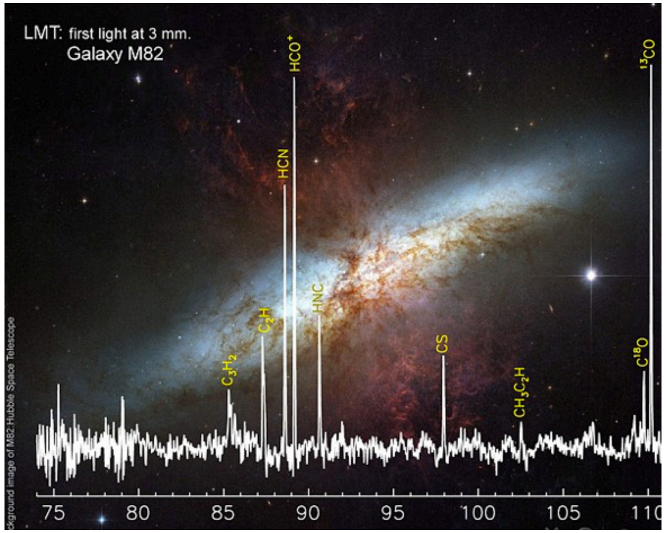
# Extragalactic molecular studies…

Have seen a progressive steady growth

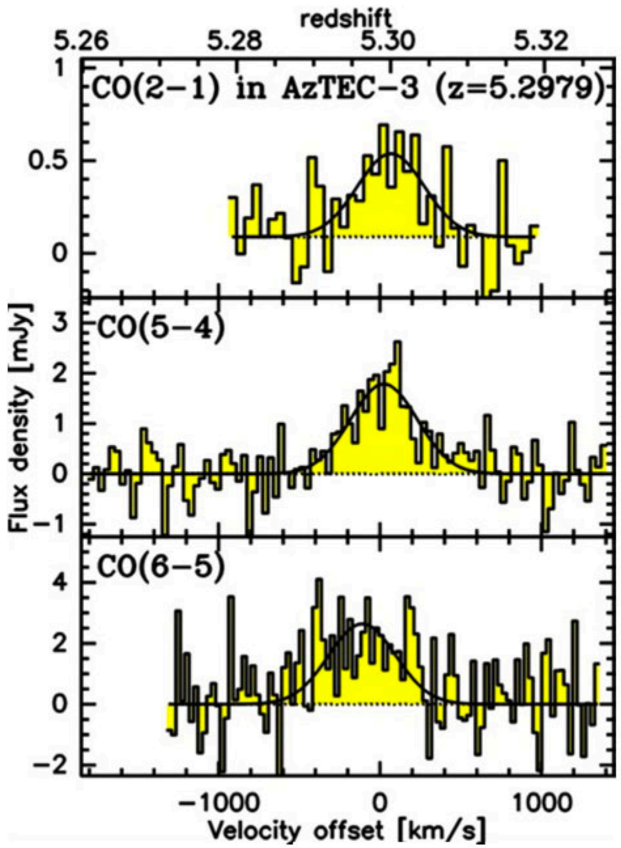
-thanks to the improved sensitivities of many observatories

Line emission studies – HI, OH megamasers, $H_2O$ water masers… in the cm regime

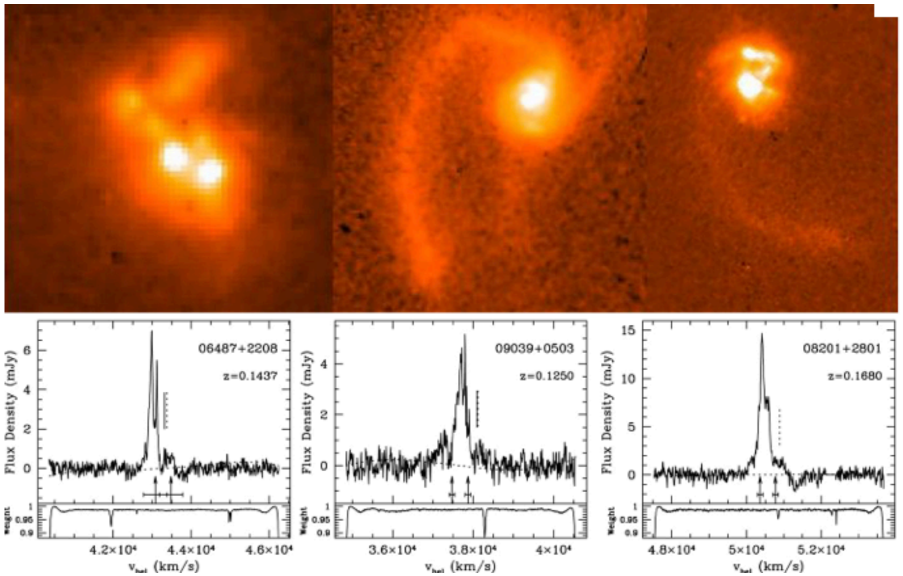
- CO, HCN, $HCO^+$ … in the sub-mm regime




