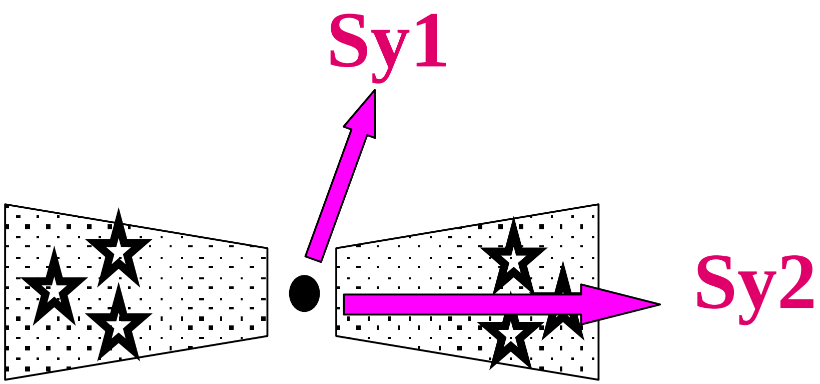
Molecular absorption in the cores of AGN:

On the Unified Scheme

C. M. Violette Impellizzeri (MPIfR)
Alan L. Roy, Christian Henkel, John P. McKean, Andreas Brunthaler (MPIfR)
Paola Castangia (OAC)
Olaf Wucknitz (Bonn Universität)

The Torus

N_H 10^{22} cm^{-2} ; OH opacities << 1



N_H 10^{24} cm^{-2} ; OH opacities > 1

- Molecular abundances in tori : N(OH) / N(HI) ≤ 10^{-3}
- (Krolik & Lepp 1989)

Dusty AGN torus is molecular gas rich

OH Surveys

- If true, expect to observe molecular absorption against the compact, flat spectrum radio cores of NLRs.
- not only confirm the existence of torus, but also derive valuable physical and kinematic information.

OH surveys at 1.6 GHz
- Schmelz et al. 1986,
- Staveley-Smith et al. 1992,
- Baan et al. 1992
- ... (sensitivities of few percent)

CO, HCN and HNC searches
- Drinkwater et al. 1997

→

Observed ~ 300 galaxies
Low detection rates
(absorption towards two Seyferts
maser emission in five).

Surprisingly few detections!

OH abundance lower than predicted ? No torus ?

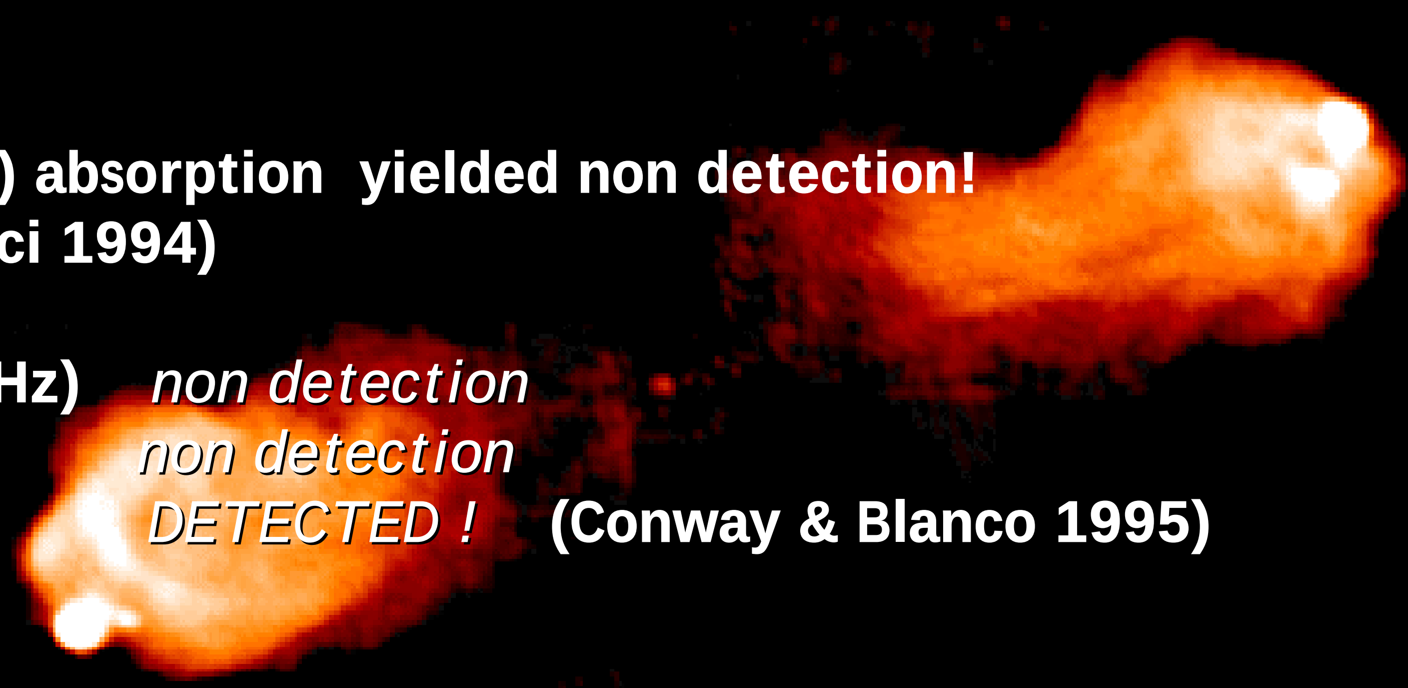
No CO Absorption in Cygnus A !

- Of all AGN, Cygnus A is expected to have a molecular torus

NLRG
large X-ray absorbing column ($10^{23.5}$ cm^{-2})
very bright core

Searched for CO (0-1) absorption yielded non detection!
(Barvainis & Antonucci 1994)

Search for OH (1.6 GHz) *non detection*
H2CO *non detection*
HI *DETECTED !* **(Conway & Blanco 1995)**



Radiative Excitation

→

1. gas is in a hot (5000-10000 K) mainly atomic phase.
2. Radiative excitation of OH, CO and NH3 due to the central radio source causes the non-detection of molecular absorption ?? (Maloney, Begelman & Rees 1994).

Radiative Excitation

1. gas is in a hot (5000-10000 K) mainly atomic phase.
2. Radiative excitation of OH, CO and NH3 due to the central radio source causes the non-detection of molecular absorption ?? (Maloney, Begelman & Rees 1994).

Radiative Excitation Effects

Maloney, Begelman, & Rees (1994) postulate that lack of CO absorption is due to radiative excitation by non-thermal radio source:

High T_{ex} depletes lower rotational levels, decreasing optical depth

Is OH, too, radiatively excited ?

- **For torus located 10 pc from AGN:**

  - **opacity in 1.6 GHz transition suppressed by factor 10^3**
  - **opacity in 6 GHz transition suppressed by factor 10^2**
  - **opacity in 13.4 GHz transition will increase slightly by factor 2.**

- Black (1998)
- **Thus, absorption will strongly depend on transition one chooses to observe.**
- **Have we been looking at the right transitions ?**

A New Survey for OH

Search for highly excited rotational states of OH at 6.035 GHz & 6.031 GHz, and 13.4 GHz.

The sample

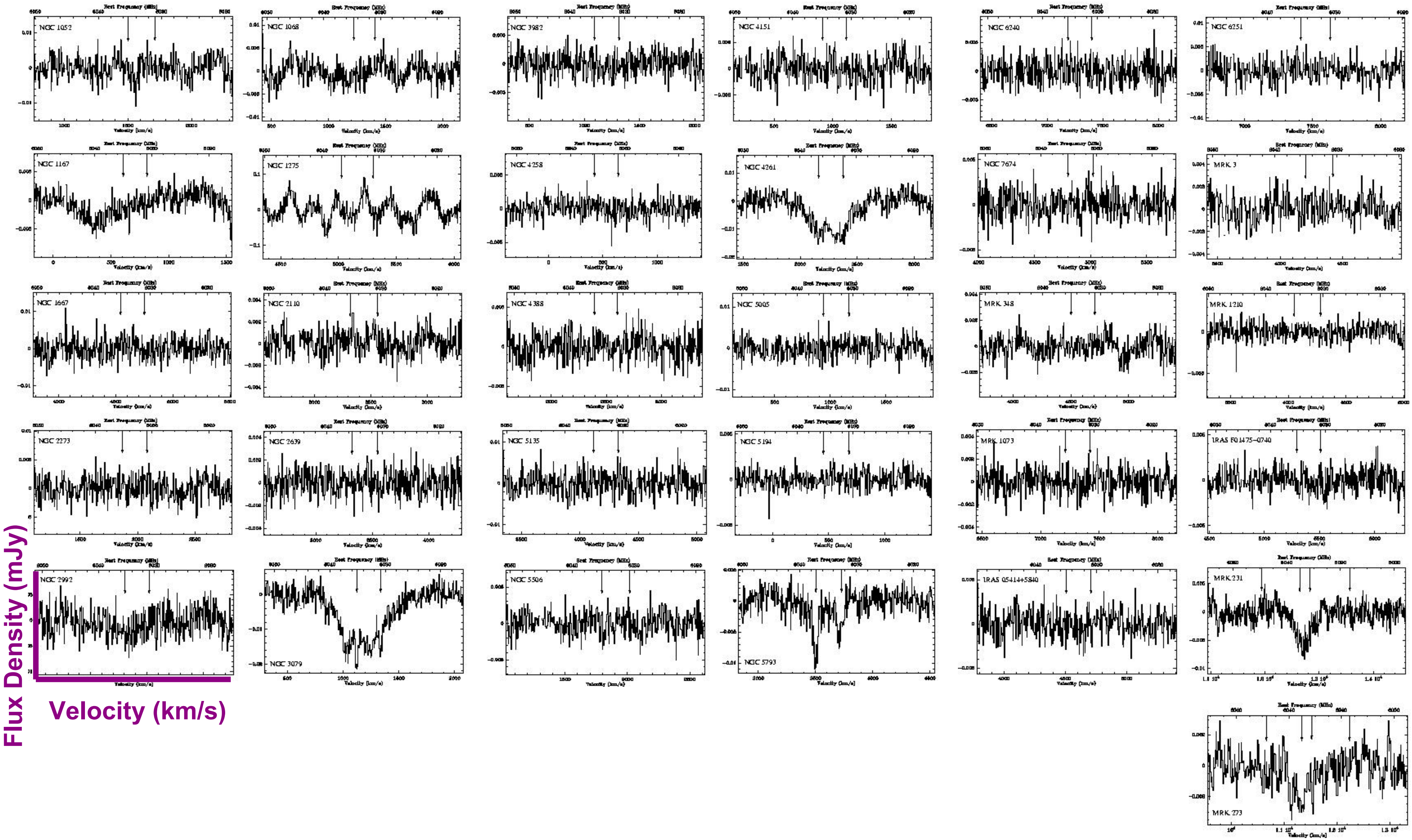
- 31 Seyfert 2 galaxies
- high X-ray absorbing columns (> 10^{22} cm^{-2})
- continuum flux density at 6 GHz > 50 mJy
- HPBL

Effelsberg observations

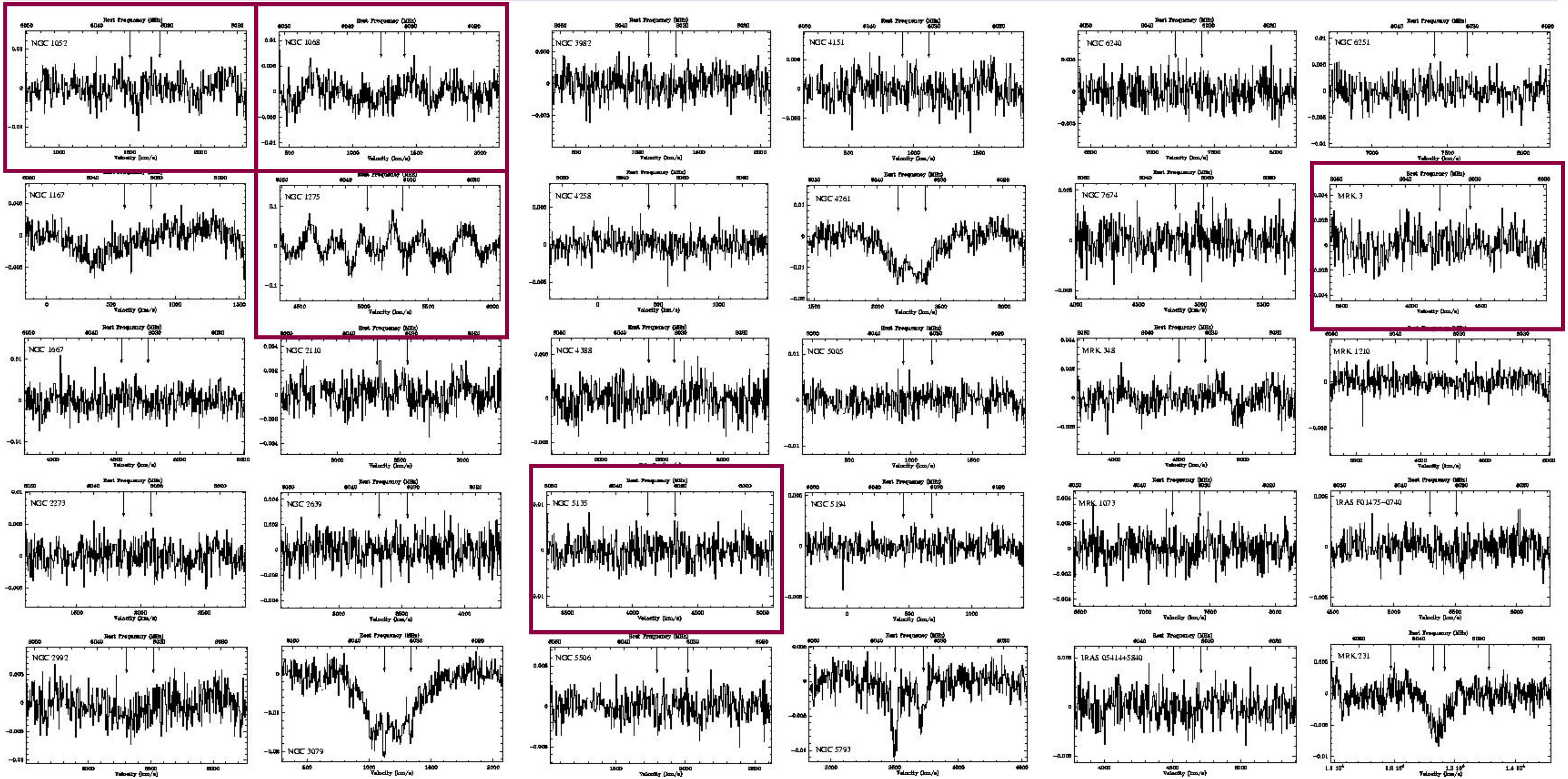
- 3-10 hours per source at 4.7 and 6 GHz, PSW
- Velocity coverage 2000 km s^{-1} (4 km s^{-1} per channel)
- Sensitivity 3.5 mJy (5σ) = line opacity of 0.002 to 0.07

