분자운 코어-갈색왜성(Brown Dwarfs) 생성 과정연구 소개

Chang Won Lee
(Korea Astronomy & Space Science Institute)

전파겨울학교, Feb. 23th, 2018,

Lecture Outline

- 갈색 왜성 (별)생성 기원연구의 과정을 살펴본다.

- 전파를 포함한 다파장 (적외선, 광학)관측을 통해…
- 분광 스펙트럼과 연속파 관측을 통해…
- 단일경, 간섭계 망원경 관측을 통해…

What is BD

- Definition

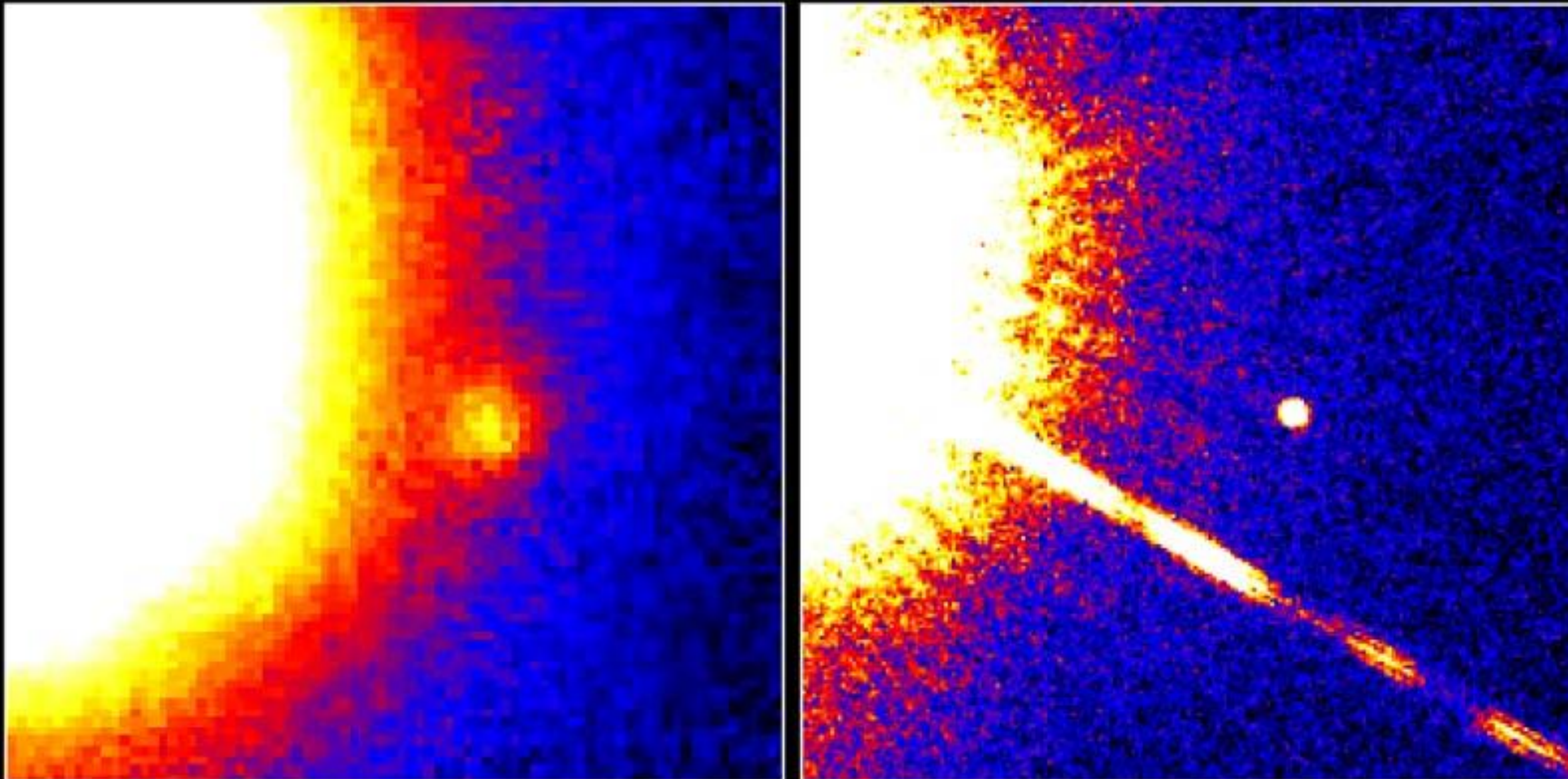
; Sub-stellar objects with too little mass (0.01 - 0.075 $M_{\odot}$) to burn their hydrogen interior, failed stars.

- First theorized by Kumar (1962)
- Observationally verified by Rebolo et al. (1995) and imaged by Nakajima & Kularni (1995)
- A few thousands (~1800) BDs so far

- Essential components in our Milky Way (expected to exist in an equivalent number to Sun-like stars from the IMF of stellar clusters or field stars !)

- Do not know how the BD forms.

Brown Dwarf Gliese 229B



Palomar Observatory
Discovery Image
October 27, 1994

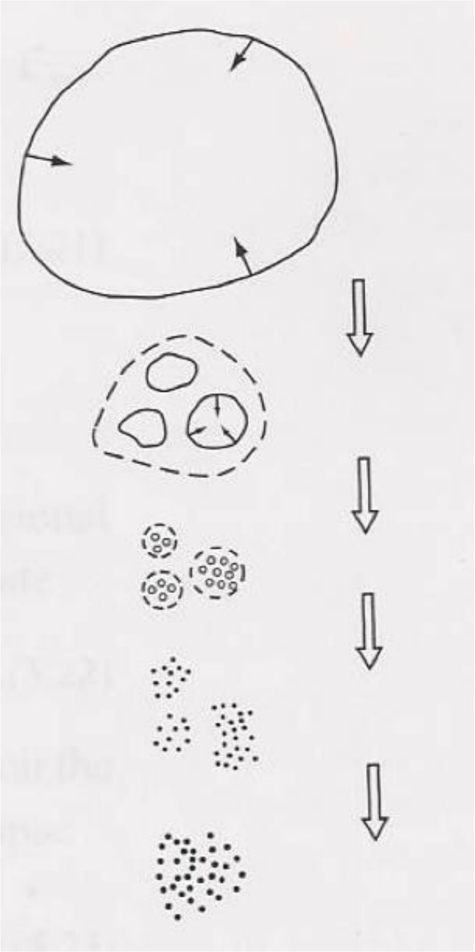
Hubble Space Telescope
Wide Field Planetary Camera 2
November 17, 1995

PRC95-48 · ST ScI OPO · November 29, 1995
T. Nakajima and S. Kulkarni (CalTech), S. Durrance and D. Golimowski (JHU), NASA

