Probing the Molecular Outflows of the Coldest Known Object in the Universe The Boomerang Nebula

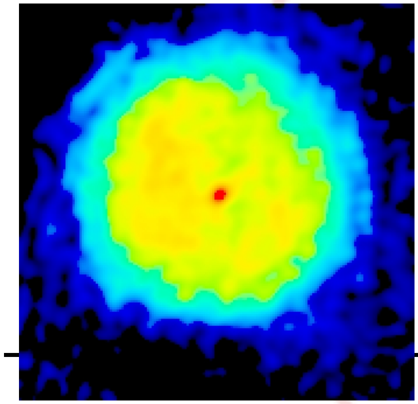
R.Sahai (JPL)
W. Vlemmings, L-A Nyman & P. Huggins

The Extraordinary Deaths of Ordinary Stars

- Planetary nebulae (PNe) evolve from AGB stars (which represent the late evolutionary fate of 1-8 Msun stars). AGB stars are generally very luminous, and lose half or more of their mass to form circumstellar envelopes (CSEs) which appear to be mostly round.
- But very few PNe are round. Most show a variety of bipolar, multipolar or elongated shapes, many with a high degree of point-symmetry (e.g., HST survey: Sahai, Morris & Villar 2011).

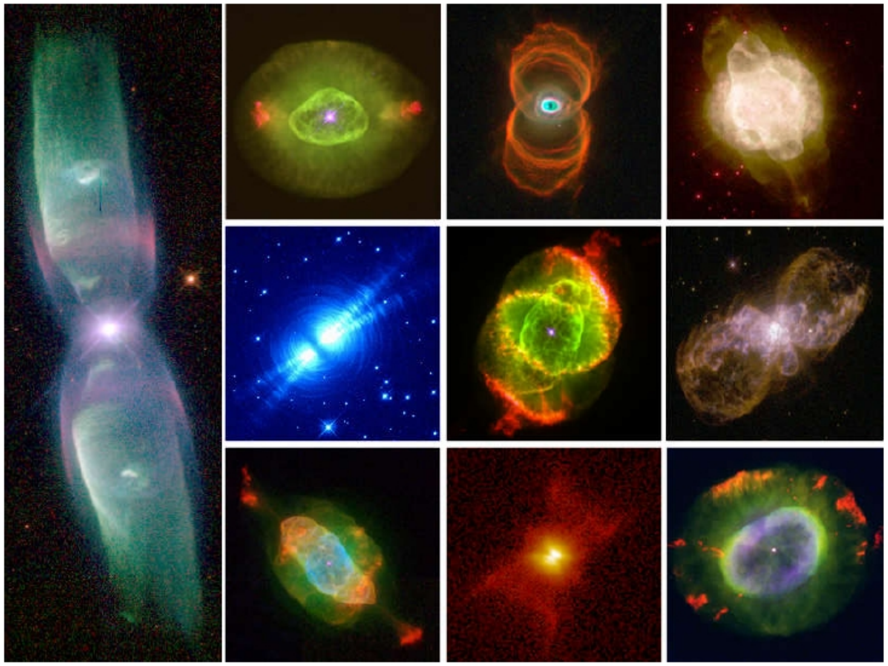
One of the most interesting unsolved questions in late stellar evolution is how the round AGB CSEs evolve into the myriad of shapes that are seen in the PNe stage (e.g., review by Balick & Frank 2000**). What is the mass-loss history & the responsible physical mechanisms?**

Based on the morphologies seen in an unbiased HST imaging survey of young PNe, *Sahai & Trauger (1998)* proposed that (episodic) collimated fast winds or jets, operating during the Pre-PN (PPN) or very late-AGB phase, are the primary agent for producing asymmetric shapes in PNe



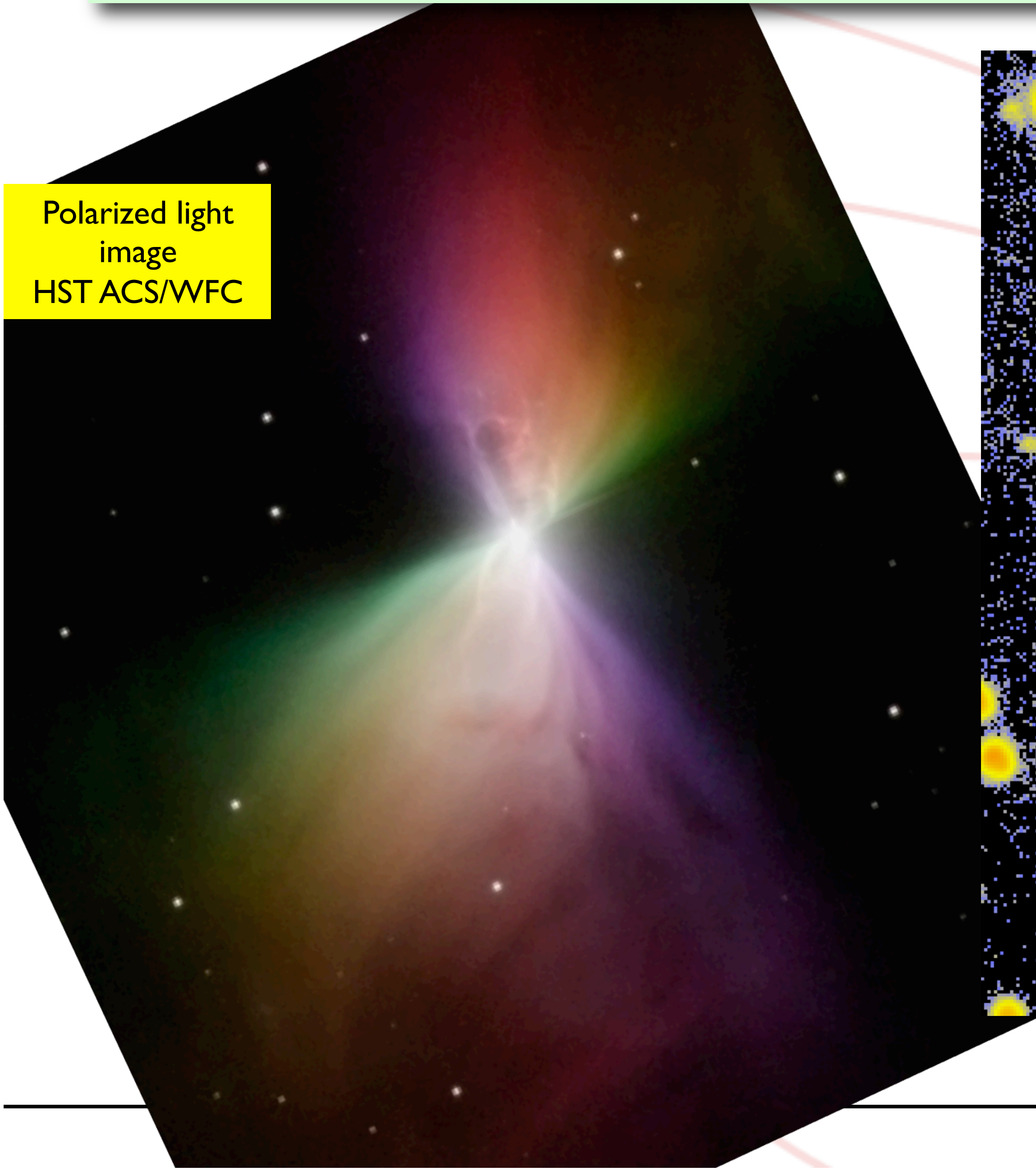
Molecular gas in AGB star IRC +10216 (EVLA: Claussen)

