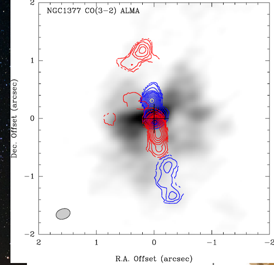
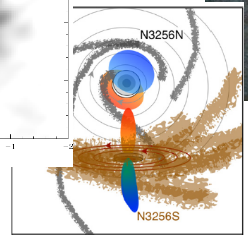
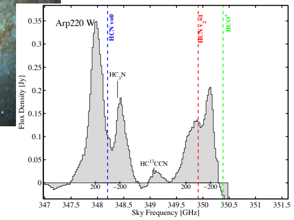
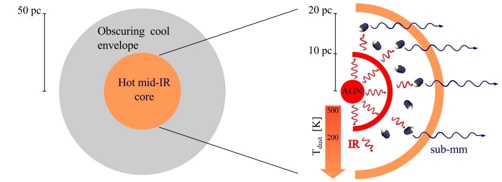








Cold jets and dense cores in galaxies with extremely opaque nuclei

Susanne Aalto

Department of Earth and Space Sciences, Chalmers

Sweden

CHALMERS

S. Muller, K. Sakamoto, F. Costagliola, S. Martin
E. Gonzalez-Alfonso, N. Falstad, S. Garcia-Burillo,
F. Combes, J. Mangum, E. Varenius et al

MASTER
MOLECULES AS TOOLS FOR EXTRAGALACTIC RESEARCH

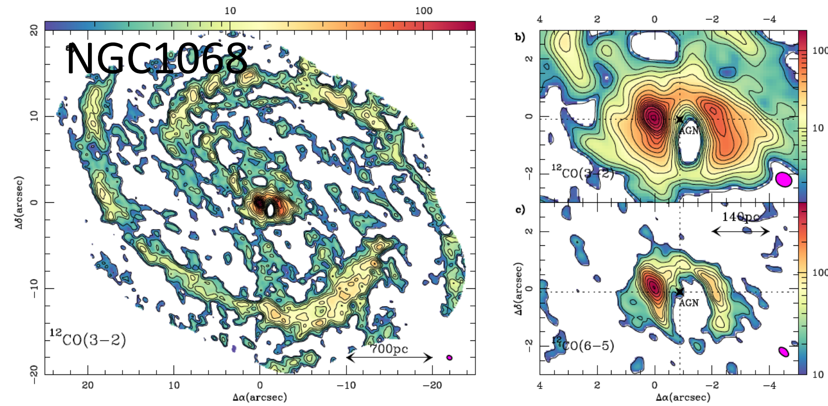
Outline

- Molecular gas and dust in galaxy nuclei.
- How can we probe the molecular gas - and why do we want to?
  – Astrochemistry
- Compact Obscured Nuclei – and what they are hiding.
  – Probing the opaque nucleus of the LIRG IC860
- Clearing the dust: cold winds
  – The peculiar radio-quiet jet of NGC1377.

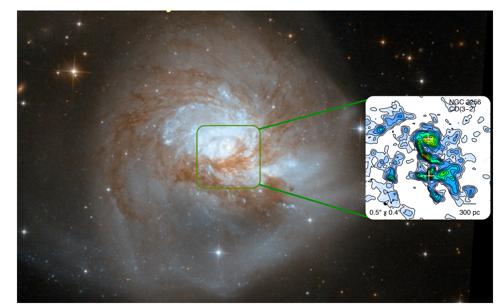
Secular evolution and interactions drive gas and dust to galaxy centers

- Spiral arms and Bars
  - Flocculent/Grand design
  - Strong/weak
  - Nested
- Cooling flows
- Major/minor mergers - interaction
  - Polar rings, dust lanes counterrotating and infalling gas
  - Tidal gas
  - "Overlap regions"

Garcia-Burillo +14



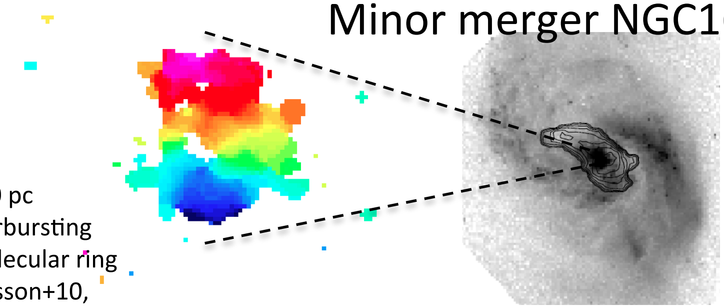
Major merger NGC3256
Sakamoto+14



In galaxy nuclei gas collects in e.g. disks, rings, mini-bars

…obscures and feeds AGNs, starbursts –in turn driving outflows and winds.

Minor merger NGC1614



600 pc starbursting molecular ring (Olsson+10, König +13, Xu +14)

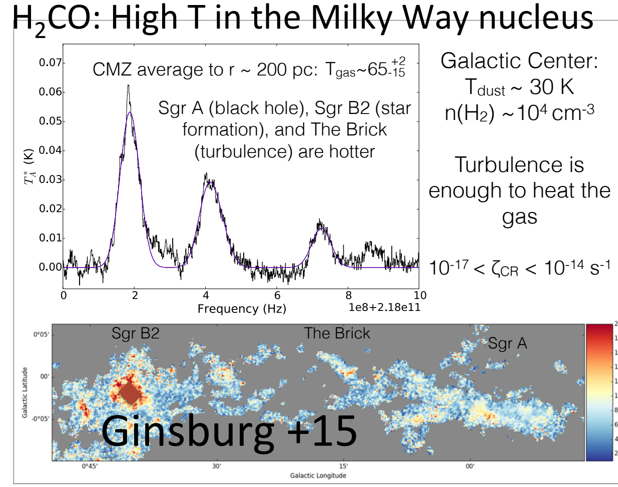
Molecular gas and dust are fundamentally important parameters for galaxy evolution

Diagnosing Starformation/AGN activity

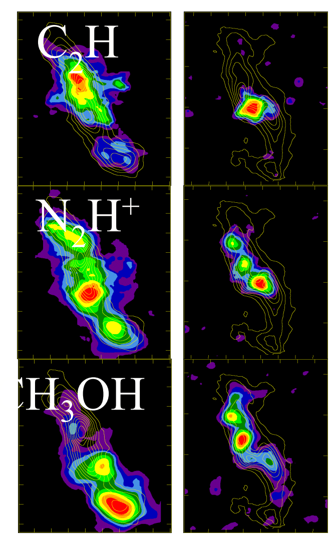
- Gas distribution and dynamics
  - Dynamical masses
  - Non circular motions – out/inflows
- Physical conditions
  - Temperature and density
  - Ionization rates
  - Impact of radiative pumping
- Astrochemistry
  - AGN vs starburst; evolution; outflow mechanisms; impact of dynamics on ISM
  - Stellar nucleosynthesis?

We are searching for key diagnostic molecular species and lines

H_2CO: High T in the Milky Way nucleus



MAFFEI 2 IC 342



Meier & Turner 06, 12
-CH_3OH tracing bar shocks

Chemistry diagnostics

- Scenarios:
  - X-ray dominated region (XDR) – large bulk temperatures > 100 K (e.g. Maloney +96; Lepp & Dalgarno 96; Meijerink &Spaans 05)
  - Photon dominated region (PDR) – large surface temperatures 300-1000 K – moderate bulk temperatures 20-50 K (e.g. Hollenbach & Tielens 97)
  - Cosmic ray dominated region (CDR) (e.g. Suchkov +93; Meijerink +11)
  - Dense shielded regions – dusty hot core-like chemistry (IR pumping), 50-300 K (e.g. Van Dishoeck 98, Requena-Torresti+06, Nomura & Millar 04)
  - Mechanically dominated region – shock-chemistry (e.g. Viti +11; Kazandjian+12,15)

- Popular diagnostic species: CO, HCN, HCO^+, HOC^+, HNC, CN, CS, HC_3N, SiO, HNCO, CH_3OH, CH_3CN, C_2H – just to mention a few
  - ..and their isotopic variants which may be used to probe stellar nucleosynthesis.

