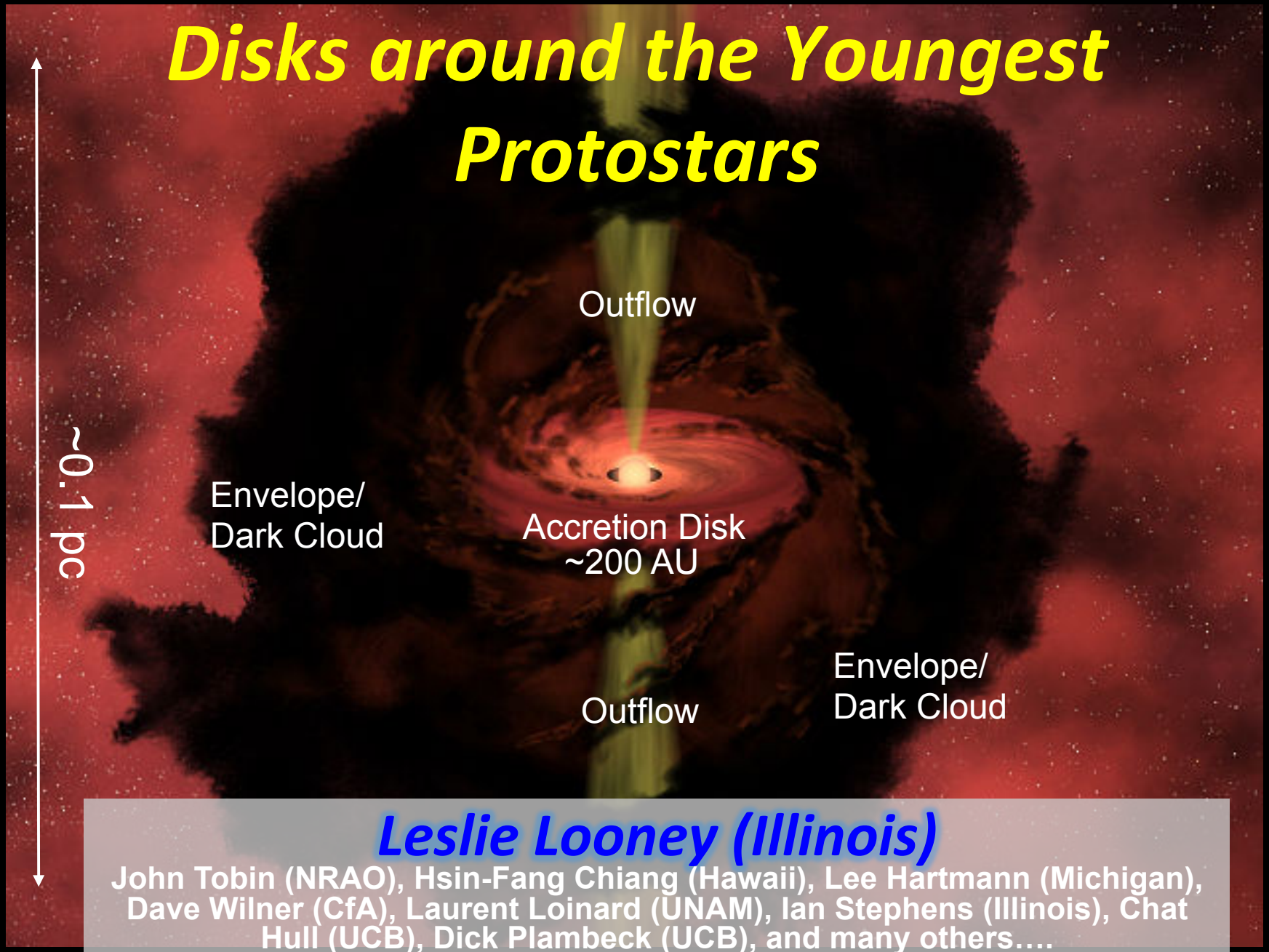
Disks around the Youngest Protostars



Credit: Robert Hurt

Leslie Looney (Illinois)

John Tobin (NRAO), Hsin-Fang Chiang (Hawaii), Lee Hartmann (Michigan), Dave Wilner (CfA), Laurent Loinard (UNAM), Ian Stephens (Illinois), Chat Hull (UCB), Dick Plambeck (UCB), and many others….

The Youngest Disk: Outstanding Questions

1 **When does the circumstellar disk form?**
- **Initial conditions for disk and planet evolution**

2 **What are their early properties and how do they evolve?**
- **Size, mass, dust properties**

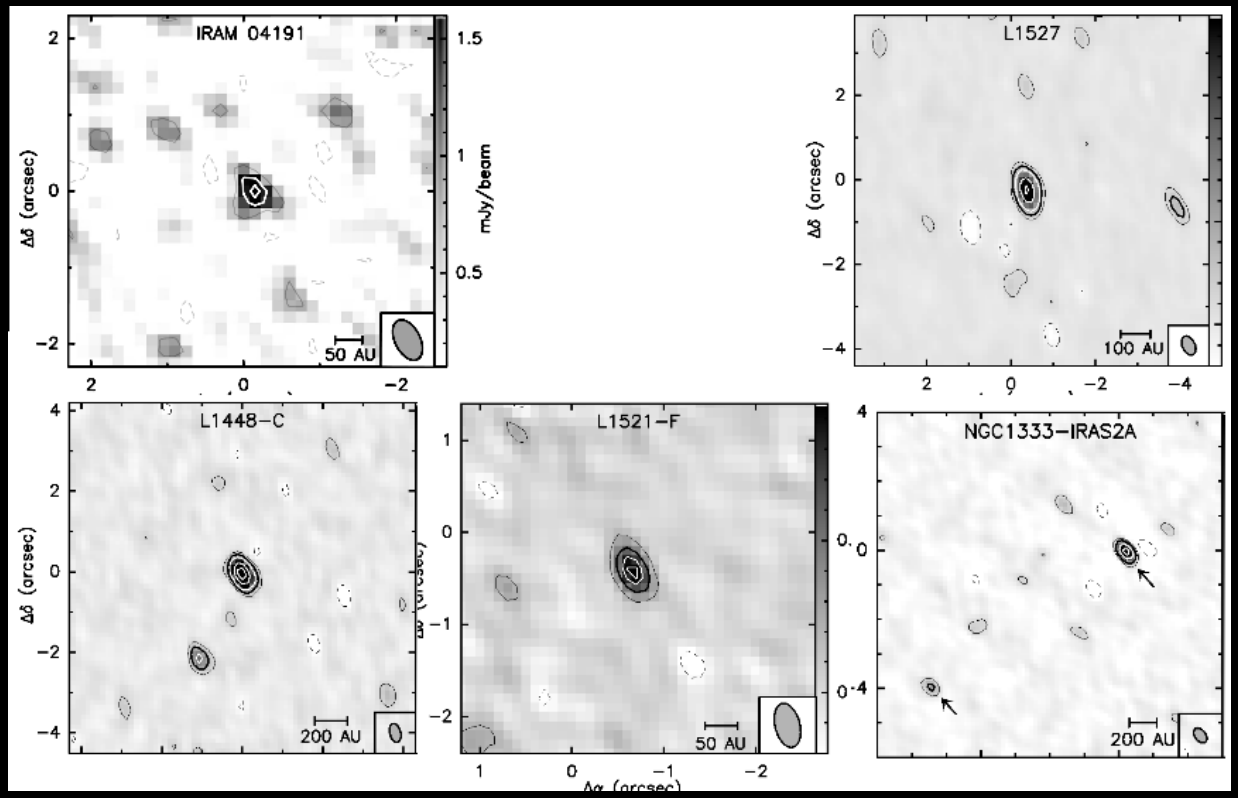
3 **What is the initial distribution of binary systems?**
- **History of binary formation**

When does the circumstellar disk form?

Expect the disk to be simple consequence of angular momentum conservation… but until recently not strong evidence for young disks

(Looney et al. 2000; Chiang et al. 2008; Jorgensen et al. 2009, Enoch et al. 2009, Maury et al. 2010)

Concluded that not common for Class 0 sources to have disks nor binaries in range of
150 AU < R < 500 AU
(cf. Chen et al. 2013)