LMT first light 3mm

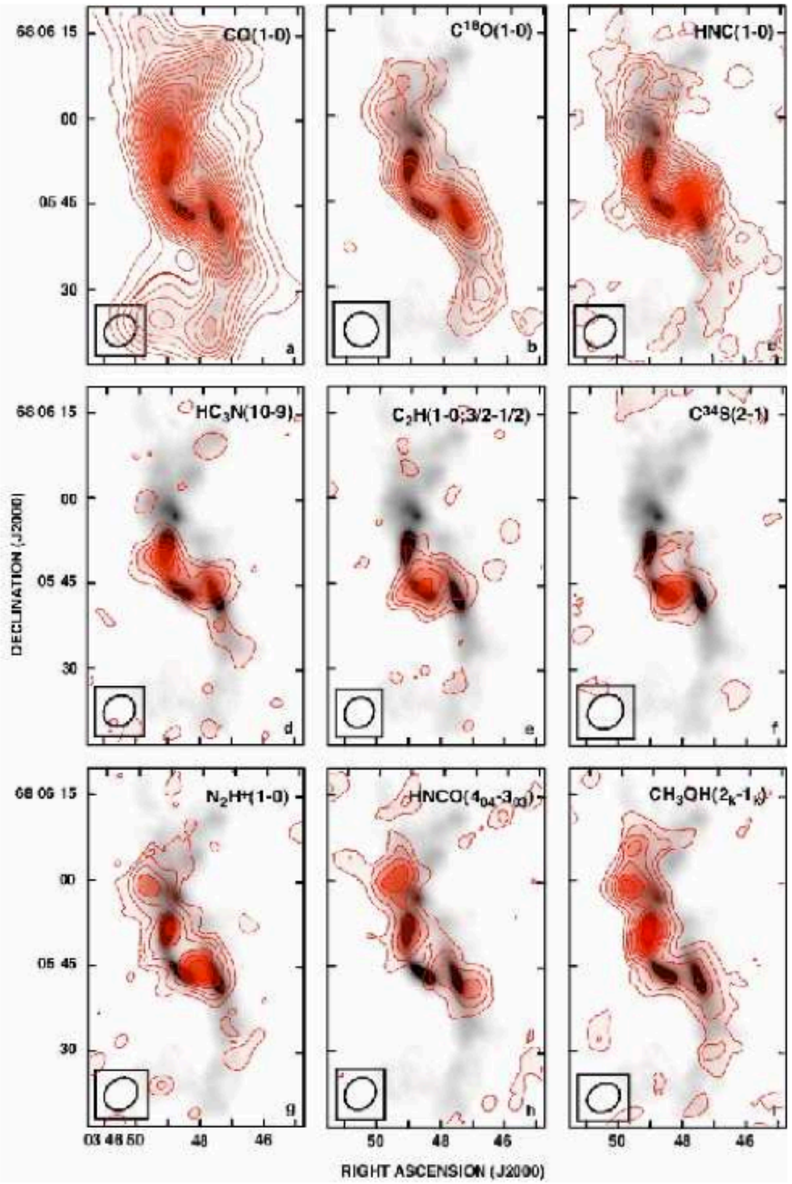



Riechers et al. 2010

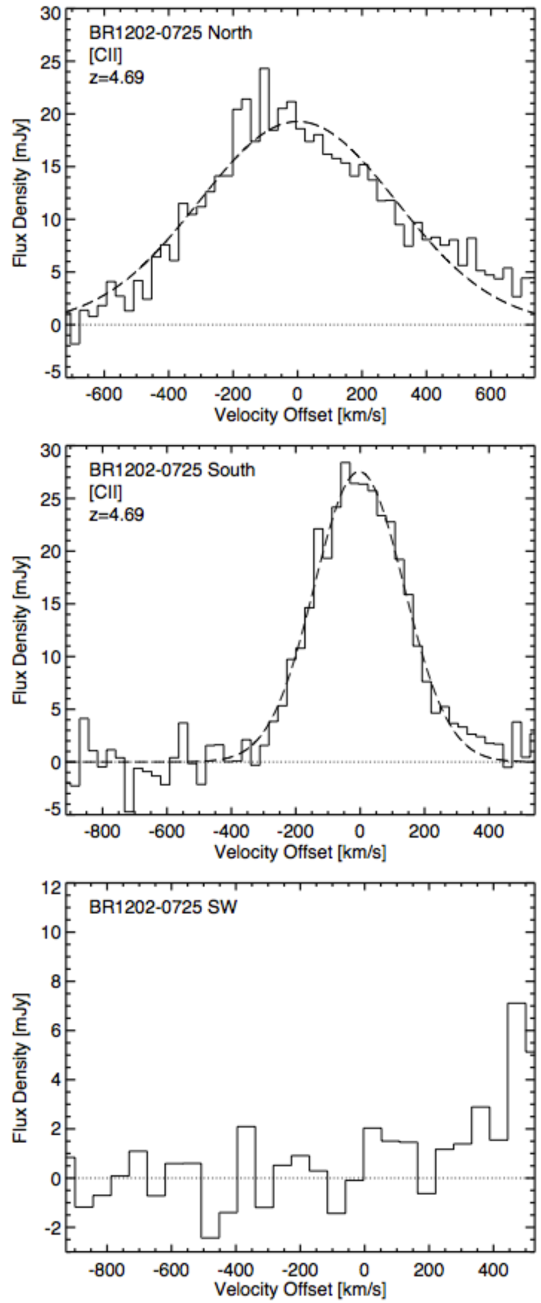



Darling et al. 2002
OH megamasers

# Extragalactic molecular studies…




IC 342
Astro-chemistry in galaxies
(e.g. Meier & Turner 2004)




ALMA result, CII
(Wagg et al. 2012)

# Limitations of studying line emission

Much of the molecular ISM in galaxies and around AGN is **clumpy**: a better understanding will require higher angular resolutions !

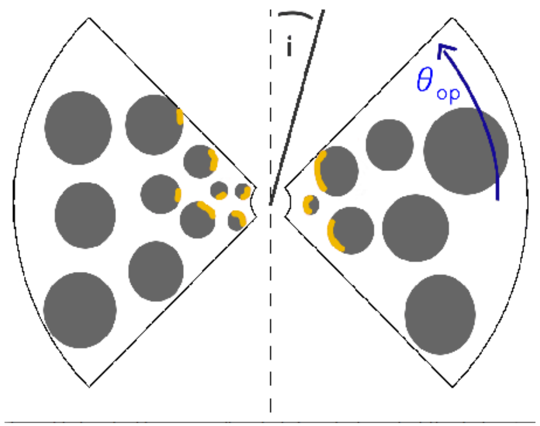
- Observed flux : $S_\nu \sim T_b \times d\Omega$

If the brightness temperature, $T_b$, matches the kinetic temperature ($T_{kin} \sim$ few hundred K) and the region around an AGN is small (few pc), the flux will be below detection threshold!

→ Study maser emission (high $T_B$ !)

→ go to higher frequencies ($I_\nu \sim \nu^2$ → study ionised gas, optical)

→ Look for absorption!




Clumpy torus model (Schartmann et al. 2008)

NASA/ESA Hubble image

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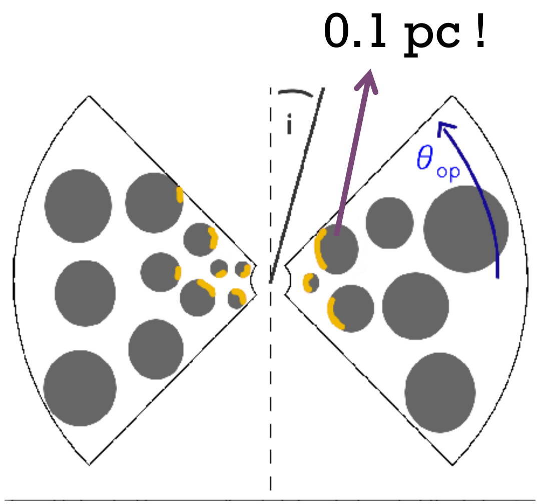


Clumpy torus model (Schartmann et al. 2008)

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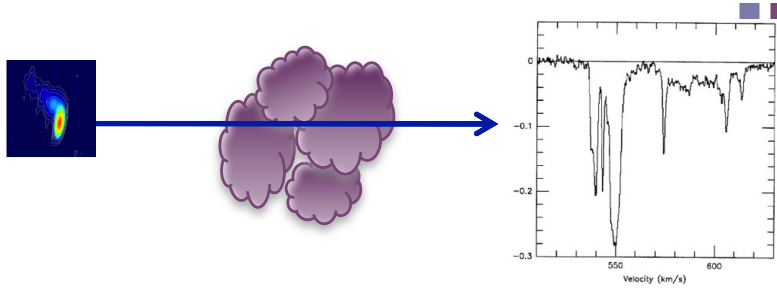
# Molecular absorption



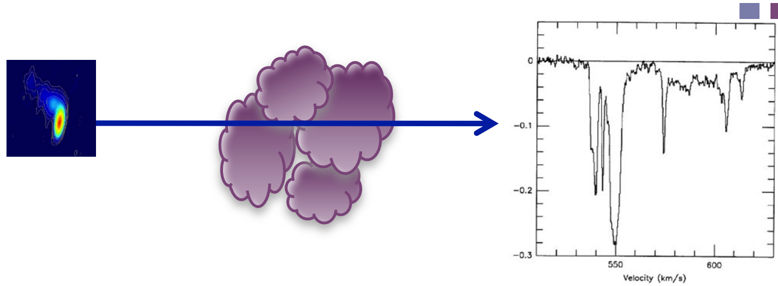

Advantages of studying molecular absorption :

- Get detailed information on the ISM → linear resolution is only limited by the size of background continuum source
- Superior sensitivity compared to emission lines (more than CO…)
  - Amount of molecular gas needed is < 1 $M_{solar}$, i.e. sensitivity ~$10^{12}$ higher than for emission!
- Compared to ionized and atomic part of the ISM, probe molecular gas component has high density and low temperatures - bulk of gas (emission biased towards warm and dense gas)

Limitations :

- sensitive to one line of sight

# + Molecular absorption




Science cases for absorption:

- Study the composition, physical and chemical conditions of diffuse gas (e.g. Lucas & Liszt 1993, 1994, 1995) -> $CO/H_2$ ratios too uncertain to provide $N(H_2)$; N(OH) and $N(HCO^+)$ most reliable indicator of $N(H_2)$ (Liszt & Lucas 1999)

- Study the neutral gas component through HI absorption (50 for $z \geq 0.1$, e.g. Carilli 1995)

- At high $z$, study the stellar formation history, column densities, kinetic and excitation temperatures ($z$ ~0.25-0.89: 5 systems e.g. Wiklind & Combes 1994, 95, 96, 98); 22 different molecules, 32 transitions. Study abundance evolution (e.g. Müller et al. 2006)

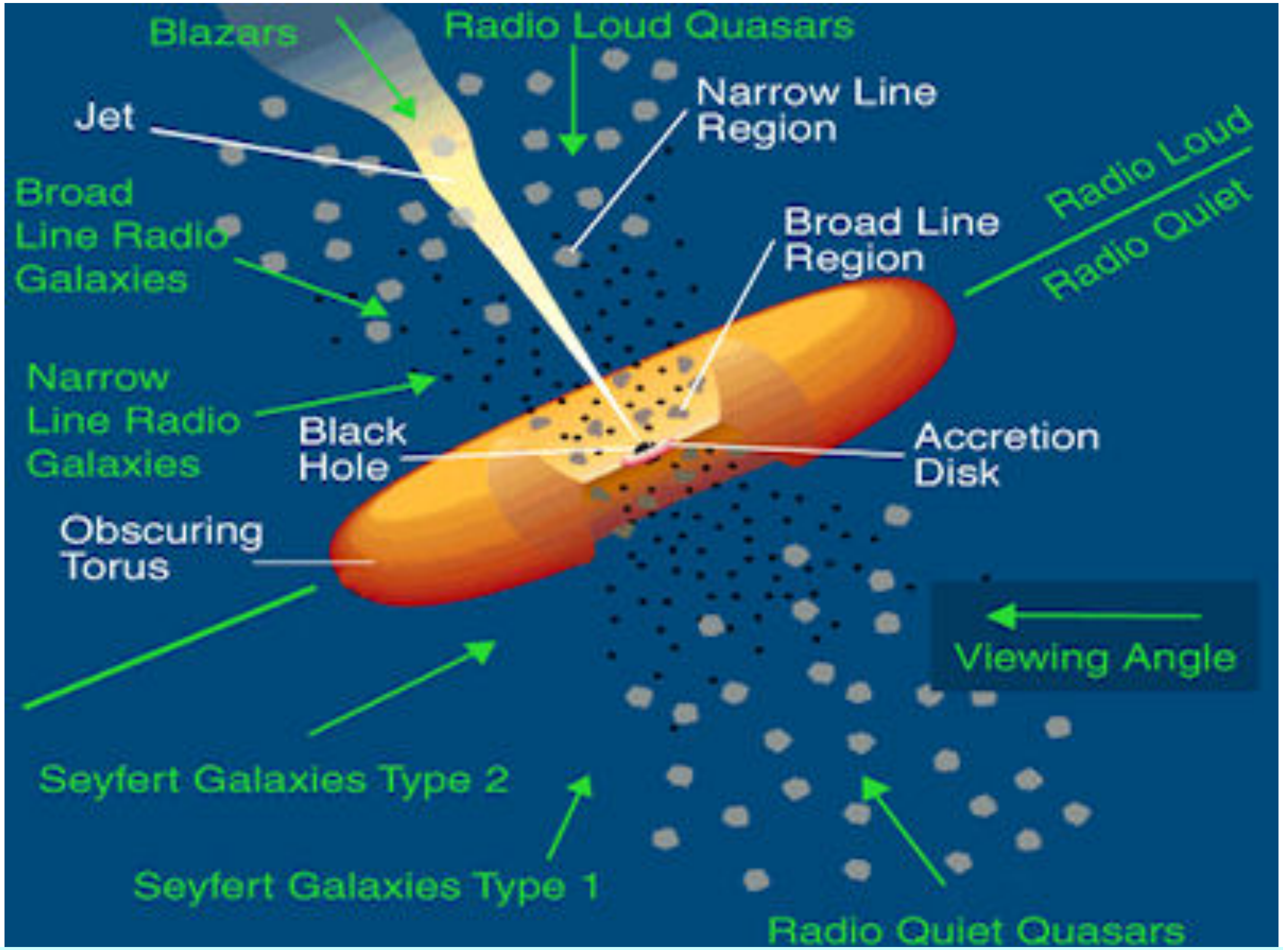
- Measure the CMB as a function of redshift, to independently estimate the Hubble constant, through time delay between lenses (e.g. Cui et al. 2005)

