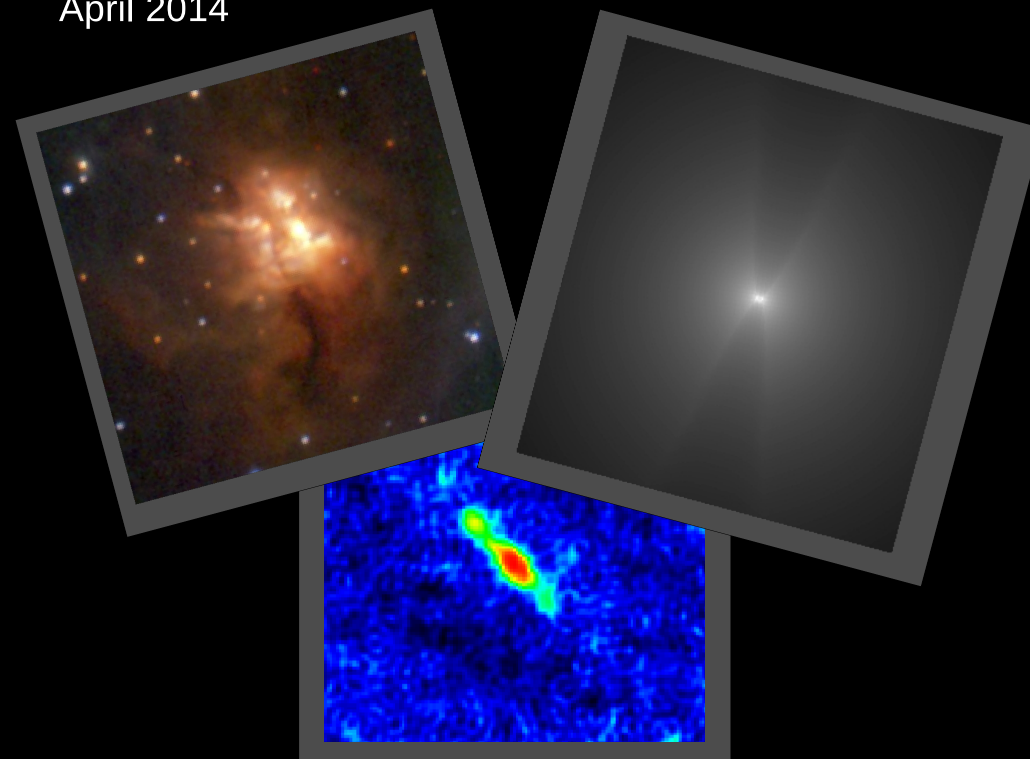
Interferometric Observations of S140-IRS1

e-MERLIN – early science workshop

April 2014



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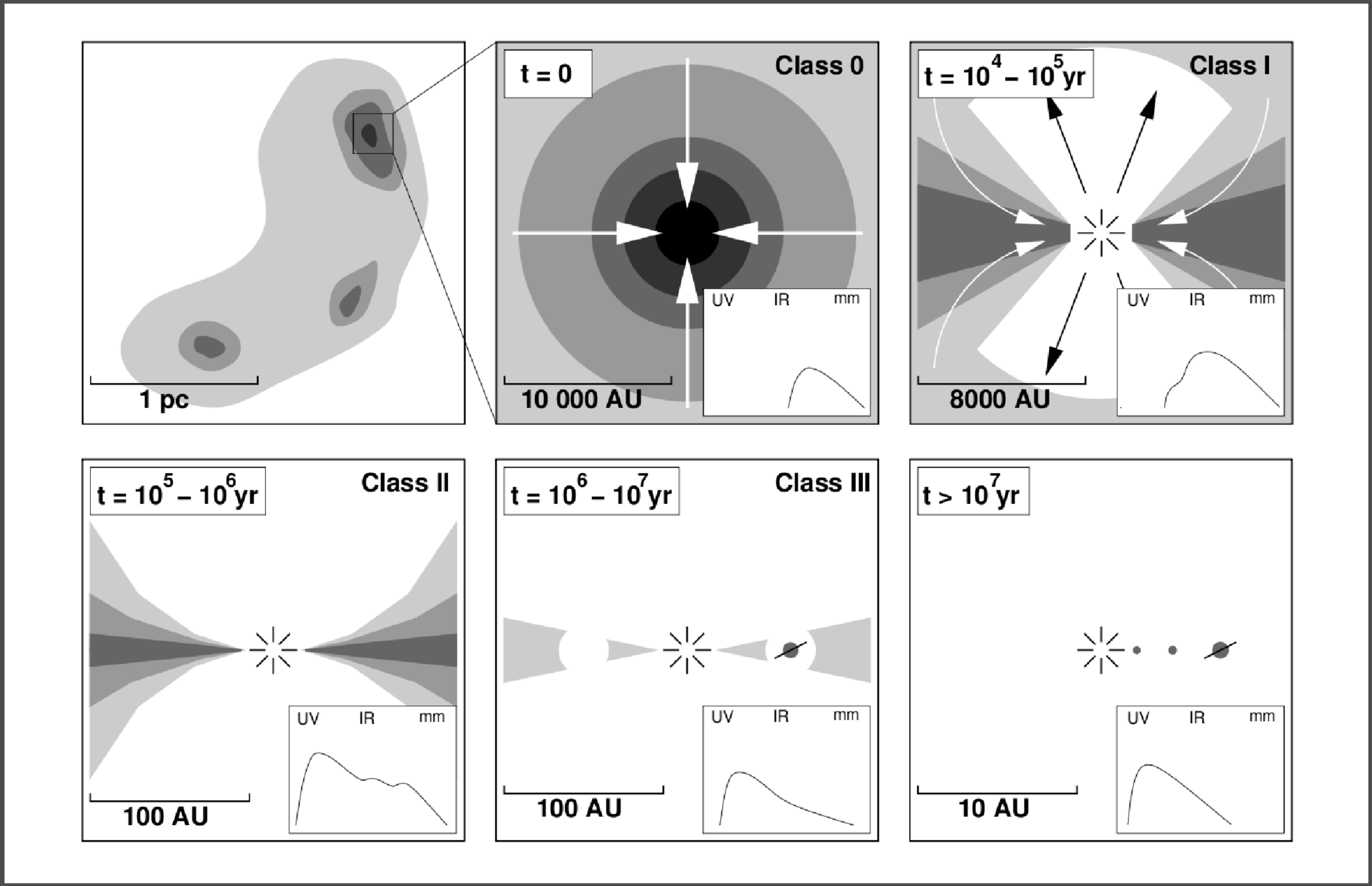
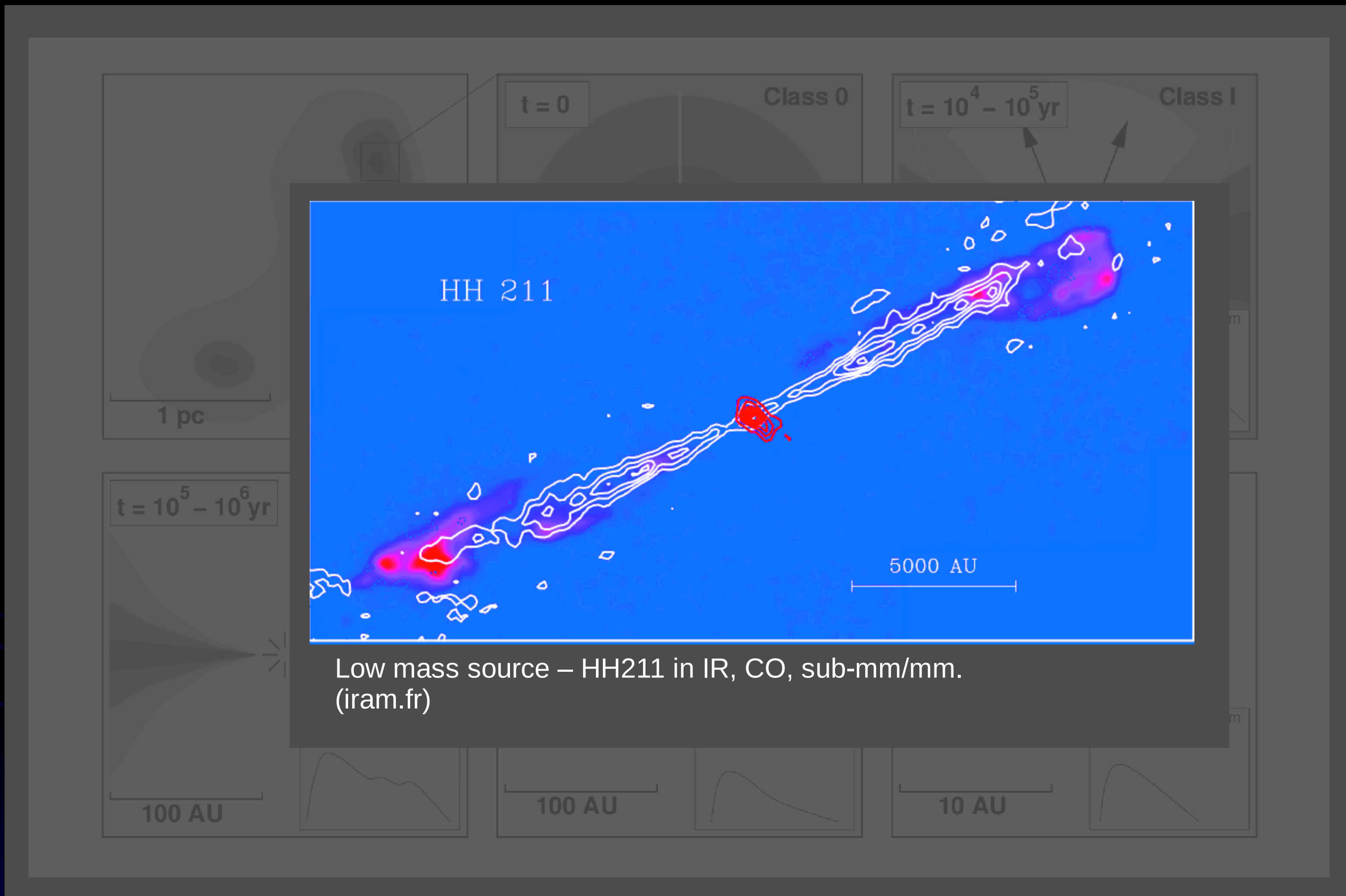
UNIVERSITY OF LEEDS

Star formation scenario



- Collapse of a core
- Disc, jets and outflows
- Disc erodes, planet formation, solar system

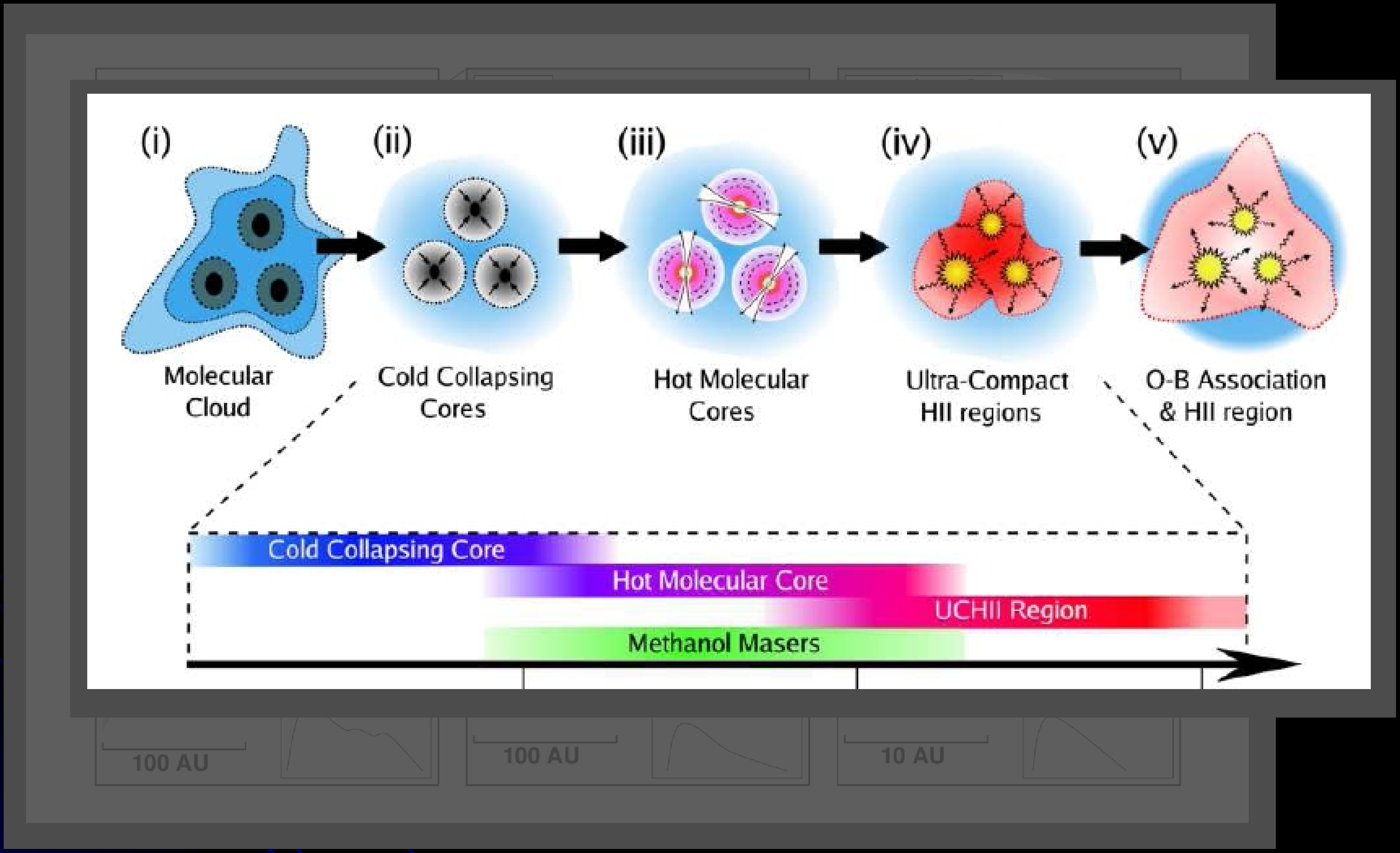
Star formation scenario



Low mass source – HH211 in IR, CO, sub-mm/mm.
(iram.fr)

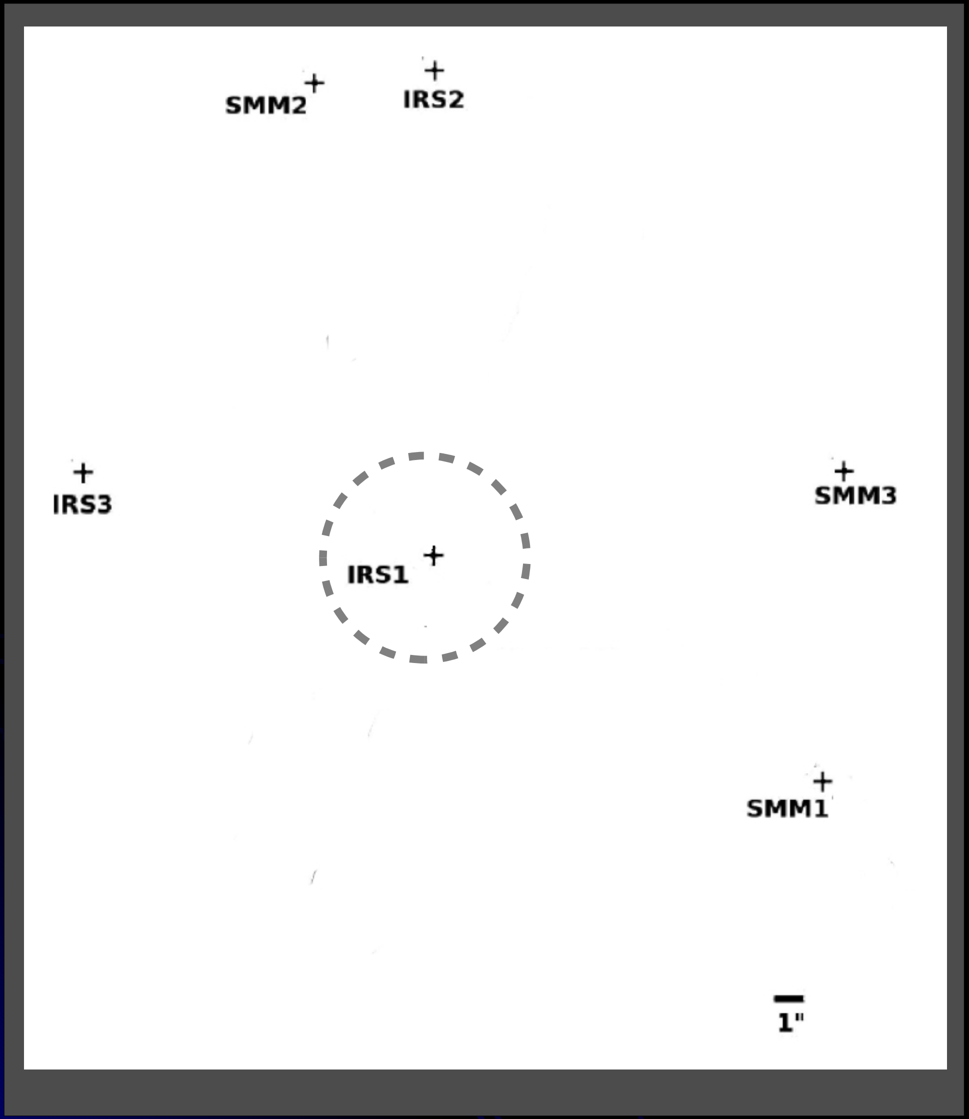
- Collapse of a core
- Disc, jets and outflows
- Disc erodes, planet formation, solar system