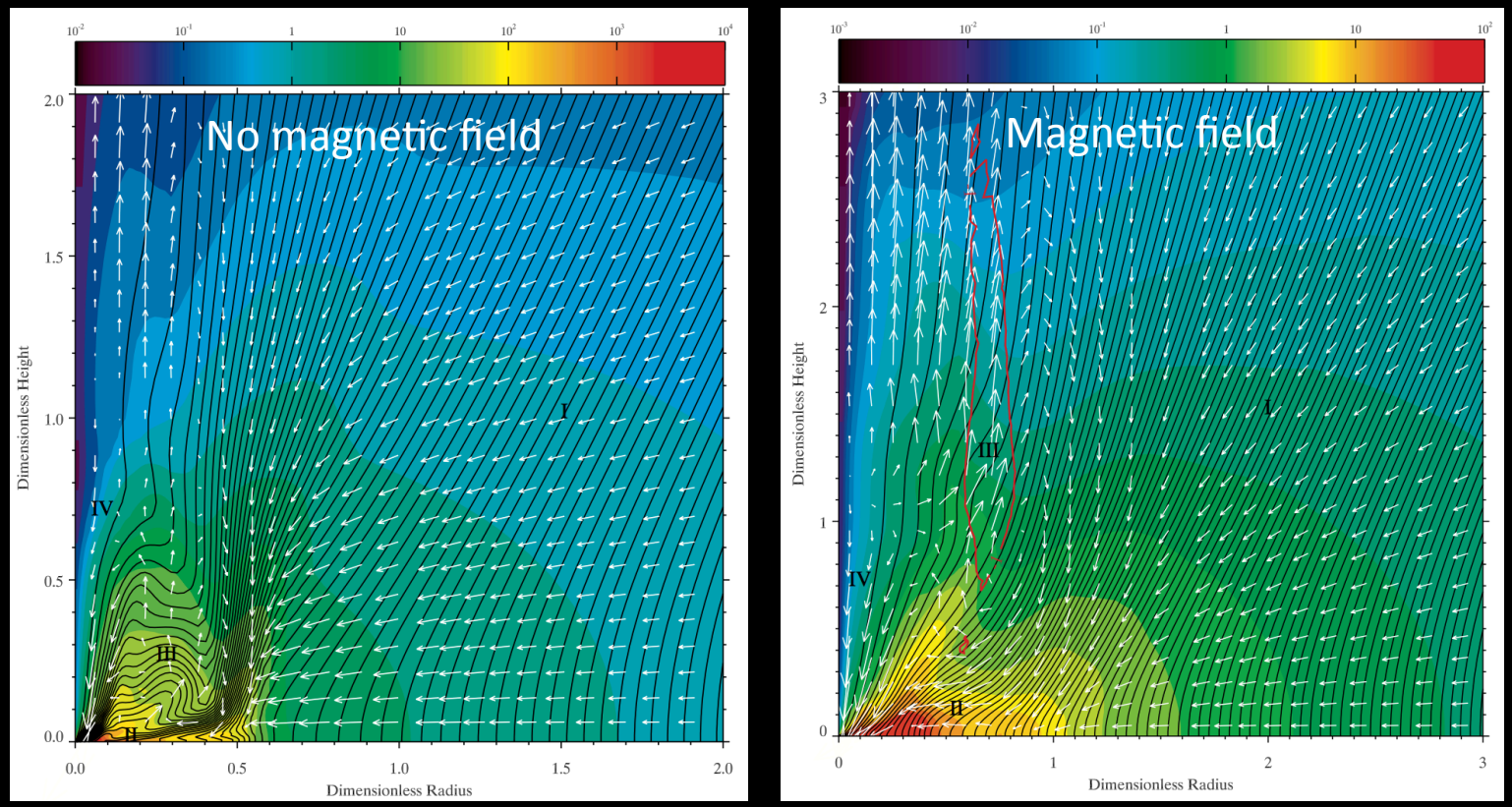


Maury et al. 2010

When does the circumstellar disk form?

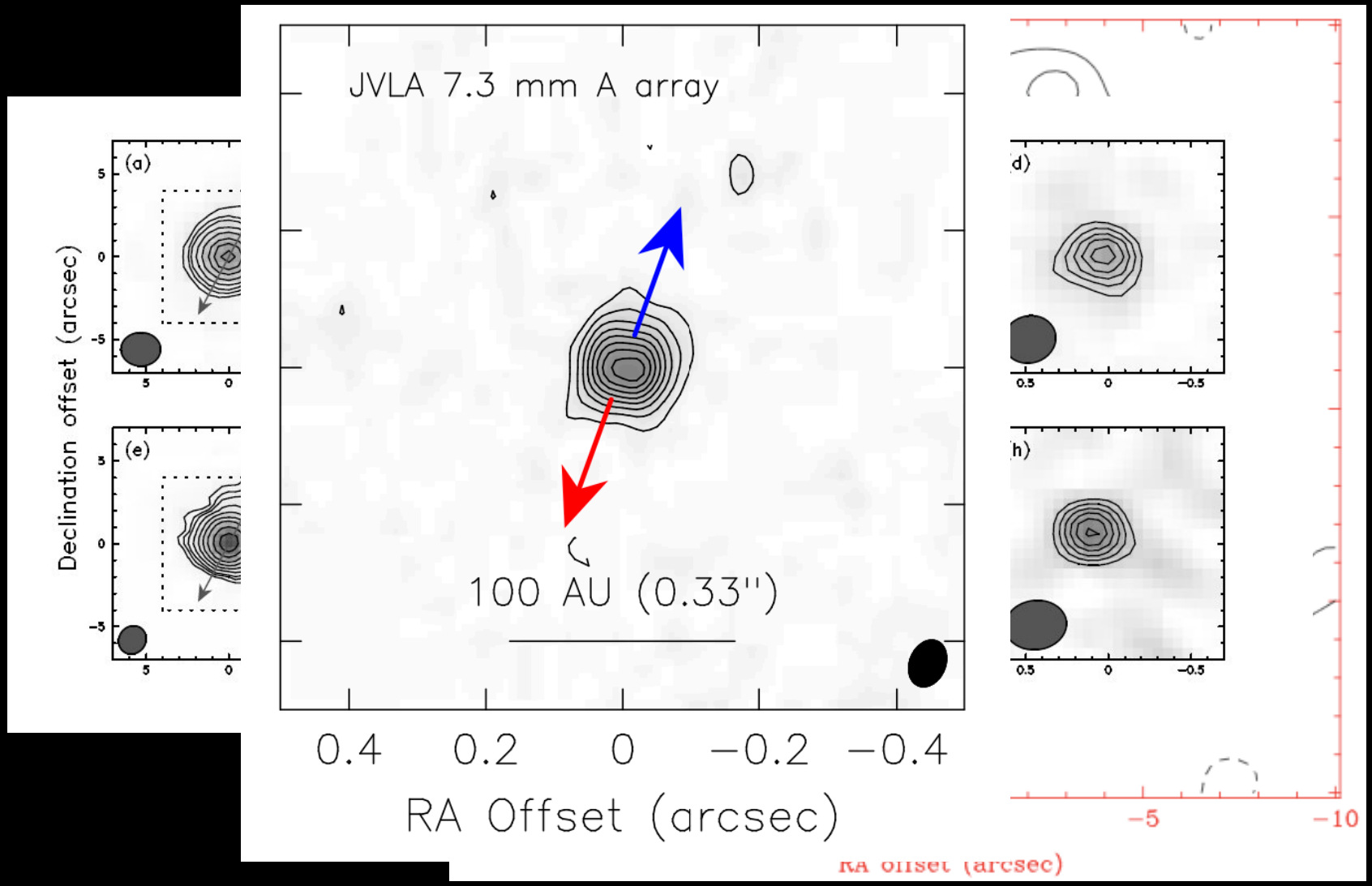
Problem for early disks:

- **Magnetic Braking, e.g. only expect small, young disks**
  (Mellon & Li 2008; Hennebelle & Fromang 2008)
- **<10 AU disks until end of Class I stage**



