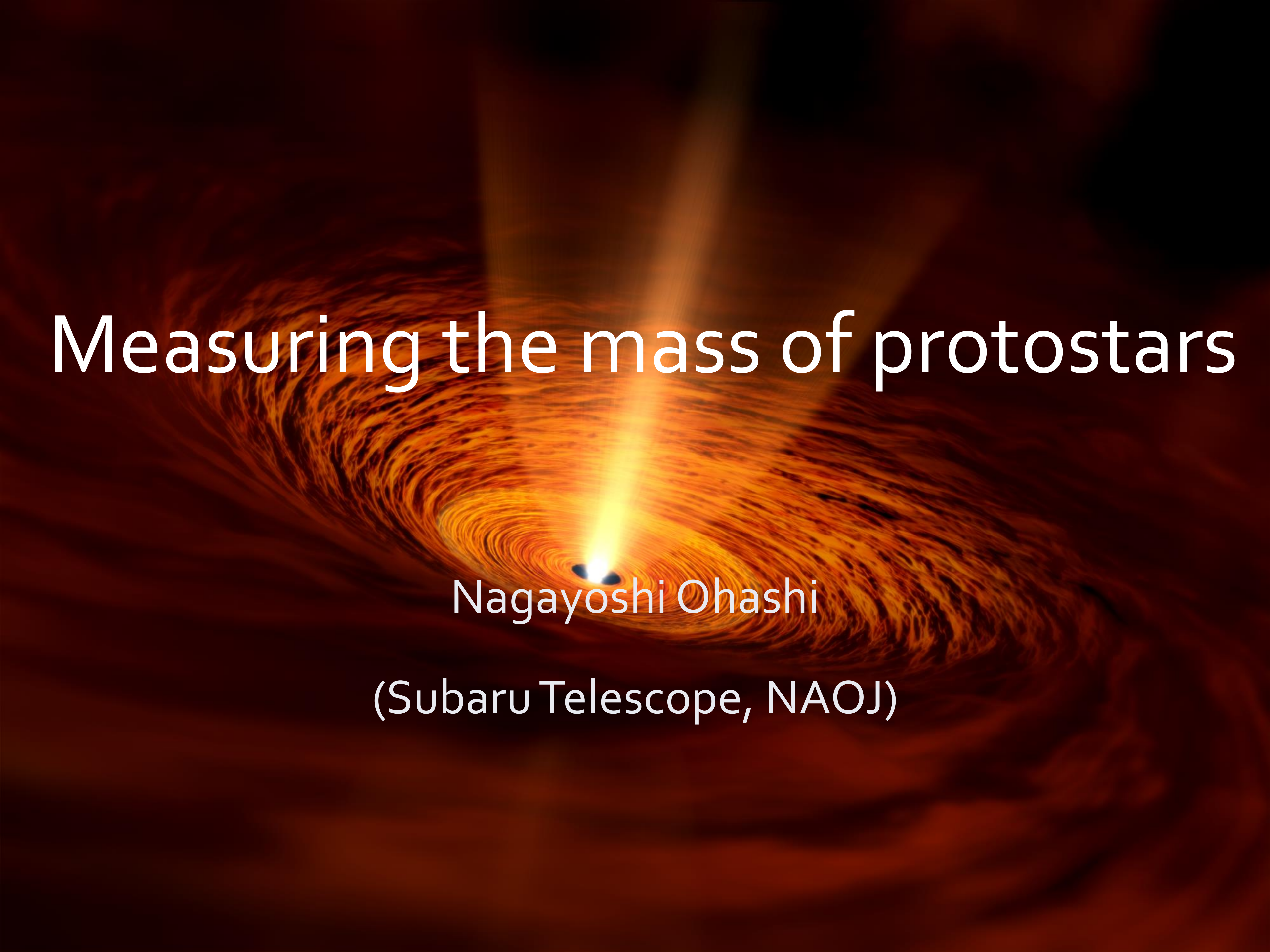


Measuring the mass of protostars

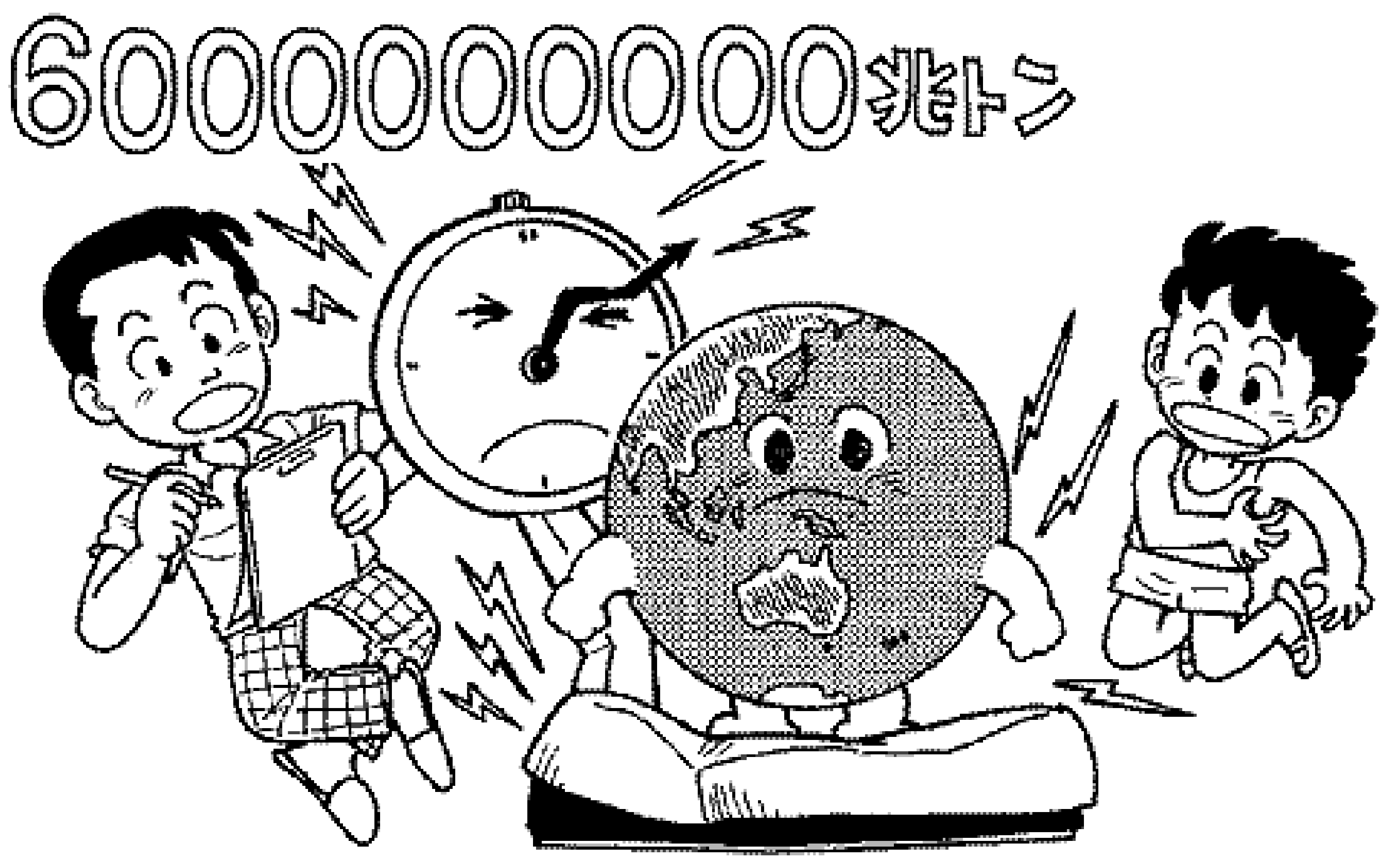
Nagayoshi Ohashi

(Subaru Telescope, NAOJ)

アブストラクト

- 星形成の研究にとって、原始星質量を測ることは極めて重要。
  - 星形成過程は、$M_*(t)$で基本的に記述できる
  - 原始星質量は、進化の指標として使用可能
- 近年、原始星周囲のケプラー円盤の観測が可能となり、ケプラー回転から原始星のダイナミカル質量の測定が可能となった。
- 原始星周囲のケプラー円盤の観測へと至った背景を概観し、原始星周囲のケプラー円盤がどのように観測されるのか、また、原始星の質量測定から明らかとなってきた、星形成過程について、解説する。

キーワード1：原始星の質量測定



学研ウエッブサイトより

キーワード2:円盤形成

本日の話

- 恒星質量の測定について
- 星の形成と円盤形成
- 原始星周囲の円盤の観測
- 原始星の力学的質量の測定とそこから見えてくる星形成の新たな側面
- まとめ

星の質量：現代天文学の基本的パラメータ

- 星の質量が現代天文学の研究、あるいは星形成の研究において、基本的なパラメータであることは、言うまでもない
  - Initial Mass Function
  - 星の質量は何よって決まるのか？
  - 星の質量により形成過程や進化過程が違う

星の質量の測定

- 直接に質量が測定できるのは、連星系の場合のみ
- 主系列星の場合、スペクトルの観測から、星の表面温度を測定し、その絶対等級を推定。質量光度関係を使って、質量を推定
- YSOsの中でも、前主系列星に関しては、HR図上にプロットすることが可能。一方、質量ごとにHR図上の理論的な進化パスがわかるので、それと比較して質量が求められる。
- しかしながら、原始星に関しては、原始星を直接観測することができないため、HRダイアグラムを用いて質量を測定することは不可能

If we can measure mass of a protstar….

$$\dot{M}_{acc} = \frac{L_{acc} R_{protostar}}{G M_{protostar}},\ t_{age} = \frac{M_{protostar}}{\dot{M}_{acc}},\ V_{freefall} = \sqrt{\frac{2 G M_{protostar}}{R}}$$

can be directly measured without any assumptions.

Estimation of protostellar masses

- Estimation from accretion luminosity

$$L_{acc} = \frac{GM_* \dot{M}_*}{R_*},$$ where L_{acc} is accretion luminosity, M_* and R_* are stellar mass and stellar radius, $\dot{M}_*$ is mass accretion rate

  - It is not trivial to measure mass accretion rate

- Estimation from mass infall velocity

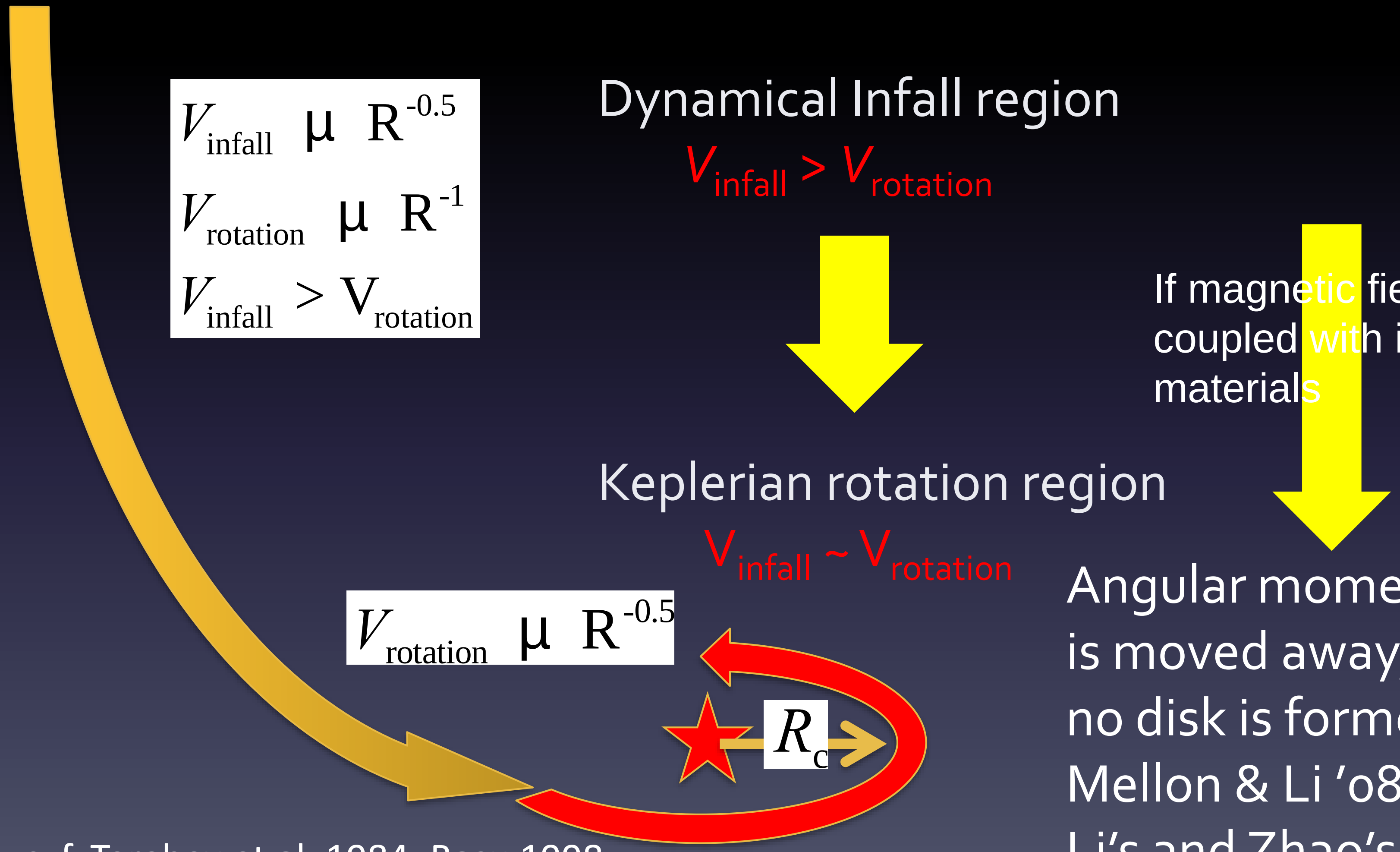
$$\frac{V_{\mathrm{infall}}^2}{2} = \frac{GM_*}{R_{\mathrm{infall}}}$$, where V_{infall} is infall velocity at R_{infall}

  - It may not necessarily correct to assume free-fall

Promising method to measure protostellar masses

- To measure dynamical masses of protstars based on Kepler rotation of their circumstellar disks would be the most promising method.

Disks are expected to be formed around protostar?