Courtesy N. Tacken

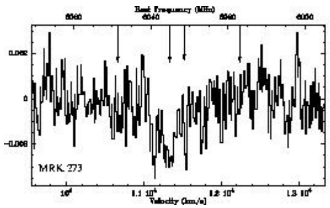
Effelsberg Spectra (6 GHz)



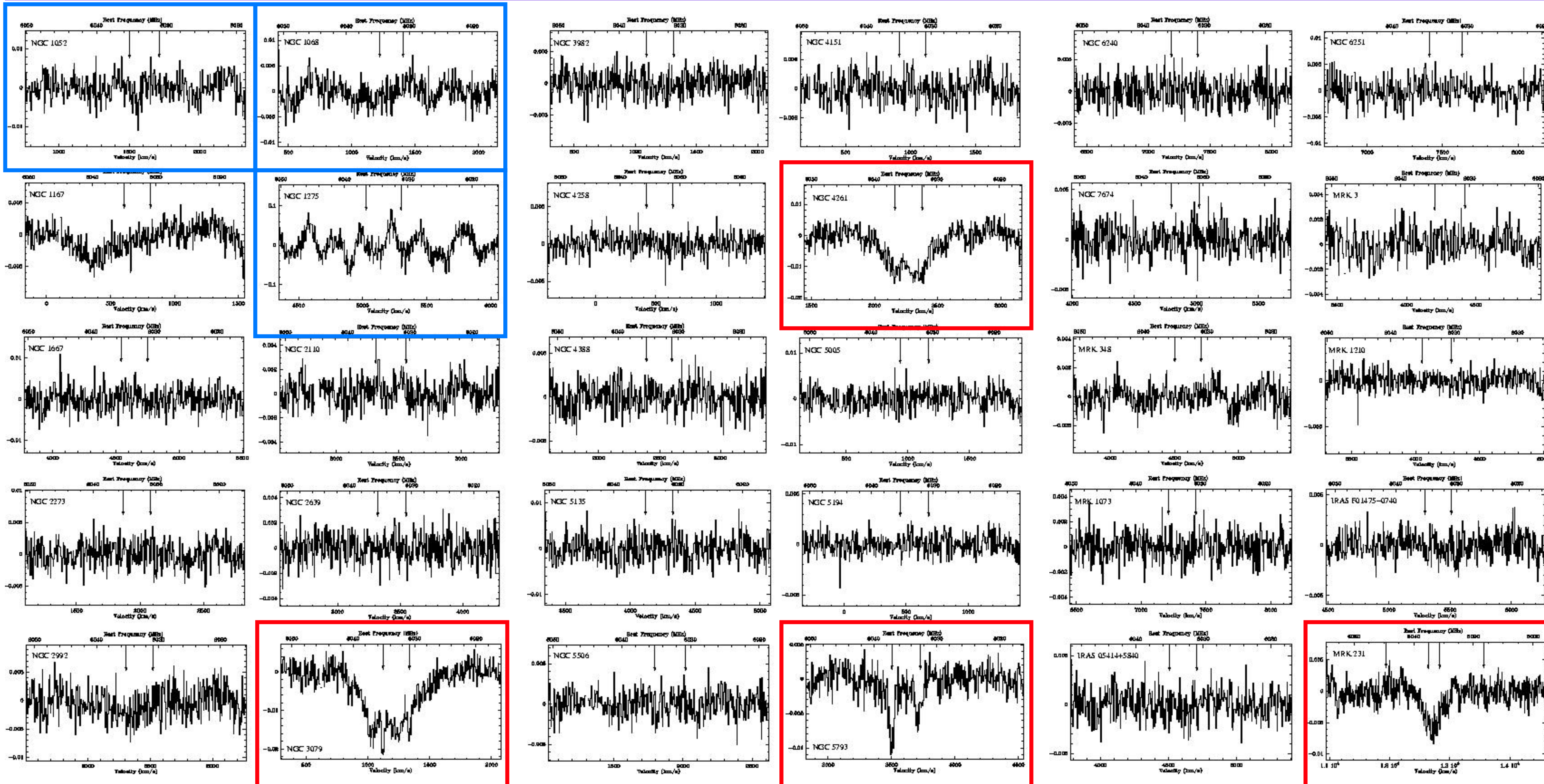
Effelsberg Spectra (6 GHz)

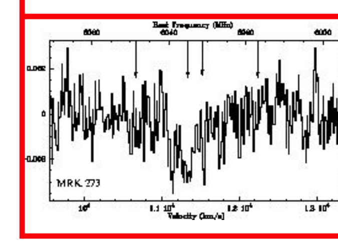


Best targets due to high X-ray columns and high background continuum at 6.0 GHz.



Effelsberg Spectra (6 GHz)

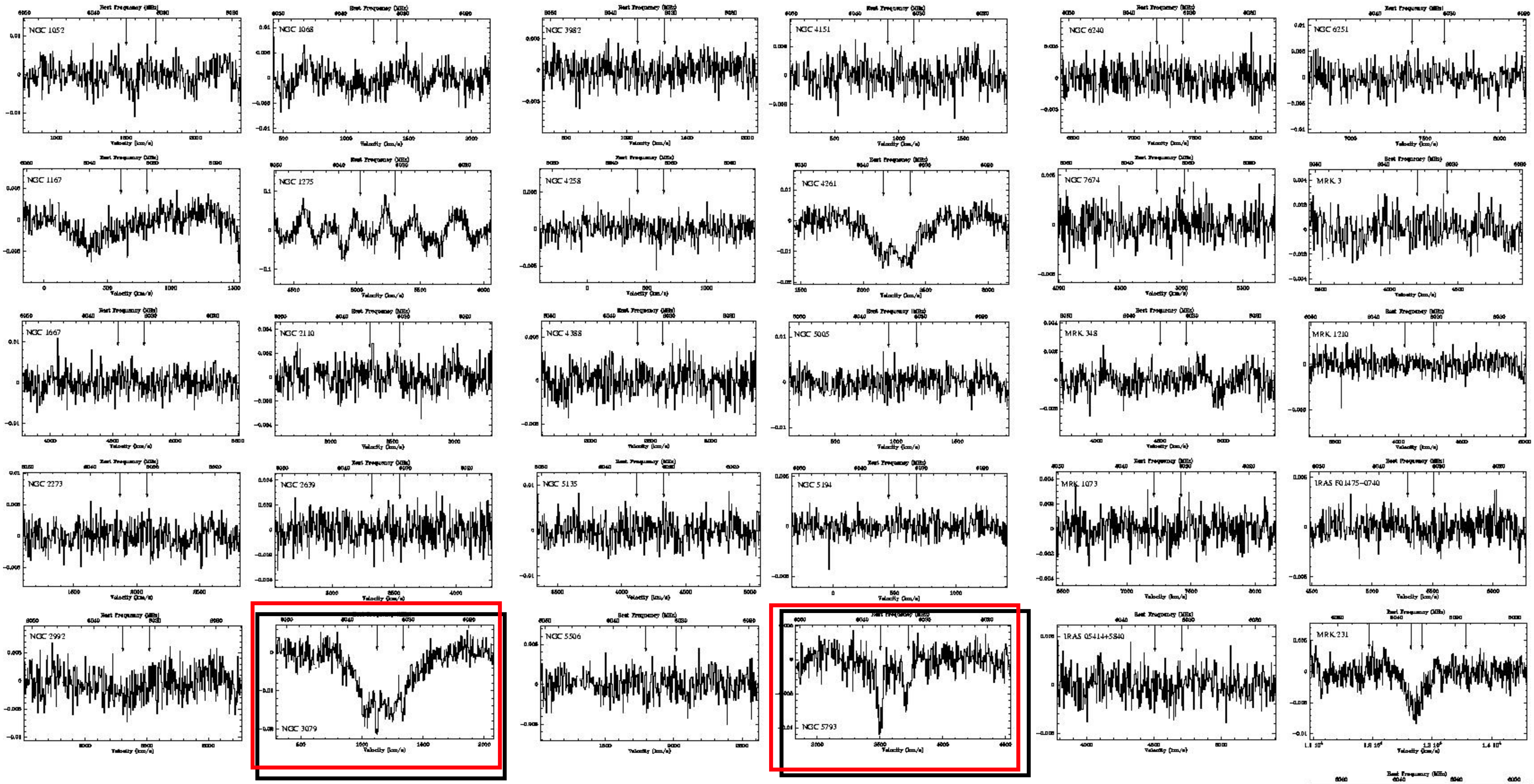




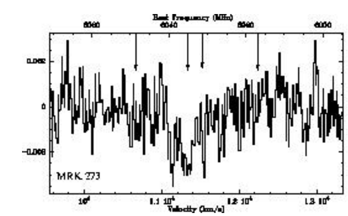
Too strong continuum - Large standing wave ripple!

5 new detections - detection rate 18 %

Effelsberg Spectra (6 GHz)



Lets look at NGC 3079 & NGC 5793.



NGC 3079

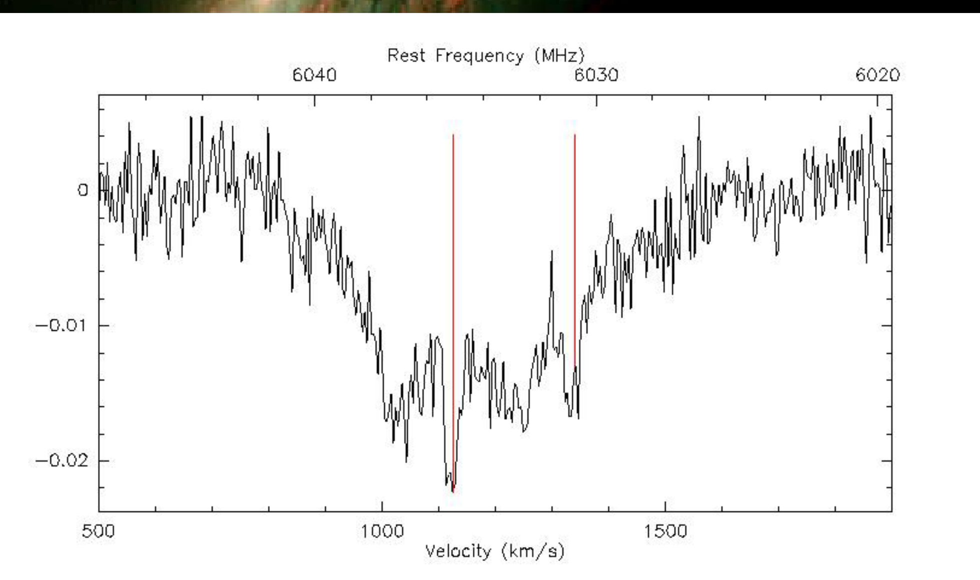
Galaxy NGC 3079
G. Cecil (University of North Carolina)

- Width ~ 800 km s^{-1}
- Line opacity τ ~ 0.055
- 4.7 GHz non-detection
- 1.6 GHz abs (Baan et al. 1995)

T_{ex} = 30 K

N_{OH} = 1.5 10^{18} cm^{-2}

from X-rays: N_H = 1.0 10^{25} cm^{-2}



NGC 5793

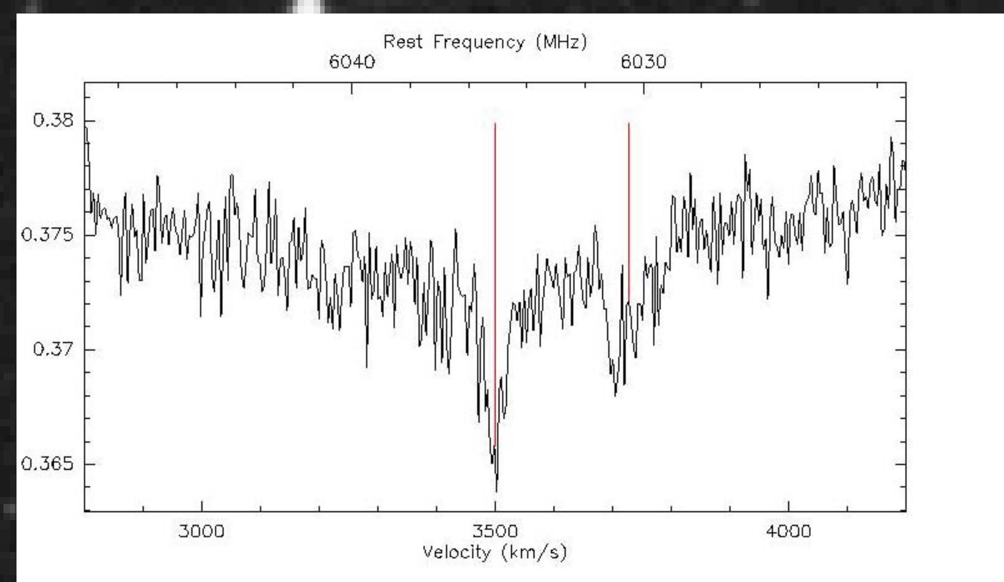
- Width ~ up to 1000 km s^{-1}
- Line opacity τ ~ 0.036
- 4.7 GHz non-detection
- 1.6 GHz abs (Hagiwara et al. 2000)

