OBSERVATIONS OF BINARY PROTOSTARS

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Multiplicity in Star Formation, Toronto, May 2007

Collaborators

- X. Chen *(MPIA; PhD student, N_2H^+)*
- T. Bourke *(CfA; ATCA & SMA observations)*
- P. Barnes *(USYD; ATCA observations)*
- Y. Pavlyuchenkov *(MPIA; line radiative transfer)*
- V. Toth *(Budapest; ISO data)*
- A. Sargent *(Caltech; OVRO)*
- H. Zinnecker *(AIP)*

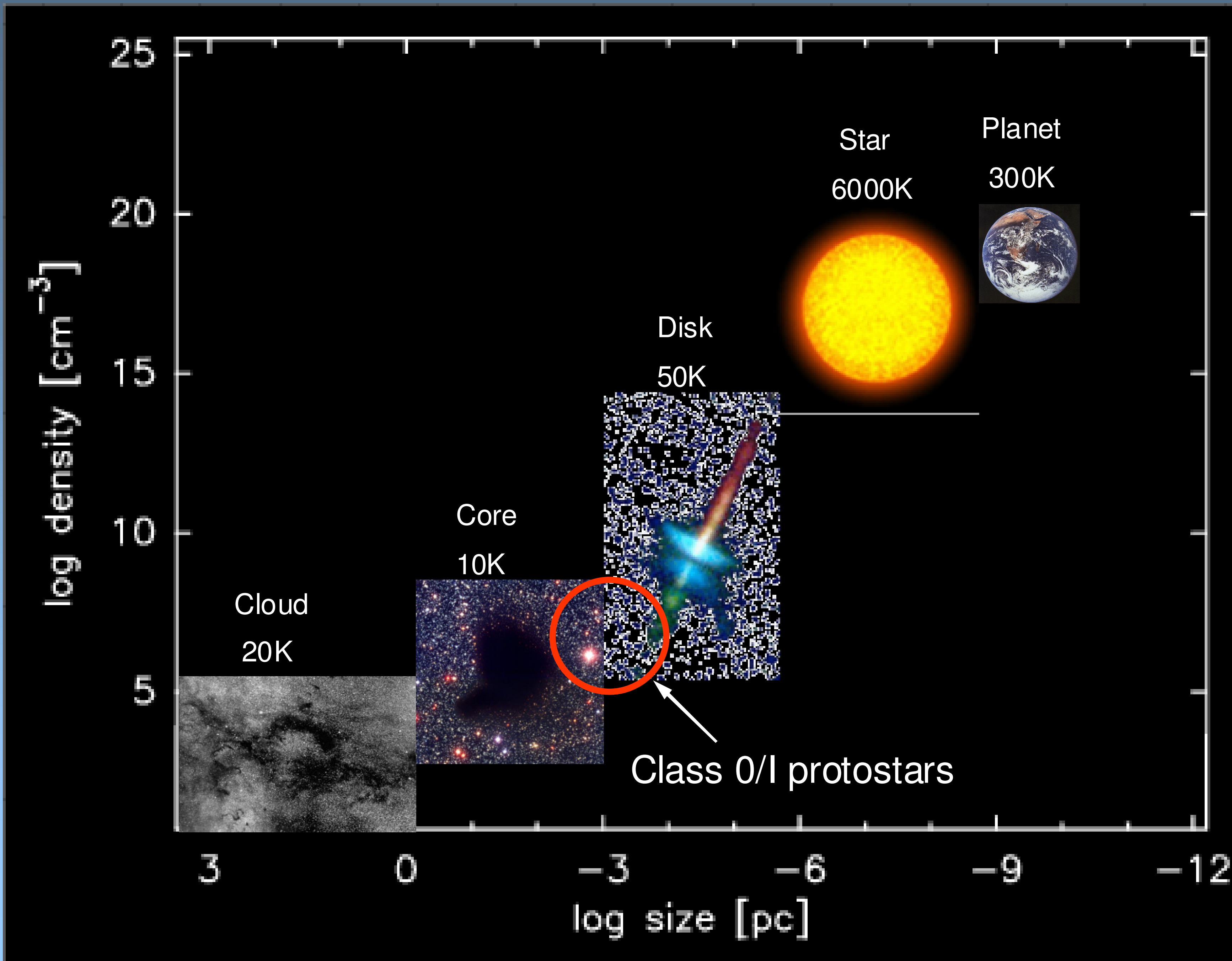
Outline

1. Introduction
2. Tracers and observing methods
3. MM dust continuum emission
4. Molecular outflows
5. Conclusions

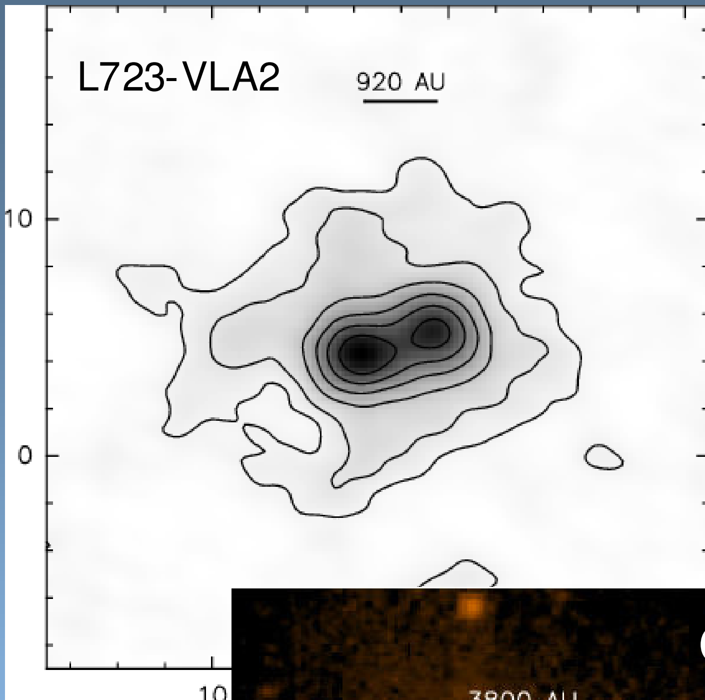
Why do we study binary protostars?

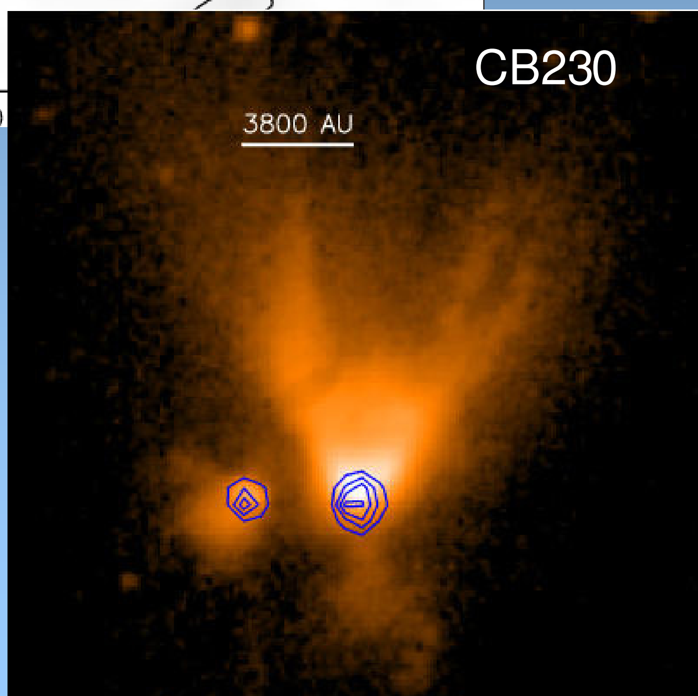
- Most PMS stars are binaries and they are coeval
  → Most stars must form as binaries !
- Multiple systems undergo dynamical evolution
  → Studies of evolved systems cannot tell us all about formation
- Not much direct observational information on binary formation
- ``Standard´´ assumption in theory and interpreting observations: formation of single stars
- State-of-the-art SF models produce binaries and make testable predictions (J, M, a, q, β)
  (Bate, Bodenheimer, Bonnell, Boss, Burkert, Durison, Tohline, ...)

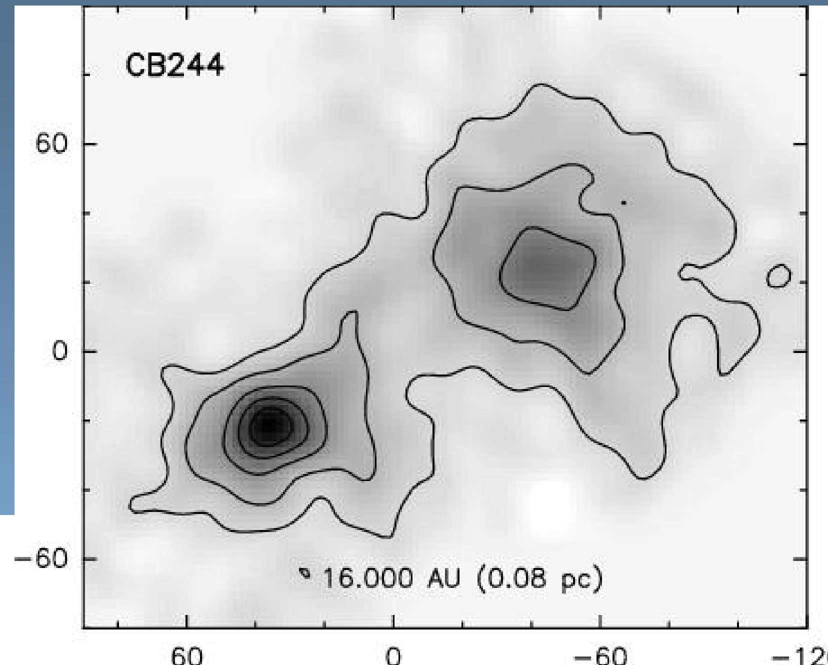
Which physical regime and evolutionary stage do we trace?