$V_{infall}\ \mu\ R^{-0.5}$

$V_{rotation}\ \mu\ R^{-1}$

$V_{infall} > V_{rotation}$

Dynamical Infall region

$V_{infall} > V_{rotation}$

Keplerian rotation region

$V_{infall} \sim V_{rotation}$

$V_{rotation}\ \mu\ R^{-0.5}$

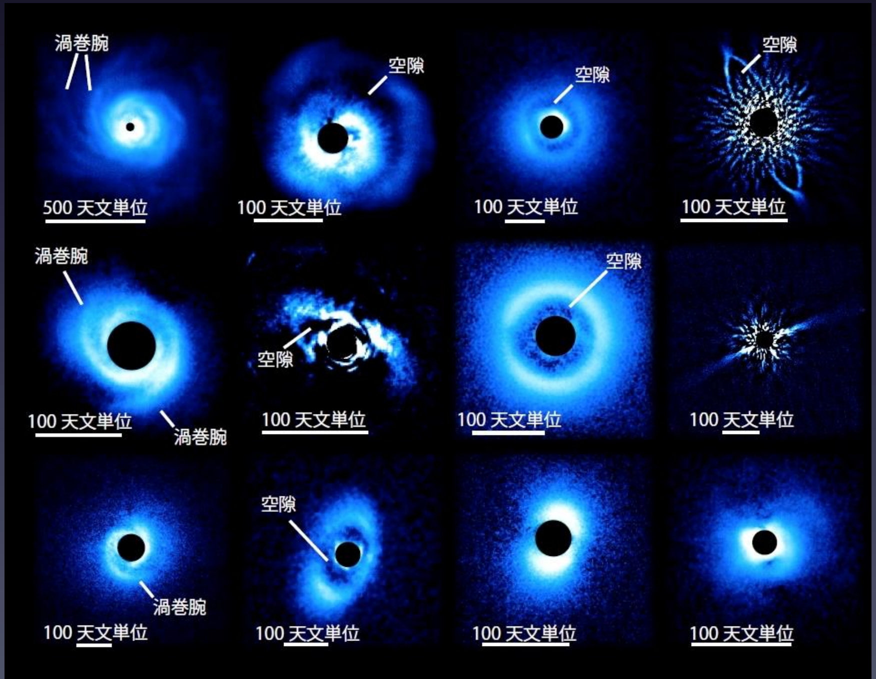
If magnetic field is coupled with infalling materials

Angular momentum is moved away, and no disk is formed (e.g., Mellon & Li ’08; see also Li’s and Zhao’s talks)

c. f. Terebey et al. 1984; Basu 1998

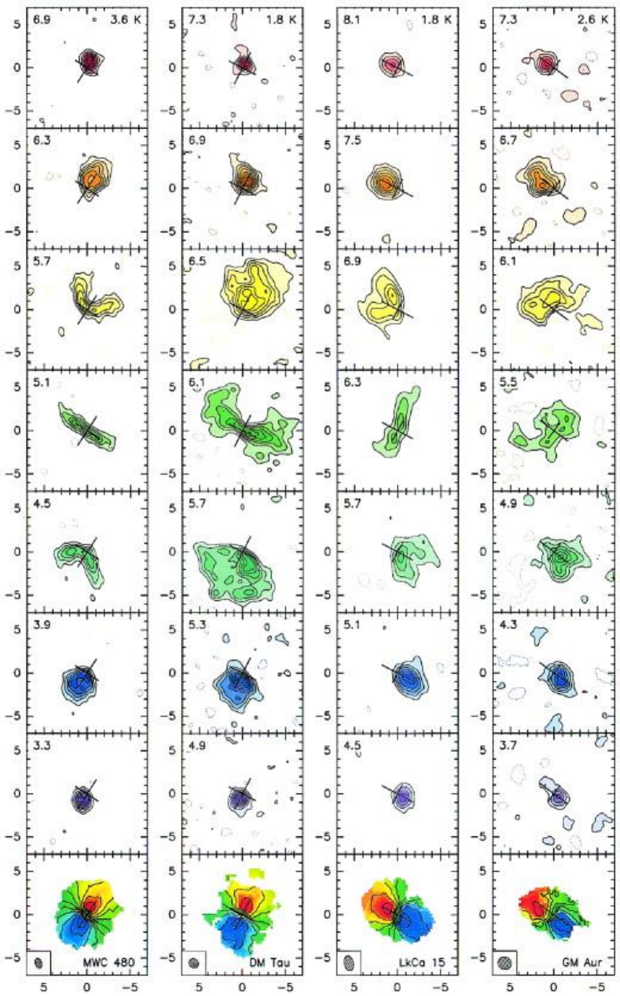
Protoplanetary disks around PMSs

- In the last two decades many studies have been done
- They usually show Keplerian motions
- Recent observations show a lot of variety of disks around PMSs

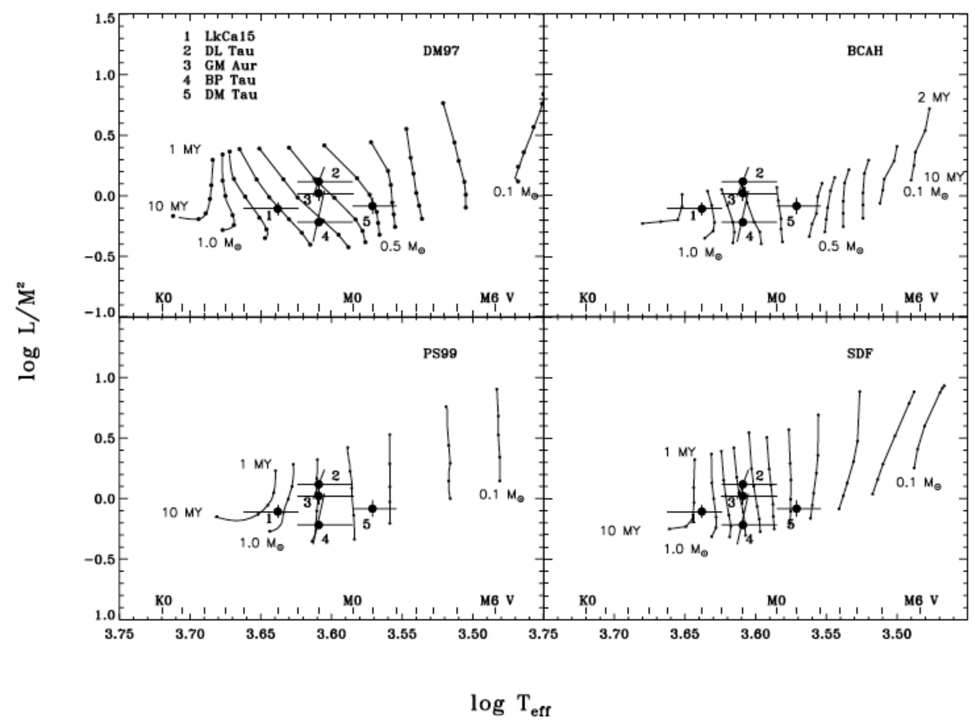


“SEEDS” project carried out by the Subaru Telescope and HiCIAO (PI: M. Tamura)

Measurements of dynamical masses of TTSs



Simon, Dutrey, Guilloteau 2000



- Measure dynamical masses of TTSs and compare with theoretical tracks on HR diagram, calibrating PMSs evolution.

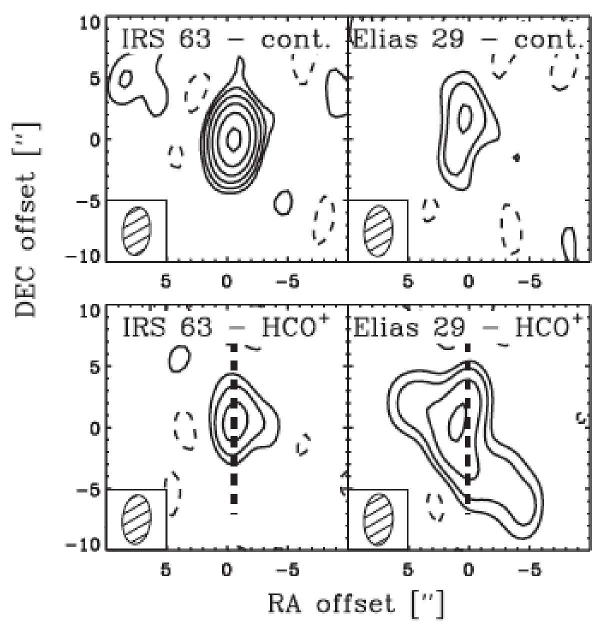
How about disks around protostars?

- Disks are also naturally expected around protostars (e.g., Terebey, Shu, Cassen 84).
- As compared with PPDs, however, less observations of disks around protostars have been done.
  - It is difficult to distinguish extended envelopes and disks embedded in the envelopes.
  - Envelopes often show disklike structures and rotation.

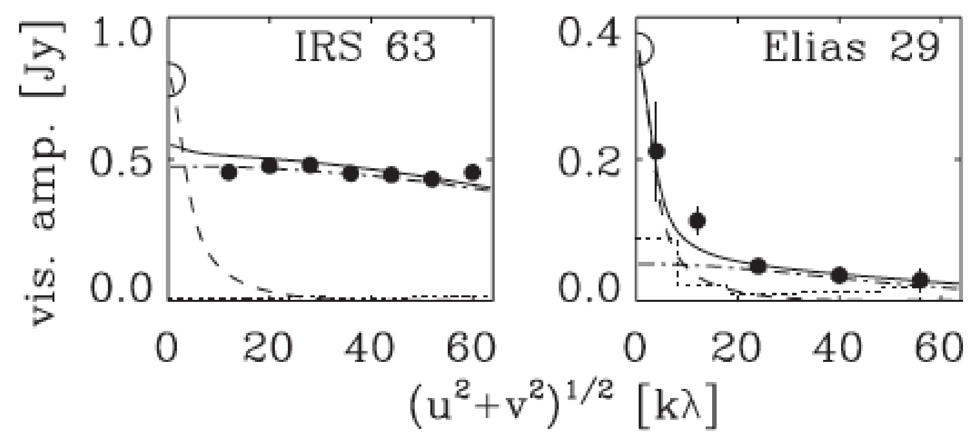
Early efforts to detect disks around protostars

- Continuum observations
  - Compact continuum sources (with disklike structures) associated with protostars were identified as disks.
  - No kinematical information, could be innermost envelope
- Line observations
  - Disklike structures around protostars with spin-up rotation were identifies as Keplerian disks
  - Infalling envelopes, which often show disklike structures, can also show spin-up rotation ($V_r \propto 1/r$)

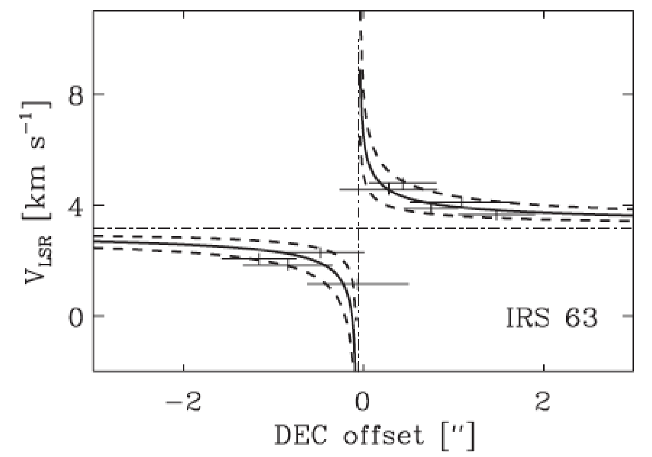
Lommen et al 2008



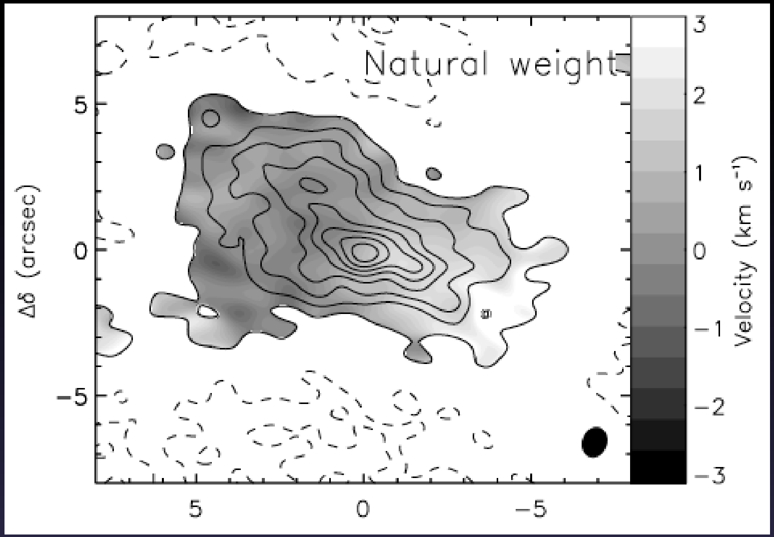
Compact continuum emission



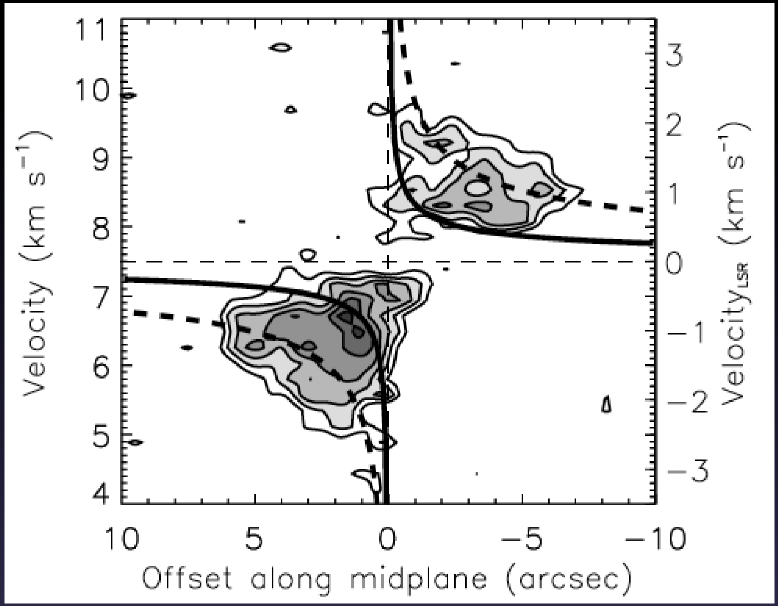
Spin-up rotation is interpreted as Keplerian rotation



Brinch et al. 2008

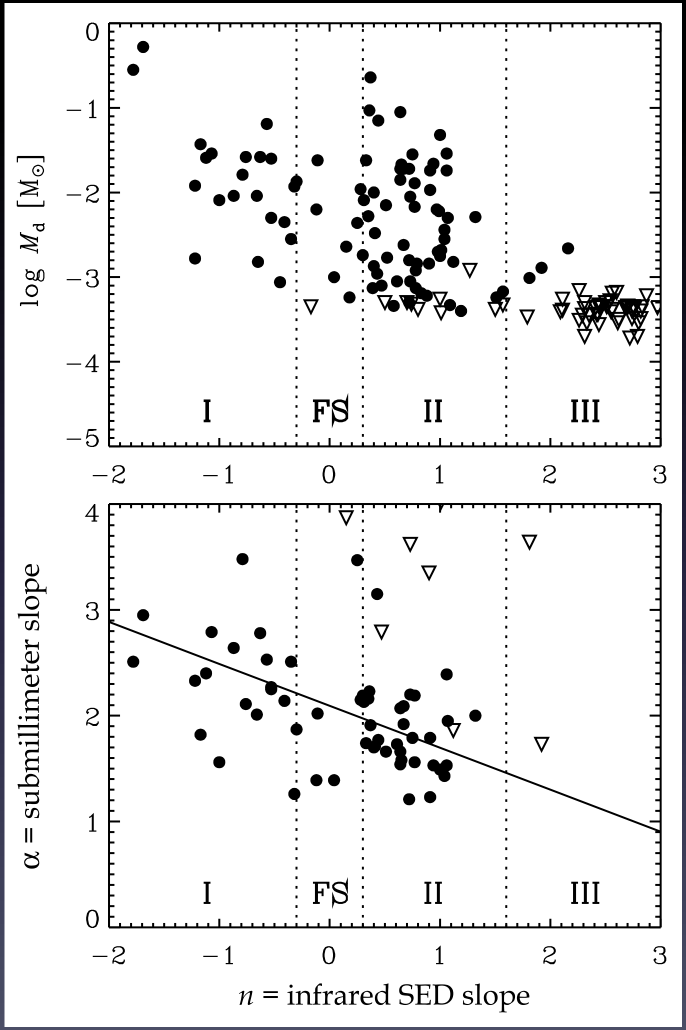


Brinch et al. 2008



Compared with only Kepler rotation curves

Disk evolution from protostars to TTSs?



