Carbon radio recombination lines in extragalactic sources with LOFAR

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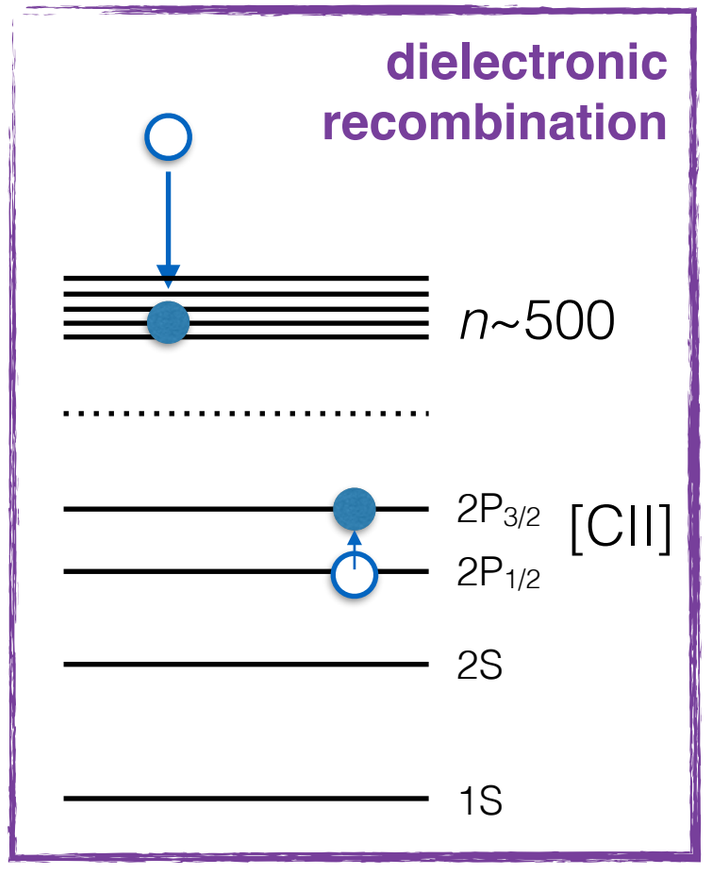
Science at Low Frequencies II
Dec. 3, 2015

Overview of CRRLs

1. <u>cold</u> (T~10–100 K), <u>diffuse</u> (n_e~0.01–1 cm^{-3})
radiation field E ~11.3–13.6 eV

2. **dielectronic recombination**
electrons at high n

3. **low frequency** (< 1 GHz)
Carbon $\alpha(\Delta n = 1)$,β transitions against bright continuum



UPDATED models of physical conditions *(Salgado+ submitted 2015a,b)*
+ radiative transfer, **atomic data** and **full n,l method**
+ with **better computing power**

Key Science of Extragalactic CRRLs

- relative abundance of neutral gas phase (large population of sources)
- density, temp, pressure of cold gas
- contributions to [CII] cooling line
- transition from HI to H_2

First we need to make an extragalactic inventory!

<u>observables:</u>

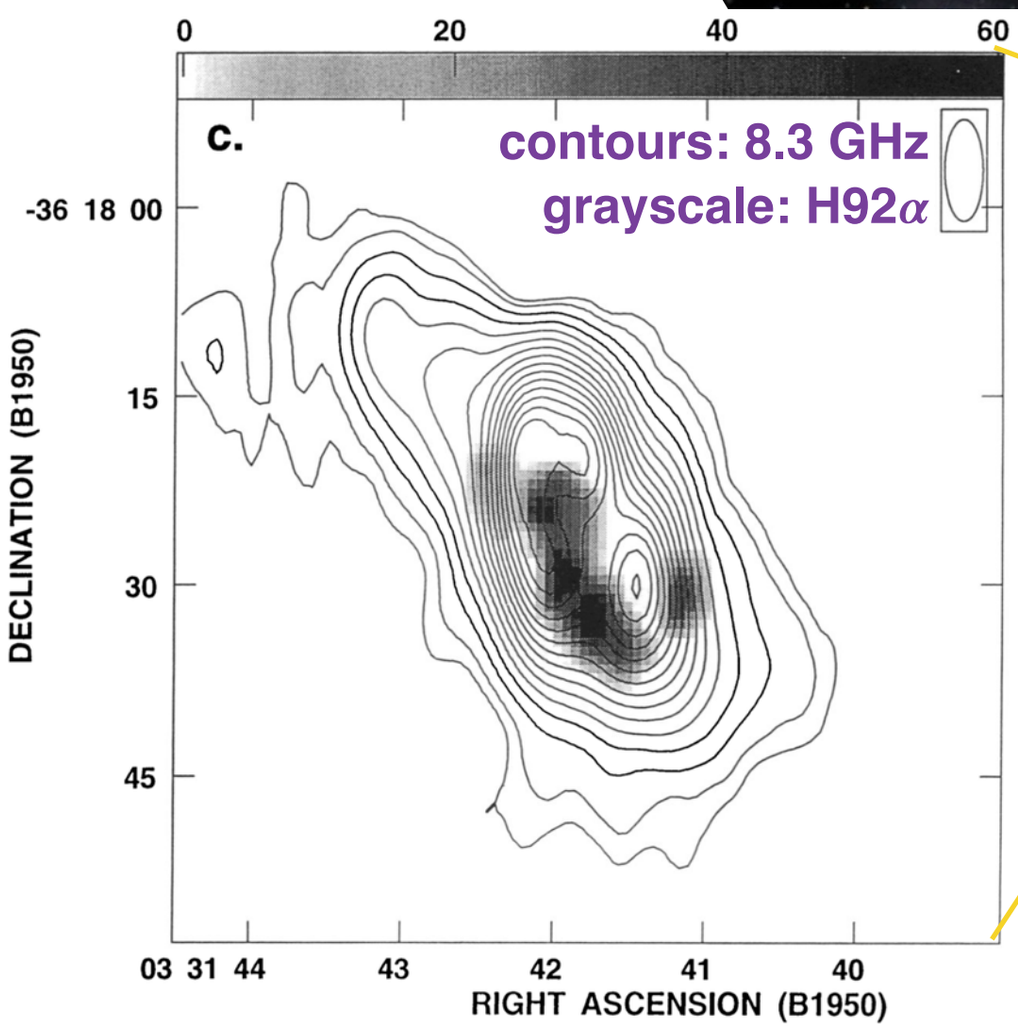
- line widths
- relative velocities (+ resolve),
- optical depths (integrated + peak)

