Observing the Earliest Phases of Proto-Planetary Disk Formation

John Tobin

Hubble Fellow
National Radio Astronomy Observatory
Charlottesville, VA

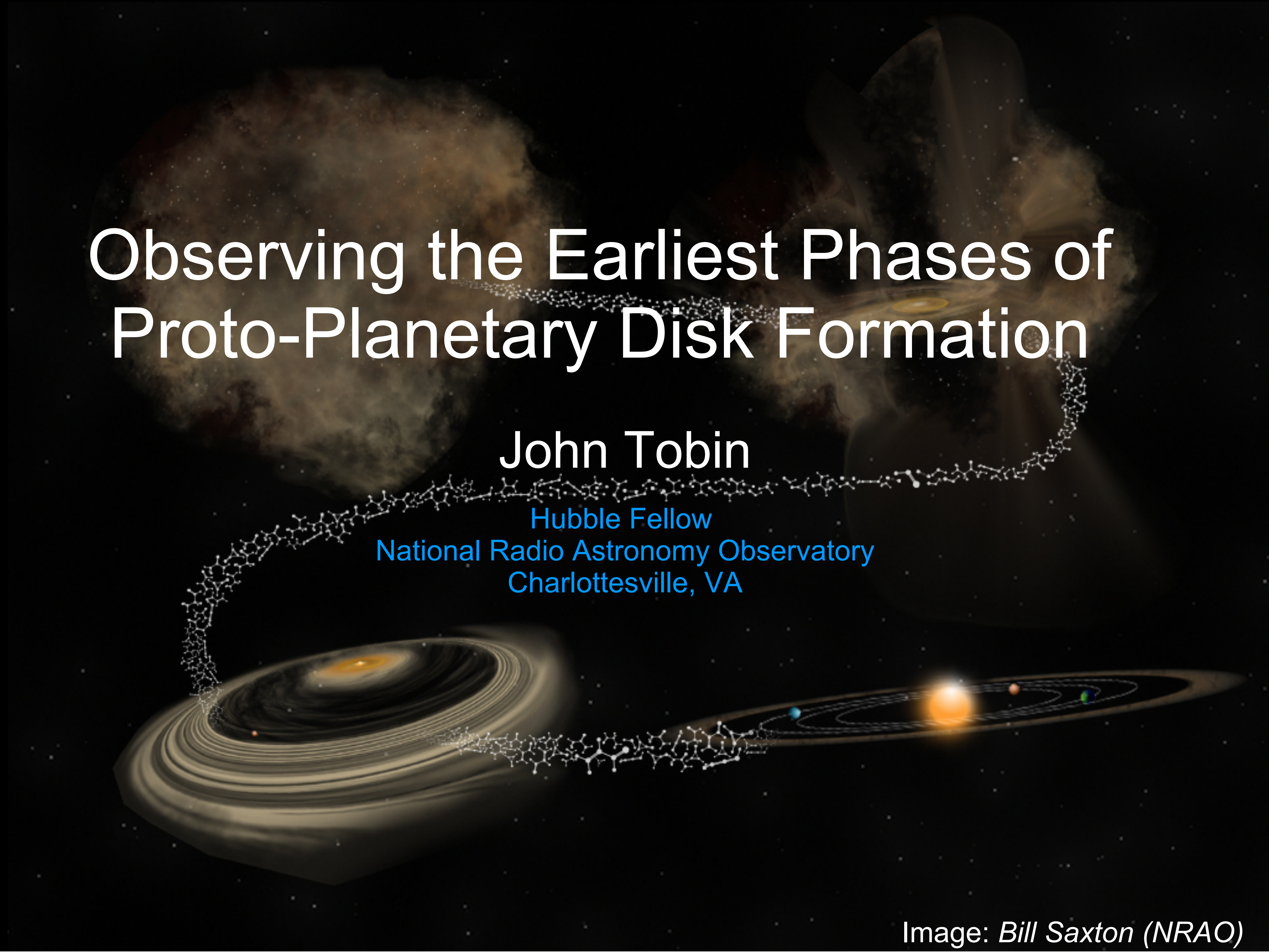


Image: *Bill Saxton (NRAO)*

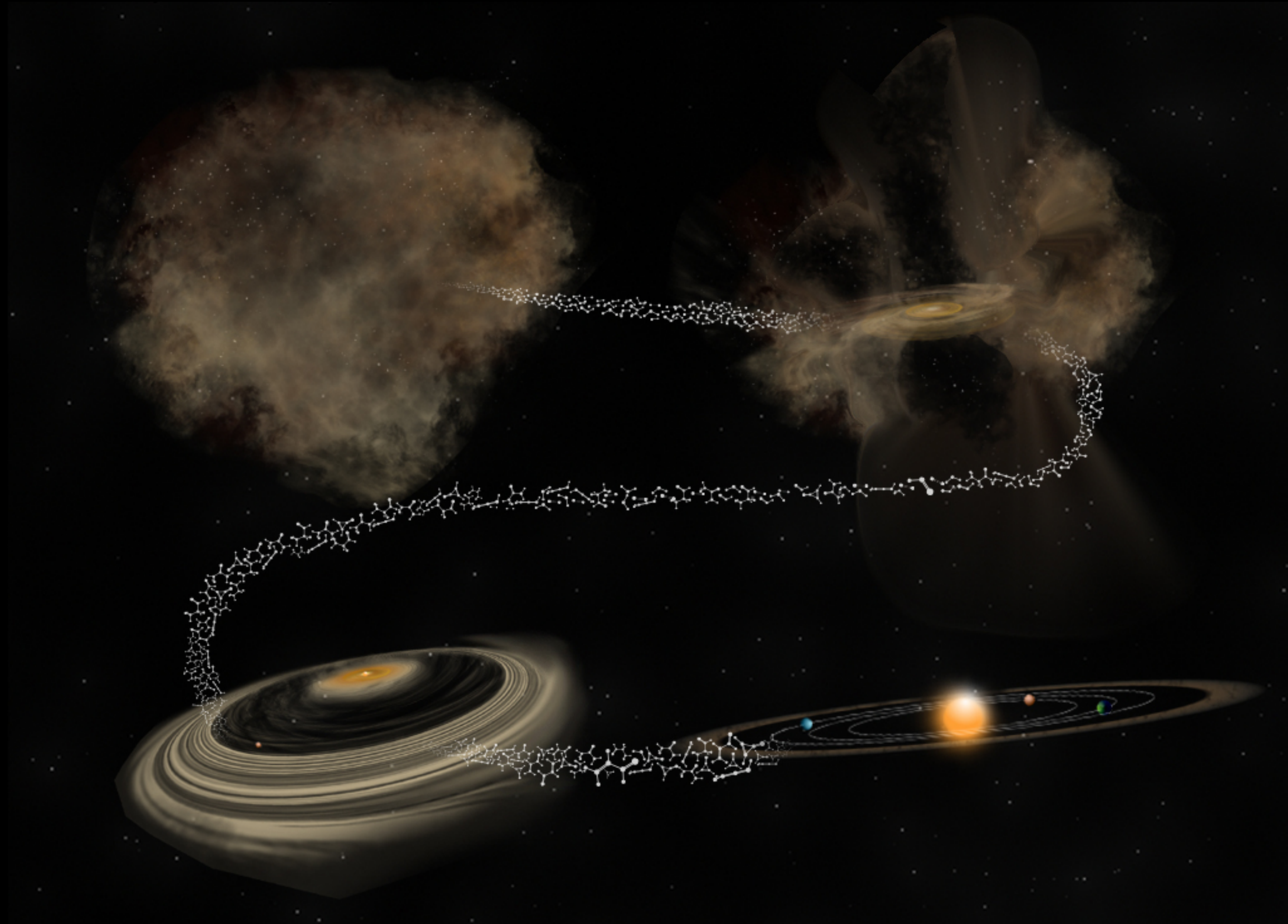


Image: *Bill Saxton (NRAO)*

Star Formation Process

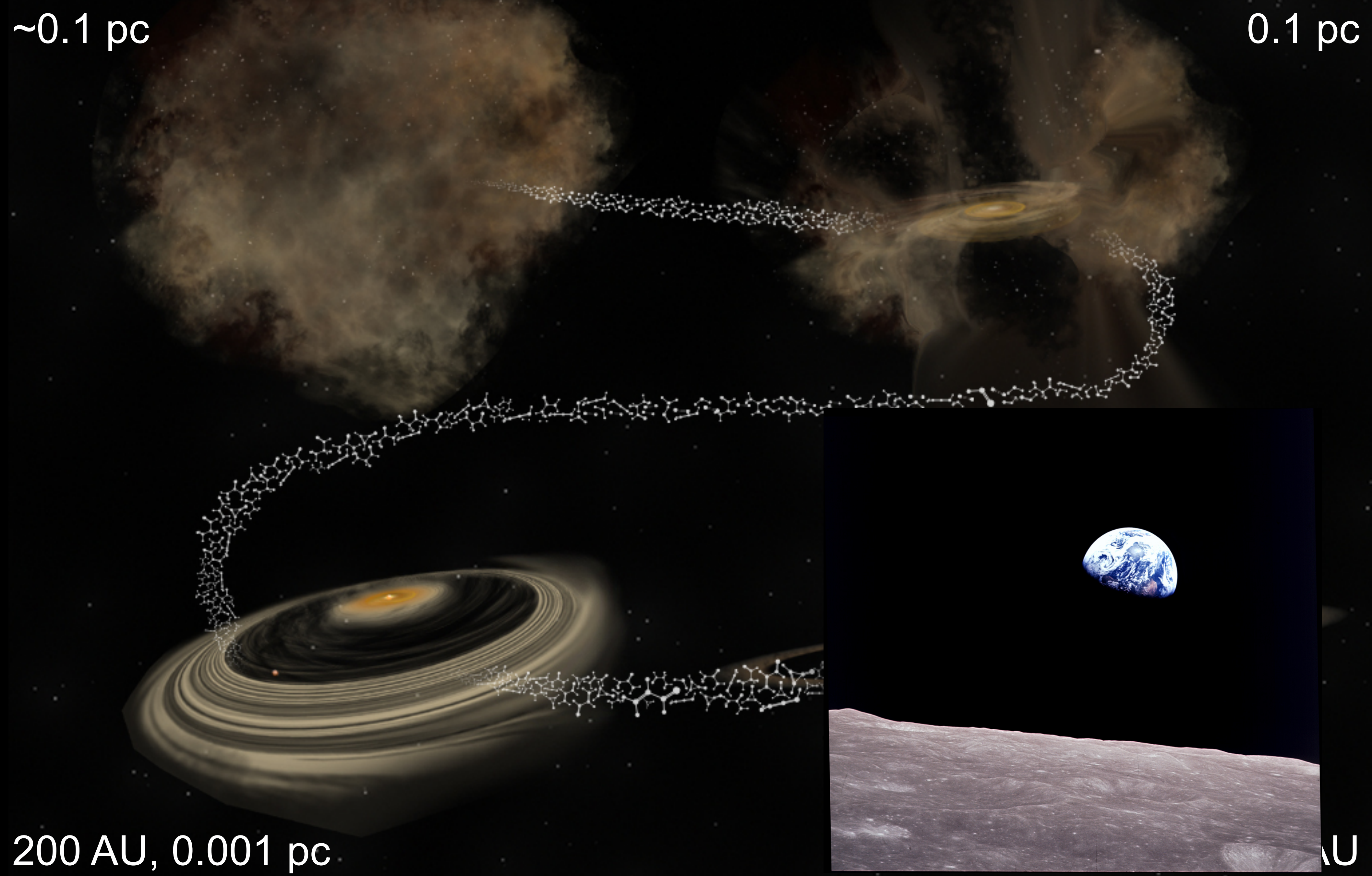
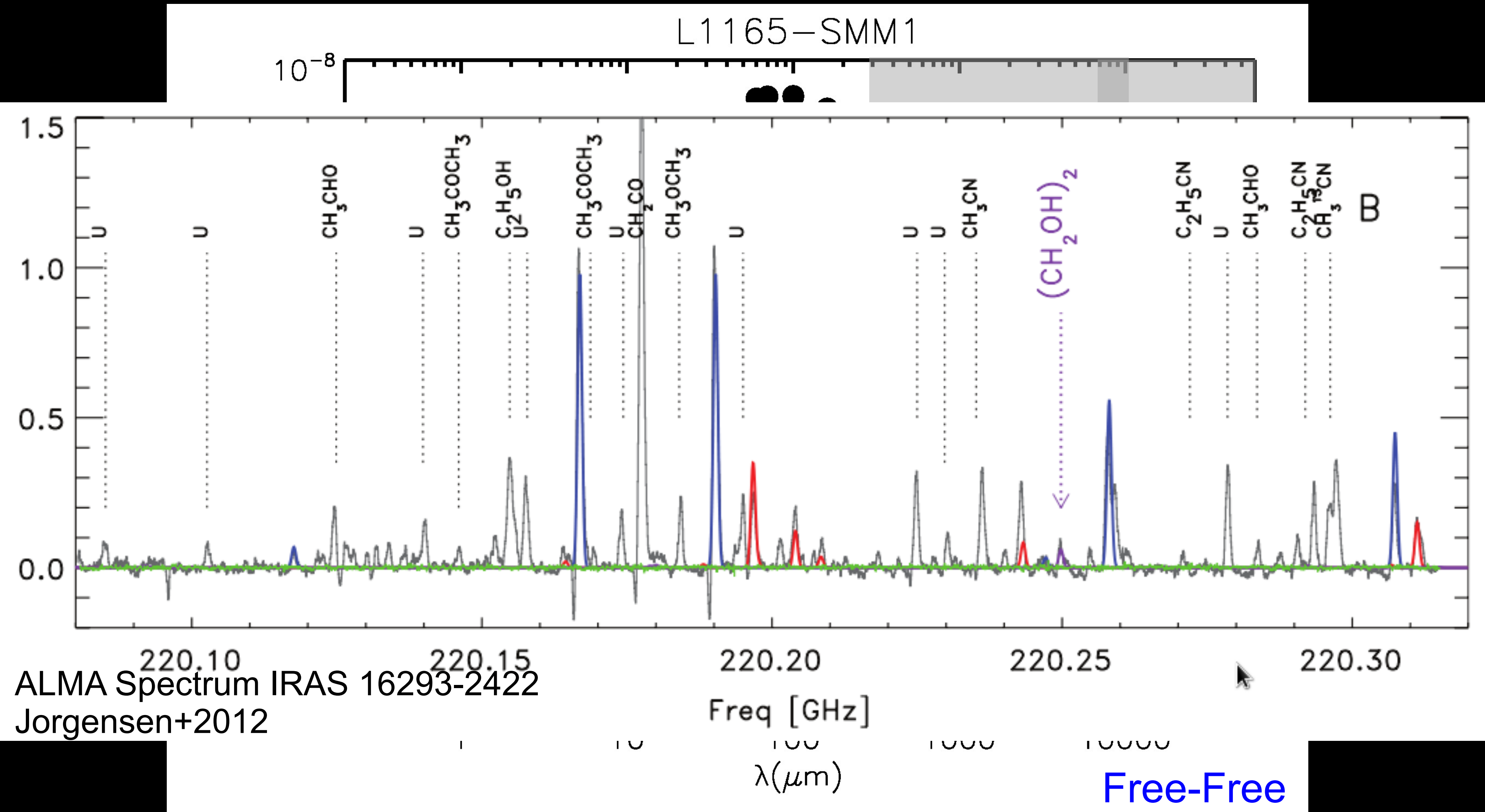


Image: *Bill Saxton (NRAO)*

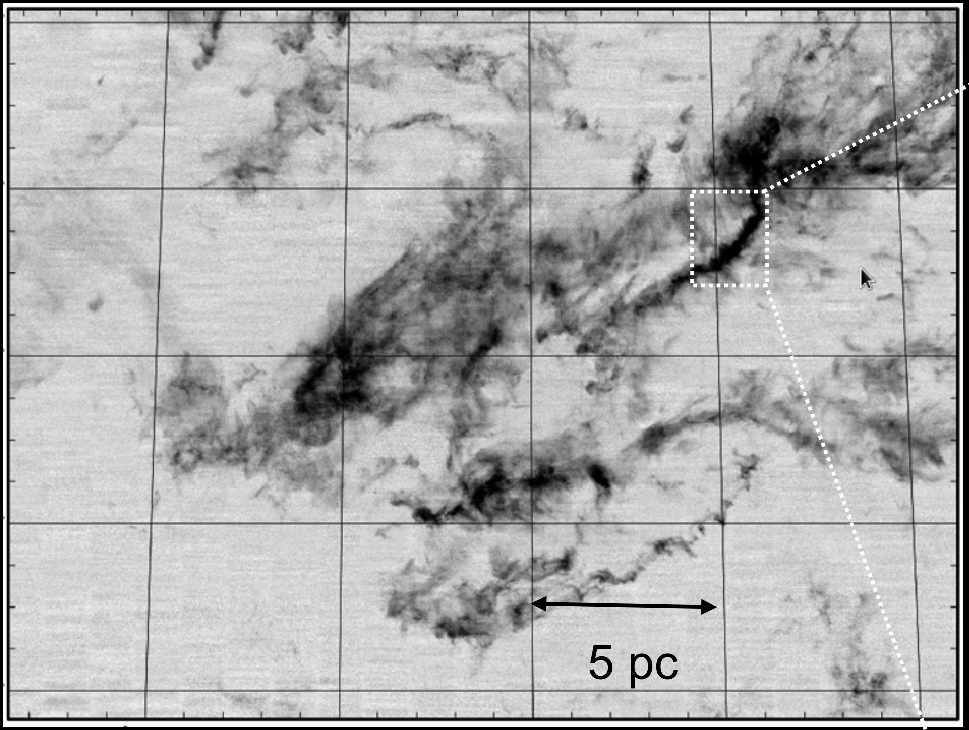
Observe Dust and Molecular Lines



ALMA Spectrum IRAS 16293-2422
Jorgensen+2012

- Dust shows structure and mass
- Molecular lines show kinematics and chemistry (+structure)

