



Space VLBI for two H_2O MMS
and
looking inside an AGN accretion disc

Willem Baan (XinJiang Astron. Obs., ASTRON)

Tao An (SHAO), Christian Henkel (MPIfR), Hiroshi Imai
(Kagoshima), Vladimir Kostenko (ASC), and Andrej Sobolev
(UralSU)

The star of the Show Spectr-R - RadioAstron



- Launch July 18, 2011 - Baykanur, Kazakstan
 - 9-day elliptical orbit
 - Apogee 350 kkm - 27 Earth Diameters
 - Perigee 10-70 kkm
 - 10 m radio antenna
 - Frequency 327 MHz, 1665 MHz, 4.83 GHz, 18-25 GHz
 - Highest resolution 8 μ as at 27 ED
 - Operational 2011 to Jan 11 2019
-
- Study of high brightness sources
 - AGN, pulsars, OH And H₂O masers
 - & gravity experiments



Extragalactic H₂O MMasers

RAO 1st MFS 22GHz window - (22.220 - 22.236 MHz)

- only 24 MM fall within lowest window (-124 to +2034 km/s)

- only five nearby sources with flux > 1 Jy

⇒ NGC3079 - 2.2 - 3.5 Jy - Outflow - 1+ detections 1.8 - 2.1 ED

⇒ NGC4258 - 9.8 Jy - Keplerian disk - 11 detections 1.9 - 26.9 ED

⇒ NGC4945 - 8.5 Jy - nuclear disk

⇒ LMC - N133 & 30Dor - 70 & 3 Jy - starformation regions

⇒ Circinus - 4.2 Jy - Keplerian disk & bi-conical outflow

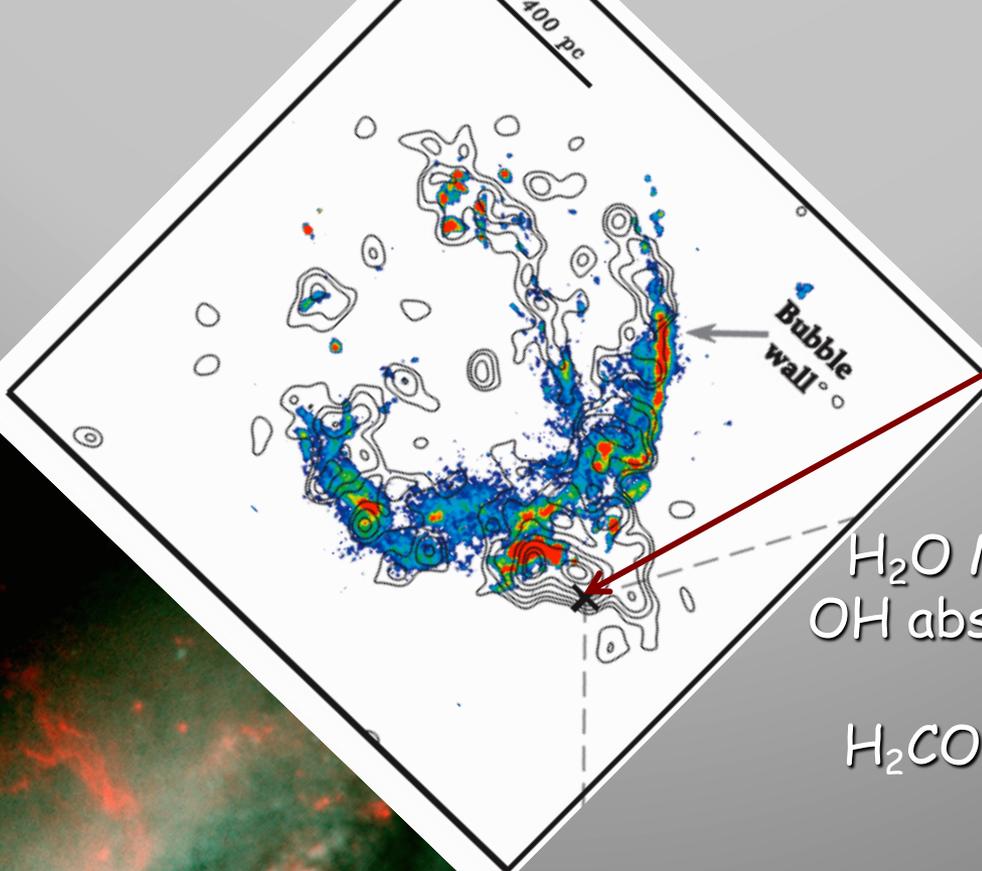
⇒ M33 - 1.5 Jy - starformation regions

⇒ (NGC1068 - 0.65 Jy - Keplerian disk)

⇒ (IC10 - 10-20 Jy - too much blueshifted)

NGC 3079

H₂OMM close to Centre of NGC3079



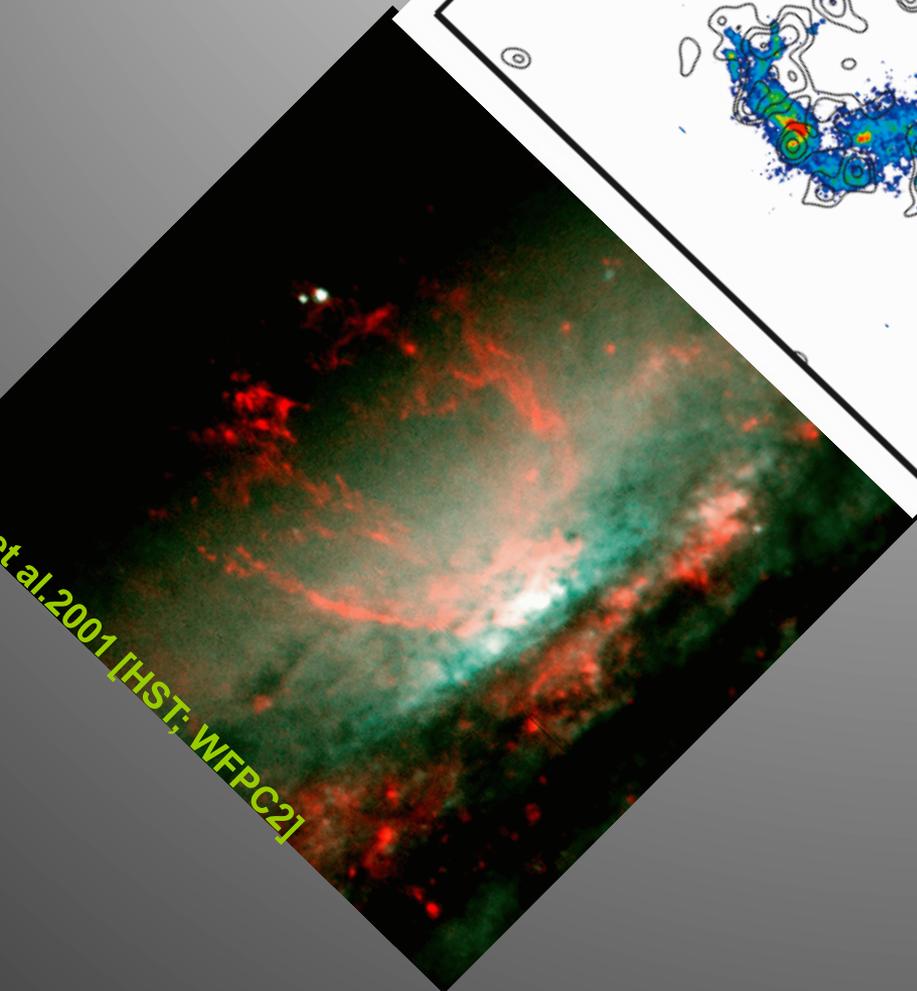
NGC 3079
Nuclear
Activity

H₂O MegaMaser emission
OH absorber (1.8 & 6 GHz)
HI absorber
H₂CO emitter & absorber
CH₃OH absorber

