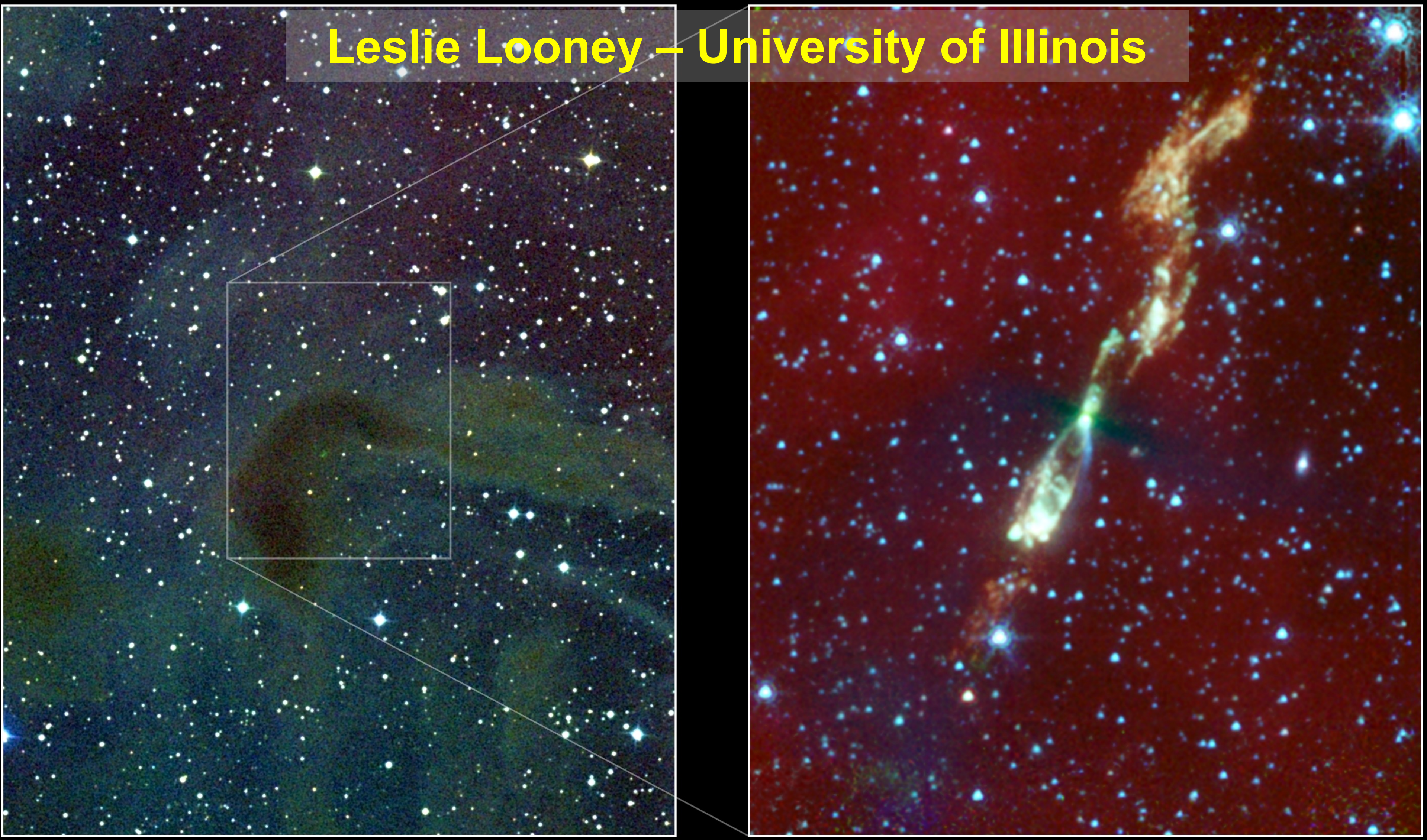
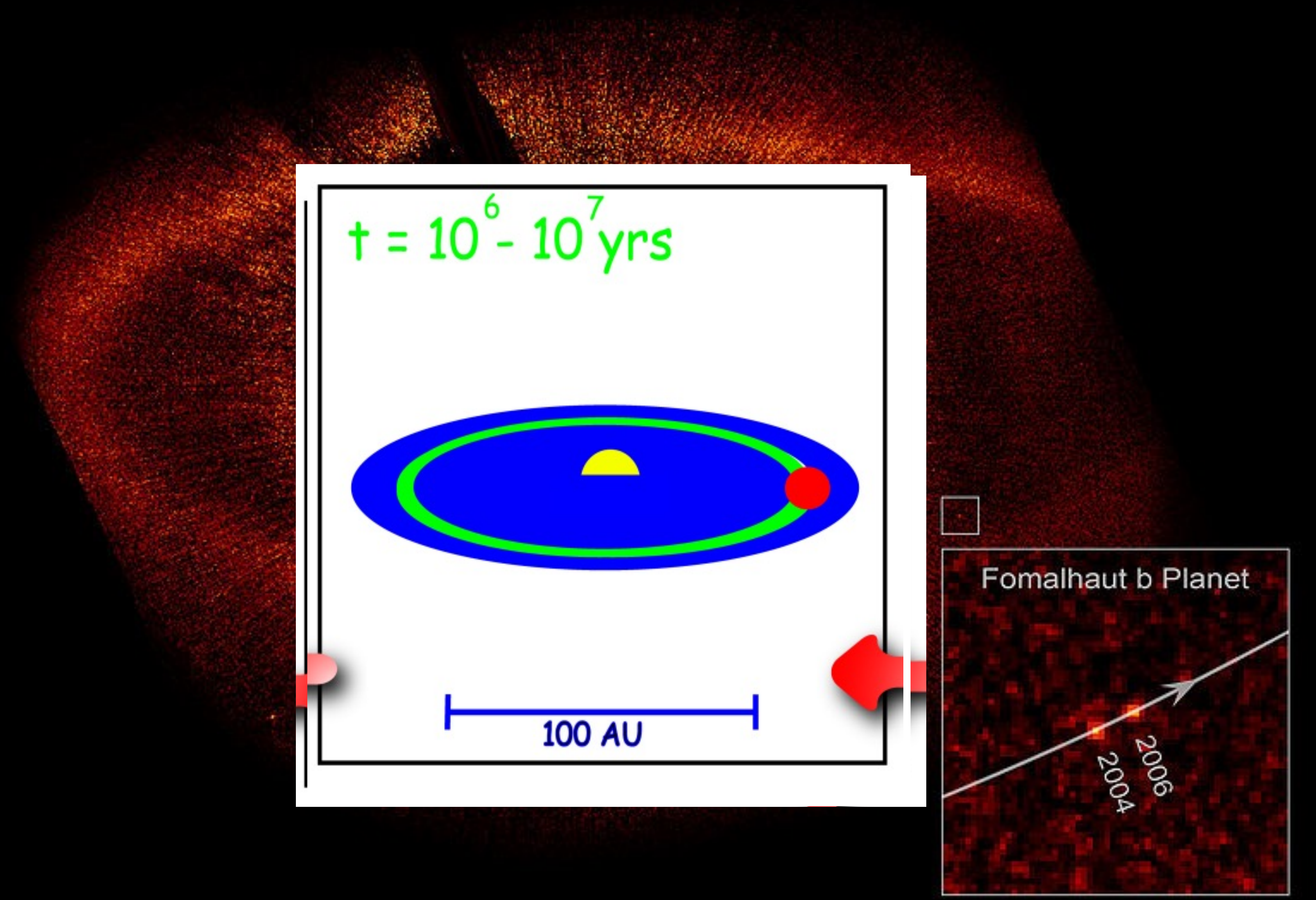


Leslie Looney – University of Illinois

Revealing the Nature of Circumstellar Envelopes Around Class 0 Protostars: A Connection Between Spitzer, CARMA, and SOFIA



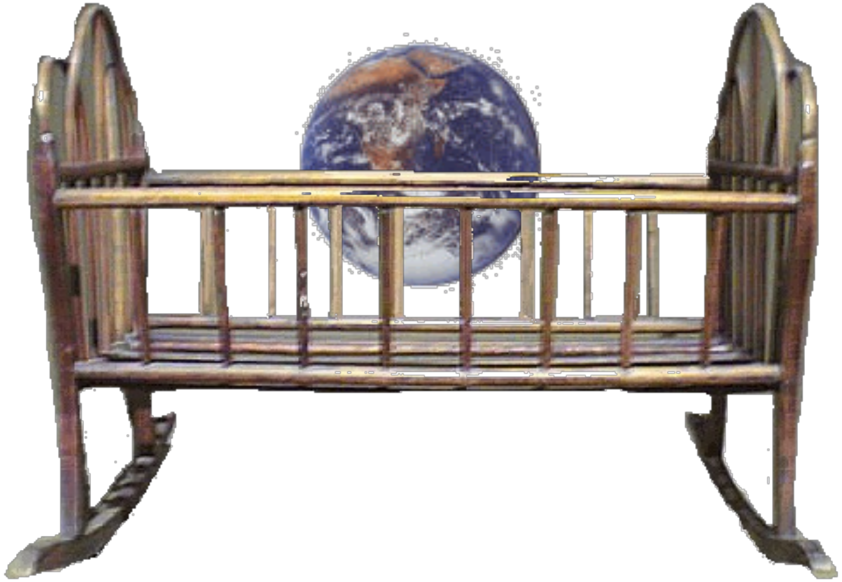
Kalas et al.

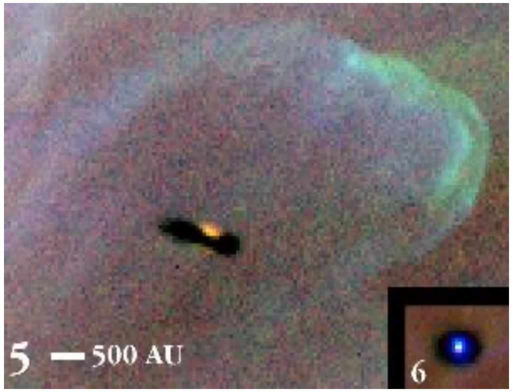
Prenatal Stars

- Deeply embedded inside molecular clouds
- Very young – 10,000 to 100,000 years old!(still cute and cuddly)
- Just a ball of dust and gas (1-10 million years until it burns hydrogen to helium– a standard star), shaped by gravity.

The Cradle of Life

- Stretching an analogy.
- The young Earth was formed in the circumstellar disk that surrounded the protosun.
- The physical conditions in that disk lead to:
  - Terrestrial planets in the 0.4 to 2 AU region
  - Gas and ice giants in the 5 to 30 AU region.

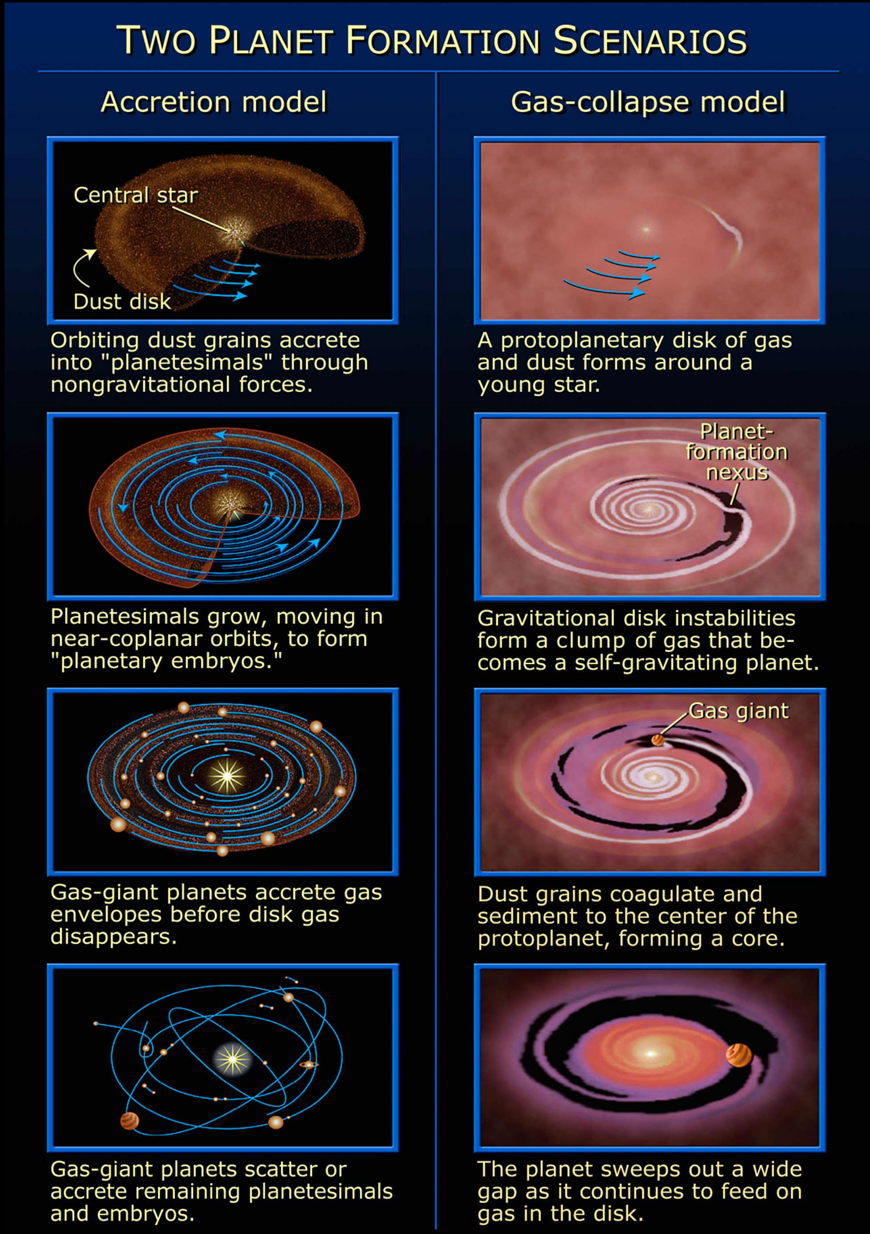




Burrows et al. 1996

The Crumbs from the Table of Star Formation

- Planets form in the circumstellar disk
  - Either through disk instabilities or dust growth
- How do they evolve to a few million years?
- Time period is central to early gas giant formation and planet migration scenarios.