T_{ex} = 67 K

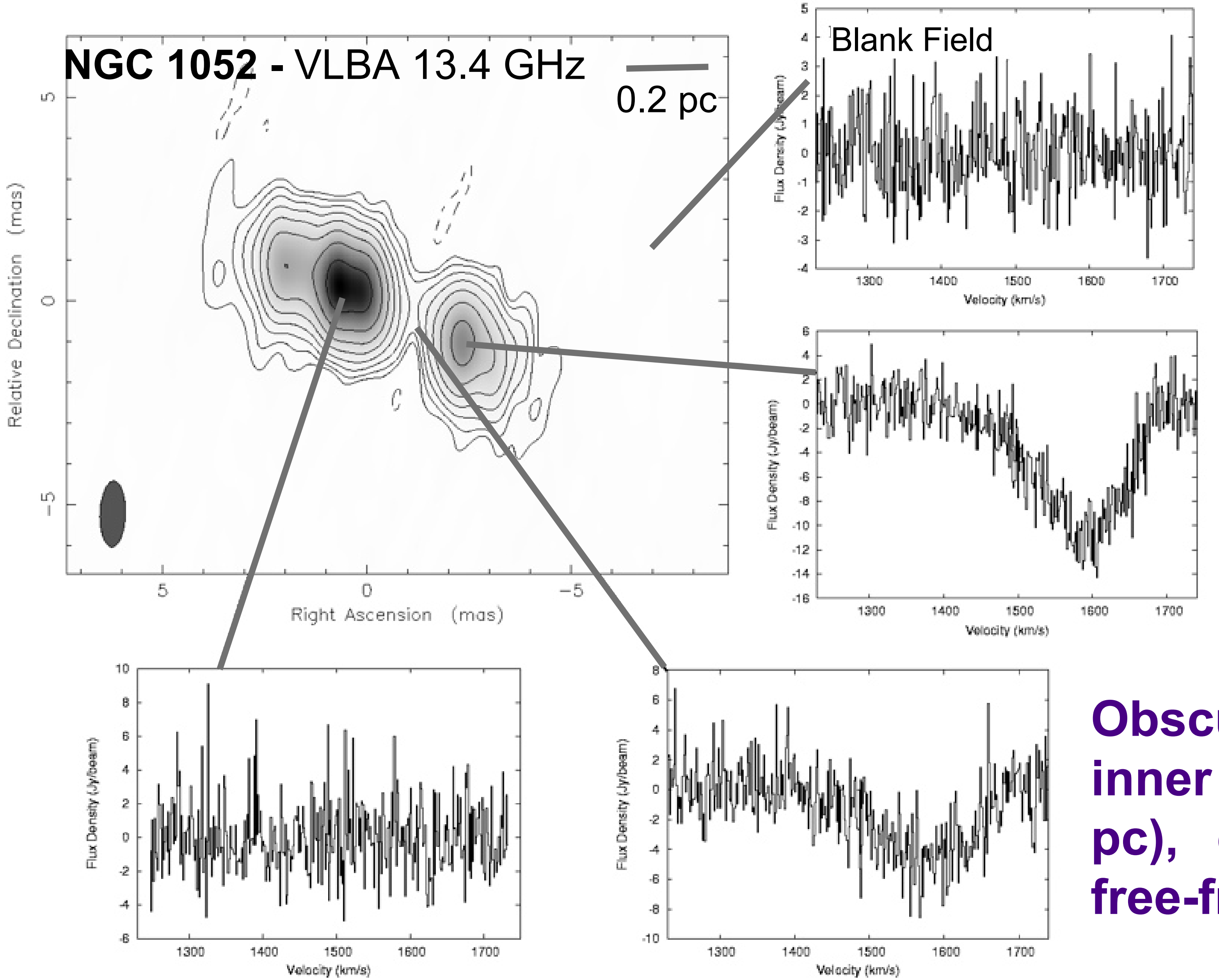
N_{OH} = 2.2 10^{17} cm^{-2}

- Narrower line components extending to 1000 km s^{-1}

τ: 0.034



Firm Detection: NGC 1052



Broad width

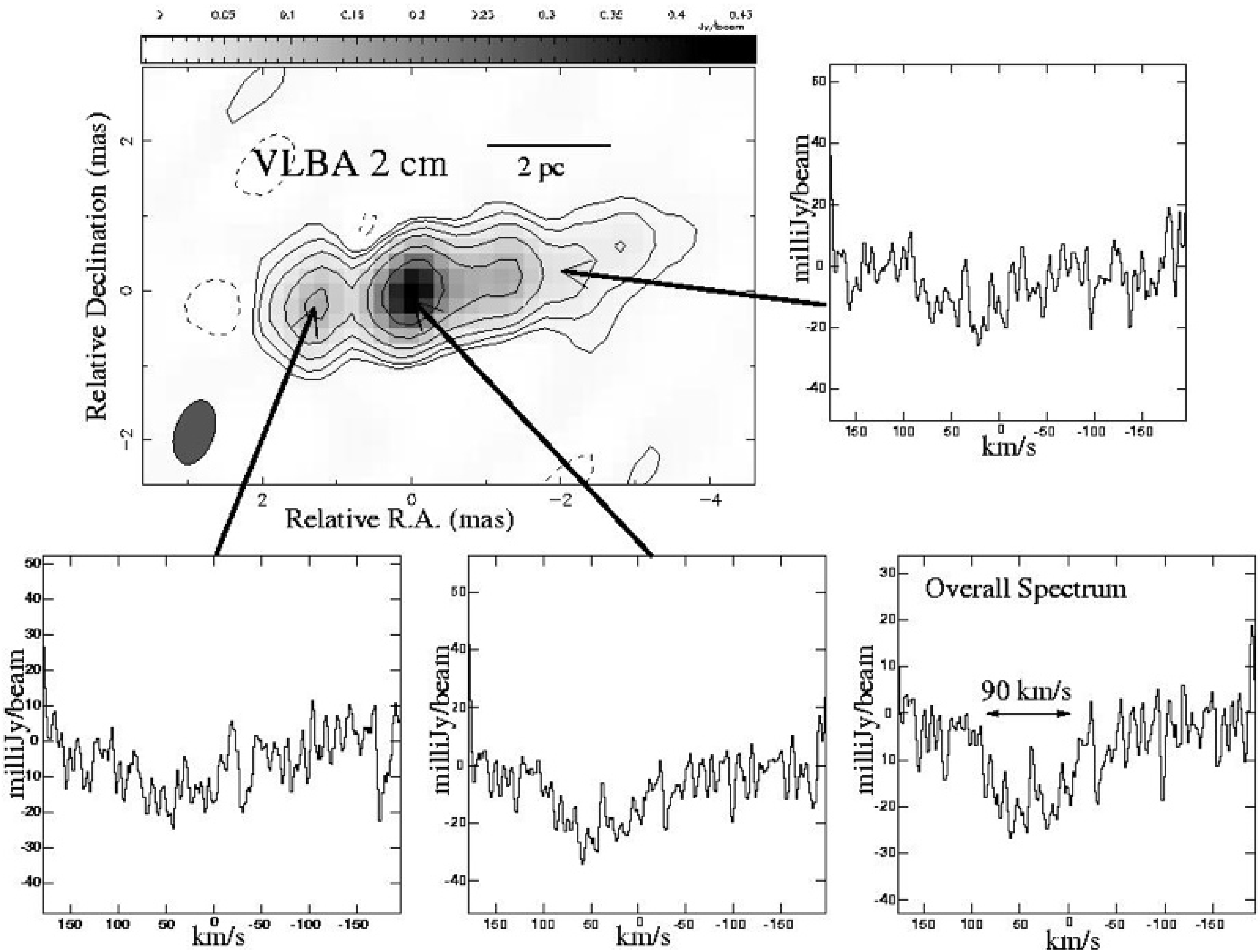
FWHM ≈ 200 km s^{-1}.

Optical depth (counter-jet)

$\tau_{OH} \approx 0.264$

Obscuration in the inner jet region (< 0.3 pc), coincident with free-free absorption.

Tentative Detection: Cygnus A



Cont. Peak Flux

453 mJy beam^{-1}

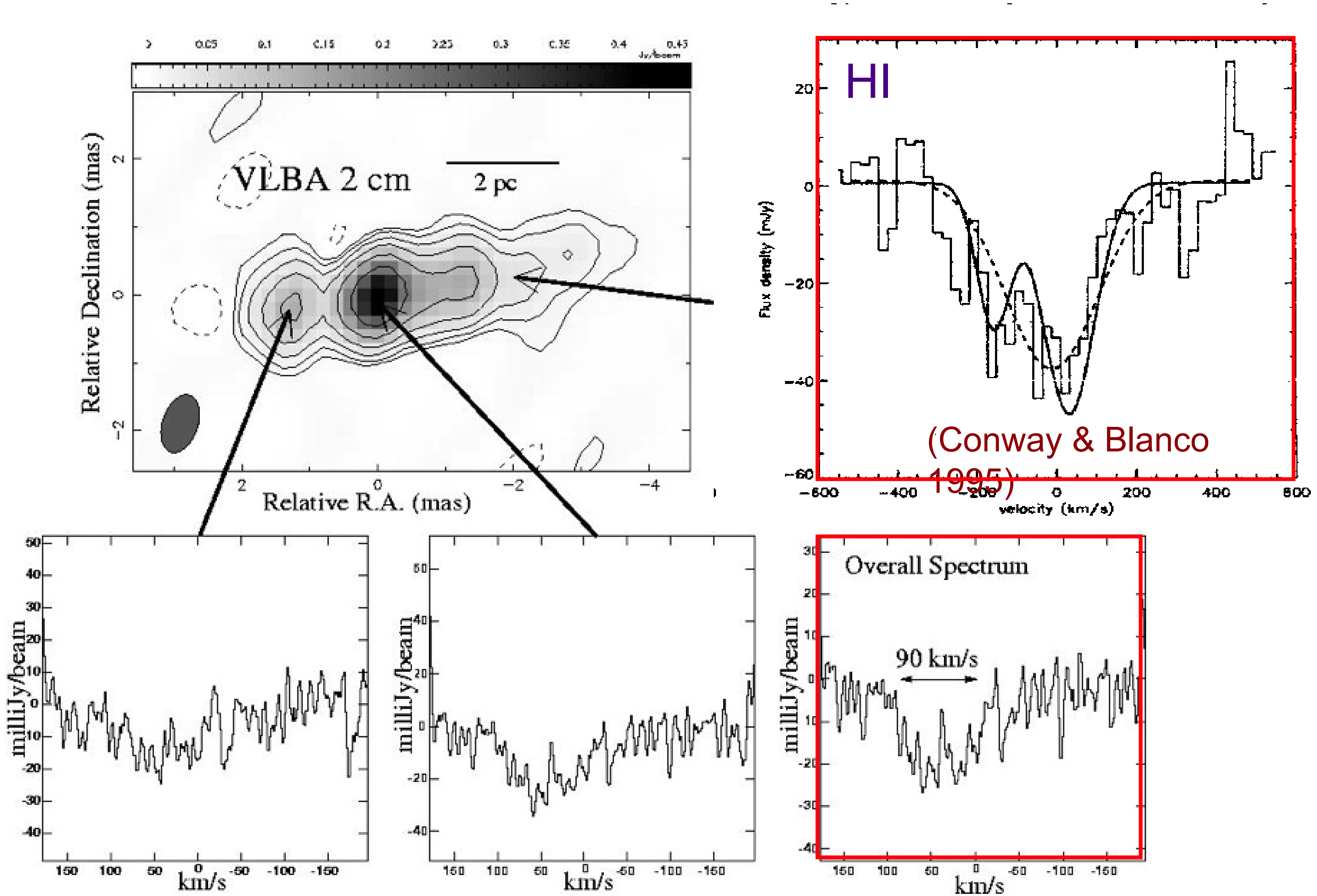
Optical depth (core)

$\tau_{OH} \approx 0.12$

Absorbing gas is diffuse around the inner jets.

Profile strongest over the entire continuum.

Tentative Detection: Cygnus A



Conclusions from OH Survey

- **A survey for 6.0 GHz OH with Effelsberg found highly excited, broad absorption lines in 5 out of 28 sources, i.e.,18%.**
- **Selection criteria improved detection rate c.f. other OH surveys (< 7 %).**
- **Line widths are 100s-1000 km s^{-1} (close to the nuclear region?).**
- **Still some sources with high column density didn't show absorption.**
- **No new detections at 6 GHz were made, when there was no previous OH absorption/emission at 1.6 GHz.**
- **But, 13.4 GHz OH was detected for the first time from the torus of an AGN (Cygnus A and NGC 1052).**

Results do not support radiative excitation models alone to explain the lack of detections.

But still the non-detections remain to be explained !!

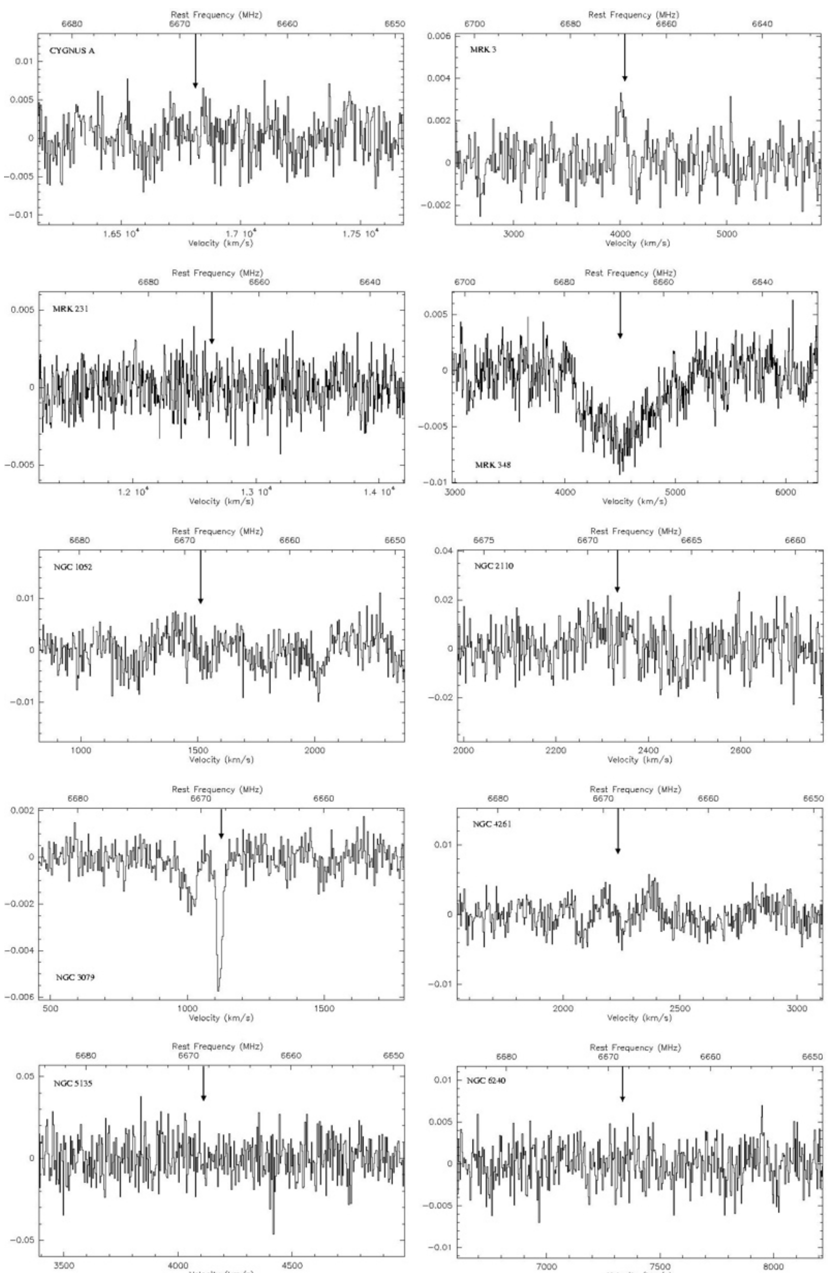
Conclusions from OH Survey

- Bimodal distribution of absorptions -> or very compact clouds ?
- Broad lines in infall/outflow ? Not a simple rotating torus ?
- X-ray absorber may be non-molecular in most galaxies ??