=> edge-on Sey 2/LINER galaxy
=> starburst disk

=> numerous HII regions & filaments
=> streaming gas in 9 kpc
=> outflow 2 kpc above disk

Distance 15.6 Mpc



Pt al. 2001 [HST; WFPC2]

Detection NGC3079 at 1.9 ED

RG11AD & RG11AE 2014
Baseline 1.9 ED

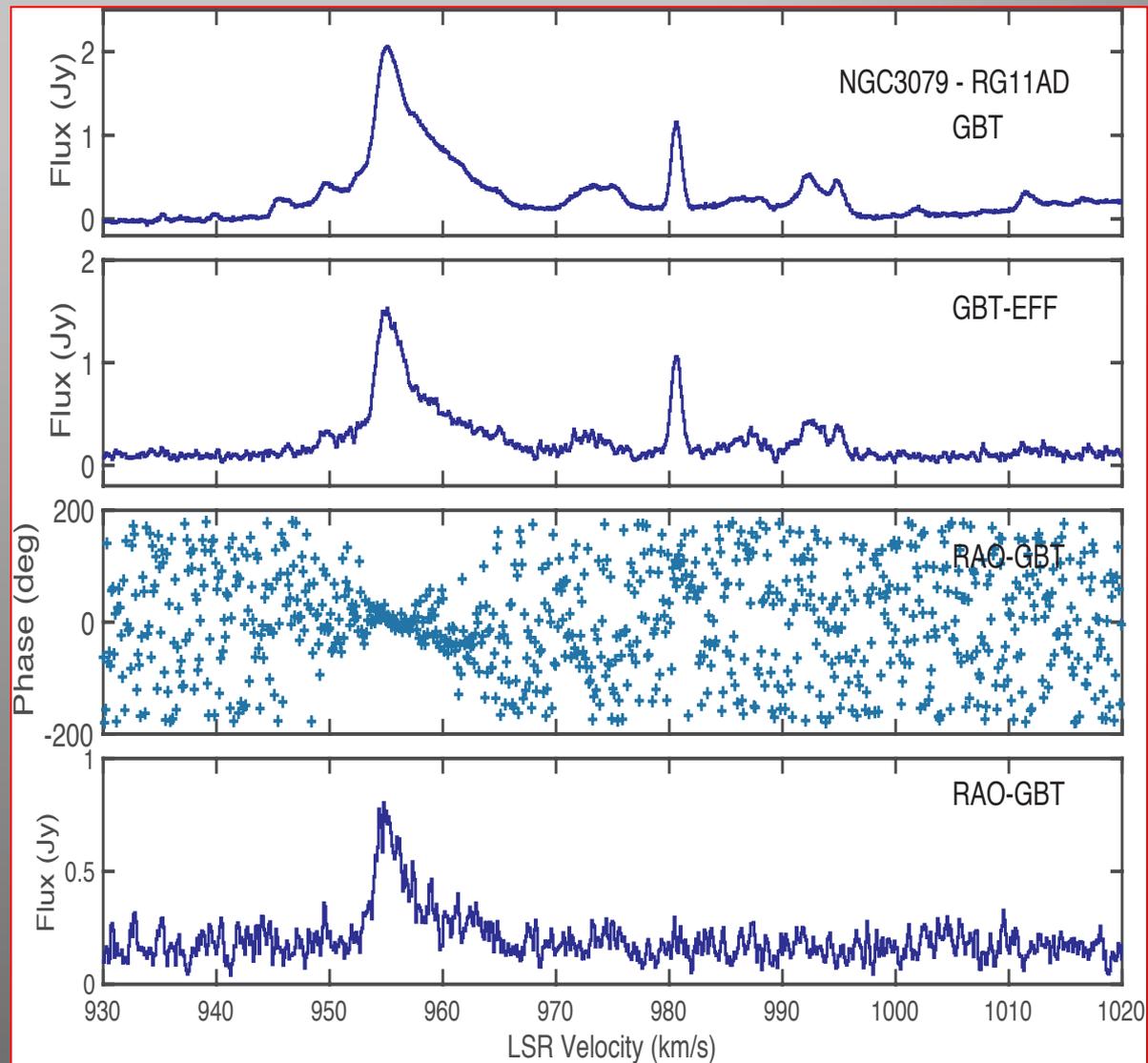
Ground based flux 1.6 Jy
RAO-GBT cross 0.6 Jy