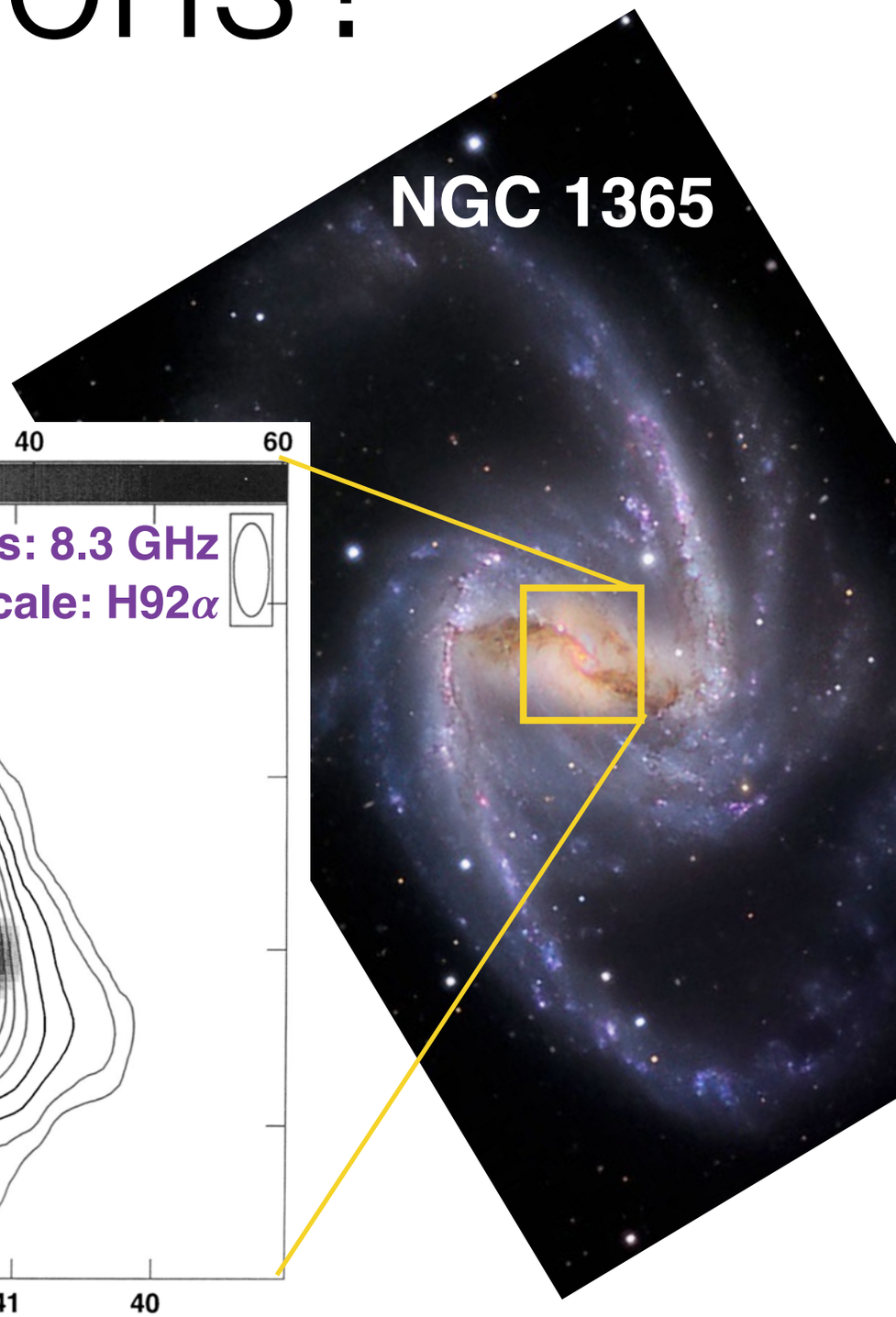
RRL detections?

"classical" **Hydrogen** RRLs
- H II regions
- above 1 GHz
- nearby galaxies

diffuse RRLs
previously searched but undetected!
- sensitivity at low-**ν**
- resolution

