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Extragalactic maser science with large radio telescopes

Amasing collaborators:

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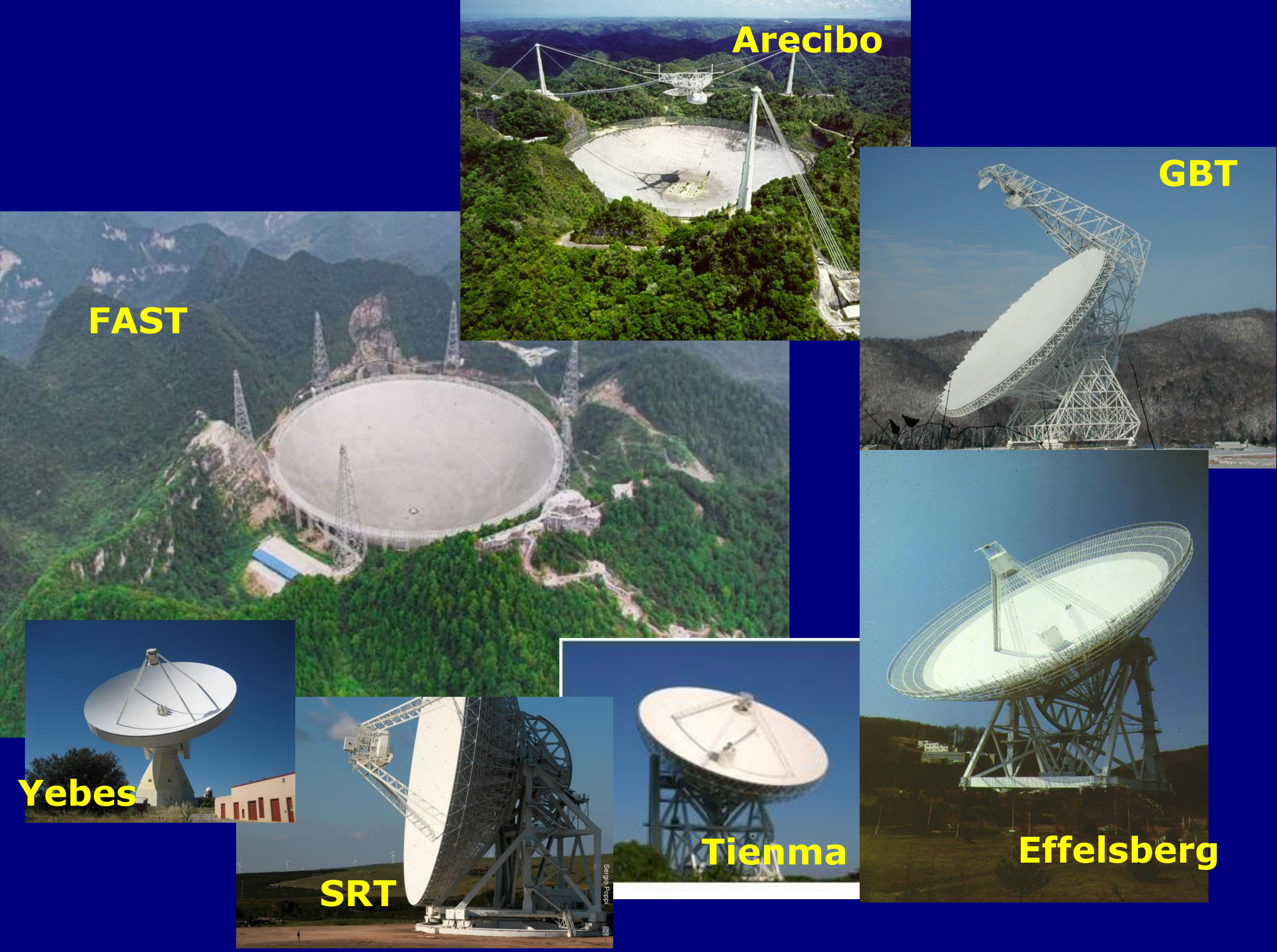
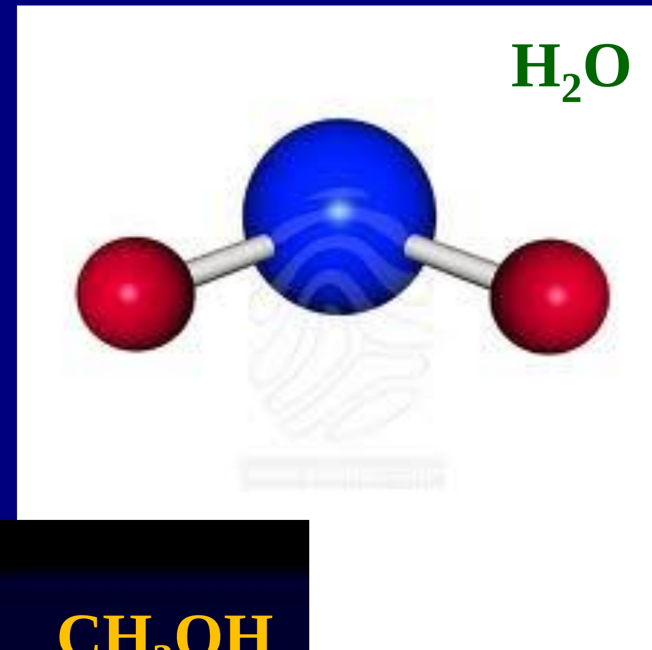
K. Menten (MPIfR Bonn)

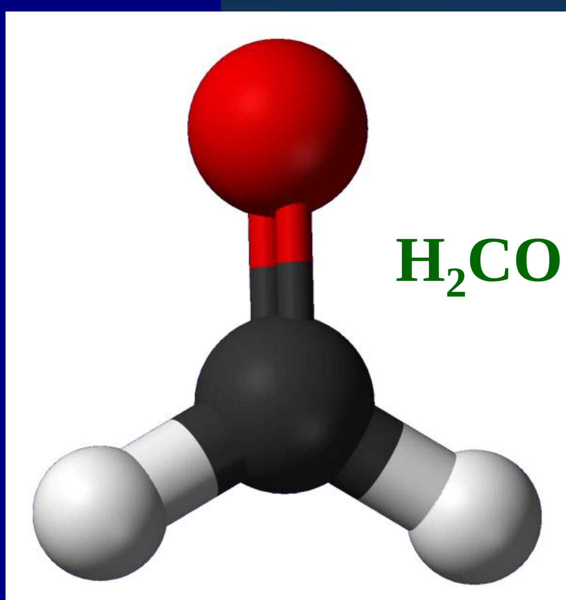
J. Braatz (NRAO, Charlottesville)…….and many others

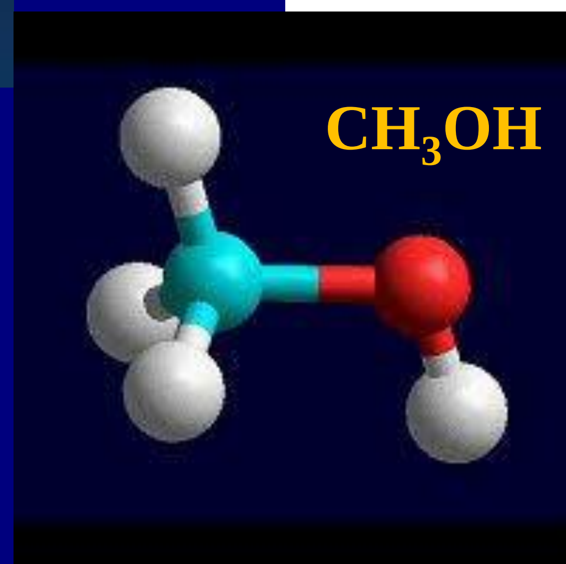
This presentation has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730562 [RadioNet]


Arecibo
GBT
FAST
Yebes
SRT
Tienma
Effelsberg

(Mega)Masing detected molecules







OH and H_2O (…and others)

Main OH maser lines (hyperfine transitions of rotational levels):

- Rest frequencies **1665, 1667,** 1612, 1720 **MHz (L-Band)**
- Trace a relatively warm and dense gas
  - $100 < T < 300$ K
  - 10^4 cm^{-3} $< N(H_2) < 10^6$ cm^{-3}

Main H_2O maser line ($6_{16} \rightarrow 5_{23}$ rotational transition):

- Rest frequency **22.23508 GHz (λ =1.3 cm)**
- Traces a warmer and denser gas
  - $300 < T < 1000$ K
  - 10^7 cm^{-3} $< N(H_2) < 10^{11}$ cm^{-3} (also 183 and 321 GHz)

Other main masers: CH_3OH (6.7, 36, 44 GHz) and H_2CO (5, 15 GHz)

Extragalactic H_2O masers

Maser sources are found:

- associated with star formation. They can reach ~ 10 L_{SUN}
(NGC2146: Tarchi et al. 2002; NGC3256: Surcis et al. 2009)

- in the central regions of AGN, at a few parsecs from the nuclear engine. They are typically luminous and can reach up to 30,000 L_{SUN} (MGJ0414+0534: Impellizzeri et al. 2008, Castangia et al. 2011)

Extragalactic H_2O masers in AGN

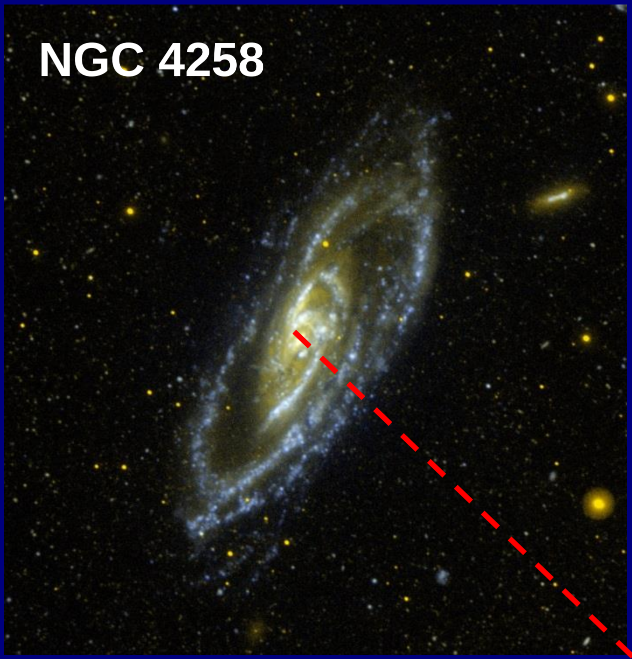
H_2O Masers allow us to study the structure and the dynamics of the gas in the inner parsecs of AGN:

Disk-masers → **Disk geometry and black hole masses (e.g. NGC 4258, Herrnstein et al. 1999)**

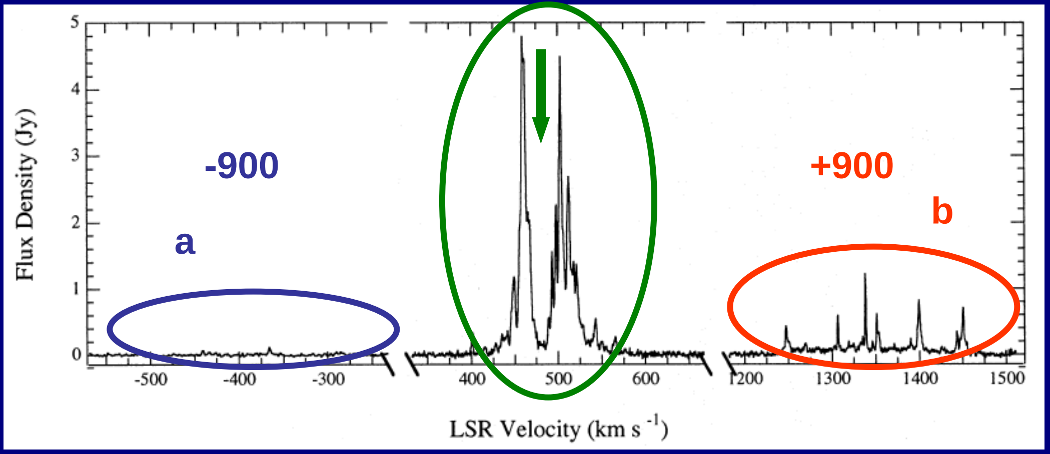
Jet-masers → **Evolution of the jet (e.g. NGC1052, Claussen et al. 1998)**

Outflow-masers → **Geometry of the outflow (e.g. Circinus, Greenhill et al. 2003)**

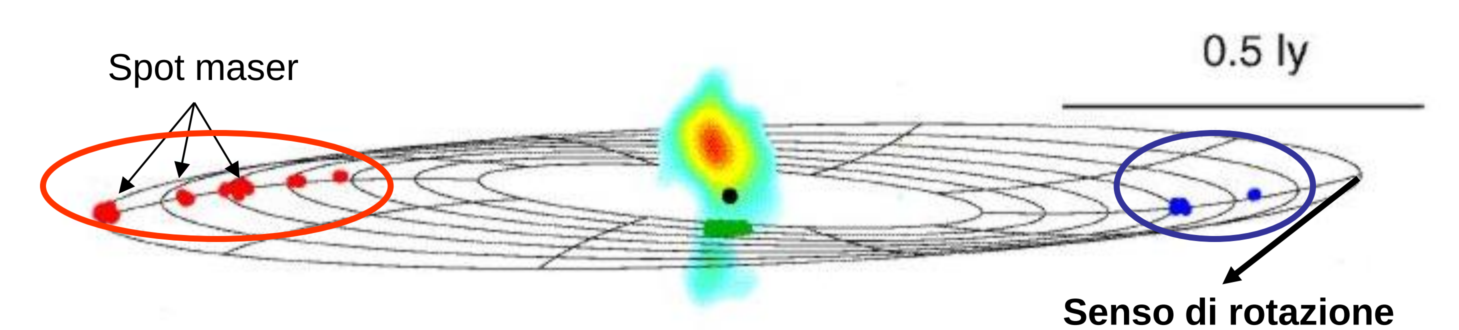
Disk-masers



Triple-peak profile



Maser spots trace the accretion disk



Estimate of the black hole mass and geometry of the keplerian accretion disk → Distance to the host galaxy

Extragalactic H_2O masers as astronomical tools

H_2O Masers allow us to study the structure and the dynamics of the gas in the inner parsecs of AGN:

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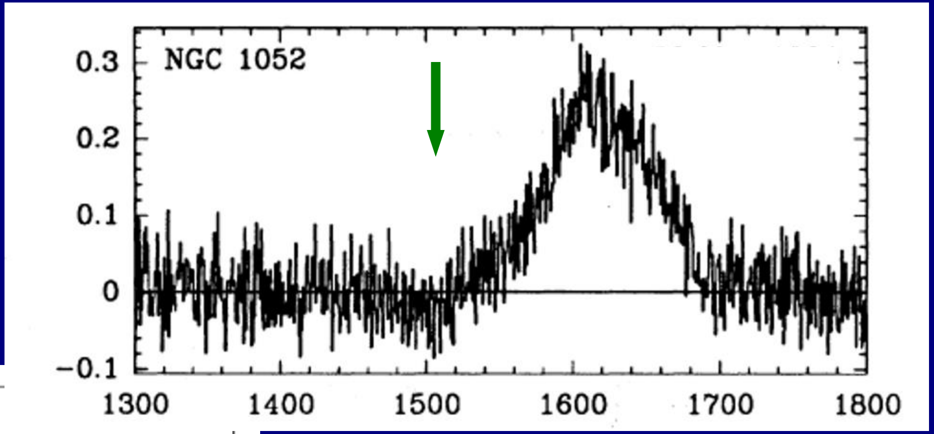
Outflow-masers → **Geometry of the outflow (e.g. Circinus, Greenhill et al. 2003)**