Line ratio Auto/Cross =
0.75

Size = 0.027 mas

$T_b = 4.2 - 5.3 \times 10^{12}$ K

Regions are resolved at
longer baselines

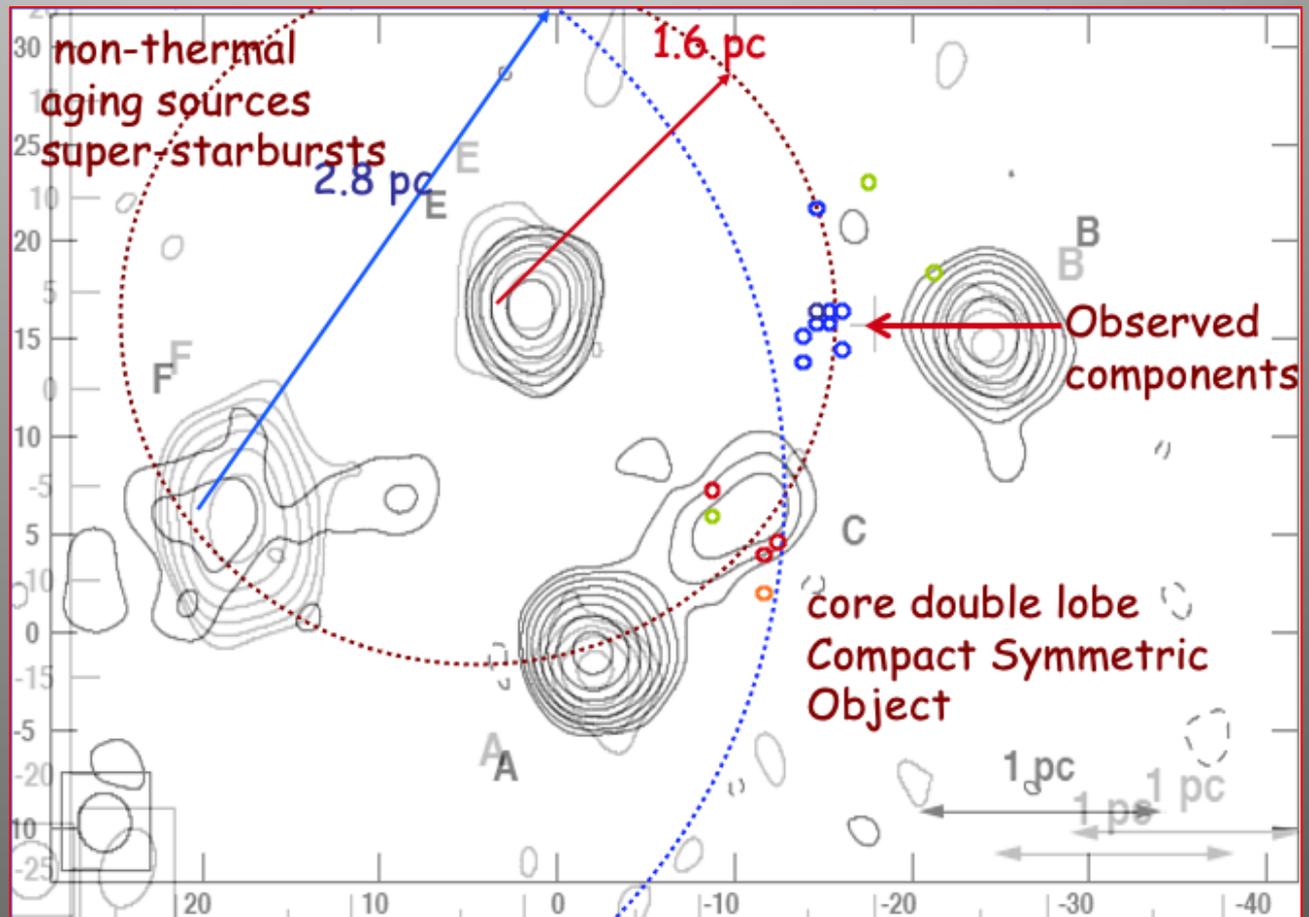




Location of MM features in NGC3079

This is NOT a disk maser => extended/diffuse regions

Possible scenario



Middelberg et al 2003, 2005;
Hagiwara, Klöckner, Baan 2004

Expansion 1 pc = 10^4 yr @ 100km/s



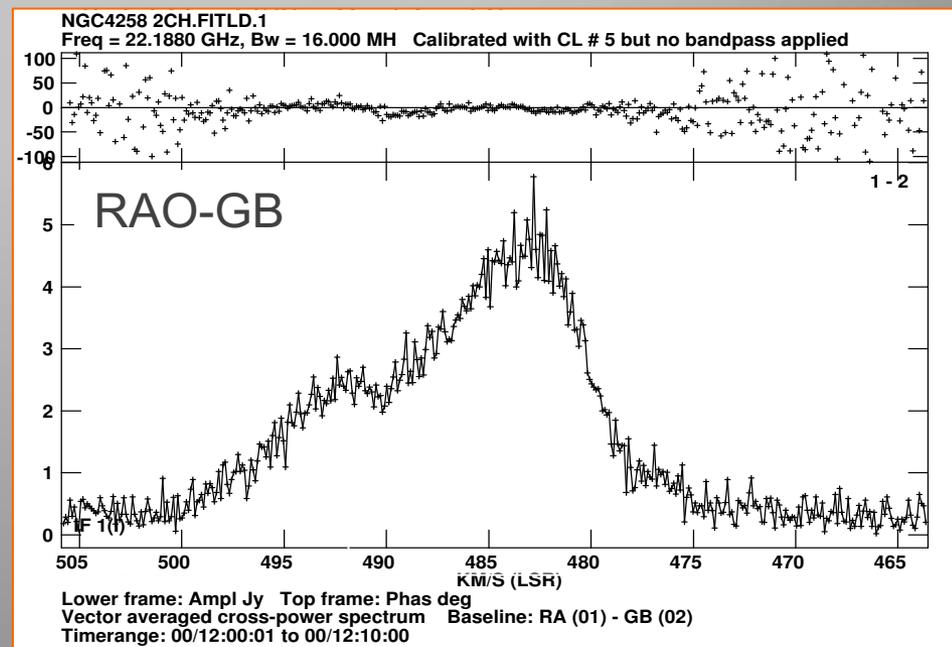
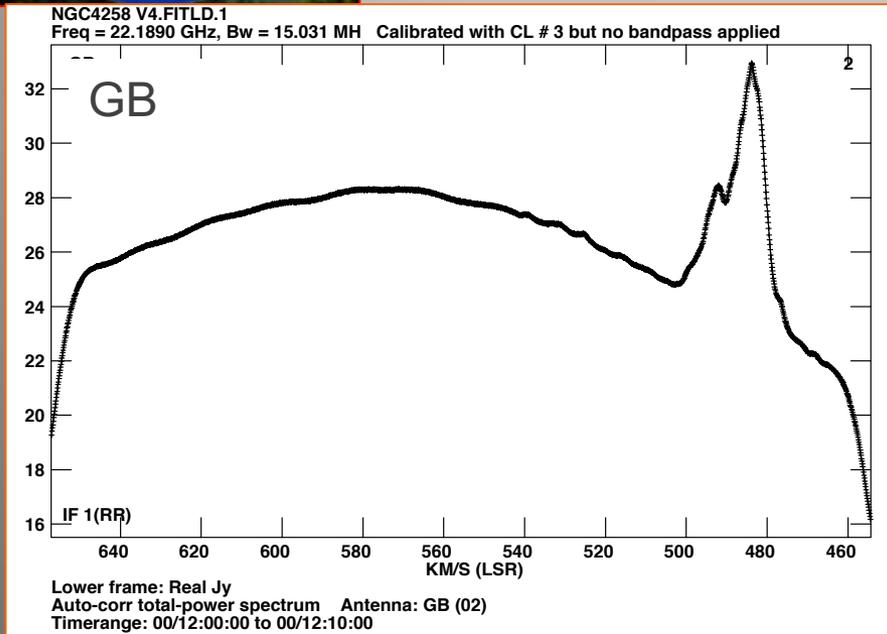
NGC 4258

H₂OMM at CSO in Centre of NGC4258

X-ray purple, Radio blue, Hubble yellow & blue, FIR red



Eleven NGC 4258 detections



Experiment RAGS11AF 2014-12-18 at 1.3 ED (165 μ as beam)
 Single line profile - *Simple spectrum*

Auto / Cross => ratio 0.420

Single baseline experiments - only spectral data
 Flux calibration not so accurate

Maser Location

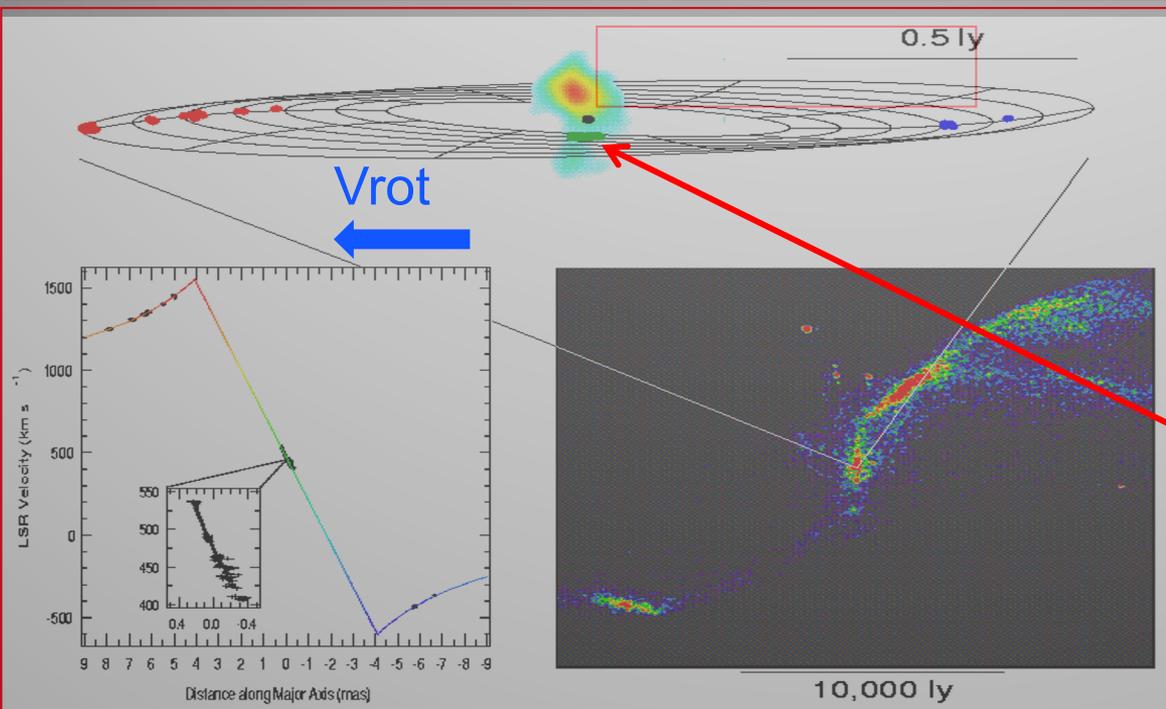
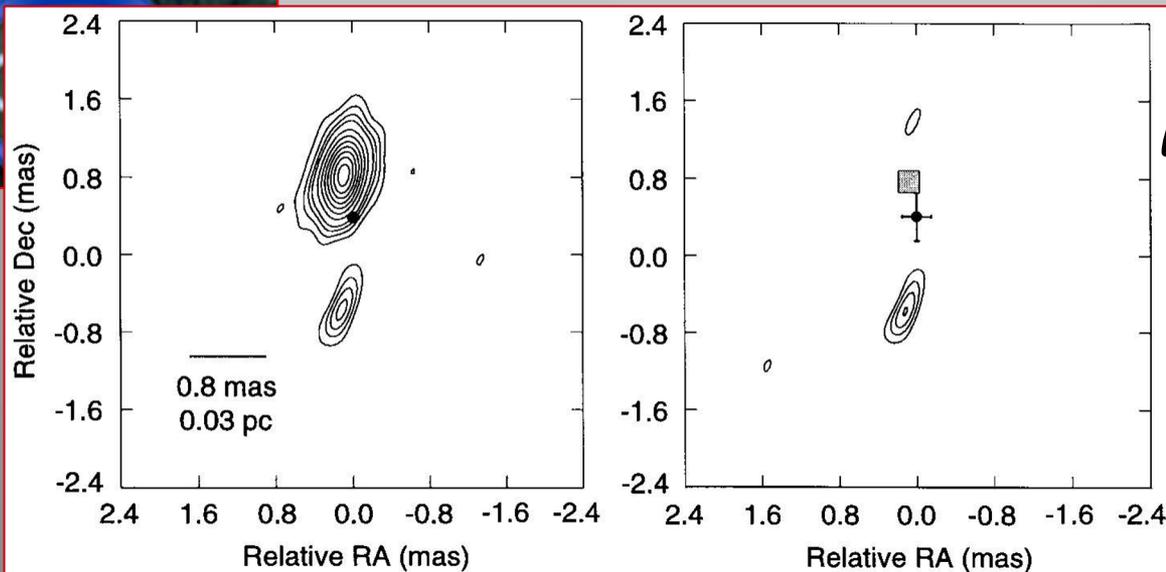
Distance 7.6 Mpc