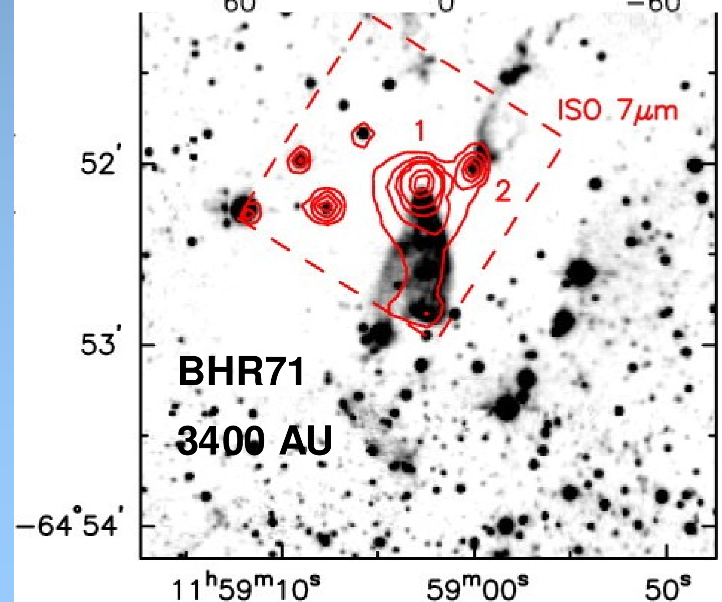


Star Formation and Multiplicity









Star Formation and Multiplicity

- 78% of star-forming cores in globules are multiple (sample of 23 studied)
- Range of scales: 500 AU - 20.000 AU (0.1 pc)
- → Fragmentation/multipicity and star formation are inherently coupled, even in simple Bok globules!

What do we want to know?

→ The formation mechanism

- Initial (turbulent) fragmentation vs. prompt fragmentation during collapse
- Delayed breakup → currently not directly accessible to observations

→ Efficiency of binary / triple formation, separations, mass ratios, relative orientation

→ Dependence of outcome on initial conditions

(Density profiles, Angular momentum, Turbulence, …)

Key parameters:

1. Envelope structure and mass
2. Protostar masses and mass ratios
3. Separations
4. Distribution of angular momentum
5. Rate and distribution of mass accretion
6. Energy balance (e.g., $\beta = E_{grav}/E_{rot}$)

Which tracers?

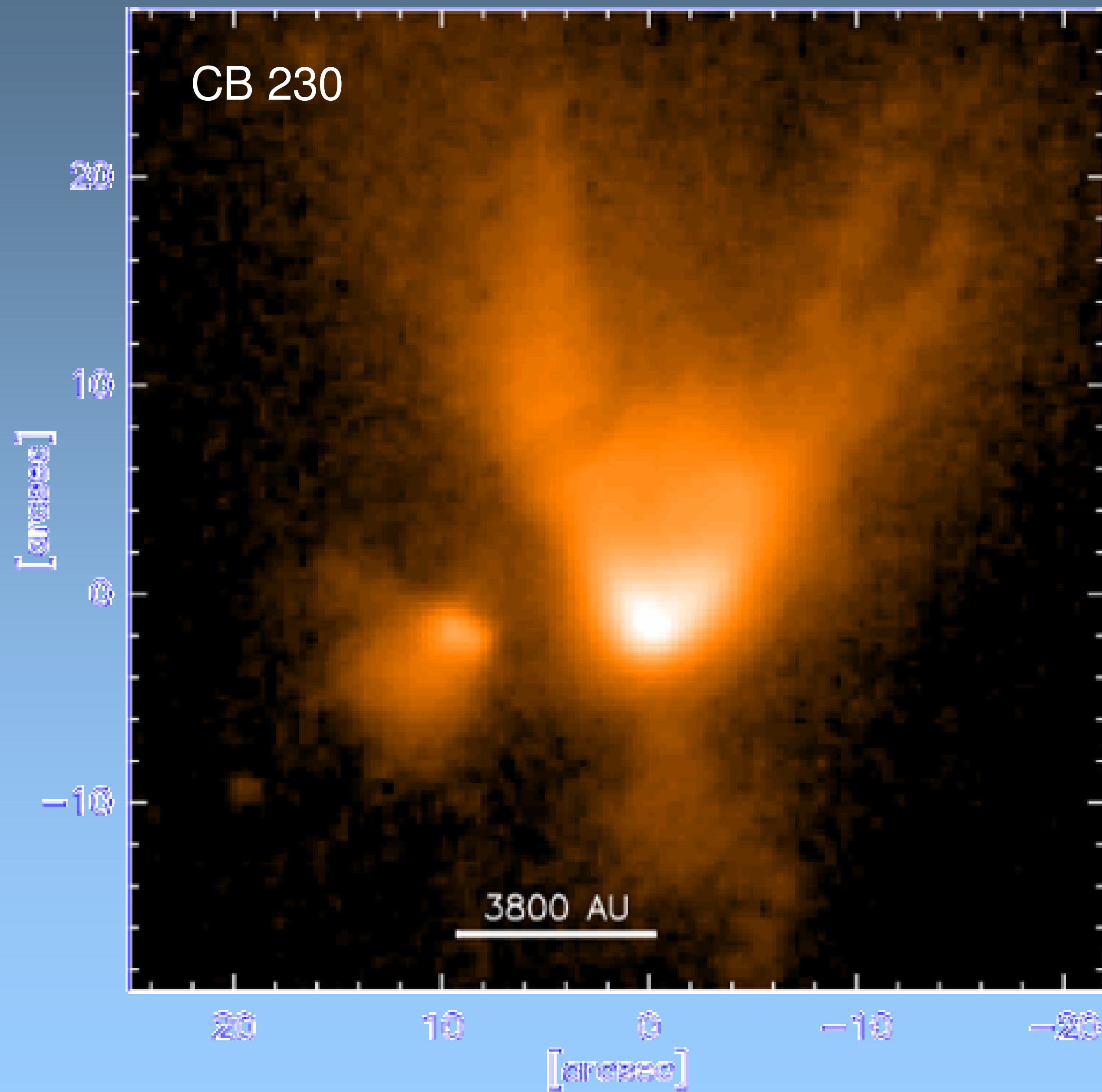
- Near-infrared

  Scattered light

- NIR jets

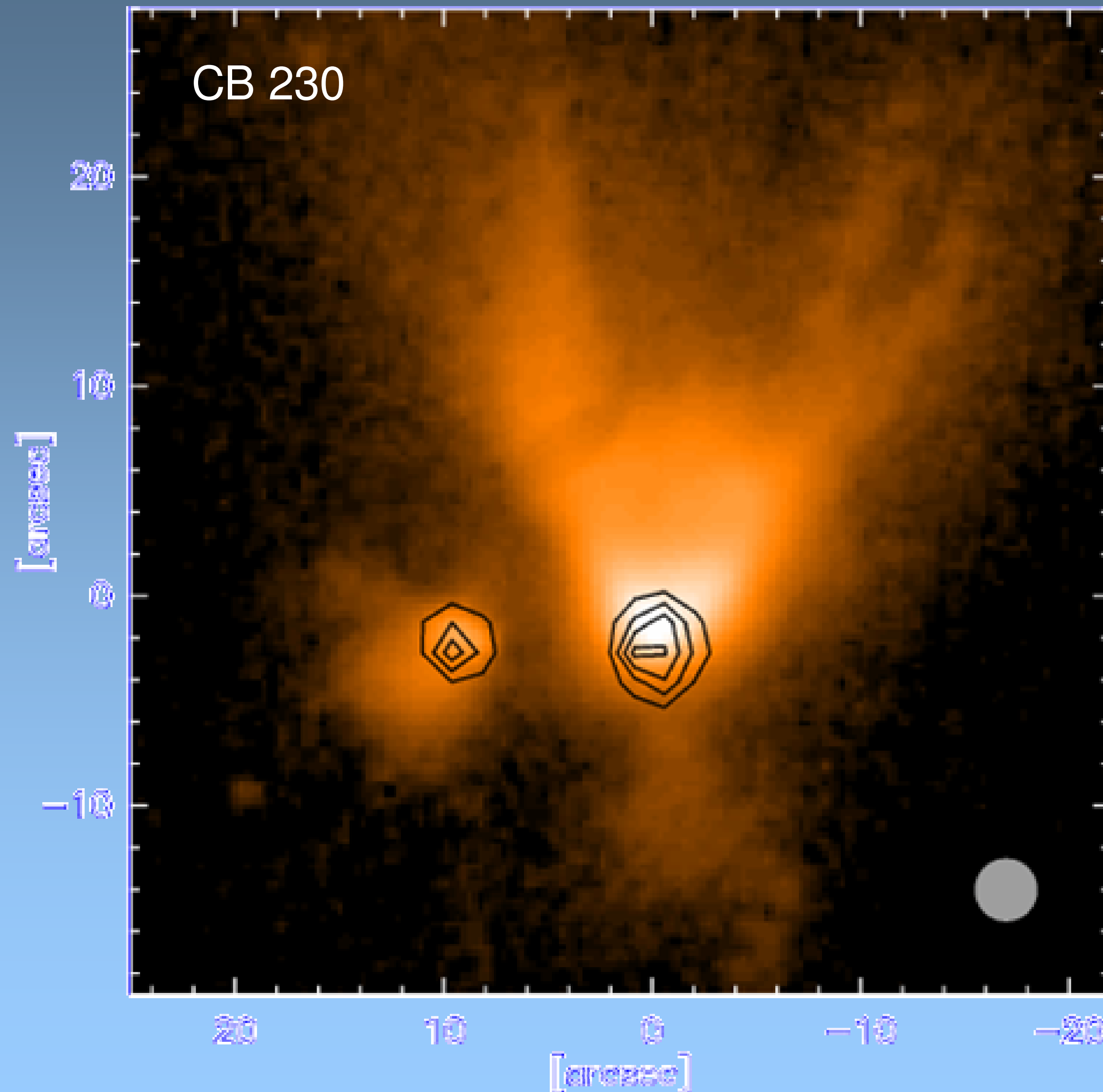
  Line emission

  + scattered light



Which tracers?