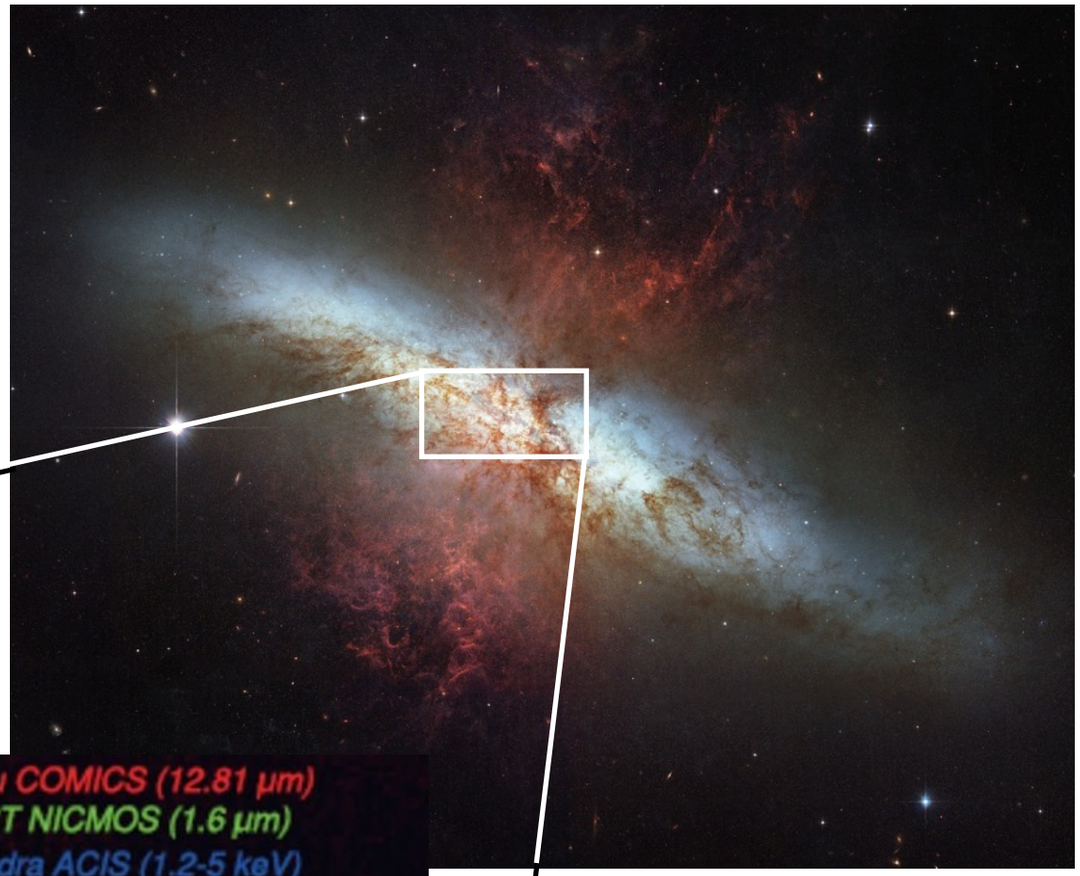
Anantharamaiah et al. 1993



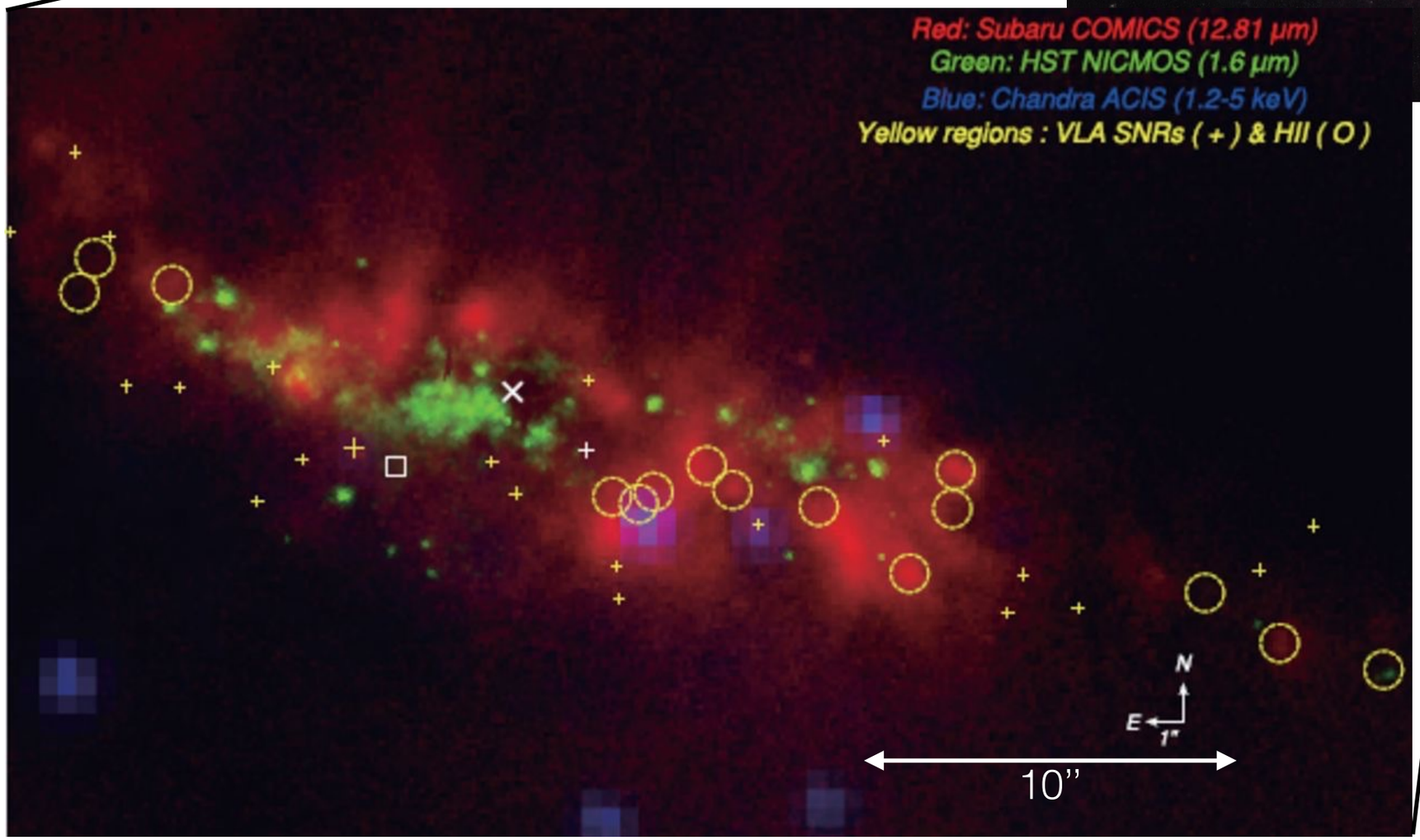


M82

prototypical starburst
~3.5 Mpc



NASA, ESA, and The Hubble Heritage Team (STScI/AURA)