Low-mass Star formation

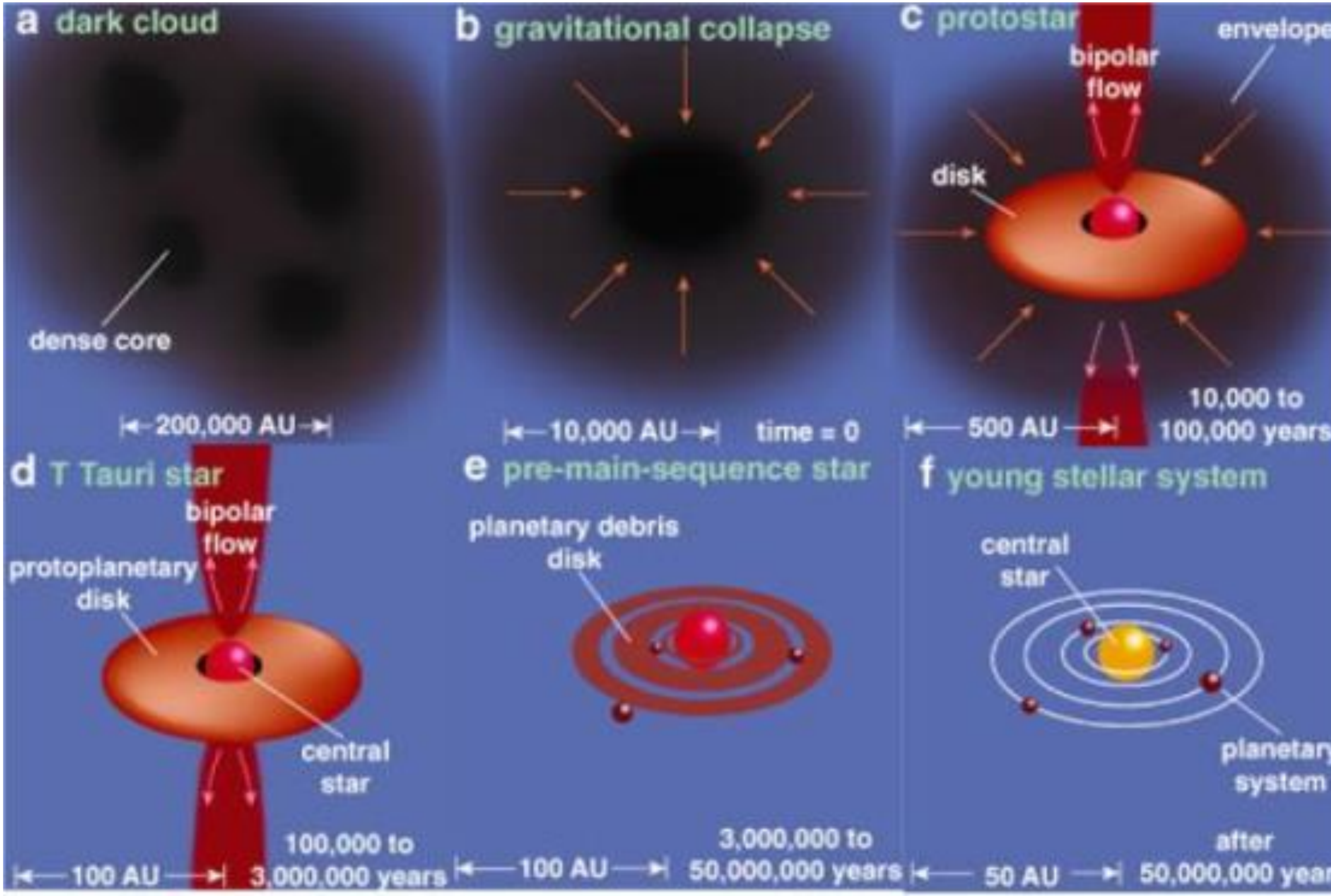
- Fragmentation of molecular clouds
  - Self-Gravity pressure > Gas Pressure
  - Isothermal Contraction
    Jeans Mass ($\sim T^{2/3}\rho^{-1/2}$) becomes smaller.
  - Dense cores ($10^4 \sim 10^{11}$ H_2 /cm^3)
    T= 10K, $\rho = 10^5$ H_2 /cm^3 ➔ $M_J \sim 2\ M_\odot$
  - Protostars (by accreting matter)
    in contracting cores

- Filaments with flow motions



From D. Ward-Thompson & A. P. Whitworth (2011)

Low-mass Star formation

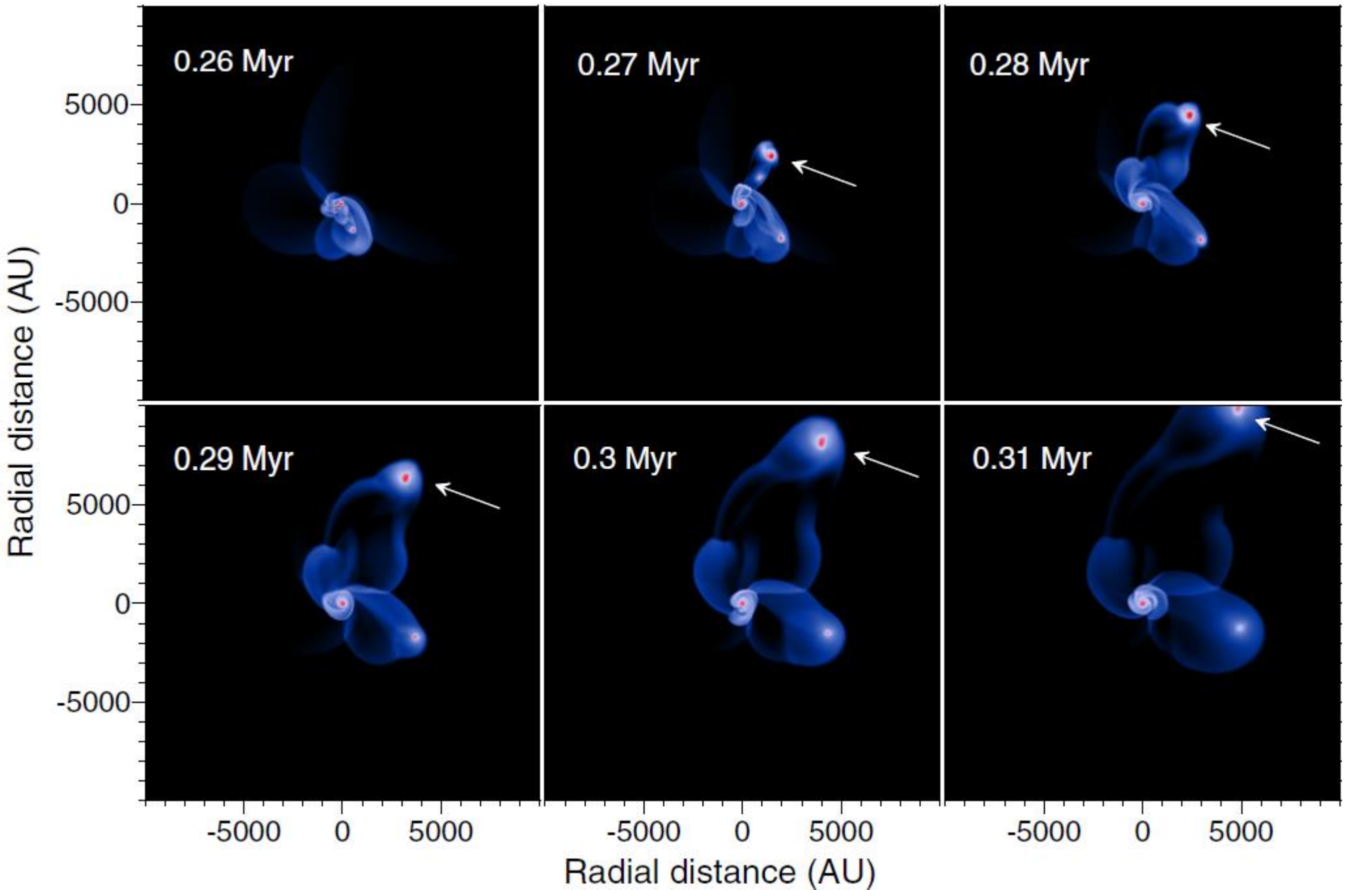


Greene (2001)