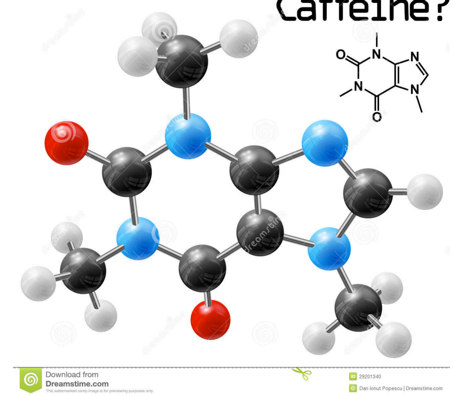
Molecular gas conditions range from:
T=5-500 K
$n>10^2$ cm^{-3}

Extragalactic molecules: >60 detected

2 atoms	**3 atoms**	**4 atoms**	**5 atoms**	**6 atoms**	**7 atoms**	**8 atoms**	**>8 atoms**
OH	H_2O	H_2CO	$c\text{-}C_3H_2$	CH_3OH	CH_3CCH	HC_6H	$c\text{-}C_6H_6$ *
CO	HCN	NH_3	HC_3N	CH_3CN	CH_3NH_2		C60* (?)
H_2 *	HCO+	HNCO	CH_2NH	HC_4H *	CH_3CHO		
CH	C_2H	C_2H_2 *	NH_2CN	$HC(O)NH_2$	HC_5N		
CS	HNC	H_2CS ?	$l\text{-}C_3H_2$				
CH^+ **	N_2H^+	$HOCO^+$	H_2CCN				
CN	OCS	$c\text{-}C_3H$	H_2CCO				
SO	HCO	H_3O^+	C_4H				
SiO	H_2S	$l\text{-}C_3H$					
CO^+	SO_2						
NO	HOC^+						
NS	C_2S						
NH	H_2O^+						
OH^+	HCS^+						
HF	H_2Cl^+						
SO^+	NH_2						

see updates on http://www.astro.uni-koeln.de/cdms/molecules

Caffeine?



…no not yet…

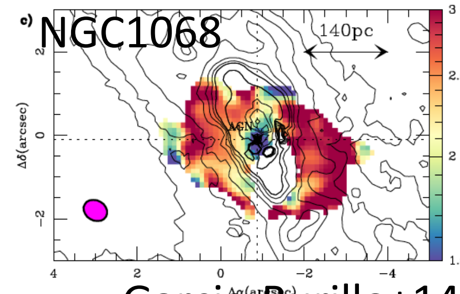
* indicates molecules that have been detected by their rotation-vibration spectrum,
** those detected by electronic spectroscopy only.

What lines are good indicators?

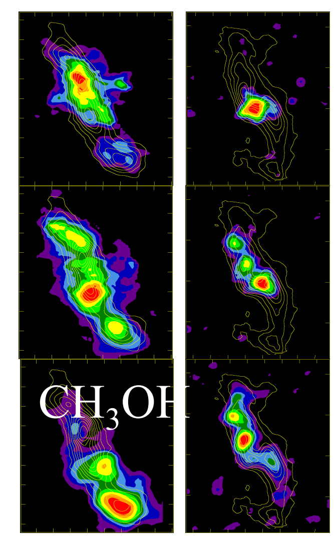
- <u>UV, X-ray, CR:</u>
  - HCN/HCO^+ - XDR tracer?
    - Is this line ratio an indicator of "warm chemistry" – rather than a tracer of X-ray driven chemistry?
    - Tracing compact vs extended activity?
  - CN – should be good tracer of XDR/PDR. Faint CN in LIRG/ULIRG survey (e.g. Aalto+02, Loenen+11). Elevated CN in outflows? e.g. Mrk231 (Cicone in prep.), NGC3256 (Sakamoto+14)
  - HOC^+, CO^+, H_3O^+, H_2O^+, OH^+, N_2H^+ - Ionization rates
  - CH enhanced in AGN? (Rangwala+14)

- <u>Shocks</u>
  - SiO, HNCO, CH_3OH, H_2O – classical shock tracers (Garcia-Burillo+01, Meier&Turner 06,12; Snell 05, Bjerkeli+09,Appleton+13, Meier+15)
  - HCN – shock enhanced? (in extragalactic outflows: Aalto+12a, Garcia-Burillo+14, Matsushita+14)

HCN/HCO^+ in NGC1068

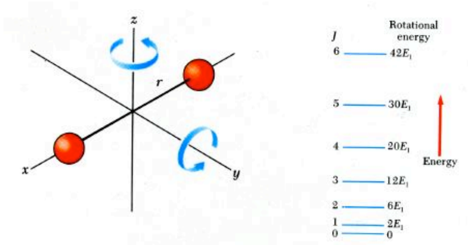


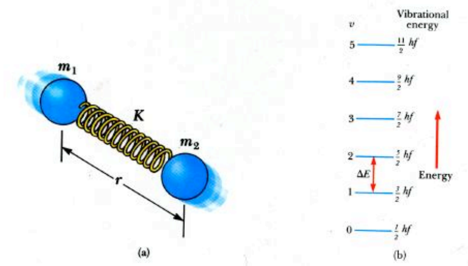
Garcia-Burillo+14

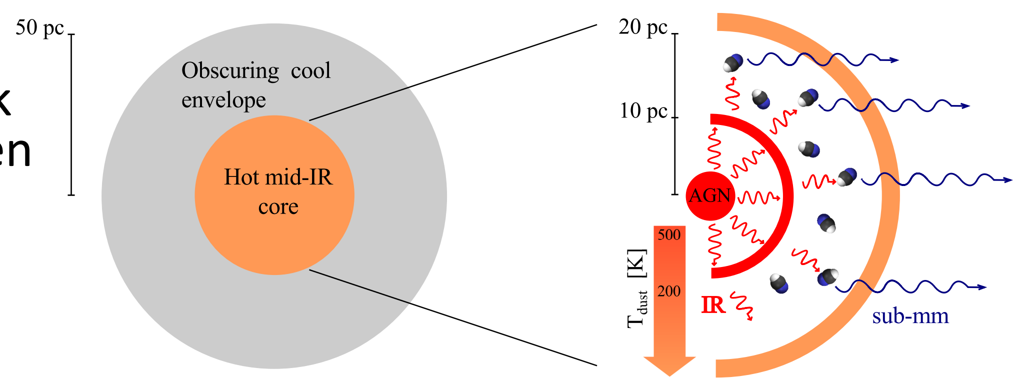


Meier & Turner 06, 12 -CH_3OH tracing bar shocks

- <u>IR radiative feedback- galaxy nuclei</u>
  - Dusty (U)LIRG nuclei: IR radiative excitation will be important.
    - Many lines that can be IR excited/pumped– for example HCN, HNC, HC_3N, H_2O, OH
    - HC_3N - bright in dusty nuclei. Tracing young activity? IR pumped? Correlates with HNC (Lindberg+11, Costagliola+11)
  - Vibrational lines serve as important tracers and can peek behind the optically thick screen (Aalto+15) analogy to Galactic hot cores (e.g. Rolffs+11)







Telescopes

ALMA=The Atacams Large Millimeter/ submillimeter Array

the European Southern Observatory (ESO), the U.S. National Science Foundation (NSF) and the National Institutes of Natural Sciences (NINS) of Japan, together with NRC (Canada), NSC and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. ALMA -the largest astronomical project in existence- is a single telescope of revolutionary design, composed of 66 high precision antennas located on the Chajnantor plateau, 5000 meters altitude in northern Chile.

NOEMA (NOrthern Extended Millimeter Array)


SMA – Submillimeter Array

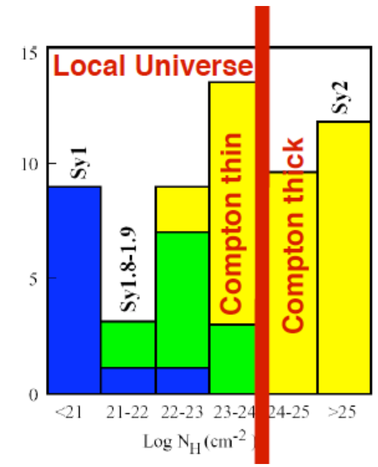
Why is obscured activity important?

- Studying obscured galaxy nuclei will **complete the AGN census** allowing us to explore the full range of environments and conditions that drive AGN evolution and SMBH accretion. The host galaxy –SMBH growth coevolution can be addressed with all phases repesented.

- **Starburst-AGN connection**
  – How is the growth of the SMBH linked to that of the nuclear stellar component?

- **Most rapidly growing black holes may be the most obscured**. Even if SMBH growth and SF peak at z=1-2 – obscured nuclear growth is not understood, nor fully charted, in the local Universe.

- **How is the small scale (< 1 pc) obscuration linked to that at 10-100 pc – or on larger scales?**



Images from Alexander 2011

A hidden AGN population – or extreme starbursts?

COMPACT OBSCURED NUCLEI

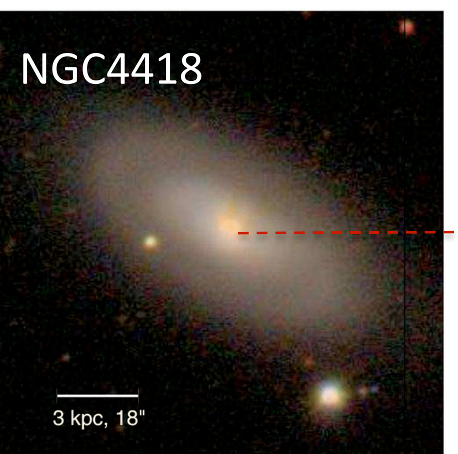
CONs – Compact Obscured Nuclei - $N(H_2)>10^{24}$ (and it is also means "thick/stupid" in French*)

*or something worse…

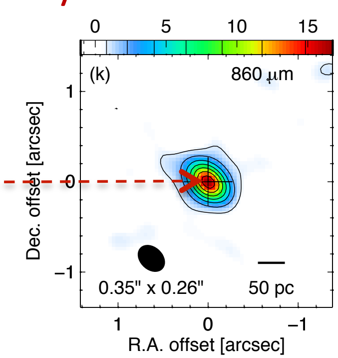
- – Some (U)LIRGs harbour CONs - Still unknown how common they are
- – Extremely important to understand obscured phase:
  - AGN statistics
  - Growth of nuclear stellar spheroid
  - ?