TWO PLANET FORMATION SCENARIOS

Accretion model

Orbiting dust grains accrete into "planetesimals" through nongravitational forces.

Planetesimals grow, moving in near-coplanar orbits, to form "planetary embryos."

Gas-giant planets accrete gas envelopes before disk gas disappears.

Gas-giant planets scatter or accrete remaining planetesimals and embryos.

Gas-collapse model

A protoplanetary disk of gas and dust forms around a young star.

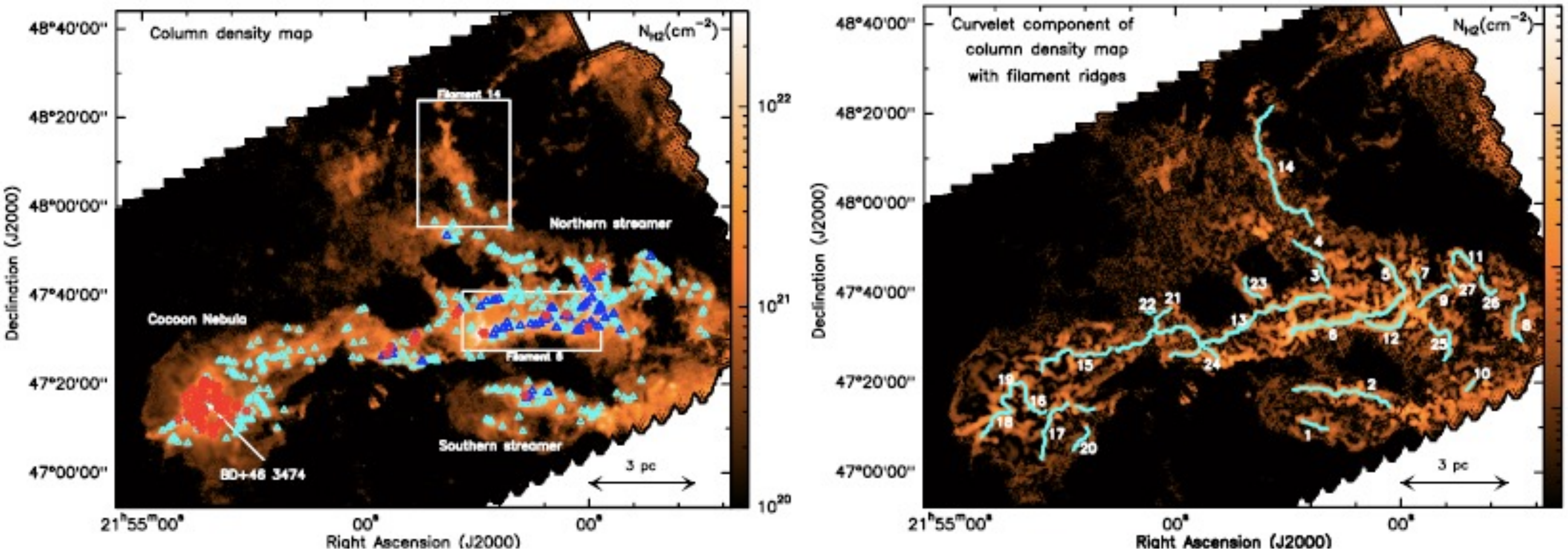
Gravitational disk instabilities form a clump of gas that becomes a self-gravitating planet.

Dust grains coagulate and sediment to the center of the protoplanet, forming a core.

The planet sweeps out a wide gap as it continues to feed on gas in the disk.

NASA And A. Feild

Star Formation:
A Multi-Scale Problem



Arzoumanian et al. 2011

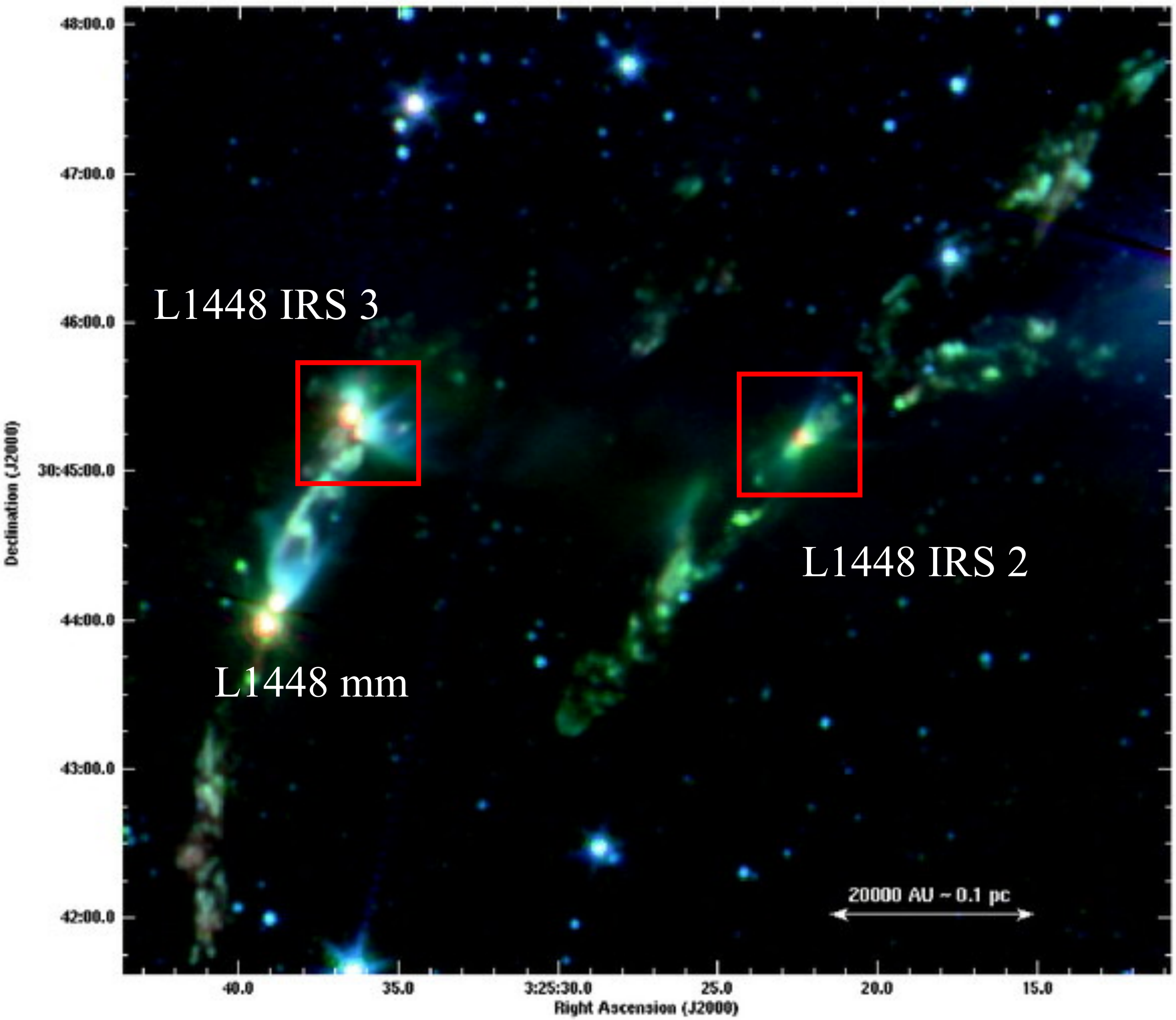
- What is the connection from large-scale clouds to low-mass cores
- Herschel shows the complexity and filaments– thickness of ~0.1 pc and $r \sim r^{-1.5 \text{ to } -2}$

Spitzer: New Regime for Class 0 Protostars

- The sensitivity necessary to image the scattered light of the youngest outflow cavities.
- The morphology used to probe fundamental properties of source such as opening angle, envelope mass, etc. (e.g., Whitney et al. 2003b,a; Tobin et al. 2007; Robitaille et al. 2007; Seale & Looney 2008).

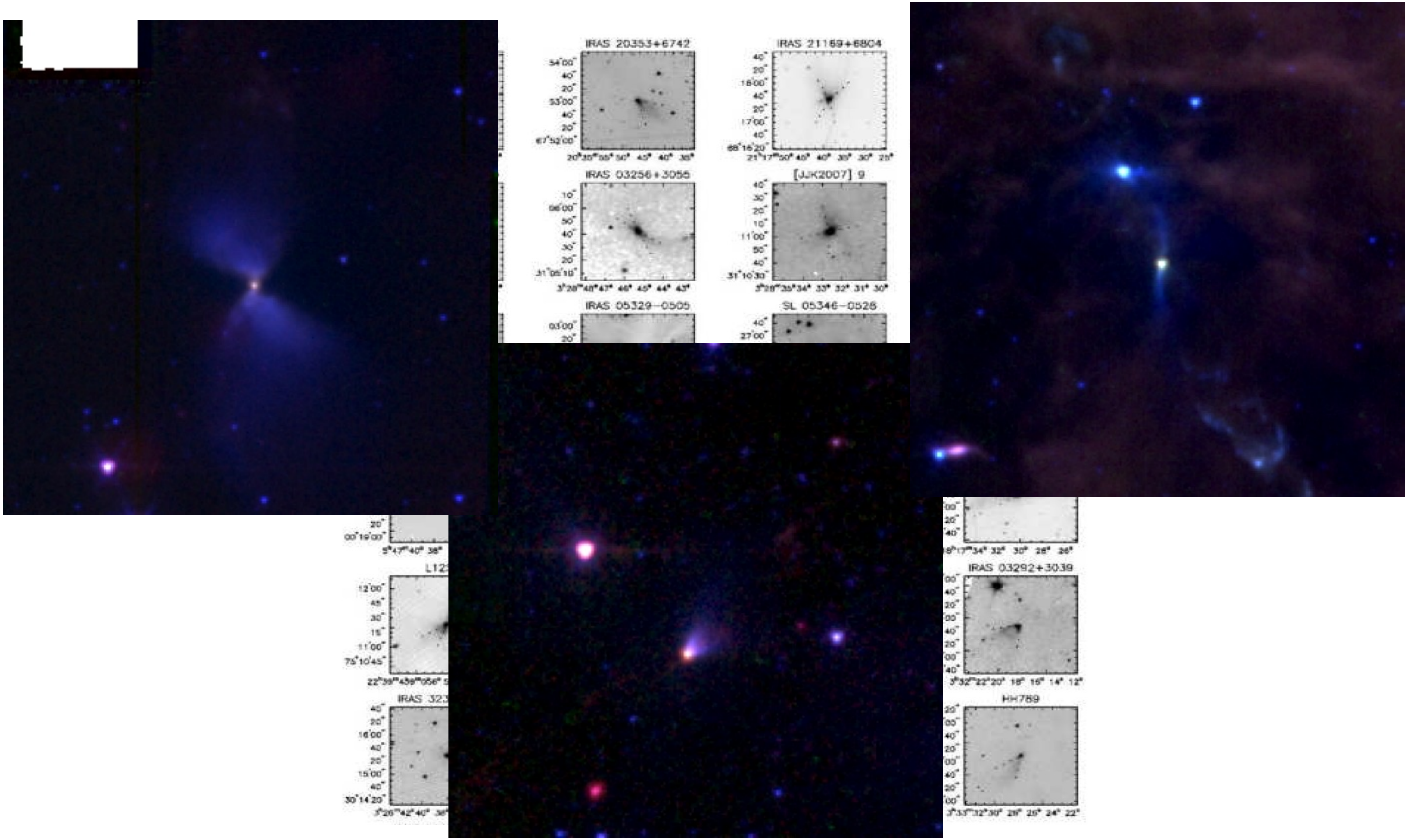
Scattered Light

Outflows carve cavities that allow detection of these deeply embedded objects and shock gas in the outflows