Detailed Studies of "extreme" PPNe provide the most stringent tests of formation hypotheses

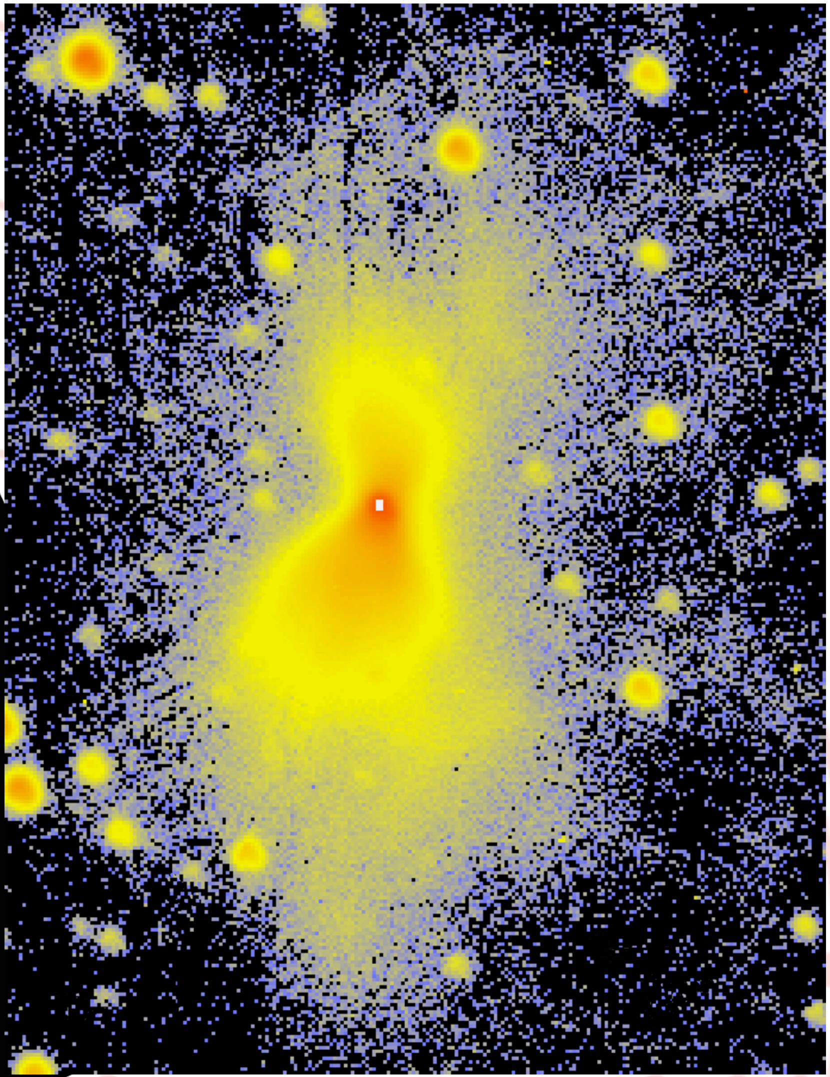


A montage of PNe and PPNe imaged using the HST by Balick, Bond, Sahai, and collaborators

An Extreme Bipolar PPN: The Boomerang Nebula



Polarized light
image
HST ACS/WFC



Ground-based R-band image

Binary and/or magnetic fields?

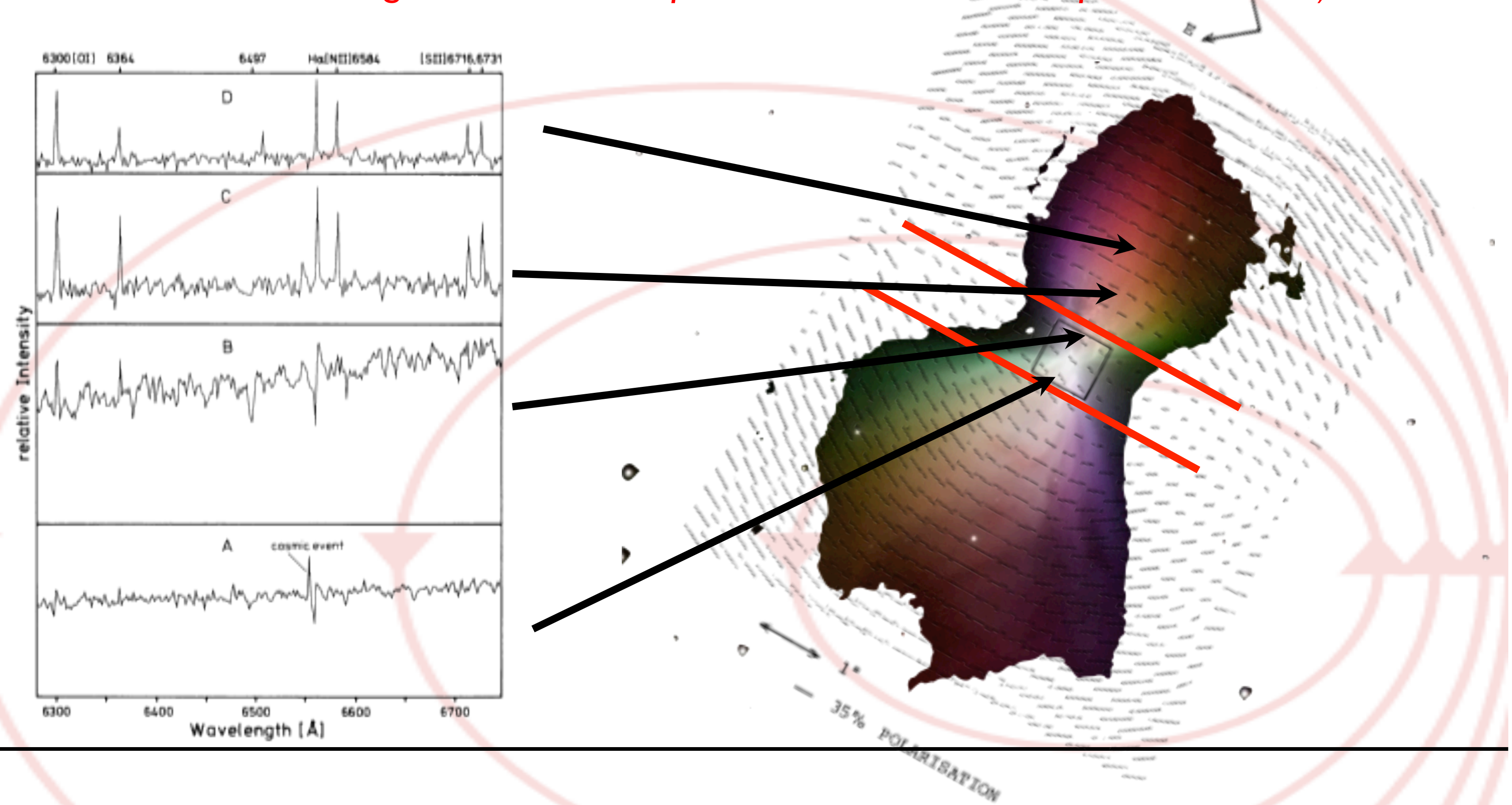
- 1-2 M_{sun} binary pair?

  Spectra indicate potential N-S binary separated by 1”-2” (Neckel et al. 1987)

- Strong magnetic fields?