Systemic features superposed on 22 GHz continuum

Active CSO at nucleus
Thin accretion disk
BH mass $4 \times 10^7 M_{\text{sol}}$

Observed maser regions

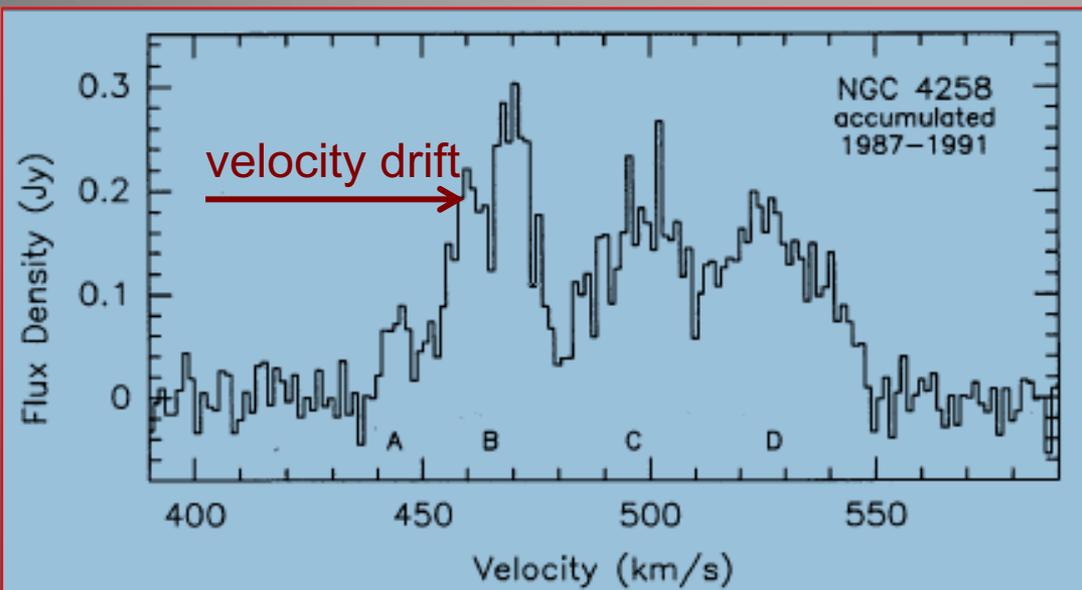
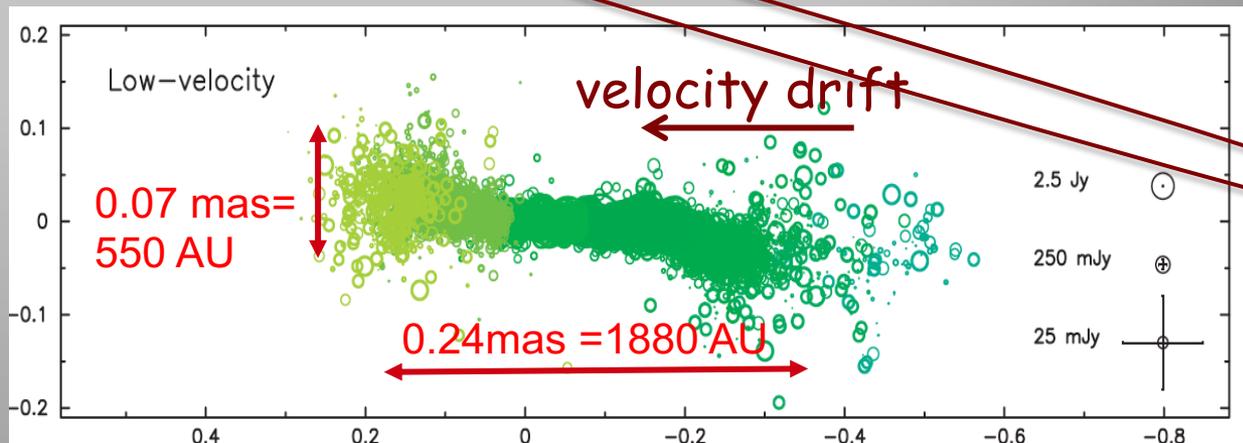
Herrnstein et al 1998
Greenhill et al 96





Central Disc region

Baseline 1.3 - 26.9 ED
 Beam 160 - 8 μ as
 Beam 1257 - 62 AU



Clouds drift/pass in front of continuum background

Variable features move from West to East and from 440 to 550 km/s

Triple emission structure ??