Filamentary Molecular Clouds



Taurus ^{13}CO Goldsmith+08

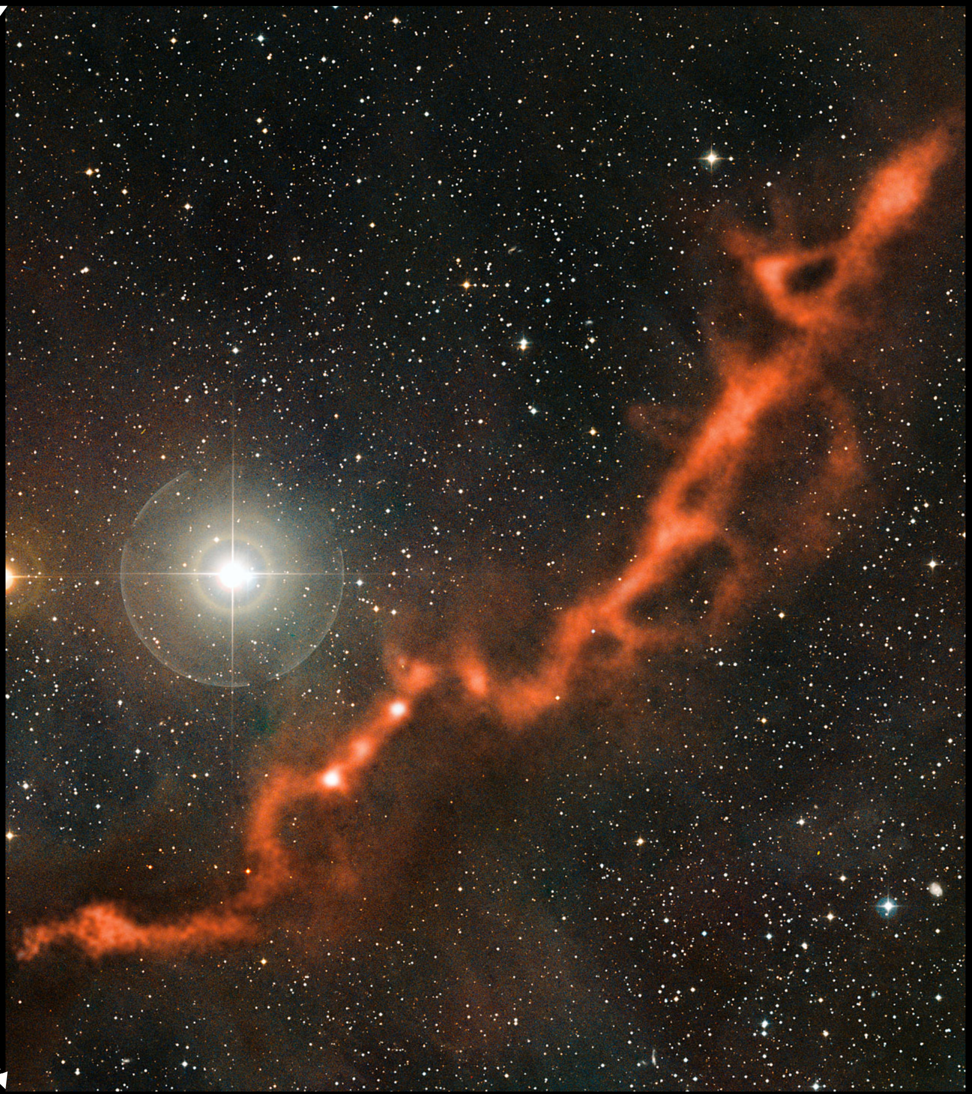
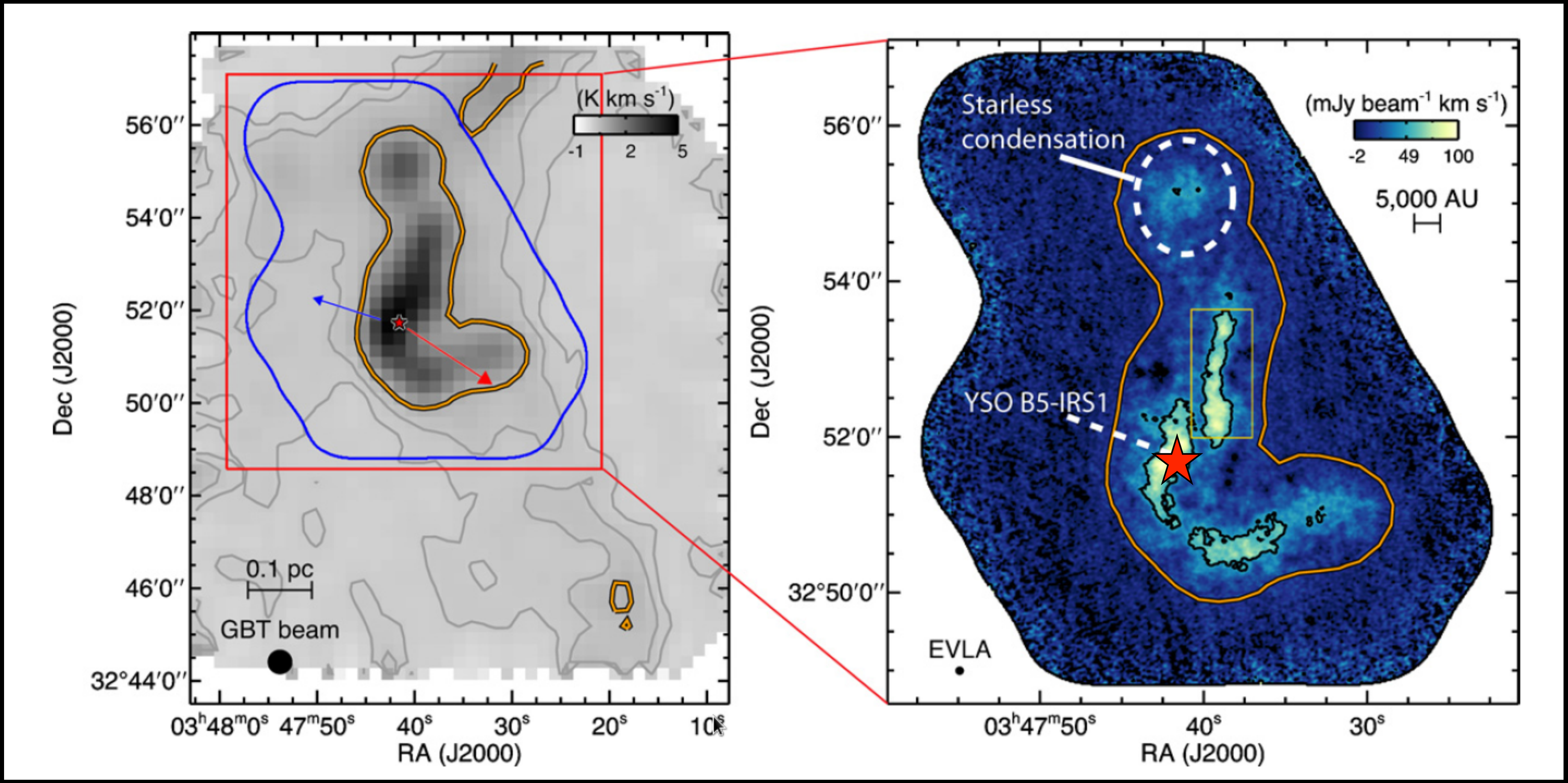


Image: ESO - Optical (DSS) + 870 μm (APEX)

- ~0.1 pc cores form in parsec+ scale filaments
- How does large-scale reflect on on smaller scales?