Brown Dwarf Formation

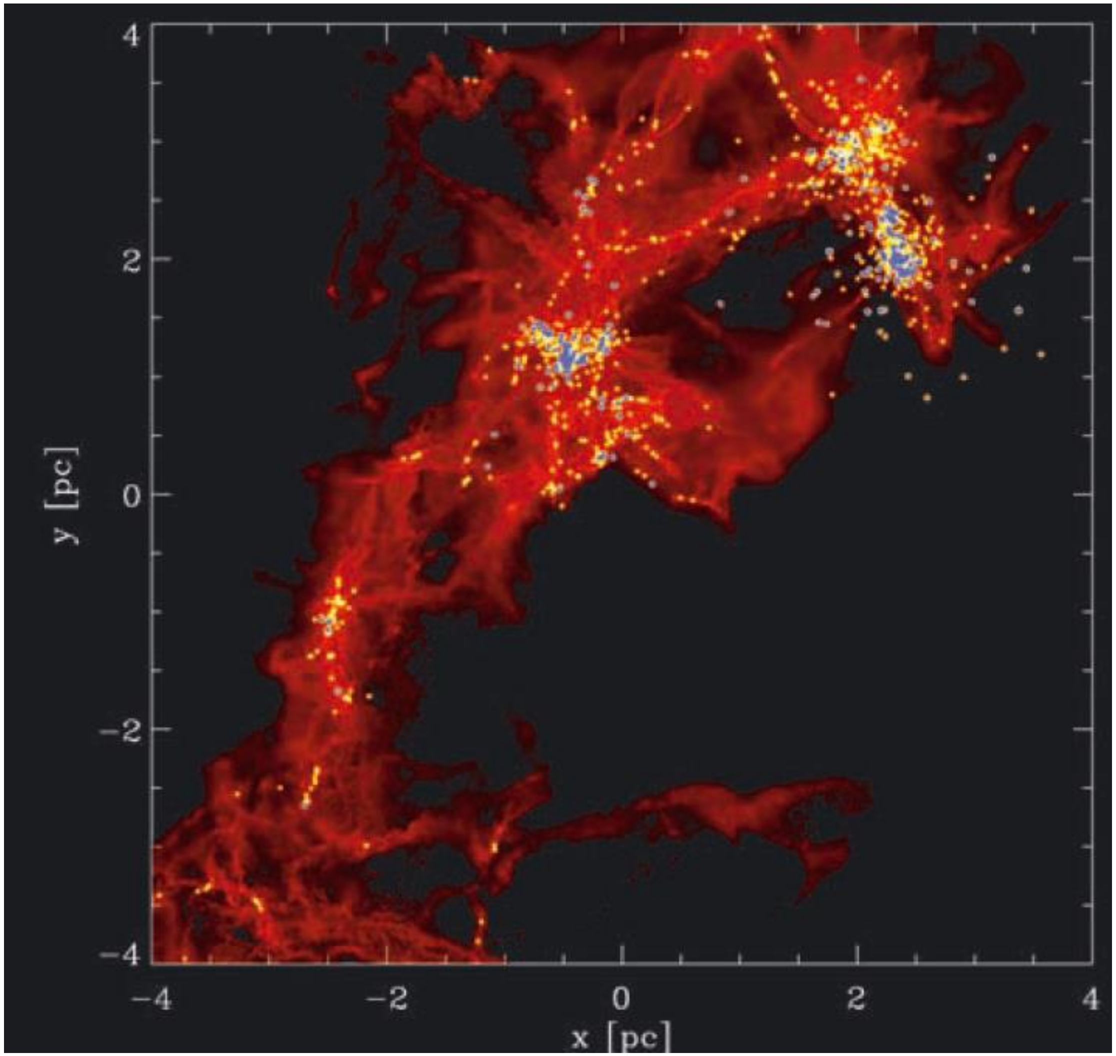
- Most of the existing models for the brown dwarf formation involve *premature termination of accretion* (Luhman 2012).

-Dynamical ejections of immature substellar objects or clumps of a brown dwarf mass from fragments (e.g., Basu & Vorobyov 2012)



Hydrodynamic simulation

Brown Dwarf Formation



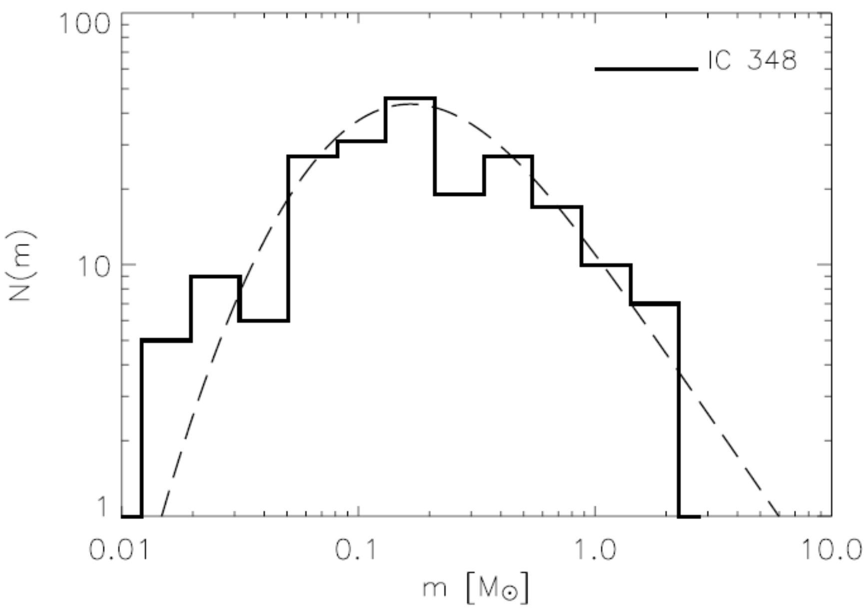
- Tidal shear and high velocity dispersion in a stellar cluster preclude any subsequent accretion, thus resulting in the formation of brown dwarfs or very low mass stars. (Bonnell + 2008)

SPH simulation

Brown Dwarf Formation

- Photo-erosion of a prestellar core by the ionizing radiation from a nearby OB star (Whitworth & Zinnecker 2004) .

-BDs can form like normal stars (e.g., Padoan & Nordlund 2004)
➔ with density, temperature, and rms Mach number typical of cluster-forming regions, turbulent fragmentation can account for the observed BD abundance.



Numerical simulations of supersonic MHD turbulence

➔Observational test is rare

Start, long time ago

- Finding Dense Cores

- Locally density-enhanced regions in the dark clouds

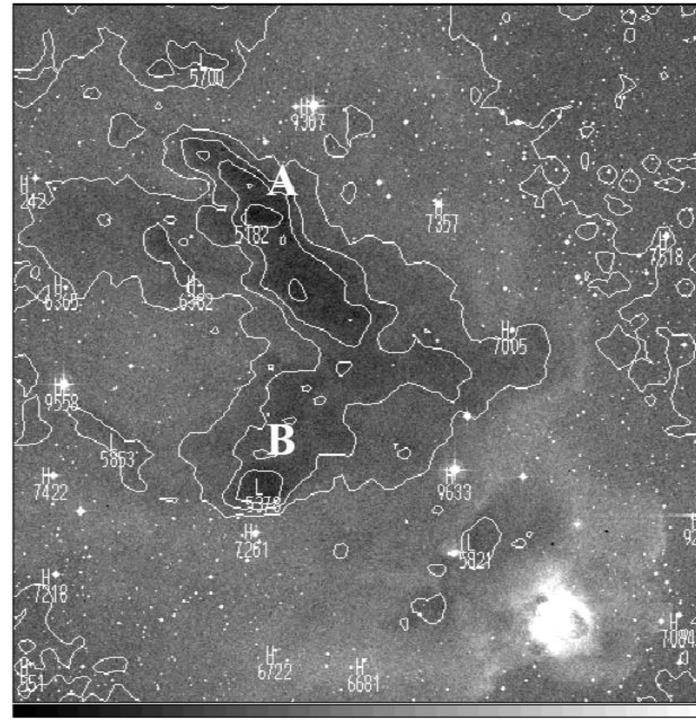
→Typical size of ~0.1 pc, Mass of a few $M_{\odot}$,T~10 K, and mean density of a few 10^4 cm^{-3}.