Jet-masers

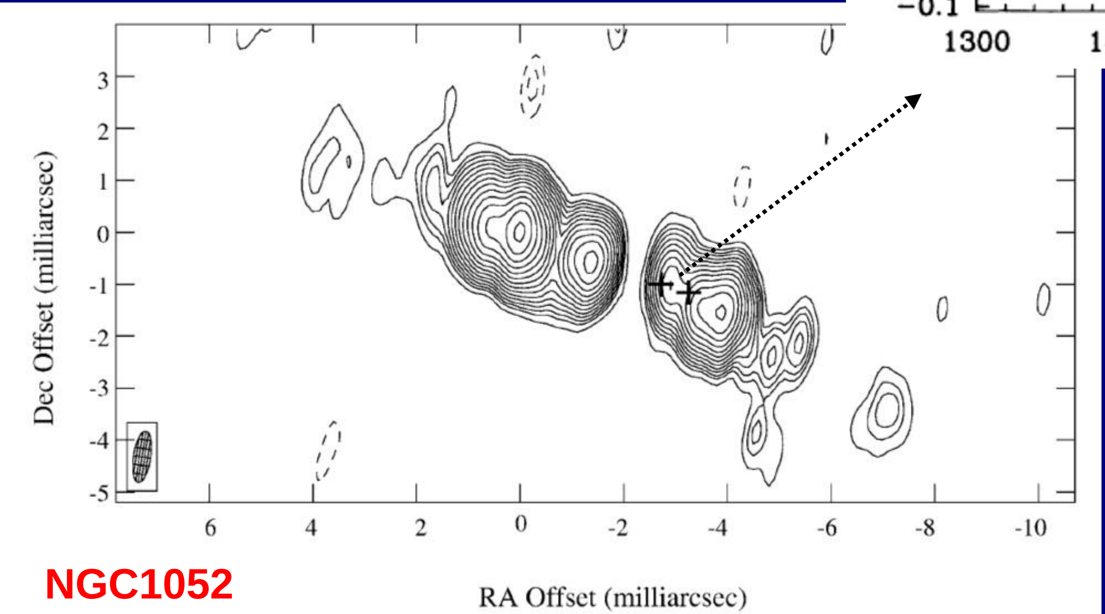
Single broad line



Jet-cloud interaction or

overlapping cloud - jet

radio continuum



NGC1052

Information on the geometry and expansion velocity of radio jets

Extragalactic H_2O masers as astronomical tools

H_2O Maser VLBI technique allow us to study the structure and the dynamics of the gas in the inner parsecs of AGN:

Disk-masers → **Disk geometry and black hole masses (e.g. NGC 4258, Herrnstein et al. 1999)**

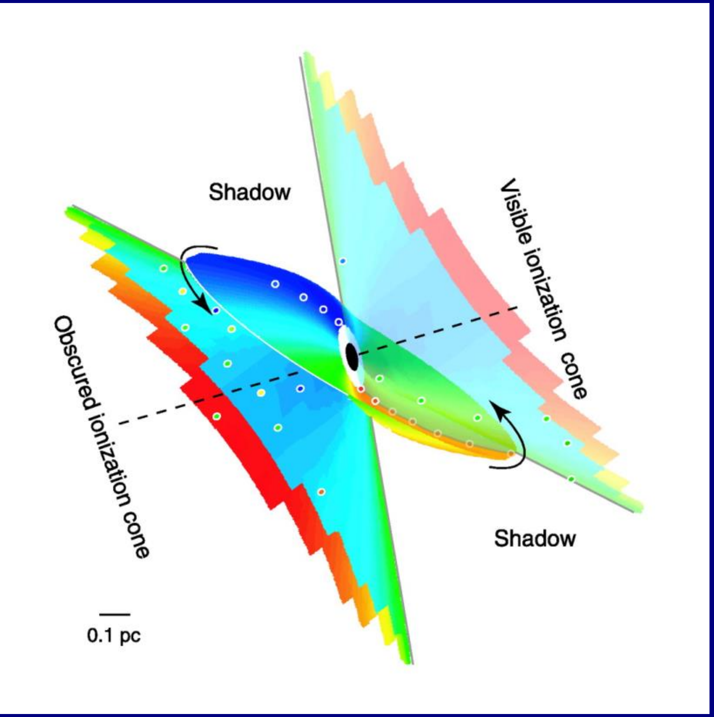
Jet-masers → **Evolution of the jet (e.g. NGC1052, Claussen et al. 1998)**

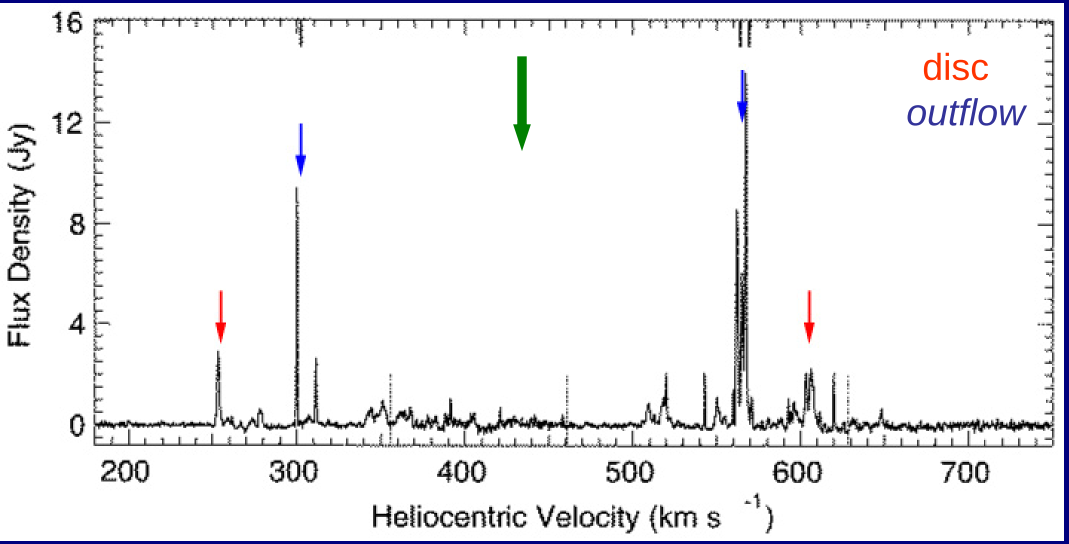
Outflow-masers → **Geometry of the outflow (e.g. Circinus, Greenhill et al. 2003)**

Outflow-masers: Circinus

H_2O masers trace a warped edge-on accretion disk and a wide-angle outflow

Line complex





Determination of the nature and origin of the outflow

OH (mega)masers

- **OH (mega)masers (~100) are almost uniquely associated with LIRGs ($L > 10^{11}\ L_{sun}$) and ULIRGs ($L > 10^{12}\ L_{sun}$) and are IR radiatively pumped ($L_{OH} \alpha (L_{FIR})^{1.2}$**

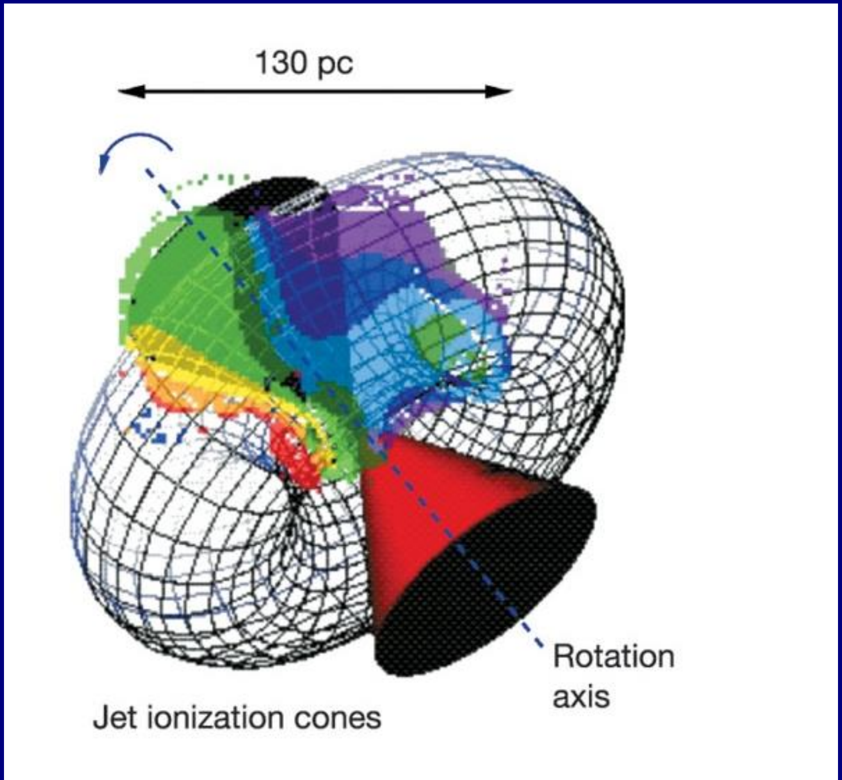
  (e.g., Baan 1989; Darling & Giovanelli 2002)

- **Extent ≤ 100 pc and found in high concentration of molecular gas where intense/extreme starbursts are ongoing (in rotating disks, tori, else?).**

  Association with starburst → short-lived phenomenon (?)

  (e.g., Lo 2005, and references therein)

OH (mega)masers: Mrk231



OH maser emission (mapped with the EVN) traces a rotating, dusty, molecular torus (or thick disk) located between 30 and 100 pc from the central engine.

Klöckner, Baan, & Garrett (2003) Nature

(Single-dish) Surveys

Find them in nearby galaxies (extended mapping)

→ Multi-feed capabilities

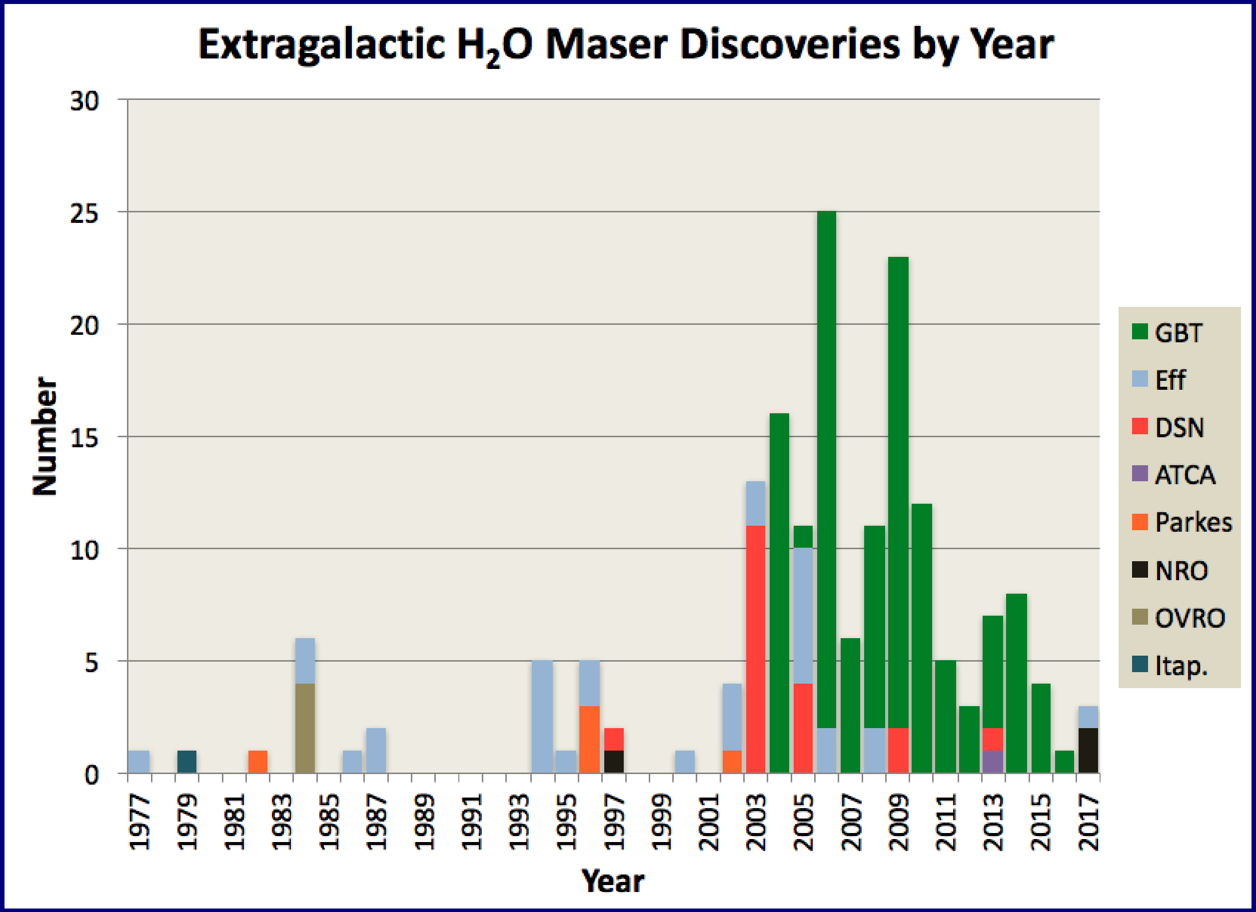
Find them in far-away objects (high-z luminosity function)

→ sensitivity, minimal overheads

Find them, at all (extensive searches, focused samples)

→ sensitivity, samples criteria

A History of Surveys



https://safe.nrao.edu/wiki/bin/view/Main/MegamaserCosmologyProject

- **178 galaxies currently known as maser hosts**
- **MCP: 85/2800 = 3%**
- **~ 37 are in disks and suitable for M_{BH} measurement**
- **10 targeted for distance measurement**
- **Primary sample for MCP surveys: Type 2 AGNs at $z < 0.05$ from SDSS, 6dF, 2MRS**

Courtesy: J. Braatz

H_2O masers in E/radio-loud hosts

So far, (almost) no water masers in elliptical and/or radio-loud galaxies:

50 FRI with *z* < 0.15 (Henkel et al. 1998)

274 Type 2 QSOs with 0.3 < z < 0.83 (Bennert et al. 2009)

30 FRII (*unpublished*, Braatz, Priv. Comm)

5 Grav. Lensed Quasars with 2.3 < z < 2.9 (McKean et al. 2011)

17 Type 1 QSOs with z < 0.06 (Koenig et al. 2012)

How about a well-planned FRII sample?

