ALMA scientific capabilites and its science with AGN

Paola Andreani
ESO-ALMA

Talk outline

- Review of the ALMA scientific capabilities
- ALMA and the AGN
  - Outflows/AGN feedback in nearby active galaxies
  - Imaging the obscuring torus/nucleus in intensity and polarisation
  - Megamasers in AGN and H_0
  - QSO as lighthouses: absorption lines and lenses
  - Role of AGN/SMBH in shaping galaxies physical properties
  - Search for the first quasars
- Future plans

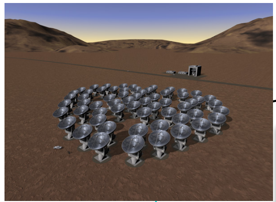
ALMA Observatory

The Atacama Large Millimeter Submillimeter Array (ALMA)

located in the Atacama desert in Chile on the Chajnantor plateu at 5000m
ALMA works at low frequencies (from 30GHz to 900 GHz)
50+4 12m + 12 7m high-precision antennas with baselines up to 16km.:
    50x12m antennas (high-angular resolution and sensitivity)
+ ACA (Morita Array) 4x12m +12x7m (for extended structures)

10-100 times more sensitive
10-100 times better angular resolution
compared to current millimeter interferometers.

ALMA Sites in Chile



Antenna Operations Site (AOS)

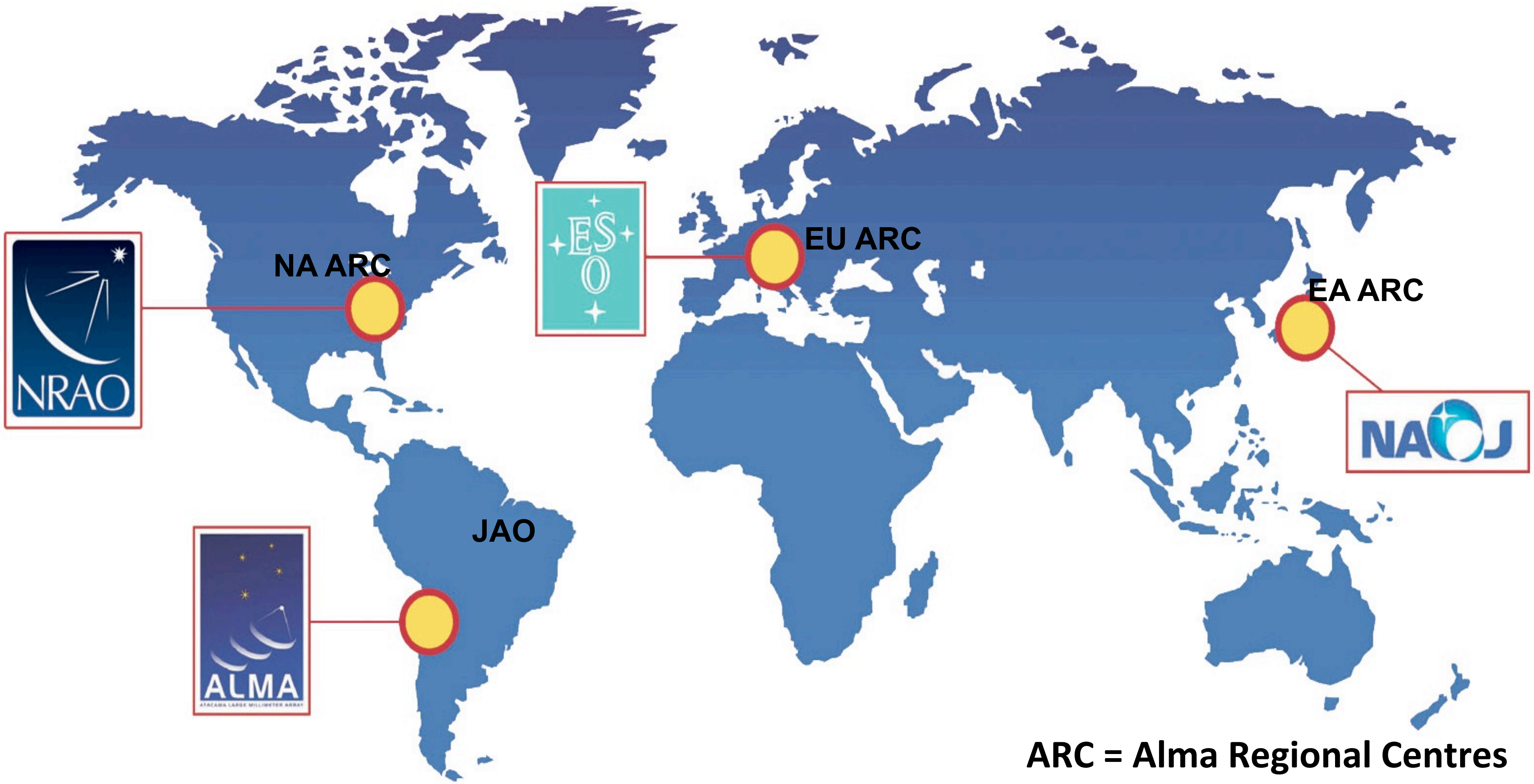
40 MB/s (peak)

Operation Support Facility (OSF)

6 MB/s (average)

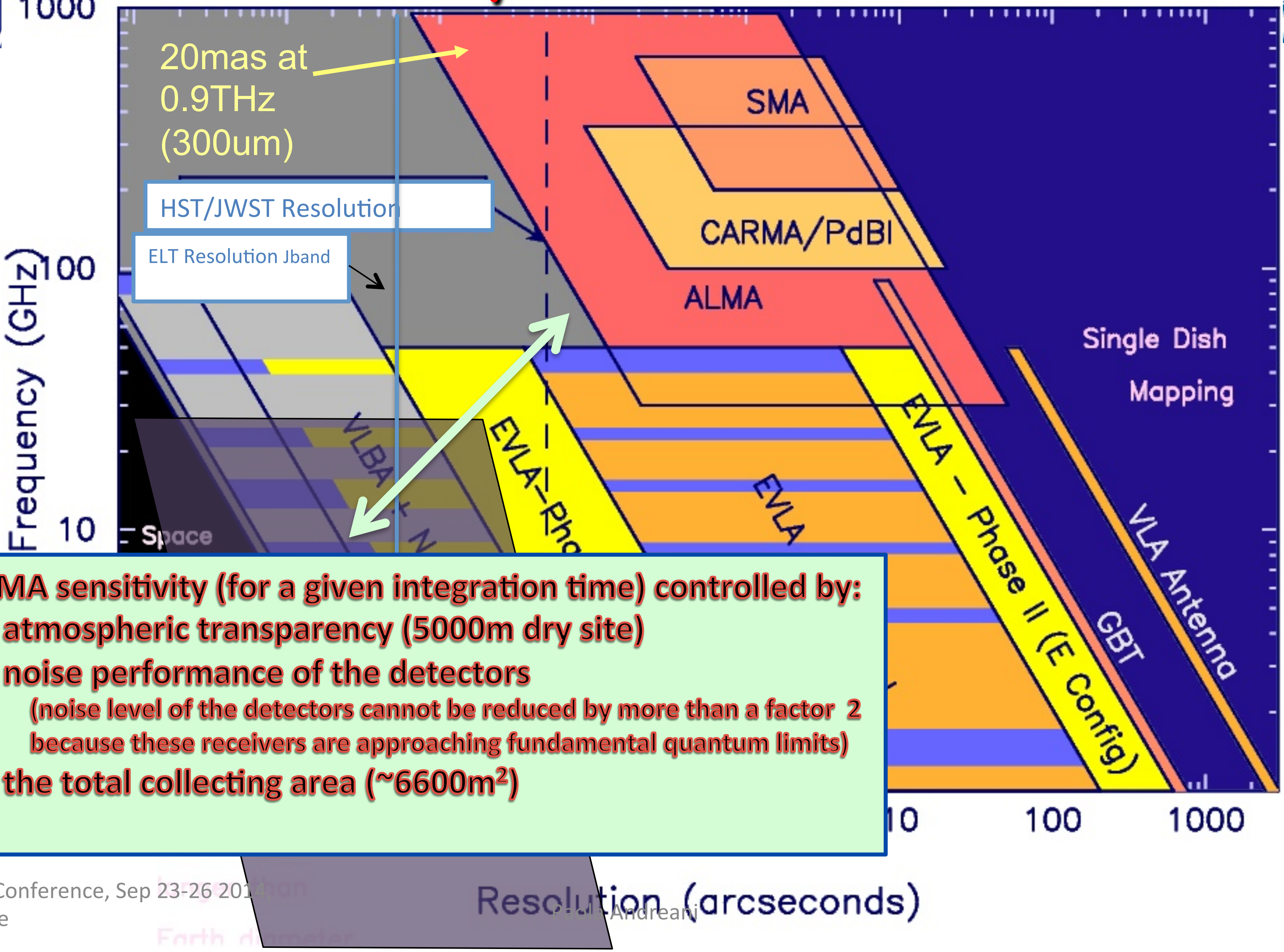
Santiago Central Office (SCO)

ALMA Operations Centres



ARC = Alma Regional Centres
JAO = Joint ALMA Observatory

Sensitivity and Resolution



ALMA sensitivity (for a given integration time) controlled by:

- ❖ atmospheric transparency (5000m dry site)
- ❖ noise performance of the detectors
  (noise level of the detectors cannot be reduced by more than a factor 2 because these receivers are approaching fundamental quantum limits)
- ❖ the total collecting area (~6600m²)

Highest Level Science Goals

Bilateral Agreement Annex B:

ALMA has three level-1 science requirements:

Ability

- To detect spectral line emission from CO or C+ in a normal galaxy like the Milky Way at a redshift of z = 3, in less than 24 hours of observation.
- To image the gas kinematics in a solar-mass protostellar/protoplanetary disc at a distance of 150 pc (~ distance of the star-forming clouds in Ophiuchus or Corona Australis), enabling the study of the physical, chemical, and magnetic field structure of the disc and to detect the tidal gaps created by planets undergoing formation.
- To provide precise images at an angular resolution of 0.1" (accurately representing the sky brightness at all points where the brightness is greater than 0.1% of the peak image brightness). This requirement applies to all sources visible to ALMA that transit at an elevation greater than 20 degrees.

-

These requirements drive the technical specifications of ALMA

These science goals cannot be achieved by any other instrument

ALMA Full Array specification

	Specification
Number of Antennas	*50×12-m (12-m Array), plus 12×7-m & 4×12-m (ACA)*
Maximum Baseline Lengths	*0.15 - 16 km*
Angular Resolution (")	*~0.2" × (300/ν GHz) × (1 km / max. baseline)*
12-m Primary beam (")	*~20.6" × (300/ν GHz)*
7-m Primary beam (")	*~35" × (300/ν GHz)*
Number of Baselines	*Up to 1225 (ALMA correlators can handle up to 64 antennas)*
Total Bandwidth	*16 GHz (2 polarizations × 4 basebands × 2 GHz/baseband)*
Spectral Resolution	*As narrow as 0.008 × (ν/300 GHz) km/s*
Polarimetry	*Full Stokes parameters*

Full Science Capabilities					Most Compact		Most Extended	
Band	Frequency (GHz)	Wavelength (mm)	Primary Beam (FOV; ")	Continuum Sensitivity (mJy/beam)	Angular Resolution (")	Spectral Sensitivity ΔT_{line} (K)	Angular Resolution (")	Spectral Sensitivity ΔT_{line} (K)
1	31.3-45	6.7-9.5	197-137	0.04	13-9	0.006	0.12-0.08	255
2	67-90	3.3-4.5	92-69	0.06	6-4.4	0.009	0.06-0.04	413
3	84-116	2.6-3.6	73-53	0.07	4.8-3.4	0.04	0.045-0.032	430
4	125-163	1.8-2.4	49-38	0.06	3.2-2.4	0.048	0.030-0.023	330
5	163-211	1.4-1.8	38-29	0.11	2.5-1.9	0.06	0.027-0.021	641
6	211-275	1.1-1.4	29-22	0.085	1.9-1.5	0.05	0.018-0.014	490
7	275-373	0.8-1.1	22-16	0.15	1.5-1.1	0.08	0.014-0.01	814
8	385-500	0.6-0.8	16-12	0.28	1.04-0.8	0.28	0.01-0.008	1900
9	602-720	0.4-0.5	10-8.6	1.1	0.66-0.55	0.9	0.006-0.005	8900
10	787-950	0.3-0.4	7.8-6.5	1.2	0.51-0.42	1.6	0.005-0.004	—

Spatial resolution
Physical size at redshift z=0.01 and z=2

Frequency	Most compact	Most extended
100GHz/ 3mm	700pc – 28.9kpc	6pc - 250pc
250GHz/ 1mm	310pc – 12.8kpc	3pc - 120pc
340GHz/ 870um	220pc – 9.4kpc	2pc - 85pc
450GHz/ 670um	165pc – 6.8kpc	1.6pc – 70pc
660GHz/ 450um	110pc – 4.7kpc	1pc - 42pc

Spectral capabilities

per baseband for observations in dual polarization

Single polarization modes
for all bandwidths:
double # of channels and
1/2 channel spacing
Full Stokes polarization
mode ½ # channels.