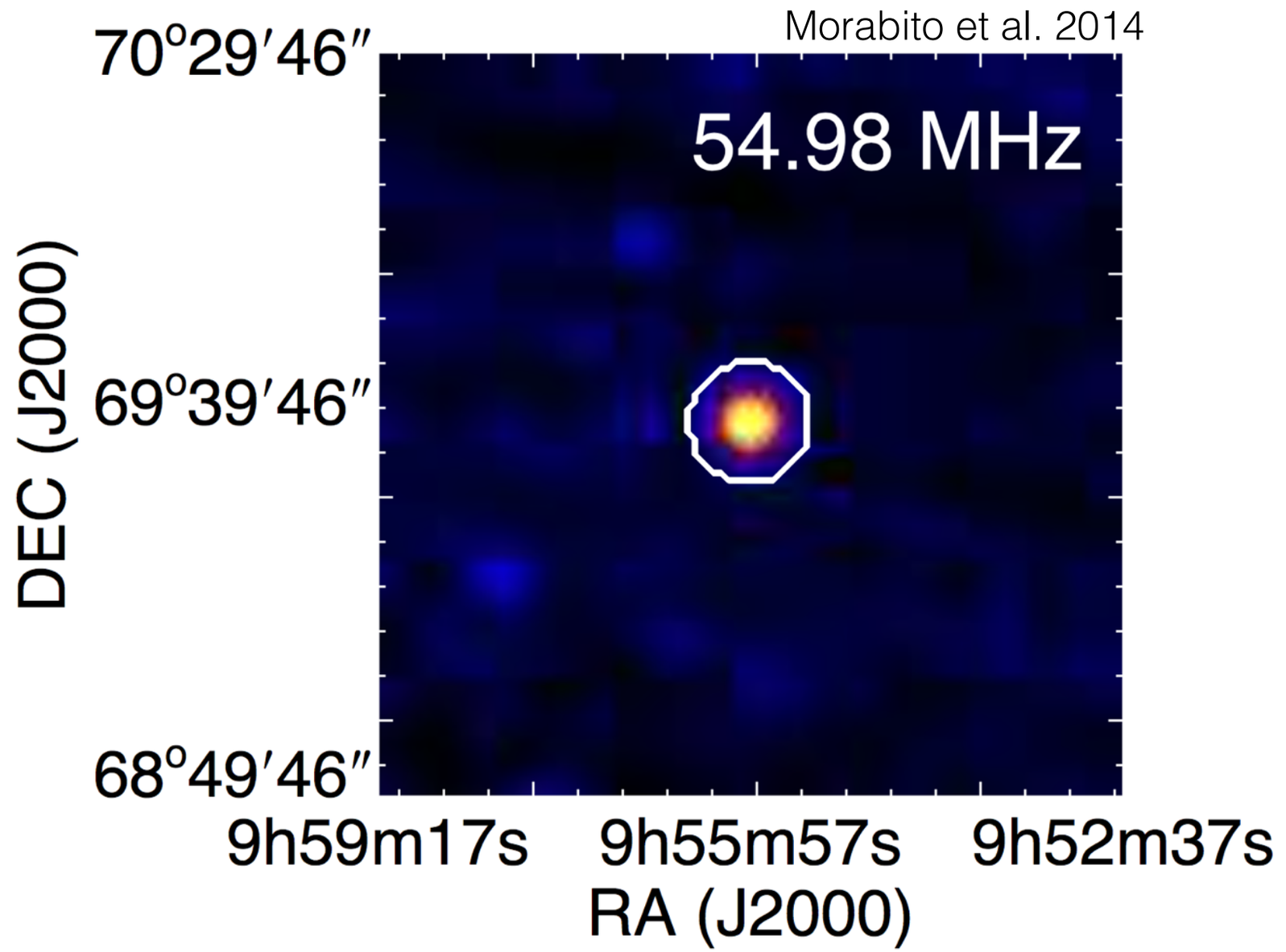
Gandhi et al. 2011

M82 in LBA

<u>Observations</u>

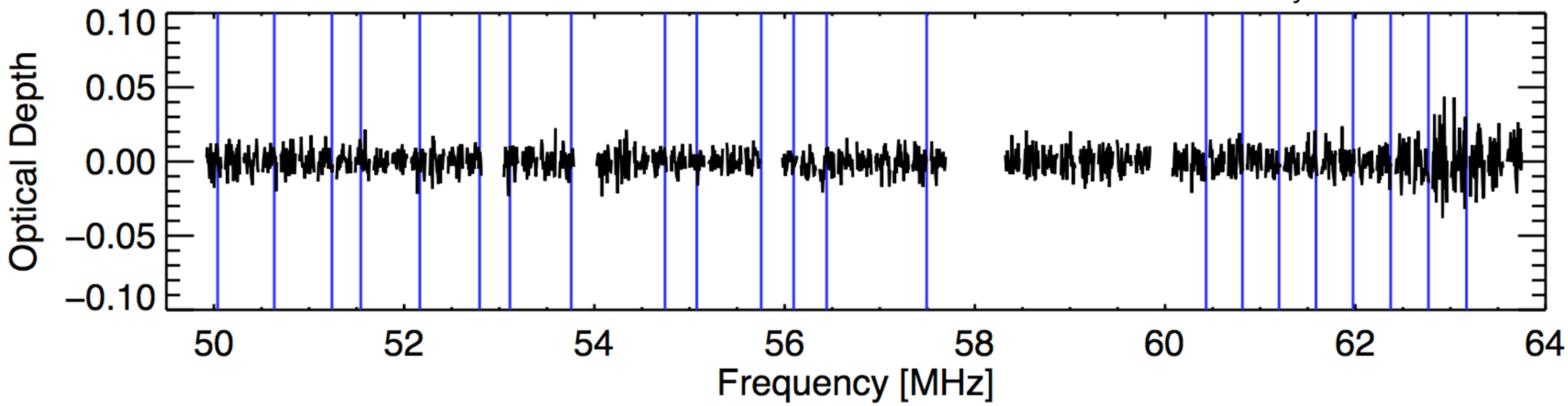
- 5 hrs on source
- 30-78 MHz
- $\Delta v \sim 10$ km/s
- 5 x 6 arcmin^2 (CS only)