(Massive) Star formation scenario



- Collapse of a core
- Jets and outflows from hot cores (+ rotation)
- UV photons, ionize the surrounding

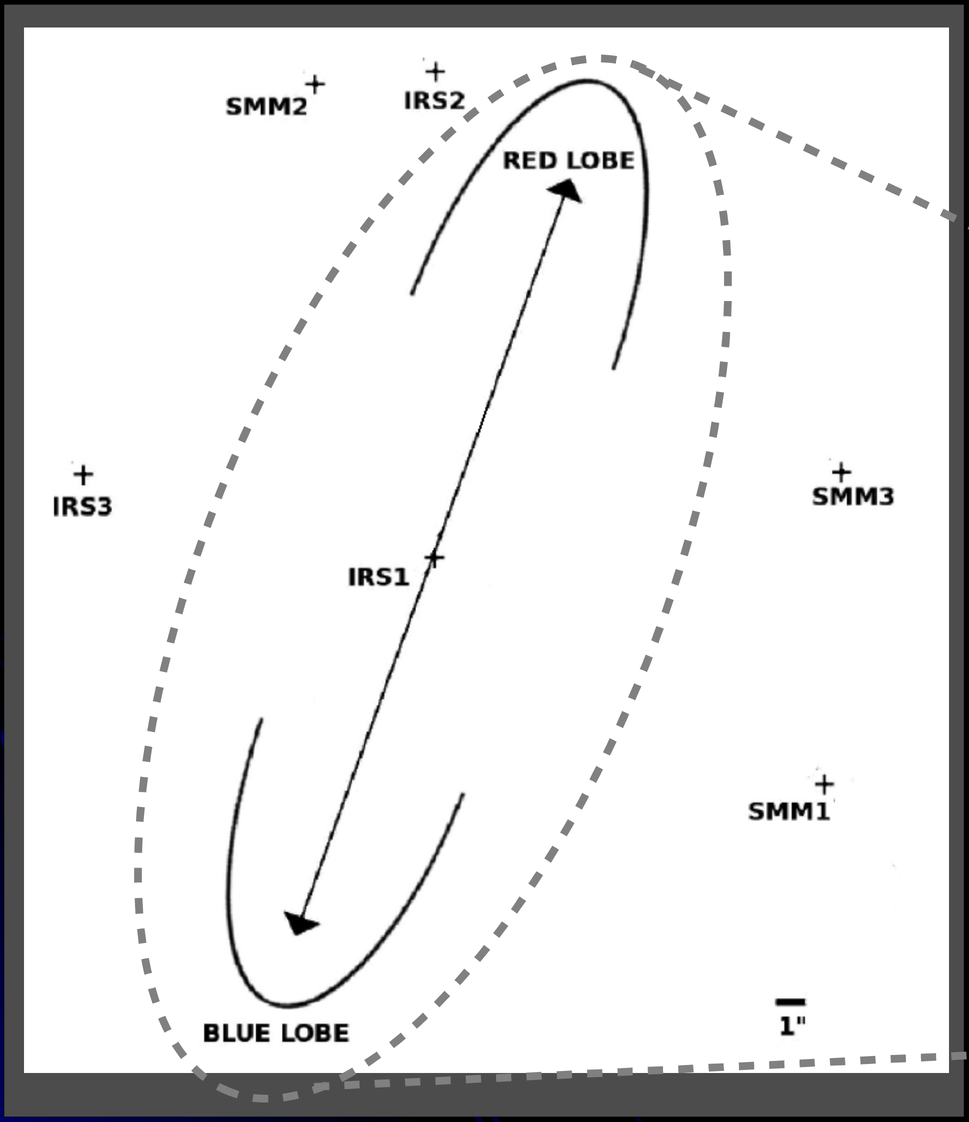
S140



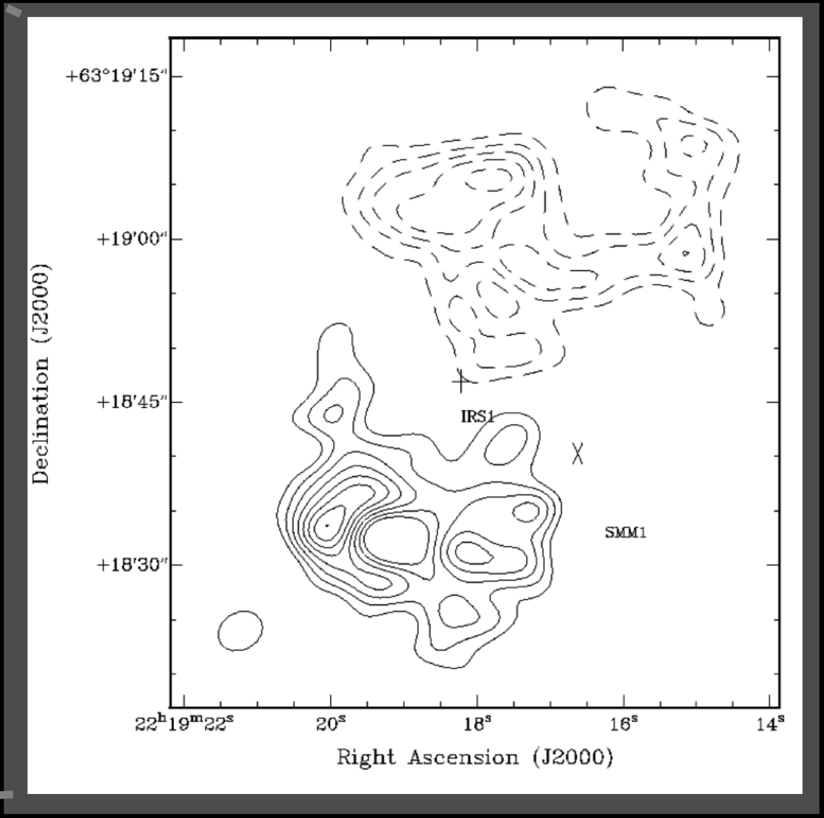
- Close region at ~**760 pc** (Hirota et al. 2008)
- **IRS1 brightest**

  L ~ 8.5 x 10^3 L⊙ (Maud et al. 2013)

S140 - IRS1

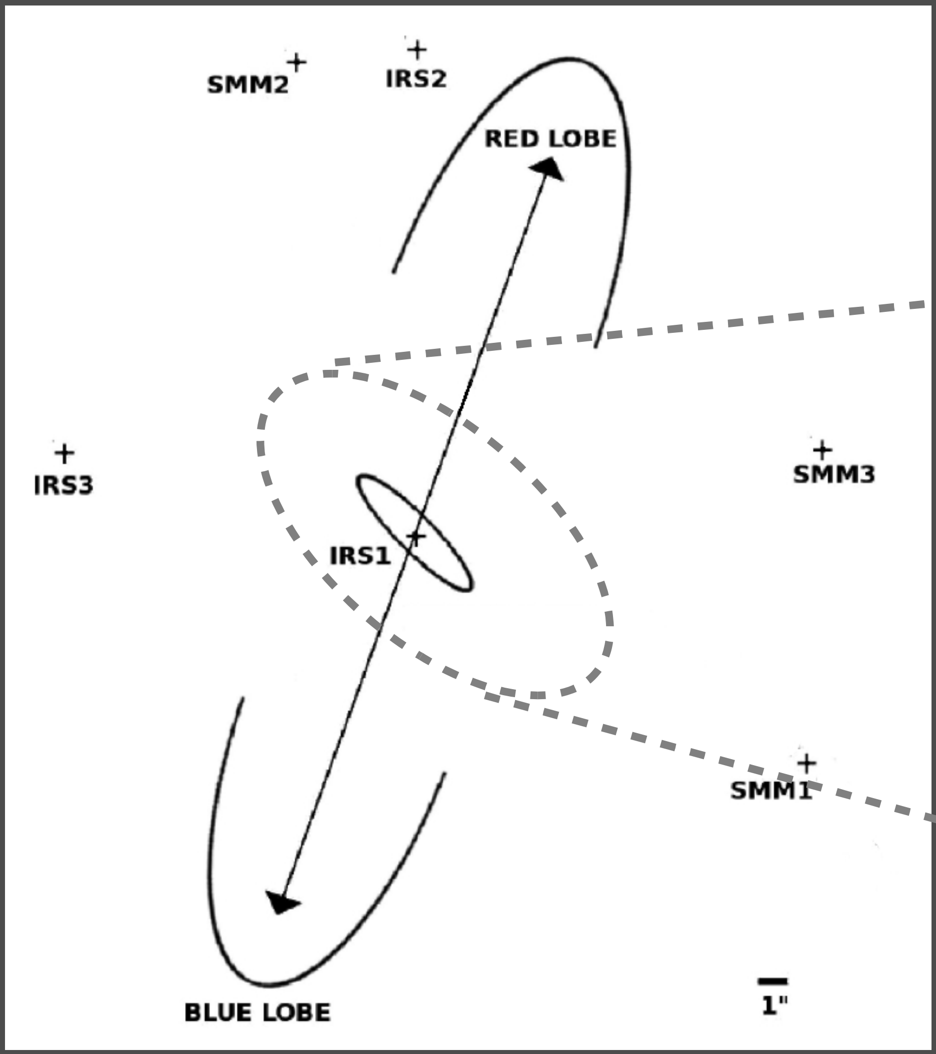


- Bipolar molecular **outflow**
- OVRO – CO (1-0) – 6” resolution

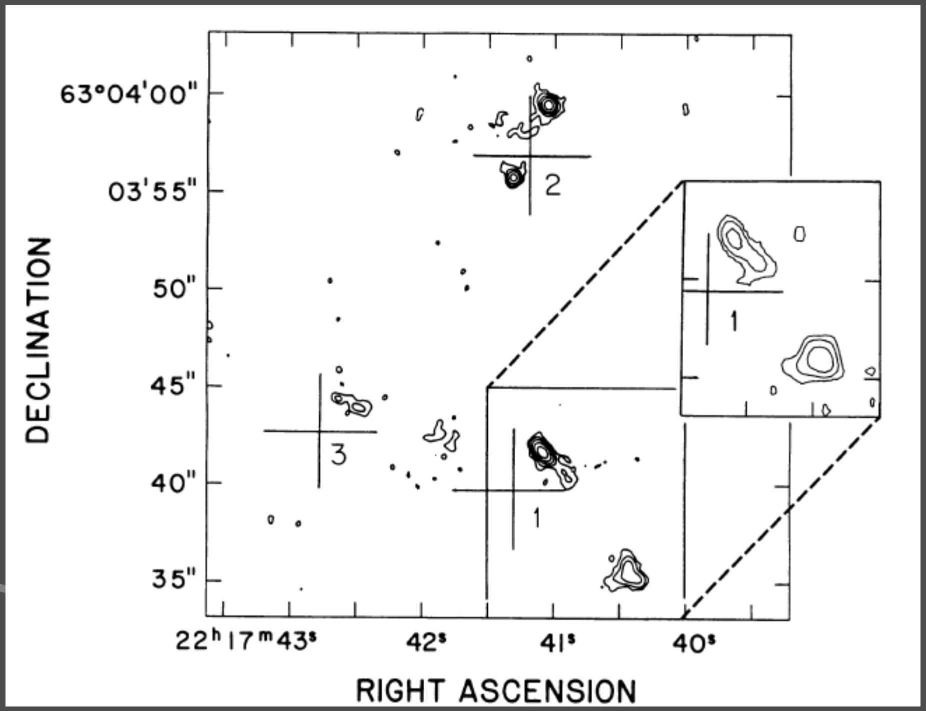


Outflow lobe position not to scale

S140 - IRS1



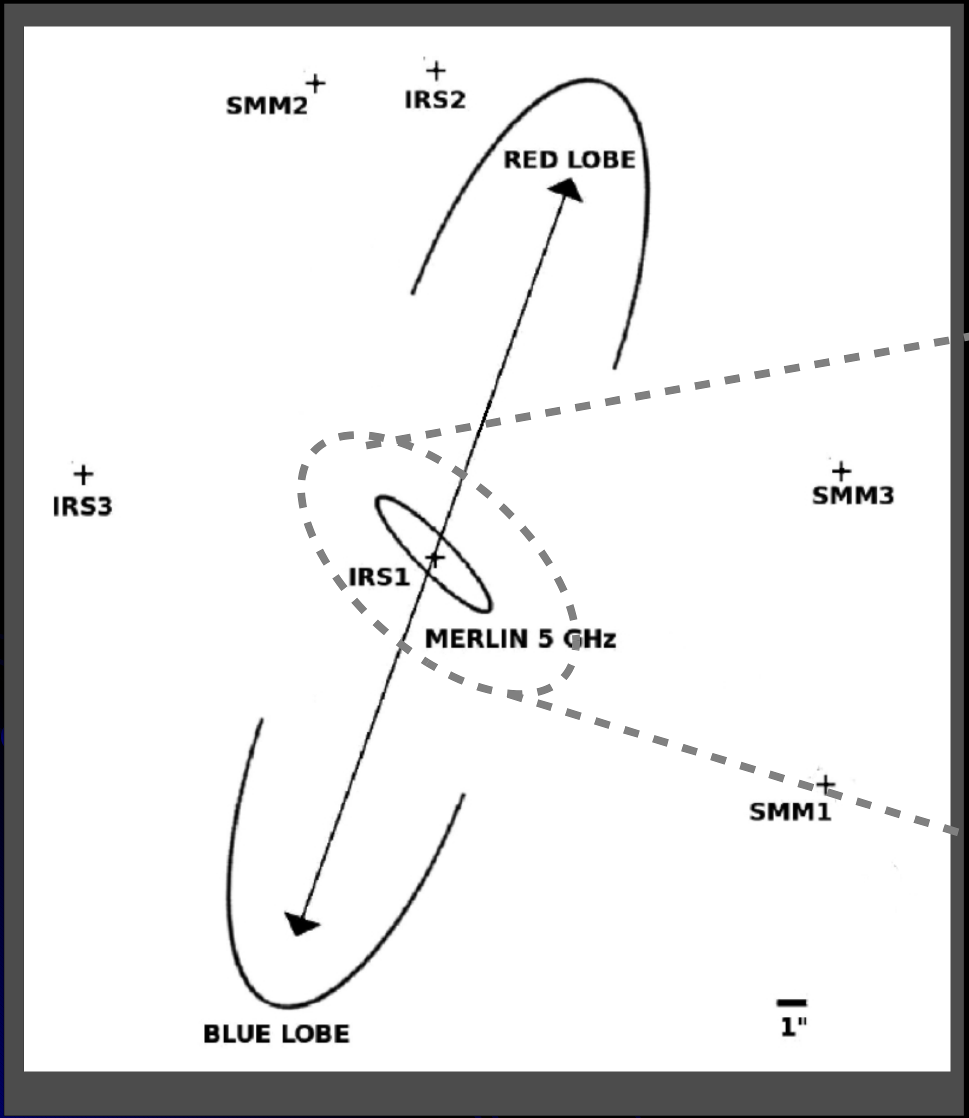
- Elongated radio emission (Schwartz 1989)
- C and L band (inset) 0.3 – 1.0” resolution
- Jet interpretation **problematic**



- Bullet to the SW ?