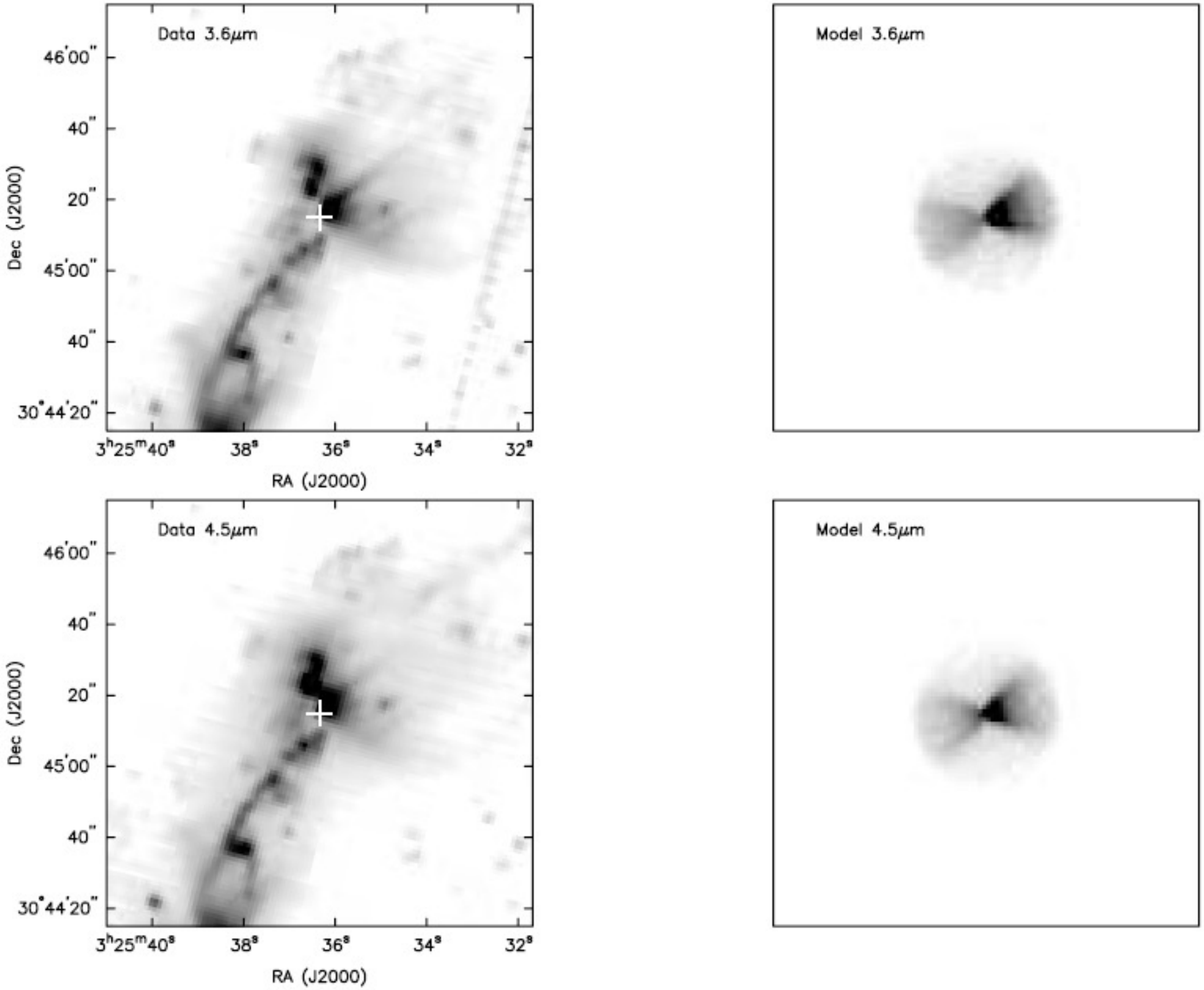
Tobin et al. 2007

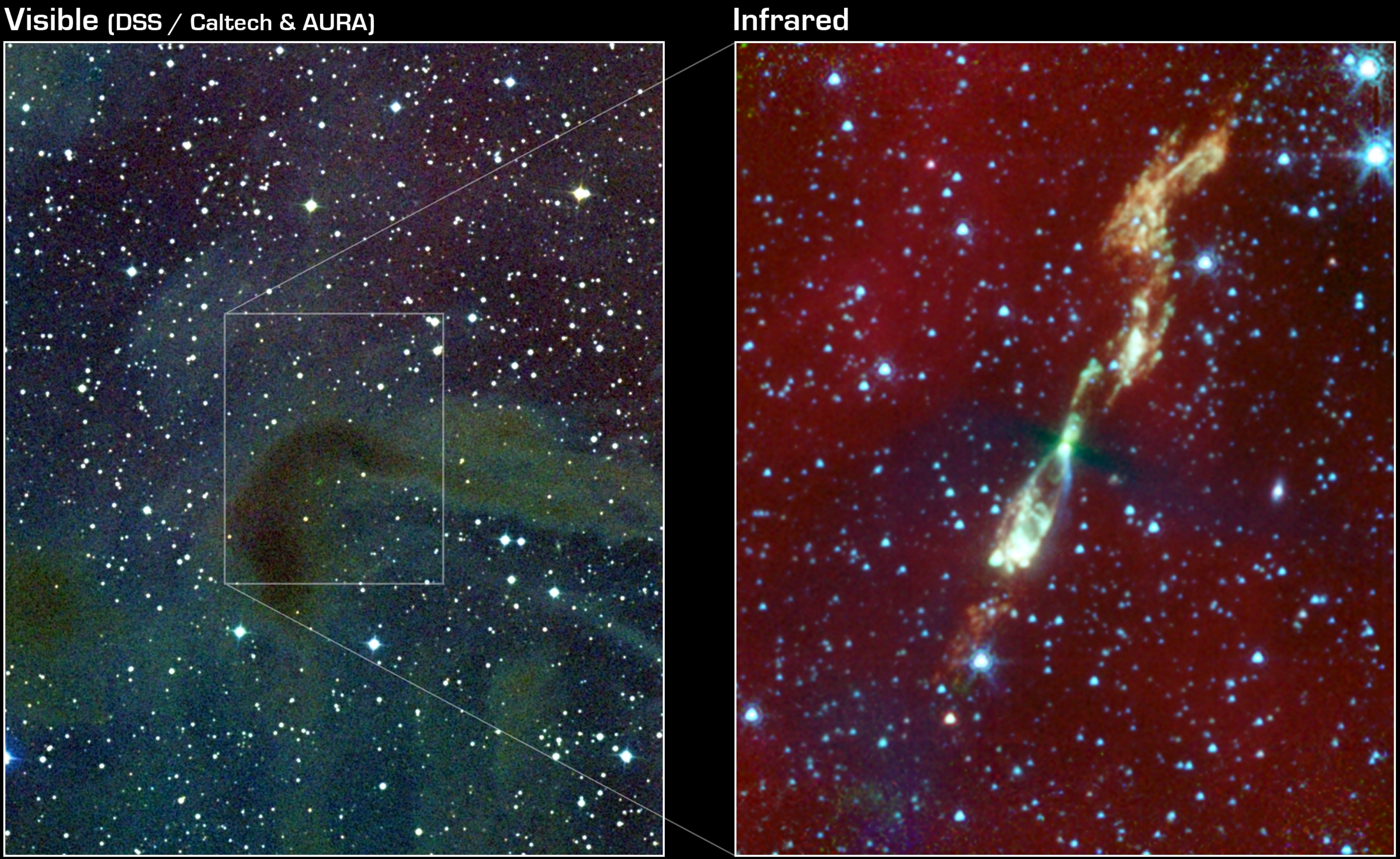
Scattered Light Class 0



Seale & Looney 2008

Modeling the Scattered Light





Visible (DSS / Caltech & AURA)

Infrared

Flattened Envelope around L1157 Protostar

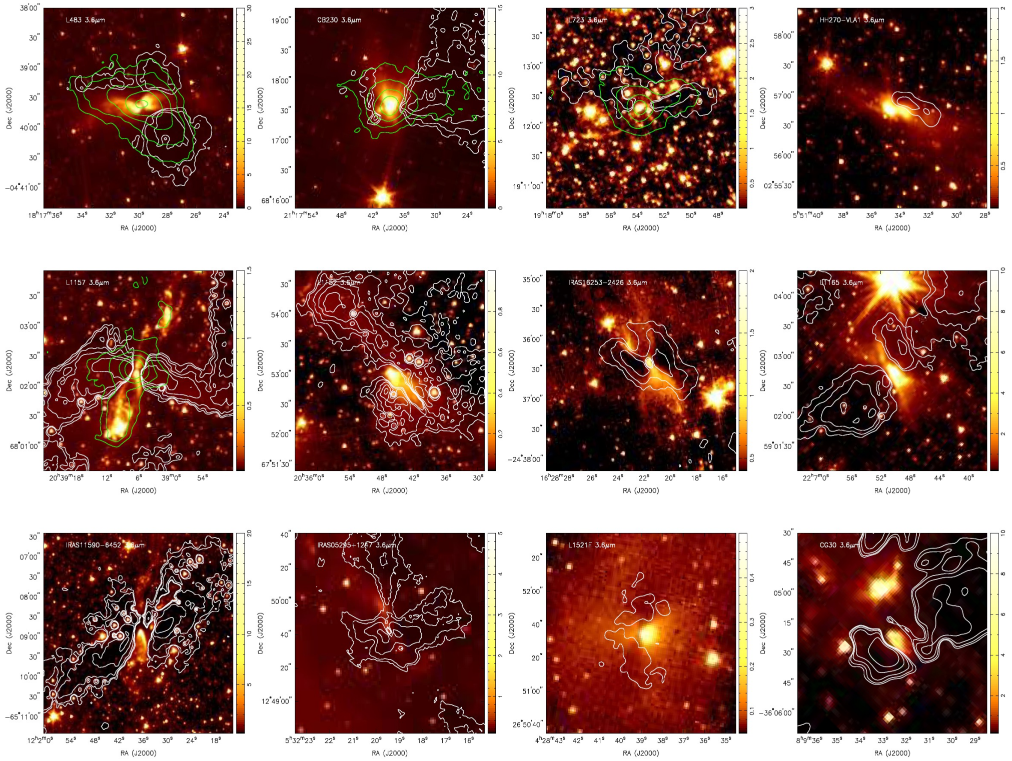
NASA / JPL-Caltech / L. Looney (University of Illinois)