- Initial studies based on the optical inspection of the Palomar plates with molecular (especially NH_3) observations by Myers and his collaborators (1983, 1989)

- Study by Lee & Myers (1999)

  Collection of dense cores using DSS images ~200 cores

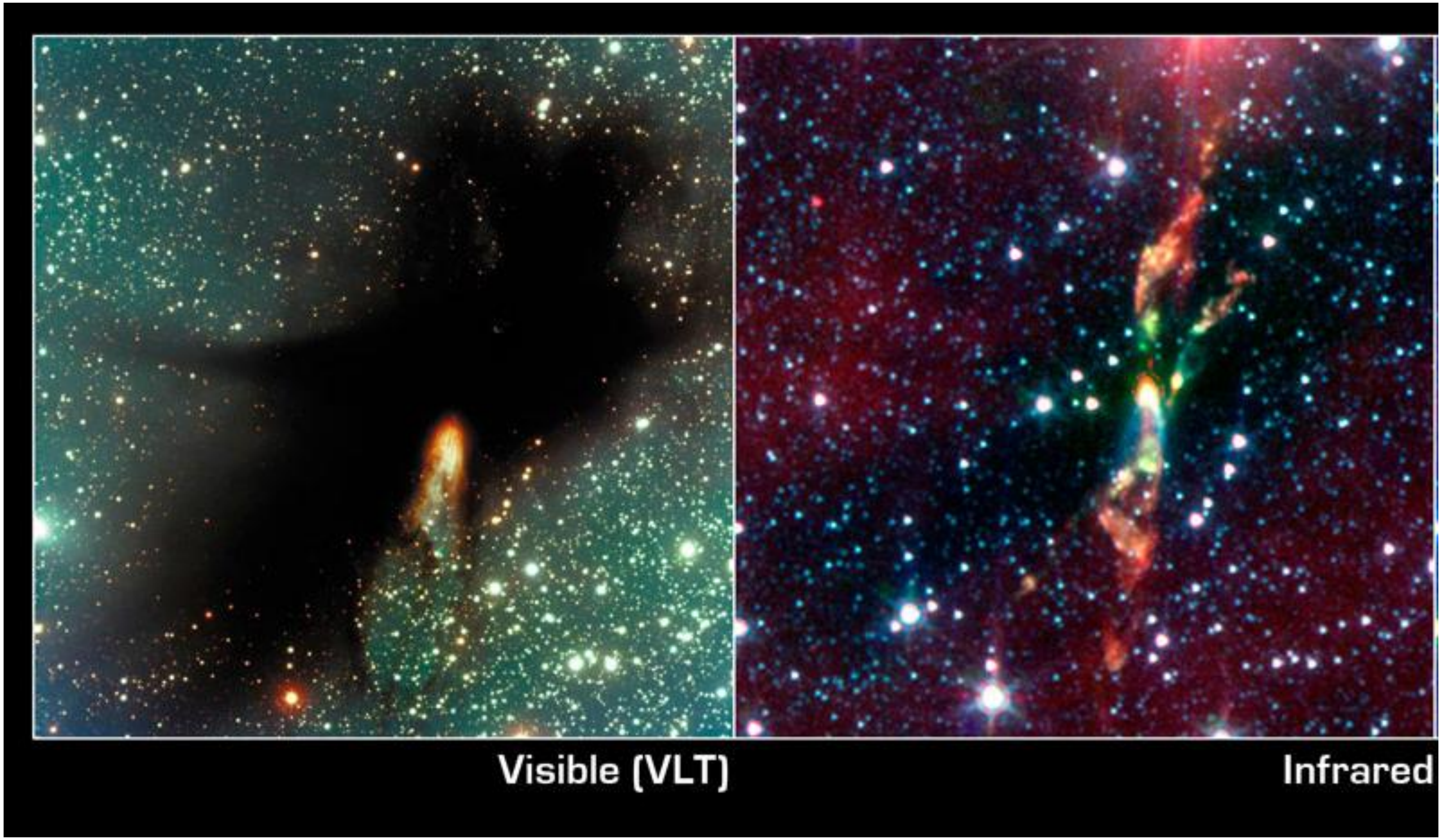
From languagegallery.blogspot.com/2011/05/what-mil…



Lee & Myers 1999

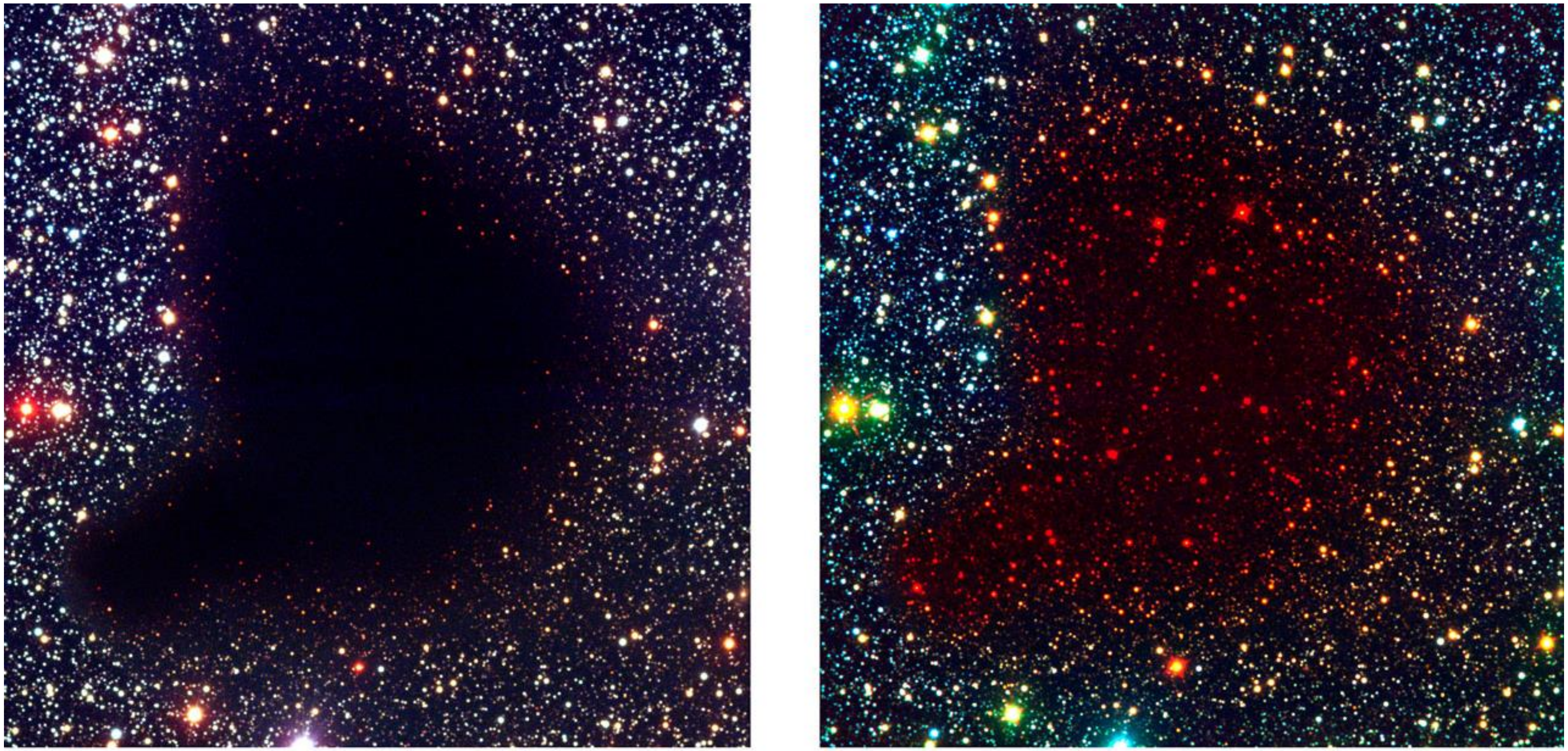
- “The sites of stellar birth” from the correlation of dense cores with IRAS point sources (Beichman et al. 1986)