Mode	Polari-zation*	Band-width (MHz)	Nchan	Chan. Spacing (MHz)	Spectral Resolu-tion† 300 GHz (km/s)
FDM	Dual	1875	3840	0.488	0.98
FDM	Dual	938	3840	0.244	0.49
FDM	Dual	469	3840	0.122	0.24
FDM	Dual	234	3840	0.061	0.12
[illegible]	[illegible]	[illegible]	40	0.0305	0.061
[illegible]	[illegible]	[illegible]	40	0.0153	0.031
TDM	Du	[illegible]	[illegible]	[illegible]	[illegible]

Each receiver outputs four 2 GHz-wide basebands
in each polarization, which are fed into the correlator.
These basebands can be tuned independently

The channels within a mode may be set up as one contiguous
spectral window, or split up into 2/4 narrower windows.

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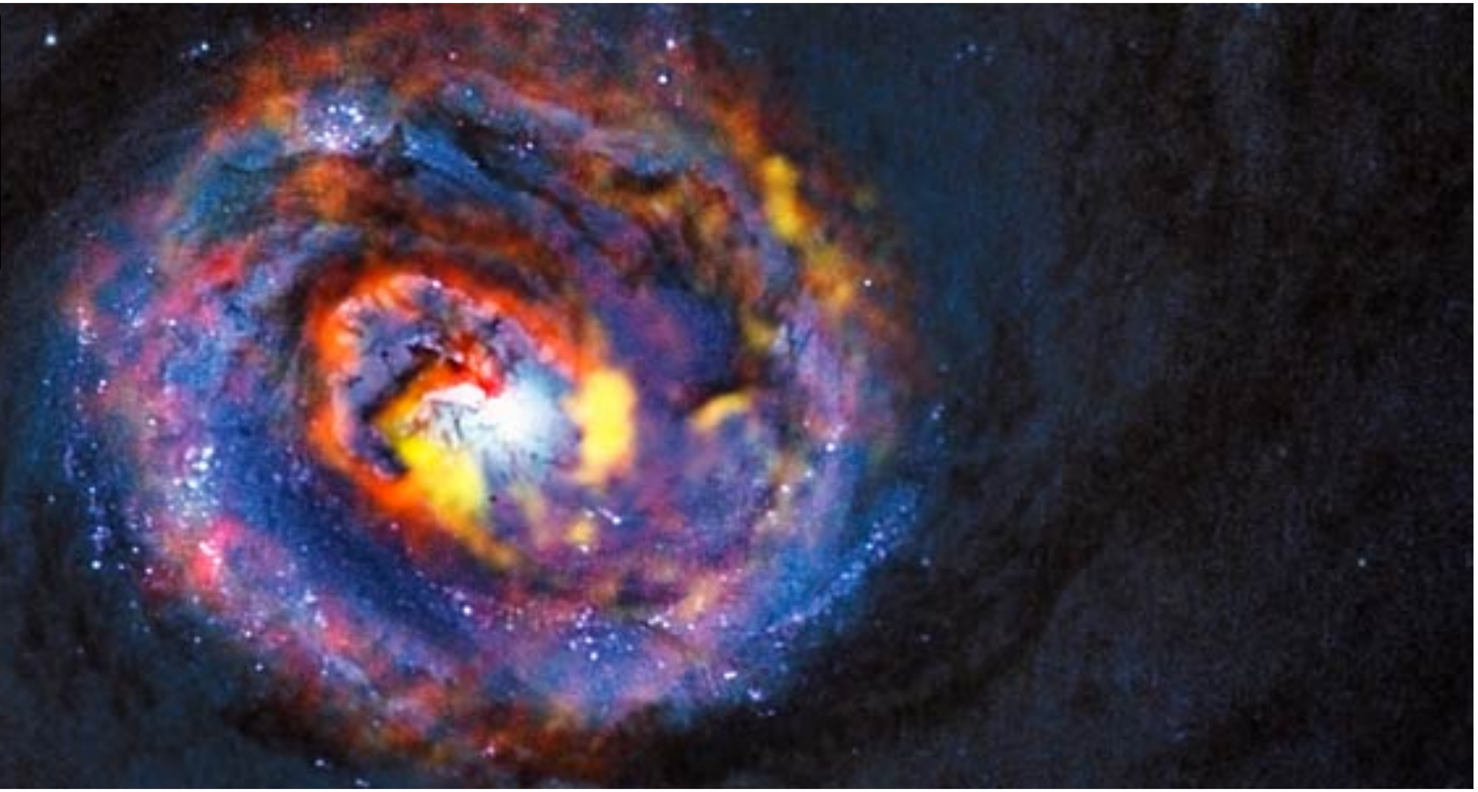
A surprising molecular gas spiral structure close to the centre and an outflow: an AGN jet quenching SF and fueling the AGN?

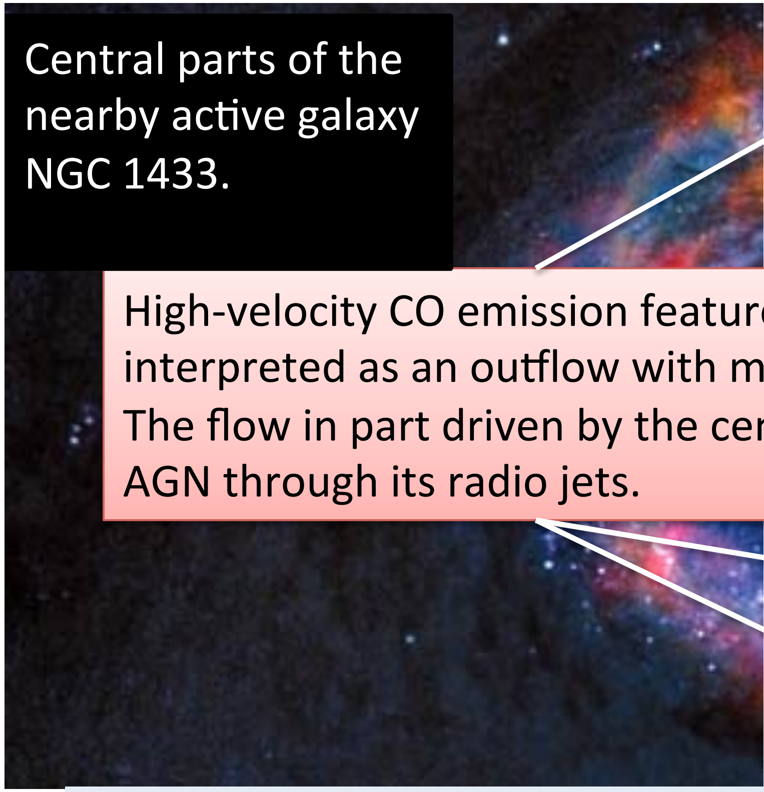


Central parts of the nearby active galaxy NGC 1433.

Central dust lane (dim blue background image, HST)
Coloured structures near the centre: ALMA CO(3-2), spiral shape, as well as an unexpected outflow.
No HCO^+ HCN → no high density gas in the centre.

Combes el, 2013

A surprising molecular ga[s] ... [st]re
and an outflow: an AGN j[et] ... [A]GN?



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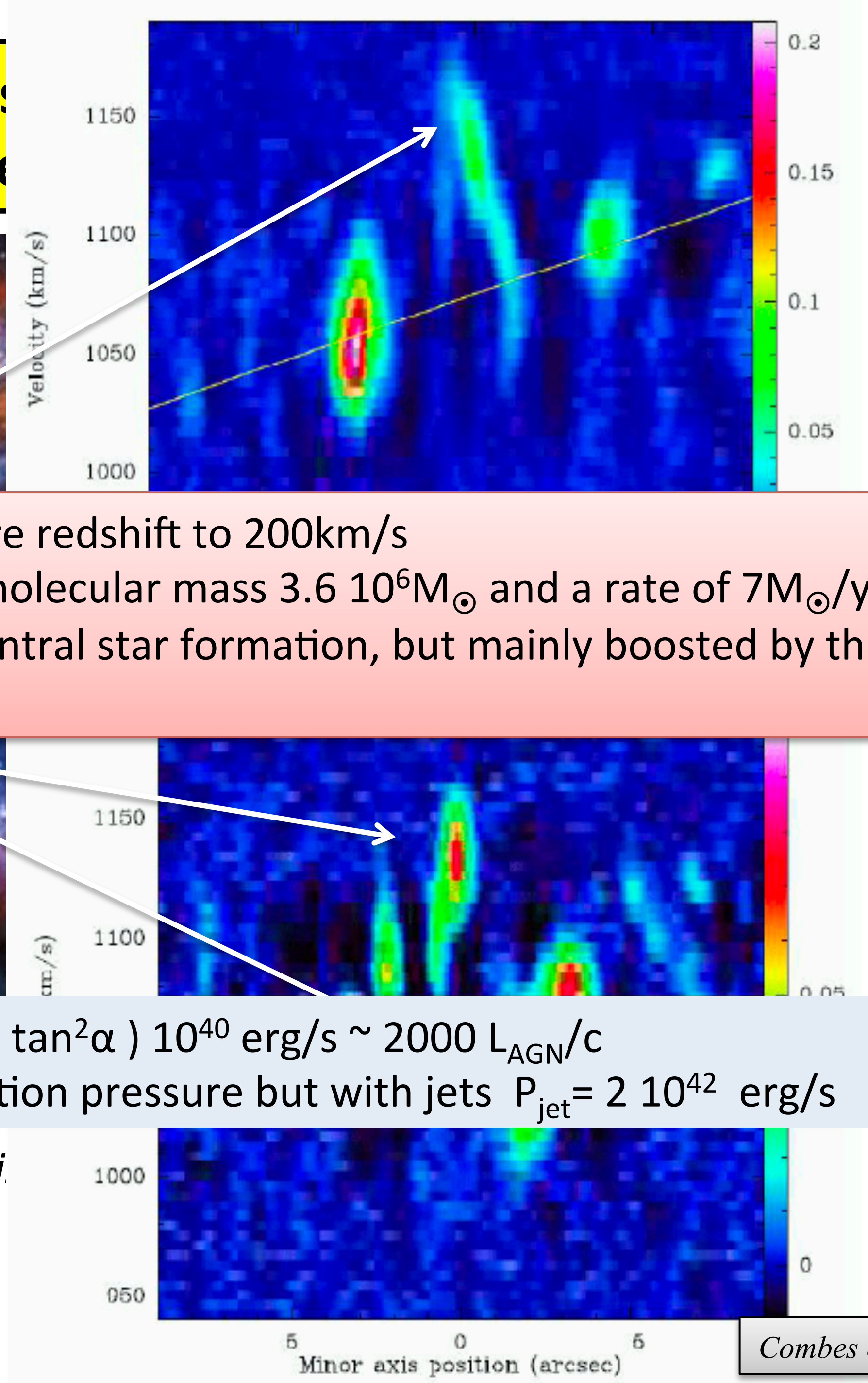


High-velocity CO emission feature redshift to 200km/s interpreted as an outflow with molecular mass 3.6 $10^6 M_\odot$ and a rate of $7 M_\odot$/yr. The flow in part driven by the central star formation, but mainly boosted by the AGN through its radio jets.

$L_{kin} = 0.5\, dM/dt\, v^2 = 2.3 \tan\alpha\, (1+ \tan^2\alpha)\, 10^{40}$ erg/s ~ 2000 L_{AGN}/c

→ AGN contributes not with radiation pressure but with jets $P_{jet} = 2\ 10^{42}$ erg/s

Ce...