Spitzer Space Telescope • IRAC

ssc2007-19a

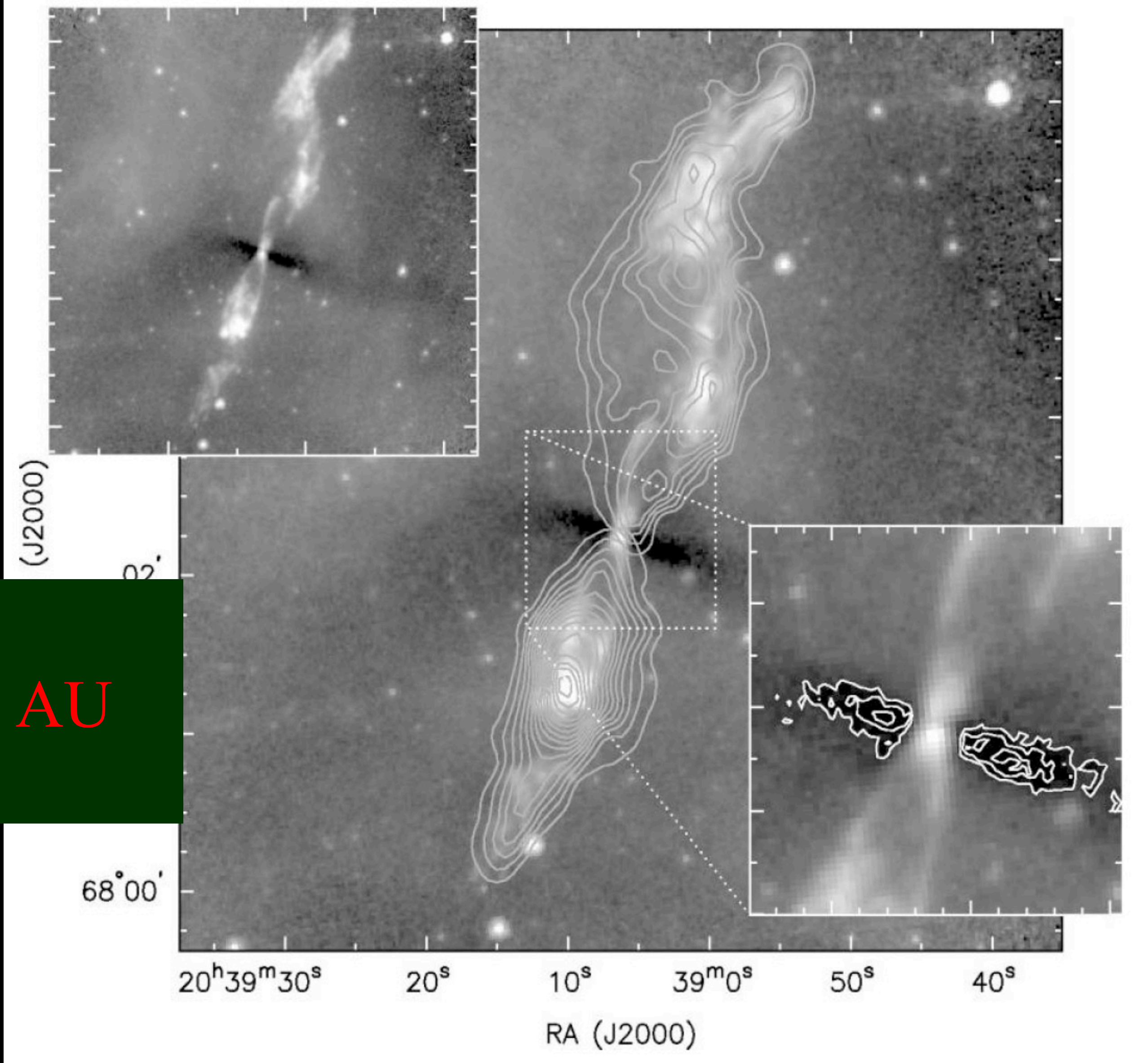
8 Micron Absorption

- Mass-weighted tracer– not dependent on temperature
- About 22 sources
- Highly irregular and non-axisymmetric morphologies on scales >1000 AU, with a quarter of the sample with filamentary or flattened dense structures



Tobin et al. 2009

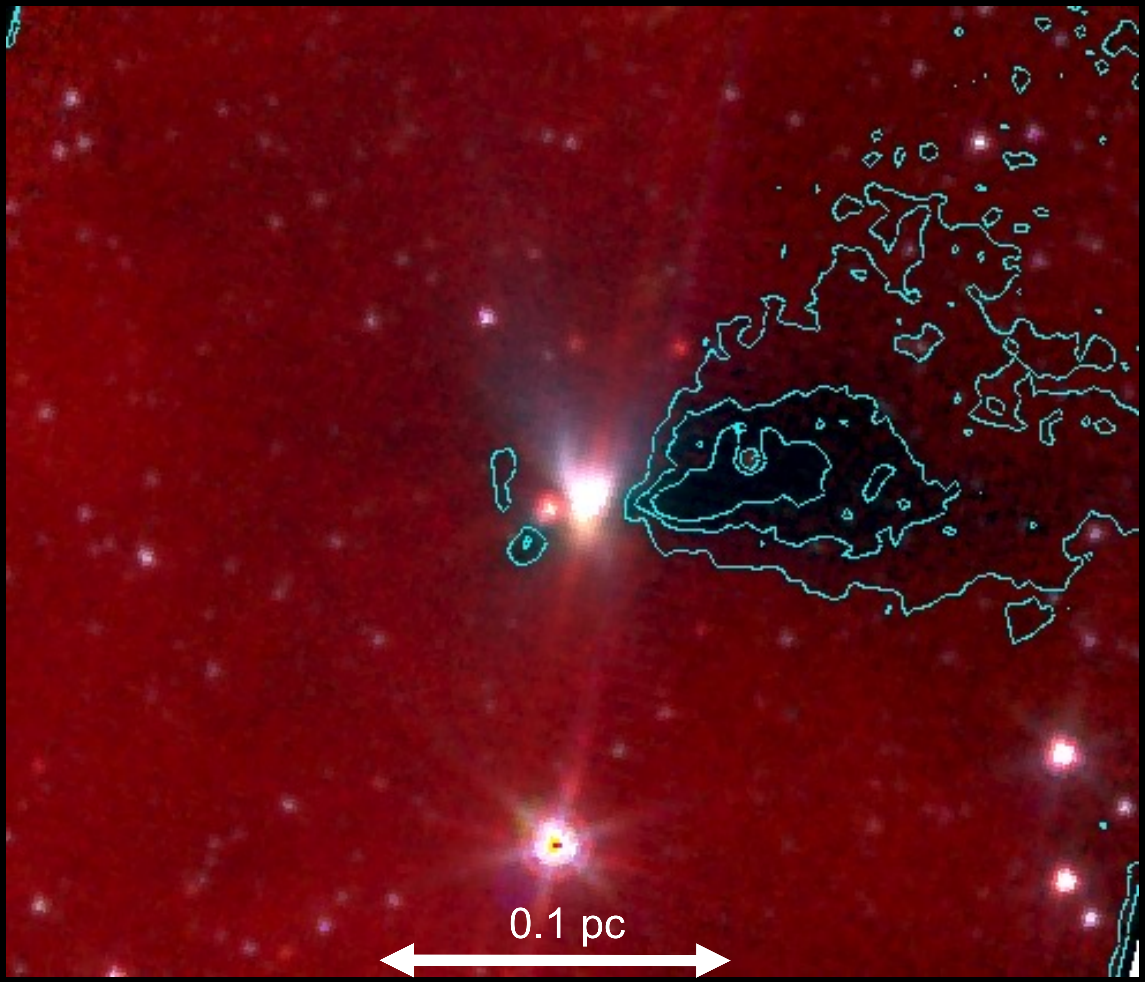
Flattened Envelope



Huge! >30,000 AU

Protostellar Zoo

CB230

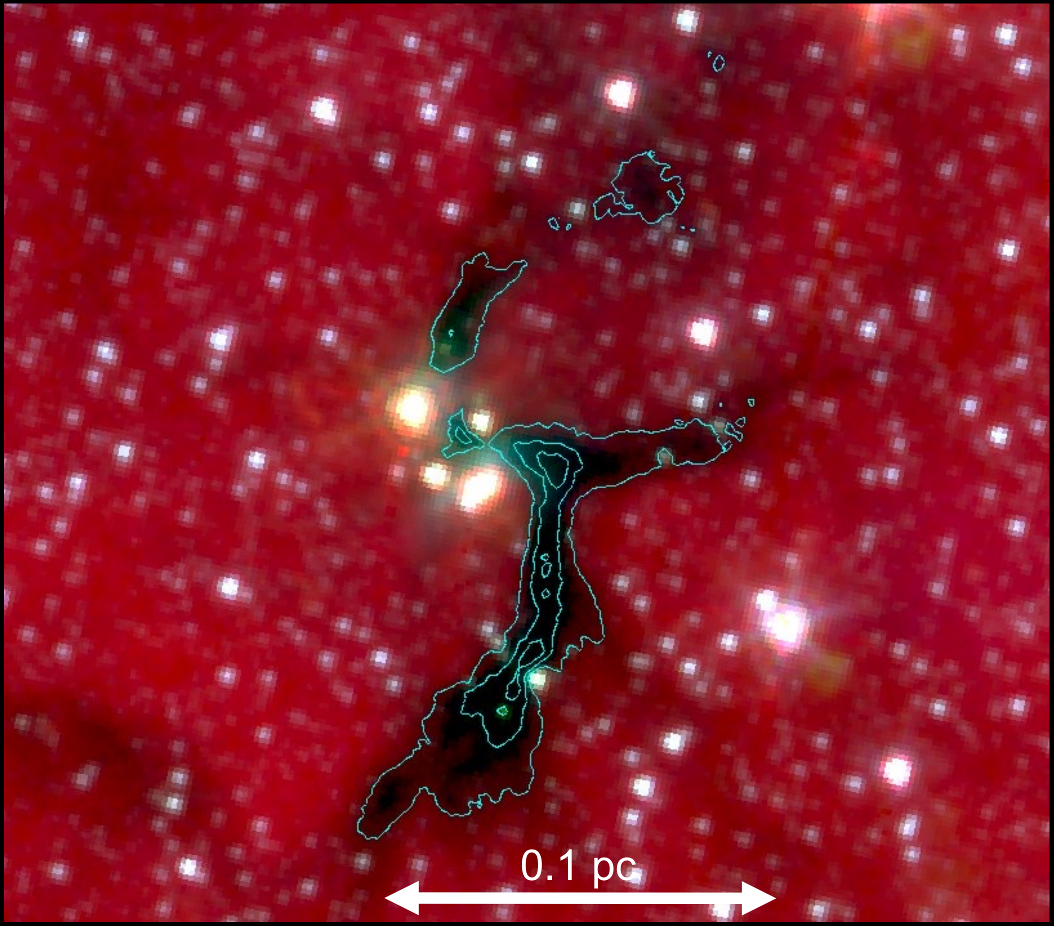


Contours: A_V =10, 20, 30

Tobin et al. (2010)

Protostellar Zoo

L673

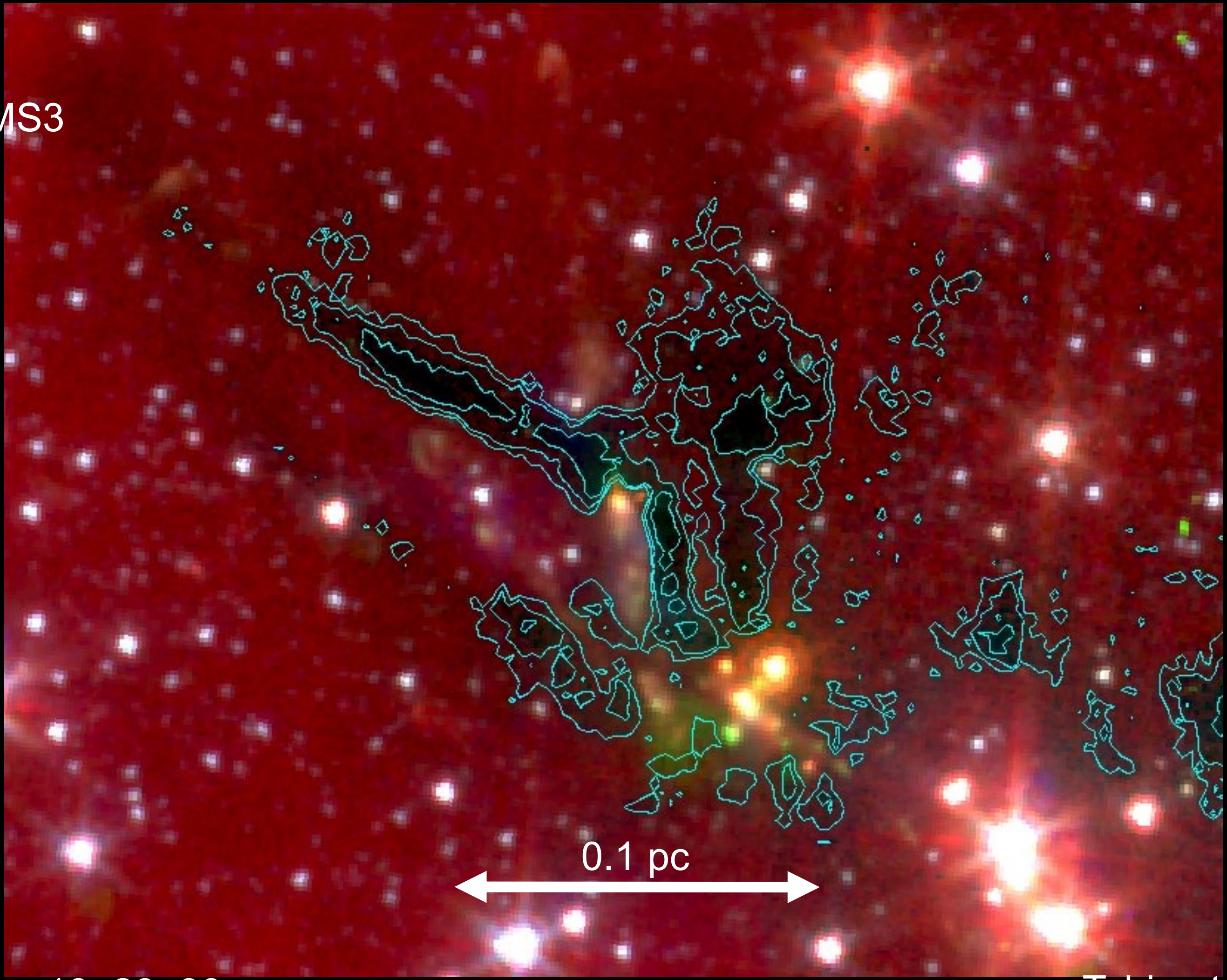


Contours: A_V =10, 20, 30

Tobin et al. (2010)

