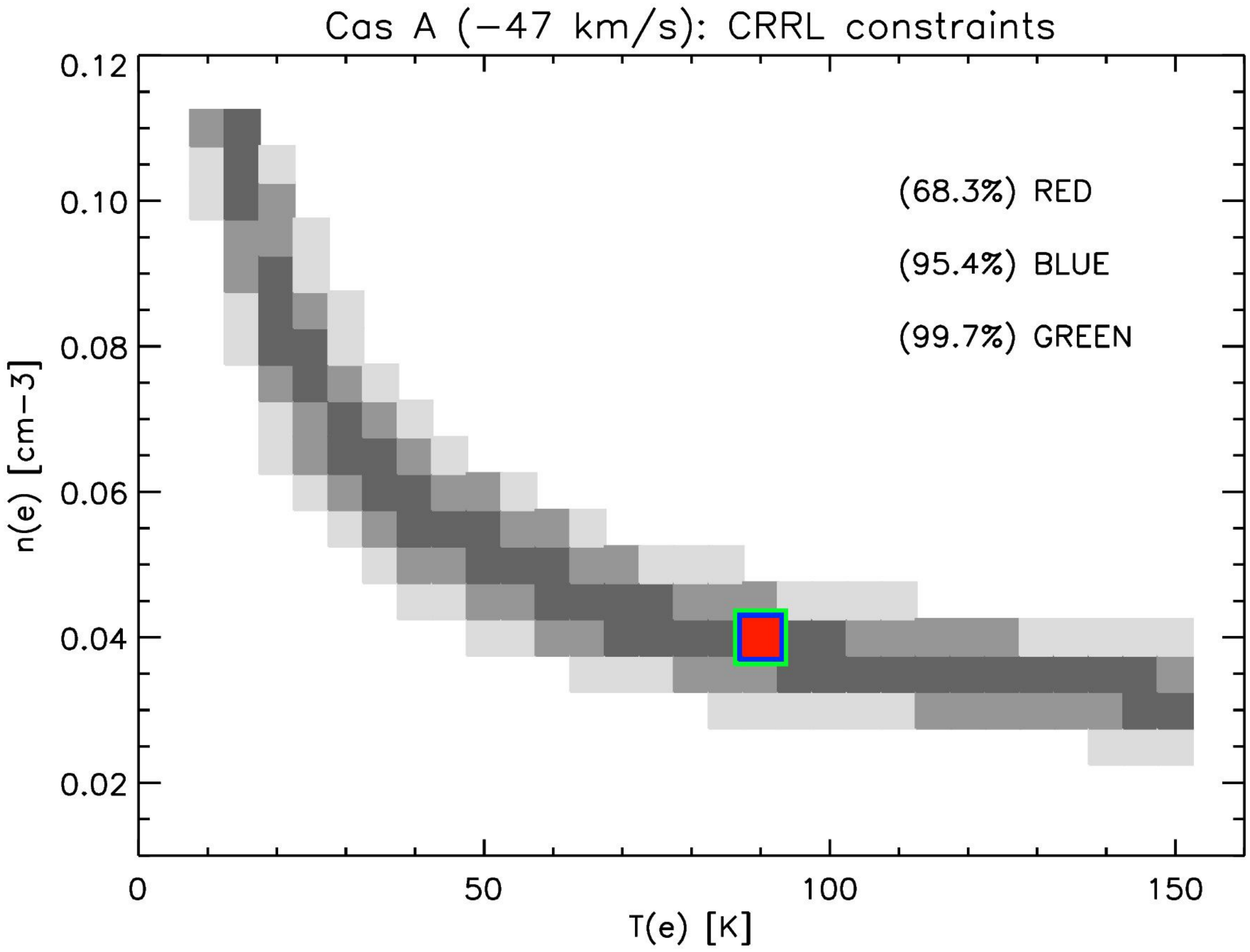
(LOFAR-LBA)
Declination
52
50
48
46
58° 44'
23h 24m 00s
23m 50s
40s
30s
20s
10s
00s
22m 50s
Right Ascension
(69 MHz: 10")



0.000
−0.001
−0.002
−0.003
−0.004
−200
−100
0
100
200
Radio velocity (km s−1)
64.39 MHz
Cα(467)