Mellon & Li 2008

Magnetic Field & No Disk



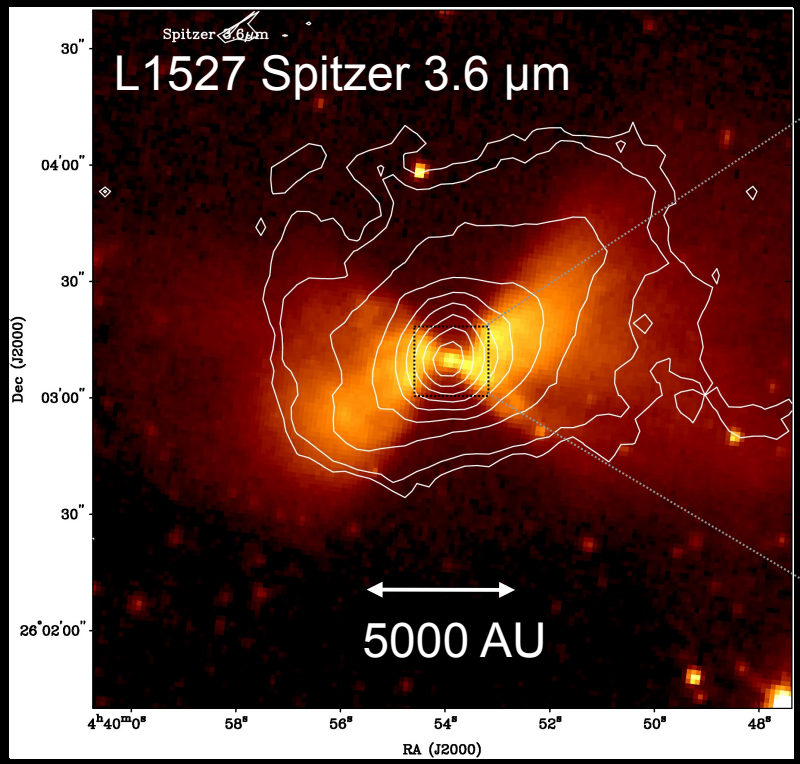
L1157: Chiang et al. 2012

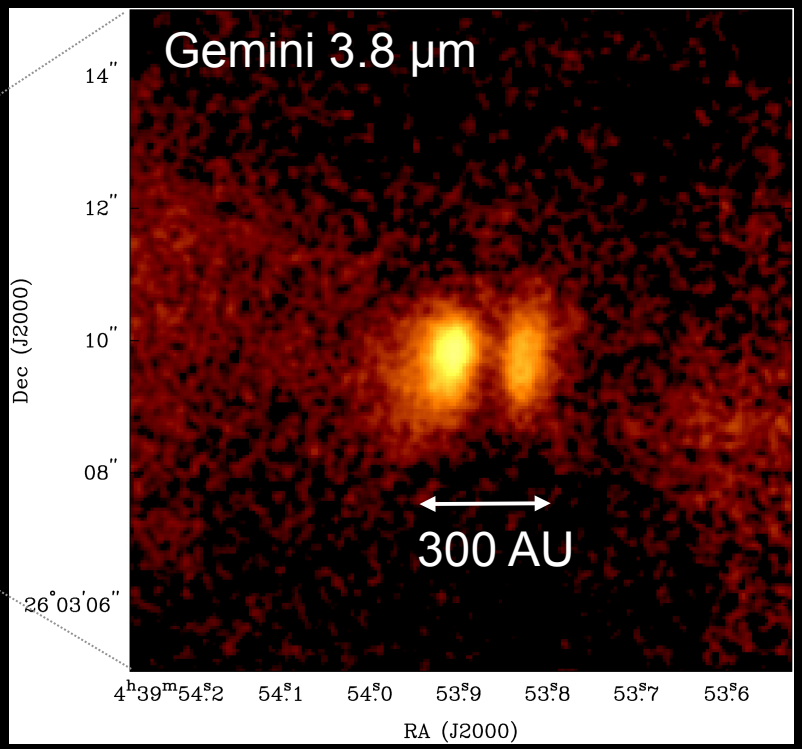
Tobin et al. 2013

Stephens et al. 2013

A New Hope for Class 0 Disks

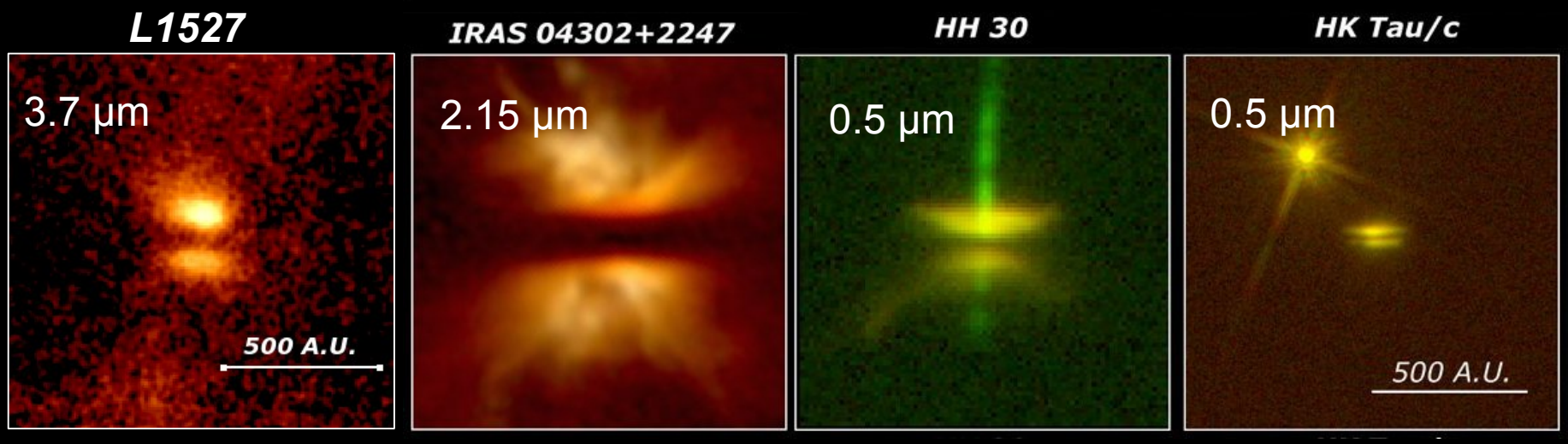
- L1527-IRS in Taurus, D = 140 pc
  - Class 0 protostar, large envelope ~ 1 M_{sun}
  - 0.3” (42 AU) mid-IR imaging suggests a R ~ 200 AU disk





Tobin et al. 2010

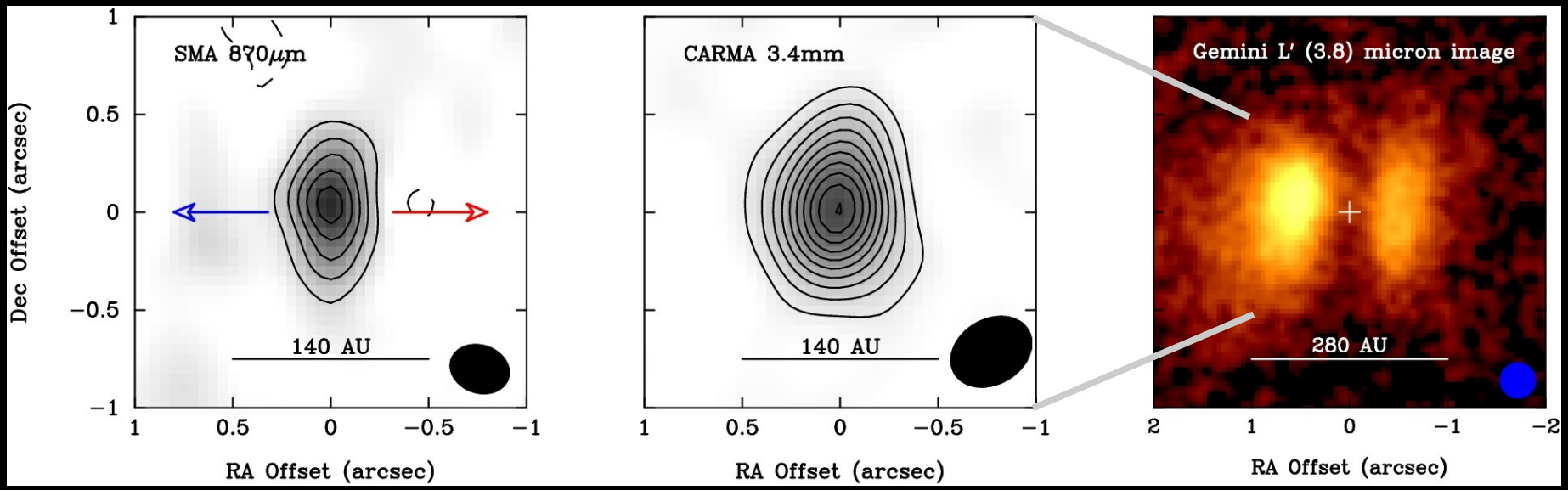
Scattered Light Disks vs. L1527



Padgett+99, Burrows+96, Stapelfeldt+03

Sub/mm Imaging

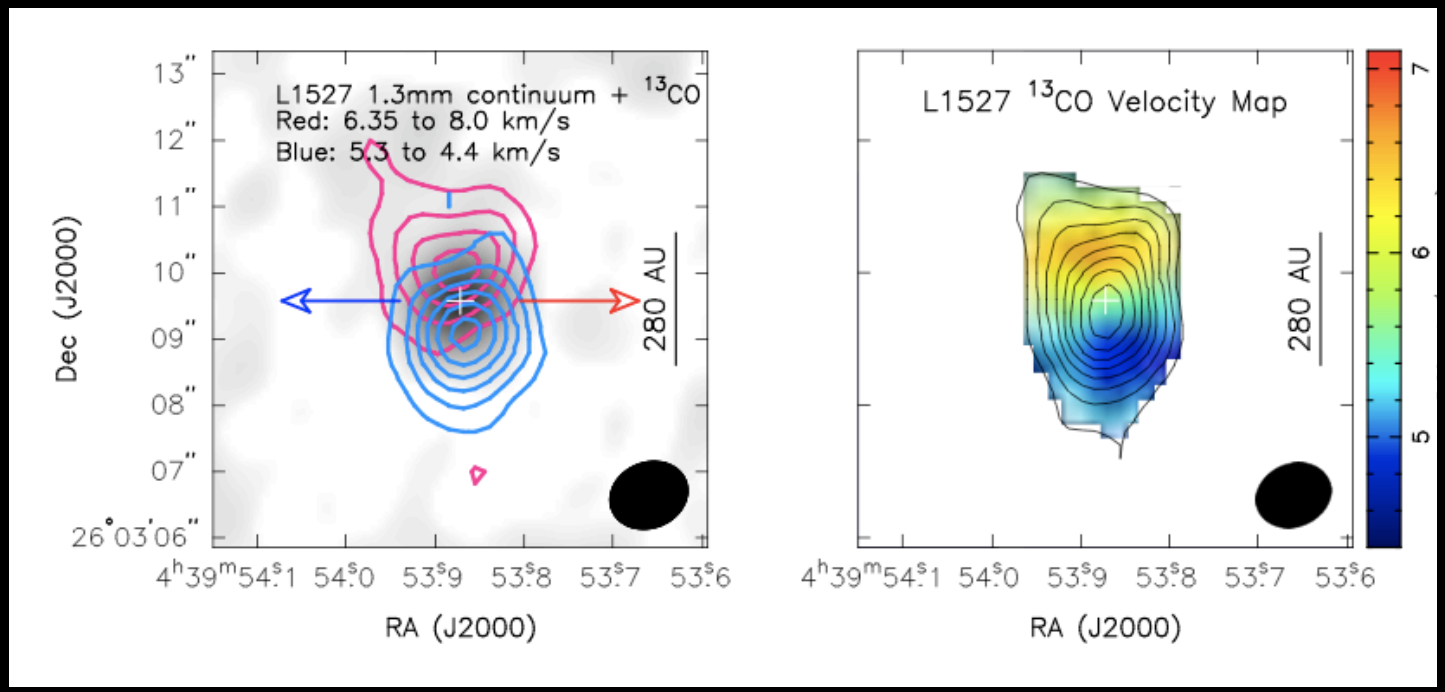
870 μm | 3.4 mm | Gemini L'-band



Tobin+12 Nature

- SMA (870 μm) and CARMA (3.4 mm) data
  - Dust emission to probe bulk of disk
  - 0.3” (870 μm) and 0.35” (3.4 mm)
  - A resolved dust disk!
  - But..... What about the kinematics?