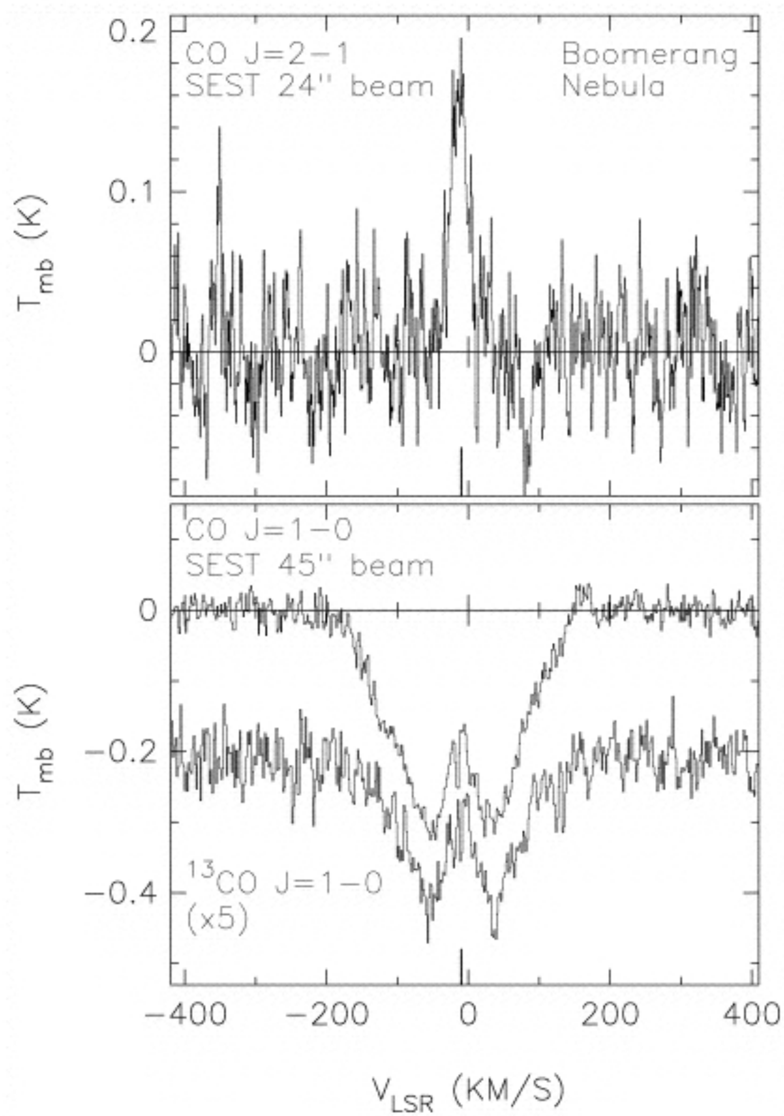
  High (anomalous) optical polarization in torus: aligned dust grains? (Taylor & Scarrott, 1980)

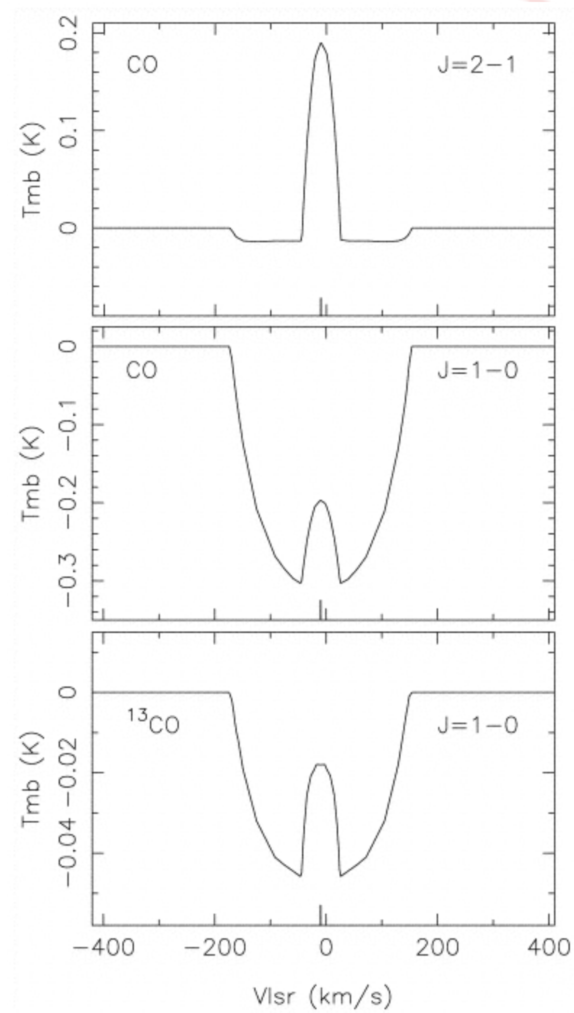
  (But these conclusions must be regarded as rather speculative, as alternate explanations exist)



The Boomerang Nebula is...

- *The coldest object in the universe!*





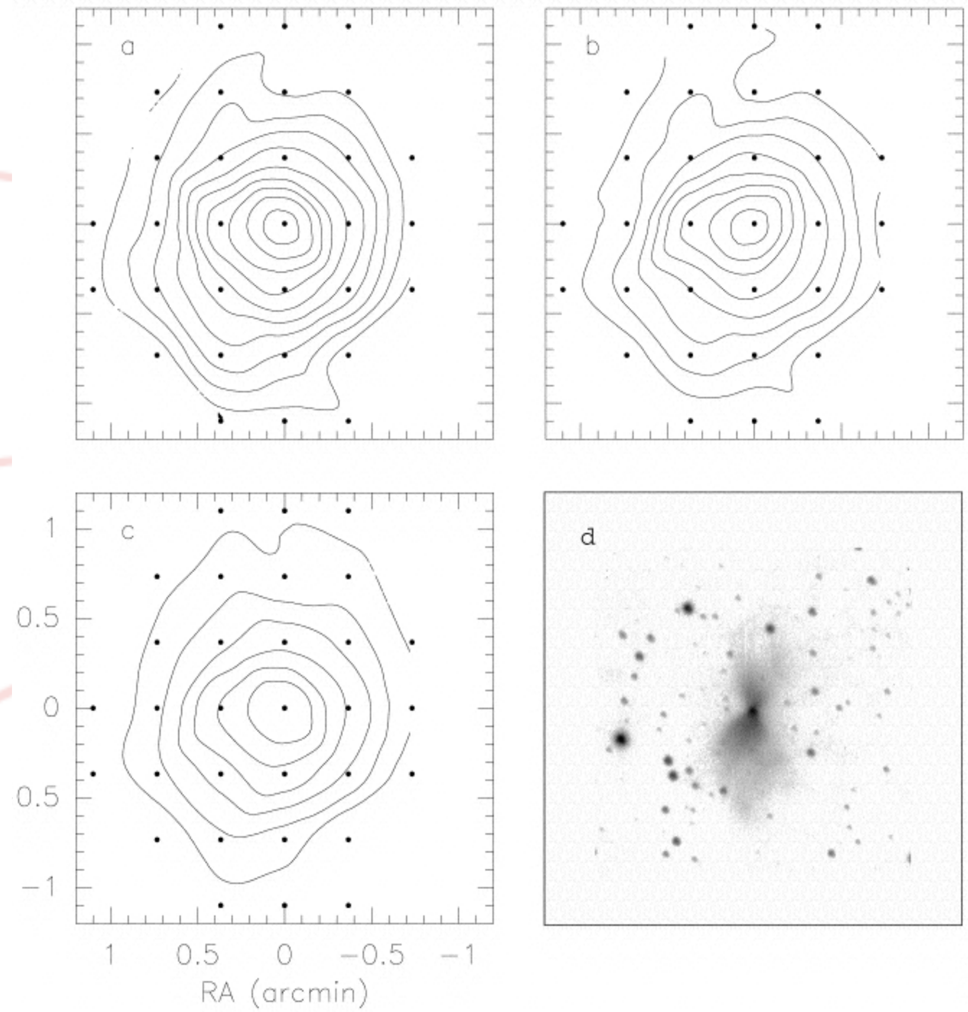
SEST data show CO(1-0) absorption against CMB