Integrated spectrum over 4 yr

Argon et al 2007

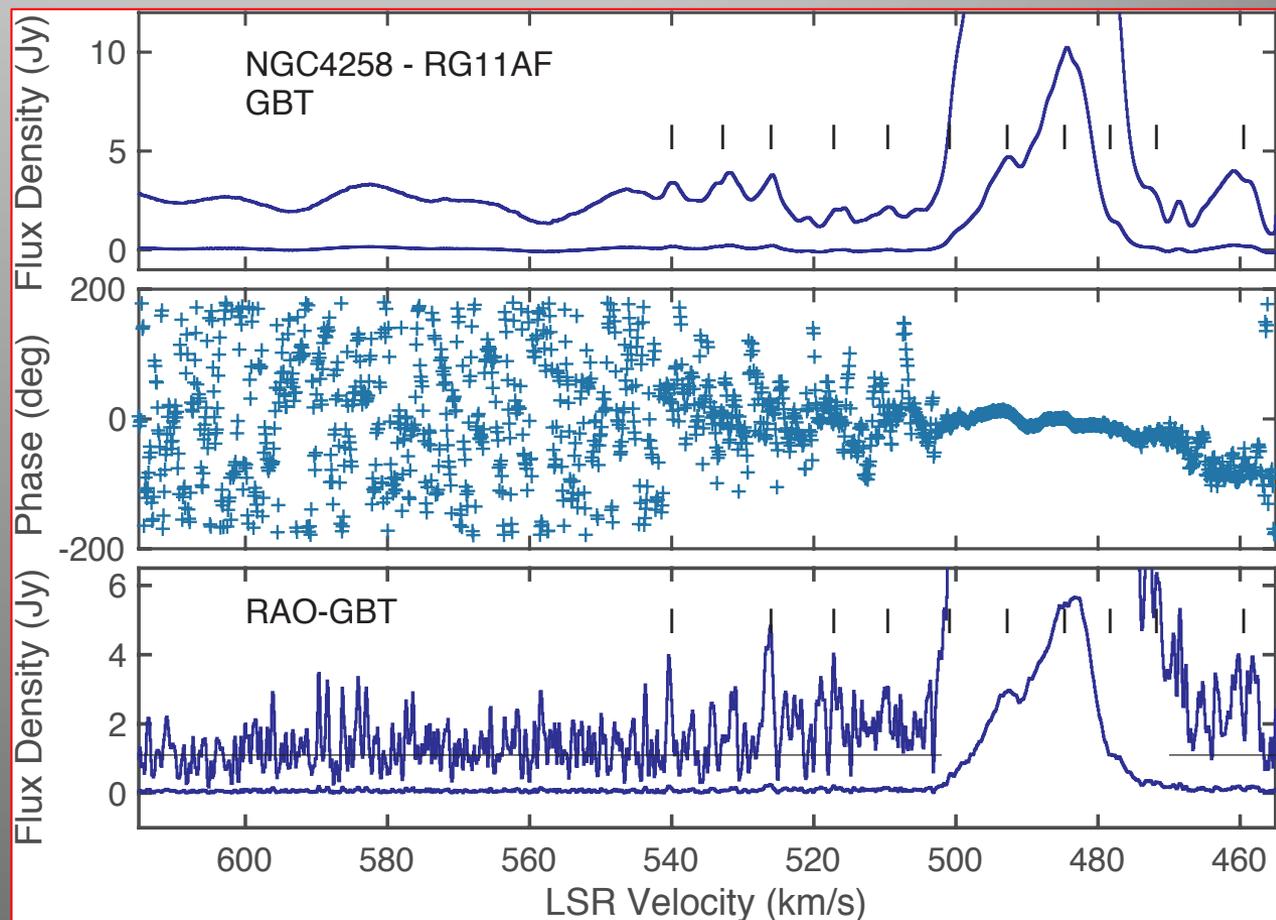
Haschick Baan & Peng '94

Greenhill et al 98



Detection NGC4258 at 1.3 ED

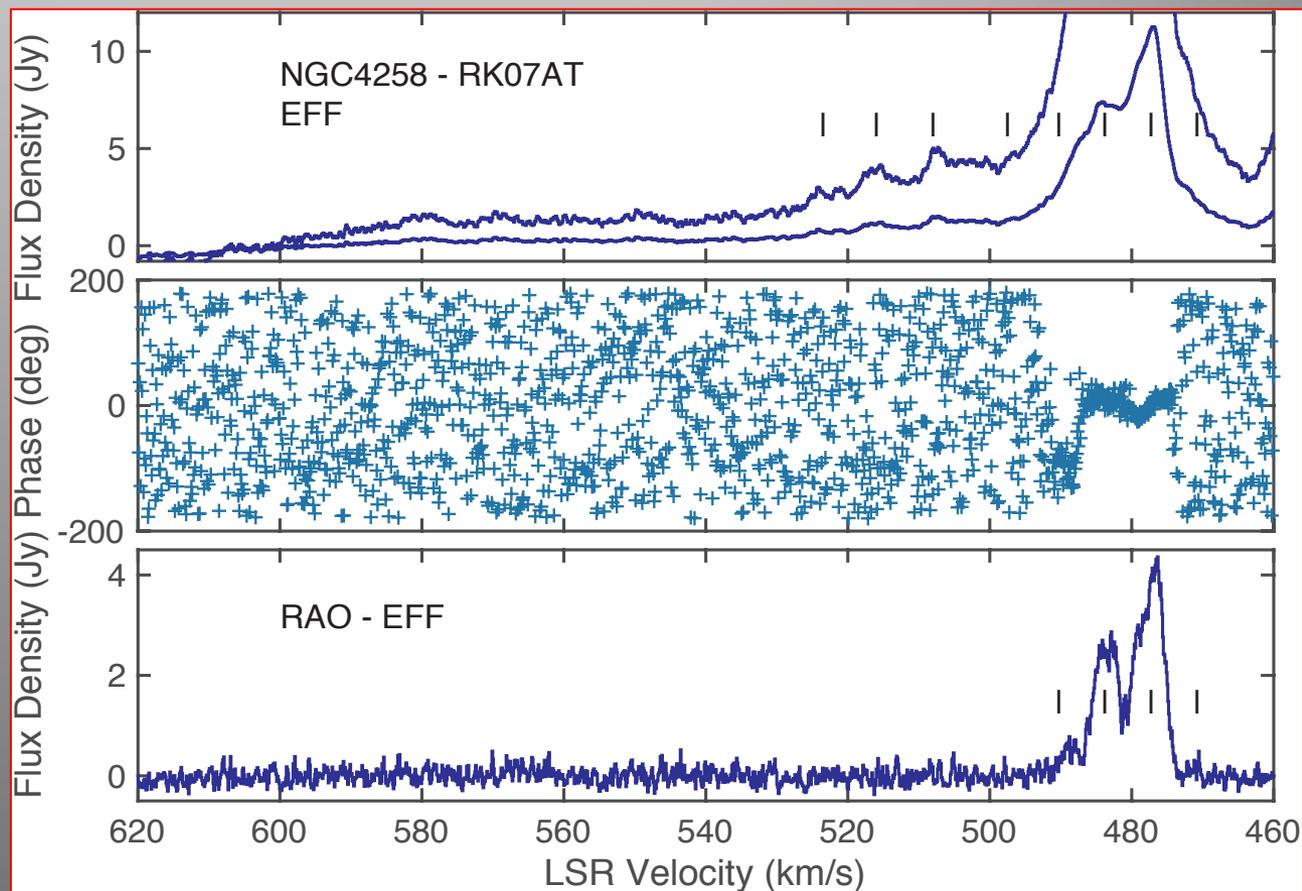
Experiment RAGS11AF
Date: 2014.964
Baseline: 0.5 - 1.9 ED
Stations: GBT, TR
Beam: $113 \mu\text{s}$
Spot size: 861 AU