Proto-stellar Core



BHR71 : Optical & Infrared images

Starless Core



B, V, I

B, I, K

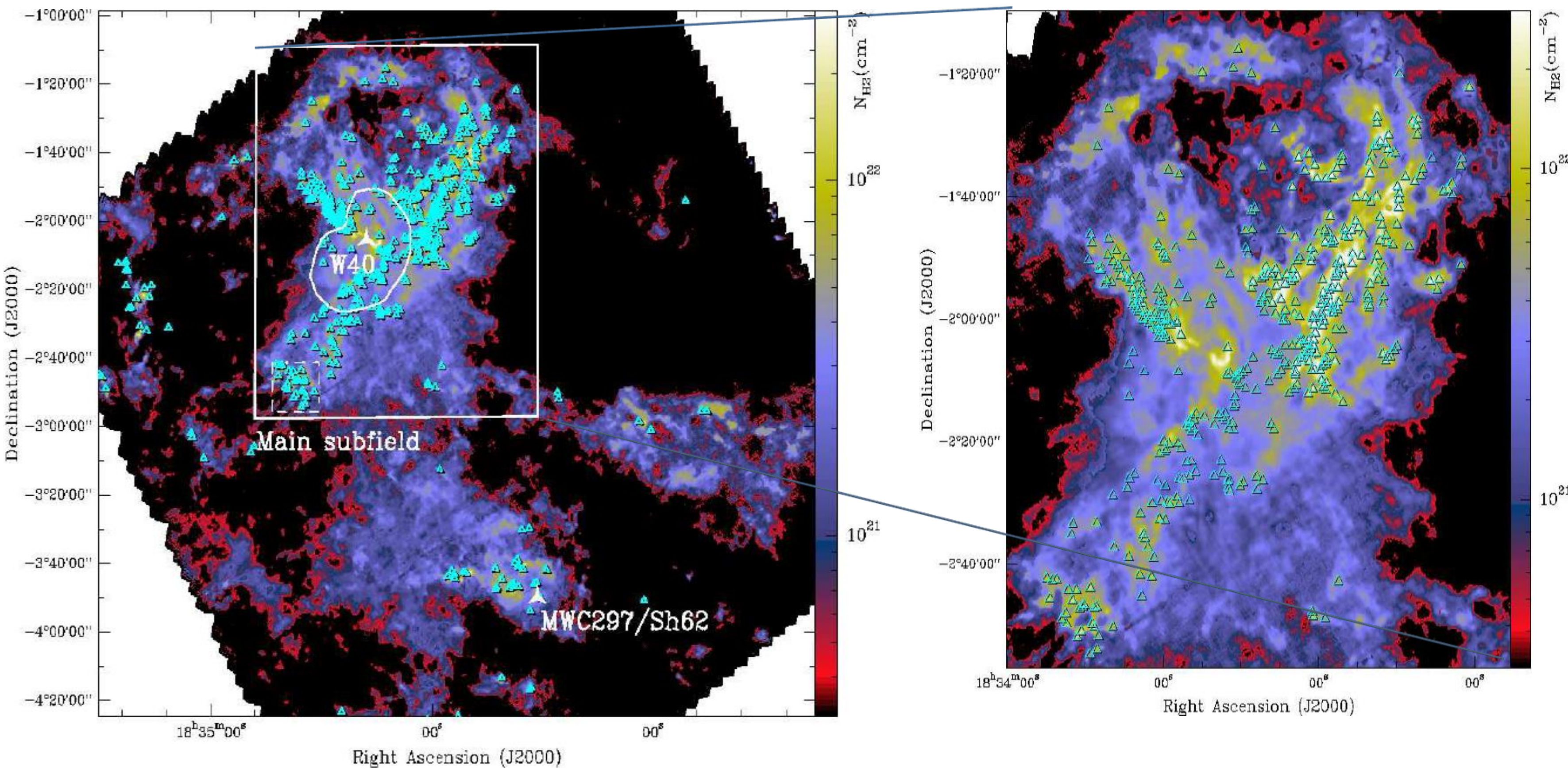
B68 : Optical & IR images (Alves et al. 2001)

Starless Cores

1) Cores that are gravitationally bound : *Pre-stellar cores*
(Pre-protostellar core)
- can evolve towards higher degree of central concentration, but no protostar exists yet within them.
- detected with sub-mm dust continuum or high density molecular line tracers (such as NH3 or N2H+), infall motions

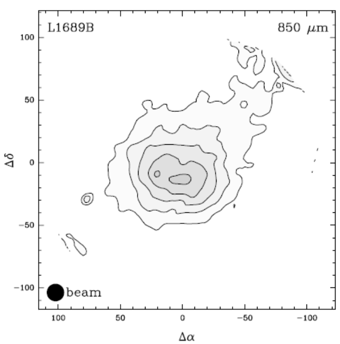
2) Cores that are not gravitationally bound
- difficult to tell observationally whether or not they will go on to form a star.

More cores with better sensitivity and better resolution

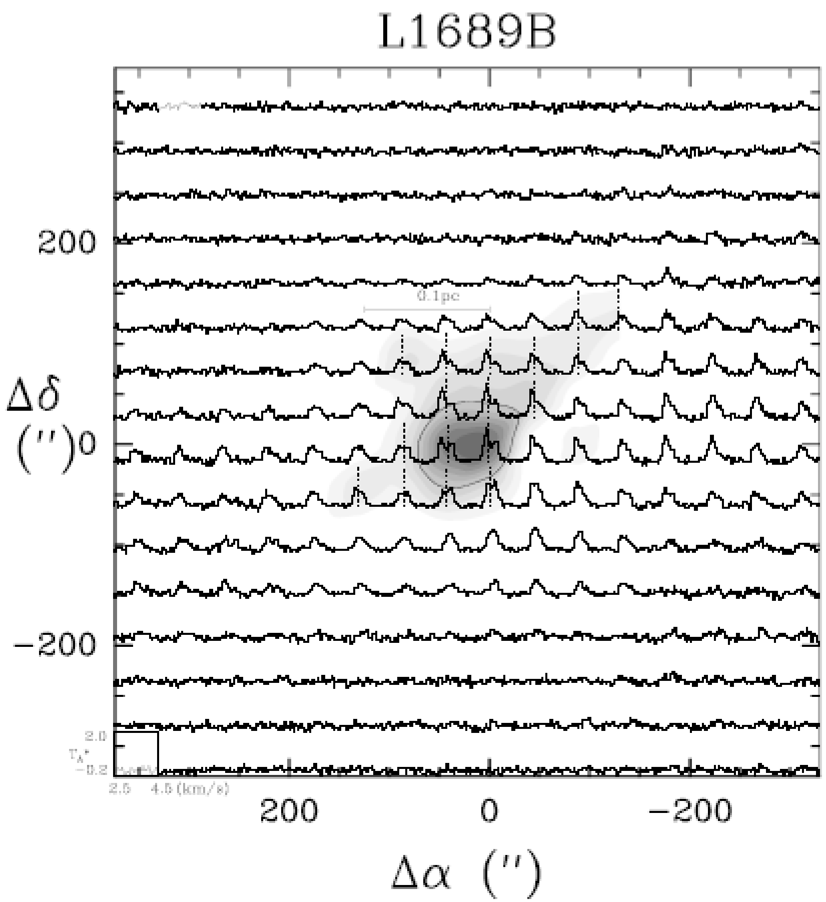


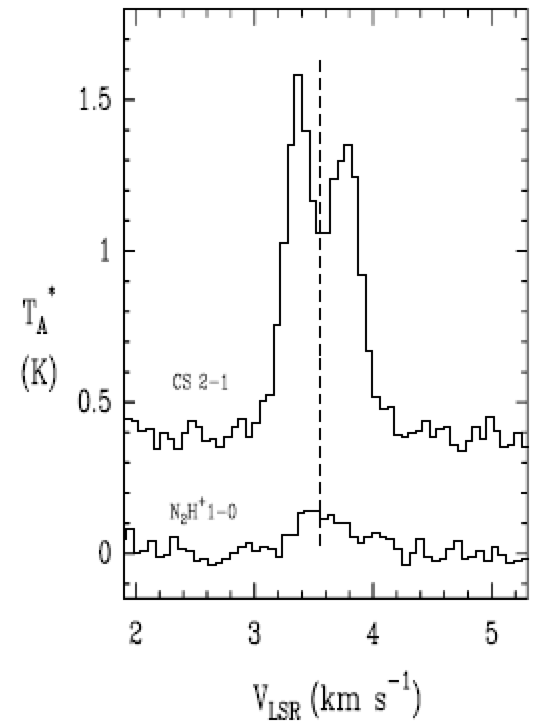
Aquila Column density map with Hershel/PACS :
~541 starless cores (c.f 38 cores from LM catalog) (Konyves et al. 2011)