Model indicates $T_{kin} < 2K$

Sahai & Nyman 1997

Previous observations & models

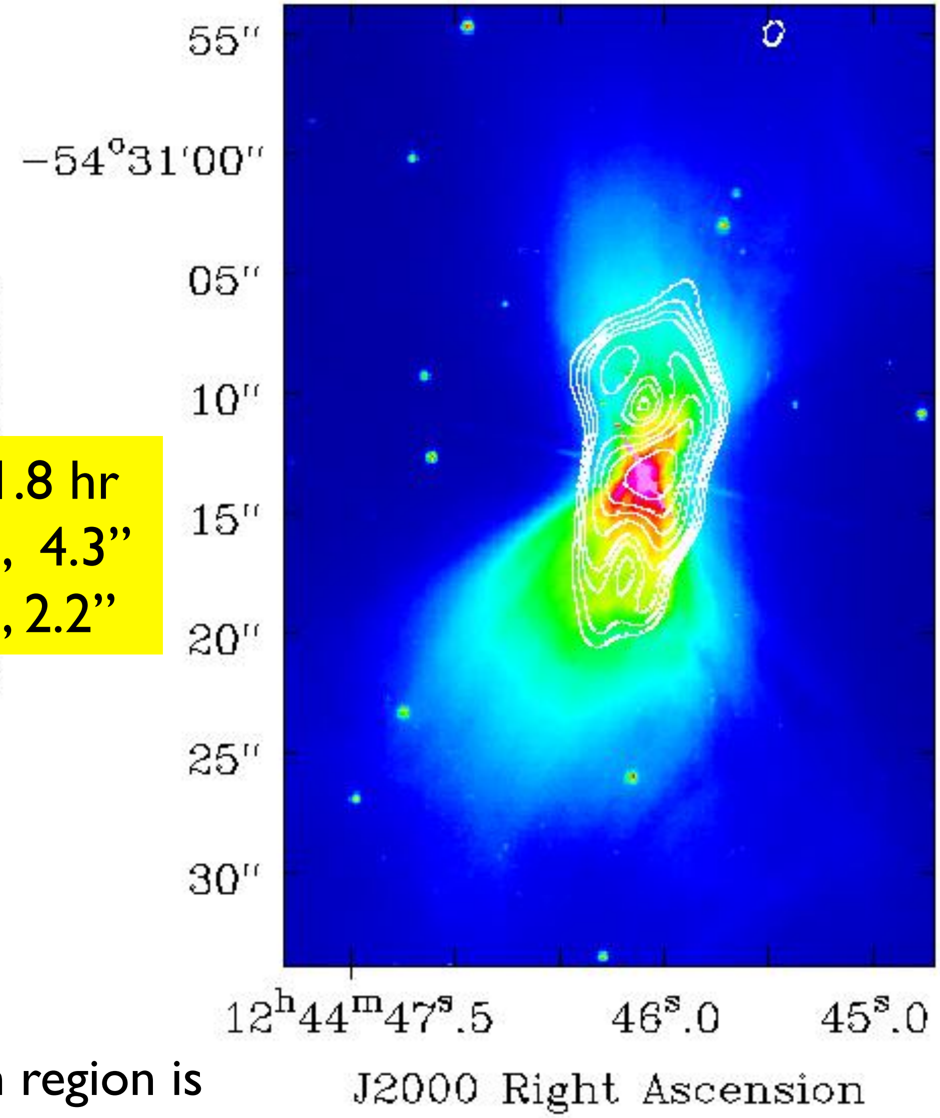
- Sahai & Nyman model CO(1-0) and CO(2-1) as two spherical envelopes
  - Adiabatic cooling dominates
  - SEST map of CO(1-0) with 45" beam did not show asymmetries
- Models showed (for d=1.5 kpc)
  - dM/dt: (*outer*) 10^{-3} M_{sun}/yr, (*inner*) >10^{-4} M_{sun}/yr
  - nebula mass: (*outer*) 1.9 M_{sun}, (*inner*) >0.13 M_{sun}
  - outflow speed: (*outer*) 164 km/s, (*inner*) 35 km/s
  - luminosity: 300 L_{sun}
  - Wind momentum/radiative momentum: (*outer*) 4×10^4, (*inner*) > 650



Radiation pressure driven outflows impossible!

ALMA CO(2-1) data

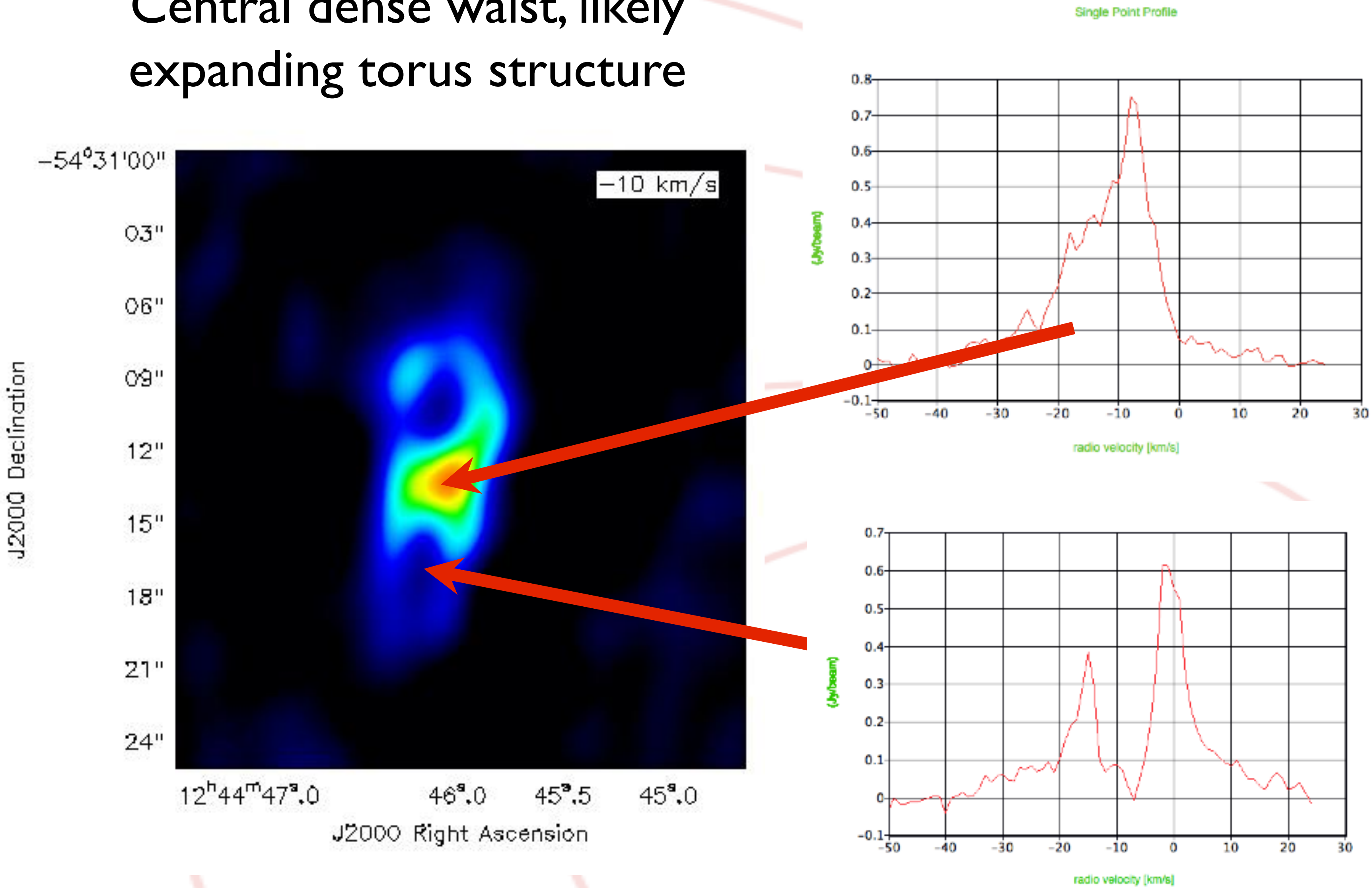
Cyc0, 1.8 hr
Band 3, 4.3”
Band 6, 2.2”