FRII galaxies from 3CR catalog

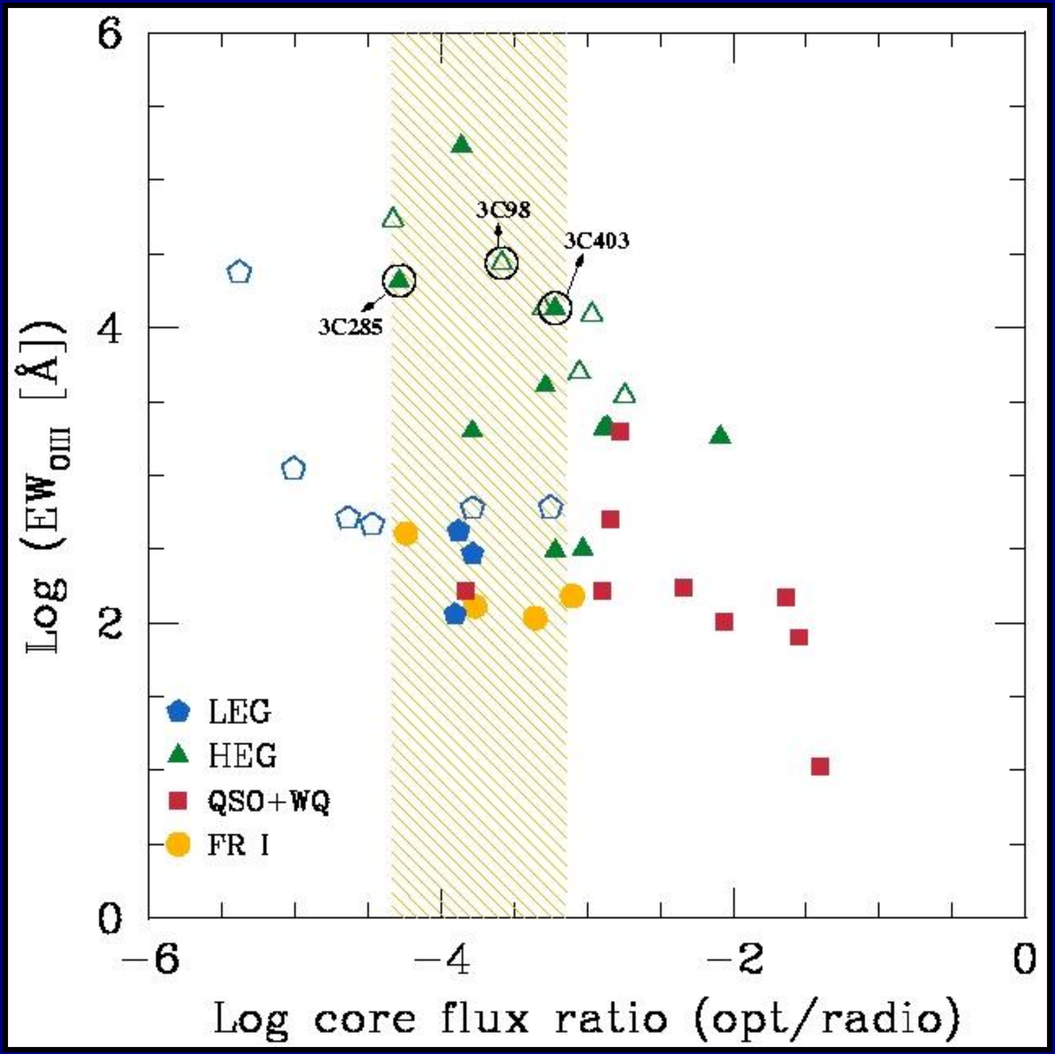
z < 0.1

Spectrally classfied HEG

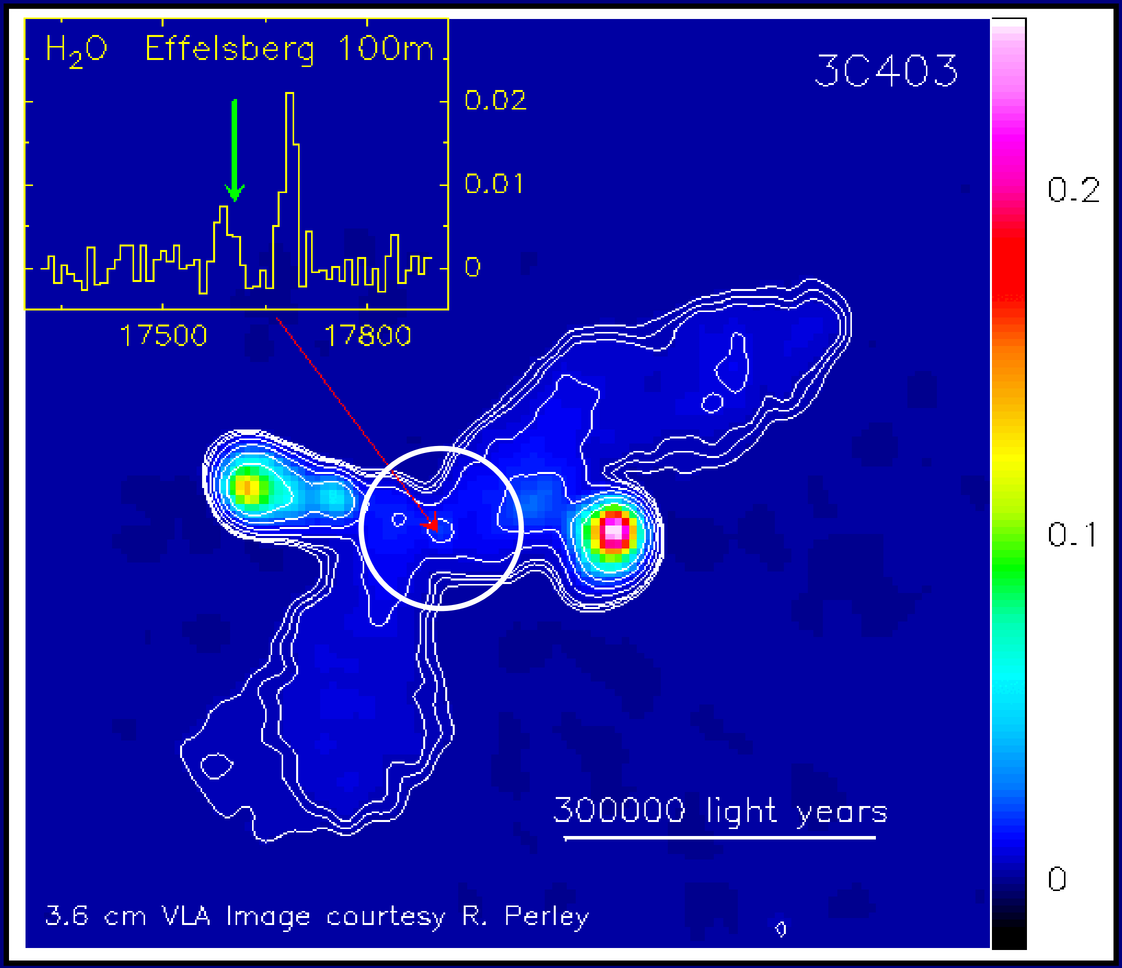
Nuclear $EW_{[OIII]} > 10^4$ Å

Obscuration of the central ionizing source?

Chiaberge et al. (2002)



3C403 and its water maser



3C403

- **D ~ 235 Mpc**
- **V_{sys} ~ 17688 km/s**
- **X-shaped radio galaxy**

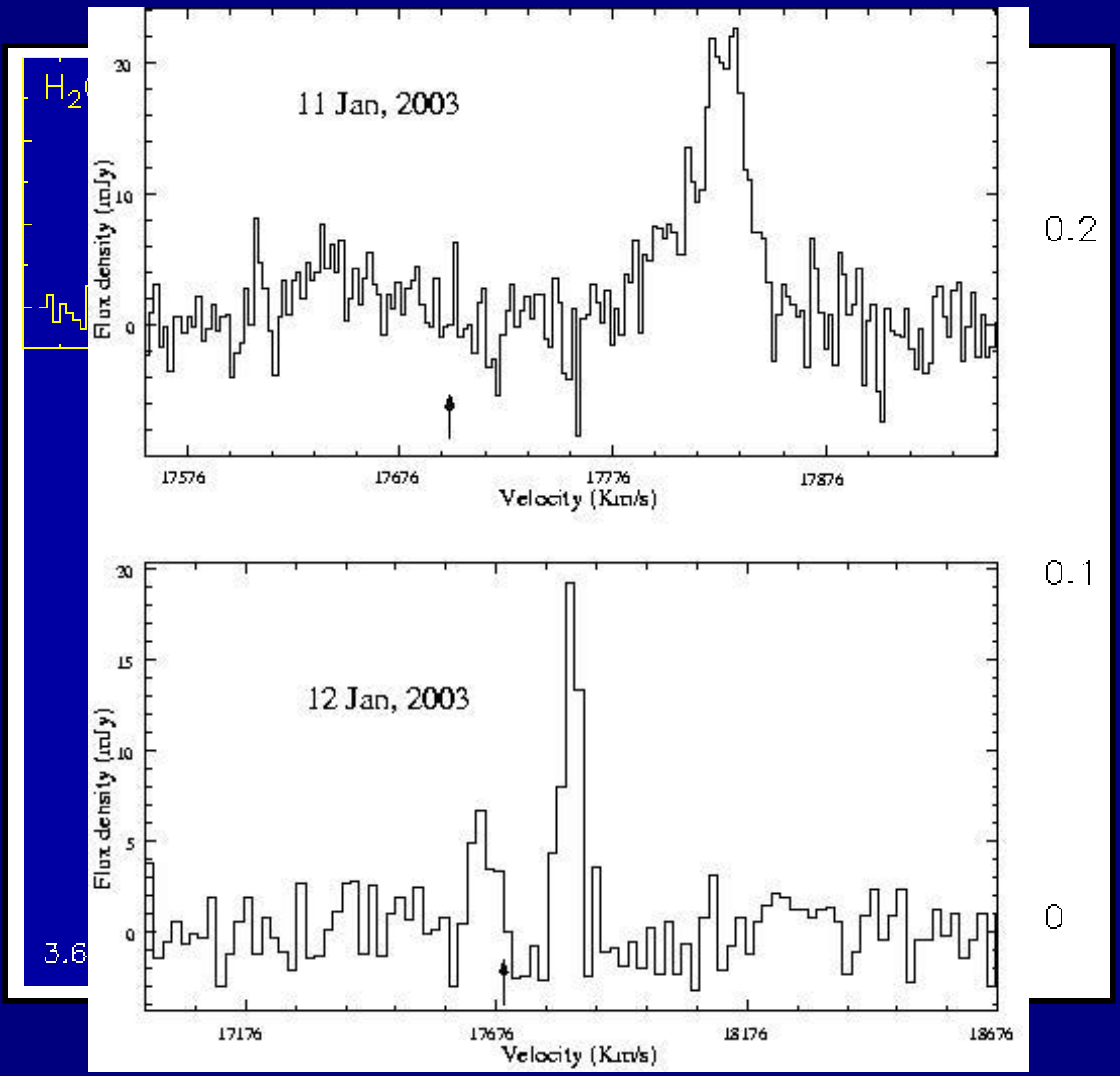
H_2O Maser

- **Two main components**
- **Bracketing the systemic velocity**
- **Isotropic luminosities**

  ~ 950 L_{sun}

  ~ 280 L_{sun}

3C403 and its water maser



3C403

- D ~ 235 Mpc
- V_{sys} ~ 17688 km/s
- X-shaped radio galaxy

H_2O Maser

- Two main components
- Bracketing the systemic velocity
- Isotropic luminosities
  ~ 950 L_{sun}
  ~ 280 L_{sun}

3C403 (Tarchi et al. 2003, A&A, 407, L33)

"Discovery of a luminous water megamaser in the FRII radiogalaxy 3C403"

file:///homes/pulsar/atarchi/INAF_files/center_data/centro_cs.ht

INAF

Comunicato Stampa
Roma, 29 luglio 2003

SPAZIO: SCOPERTA EMISSIONE MASER DA VAPORE ACQUEO
IN UNA *POTENTE* RADIO GALASSIA

Un gruppo di astronomi italiani e tedeschi è riuscito a osservare per la prima volta emissione maser da vapore acqueo nelle regioni circostanti un Buco Nero super-massivo in una radio galassia. Andrea Tarchi dell'Istituto di Radioastronomia del Consiglio Nazionale delle Ricerche (IRA-CNR) e dell'Osservatorio Astronomico di Cagliari dell'INAF, Marco Chiaberge dell'IRA-CNR, Christian Henkel e Karl Menten entrambi del Max-Planck-Institut für Radioastronomie di Bonn (MPIfR), hanno rilevato per la prima volta un'intensa riga di emissione maser dell'acqua proveniente da una radio galassia "classica".

Una goccia d' acqua in una radio galassia. Un fenomeno straordinario, osservato per la prima volta da un gruppo di ricercatori italiani, del CNR e dell' INAF, e tedeschi, del Max Planck Institut für Radioastronomie di Bonn (MPIfR) grazie all' effetto MASER, acronimo per

Max Planck Gesellschaft - Presseinformation http://www.mpg.de/bilderBerichteDokumente/dokumentation/pr...

MAX-PLANCK-GESELLSCHAFT
Presseinformation

SP 12 / 2003 (87) 16. Juli 2003

Wasser in der Nähe eines Schwarzen Lochs gefunden

Deutsch-italienisches Radioastronomen-Team entdeckt mit dem Effelsberger 100-Meter-Radioteleskop den bisher am weitesten entfernten Megamaser

In der Radiogalaxie 3C403 wurde eine Quelle entdeckt, bei der die Intensität der Strahlung einer einzigen Spektrallinie tausendfach stärker ist als die der Sonne im gesamten Spektralbereich. Die intensive Strahlung eines Wasserdampf-Masers hat ihren Ursprung in der direkten Nachbarschaft eines Schwarzen Lochs. Andrea Tarchi und Marco Chiaberge vom Istituto di Radioastronomia (IRA) in Bologna sowie Christian Henkel and Karl Menten vom Max-Planck-Institut für Radioastronomie (MPIfR) in Bonn beobachteten zum ersten Mal eine solche Emission in einer "klassischen" Radiogalaxie, bei der ein Schwarzes Loch von vielen Millionen Sonnenmassen Energie bis in eine Entfernung von mehr als 100 000 Lichtjahren aussendet. Dieser Wasser-Megamaser ist etwa 750 Millionen Lichtjahre von der Erde entfernt.