Example:

NGC4418 (e.g Sakamoto+10,13, Costagliola+13 – see also Varenius+14 for VLBI imaging)



mm/submm continuum

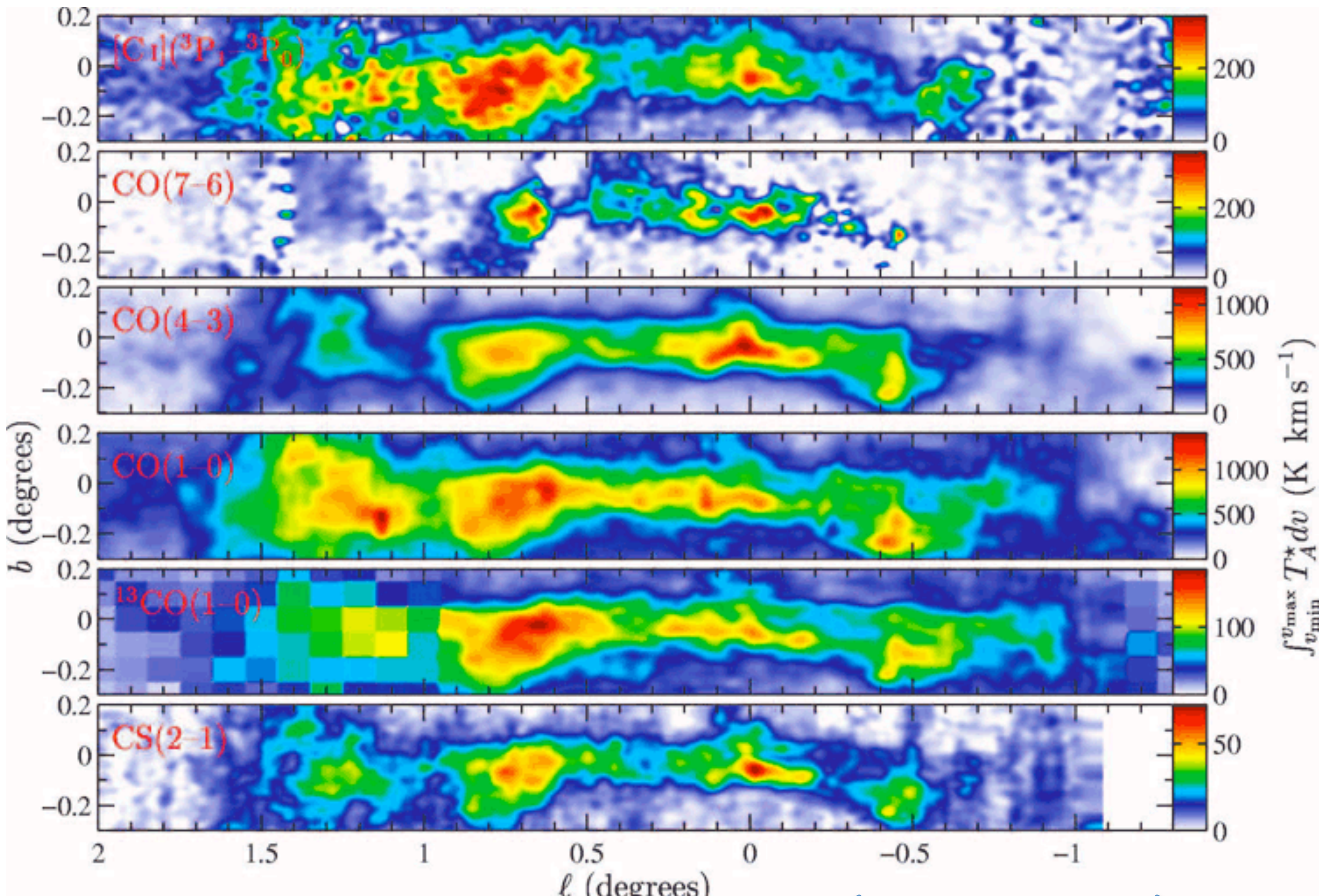


- <0. "1 (<20 pc) nuclear emission
- Core luminosity: $10^{11.0}\,L_\odot$ - bulk of total FIR luminosity of NGC4418.
- T_B(860 µm)=120-210 K, τ(860 µm) = 1 (i.e., $N_H>10^{25}$ cm^{-2}).

Central Molecular Zone (CMZ) of the Milky Way

Size - 450 x 150 pc
$M(H_2)$ - $5 \times 10^7\ M_{sun}$

(Martin+04, ApJS, 150, 239-262).



In comparison:
Extreme properties of NGC4418 nucleus.

$10^8\ M_{sun}$

20 pc

100 pc

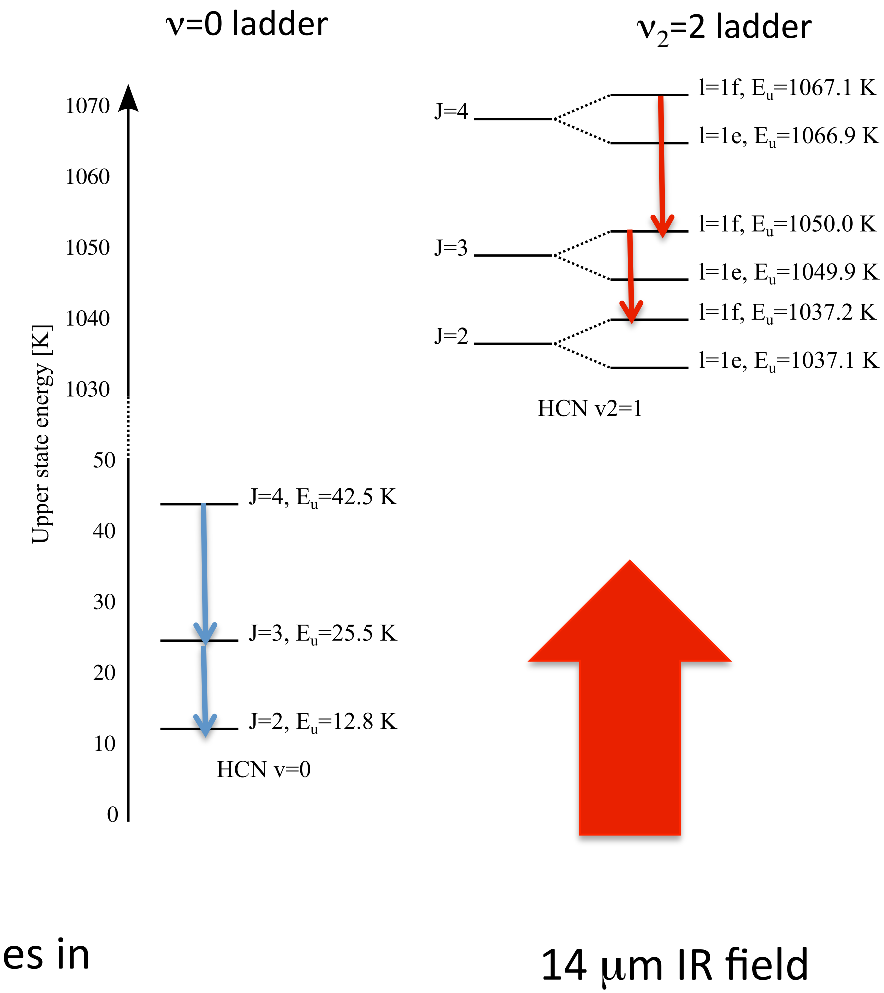
How can we probe behind the veil of dust?

mid-IR diagnostics are compromised by extreme dust obscuration. X-rays suffer attenuation when $N(H_2)>10^{24}$ cm^{-2}

Use (e.g.):

- High resolution mm/submm continuum imaging (e.g. Sakamoto +13, Costagliola+13, Wilson+14)
- Vibrationally excited HCN (HCN-VIB) requiresT_B(14 micron) > 100 K (e.g. Sakamoto+10, Aalto+15a,b, Imanishi+13, Aalto+15ab, Martin +16, Aalto+16, Imanishi+16)