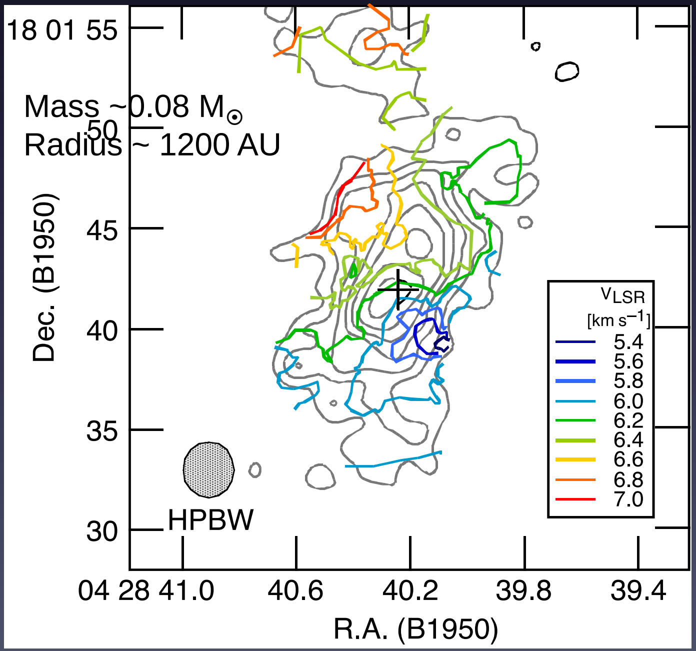
Andrew et al. 2005

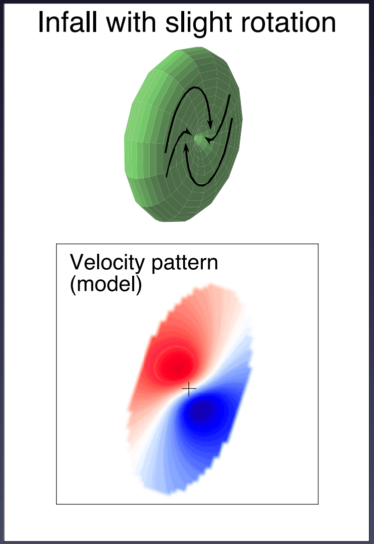
- Disk masses decrease as protostars evolve into T Tauri stars?
- We should note that continuum emission from protostars arises from envelopes as well as disks, suggesting that disk masses are overestimated from single dish observations.

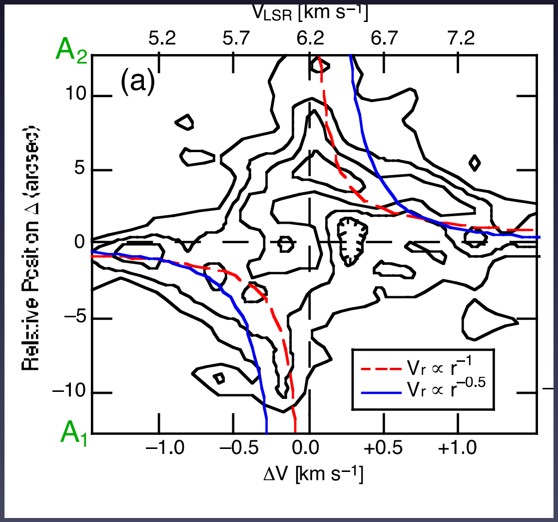
Envelopes around protostars

- Disks are not easily identified around protostars because they are surrounded by envelopes, which are often flattened and rotating.

L1551 IRS5 $C^{18}O$ 1-0 with NMA







$C^{18}O$ (1-0) with NMA
(Momose, Ohashi et al. 1998)

Envelopes around protostars

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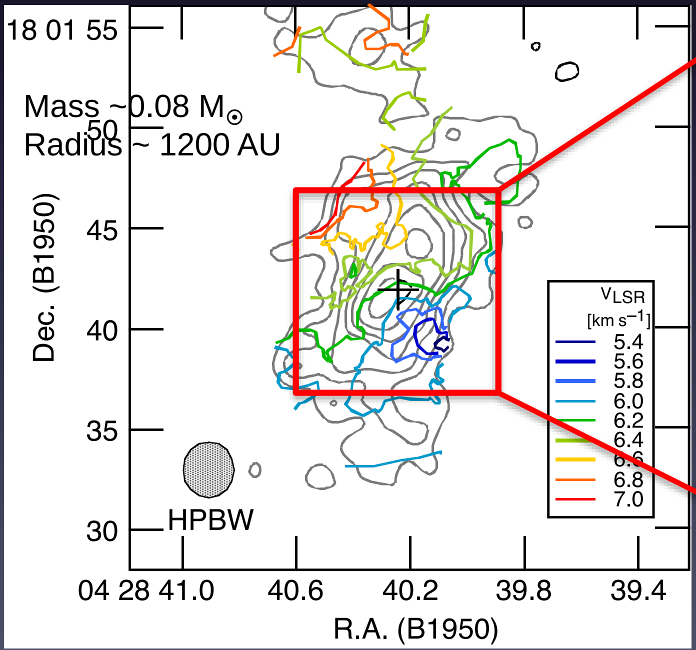
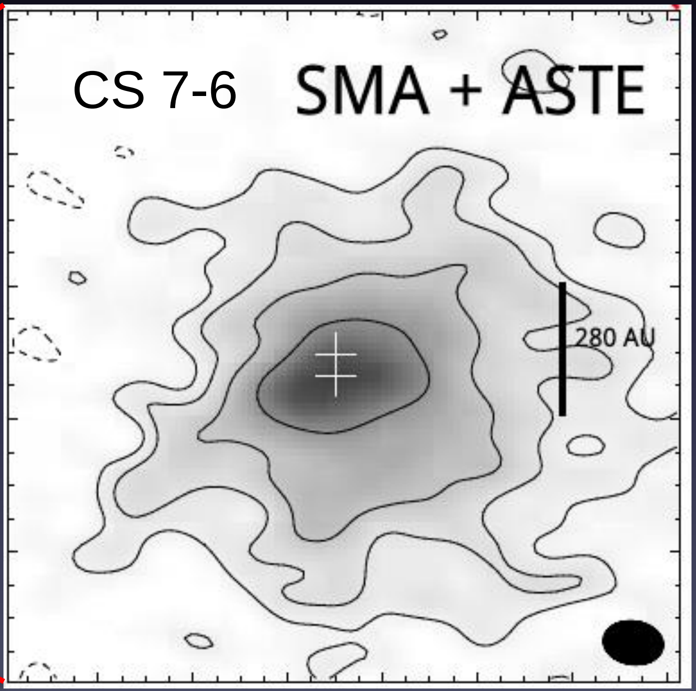

L1551 IRS5 $C^{18}O$ 1-0 with NMA



Chou et al. 2014

Envelopes around protostars

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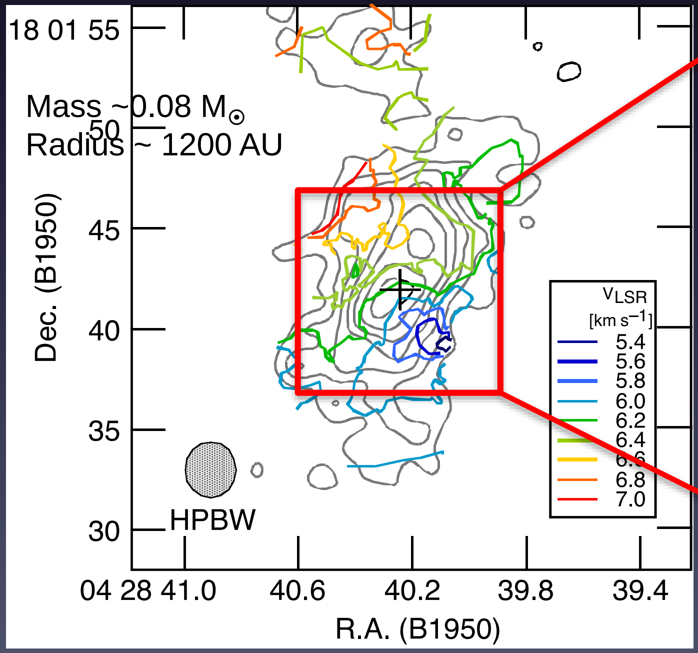
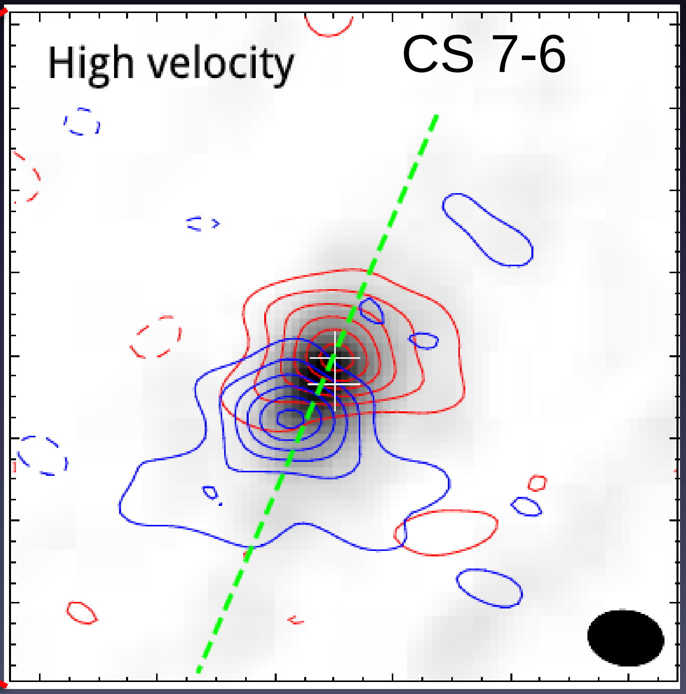
L1551 IRS5 C^{18}O 1-0 with NMA





Chou et al. 2014

Envelopes around protostars

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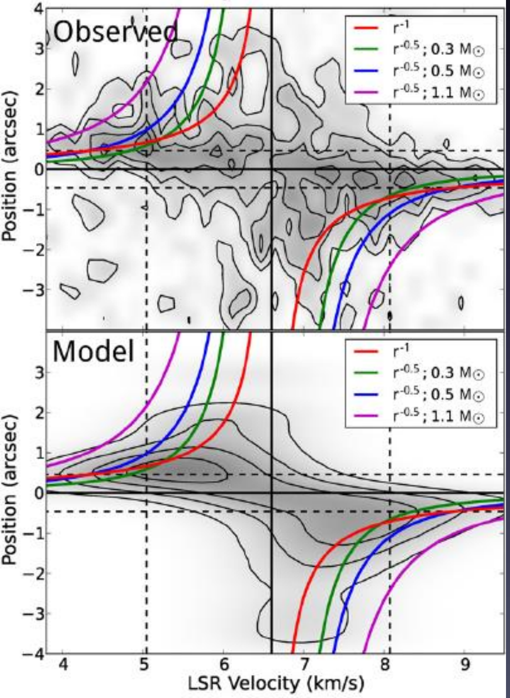
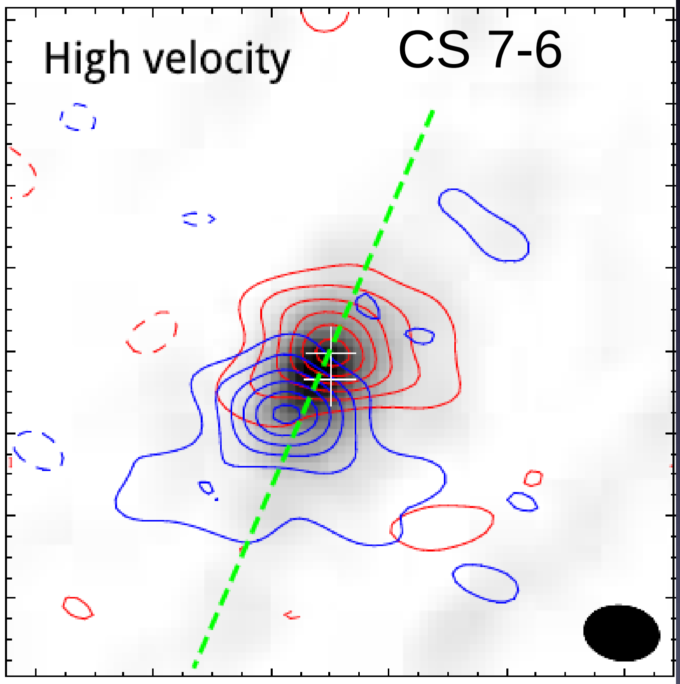




Chou+ 2014 (see also Lommen+ 2008)

How about disks around protostars?

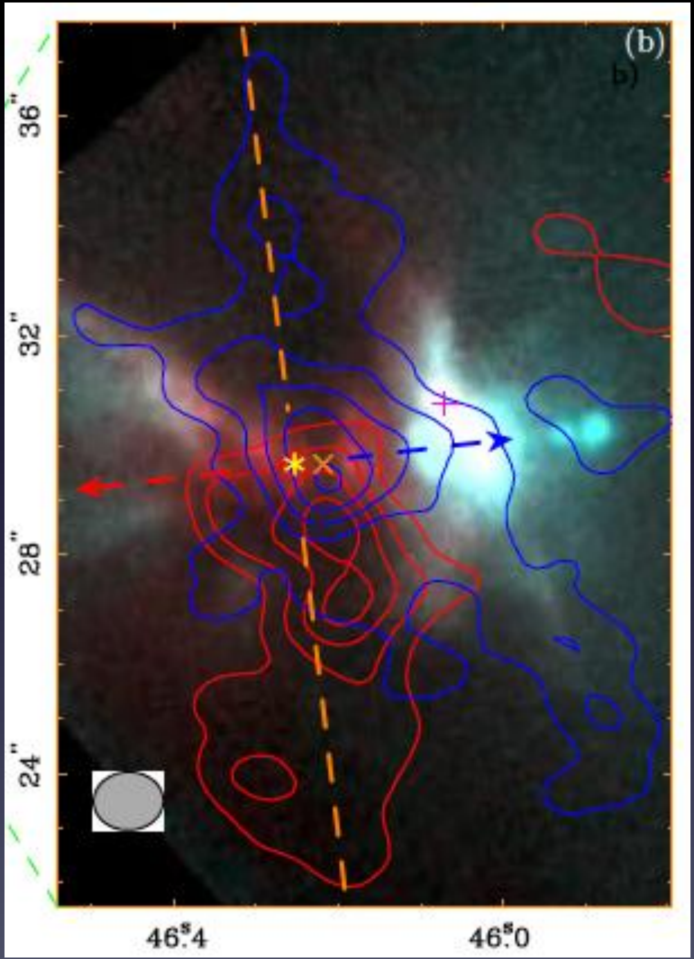
- Disks are not easily identified around protostars because they are surrounded by envelopes.
- Observations of disks around protostars have been done in continuum emission in the early days
  - Compact structures were identified
  - It was difficult to unambiguously distinguish disks and envelopes