Die Radioastronomie ermöglicht es, Bereiche des Weltalls zu erfassen, die der optischen Astronomie nicht zugänglich sind. Dazu gehören kosmische Maser (Microwave Amplification by Stimulated Emission of Radiation) dem Laser vergleichbare Verstärker von Radiowellen. Als Megamaser

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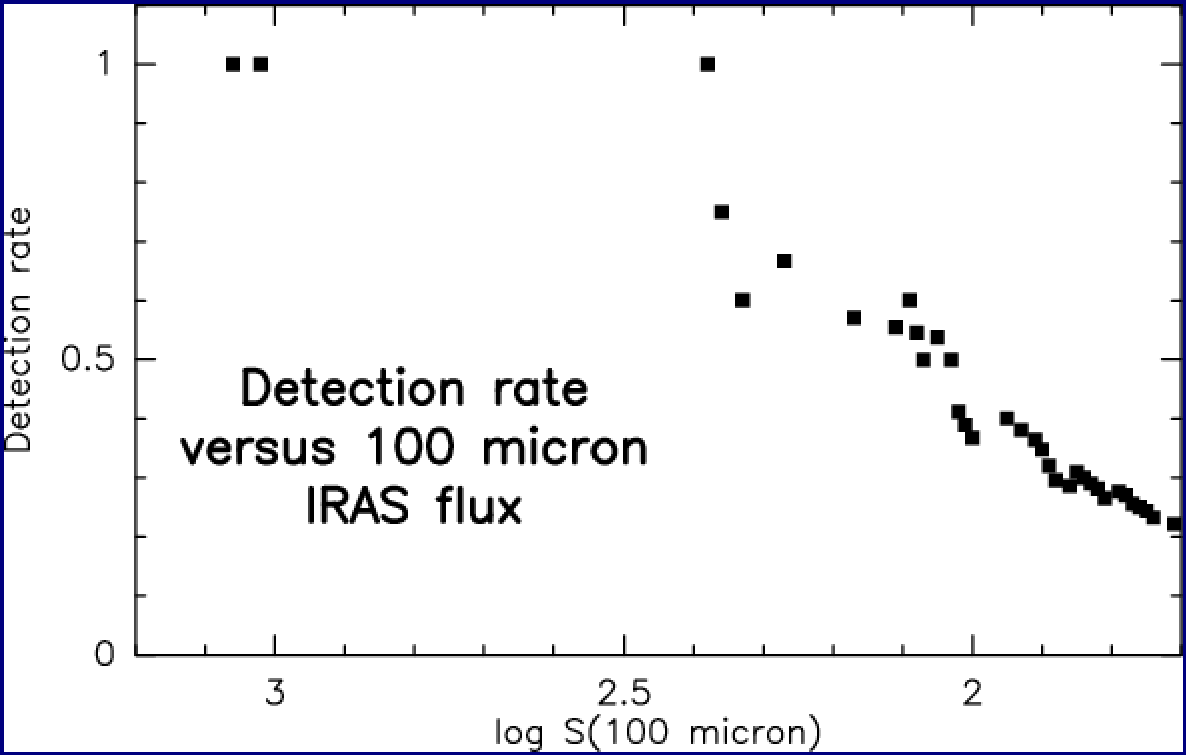
The IRAS-bright sample



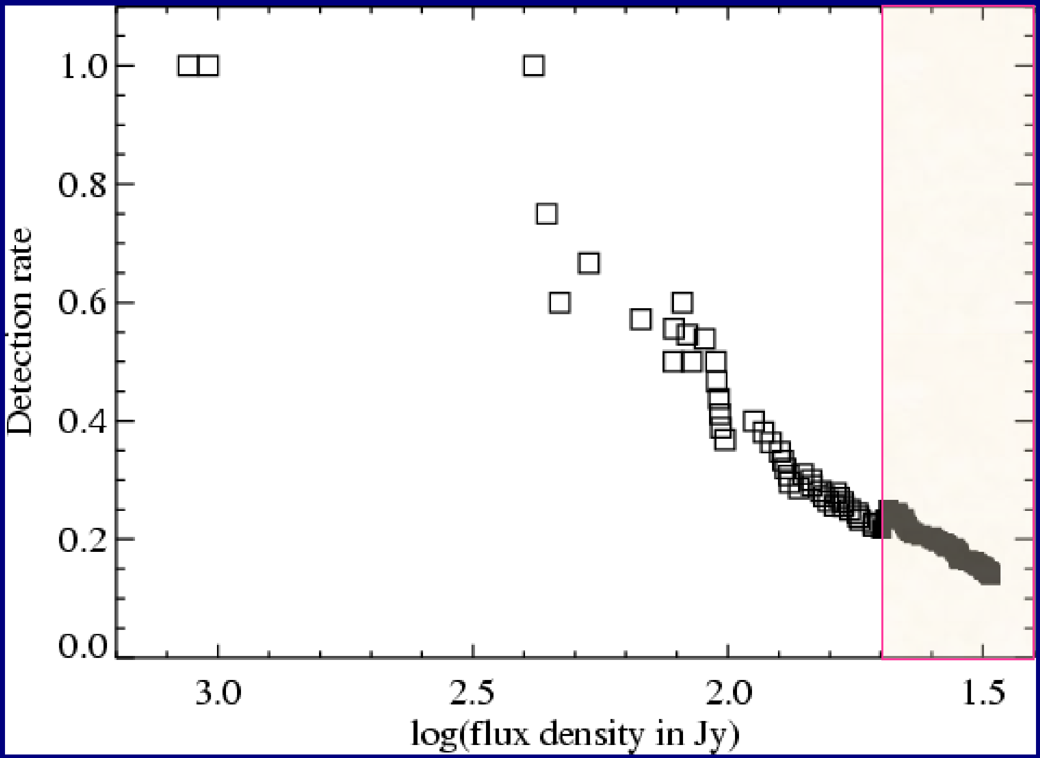
H2O masers in Northern galaxies with 100 micron flux > 50 Jy

Detection rate of 22% (10/45)

Among the highest ever obtained

Henkel et al. (2005)

The IRAS-bright sample



H2O masers in Northern galaxies with 100 micron flux 30- 50 Jy

Two new detections:

NGC520 and NGC613

Castangia et al. (2008)

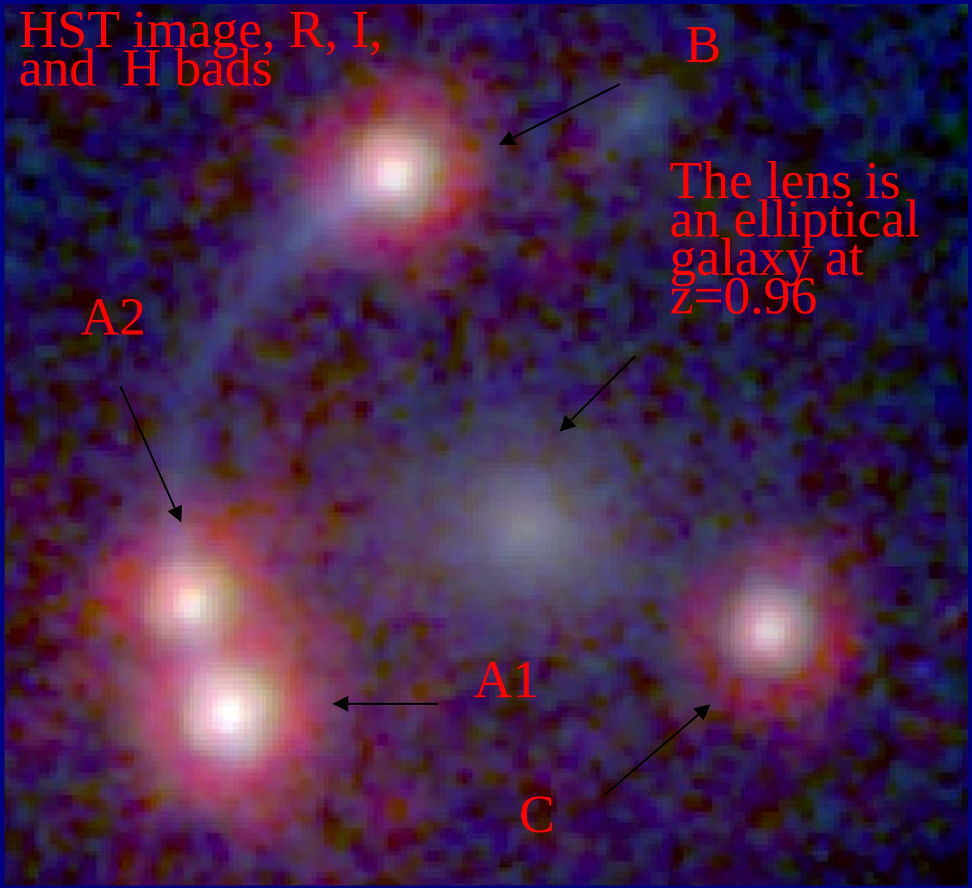
MGJ0414+0534

z=0.66 → z=2.64!!

MG J0414+0534

• is a **radio-loud type 1 quasar**, rich of molecular gas and dust

• has a **magnification factor of ~35**



An H_2O maser at redshift 2.64

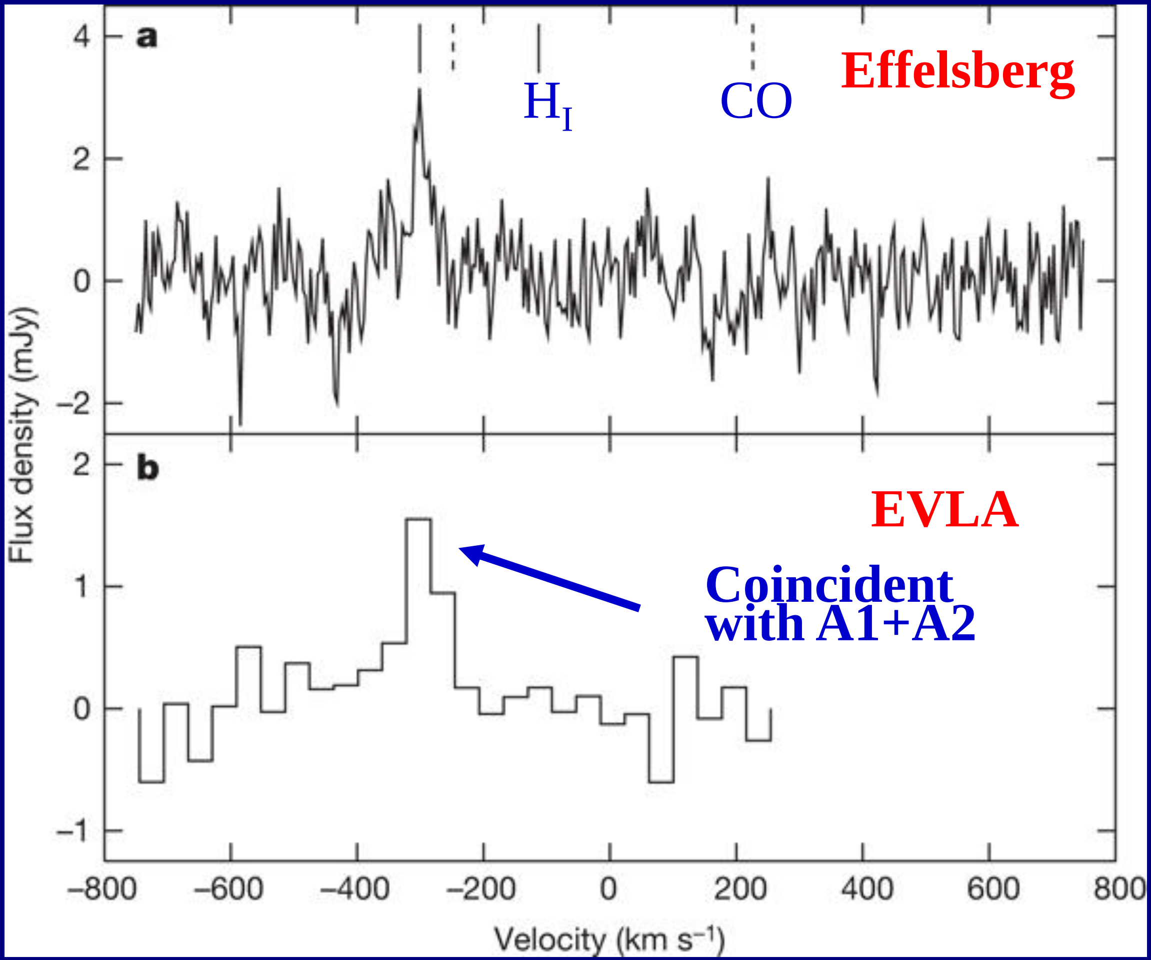
- Observing frequency:
  6.1 GHz

- Isotropic luminosity:
  10,000 L(sun)

Line Monitoring:

with Arecibo - stable

Castangia et al. (2011)



Impellizzeri, McKean, Castangia et al. (2008) Nature

Why NLS1?

Unified Scheme for AGN:

Seyfert 2 →Obscuring structure (disk or torus) along the l.o.s. toward the nucleus

→enough molecular reservoir and amplification paths

→ **maser action quite likely**

Seyfert 1 → disks or tori (if present) not favourably oriented

→ **maser action highly unlikely**

Indeed only VERY few maser detections in type 1 Seyfert but…

…nicely…

…the majority of these are in NLS1!!!

H_2O masers in NLS1

Overall H_2O maser detection rate:

5/72 = 7 %

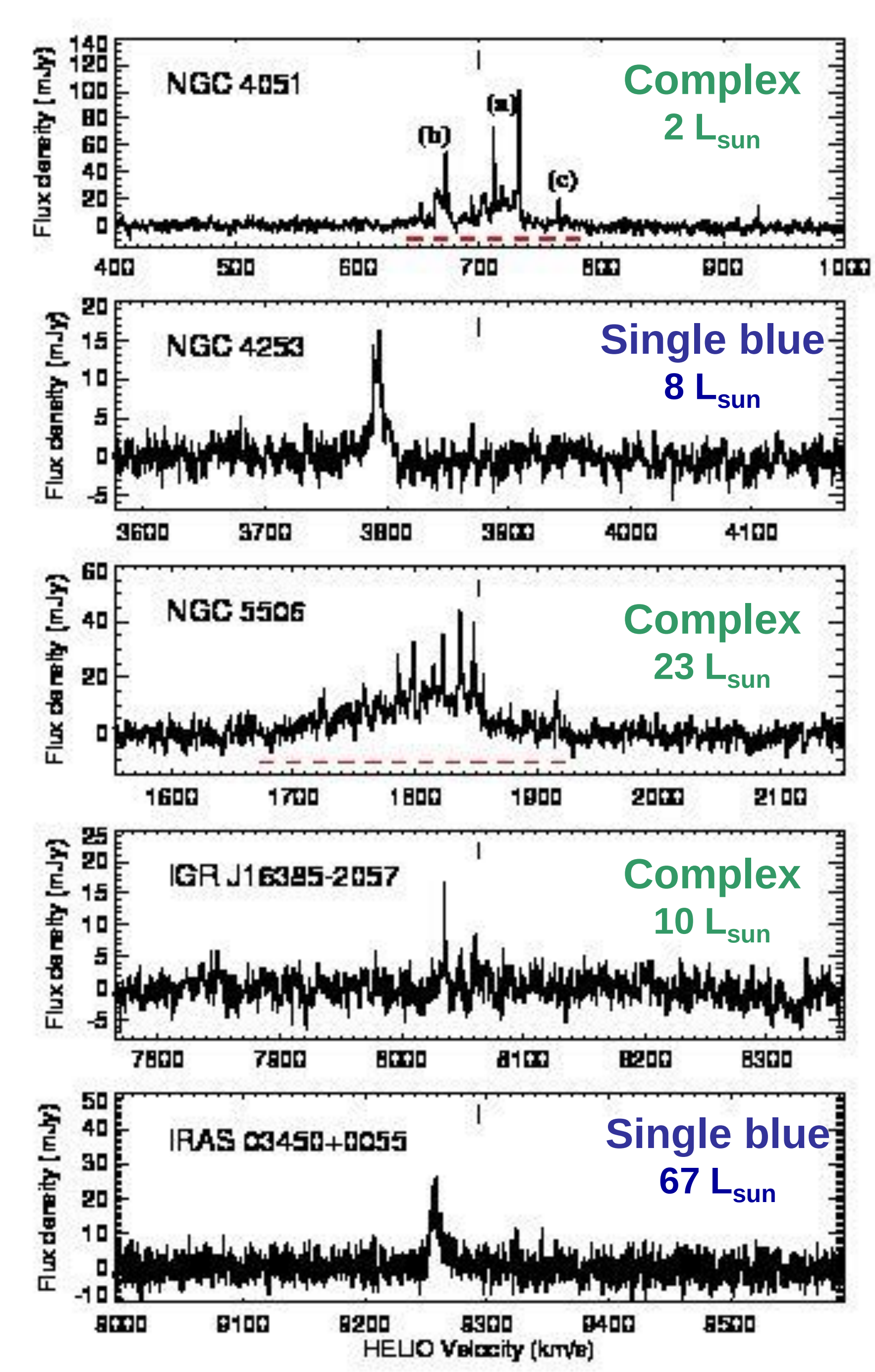
Already surprising given the type 1 nature of the targets

Detection rate for ‘nearby’ NLS1 (with V< 10000 km/s):

5/25 = 20 %

Among the highest ever obtained!

