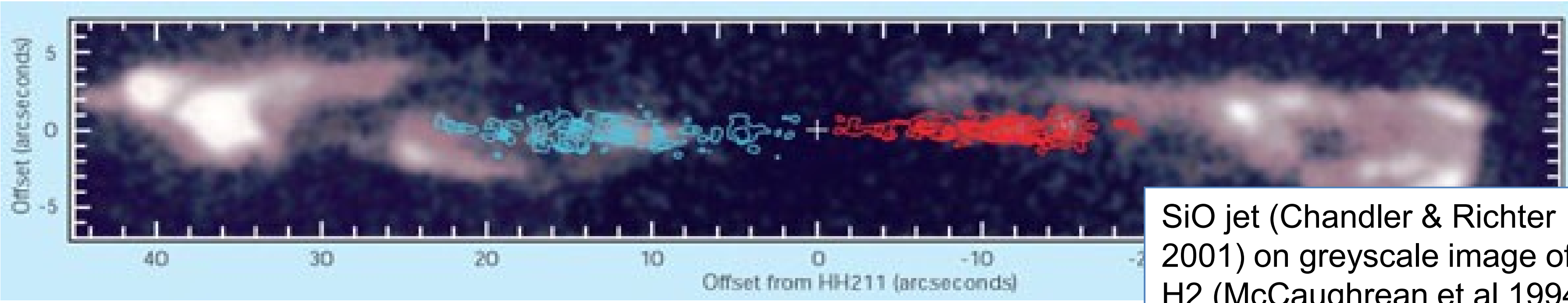
Outflows in regions of massive star formation

Suzanne Ramsay (ESO), Watson Varricatt (UKIRT), Chris Davis (NSF)

How do massive stars form?

- Do high mass stars (>8Msolar) form in the same way as low mass stars?
- Formation mechanisms for massive stars
  - Via gravitational collapse and disk accretion as for low mass stars?
  - Via competitive accretion? (e.g. Bonell et al. 2005, Bate et al. 2005)
- Problems with disk accretion mechanism
  - For M>~ 10Msolar, Kelvin Helmholtz timescale exceeds the free fall timescale (t_{KH}~10^4 years for an O star)
  - Contraction proceeds faster than accretion and hydrogen burning begins while the protostar is still embedded in the cloud
  - Radiation pressure prevents further accretion of mass (but see e.g. Krumholz et al. 2009, Kuiper et al. 2010,2011, Zinnecker & Yorke 2007 review)

Surveying for outflows



SiO jet (Chandler & Richter 2001) on greyscale image of H2 (McCaughrean et al 1994)

- Sample of 50 HMYSOs selected
  - NH_3 (1,1) and (2,2) emission (Molinari et al. 1996), H_20 and CH_3OH maser emission (Sridharan et al. 2002), High velocity CO (Shepherd & Churchwell 1996, Beuther 2002)
- Imaging survey searching for outflows around HMYSO candiates with the UKIRT-UFTI
  - Filters: K, 1-0 S(1) H2 at 2.122μm, also HI Br γ
  - 2.2’x2.2’ images, 5σ limit: K=19, 1.3×10^{-18} $wm^{-2}arcsec^{-2}$

Results

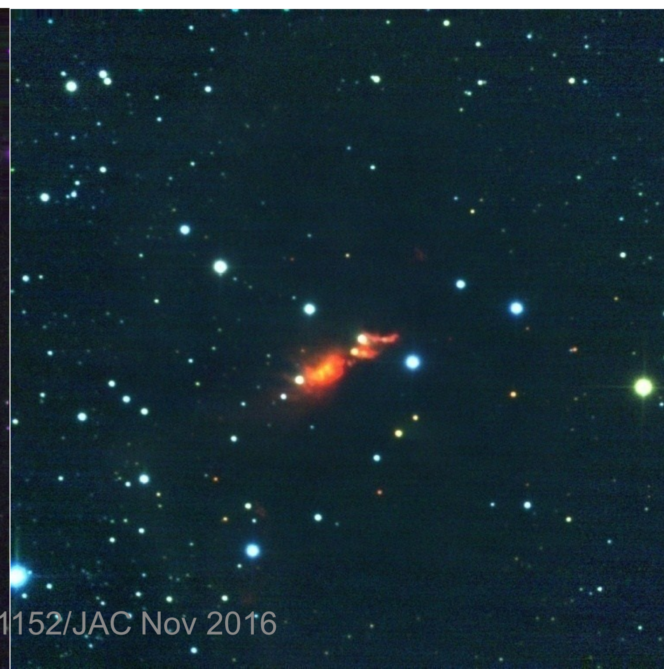
- New detections of embedded young stellar clusters
- 76% of sources have H_2 emission
- Br γ not detected in any of the sources

IRAS 20062+3550

d=4.9kpc, L=3.2x$10^3 L_o$

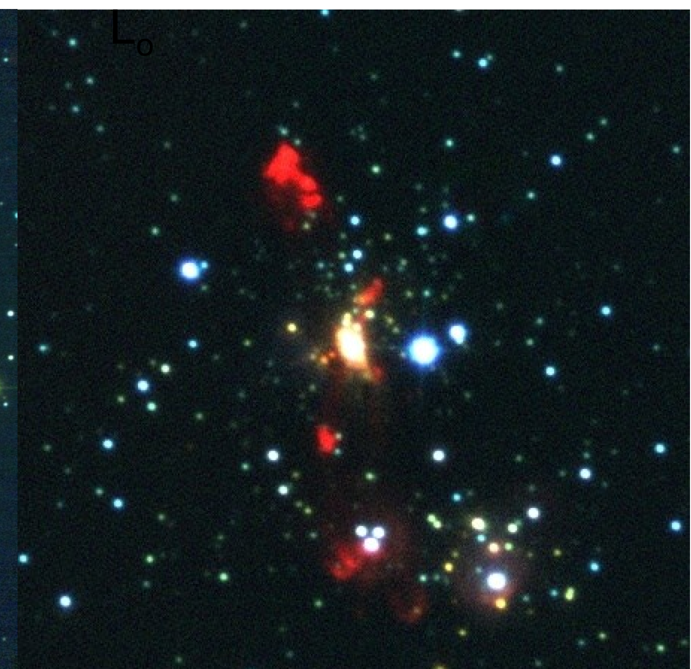
IRAS 20162+4104

d=1.7kpc, L=10.0x10^3 L_o



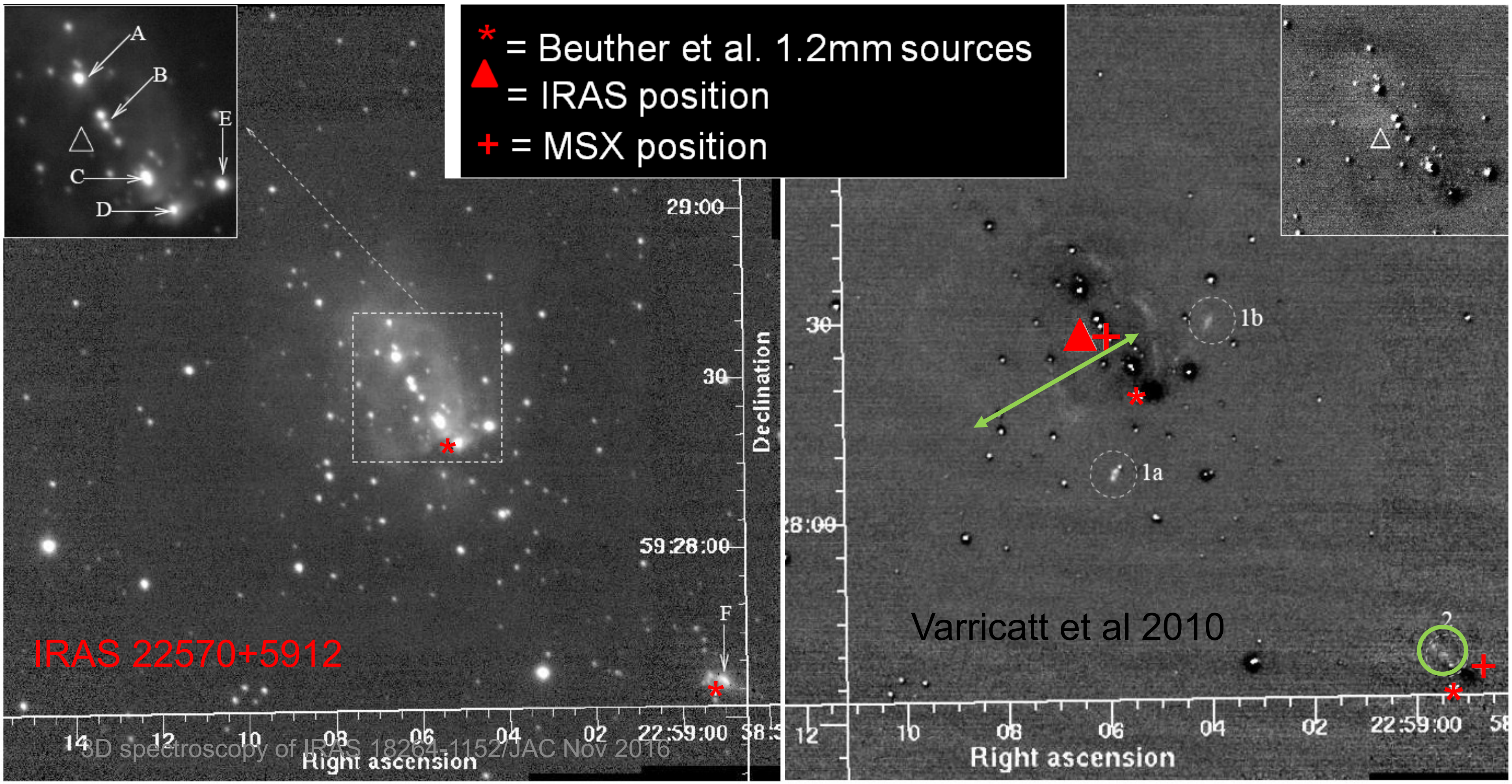
IRAS 05137+3919

d=11.5kpc, L=225.0x10^3 L_o



Results

- 2MASS and IRAS colours used to identified YSOs that may be the driving sources of the outflows