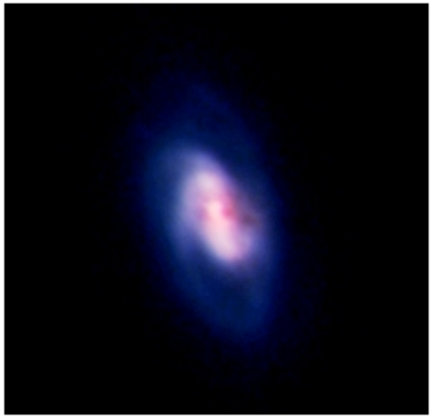
Vibrationally excited HCN (HCN-VIB)

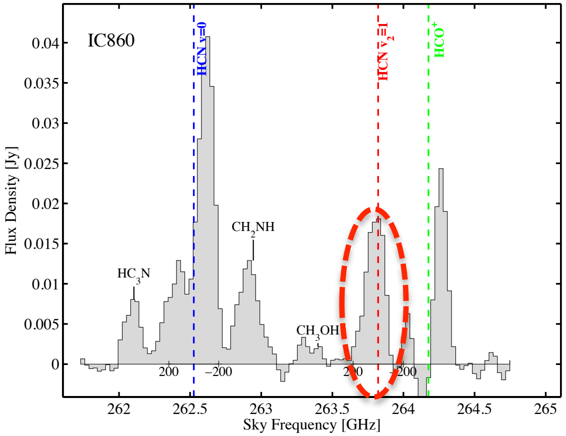


HCN-VIB lines appear close to the ν=0 lines in the mm and submm

Extremely luminous HCN-VIB in CON ULIRGs and LIRGs (Aalto+15b)

Early-type spiral LIRGs: Example IC860





- HCN and HCO^+ ***self- and continuum absorbed in nuclear region –*** due to large column densities and steep temperature gradient

- **Extremely luminous vibrationally excited HCN line emission** emerging from buried, compact (*r*<15-70 pc) nuclei

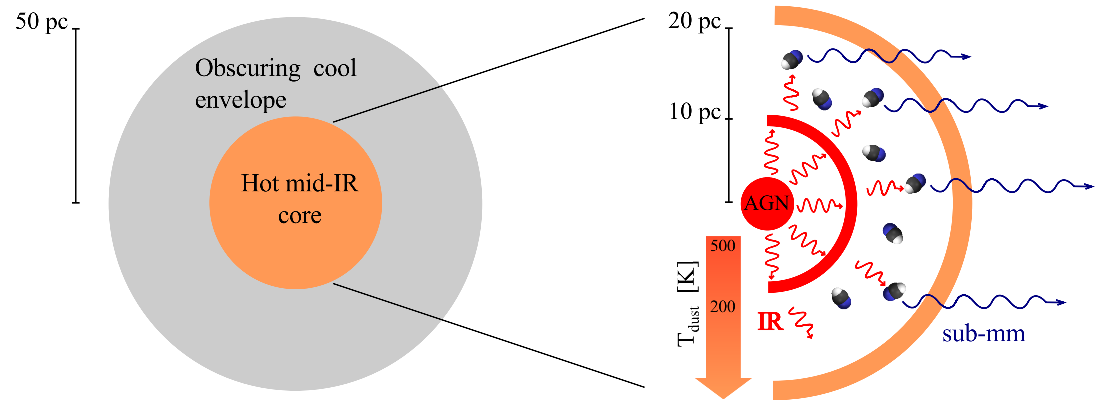
(Compare to hot cores in the Milky Way – e.g. Rolffs+11))

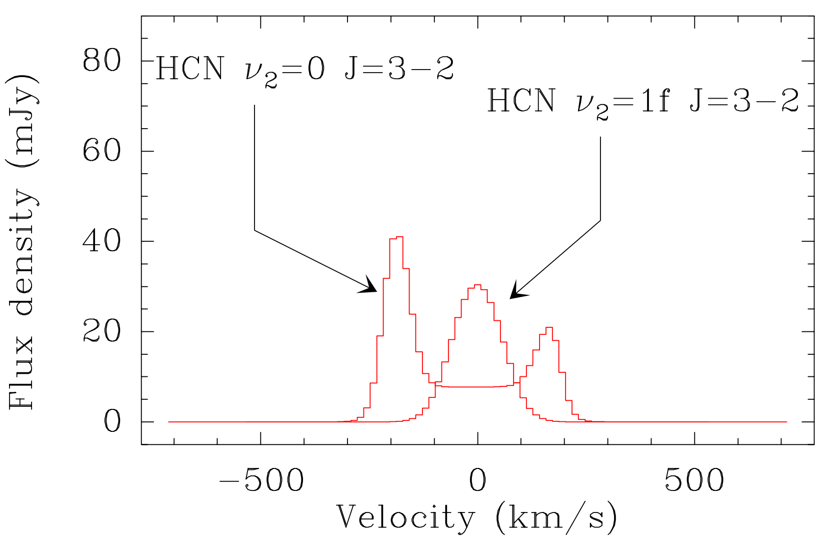
Luminous HCN-VIB found in ULIRGs (e.g. Arp220 (Aalto +15b, Martin+16), IRAS17208-0014 (Aalto+15b), IRAS20551-4250, IRAS 12112+0305 (Imanishi+13,16), Mrk231 (Aalto+15a), UGC5101 (König in prep)

And in early-type spirals (Sakamoto+10,13, Costagliola +13, Aalto+15b, Aalto+16)

Buried nucleus - better traced by vibrationally excited HCN?

- *r*(HCN-VIB)<<*r*(HCN), r(HCO^+)
- HCN-VIB emerging from extreme mid-IR cores since ***HCN-VIB requires a mid-IR surface brightness > 5x10^{13} L_{sun}/pc^2***
- 30-100% of total IR luminosity of galaxy may emerge from HCN-VIB region.
- Self-absorption HCN,HCO+ profiles P-Cygni or reversed P-Cygni – non-circular motions (infall? outflow?)





What is buried at the core?

Global L(HCN-VIB)/L(FIR) 10x that of a single massive star forming region like SgrB2. HCN-VIB requires a mid-IR surface brightness > 5×10^{13} L_{sun}/pc^2

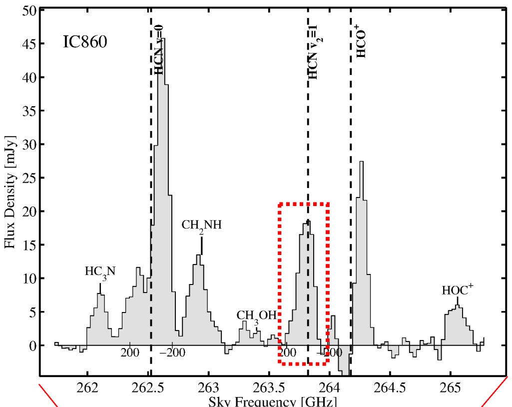
- Starburst?
  - *"Hot" , optically thick starburst possible* (existence predicted by Andrews and Thompson 2011)
  - Build-up of stellar spheroid?
- AGN?
  - Results would be consistent with a SMBH accreting at near-Eddington

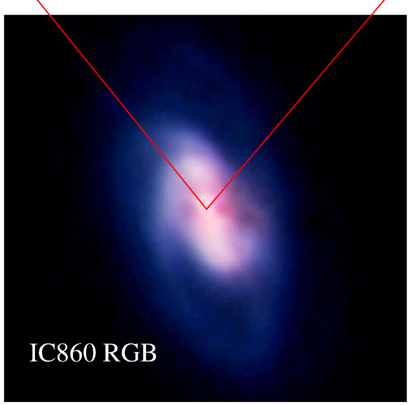
So far – HCN-VIB only detected in: ULIRGs and LIRG early type spirals

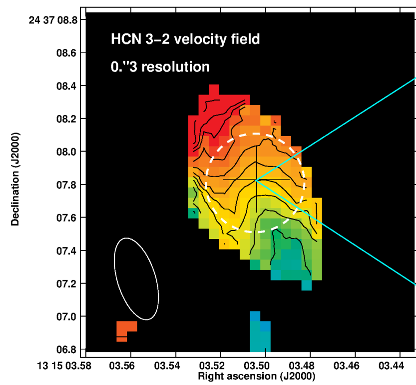
Preliminary statistics: 70% of nearby ULIRGs have HCN-VIB emission

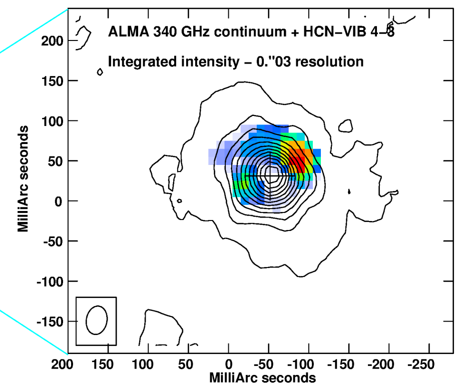
ALMA 0.”03 (7 pc) observations of HCN-VIB in IC860 (ongoing work)