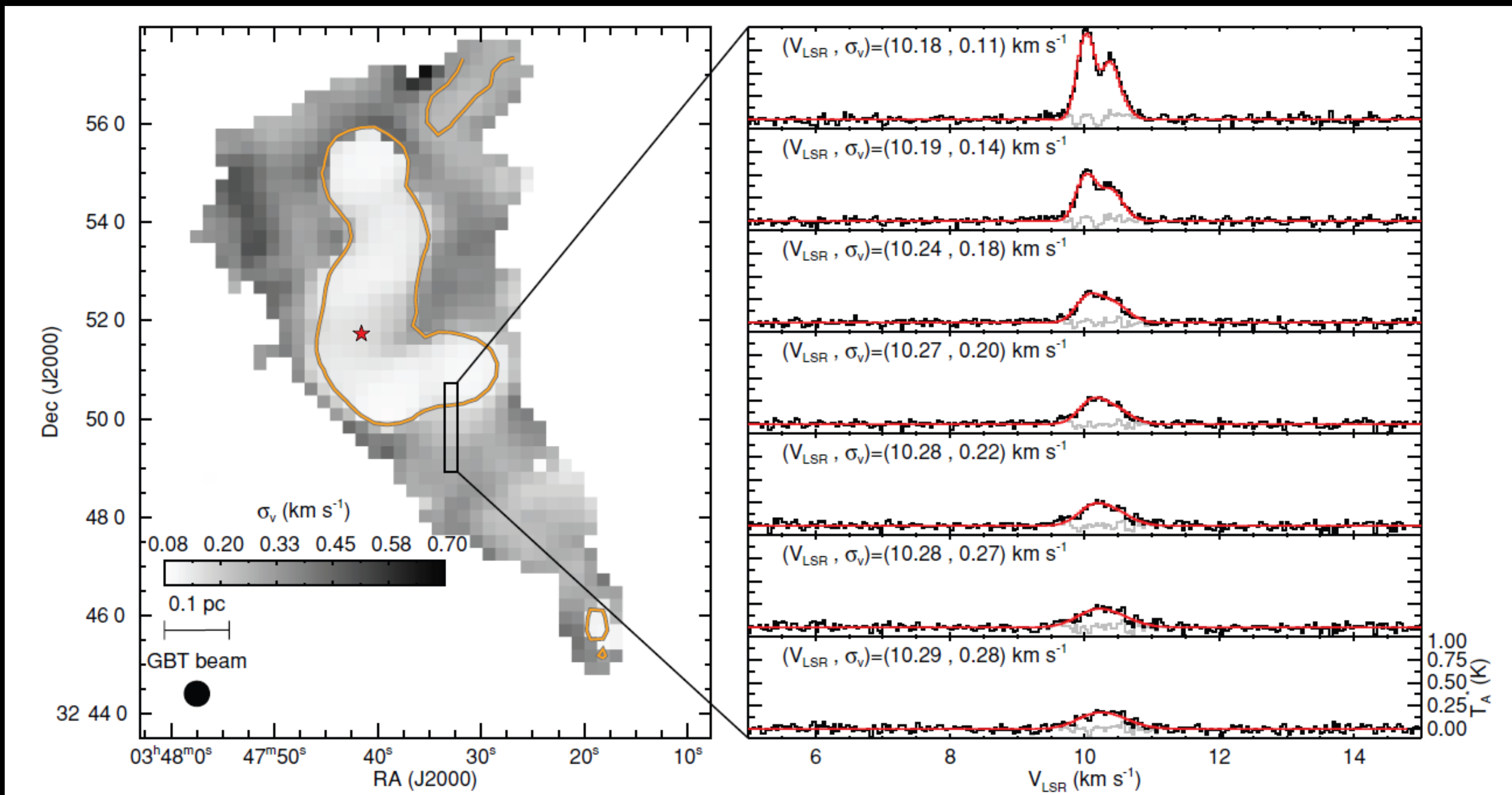
Stars Form in Quiescent Filaments



Pineda+2011

- Star forming cores themselves can have filamentary structure

Stars Form in Quiescent Filaments

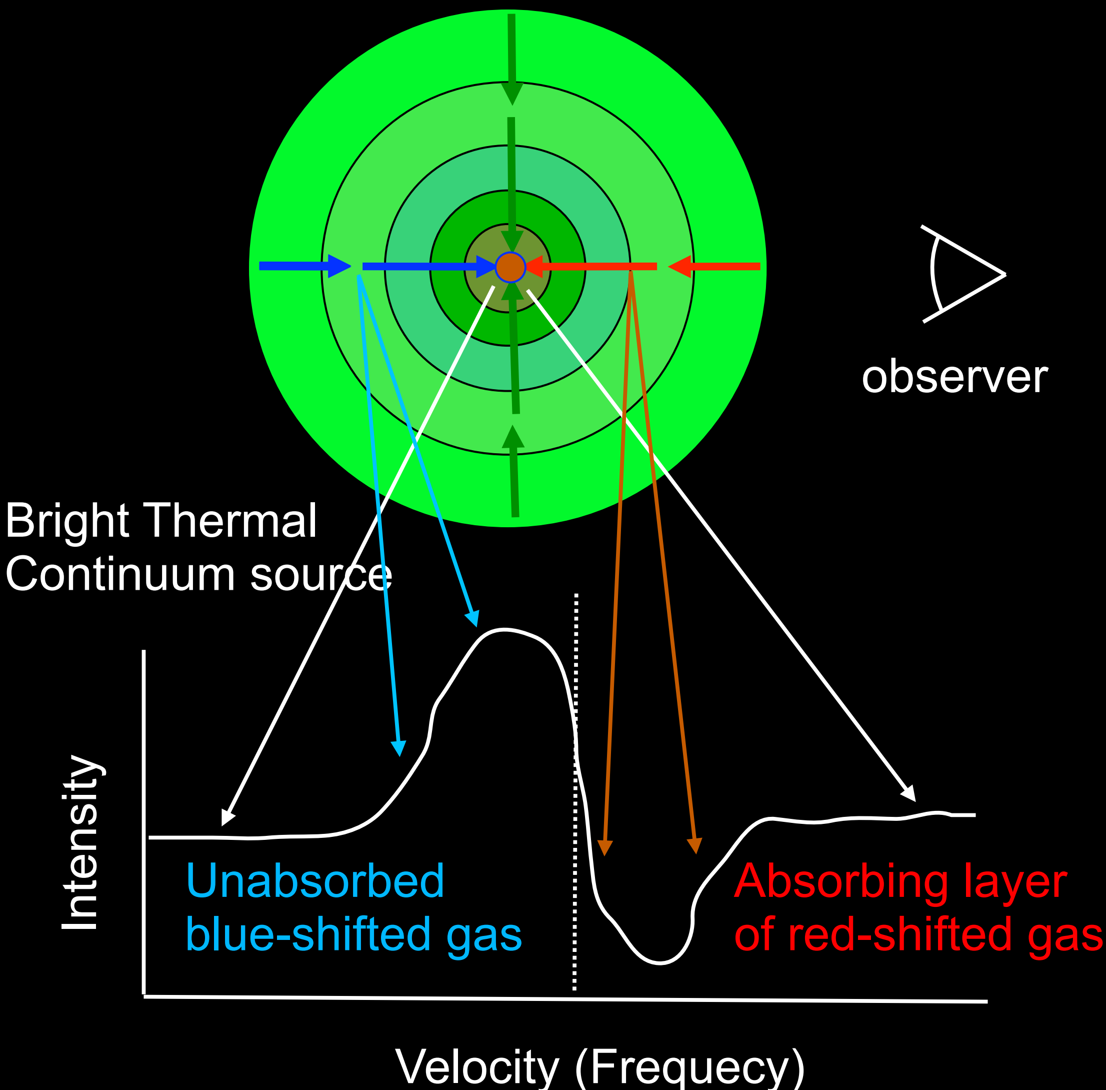


Pineda+2010

- Cores are "...islands of calm in a more turbulent sea." Goodman+1998

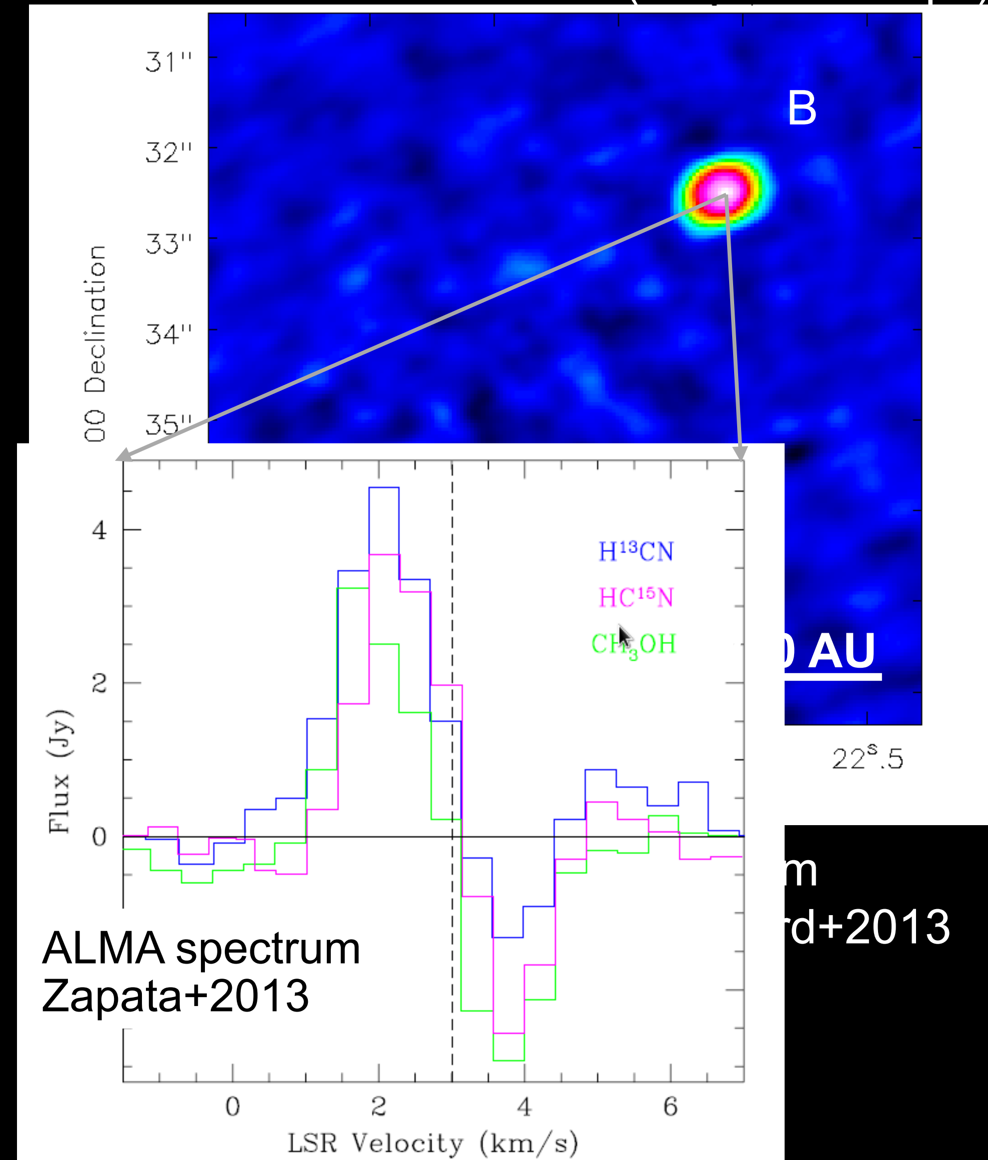
Assembling a Star in a Core

Infalling Protostellar cloud

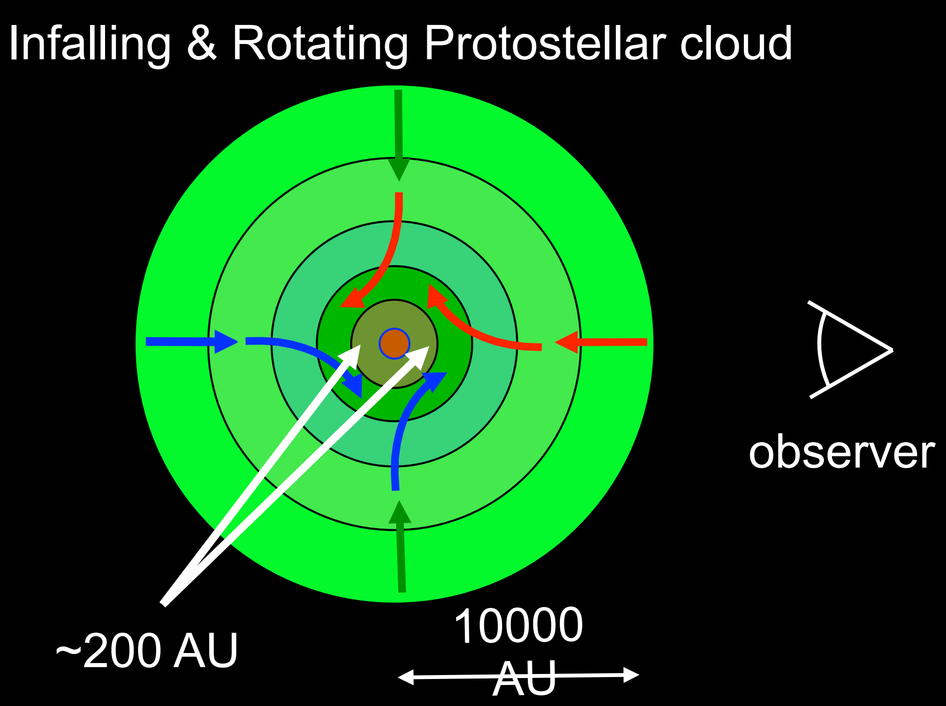


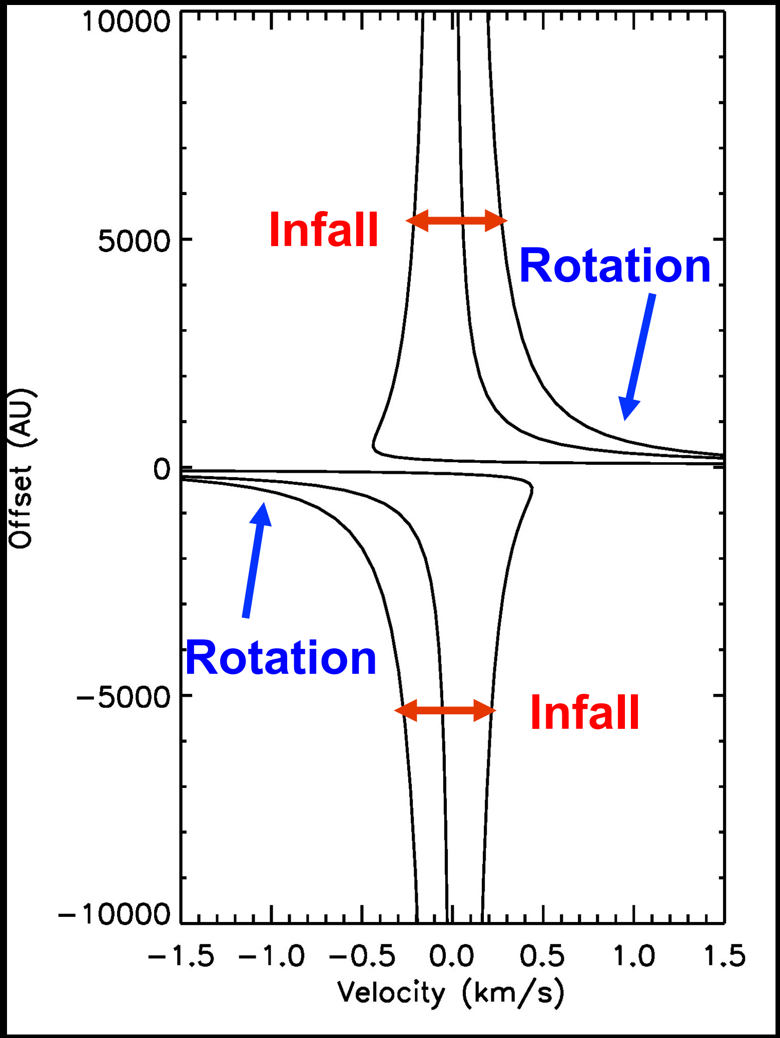
Molecular line spectrum

Protostar IRAS 16293-2429 (distance 125 pc)



Assembling the Disk



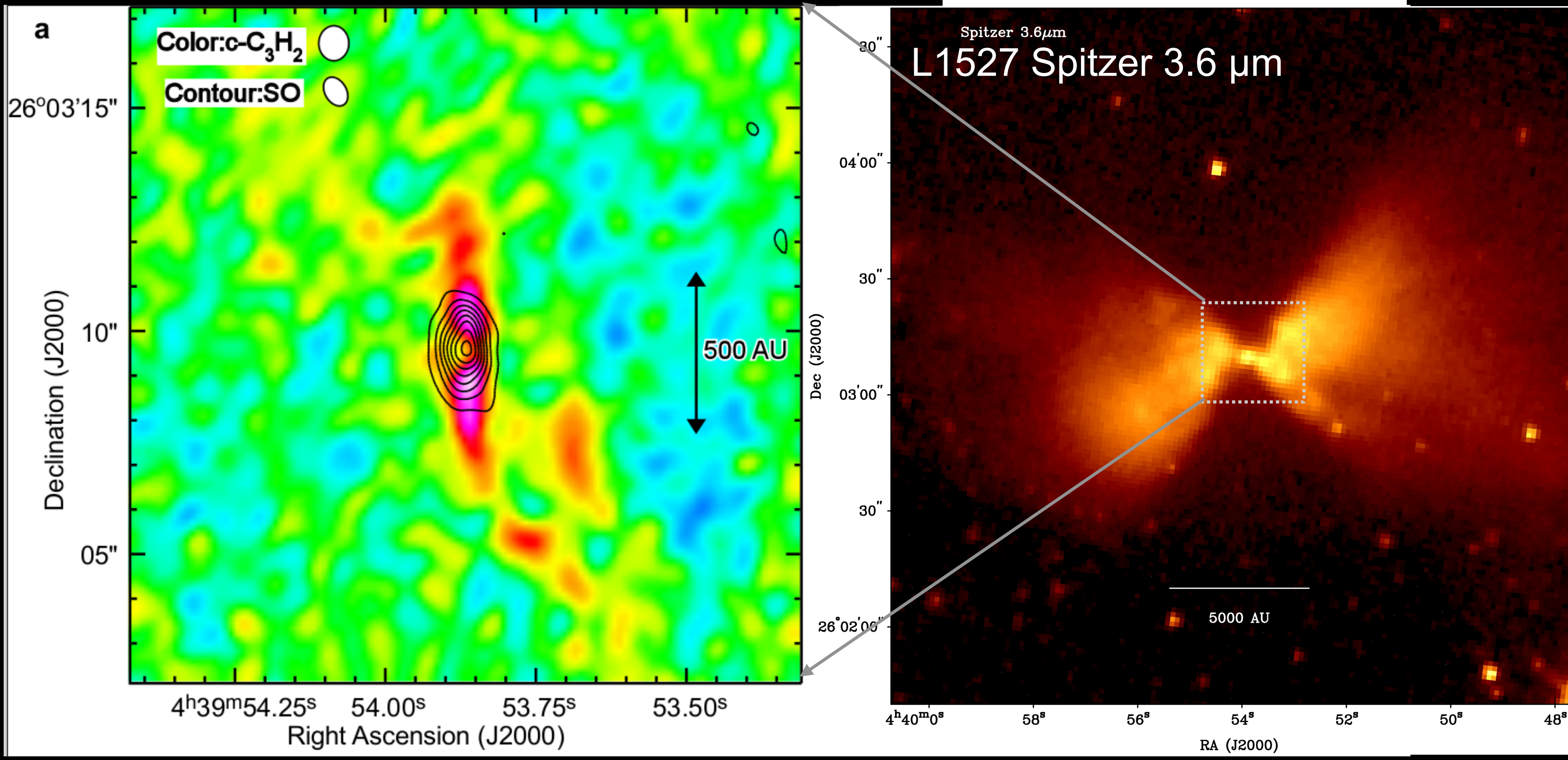


- Angular momentum conserved during collapse

- Slow rotation of cloud (or net angular momentum) enables formation of protostellar disk

- Magnetic fields may `regulate' disk sizes by slowing rotation

Observing Disk Formation

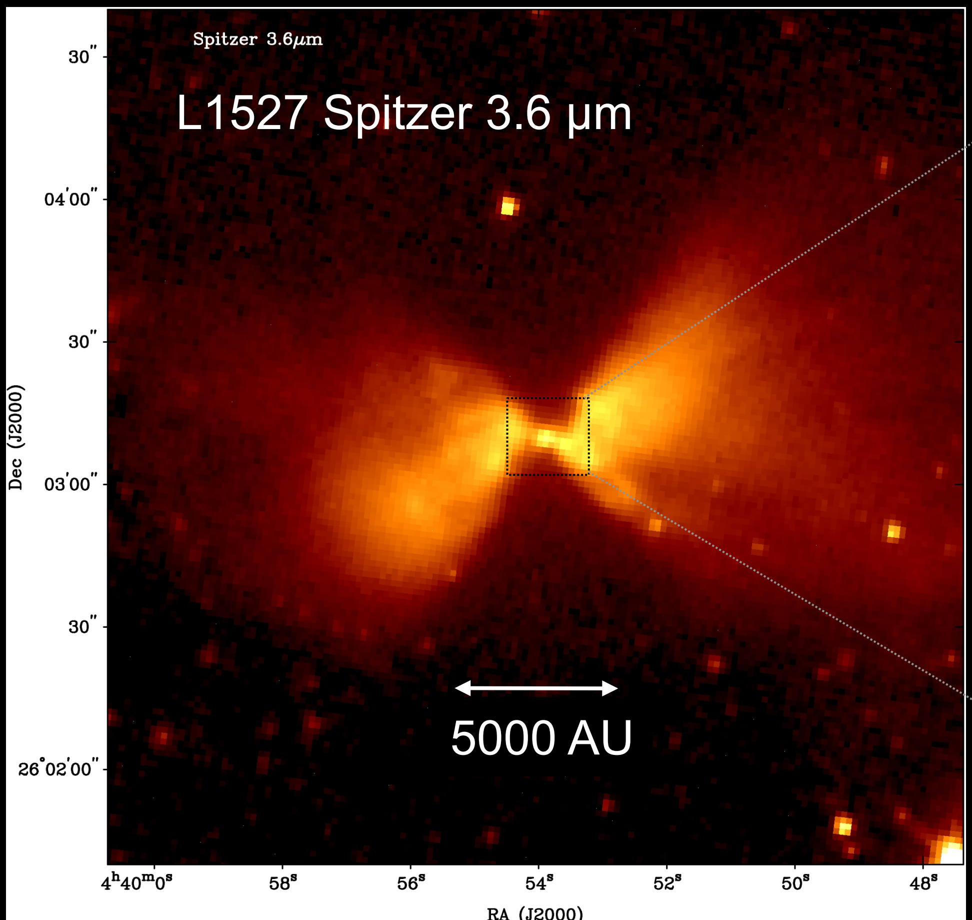


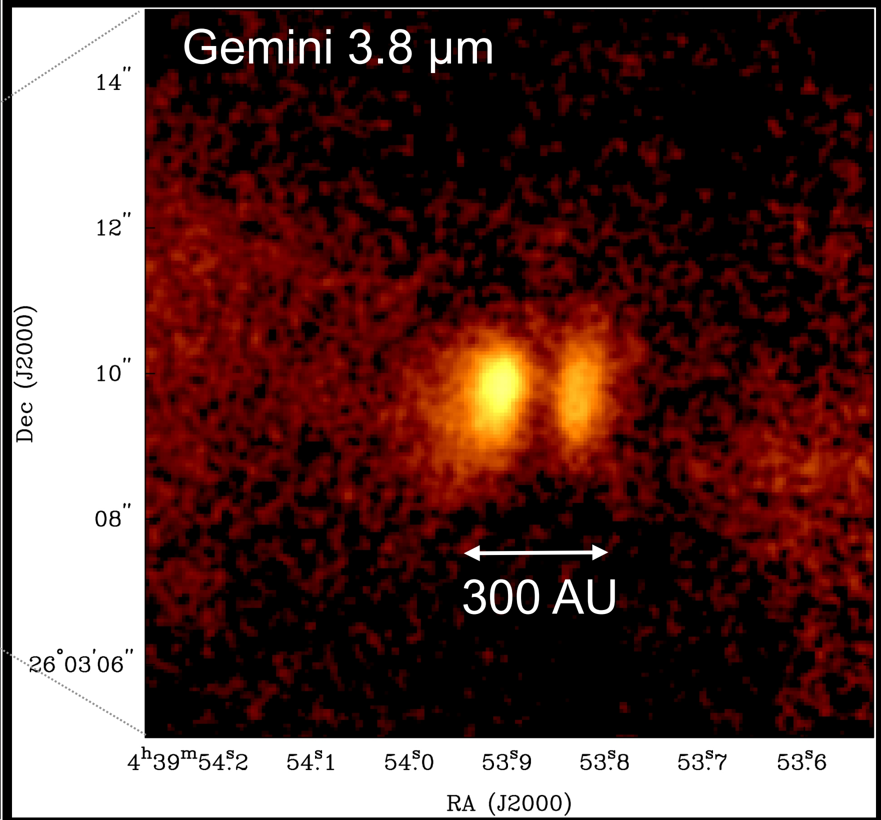
Sakai+2014, *Nature*

- Protostar L1527 IRS, distance ~ 140 pc
- ALMA (λ ~ 870 μm) c-C_3H_2 ($J= 5_{51}- 4_{40}$) and SO ($J_N=7_8-6_7$) observations
- SO and c-C_3H_2 trace different components spatially and kinematically
- Dramatic chemical change at 100 AU; accretion shock onto disk?