Signature of gas infalling motions



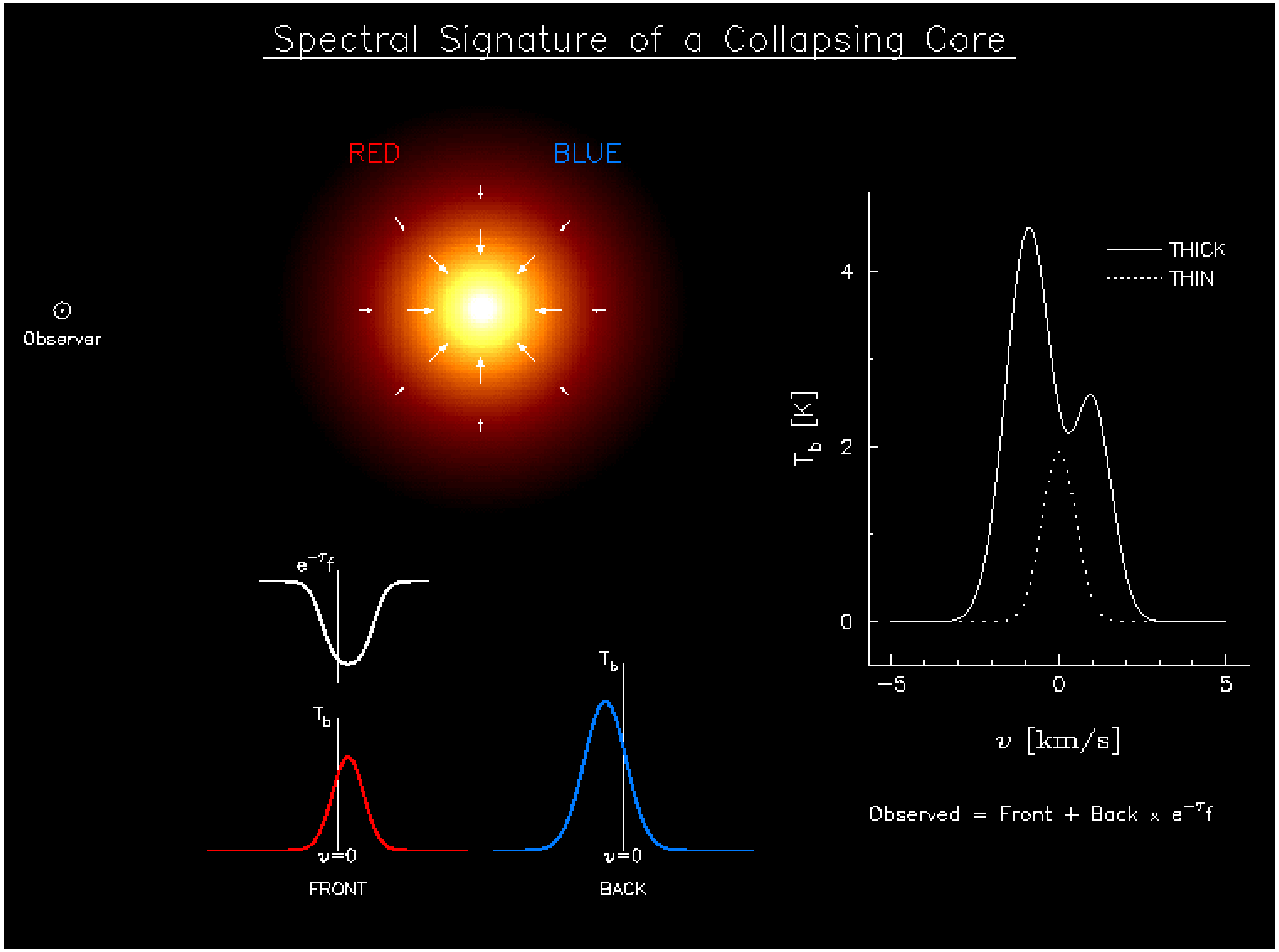
Shirley + (2000)
: 850 μm map





Lee + (1999, 2001, 2004), Sohn + (2007)

Spectral Infall Asymmetry in starless cores



-Optically *thick* high density tracers : HCN 1-0, CS 2-1, 3-2, HCO+, H2CO lines

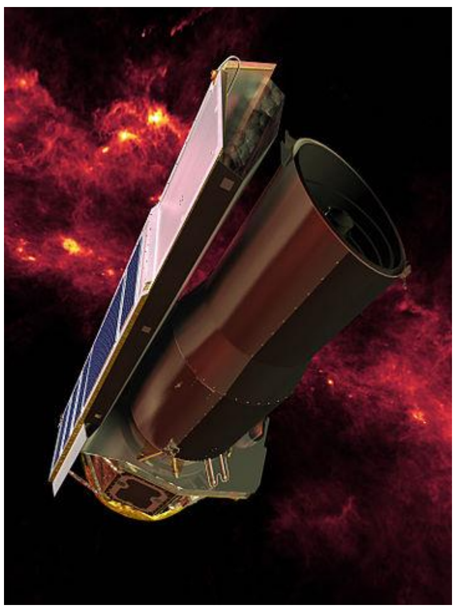
- Optically *thin* tracers; Isotopologue lines such H13CO+, C34S lines, or N2H+ line

Courtesy by J. Williams

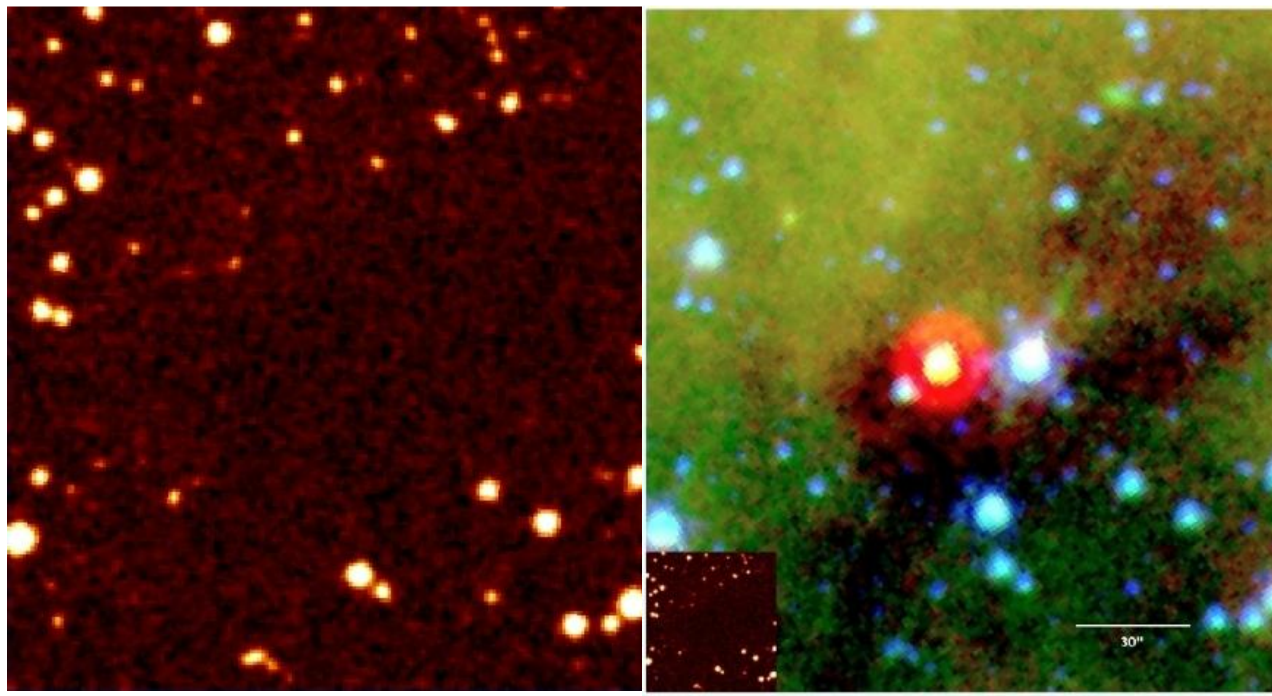
Spitzer's Observations

:Discovery of Very Low Luminosity Objects (VeLLOs)