Results on outflows

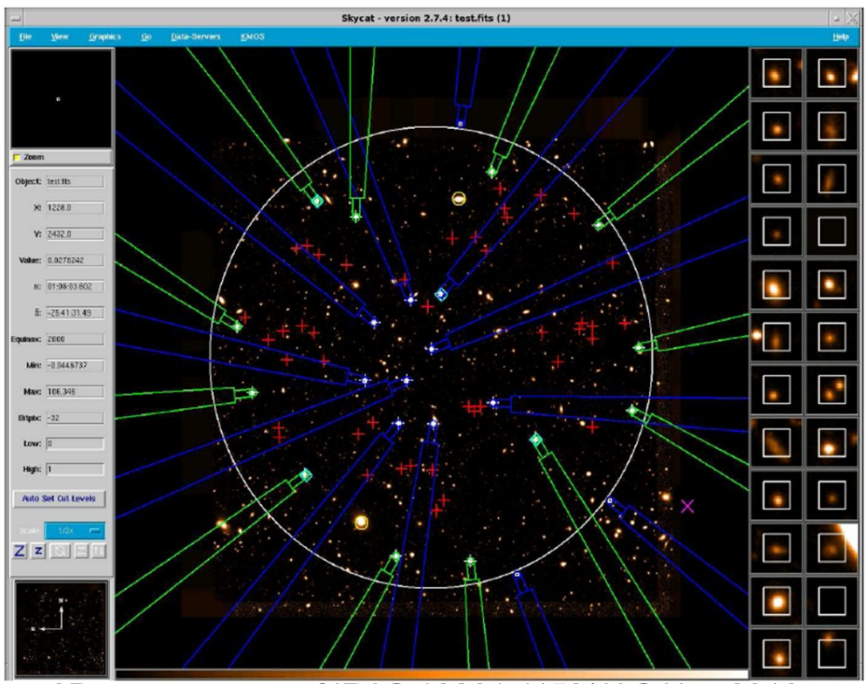
- 76% of sources have H_2 emission; 50% aligned
  - collimation factor: max=19; min=2; typically 4-8
  - factors typical of low mass YSOs
- Where CO data exist, outflow origin and direction agree
- Aligned knots of H_2 due to shock excitation in jets
  - Caratti o Garatti et al. 2008, Davis et al. 2004, Todd & Ramsay Howat 2006
- Objects from early B to late O spectral type form collimated outflows. Accretion happens in the pre-UCHII phase
- Survey supports disk accretion as the main mechanism for formation

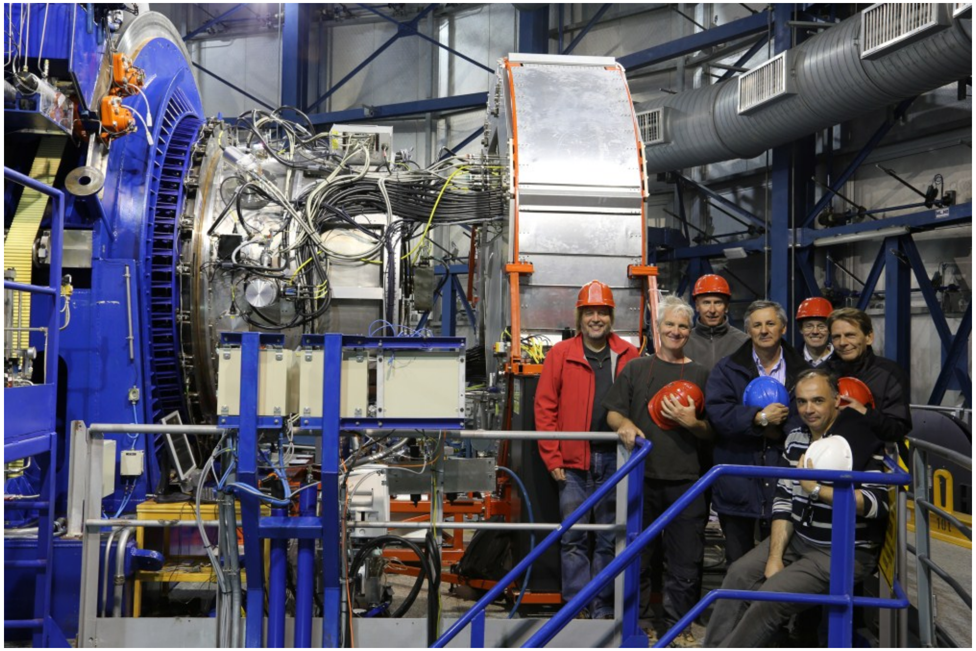
Open questions/next steps

- Improve association of NIR sources with the outflows and sources at other wavelengths
- Determine outflow characteristics
  - Mass flow rates; Opening angles; Kinematics; Excitation conditions
- K band spectroscopy offers the possibility to determine these at high spatial and spectral resolution (Caratti o Garatti et al. 2008, Davis et al. 2004, Caratti o Garatti et al. 2015)
- ‘Wide’ field IFU spectroscopy with KMOS has the potential to survey and characterize simultaneously

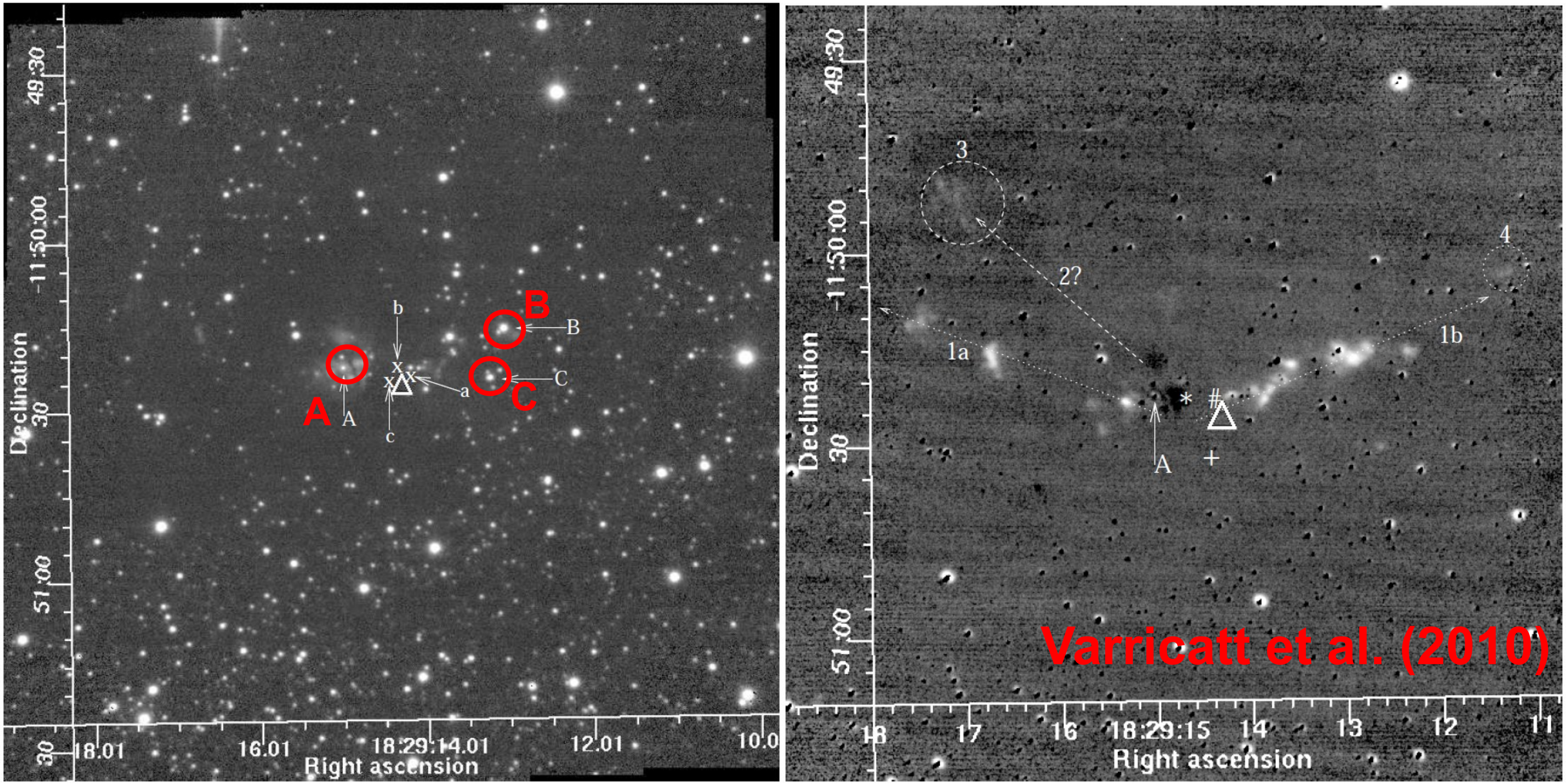
KMOS on VLT

- Near infrared 0.8-2.5um
- 24 fields of 2.8 x 2.8 arcsecs, 0.2 arcsec per spaxel
- Our observations: mosaic mode, K band grating with R~4000 (75km/s), 70 000 spectra over ~1'sq