A Search for Methanol

- **Methanol (CH_3OH) transition at 6.7 GHz is one of the strongest galactic maser lines.**
- **Often found in regions of high mass star-formation.**
- **In our Galaxy, Methanol and OH masers are coincident on subarcsec scales => molecules cohabit.**
- **There are ~400 Galactic 6.7 GHz masers known, but only three extragalactic (all in the LMC).**
- **Observations of known OH megamasers galaxies, have failed to detect methanol in ~125 nearby Seyferts -> missing Methanol?**

Effelsberg Spectra (6.7 GHz)



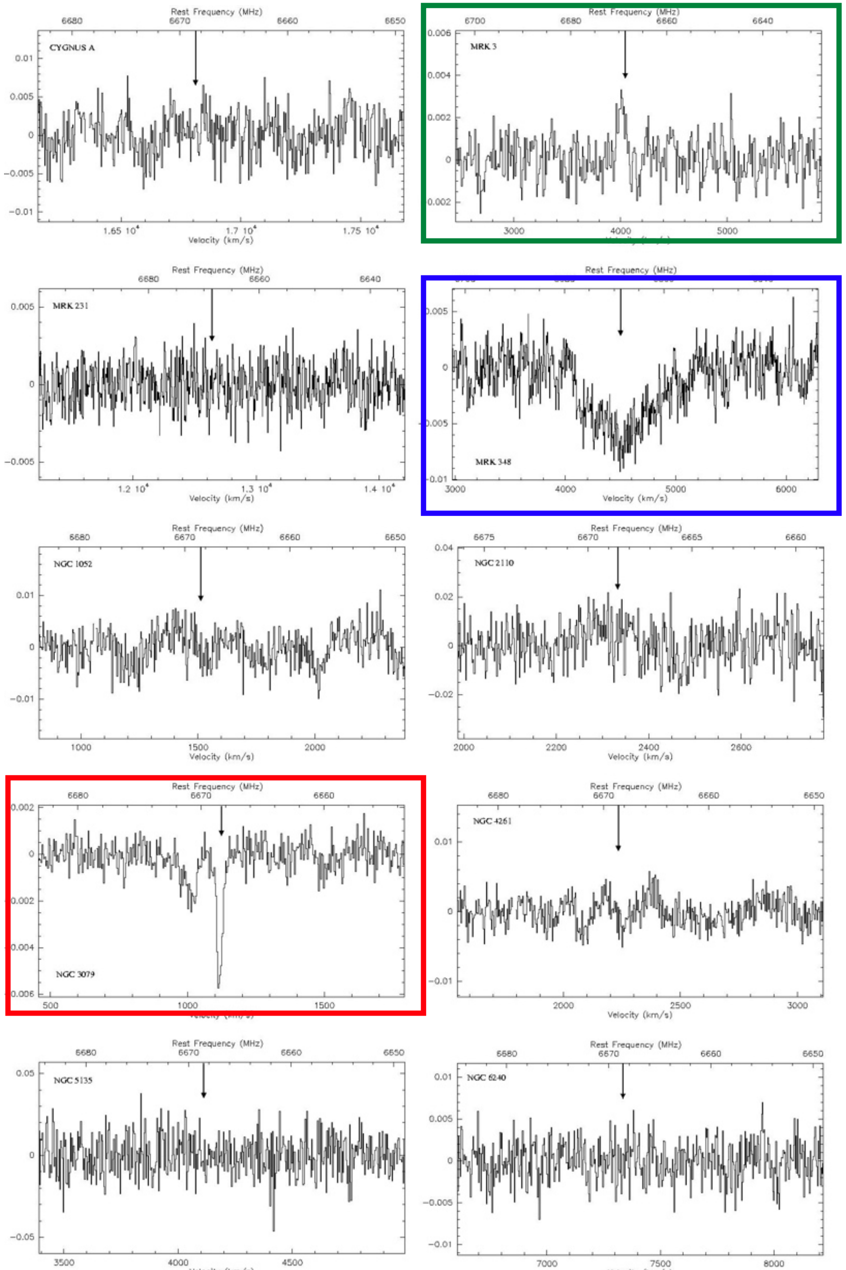
A sub-sample of 10 sources, already known to have molecular absorption, were also observed for methanol at 6.7 GHz.

Sources observed for 3 to 113 minutes, in PWS, 40 MHz BW, 512 channels.

Achieved a sensitivity level of 3.5 mJy (5σ) Corresponding to a line opacity of 0.002 to 0.07.

Total velocity covered in BW 2000 km s^{-1} (4 kms^{-1} per channel).

Effelsberg Spectra (6.7 GHz)



MRK 3 - The emission line peak is 3.4 mJy (rms is 1.2 mJy channel^{-1}). The line width is ~47 km s^{-1}.

MRK 348 - The absorption line has a width of ~634 km s^{-1} and a peak of −4.2 mJy peak

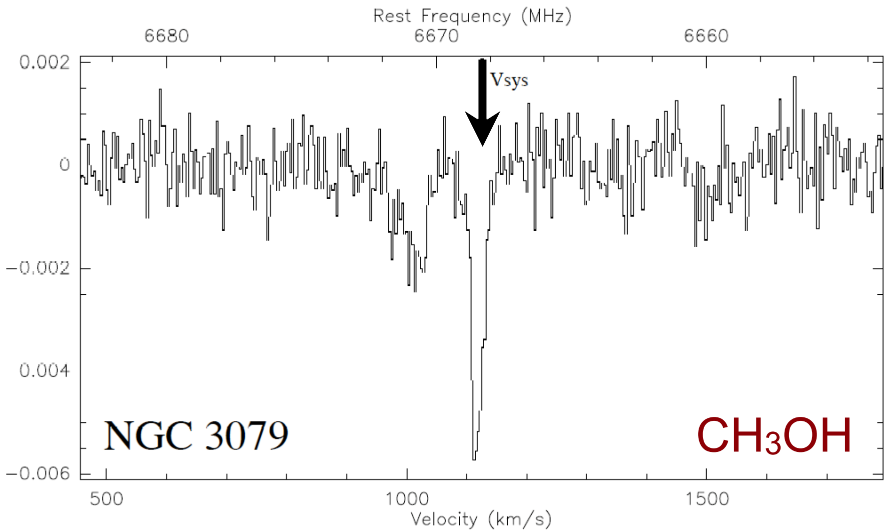
NGC 3079 - Two absorption lines detected (see later).

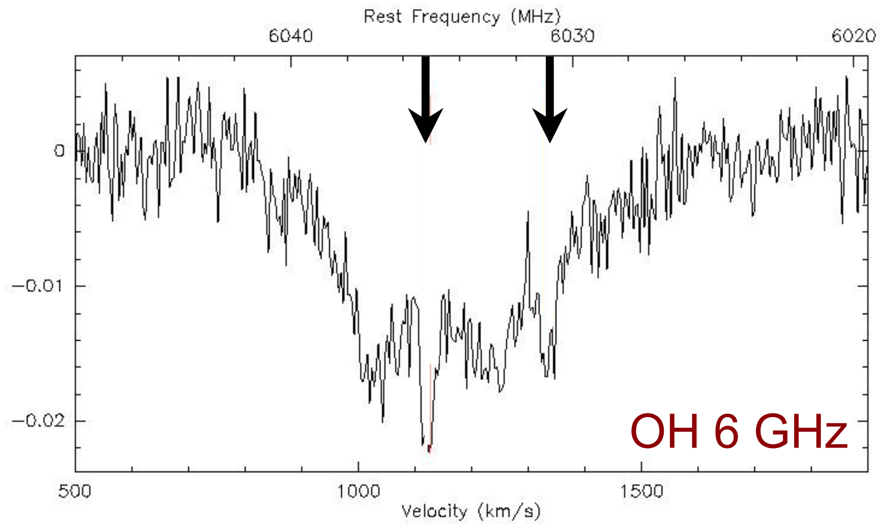
Methanol has been found in 30% of the sample!!!!

These are the first Methanol detections ever from a (proper) extra-galactic source at 6.7 GHz.

Impellizzeri et al., 2008, A&A, 484, 43

Methanol in NGC 3079



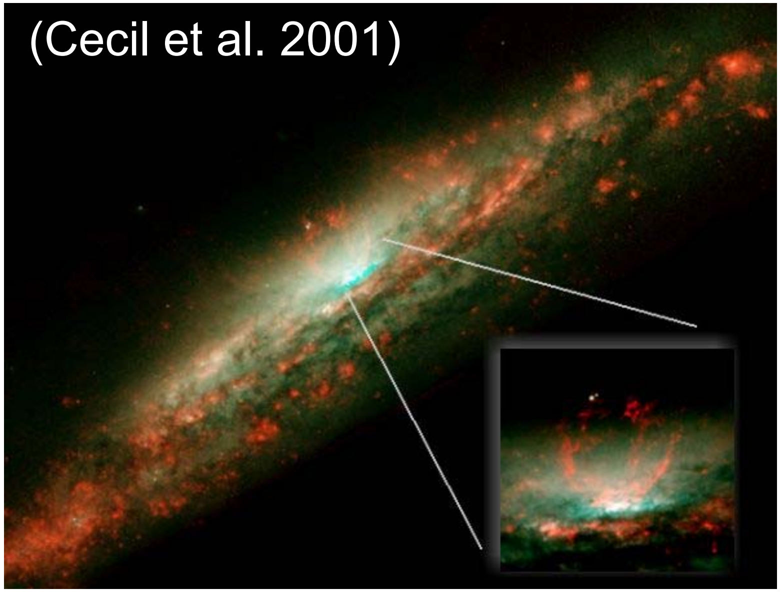


Two absorption lines detected (N_{CH3OH} = 10^{13} - 10^{15} cm^{-2})

i) Narrow feature at systemic
FWHM ~ 24 km s^{-1}
$\tau > 0.02$

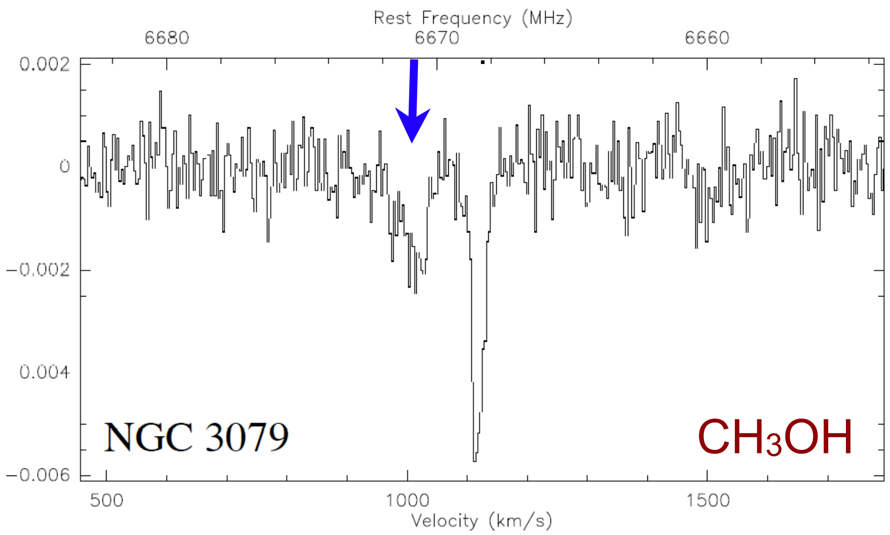
ii) Broader feature at −108 km s^{-1}
FWHM ~ 57 km s^{-1}
$\tau > 0.01$

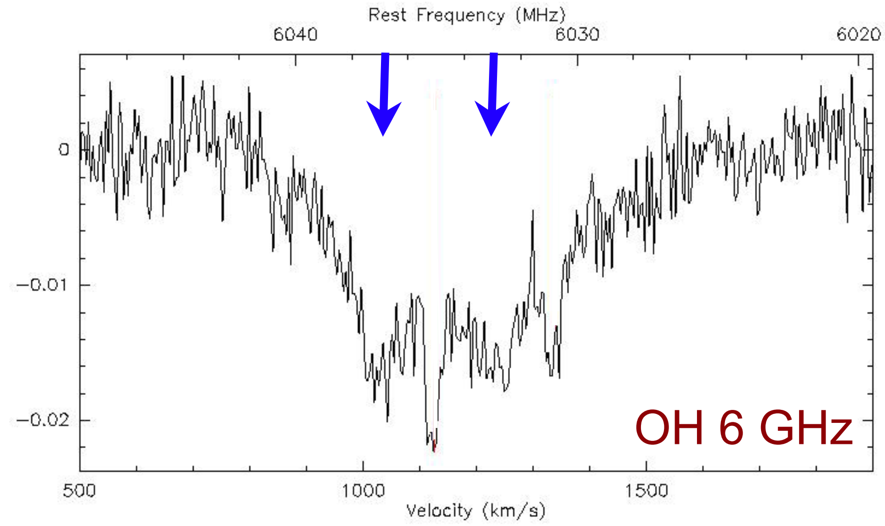
Strong radiation field needed for pumping the 6.7 GHz maser not the dominant excitation mechanism toward the nuclear region here.



Impellizzeri et al., 2008, A&A, 484, 43

Methanol in NGC 3079



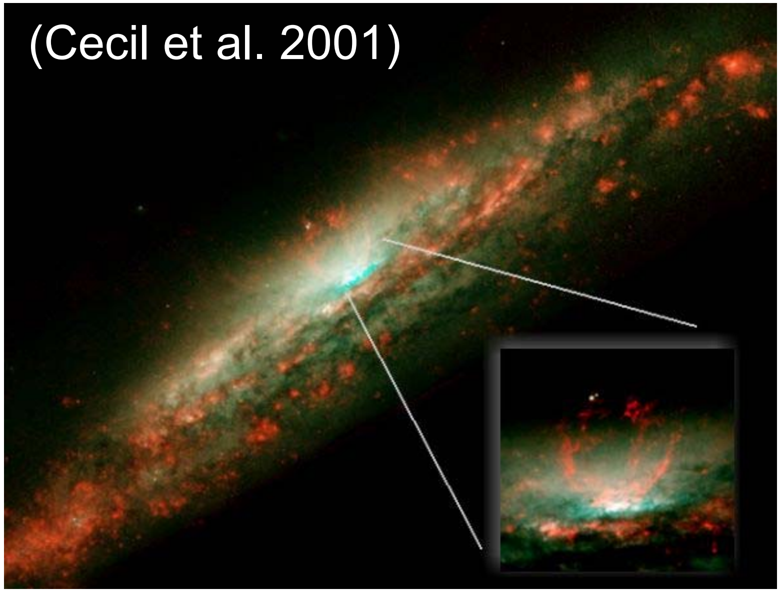


Two absorption lines detected (N_{CH3OH} = 10^{13} - 10^{15} cm^{-2})

i) Narrow feature at systemic
FWHM ~ 24 km s^{-1}
$\tau > 0.02$

ii) Broader feature at −108 km s^{-1}
FWHM ~ 57 km s^{-1}
$\tau > 0.01$

Strong radiation field needed for pumping the 6.7 GHz maser not the dominant excitation mechanism toward the nuclear region here.