- Mid-infrared
  - Hot protostellar cores, inner accretion disks

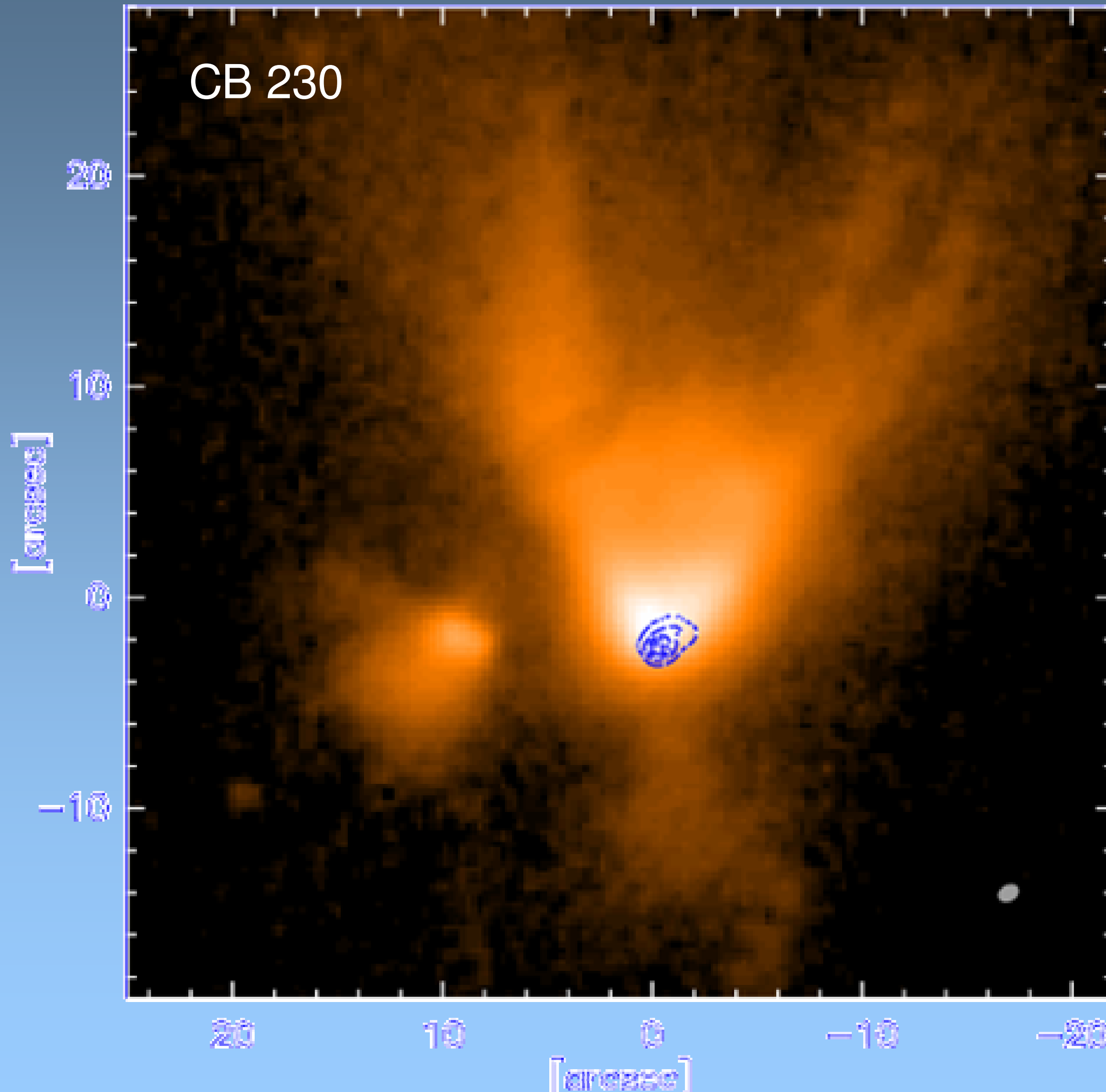


Which tracers?

- Millimeter dust continuum
  - Inner protostellar cores, accretion disks
  - Masses

  - Problem:

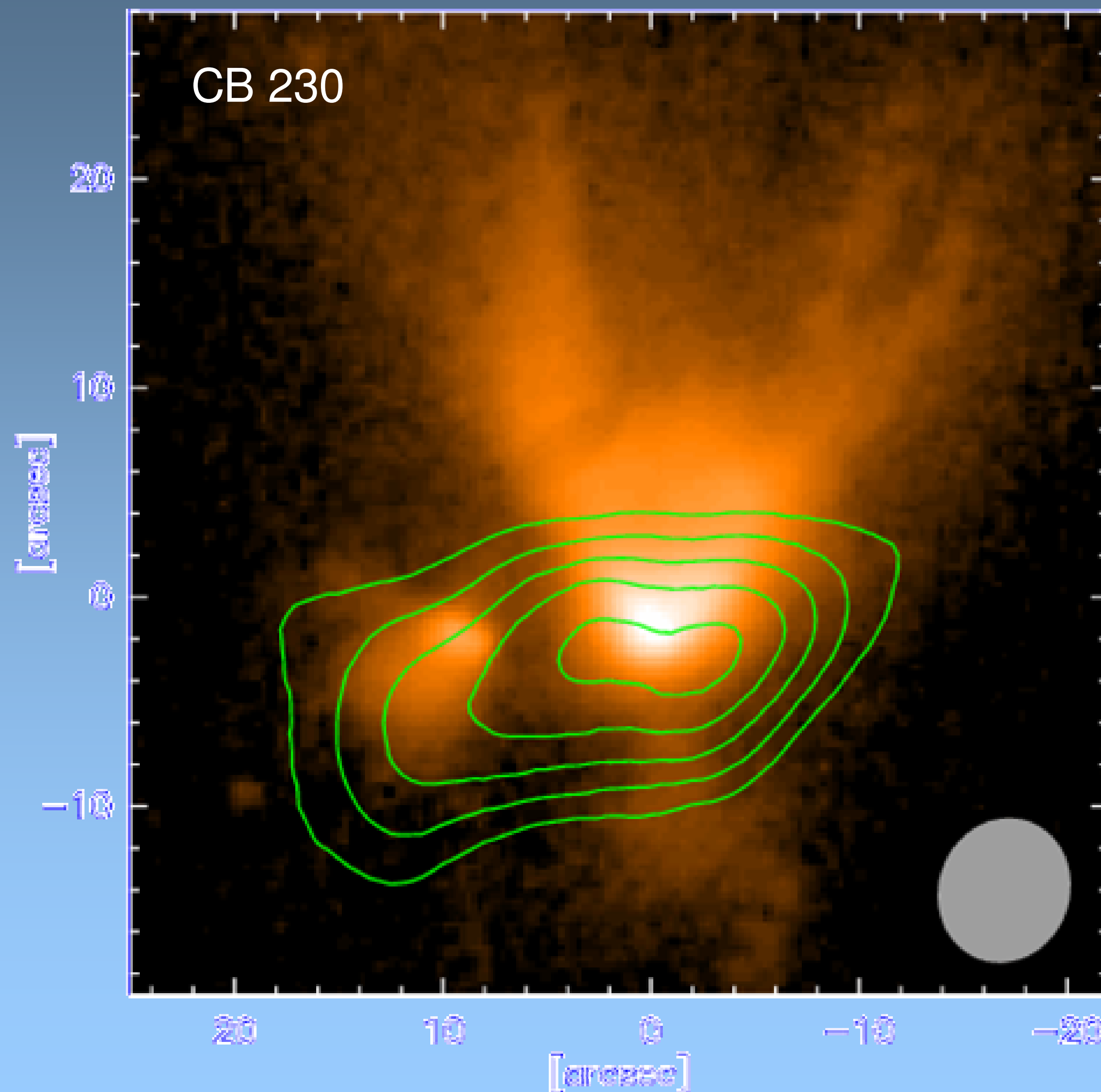
  Need high angular resolution
  ⇨ Interferometers



Which tracers?