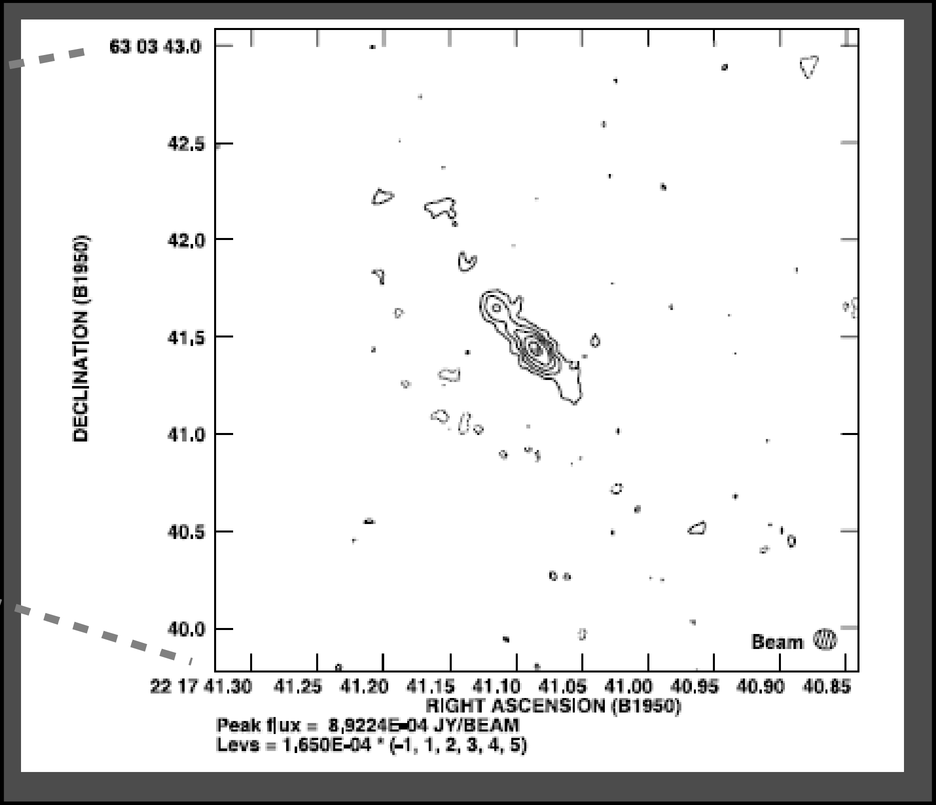
Outflow lobe position and radio emission not to scale

S140 - IRS1



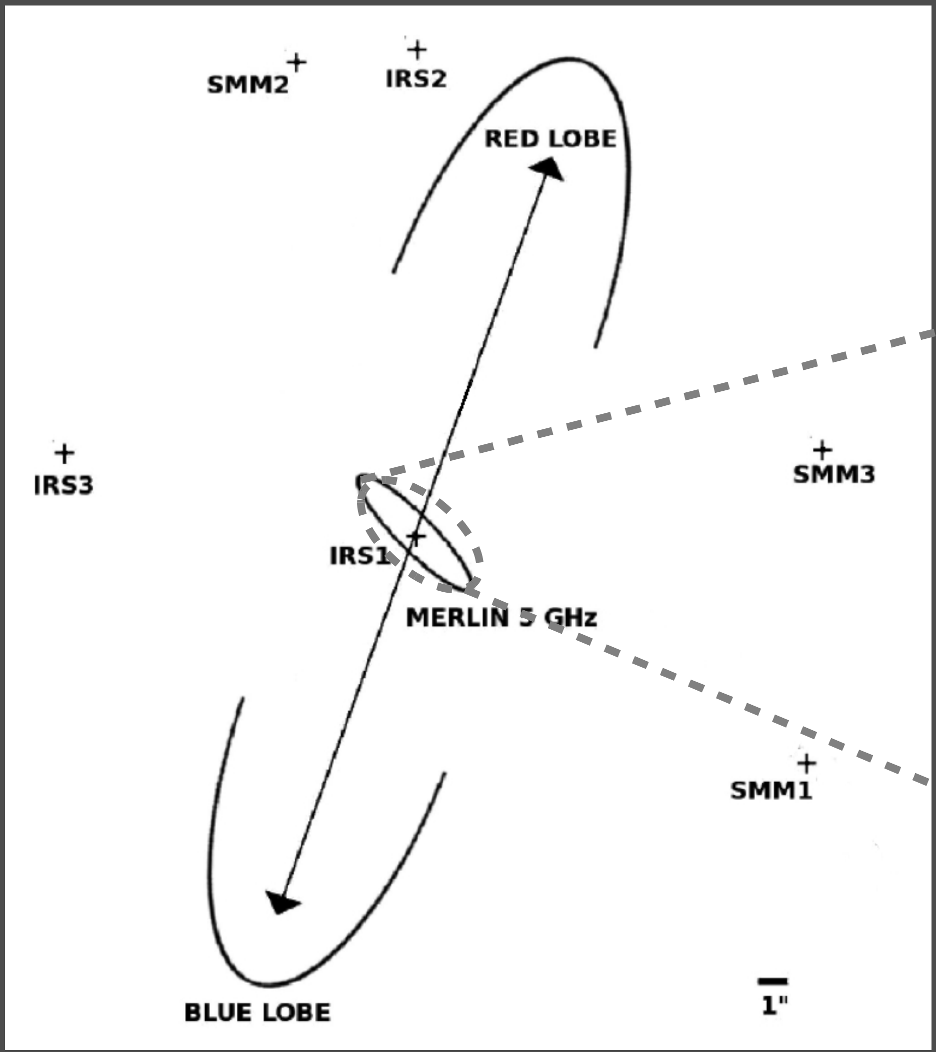
Outflow lobe position and radio emission not to scale

- Multi-epoch 5 GHz obs. (Hoare 2006)
- **Prototype equatorial disc wind source**
- One of two such sources (other - S106 IR)



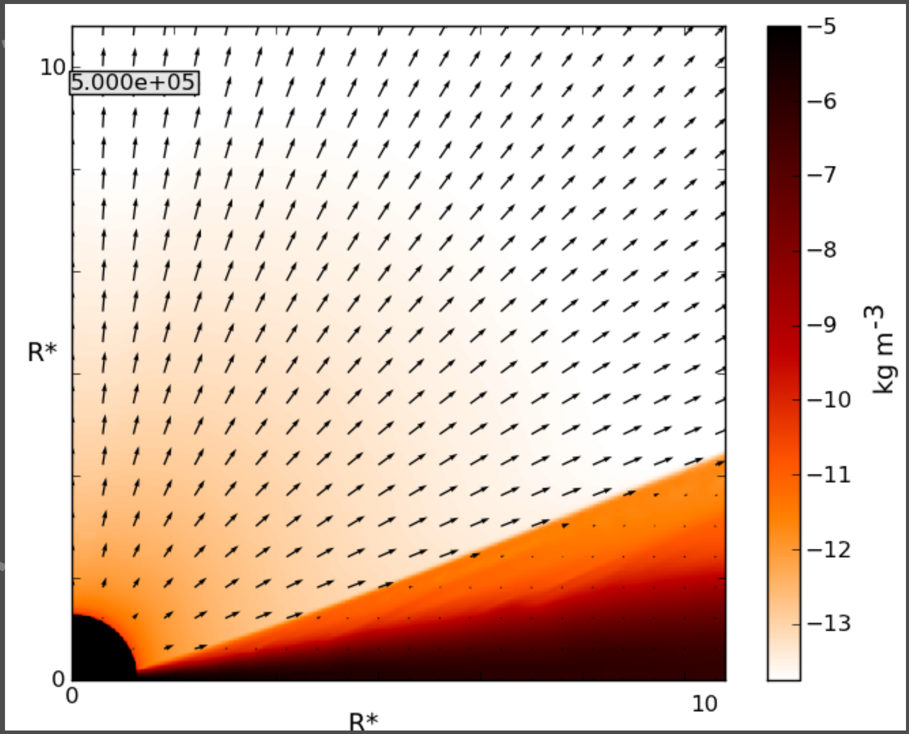
- **PA ~ 44º**

S140 - IRS1



Outflow lobe position and radio emission not to scale

- Massive young OB star – near MS config.
- Stellar radiation pressure acting on the surface of a disc – **ionized equatorial wind**

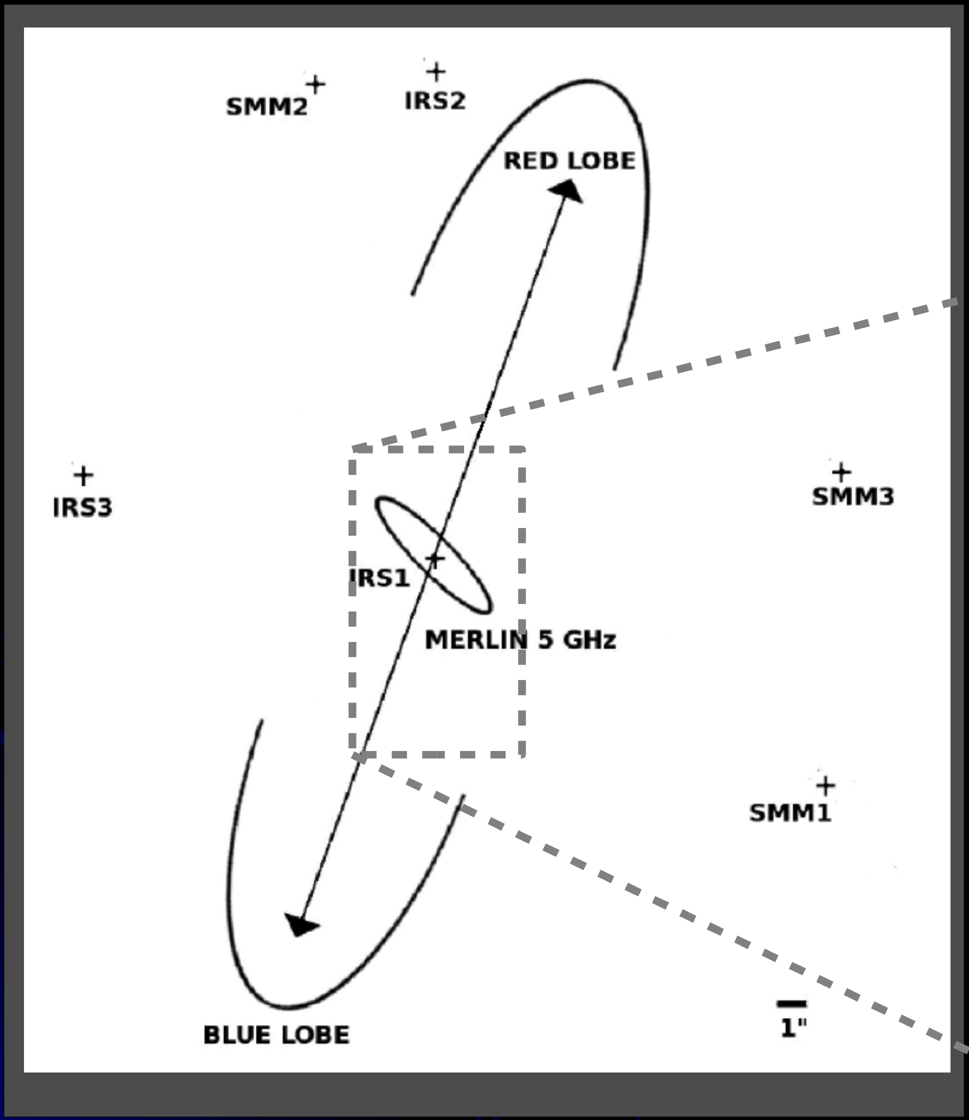


Douglas (Uni. of Leeds, in prep)

- **Radiation driven disc wind model**

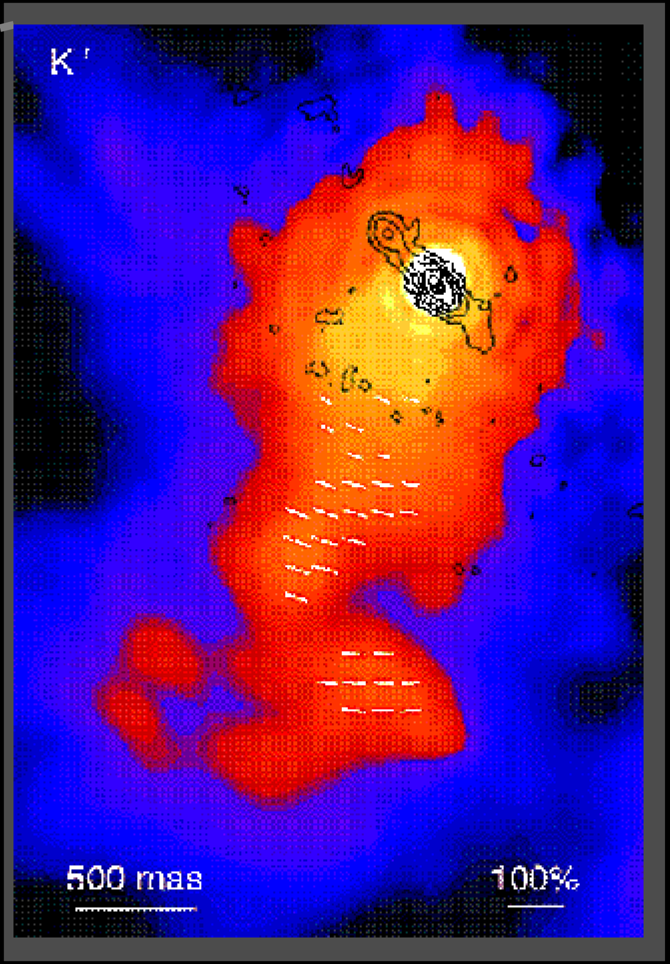
c.f. Drew, Proga & Stone (1998)

S140 - IRS1

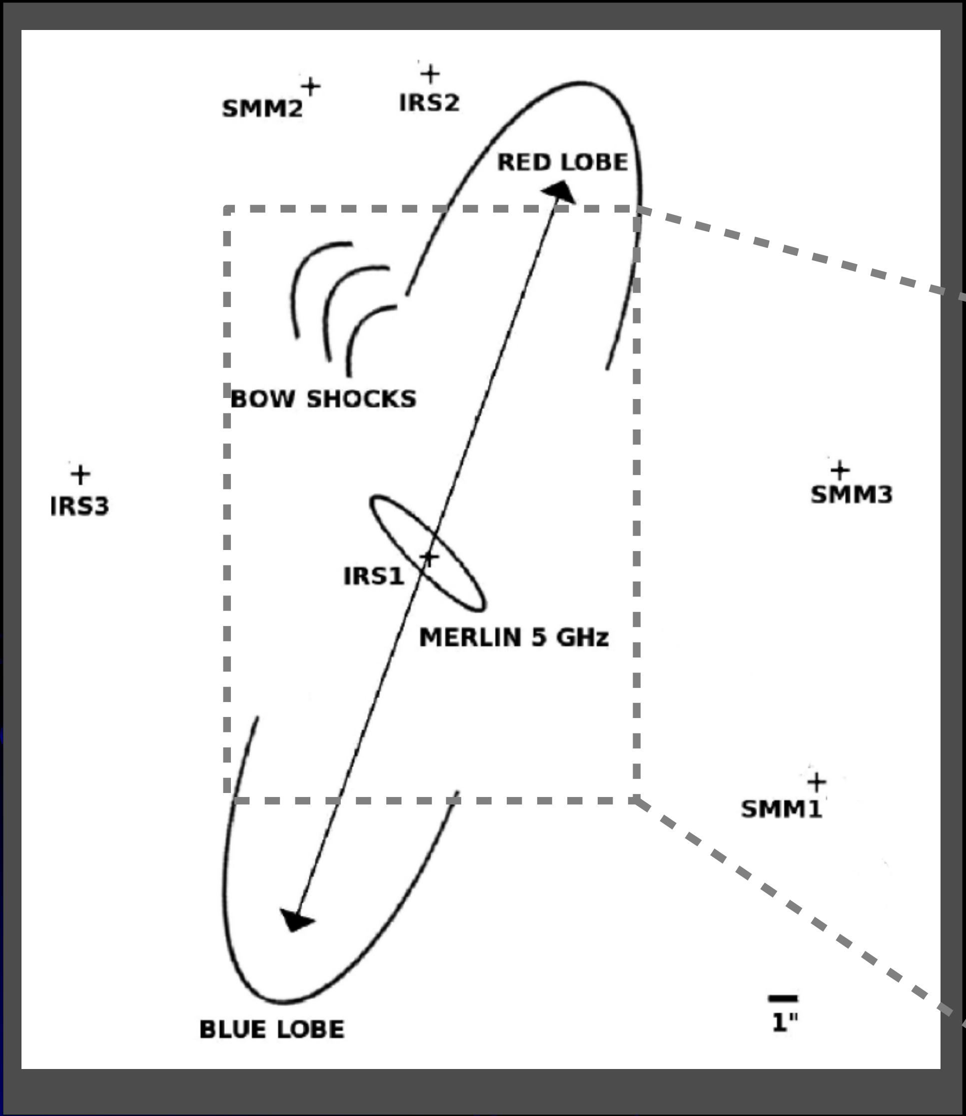


Outflow lobe position and radio emission not to scale

- NIR speckle image (Schertl et al. 2000)
- Reflection nebula associated with outflow
- Different to deeply embedded MYSOs?

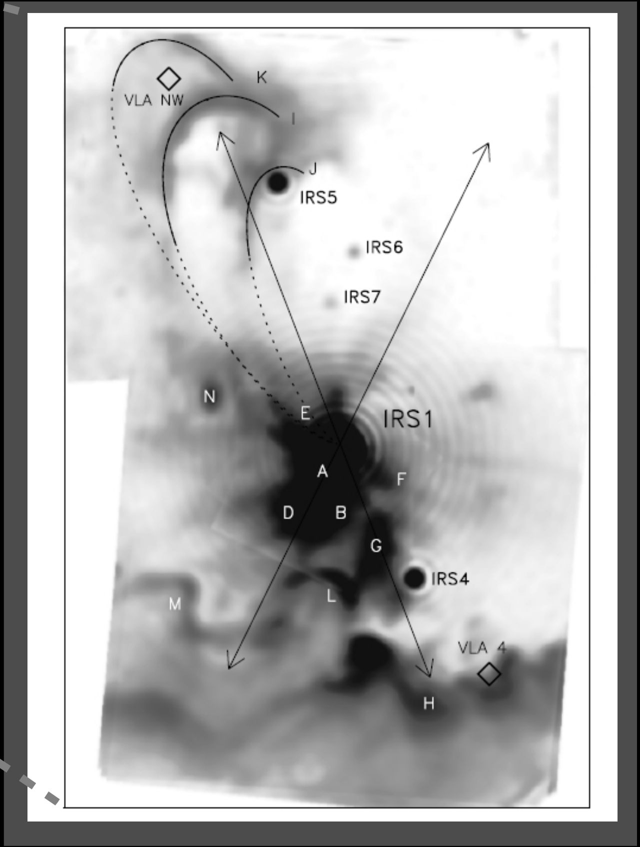


S140 - IRS1



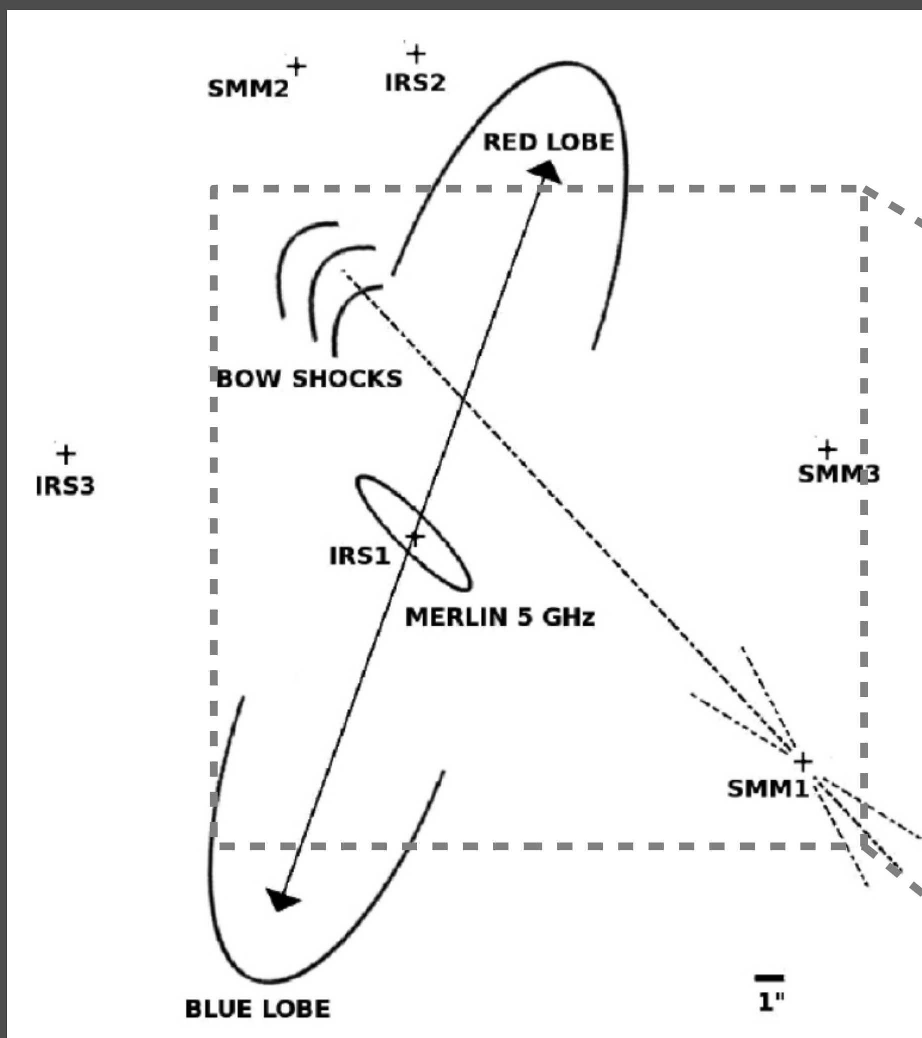
Outflow lobe position and radio emission not to scale

- Bow shocks – **jet interpretation** of radio (Weigelt et al. 2002, Preibisch & Smith 2002)
- Position angles **not consistent**
- **Multiple** sources ?