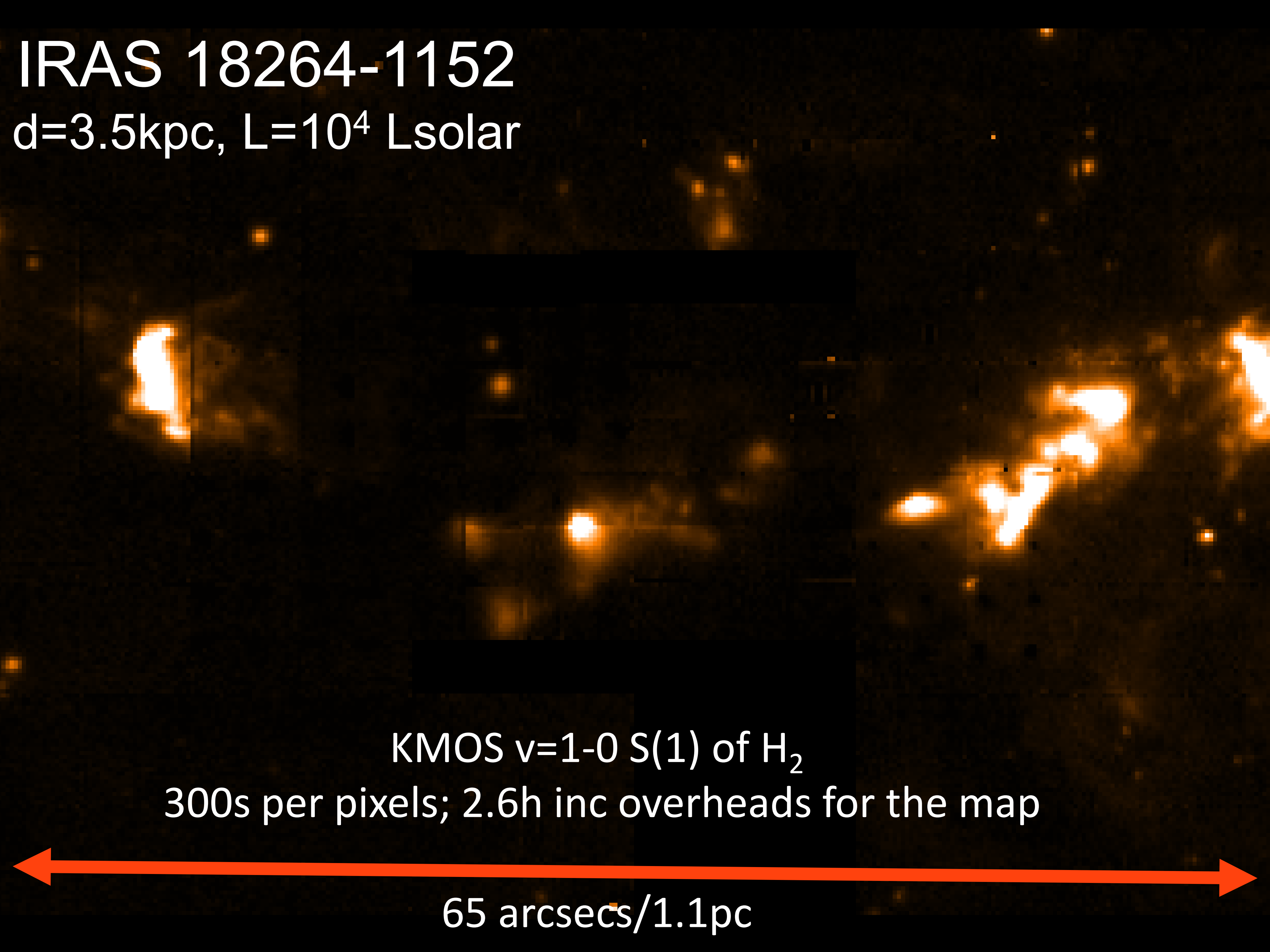


Introducing IRAS 18264-1152



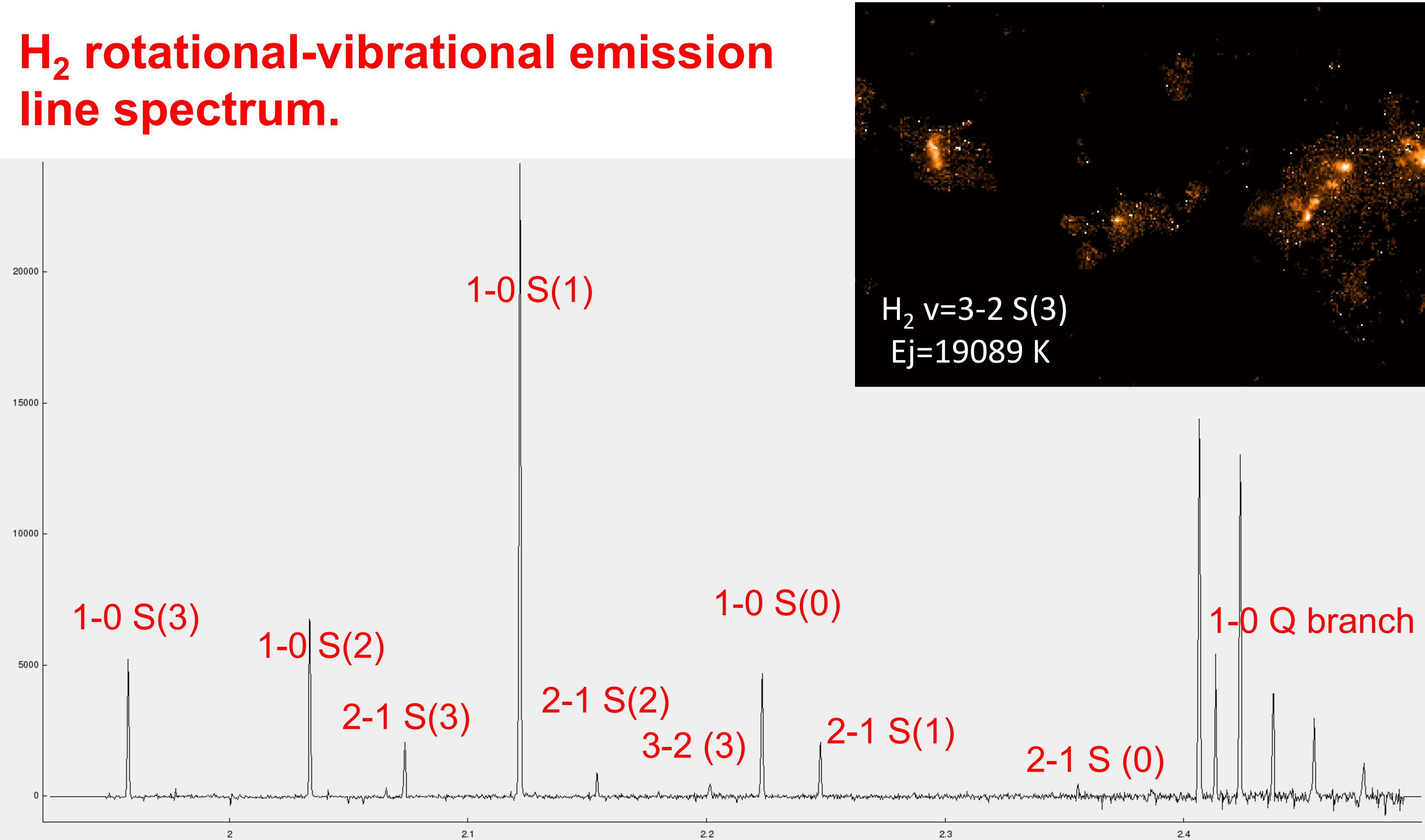
d=3.5kpc, L=10^4 Lsolar, outflow length~45arcsecs/0.75parsec

IRAS position=open triangle; 1.3cm sources='x', 7mm source='#;,1.2mm-source ='*'

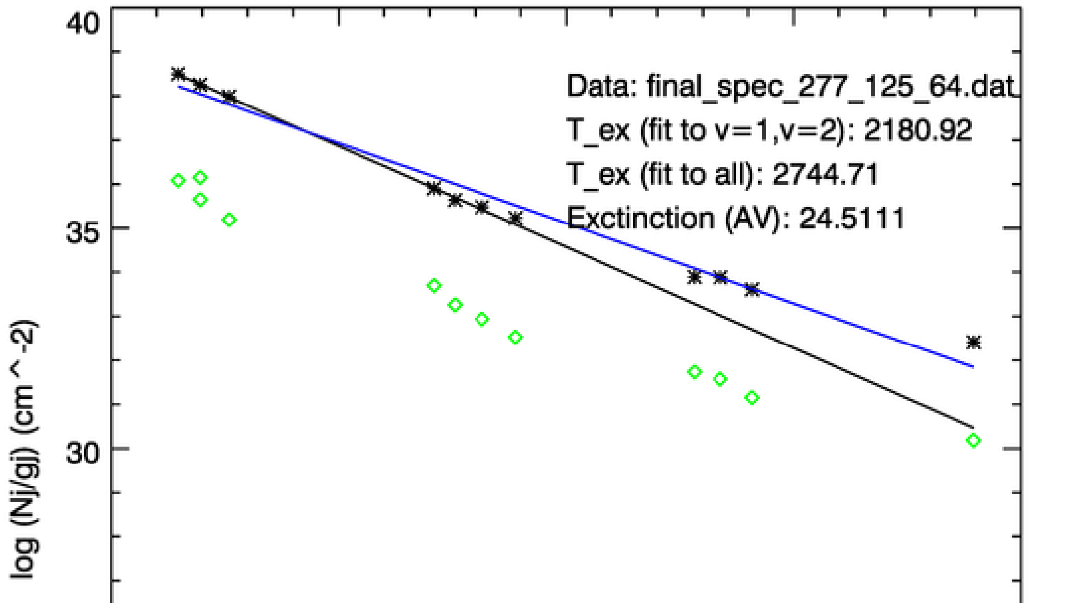

IRAS 18264-1152
d=3.5kpc, L=10^4 Lsolar
KMOS v=1-0 S(1) of H2
300s per pixels; 2.6h inc overheads for the map
65 arcsecs/1.1pc

Properties of the outflowing gas

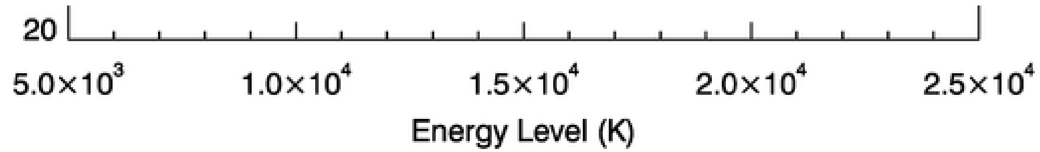
H_2 rotational-vibrational emission line spectrum.