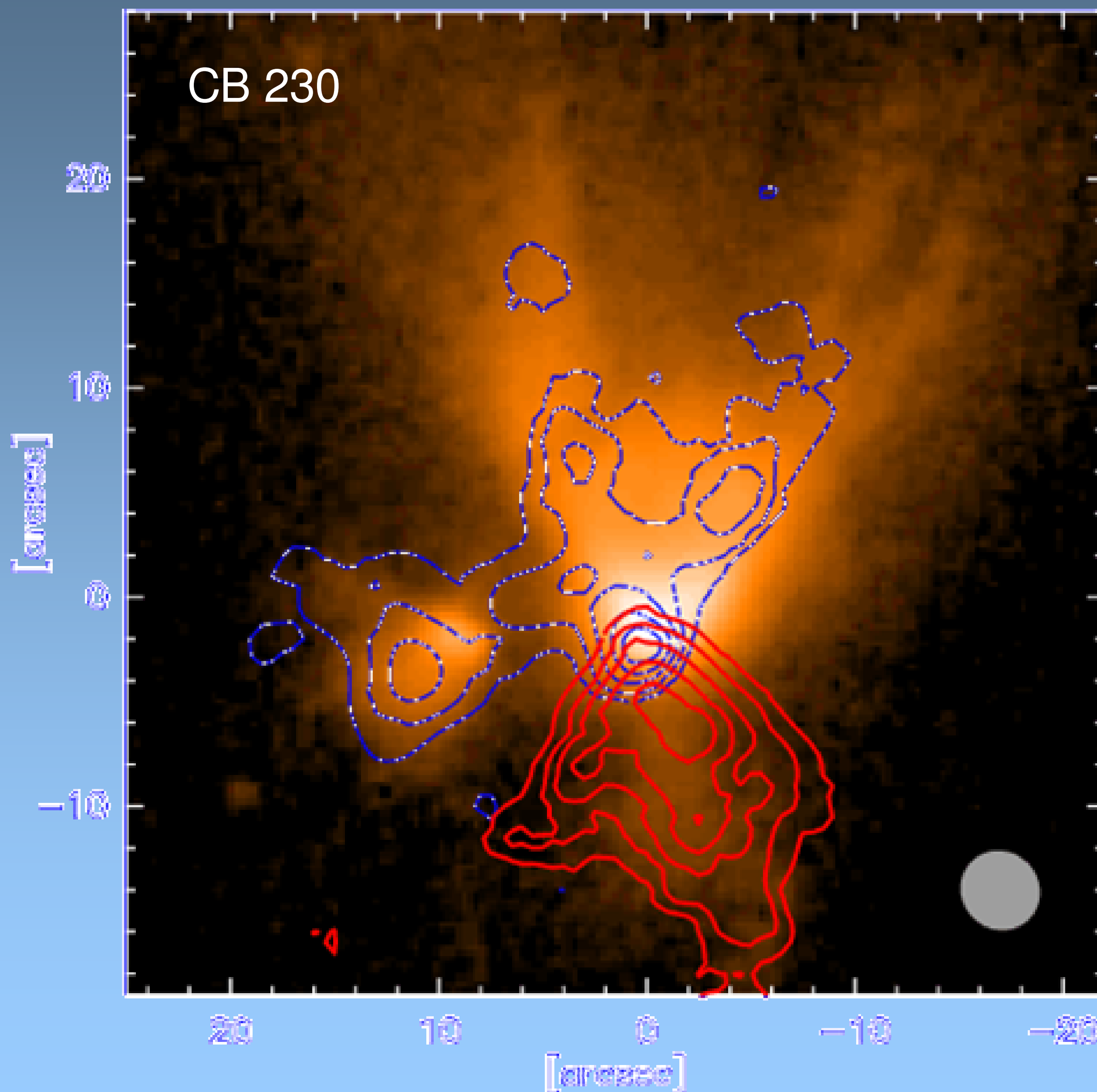
- Molecular lines
  (e.g., N_2H^+)
- ➢ Dense gas in envelopes
- ➢ Kinematics

- ➢ Problems:
  - Depletion
  - Chemistry
  - Outflow-envelope interaction



Which tracers?

- CO line wings
  - Outflows
  - Driving sources
  - Problems:
    - Outflow-envelope interaction
    - Spatial filtering

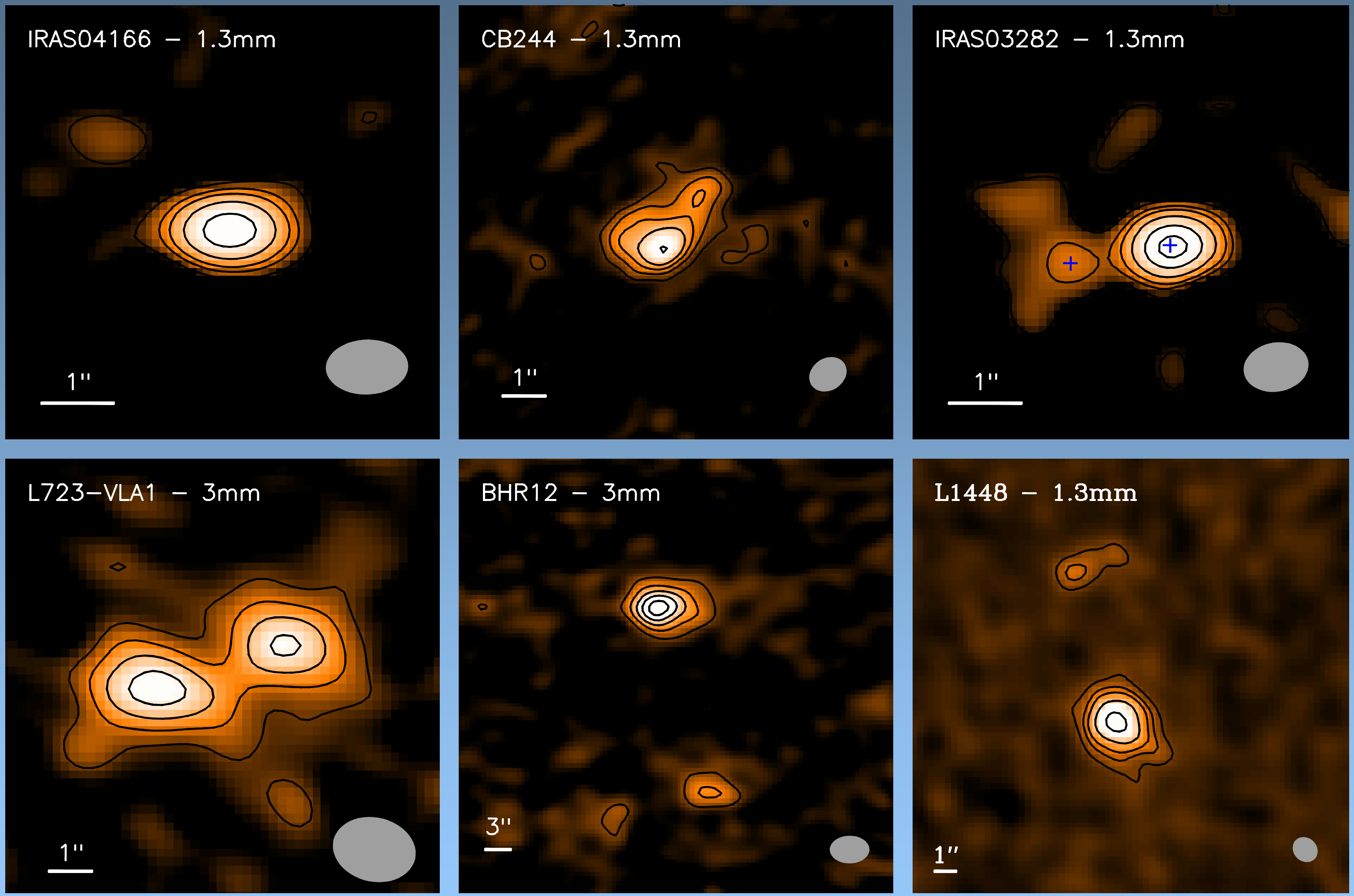


Millimeter dust continuum observations

- Traces dust in protostellar cores and accretion disks
- Circumstellar masses, mass ratios, projected separation of embedded sources
- Major work on binary protostars done at
  BIMA *(Looney, Mundy et al.)*
  OVRO *(Launhardt et al.)*
  continued at ATCA and IRAM PdBI *(Chen, Launhardt, …)*
- Other facilities? CARMA, SMA, VLA, ALMA, …

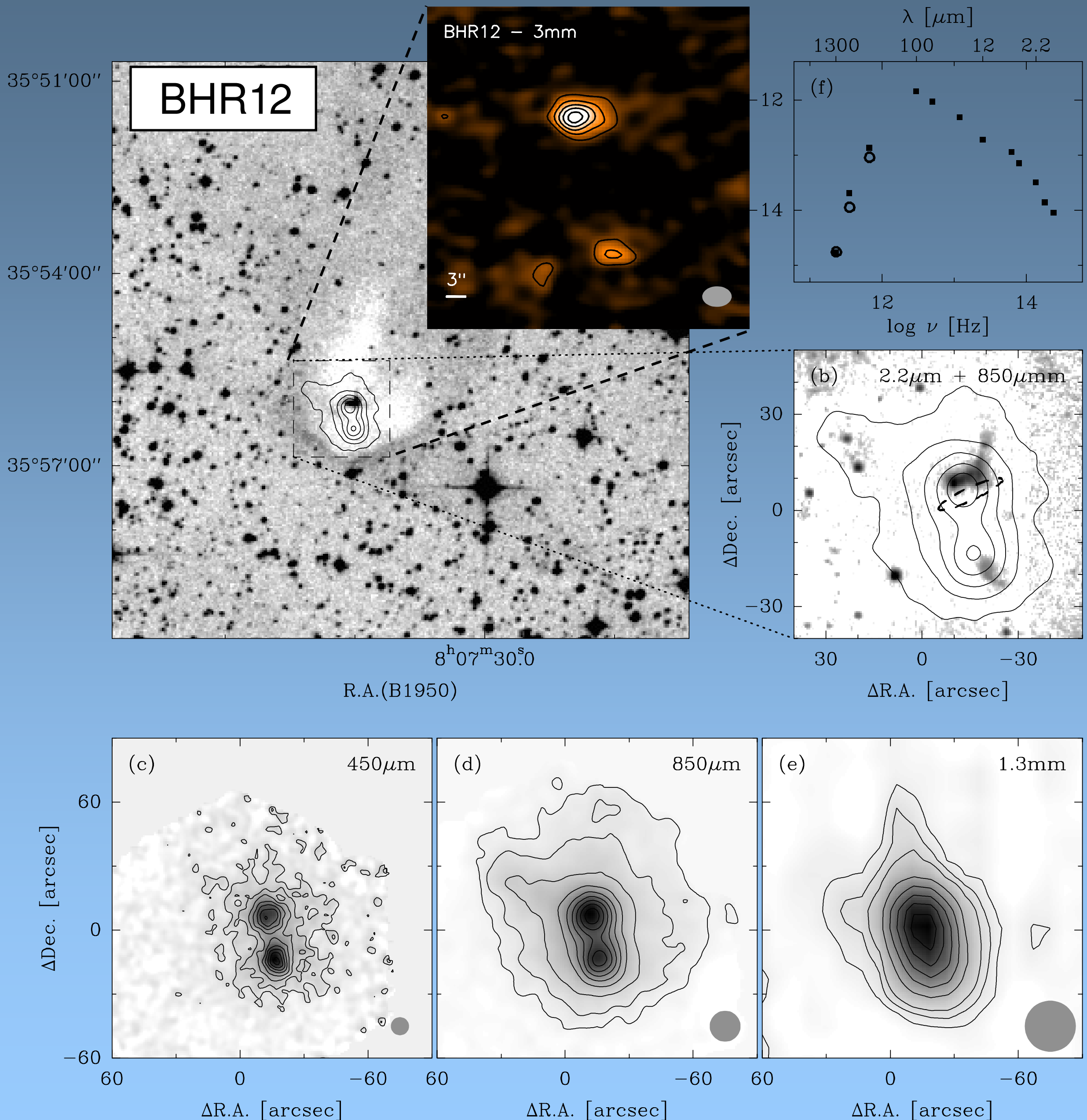
Survey results: isolated Class 0 protostars