- Test of the invariance of fundamental physical constants ( $\alpha$ , $\mu$ , $g_{p;}$ e.g. Thompson 1975, Murphy et al. 2003, Kanekar et al. 2010; Uzan 2011 for a review )

The main uncertainty in the mm/HI comparison is that velocity differences between the mm and HI absorption lines are introduced if the lines of sight to the mm and radio continuum emission of the quasar differ (Carilli et al. 2000)

-> require **better spatial resolution**, and a statistical sample of millimeter absorbers: we need more detections! **surveys for absorption systems!**

## Molecular absorption : study the unified scheme of AGN

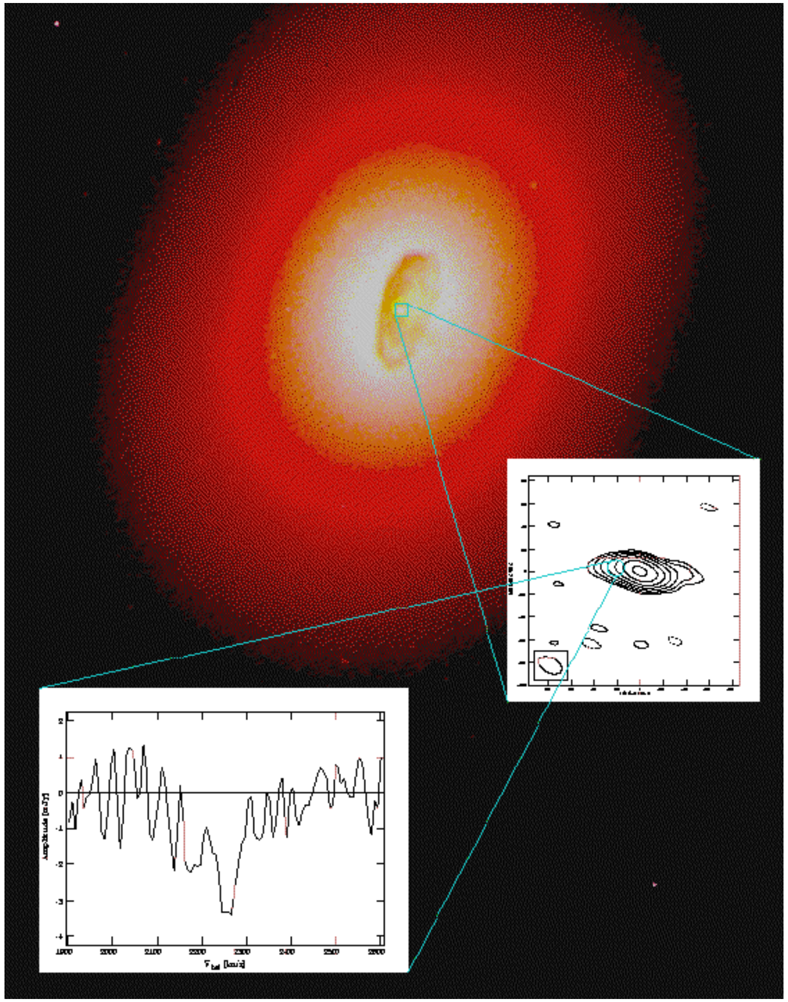



**Dusty AGN torus is molecular gas rich**

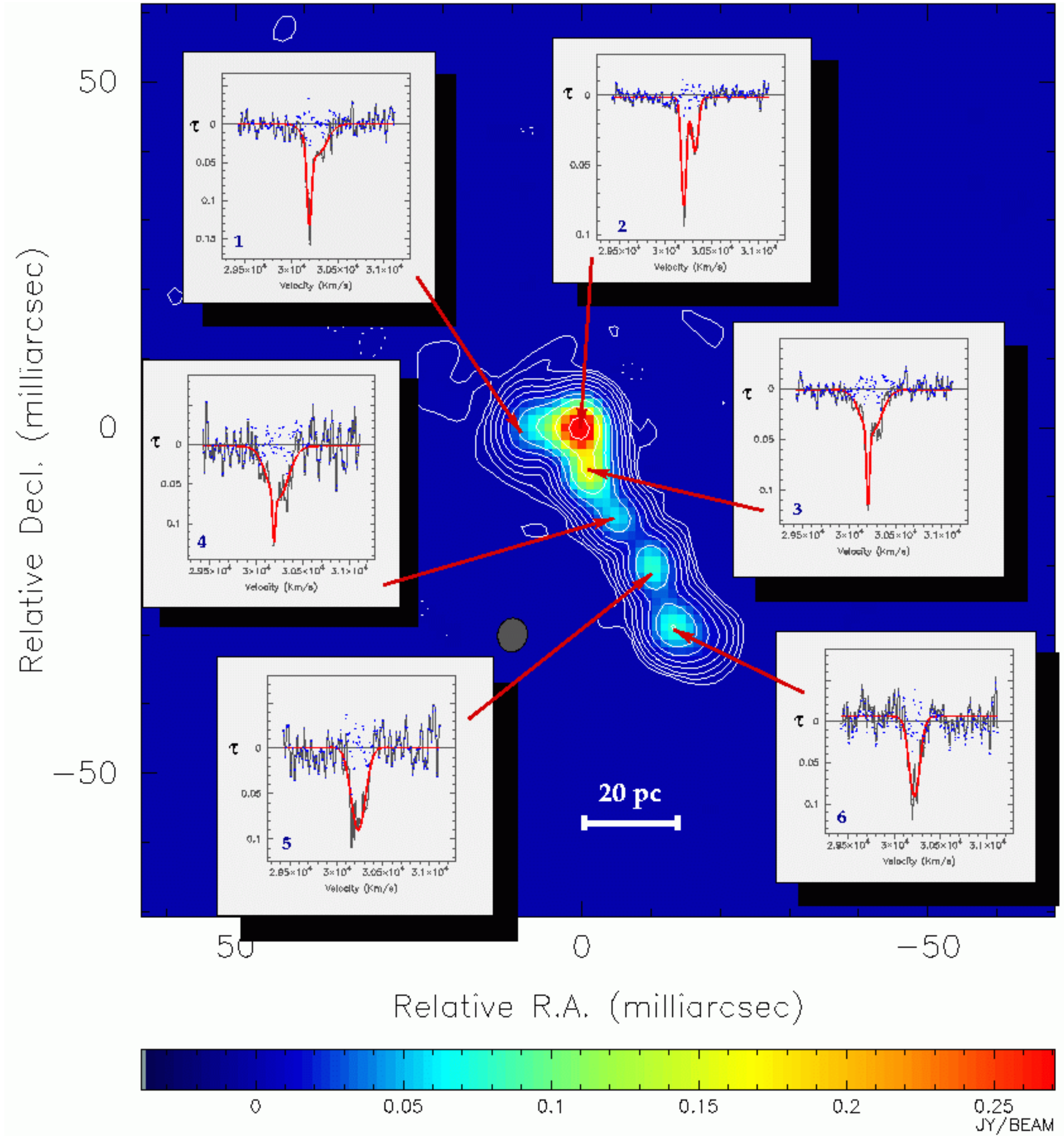
# The torus size

- Pier & Krolik (1992) approximate the density distribution with a uniform one : outer radius **R ~ 5 pc – 10 pc**.
- Pier & Krolik (1993) : later speculated that compact structure might be embedded in a much larger, and more diffuse, torus with **R ~ 30 pc –100 pc**.
- Granato and Danese (1994) elaborate toroidal geometries, concluded that the torus must have an outer radius **R ~ 300 pc – 1000 pc**.
- Granato et al (1997) settled on hundreds of pc. Subsequently, **R > 100 pc** became common lore.
- High-resolution IR observations brought unambiguous evidence in support of compact torus dimensions. VLTI interferometry shows that the 10 $\mu$m flux comes from a hot (T > 800 K) central region of ~ **1 pc** and its cooler (T ~ 320 K) surrounding within **R ~ 2 pc** and **3 pc** (for NGC 1068; Jaffe et. al 2004).