CO 2-1 (and 1-0) emission region is bipolar, and oriented along same axis, as the optical hourglass shape

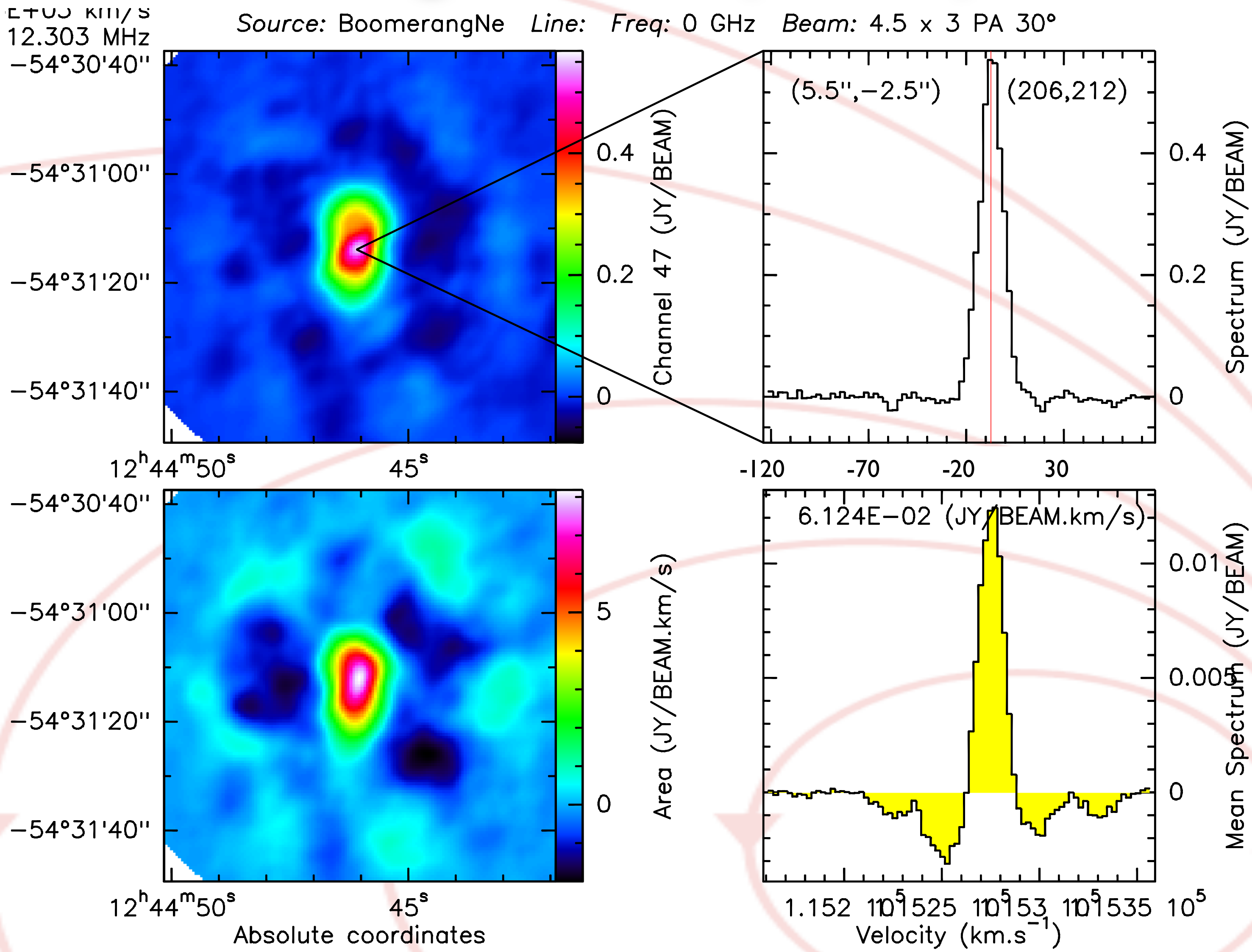
CO bubbles

Central dense waist, likely expanding torus structure



obes have bubble structure

Boomerang CO 1-0 (ALMA)