Protostellar Zoo

Serpens MMS3

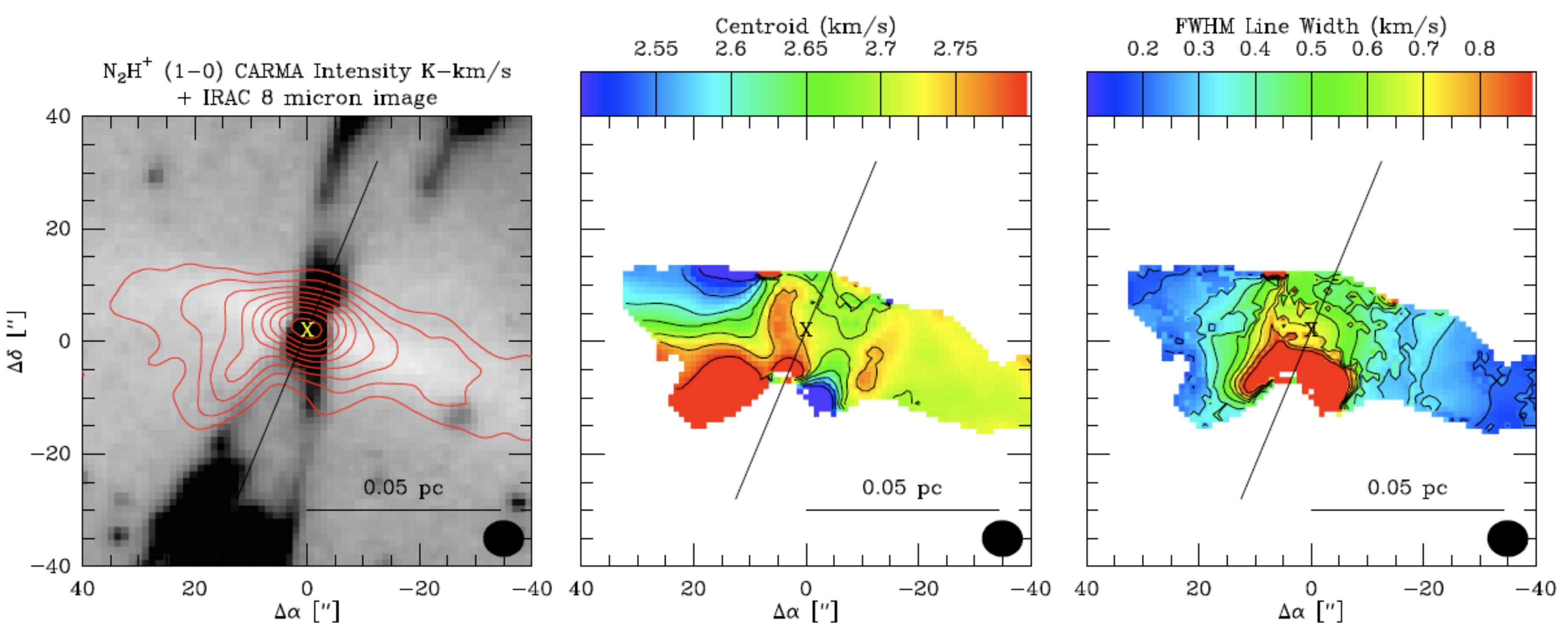


Contours: A_V =10, 20, 30

Tobin et al. (2010)

Kinematics Example 1: L1157

CARMA N_2H^+ (1-0) Velocity Linewidth

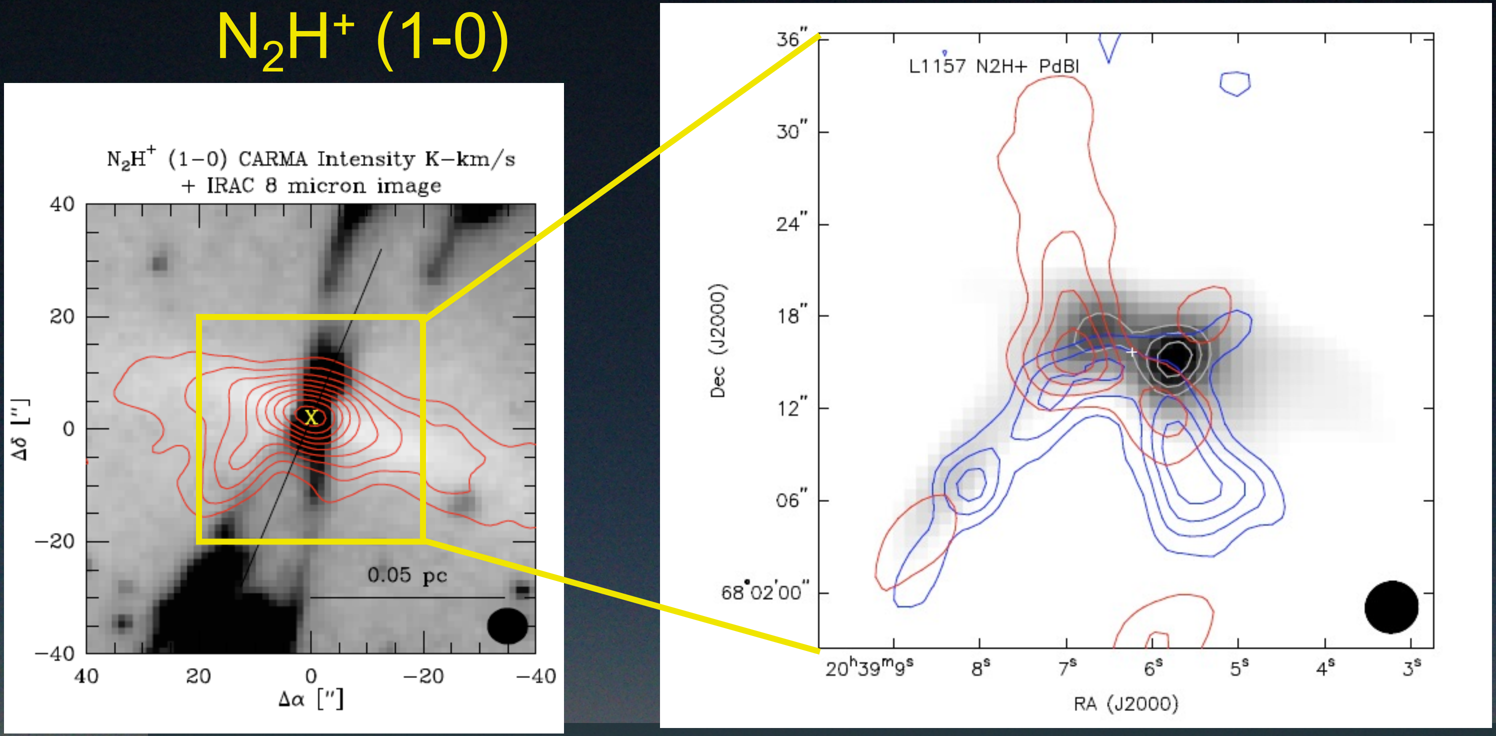


- Large-scale rotation ⊥ outflow direction
- Broader linewidth in the inner envelope
  infall or outflow?

Chiang et al. 2010, Tobin et al. 2011

Kinematics Example 1: L1157

N_2H^+ (1-0)



PdBI

at different velocity range

Red: 3.2-4.0 km/s

Blue: 1.6-2.2 km/s

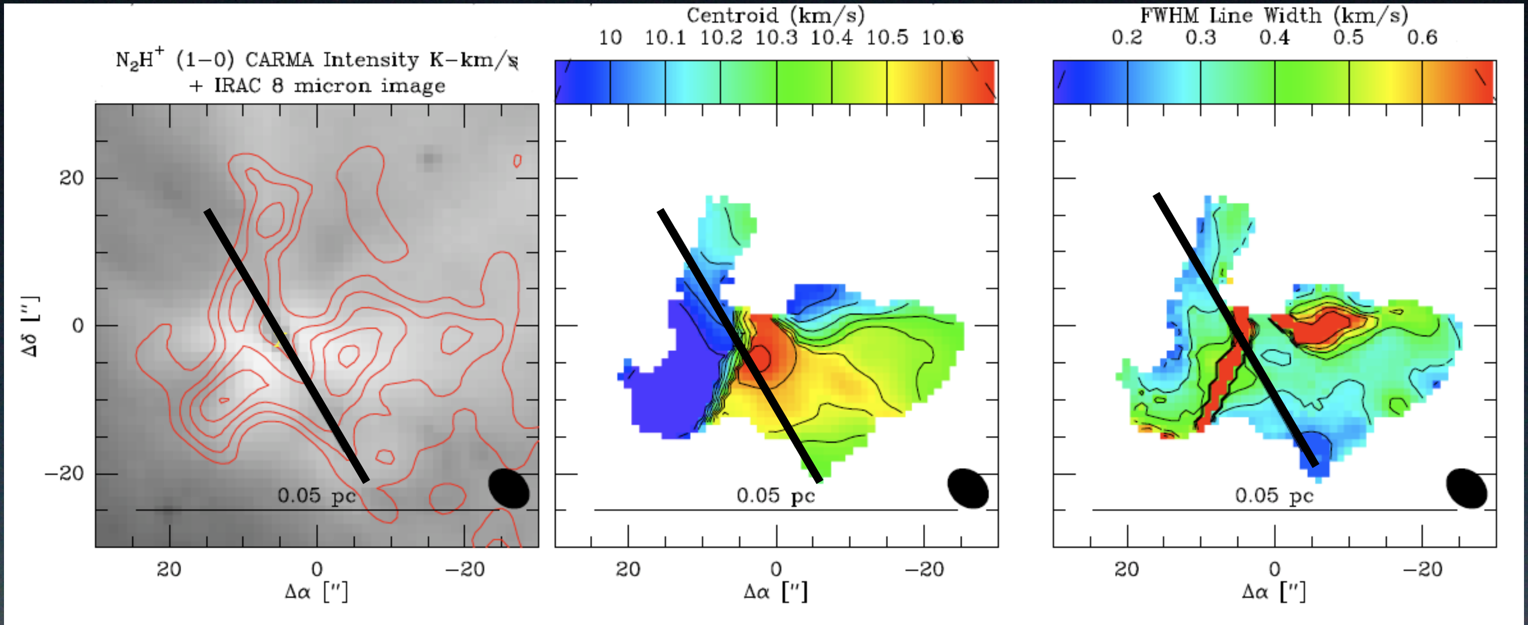
Gray: Line-center

- Large-scale rotation ⊥ outflow
- Broader linewidth in the inner envelope: envelope-outflow interaction: envelope material entrained by outflow (Arce & Sargent 2006)