# HI absorption

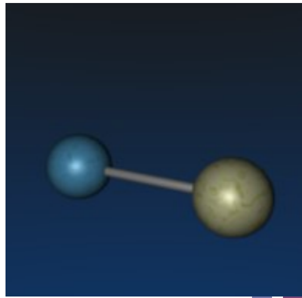


NGC 4251, EVN (van Langevelde et al. 2000)




EVN+VLBA+GBT (Peck & Taylor 2001)

# OH surveys



- Expect to observe molecular absorption against the compact, flat spectrum radio cores of NLRs.
- Not only confirm the existence of a torus, but also derive valuable physical and kinematical 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).

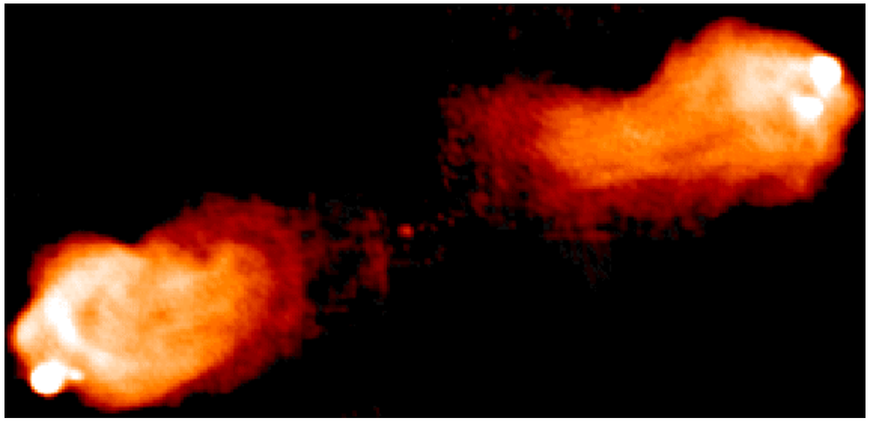
***Surprisingly few detections!***

**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
- NLR
- Large X-ray absorbing column ($10^{23.5}$ cm$^{-2}$)
- Search for CO (1-0) absorption yielded non detection!
- Search for OH (1.6 GHz) non detection

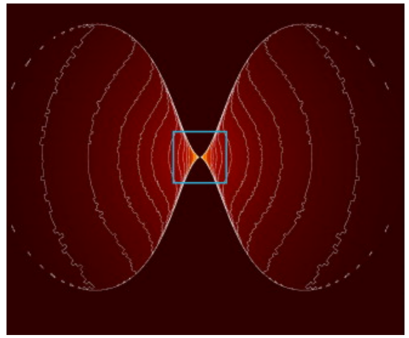
| | | |
|---|---|---|
| Search for | OH (1.6 GHz) | non detection |
| | $H_2CO$ | non detection |
| | HI | detected (Coway & Blanco 1995) |



# A new survey for OH absorption

- Search for highly excited rotational states of OH at 6.035 GHz & 6.031 GHz, 4.750 GHz and 13.4 GHz.

The sample:

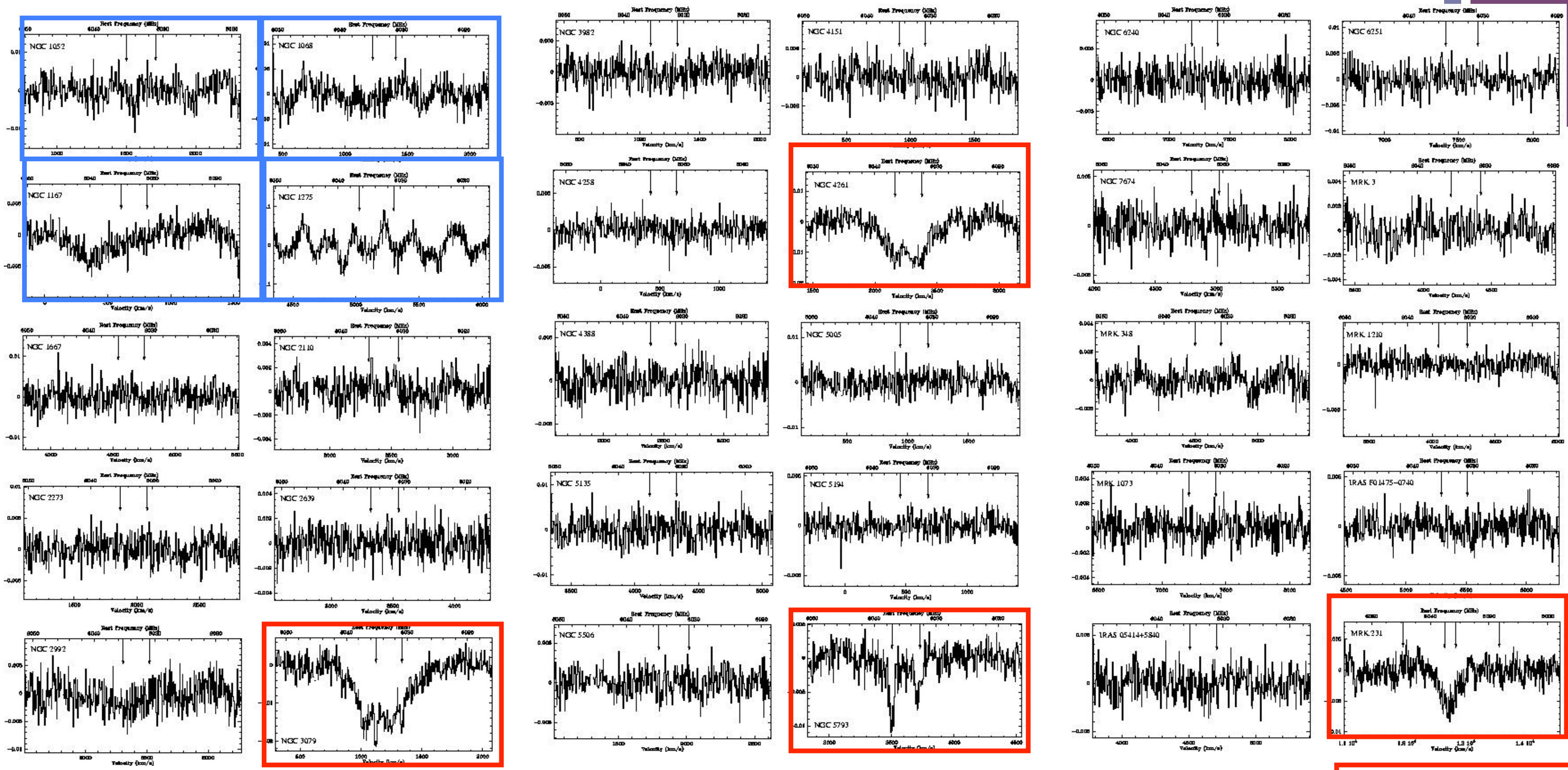


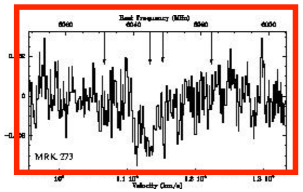
- 31 Seyfert 2 galaxies
- High X-ray absorbing columns (> $10^{22}$ $cm^{-2}$ )
- Continuum flux density at 6 GHz > 50 mJy
- HPBL

Effelsberg observations:

- 3-10 hours per source at 4.7 GHz and 6.0 GHz, PSW
- Velocity coverage 2000 km/s (4 km/s per channel)
- Sensitivity 3.5 mJy (5 $\sigma$ ) = line opacity of 0.002 to 0.07

# Effelsberg spectra at 6.0 GHz




Too strong continuum - Large standing wave ripple!

5 new detections - detection rate 18 %

Broad lines -> inflow/outflow?

Bimodal distribution of absorptions –> very compact clouds ?