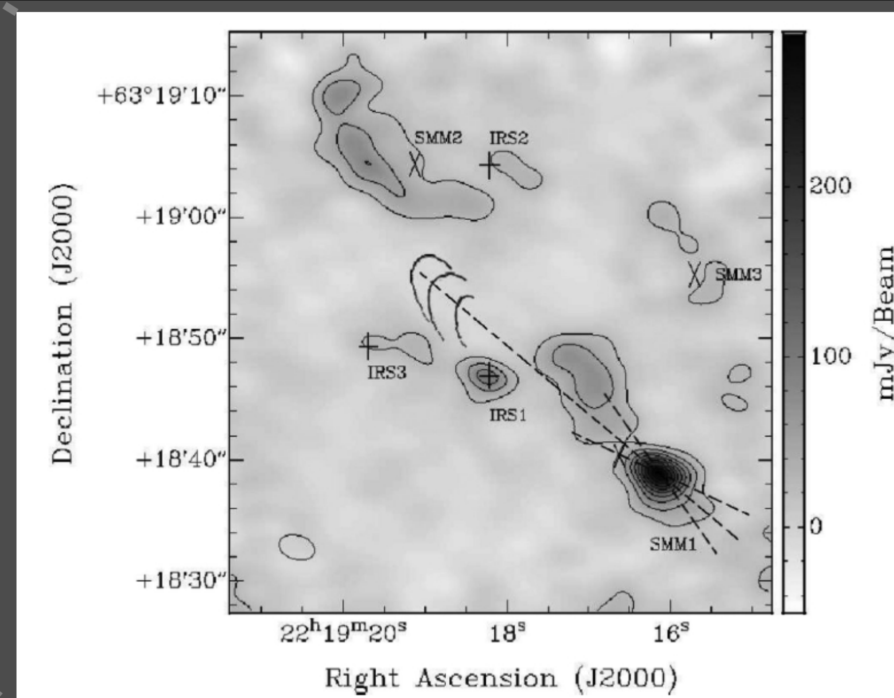


S140 - IRS1

- **Updated** location of SMM1 (SMA ~3” res.)
- Coincident with **proper motion masers** (Asanok et al. 2010 – MERLIN obs.)
- SMM1 **responsible** for bow shocks



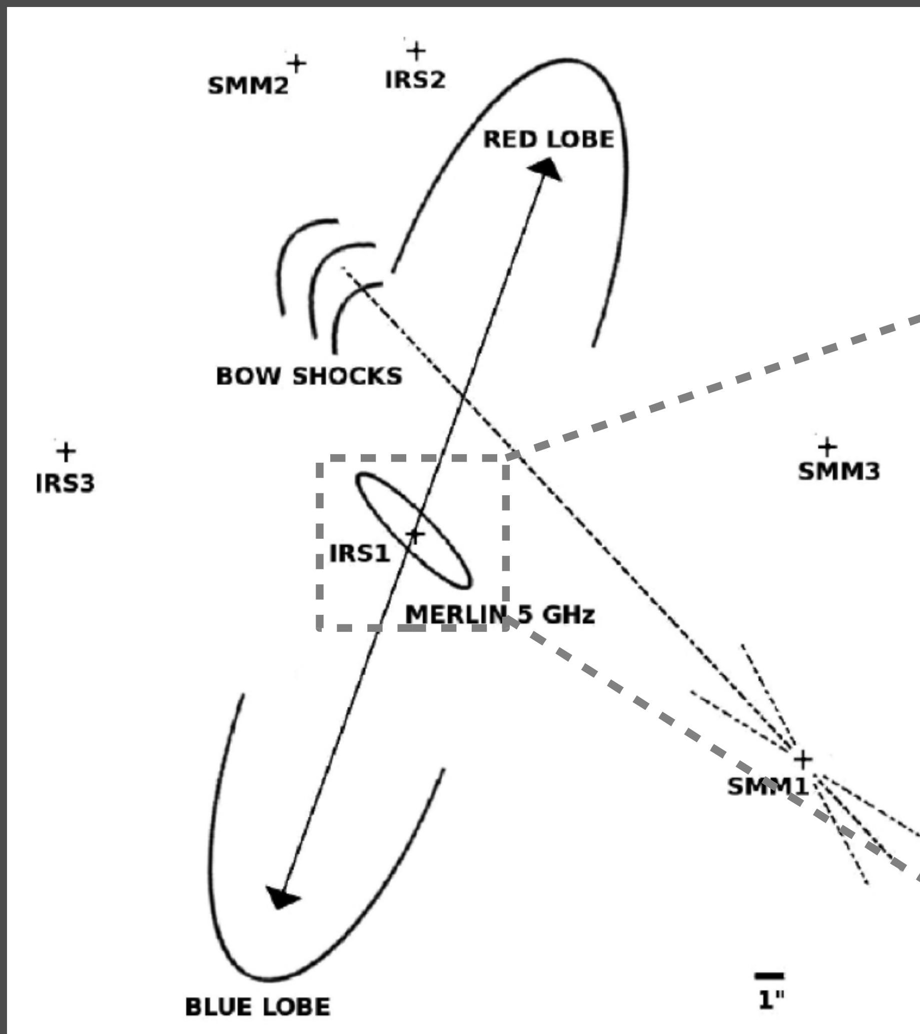
Outflow lobe position and radio emission not to scale



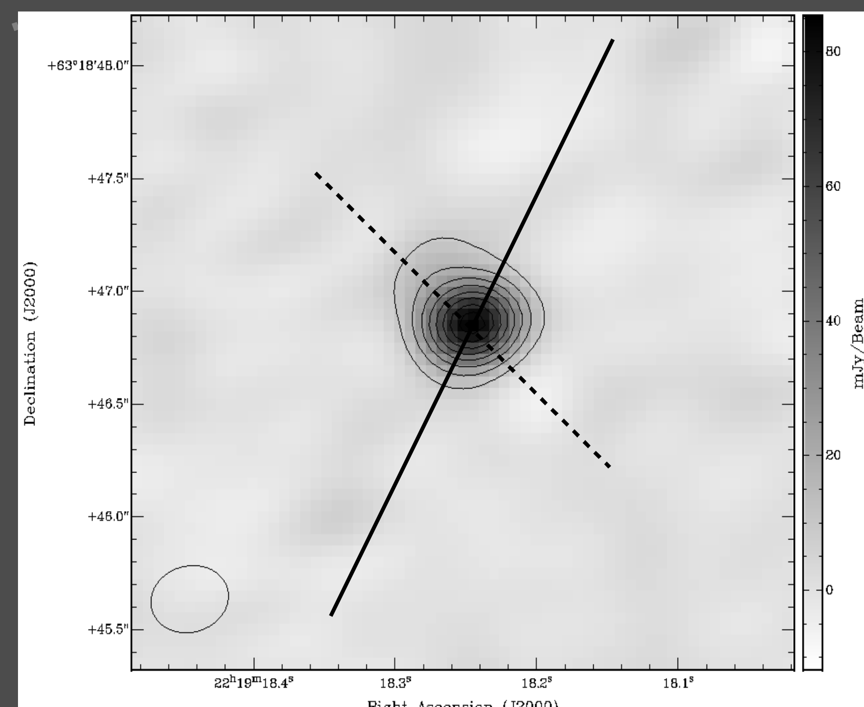
Maud et al 2013

S140 - IRS1

- **<u>High resolution mm</u>** observations
- CARMA B – 1.3 mm, 0.3” res, scales <300au
- Compact component



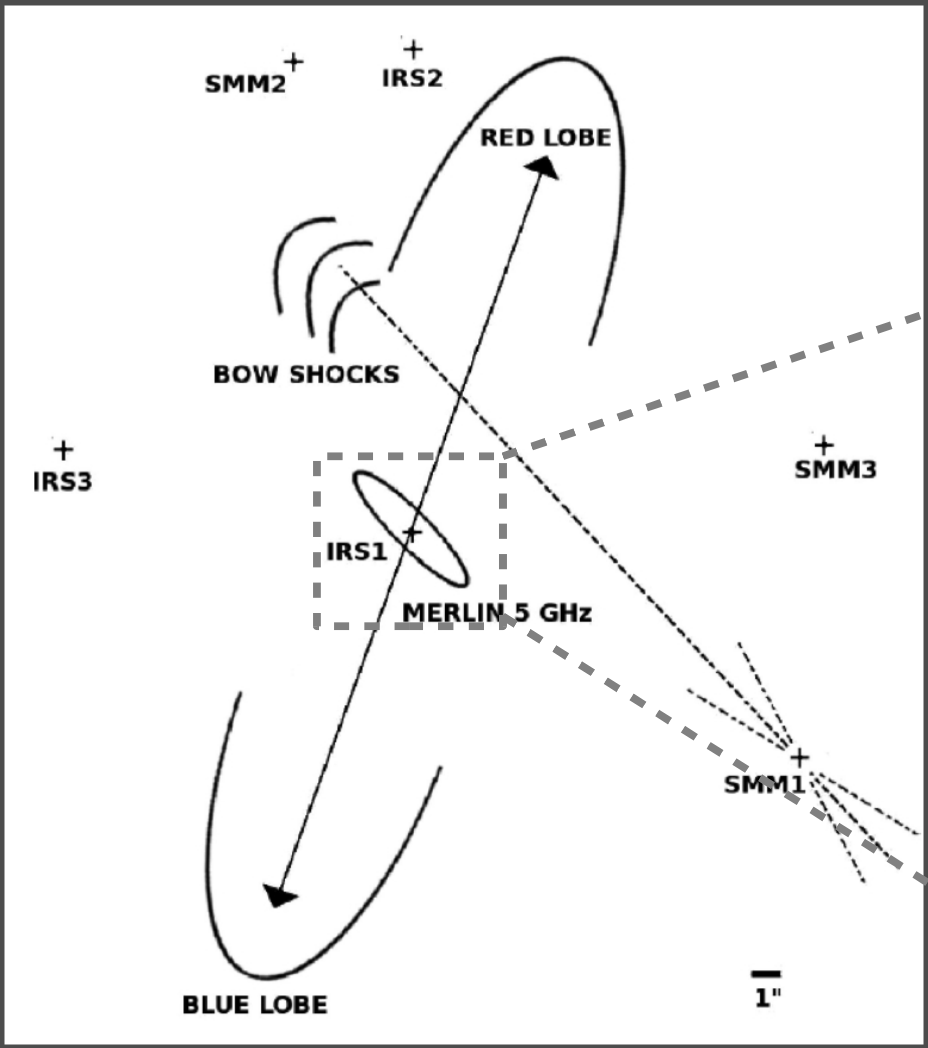
Outflow lobe position and radio emission not to scale



Maud et al 2013

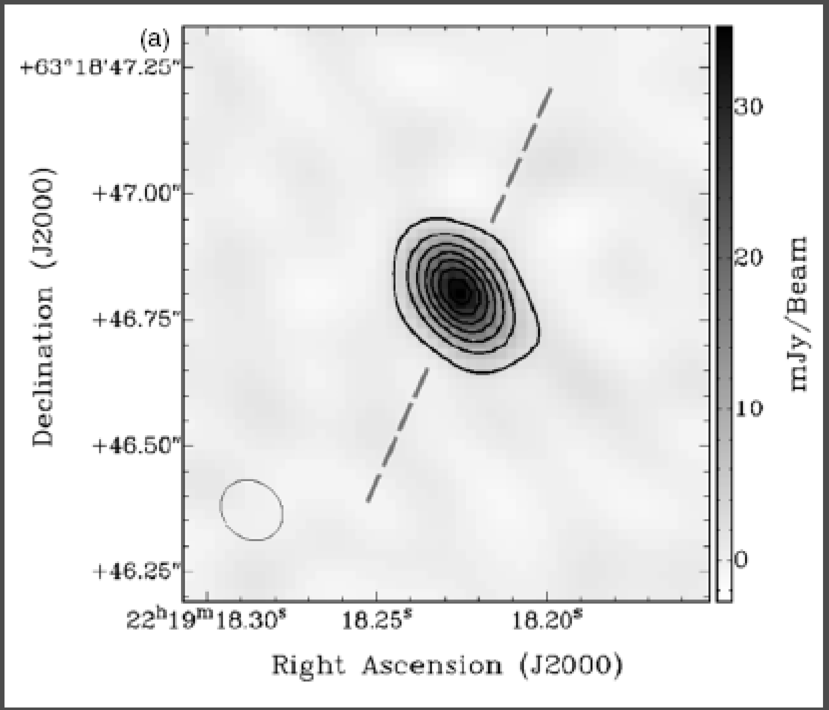
- Elongation – PA ~35 deg – rules out jet
- <u>Comprehensive models require a central disc</u>

S140 - IRS1



Outflow lobe position and radio emission not to scale

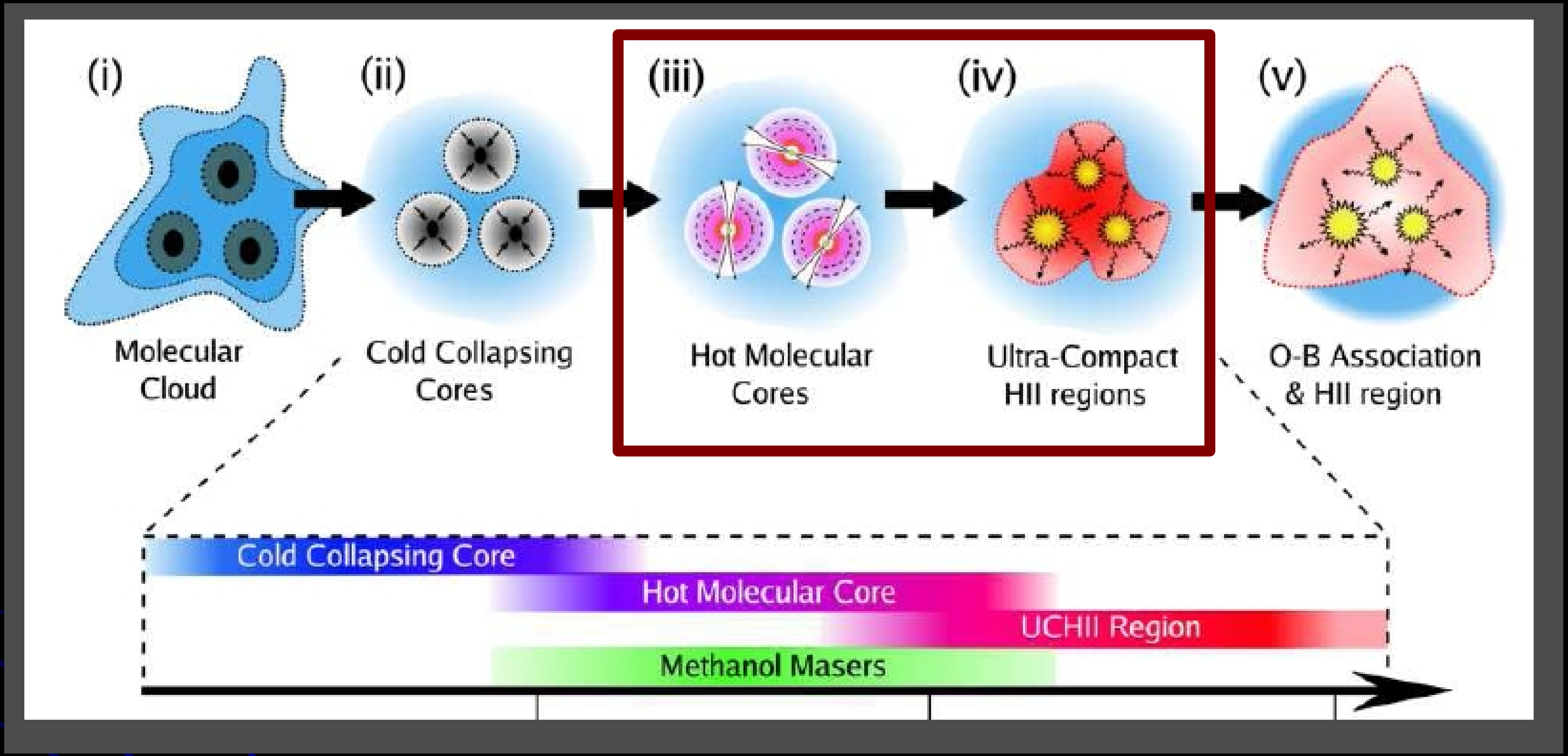
- CARMA A – 1.3 mm, 0.1” res, scales <100au
- Dust disc resolved in continuum
- PA ~43 deg. matches 5 GHz emission



Maud & Hoare 2013

- Disc detection confirms 'disc wind' nature of radio emission – implications on feedback ....