OVRO, ATCA, PdBI



- ⇨ 15 objects, growing
- ⇨ Statistical analysis includes other published results

Real object 1: BHR12 (CG30)



- d = 200 pc
- λ = 0.45 – 3 mm
- HPBW = 2´´ - 22´´

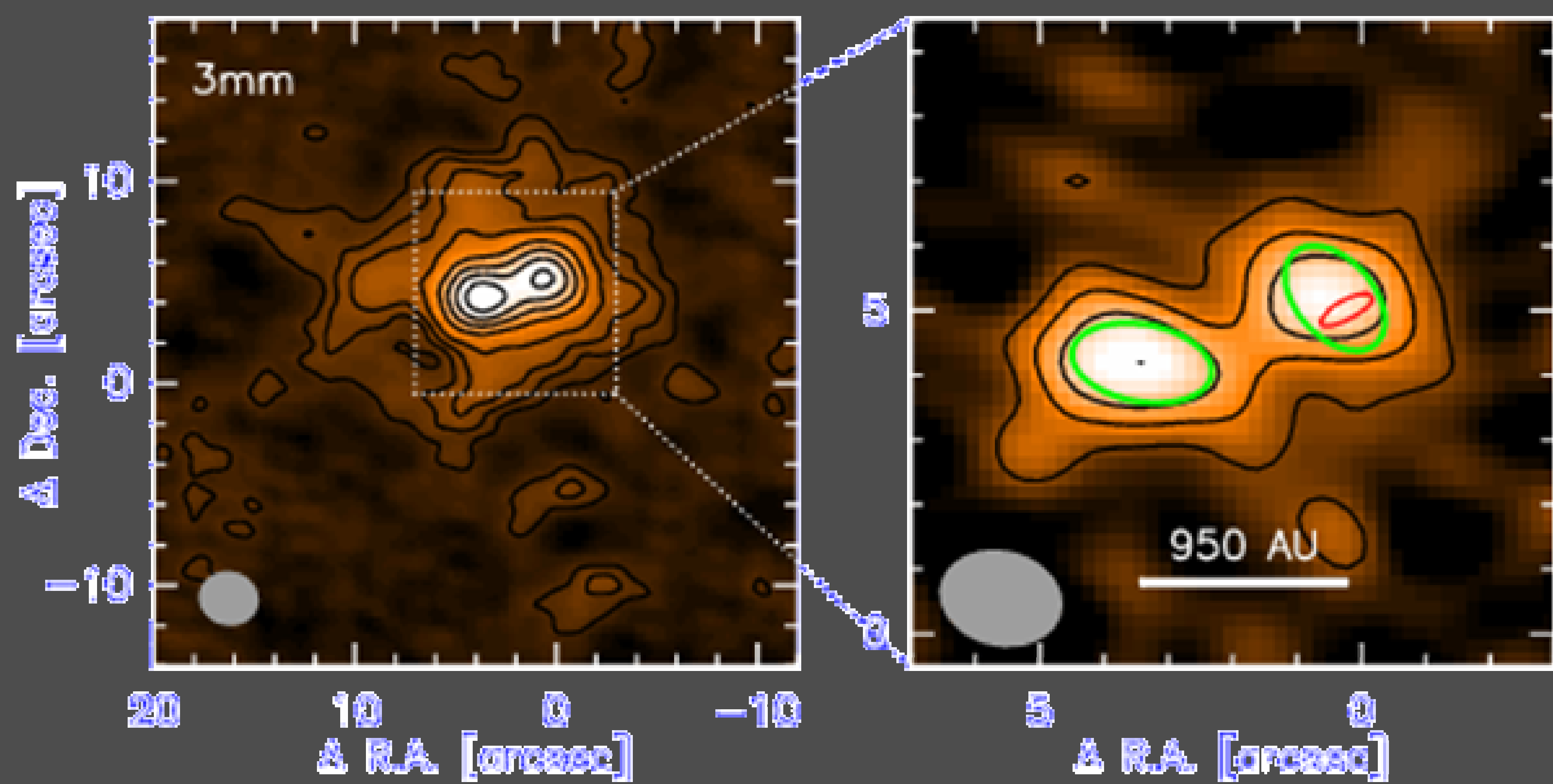
- Separation ≈ 4000 AU
- Mass ratio ≈ 0.5

- *Sources have different mm spectral slopes*
- *More massive component more evolved?*
- *Difficult to infer mass ratio from fluxes without model*