## NGC 3079

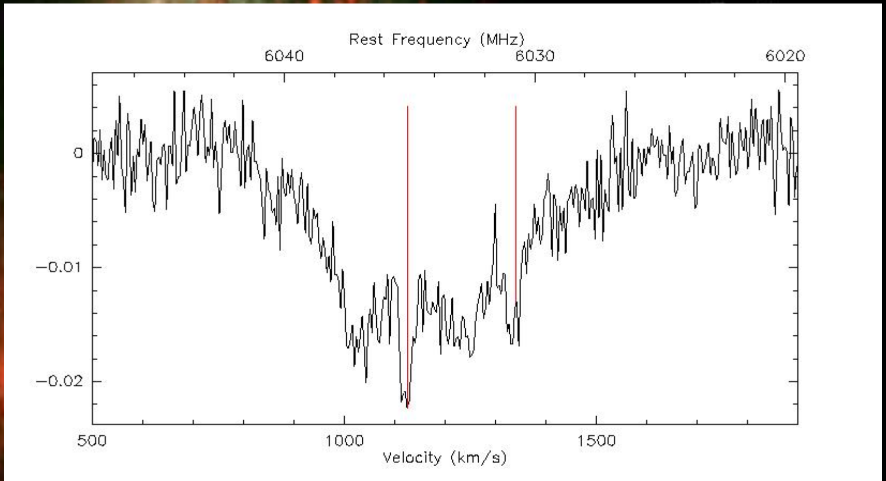
Galaxy NGC 3079
G. Cecil (University of North Carolina)

- Width ~ 800 km $s^{-1}$
- Line opacity $\tau \sim 0.055$
- 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$^{-2}$

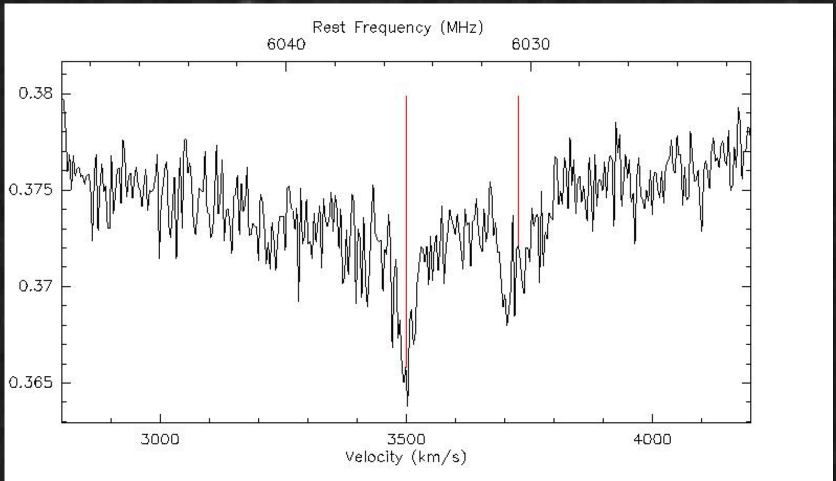



## NGC 5793

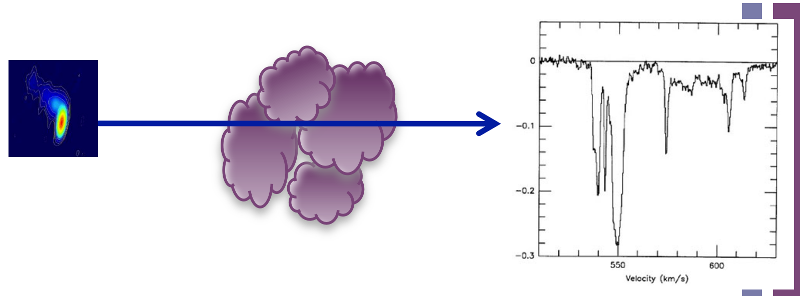
- Width ~ up to 1000 km $s^{-1}$
- Line opacity $\tau \sim 0.036$
- 4.7 GHz non-detection
- 1.6 GHz abs (Hagiwara et al. 2000)

$T_{ex} = 67$ K

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



# Molecular absorption




True optical depth $\tau$ : $= - \ln (-S_l / f_c \times S_c)]$

$f_c$ = filling factor

- The opacity (and thus column density) depends on the excitation temperature (non-linearly) and on the covering factor (both unknown)
- Estimate $T_{ex}$ by studying several transitions
- Background source is finite, and small dense structure influence the estimation of the column density

$N_{H2} = 4/3\ n_H\ r_c \times (1 - \text{expt}\ (- \ \tau_{obs}) /\ f_c\ f_v\ )\ \text{cm}^{-2}$

→ The column density can be under-estimated by **three orders of magnitude** if the molecular ISM is made up of small dense clumps rather than diffuse medium !

→ **Clumpy media are common ! Require VLBI resolution !**

In the Milky Way the molecular ISM is clumpy on scales from 20 AU to 100 pc. Time variability of $H_2CO$ absorption suggests structures of ~ 10 AU (e.g. Marscher et al. 93)

# VLBI observations of OH

- VLBA observations carried out with interferometric observations to detect OH at 13.4 GHz towards the core of NGC 1052 and Cygnus A.

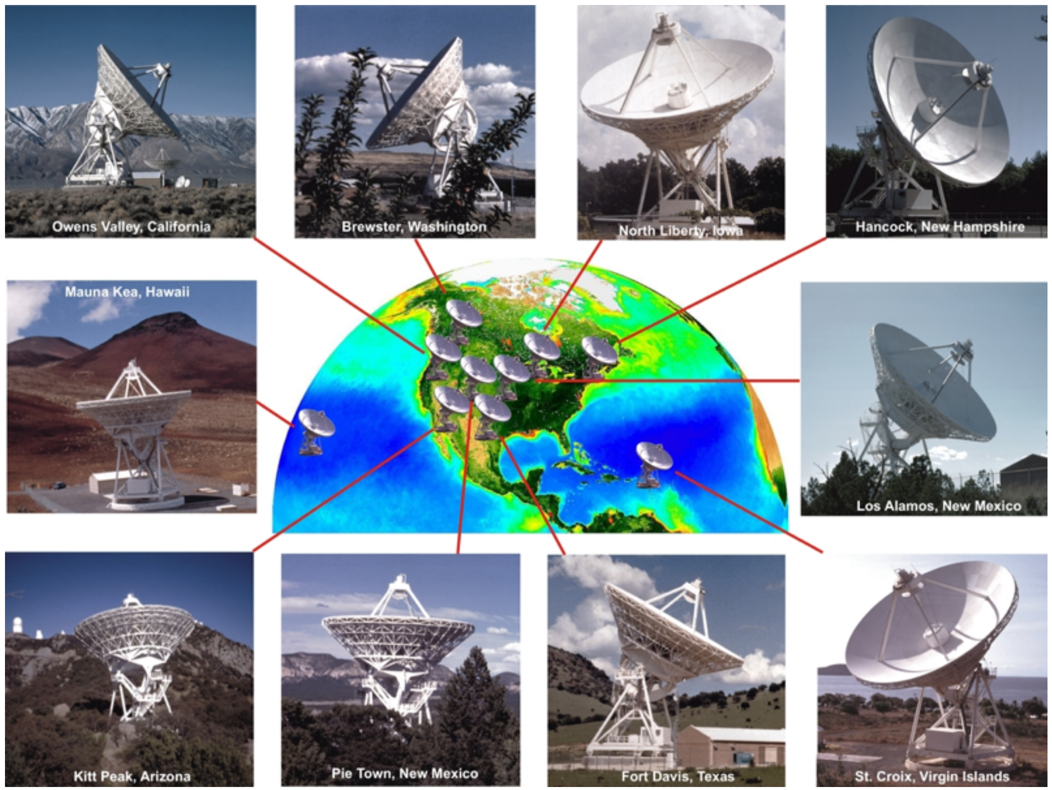
$\alpha \propto \frac{\lambda}{D}$ => 0.9 mas beam

Observing time:

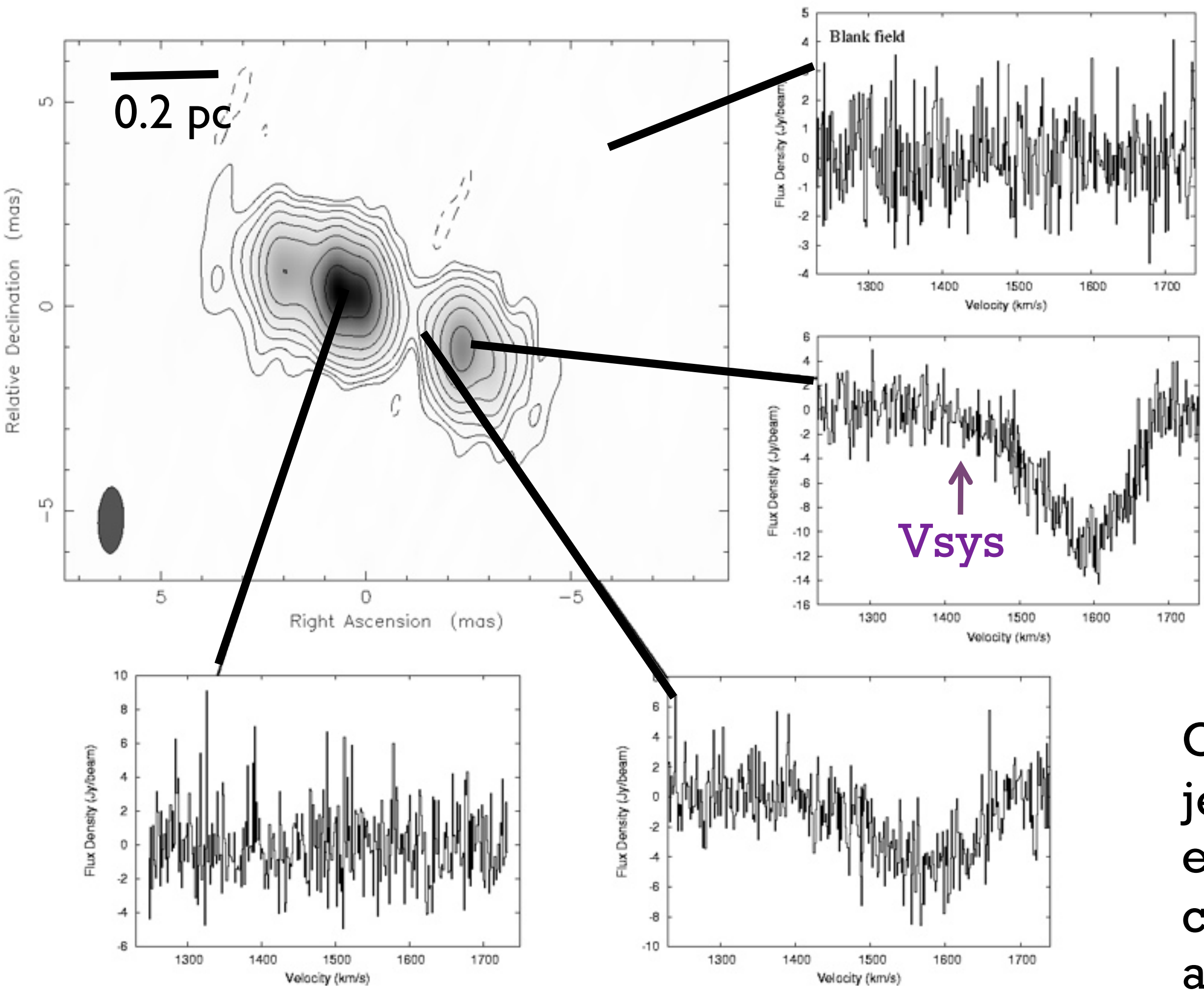
NGC 1052 – 7 hours
Cygnus A – 8 hours

Bandwidth 16 MHz (256 channels) per IF.

Velocity coverage ~ 560 km/s.



# NGC 1052 VLBA results



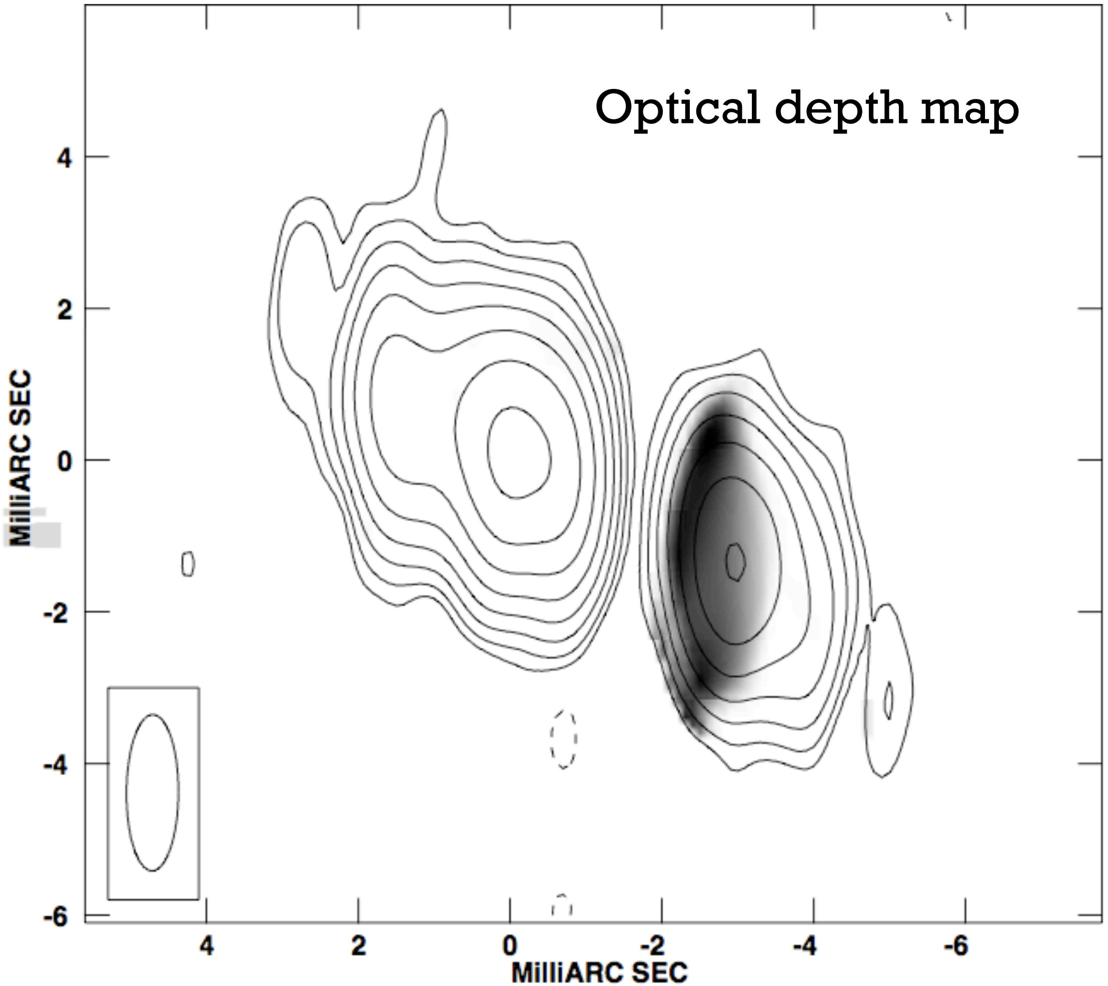

Broad Width:
FWHM ≈ 200 km/s

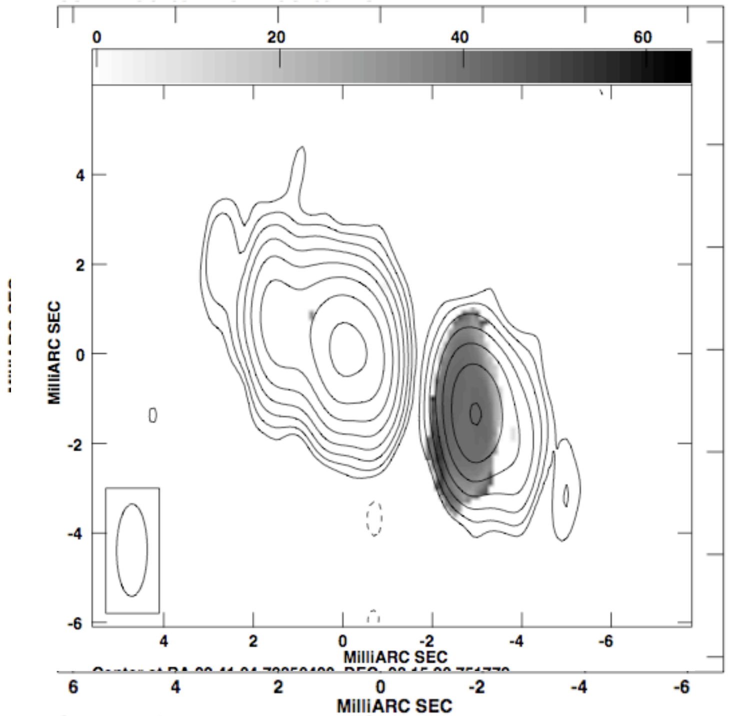
Optical depth
(counter jet)

