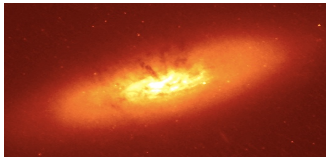
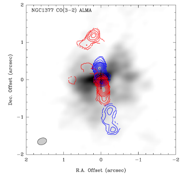

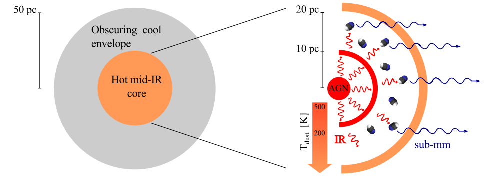

Dust as a probe
- luminous dusty galaxies and enshrouded nuclei

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Sweden

CHALMERS

J. Gallagher, N. Falstad, S. König, S. Muller,
K. Sakamoto, S. Garcia-Burillo, L. Kristensen,
MasTER collaboration et al

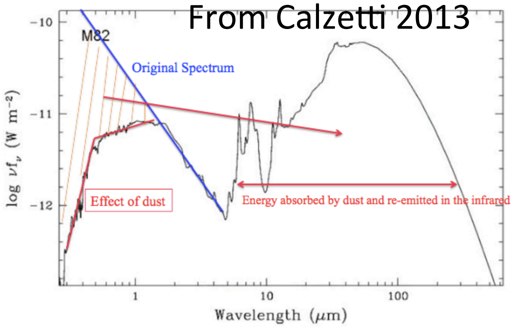
MASTER
MOLECULES AS TOOLS FOR EXTRAGALACTIC RESEARCH

Where am I on the "dust evolution" scale?

- A mix of stage 2, 3, 4 and 5
  - Extremely annoyed (it is getting in the way even at λ=1mm…)
  - Accepting (its there…)
  - Stage 4 and 5: We need to probe dust to understand rapidly growing galaxies near and far

Starbursts and growing supermassive black holes are enshrouded in dust

From Calzetti 2013



Outline

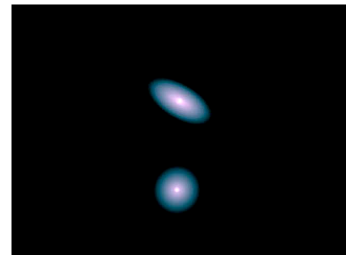
- Dusty luminous galaxies – what are they and why do we care?
- How can we study them?
- Extremely opaque dust nuclei –the CONs!
- Dusty outflows
- Conclusions

LIRGs and ULIRGs – dusty luminous galaxies

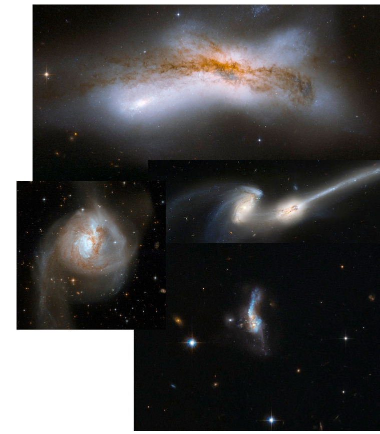
- Luminous and Ultraluminous Infrared Galaxies, (U)LIRGs, are **dusty galaxies** with IR luminosities $L_{IR}>10^{10\text{-}11}$ and $>10^{12}$ L_{sun}

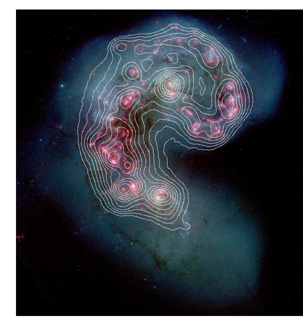
- (U)LIRGs are often **interacting** and are fundamental to galaxy mass assembly over cosmic time (e.g. Elbaz & Cesarsky 2003; Sanders & Mirabel 1996).
  - U/LIRGs start dominating the SF density with increasing z
- Some (U)LIRGS have even more **embedded nuclei** that harbour a very active evolutionary stage of AGNs and/or starbursts.
  - The nuclear activity will often drive **mechanical feedback** in the form of molecular winds, jets and outflows (e.g. Banerji et al. 2012; Fabian 1999; González-Alfonso et al. 2012).

Dynamical simulation



Gallery of interacting ULIRGS (HST)



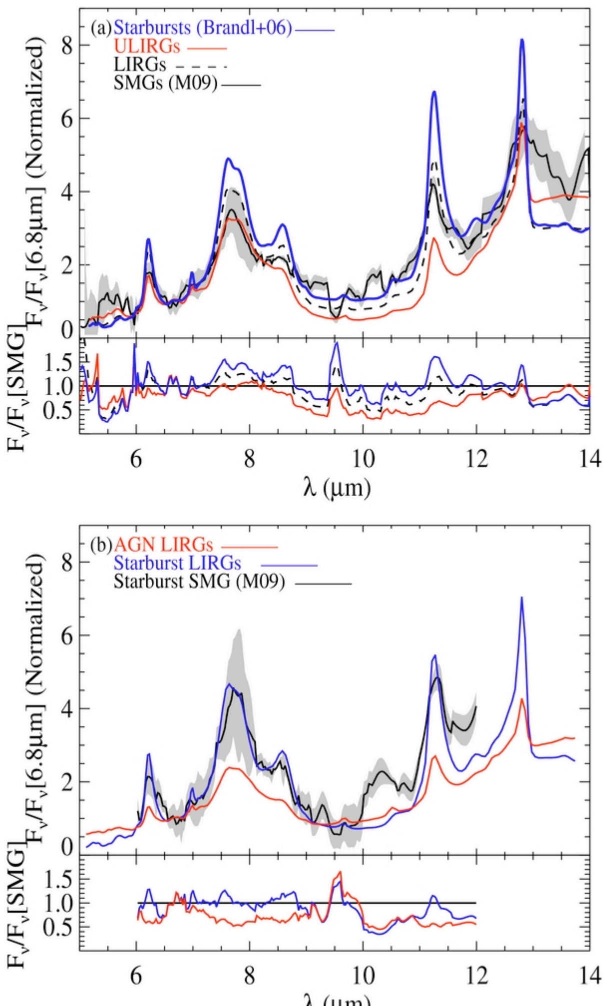


The Antennae:
100 μm PACS
on HST (Klaas +10)

Winds and jets

HOW STUDY U/LIRGS?

Mid-IR properties of LIRGs



Comparison of average LIRG and ULIRG spectra to average submillimeter galaxy spectra from Menéndez-Delmestre et al. (Stierwalt+13)

- Large range in PAH EQW, silicate absorption, mid-IR slope
  - Obscuration
  - Evolution with merger stage
  - PDRs, ionization rates, grain sizes
  - Compactness and temperature
  - PAHs: gas tracer on global scales (Poster 175)
- Mid-IR imaging to reveal buried AGN (e.g. Martinez-Paredes+17)

Mid-IR properties of LIRGs

- **9.7 μm silicate absorption**
  - Obscured galaxy nuclei – and/or cold diffuse foreground dust?
  - Amorphous or crystalline silicates, SiC (see e.g. Kemper+04, Spoon+06, Roche+15) poster 109 (Kemper) – link to massive stars/cosmic ray processing
- **Mid-IR water ice features** In most obscured U/LIRGs (Spoon+01)
  - Evolutionary sequence from obscured systems showing ice features – to evolved PAH in luminous LIRGs with PDRs?
- Steeper **mid-IR slopes** in more compact distributions with warmer dust
- **Molecular lines** – e.g. 14 μm absorption line of HCN (Lahuis+07)

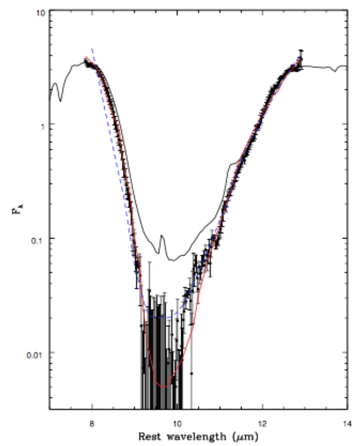
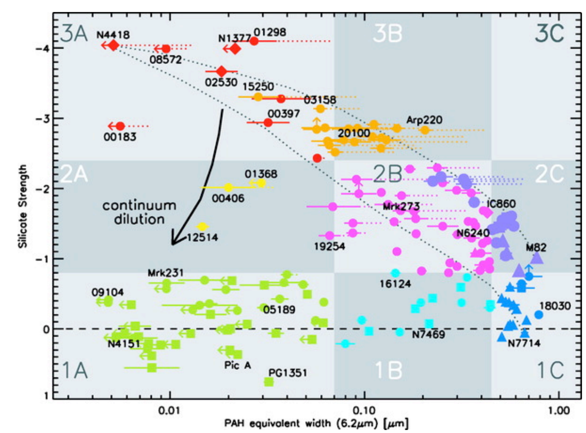


Figure 1. The spectra of the nucleus of NGC 4418 obtained with *Spitzer* (solid line) and TReCS filled circles, in units of 10^{-18} W cm^{-2} μm^{-1}. The thin solid (red) and dashed (blue) lines represent fits to the TReCS spectrum using the μ Cep and Trapezium silicate profiles, respectively.