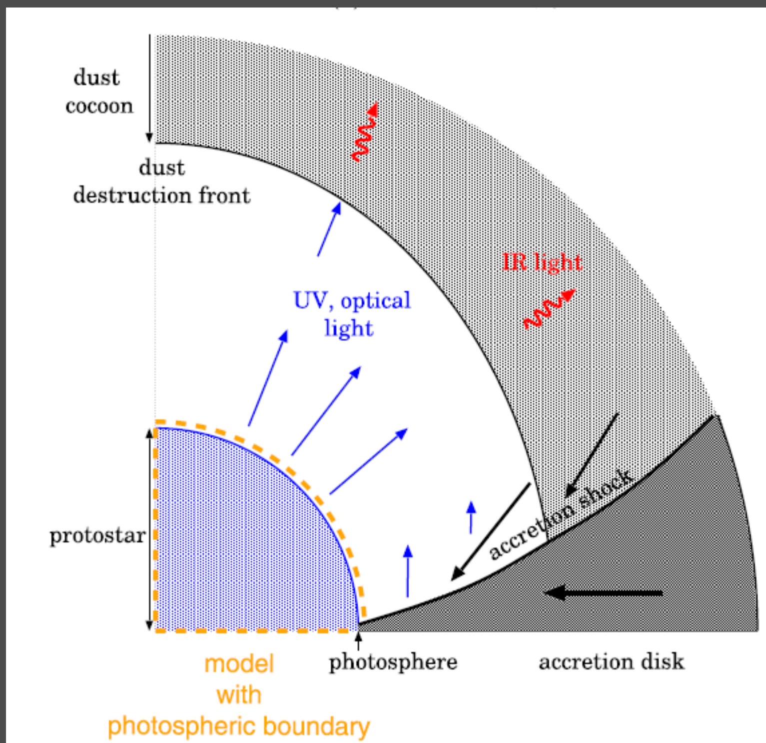
The MYSO to UCHII transition

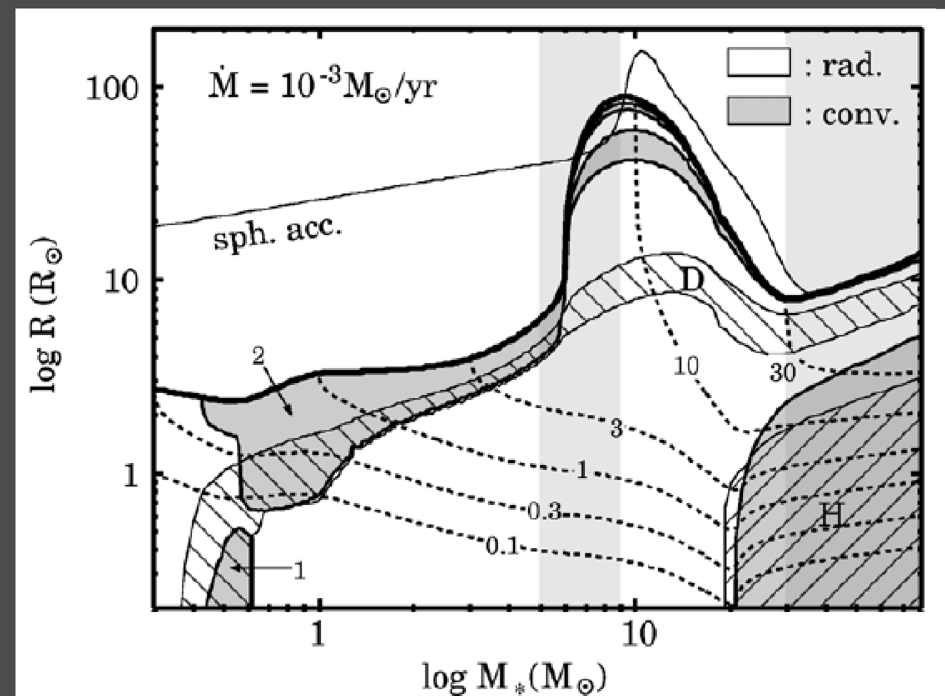


- L > 10^4 L⊙ sources should emit copious Lyman Continuum – **but MYSOs have no HII**
- Quenching? Perfectly spherical infall required – neglects outflows/winds & density asymmetry
- HII region propagating along jet – narrow radio jets, disagree with observations
- MYSOs not generating Lyman Cont. - **swelled star with low effective temperatures**

Hoare & Franco 2007

The MYSO to UCHII transition

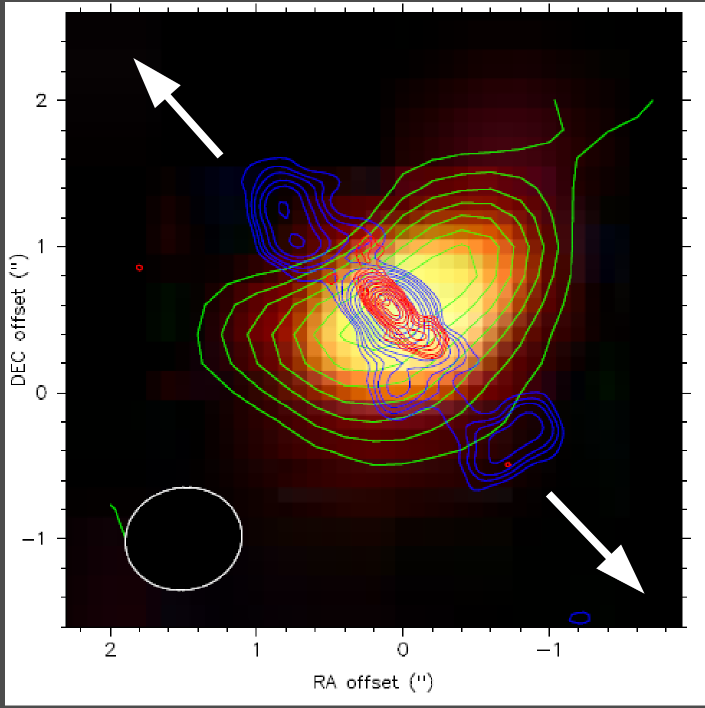




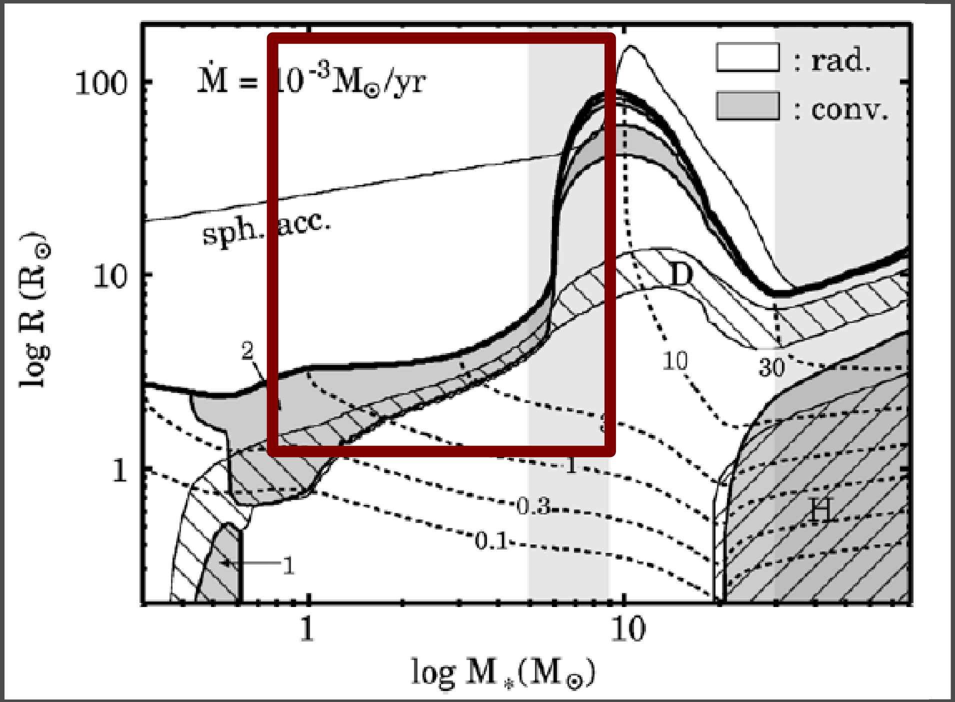
Hosokawa et al. 2009 & 2010

- High accretion rates – convection, swelling, contraction, MS accretion stages
- Low UV luminosity delays onset of HII region (explains MYSOs with L > 10^4 L⊙)

The MYSO to UCHII transition



CEP A HW2 - Patel et al. 2005



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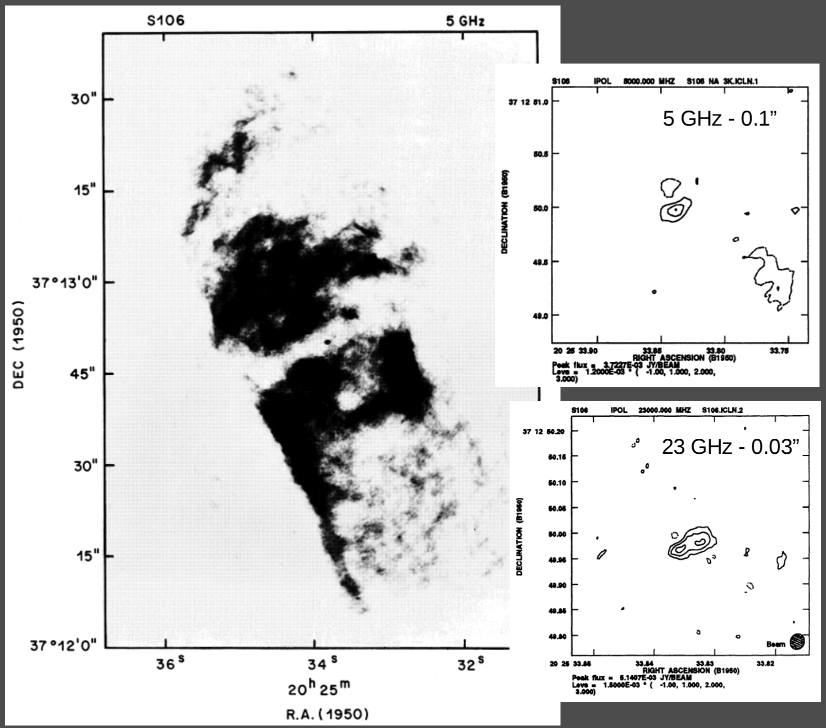
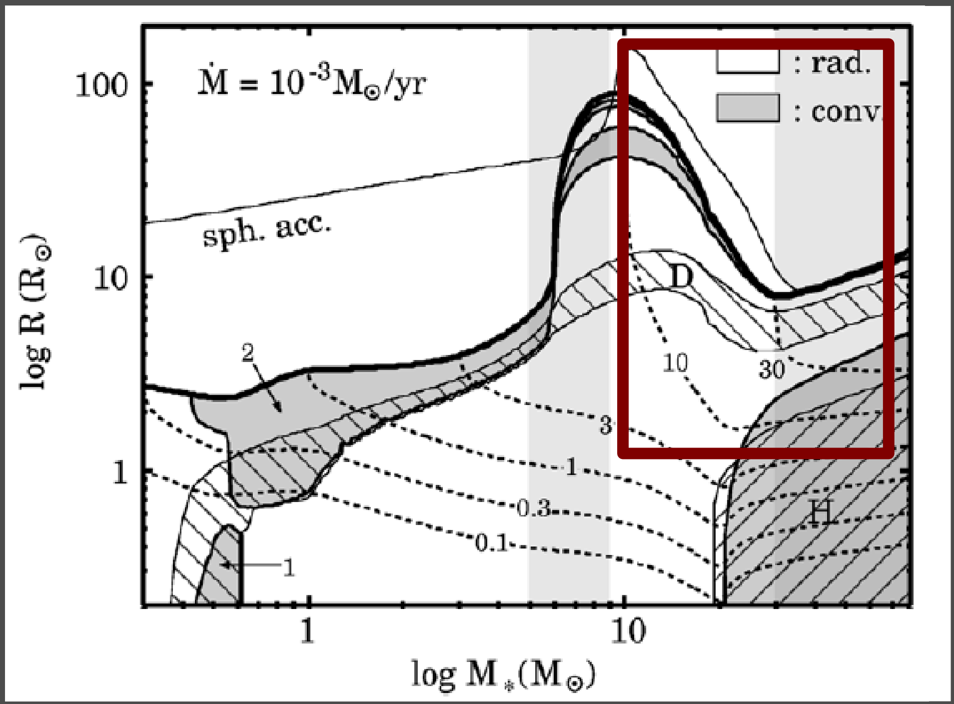
- **Early convection – MHD driven jets** (Cep A HW2, GGD 27, AFGL 2591)

The MYSO to UCHII transition



S106 -Bally et al 1983 (0.5") inset: Hoare et al 1994 & 1996



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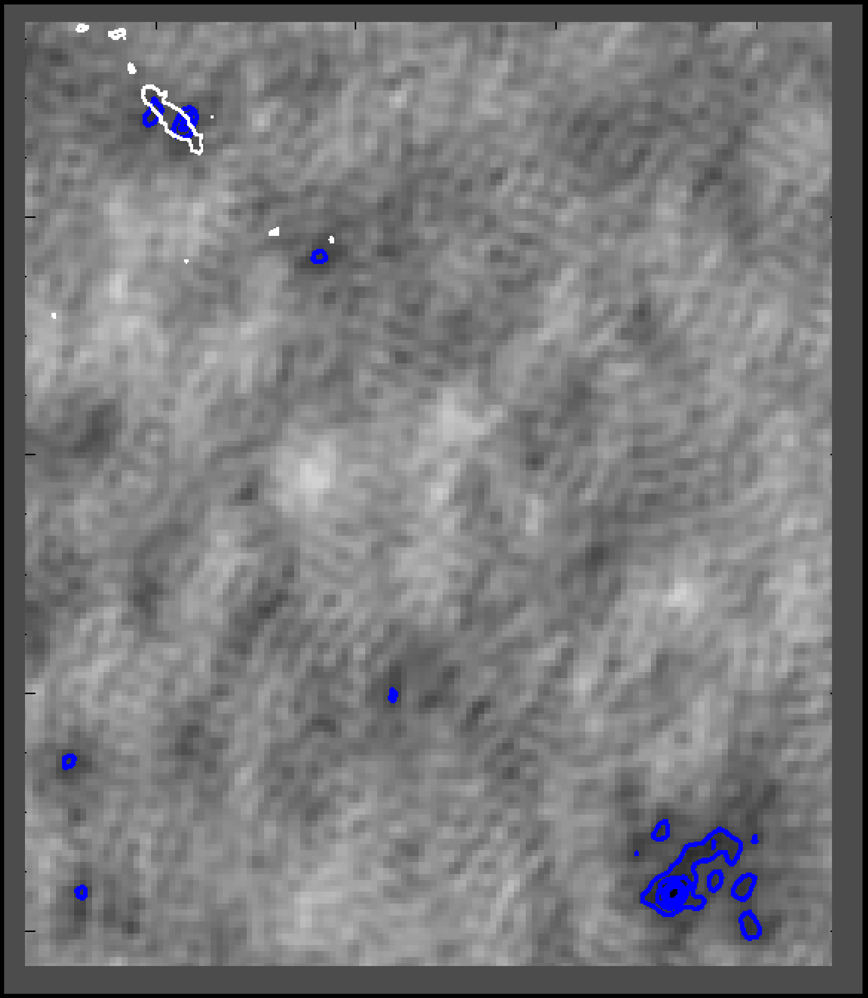
- **Early convection – MHD driven jets** (Cep A HW2, GGD 27, AFGL 2591)
- **Contracting (near MS) – UV photons ionizing disc and cavity (bipolar HII region)**

(**S140 IRS1**, S106 IR, GL490?)

e-MERLIN cycle 0 data

S140 – IRS1 – A key evolutionary source

- Right at transition stage
- Observed at L-band (complementary scales to CARMA A)
- Lateral continuation of disc wind or redirection into bi-polar configuration?
- Clues to evolutionary status



- IRS1 detected
- Noise too high to see faint emission...