- Deeply "embedded" faint ($L_{int} < 0.1\ L_{\odot}$) objects in dense cores discovered by ***Spitzer*** that have not been detected from previous space missions such as IRAS or ISO.



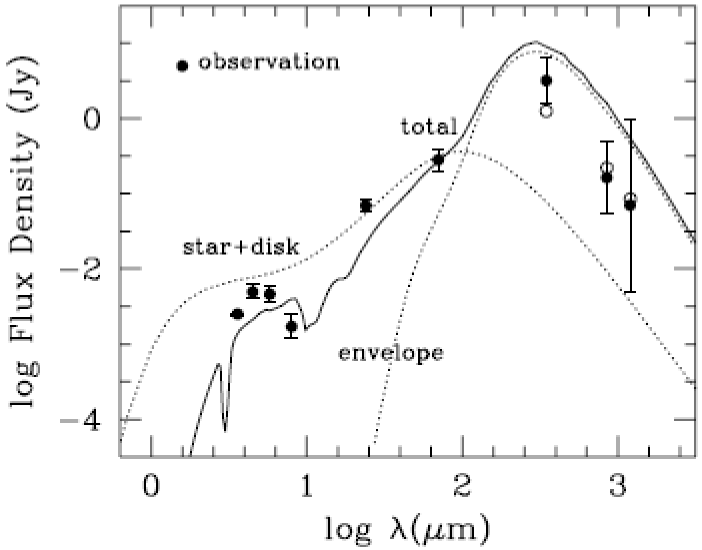
Launching in 2003
D=0.85 m, 3 ~ 180 μm



DSS-R band (left)and Spitzer 3color image (Right :3.6 μm-B, 8.0 μm-G, and 24 μm-R) for L1014-IRS (Young et al. 2004)

Astronomical Importance of VeLLOs ?

L328-IRS, Lee et al. 2009



- Their physical properties (SED, T_{bol}) are like protostars, but their luminosity is an order of magnitude fainter than the accretion luminosity that the lowest mass protostar can produce by standard star formation model of Shu et al. (1987)

e.g., Accretion Luminosity by a protostar with M=0.08 $M_\odot$ and R~3$R_\odot$:

$L_{acc}= GM_* \dot{M}_{acc}/2R \sim 1.6\ L_\odot$ (assuming $\dot{M}_{acc} \sim 2 \times 10^{-6}\ M_\odot\ yr^{-1}$)

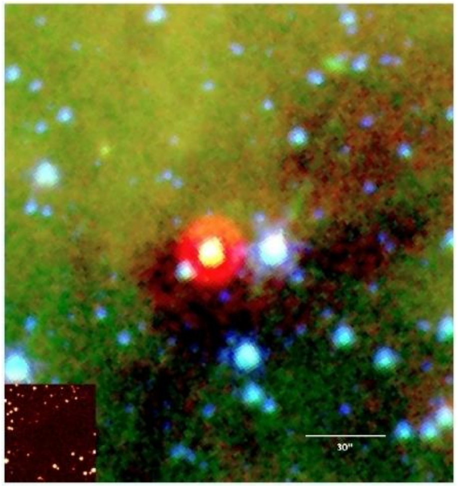
$>> \sim 0.1 L_\odot$ (Dunham et al. 2008)

- *An extreme case of luminosity problem* by Kenyon et al. (1990)

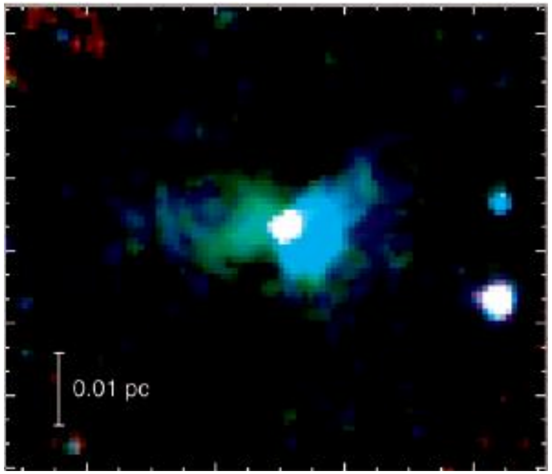
- Some of VeLLOs may be good candidates of proto-BDs with small M_* and low $\dot{M}_{acc}$, giving new constraints in the formation of sub-stellar objects !!

VeLLOs Discovered by Spitzer

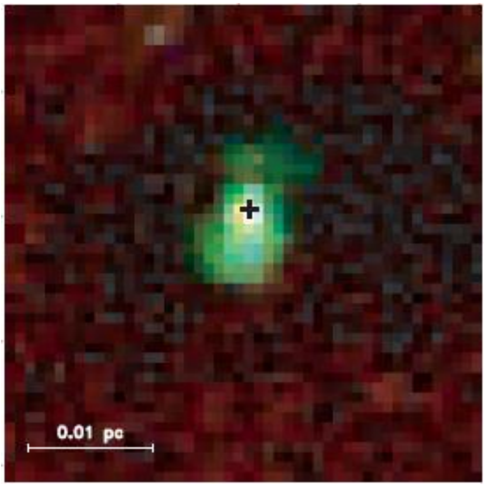
L1014-IRS : Lint ~0.09$L_\odot$
(Young et al. 2004)

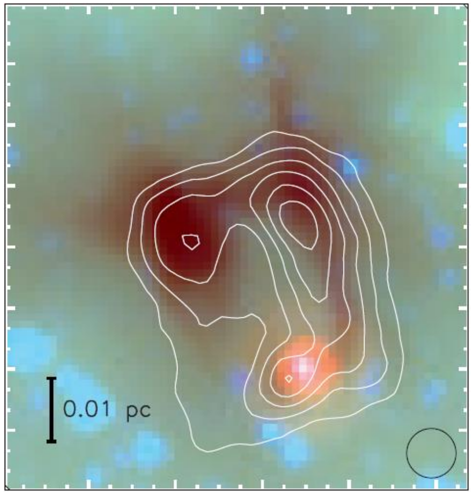


L1521F-IRS : Lint ~0.06$L_\odot$
(Bourke et al. 2006)

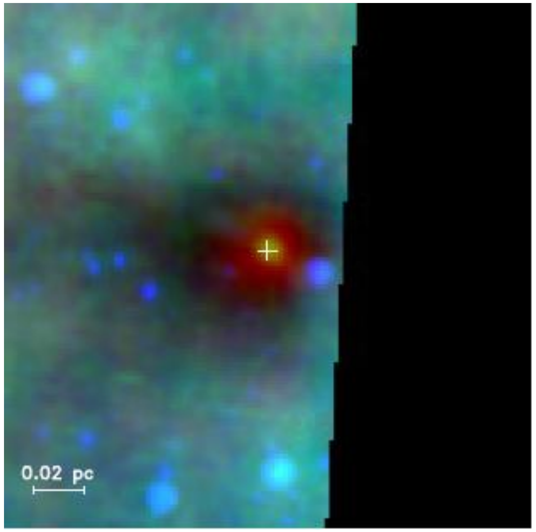


IRAM04191+1522: Lint ~0.08$L_\odot$
(Dunham et al. 2006)