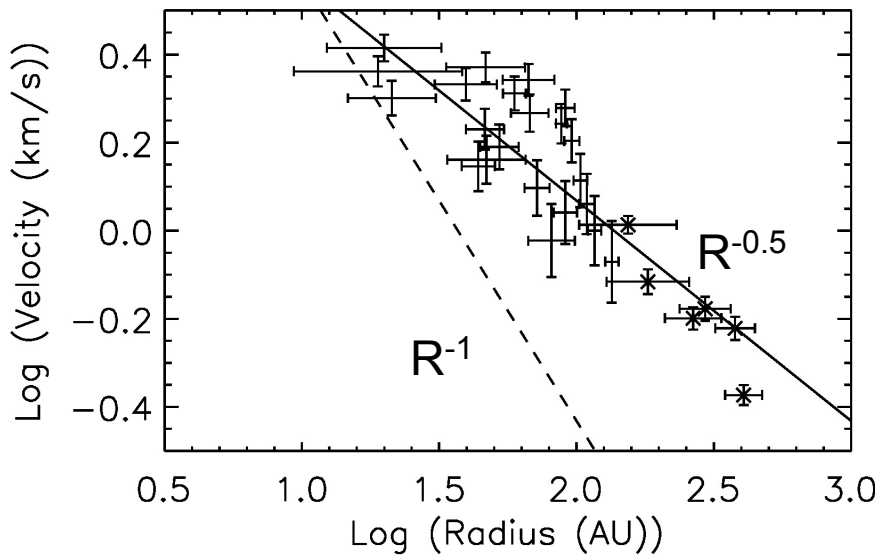
Disk Kinematics

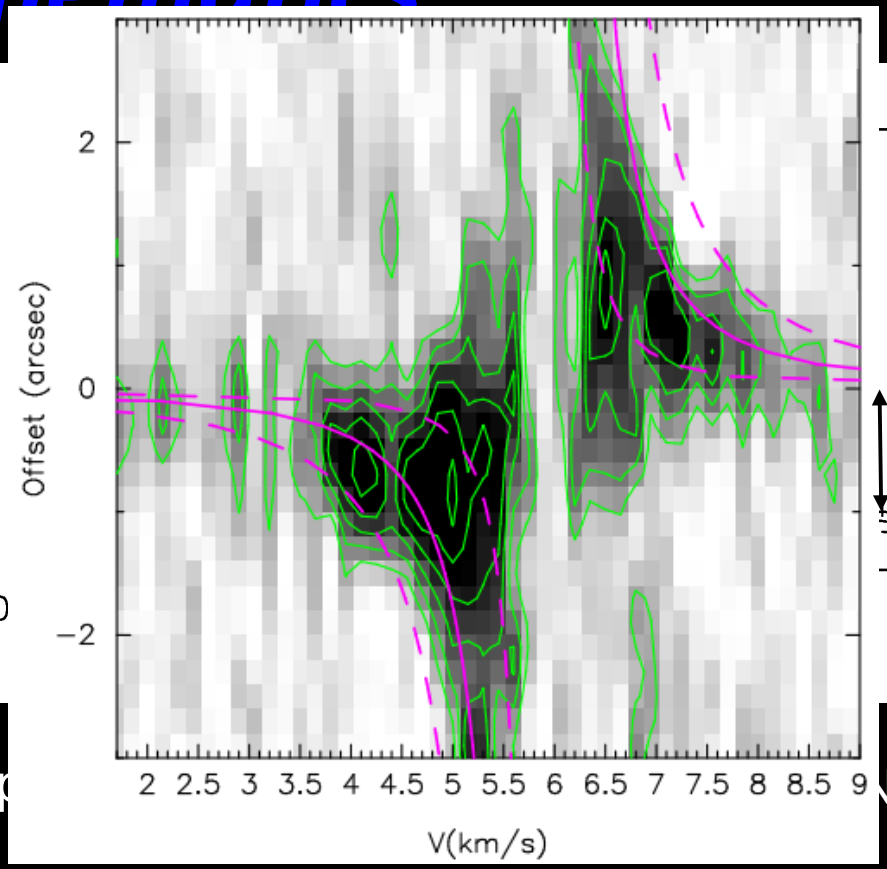


- CARMA ^{13}CO observations of structure
- Clear velocity gradient along elongation, very suggestive of disk rotation.

Tobin et al. 2012

Disk Kinematics





- Rotation curve consistent with Kep ature

- ^{13}CO position-velocity fit gives M_{ps} = 0.19 +/- 0.04 M_{sun}
- Youngest directly measured protostellar mass, ~20% of envelope mass
- Can begin to classify protostars with M_*/M_{env}
  - True spirit of Class 0 definition $M_*/M_{env} < 1$ (Andre+93)

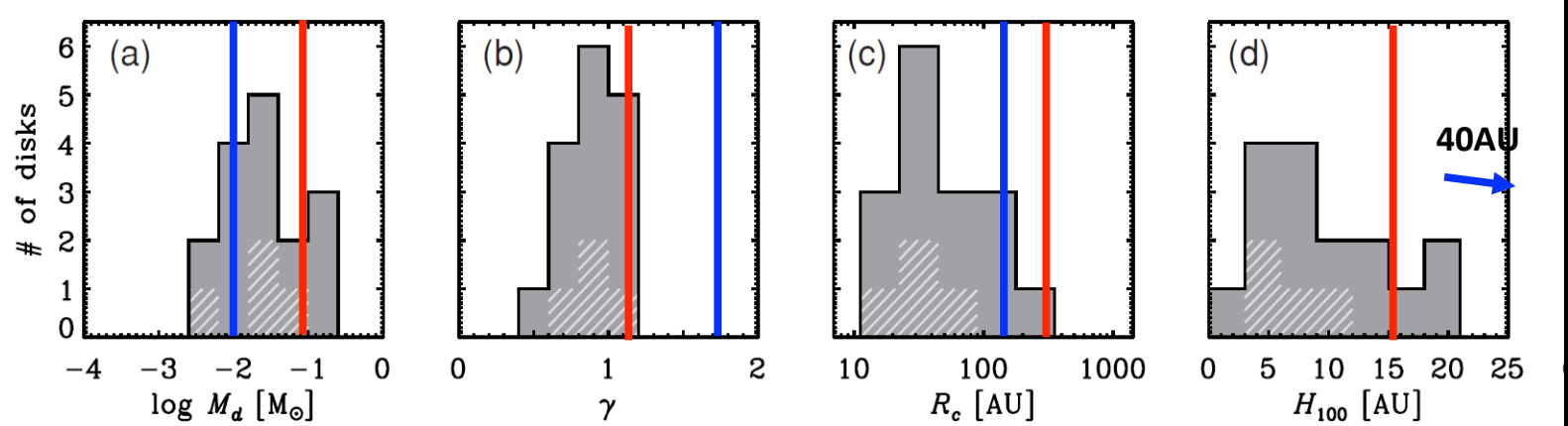
Disk Properties

Sub/millimeter and Mid-Infrared Modeling Results:

- Disk mass = 0.01 M_{sun}
- Surface Density ~ $r^{-1.7}$
- Disk radius ~150 AU
- Scale height H ~ $R^{1.3}$; H (100 AU) = 39 A
- Dust opacity β ~ 0.25