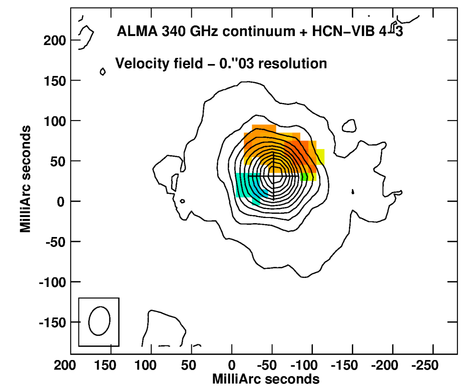
Redshifted absorption profiles on 0.”1 – 0.”5 scales

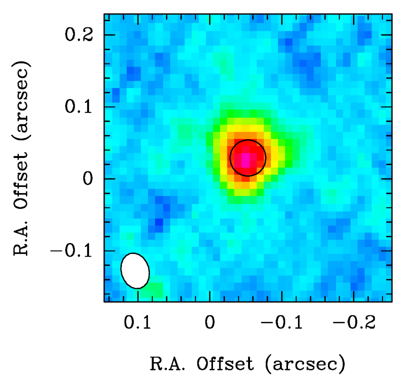


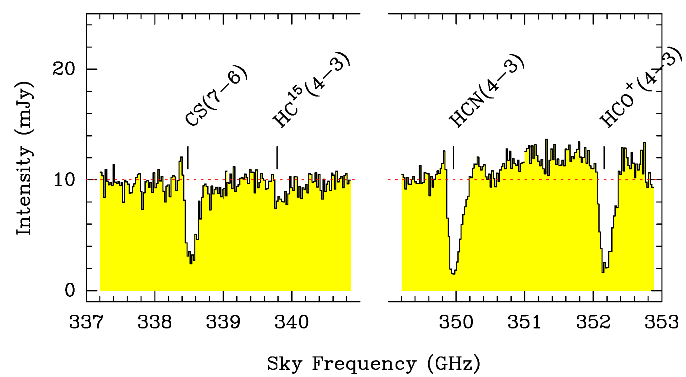






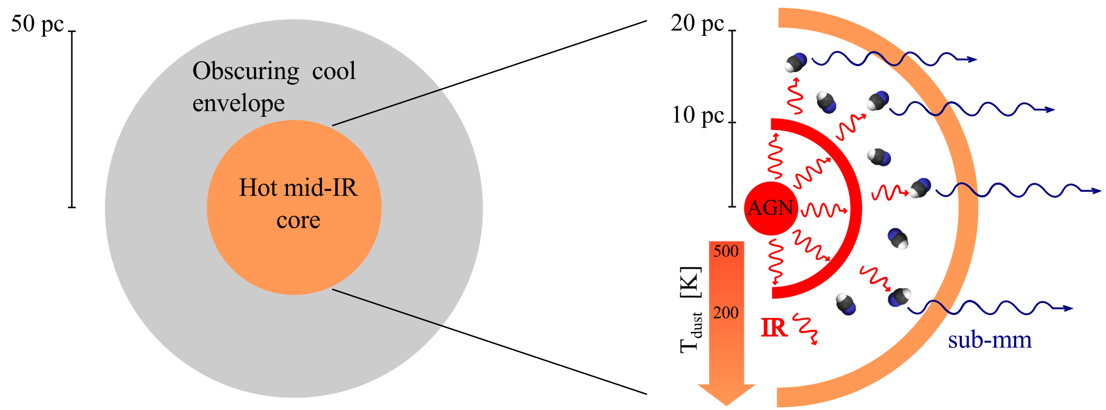






Blueshifted absorption profiles on <0.”1 scales

Environment



Column density > 5×10^{25} cm^{-2} (τ>1 at 345 GHz) ; L <3 pc
AVERAGE gas density: $n>10^7$ cm^{-3} (!)

- X-rays: Even hard X-rays are absorbed – emission from reflection can be detected (x100 fainter)
- mid-IR: Optically thick - will scattered emission leak out?
- Gamma rays?

MOLECULAR OUTFLOWS AND WINDS

Massive cold winds may

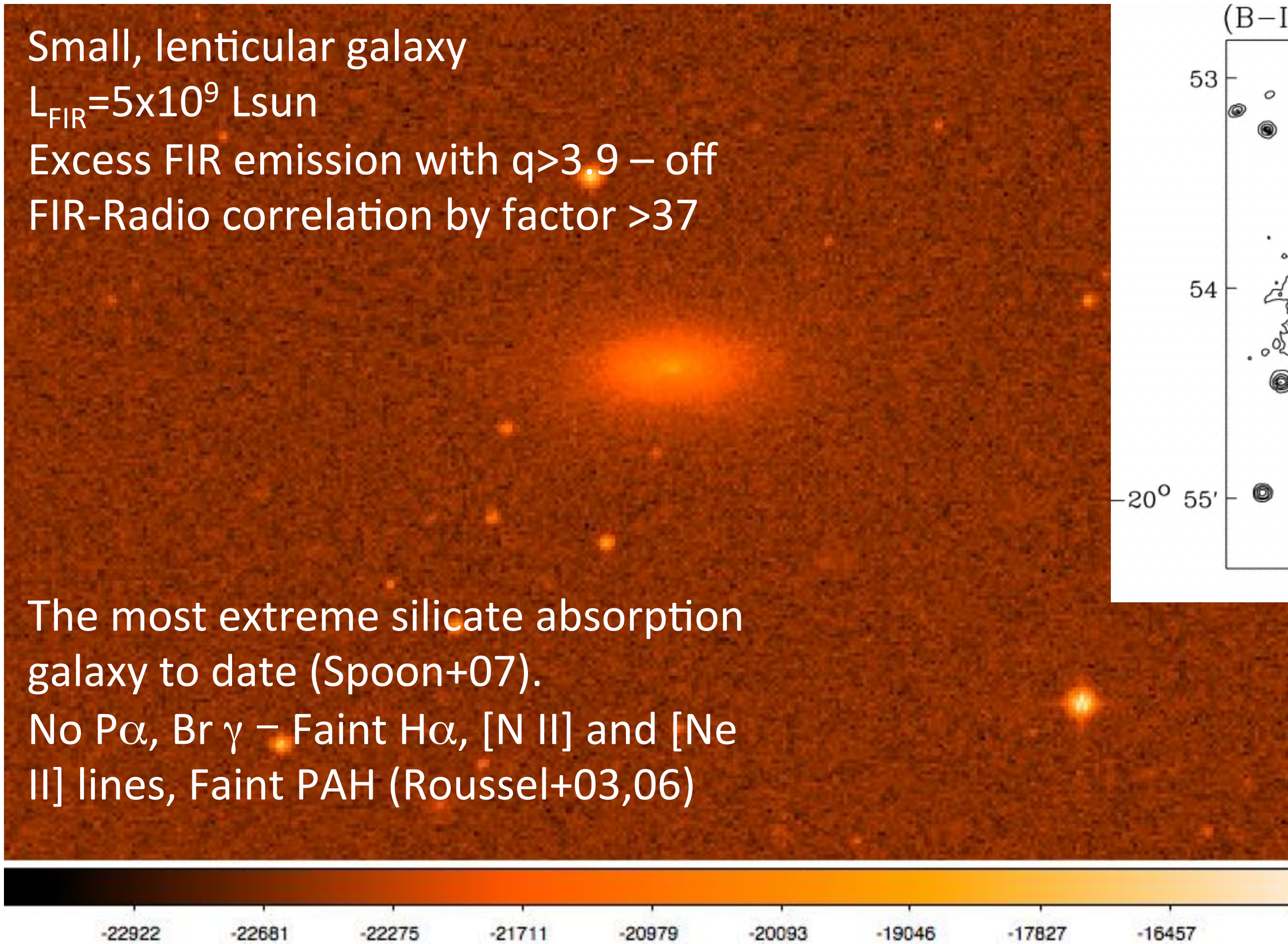
- stop black holes from growing to big
- stop star formation in galaxy centres

But what happens to the expelled gas?

Does it rain back again?

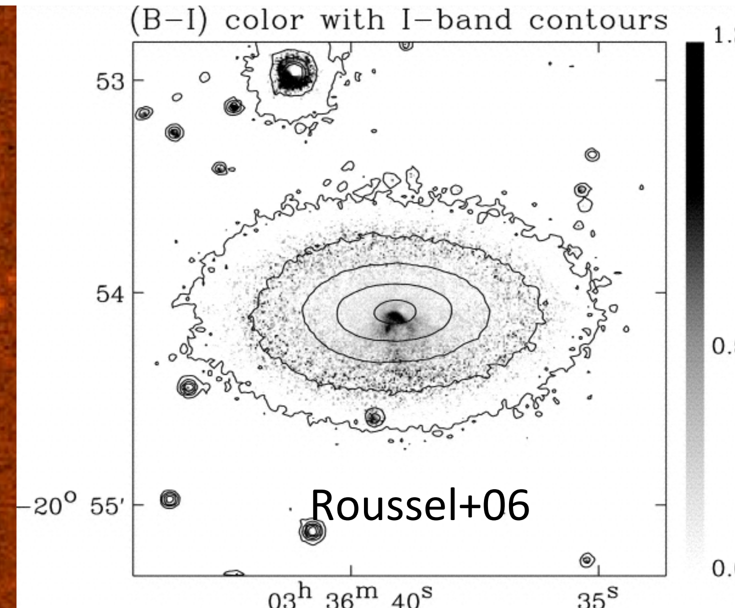
Or is it blown away?