Silicate profile of LIRG NGC4418 (Roche+15)

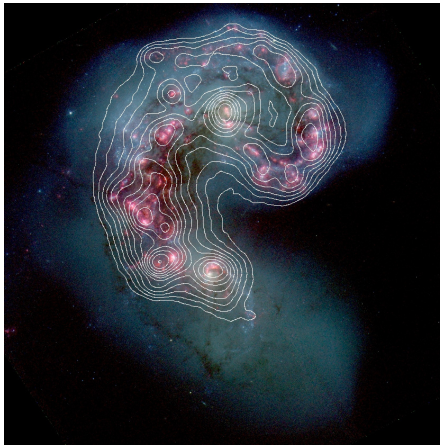


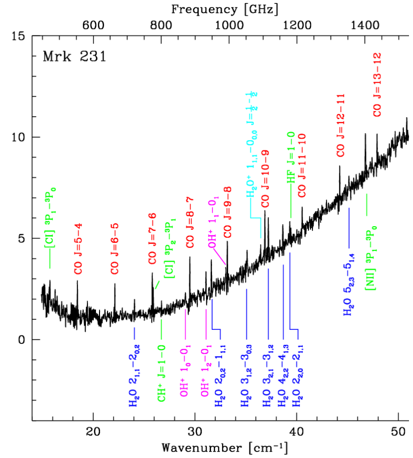
Spoon+07

FIR emission and absorption

- 50-200 μm continuum reveal *embedded* star formation.
    - Star formation laws.
- Dust spectral energy distributions SEDs peaks
    - dust content, dust-to-gas ratios, dust temperatures
- high-J CO and HCN, H_2O, OH, OH^+, H_3O^+ probe
    - Molecular gas excitation and chemistry
    - Dust grain processing
    - Dynamics - Infall/outflow (Sturm+11, Veilleux+13)

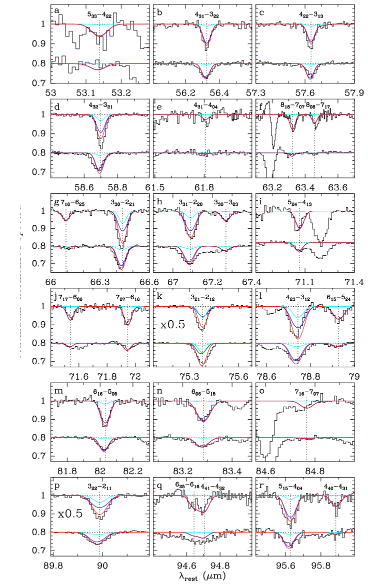
The Antennae: 100 μm Herschel PACS on HST (Klaas et al 2010)





Herschel SPIRE spectrum of the quasar Mrk231 (van der Werf +10

The rich water spectra of NGC4418 and Arp220 (Gonzalez-Alfonso et al 2012)



Dust and molecules at mm/submm wavelengths

ALMA/NOEMA/SMA - with ALMA at extremely high spatial resolution − 20 milli arcseconds

Spiral arms and bars

Flocculent - Grand design

Strong/weak - Nested

Interactions

Polar rings, dust lanes, counterrotating and infalling gas

Tidal gas

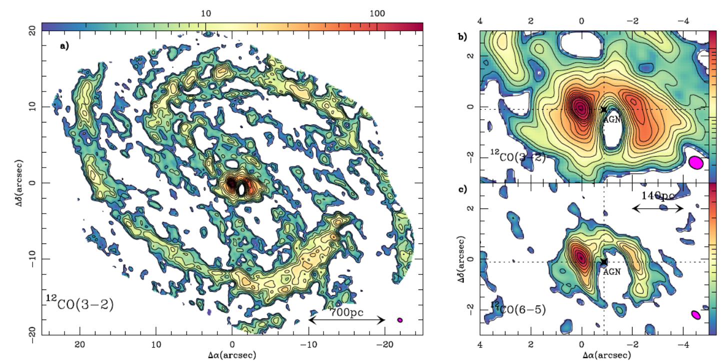
”Overlap regions”

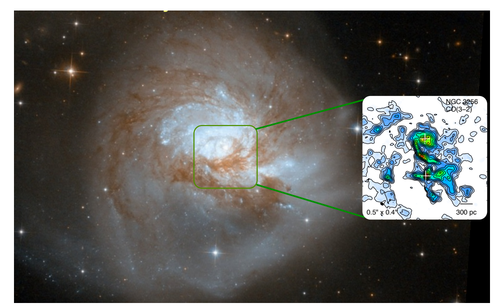
Nuclear gas - Outflows and winds

Molecules probe e.g.

- dust grain processing, SiO, H_2S, CH_3OH etc
- Stellar enrichment − ^{18}O, ^{13}C etc
- proxies for buried NIR/MIR energy densities

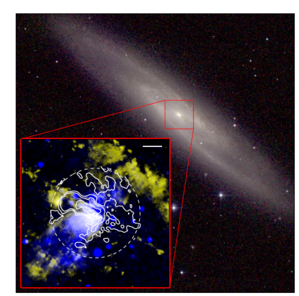
Garcia-Burillo+14





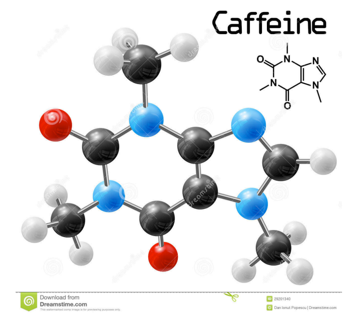
Sakamoto +14

Bolatto +13



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-C_3H_2	CH_3OH	CH_3CCH	HC_6H	c-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*-C_3H_2				
CH^+ **	N_2H^+	$HOCO^+$	H_2CCN				
CN	OCS	c-C_3H	H_2CCO				
SO	HCO	H_3O^+	C_4H				
SiO	H_2S	*l*-C_3H					
CO^+	SO_2						
NO	HOC^+						
NS	C_2S						
NH	H_2O^+						
OH^+	HCS^+						
HF	H_2Cl^+						
SO^+	NH_2						
ArH^+							
CF^+							

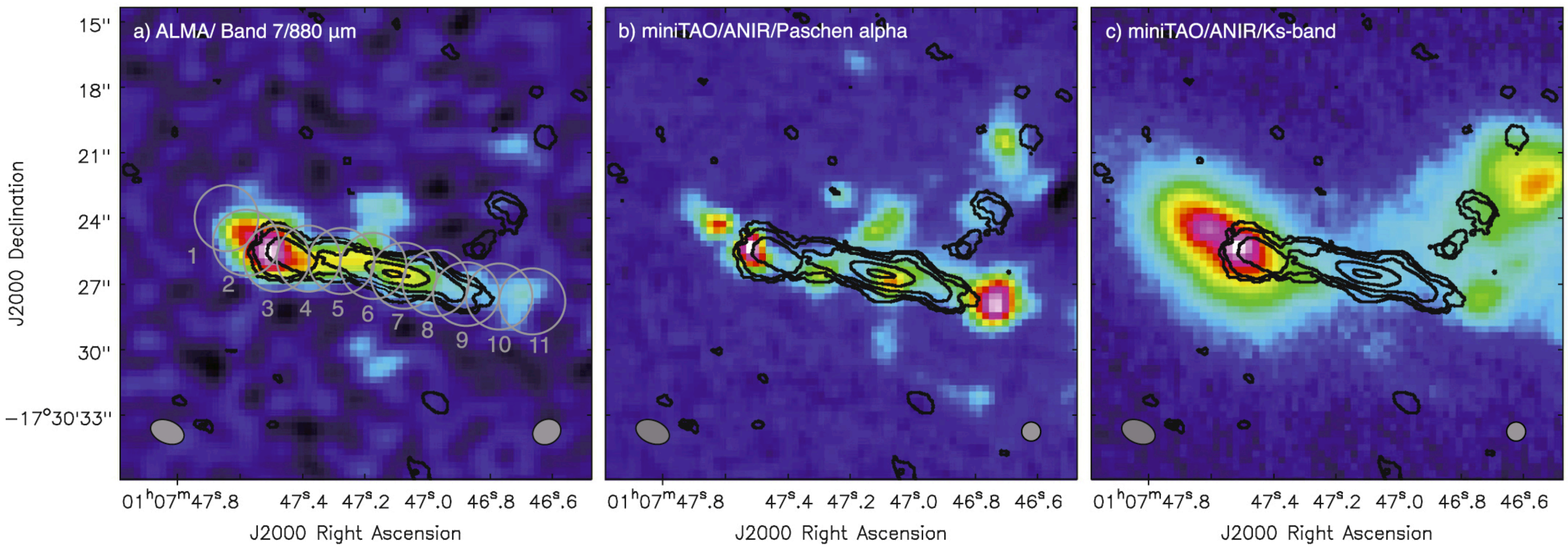


...not yet...

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

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

Methanol tracing kpc-scale shocks in luminous merger VV114 (Saito+17)



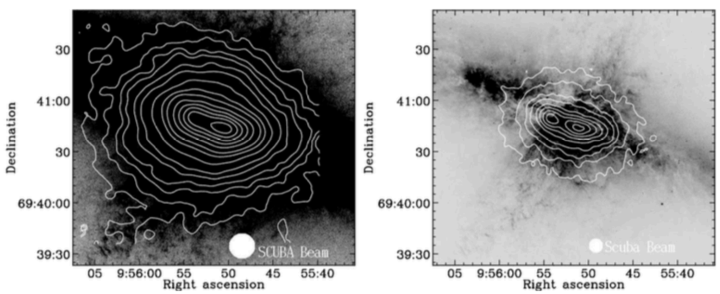
Integrated intensity contour of CH_3OH (3K–2K) overlaid on (a) 880 µm dust emission, (b) Paschen α emission, and (c) Ks

- CH_3OH also tracing bar shocks and grain processing in IC342, Maffei2 (Meier and Turner 06, 12)
- **SiO** tracing faster shocks in outflows − e.g. Tunnard+15, Imanishi+18

Submm/mm dust maps

Extended cold dust

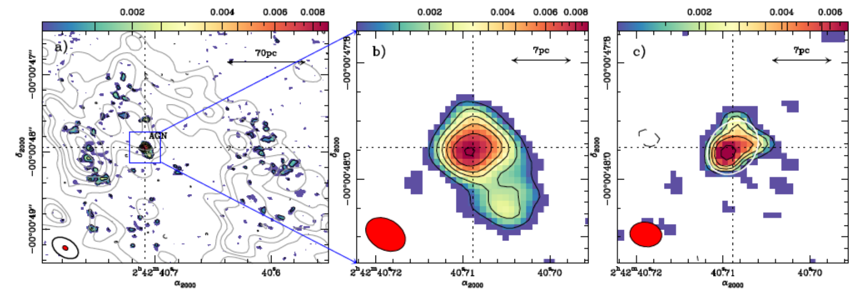
- Disks and outflows



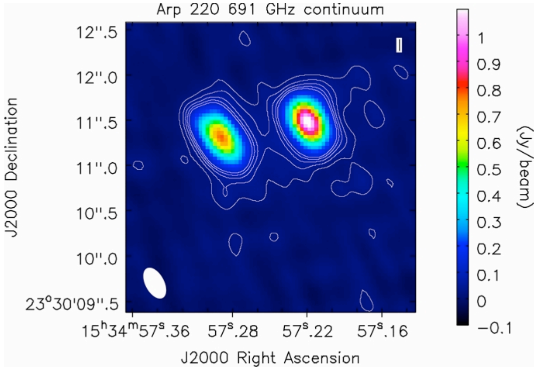
Submm continuum in center and outflow of starburst M82 (Leeuw and Robson 09

Submm/mm dust continuum good tracer of mass.
(e.g. Groves+14, Scoville+14)

Obscured nuclei and torii



NGC1068: r=3.5 pc dusty turbulent torus with M_{gas}=1x10^5 M_{sun} (Garcia-Burillo+16, Gallimore+16).