Blue: L1527 and Red: IRAS 04325+2247

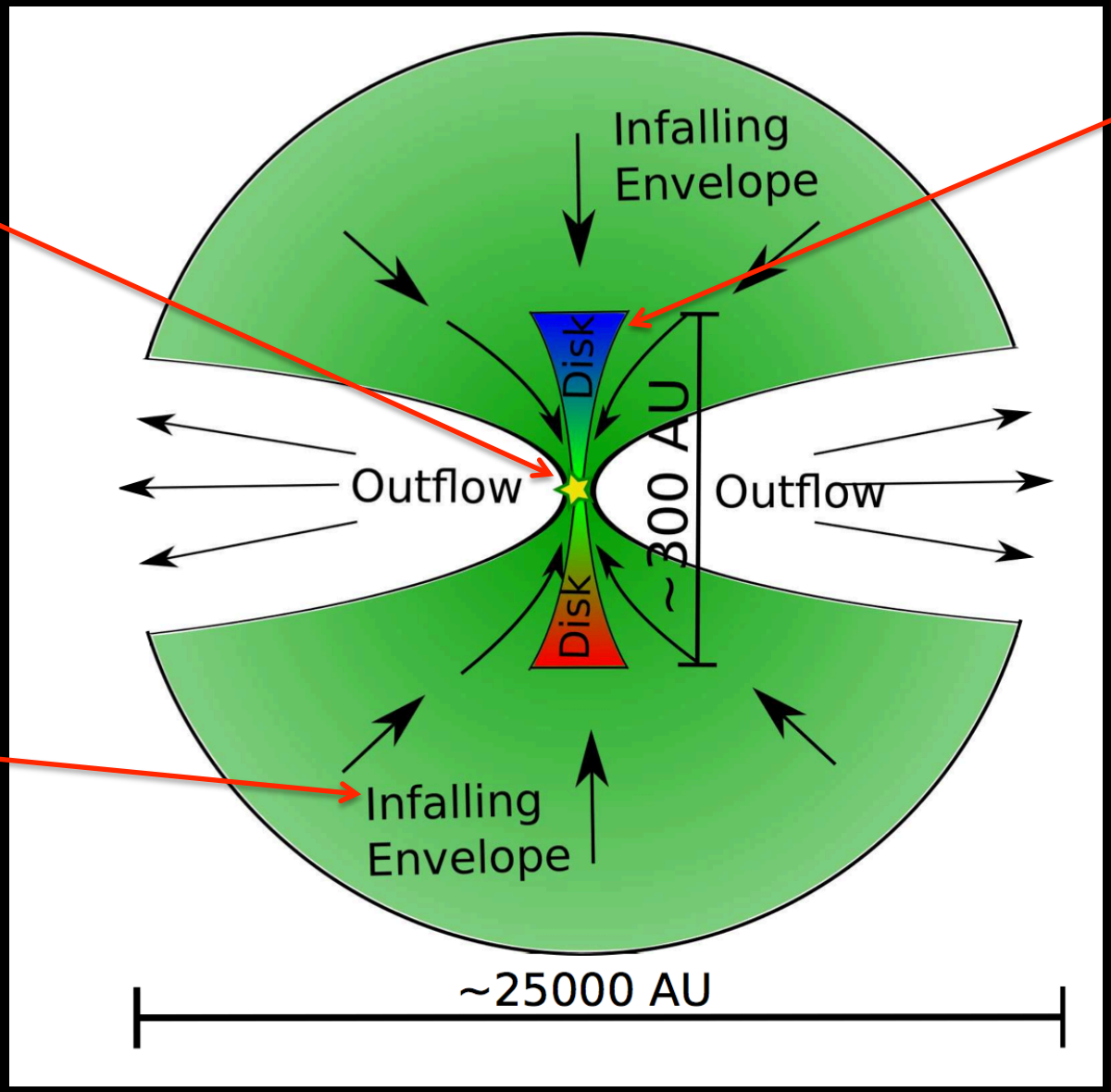
Andrews et al. 2009, 2010



Class 0 System

0.2 solar mass central object

0.01 solar mass disk



~1 solar mass envelope

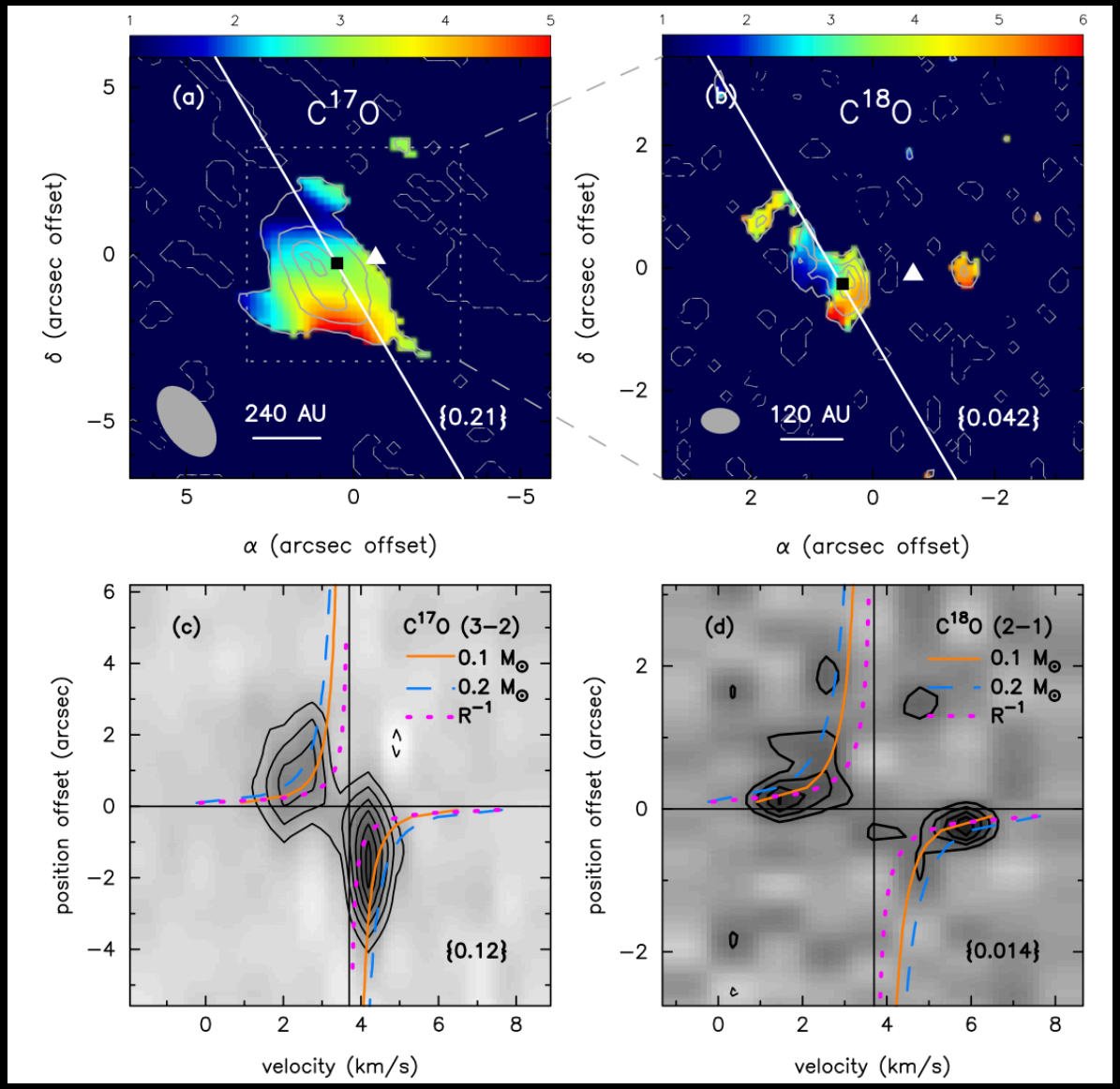
Tobin et al. 2012

2nd Keplerian Disk

VLA 1623 system with similarly massed central object

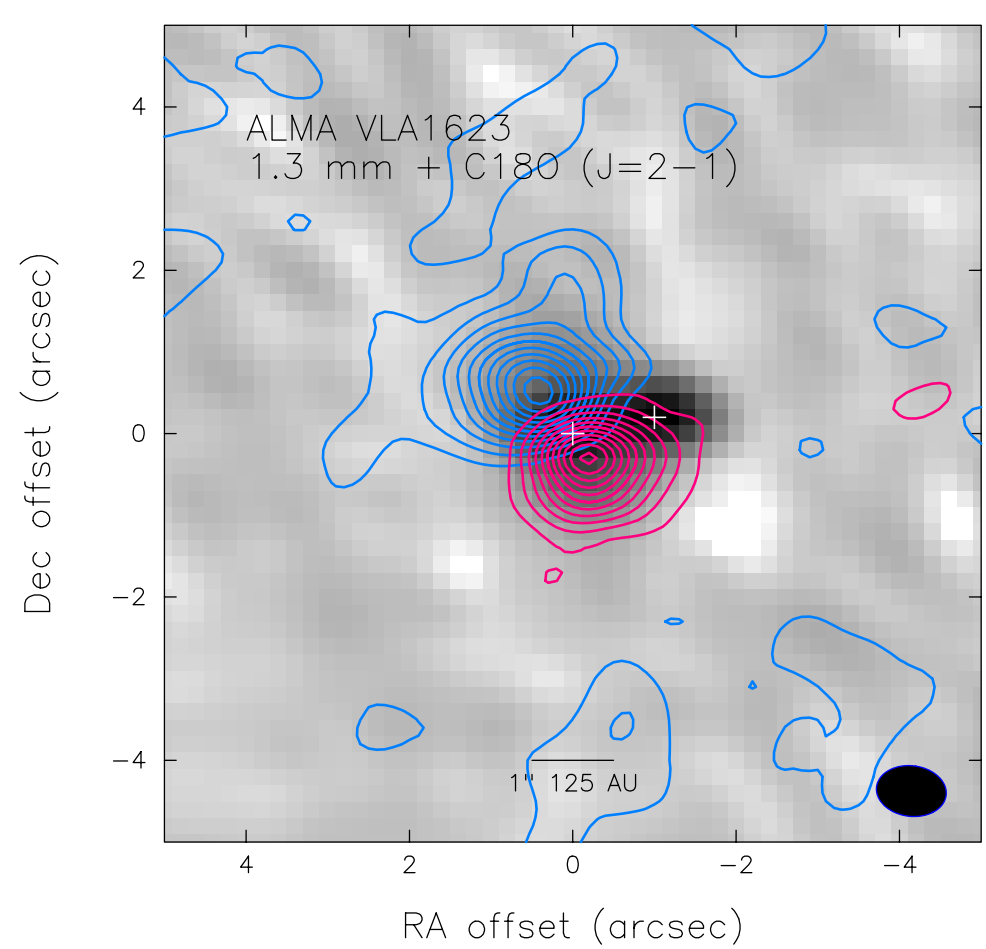
Murillo & Lai 2013

Recently released ALMA data give nice Keplarian motion– best fit of 0.18 M_{sun}



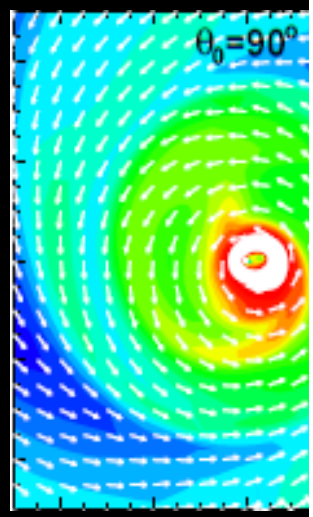
2nd Keplerian Disk

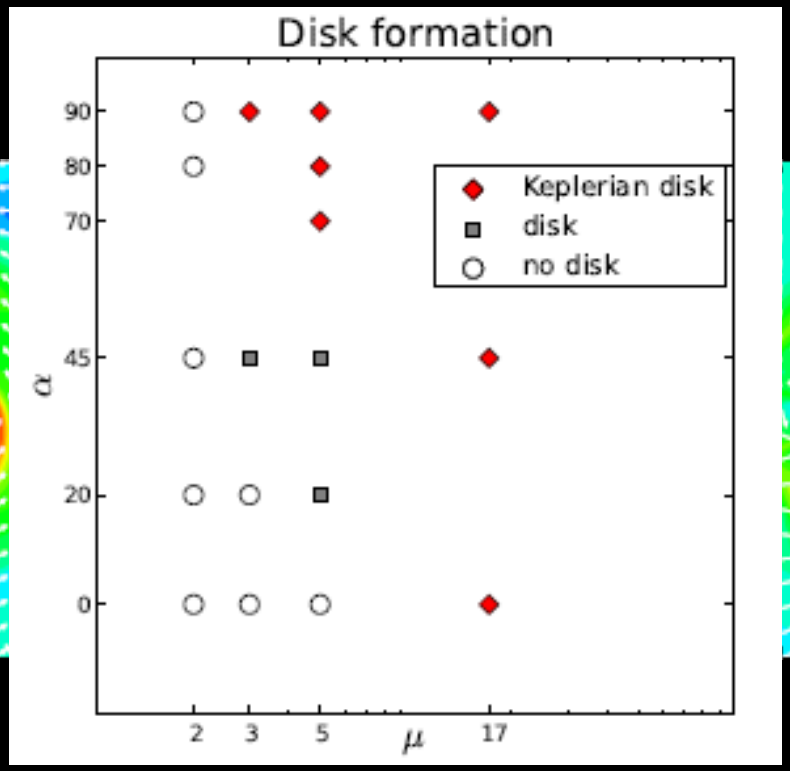
Just released ALMA data shows the velocity gradient really nicely.