A molecular outflow in the most extreme FIR-excess, radio-quiet galaxy NGC1377



Small, lenticular galaxy
$L_{FIR}=5x10^9$ Lsun
Excess FIR emission with q>3.9 – off FIR-Radio correlation by factor >37

The most extreme silicate absorption galaxy to date (Spoon+07).
No Pα, Br γ – Faint Hα, [N II] and [Ne II] lines, Faint PAH (Roussel+03,06)

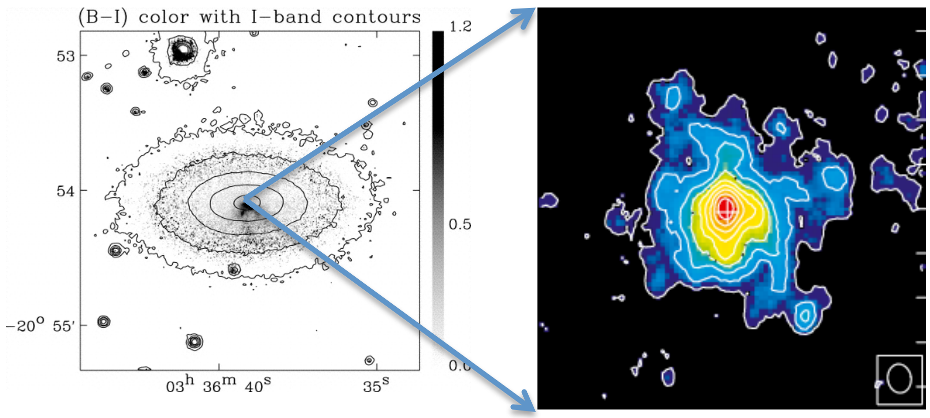


Featureless morphology apart from southern minor axis dust structure

Post starburst/LINER optical characteristics

What is powering the compact IR luminosity - Obscured AGN or nascent starburst?

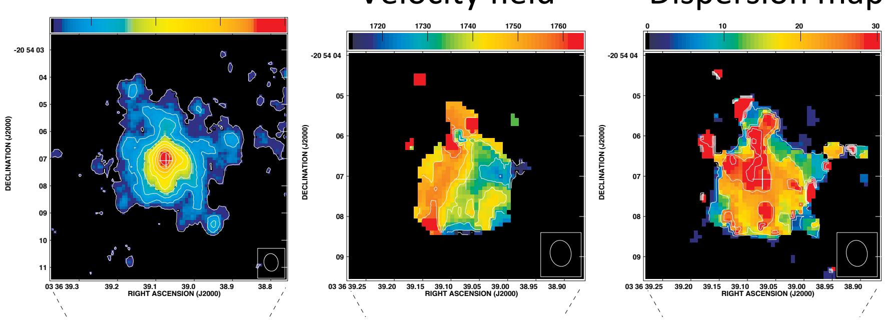
SMA CO 2-1 imaging: a molecular outflow (Aalto+12b)



CO 2-1 integrated intensity

- Molecular mass: 1-6x10^7 M$_\odot$
- Extent: 400 pc
- Opening angle: 60°–80°
- Age: 1-2 Myr
- Outflow velocity: 150 - 200 kms^{-1}
- dM/dt: 8–38 M$_\odot$ yr^{-1}
- Molecular core of N(H$_2$)>10^{23} cm^{-2}

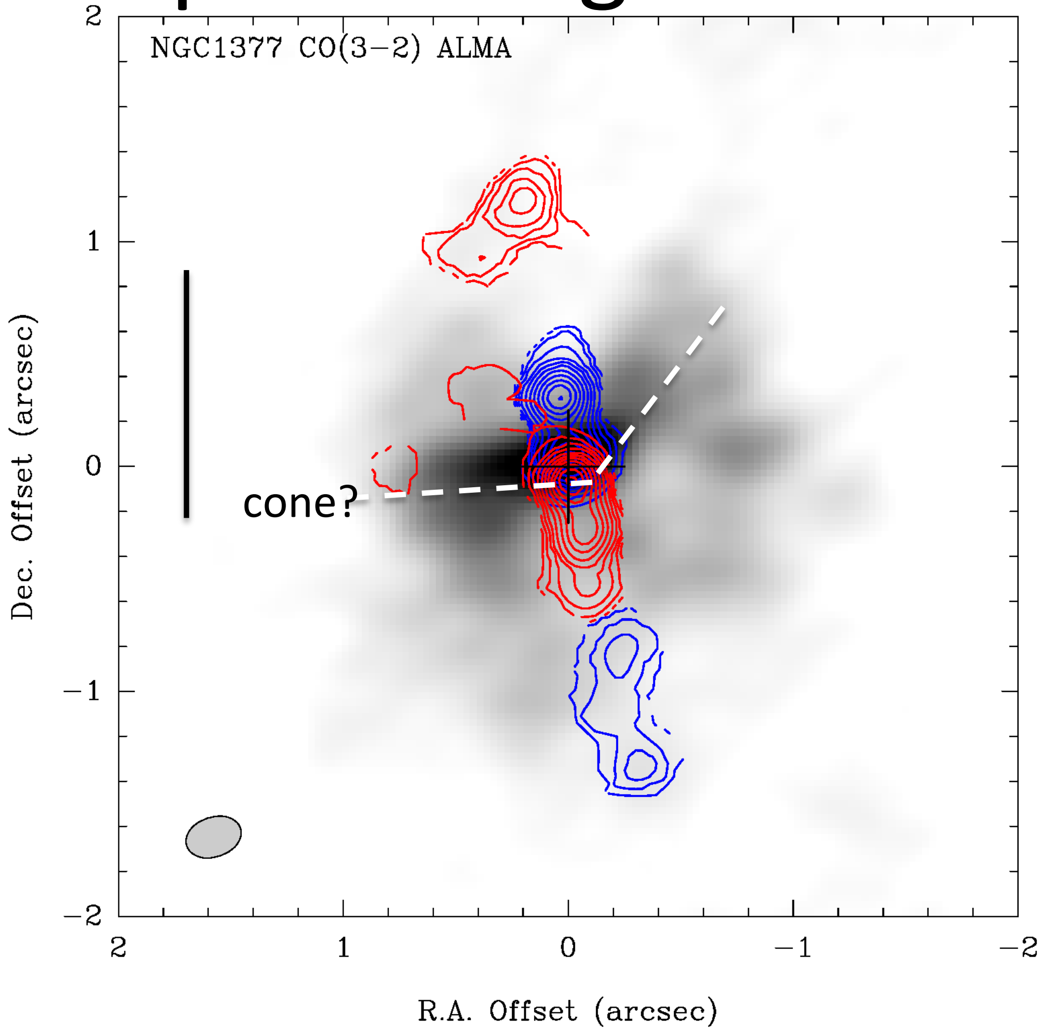
Velocity field Dispersion map



X-shaped structure outlining the walls of a bicone??

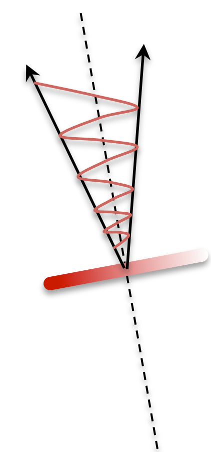
The inner region will be clear of molecular gas within 5-25 Myr.