e-MERLIN legacy program

Feedback Processes in Massive Star Formation

- Deep 5 GHz observations of 75 massive young protostars
- Embedded (active IRDCs) to IR bright (MYSOs)
- Address when MHD jets 'turn on' and at what stage they evolve into radiatively driven disc winds, and eventually bi-polar HII regions
- e-MERLIN uniquely positioned to offer resolution, fidelity and sensitivity

- JCMT outflows for jet/disc wind
- VLA follow ups (underway) for extended structure + spectral index
- CARMA, ALMA, PdBI sub-mm/mm follow-ups

  - these are beginning to resolve the disc/toroid structure

  - CARMA data taken for some sources
- e-MERLIN complementary L-band observations of other key sources

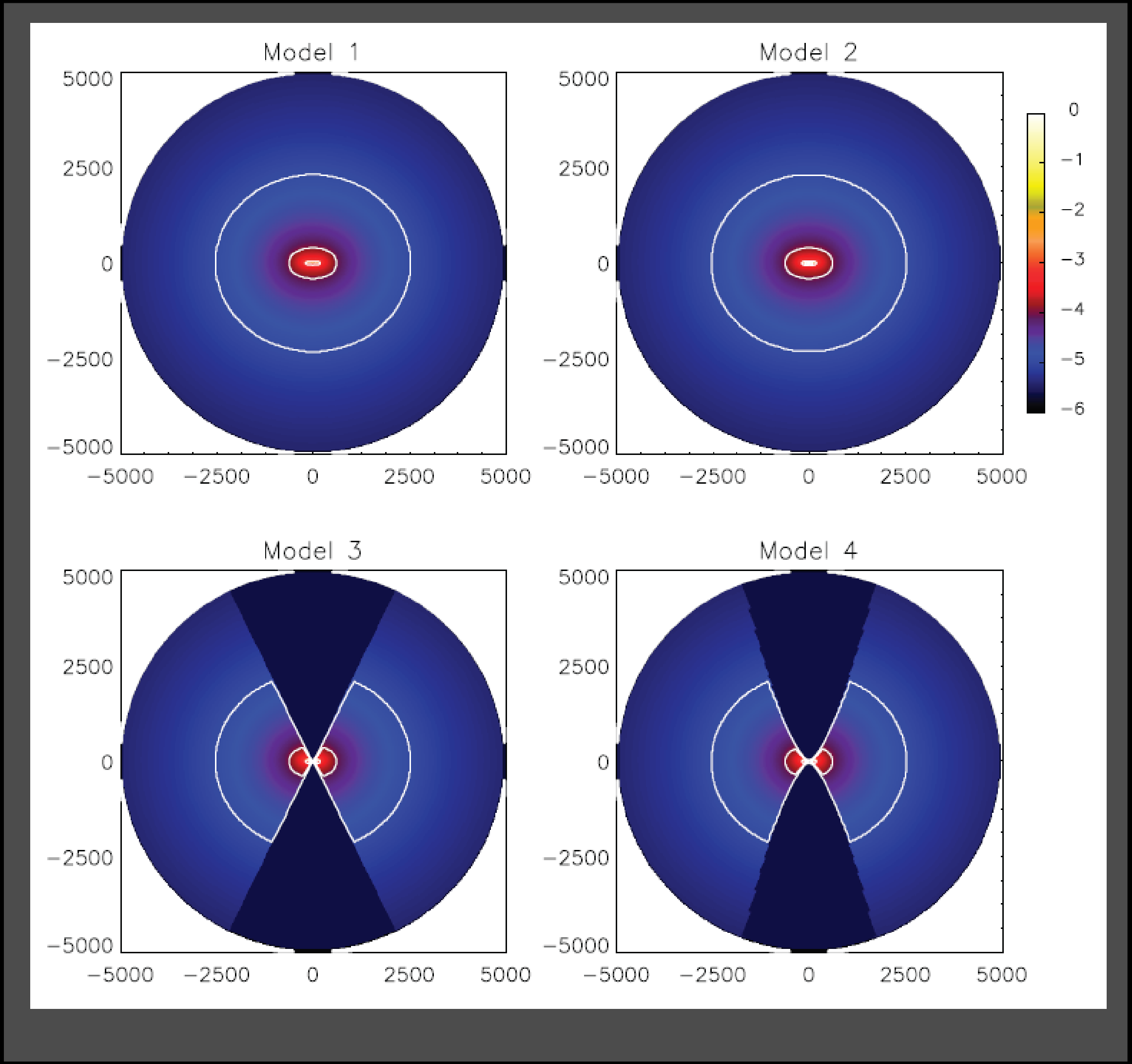
Summary

- **Confirmed** dusty disc around S140 IRS1
- S140 IRS1 **different** – ionized equatorial disc wind source – key evolutionary stage
- L-band cycle 0 currently inconclusive
- Legacy program to begin piecing together evolutionary stages
- Continual follow ups (sub-mm/mm) at complementary resolution

Modelling

- **Compare** observations and modelled region
- Whitney - 2D Axisymmetric Radiative Transfer model
- Standard flared disc prescription

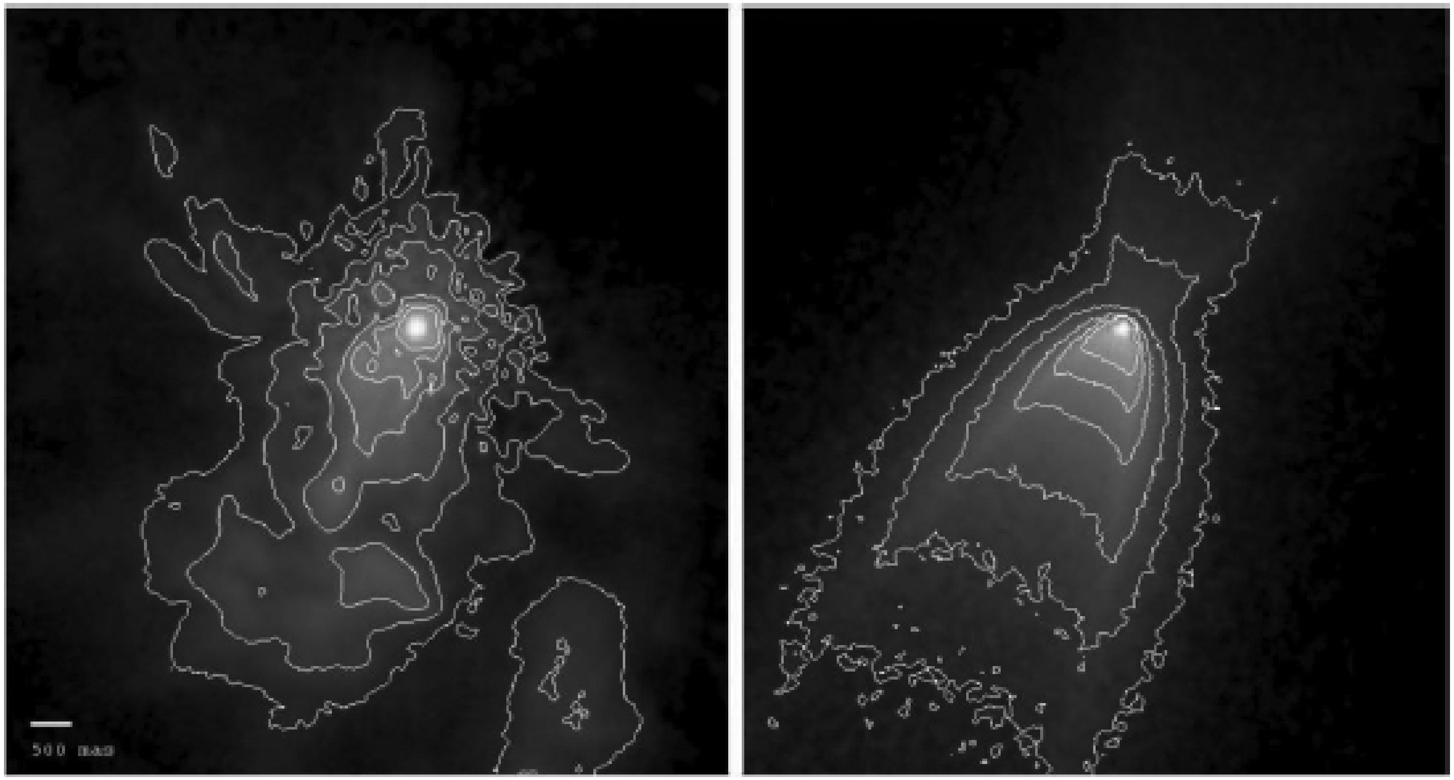
- Use sensible inputs and **refine**
- Compare **without** and **with** a disc



Whitney et al. 2003 (ApJ 591:1049-1063)

Modelling

- **IR Scattering only model** (Whitney et al. 1992) for general geometry
- $L \sim 8.5 \times 10^3 L_\odot$, $T = 25000$ K, $M = 11.1 M_\odot$, $R_* = 4.92 R_\odot$, $R_{outer} \sim 23000$ au

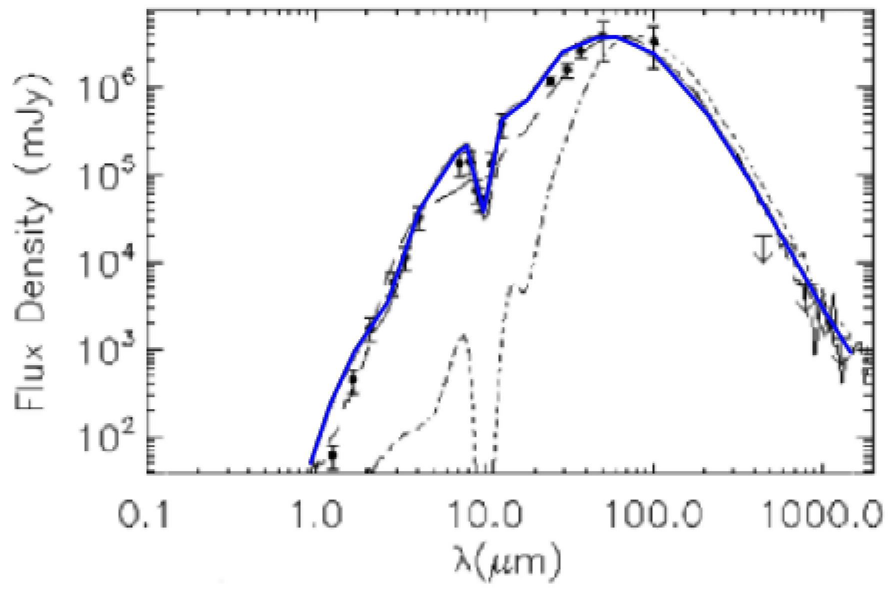


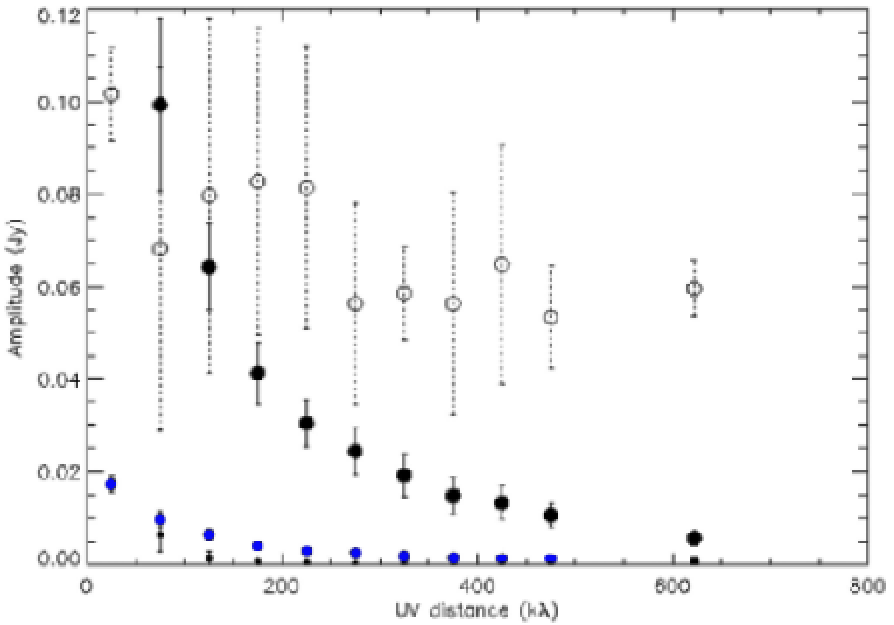
- Find inclination 40-60^o and cavity half angle 7^o

Modelling

- Thermal model → Ray tracing code → mm model images → MIRIAD → simulated interferometric images
- **Simultaneous** comparison of SED and mm visibilities

NO DISC SED VISIBILITIES FLUX IMAGE





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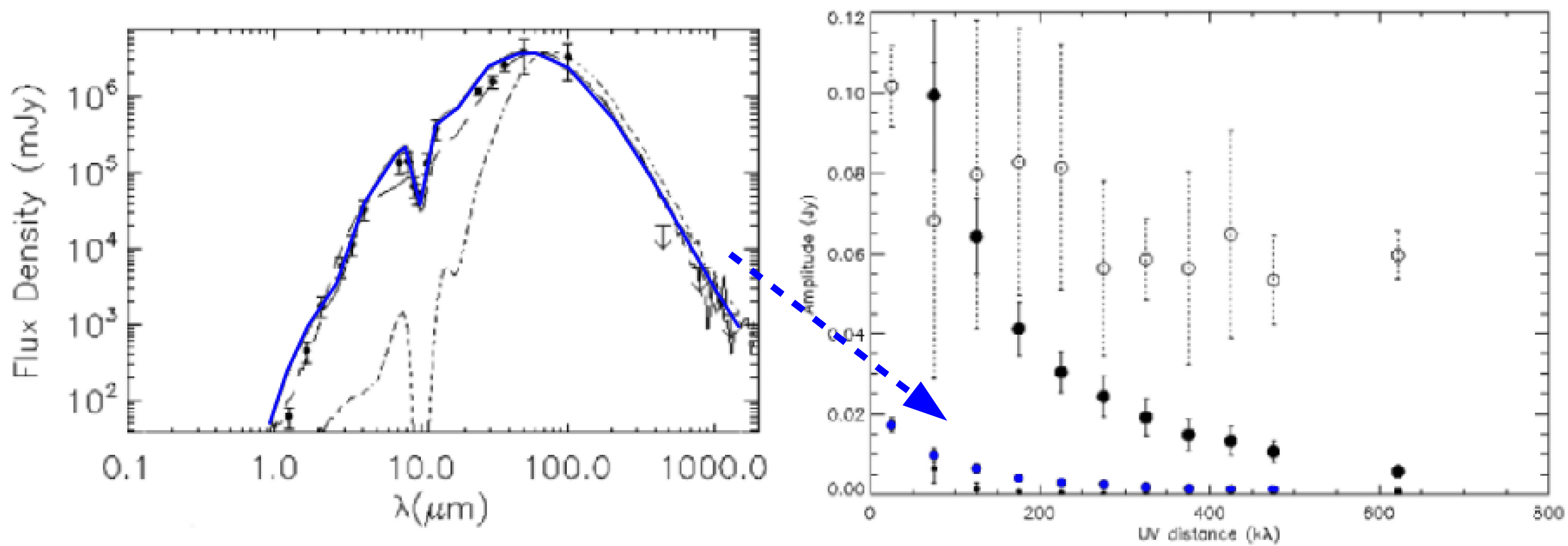
<u>NO DISC</u> SED ✓ VISIBILITIES FLUX IMAGE