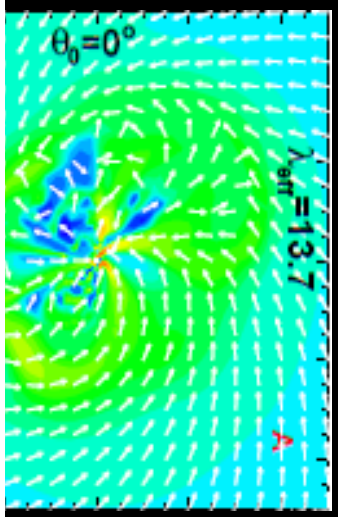


Disks? What about magnetic braking?

In the case of misaligned magnetic fields and rotation axis, we expect larger disks. (Joos et al. 2012, Zhao & Li 2013, and Krumholz et al. 2013)





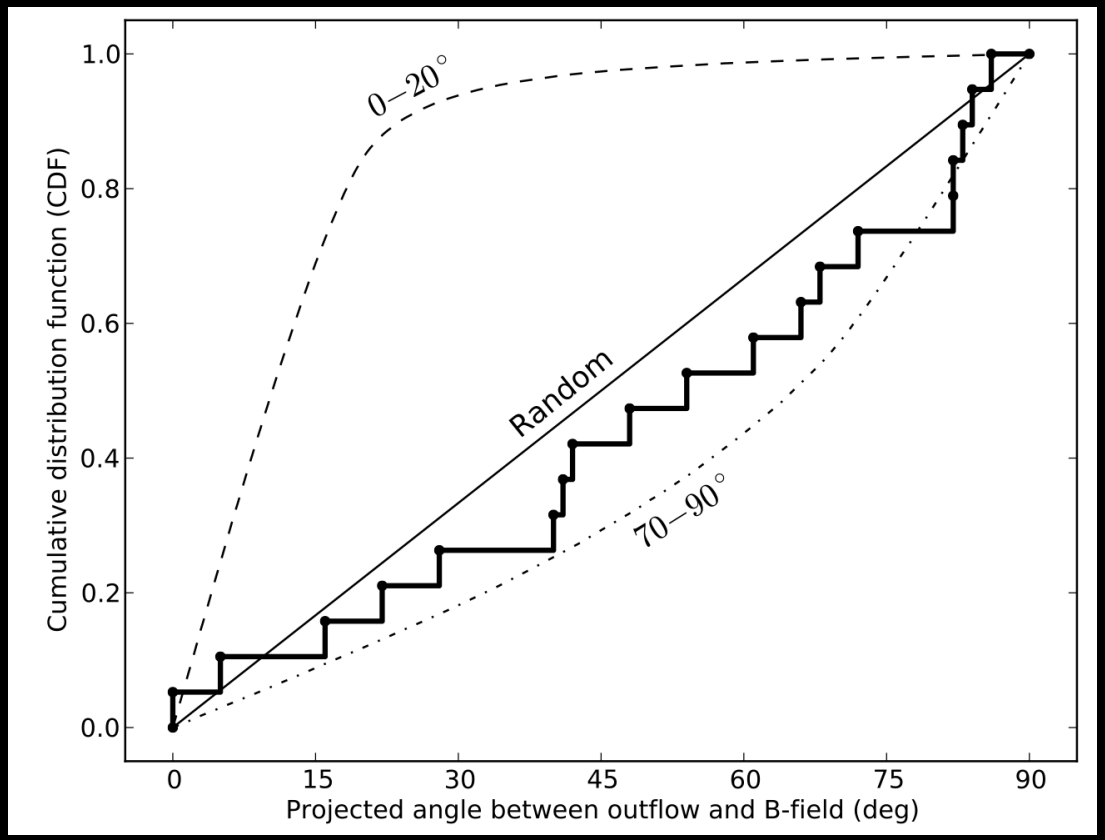


Joos et al. 2012

Li et al. 2013

Disks? What about magnetic braking?

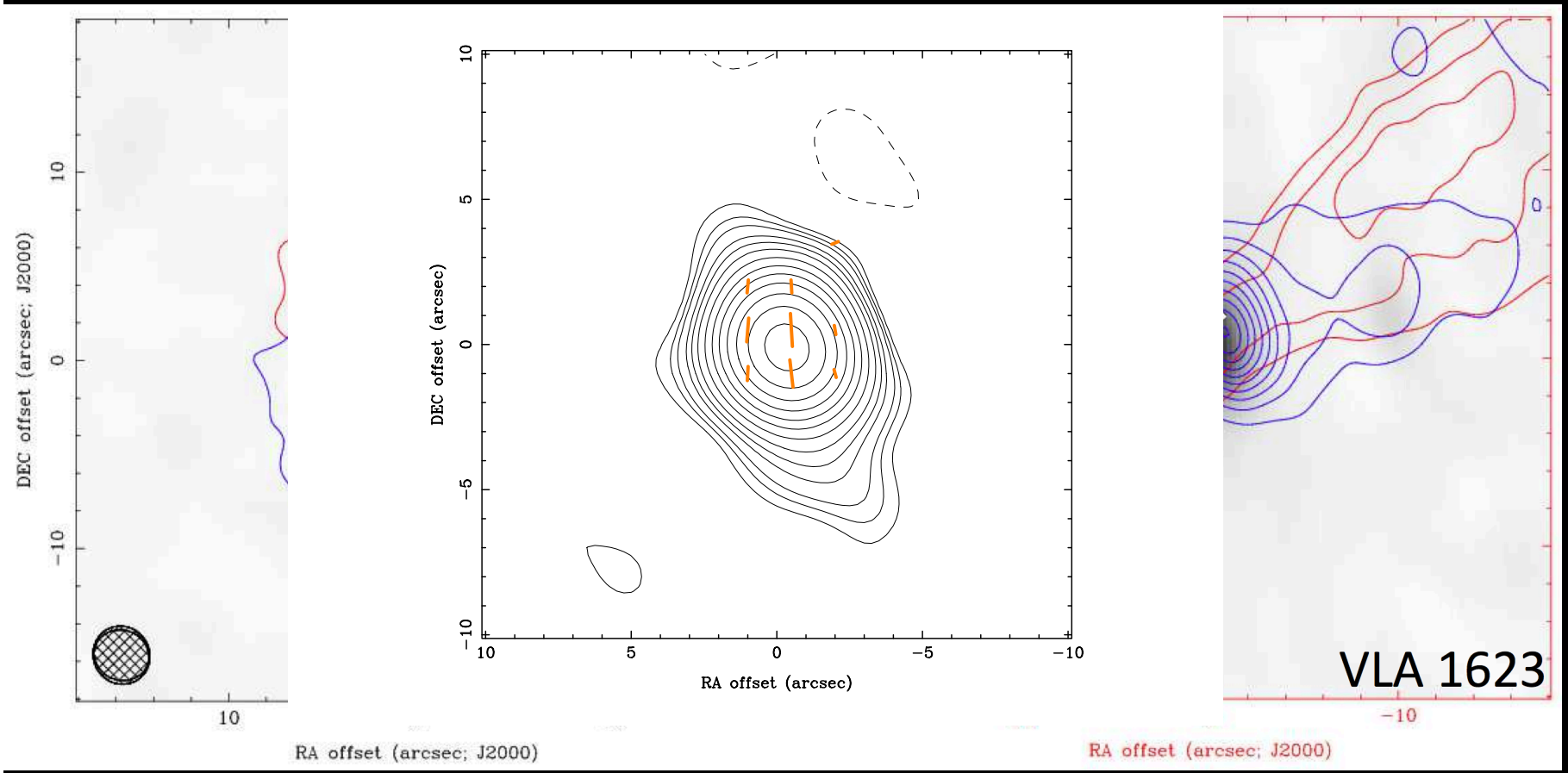
And, TADPOL shows that unaligned magnetic field and rotation axis is typical scenario.