ALMA CO 3-2 imaging reveals a precessing molecular jet?? (Aalto+16)



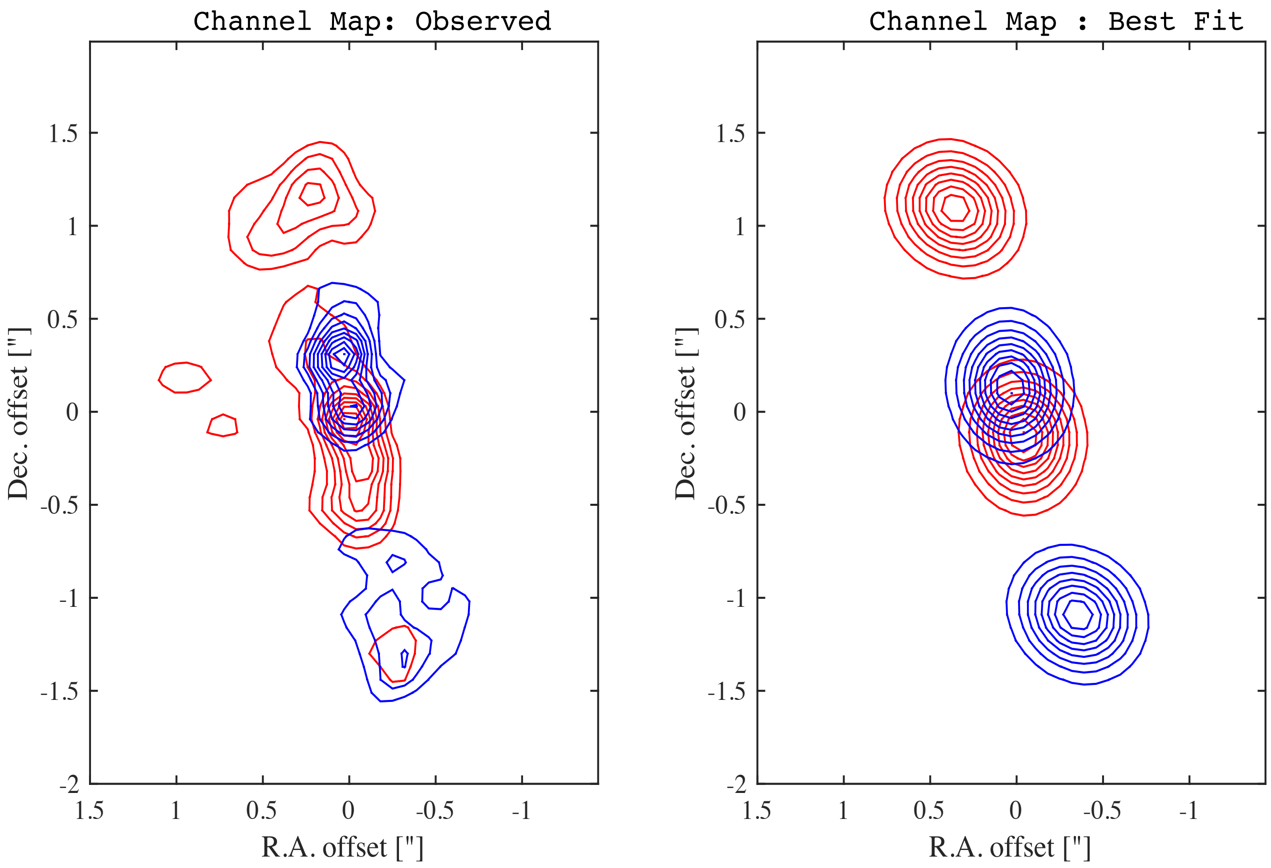
High velocity gas extremely well aligned along line-of-sight. *It is very radio quiet.*

A molecular "jet" rotating around an axis perpendicular to the line of sight may reproduce observations.

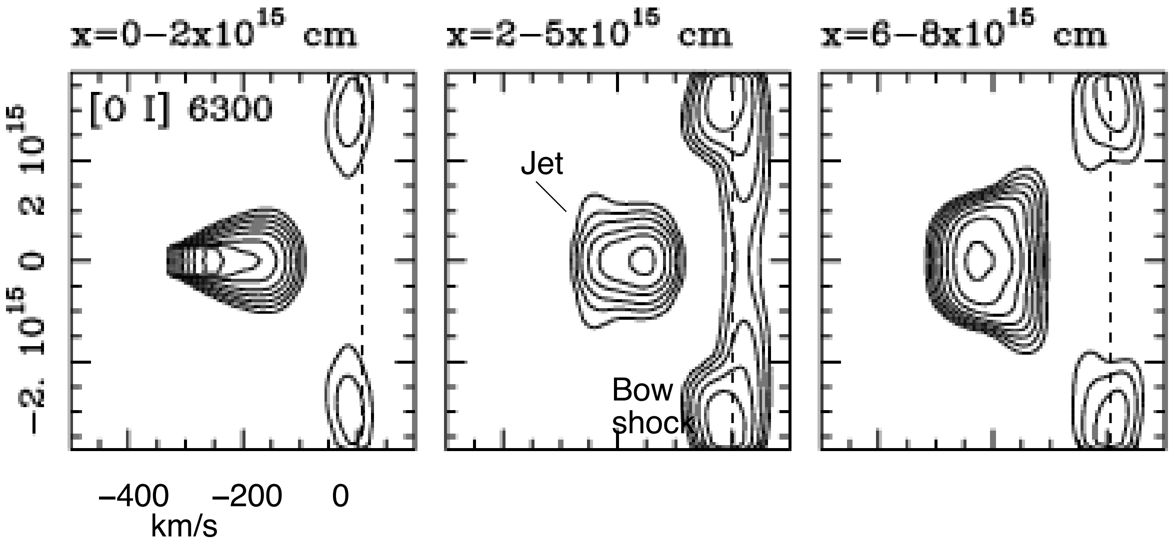


Grey scale: Systemic velocities
Red and blue: High velocity gas

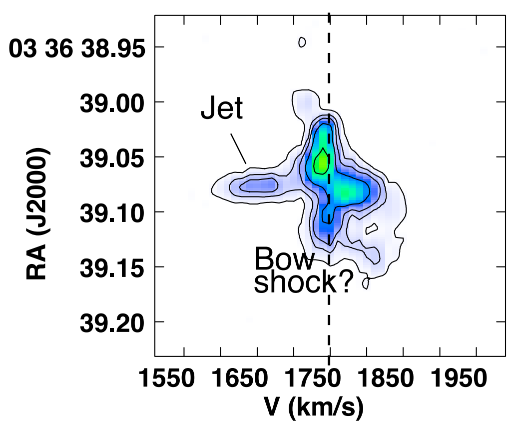
Model example



PV-diagrams: Jet emission and bow shocks



Models from
Raga et al –01
On a precessing
protostellar
jet and resulting
bow shocks.