Morabito et al. 2014



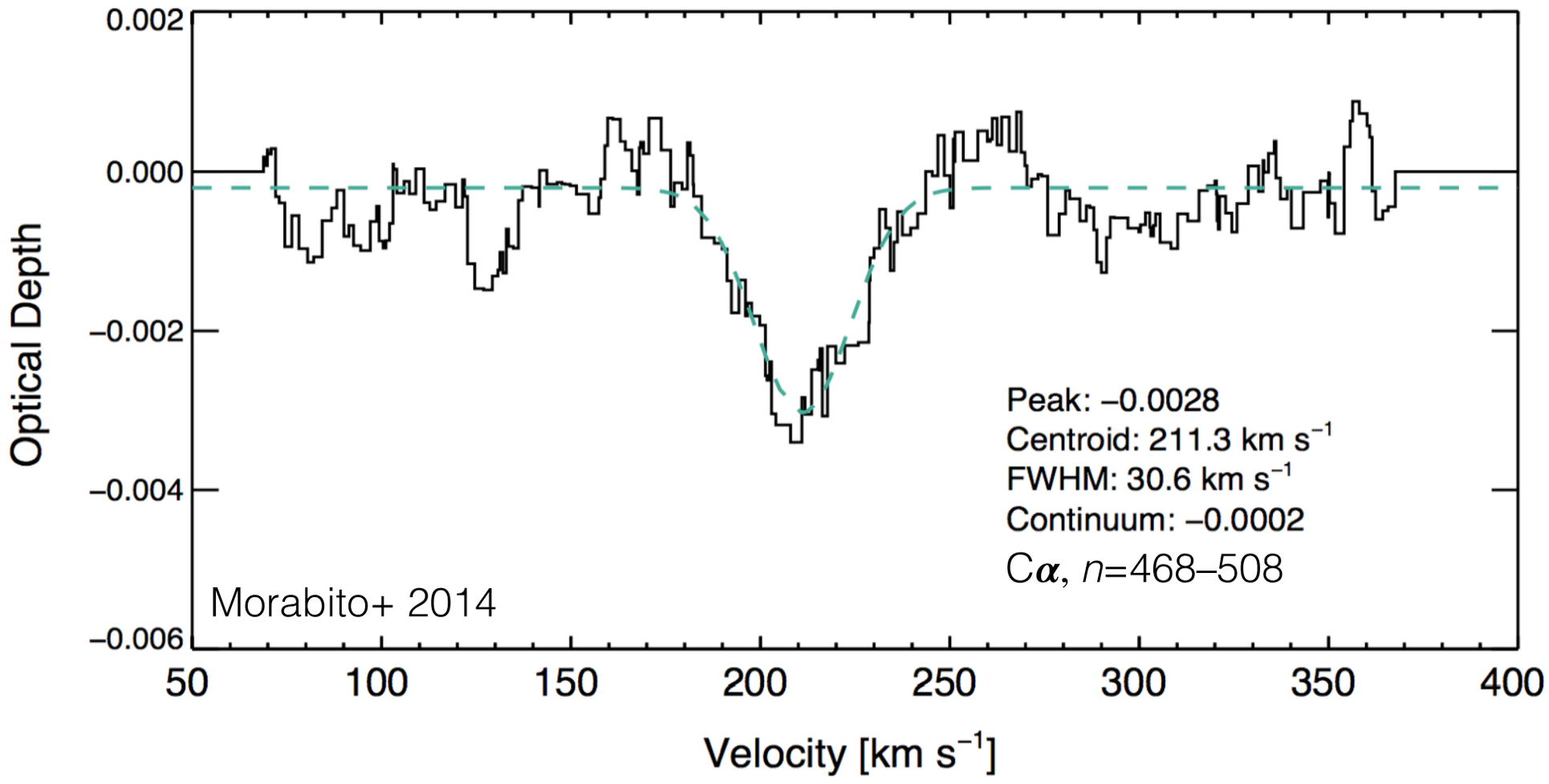
Full LBA spectrum

courtesy of L. Morabito



- lines not detected individually
- properties correlated
- stack to increase sensitivity