450 μm nuclear dust disks in Arp220 merger (Wilson+14)

A hidden AGN population – or extreme starbursts?

COMPACT OBSCURED NUCLEI

CONs – Compact Obscured Nuclei - $N(H_2)>10^{24}\ cm^{-2}$ $A_V>1000$

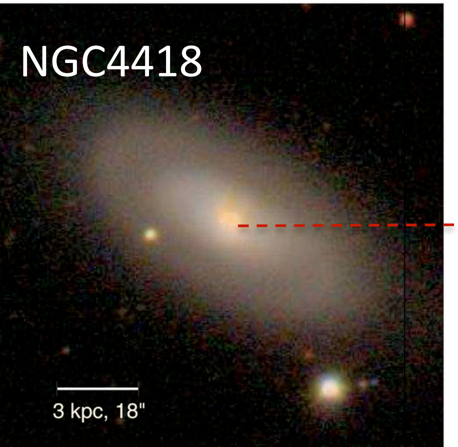
Some (U)LIRGs harbour CONs - Still unknown how common they are

Extremely important to understand obscured phase:

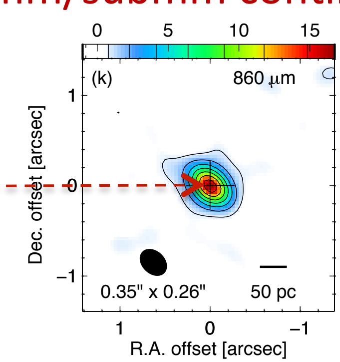
- AGN statistics.
- Growth of nuclear stellar spheroid. Starburst-AGN connection
- Potential sources of cosmic neutrinos (e.g. Berezinskii & Ginzburg 1981; Bahcall & Waxman 2001, Yoast-Hull+17).
- Relation to distant DOGs? SMGs?

Example:

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



mm/submm continuum

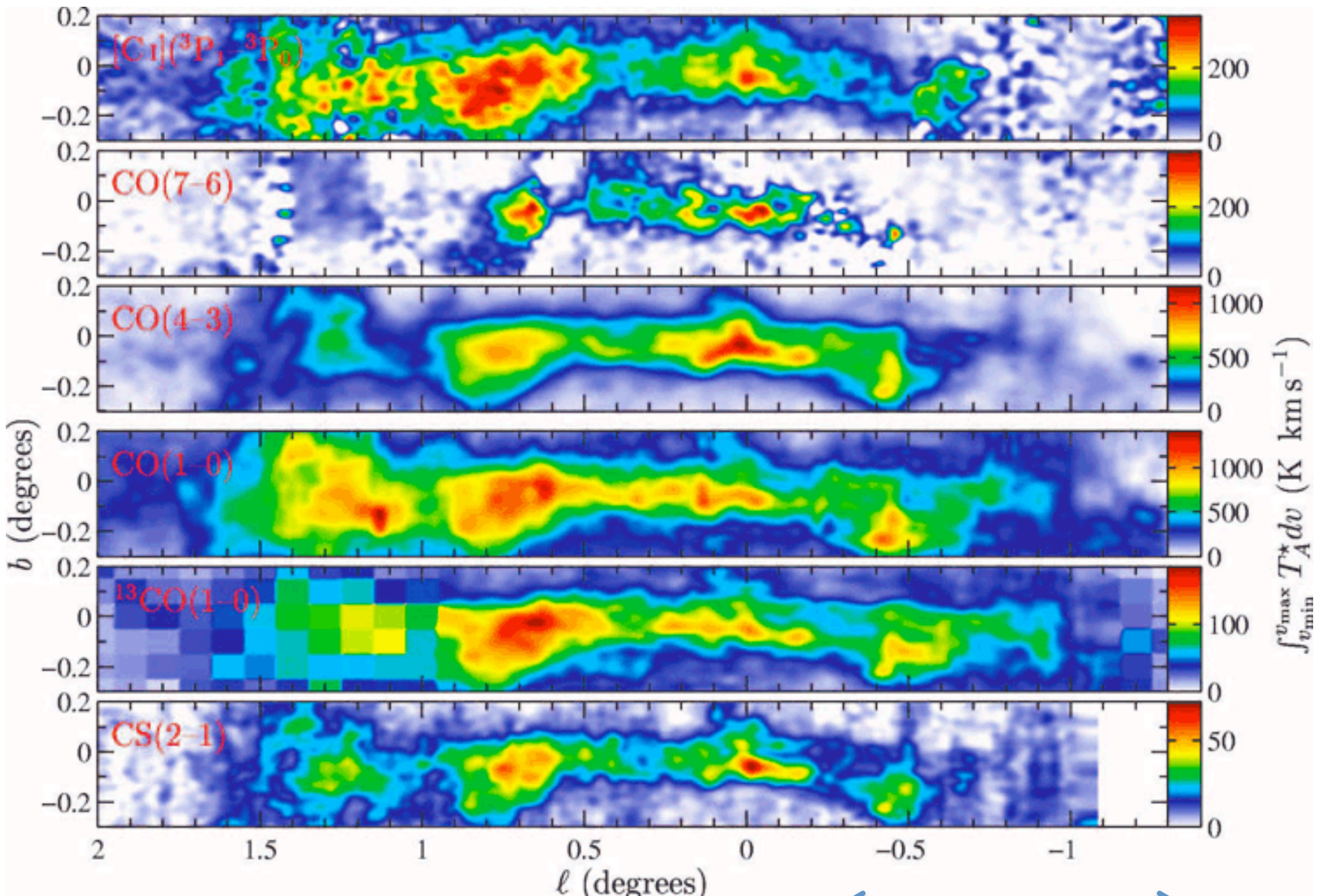


- <0. "1 (<20 pc) nuclear emission
- Core luminosity: $10^{11.0}\ L_\odot$ - bulk of total FIR luminosity of NGC4418.
- T_B(860 μm)=120-210 K, τ(860 μm) = 1 (i.e., $N_H>10^{25}\ cm^{-2}$).

Central Molecular Zone (CMZ) of the Milky Way

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

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



In comparison:
Extreme properties of NGC4418 nucleus.

10^8 M_{sun}

20 pc

100 pc

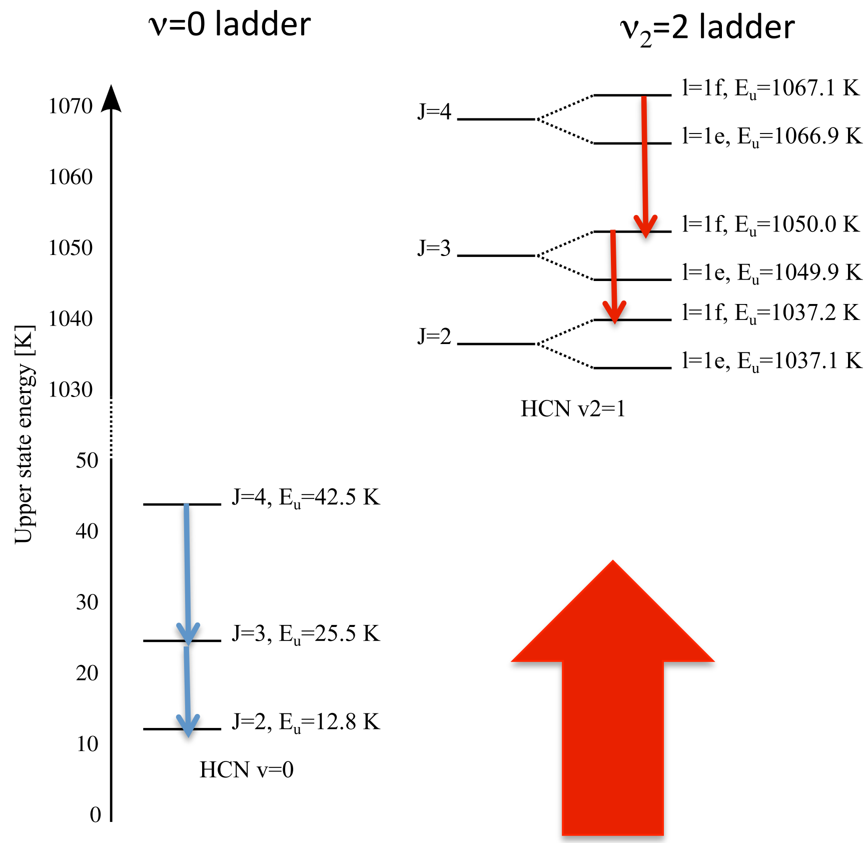
How can we probe behind the veil of dust?