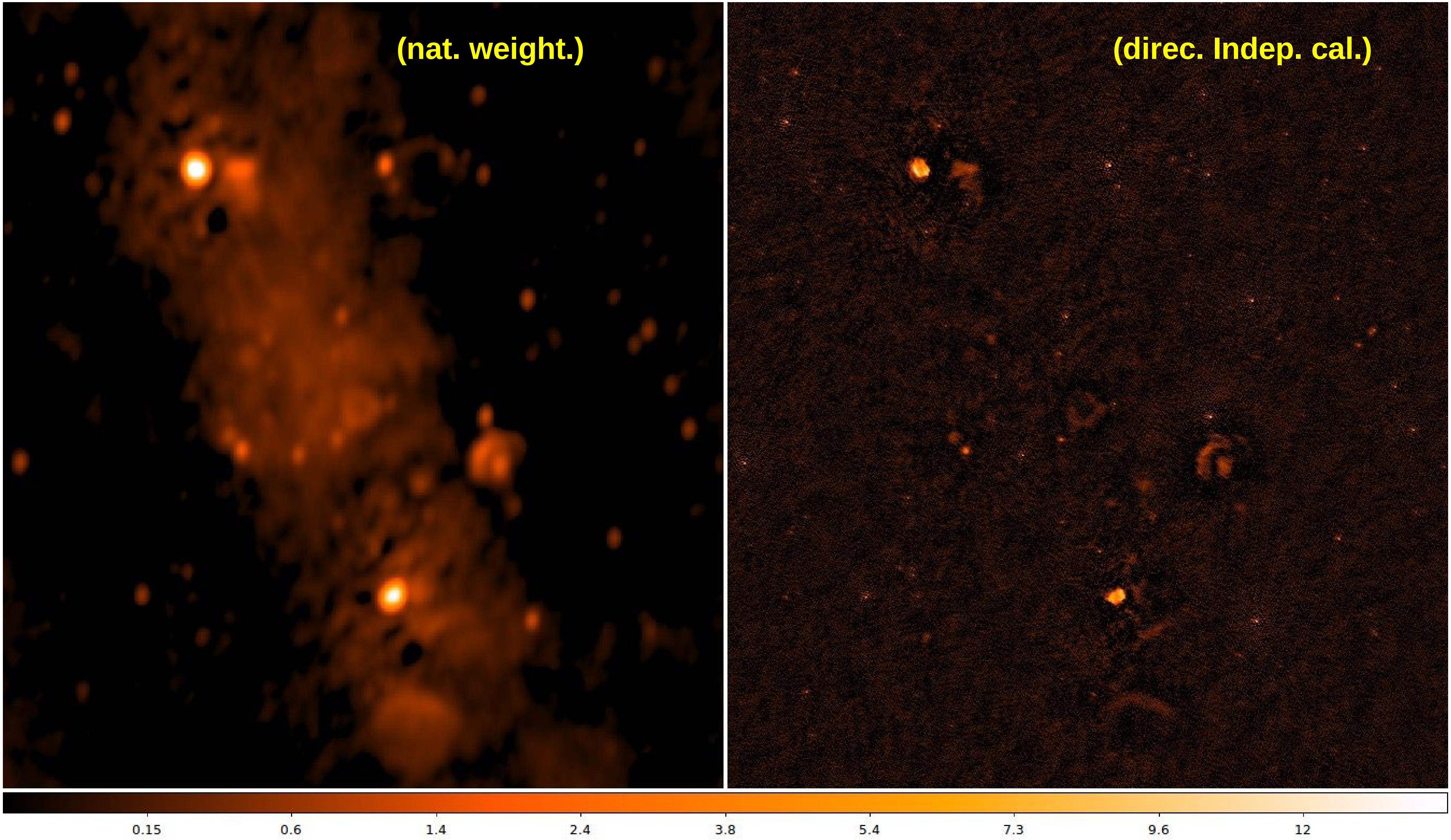
Cas A: Optical depth





* Uncertainty T_e , n_e is about 10 %

G42 (inner GP: HBA 150 MHz, 4 MHz BW, 4hr)



*** CRRL basic quantity is optical depth, <u>need</u> to understand the continuum**

LOFAR (line) surveys

*** Total power spectroscopy ***

RRL Surveys

The Power of LOFAR:

Sensitivity , Resolution , FoV , BW

=> *"Survey speed"*   *(α , δ , λ)*

LBA   10 -   70 MHz : 400 RRL α-lines
HBA 105 - 250 MHz : 100 RRL α-lines

ASTRON

LOFAR

A) Medium resolution Galactic survey

From degree-scales to >10'-scales

B) Galactic pinhole survey (<10')

=> see talk by <u>P. Salas</u>

C) Extragalactic survey

=> see talks by <u>C. Toribio</u> & <u>K. Emig</u>

Galactic plane RRLs: (before 2011)

(Kantharia & Anantharamaiah 2001)

Major issues:

(1) Beam FWHM > 2 deg.
(unresolved cloud sizes)

(2) Resolution mismatch
(spatial & spectral)