Chiang et al. 2010, Tobin et al. 2011

Kinematics Example 2: RNO 43

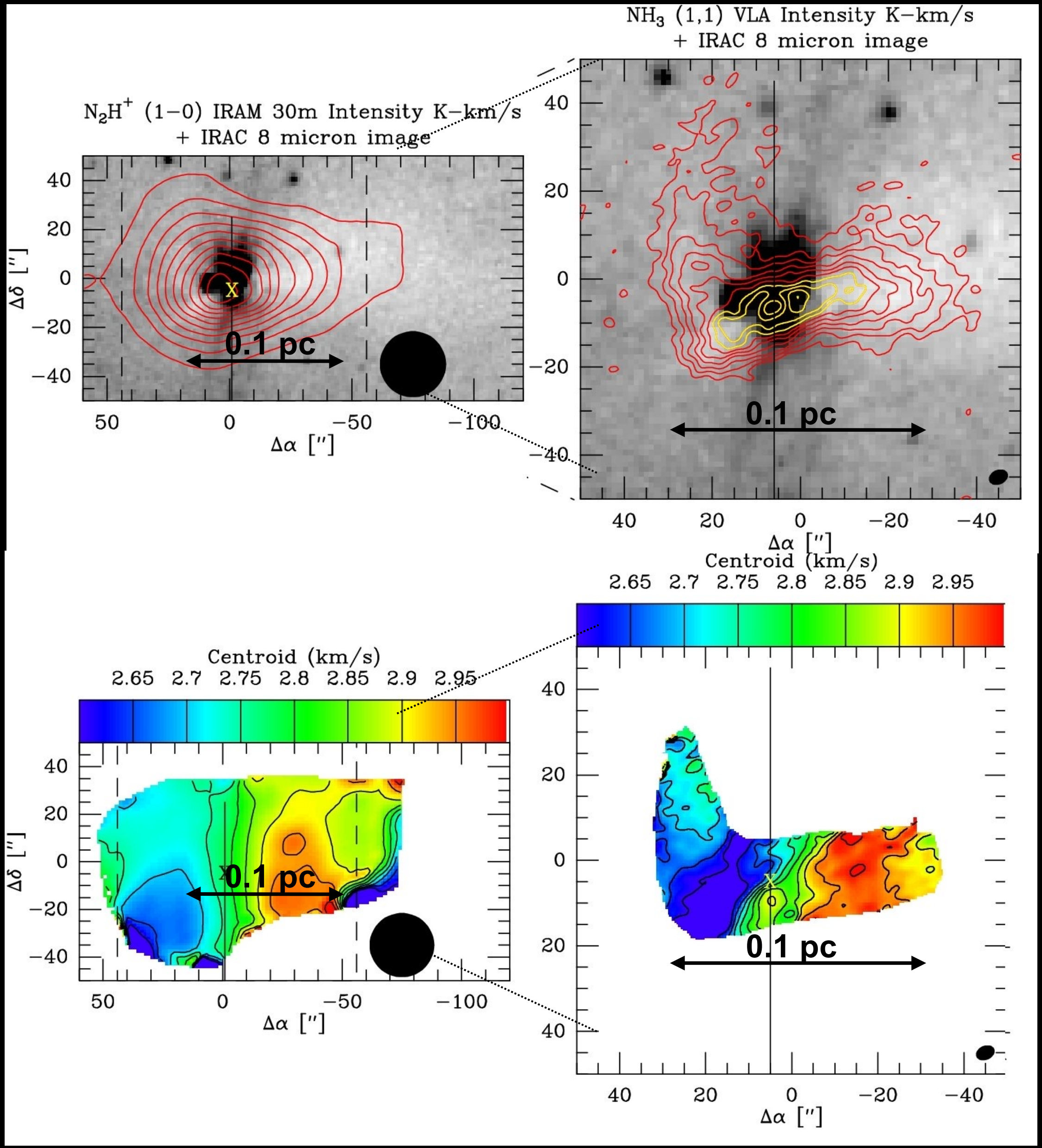
CARMA N_2H^+ (1-0)   Velocity   Linewidth



- Large-scale velocity gradient at NE side
- Velocity jump of ~0.7 km/s :
  - – Another cloud layer along line of sight (Chen et al. 2007)
  - – Colliding flow? (Heitsch et al. 2006)

Tobin et al. 2011

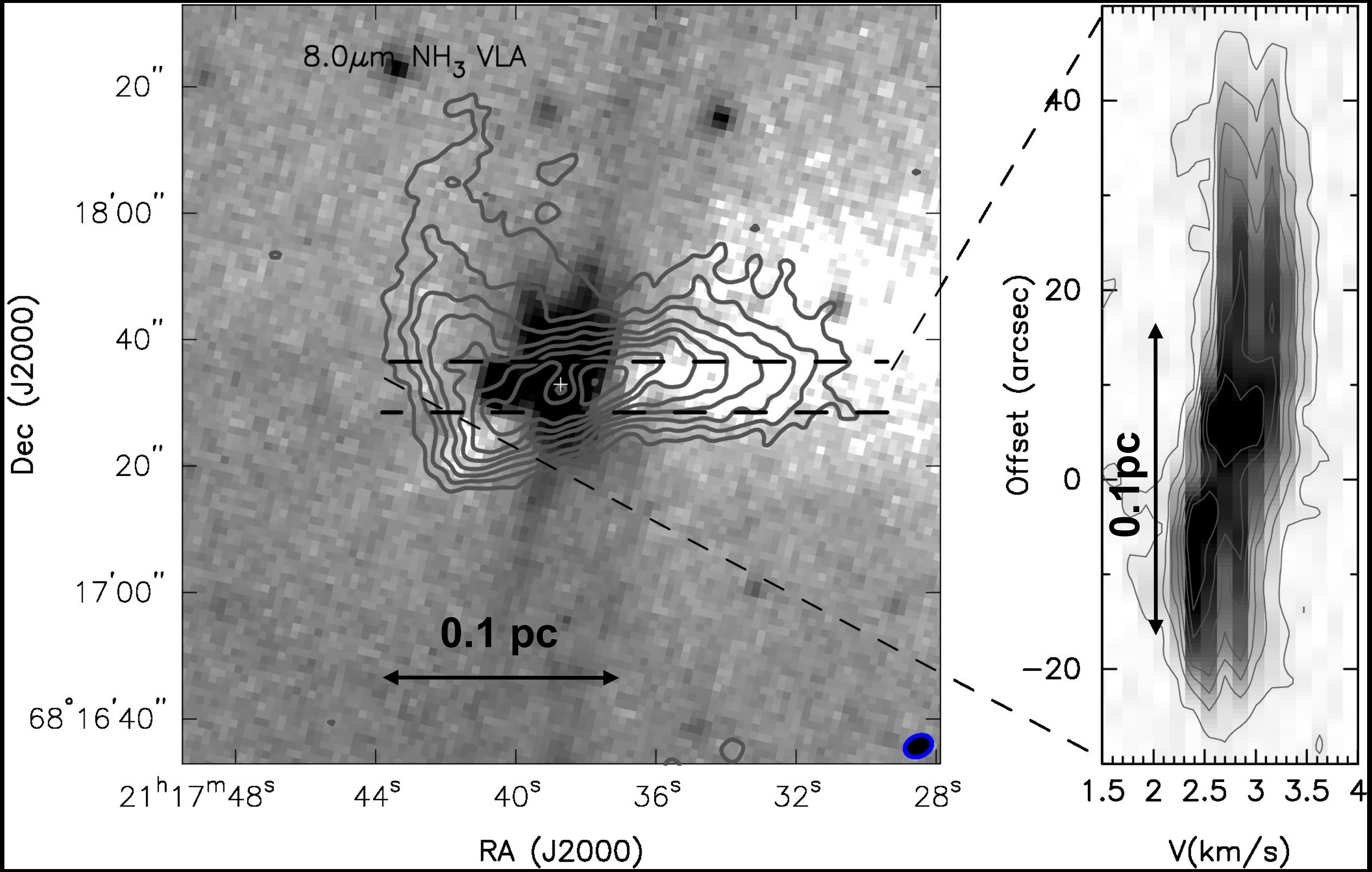
Kinematics Example 3: CB 230



CB230

Tobin et al. (2011)

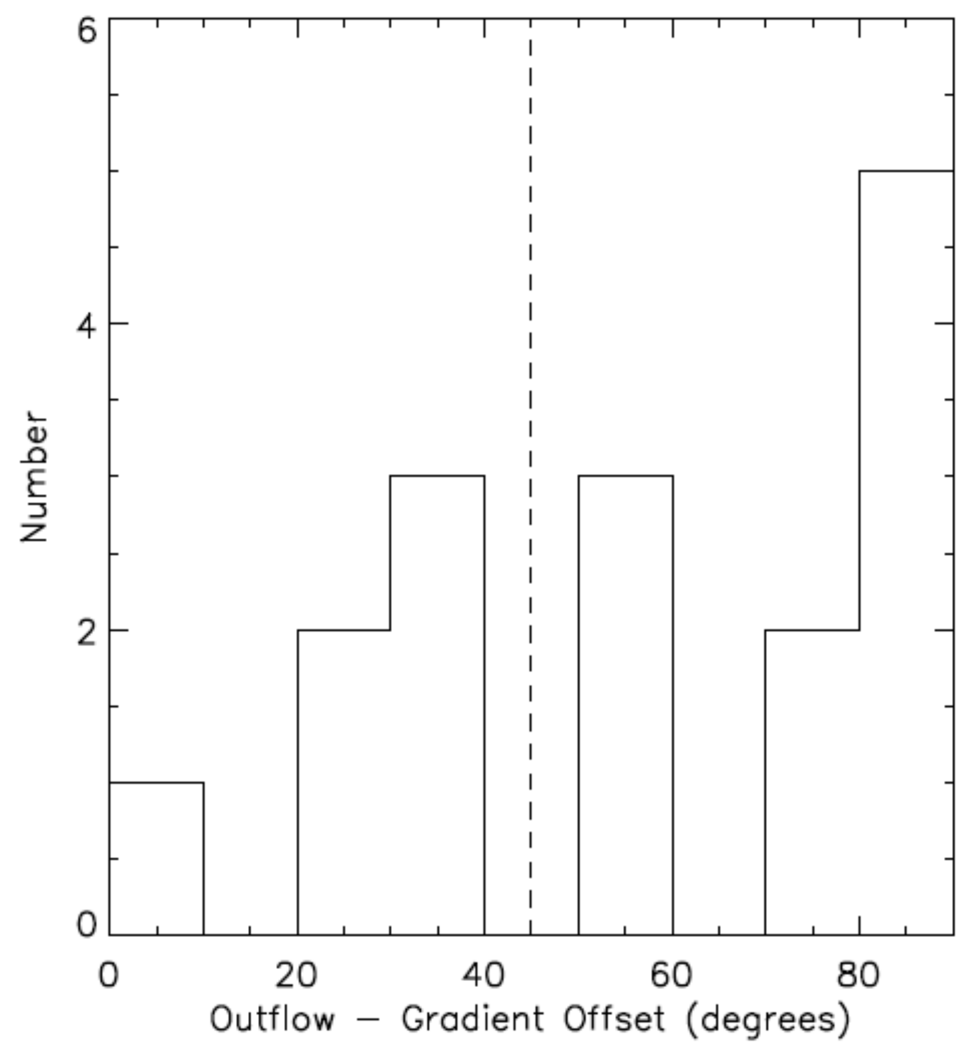
Detailed Line Structure



CB230

Tobin et al. (2011)