Vibrationally excited HCN (HCN-VIB)

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

-mm/submm continuum observations: luminosity density, $N(H_2)$

-Vibrationally excited HCN (HCN-VIB) requires T_B(14 μm) > 100 K. Observe rotation transitions in the mm/submm. (e.g. Sakamoto+10, Aalto+15a,b, Imanishi+13, Aalto+15ab, Martin+16, Aalto+16, Imanishi+16). Or in the cm wavelengths (e.g. Salter+08)



14 μm IR field

Buried nuclei traced by vibrationally excited HCN

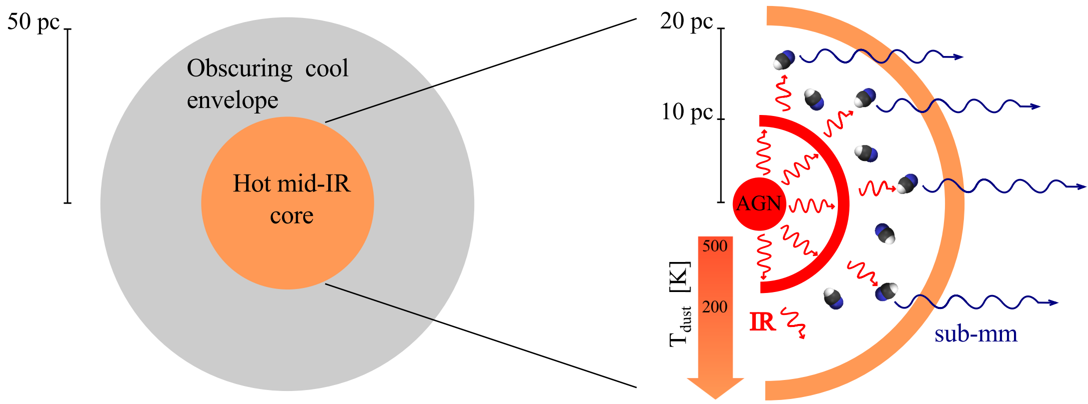
- HCN-VIB emerging from extreme mid-IR cores since ***HCN-VIB requires a mid-IR surface brightness > 5x10^{13} L_{sun}/pc^2 :***
  - ***Extreme compact opaque starburst (Andrews and Thompson 2011)***
  - ***Obscured AGN***

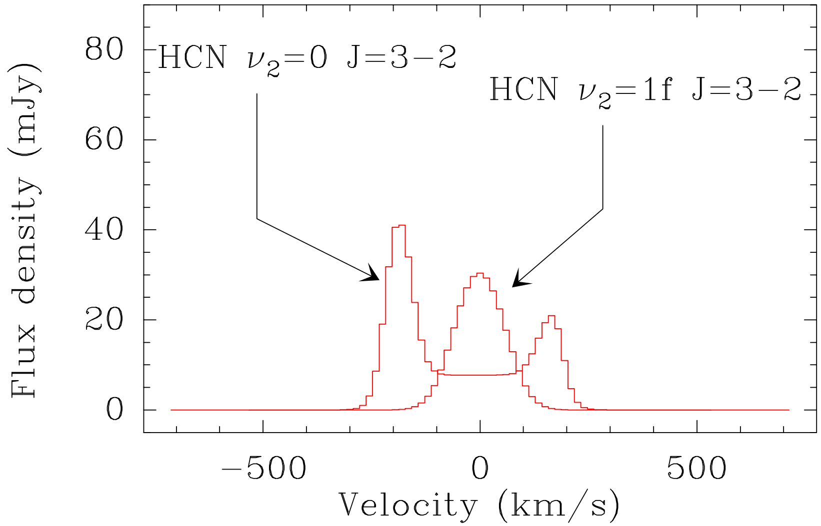
- So far – luminous HCN-VIB only detected in: ULIRGs and LIRG early type spirals

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

- 30-100% of total IR luminosity of galaxy may emerge from HCN-VIB region.

Very luminous HCN-VIB emission detected at redshift z=2 (Riechers in prep.)

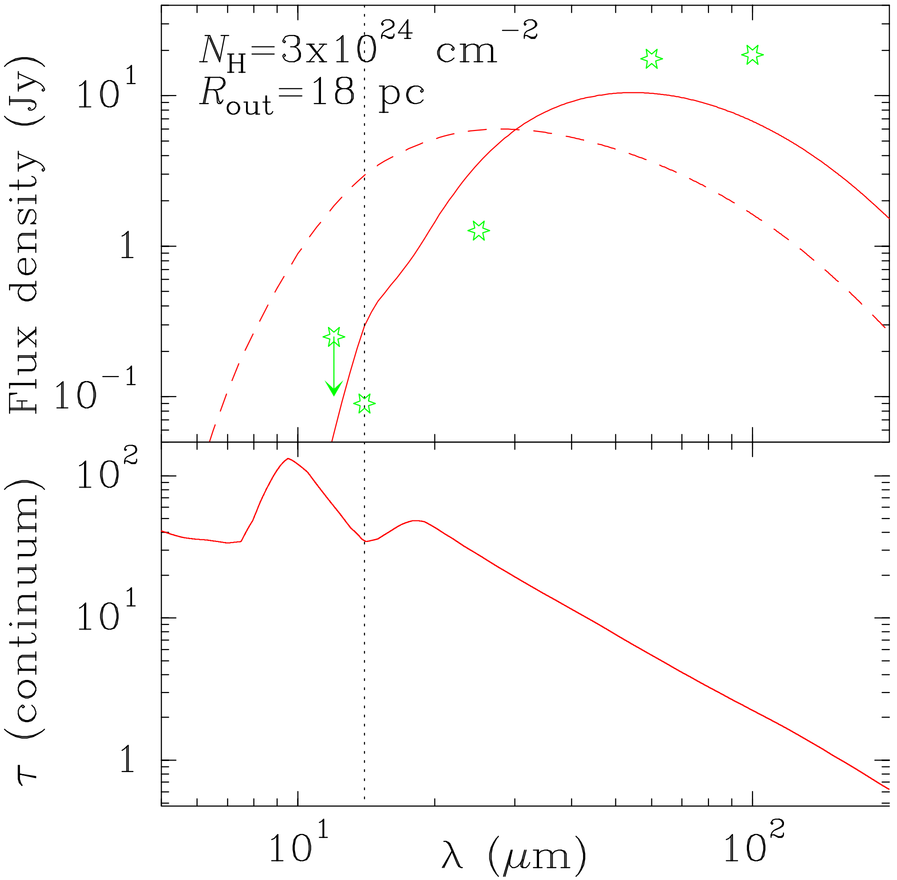




”Too cold” dust SEDs?

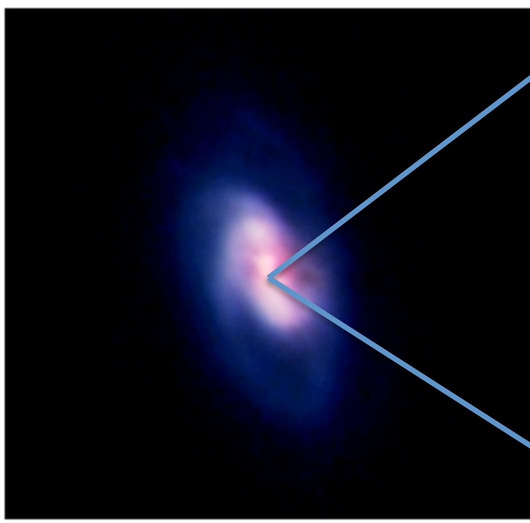
- Dust Spectral Energy Distribution (SED) may shift due to absorbed nuclear emission.
- high surface brightness mid-IR may be attenuated/buried (e,g, IRAS17208! No nuclear mid-IR Soifer+01) but very bright mid-IR excited HCN-VIB)
- Trapped radiation from the embedded source may raise the internal temperature =”Greenhouse effect”. (See e.g. Rolffs+11)

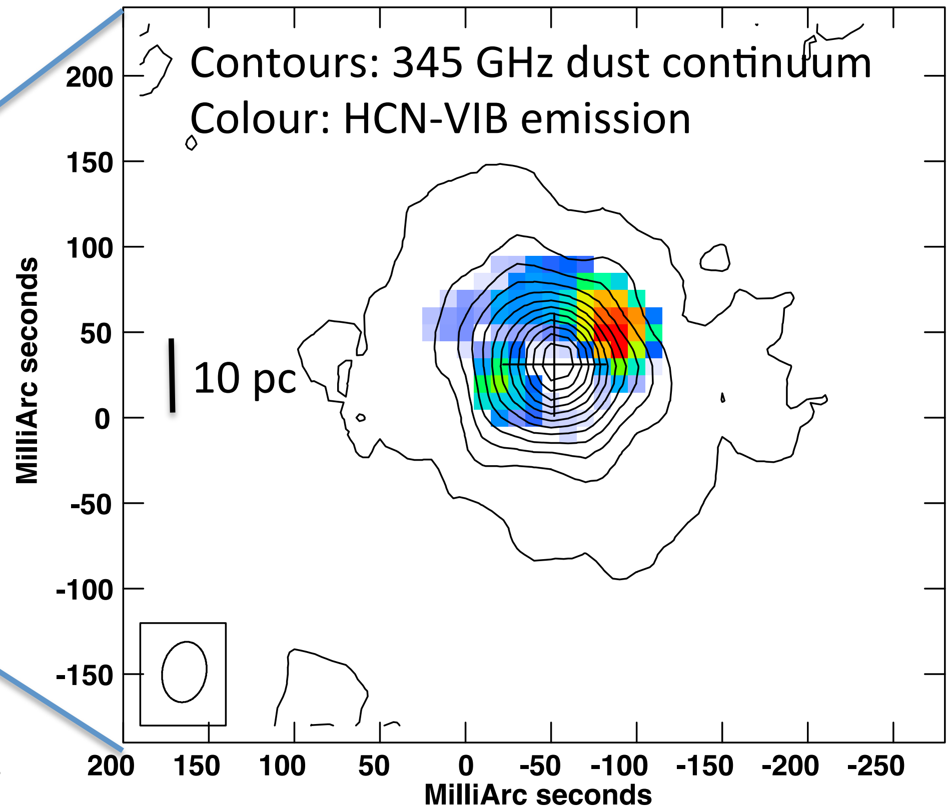
Dust SED can shift to longer wavelengths.