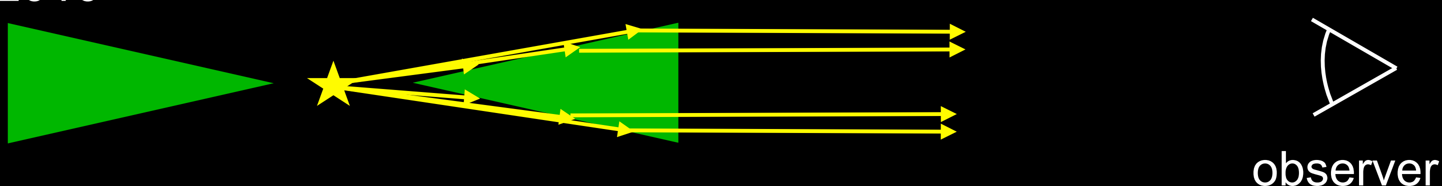
Observing the Protostellar Disk

- 0.3” (~40 AU) mid-IR imaging suggests a R ~ 200 AU disk



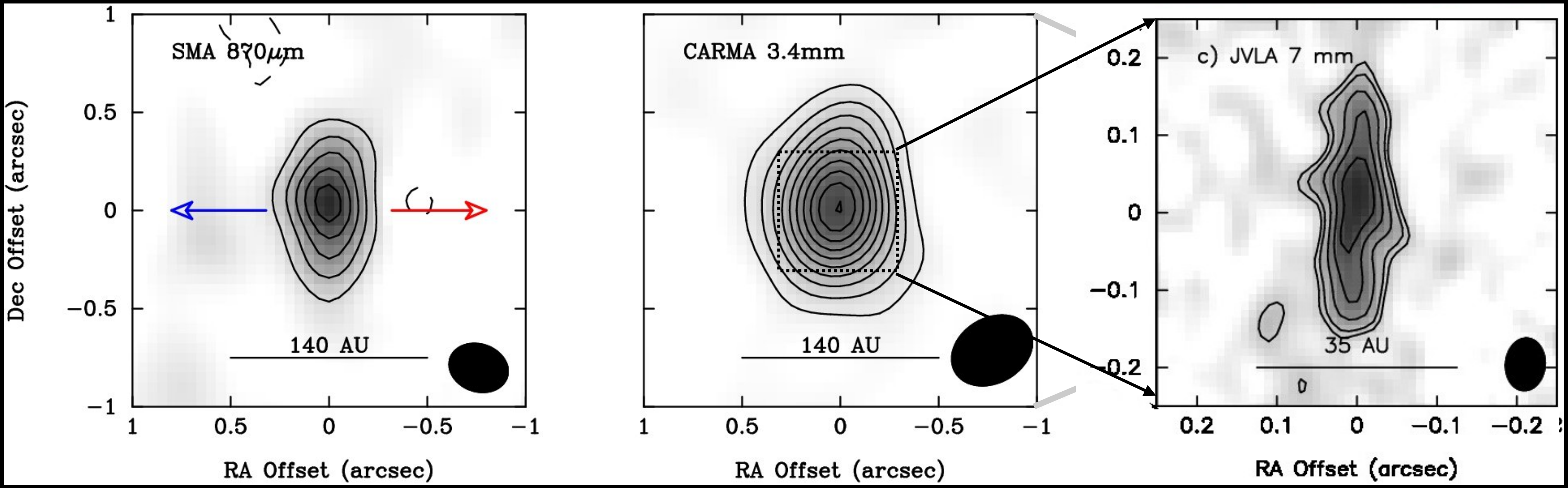


Tobin+2010



Observing the Protostellar Disk

870 μm 3.4 mm Gemini L'-band



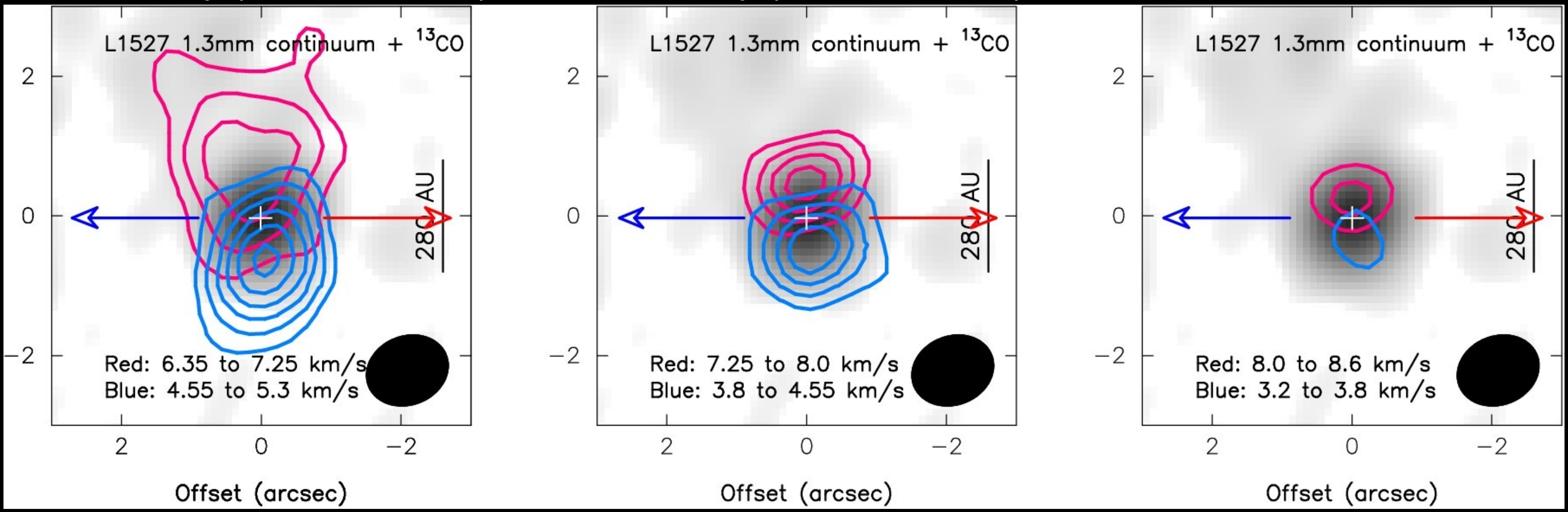
Tobin+2012, *Nature*
Melis+2014

- SMA (870 μm), CARMA (3.4 mm), and VLA (7.3 mm) data
  - Dust emission to probe bulk of disk
    - A resolved disk! M_{disk} ~ 0.007 M_{sun}

But..... need kinematics to confirm

A Keplerian Protostellar Disk

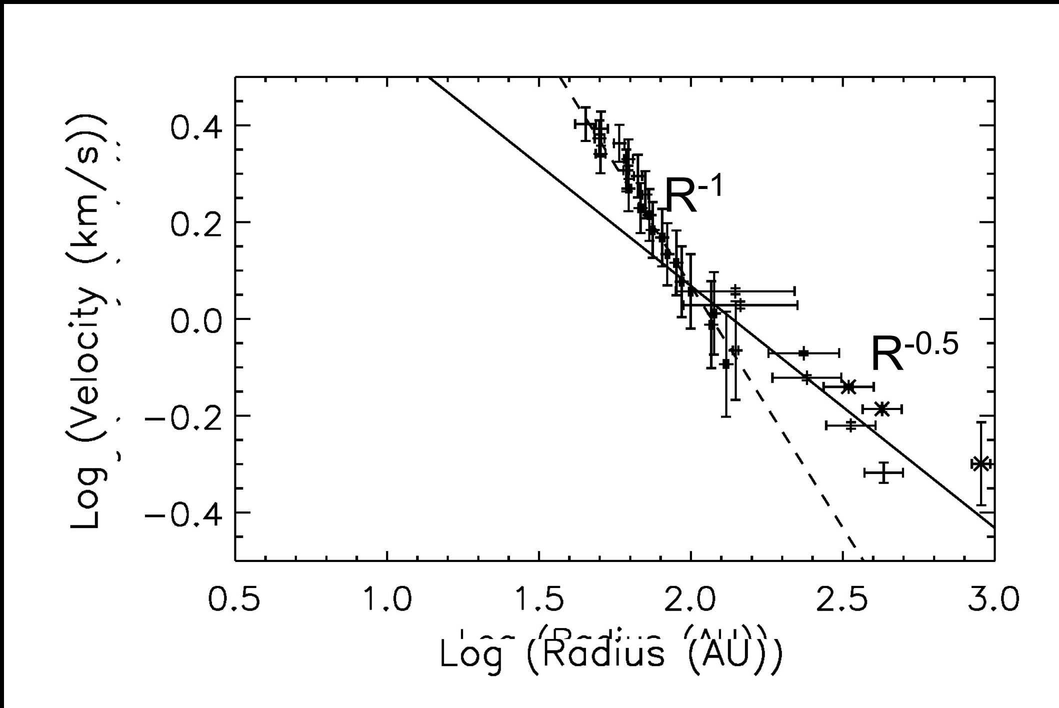
Low Velocity (0.6 – 1.4 km/s) Mid-Velocity (1.4 – 2.1 km/s) High Velocity (2.1 – 2.7 km/s)



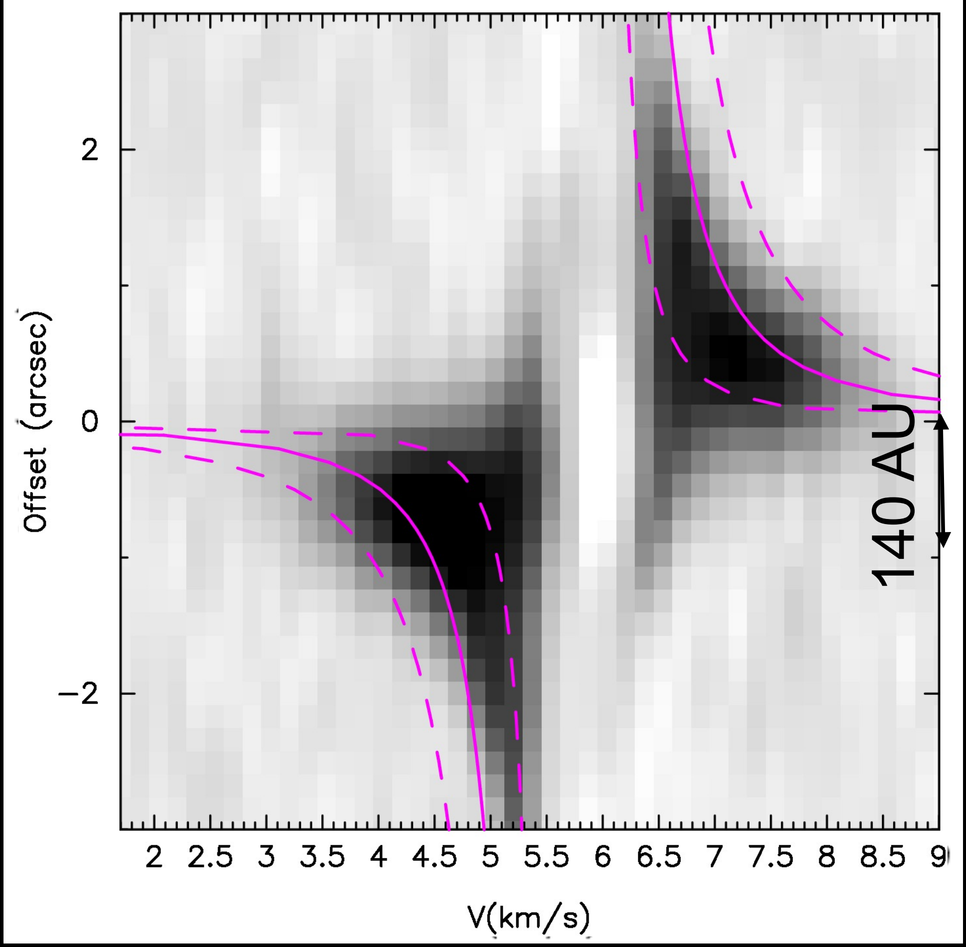
Tobin+12, *Nature*

- CARMA ^{13}CO (J=2-1) molecular line tracing disk rotation
- Consistent with Keplerian motion in the disk

A Keplerian Protostellar Disk



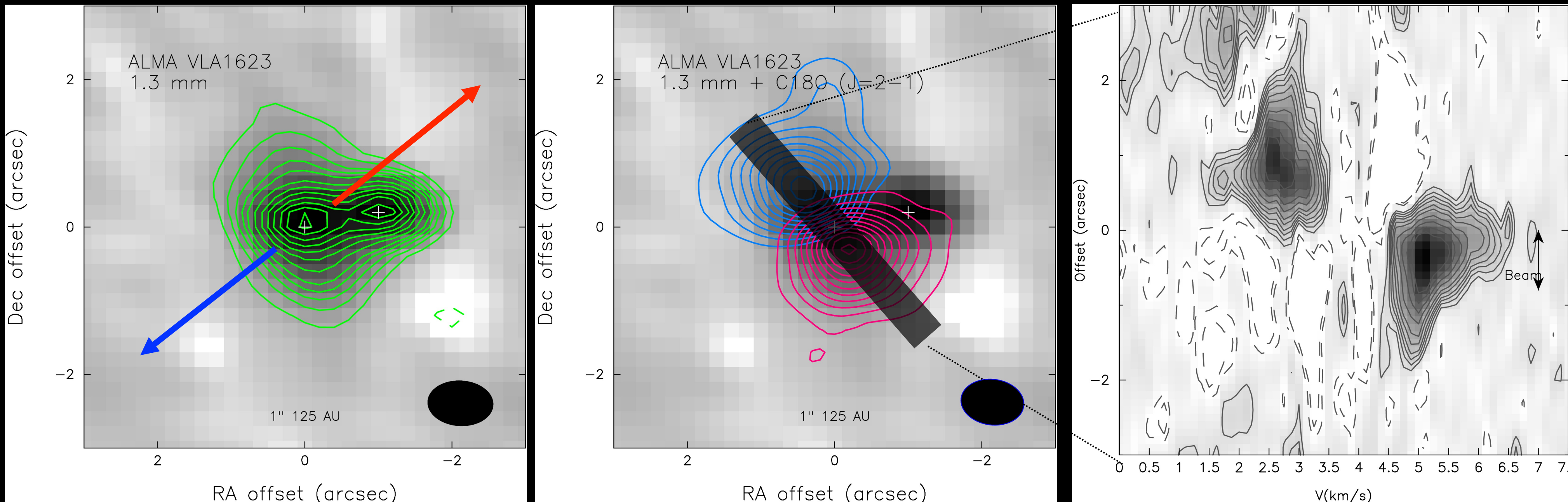
Tobin+12 Nature



Ohasi+2014 in prep.