Tarchi et al. (2011)



H_2O masers and X-rays

H_2O maser sources associated with AGN tend to show a **high column density** ($N_H > 10^{23}$ cm^{-2}) or are even **Compton-thick** ($N_H > 10^{24}$ cm^{-2}) **(Braatz et al. 1997, Zhang et al. 2006, Greenhill et al. 2008, Castangia et al. 2013, Masini et al. 2016)**

- ✓ A rough correlation have also been found between **maser** isotropic luminosity and unabsorbed **X-ray** luminosity

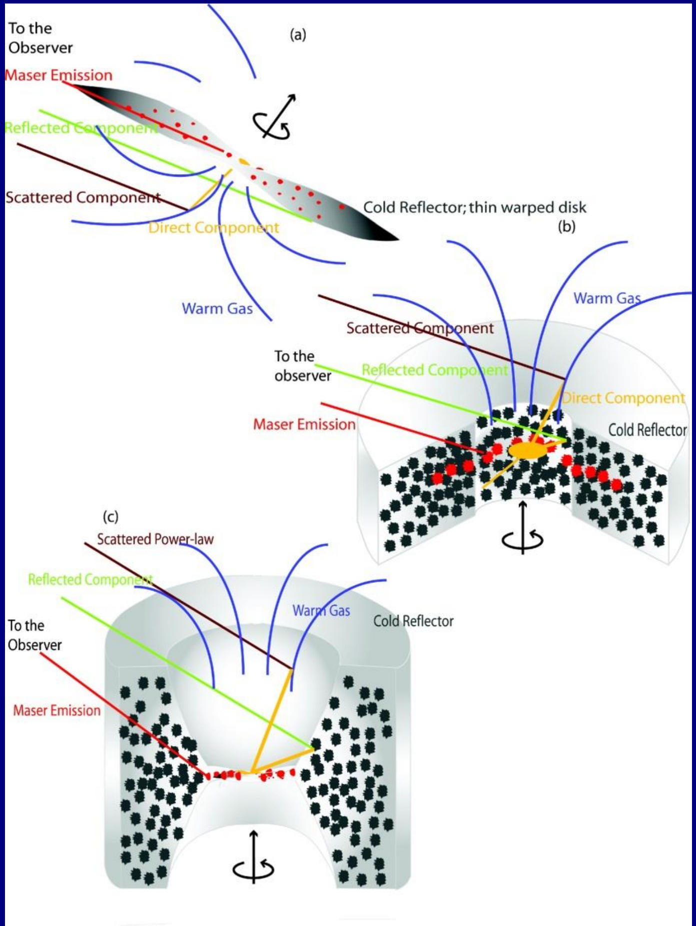
  Kondratko et al. (2006)

- ✓ **L_X** may shape the accretion **disk structure**

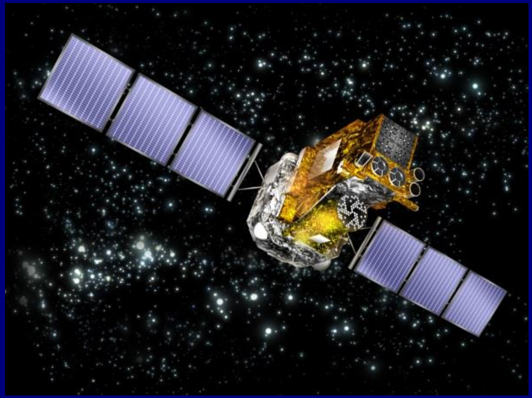
  Tilak et al. (2008)

Statistics is poor!

Lack of X-ray data for most of the known maser sources!



INTEGRAL hard X-ray sky: statistics



INTEGRAL AGN sample
20-40 keV

→ Total sample 380 AGN

- ✓ 193 observed
- ✓ 29 water maser detection
- ✓ 187 not observed

→ 15 (+42) (-7) % detetcion rate

→ Complete sample 87 AGN

- ✓ 65 observed
- ✓ 12 water maser detection
- ✓ 22 not observed

→ 18.5 (+20.5) (-4.7) % detection rate

Panessa, Castangia, Tarchi et al. (2018)

The CT AGN sample

36 Compton-thick AGN

- **Selection method:**

  FIR and X-ray flux and colours

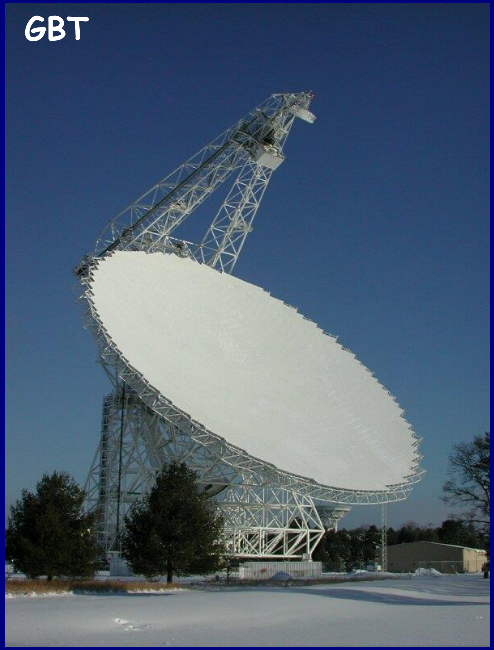
  (Severgnini et al. 2012)

- **All searched for H2O maser in past surveys**

  some with shallow detection limit

- **5 reobserved to improve detection threshold**

  → A new water megamaser (IRAS15480)



Castangia et al. (2016, 2018)

The CT AGN sample

36 Compton-thick AGN

- **Selection method:**

  FIR and X-ray flux and colours

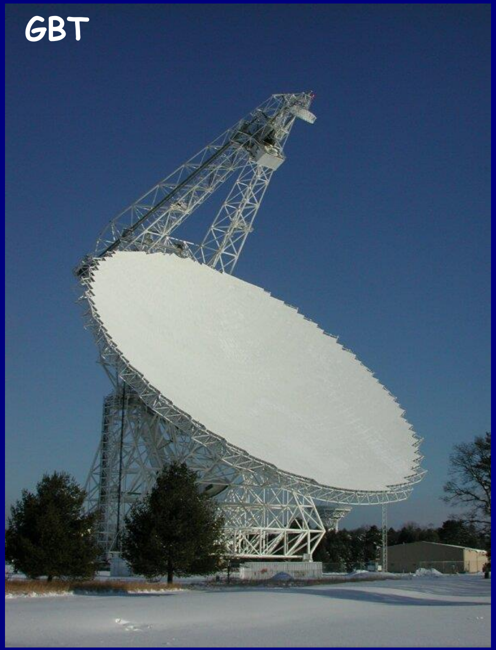
  (Severgnini et al. 2012)

Maser detection rate of the entire sample: 50%!

some with shallow detection limit

- **5 reobserved to improve detection threshold**

  → A new water megamaser (IRAS15480)



Castangia et al. (2016, 2018)

(Single-dish) Surveys In extended objects

(e.g.) Maser searches in LG galaxies

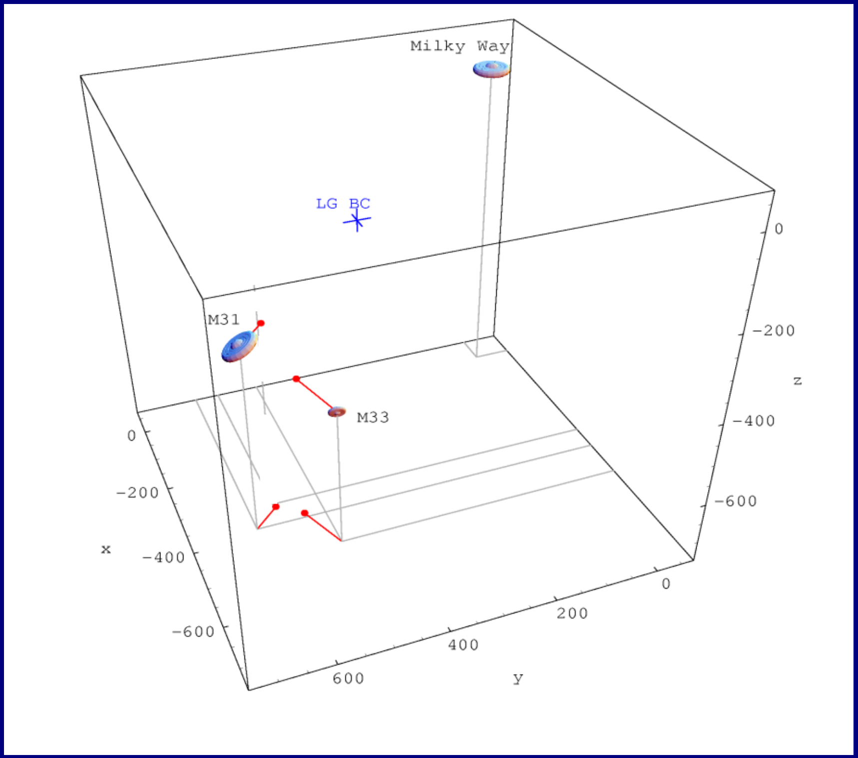
Courtesy: A. Brunthaler

Astrometry of M33

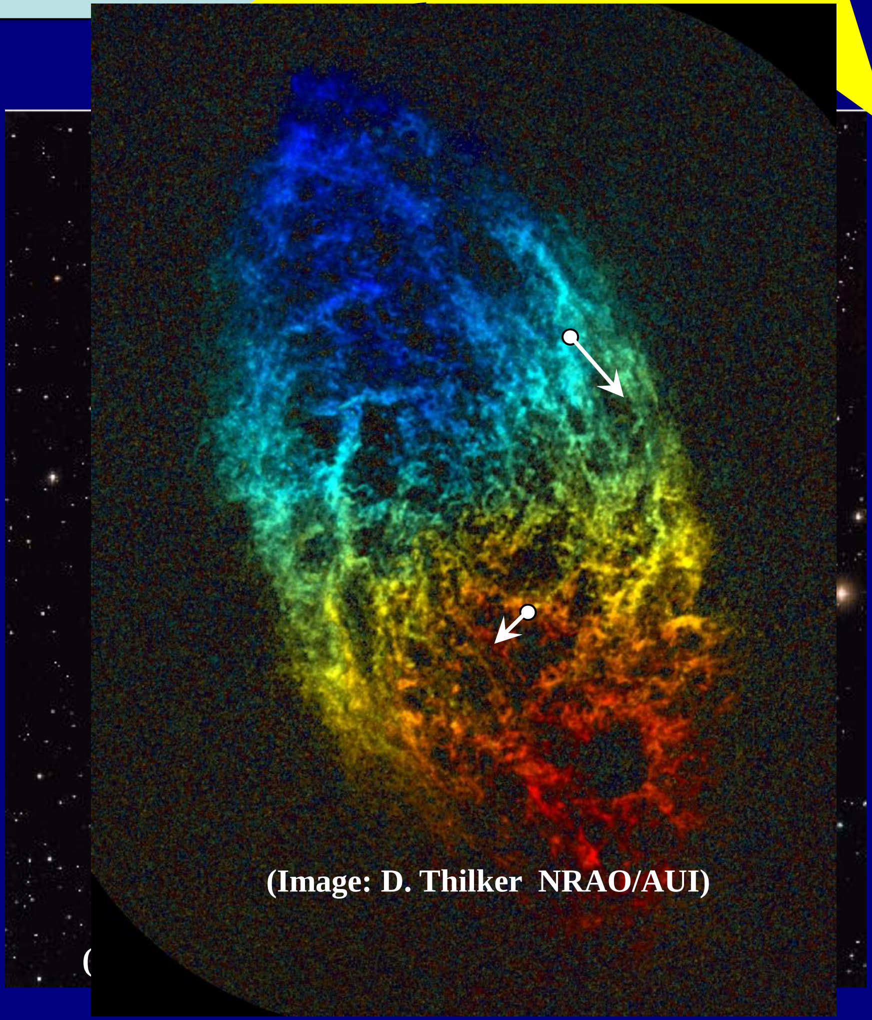
VLBA observations of water masers:

- **3d motion relative to Milky Way: v = 190 ± 59 km/s**
- **rotation known => geometric distance: 730 ± 168 kpc**

3-8 μas/yr in 4.5 years

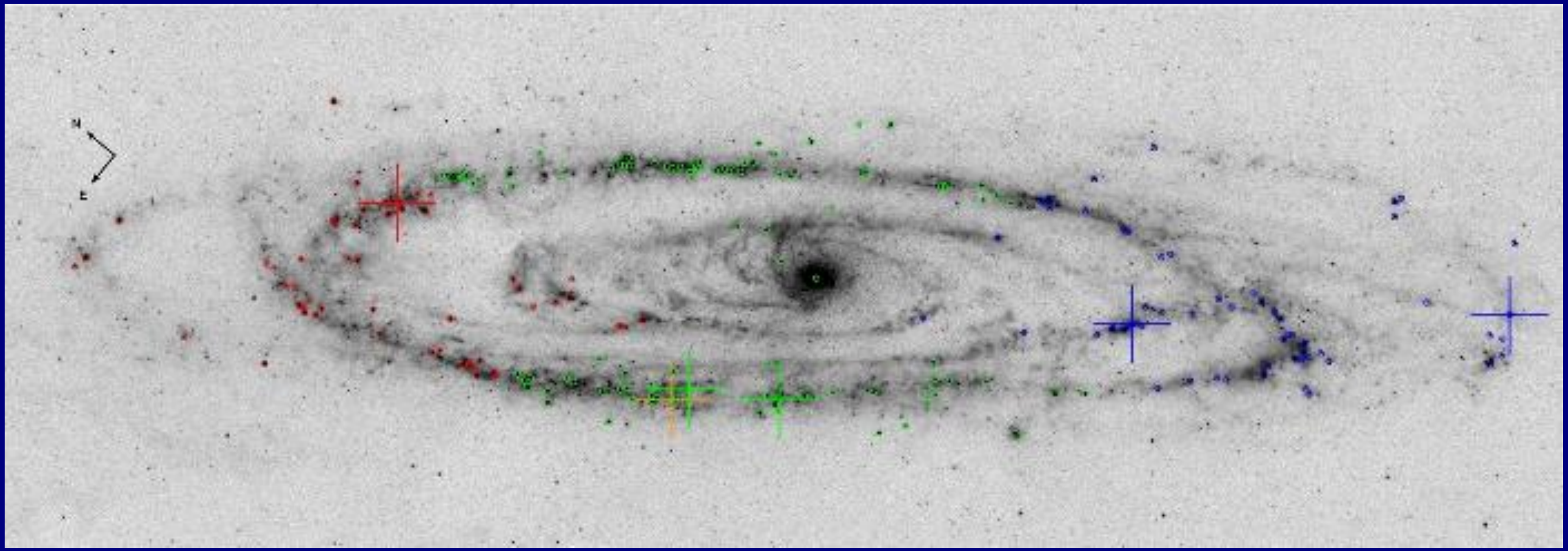


(Brunthaler et al. 2005, Science)



(Image: D. Thilker NRAO/AUI)