Real object 2: L723-VLA2

- d = 300 pc
- λ = 3mm
- HPBW = 1.7´´

- Separation = 950 AU
- Mass ratio ~ 0.8
- *Missaligned accretion disks*



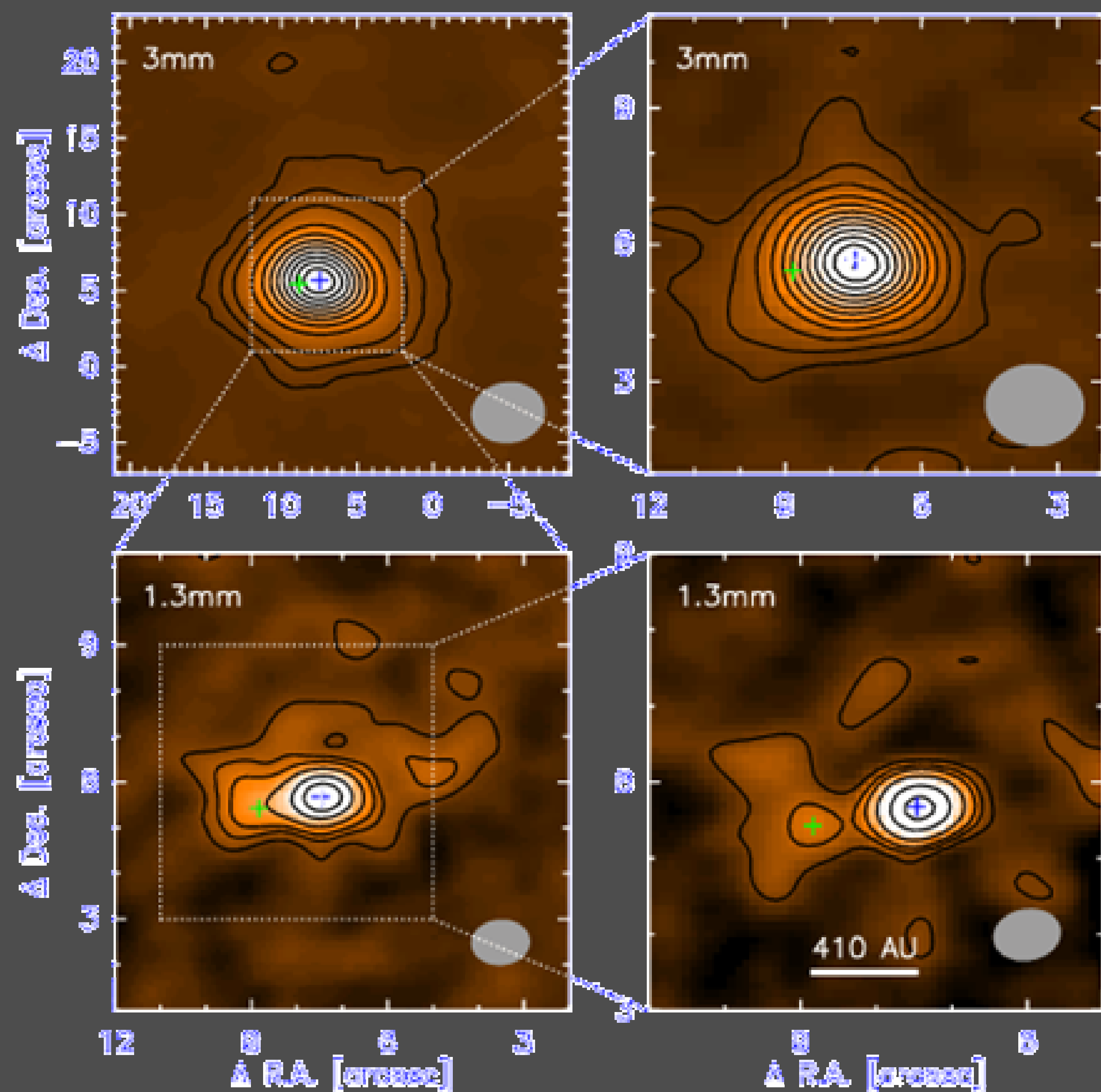
Launhardt et al. 2003

Real Object 3: IRAS 03282+3035

- d = 300 pc
- λ = 3 and 1.3mm
- HPBW = 2´´ and 0.7´´

- Separation = 420 AU
- Mass ratio ~ 0.2

- *Unequal masses*



Launhardt et al. 2003

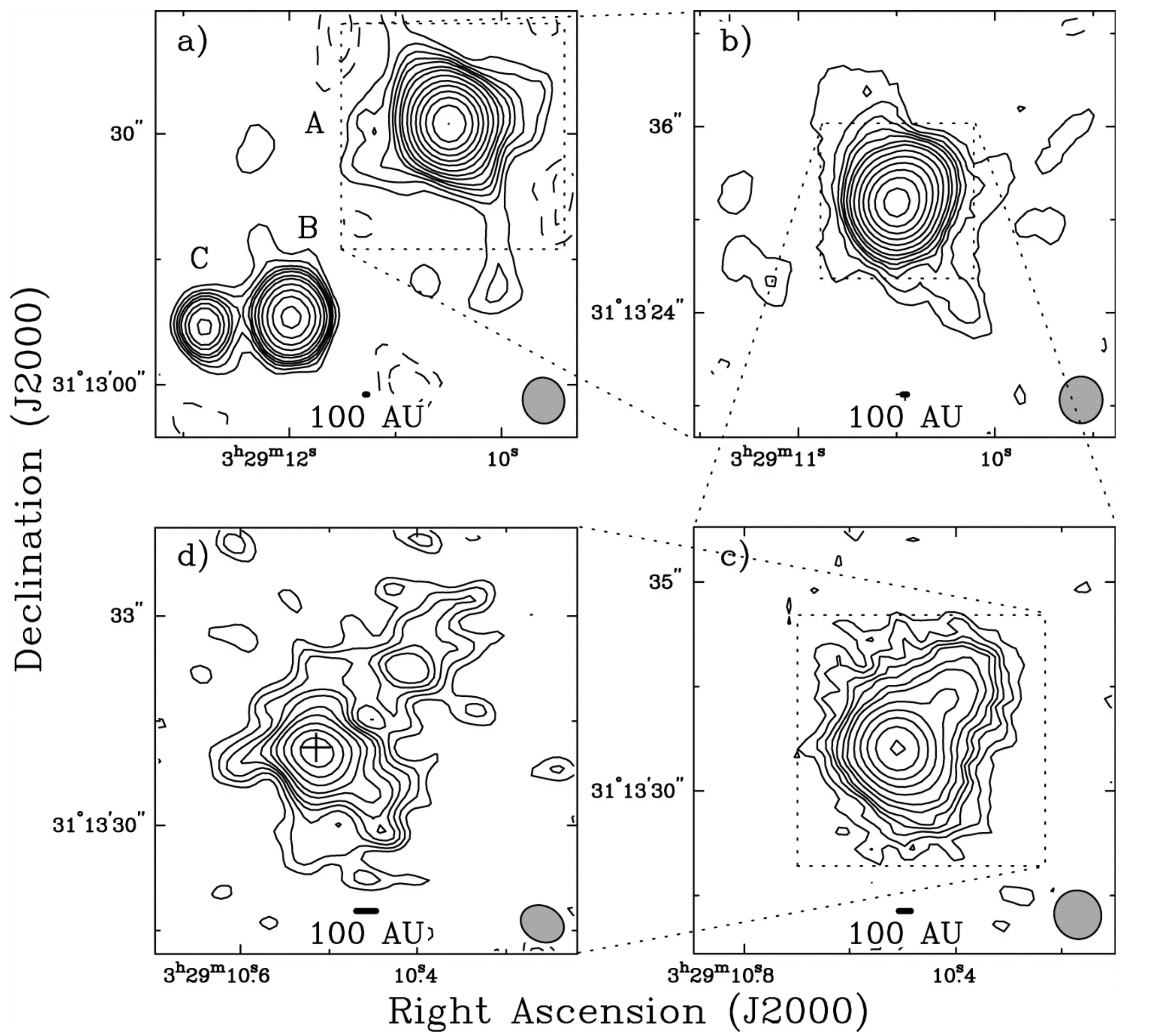
Real object 4: NGC1333 IRAS4A-C

- d = 350 pc
- λ = 3mm