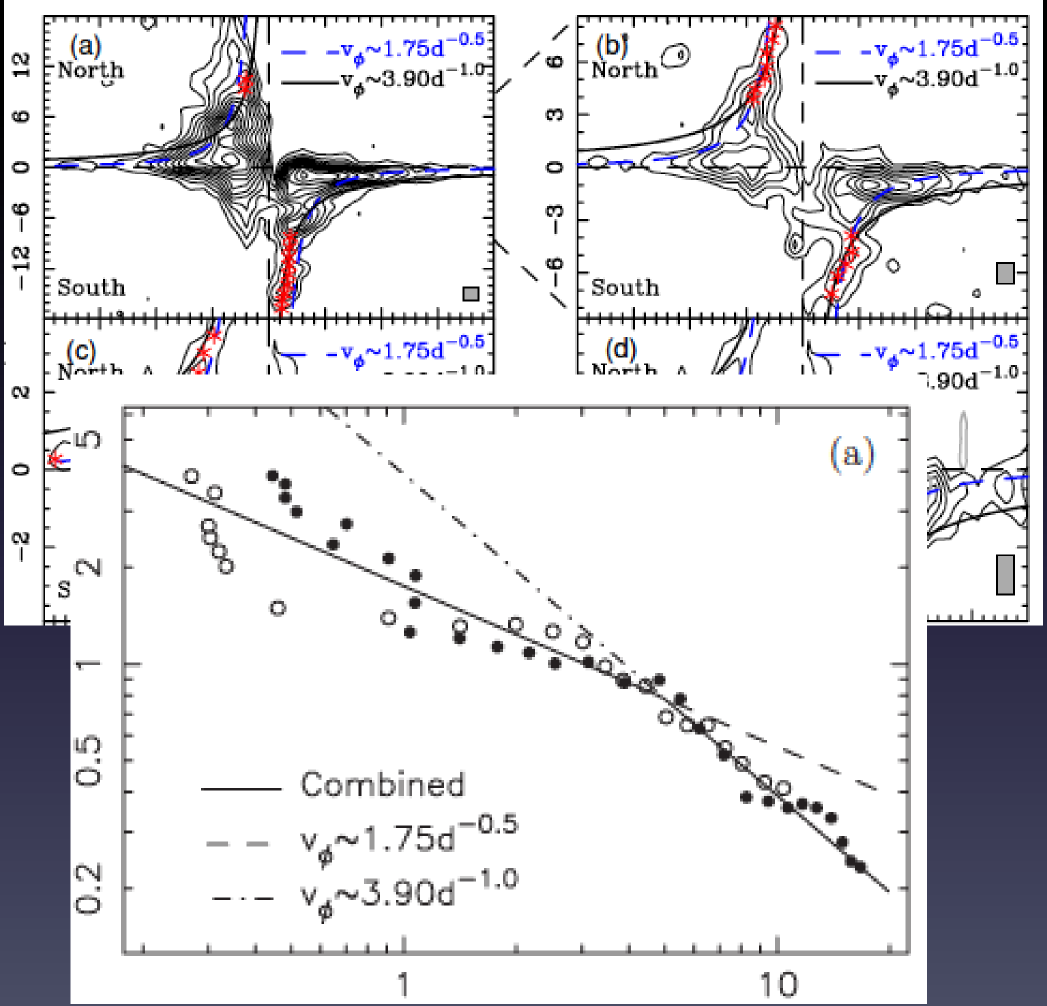
How to unambiguously identify disks around protostars?

- It is the best way to kinematically distinguish disks from envelopes
  - Envelopes rotates as r^{-1}
  - (Keplerian) disks rotate as $r^{-0.5}$
  - Estimate powers of rotation curves

Searching for Keplerian disks around protostars I

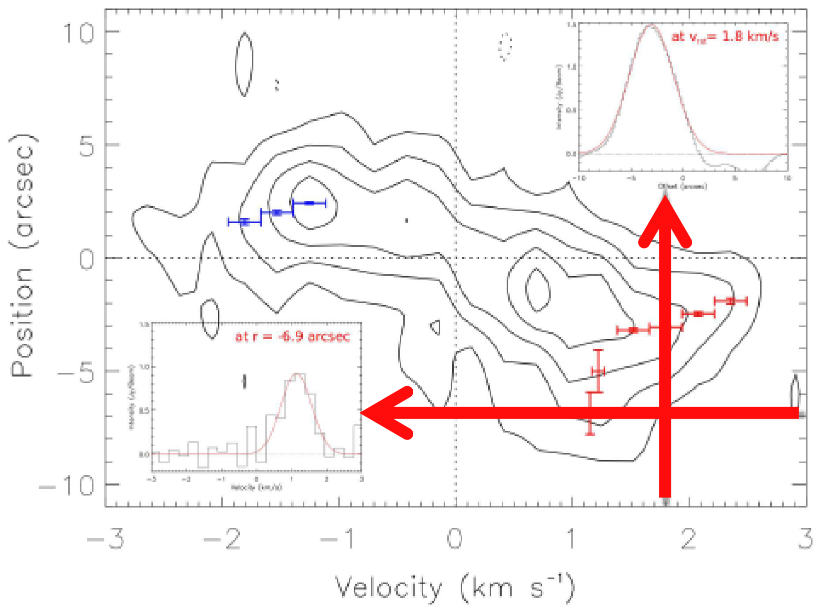
HH111 C^{18}O 2-1 with SMA

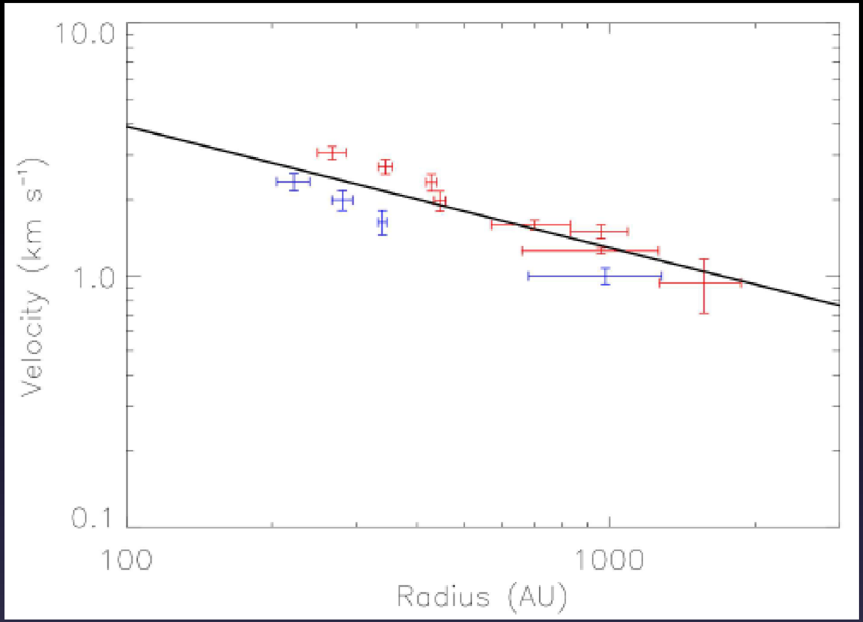




Lee 2010

Searching for Keplerian disks around protostars II

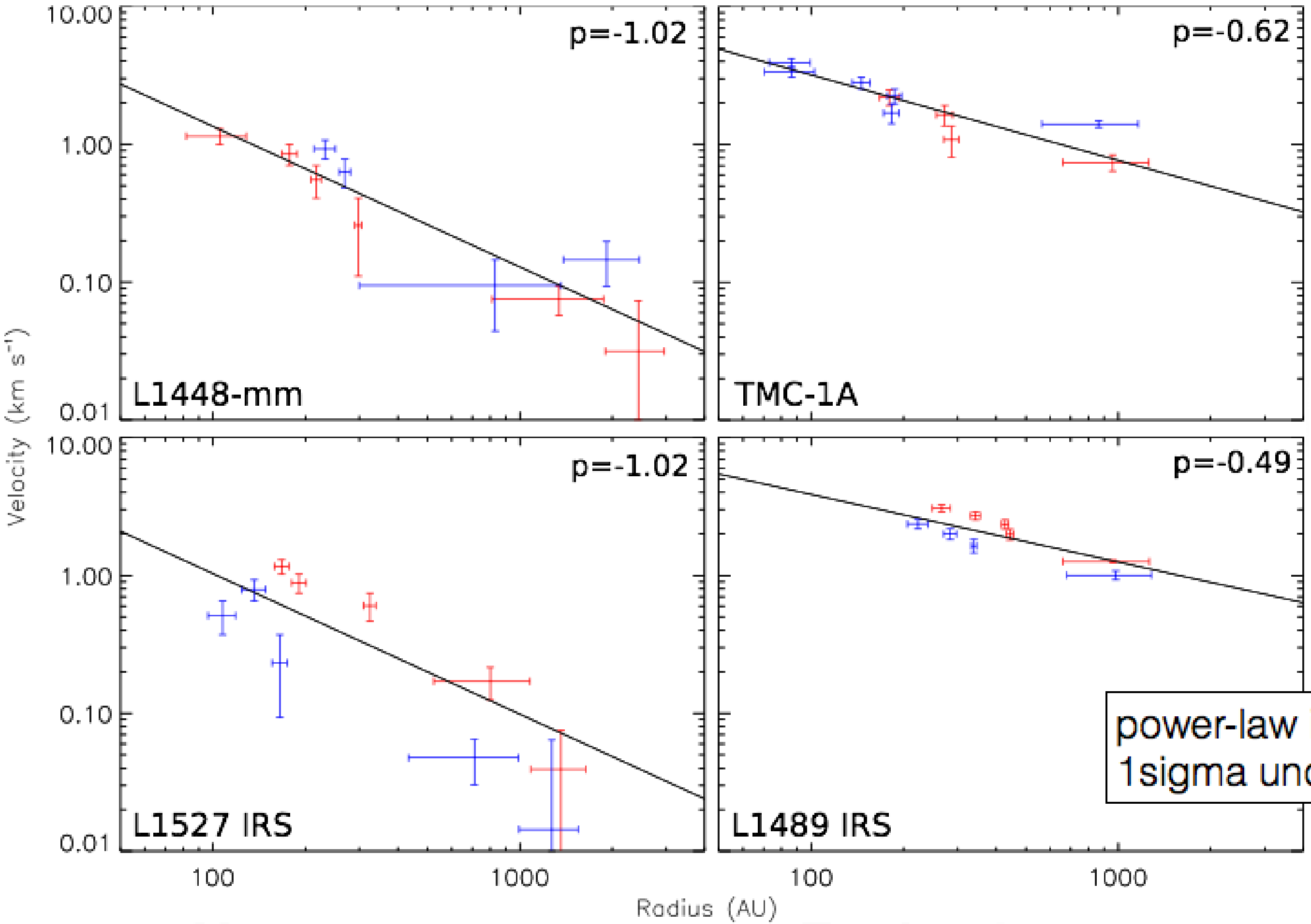




rotation curve with a logarithmic scale

Representative data points on a PV diagram is measured based on Gaussian fittings along either the velocity axis or the position axis of the PV diagram (Yen+ '13)

Searching for Keplerian disks around protostars I



power-law index:
1sigma uncertainty ~ 10%

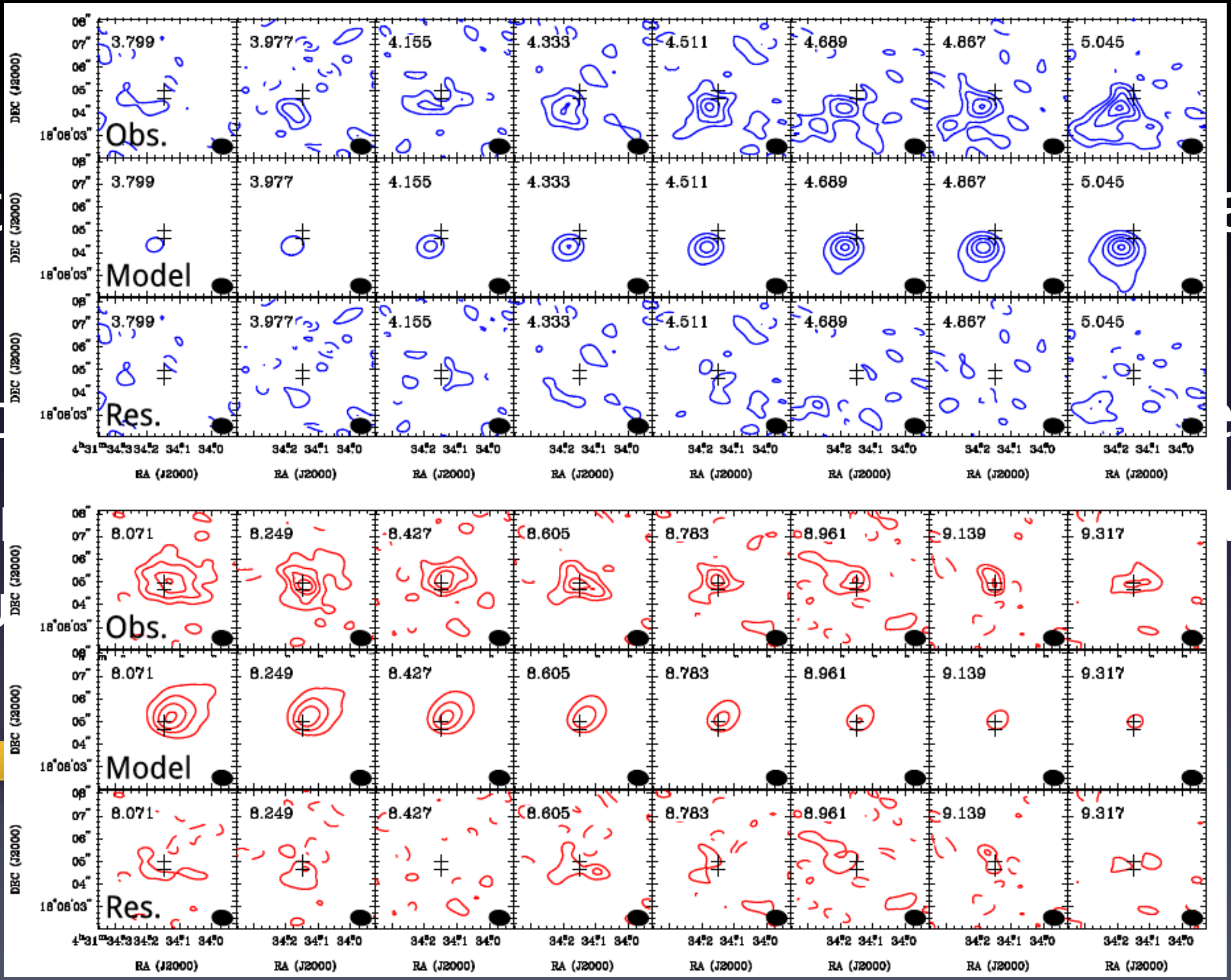
Younger sources:
slower rotation
steeper profile