Hull et al. 2013

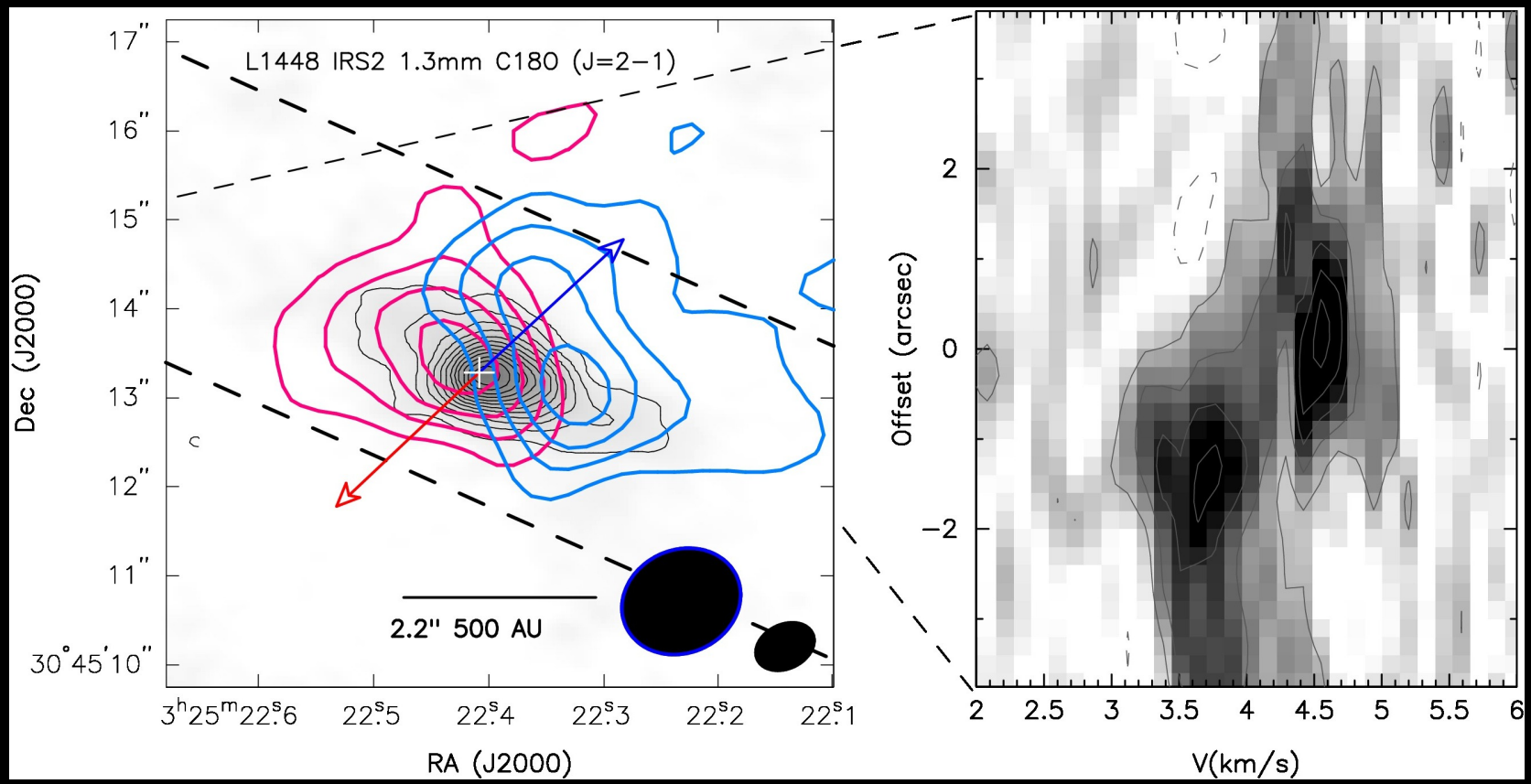
Disks? What about magnetic braking?

TADPOL results for L1527 and VLA 1623– coupled with no disk detection of L1157— interesting trend



Hull et al. 2013

More Candidates: L1448 IRS2

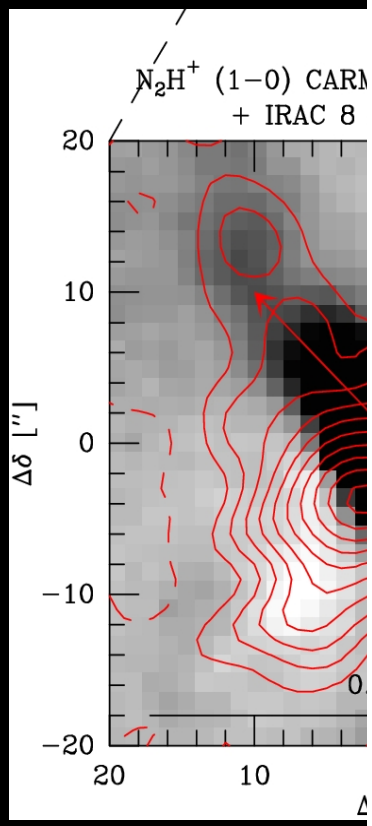


- Rotation evident in $C^{18}O$ emission, higher resolution/sensitivity need to determine if Keplerian

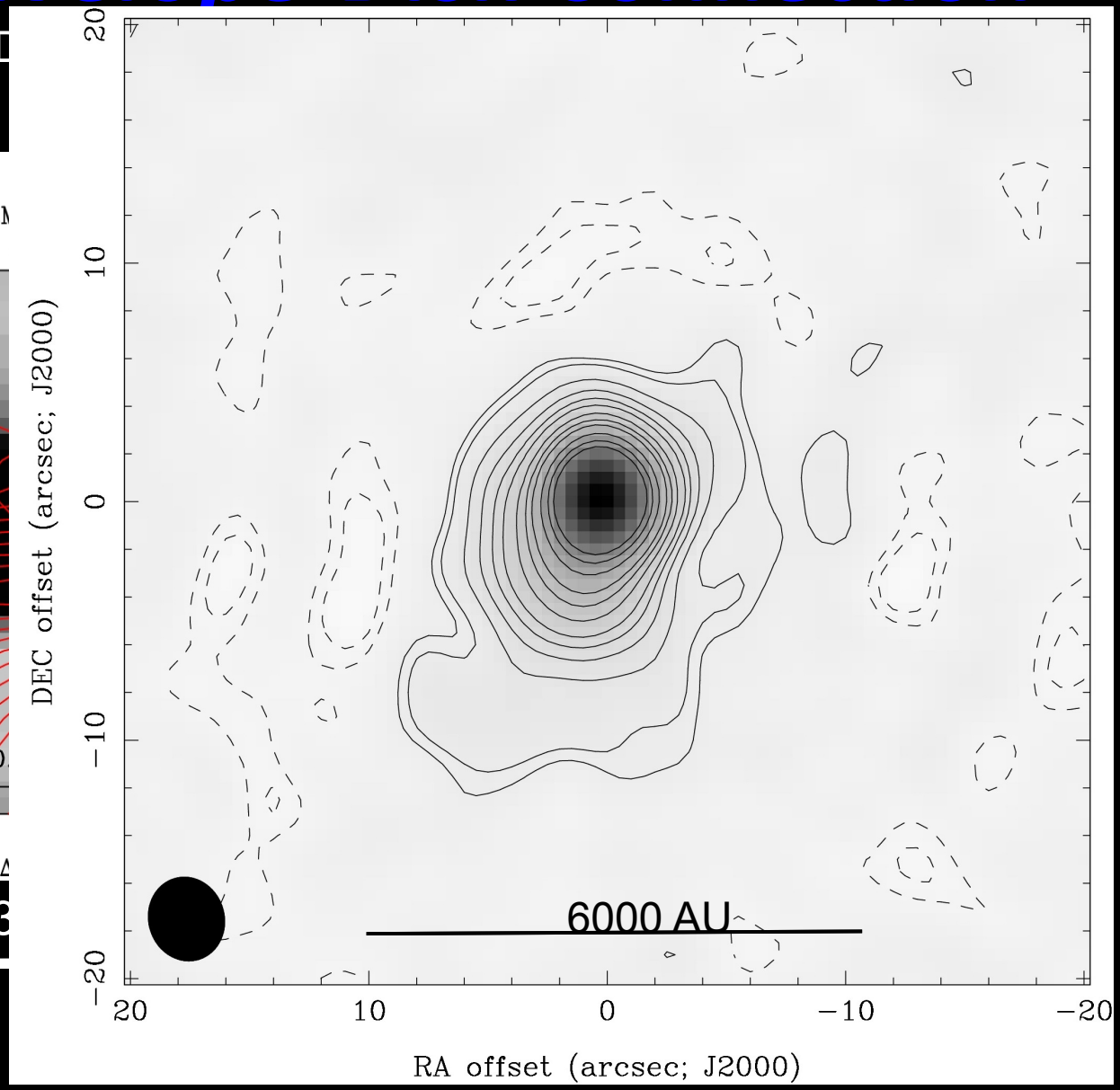
Tobin+ in prep.