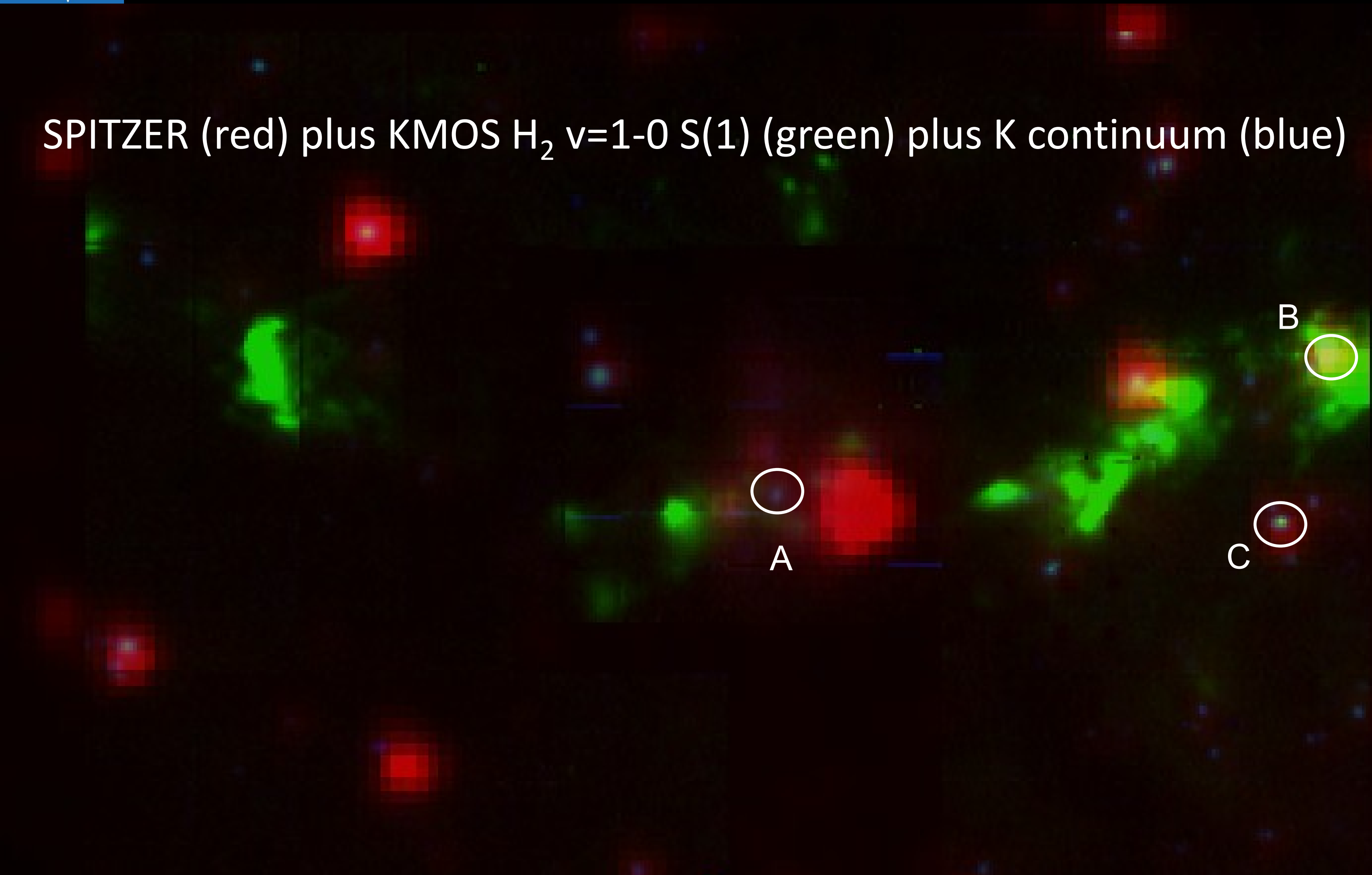
H_2 Excitation Mechanism



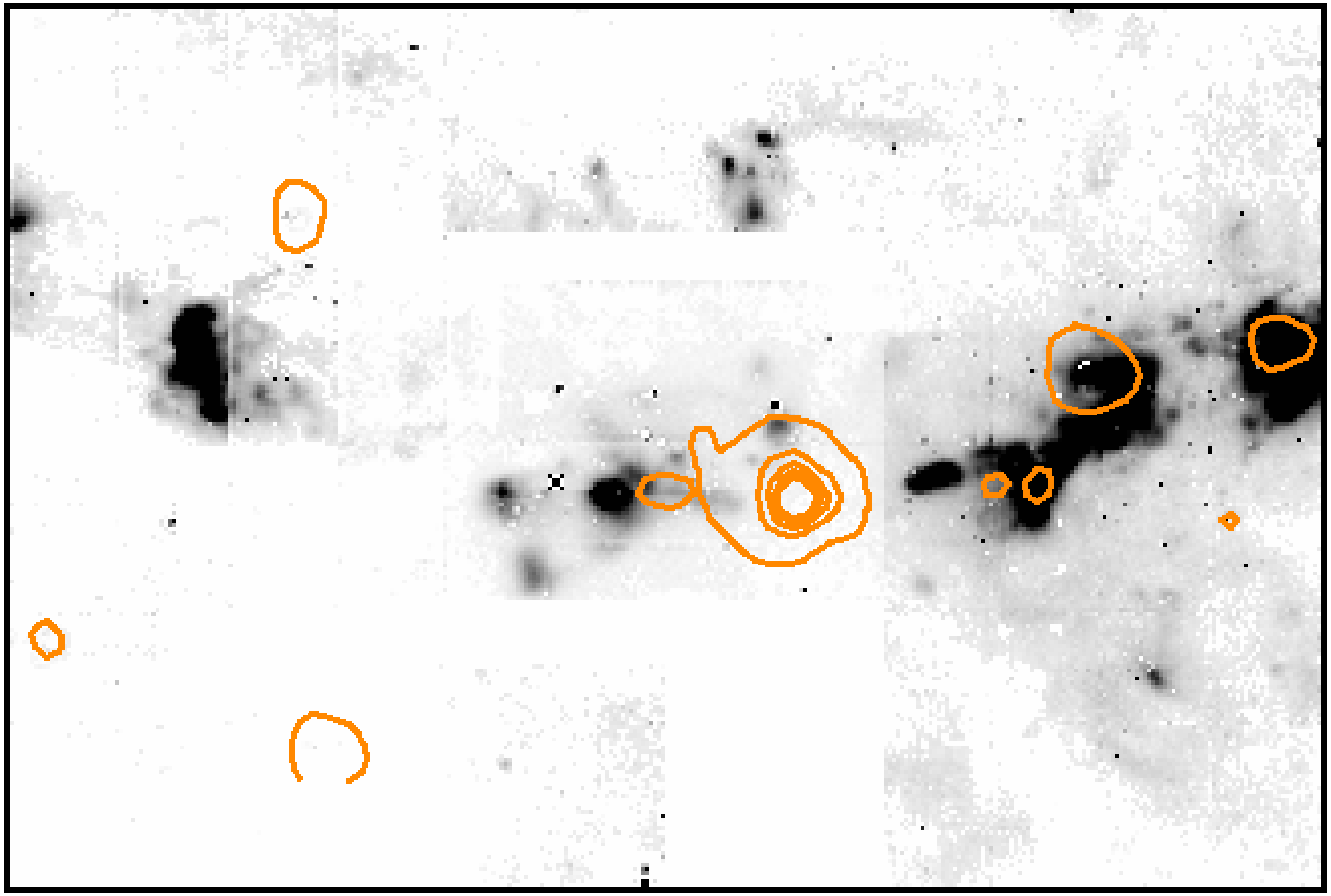
Boltzmann diagram of log (H2 column density) vs energy level.
Fully thermalized, shock excited gas has a single characteristic temperature.
Deviations indicate non-LTE distribution e.g. UV excited, fluorescent emission.
Detected emission is characterized by temperatures in the range 2000-2500K.



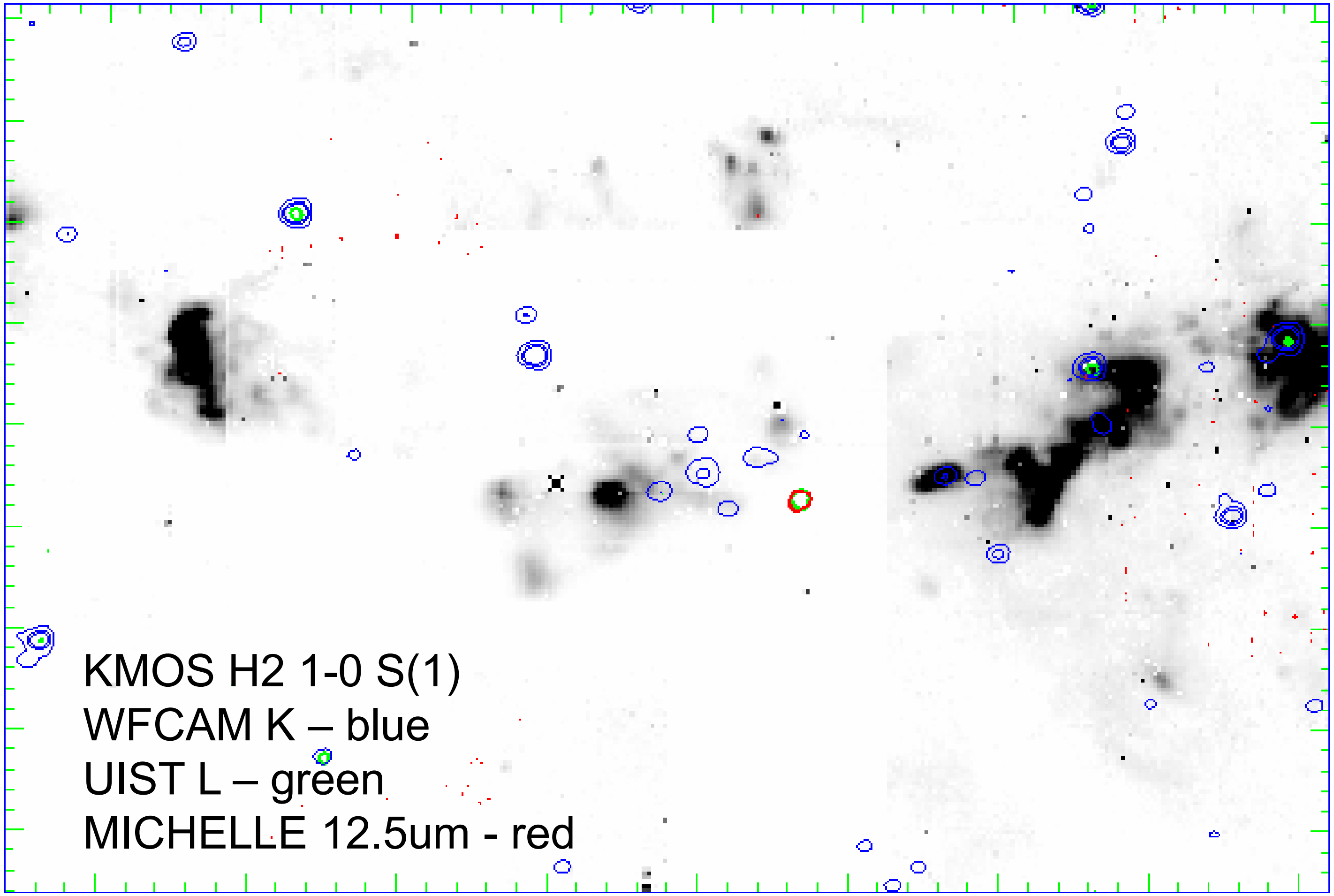
Counterpart of the HMYSO?