- Rotation curve consistent with Keplerian
- Protostar mass 0.19 +/- 0.04 M_{sun}, ~20% of surrounding envelope mass
- ALMA data suggest revisions needed, but still probably a disk

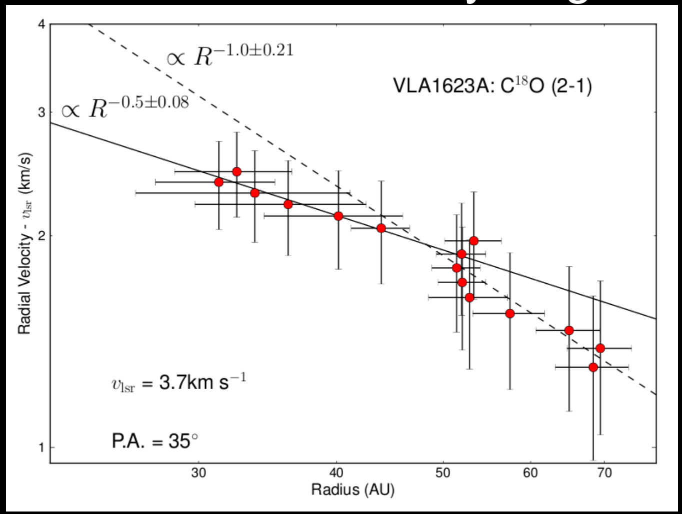
Youngest Known Protostellar Disk



1.3 mm Continuum

Red and Blue shifted $C^{18}O$ (J=2-1)

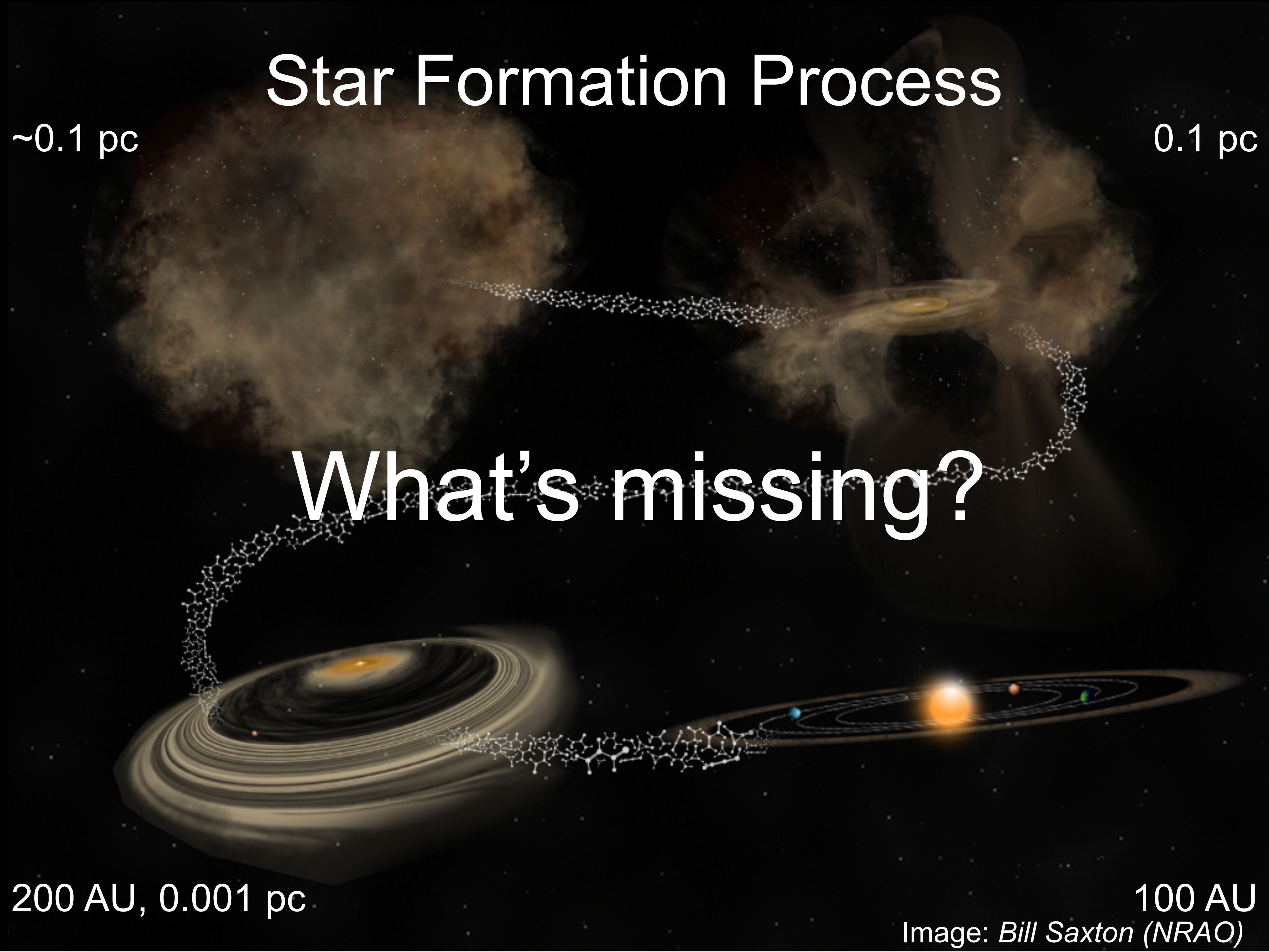
$C^{18}O$ (J=2-1) Position-velocity diagram



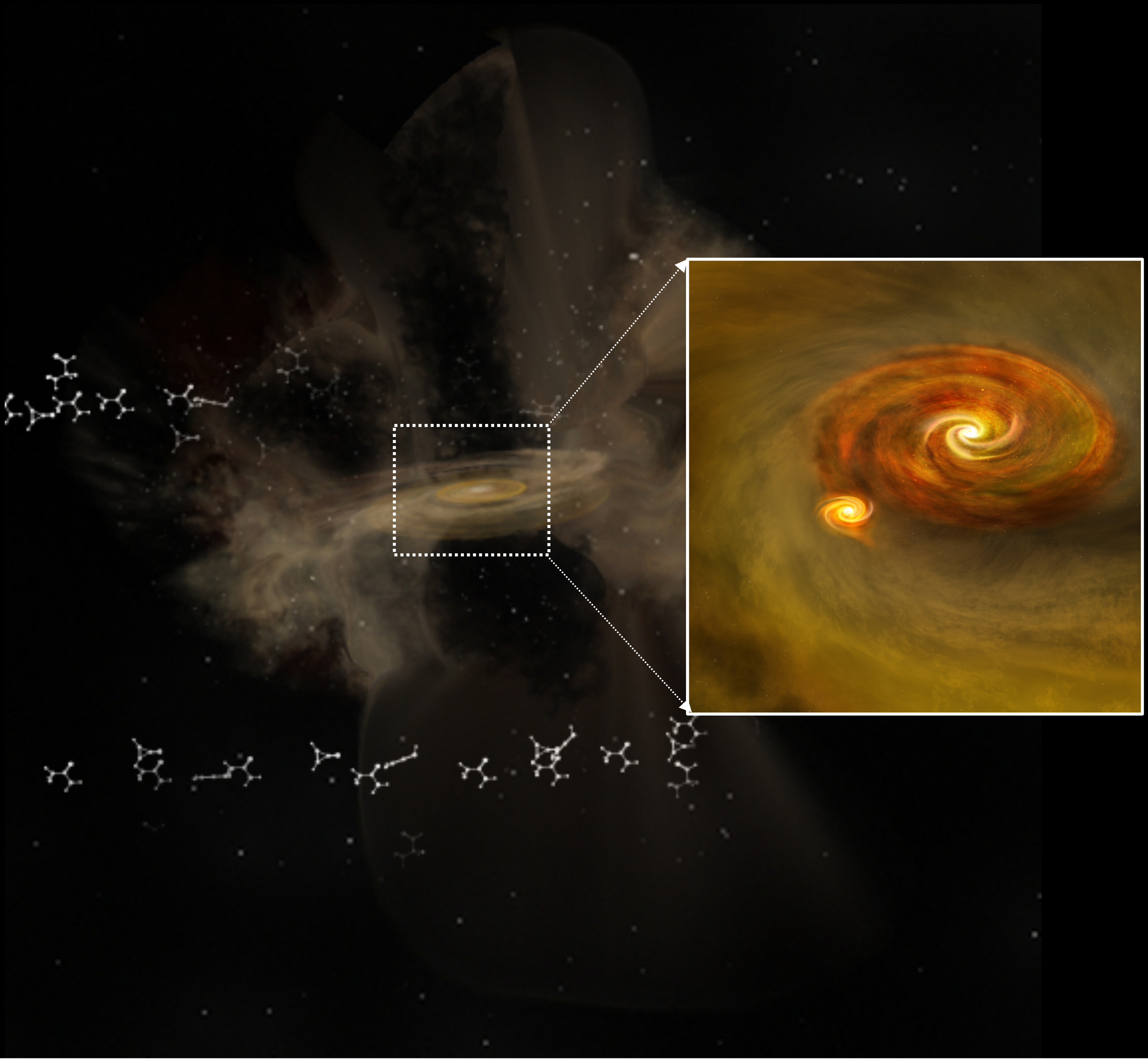
- VLA 1623 – distance 125 pc
- ALMA 1.3 mm resolve disk in continuum
- Keplerian rotation detected with $C^{18}O$ (J=2-1) line
  - M_{ps} = 0.2+/- 0.02 M_{sun}

Murillo+2013

Star Formation Process

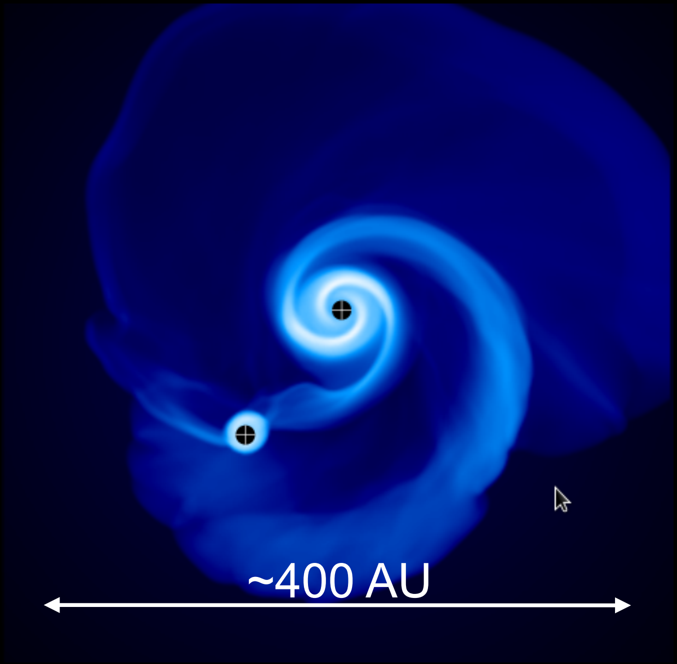


Binary Star Formation



How to Fragment?

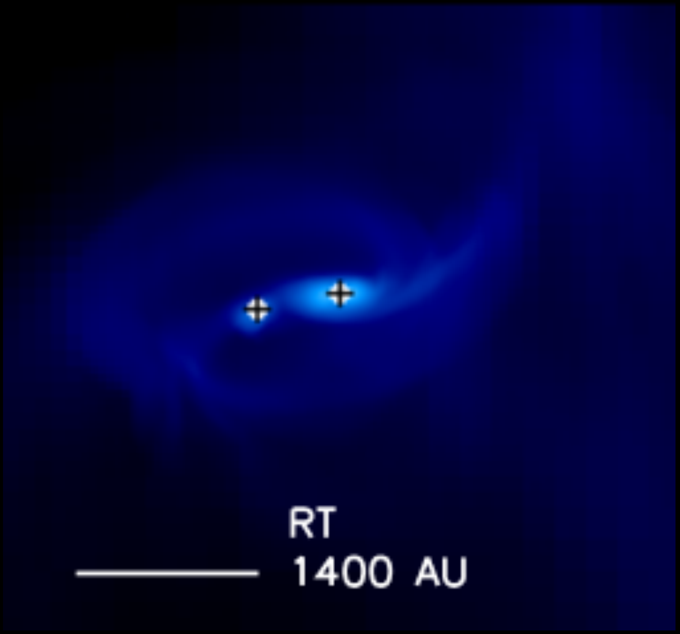
Disk Fragmentation



Kratter+2010

100s AU

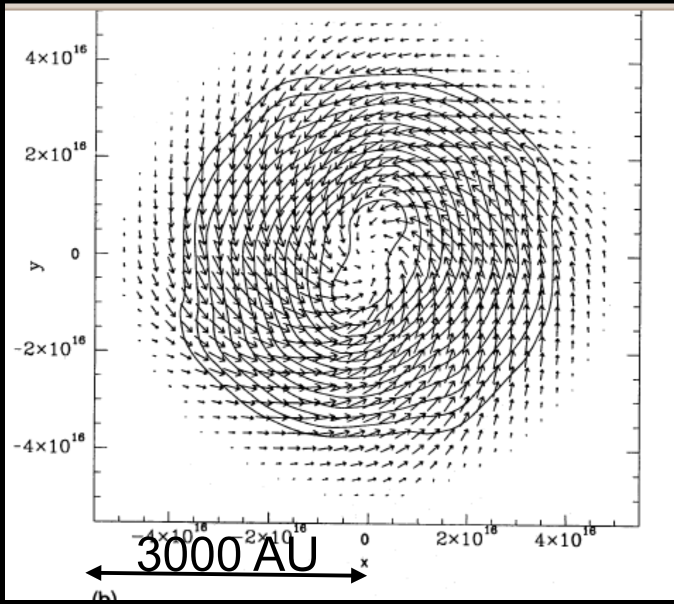
Turbulent Fragmentation + Dynamical Evolution