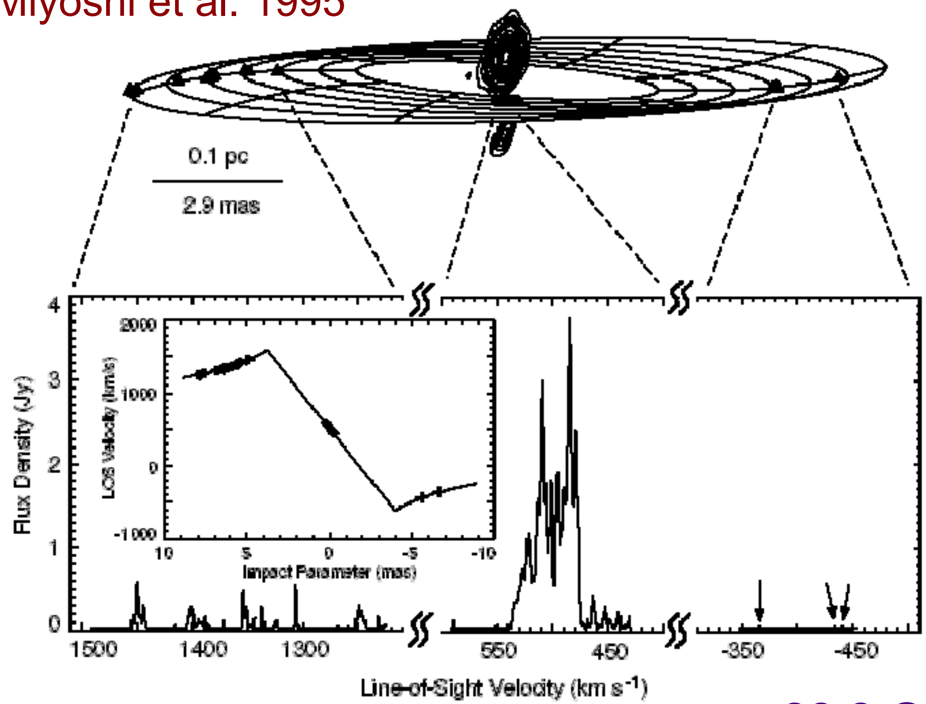
Impellizzeri et al., 2008, A&A, 484, 43

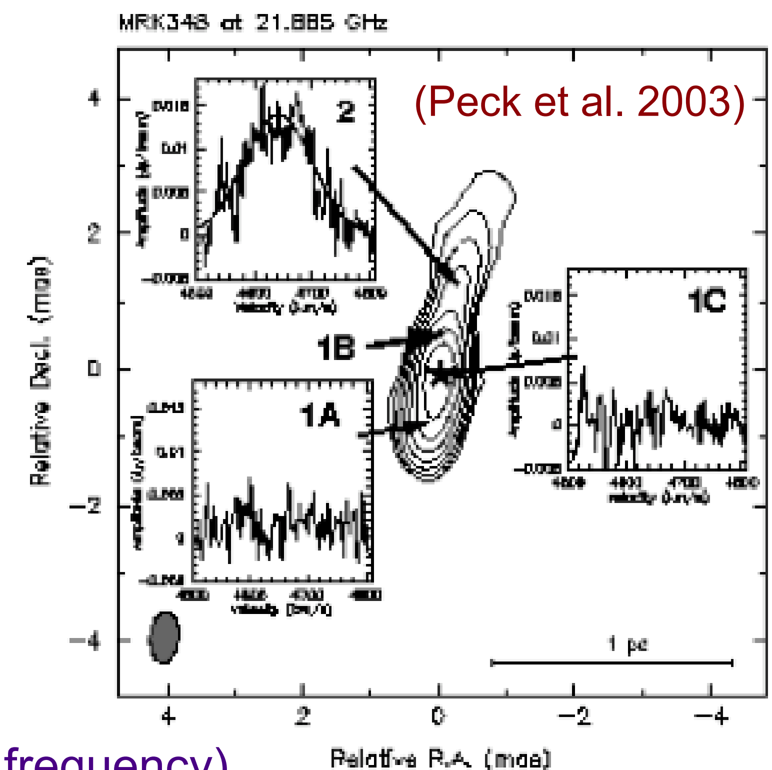
Conclusions from Methanol Survey

- There is methanol in AGN with sufficient abundance to be detected!
- NGC 3079 has the appropriate excitation conditions to produce the 6.7 GHz transition in absorption.
- This is the signature of a Class I environment, where the absence of a strong infrared radiation field inhibits the inversion of the level populations. Instead, the line is characterised by “anti-inversion” or “over-cooling”.
- The methanol column densities are comparable to those found towards the Galactic Centre.

Probing the AGN

Miyoshi et al. 1995





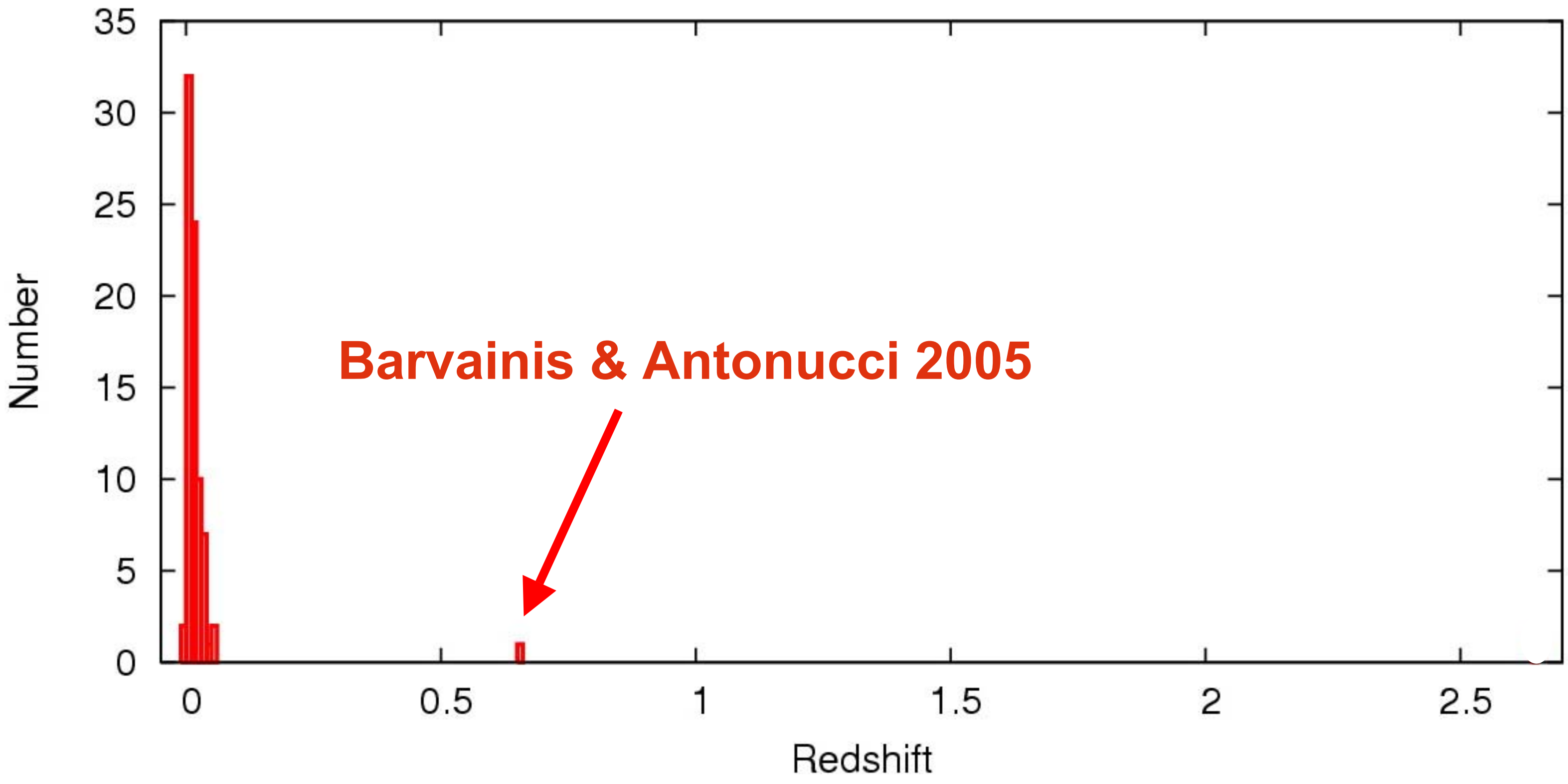
22.2 GHz (rest frequency)

Blueshift, redshift and systemic components and tend to have narrow emission lines (<1--3 km s^{-1}.)

Broad line (<100 km s^{-1}) emission in the radio jet out to 30 pc.

Measure black hole masses (e.g. Miyoshi et al. 1995), accurate geometrical distances (e.g. Herrnstein et 1998) and jet-outflows (Peck et al. 2003).

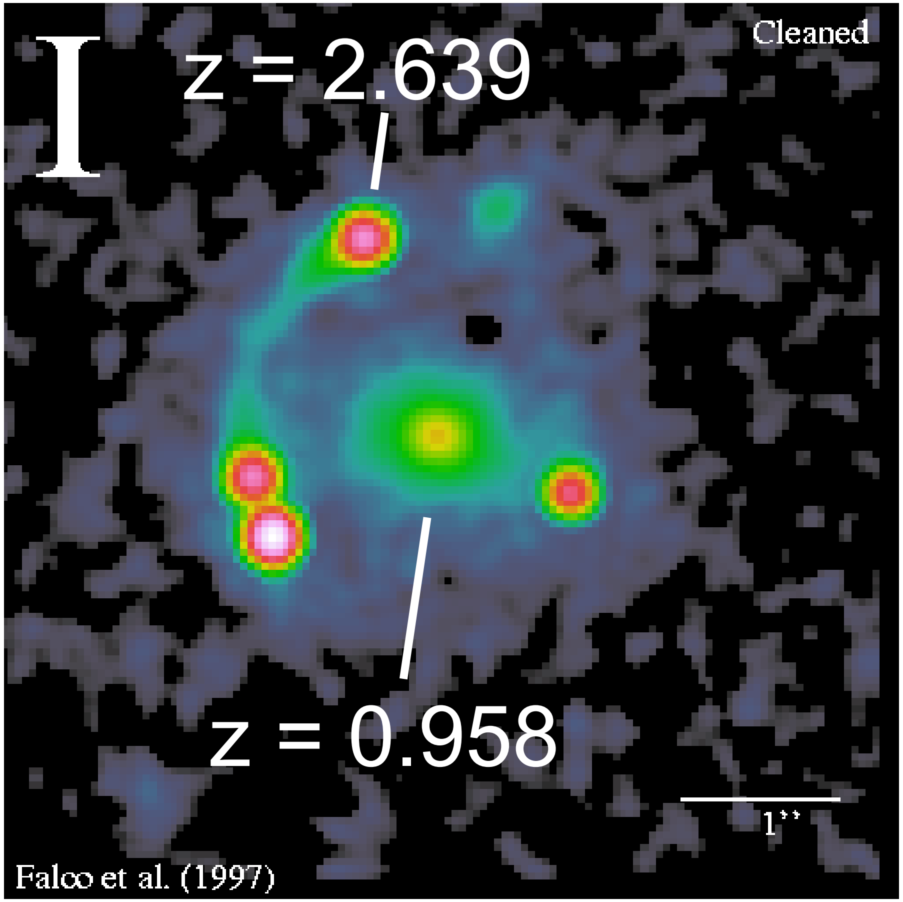
Nearly All Found at Low Redshift

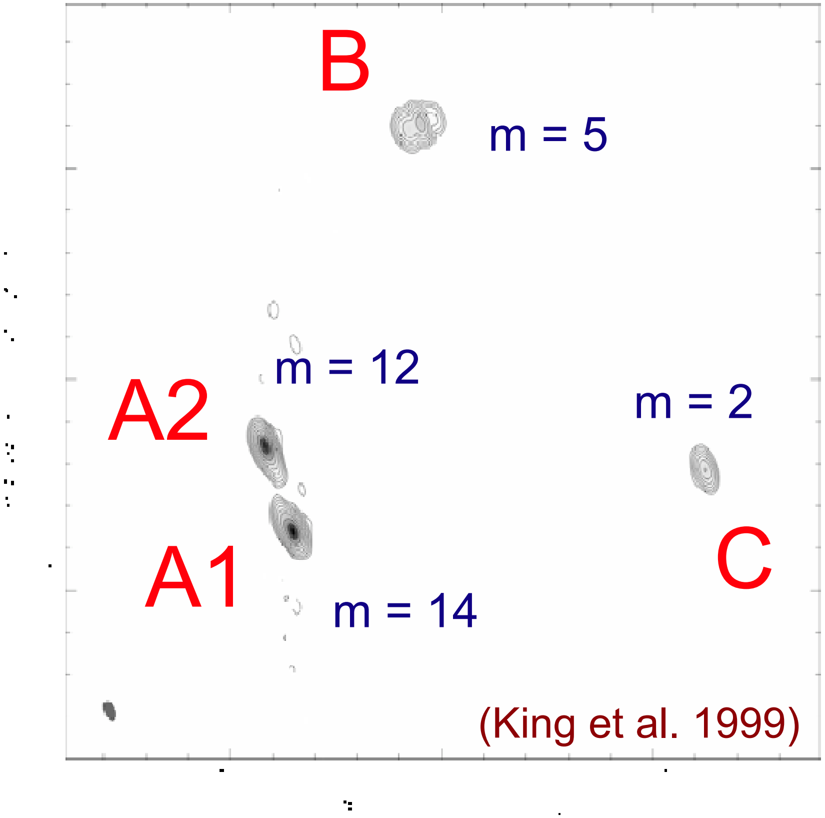


Almost all extragalactic water masers are found in Seyfert 2 or LINER galaxies at z << 0.06.

The most distant water maser known was at z = 0.66 (type 2 quasar; L ~ 10^4 L_{solar}.)