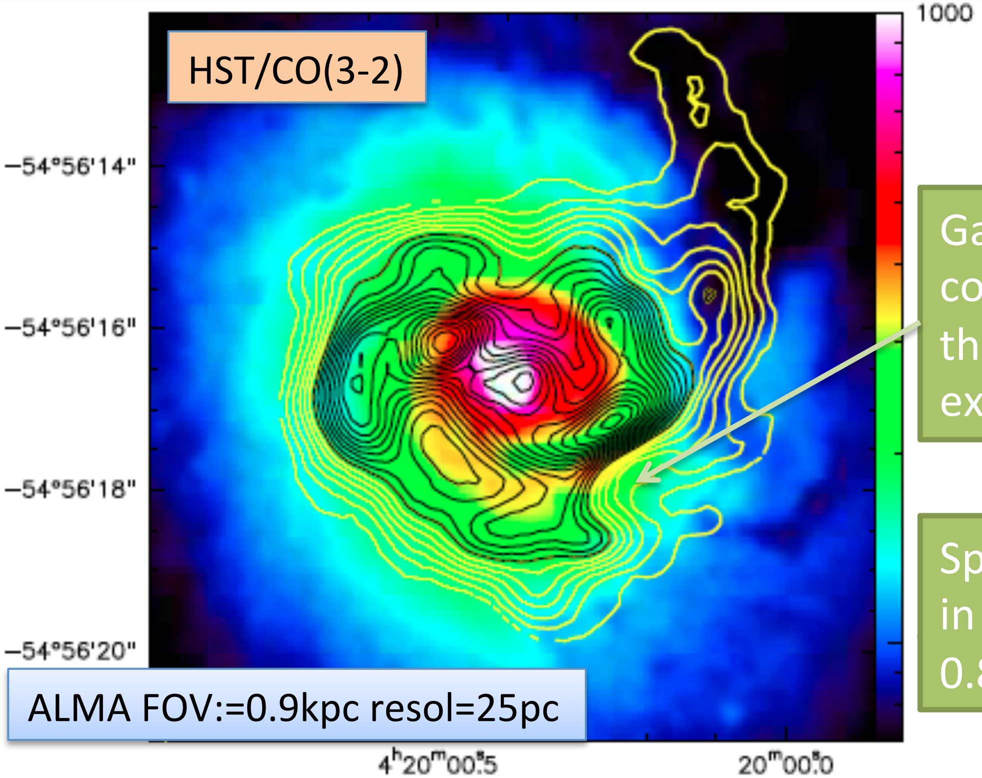
Co... [dete]cted outflow.

No HCO^+ HCN → no high density gas i...

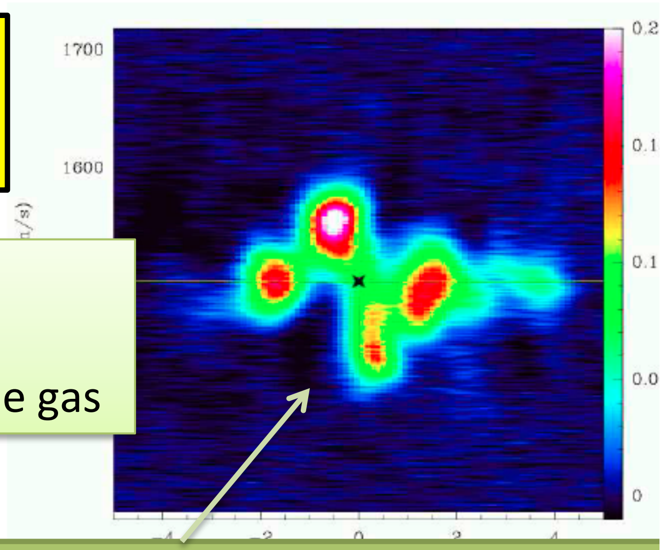
Combes el, 2013

Nuclear fueling and feedback in the Seyfert 1 NGC 1566 CO(3-2)

Dynamics inside central 1 kpc: molecular trailing spiral structure of ~ 100pc size inside the Lindblad resonance of the nuclear bar
→ massive central BH significantly influences the dynamics of the gas



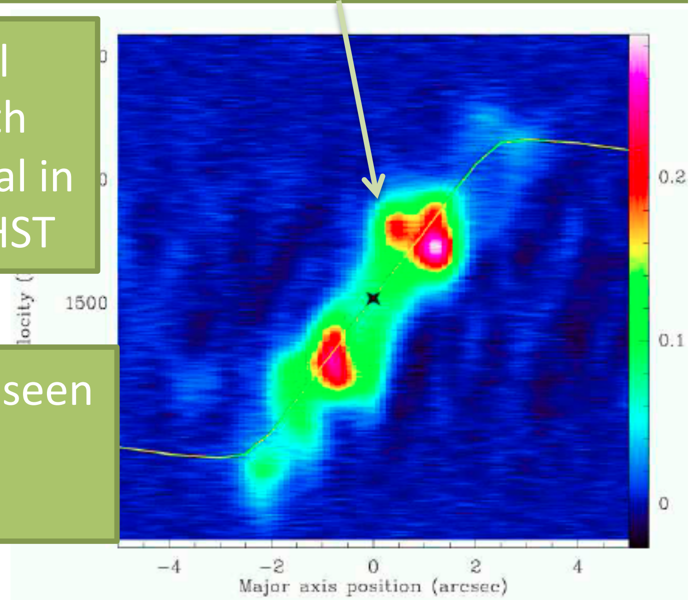
ALMA FOV:=0.9kpc resol=25pc



CO(3-2) PV along the minor/major axis: no outflow

Gaseous spiral correlated with the dusty spiral in extinction in HST

Spiral feature seen in emission at 0.87mm



HCO+(4-3) ~ 3 x HCN(4-3) → SF excitation dominates over AGN heating

Combes el, 2014

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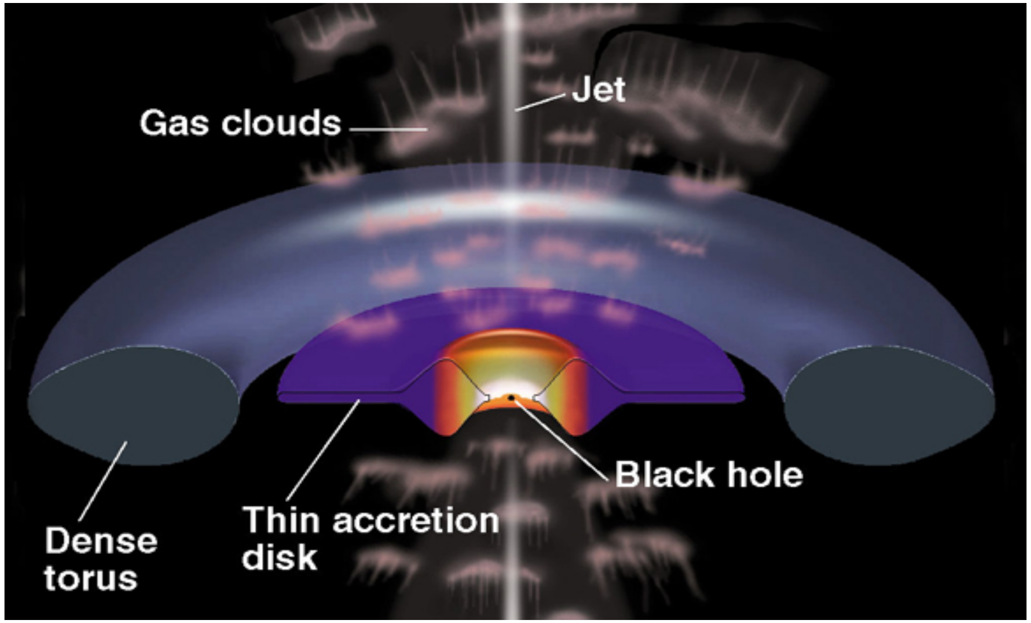
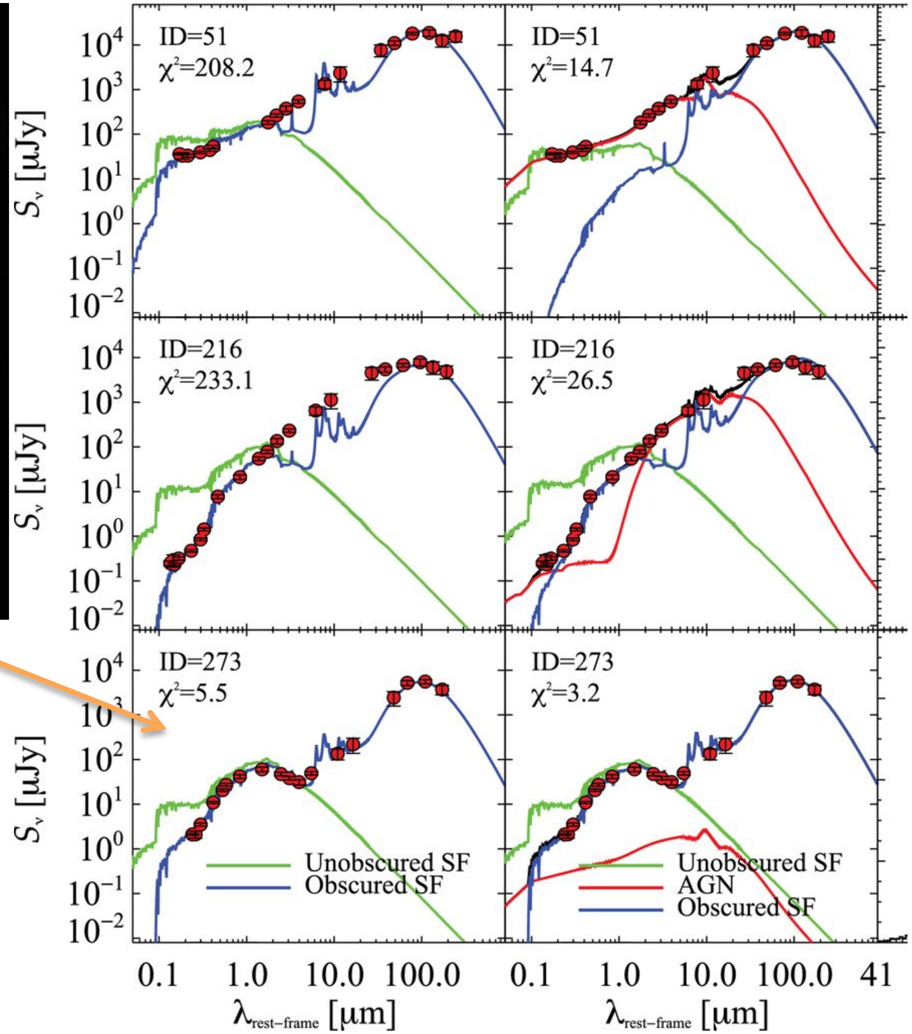
The central torus/nucleus

SED decomposition without AGN

with AGN





no AGN addition

In absence of high-resolution IR obs estimates of the torus size comes from theoretical analysis of the (SED): only SED cannot determine the size of the inner region

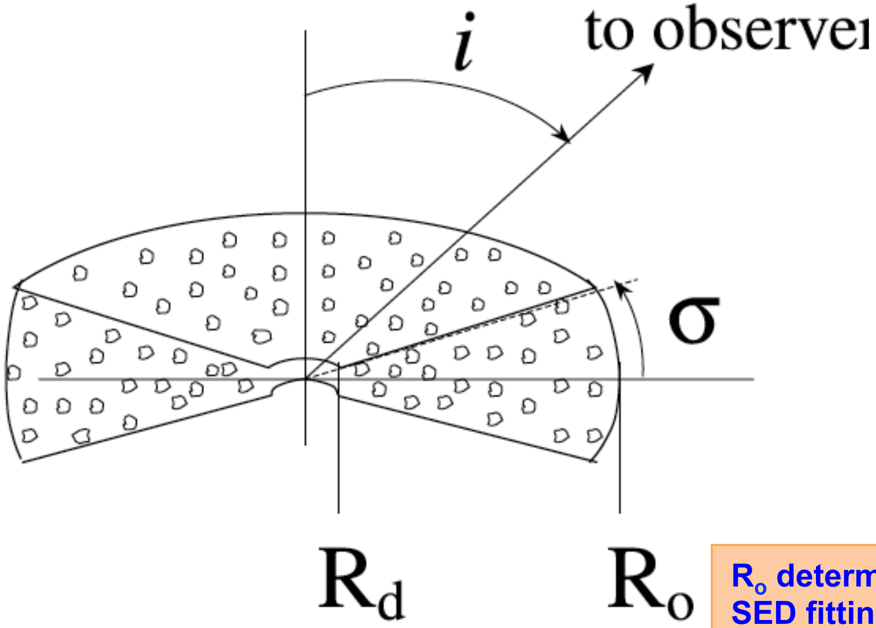
Delvecchio et al. 2014

The central torus/nucleus

dust temperature varies radially with $r=R_d$

only radial size determined from SED modeling is the relative thickness $Y = R_o/R_d$