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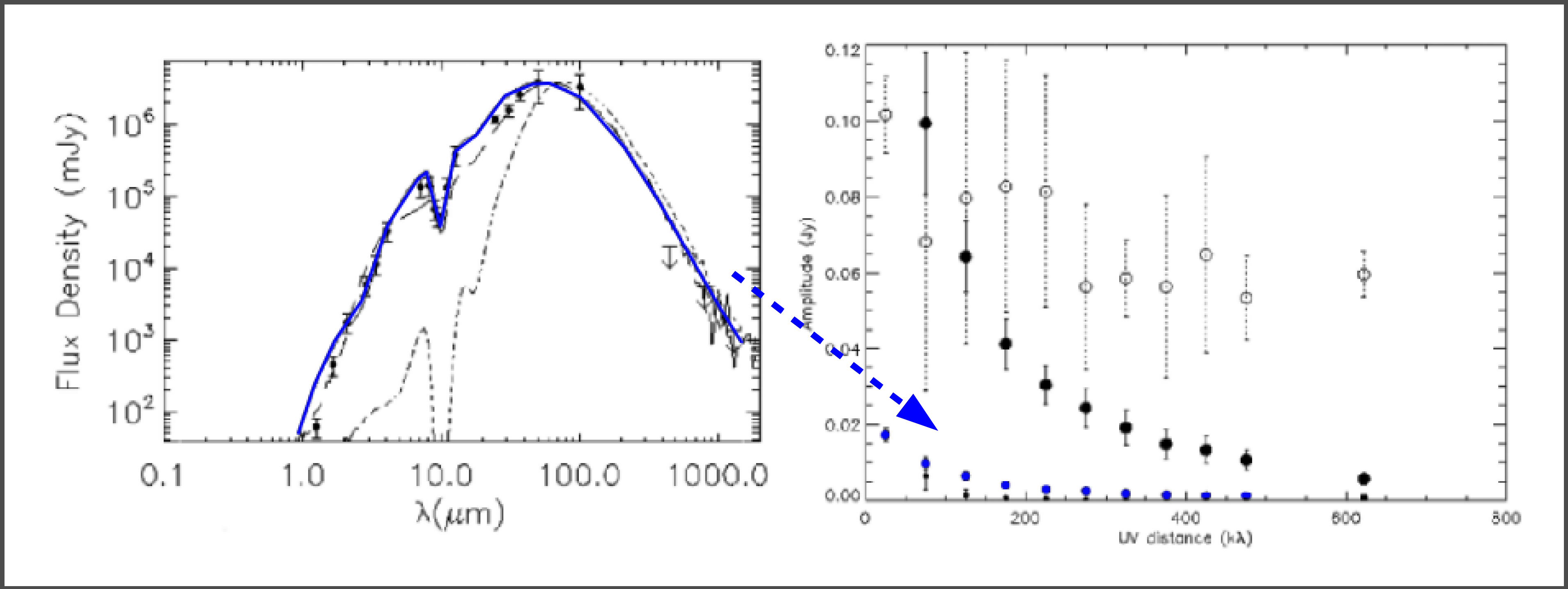
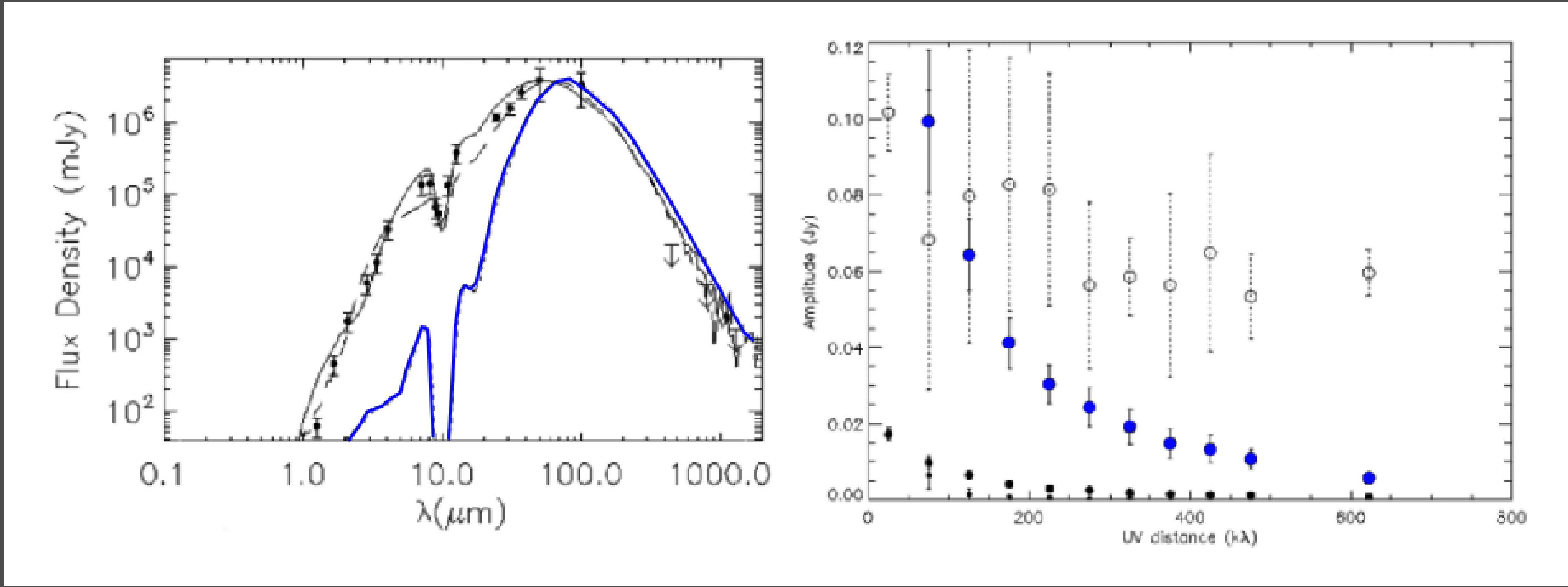
NO DISC SED VISIBILITIES FLUX IMAGE



Modelling

- Need **more mm** flux → **Increase** infall

NO DISC SED VISIBILITIES FLUX IMAGE



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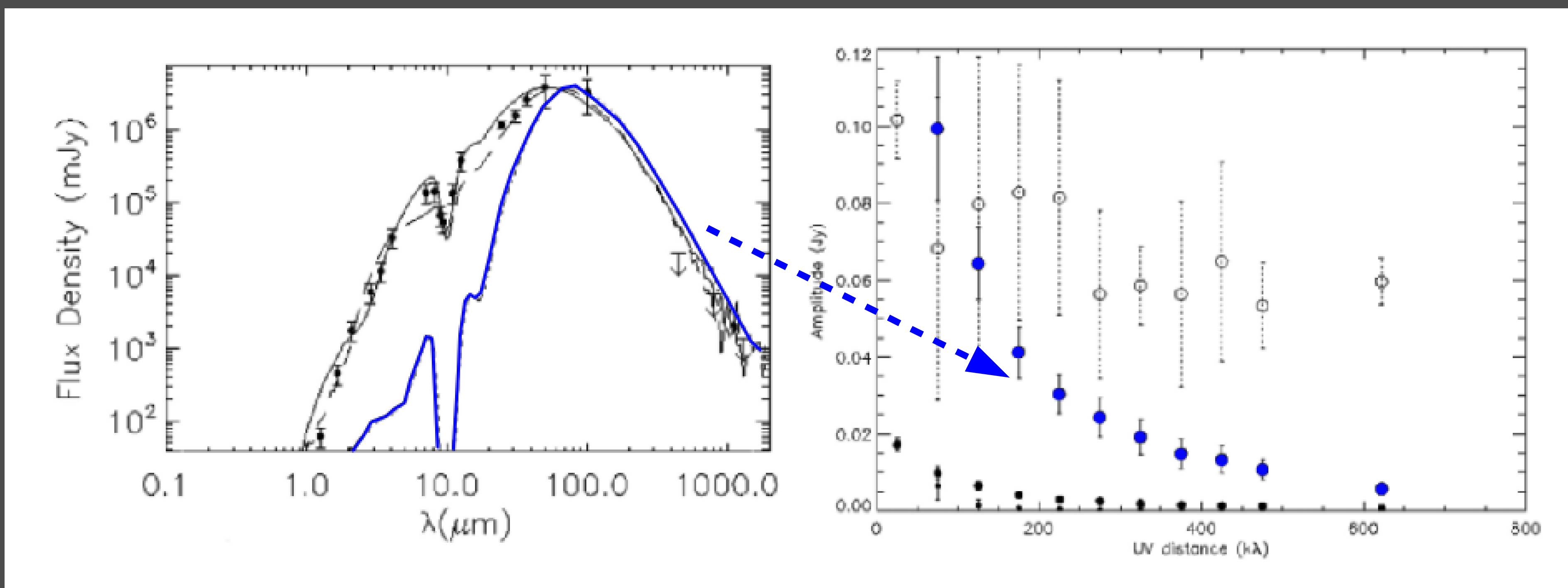

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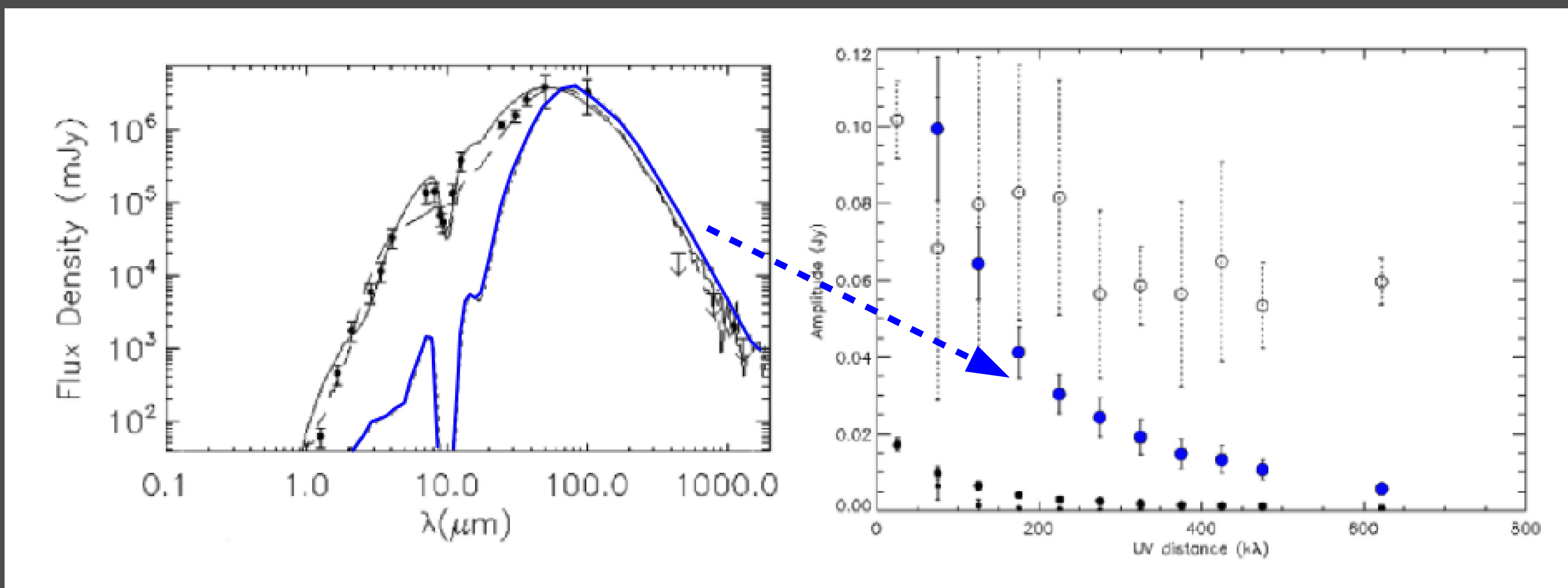
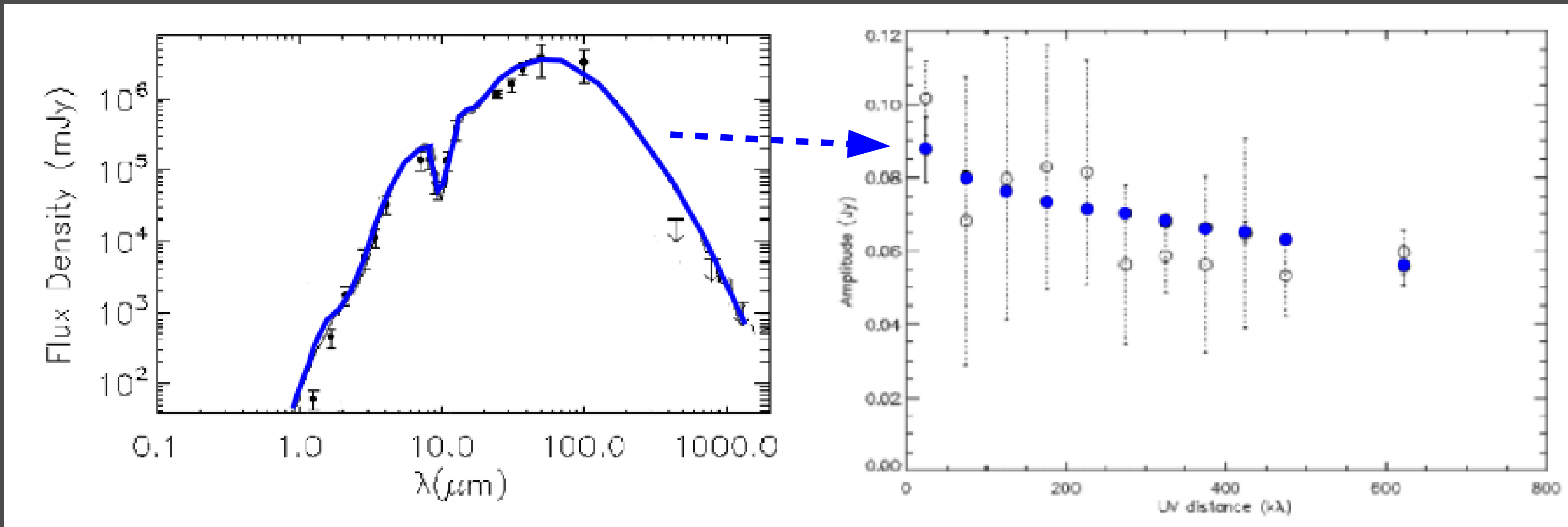


- Flattened envelope only **CANNOT** provide flux on smallest scales

Modelling

- Best Envelope only model **plus** a disc → Variable **mass** and **radius**
- Constant density distribution degeneracy
- Fix radius at 60 au → $X^2_{VIS} < 1$ when mass 0.012-0.020 M⊙*