The Gravitational Lens MG J0414+053





The lensed quasar is known to have a dusty host galaxy which is rich in molecules.

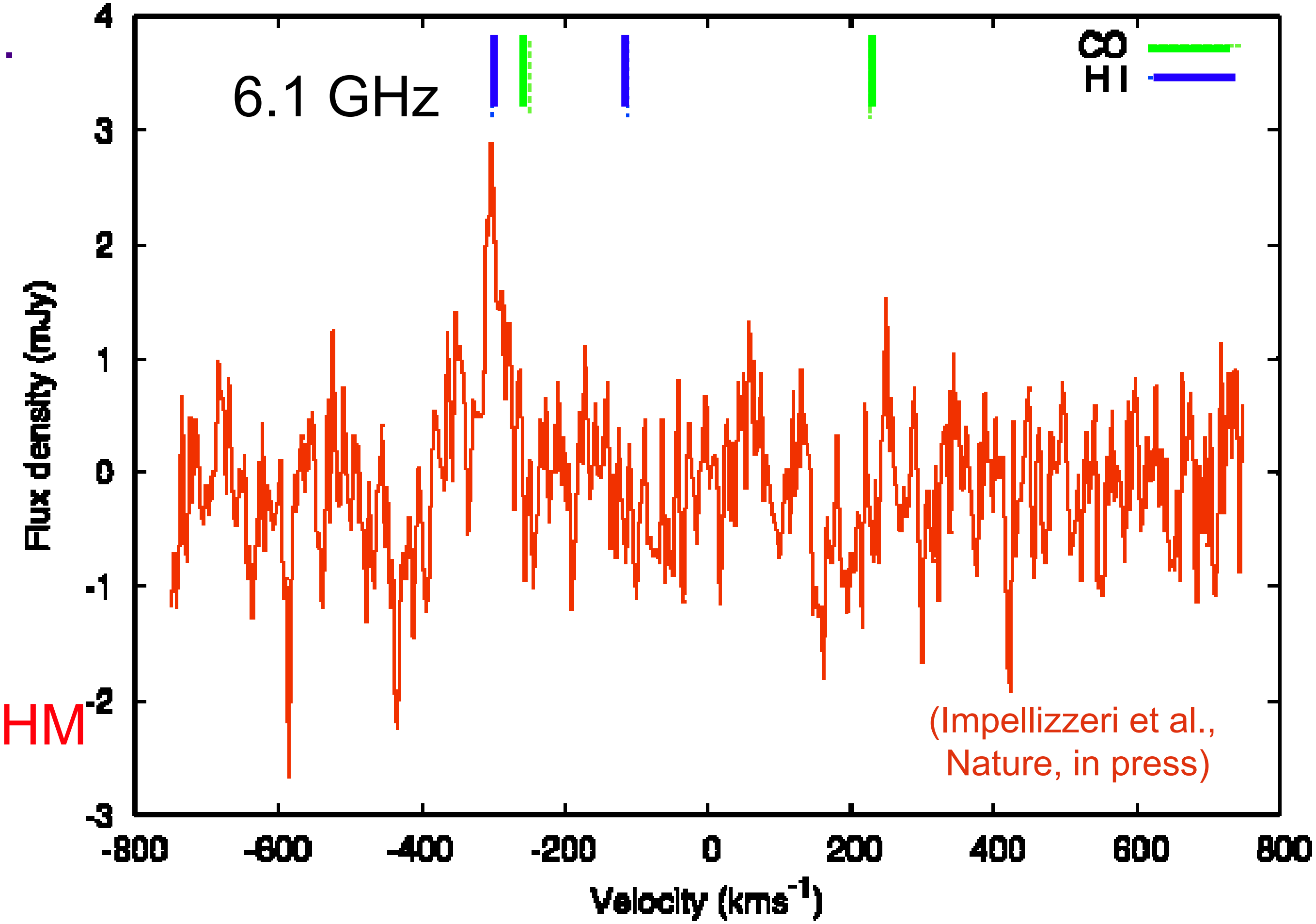
There is CO emission at ±300 km s^{-1} (Barvainis et al. 1998) around the systemic, and HI absorption at −300 km s^{-1} (Moore et al. 1999).

Effelsberg Observations

Total integration time 14 h.

rms is 0.6 mJy $channel^{-1}$.

Channel width 3.8 km s^{-1}
bandwith 40 MHz.

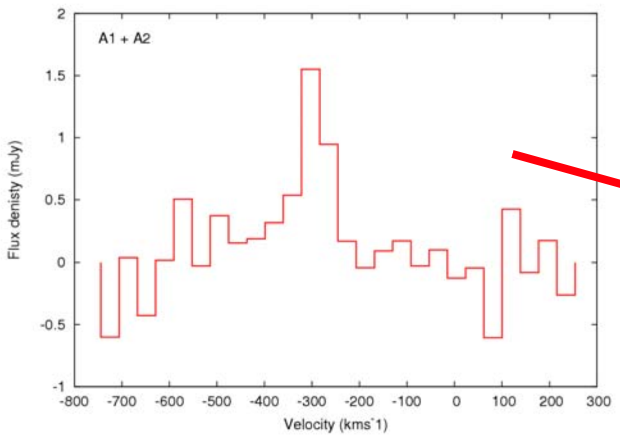


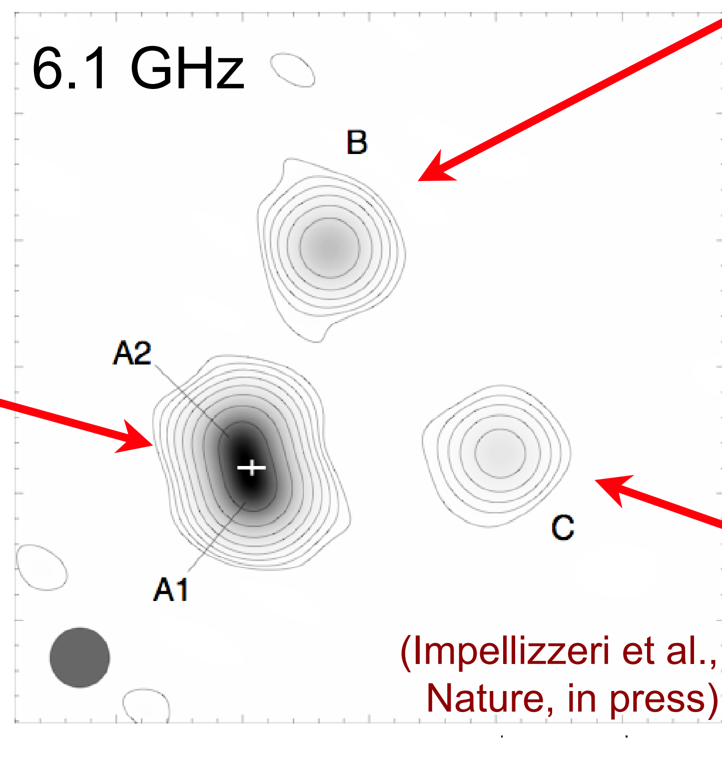
Line at −300 km s^{-1}, the FWHM is ~40 km s^{-1}.

The apparent isotropic luminosity is ~ 300 000 L_{solar}.
The estimated unlensed (isotropic) luminosity is ~10 000 L_{solar}.

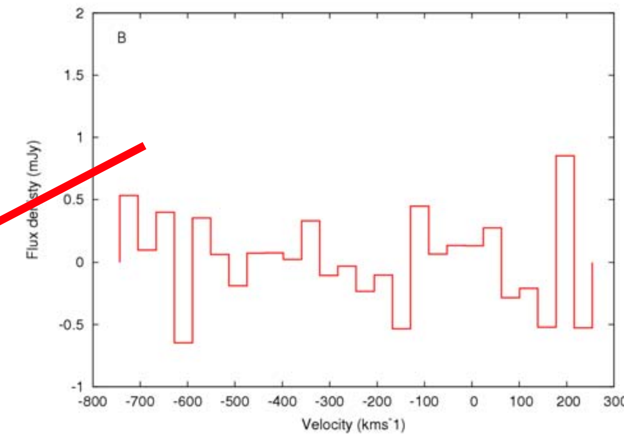
EVLA Map and Spectra

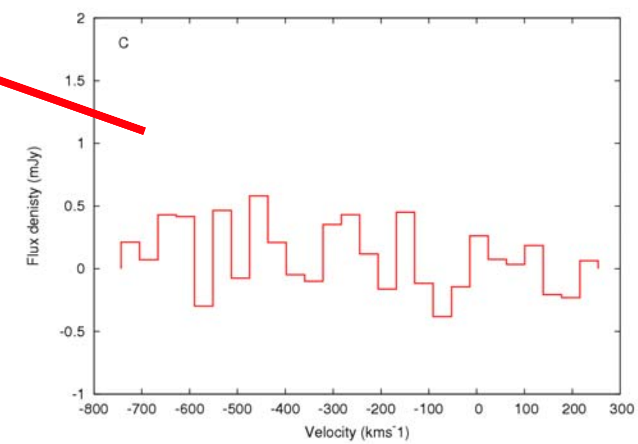
A water maser emission line is detected at −300 km s^{-1} in the integrated spectrum of images A1 and A2.





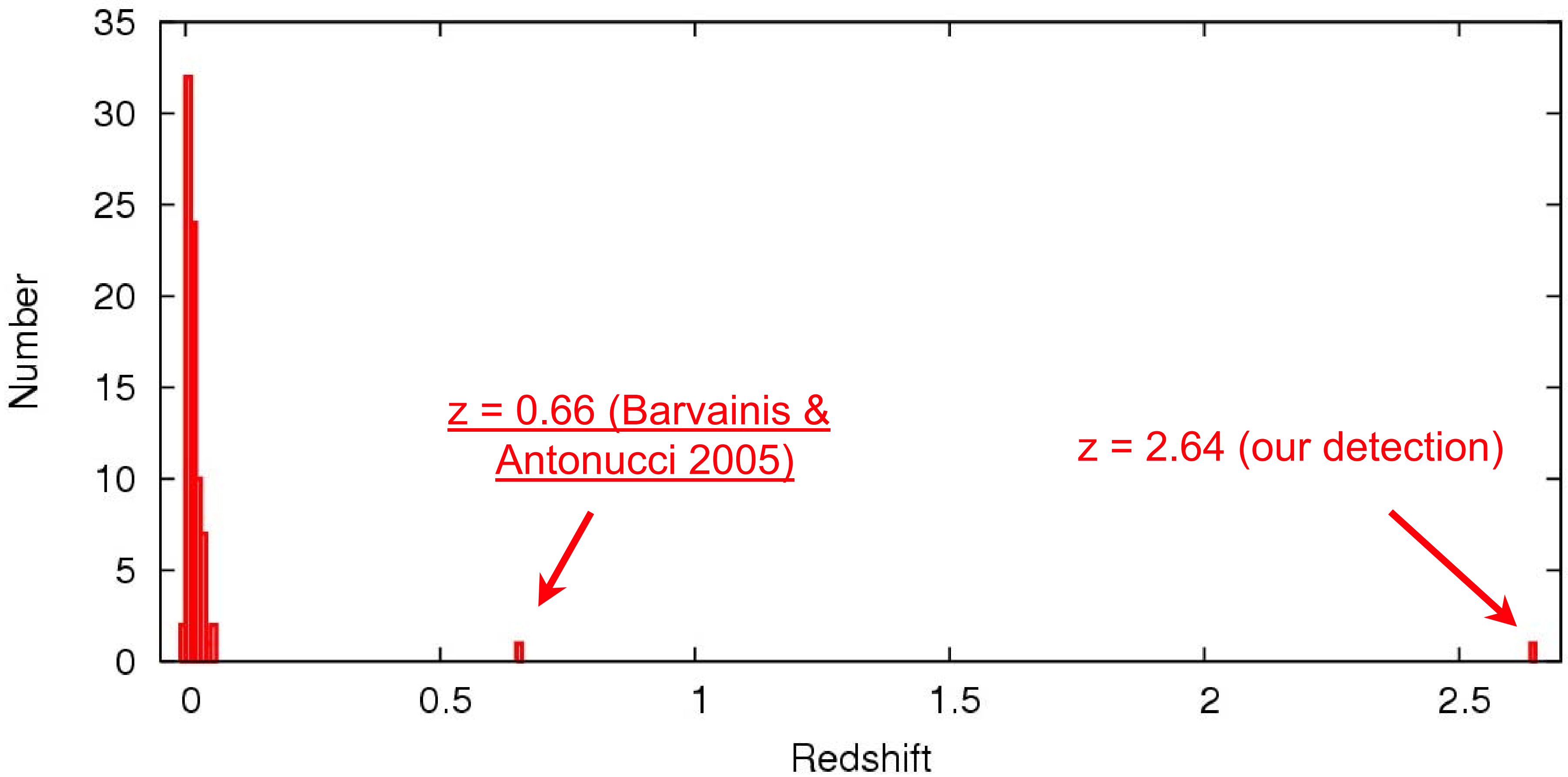
(Impellizzeri et al., Nature, in press)





Nothing is detected in images B and C (as expected due to their lower image magnifications).

Water in the Early Universe



MG J0414+0534 is by far the most distant source water has been detected (lensing decreases the integration time by ~1000).

The water maser transition requires gas temperatures > 300 K and $n(H_2) > 10^7$ cm^{-3}.

Jet or disk ?

Is the maser in the jet or accretion disk?

Not conclusive from the current data, but....