Detection NGC4258 at 9.5 ED

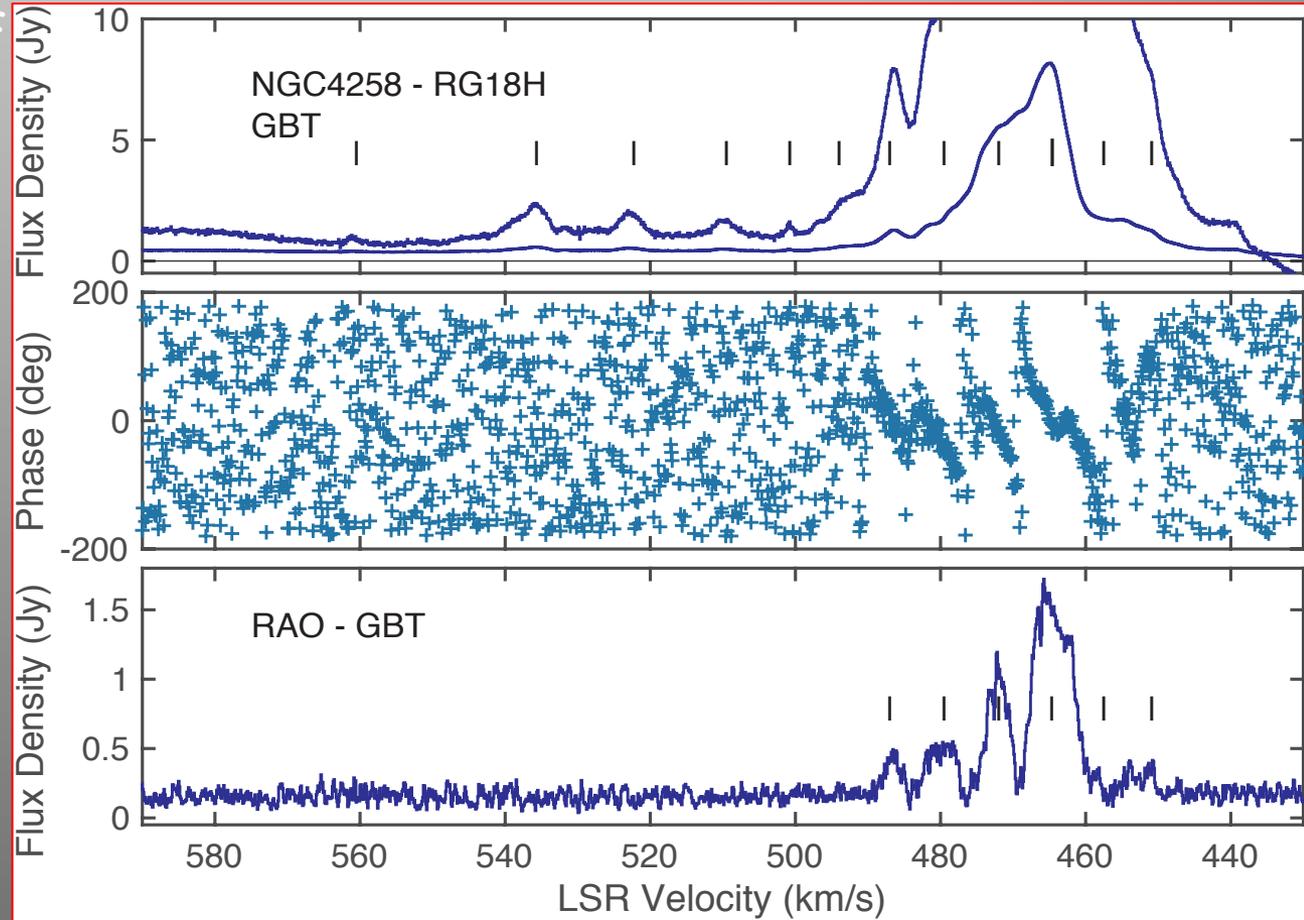
Experiment RAKS07AT
Date: 2014.964
Baseline: 9.1 - 9.8 ED
Stations: EFF, TR, BD
Beam: 23 μ as
Spot size: 173AU





Detection NGC4258 at 19.5 ED

Experiment RAGS11AF
Date: 2014.964
Baseline: 19.5 ED
Stations: GBT, YB, TR
Beam: $11 \mu\text{as}$
Spot size: 84 AU





Detection at 27 ED = highest resolution

RAKS07AV experiment

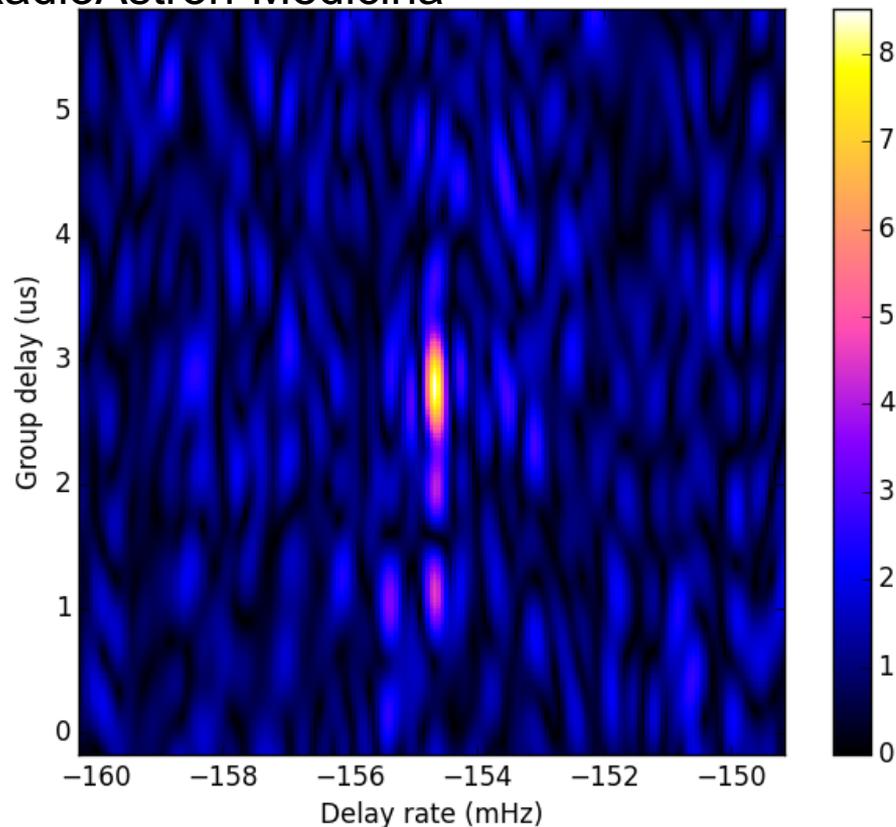
27 ED baseline
group delay - delay rate

8 μs resolution
or
62 AU at NGC4258

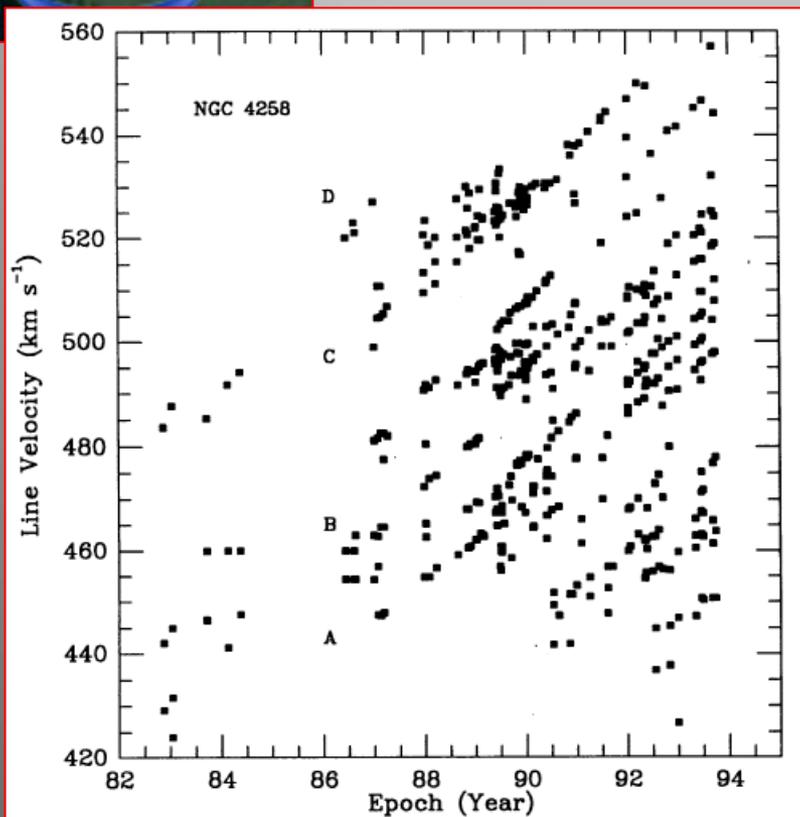
Multi-component structure

Not able to correlated yet

Fringe amplitude at St1: RADIO-AS St2: MEDICINA Sou: NGC4258 Exp: RK07AV
RadioAstron-Medicina