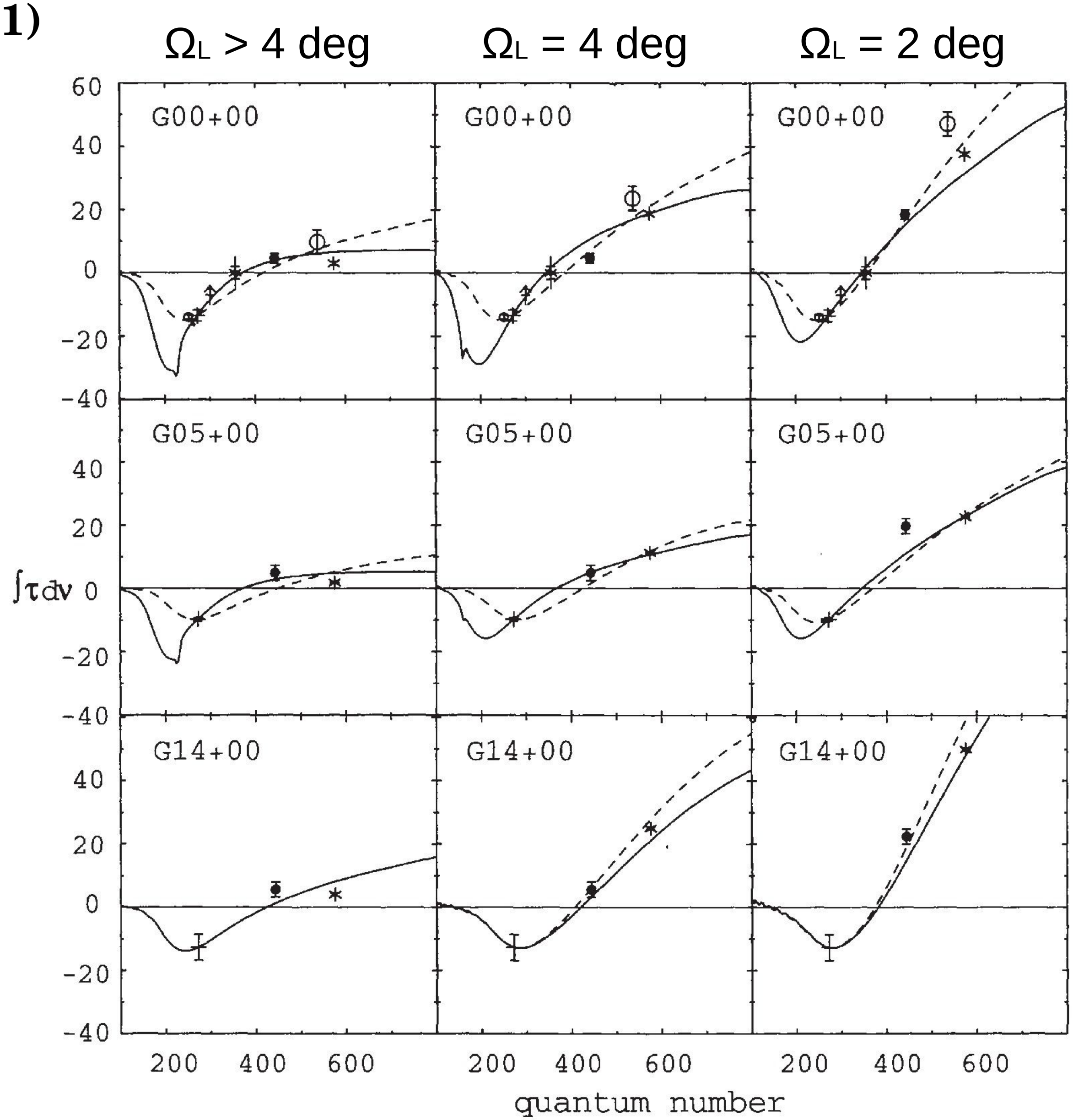
(3) Limited frequency coverage

Data:

***** 328 MHz , Anantharamaiah (1985)****

***** 76 MHz , Erickson et al. (1995)****

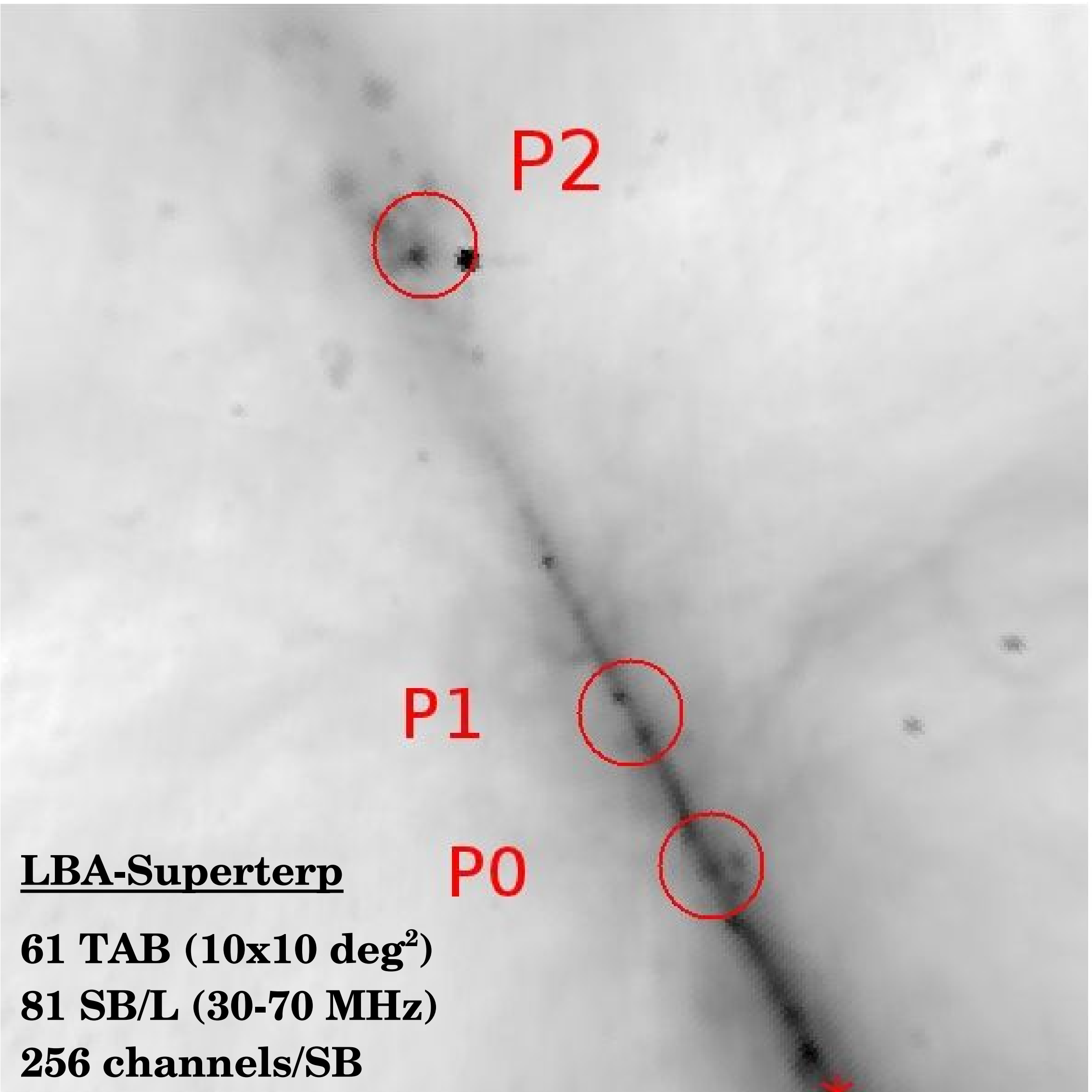
***** 34 MHz , Kantharia et al. (2001)****