…and this model still underestimates the opacity at mm wavelengths.

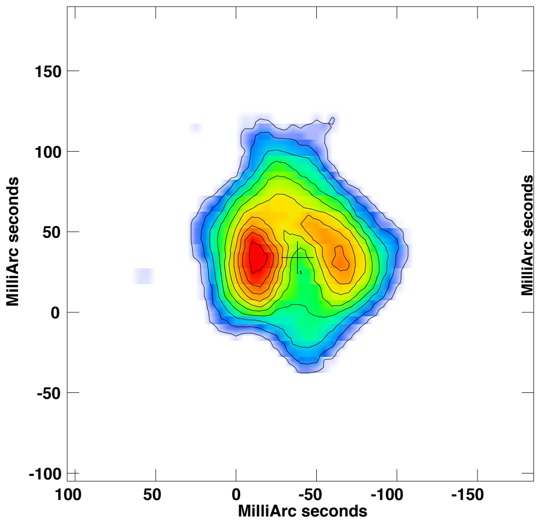
ALMA 345 GHz (850 μm) 30 milli-arsecond observations of IC860

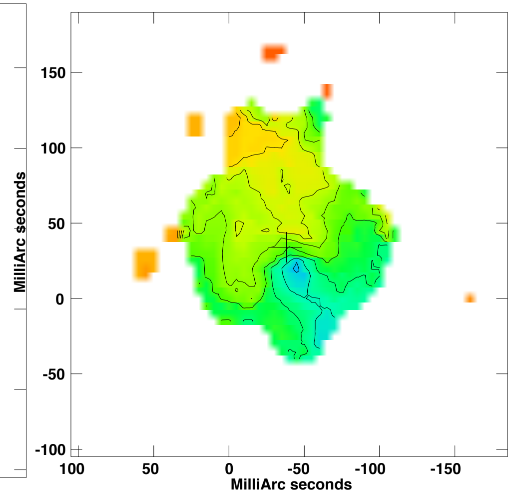




- Confirm ground state HCN, HCO+, CS lines continuum and self absorbed in Inner 50 pc.
- HCN-VIB tracing emission close to nucleus – but ”vanishing” in the inner 0.”03 (7 pc).
  - T_{ex}(HCN-VIB) – T_B(cont) + opacities?
- Nuclear column density N(H_2) >10^{25} cm^{-2} - ”brick wall”. Must go to even longer wavelengths to probe inside inner 7 pc.

Problem continues at λ=1-3 mm





HCN-VIB structure may be modelled as compact (10 pc) molecular outflow – perpendicular to nuclear rotation

Does the standard dust-to-gas ratio hold here?.

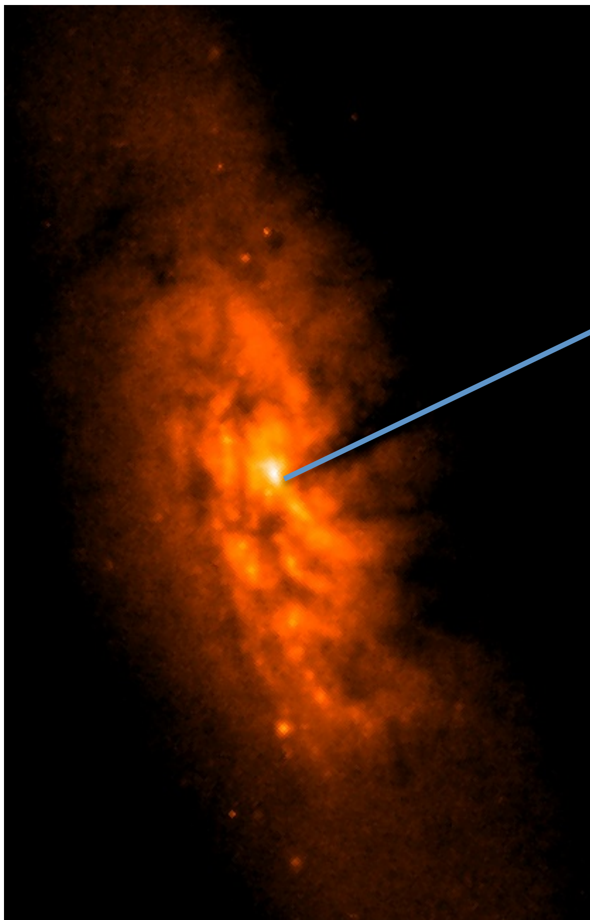
Use e.g. molecular isotopic ratios to search for evidence of recent nuclear processing – gas-to-dust ratio

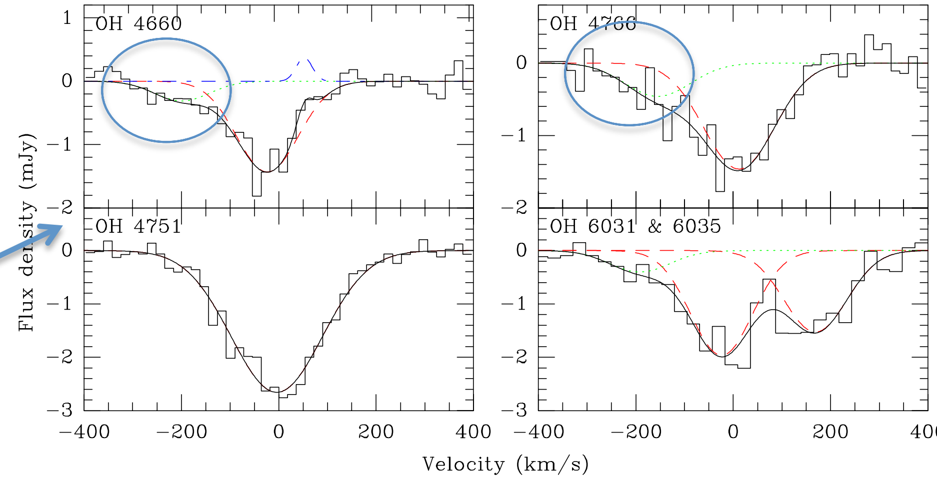
Most of λ=3mm emission is still dust (70 %). T_B=250-300 K from λ=6 mm to λ=0.8 mm.

HIDDEN DUSTY OUTFLOWS

Hidden outflow in the LIRG Zw049

(Falstad+17)



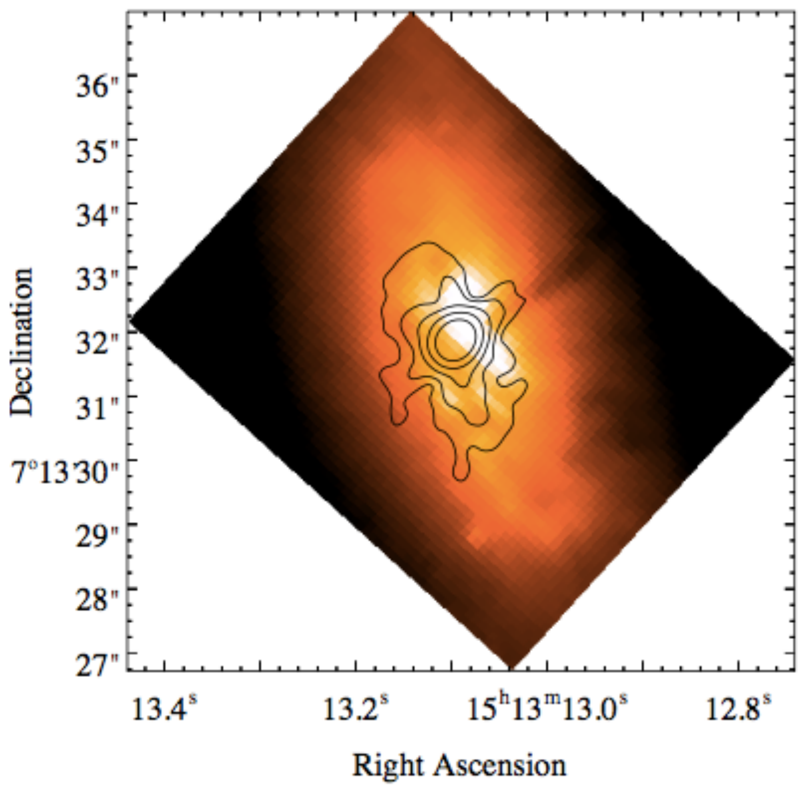


400 km/s OH (4-6 GHz) line wing seen with the VLA.
Very compact on radio continuum nucleus

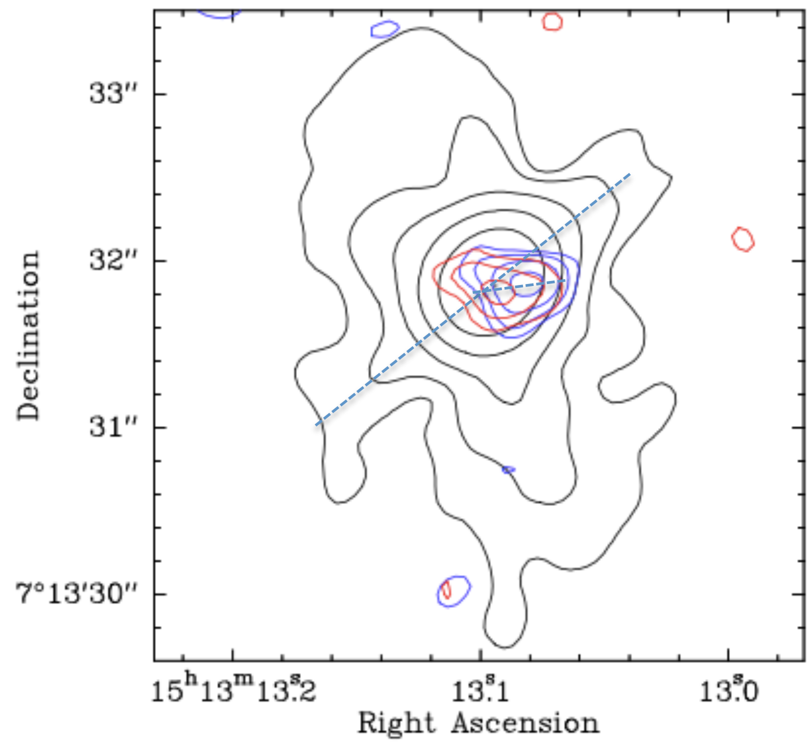
Outflow not seen with Herschel (Falstad+15,+17)
Hidden inside dust that is opaque in the FIR.