$\tau_{OH} \approx 0.264$

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

# Where is the absorption located?



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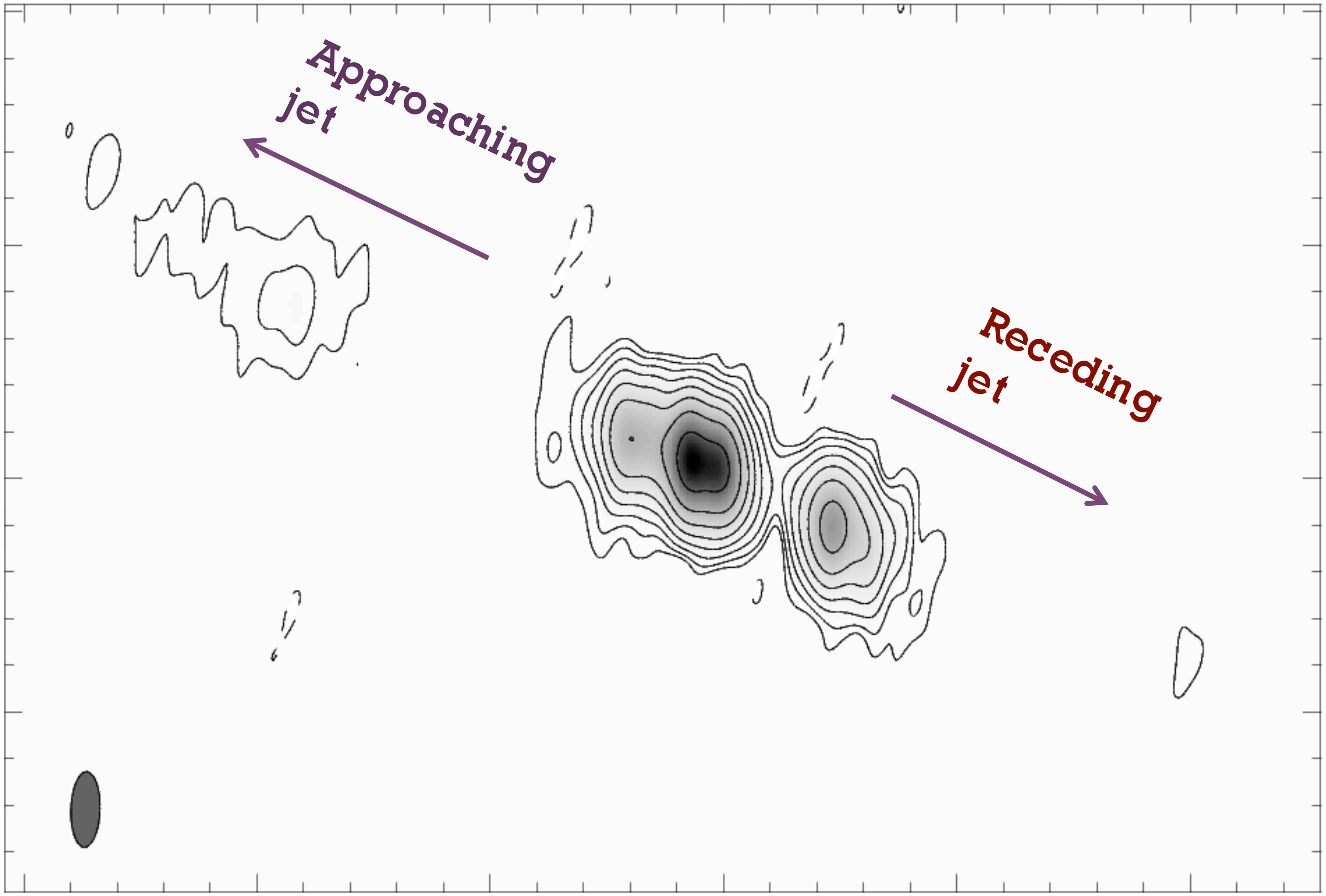

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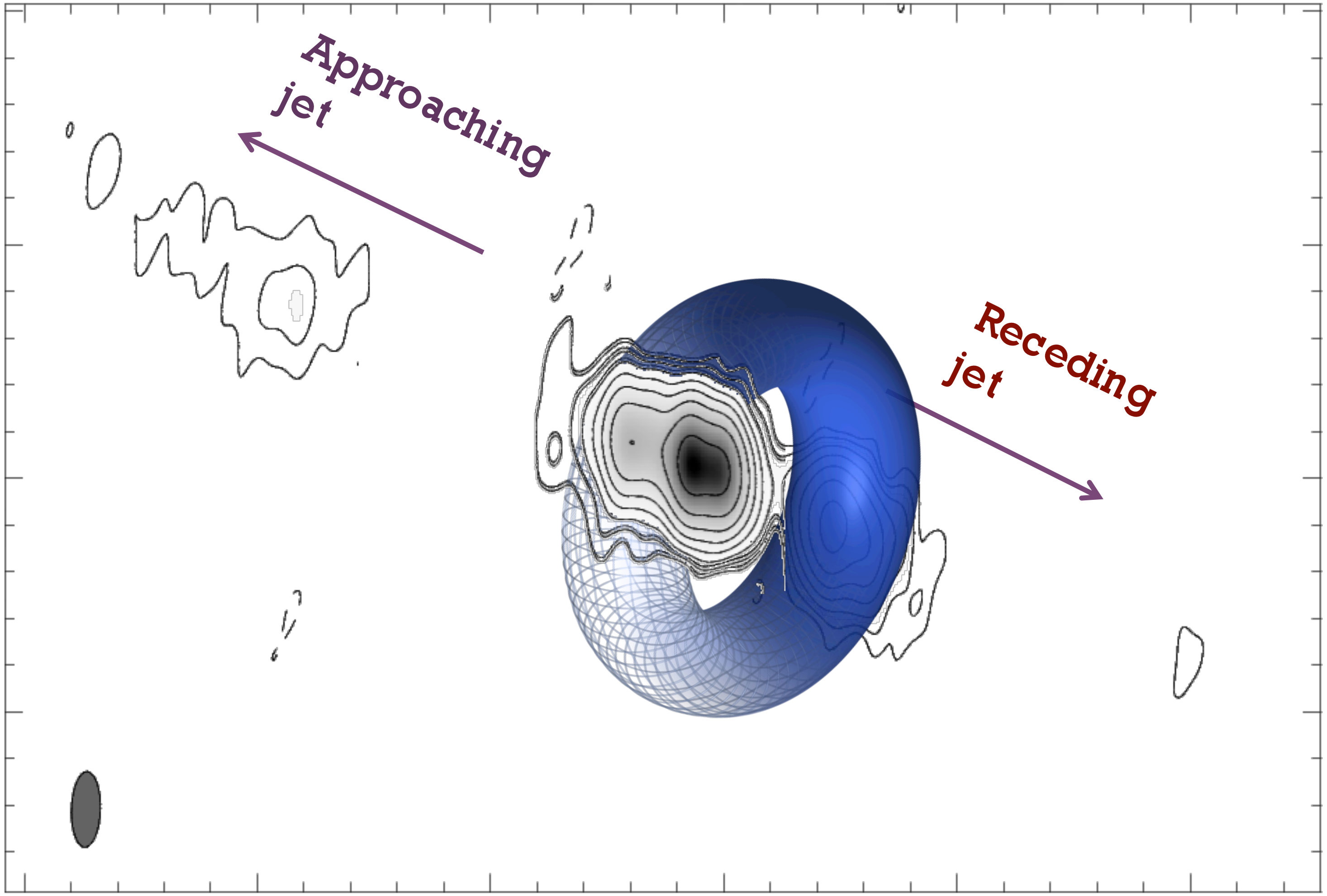
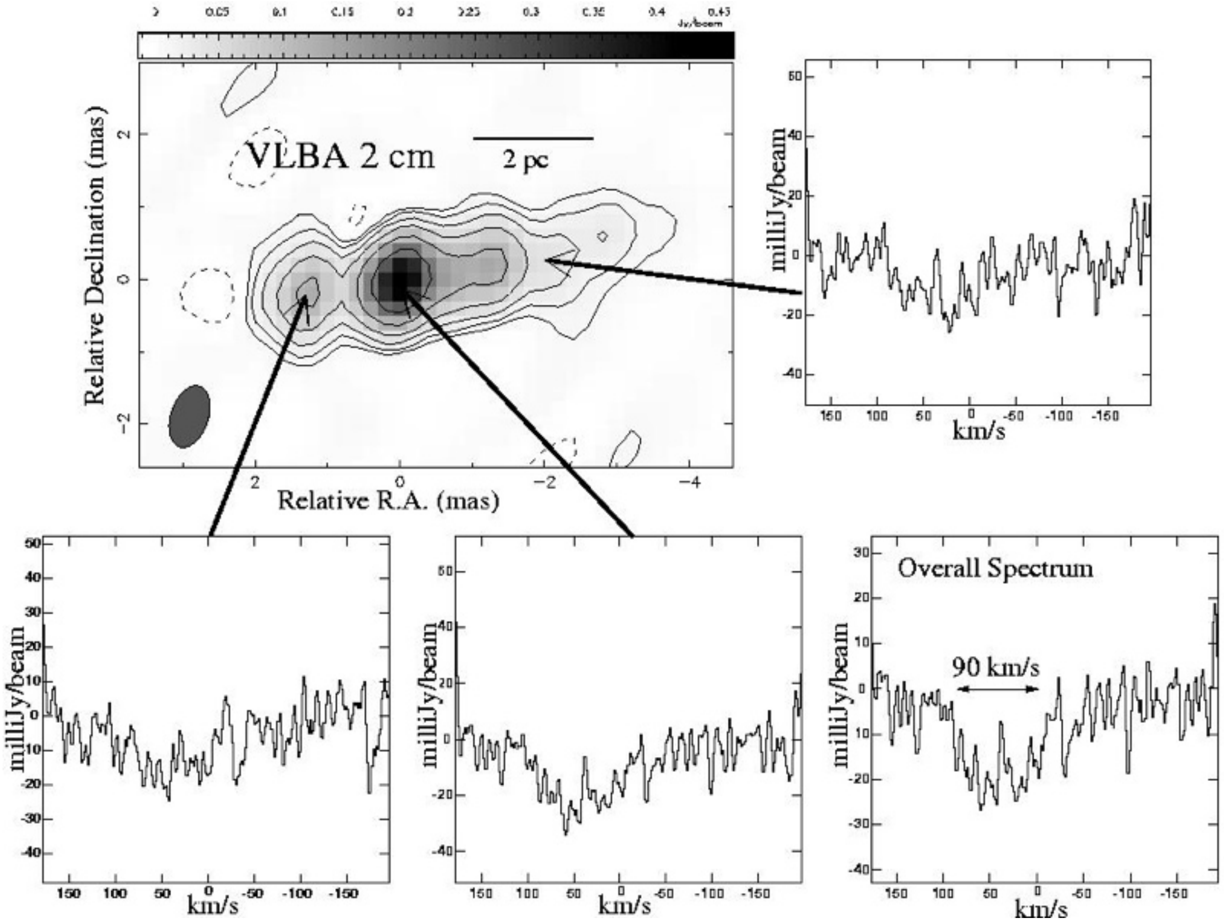