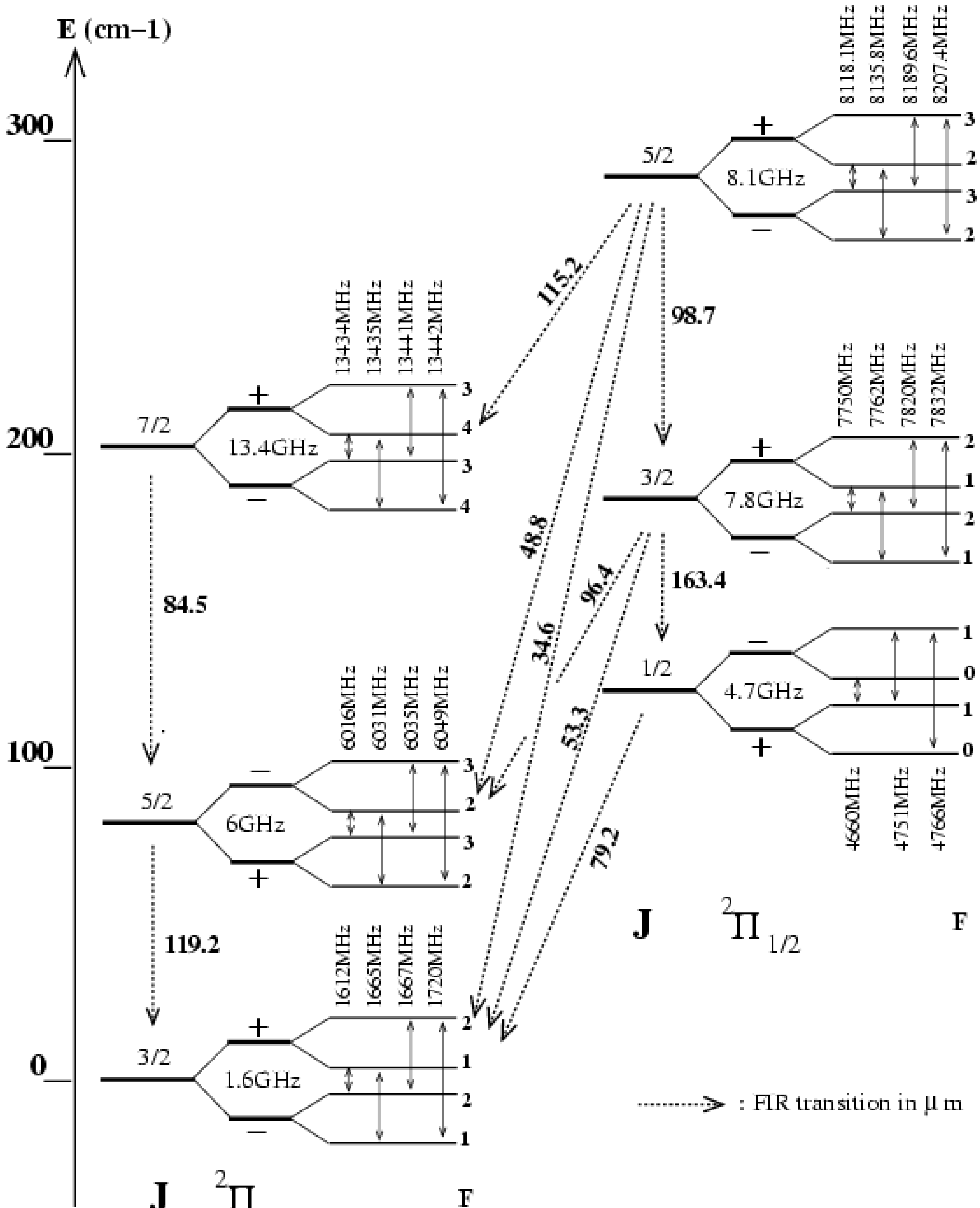
...the maser is broad (FWHM ~ 40 km s^{-1}), offset from the systemic velocity, coincident with HI gas, MG 0414+0534 is a type 1 AGN...

Therefore, the jet maser scenario is currently favoured.

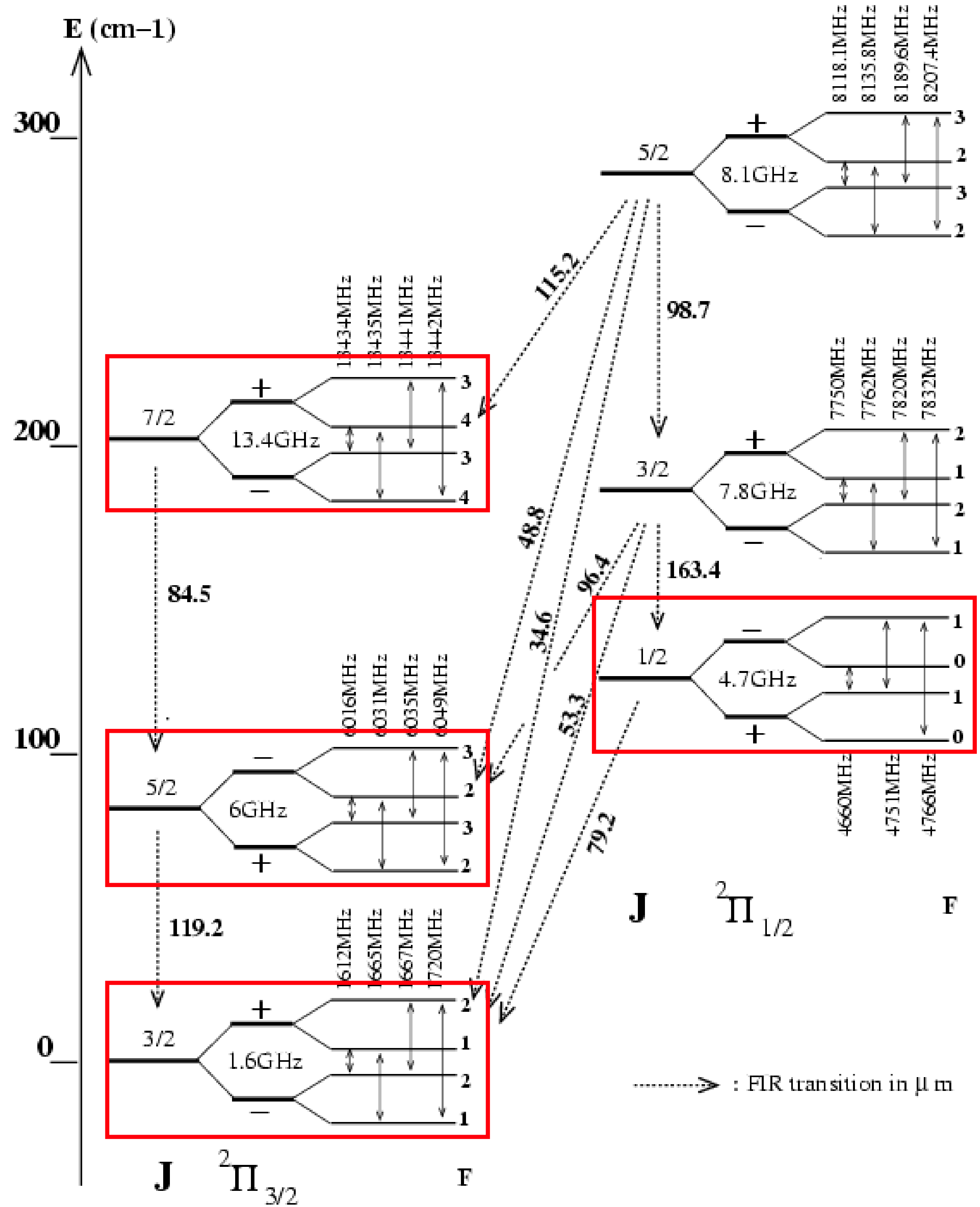
Future Work:
Single dish monitoring to look for any time variability (w/ Arecibo).
High resolution imaging with VLBI will determine if the maser is in the jet or disk.
New VLBI imaging to constrain the lens mass model.

Summary

- Evidence for a molecular torus was found in the form of excited OH and CH_3OH as expected from unification models for AGN.
- In particular, my results show that the 13.4 GHz transition of excited OH is most promising (as expected).
    - ★ The advent of the EVLA will allow much larger surveys for 13.4 GHz excited OH.
- The detection of CH_3OH at 6.7 GHz has provided a new molecular tracer of galaxies.
    - ★ Searches for CH_3OH at 12.2 GHz will compliment this result and allow the excitation temperatures to be determined.
- The most distant water maser known was found, indicating a higher abundance among AGN in the distant Universe.
    - ★ This is an important result for the design of e.g. the SKA.



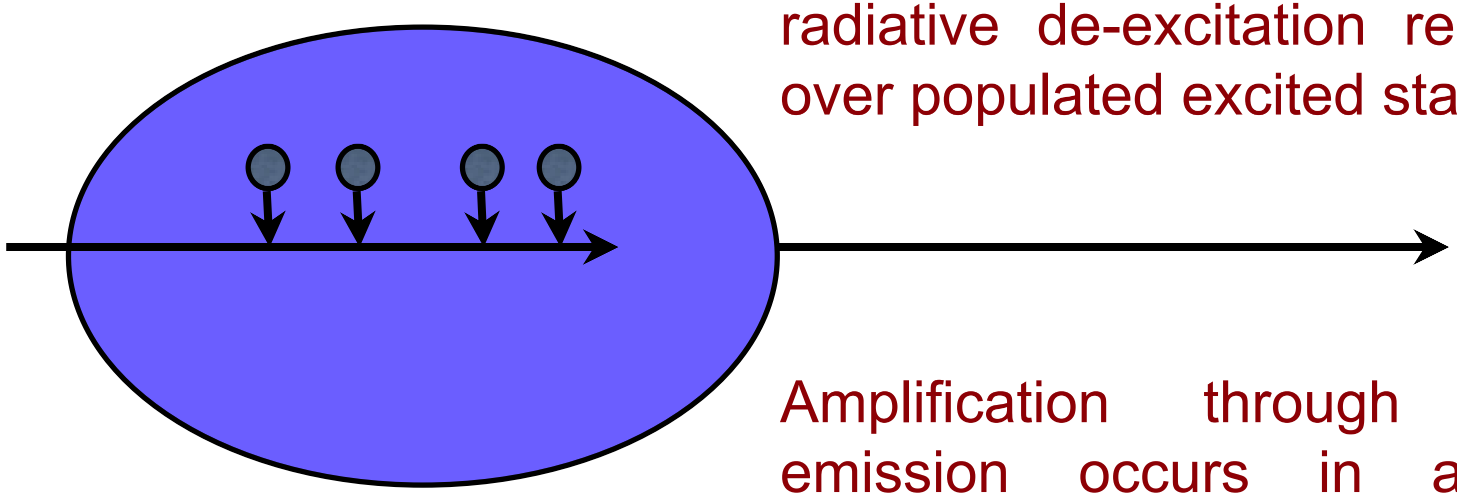
(Desmurs et al. 2001)



(Desmurs et al. 2001)

Water Masers

Maser emission from water is seen at 22.2 GHz (rest frame.)



Collisional excitation and low radiative de-excitation results in an over populated excited state.

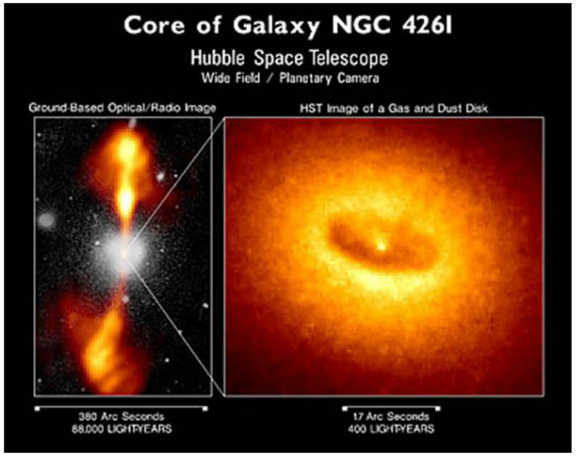
Amplification through stimulated emission occurs in a coherent (freq/velocity) gain medium.

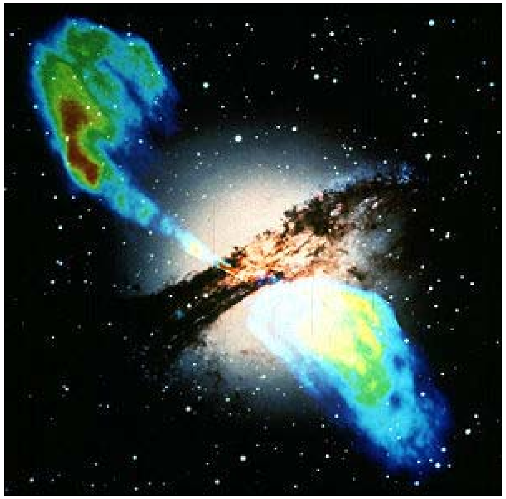
Found in regions of hot, dense gas => most luminous (> 10 L_{solar}) are found very close to the supermassive black hole of an AGN.

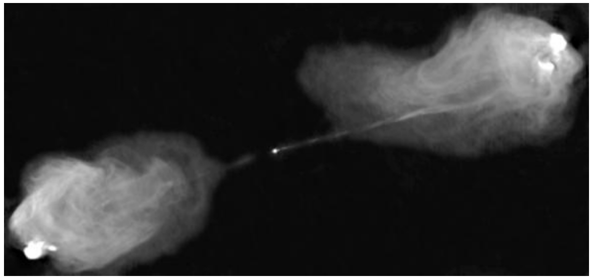
Radiation has a very high surface brightness and is beamed to the observer.

Introduction -out

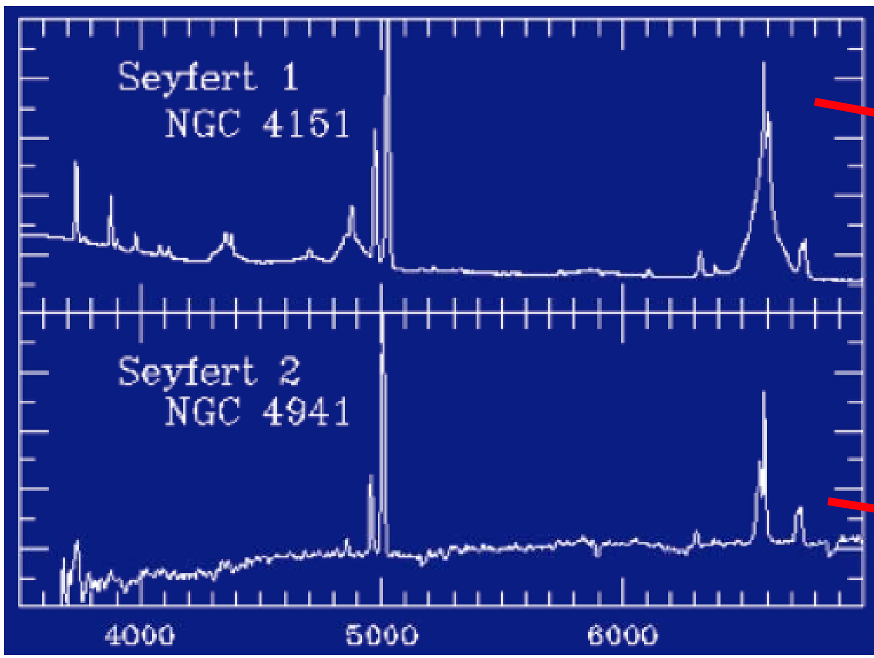
- An active galaxy is one where the bulk of the emission comes from a central point source (AGN).
- The central engine is a super-massive black hole that feeds on material via an accretion disk.
- The radio emission is non-thermal i.e. it’s not from the stellar population or the accretion disk.
- The emission is broad band (from radio to gamma).