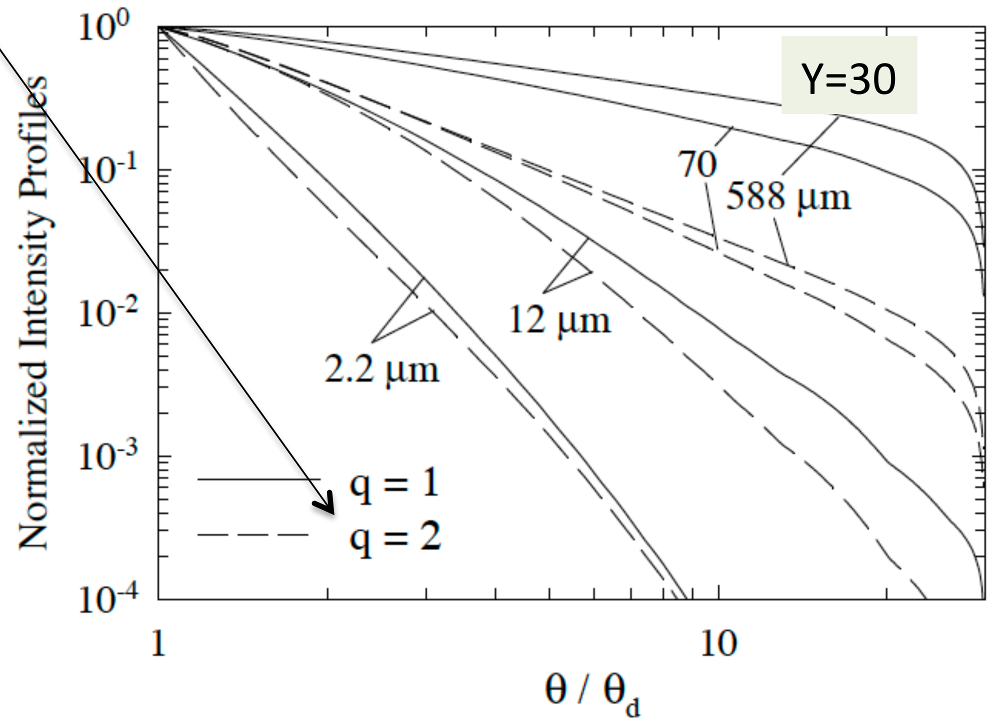
$R_d = 0.4\ L^{0.5}\ T^{-2.6}$ dust sublimation radius



R_d determined from the dust sublimation radius

R_o determined from SED fitting from $Y= R_o/R_d$

Radial variation of intensity with angular displacement from the centre for pole-on viewing



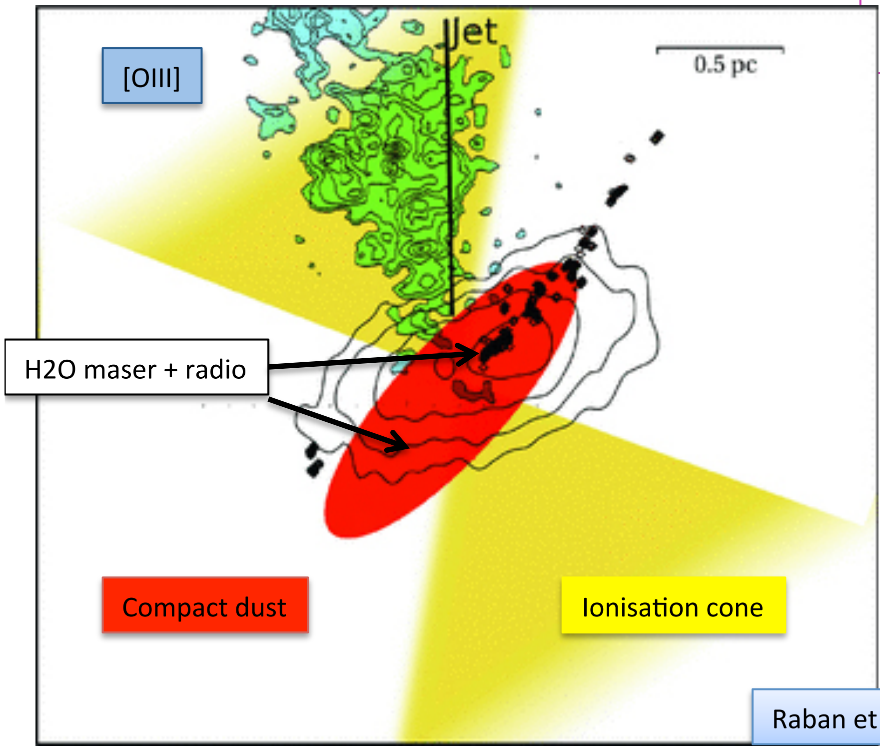
Surface brightness much shallower than at shorter λ clumpy torus SED quite insensitive to Y

Nenkova et al. 2008

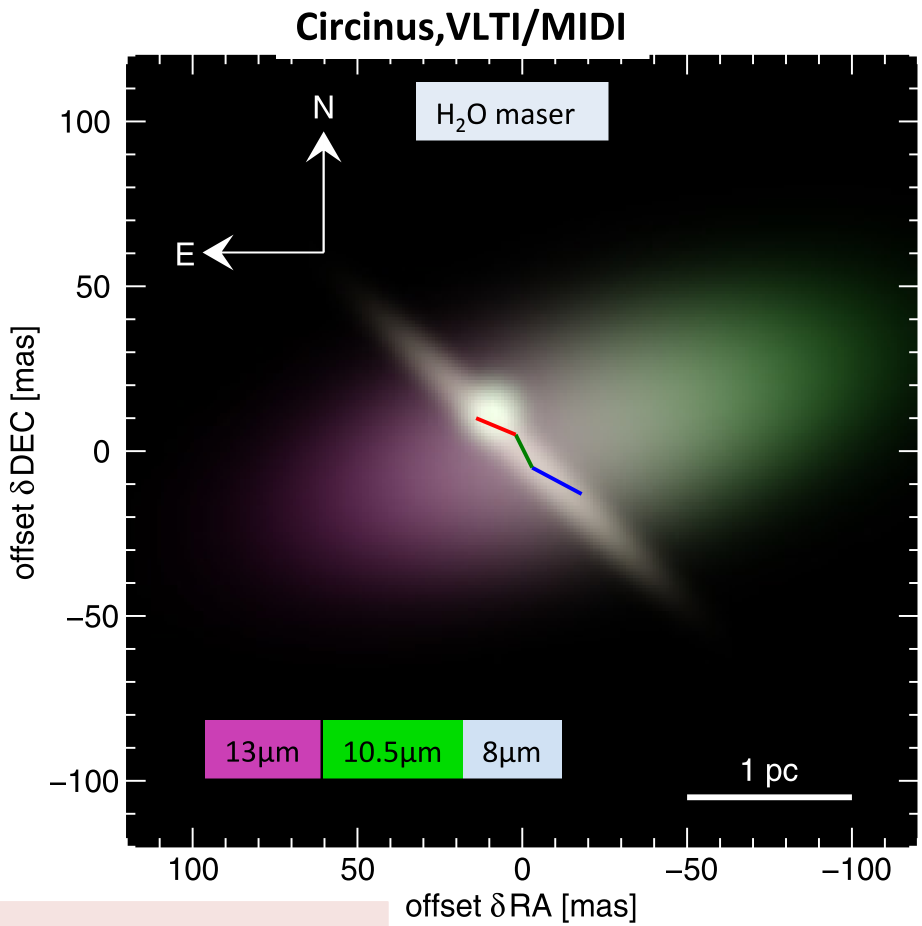
Polar outflow in the torus/nucleus?

Inflow/outflow of material traced by the magnetic field lines imaged by polarised dust

dust distributed in a polar structure on scale ~ 10pc:
Dust bearing polar outflows or equatorial inflows?



Raban et al 2009



Tristram et al. 2014

Magnetic fields trace shear pattern in the flow of ionised gas:
well aligned in winds and in accretion discs
→ map the inner site of the AGN

Expected linear polarisation 2-10%

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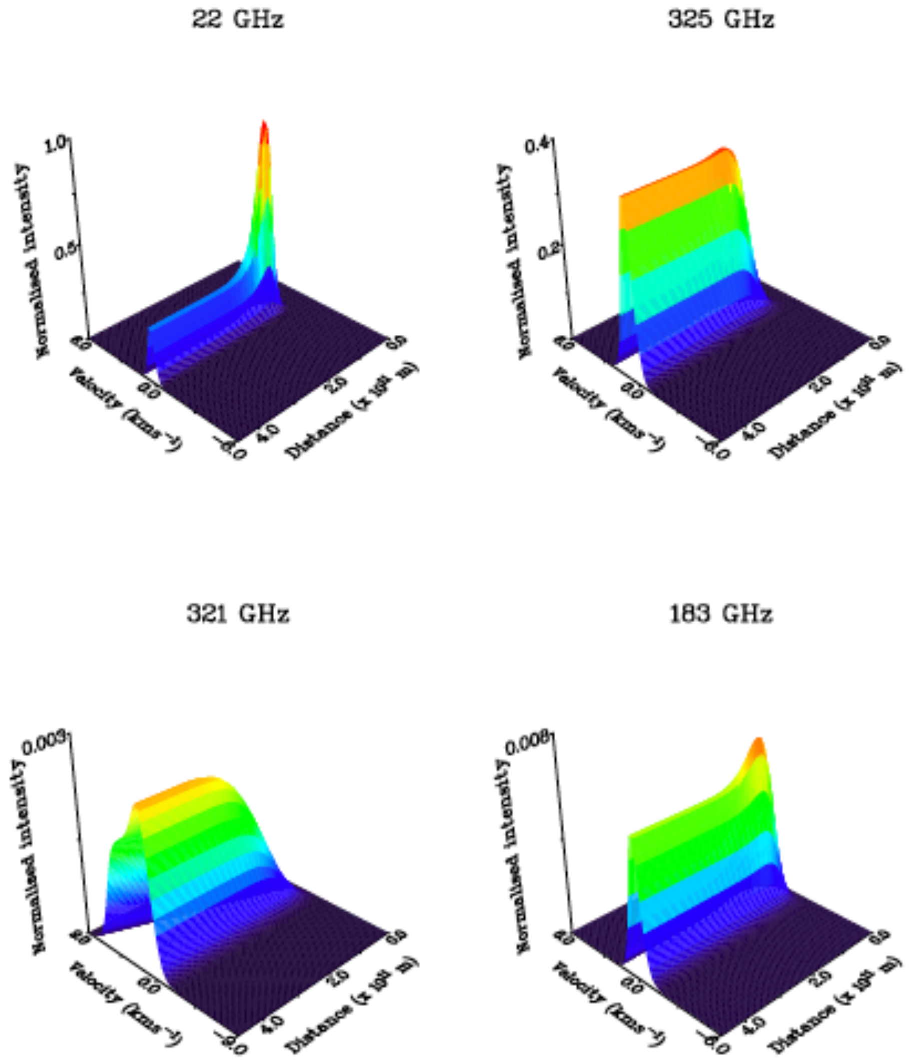
Why the Search for Mm/Submm Masers in AGN?

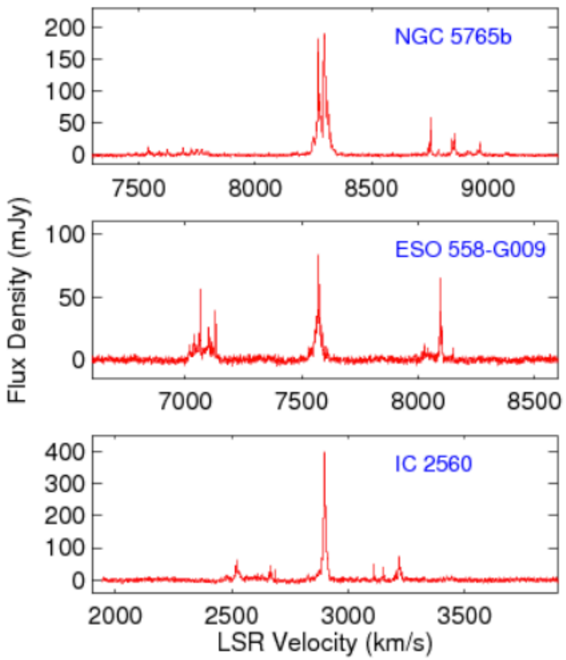
- Probe same regions of AGN as 22 GHz masers:
  - **constrain radiative transfer models**
  - **Map out density and T in AGN central engines**
- Probe different regions:
  - **trace out conditions and dynamics of uncharted portions of AGN (closer to black hole?)**
  - **Improve geometric models**
  - **test AGN unified model**
- Search for "supermasers":
  - **probe more distance sources**
- Search for masers from "back" of discs:
  - **improve geometric disc models**
- Better angular resolution
  - **Higher accuracy H_0**
- Probe different SMBH mass range?
  - **Constrain the $M - \sigma$ diagram**