Evolved sources:
faster rotation
shallower profile

Yen et al. 2013

Searching for Keplerian disks around protostars III

- Fit c an disk
  - Lo elopes
  - Or by su

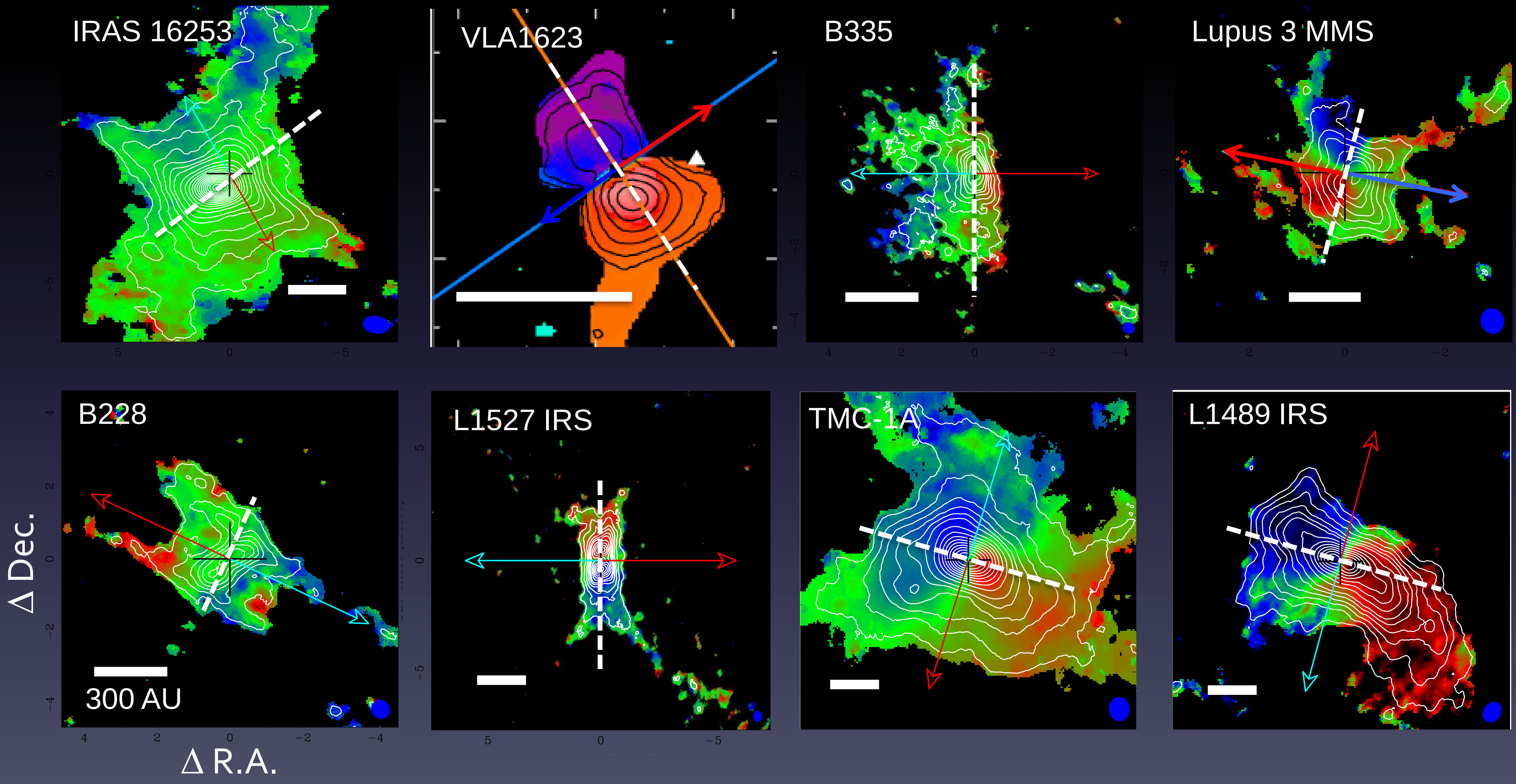


Chou+2014

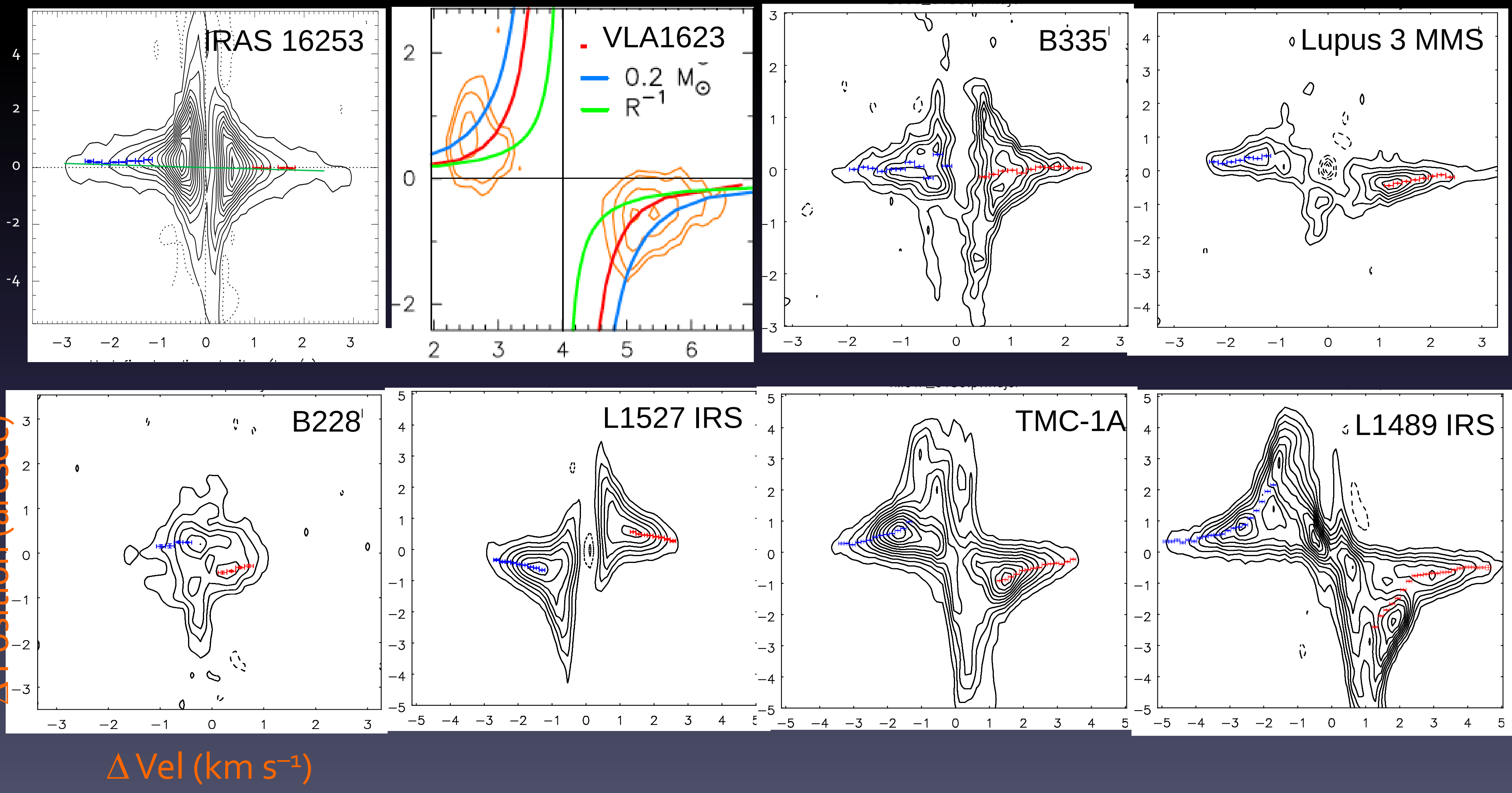
ALMA $C^{18}O$ 2-1 observations of disks around protostars

Object	Region	Class	T_{bol} (K)	L_{bol} (Lo)	D (pc)	ALMA Cycle	θ	reference
IRAS 16253	Oph	0	35	0.24	125	2	1.0”	Yen+ 17
VLA1623	Oph	0	35	2.6	120	0	0.7”	Murillo+ 13
B335	Isolated	0	39	0.68	150	2	0.3”	Yen+ 15
Lupus 3 MMS	Lupus	0	40	0.41	200	2	0.5”	Yen+ 17
B228 (IRAS 15398)	Lupus	0/I	61	1.2	150	2	0.5”	Yen+ 17
L1527 IRS	Taurus	0/I	67	1.7	140	1	0.5”	Aso+ 17†
TMC-1A	Taurus	I	164	2.5	140	0	0.9”	Aso+ 15
L1489 IRS	Taurus	I	226	3.5	140	0	0.9”	Yen+ 14

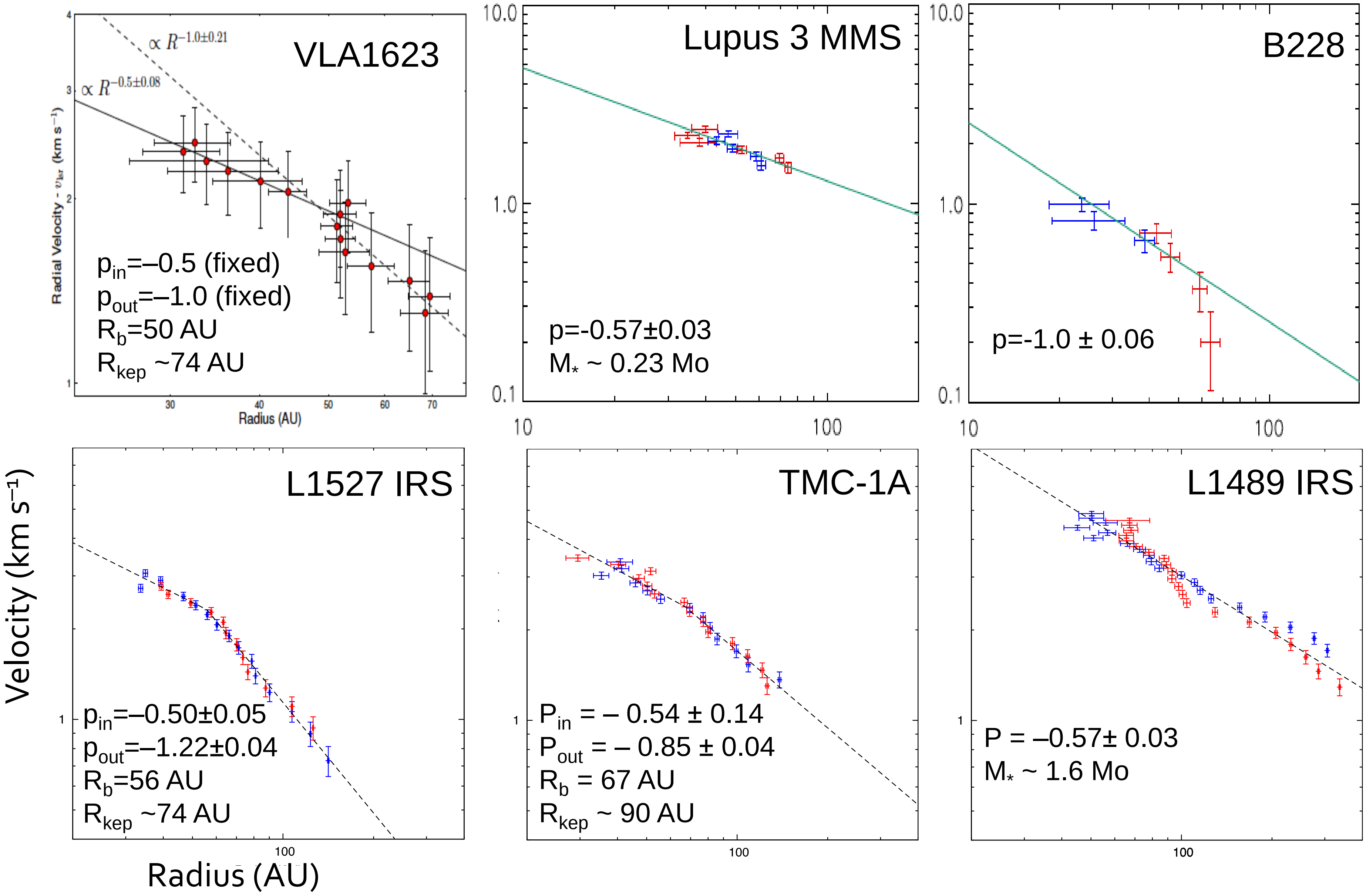
ALMA C^{18}O 2-1 observations of disks around protostars



ALMA $C^{18}O$ 2-1 observations of disks around protostars



Rotation Curves



VLA1623

p_{in}=–0.5 (fixed)
p_{out}=–1.0 (fixed)
R_b=50 AU
R_{kep} ~74 AU

Lupus 3 MMS

p=-0.57±0.03
M_* ~ 0.23 Mo

B228

p=-1.0 ± 0.06

L1527 IRS

p_{in}=–0.50±0.05
p_{out}=–1.22±0.04
R_b=56 AU
R_{kep} ~74 AU

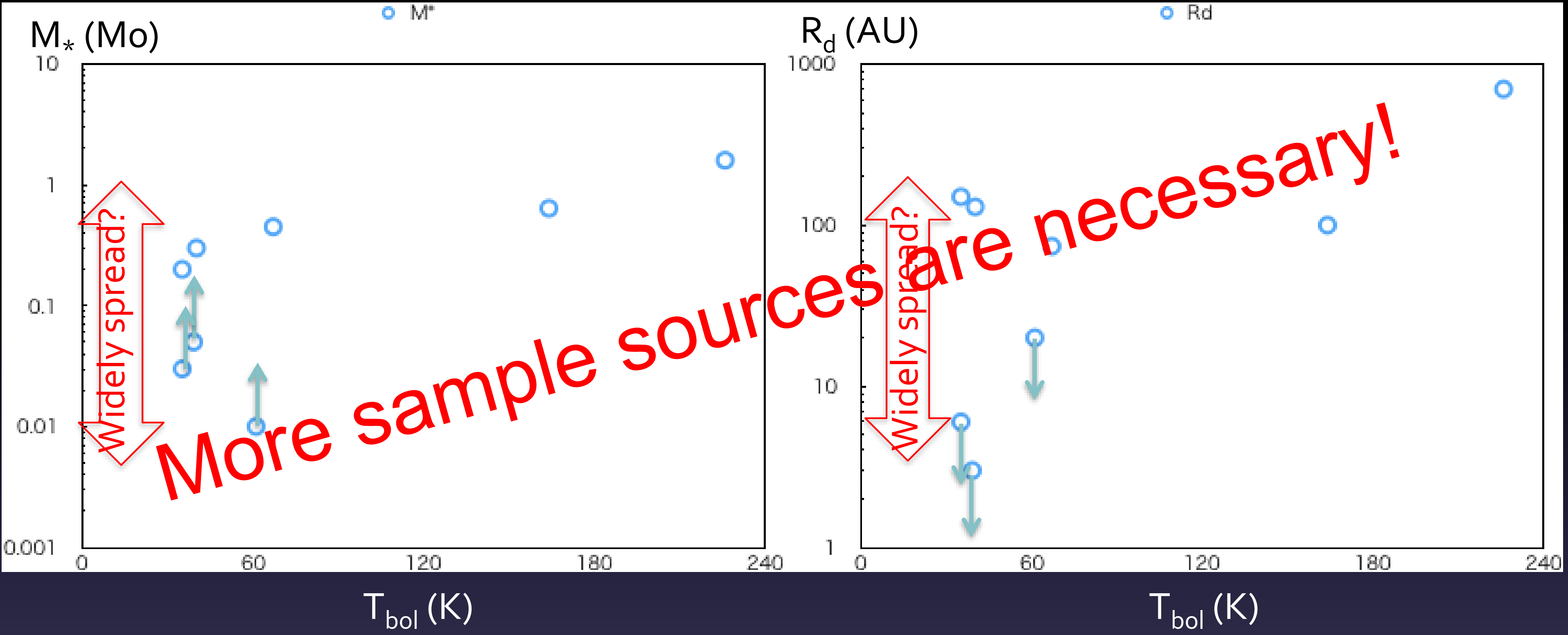
TMC-1A

P_{in} = – 0.54 ± 0.14
P_{out} = – 0.85 ± 0.04
R_b = 67 AU
R_{kep} ~ 90 AU

L1489 IRS

P = –0.57± 0.03
M_* ~ 1.6 Mo

Evolutional Trend: M_d and R_d



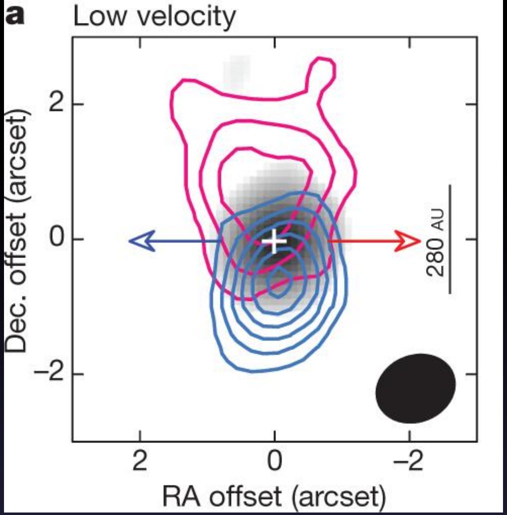
More sample sources are necessary!