Offner+2010

1000s AU

Envelope Rotational Fragmentation

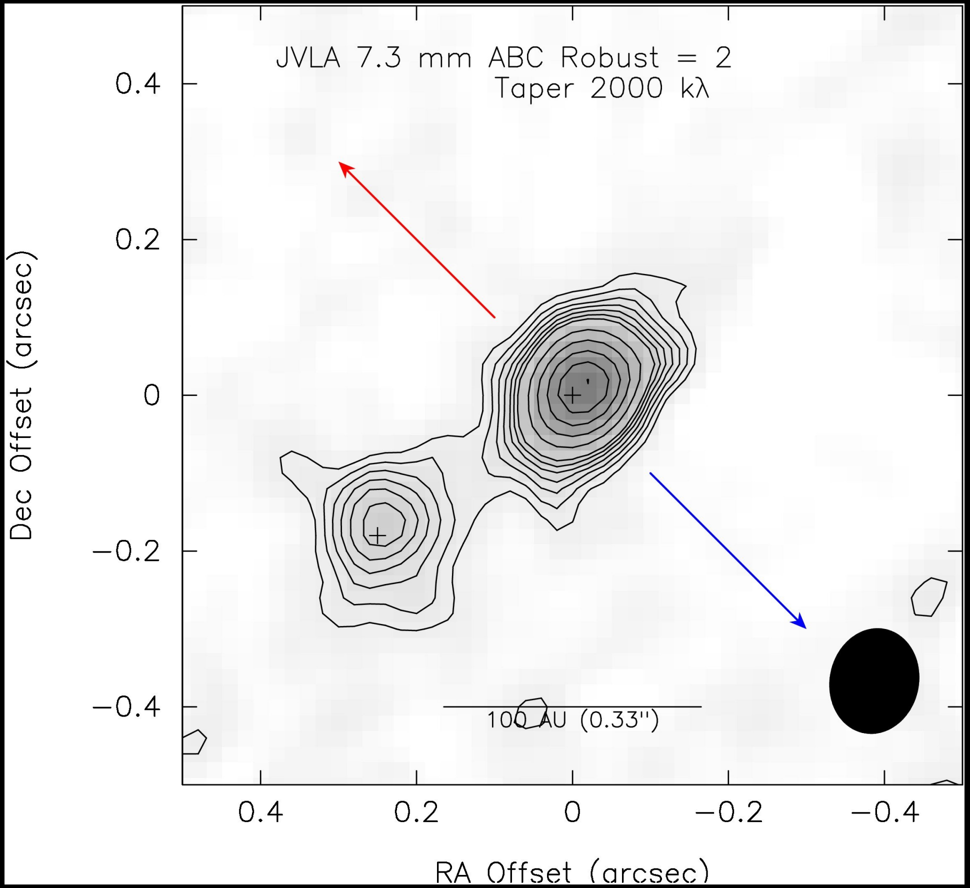


Burkert & Bodenheimer 1993

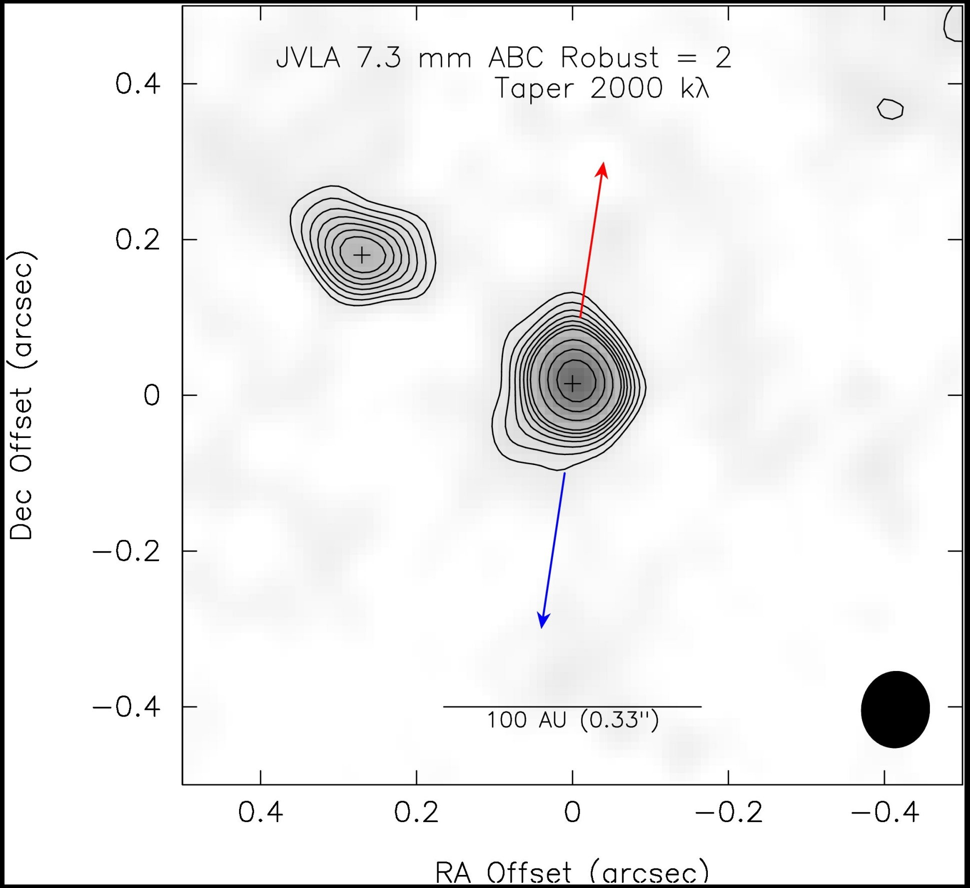
1000s AU

Proto-stellar Binaries with the VLA

L1165



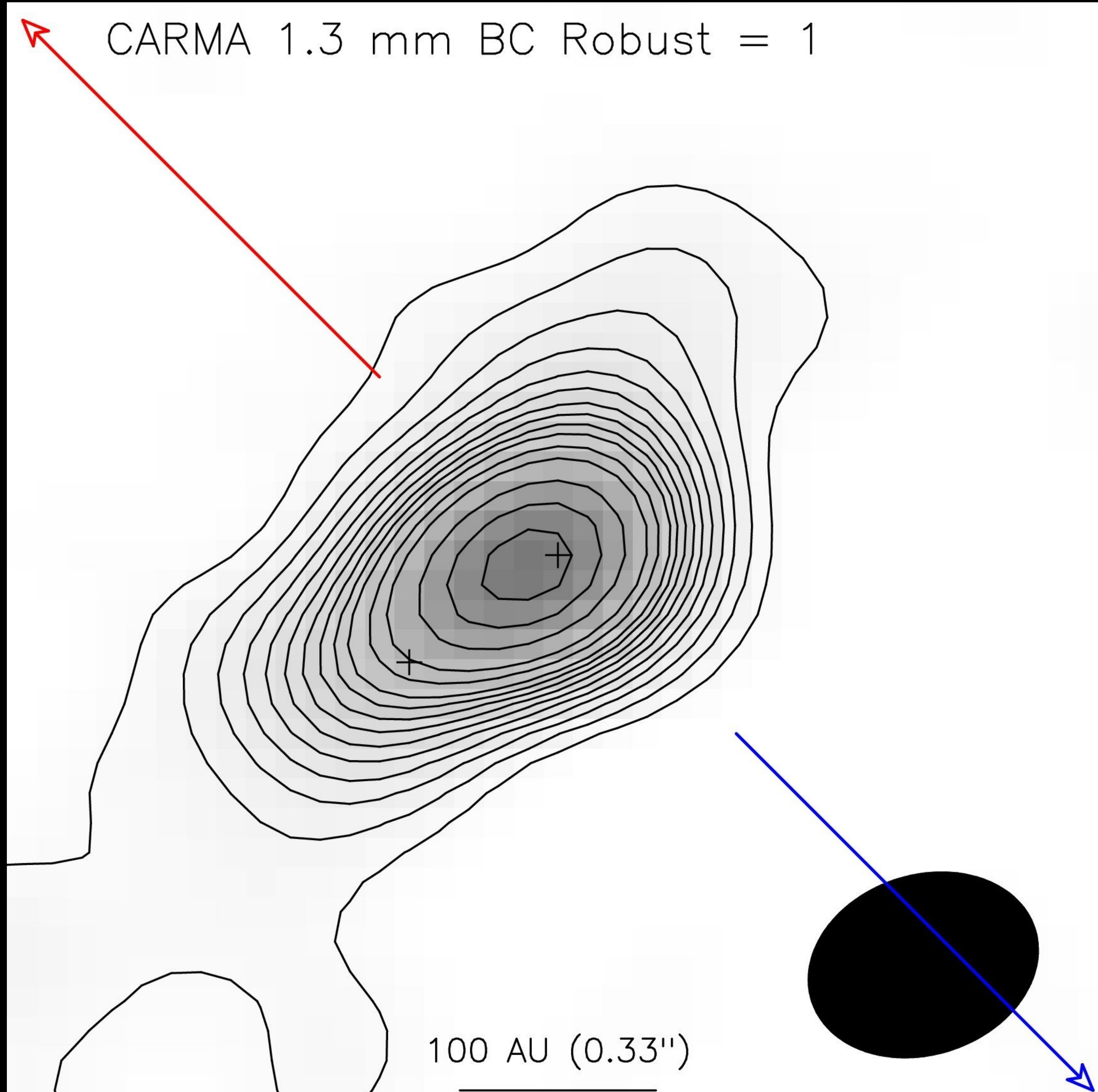
CB230



λ = 7.3 mm

Tobin+2013

- Extended disks not observed, but detect binaries!

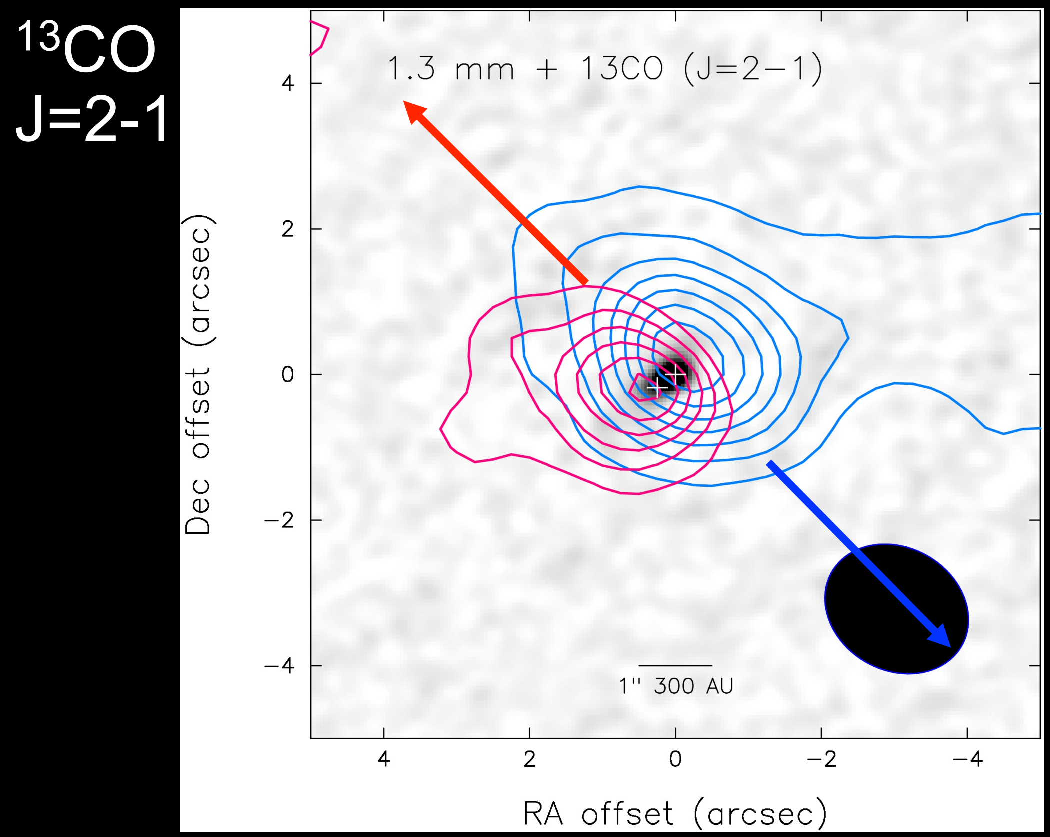


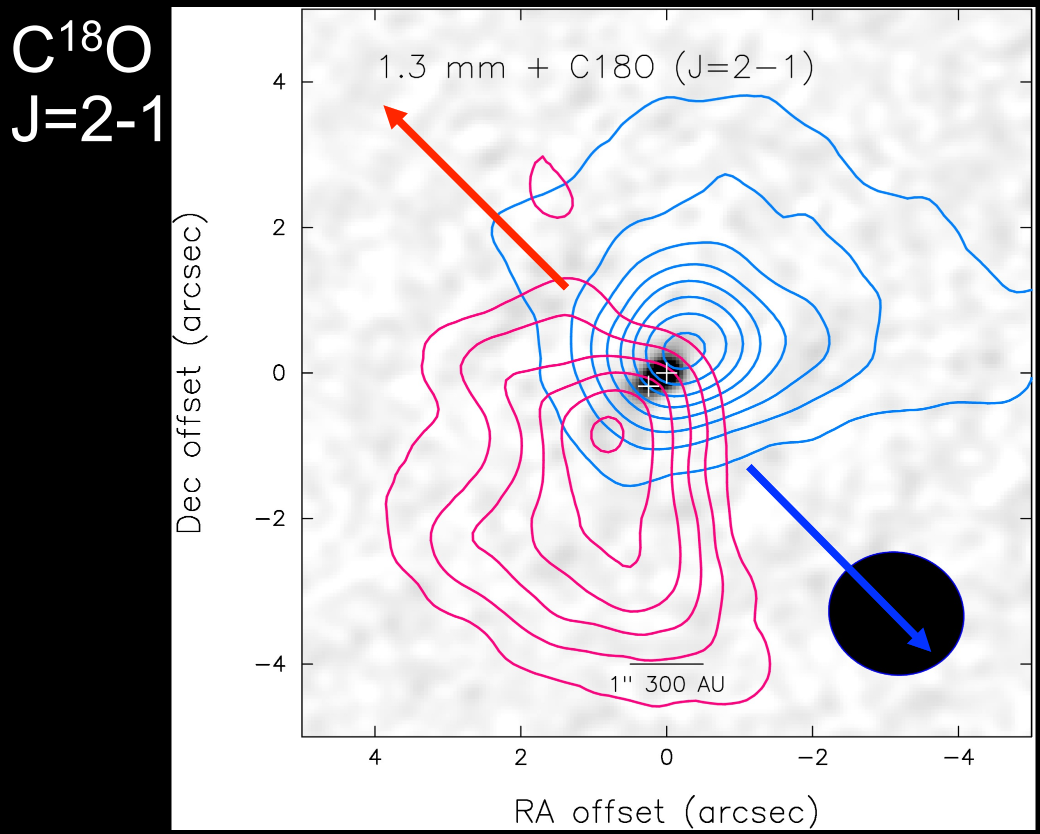
CARMA
1.3 mm

VLA
7 mm

Tobin+2013

Rotating, Circumbinary Disk



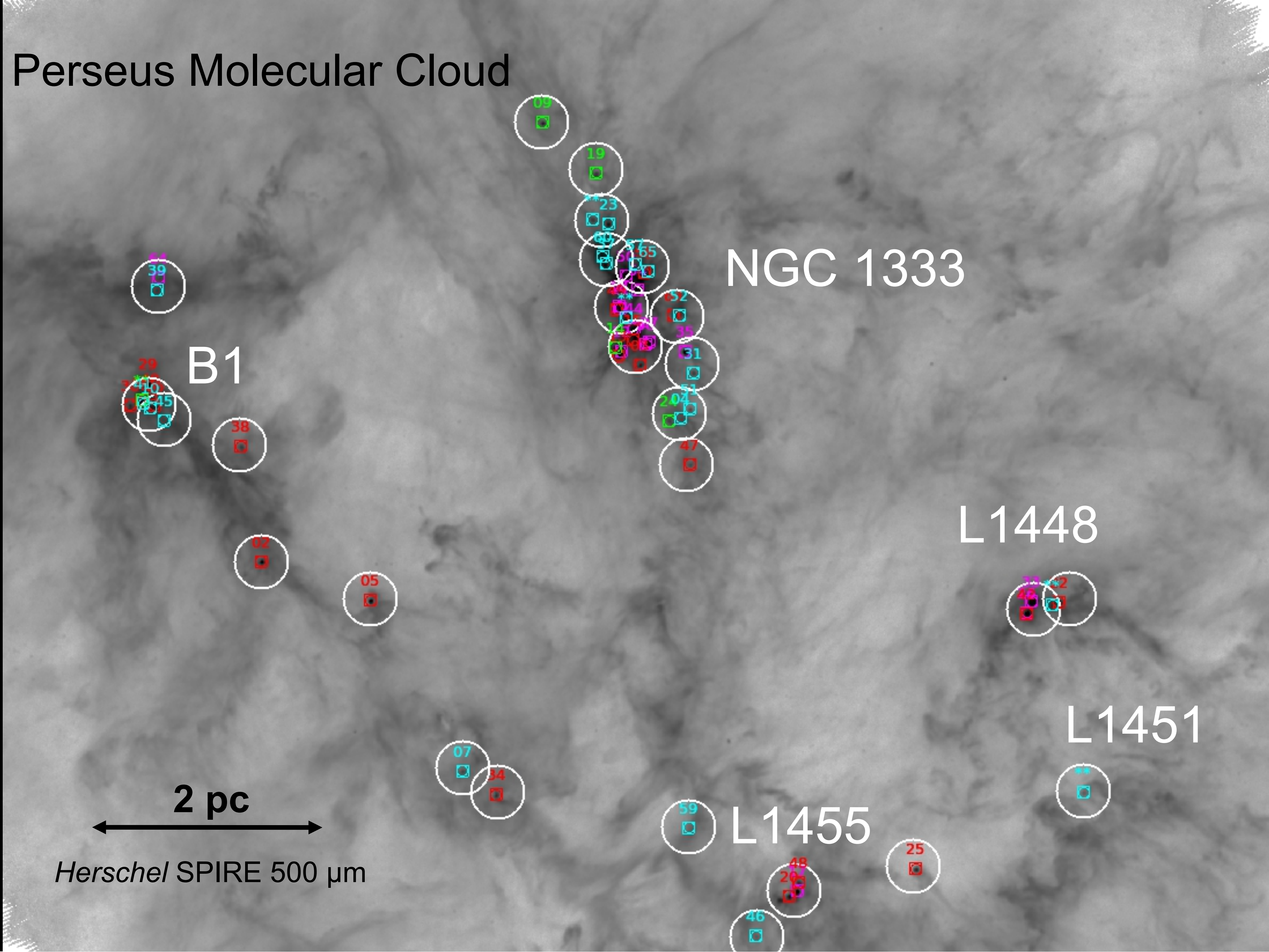


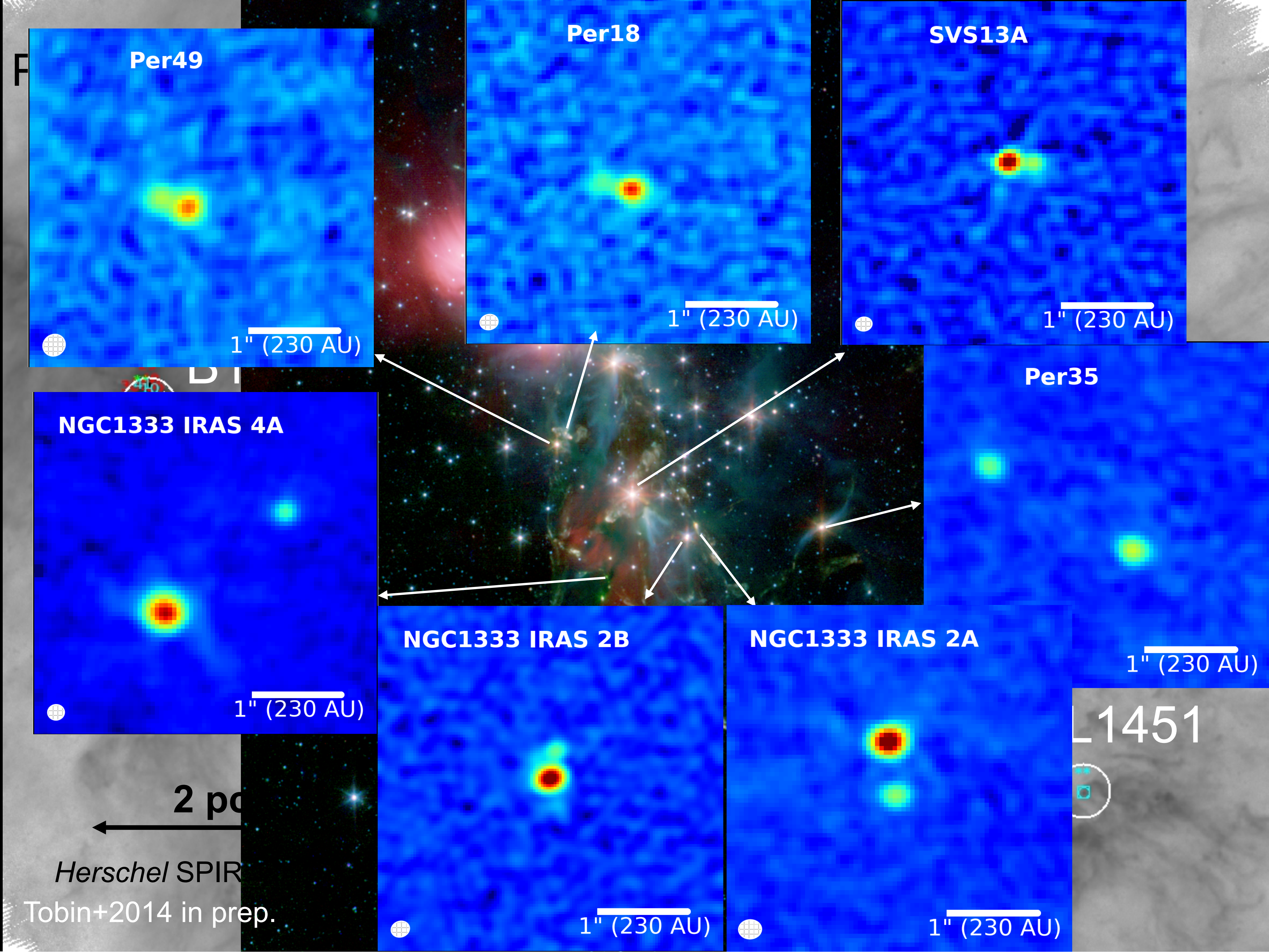
Tobin in prep.