=> but, expect: Ω(L,v) ~ arcmin-scales !!

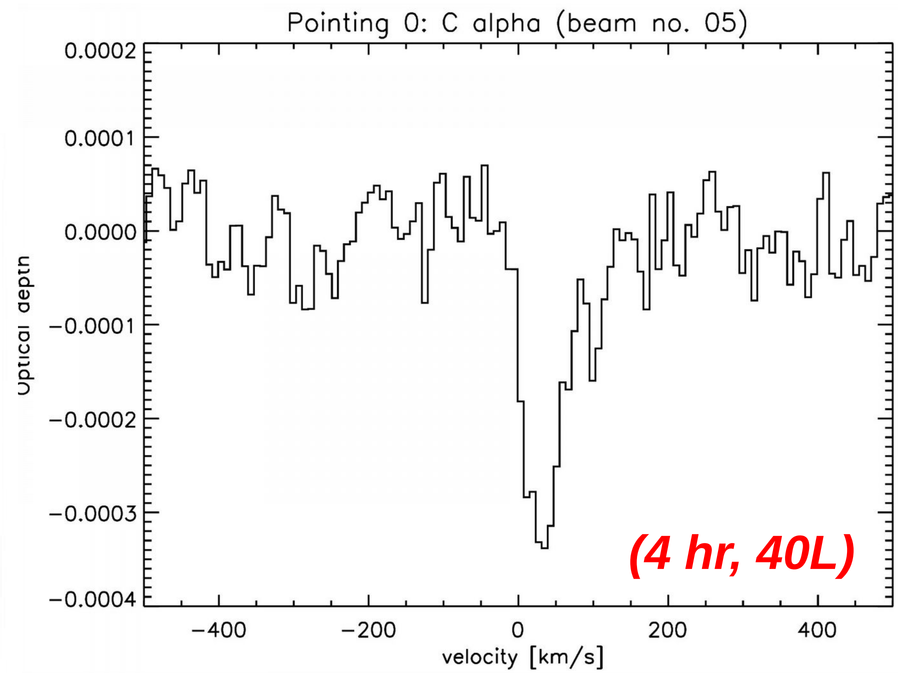
Galactic Medium Resolution CRRL Survey

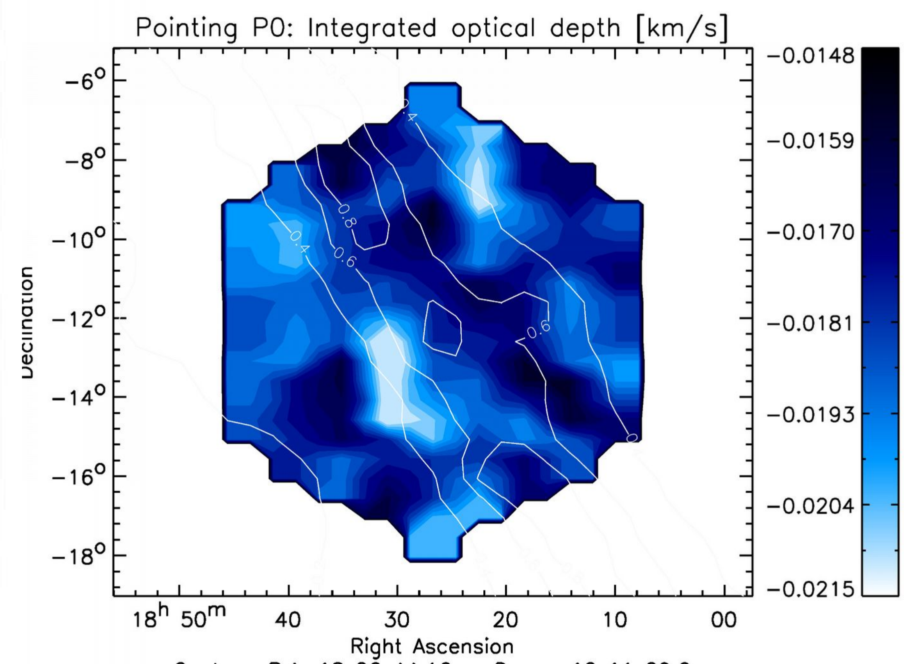