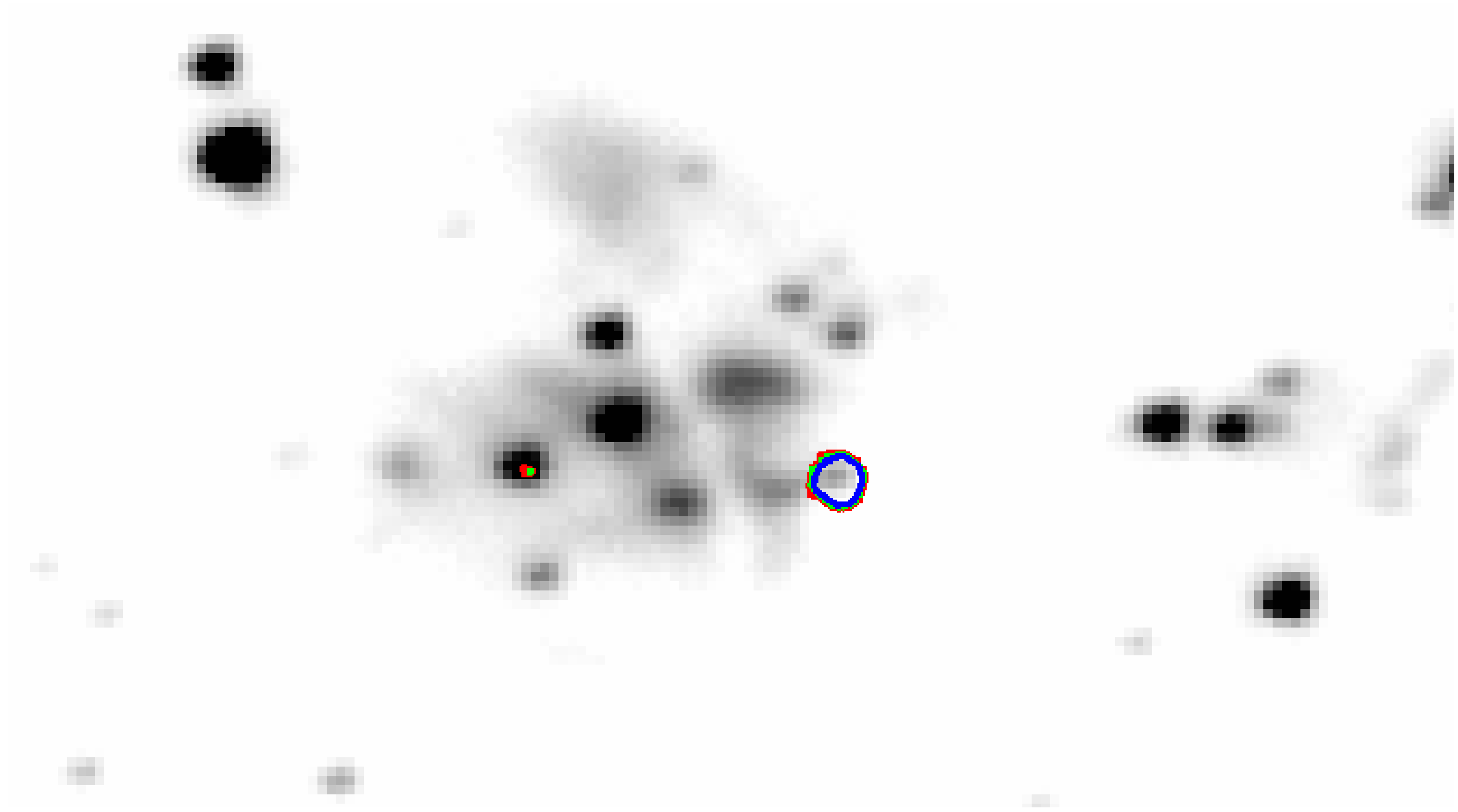
KMOS H_2/SPITZER IRAC-2

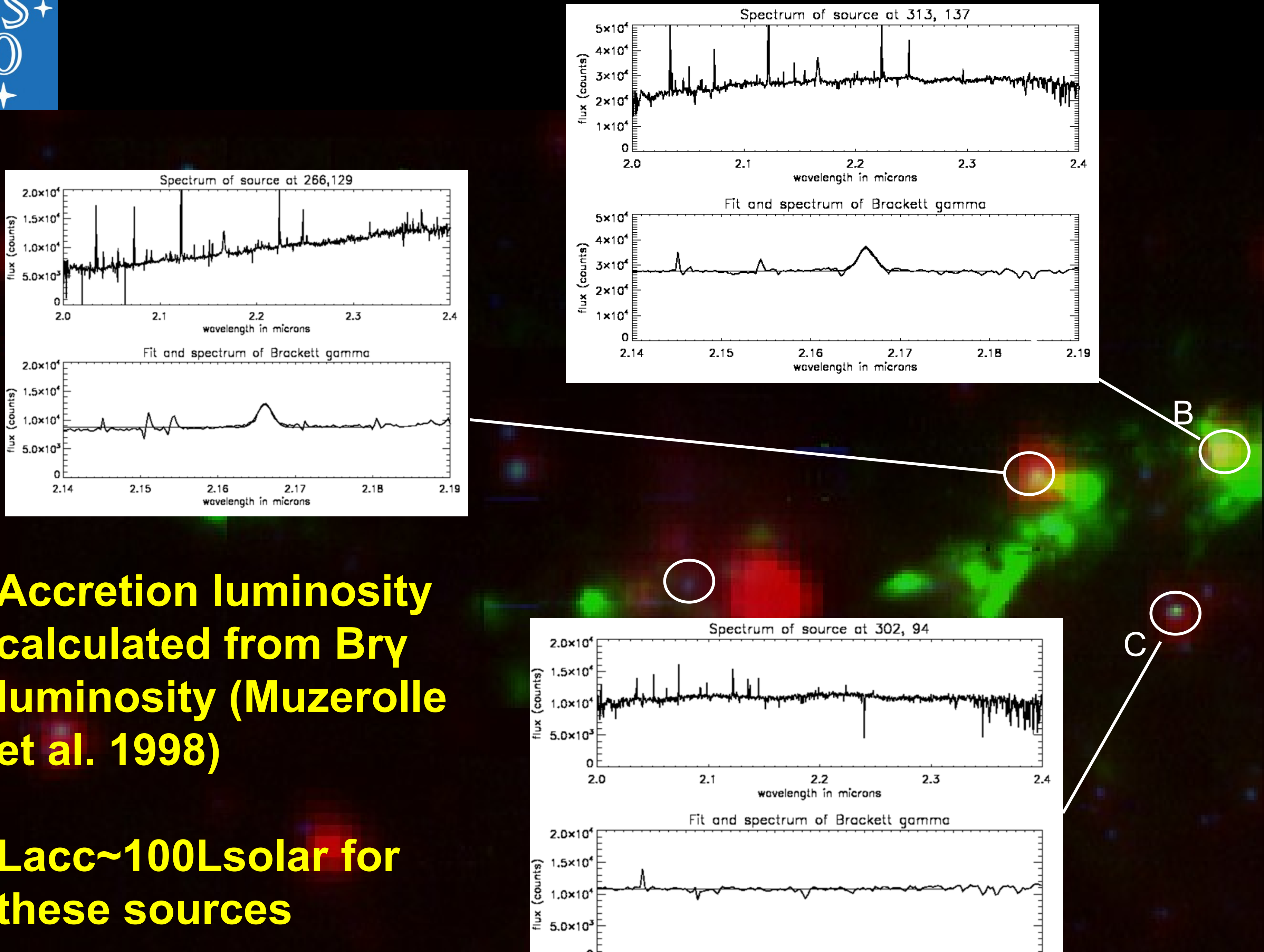


Counter part of the HMYSO?



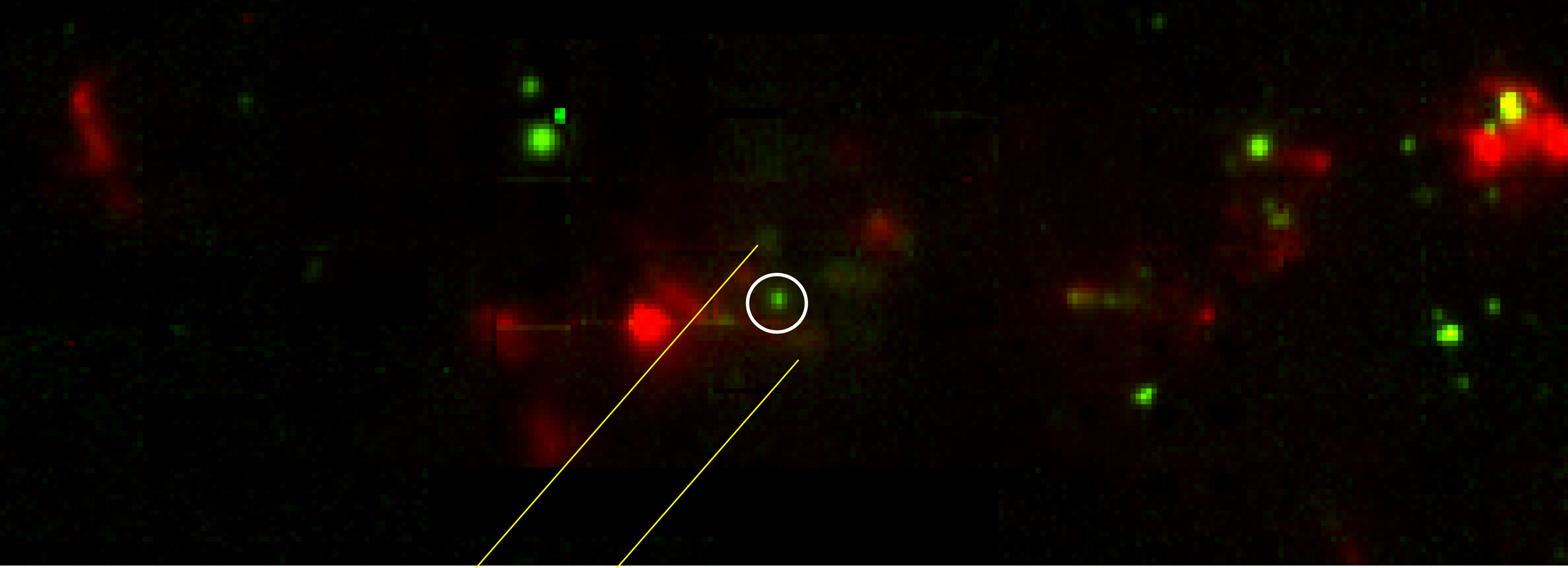
WFCAM K band/UIST L band

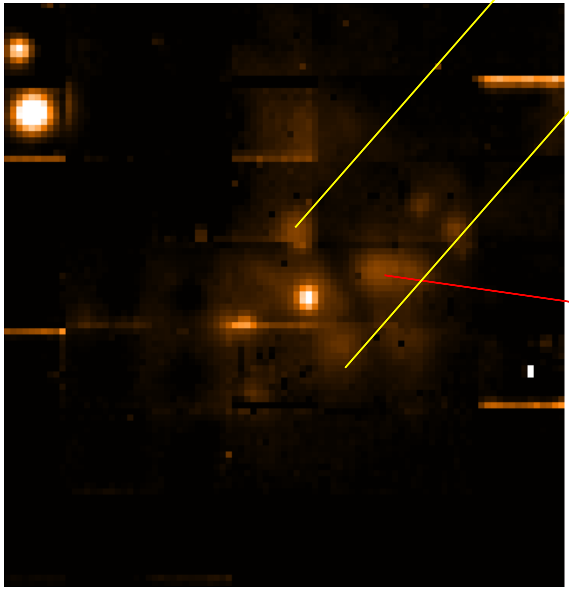




Accretion luminosity calculated from Brγ luminosity (Muzerolle et al. 1998)