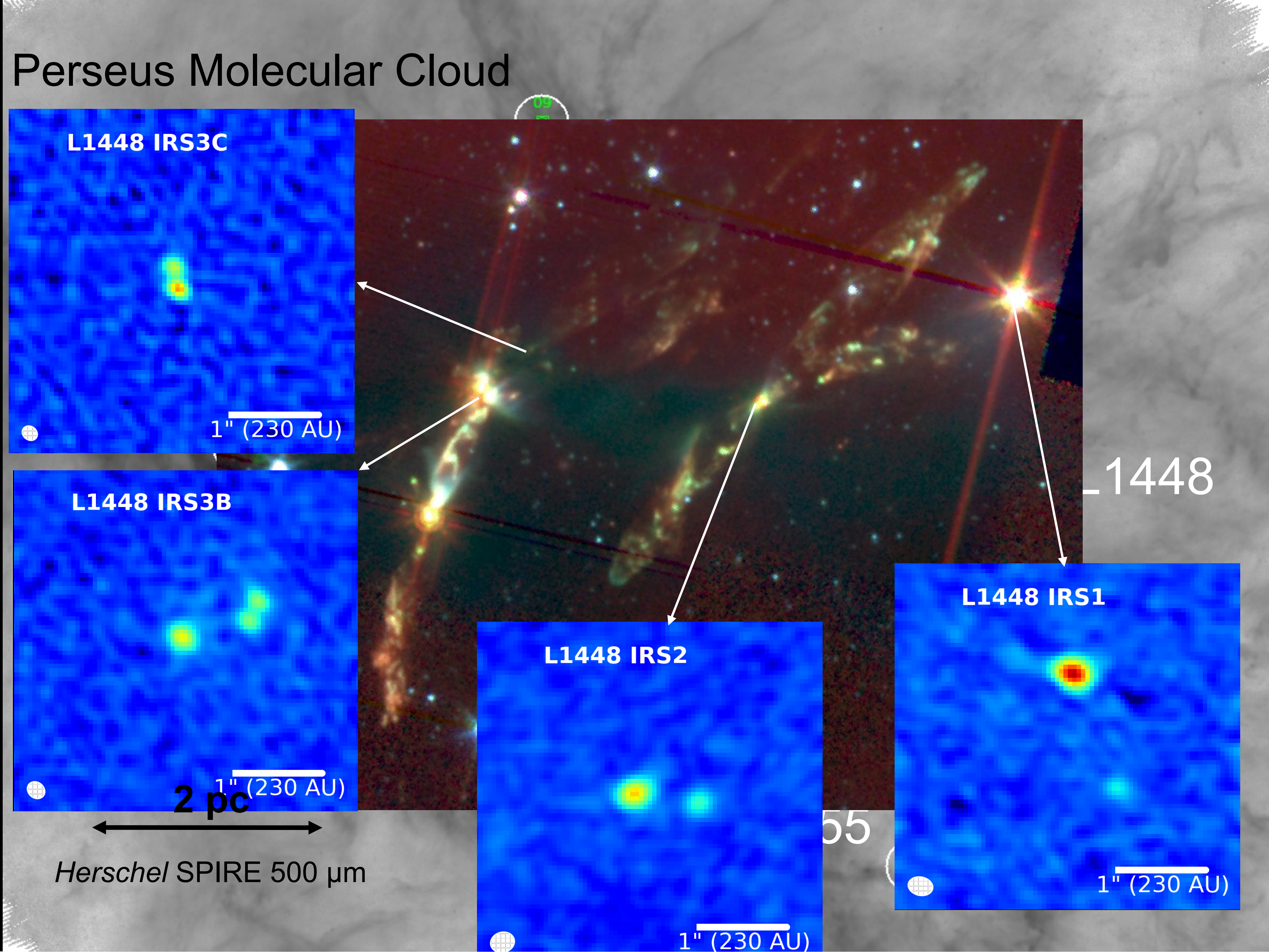
- Rotation curve consistent with Keplerian rotation
- Total mass of protostars ~ 0.5 M_{sun}
- Disk Fragmentation seems most likely binary formation mechanism

VLA Multiplicity and Disk Survey

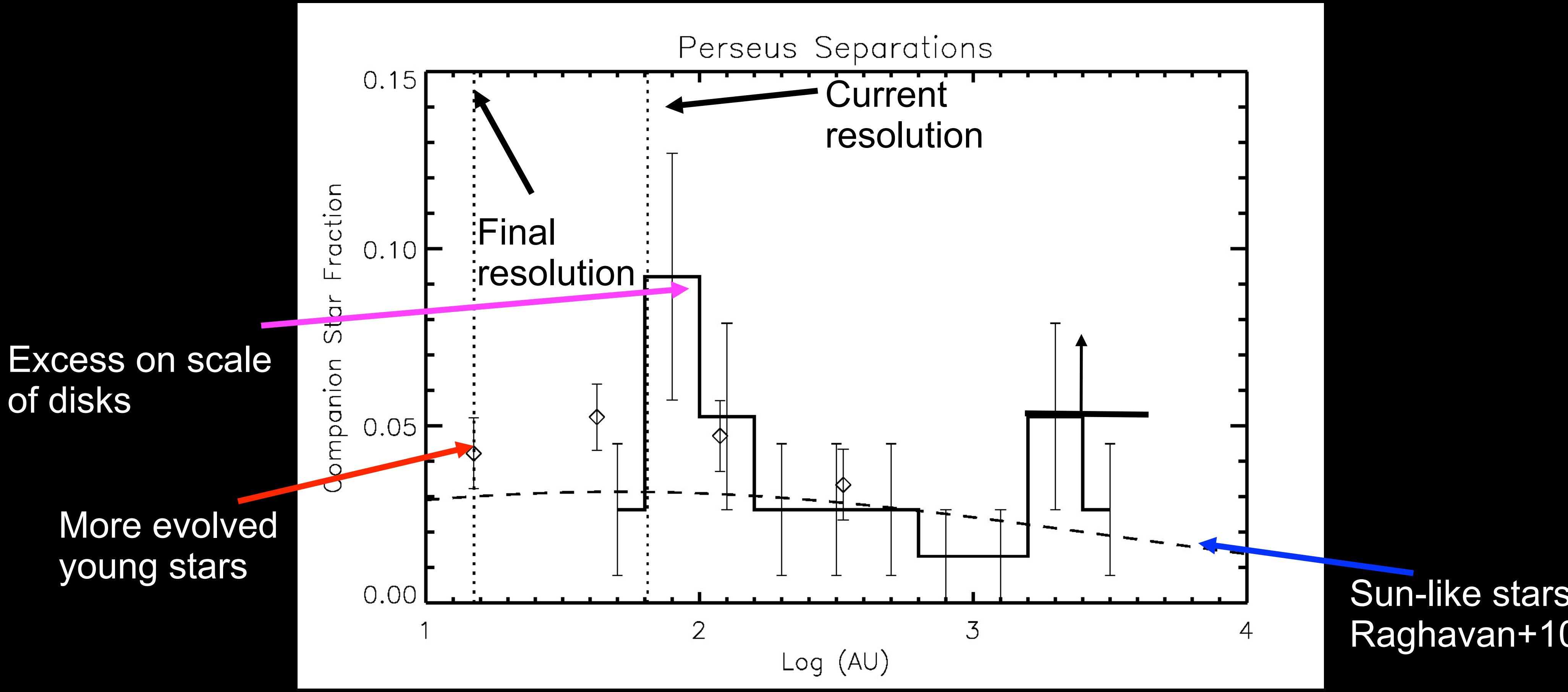
- Isolated case studies may not be giving the big picture, want to characterize ensemble properties
- Diversity of protostellar disks and multiplicity fractions need to be characterized for large samples with <u>*homogeneous resolution and sensitivity*</u>
- VLA large program observing all protostars in Perseus molecular cloud
  - Ultimate resolution of 0.06” (15 AU)
  - Sample of ~80 protostars
  - Luminosities range 0.1 L_{sun} to 30 L_{sun}


Perseus Molecular Cloud
NGC 1333
B1
L1448
L1451
L1455
2 pc
Herschel SPIRE 500 μm


Per49
1" (230 AU)
Per18
1" (230 AU)
SVS13A
1" (230 AU)
Per35
1" (230 AU)
NGC1333 IRAS 4A
1" (230 AU)
NGC1333 IRAS 2B
1" (230 AU)
NGC1333 IRAS 2A
1" (230 AU)
L1451
Tobin+2014 in prep.


Perseus Molecular Cloud
L1448 IRS3C
1" (230 AU)
L1448 IRS3B
1" (230 AU)
2 pc
L1448 IRS2
1" (230 AU)
L1448 IRS1
1" (230 AU)
L1448
Herschel SPIRE 500 µm

(Preliminary) Binary Population



Tobin+2014 in prep.

- Perseus Class 0 and Class I Separation Distribution
  - Excess relative to field at ~100 AU and > 1000 AU

Summary

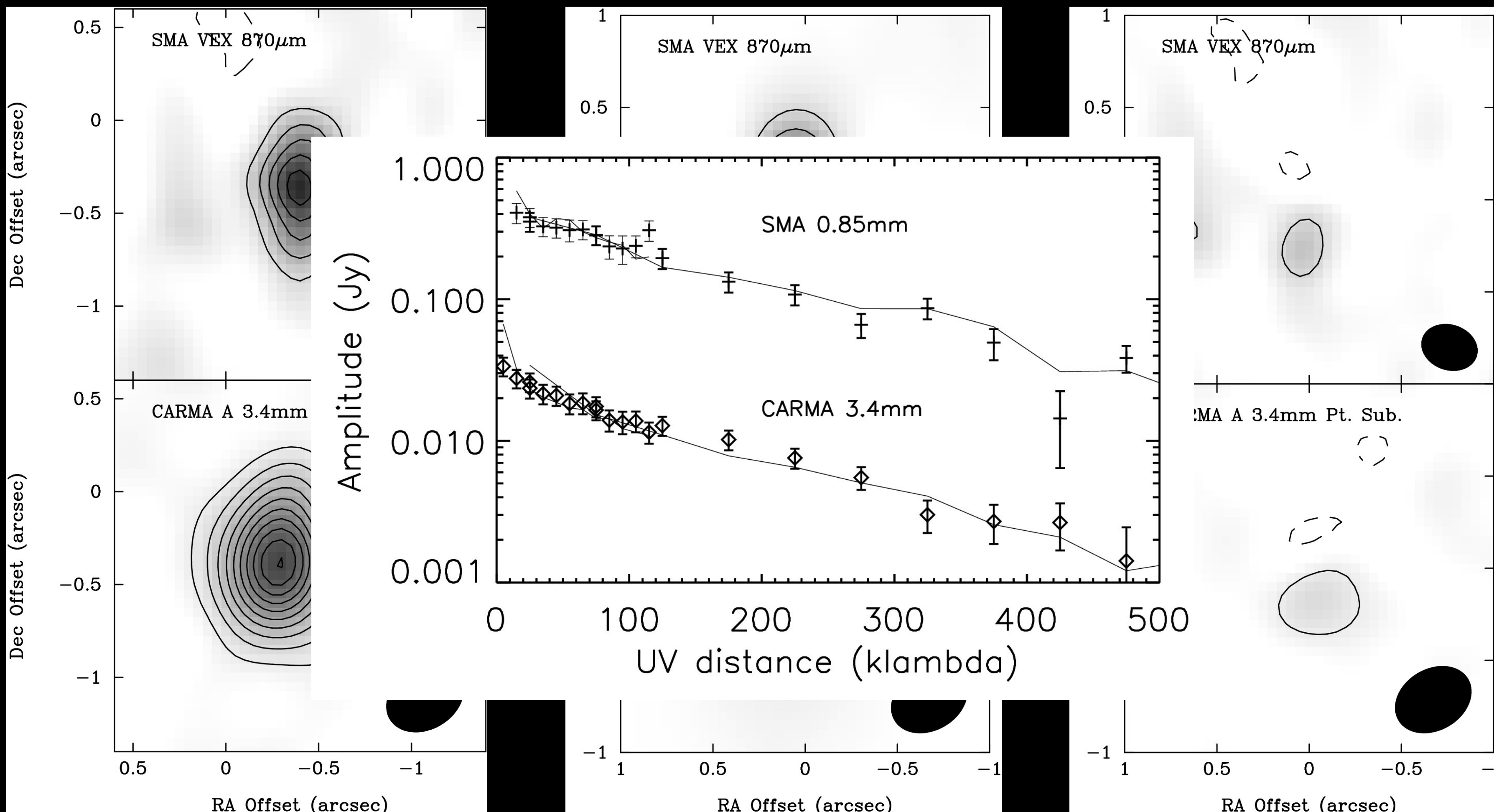
- Structure and kinematics of star forming cores able to be examined with high sensitivity of VLA and GBT
  - Cores themselves filamentary and reside in turbulent medium
- Sensitivity and access to unexplored frequencies by ALMA enabling formation of protostars and disks to be examined in great detail
  - Infall and chemical changes at the disk observed
- Complementary use of VLA and ALMA/CARMA will enable processes of binary star formation to be revealed
- VLA enabling new progress on protostellar multiplicity
  - Large numbers of protostars observed with unprecedented spatial resolution