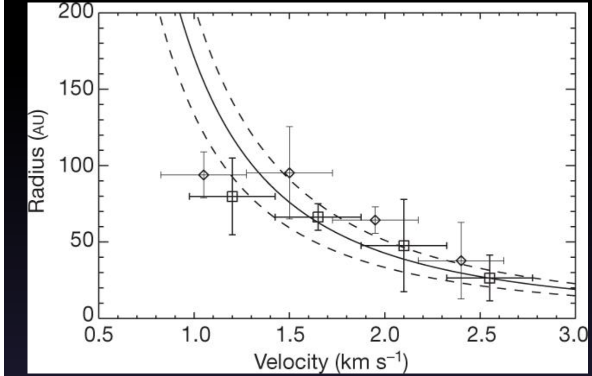
- If T_{bol} can be an evolutional indictor, M_* and R_d increase as the central star evolves
- At the earliest evolutionary stage, M_* and R_d increase quickly by more than a factor of 10?

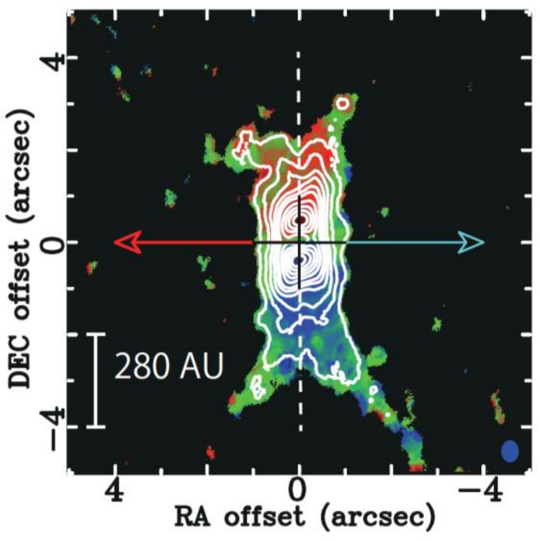
Distribution of M_* and R_d at the earliest stage would be important.

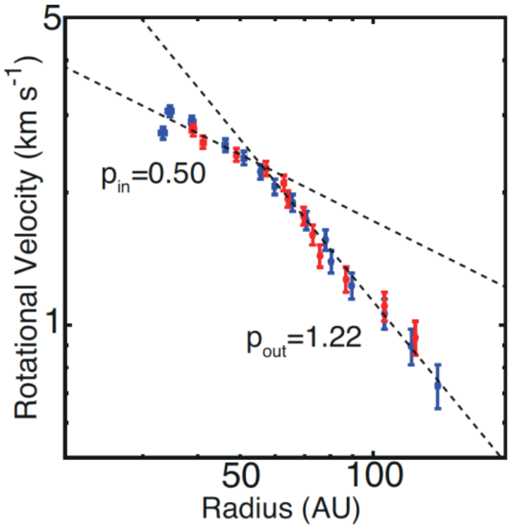
Case Study: L1527 IRS

- Class 0/I object
- L_{bol} ~ 1.7 Lo
- T_{bol} ~ 67 K
- Associated with an infalling envelope (Ohashi+ 1997)
- Associated with a Keplerian disk (Tobin+ 2012; Ohashi+ 2014; Aso+ 2017)
  - R_k ~74 AU
  - M_* ~0.45 Mo
- Chemistry of the disk forming region is also studied in detailed (Sakai+ ‘14, ‘17)







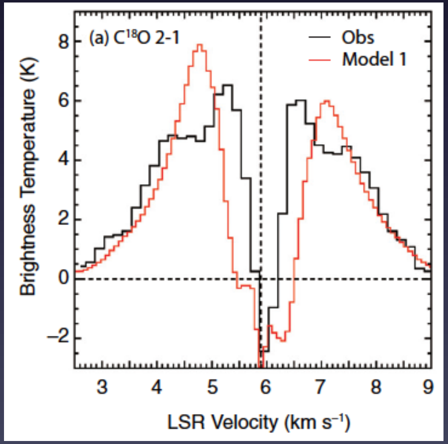


Case Study 1: L1527 IRS

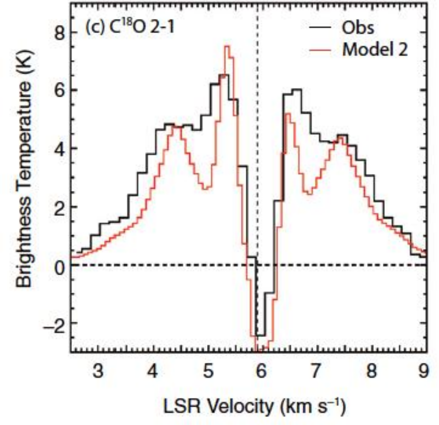
- ➢ Infall motions in the envelope are free-fall yielded by the central star?

V_{infall} ~ 0.3 km s^{-1} at 2000 AU in radius (measured)
$V_{freefall}$ ~ 0.6 km s^{-1} at 2000 AU in radius estimated from the dynamical mass

free-fall



0.2-0.5 of free-fall



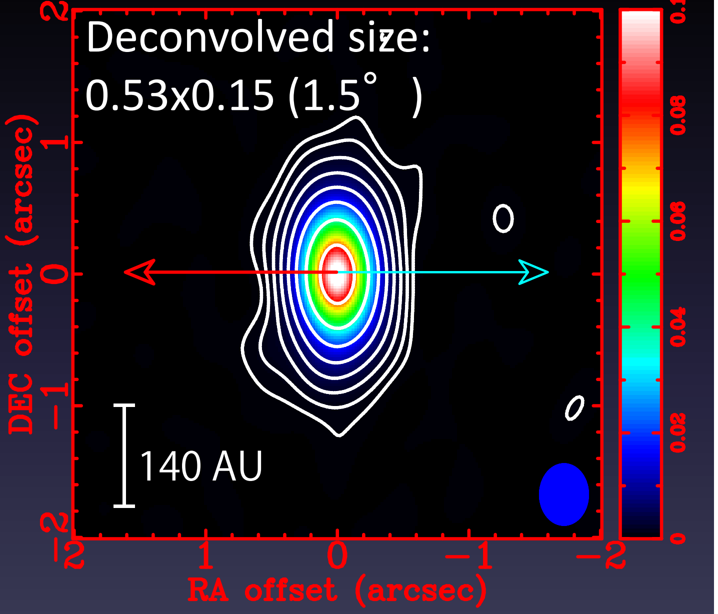
Ohashi+ 2014

- Infall motions may be suppressed by magnetic field?
- Infall motions may be reduced before landing to the disk?
- Other protostars such as L1551 IRS5 (Chou+ ’14), TMC-1A (Aso+ ‘15), and HH111 (Lee+ ‘10) also show similar features.

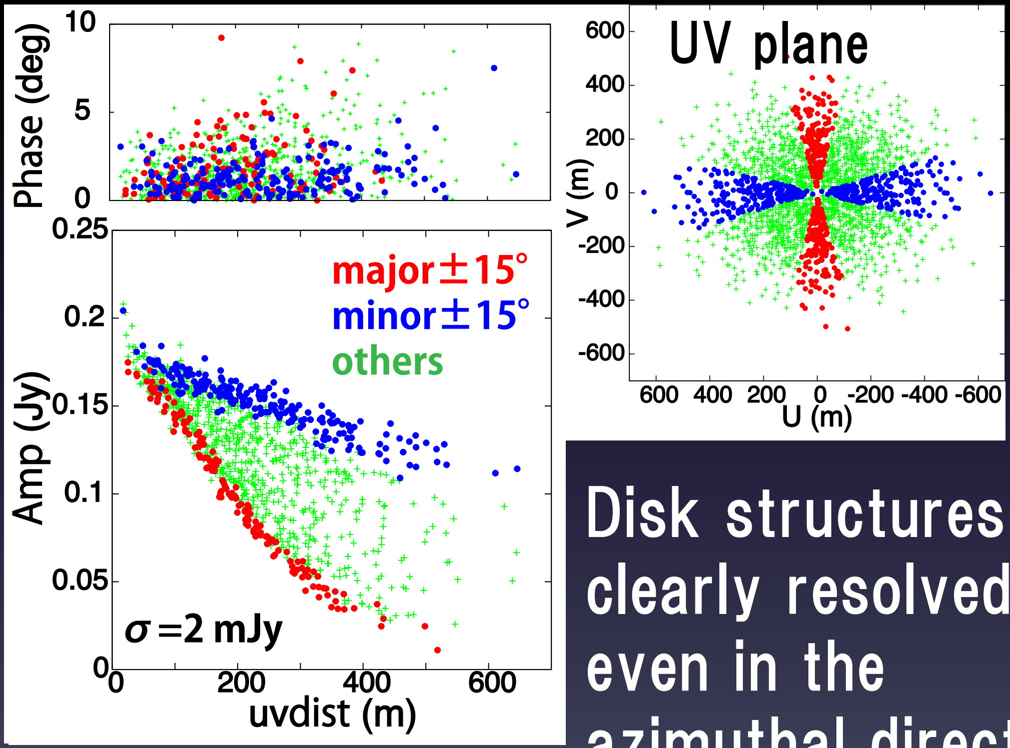
Case Study: L1527 IRS

- What are disk structures?

220 GHz Continuum



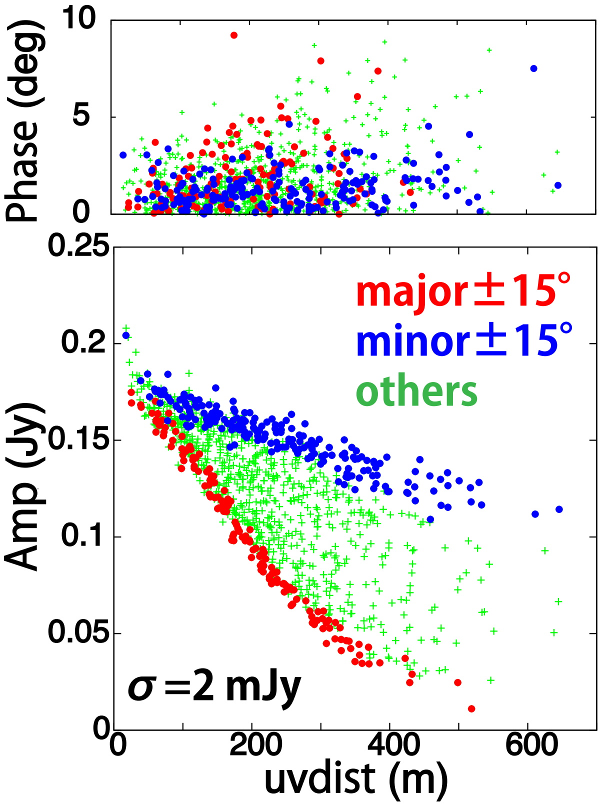
Contours: 3,6,12…σ



Disk structures are clearly resolved even in the azimuthal direction.

- **Visibility data should be analyzed without azimuthal averaging.**

Case Study: L1527 IRS



- ➢ Model fitting w/o annulus averaging.

➔Vertical and radial information are not merged in the edge-on case.

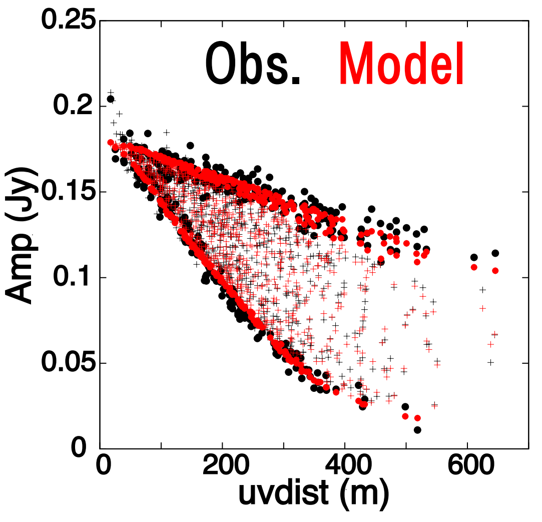
6 parameters: M_{disk}, R_{out}, p, S_{damp}, H_1, h

$$\Sigma(R) \propto R^{-p} \times \begin{cases} 1 & (R \leq R_{\rm out}) \\ S_{\rm damp} & (R > R_{\rm out}) \end{cases},$$

$$H(R) \propto R^{-h}$$

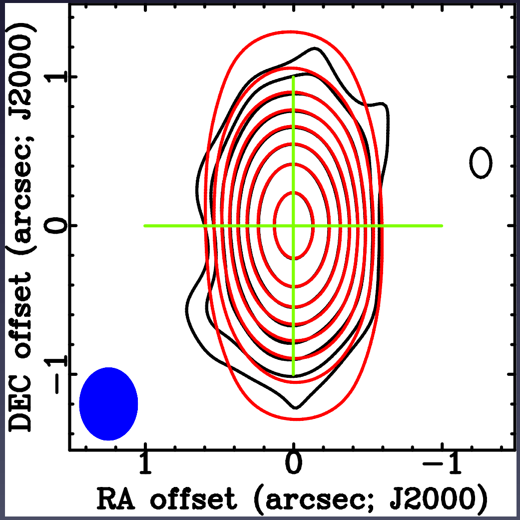
- ➢ Temperature is fixed (T_1=403.5 K, q=0.5; Tobin+13).