Masers in AGN: probing the inner accretion disc

Masers probe sub-pc portion of nuclear disc

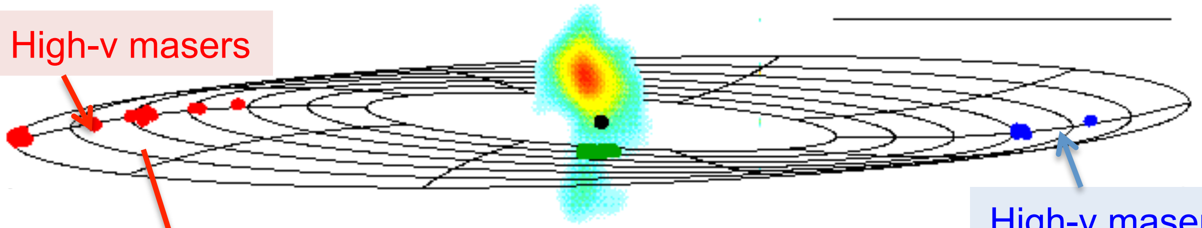
22GHz GBT



Gao et al., 2014

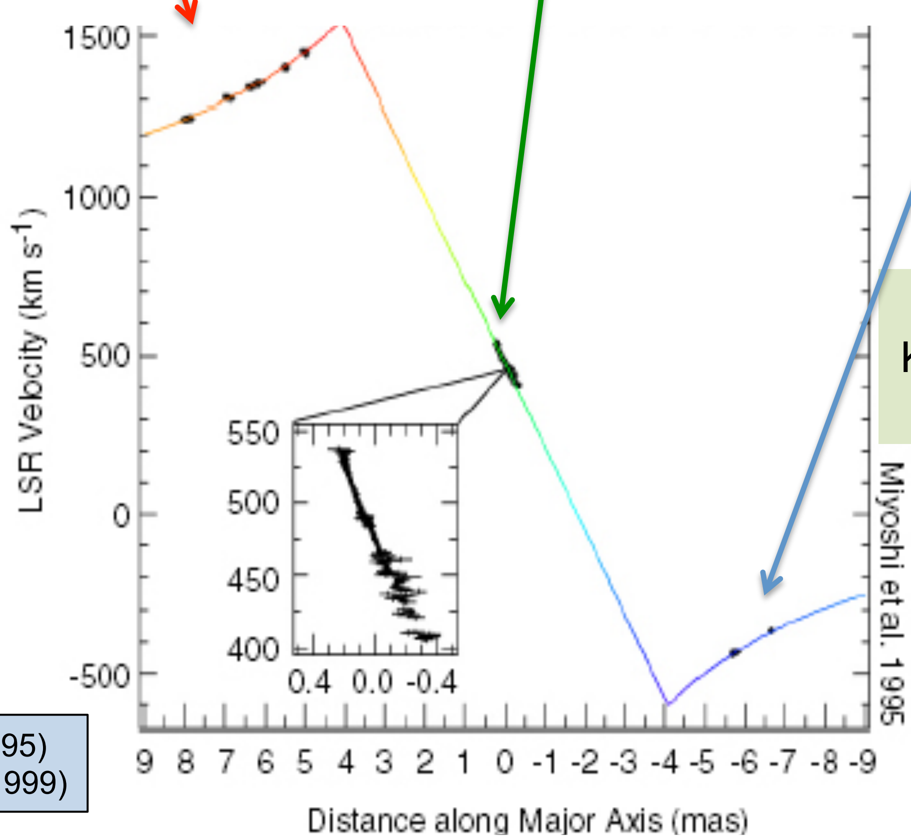
0.15 pc

High-v masers



High-v masers

$40\,000\ R_{Sch}$

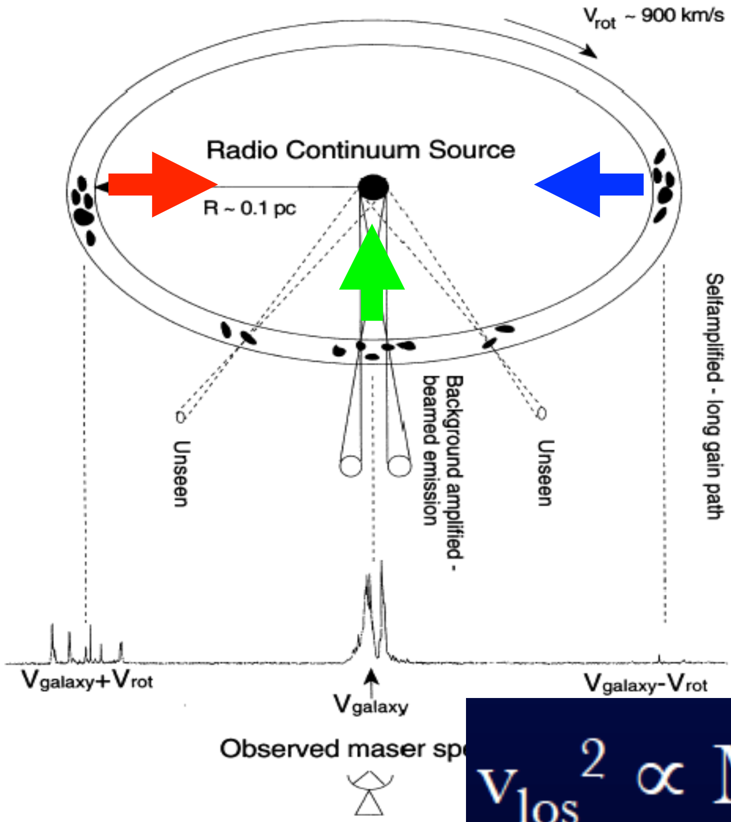


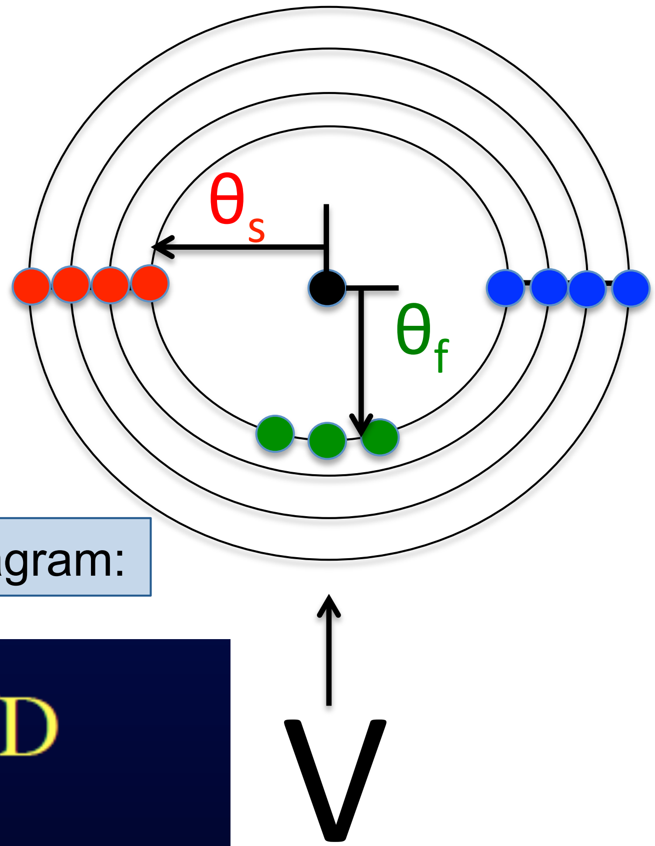
Almost perfect Keplerian rotation to ~ 1%

Miyoshi et al. (1995)
Herrnstein et al. (1999)

AGN Conference,
Sep 23-26 2014, Trieste

Calculating Maser Distance → the value of H_0





Using the P-V diagram:

$$v_{los}^2 \propto M/D\theta_s \rightarrow M/D$$

$$dv_{los}/d\theta \propto [M/D\theta_f^3]^{1/2} \rightarrow \theta_f$$

$$a_{los} \propto v^2/D\theta_f \rightarrow D \rightarrow M$$

Greenhill 1995

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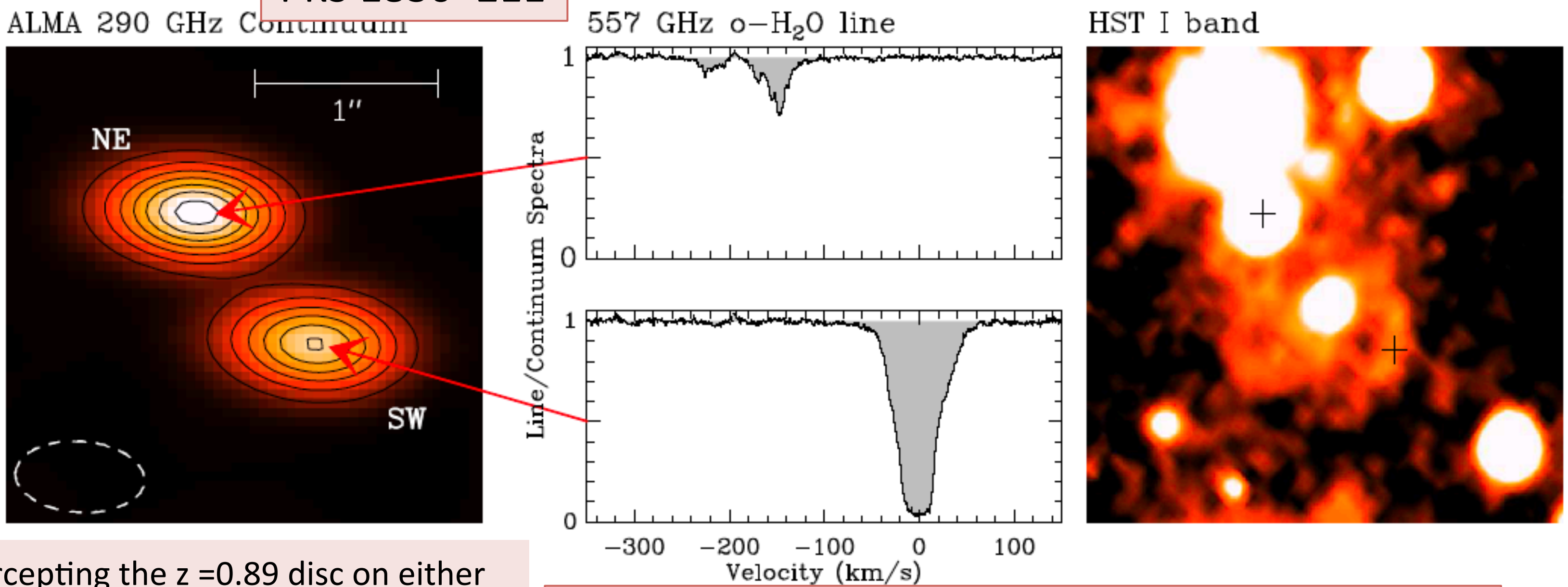
Quasars as lighthouses of obscured galaxies

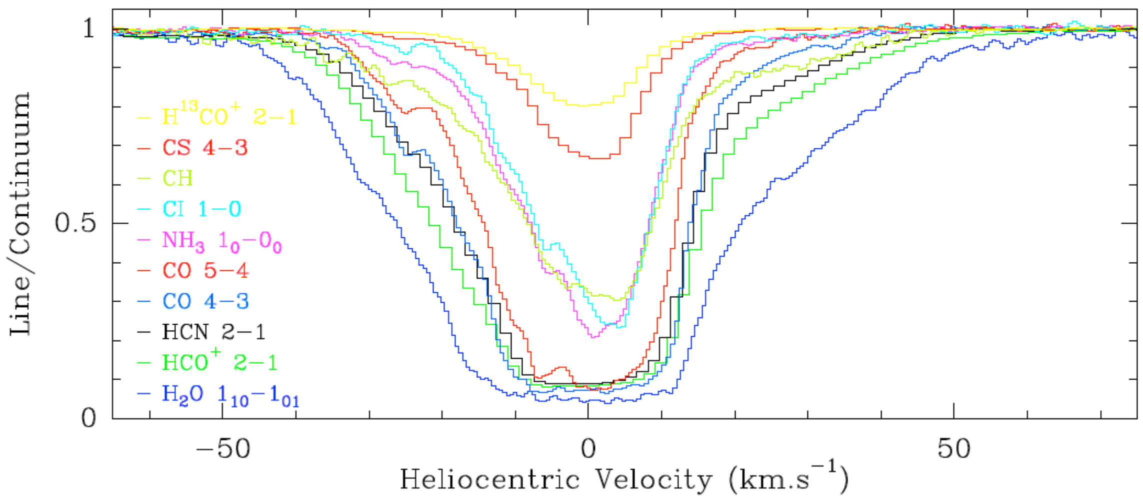
PKS 1830−211



z=0.89

intercepting the z =0.89 disc on either side of its bulge.

fundamental 557GHz transition of ortho-water toward each line-of-sight



42 species detected:

14 rare isotopologues

Strong or saturated lines for the main v=0 km/s velocity componen toward the SW Image.