Haslam+1982 (408 MHz) map



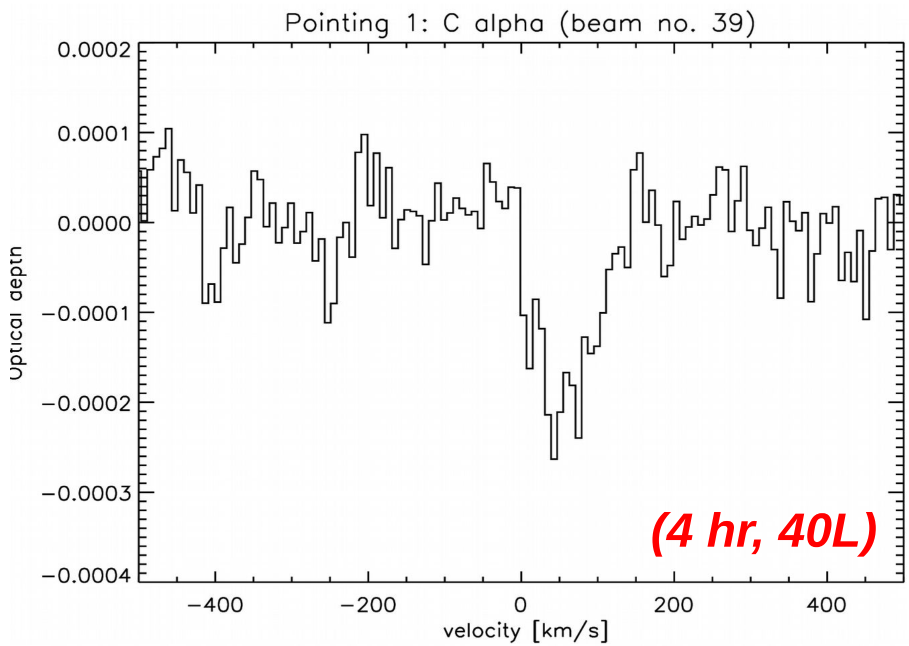
LBA-Superterp

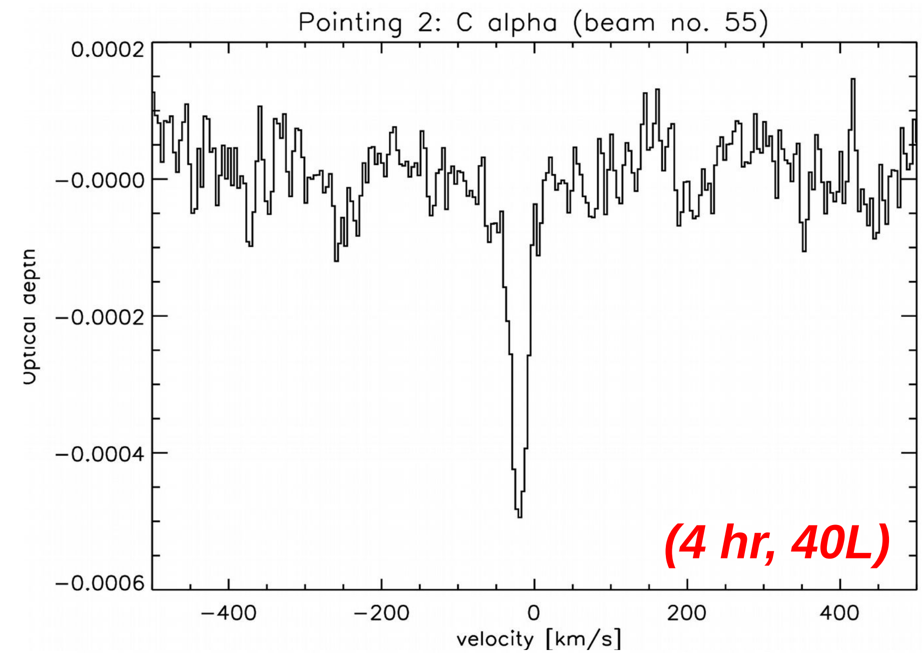
61 TAB (10x10 deg^2)
81 SB/L (30-70 MHz)
256 channels/SB