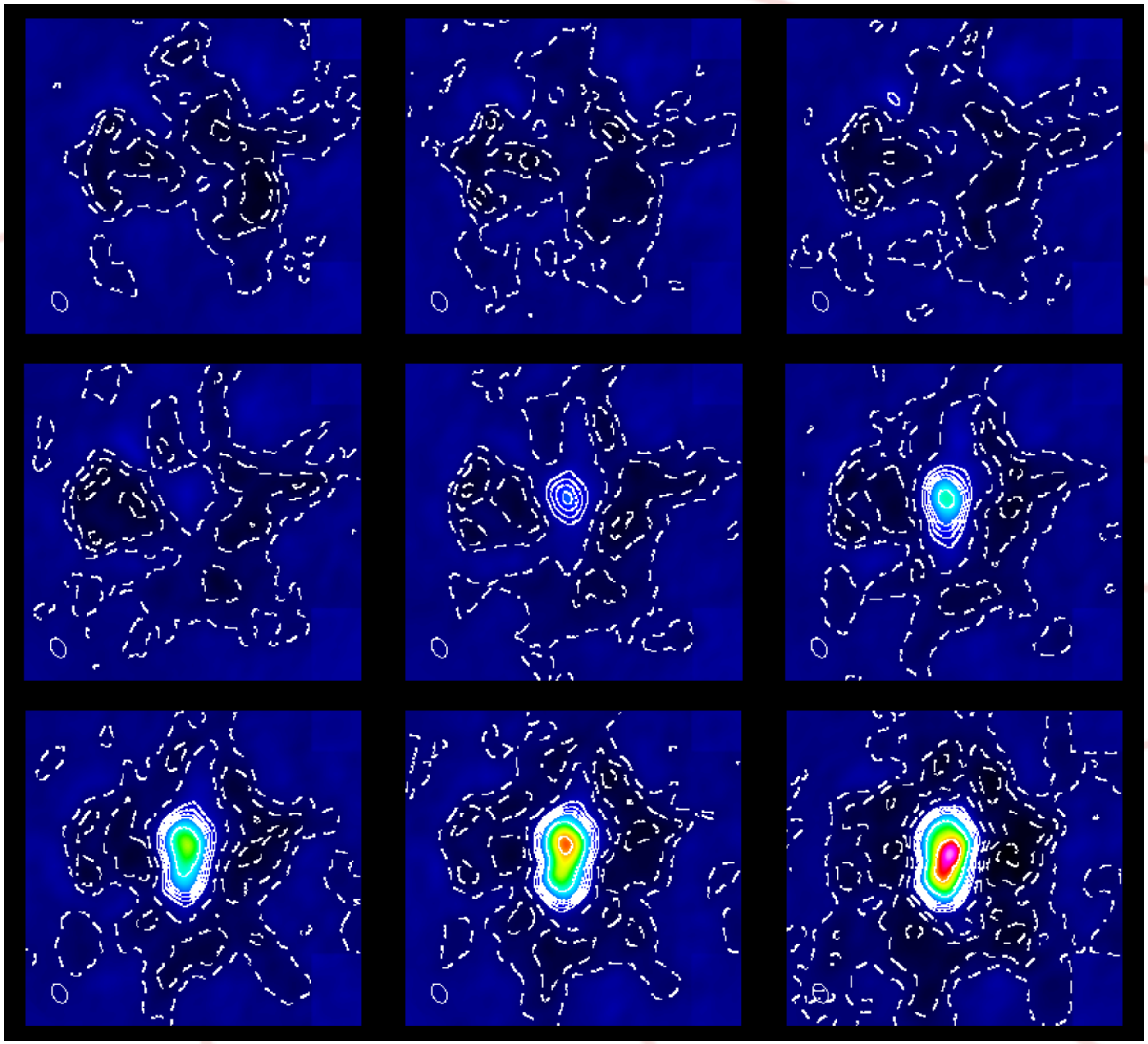


Note weak patchy emission on the periphery of the ultra-cold shell

CO(1-0)

42 km/s

ALMA + SEST

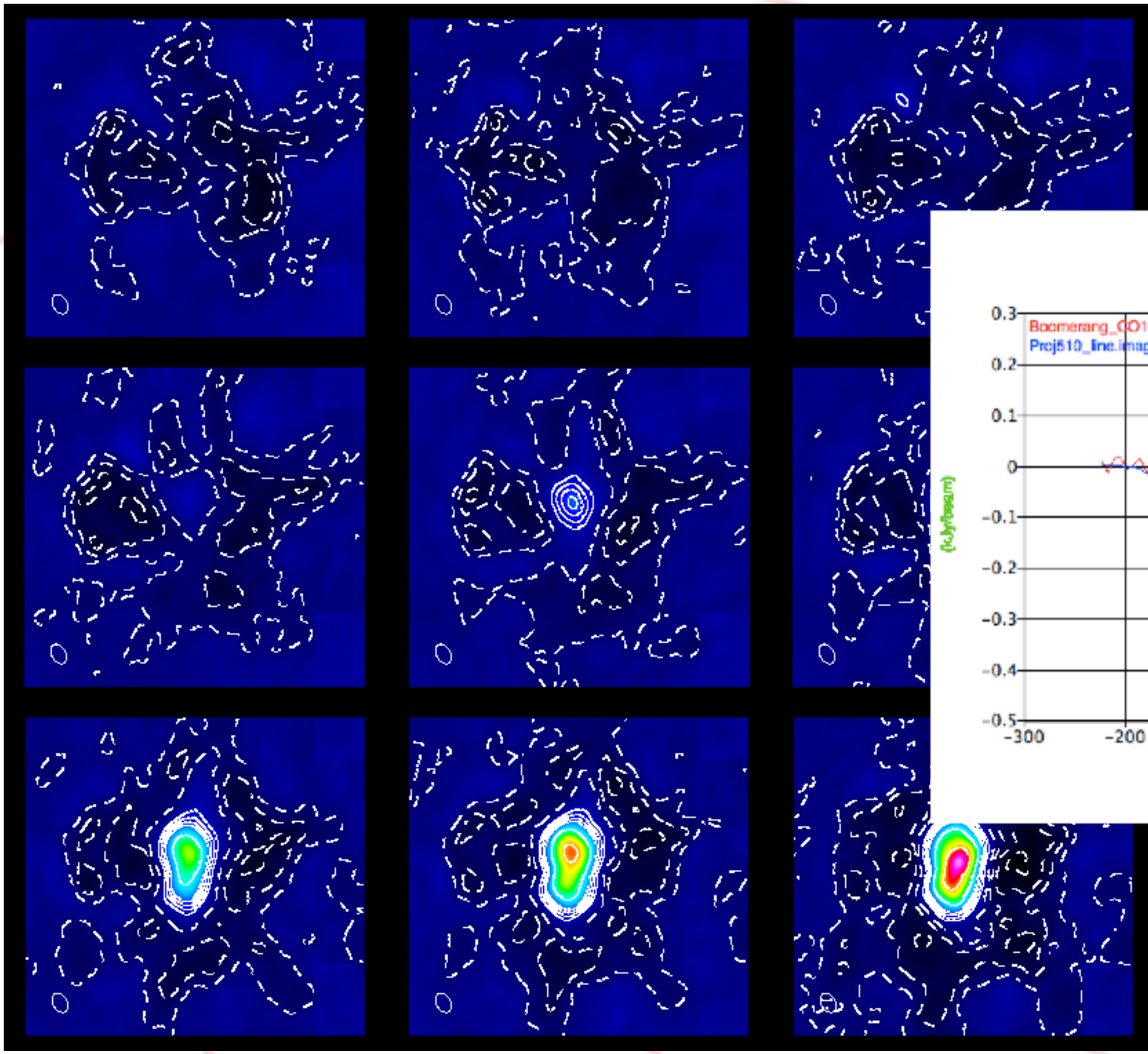


1.1x1.1 arcmin

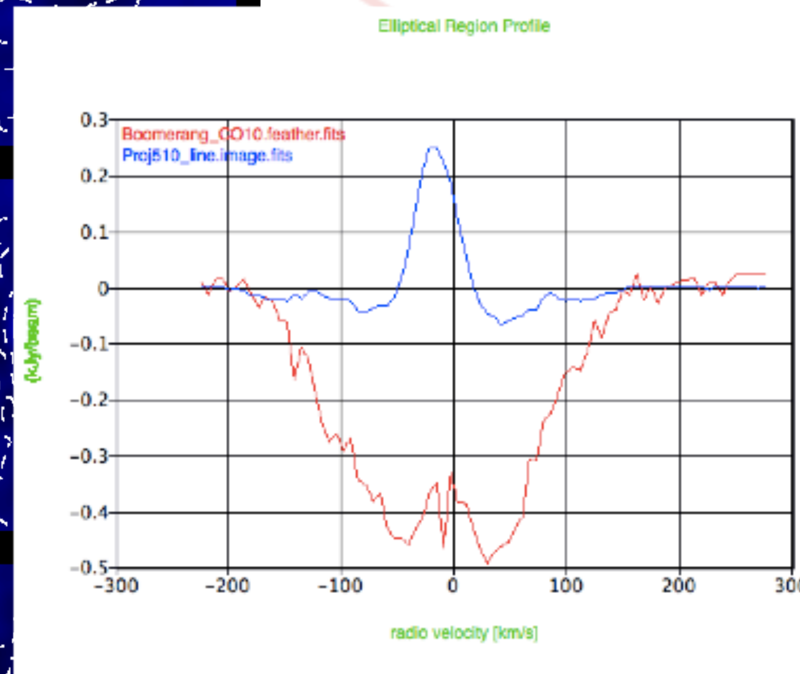
-9 km/s

CO(1-0)