Lines are listed based on their increasing peak opacity, from H_{13} CO^+ to H_2O

Muller et al. 2014

Gravitational lenses of PKS 1830-211

Blazar located at z=2.507 lensed by a foreground z =0.89 galaxy

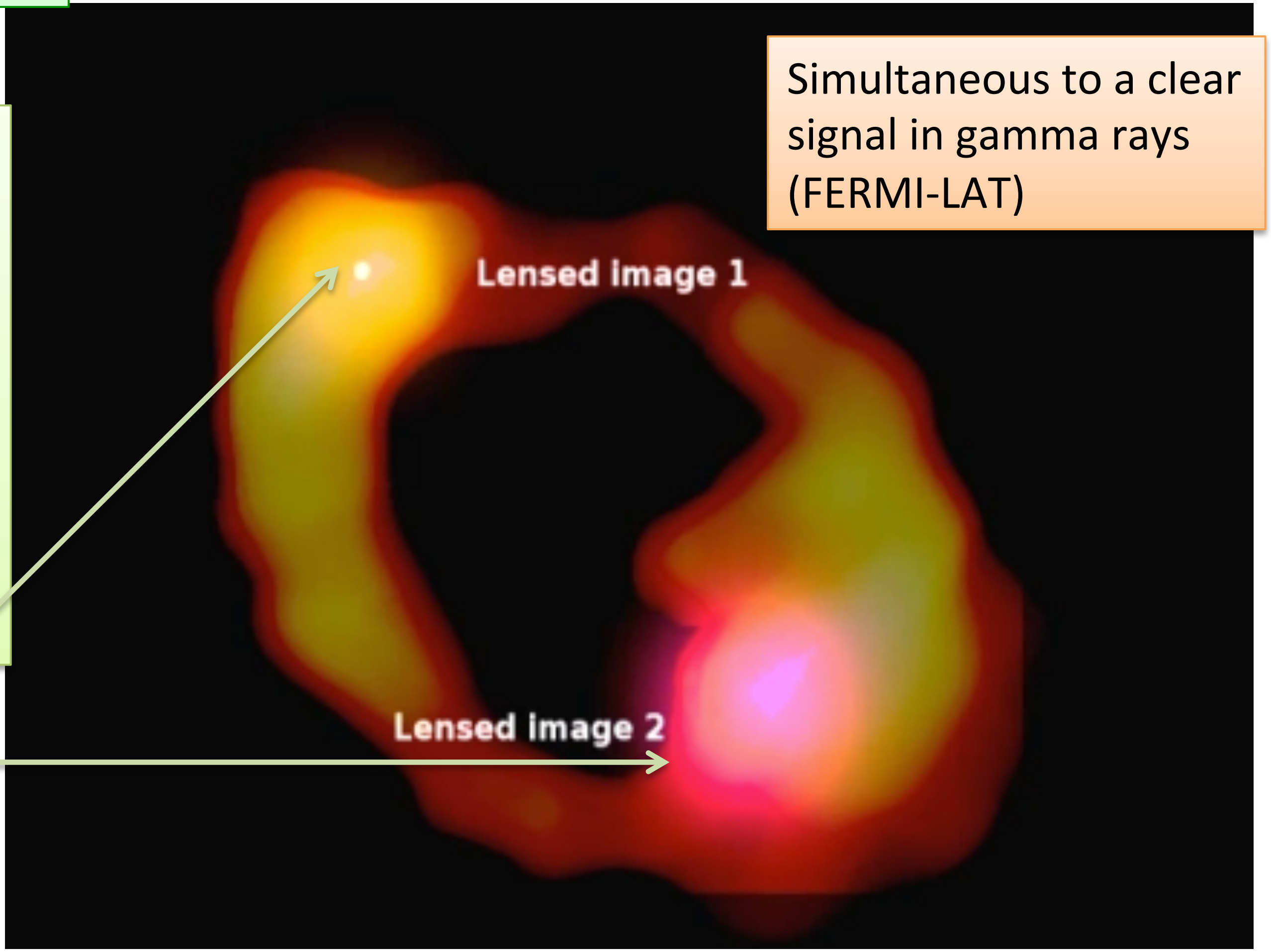
Chromatic behaviour not due to micro/milli-lensing (too tight variability timescale) but to intrinsic variability in the jet

Simultaneous to a clear signal in gamma rays (FERMI-LAT)

Temporal/spectral variations of the flux ratio (Band 3, 6 and 7) between the 2 images

fresh new matter entering into the jet base of the black hole **(core-shift effect)**
Structural changes in the blazar's jet needed to explain the observations.

accretion of material into the SMBH triggers the injection of plasma into the jet



Ivan Martí-Vidal et al. 2013

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Finding the first QSOs

- Target the central X-ray dominated region (XDR): X-rays photons
  - penetrate molecular clouds even at high column densities (1keV $2x10^{22}$ cm^{-2}, 10keV $4x10^{25}$ cm^{-2},100keV 10^{29} cm^{-2})
  - high heating efficiencies (order of 30%)
  - inefficient in the dissociation of molecules
- at its largest baseline, ALMA can resolve spatial scales of ~30 pc at z = 5, and detect and thus resolve the central XDRs

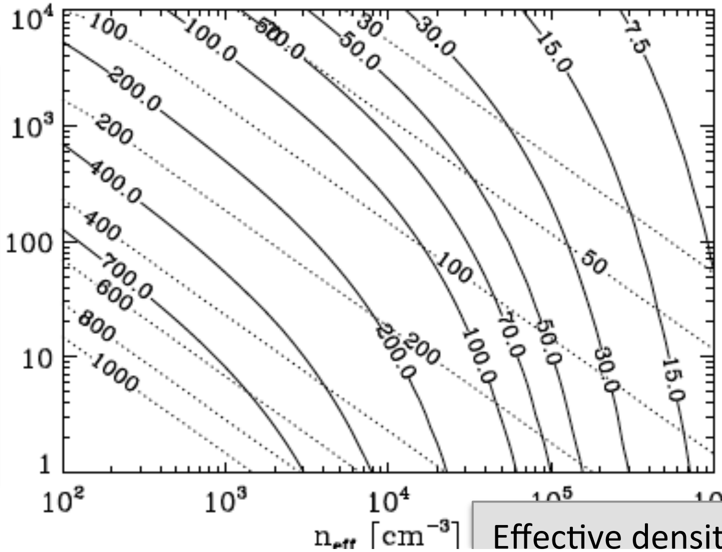
In XDRs: gas and dust at high-T and in dense clouds
If heating is due to shocks gas and dust ≠ T

→

ALMA can distinguish between X-ray chemistry and an intense SF burst on the same spatial scales

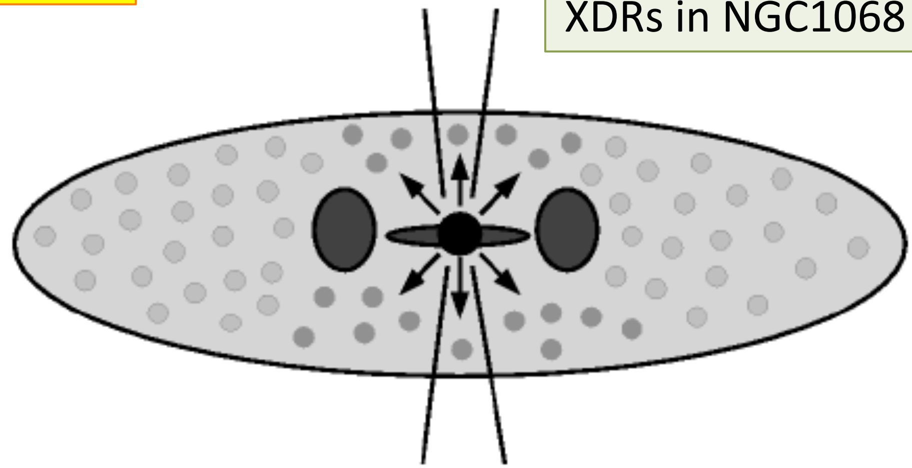
Expected size of the XDRs in pc for a BH=$10^7 M_\odot$

soft UV radiation field



Effective density

XDRs in NGC1068



Schleicher et al. 2010

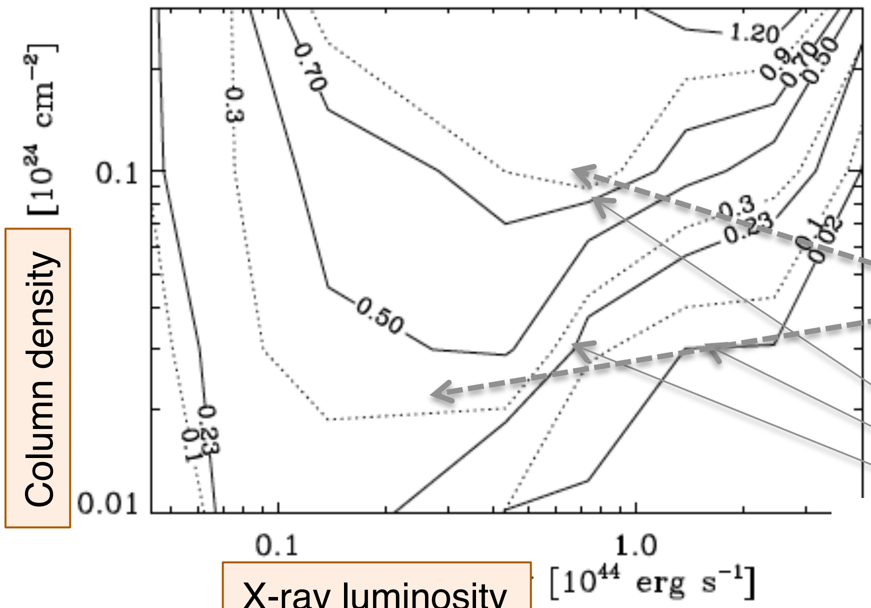
Expected fluxes and number of high-z QSOs

High-J CO flux (mJy)

ALMA Band 6

central XDR 200 pc

molecular clouds 10^5 cm^{-3}



Column density

X-ray luminosity

Z=8 CO(14-13)

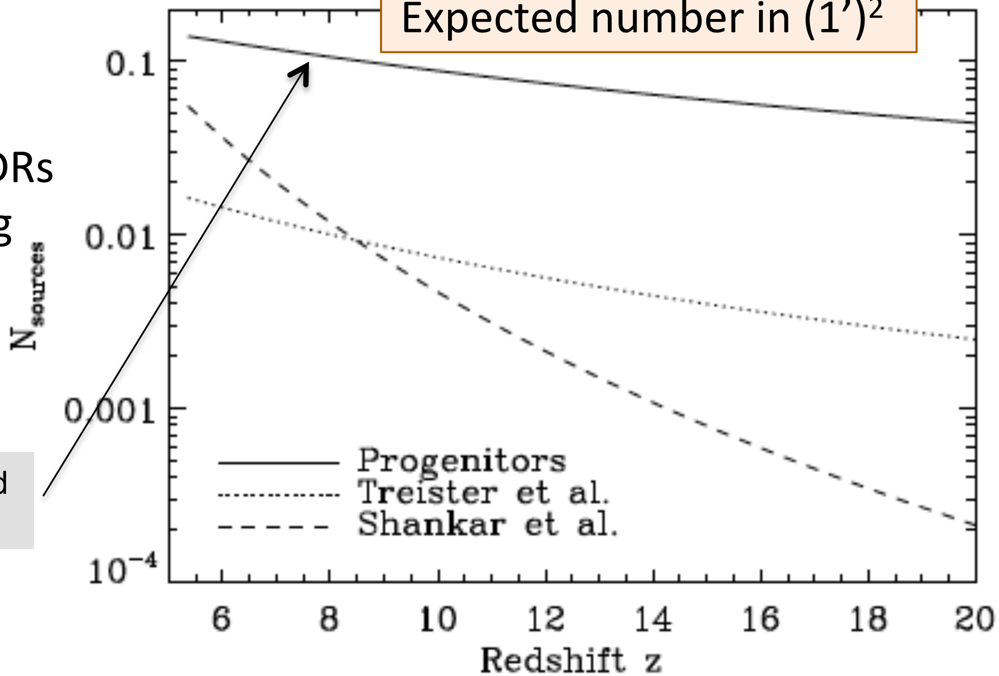
z=5 CO(10-9)

CO SED not expected to drop because of the high T

The high-J CO transitions as a signature of the XDRs

CO abundance is still higher than in typical PDRs and the CO intensity is high, due to the strong thermal excitation in the hot gas.