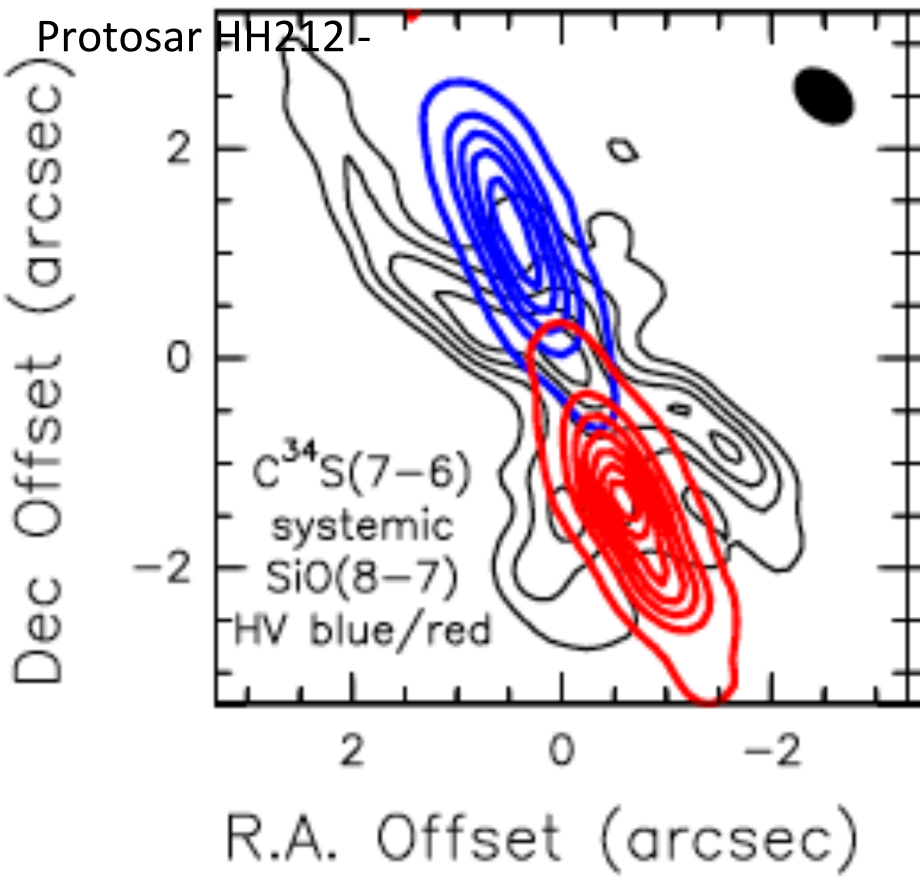
PV diagram perpendicular
to N1377 jet

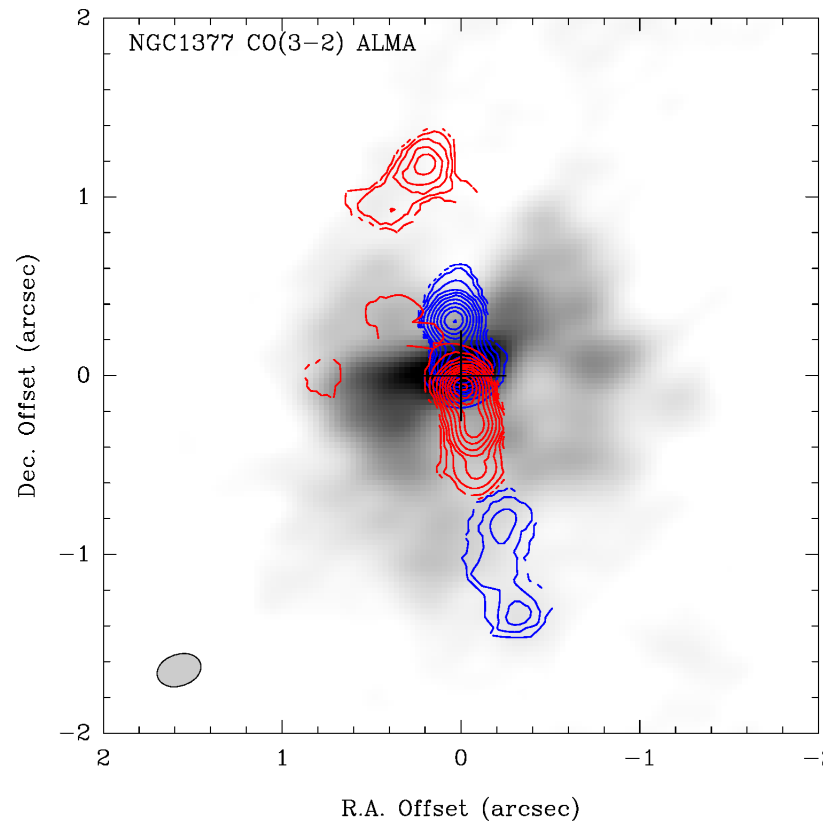
Jet bow shocks can entrain gas partially causing the 45 degree inclined wind.

Precessing molecular jet signals accreting SMBH?

- Highly collimated precessing molecular jet consistent with dynamics. Origin of precession:
  - binary SMBH?
  - warped accretion disk?
    - Lense-Thirring -> Bardeen-Peterson effect
    - Uneven accretion.
- What else may cause the velocity reversals in the jet? Helical jet? Shocks? Multiple jets?

Analogy: protostellar jet?

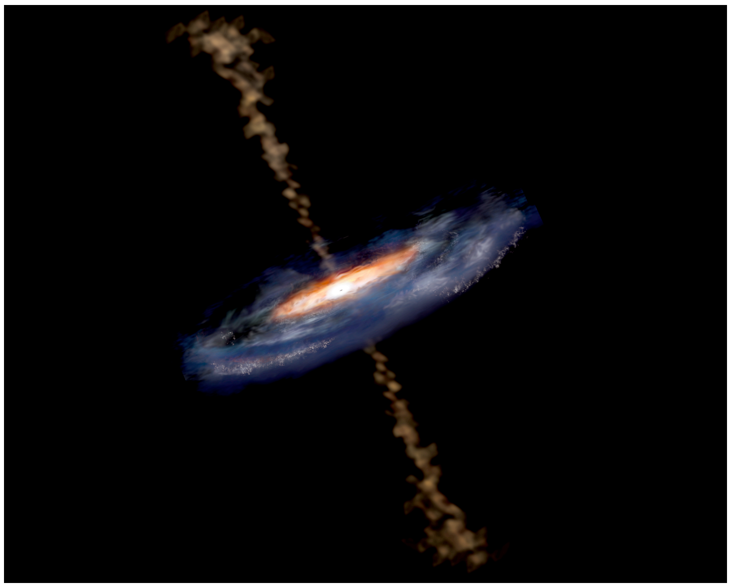




Codella+14: High velocity SiO jet surrounded by systemic emission outlining the cavity and a wide angle flow. Here – no evidence for jet rotation

NGC1377

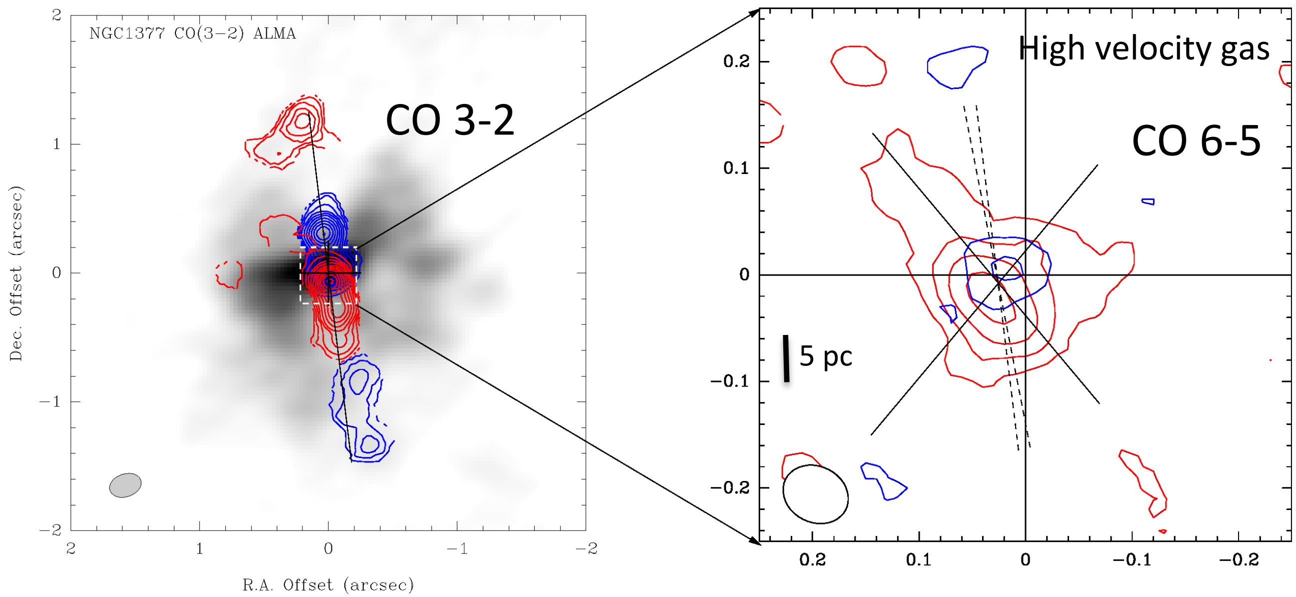
Or: synchrotron-quiet radio jet?



(Image credit: Aurore Simonnet, Sonoma State University)

- Jet energy does not go into producing synchrotron emission – but instead is used up for e.g. pushing dense gas, shocks. -> Underluminous radio jet. (Weak link between radio luminosity and jet power suggested by Godfrey+2016.)
- ”Hot accretion” – inefficient accretion mode compared to cold accretion. What is the accretion state of the SMBH of NGC1377?
- *First detection of radio emission towards NGC1377 (Costagliola +16). Faint, with synchrotron spectrum between 1.4 and 9 GHz. Morphology not clear yet (ongoing VLA observations)*

New ALMA Band 9 observations with 50 mas (5 pc) beam.



- Complex dynamics in the inner 5-10 pc
  - High velocity gas either in warped nuclear rotation and/or jet.
  - Near-systemic jet-like features on 5-10 pc scales.
  - ”Extra” high-velocity red feature to the north-east.
- Hot (>200 K) nuclear gas – shocks?
- No 690 GHz continuum detected. Very faint 345 GHz continuum
- No X-rays detected from the nucleus – only very faint emission along the jet. Faint radio emission finally detected (Costagliola+16)

- Possibilities:
  - CT AGN: 10^{25} cm^{-2} obscuration on very small scales – 0.2 – 0.5 pc, with average gas densities $n>10^7$ cm-3. Accretion rates would then be 2-10% Eddington.
    - Jet outflows have cleared away obscuration on 1-10 pc scales?
  - Or: No CT AGN. Lower accretion rate?
- How is the gas cleared? Where does the gas come from?
  - Has the jet cleared away gas and dust from the 1-10 pc disk?
  - Has the jet swept up gas in a wind?
- CO 6-5 likely not radiatively heated – shocks from outflow/ jet-action?

Conclusions

- A population of enshrouded nuclei may have extreme obscurations $N(H_2)>10^{25}$ cm^{-2} and extreme, buried mid-IR surface brightnesses. Optically thick even at 345 GHz. Gas densities may exceed 10^7 cm-3
  - What is lurking inside? Hot, opaque starbursts? Eddington limited AGNs?
- Use vibrationally excited HCN to probe them.
  - IC860: ALMA resolves HCN-VIB, but very nucleus still opaque.
  - Slow large scale inflow – slow nuclear outflow.
  - HCN-VIB luminous galaxies show none or slow outflows (but very few have been studied)
- Winds and jets clearing the dust: NGC1377.
  - Radio-quiet, molecular-rich jet!
  - Velocity structure consistent with precession.
  - Probing nucleus on 5 pc scales with ALMA. Luminous, compact CO 6-5 T>200 K – NO 690 GHz continuum on scales 10-1 pc
    - Accretion state of SMBH may be in ”quasar mode” – but still needs to be proven