M31



Darling 2011

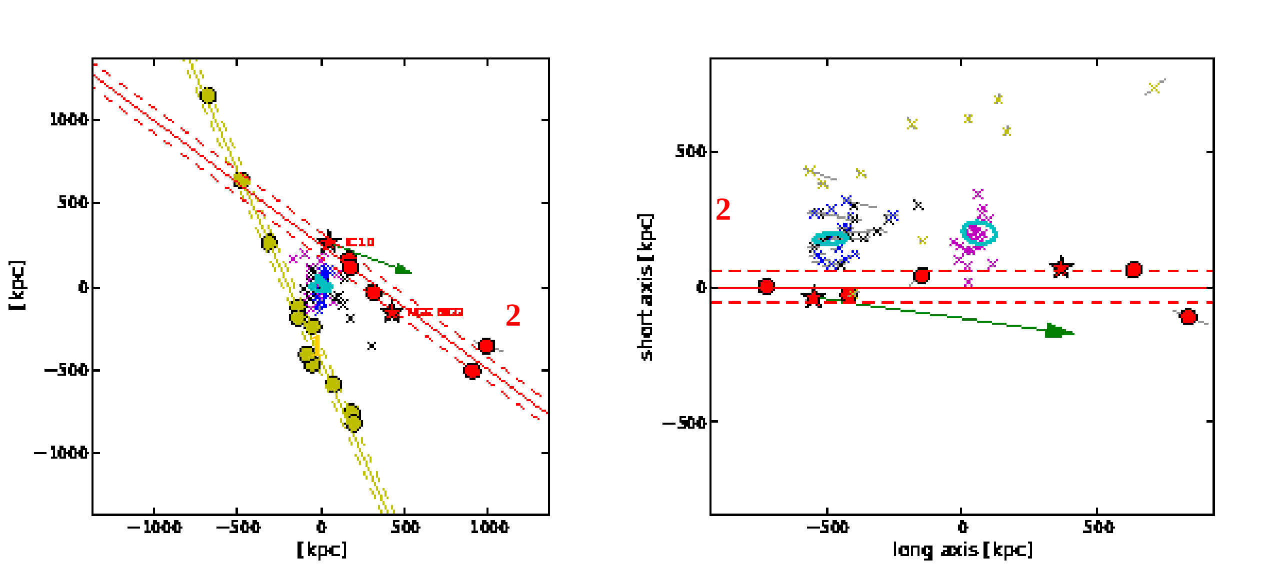
5 water masers detected, so far (Darling+ 2016)

Ongoing effort to derive water masers proper motions in M31

1 Methanol maser (Sjouwerman+ 2010)

SRT ESP S0003: Motivation(s)

Collaborators: P. Castangia, G. Surcis, A. Brunthaler, K. Menten, M. Pawlowski, A. Melis, S. Casu, M. Murgia, A. Trois, R. Concu, C. Henkel, J. Darling



Created using Pawlowski+ 2012,2013,2015; Ibata+ 2013

- To detect, for the first time, water and/or methanol maser emission in non satellite dwarfs (but IC10) associated with Planes 1 and 2

- To derive (with VLBI follow-ups) full velocity vectors for these galaxies
  → Origin of dwarfs structures, total mass of matter (also dark) of the LG

- Sensitive radio continuum maps of these galaxies
  → Spectral indices, SFRs

SRT ESP S0003: Sample & Setup

Sample: 14 Local Group dwarf galaxies 'associated' with Planes 1 and 2

Time: about 200 hours in total (C and K bands)

Backend: SARDARA
BW: 1.5 GHz (2 GHz were not proposed at that time)
Channels: 16384
Res=91 kHz; 4 km/s@6.7-GHz; 1.2 Km/s@22-GHz
Full Polarization

Mapping technique: On-The-Fly (RA-DEC)
scanning speed 3'/sec (for all, but small K-band maps)

Data reduction: SCUBE (Murgia et al. 2016)

…a few preliminary results…
Tarchi et al. (2018)

Masers search: results

<u>**No maser emission above 5 sigma has been detected in the three targets analysed, so far: NGC6822, IC1613, and WLM**</u>

In principle, not surprising, though:

expected masers number: $N = 10$^[-0.6x(1 + log(L_{H2O}))] x SFRgal/SFR_{MW}

with L_{H2O}= 0.0023 x $\int$Sdv x D2 **(Brunthaler et al. 2006)**

Noise in the SRT cubes

NGC6822: 20 mJy@C-band and 90 mJy/beam@@k-band

IC1613: 30 mJy and 70 mJy/beam@K-band

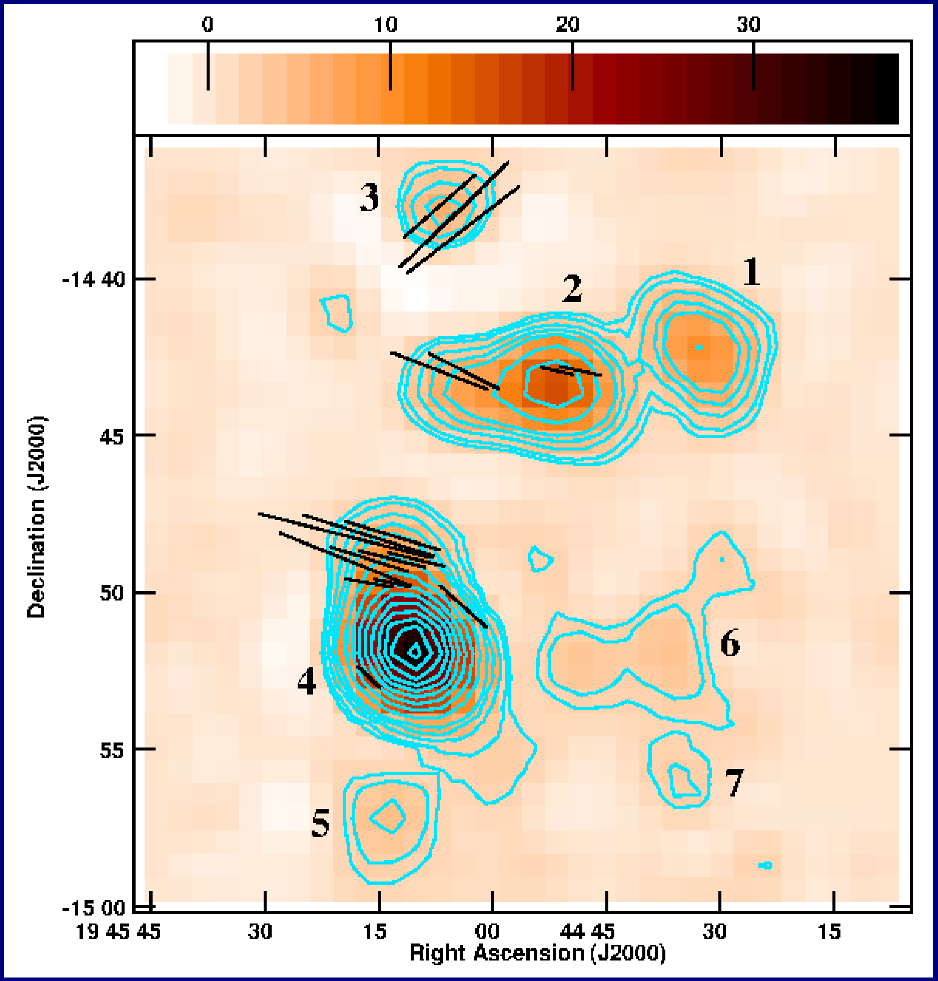
At 5 sigma: for water, in NGC6822, N~0.1 and in IC1613, N~0

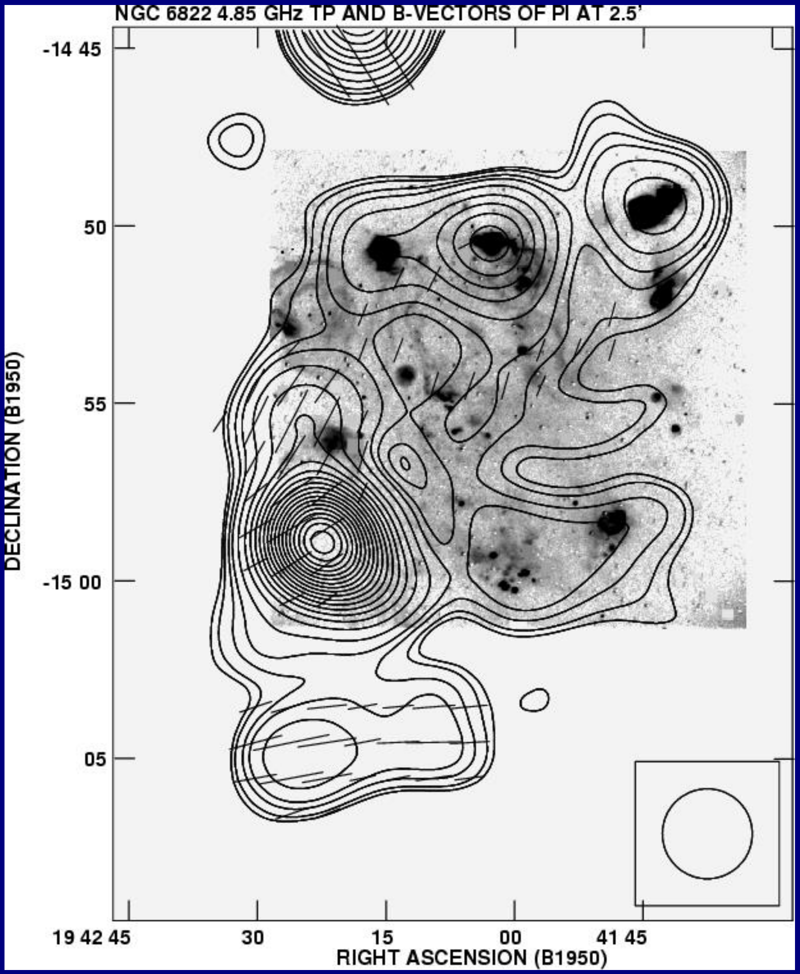
But: <u>for IC10, N~0.3, 2 masers has been found, though</u>

(flares?, wrong SFRs?)…see later slides

…in the meanwhile…

Radio continuum maps of NGC6822





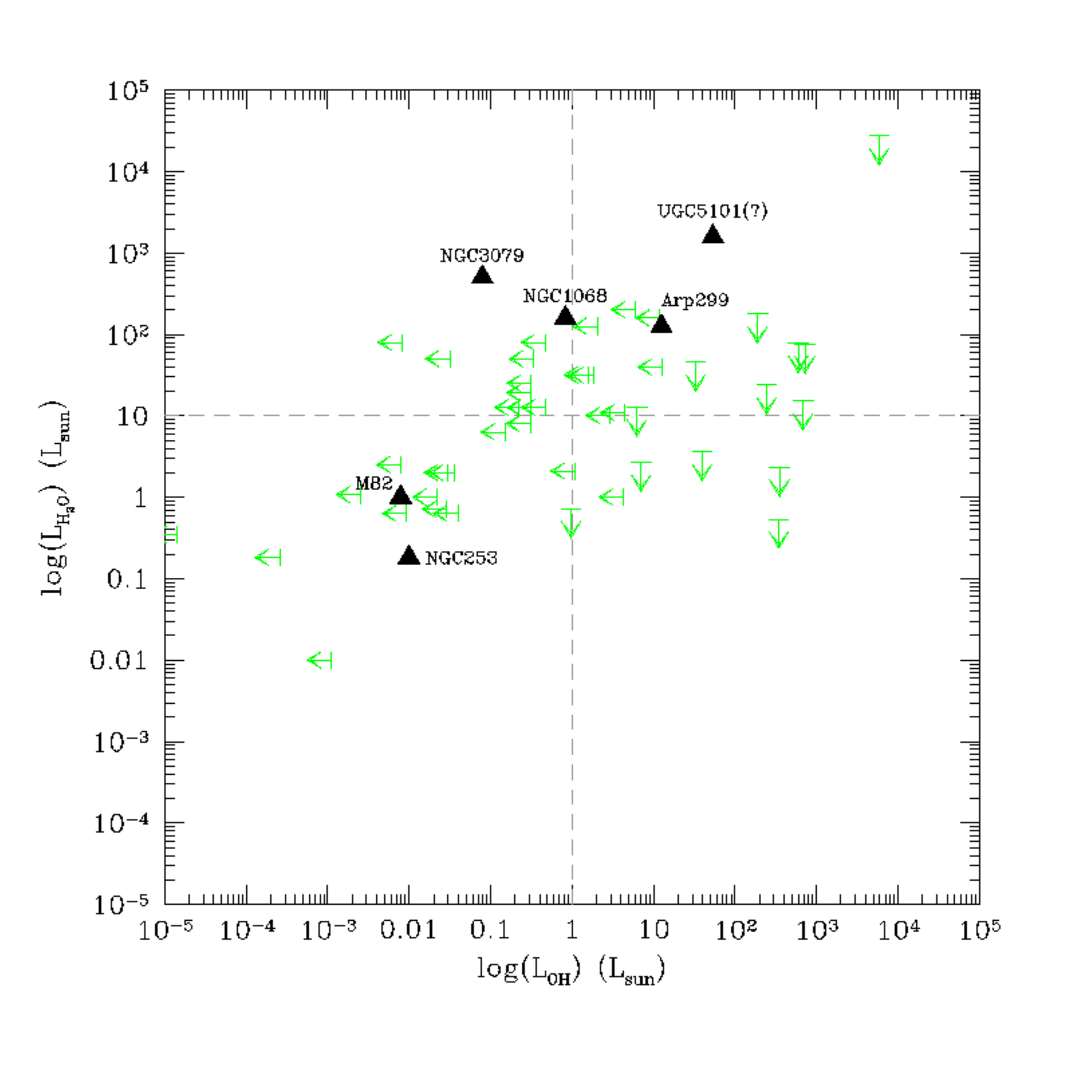
SRT 6 GHz

Tarchi et al. (2018)

Effelsberg 5 GHz

Chyzy et al. (2003)

H_2O and OH



Surcis et al. (2009 /Tarchi et al. (2011)

Only IC694 (in Arp299) shows the contemporary presence of luminous OH and H2O maser emission!

Possibility to investigate different physical conditions and dynamic structures in the same AGN.