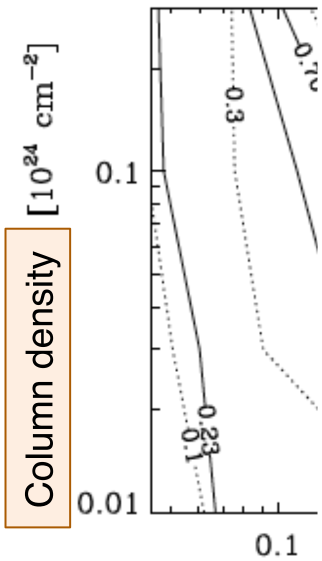
Expected number in (1')^2



number of high-redshift black holes required to produce the present-day 10^9 $M_\odot$ BHs

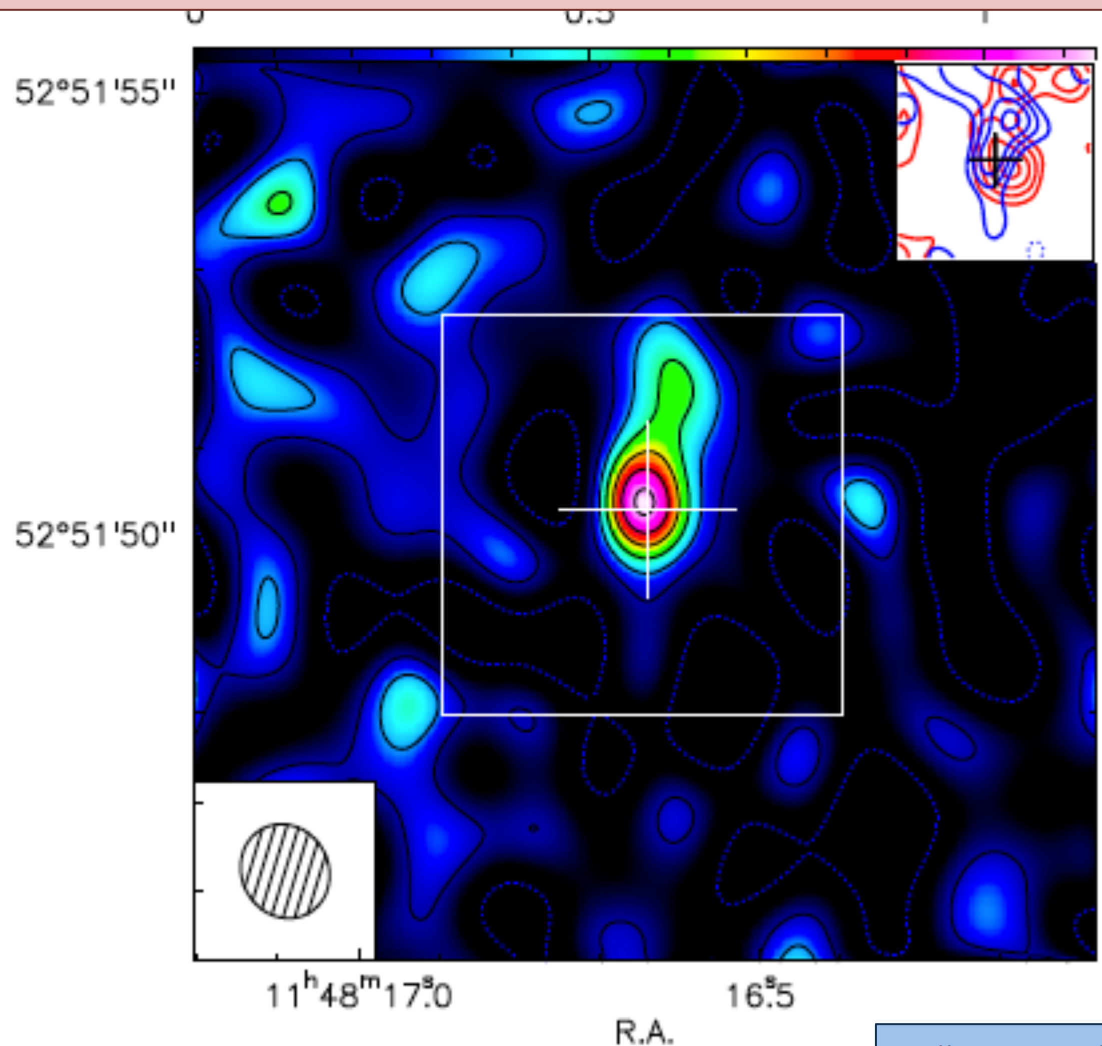
PdB observation of CO(17-16) of SDSS J114816.64+525150.3 at z=6.4

Hig



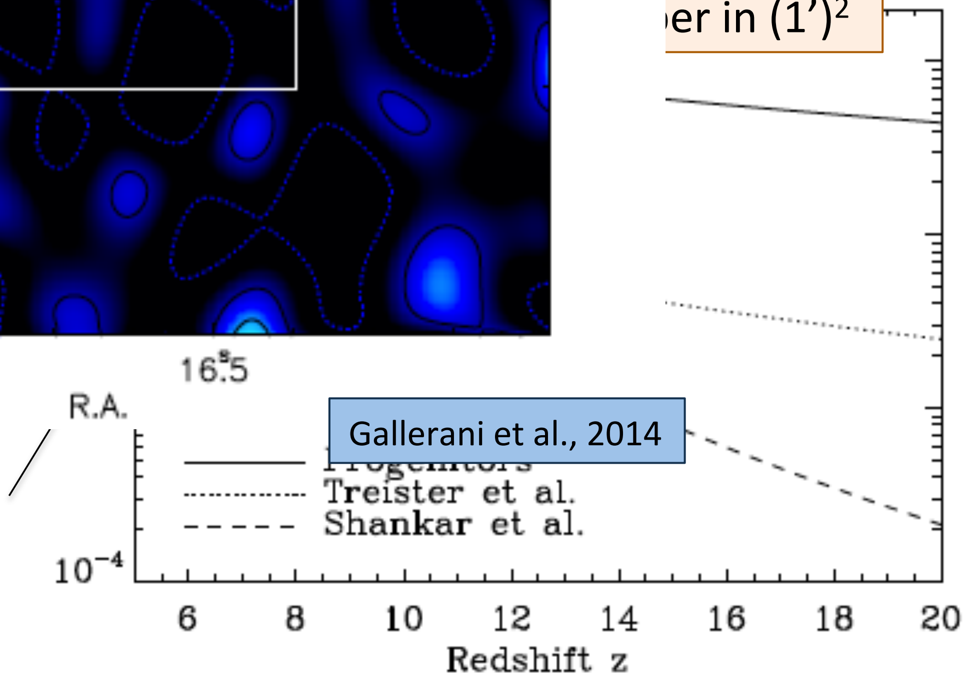
X-ray

CO abundance is
and the CO inten
thermal excitatio



pected to drop
high T
transitions as
the XDRs

er in (1')^2



Gallerani et al., 2014

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ALMA beyond ALMA

- ALMA will allow transformational science thanks to the sensitivity, angular resolution, spectral coverage and image fidelity, but...

- The baseline ALMA project will only achieve a fraction of the full potential of the site and instrument

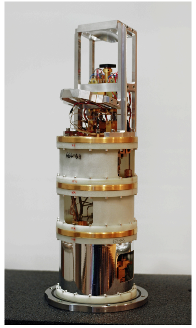
- Incomplete Receiver Complement
- Limited Wide Field Capabilities
- Limited Correlator and Data Rate Capabilities
- Extended baselines (30-50km), VLBI (200-10000km)
- Advanced Calibration, Software, Science Tools....

Band 5 Science

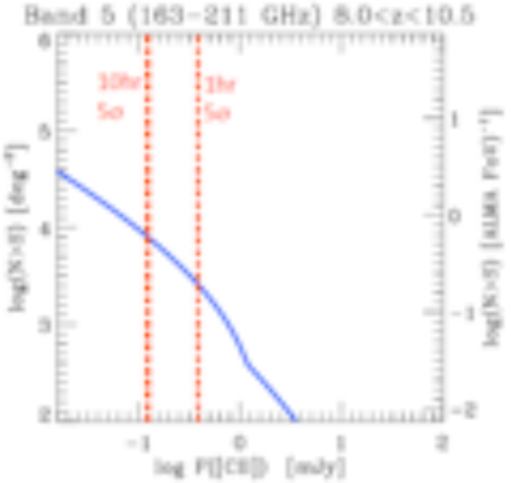
ALMA

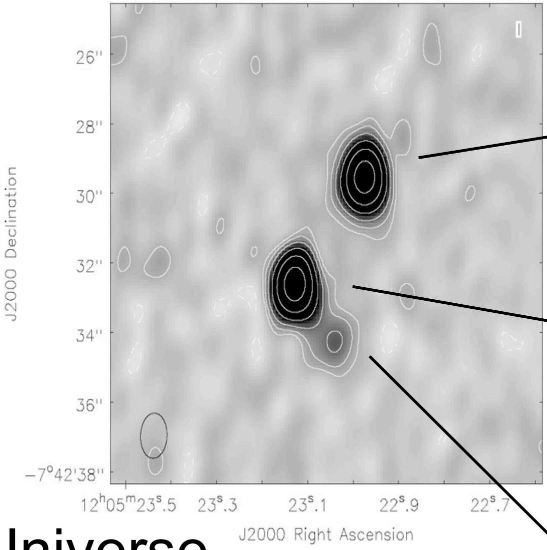
SIXTH FRAMEWORK PROGRAMME

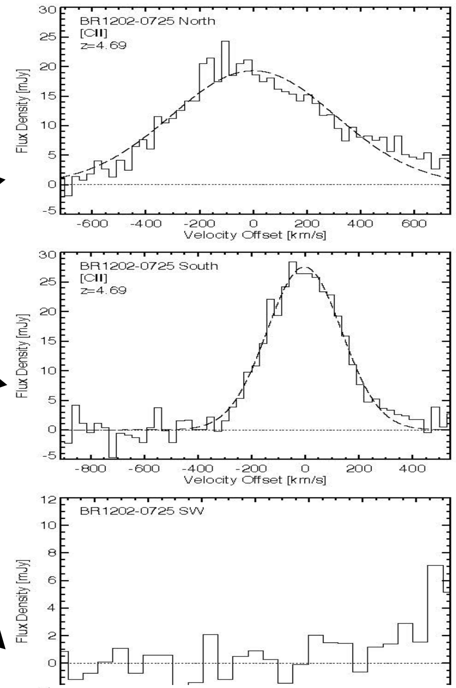
ESO



- [CII] in z~(8-10) and high-ex CO at high-z

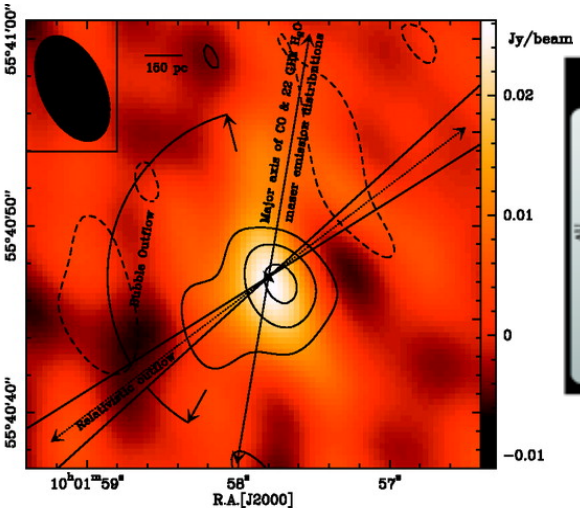




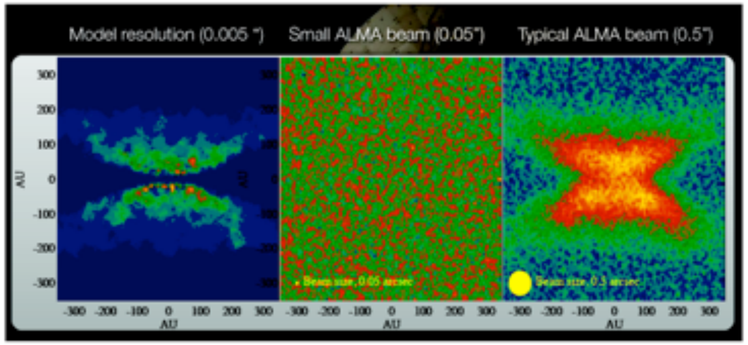


(Wagg et al. 2012)

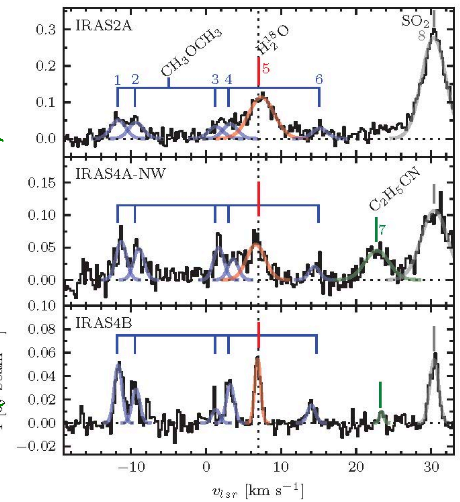
- Water in the local Universe



(Humphreys et al. 2005)



(Brinch 2010)