Case Study: L1527 IRS

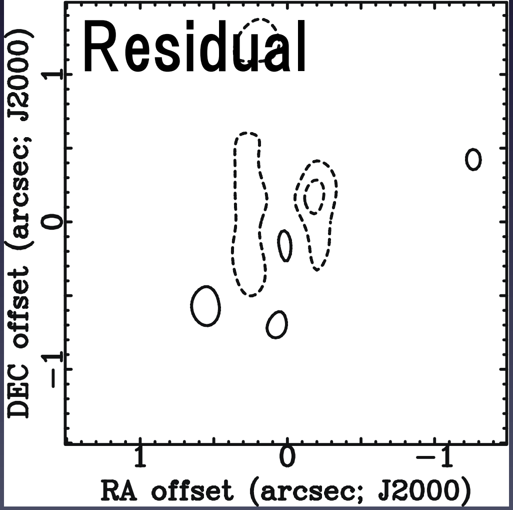


best model: reduced χ^2=5.7

M_{disk} (1e–3$M_\odot$)	R_{out} (AU)	p	S_{damp}	H_1 (AU)	h
6.0	84	1.7	0.19	0.11	1.2
+1.5 –1.8	+16 –24	+0.1 –0.3	+0.03– 0.09	+0.02 –0.03	+0.1 –0.1



Contours: 3,6,12,24,...σ

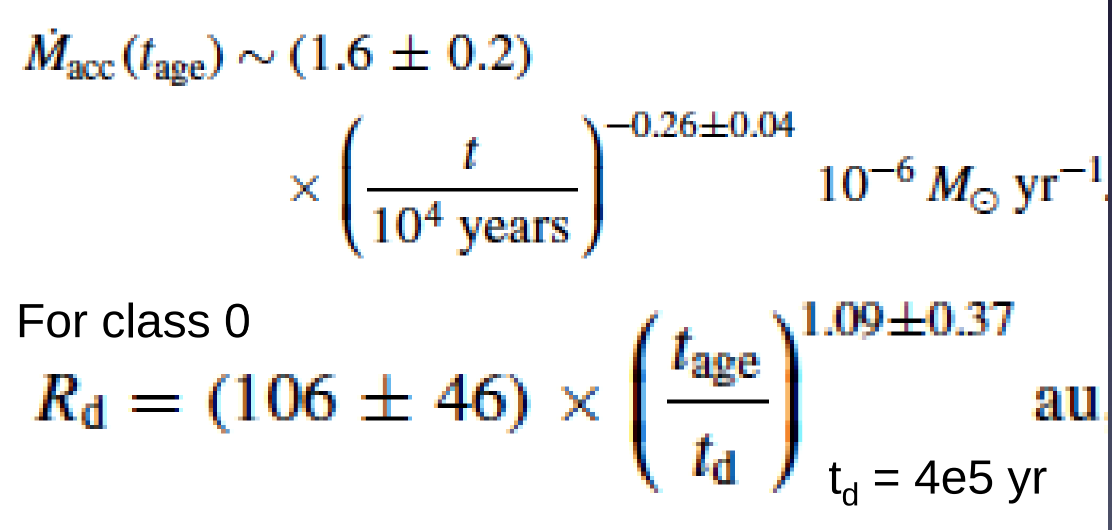


Contours: 3,6,9,12,...σ

- R_{out} corresponds to the kinematic R_{kep} within uncertainty.
- Scale height appears in hydrostatic equilibrium: H(84 AU)~1.3 H_{HSEQ}.

A statistical study

- Yen+ 2017 use 18 of protostars associated with Keplerian disks to study disk formation and evolution of protostars, investigating;
  - evolutional trend of specific angular momentum
  - M_d – R_d relation
  - evolutional trend of $\dot{M}_{acc}$ and R_d



$$\dot{M}_{\rm acc}(t_{\rm age}) \sim (1.6 \pm 0.2) \times \left(\frac{t}{10^4\ \rm years}\right)^{-0.26\pm0.04} 10^{-6}\, M_\odot\ \rm yr^{-1}$$

For class 0

$$R_{\rm d} = (106 \pm 46) \times \left(\frac{t_{\rm age}}{t_{\rm d}}\right)^{1.09\pm0.37} \rm au$$

t_d = 4e5 yr

Keplerian disks are formed around class 0 within a timescale of ~ 4e5 yr

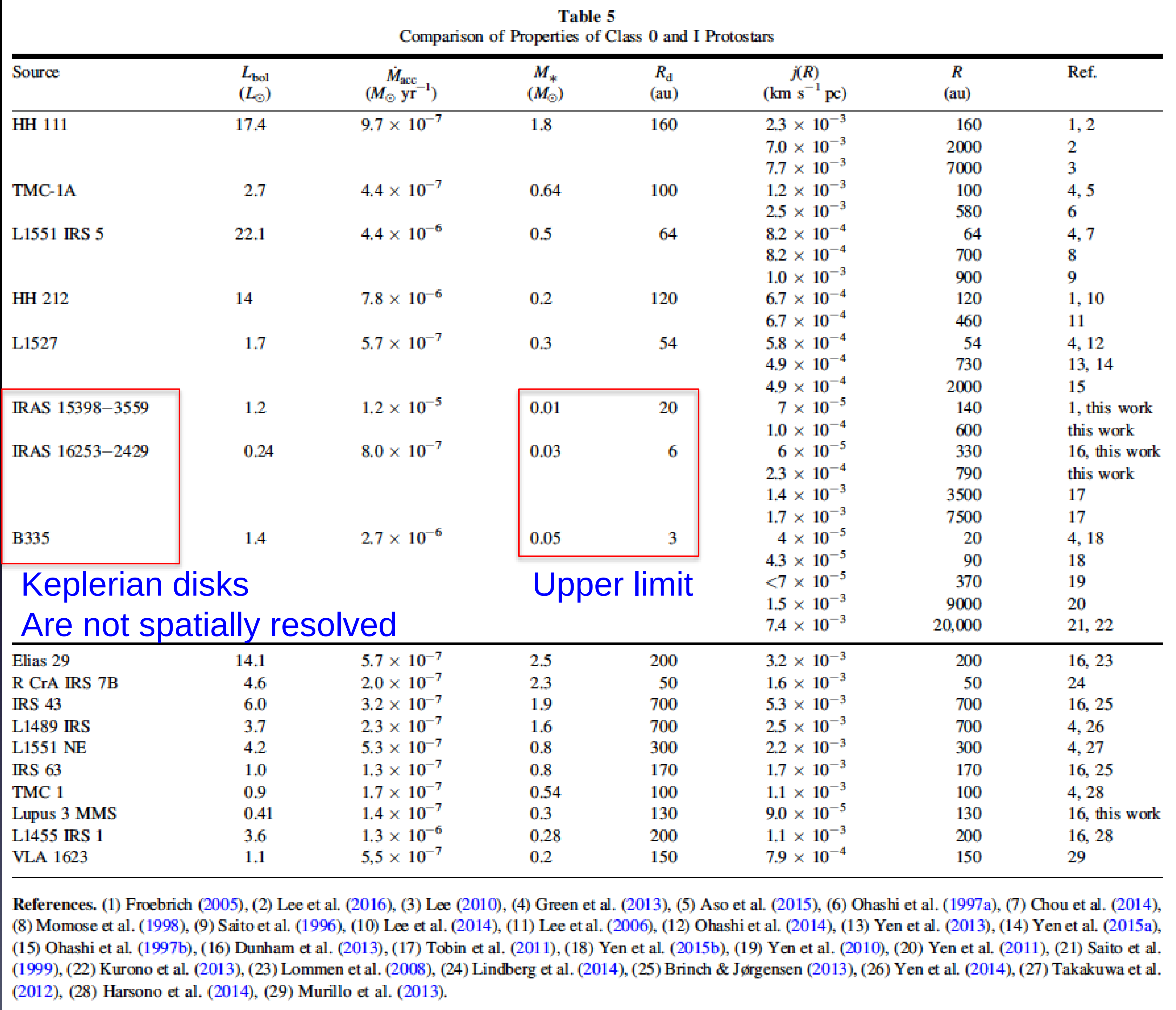


Table 5
Comparison of Properties of Class 0 and I Protostars

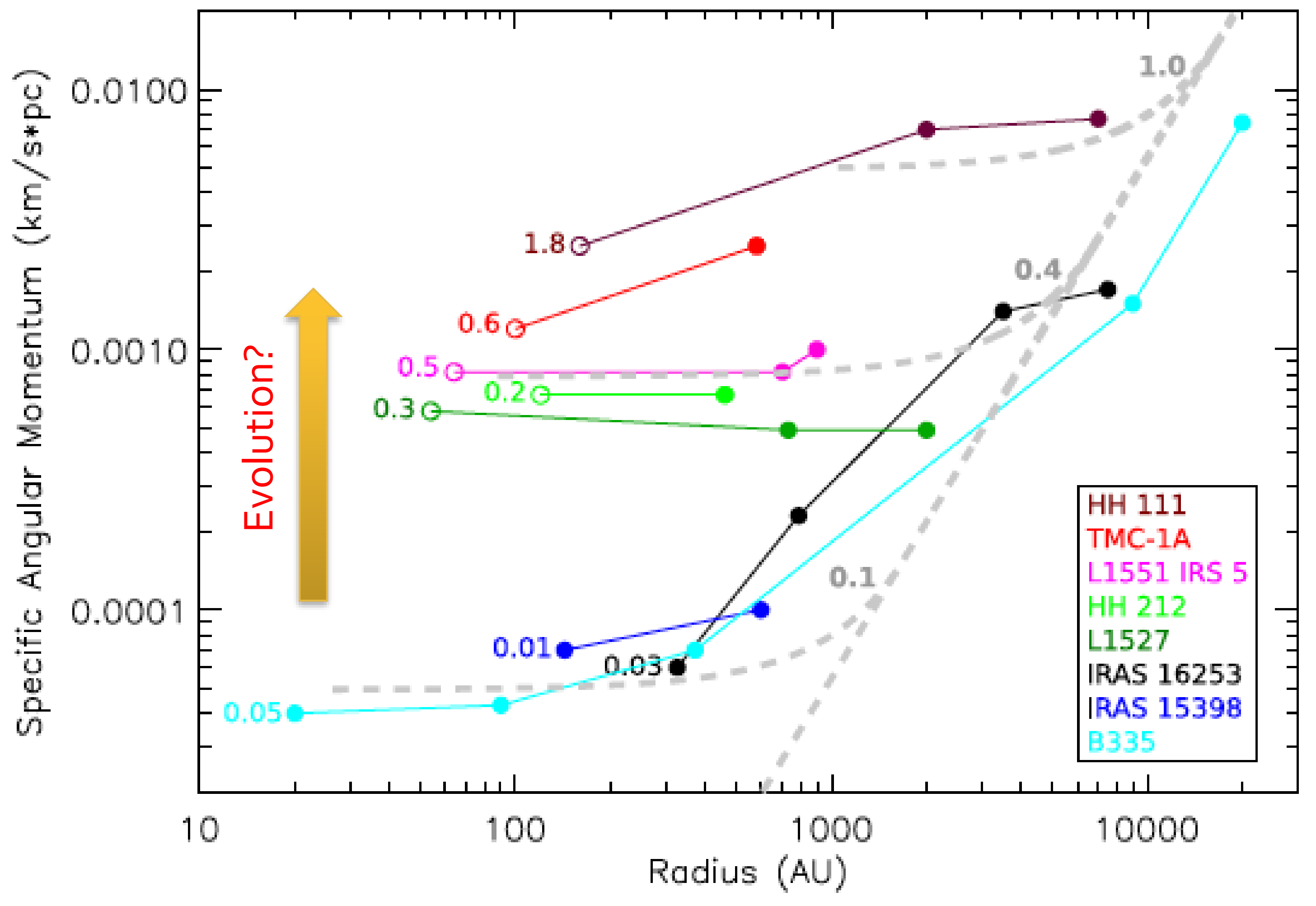
Source	$L_{\rm bol}$ ($L_\odot$)	$\dot{M}_{\rm acc}$ ($M_\odot$ yr^{-1})	M_* ($M_\odot$)	$R_{\rm d}$ (au)	$j(R)$ (km s^{-1} pc)	R (au)	Ref.
HH 111	17.4	9.7×10^{-7}	1.8	160	2.3×10^{-3}	160	1, 2
					7.0×10^{-3}	2000	2
					7.7×10^{-3}	7000	3
TMC-1A	2.7	4.4×10^{-7}	0.64	100	1.2×10^{-3}	100	4, 5
					2.5×10^{-3}	580	6
L1551 IRS 5	22.1	4.4×10^{-6}	0.5	64	8.2×10^{-4}	64	4, 7
					8.2×10^{-4}	700	8
					1.0×10^{-3}	900	9
HH 212	14	7.8×10^{-6}	0.2	120	6.7×10^{-4}	120	1, 10
					6.7×10^{-4}	460	11
L1527	1.7	5.7×10^{-7}	0.3	54	5.8×10^{-4}	54	4, 12
					4.9×10^{-4}	730	13, 14
					4.9×10^{-4}	2000	15
IRAS 15398−3559	1.2	1.2×10^{-5}	0.01	20	7×10^{-5}	140	1, this work
					1.0×10^{-4}	600	this work
IRAS 16253−2429	0.24	8.0×10^{-7}	0.03	6	6×10^{-5}	330	16, this work
					2.3×10^{-4}	790	this work
					1.4×10^{-3}	3500	17
					1.7×10^{-3}	7500	17
B335	1.4	2.7×10^{-6}	0.05	3	4×10^{-5}	20	4, 18
					4.3×10^{-5}	90	18
					$<7 \times 10^{-5}$	370	19
					1.5×10^{-3}	9000	20
					7.4×10^{-3}	20,000	21, 22
Elias 29	14.1	5.7×10^{-7}	2.5	200	3.2×10^{-3}	200	16, 23
R CrA IRS 7B	4.6	2.0×10^{-7}	2.3	50	1.6×10^{-3}	50	24
IRS 43	6.0	3.2×10^{-7}	1.9	700	5.3×10^{-3}	700	16, 25
L1489 IRS	3.7	2.3×10^{-7}	1.6	700	2.5×10^{-3}	700	4, 26
L1551 NE	4.2	5.3×10^{-7}	0.8	300	2.2×10^{-3}	300	4, 27
IRS 63	1.0	1.3×10^{-7}	0.8	170	1.7×10^{-3}	170	16, 25
TMC 1	0.9	1.7×10^{-7}	0.54	100	1.1×10^{-3}	100	4, 28
Lupus 3 MMS	0.41	1.4×10^{-7}	0.3	130	9.0×10^{-5}	130	16, this work
L1455 IRS 1	3.6	1.3×10^{-6}	0.28	200	1.1×10^{-3}	200	16, 28
VLA 1623	1.1	$5{,}5 \times 10^{-7}$	0.2	150	7.9×10^{-4}	150	29

Keplerian disks
Are not spatially resolved

Upper limit

References. (1) Froebrich (2005), (2) Lee et al. (2016), (3) Lee (2010), (4) Green et al. (2013), (5) Aso et al. (2015), (6) Ohashi et al. (1997a), (7) Chou et al. (2014), (8) Momose et al. (1998), (9) Saito et al. (1996), (10) Lee et al. (2014), (11) Lee et al. (2006), (12) Ohashi et al. (2014), (13) Yen et al. (2013), (14) Yen et al. (2015a), (15) Ohashi et al. (1997b), (16) Dunham et al. (2013), (17) Tobin et al. (2011), (18) Yen et al. (2015b), (19) Yen et al. (2010), (20) Yen et al. (2011), (21) Saito et al. (1999), (22) Kurono et al. (2013), (23) Lommen et al. (2008), (24) Lindberg et al. (2014), (25) Brinch & Jørgensen (2013), (26) Yen et al. (2014), (27) Takakuwa et al. (2012), (28) Harsono et al. (2014), (29) Murillo et al. (2013).