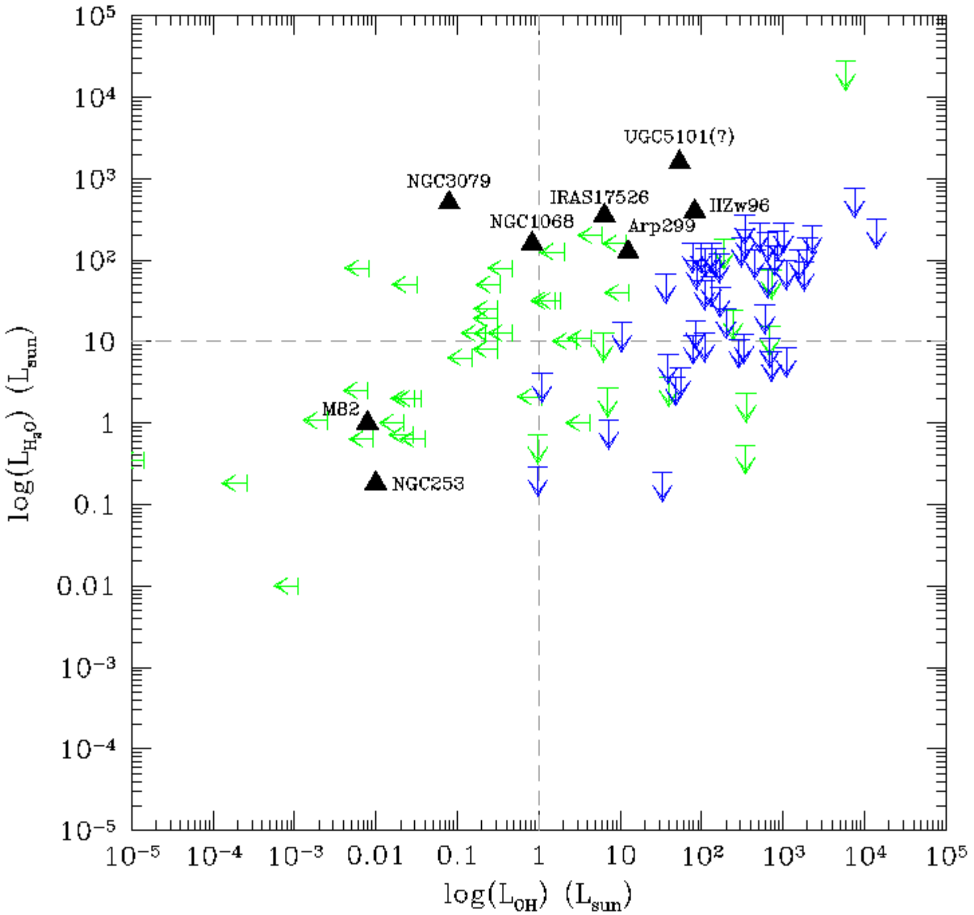
Why only one case?

Duration of the maser phenomena?

Merger stage?

Else?

H_2O and OH



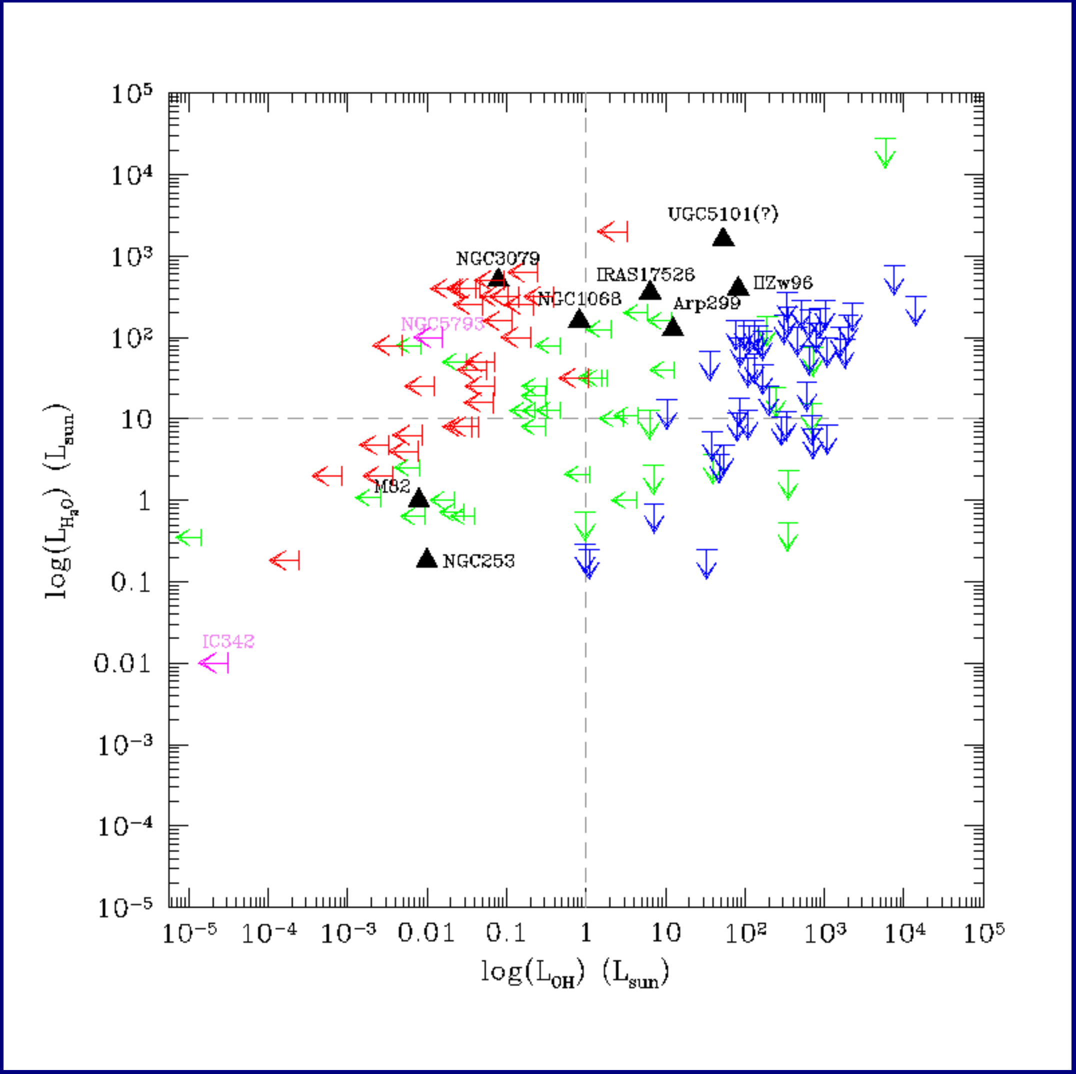
Search with the GBT for 22 GHz masers in OH maser galaxies

Two new cases of 'dual' maser

A brief phase along the merger sequence.

Surcis + (2009)/Tarchi + (2011) & Wagner (2013))/Wiggins + (2016)

H_2O and OH



Search with Effelsberg and the GBT for 1.6 GHz OH maser in H2O galaxies

45 galaxies in total

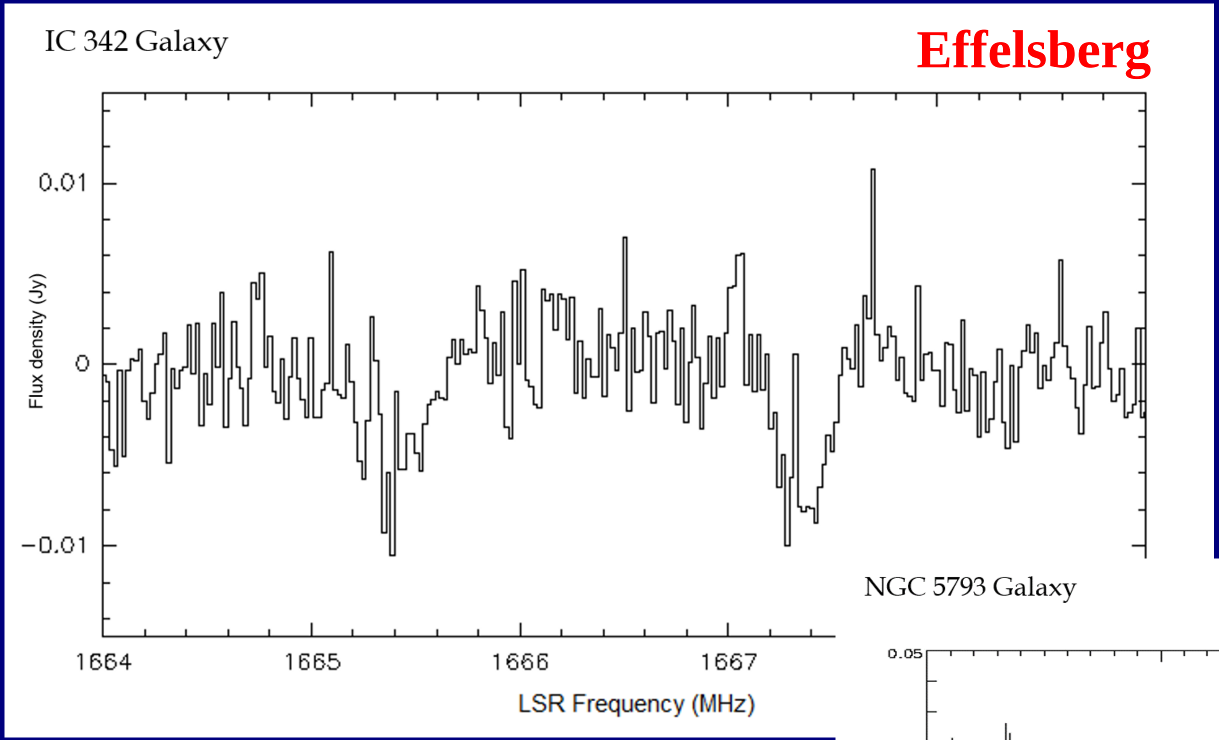
10 discarted due to severe RFIs

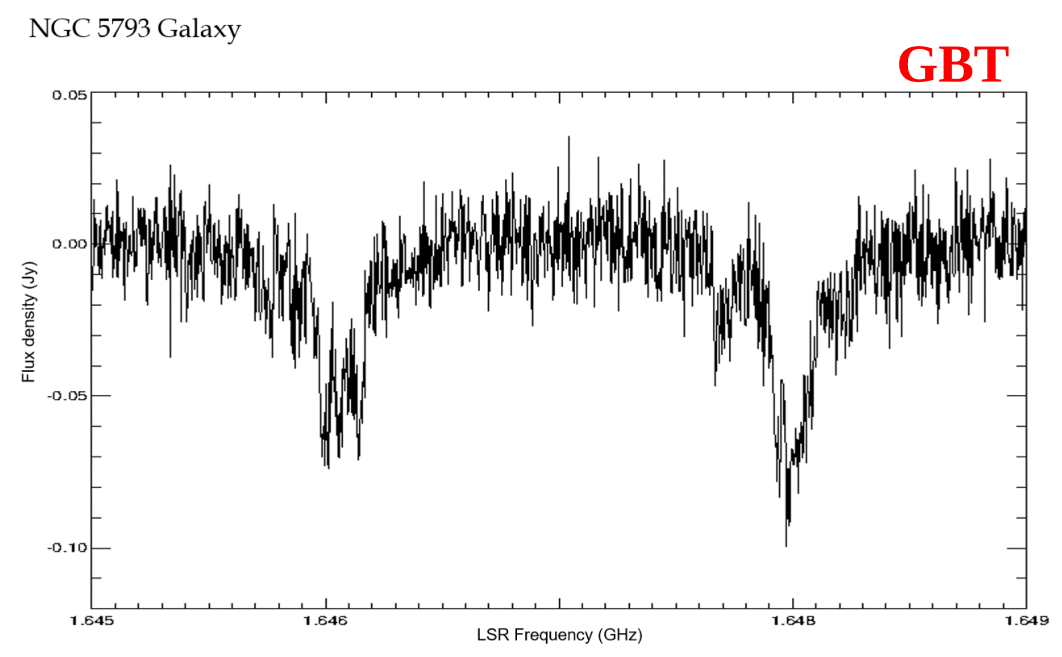
New or refined upper limits

No new masers, but ...

Surcis + (2009)/Tarchi + (2011) & Wagner (2013))/Wiggins + (2016) & Ladu+ (2018)

OH absorption in H_2O maser galaxies





Ladu et al. (2018)

Monitoring

Disk masers (3 well-separated groups of narrow features)

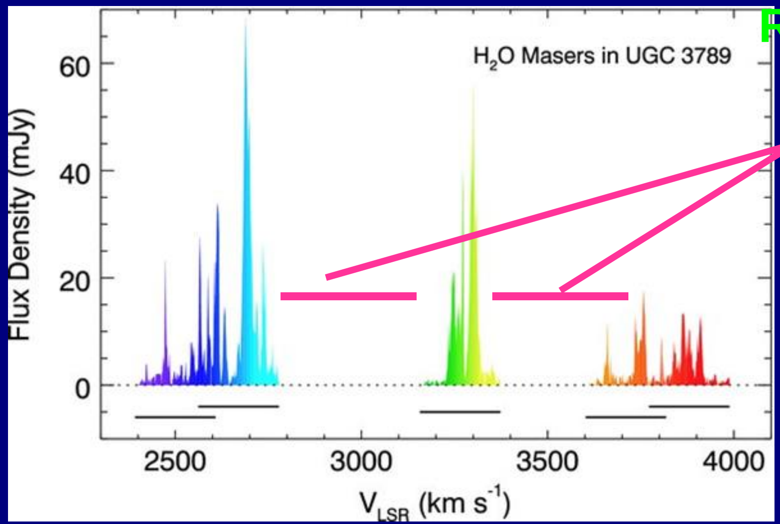
→ Large istantaneous BWs and good spectral res.

Jet/outflow masers (source nature, reverberation mapping)

→ simultaneous line and continuum obs.
→ accurate calibration

All kinds (ToO triggers)

→ dedicated campaigns on promising objects



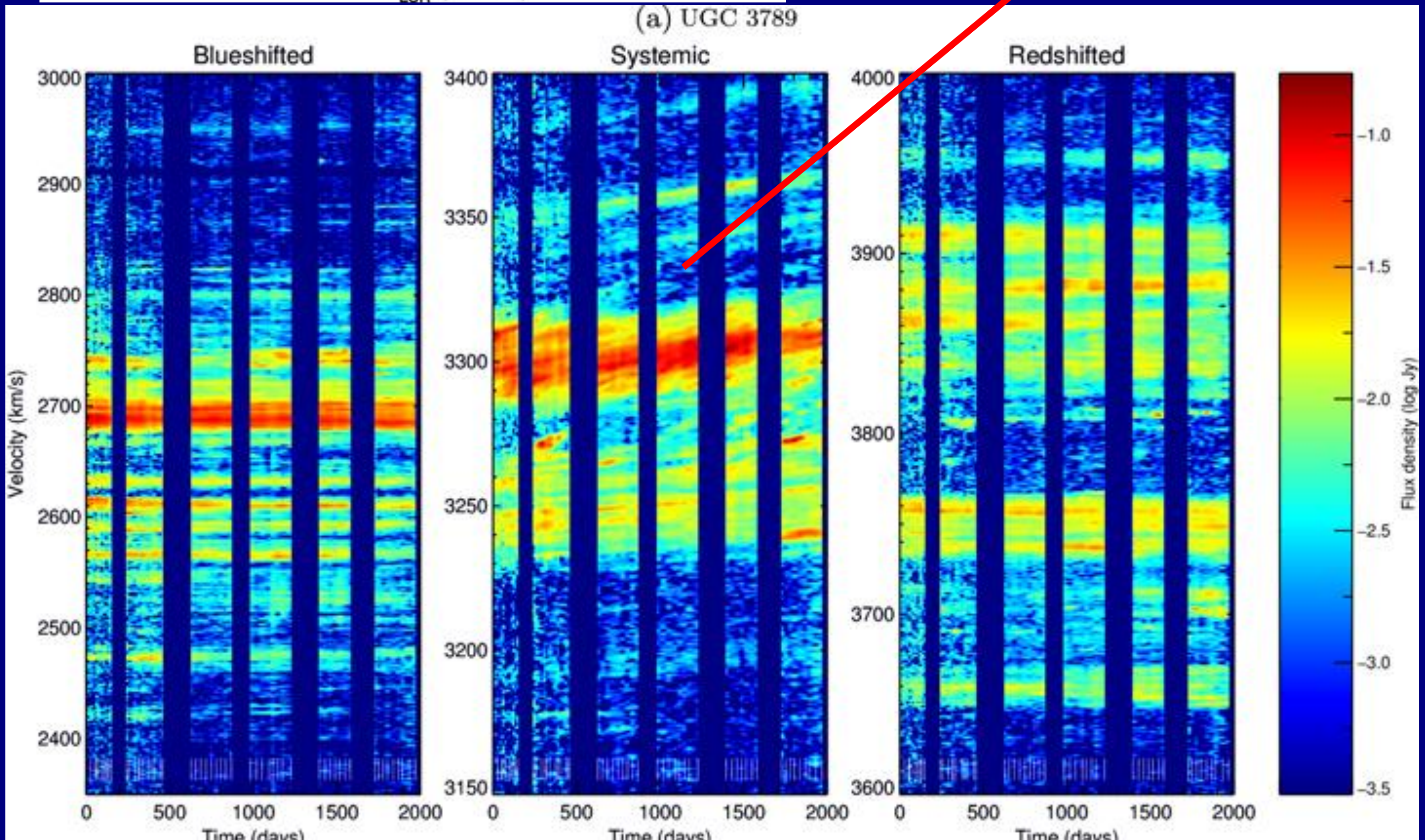
Reid et al. (2010)