What role is the dust playing in the powering oftThe outflow – radiation pressure

Dusty winds – see also poster 49

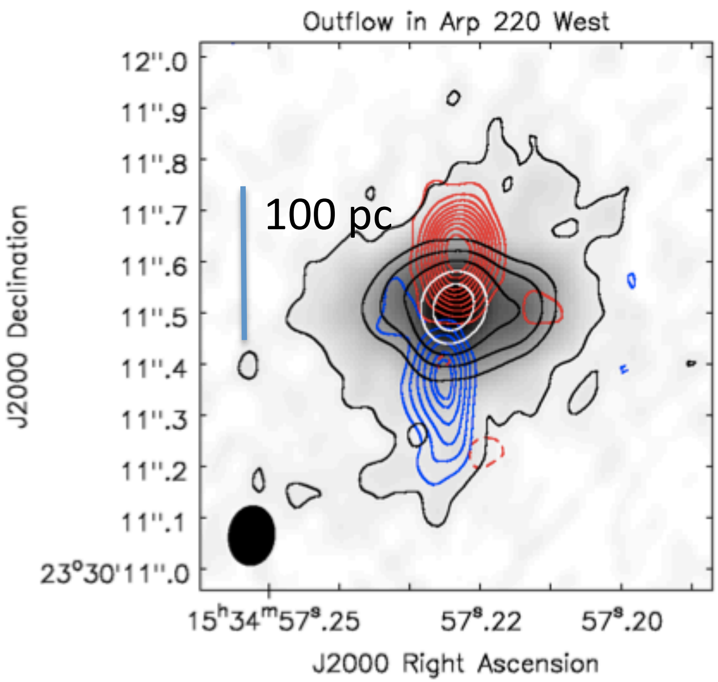


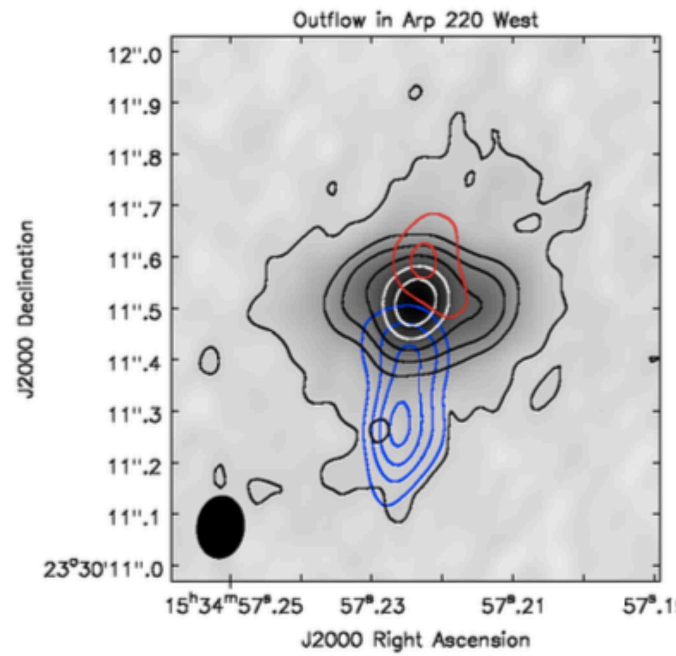
Weak radio continuum (5 GHz) associated with NIR dust ”jet”



CO 2-1, 6-5 tracing very dense nuclear outflow . ***The 690 GHz dust is tracing the nuclear ouflow.*** (ALMA+SMA)

An HCN-"jet" in Arp220 (Barcos-Munos+18)

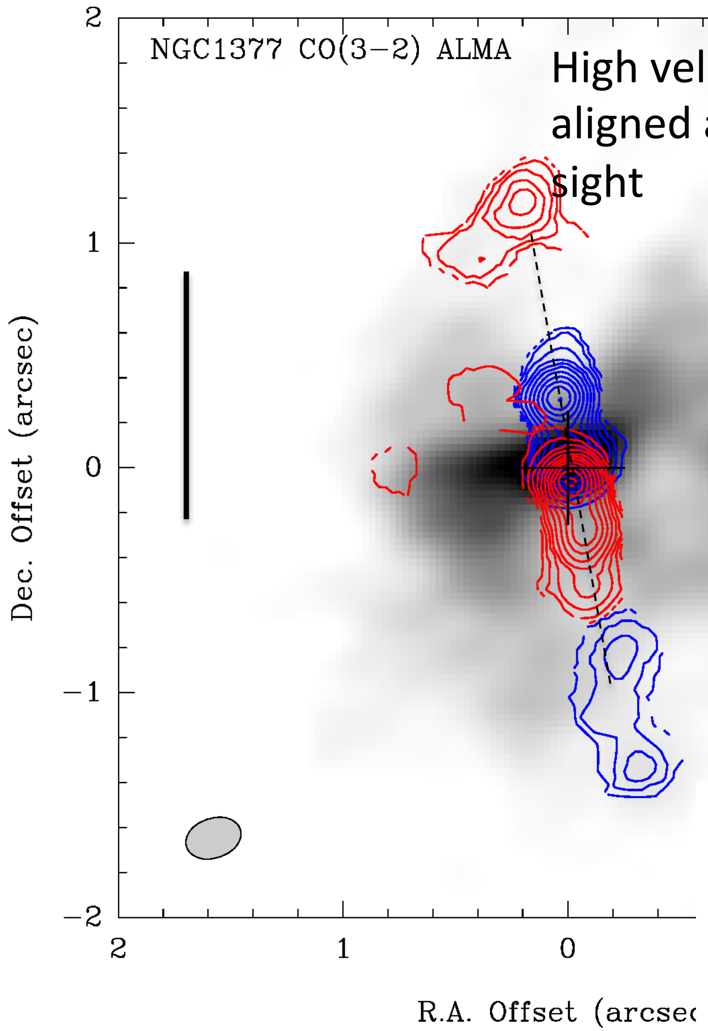




- ALMA reveals **extremely dense and fast (850 km/s) outflow** in iconic ULIRG Arp220. T_B(HCN) > T_B(CO)! (Barcos-Munos+17). (HCN detected in several fast AGN outflows (Aalto+12) – very dense gas and dust distributions.)

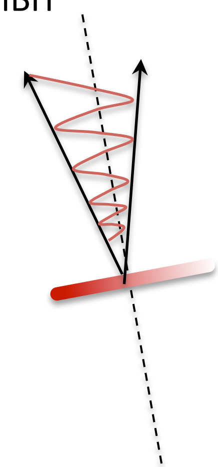
- 3mm dust emission – *very opaque dust in the cores T_D 500* K - dust also reaches out into outflow (Sakamoto+17). **Luminosity density $10^{15.5}$ L_{sun} kpc $^{-2}$ on a scale of 20 pc. More than twice higher than any observation of dust brightness temperature in Arp220 (e.g. Downes and Eckart 07, Wilson+14, Scoville+17)**

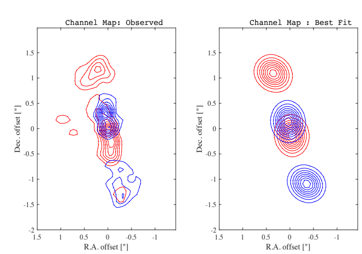
ALMA reveals a radio-quiet, precessing molecular jet?



High velocity gas aligned along line-of-sight

A molecular "jet" rotating around an axis perpendicular to the line of sight may reproduce observations. May signal obscured, accreting SMBH