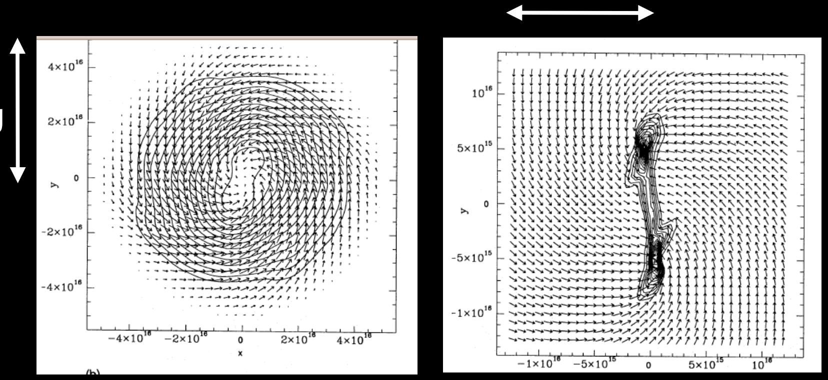
Orientation of The Outflow



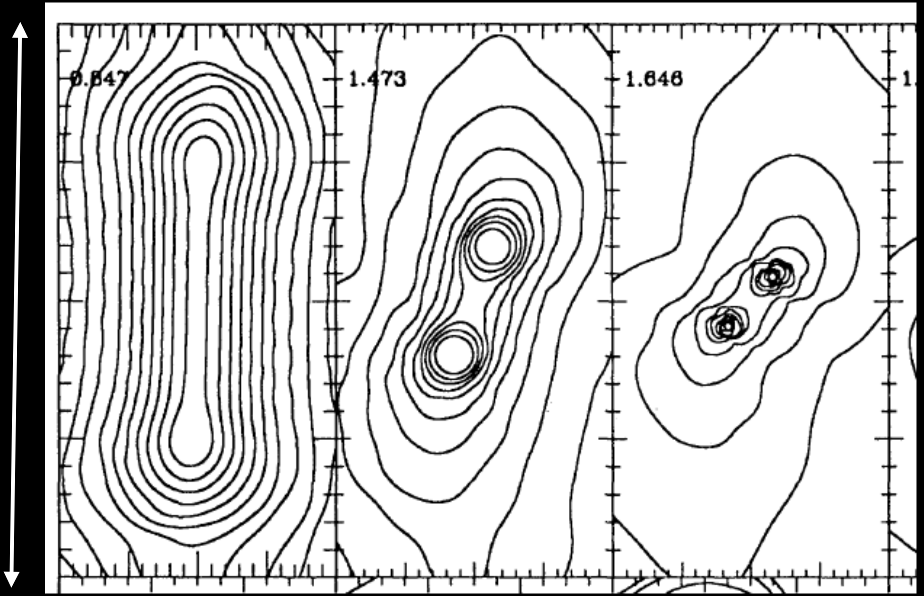
Tobin et al. 2011

Binary Formation

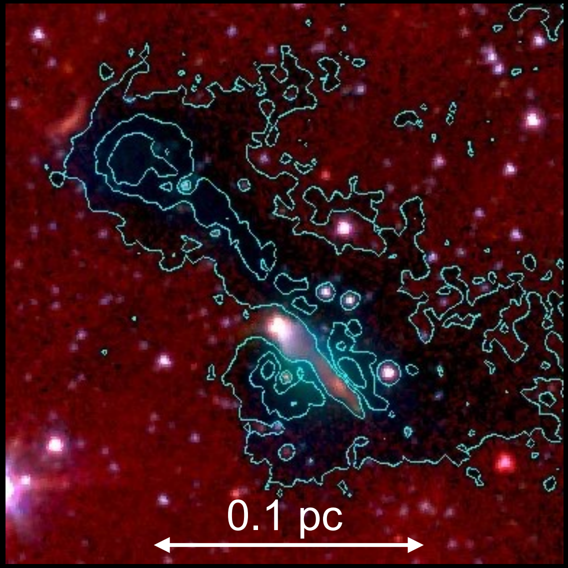
- Non-axisymmetry may induce formation of binary stars
  - Mild perturbations shown to induce fragmentation (Burkert & Bodenheimer 1993)
  - Bonnell et al. (1992) shows binary formation at large and small scales



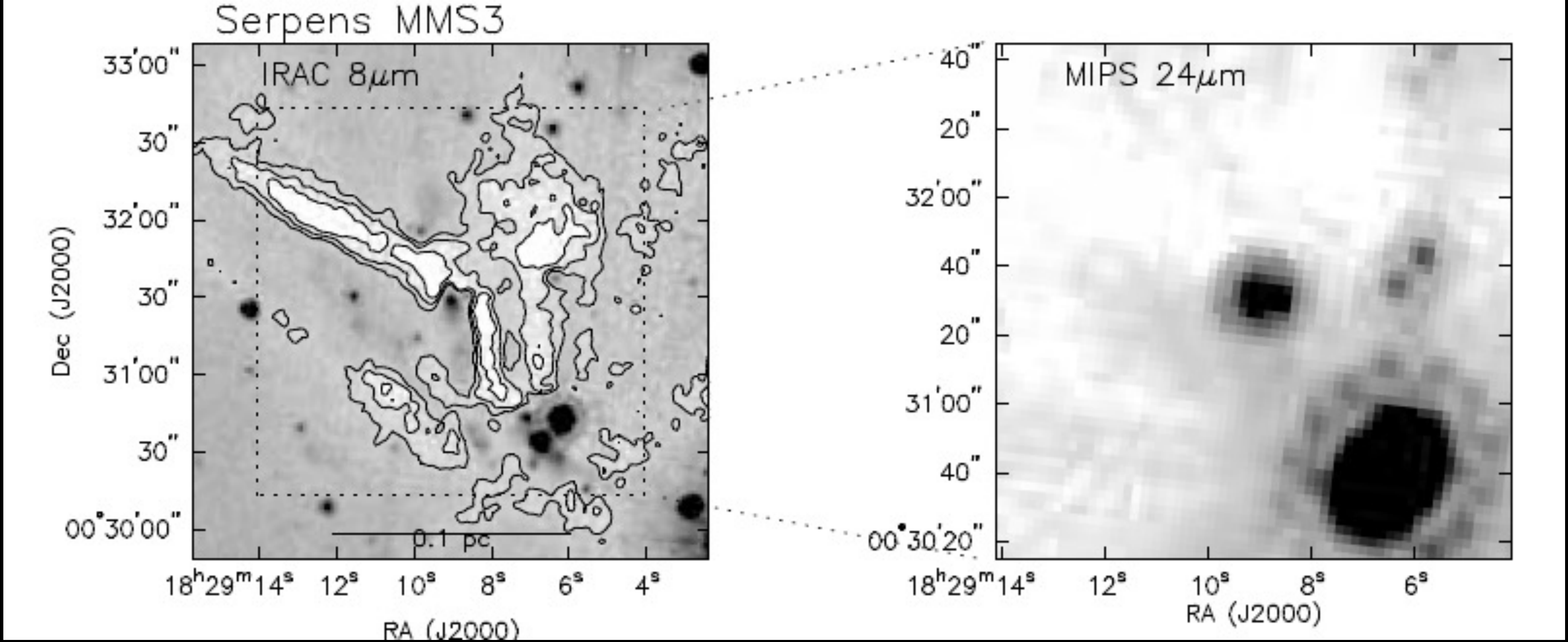
Burkert & Bodenheimer (1993)



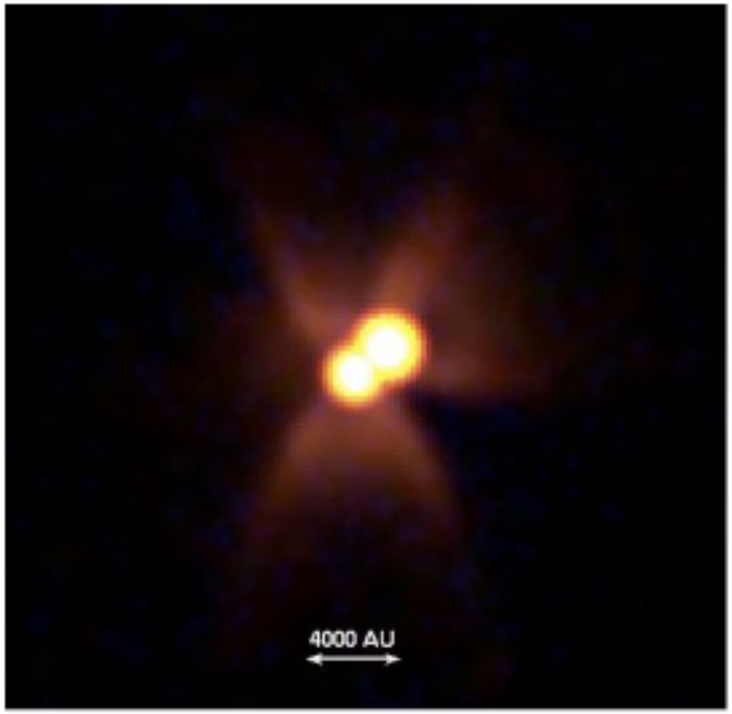
Bonnell et al. (1992)

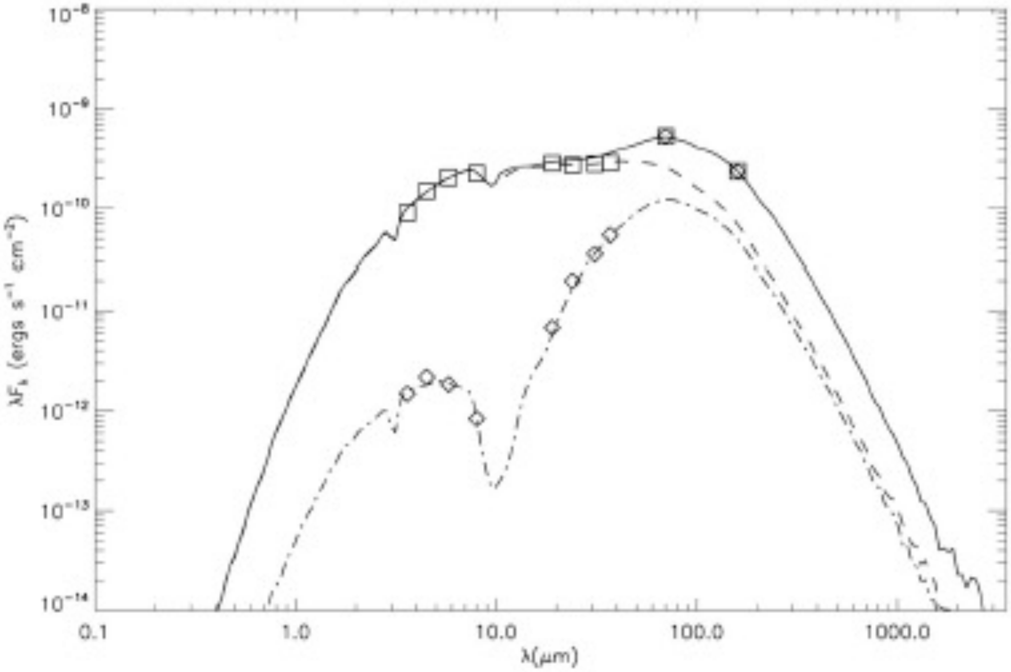


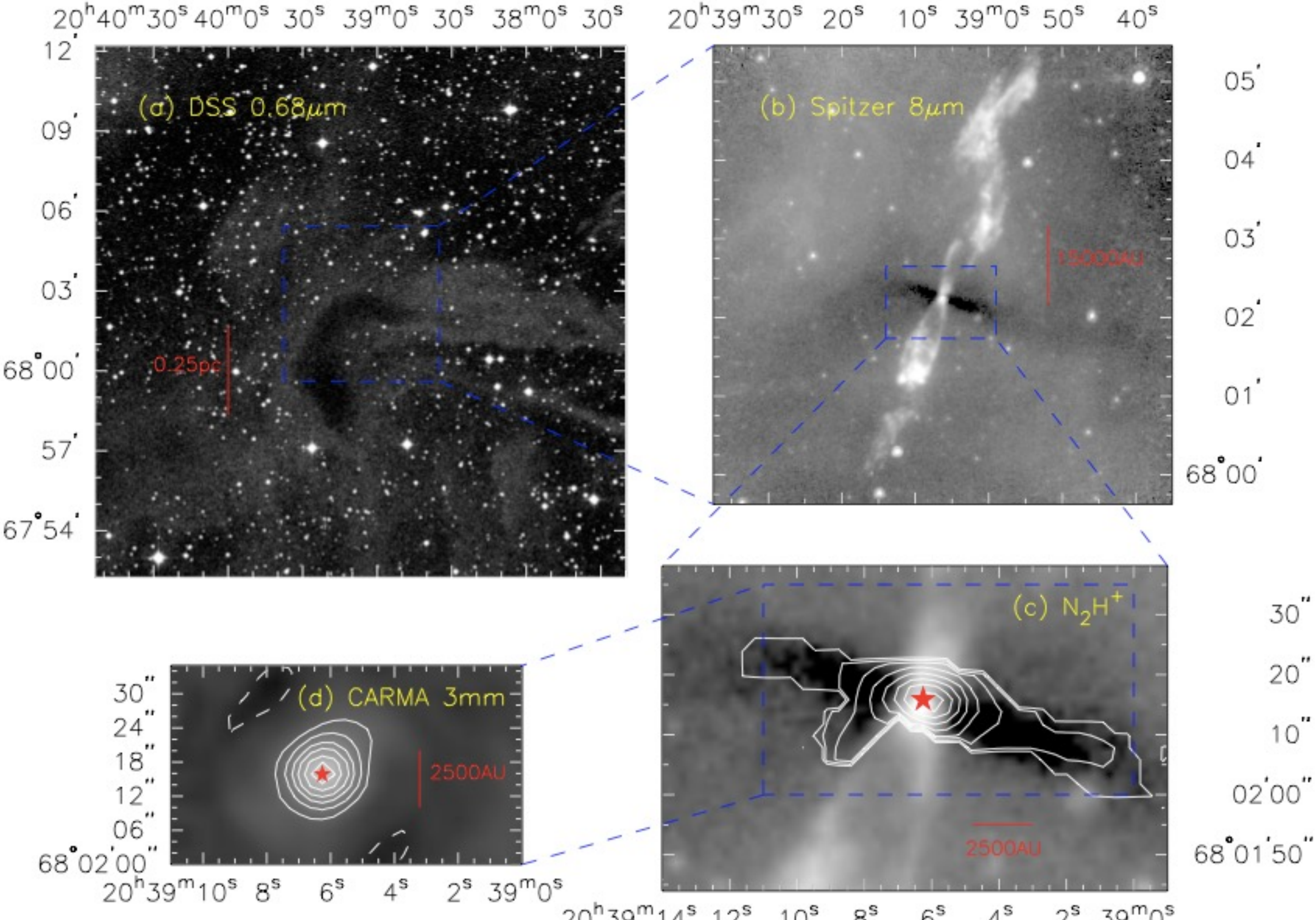
Detected Binary Systems



SOFIA Observations





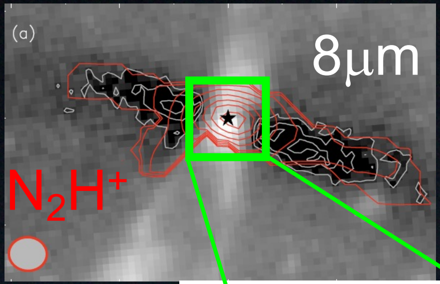


Chiang et al. 2010

Dust Continuum of Class 0 YSOs

- Examines the physical structure of protostellar envelopes
- Reveals the embedded circumstellar disk
- Envelope modeling
  with multi-wavelength data and theoretical models
  - Self-consistent temperature profiles calculated by the RADMC radiative transfer code (Dullemond 2004)