- HPBW = 5...0.6´´

➢ Separation 10000 AU
3700 AU
600 AU

➢ Mass ratios ~ 0.2-0.3

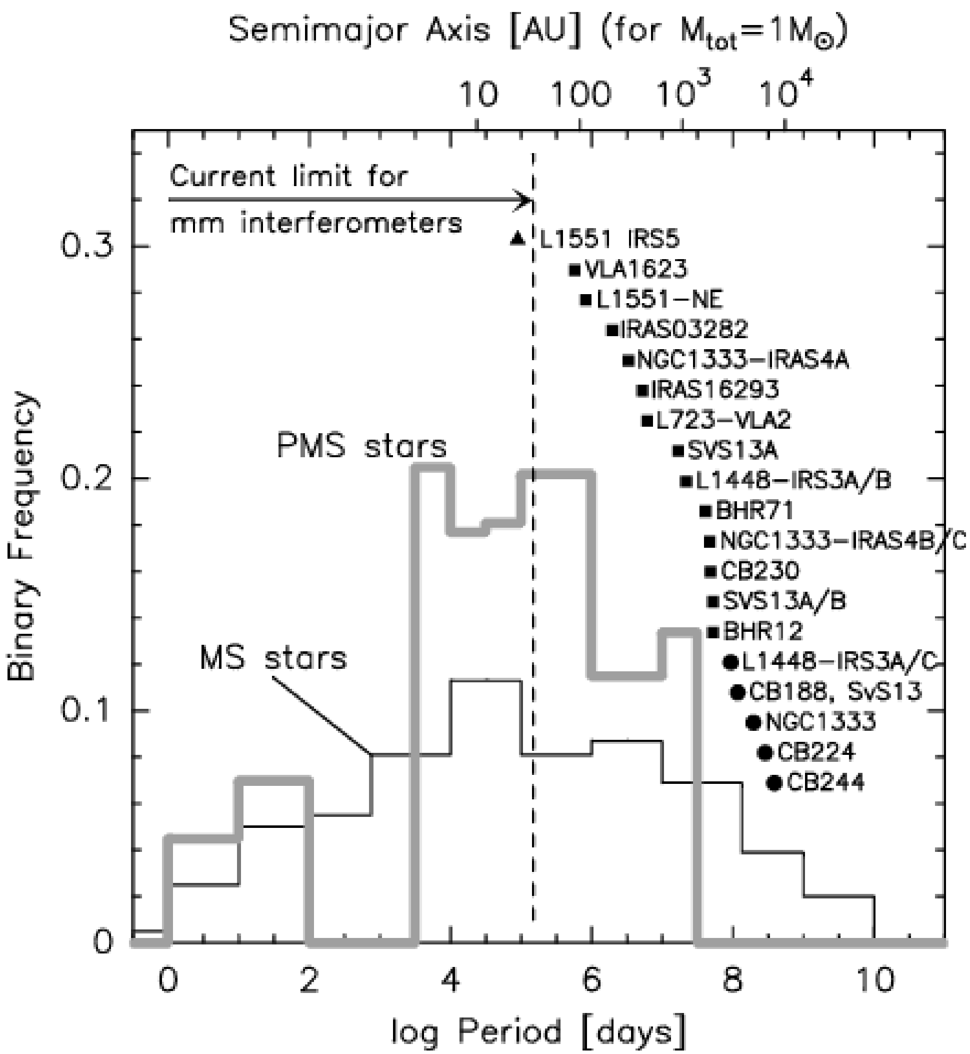
➢ *Hierarchical system*



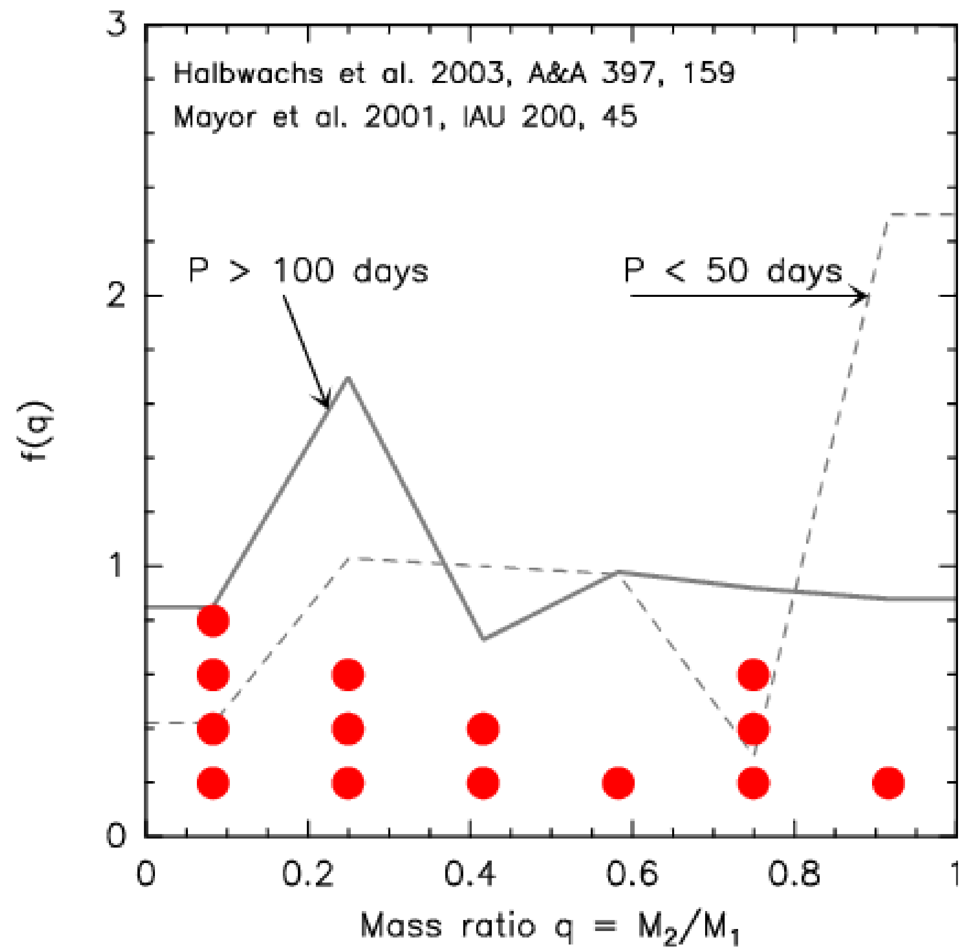
Looney et al. 2000

What do we learn from mm dust continuum?

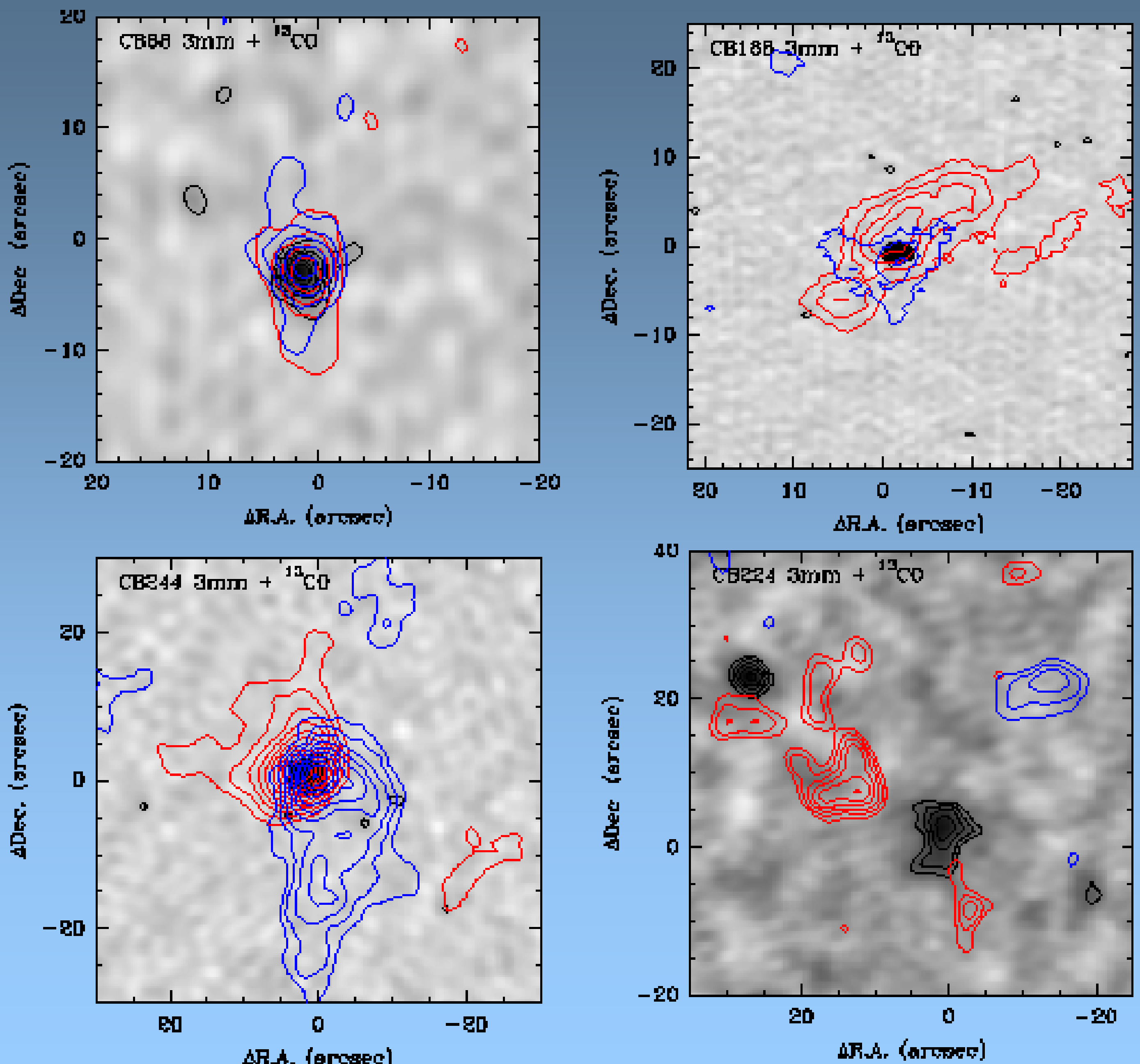
Separations:



Mass ratios:



Observations of molecular outflows



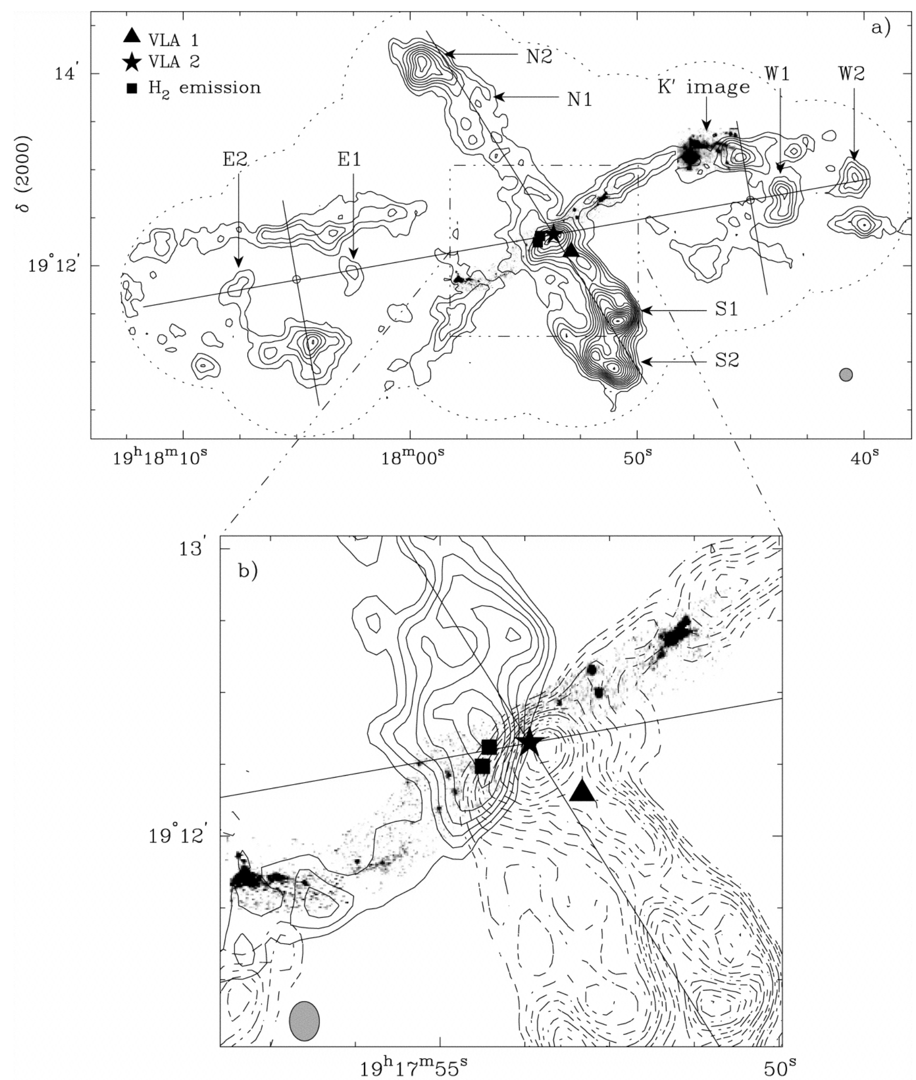
Outflows 1: L723-VLA2

- Equal-mass wide protobinary system (d~950AU, q~0.8)