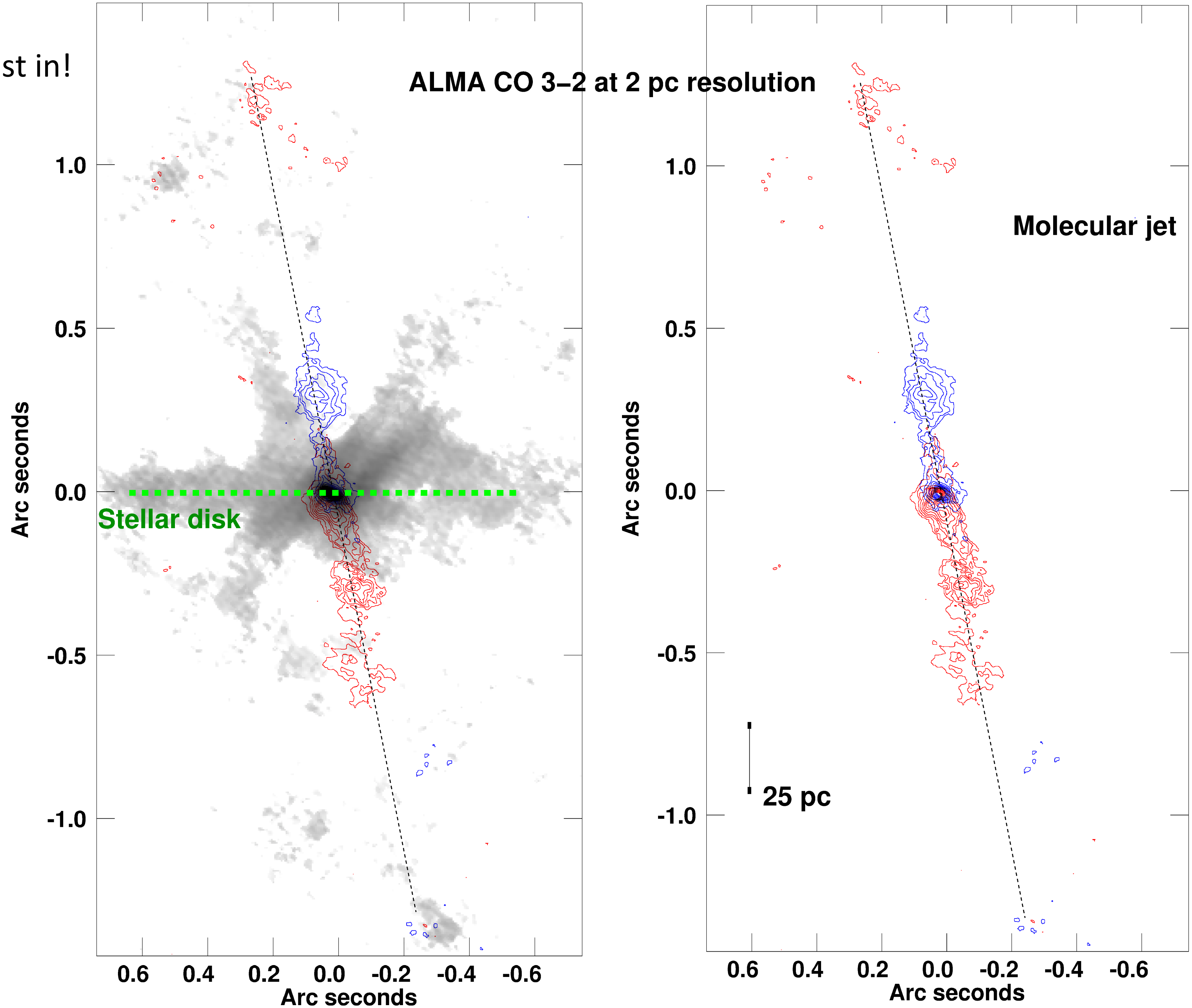
Precessing molecular jet signals accreting SMBH?

Early stages of feedback?

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

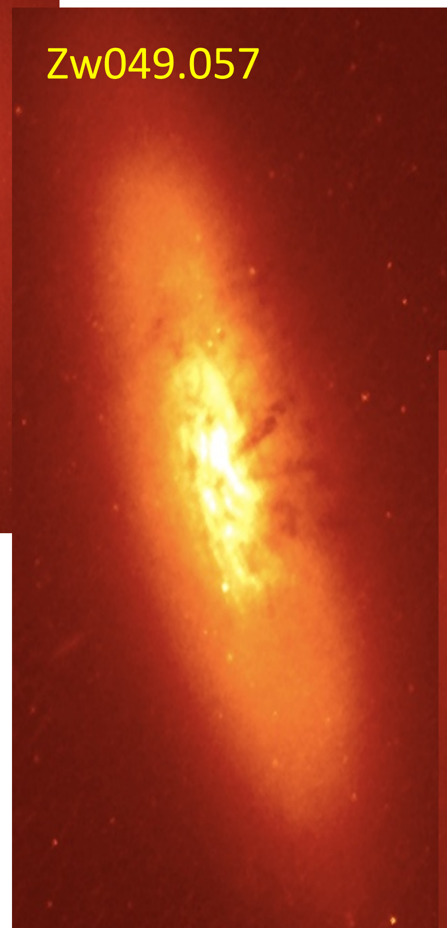
Just in!

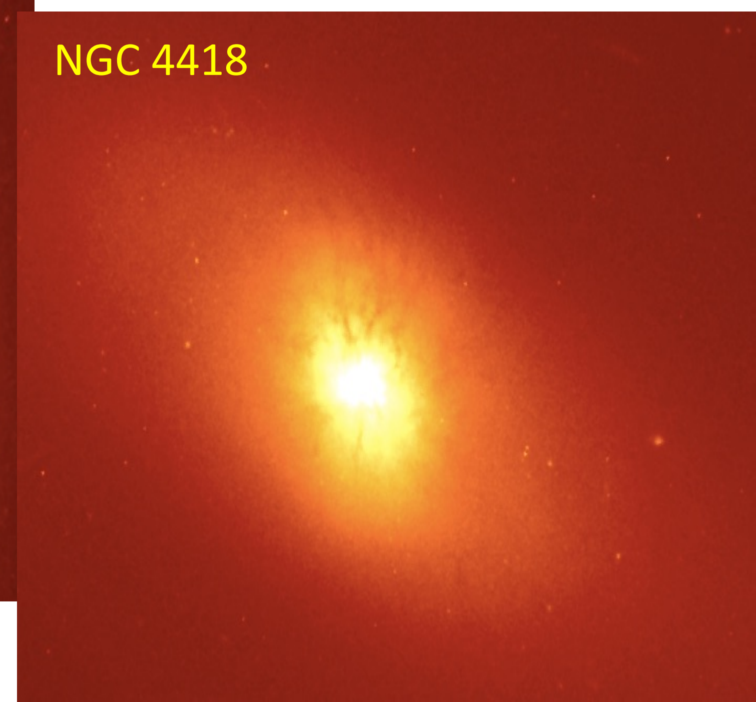
ALMA CO 3–2 at 2 pc resolution



OUTFLOW SHADOWS

Highly Obscured Nuclei: Dusty S0/a Galaxies: HST “V-band” Images

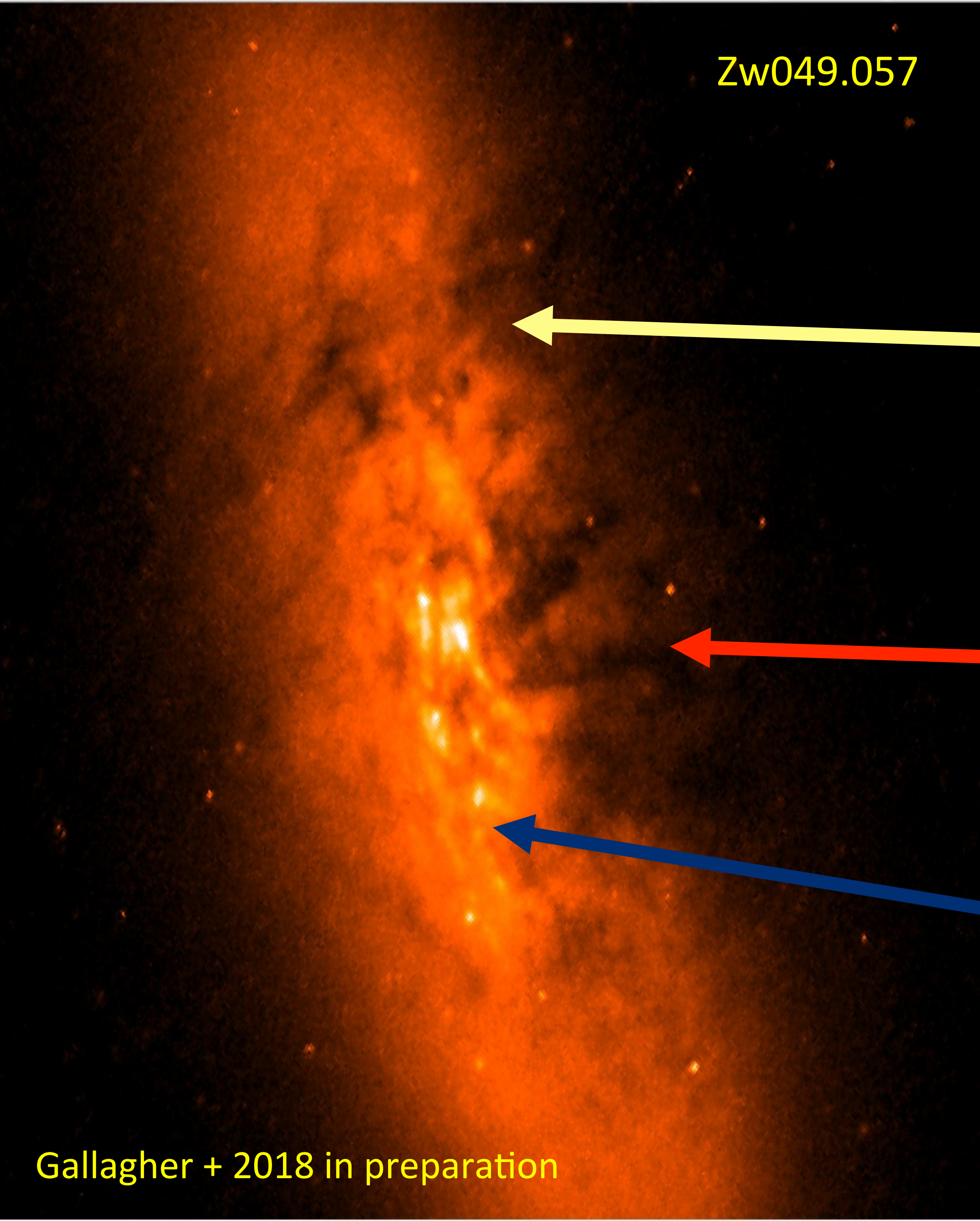




Dusty inner disks + dusty “galactic geyser” bipolar structures on kpc scales
More extended than nuclear dusty outflows