New Profiles and Velocity Drift

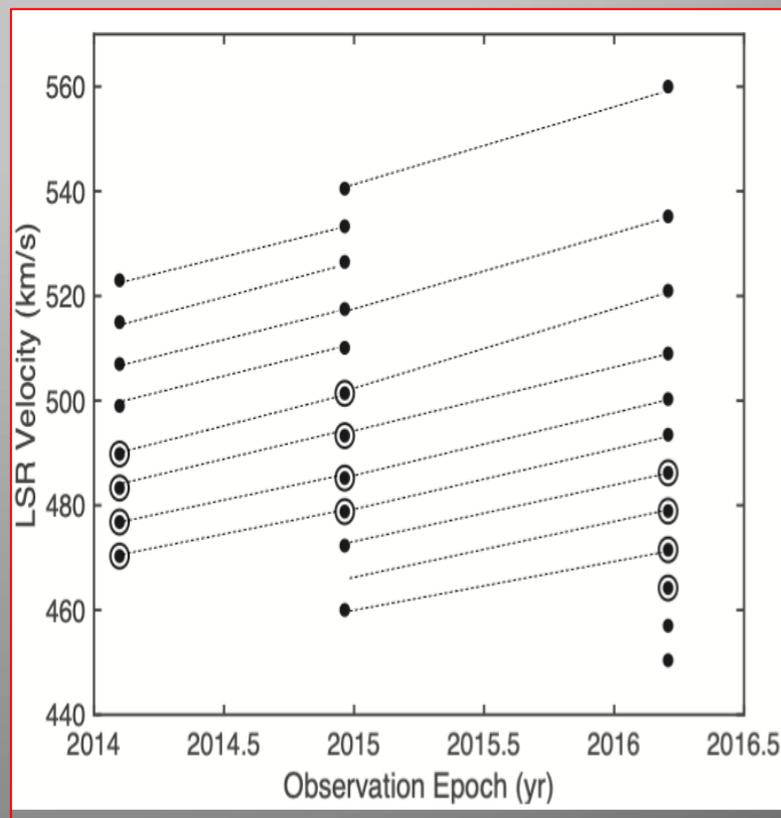


'82-'94 Velocity Drift of features

Early values 6.2 - 11.6 km/s/yr

Current value 11.1 km/s/yr

Current radius 0.126 pc



Velocity Drift for NGC4258 features at 3 epochs

Haschick, Baan & Peng 1994

Humphreys, Reid, Greenhill et al 2008



How to get masering from an AGN disc ?

- Emission regions at radius: 0.126 pc (using drift rate)
- Orbital Velocity: 1172 km/s in disc of $4 \times 10^7 M_{\text{sol}}$ AGN
- Periodic/Geometric cloud separation: 172 AU
- Beam size highest resolution: 62 AU

- Maser amplification of background continuum requires velocity-coherent radial column in foreground
- Differentially rotating environment does not make radial columns

- Actively manipulate the shear layers to make radial columns
- Some Instability operating in disc ???



Periodic Instability & masering columns ?

- NO Global Kink or Sausage instability - does not work in thin disk
- NO Global Gravitational instability IF
- Toomre stability $Q = \text{AGN mass/disk mass} < 1$
 - === in galactic disk instability can make nodules on a string
 - === NO because disk is not massive enough ($Q = 24$)
- YES Local shear-driven magneto-rotational instability - MRI
- Or Alternative Models
 - => Modulation of interferometric fringes
 - => Bi-refringence conditions
 - => Special scattering and propagation conditions
- Unlikely because these also require 'building a column'