➢ True quadrupolar outflow

➢ Missaligned axes

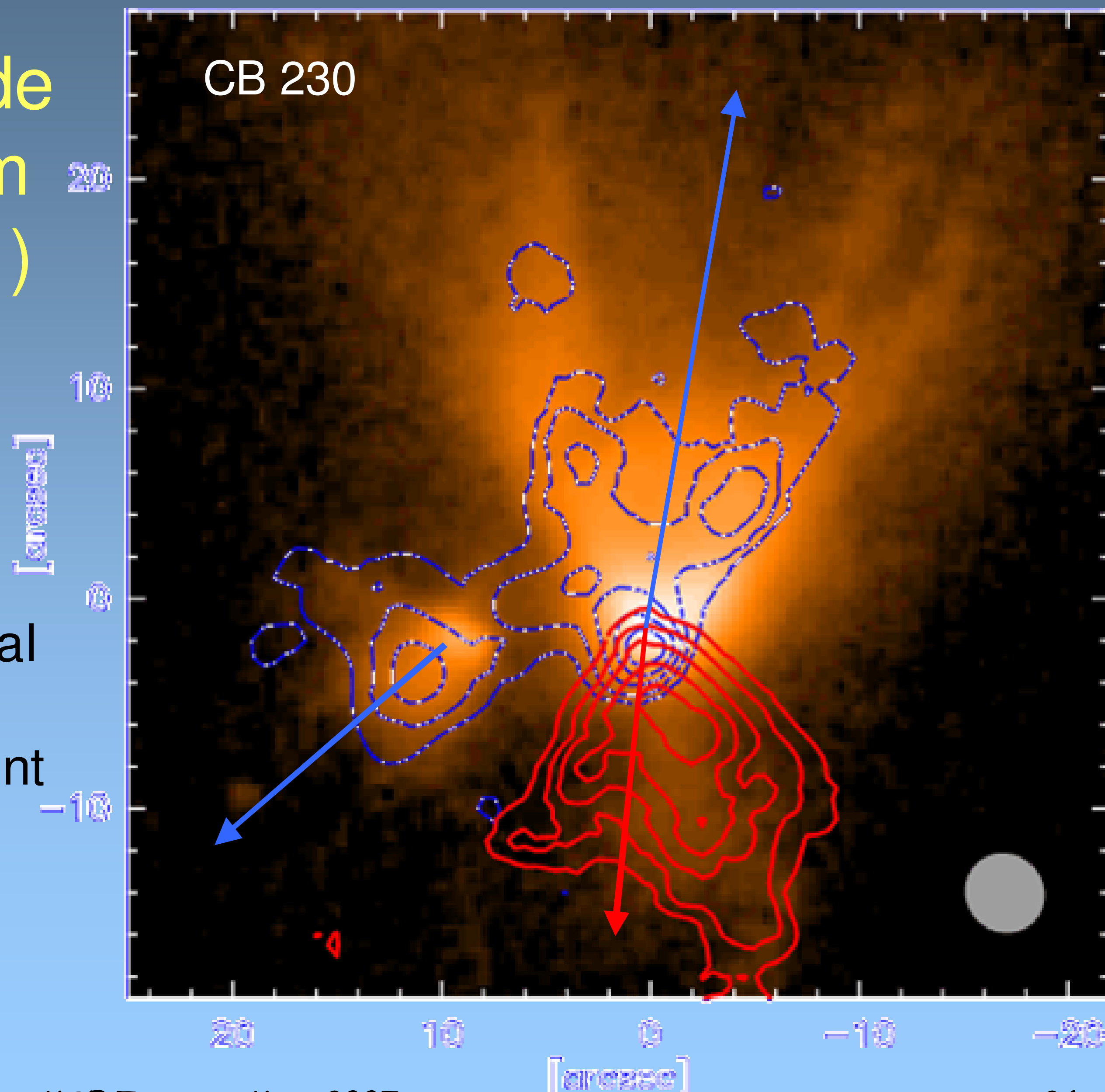
➢ Equal outflow strengths



Lee et al. 2002

Outflows 2: CB230

- Unequal mass wide protobinary system (d≈3800AU, q≈0.1)

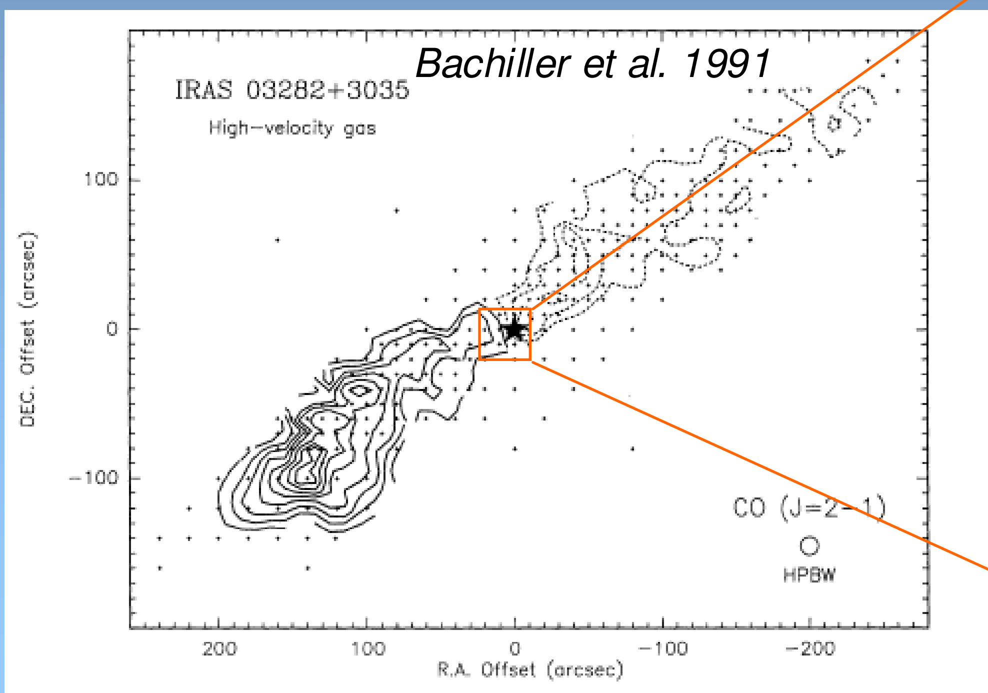


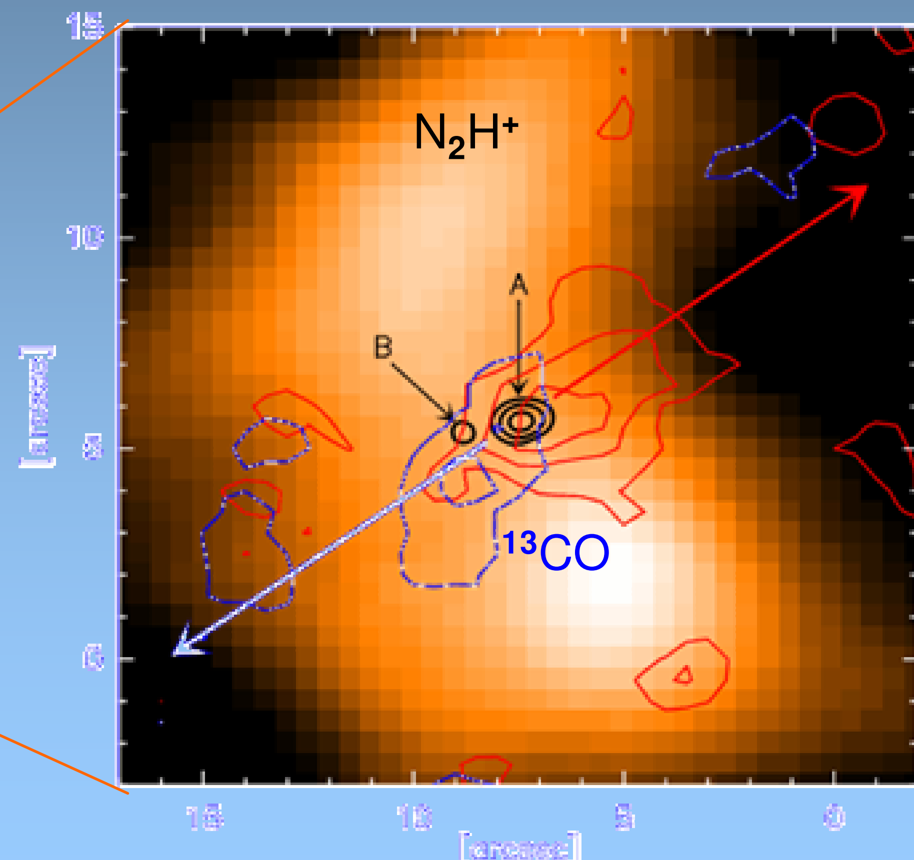
- Large scale: one bipolar outflow
- Interferometer: additional fainter outflow (blue lobe) from secondary component
- Missaligned axes

Outflows 3: IRAS 03282+3025

- Unequal-mass wide protobinary system (d~420AU, q~0.2)

➢ Only one outflow from primary component detected





Launhardt et al. 2003

What do we learn from outflows?

- Outflow axes are often not aligned!
  (at least not for wide binaries >100AU)
  → so must be the angular momenta and disks

- Outflow strengths can be very unequal
  or the secondary outflow is not even detected.

- Why do we observe so few quadrupolar outflows?
  → Most (wide) systems have unequal masses
  → Unequal accretion rates
  → Unequal outflow strengths
  → Secondary outflow in most cases too weak !
  → Close binaries are expected to have q~1. Two parallel jets/winds may produce one single large-scale outflow.

What should we take home?

Observing strategies:

- Interferometric (sub)mm continuum observations most efficcient
- Mid-infrared observations seem very promising complementation
- Outflows and kinematic parameters very challenging, but we need this information

(Preliminary) Results:

1. Binary protostars are frequent and observed at all accessible separations (too early to derive separation distribution)
2. d < 4000 AU → common envelope (prompt fragmentation?)
   d > 4000 AU → separate envelopes (initial fragmentation?)
3. Disks and outflows can be misaligned
4. Flat mass ratio distribution, unequal masses prefered
   → like wide MS binaries
5. Unequal masses / accretion rates produce uneqal outflows, this may explain the observed lack of quadrupolar outflows

What do we dream off?

- ALMA …
- Lots of observing time with ALMA and manpower to reduce the data
- A 100m FIR space telescope or array …