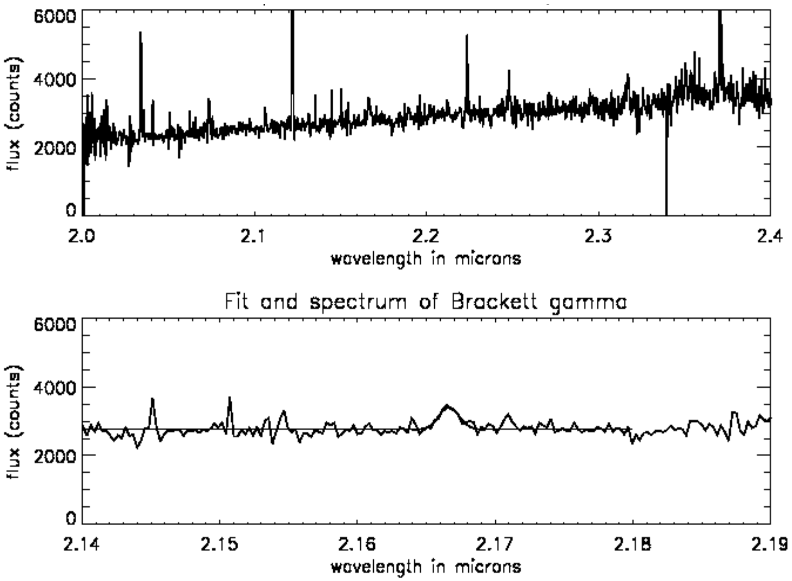
Lacc~100Lsolar for these sources

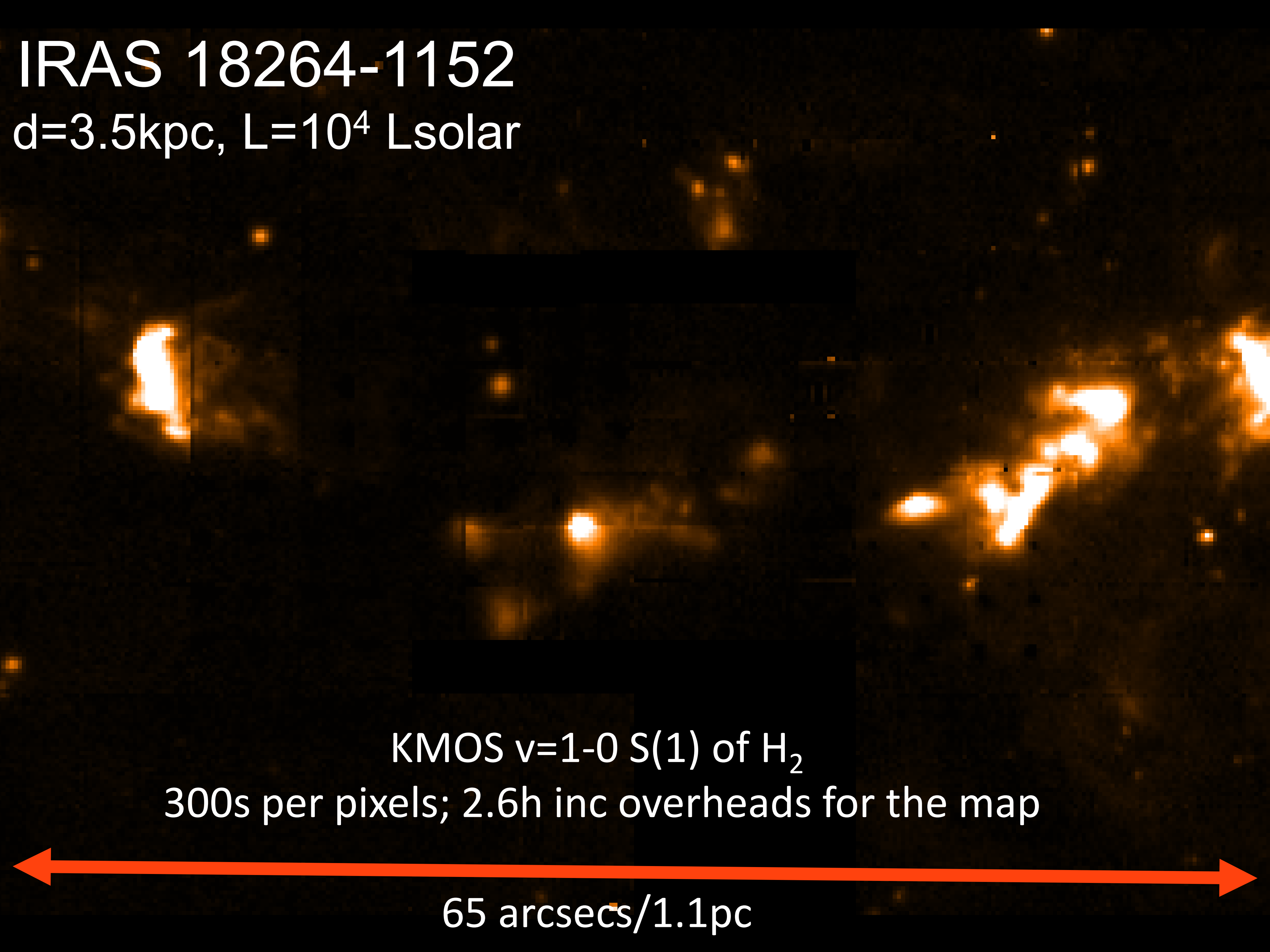




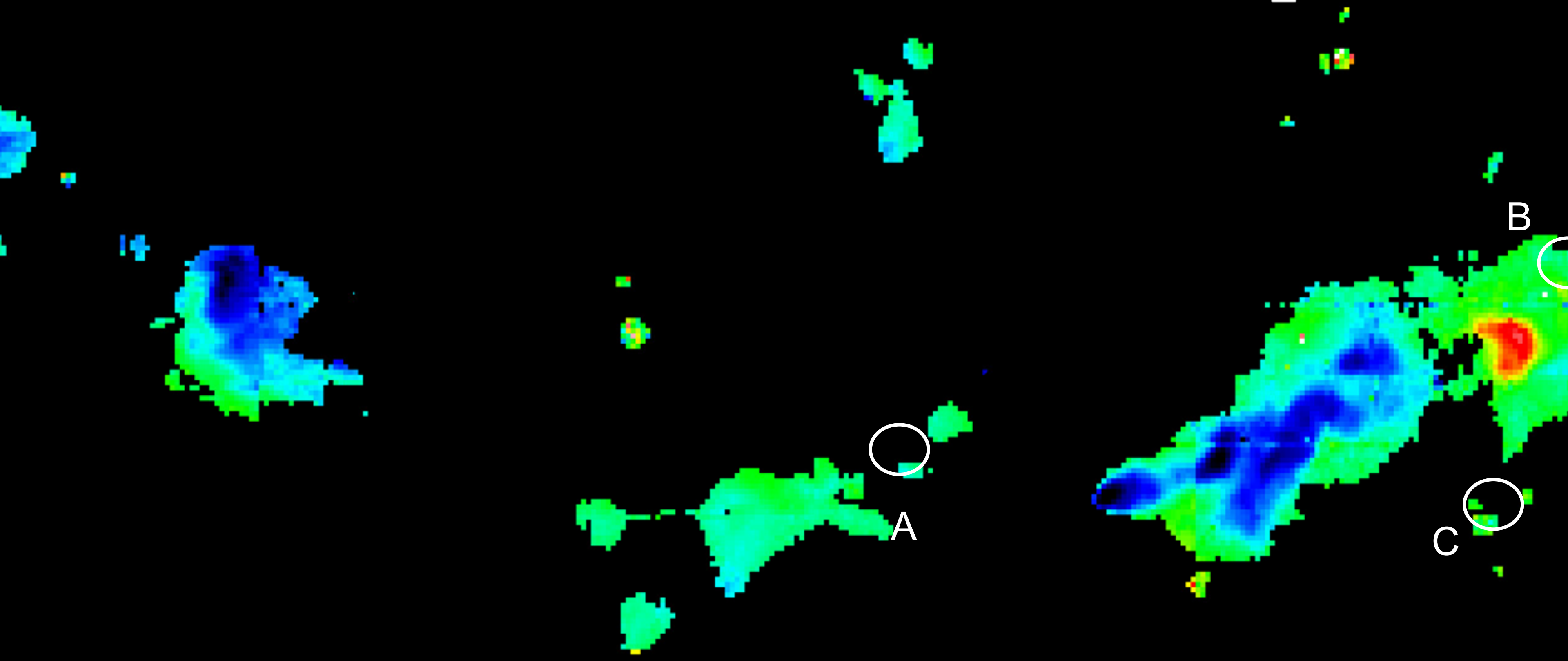
spectrally resolved Brγ (65km/s)

Estimated Lacc ~14Lsolar



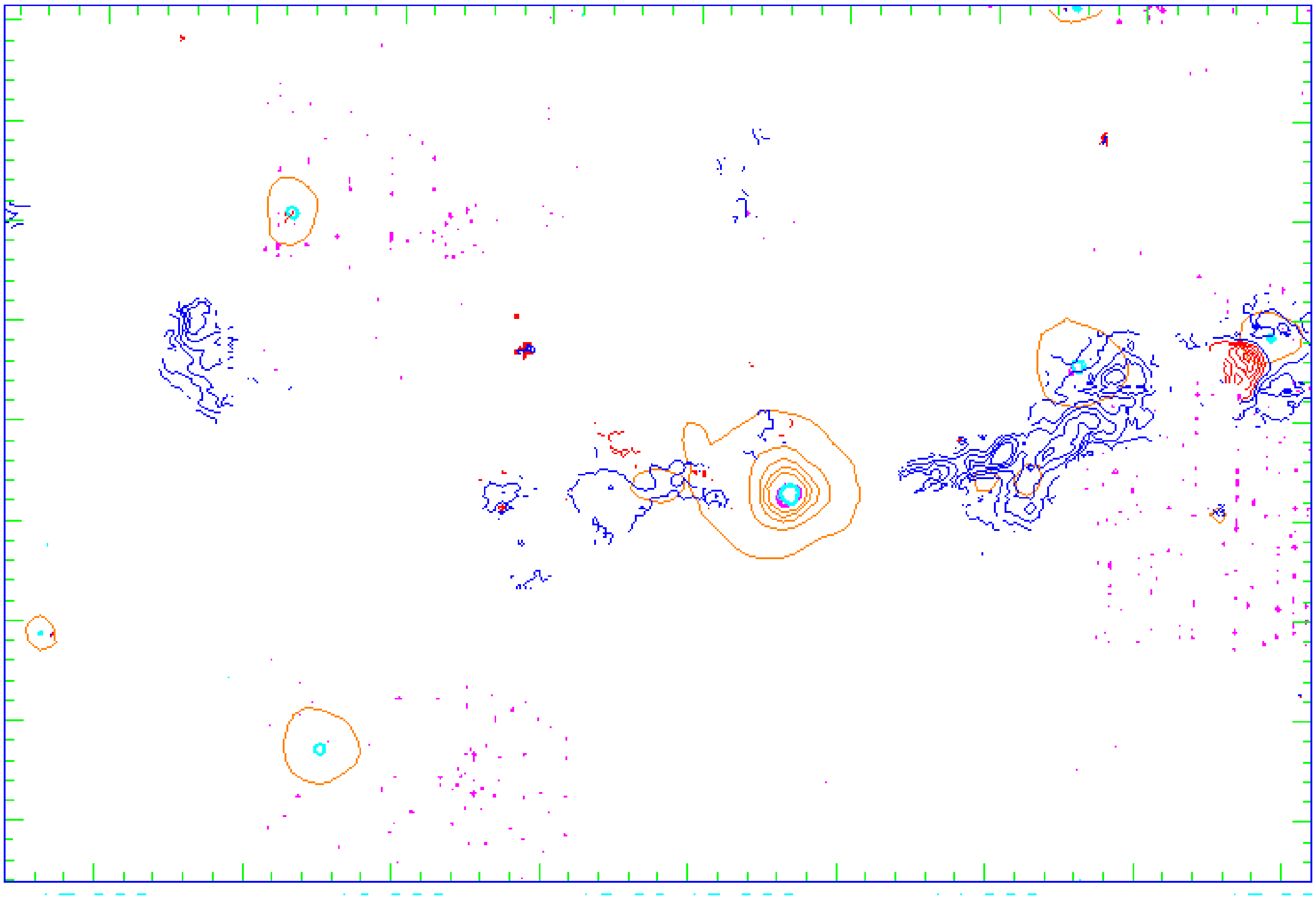

IRAS 18264-1152
d=3.5kpc, L=10^4 Lsolar
KMOS v=1-0 S(1) of H2
300s per pixels; 2.6h inc overheads for the map
65 arcsecs/1.1pc