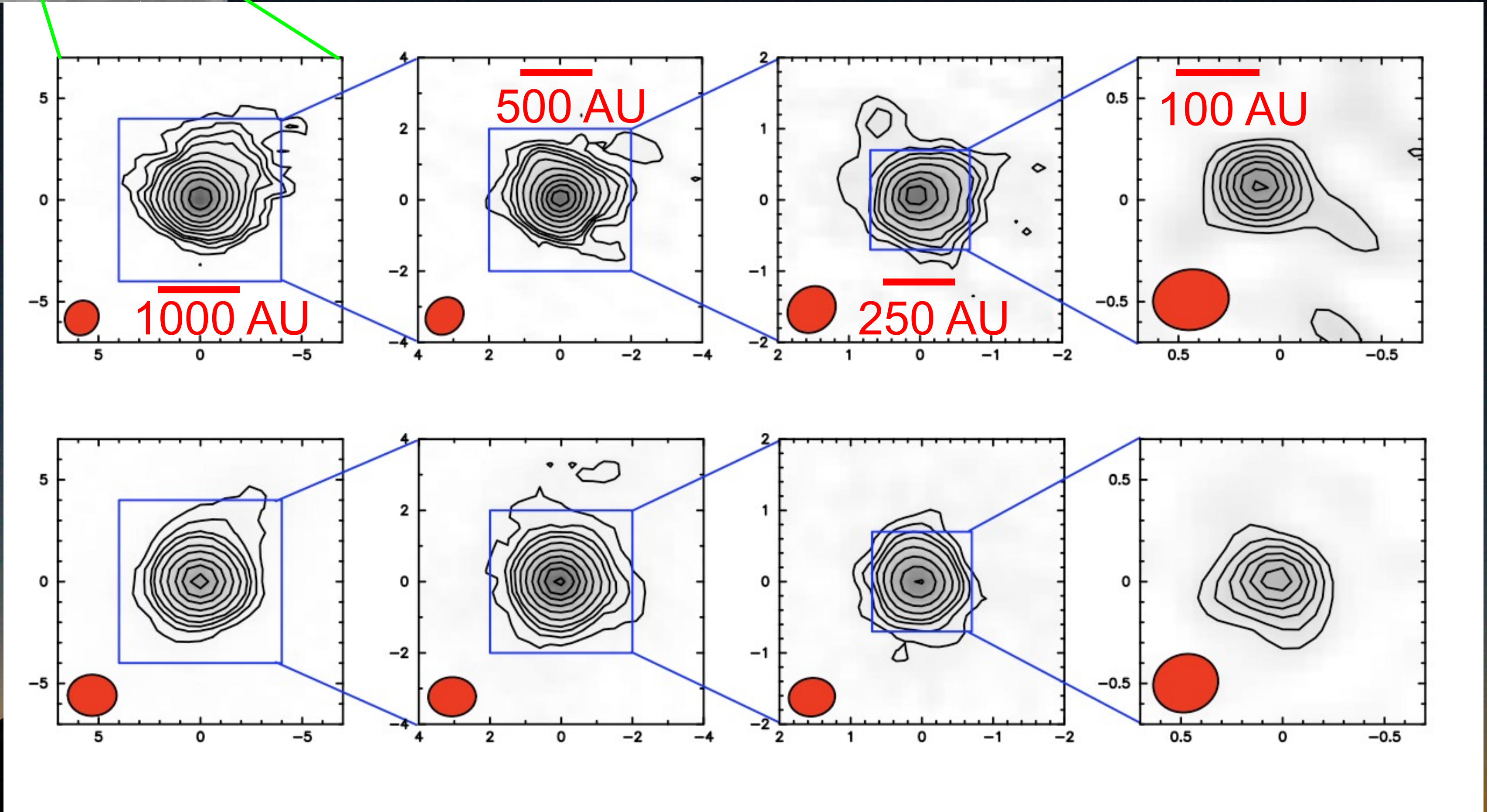
Example: L1157



Dust continuum, CARMA

1mm

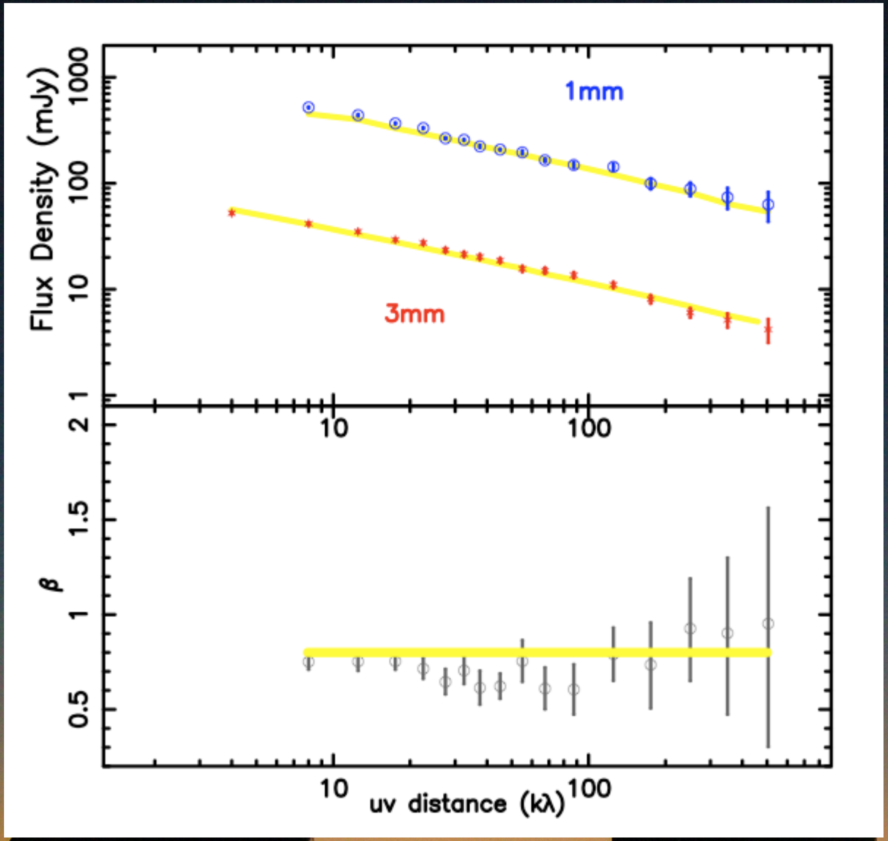
3mm



No disk larger than ~100 AU

Dust Continuum Modeling

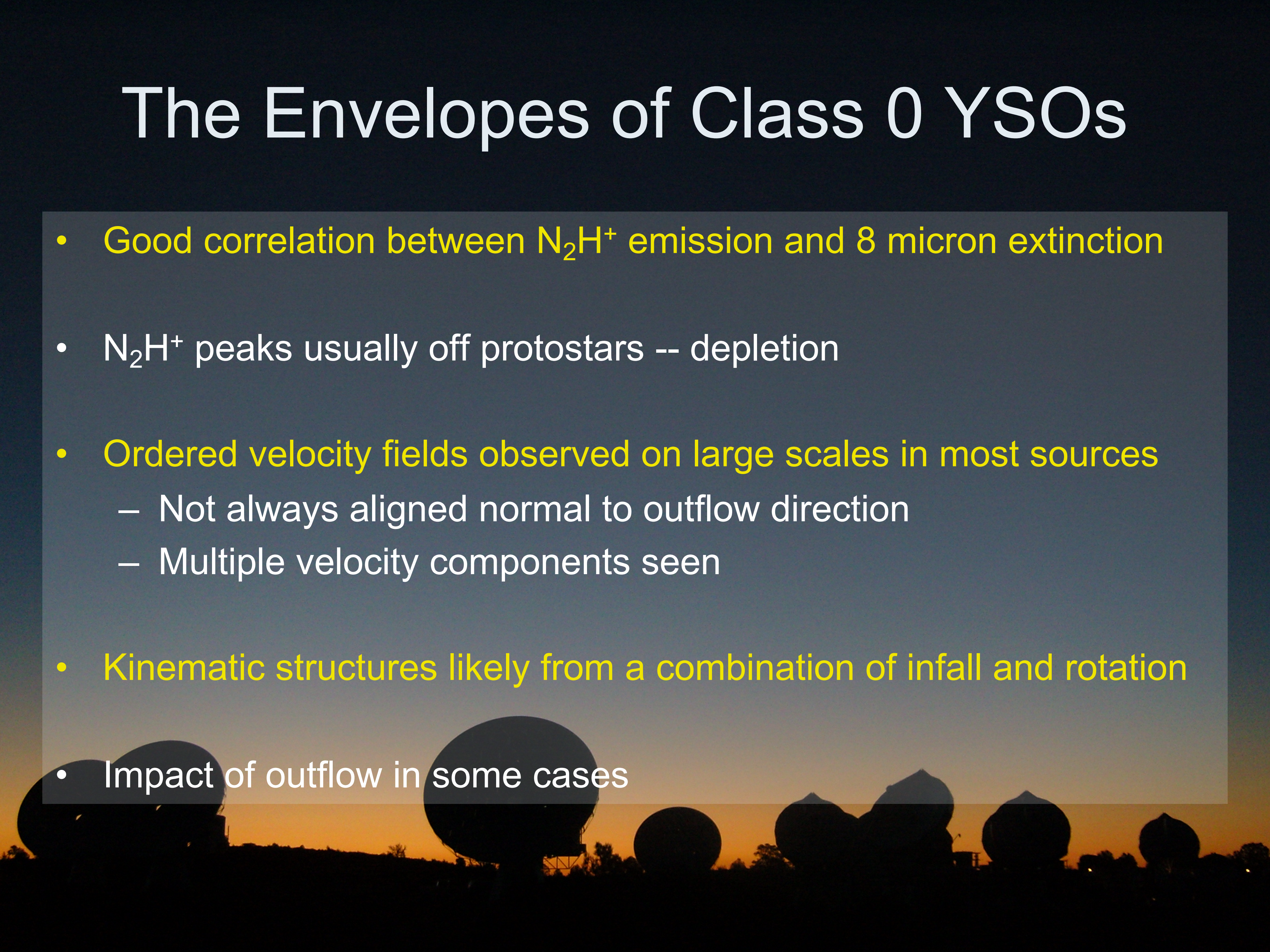
L1157



- Envelope with a power-law density profile
- Best fit (preliminary)
  - p = 2.1 $(\rho \propto r^{-p})$
  - $\beta = 0.8$ $(\kappa \propto \nu^{\beta})$
- Disk is not necessary

- Not consistent with Shu's inside-out collapse scenario
- Early grain growth

The Envelopes of Class 0 YSOs



- Good correlation between N_2H^+ emission and 8 micron extinction
- N_2H^+ peaks usually off protostars -- depletion
- Ordered velocity fields observed on large scales in most sources
  - Not always aligned normal to outflow direction
  - Multiple velocity components seen
- Kinematic structures likely from a combination of infall and rotation
- Impact of outflow in some cases

Conclusions

- Envelope kinematics is complex
  - Non-axisymmetric
  - Rotation, infall, outflow, velocity components, chemistry
  - Non-axisymmetry may induce formation of binary stars
- Envelope structure ➔ embedded disk
  - Test of theoretical models
  - Currently no need for disks (cf. Enoch et al. 2009)