L1165 Envelope-Disk Connection

SMA 1.1 mm D

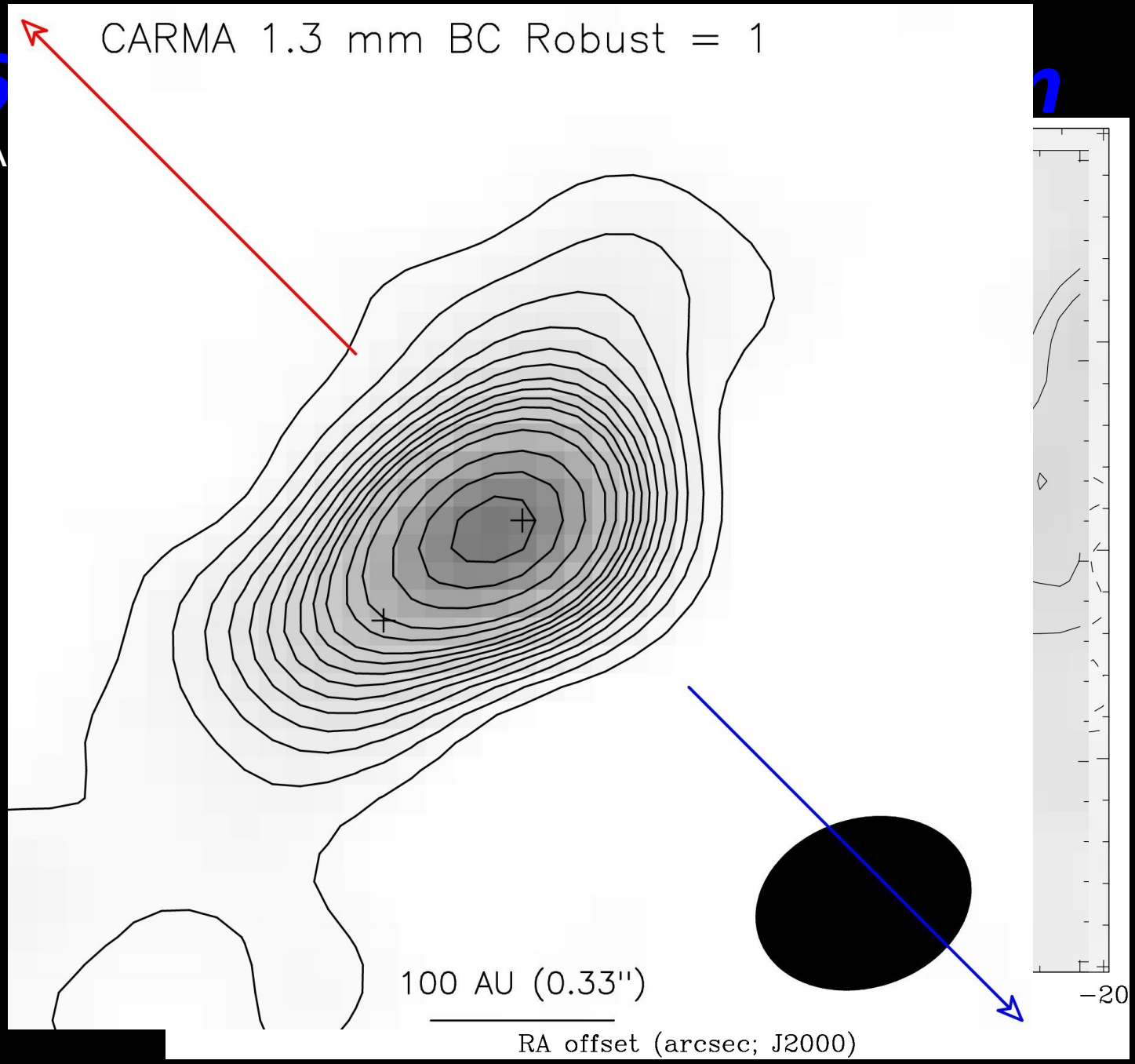


0.05 pc; 33

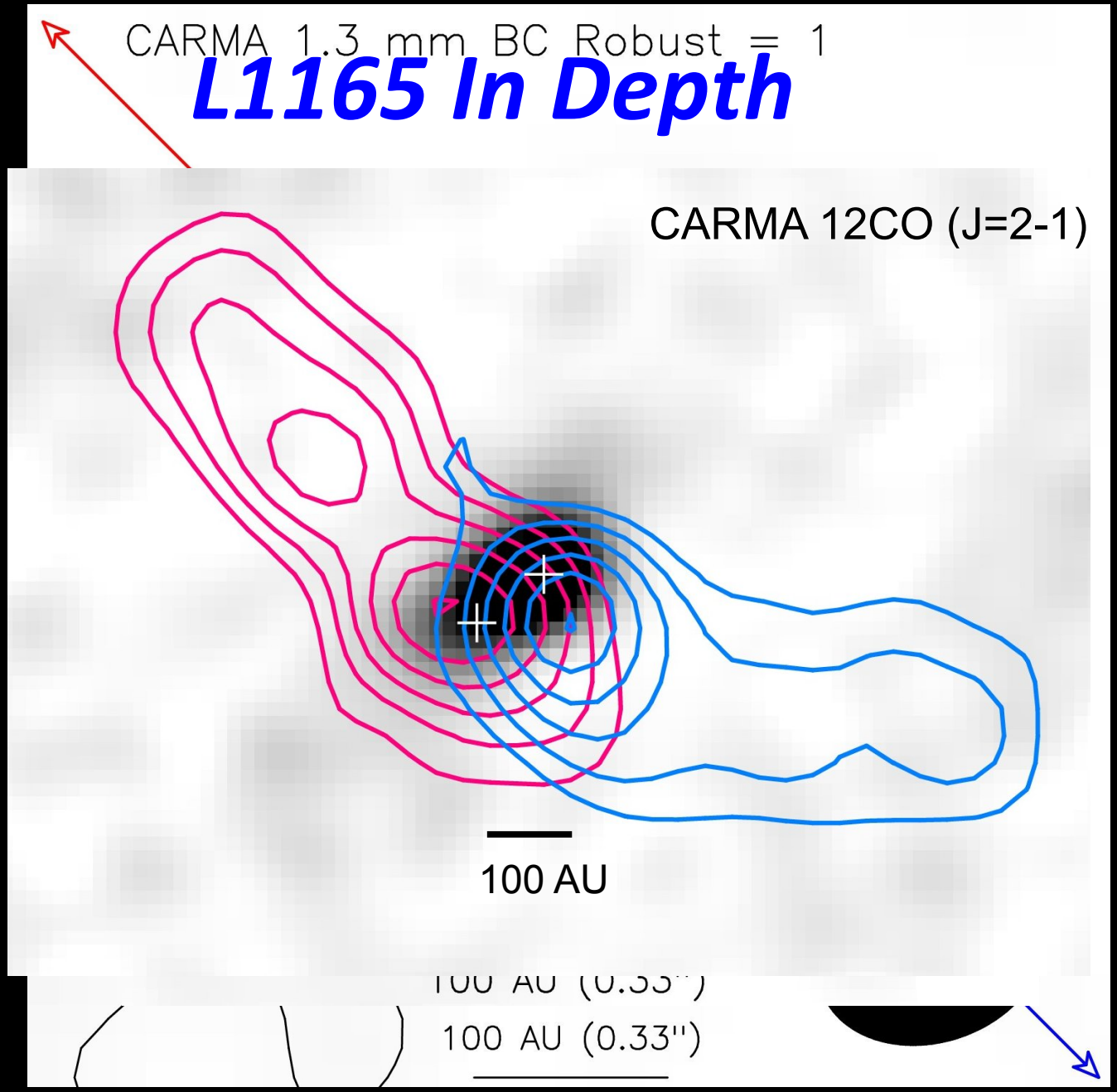


L116 n

SMA



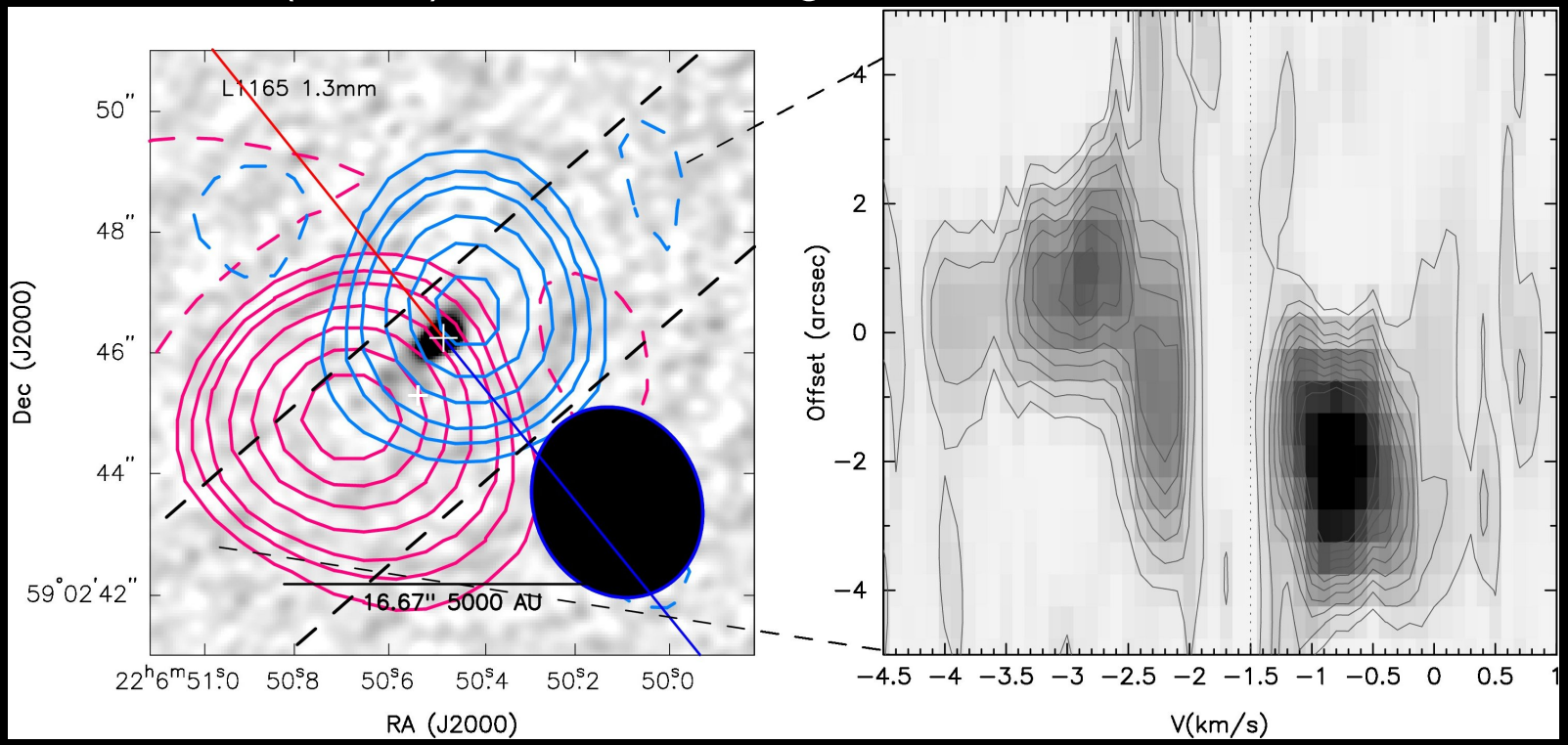
L1165 In Depth



CARMA
1.3 mm

L1165 Gas Kinematics

SMA HCO+ (J=3-2) with 1.3 mm high-resolution continuum



- ‘High’ velocity red/blue-shifted emission suggestive of rotation in the infalling material
- Disk rotation like L1527?
- Need more observations (tbd)

The Earliest Disks

- ~18 Class 0 protostars observed with resolution to detect disks (<= 80 AU) (e.g. Maury+10, Lee+09, Chiang+12, Murillo+13, ...)
  - L1527, Per-emb14, L1448 IRS2, L1165, HH211, VLA1623A; have evidence of large disks
  - L1527 confirmed rotational support
    - HH211, L1448 IRS2, VLA1623A, L1165 have rotation, Keplerian not yet confirmed
- Large rotationally supported disk fraction could be 6/18

  ~33%
- Points to a variety of disk properties, likely linked to initial conditions