Velocity map in 1-0 S(1) H_2

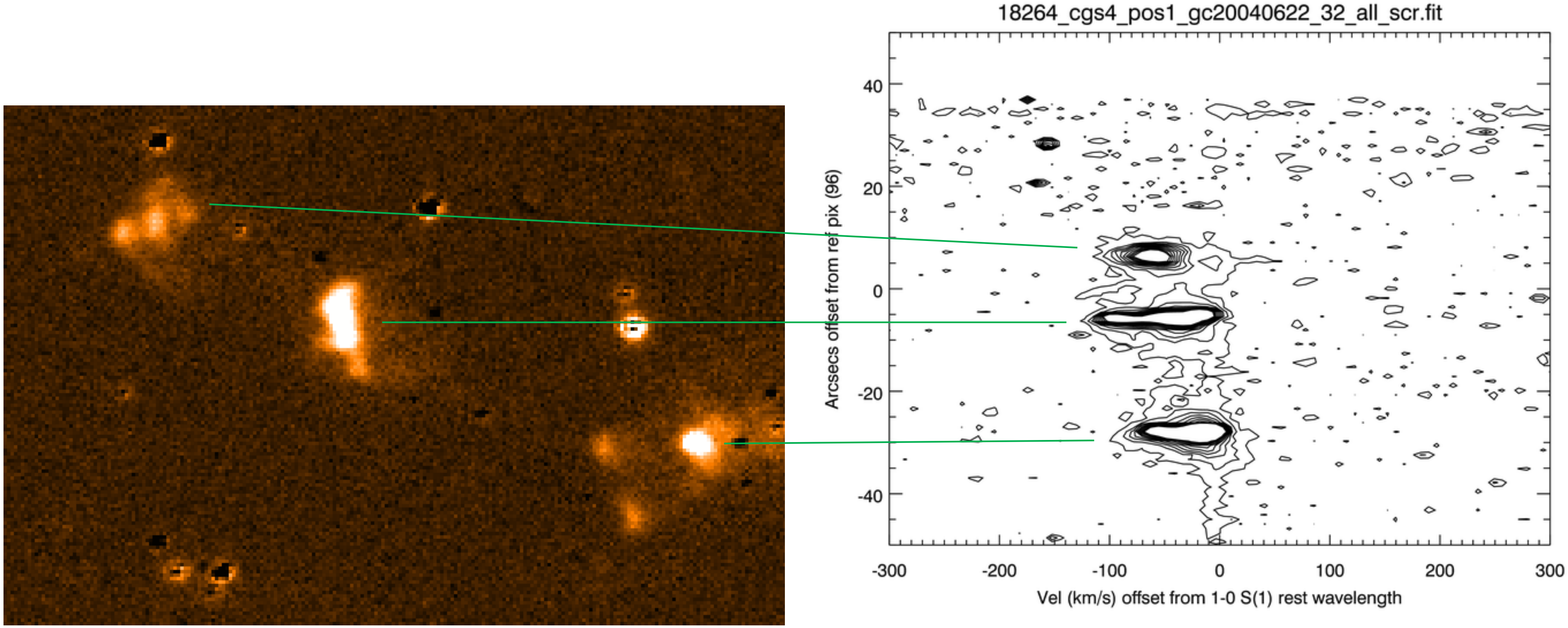


Black: -60km/s <v<-30km/s
Blue: -30km/s <v<0km/s
Green: 0<v<30km/s
Red: 30<v<60km/s
Radial velocity of IRAS18264-1152: 43.6km/s (Bronfman, Nyman & May 1996)

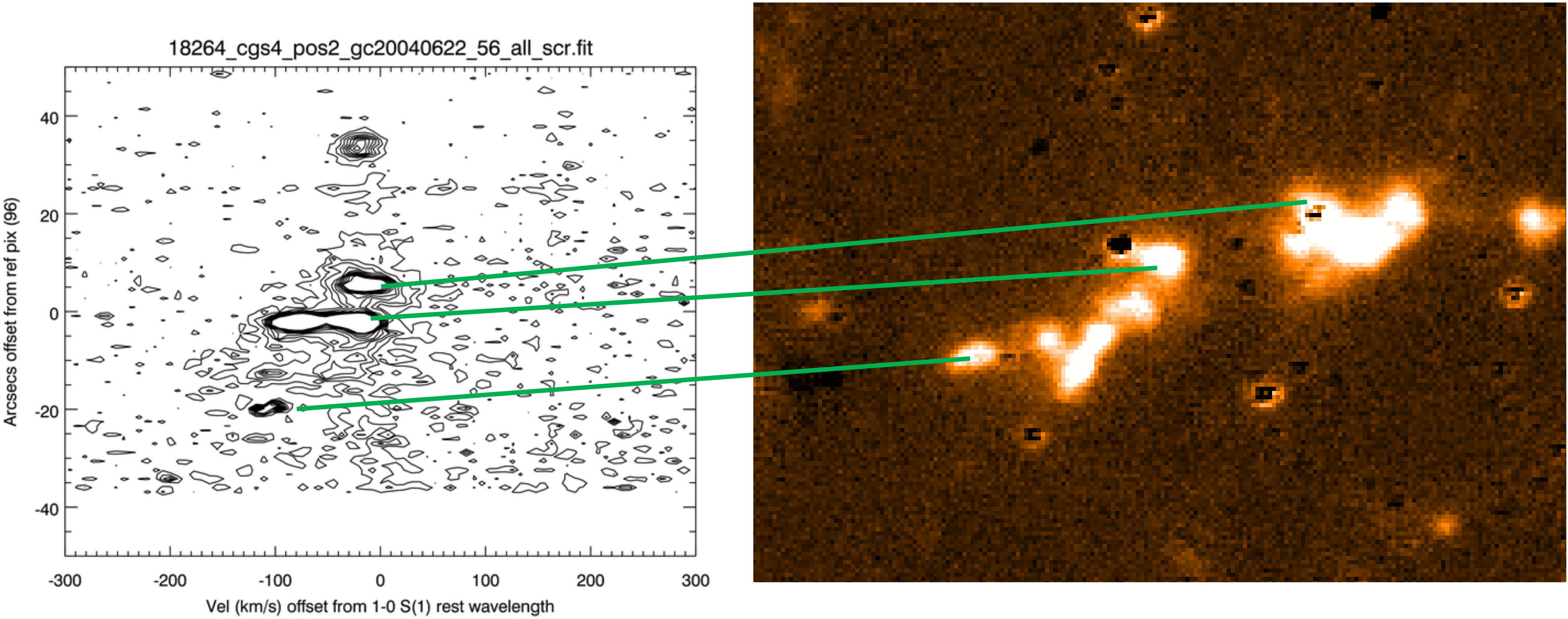
Counter part of the HMYSO?



CGS4/WFCAM H_2



CGS4/WFCAM H_2

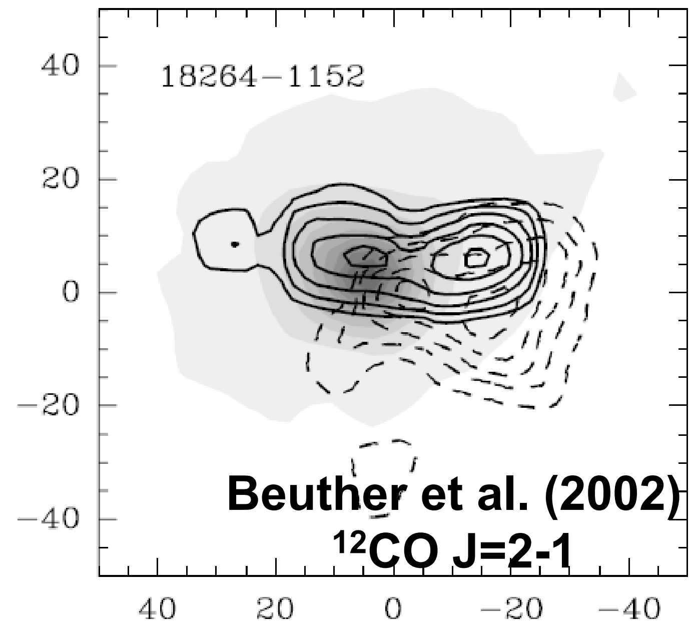


Measured velocities of the outflow

	Vmax blue, Vmax red kms^{-1}	
1-0 S(1) H_2	75.3,58.4	
SiO (2-1)	13.4,64.2	Sánchez-Monge et al. (2013)
SiO (5-4)	13.4,62.6	
HCO+ (1-0)	33.4,61.8	
SiO (8-7)	?,63	Leurini et al. (2014)
CO (4-3)	?,73	
^{12}CO (2-1)	28,52	Beuther et al. 2002

Properties of the outflow

- The brightest knots have L_{H2}~3L_{solar}, typical of other HMYSO outflows
  - In total ~17L_{solar}
- Mechanical luminosity in CO
  - ~20L_{solar} (Beuther et al. 2002)
- Typical outflow rate (warm gas), ~ $10^{-7.5}$ M_{solar} yr^{-1}
- Dynamical timescale ~2.4x10^4 years



Beuther et al. (2002)
^{12}CO J=2-1

Outflow rate:

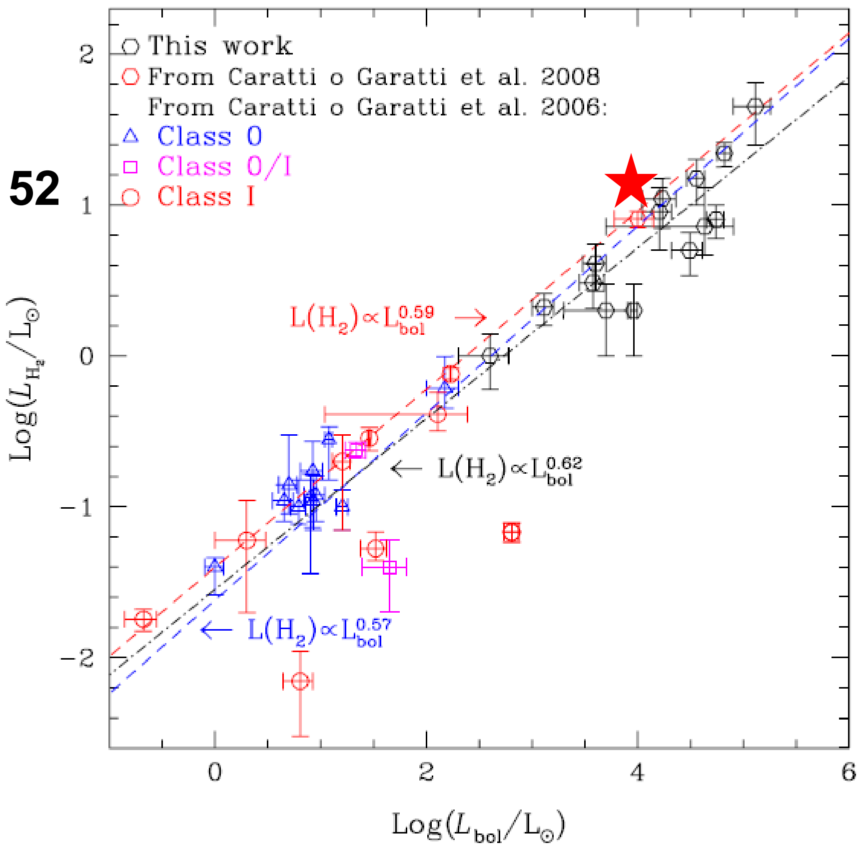
$$\dot{M}(H_2) = 2\ \mu m H N H_2 A v_t / l t$$

(Caratti o Garatti et al. 2008, Nisini et al. 2005)

H_2 luminosity versus source bolometric luminosity

- Sequence for low mass>>high mass YSOs from Caratti o Garatti et al. (2015)