LBA detection

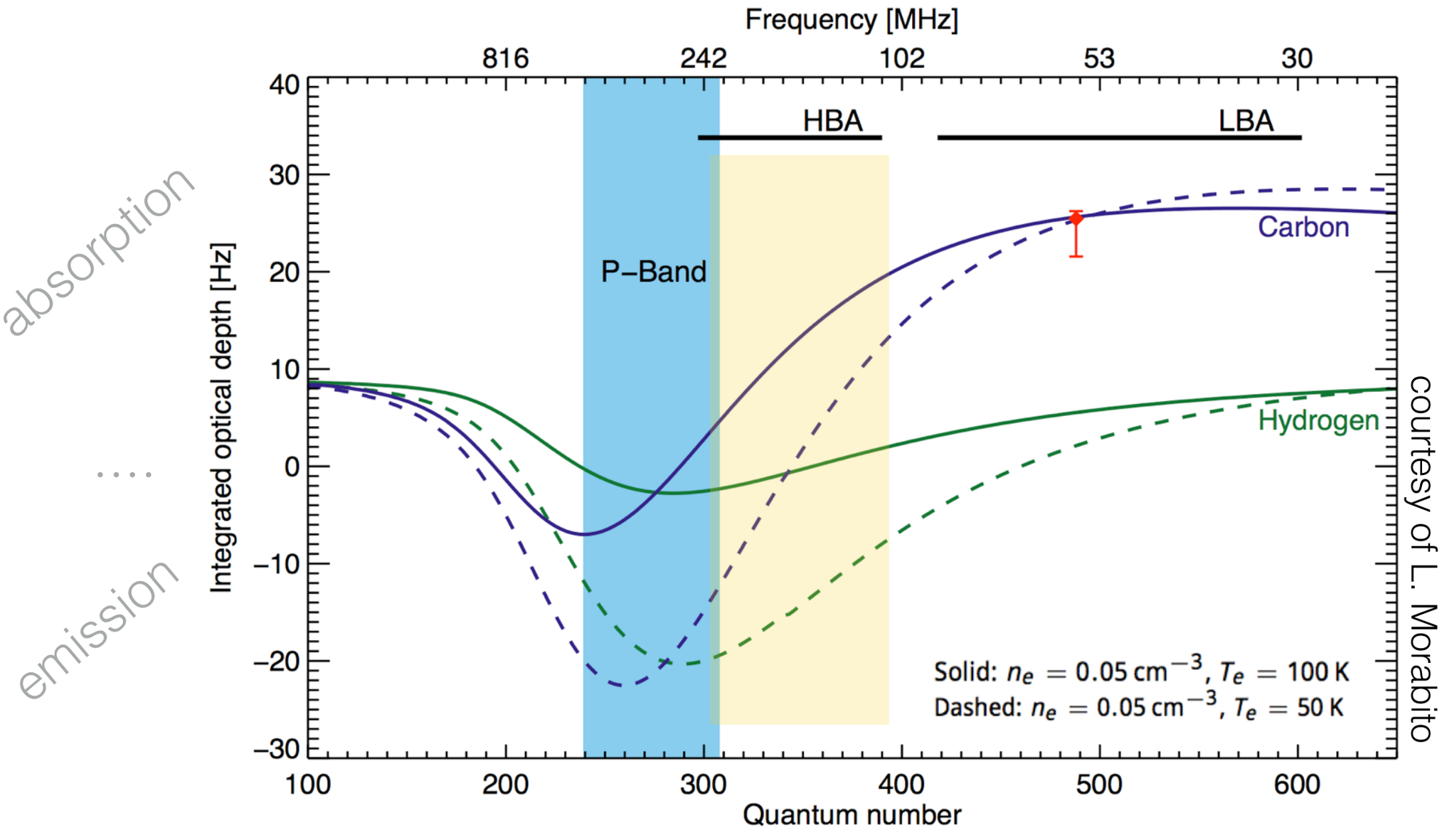


22 Cα lines, integrated 8.5σ

First extragalactic CRRL detection!

Correlates with HI absorption (Morabito+ 2014)

Modeling M82

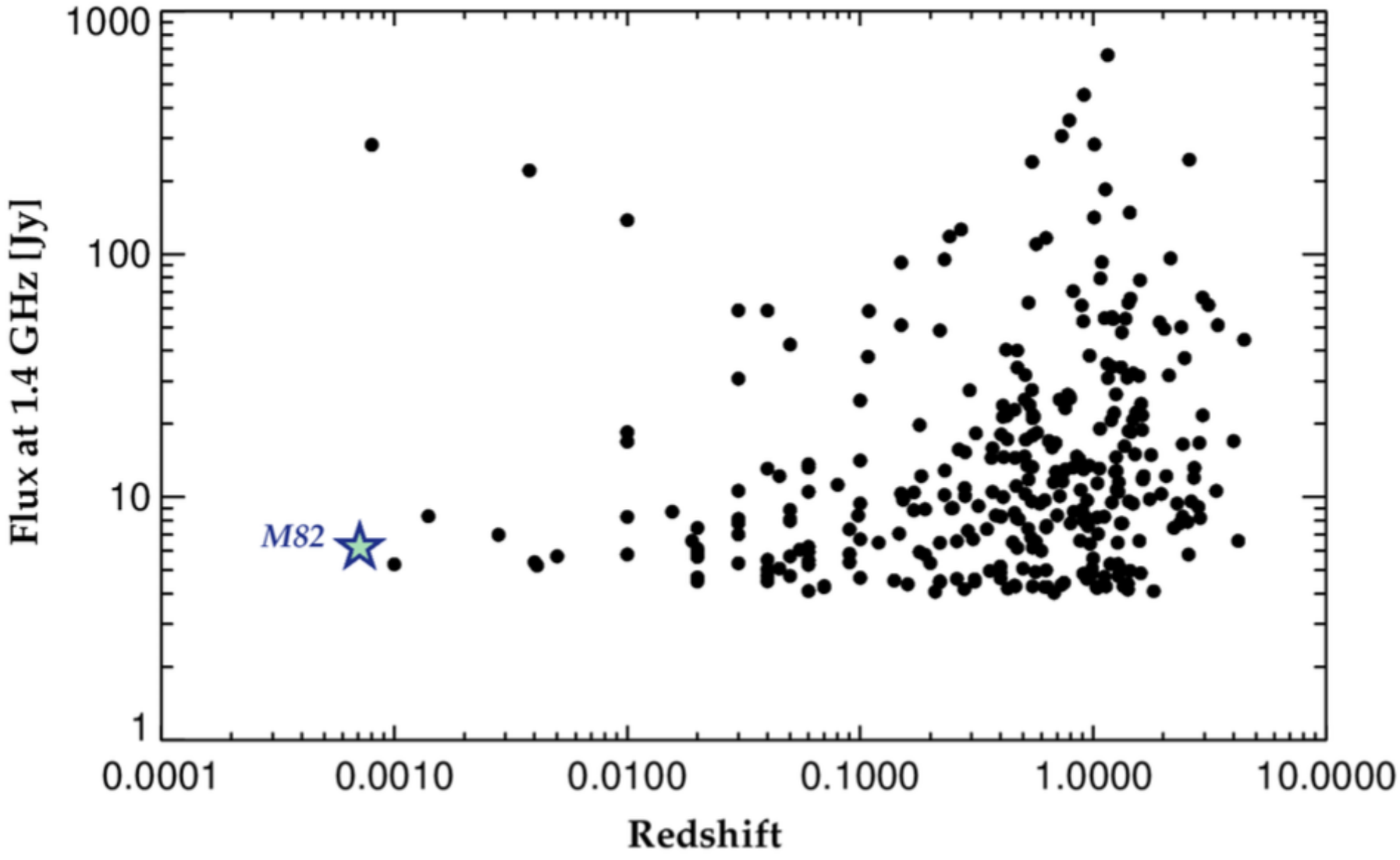


Next steps:

Resolve nuclear region
high frequencies to constrain models

→ VLA P-band 240-480 MHz
LOFAR HBA 120-240 MHz

Outlook for higher z

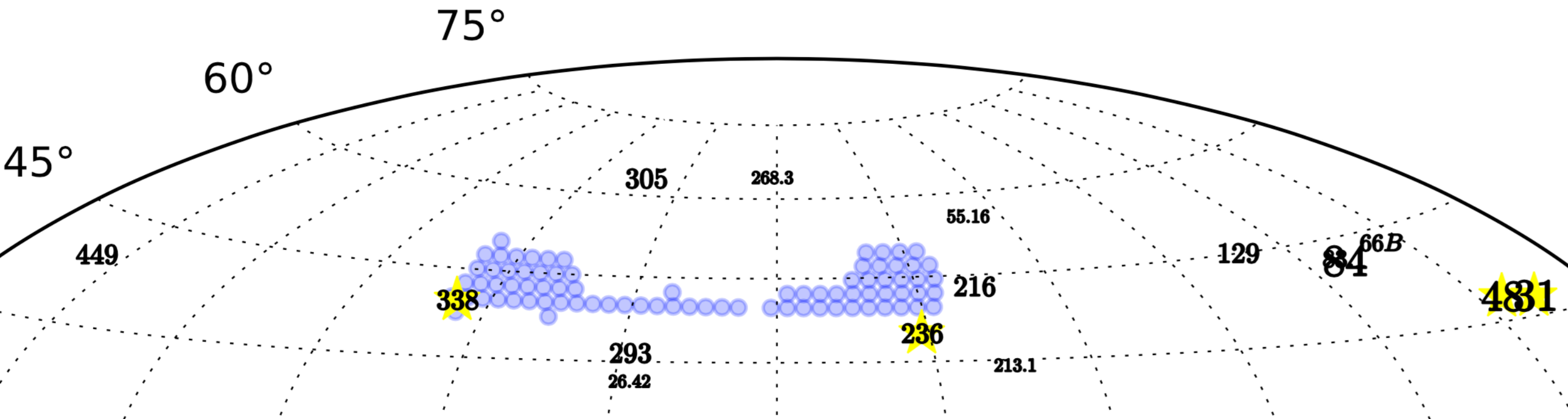


AGN candidates

- S(178 MHz) > 5 Jy
- CSS
- cold gas detection: HI (absorption), CO, H_2, etc.

- LOFAR Tier 1 survey of Northern Sky
  - 8hrs/pointing, HBA
- peak optical depths $<10^{-3}$ Hz (10 lines)
- ~300 objects

ID	z	178 MHz	HI	CO	H2	LOFAR obs
3C 31	0.017	10.0		x	x	x
3C 48	0.367	51.0	x	x		x
3C 66B	0.021	38.0		x	x	
3C 83.1	0.025	32.0		x	x	
3C 84	0.018	40.5	x	x	x	
3C 129	0.021	6.7		x	x	
3C 213.1	0.194	6.6	x			
3C 216	0.670	22.1	x			
3C 236	0.101	7.2	x	x		x
3C 268.3	0.371	10.3	x			
3C 293	0.045	12.7	x		x	
3C 305	0.042	14.3	x	x		
3C 338	0.030	46.4			x	x
3C 449	0.017	11.1		x		
4C 55.16	0.242	8.1	x			
4C 26.42	0.063	4.9	x	x		