# Cygnus A




Continuum peak flux
453 mJy per beam

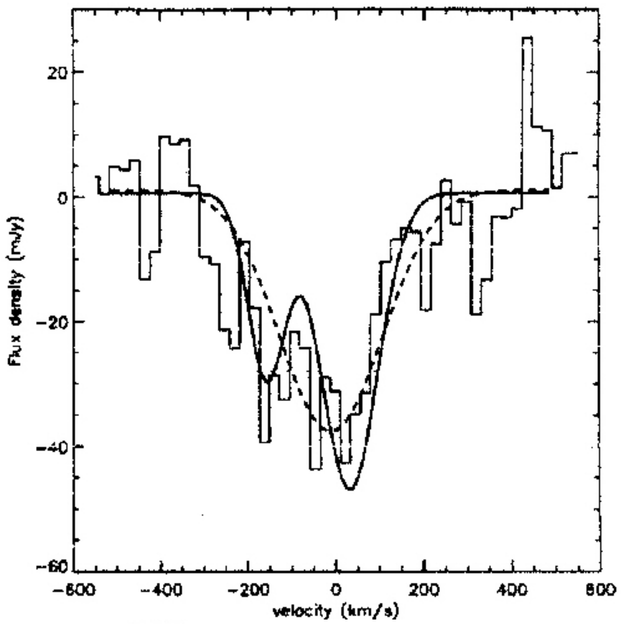
Optical depth (core)
$\tau_{OH} \approx 0.12$

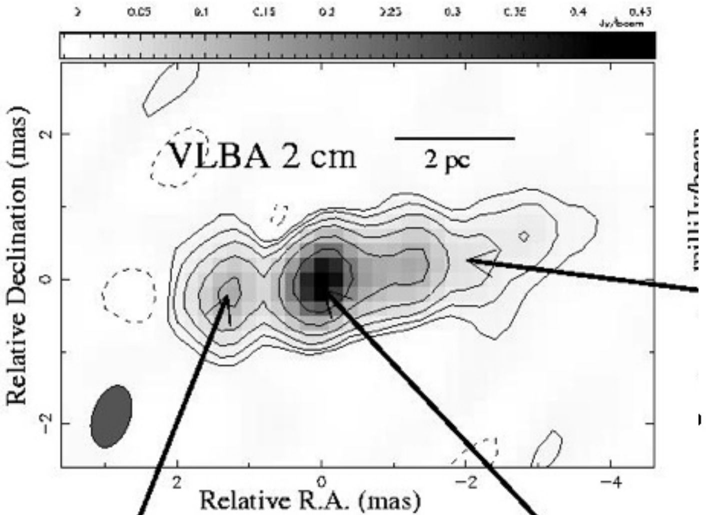
Absorbing gas is diffuse around the inner jets.

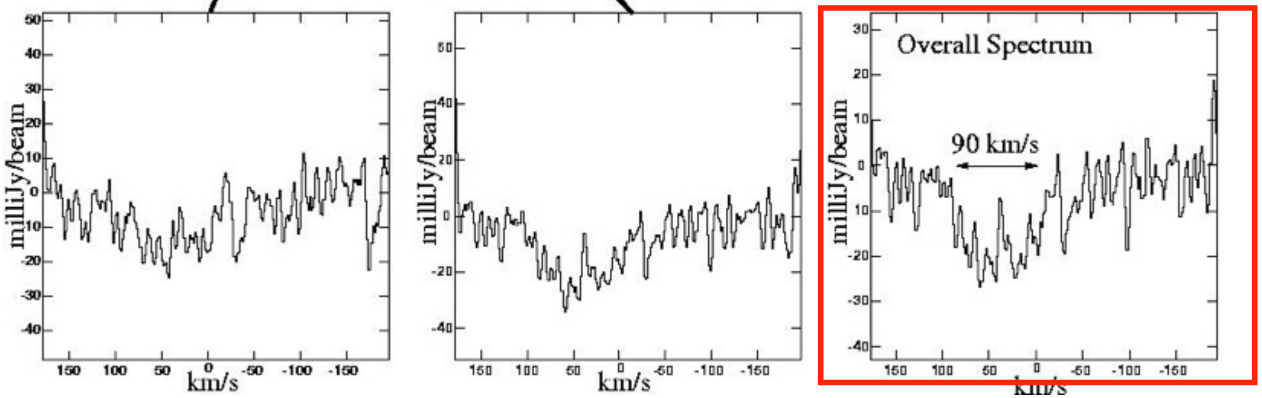
Profile strongest over the entire continuum.

# + Cygnus A

Conway & Blanco 1995

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mJy per beam

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OH ≈ 0.12

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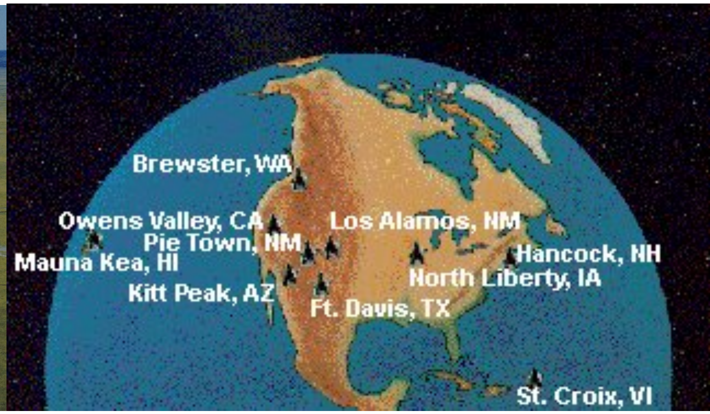
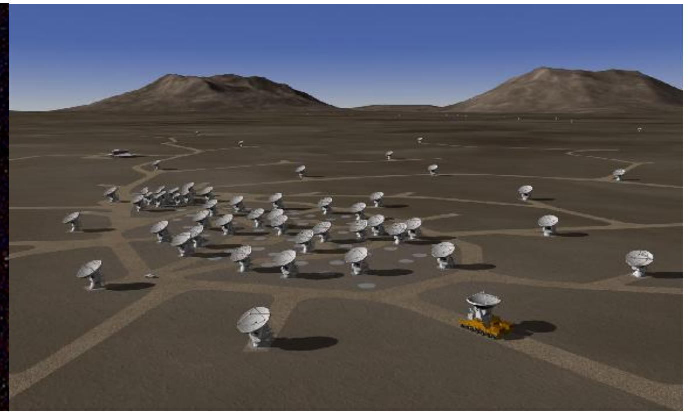
Profile strongest over the entire continuum.

# Future outlook

- Molecular absorption lines are an excellent probe to molecular rotational lines, with a sensitivity which is mainly limited by the strength of background continuum
- Future surveys for the molecular component of AGN should excited molecular lines (higher frequencies, more compact regions)
- New instruments like the VLBI, EVLA, ALMA and mm-VLBI with their increased sensitivity will hugely contribute to a high resolution, sensitive study of the molecules in AGN:

perhaps a new era also for the Torus?



# Future outlook

For a source at the distance of NGC 1052:

VLBA resolution : 1mas at 13.0 GHz : 0.1 pc
EVLA resolution : 4 arcsec at 5.0 GHz : 400 pc
ALMA resolution : 0.5 arcsec at 1mm: 50 pc
(early science)
ALMA resolution: 18mas at 1mm : 2 pc
(extended configuration 17 km)

Mm-VLBI resolution : 0.009 pc (at 3mm) !