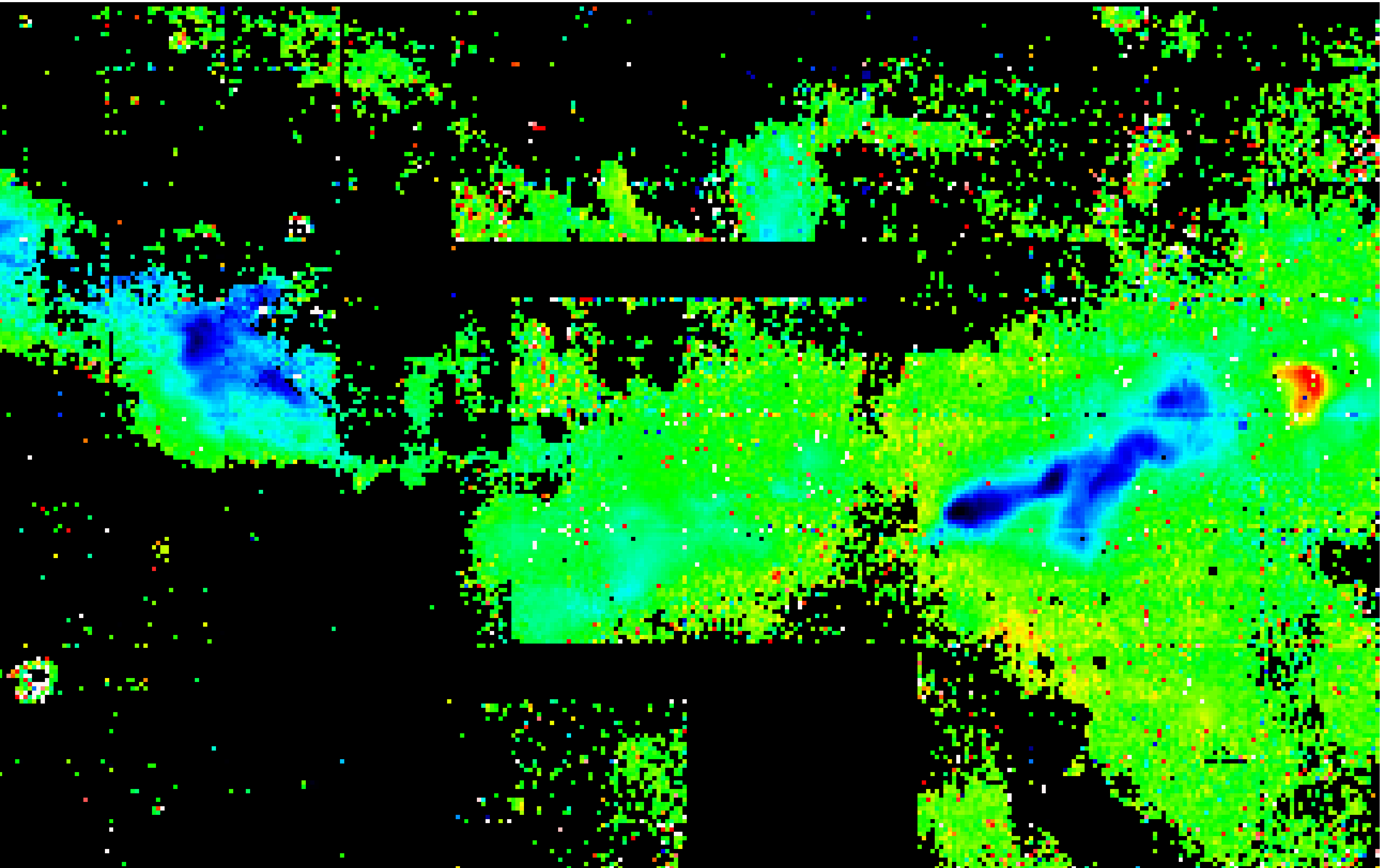
★ **IRAS 18264-1152**



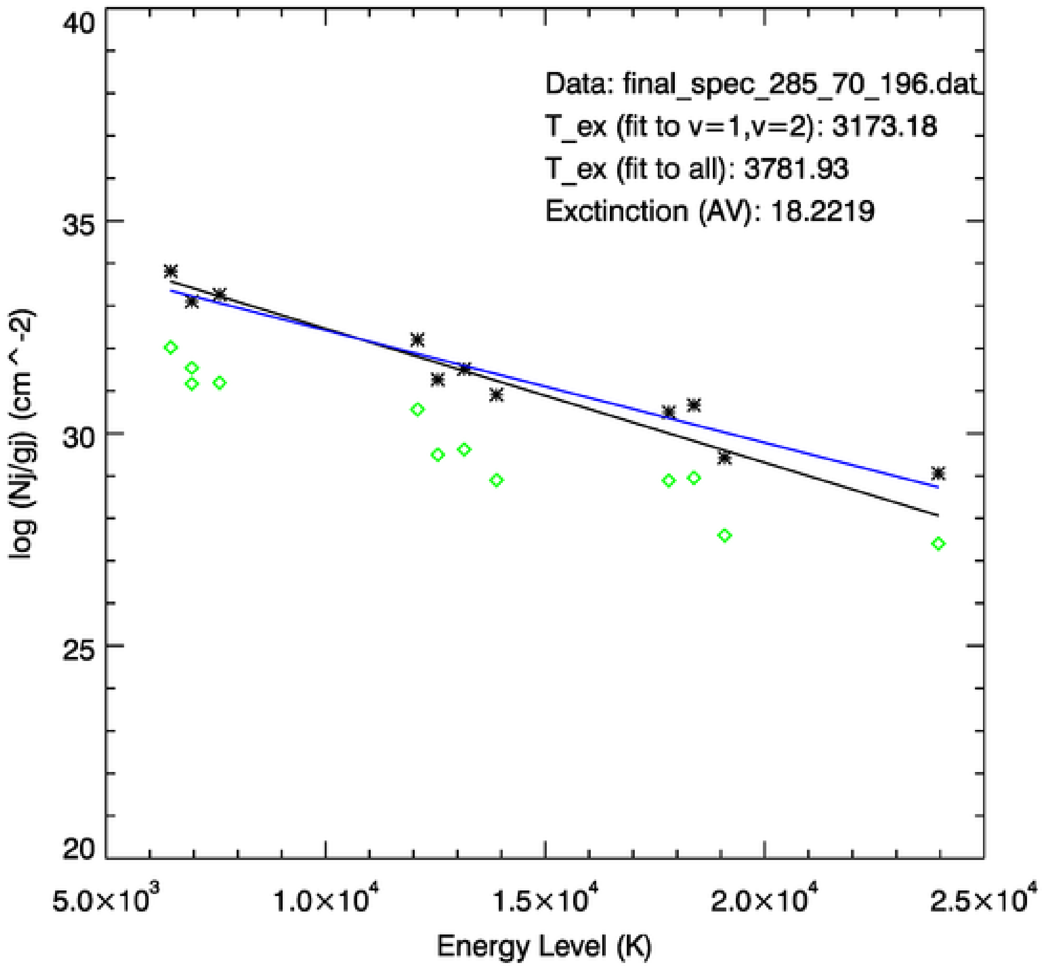
Conclusions on the outflows

- Spectral imaging with KMOS permits a complete survey of such a region with simultaneous determination of the excitation in the region, outflow rates and accretion luminosity of YSOs in the region
- Velocity information is crucial in interpreting these regions
- Identification of the driving source the outflow remains a challenge
- The properties of the outflow from IRAS 18264 may be consistent with other HMYSOs

The ambient medium



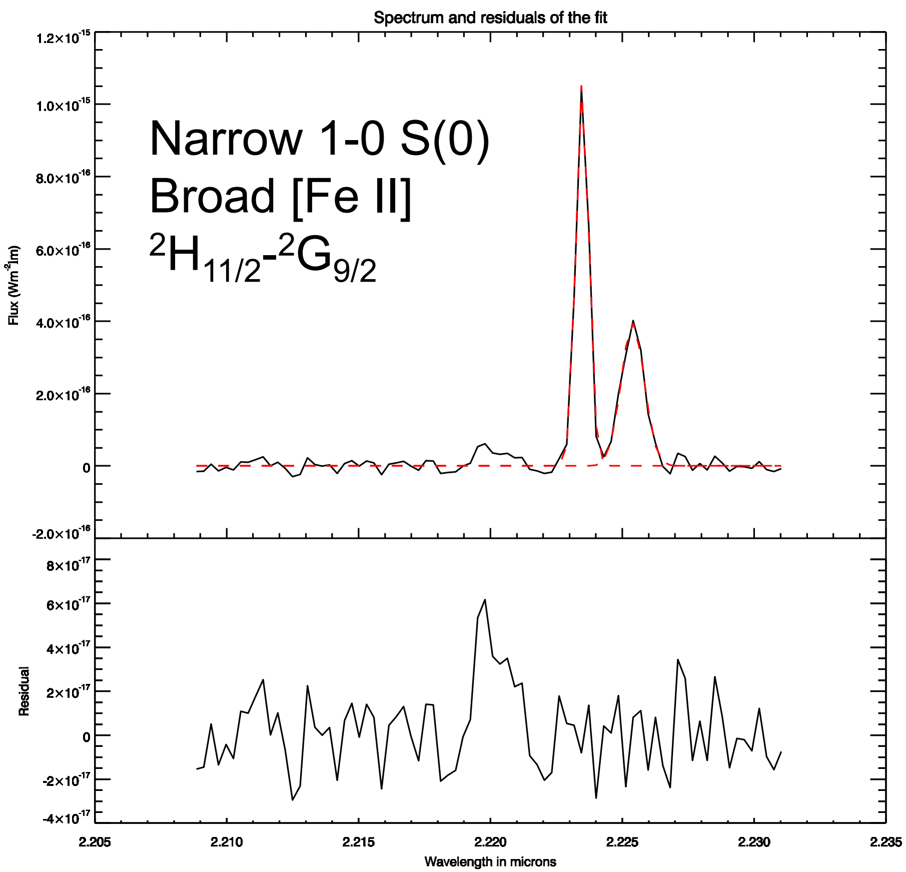
The ambient medium

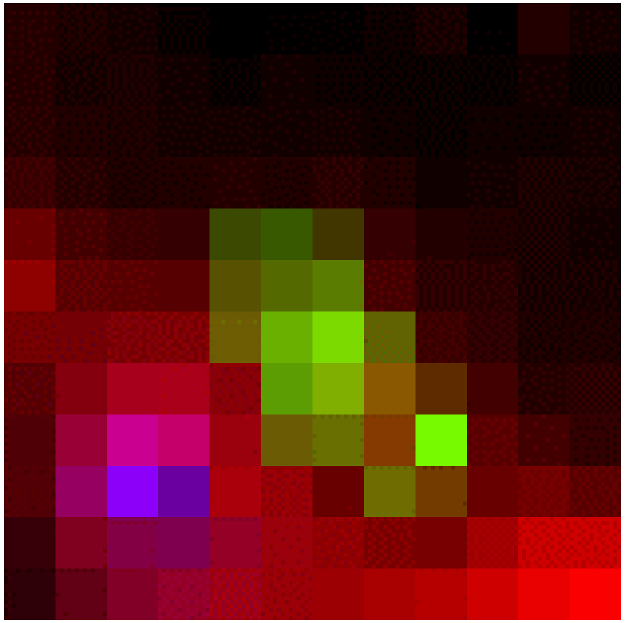


- Emission from the gas surrounding the outflow and at the rest velocity of the cloud shows evidence of fluorescent excitation and with an ortho-para ratio of 1.75

Emission from [Fe II]

- Emission from [Fe II] detected at a single location in the vicinity of source 'B' and the bow shock





Blue – Source 'B'
Red – H_2
Green - [Fe II]

Next steps

- From the existing data set
  - SED modelling of the centra source
  - Confirmation of the nature and origins of the [Fe II] emission
- Follow-up with higher angular resolution at longer wavelengths of both the outflow and the central source