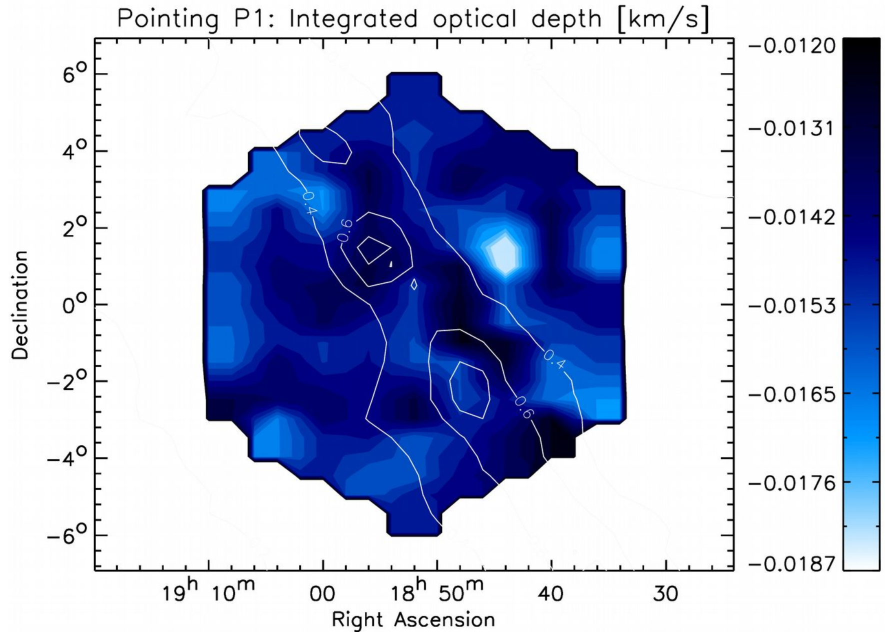


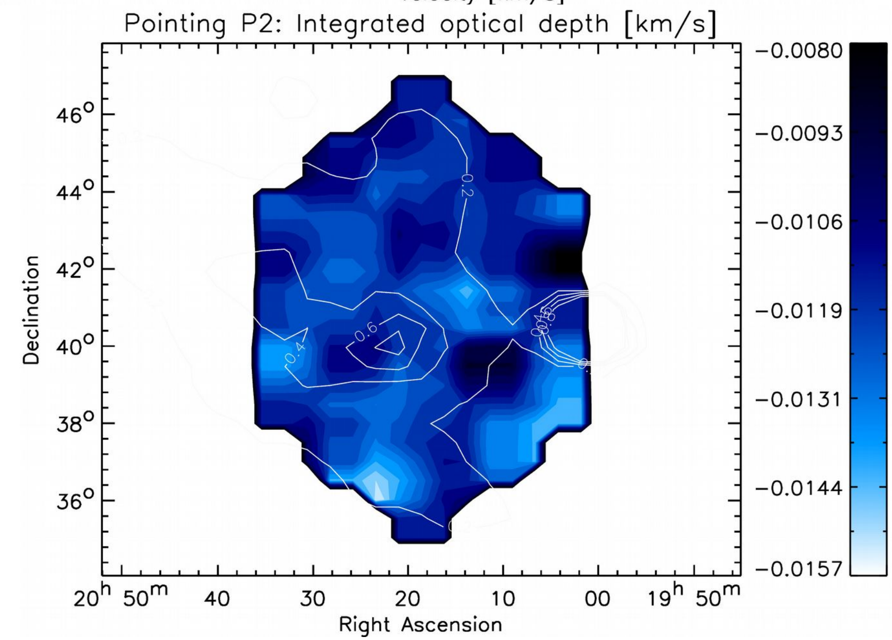


Galactic Medium Resolution CRRL Survey: P1 & P2









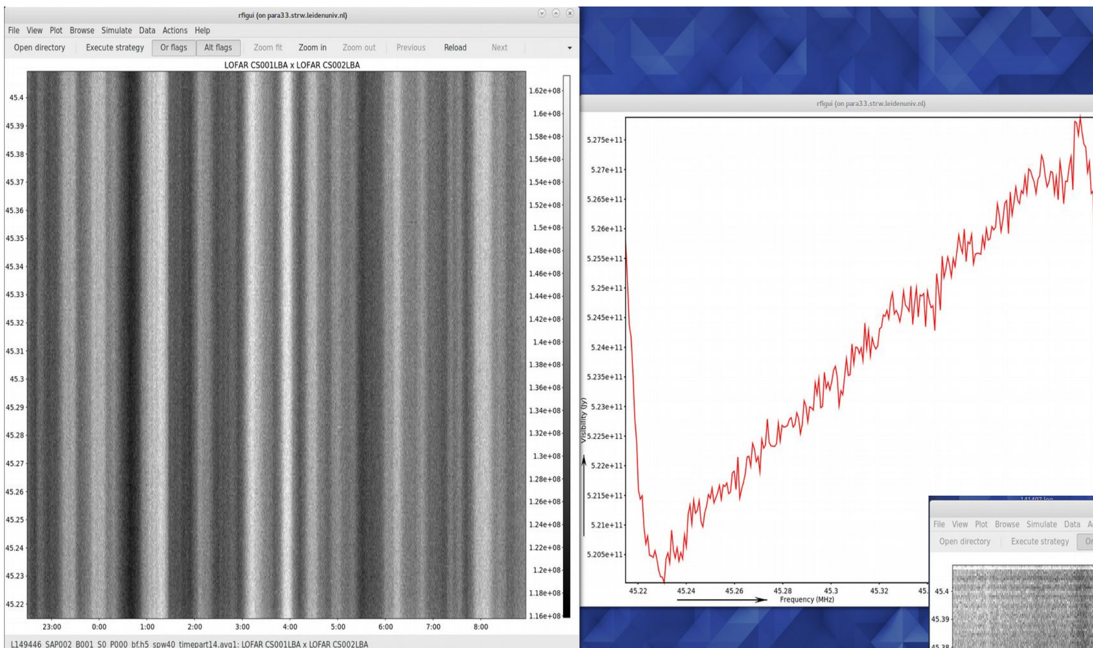
Preliminary results: → **CRRL wide spread in MW plane**