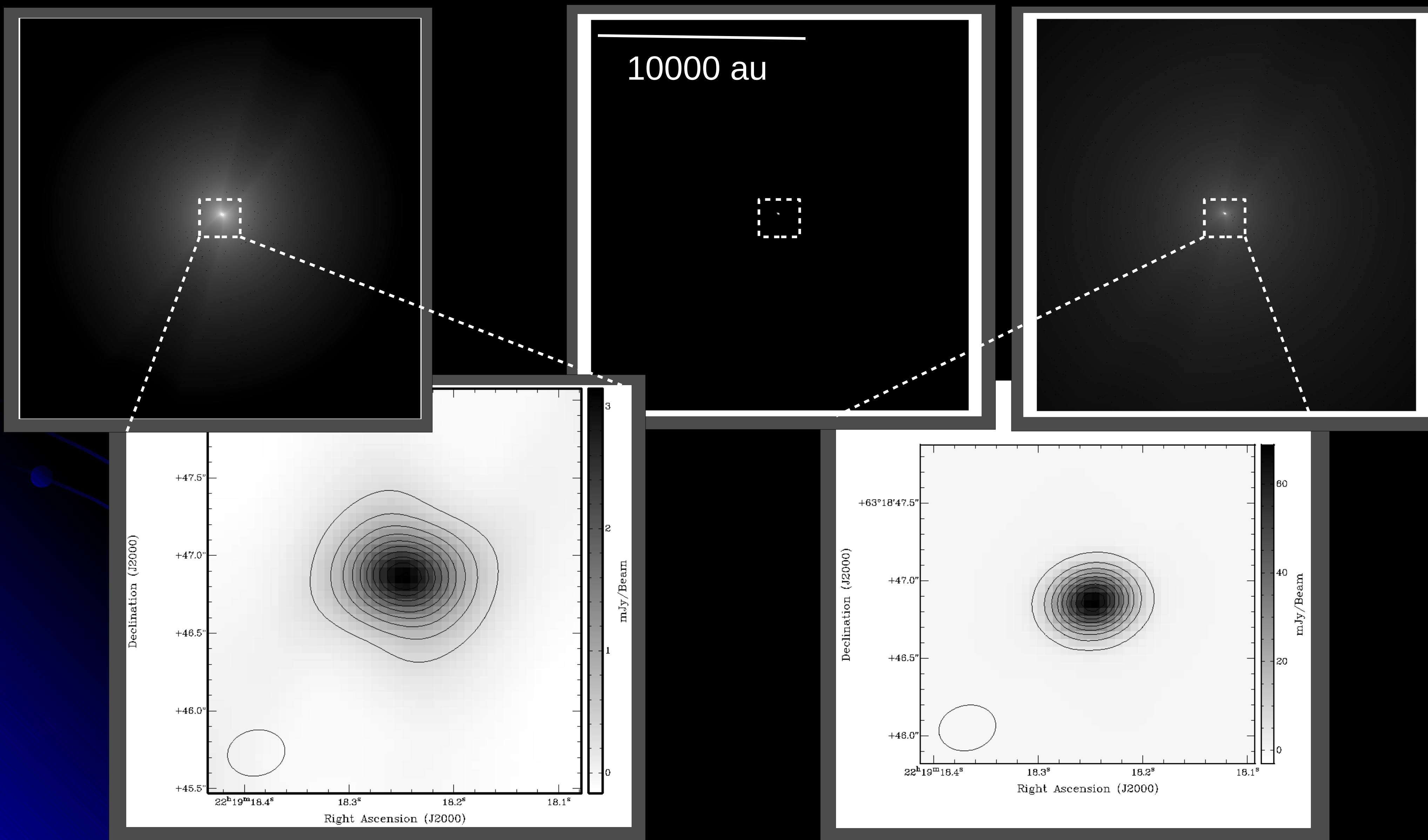
WITH DISC SED ✓ VISIBILITIES ✓ FLUX ✓ IMAGE ∿



- A disc is **required** to **match** all observables

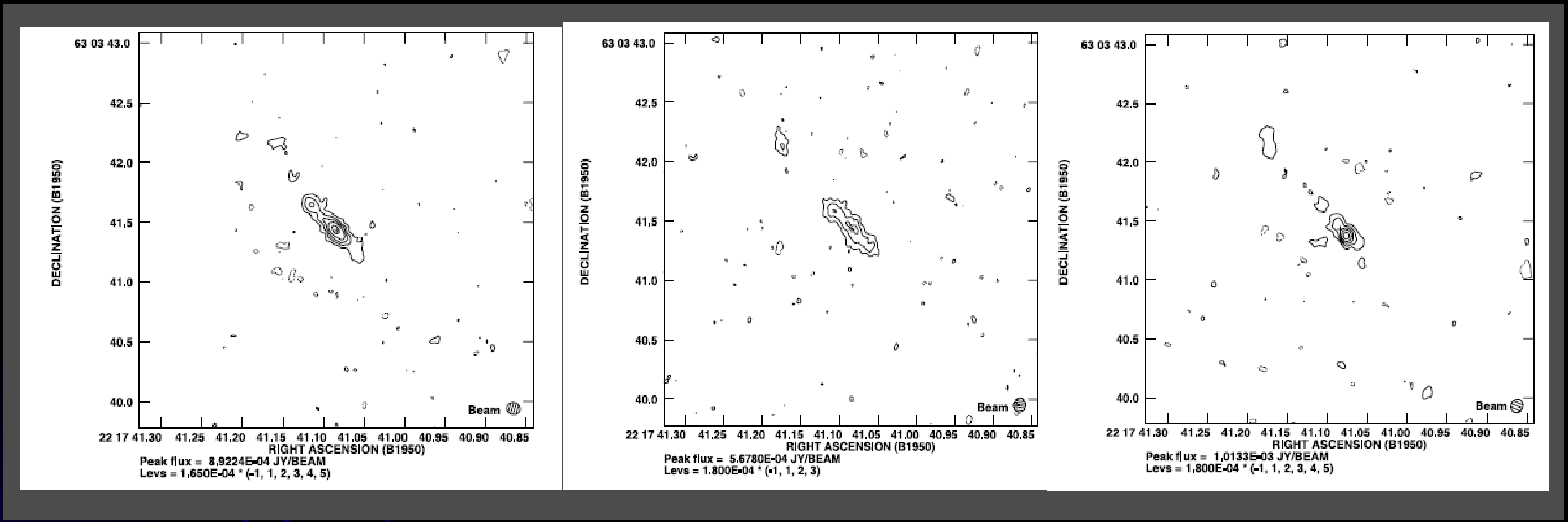
Modelling

- Model image ➔ MIRIAD ➔ simulated interferometer image



S140 – IRS1

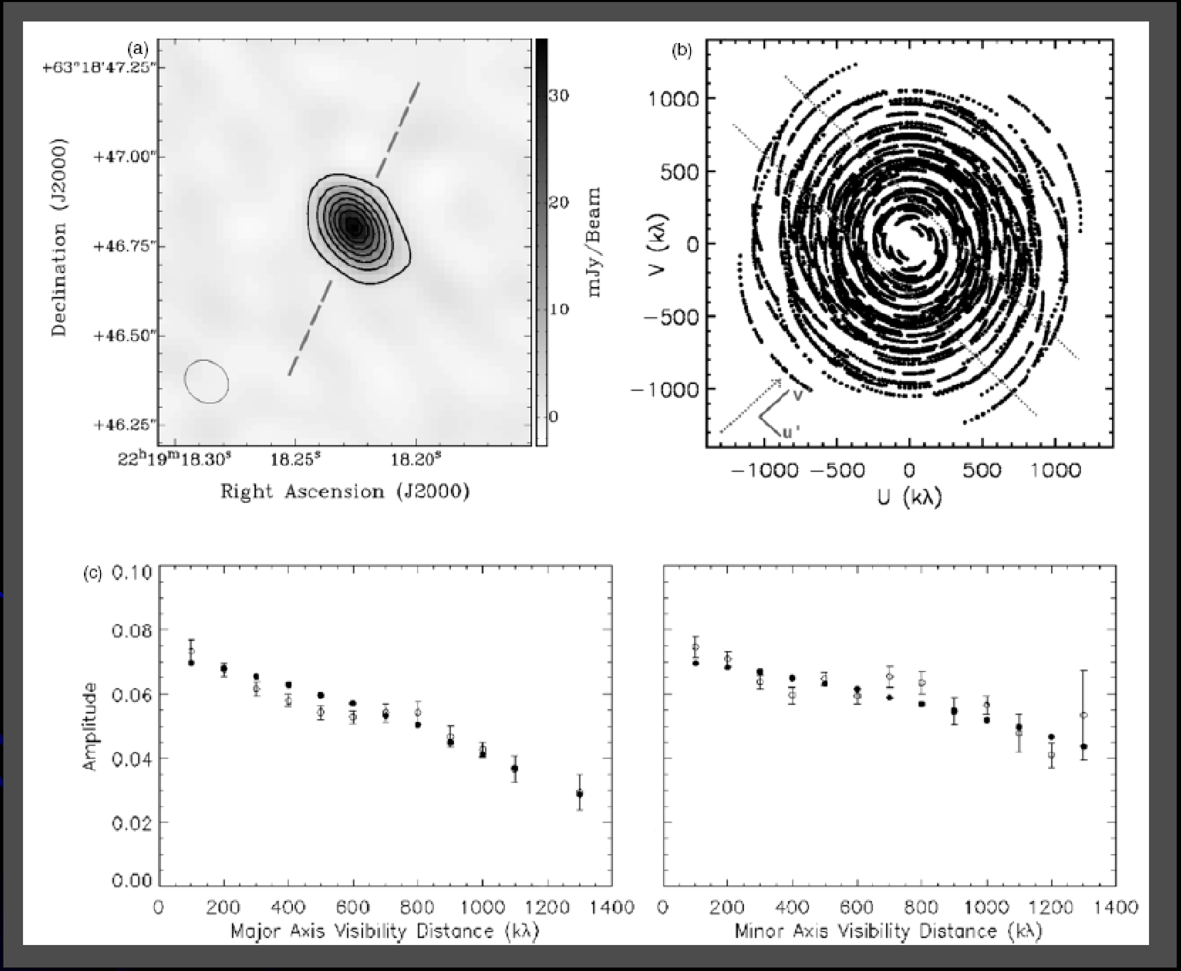
- **Multi-epoch** observations (1995 -2000) with MERLIN
- **No proper motion**, as would expected from a jet (Hoare 2006)



- Second case of an ionized equatorial wind, similar to the more evolved HII source S106 (Hoare et al. 1994)

S140 – IRS1 – CARMA A

- 2D visibility analysis
- Compare models and observations at various PA's
- Independent of beam PA

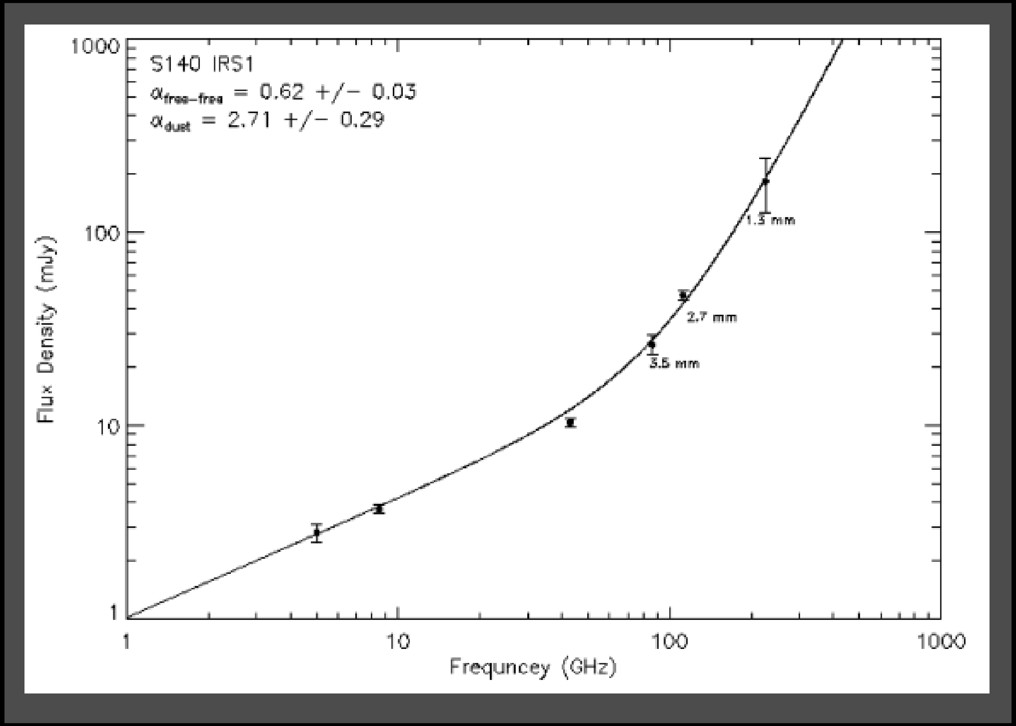


OVRO / SMA – Spectra Index

- Unresolved emission - must **match** synthesized beams – **restrict** u,v range
- **Concordant** resolution 1.3, 2.7 & 3.5 mm images
- **Subtract** free-free ionized contribution
- Dust **only** spectral index

  α_{dust} = 2.7 +/- 0.3

  β_{dust} ~ **0.7**
- **Lower** than hot cores β ~ 1-2
- Extended grain size distribution?
- Grain growth → disc?
- Optical depth ?



OVRO / SMA – Spectra Index

- Produce simulated images for SMA and OVRO (unresolved 'blob')

Obs.	Int (ff sub)	Model	Int (ff sub 5-35 kλ)	Model (5-35 kλ)
Carma B	68±5	79	.....	.....
SMA	117±29	143	154±57	174
OVRO 112	27±5	21	28±4	22
OVRO 86	15±4	9	10±3	8

- Modelled spectral slope too steep – dust opacity index β_{dust} ~ **1.2**
- Dust types not perfectly suited – future investigation – **more larger** grains
- Input dust opacity index range from β_{input}~ **1.3 – 1.5**
- Propagation through density and temperature structure **reduce** slope by ~ **0.2**
- **Measured** dust opacity likely **steeper**, $\beta_{dust\ obs}$ ~ **0.9**

OVRO – Channel Map

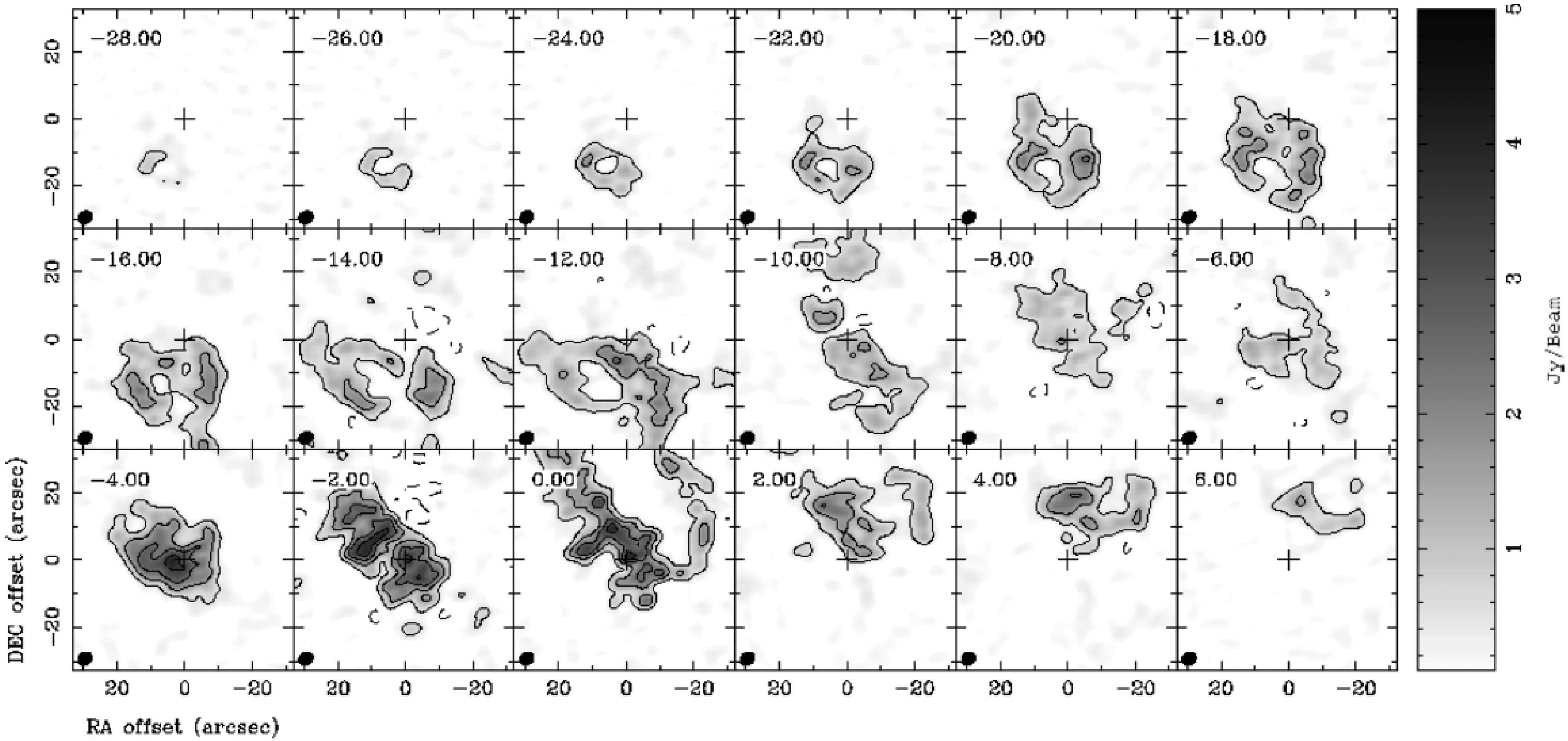


Figure 5. Channel map for OVRO CO(1–0) emission. The plus symbol marks the location of IRS1. The velocity is indicated in the top-left of each subplot and is in km s^{-1}. The OVRO beam for the line observations is indicated in the lower-left of each subplot and is 4.3 × 3.5 arcsec with a PA of −60.7°. The grey-scale images show all emission from 1σ of 97 mJy $beam^{-1}$ as measured from line free channels up to the peak emission. Contour levels are from 5σ to the peak in steps of 1 Jy. The distinct offset of the blue-shifted outflow lobe in the SE and the red-shifted lobe in the NW is clearly evident.

SMA – Channel Map

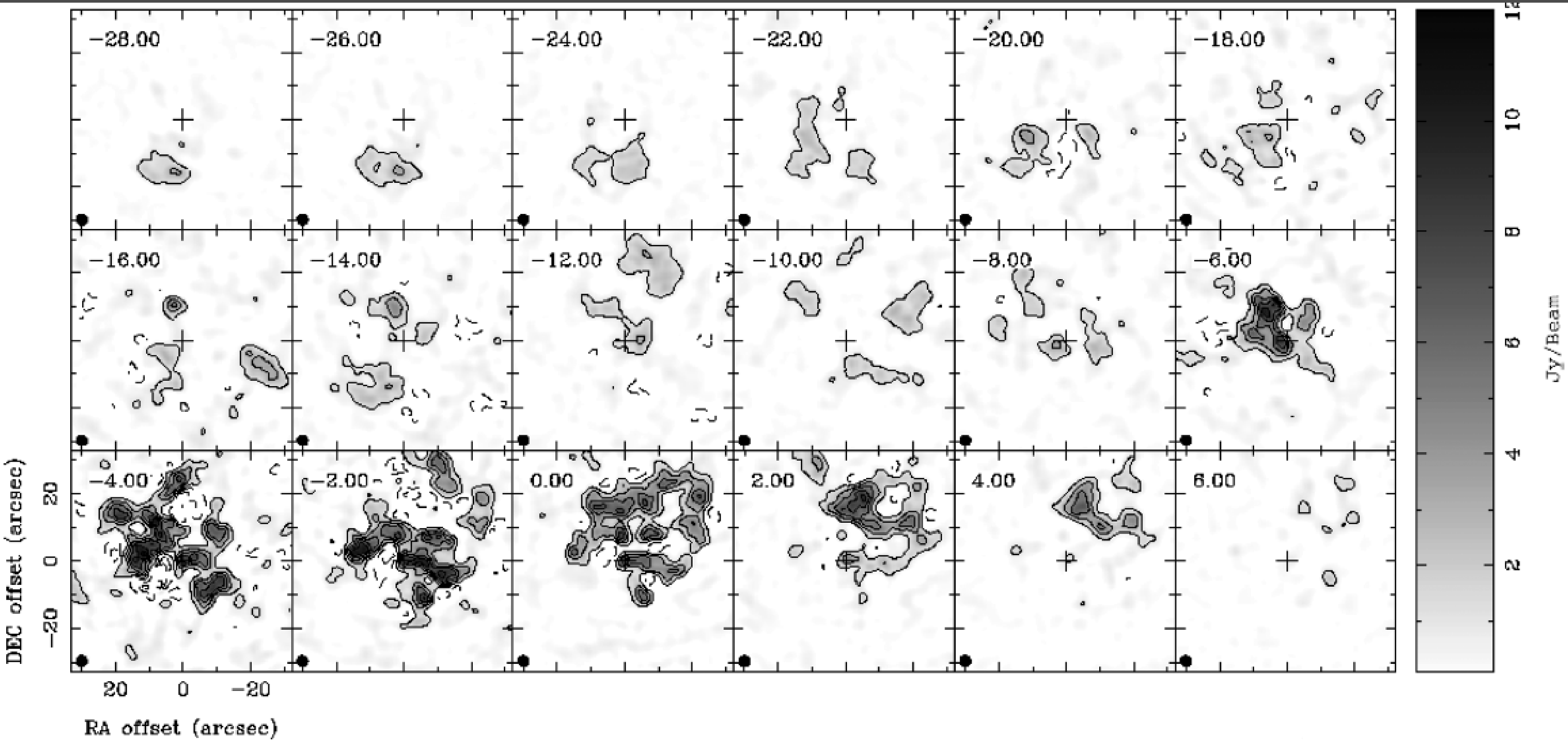


Figure 6. Channel map for SMA CO(2–1) emission. Velocities and IRS1 position as in Fig. 5. The beam size of 3.2 × 2.9 at PA of 72.4° is indicated in the lower-left of each subplot. The grey-scale images show emission from 1σ of 86 mJy beam^{-1} as measured from line free channels to the peak emission. Contours are from 10σ to the peak in steps of 2 Jy. As in Fig. 5, the shift from the blue lobe in the SE to the red lobe in the NW is evident. Note how the diffuse emission in the core region is broken up into many peaks due to the interferometer sampling and use of the clean algorithm.