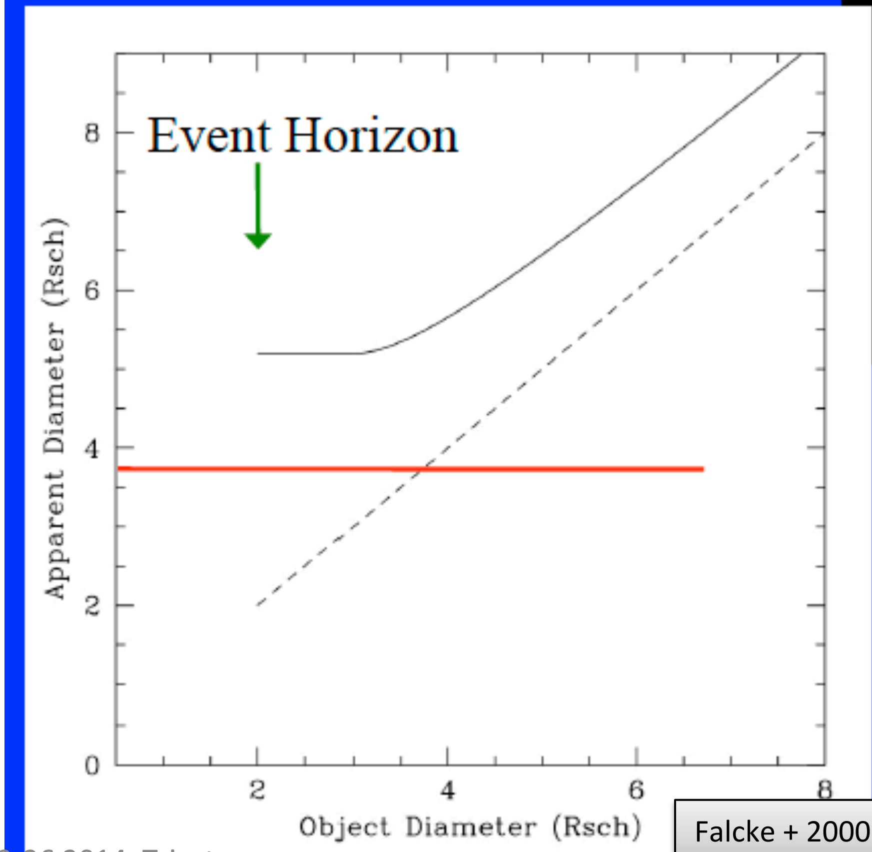
(Persson et al. 2012)

Paola Andreani

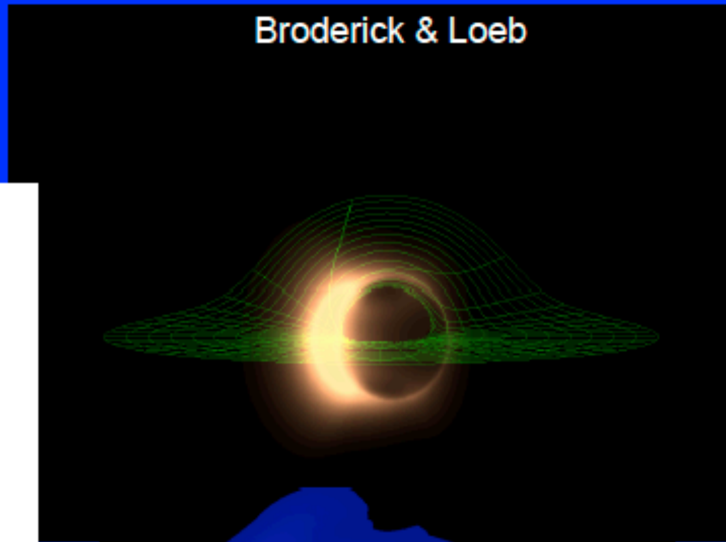
The shadow of a Black Hole

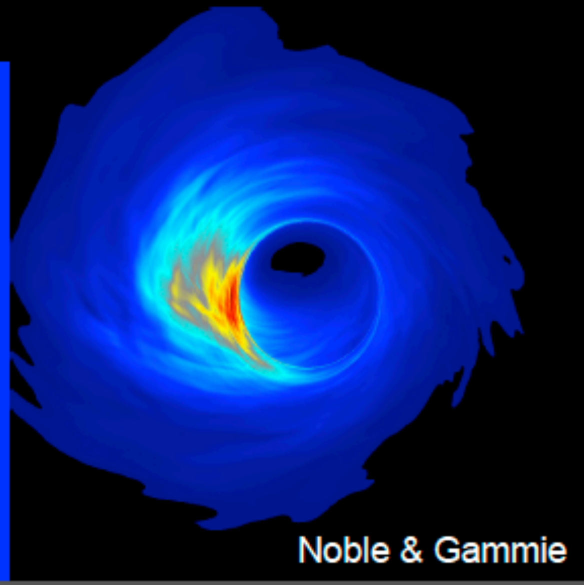
The minimum apparent size.

Event horizon casts a shadow due to the bending of light

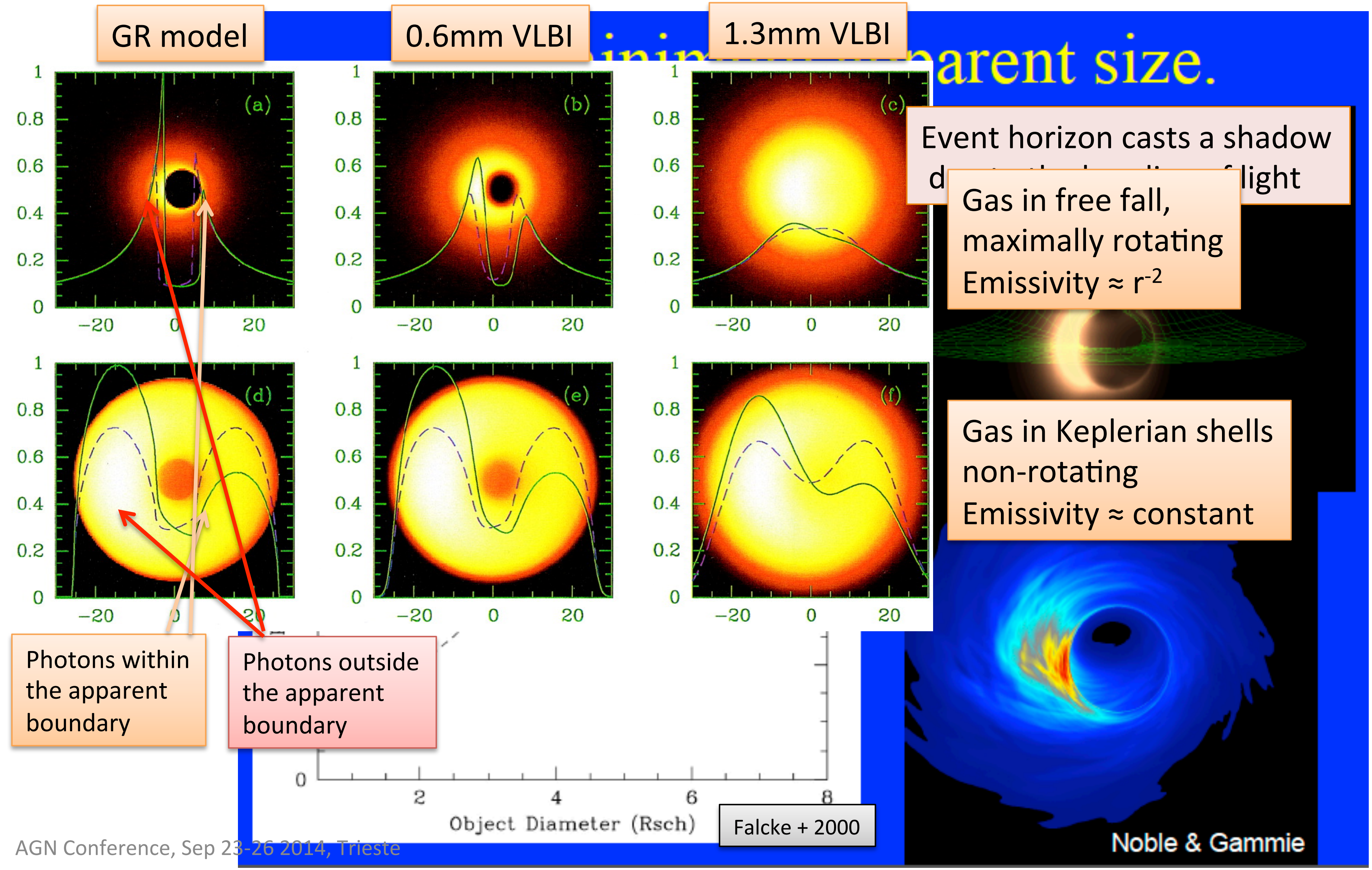


Falcke + 2000



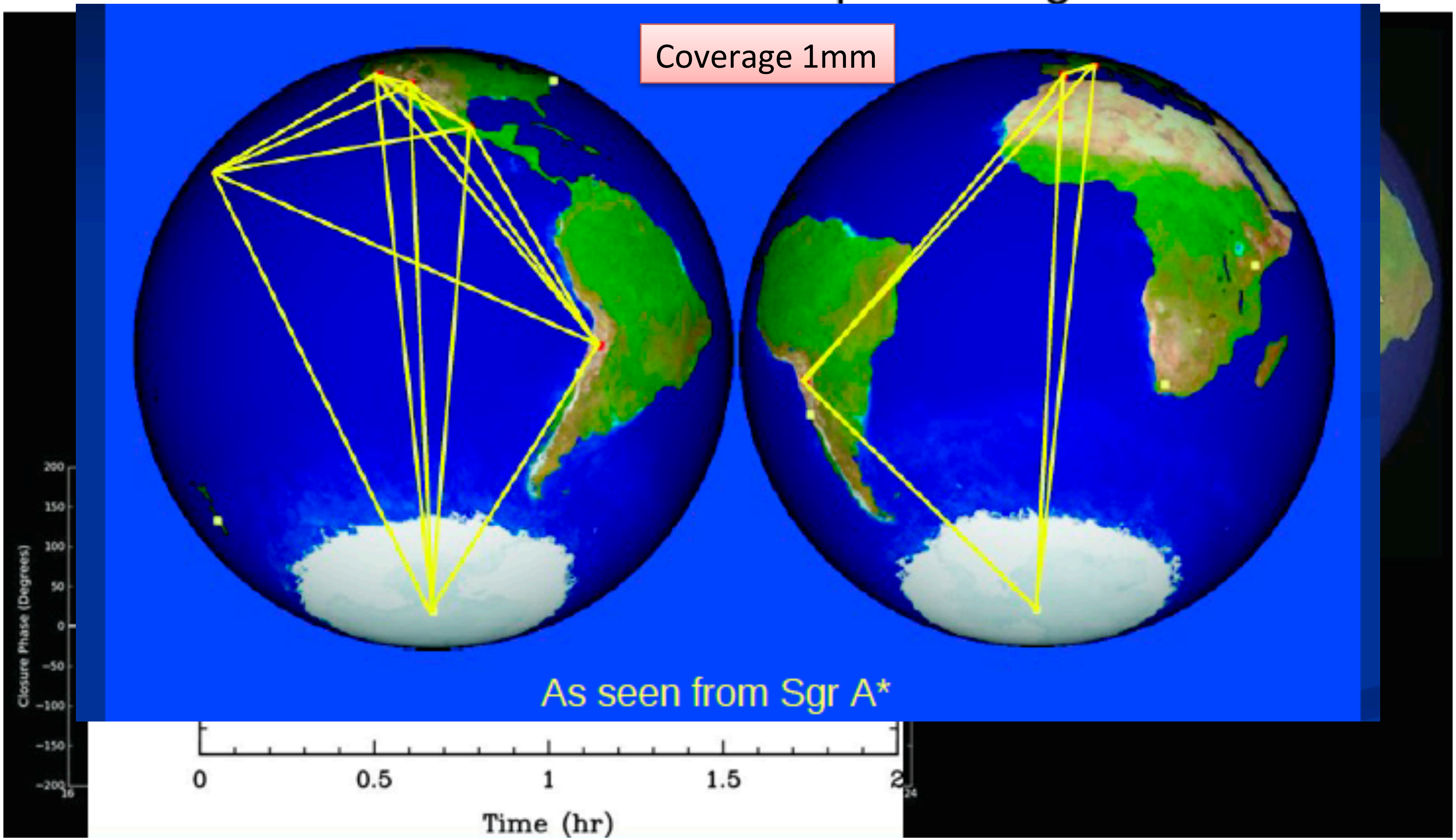


The shadow of a Black Hole



Phasing ALMA for VLBI

- The Even Horizon Telescope and Sgr A*



Summary

- ALMA Early Science is just the beginning
  - Cycle 3: end April 2015 additional capabilities time
- AGN are ideal target for ALMA
- ALMA spatial resolution can be very high

~ 0.2” x (300/ν(GHz) x (1km/max baseline)

ALMA spectral resolution can be very high

Spectral Resolution† 300 GHz (km/s)
0.98
0.49
0.24
0.12
0.061
0.031
31.2


Thank You !