Evolutional Trend: specific angular momentum

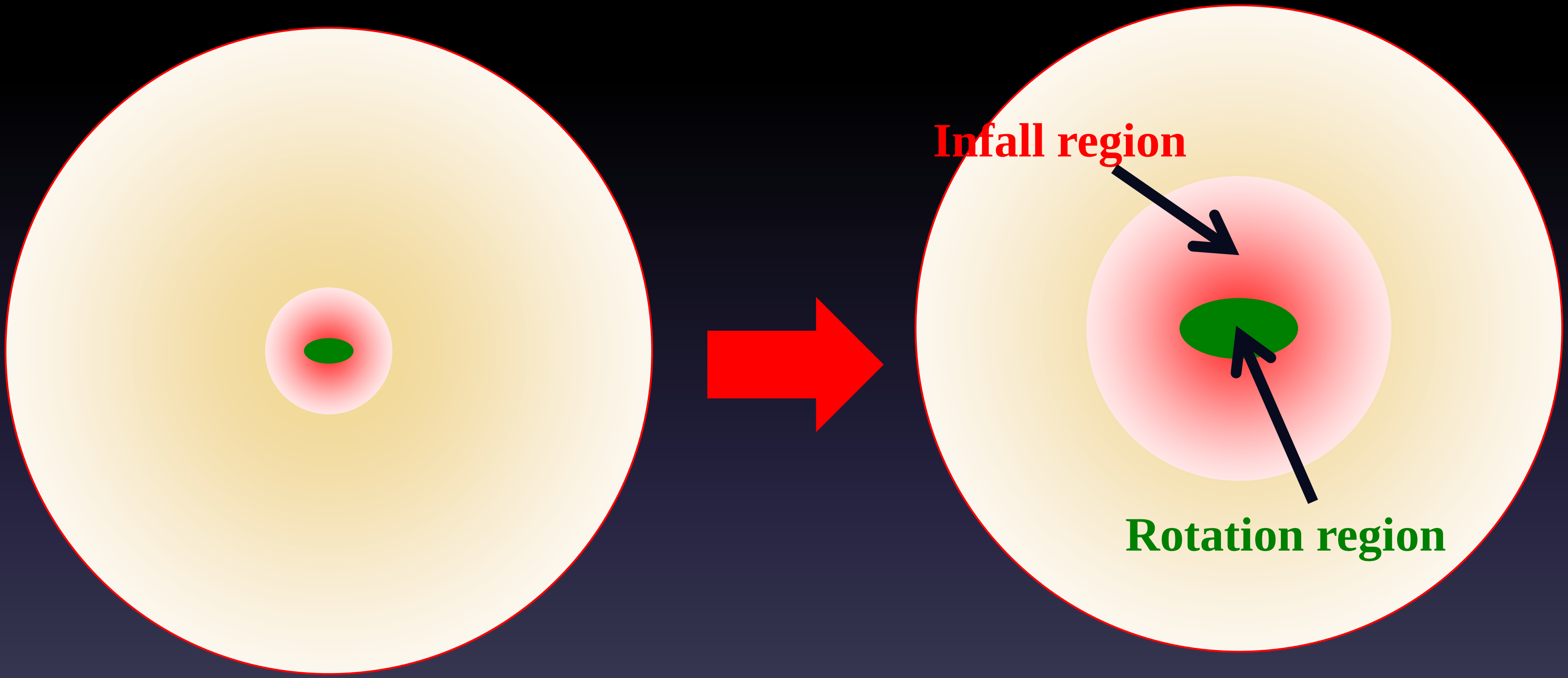


HH111: 78 K
TMC-1A: 164K
L1551 IRS5: 106 K
HH212: <56 K
L1527: 67 K
IRAS 16253: 35 K
IRAS 15398: 67K
B335: 39 K

Younger (lower T_{bol})
→ Lower j

j might increase as YSOs evolve?

Disk Formation around Protostars



Infall region

Rotation region

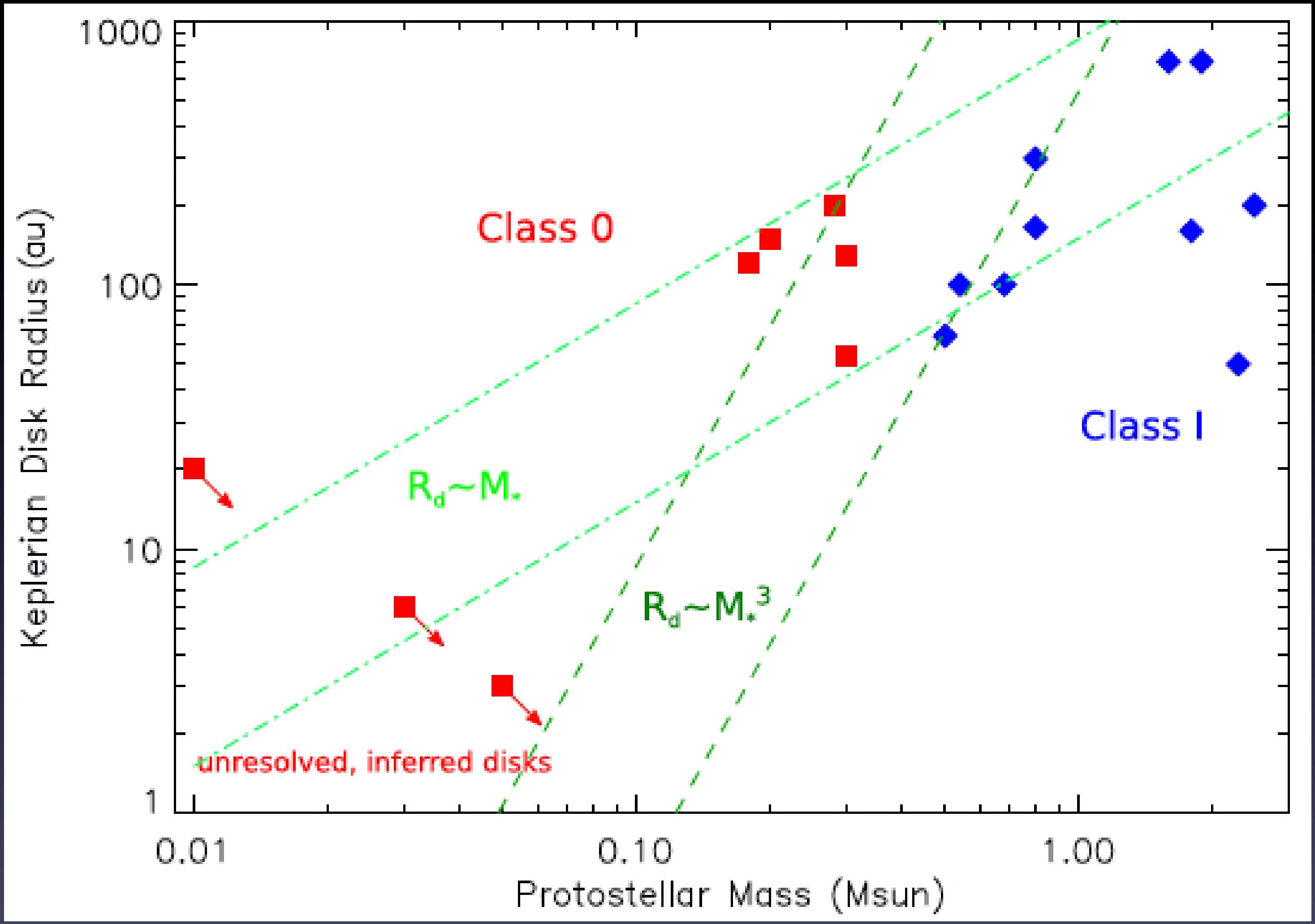
B335, IRAS 16253

Younger YSOs

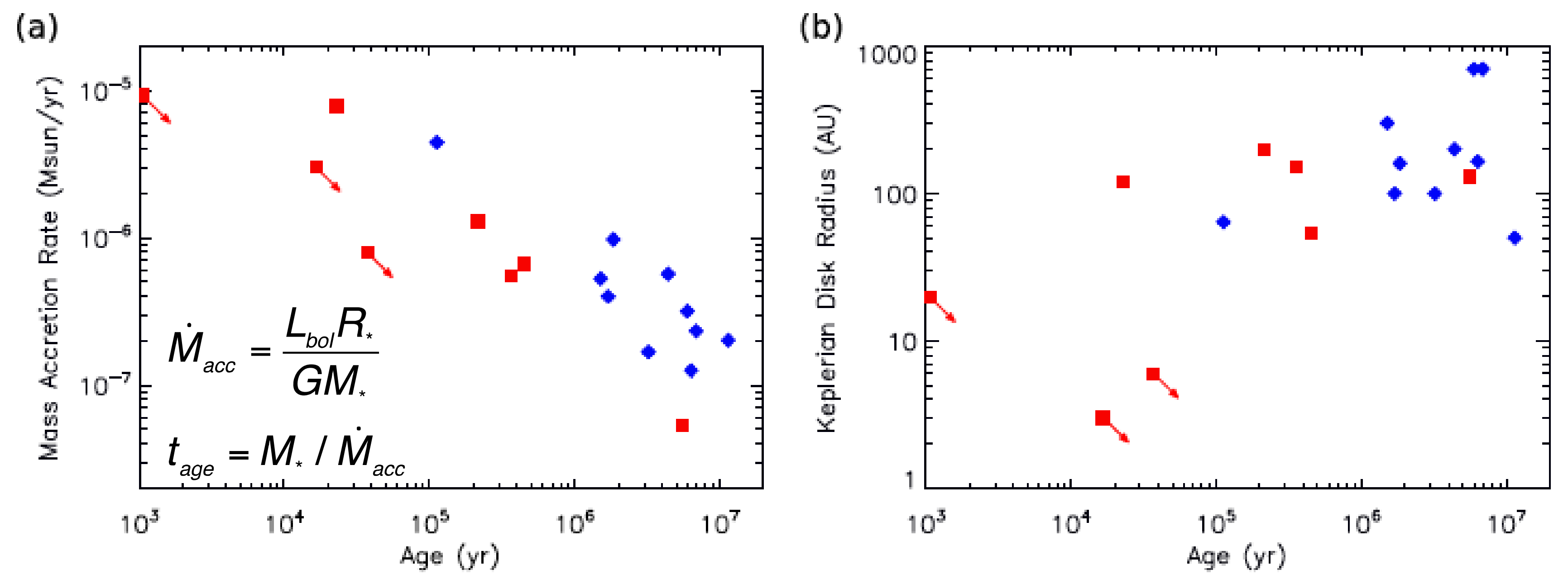
L1551 IRS5, L1527 IRS

More evolved YSOs

$M_* - R_d$ relation



Evolutional Trend: $\dot{M}_*$ and R_d



$$\dot{M}_{acc} = \frac{L_{bol}R_*}{GM_*}$$

$$t_{age} = M_* / \dot{M}_{acc}$$

$\dot{M}_{\mathrm{acc}} - t_{\mathrm{age}}$ relation

$$\dot{M}_{\mathrm{acc}}(t) = \dot{M}_{\mathrm{acc}}(t_0) \times \left(\frac{t}{t_0}\right)^{a}$$

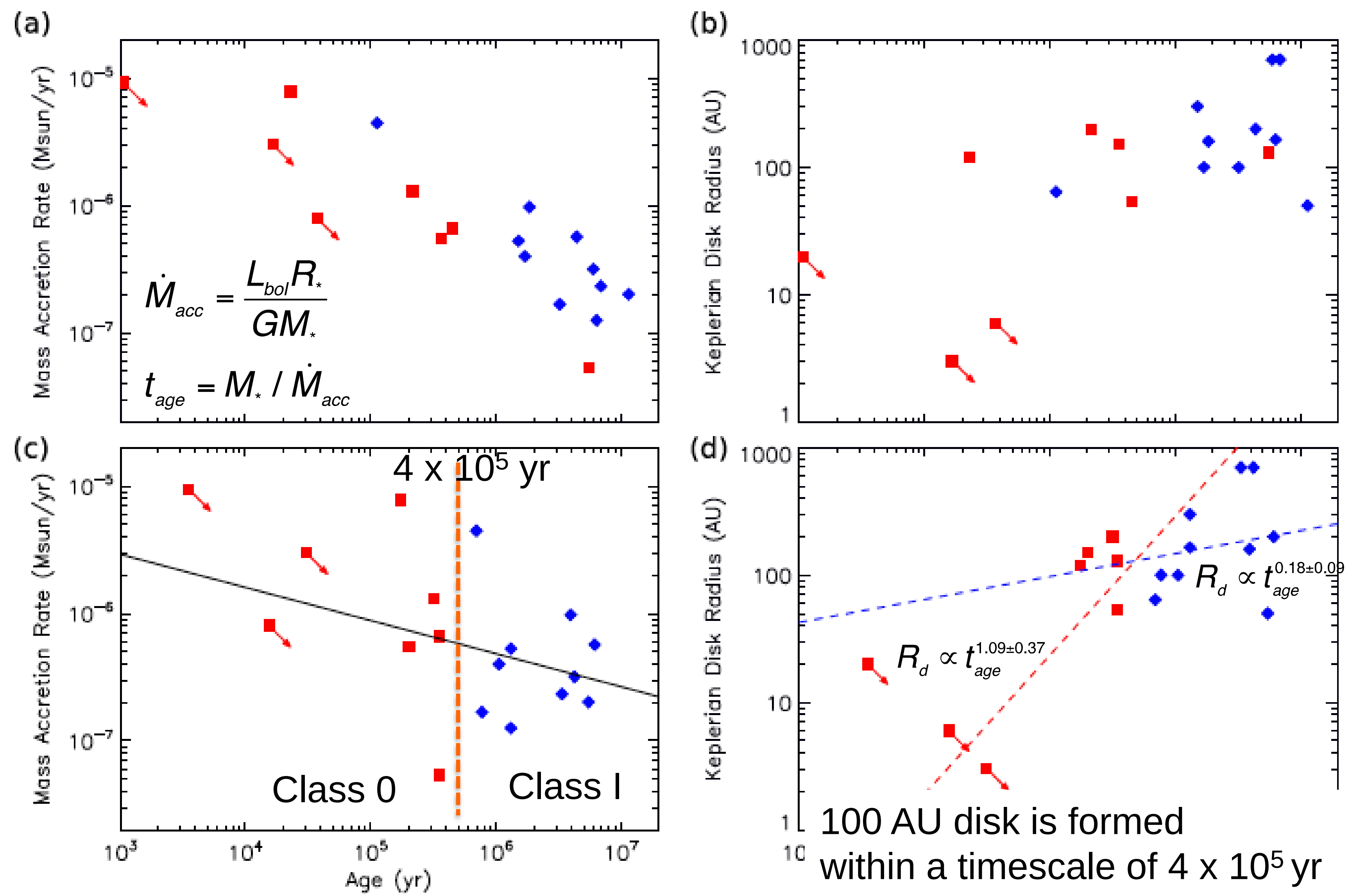
$$M_{*}(t_{\mathrm{age}}) = \int_0^{t_{\mathrm{age}}} \dot{M}_{\mathrm{acc}}(t)\,dt$$

estimate a new $\dot{M}_{acc} - t_{age}$ relation

repeat this process until $\dot{M}_{acc}(t_0)$, a, and t_{age} are converging

$$\dot{M}_{\mathrm{acc}}(t_{\mathrm{age}}) \sim (1.6 \pm 0.2) \times \left(\frac{t}{10^4\ \mathrm{years}}\right)^{-0.26\pm0.04} 10^{-6}\ M_{\odot}\ \mathrm{yr}^{-1}$$

Evolutional Trend: $\dot{M}_*$ and R_d



$$\dot{M}_{acc} = \frac{L_{bol} R_*}{G M_*}$$

$$t_{age} = M_* / \dot{M}_{acc}$$

4 x 10^5 yr

Class 0

Class I

$R_d \propto t_{age}^{0.18 \pm 0.09}$

$R_d \propto t_{age}^{1.09 \pm 0.37}$

100 AU disk is formed within a timescale of 4 x 10^5 yr

Summary

- Keplerian disks has been unambiguously identified around protostars, including class 0 sources, providing a strong method to estimate masses of protostars, and also related physical parameters, such as ages of protostars and mass accretion rates to them.
- Physical parameters obtained from disk observations could provide a new picture of star and disk formation, giving important constraint on theories of star and disk formation.
- Further observations of disks around protostars are very important to perform even better statistics.