→ **CRRL tau & FWHM decrease with Galactic longitude**

LBA TA CRRL Survey: Commissioning & Future

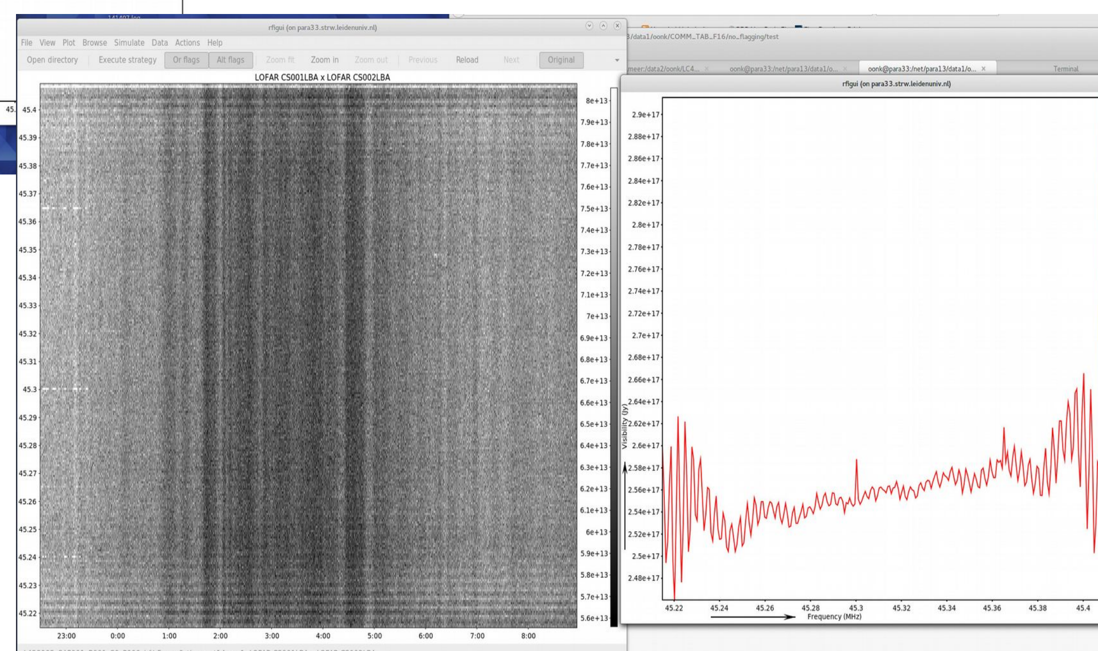
Commissioning: (zerolevel determination, Cobalt commissioning of TA-spec)

Project 1 (LBA 256chn): BG vs. Cobalt, bandpass and zerolevel determination



Cycle 5: Cobalt (bad bandpass)
τ(rms,chn) > 1e-2
systemic noise (bps)
can not detect RRL

↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓

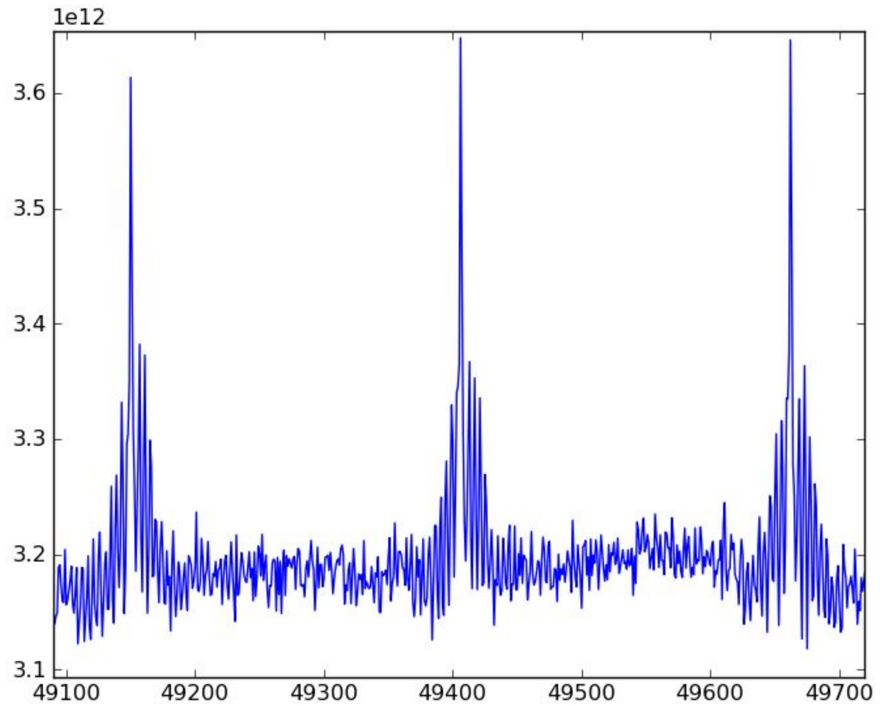


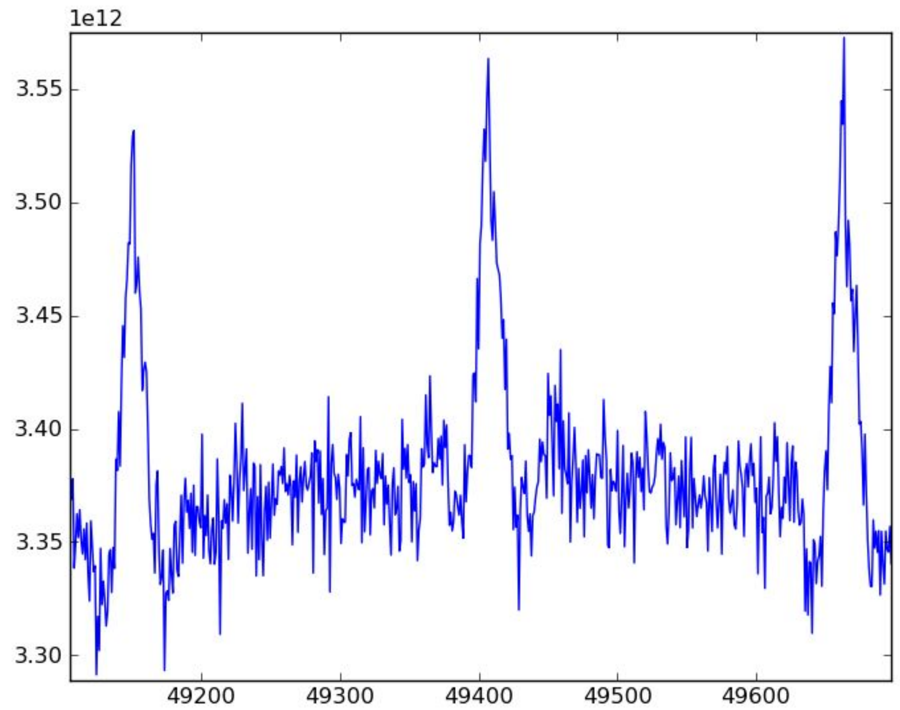
↑ ↑ ↑ ↑ ↑ ↑ ↑ ↑

Cycle 1: Bluegene (good data)
τ(rms,chn) ~ 1e-3
gaussian noise
RRL easily detected

<u>LBA TA CRRL Survey:</u> Commissioning & Future

256 channel correction test march 2016: (*plots courtesy R. Fallows*)



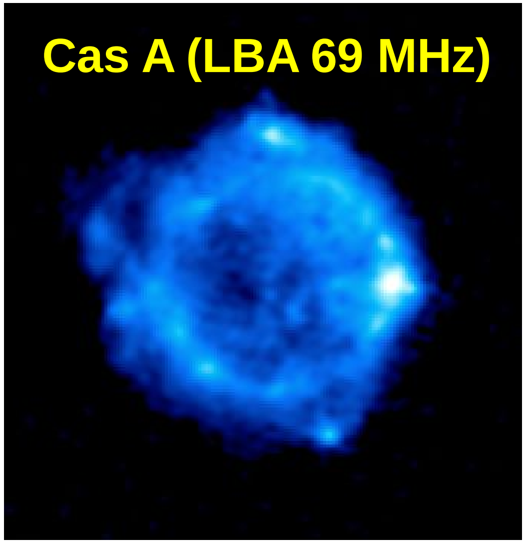


*** Improved Cobalt bandpass correction looks encouraging, but needs to quantified**

- new LBA 256 chn Cobalt commissioning observations are planned

- HBA and HBA-HIGH need commissioning with Cobalt (<u>submitted</u>)

LOFAR-RRL: Results & Outlook



CNM → $(\, T_e\, ,\, n_e\, ,\, L_C\, ,\, \zeta_H\, ,\, [C/H]\,)$

(a) new CRRL models and Cas A observations

- *New atomic data and full (n,l) treatment*
- *Cas A clouds are dense*

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

- *Pinhole Milky Way : SNR , HII regions , ...*
  ≥ 300 back ground galaxies
- *Diffuse Milky Way : 1^o LBA-TA (ok, but diluted)*

=> Cobalt tied-array commissioning necessary

LOFAR

(c) New MW lines of sight show CRRLs