42 km/s

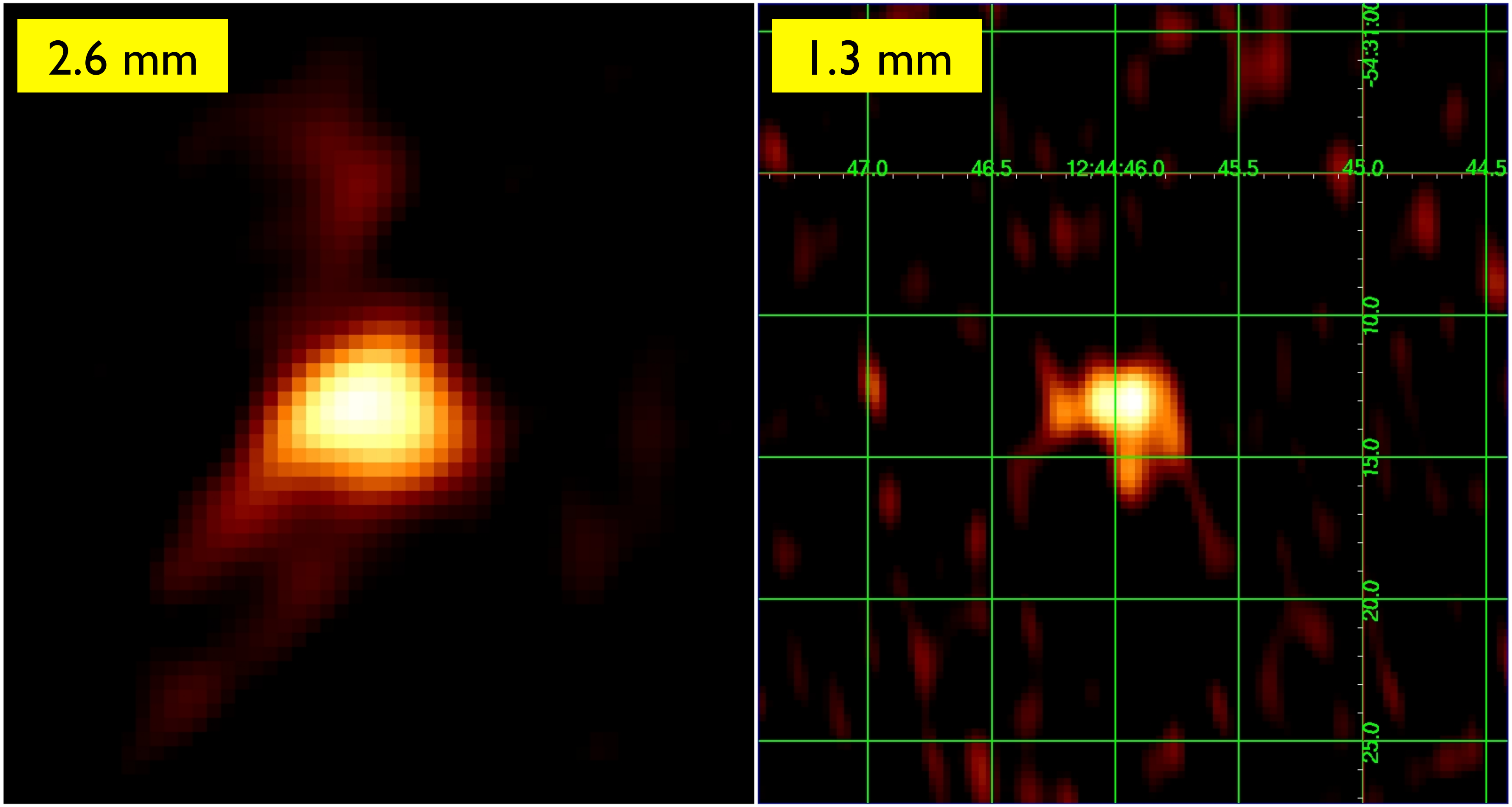


ALMA + SEST



-9 km/s

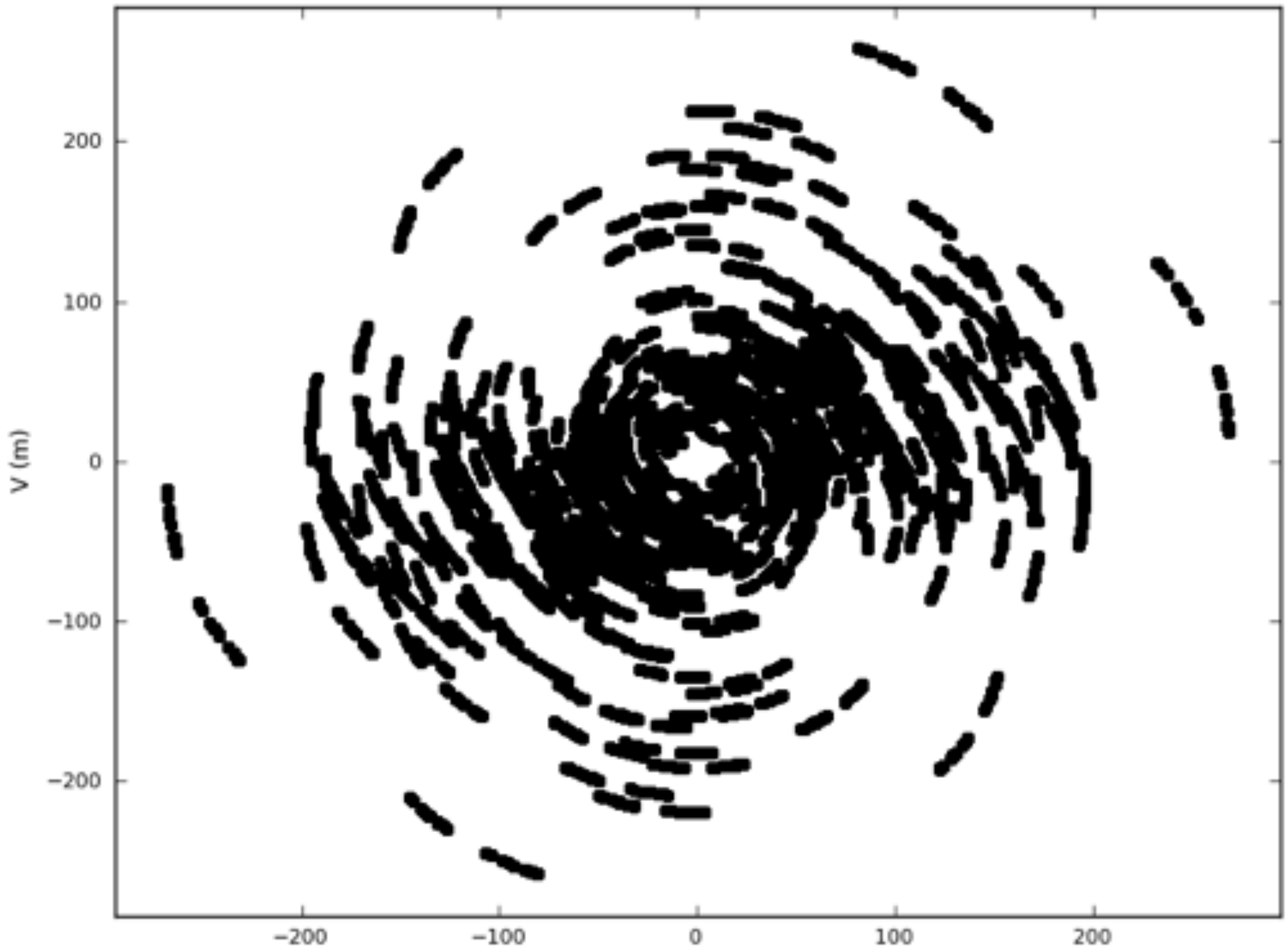
Continuum Emission



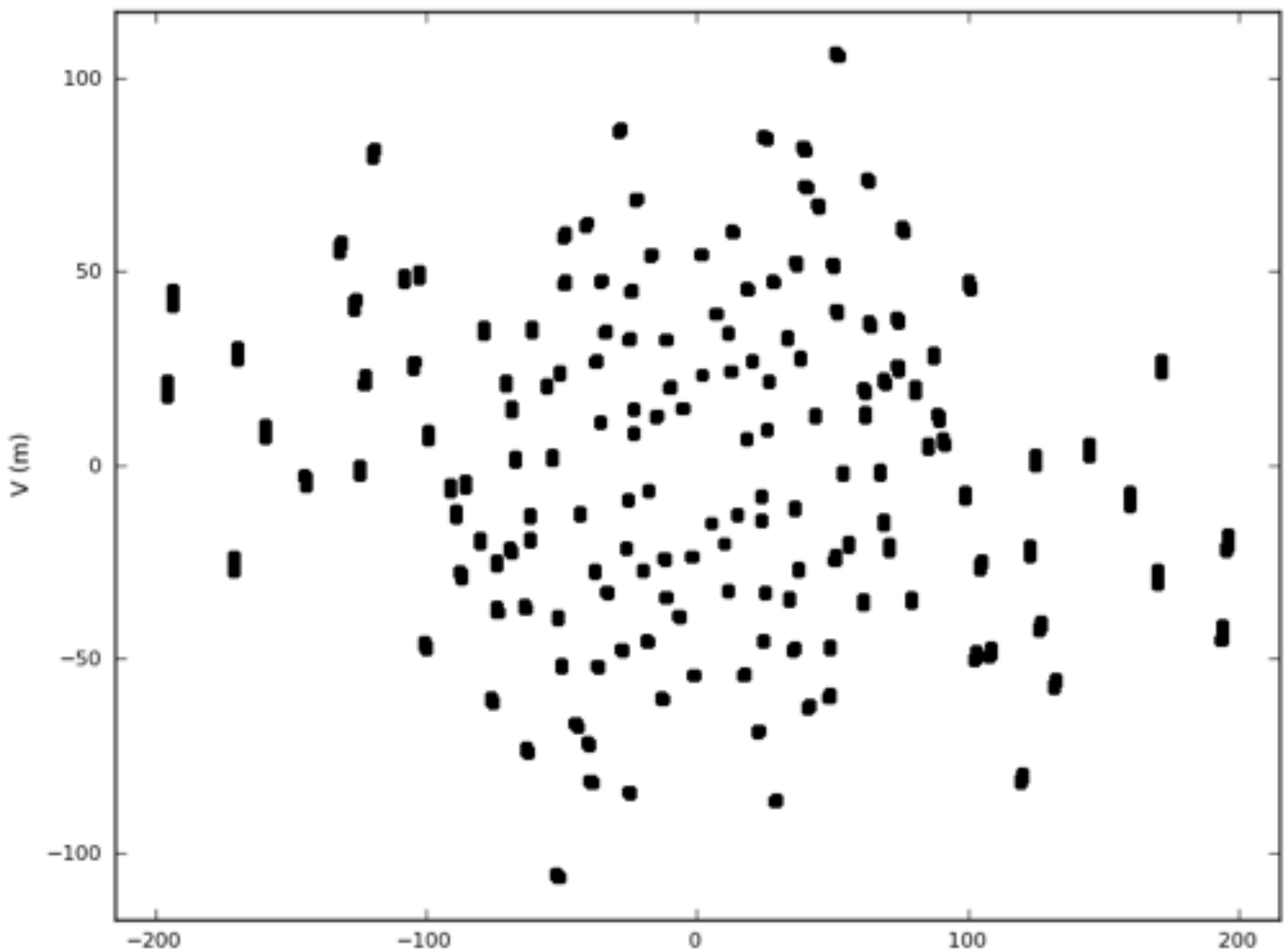
- Continuum detected at 2.6 mm and 1.3 mm,
- Strong compact central source in each case

~~(some elongated structure extending to south in 2.6 mm image)~~

2.6 mm UV-coverage



1.3 mm UV-coverage



Continuum Emission: Simple Analysis

- Peak fluxes: 3.64 mJy and 0.64 mJy; R(1.3/2.6)=5.7

(S/N is modest and 1.3 mm UV-coverage is still sparse! For analysis below, we convolve 1.3 mm image to same beam as 2.6 mm one, and assume power-law dust emissivity, i.e. $\kappa_\nu \sim \nu^p$)

- Rayleigh-Jeans limit: $R(\lambda_1/\lambda_2) \sim (\lambda_2/\lambda_1)^{(2+p)}$, hence p=0.5
- (without R-J): for p = 0.6, 1, 1.5, we get T_d= 45K, 9.5K, 5.0K and

r_d=1.9" , 236" , 6800", using $r_d=(L_* T_*^p/16\pi\sigma)^{1/2} T_d^{-(2+p/2)}$

- Since emission is from compact source, $r_d \sim 2"$, hence p ~ 0.6 and $T_d \sim 45K$

(realistically, extinction and reddening of starlight needs to be considered, allowing **somewhat** higher p and lower T_d values)

e.g., if only 10% of total stellar flux (reddened to 900K) gets thru, then p ~ 0.7 and $T_d \sim 23K$