Monitoring

$V_{HV} = V_R$

+

$dV_s/dt = V_R^2/R$



Emission is from the same radius

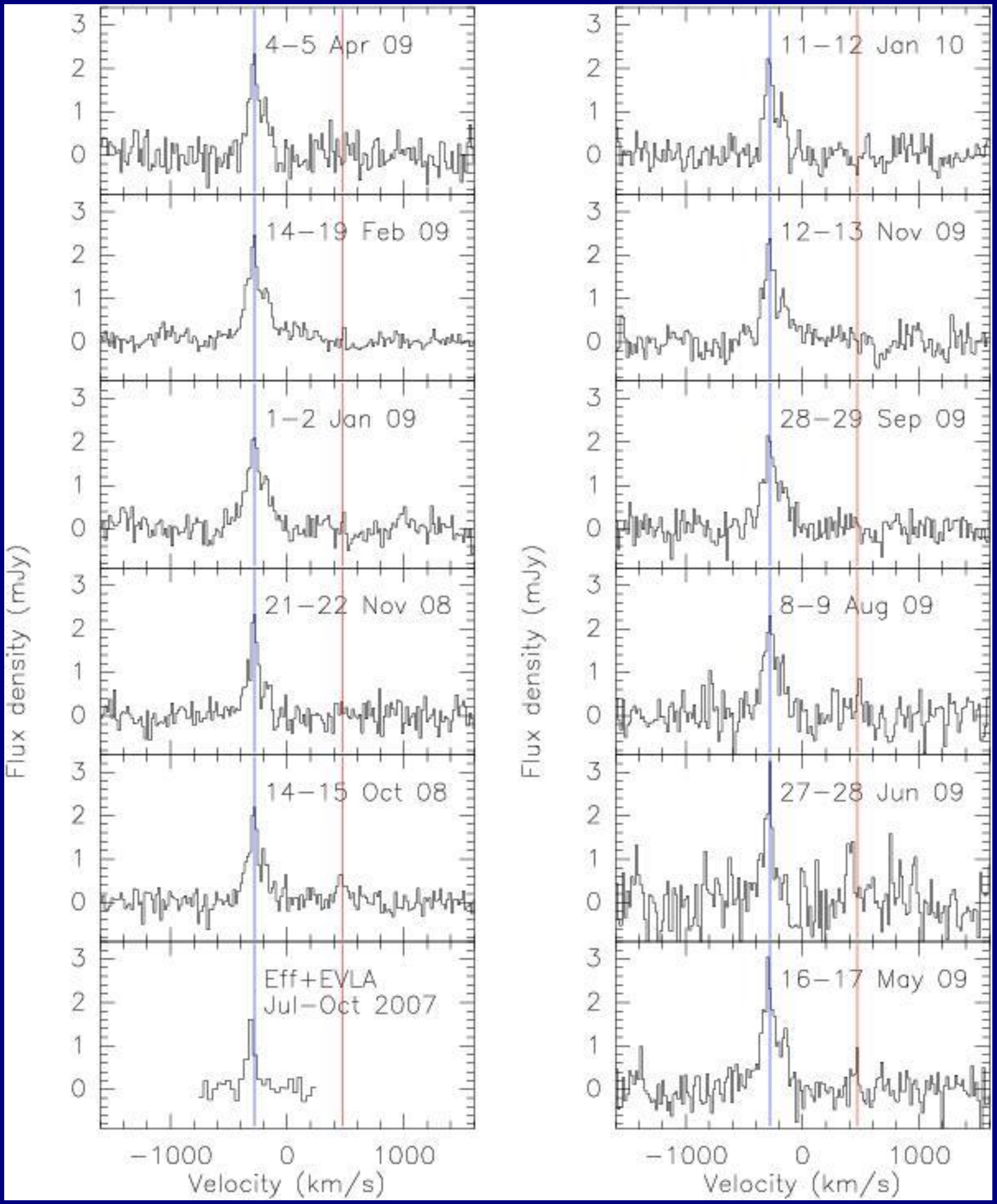
R

Edge on Keplerian

M_{BH}

Pesce et al. (2015)

MGJ0414+0534



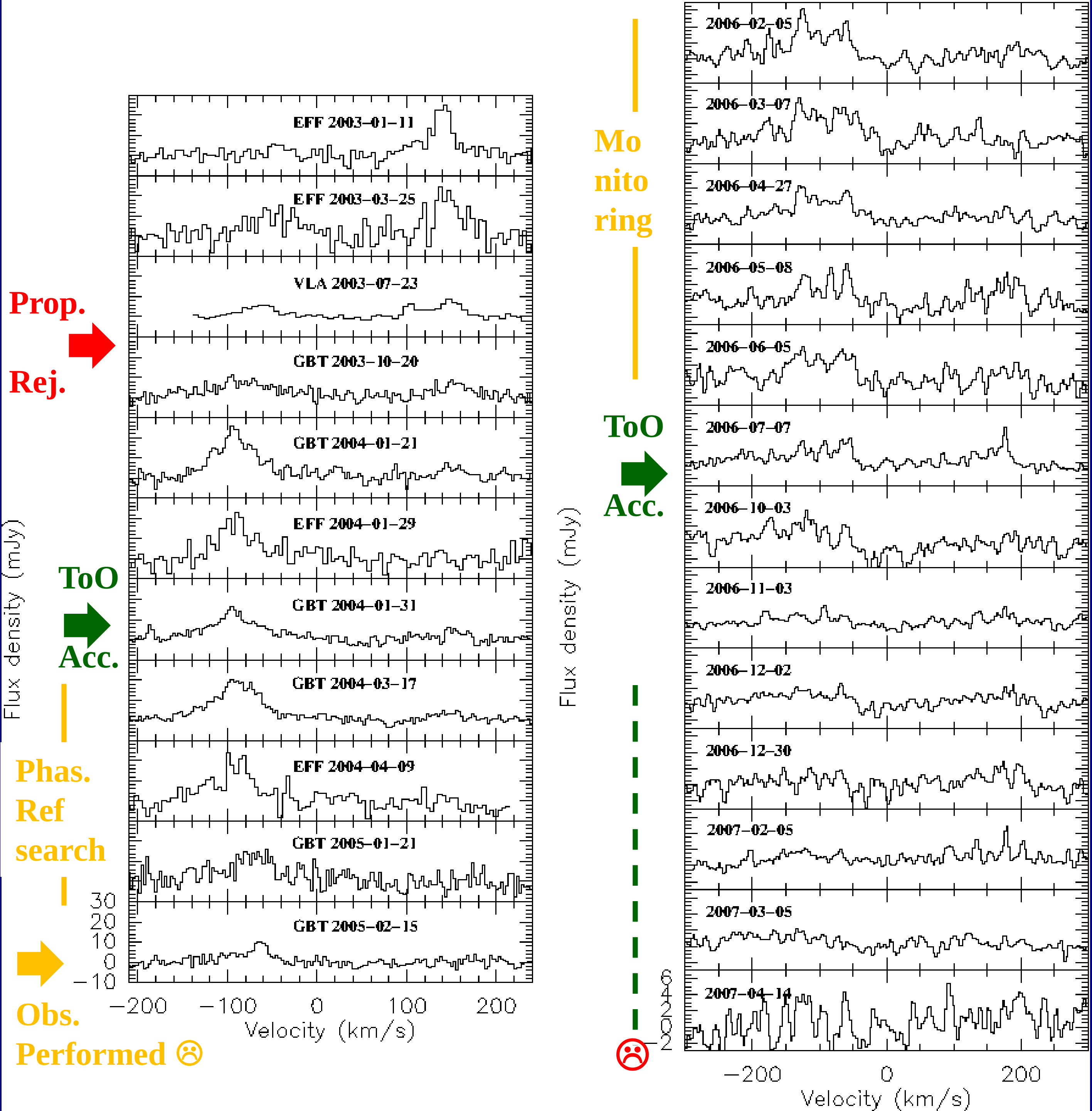
Line and Continuum Monitoring with Arecibo

Broad line & NO 3 peaks → Jet/Outflow

Extreme stability: TBE

Castangia et al. (2011)

Monitoring of 3C403



Seize the moment!

VLBI

Disk masers (geometric distances, BH masses, ..)

Jet/outflow masers (source nature, jet/outflow geometries)

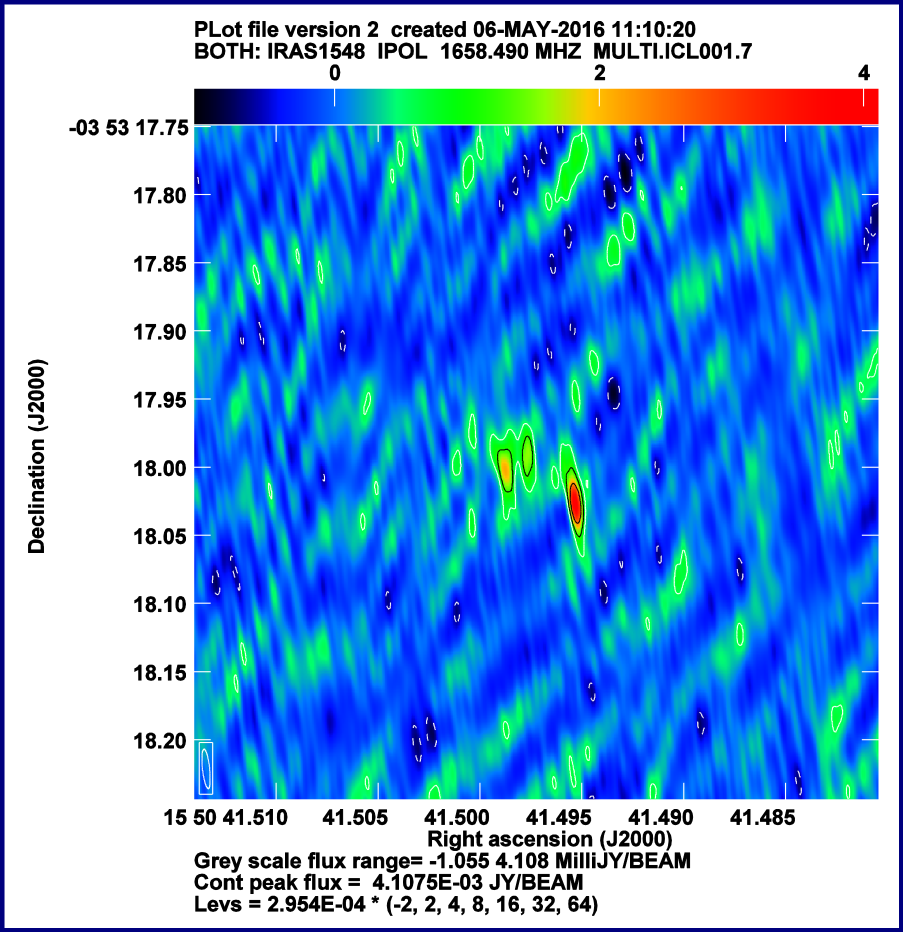
→ sensitive arrays (line and continuum)

Maser flares

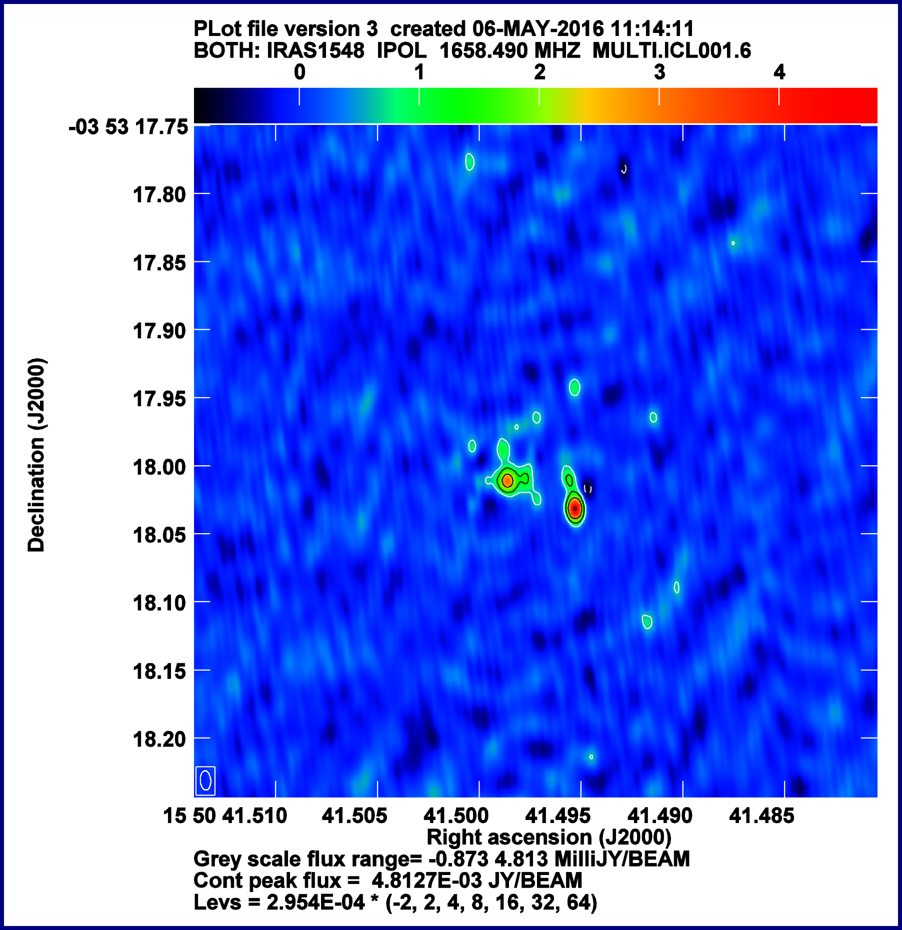
→ ToO capabilities

Megamasers: nuclear continuum with VLBI

Without the SRT



With the SRT!



Credits: P. Castangia and G. Surcis

Extragal. Maser Science. Lessons learned

Large dishes needed (extensive searches)

Multi feed receivers recommended (NODDING, Mapping)

Well-thought criteria for target searches
(see also, e.g., K. Leiter, J.-S. Zhang)

Wide bands and good frequency resolution for monitoring

Good frequency coverage (for high-z surveys)

High Sensitivity VLBI arrays (again big dishes)