Mganeto Rotational Instability --- Simulations



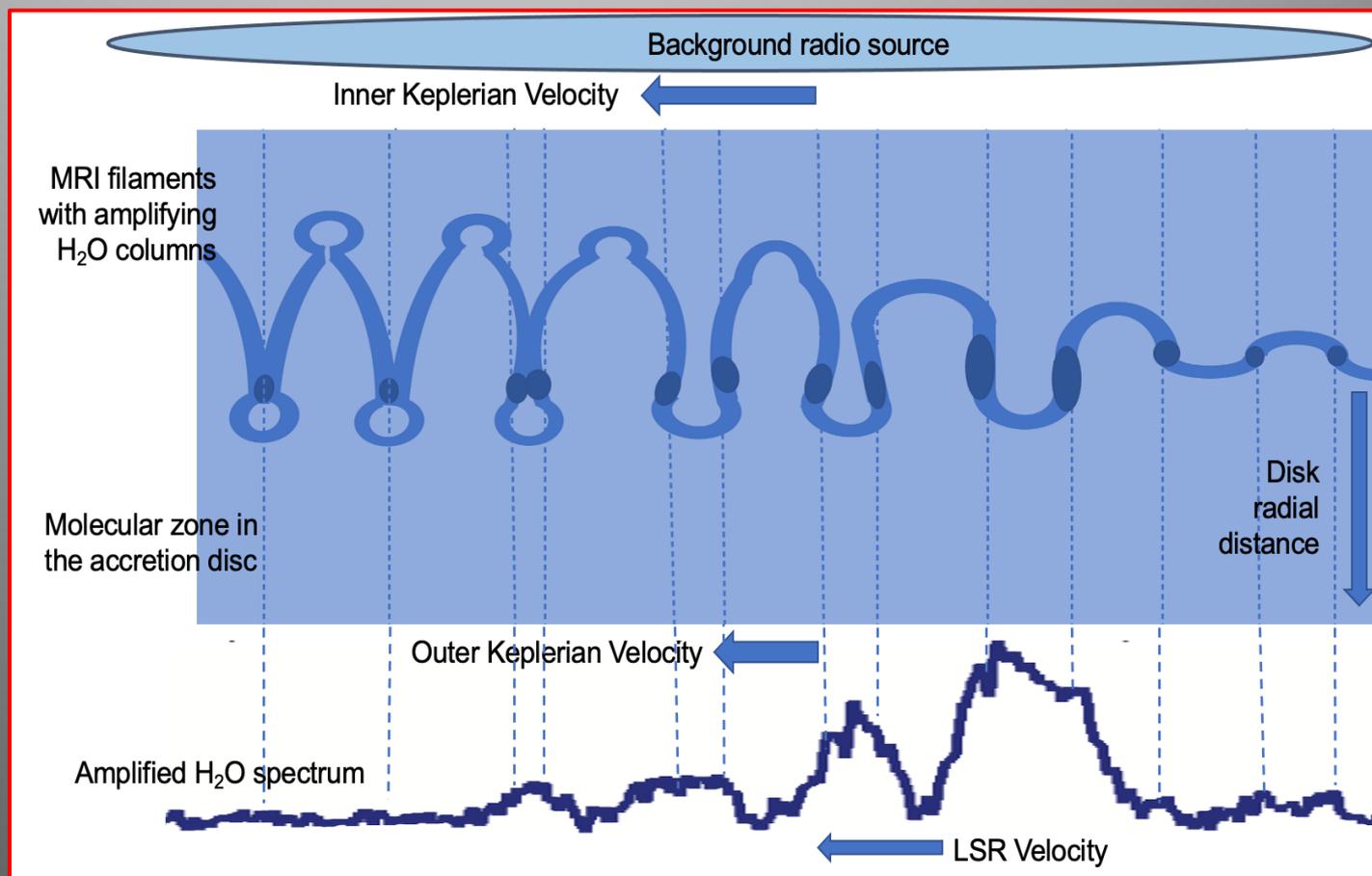
Hawley
Balbus
Stone
1991
1996

FIG. 3d

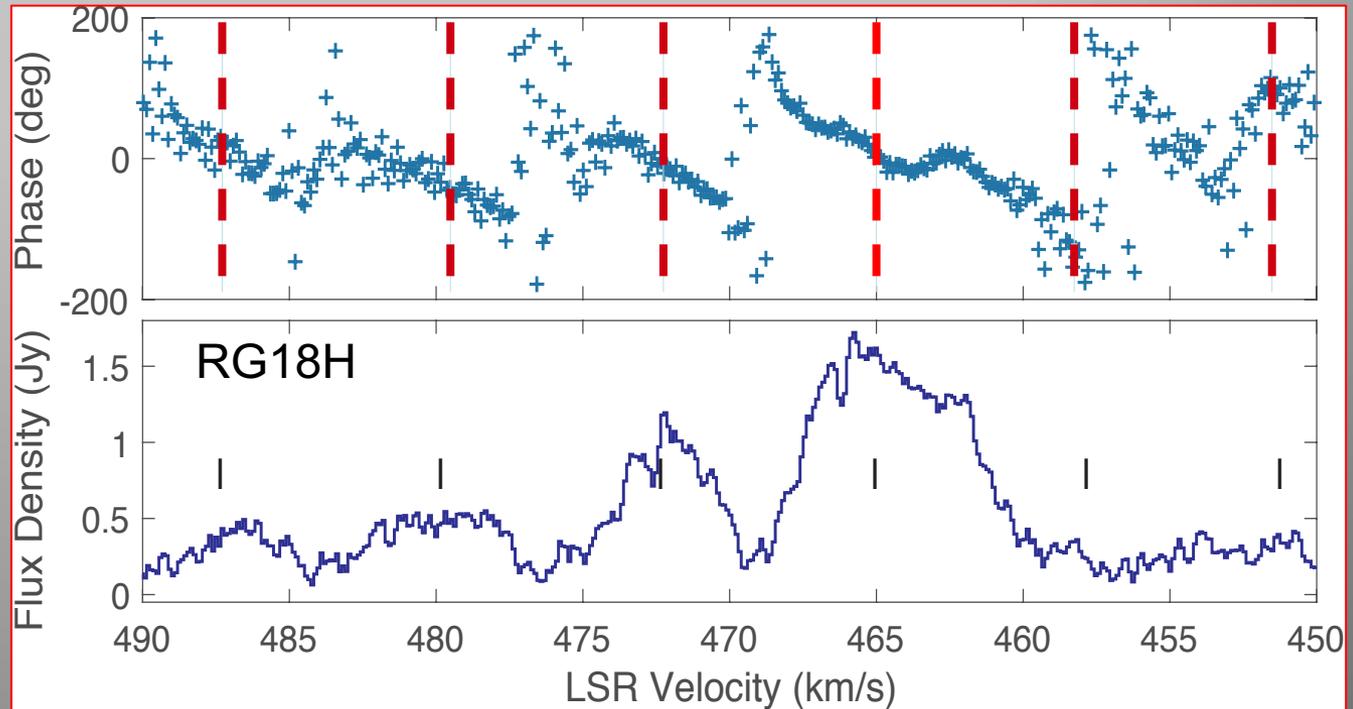
Magneto-rotational Instability

Differential rotation & Shear-driven
Cause for radial momentum exchange & transport

This disc viscosity model originally proposed in 1973
Shakura & Sunyaev



Artist conception of MRI amplifying columns



Model suggests two amplifying MRI columns
=> Two sides of feature need not be same
=> Phase jump in center of features ?



Fading of maser features

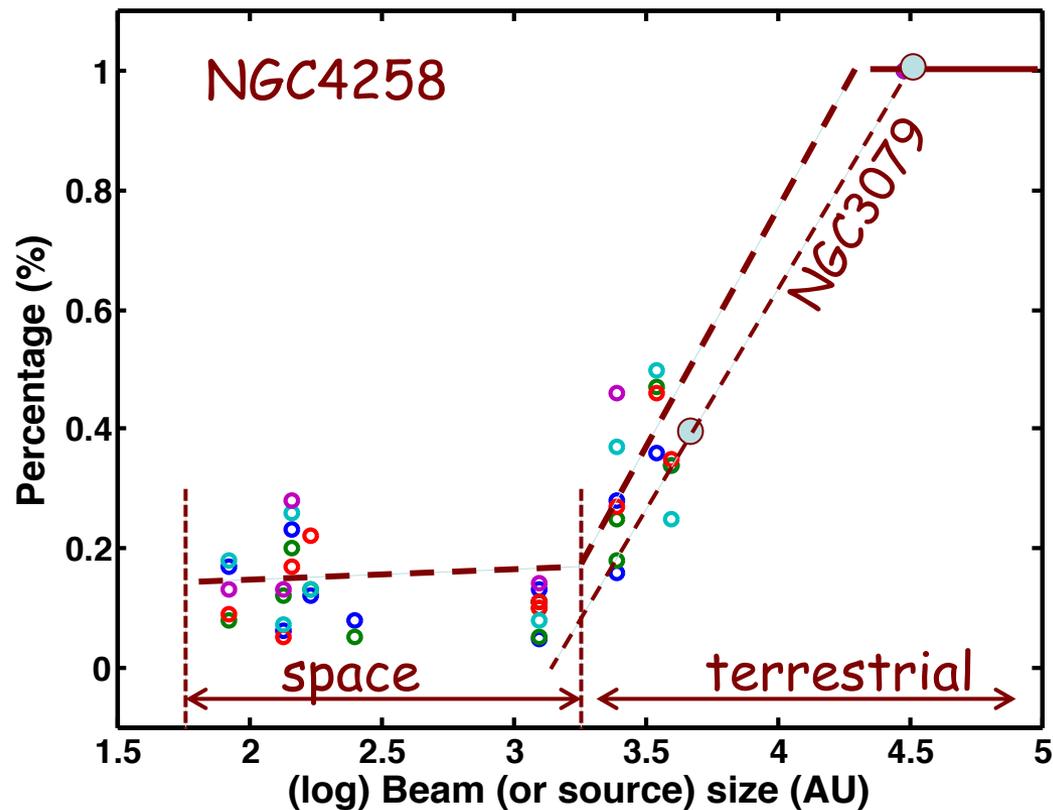
Extended emission regions
resolved at higher resolution

Compact sources remain
unresolved until high
resolution

In NGC4258
5-20% compact < 300 AU

In NGC 3079
0% compact < 300 AU

Data points not yet well
calibrated



Some Conclusions

NGC3079 features resolved at 2 ED & beam size of 300 AU

⇒ Molecular environment appears shocked/diffuse regions

⇒ Any feature shift in position and velocity ?

NGC4258 seen on whole orbit - up to baseline 350,000 km

⇒ Compact emission 5-20% at longest baselines

⇒ Maser features amplify radio background of central CSO

⇒ Isolated periodic features at radial distance 0.126 pc

⇒ Cloud formation results from MRI instability

⇒ Clouds relate to shear-driven MRI at work as viscosity agent

⇒ Confirmation of Shakura & Sunyaev 1973 prediction

⇒ *H₂O* disk maser activity relates to the accretion rate

⇒ MM activity does NOT relate to gas properties in nuclear region



感谢!

The authors dedicate this paper to the memory of our colleague and friend NIKOLAI KARDASHEV, a man of great vision, who persevered to realise the RadioAstron mission.

NGC4258 results published in *Nature Astronomy*



Imaging of NGC4258 ?

- Add all existing data at different epochs
- Determine relative positions of observed features
- Imaging experiment using
- single orbit with EVN and
- EFF & GBT - December 2017