- Assuming opacity κ(1.3mm) ~ 1.5 cm^2/g (uncertain!), $M_d \sim 3.5 \times 10^{-4}$ Msun, or

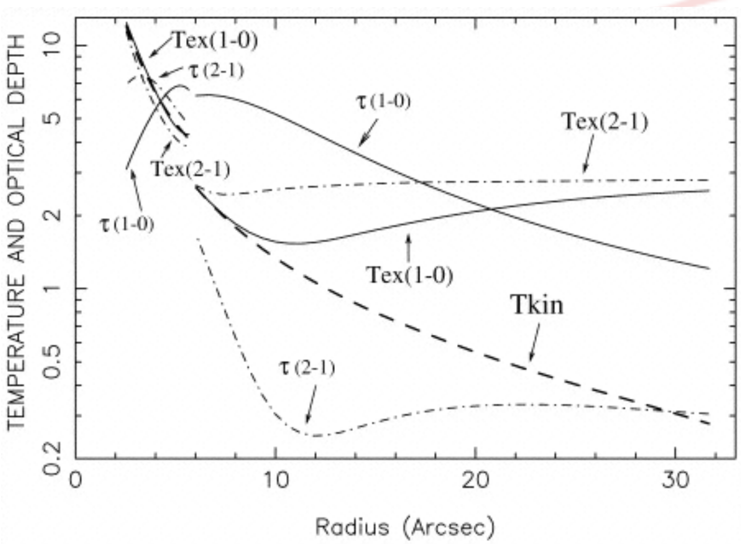
M~ 0.071 Msun (taking typical gas-to-dust ratio of 200)

expansion time scale for dust region ~ 420 yr => Mass-loss rate ~1.7×10^{-4} M_{sun}/yr

Preliminary Conclusions and Future Work

Basic features (i.e., size and location of warm inner shell, outer ultra-cold shell) of Sahai & Nyman model validated

- Inner Outflow is Bipolar (roughly hourglass shaped) with a dense waist (angular size consistent with Sahai & Nyman model)
- Outer Outflow shows patchy structure distributed in a roughly round shell (*but very significant fraction of extended emission resolved out – need ALMA compact array observations to properly image it*)
- Weak patchy emission outside the ultra-cold shell – expect latter to ultimately heat up due to (i) heating via grain photoelectric heating, (ii) turbulence/ collisions via interaction with ambient ISM
- Dust in waist likely to be composed of very large (~mm-sized) grains; ATCA (DDT) continuum observations to be done June 21 to look for free-free/ non-thermal continuum



2-D modeling of CO needed

- No signature of rotation in dense waist yet (need larger baselines to resolve inner core)