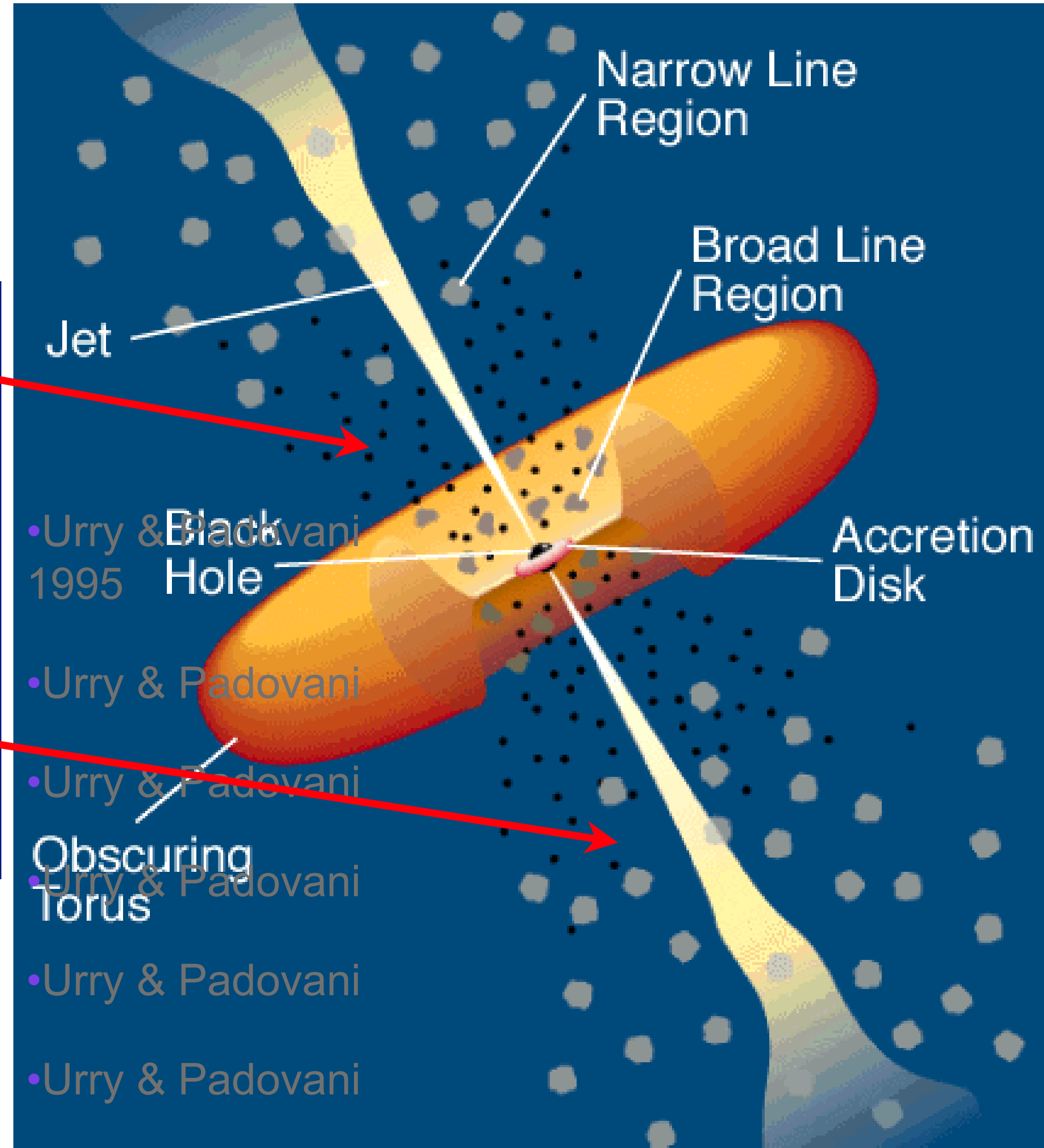




AGN Unification - out



credit: C. W. Keel
(www.astr.ua.edu/keel/agn/spectra.html)



- Urry & Padovani 1995

- Urry & Padovani
- Urry & Padovani
- Urry & Padovani
- Urry & Padovani
- Urry & Padovani
- Urry & Padovani

VLBI Follow-up - out

Cygnus A and NGC 1052 were followed up with interferometric observations to detect excited OH at 13.4 GHz towards their core.

$\alpha \propto \frac{\lambda}{D}$ => 0.9 mas beam

Observing time:
Cygnus A - 8 hours
NGC 1052 - 7 hours

Bandwidth was 16 MHz (256 channels) per IF.

Velocity coverage ~ 560 km s^{-1}.

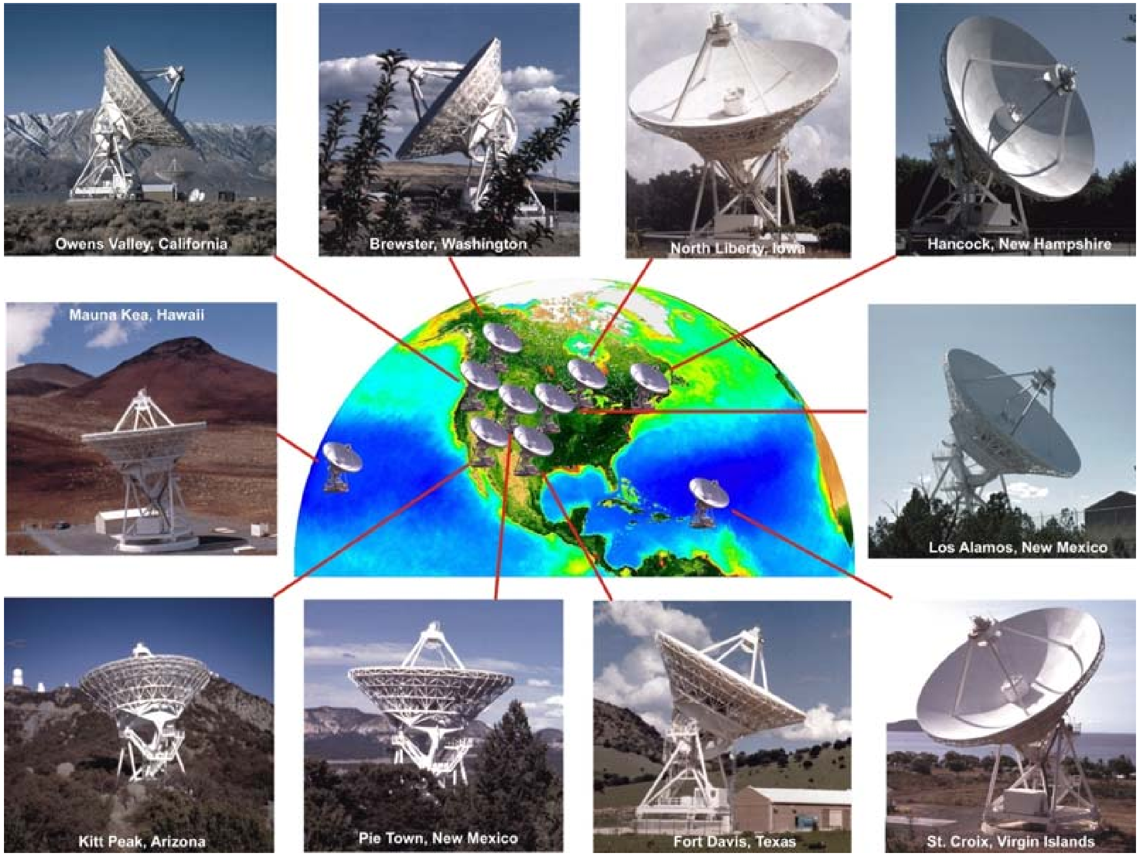


Image courtesy of NRAO/AUI and Earth image courtesy of the SeaWiFS Project NASA/GSFC and ORBIMAGE

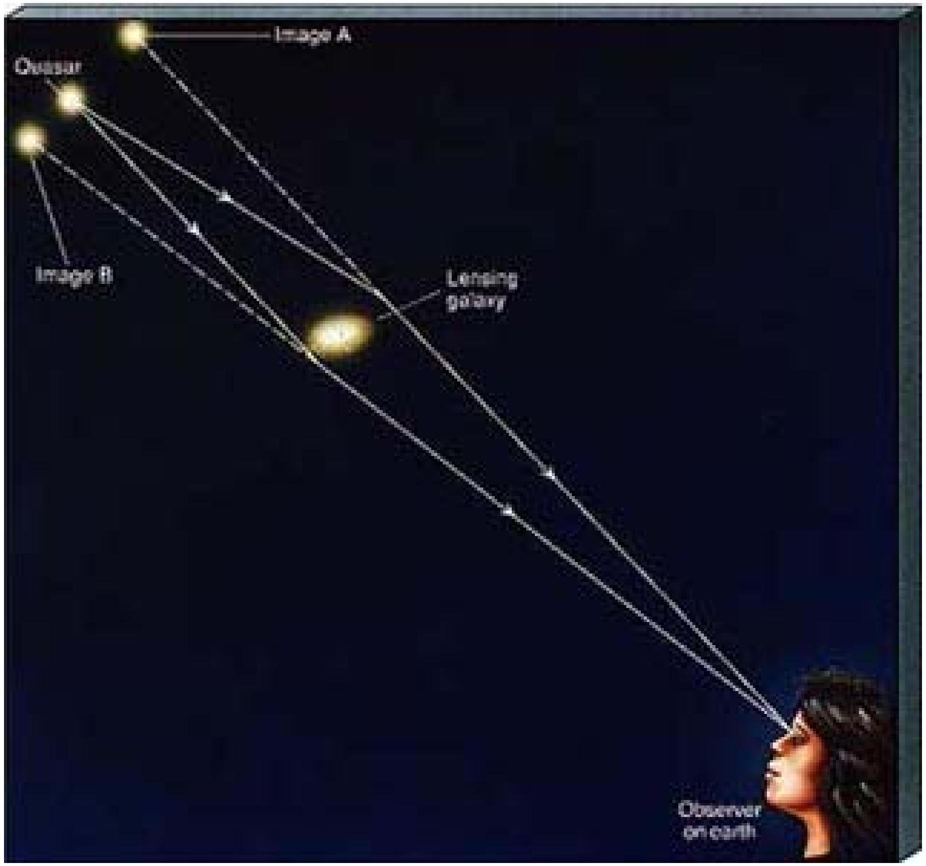
Gravitational Lensing - out

Gravitational lensing is the deflection of light by an intervening mass distribution (a galaxy).

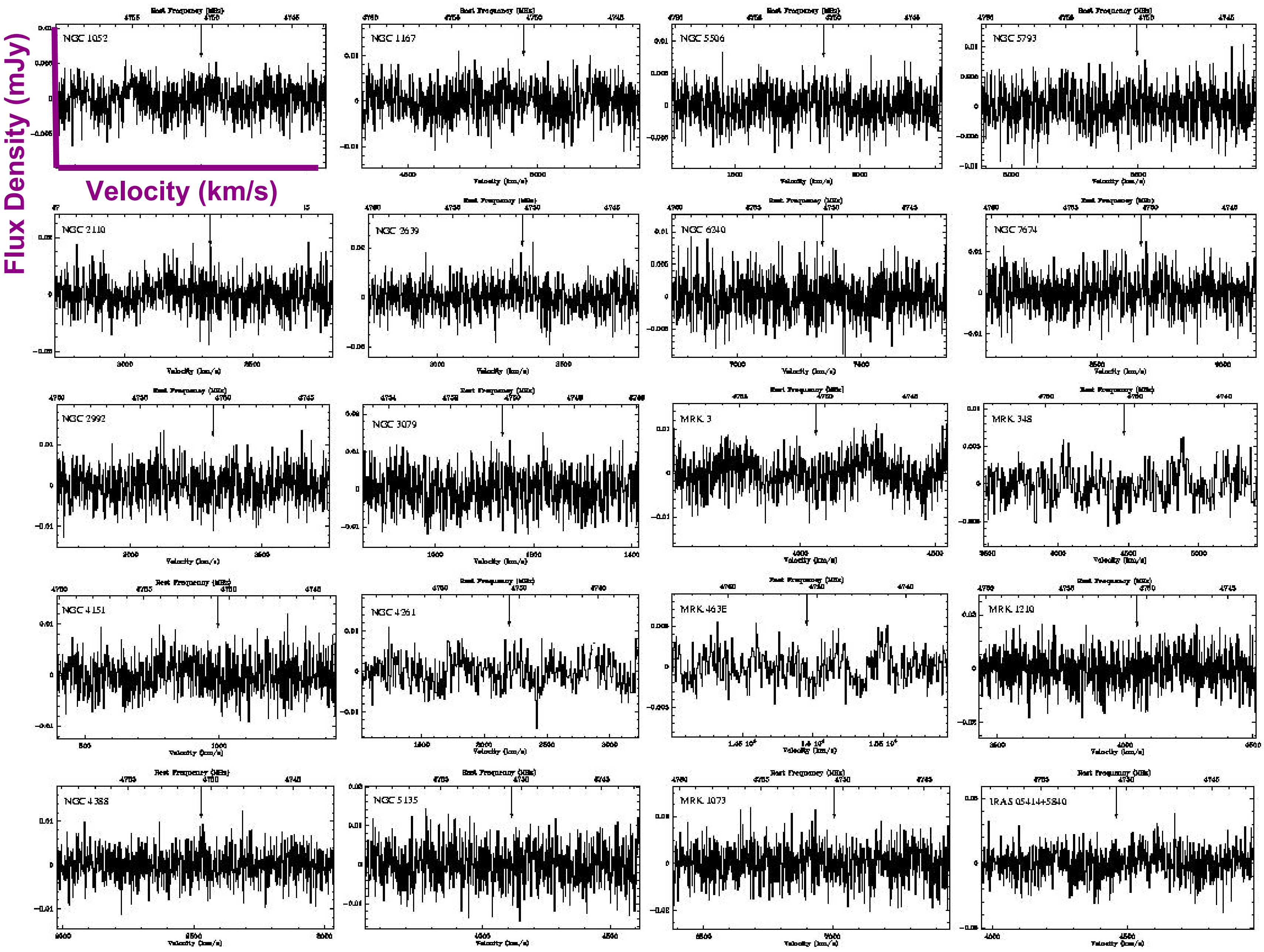
Multiple images of the background source are formed (typically 2 or 4).

The background source is magnified by the lens - factor of a few to a few tens - depending on the relative position of the source and lens.

This results in the observed flux density being higher, which allows studies of fainter sources (gravitational telescope).



Effelsberg Spectra (4.7 GHz)



Sample of 20 objects.

no detections down to 3 mJy/chan.

(channel width 1.2 km s^{-1}).

Disk maser

EVLA Follow-up - out

Spatial resolution: 0.5 arcsec beam

After data editing there was 12 h usable on-source.

Spectral setup: 32 channels of 0.781 MHz bandwidth (38 km s^{-1}).