Sub/Millimeter Models

Data　　Model　　Residual

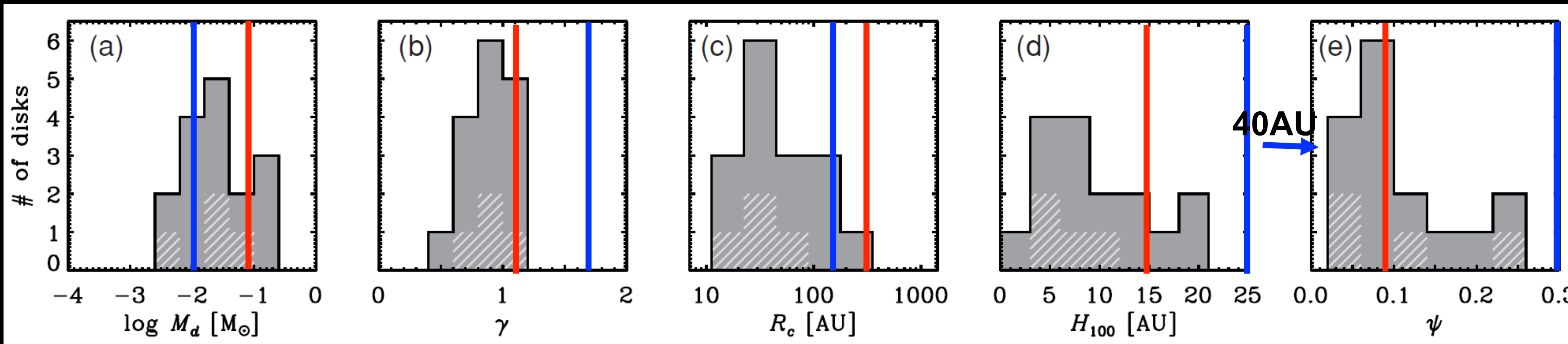
870 µm

3.4 mm



- 'Classic' signature of disk absent

Disk Parameters

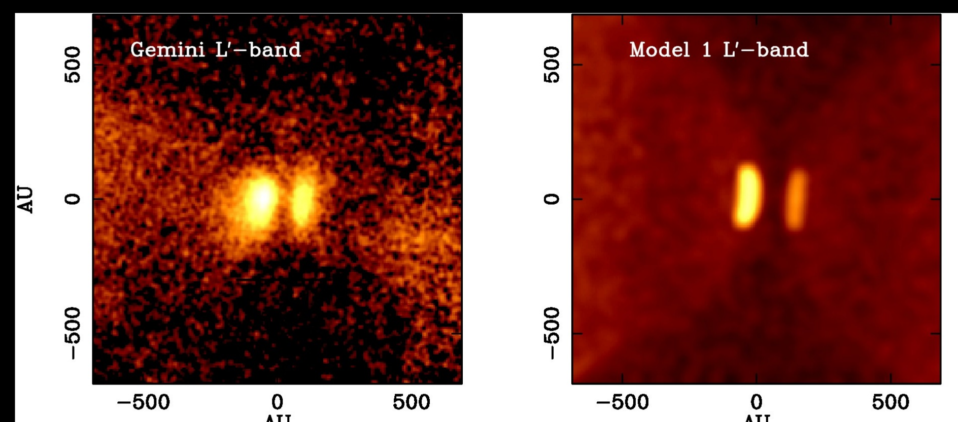


Andrews+2009, 2010

Blue: L1527
Red: IRAS 04302+2247

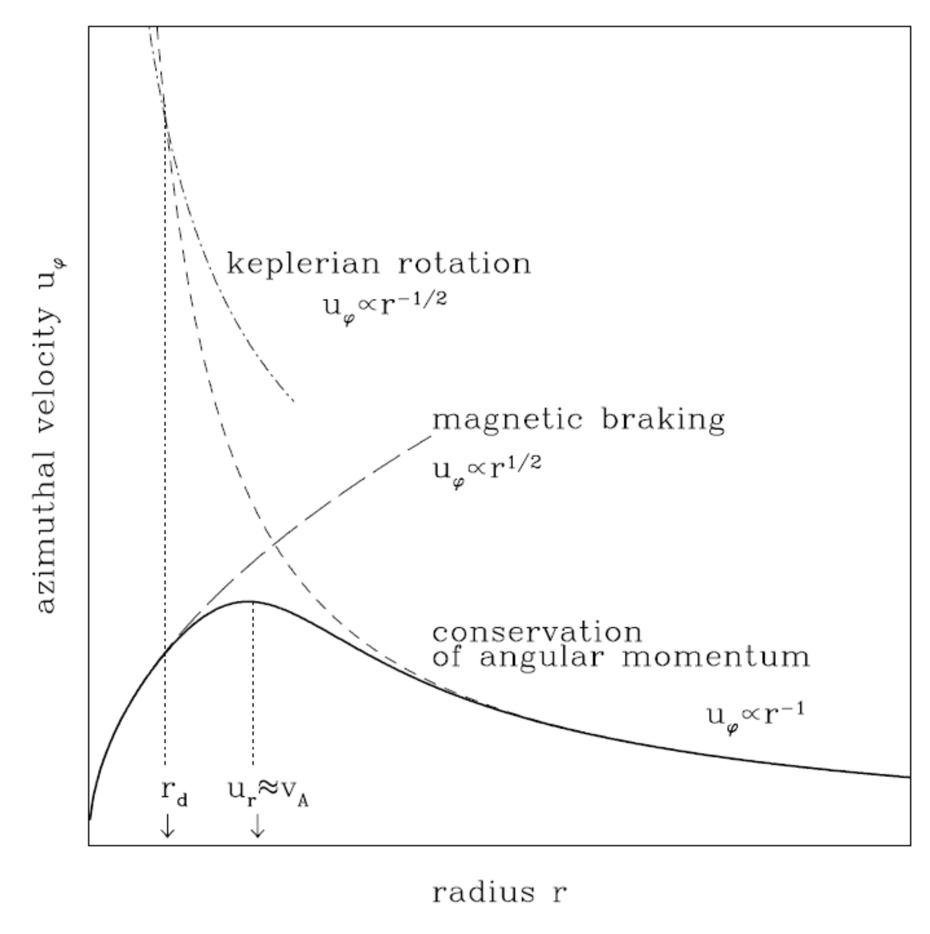
L1527 Disk

- R ~ 150 AU
- M ~ 0.01 M_{sun}
- H ~ $R^{1.3}$; H (100 AU) = 39 AU
- ρ ~ $R^{-3.0} \longrightarrow \Sigma^{-1.7}$
- β ~ 0.25



Disk Formation Not So Simple

- Magnetic fields can cause complications
  - Magnetic braking problem
  - Field dragged inward during collapse
  - Slows rotation, angular momentum transported out of cloud



Galli 2009

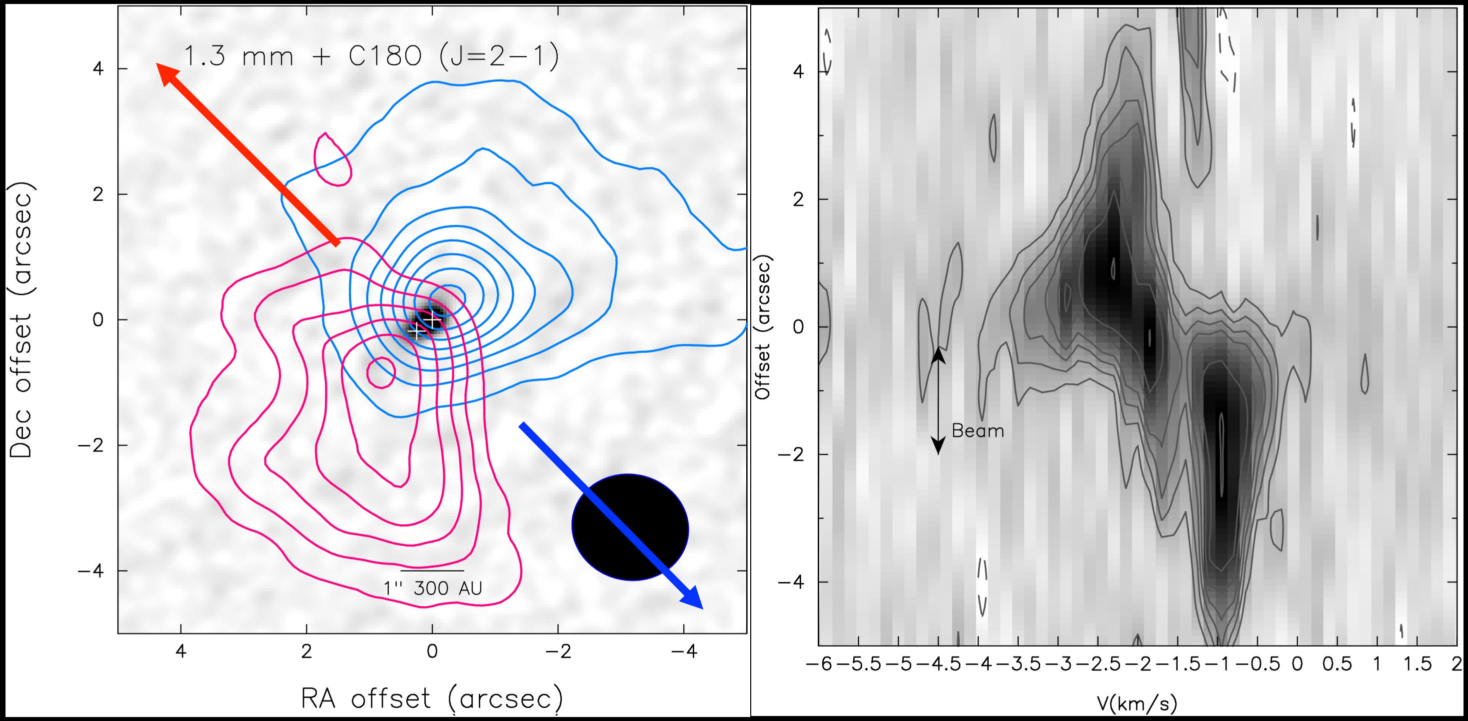
- Ways around magnetic braking problem
  - Non-ideal MHD, only small disks Dapp & Basu 2011
  - Misaligned rotation/magnetic fields allow larger disks (Joos+2012)
  - Magnetic mirroring reduces ionization, hence field coupling to gas (Padovani & Galli 2013)

A Rotationally Supported Disk

L1165

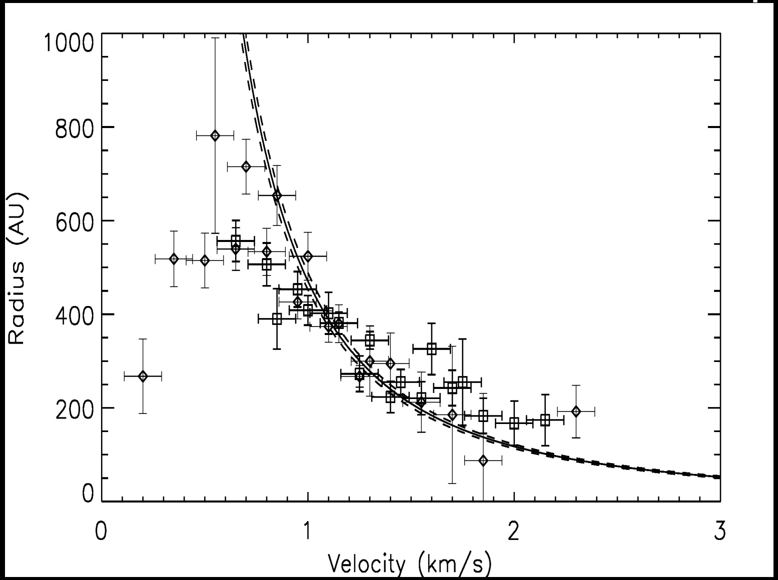
^{13}CO
J=2-1

$C^{18}O$
J=2-1

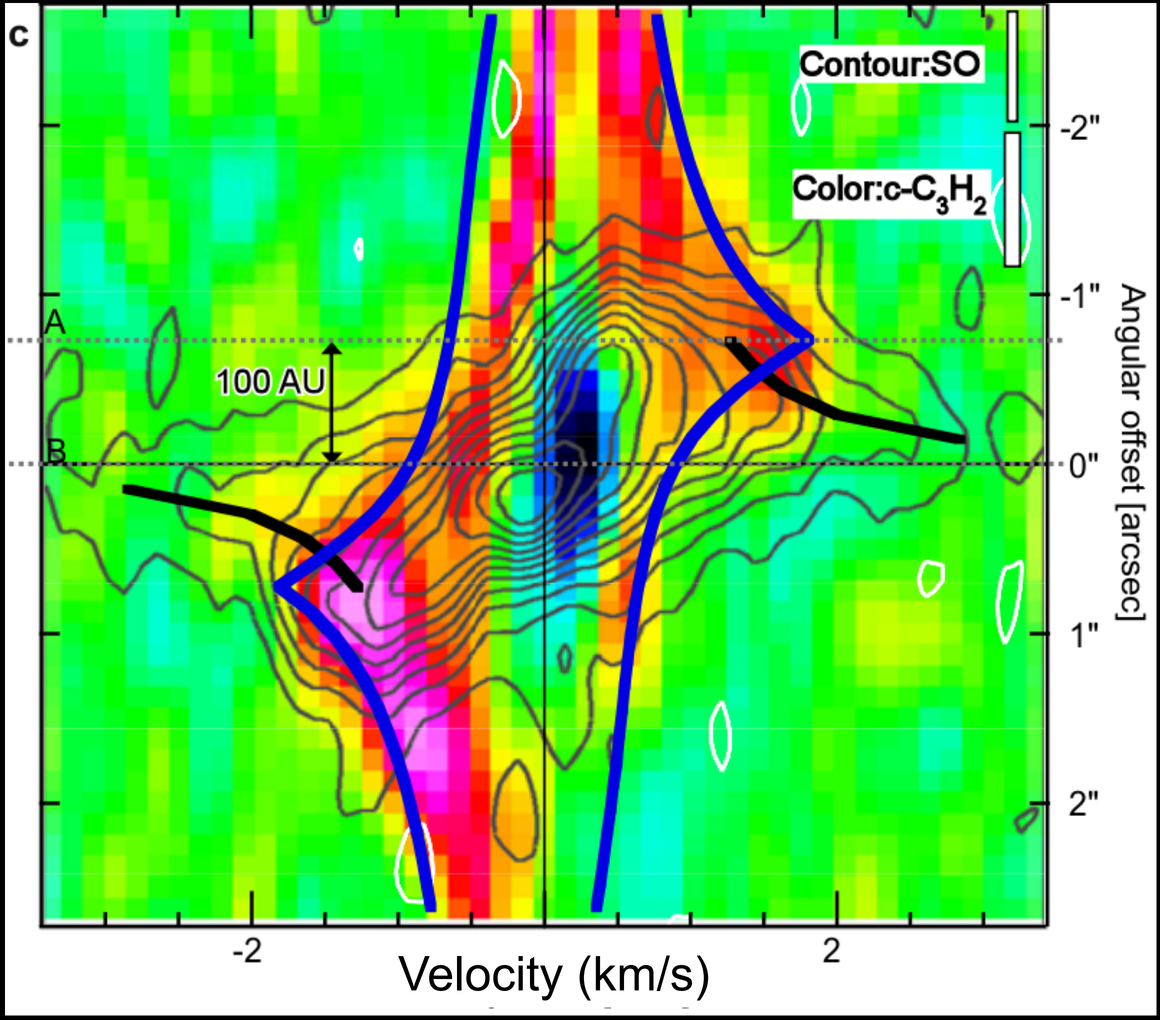


Tobin in prep.

- Rotation curve consistent with Keplerian rotation
- Total mass of protostellar objects ~ 0.5 M_{sun}
- Envelope mass ~ 0.3 M_{sun} ; confirms as Class I protostar



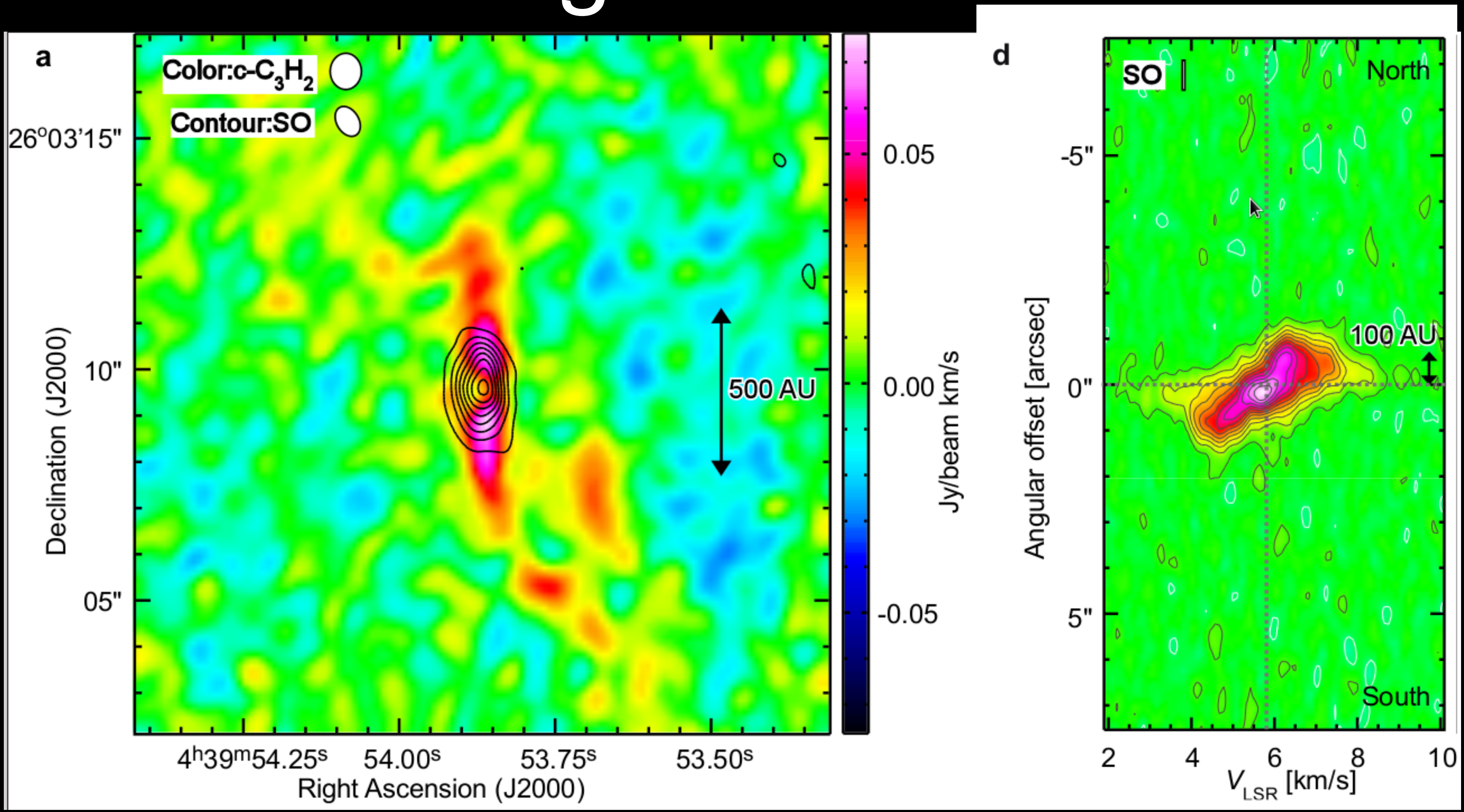
Observing Disk Formation



Sakai+2014, *Nature*

- Dramatic chemical change at 100 AU
  - c-C_3H_2 dissappears and SO becomes abundant
  - Accretion shock at the edge of proto-planetary disk suggested to cause chemical change

Observing Disk Formation



Sakai+2014, *Nature*

- Protostar L1527 IRS, distance ~ 140 pc
- ALMA (λ ~ 870 μm) $c\text{-}C_3H_2$ ($J= 5_{51}$- 4_{40}) and SO ($J_N=7_8\text{-}6_7$) observations
- SO and $c\text{-}C_3H_2$ trace different components spatially and kinematically
- Dramatic chemical change at 100 AU; accretion shock onto disk?