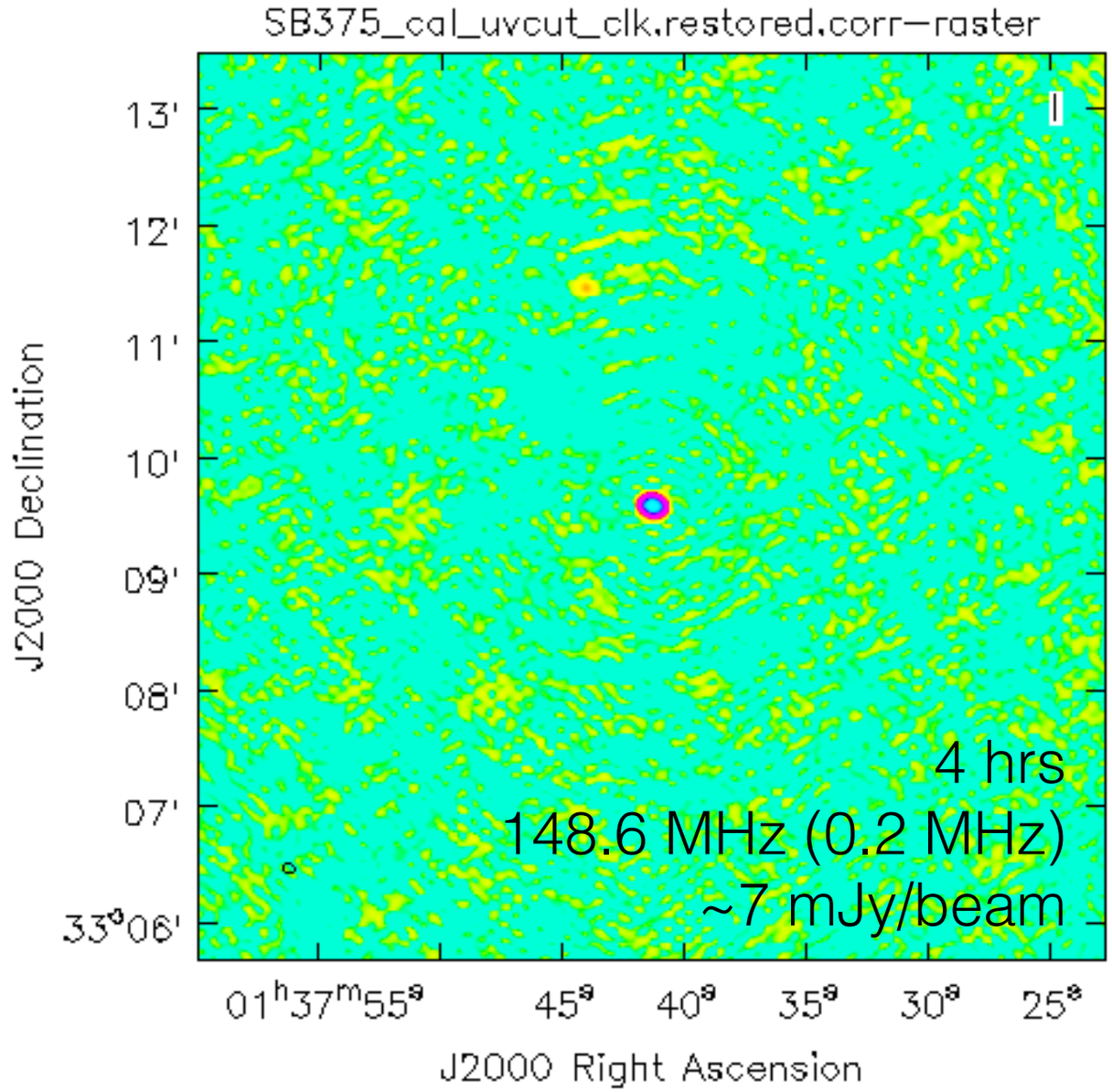
3C 48

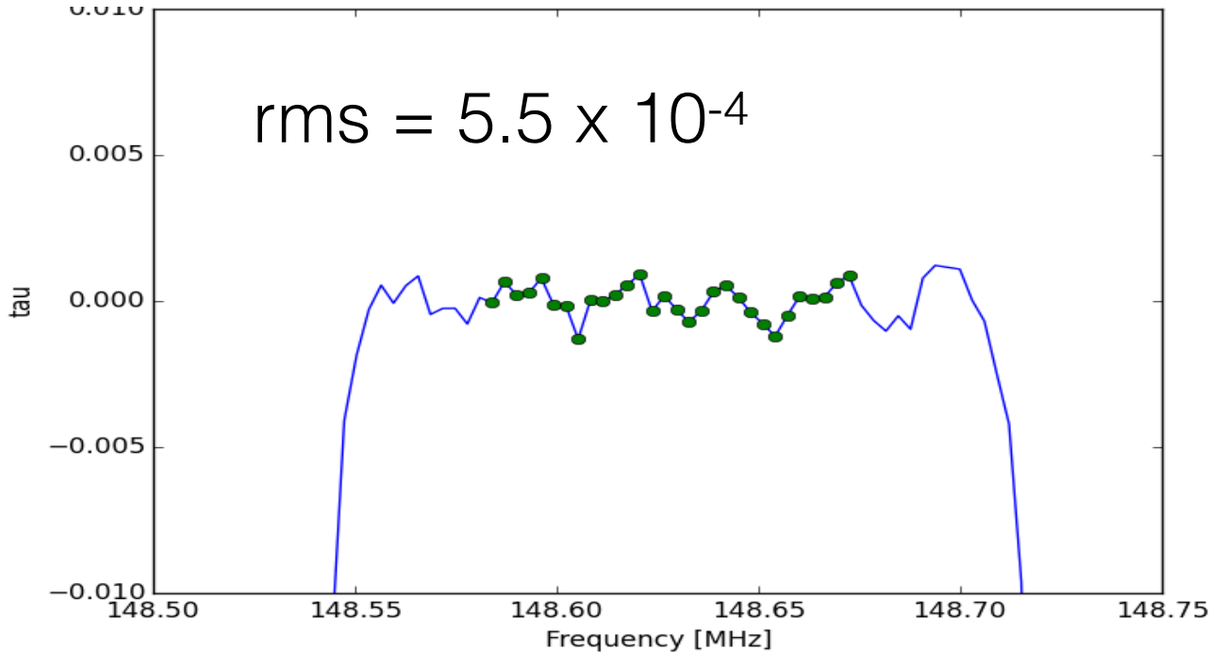
S(150MHz) ~ 65 Jy
z = 0.367

high far IR dust peak
CO detected (Scoville+ 1993)
I(CO(0-1)) = 2.4 K km/s

HBA:
10hr, 110-190 MHz
~50 Cα lines

LBA:
6 hr, 30-78 MHz
~300 Cα lines





Conclusions

- Extragalactic CRRLs:

    1. survey, make an inventory

    2. abundance of cold gas + properties (T,n_e)

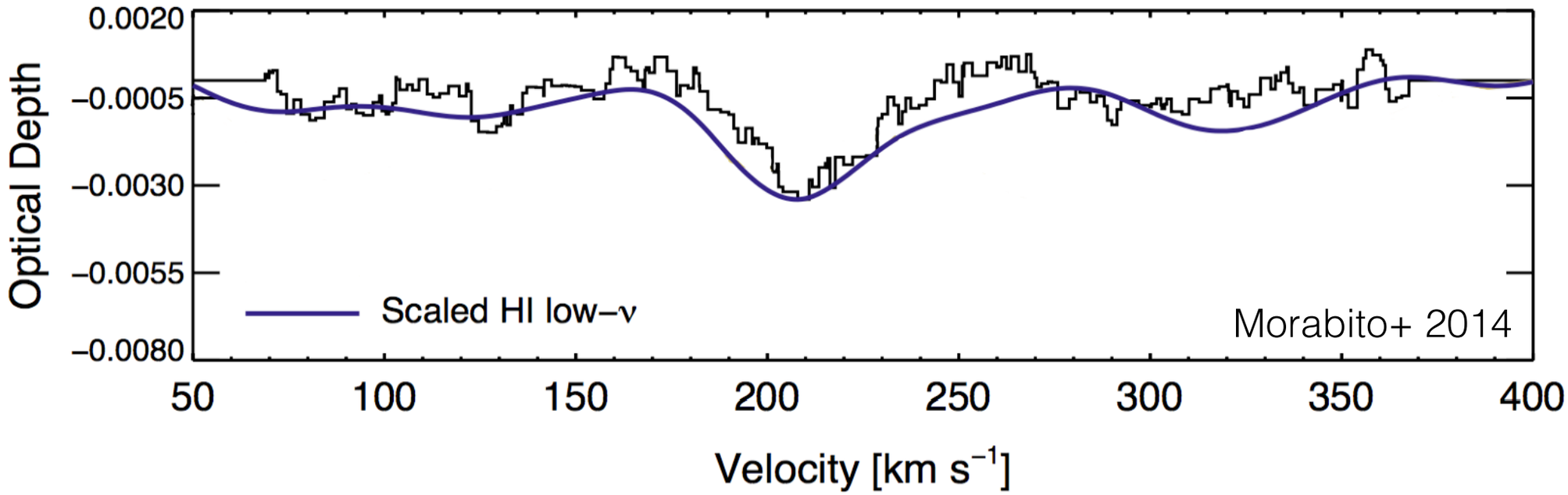
- M82 in LBA detected at 8.5σ (Morabito+ 2014)

- Preliminary M82 detection in HBA (Toribio+ in prep)

- VLA P-band data taken (Zoutendijk+ in prep)

- CRRLs in AGN coming soon, 3C48

CRRL and HI in M82



CRRLs correlate with observed HI absorption