HST GO-1 J. Gallagher, S. Aalto et al

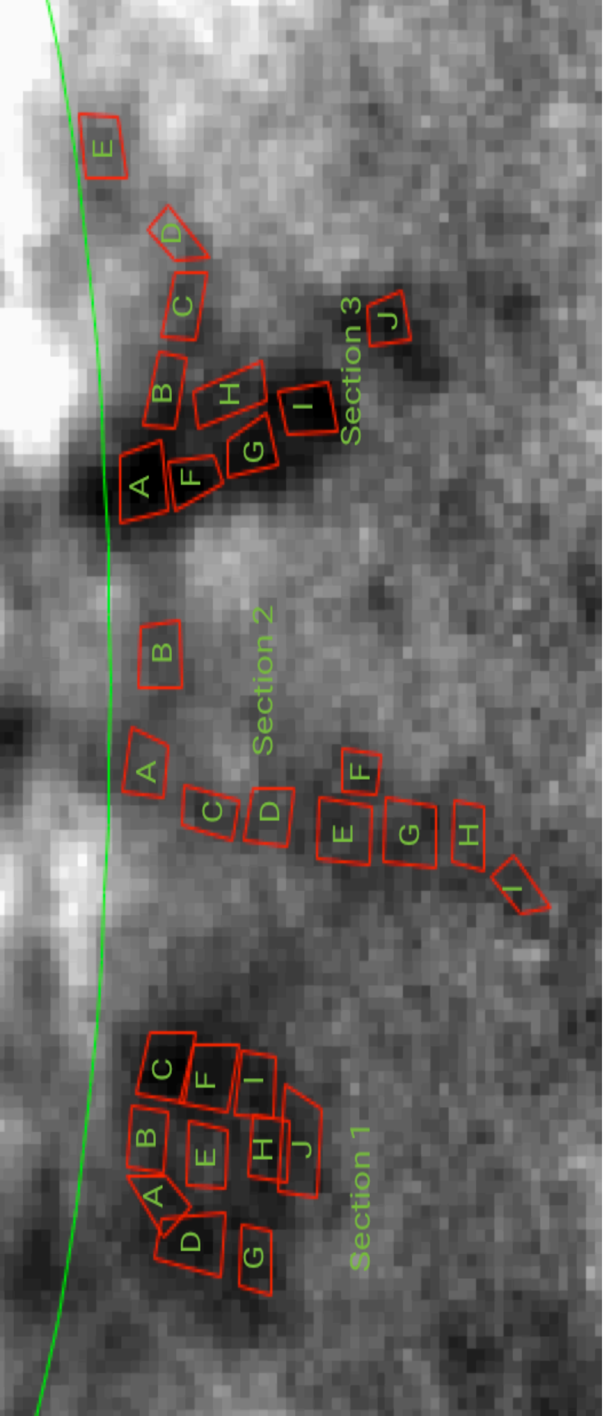
Dust Features: Evolutionary Sign Posts



Polar dust structure → past interaction

Cone/pillar structures from center—slow outflow galactic geysers?

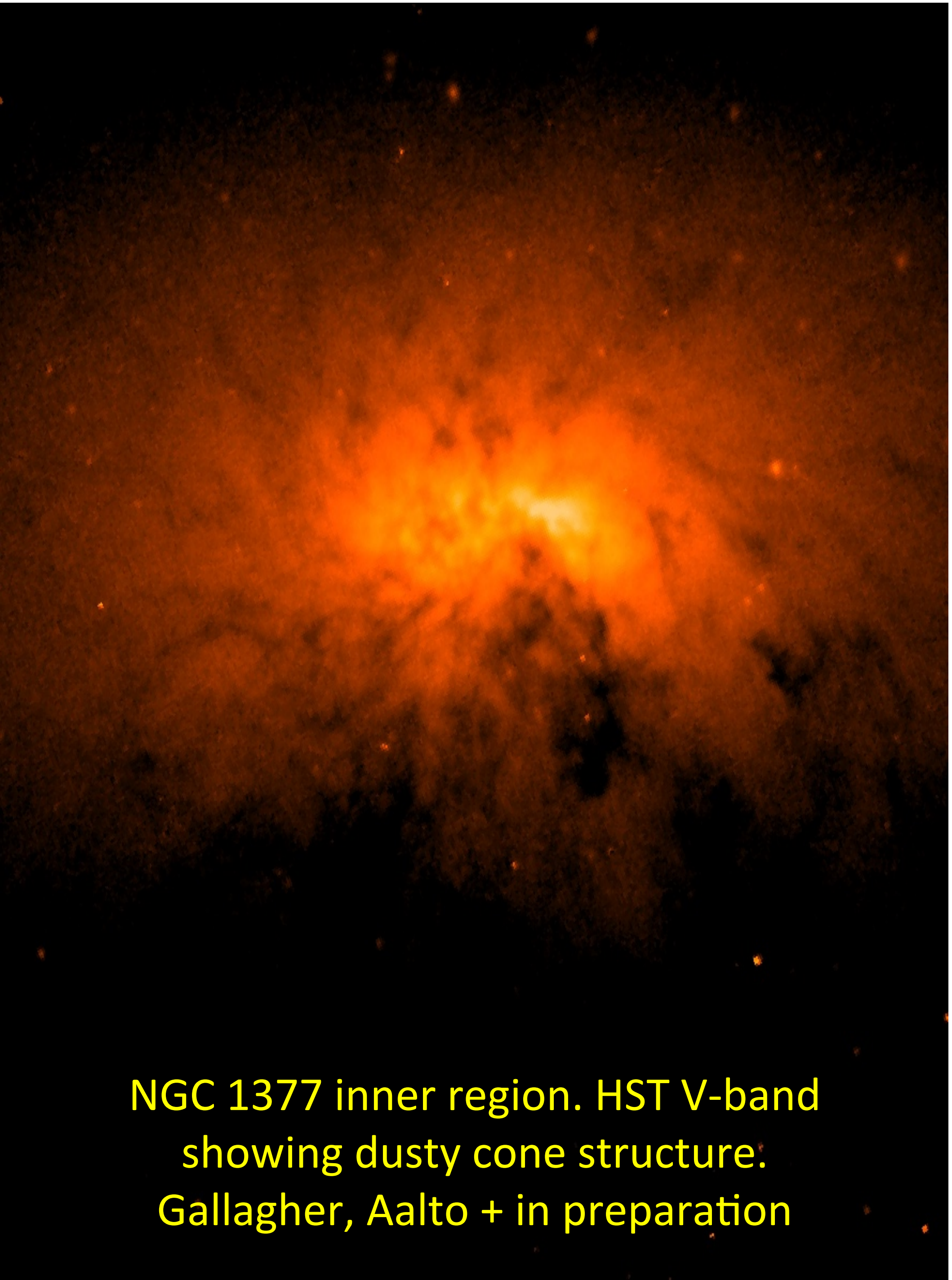
Dusty central disk with embedded star formation



Zw049.057 Dust Opacity Measurements—Estimates of gas content of outer structures

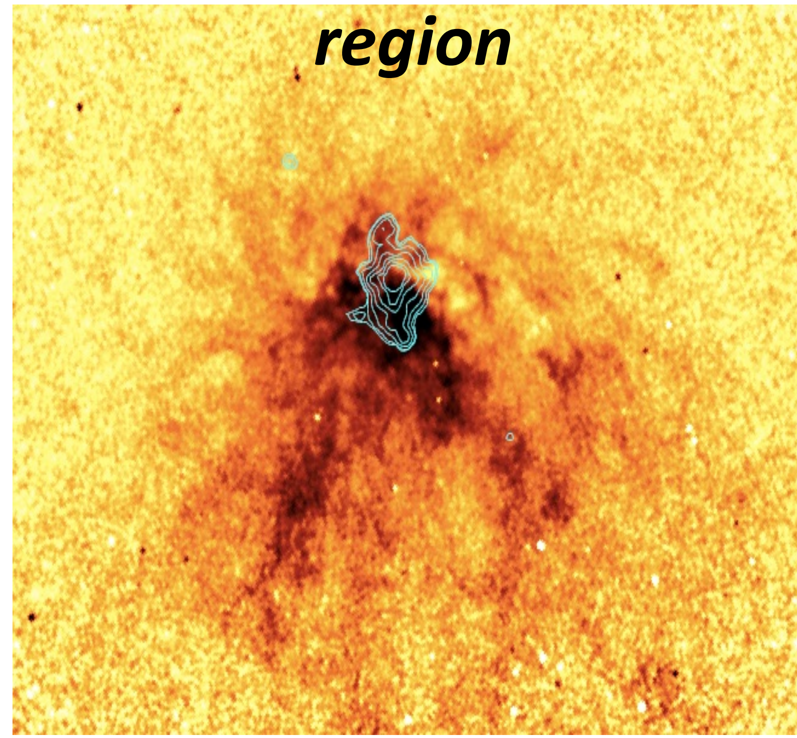
- ❖ Optical depth proportional to column N_H
- ❖ Derive τ_V from contrast in HST V, I, J bands, convert to N_H assuming Galactic gas/dust ratio. Lower bound—optically thick substructure, cloud locations.
- ❖ Average densities $n \gtrsim$ 15-20 cm^{-3}, L~50 pc
- ❖ ISM masses $M_{gas} \gtrsim 10^5 M_\odot$ per region.

Lauren Laufman—undergraduate project, U. Wisconsin
Gallagher et al. 2018, in preparation



NGC 1377 inner region. HST V-band showing dusty cone structure. Gallagher, Aalto + in preparation

NGC 1377: High density molecular gas concentrated in nuclear region



NGC 1377 V/I color map with CO 3-2 contours to show scale. Approximate absolute positioning.

Conclusions

- Mid-IR studies of
  - dust continuum, PAHs, silicate absorption, ices, AGN dust heating
- Dust peaks in the FIR
  - dust SEDs, star formation laws, dust properties and dust-to-gas ratios. Molecules as probes.
- Submm/mm continuum and lines
  - distribution of extended cold dust (dust mass and properties) and nuclear dust at high resolution. Molecules as proxies for grain processing, enrichment, buried energy density.
- The CONs: Some U/LIRGs have extremely dust enshrouded nuclei with A_v> 1000. Can be probed at long wavelengths − extreme luminosity densities.
  - Nature of buried activity? Dust properties?
  - Issues with dust opacity effects down to mm wavelengths.
- Dusty, collimated outflows − a new early phase of feedback? How are they linked to large scale bipolar outflows?
  - Role of dust in driving?

From First Stars to Life: Science with the Origins Space Telescope (OST)

- Oxford September 4-7 2018
- https://www.ost-meeting.com/