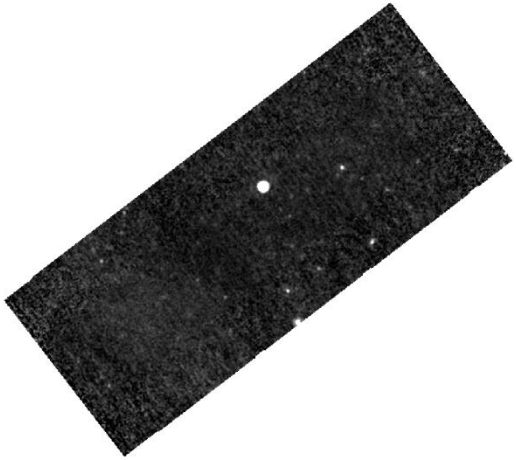




L328-IRS : Lint ~0.09$L_\odot$
(Lee et al. 2009)



L673-7-IRS : Lint ~0.04$L_\odot$
(Dunham et al. 2010)



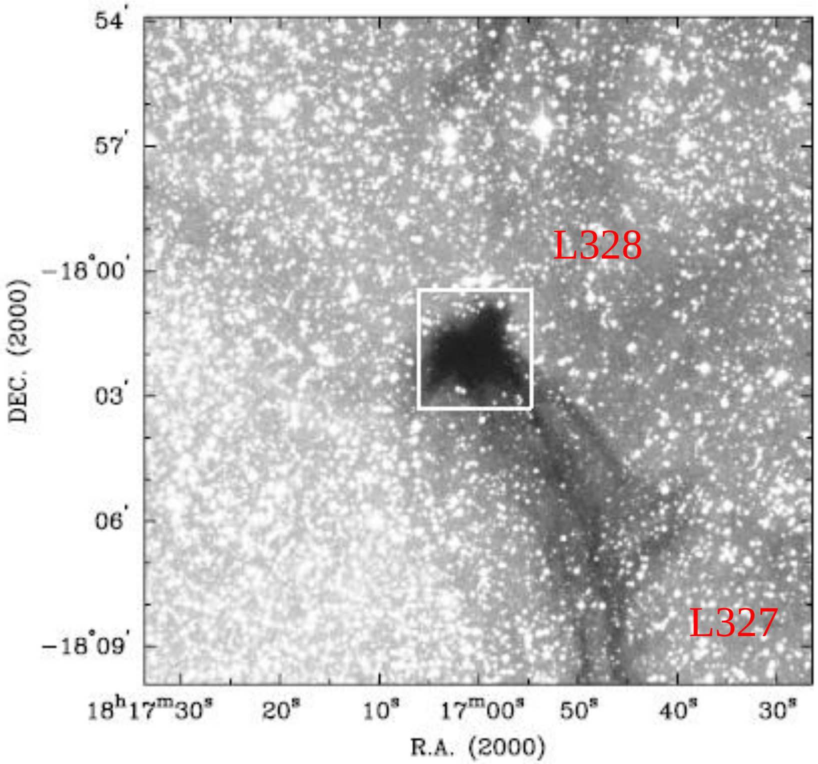
L1148-IRS : Lint ~0.08-0.13 $L_\odot$
(Kauffmann et al. 2011)

A Dense Molecular Core L328 and a VeLLO

- Located between the Ophiuchus and the Aquila Rift

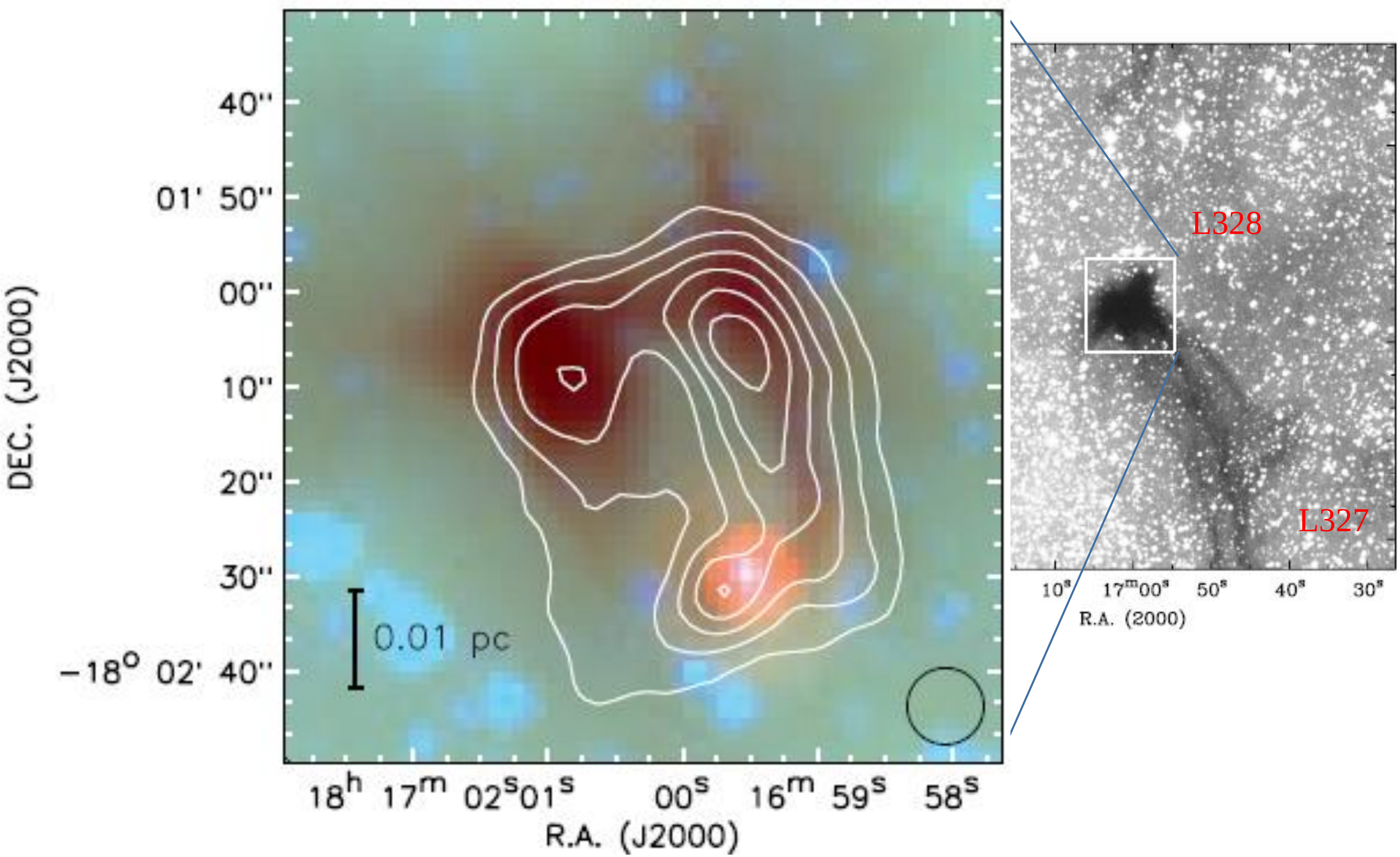
- A dark part of ~ 2 acrmin in diameter and less opaque tails of 15 arcmin long extending to the SW

- Adopted distance ~217 pc (Maheswar, Lee, & Sami 2011)



Optical Dss-red image
(Lee et al. 2009)

A Dense Molecular Core L328 and a VeLLO



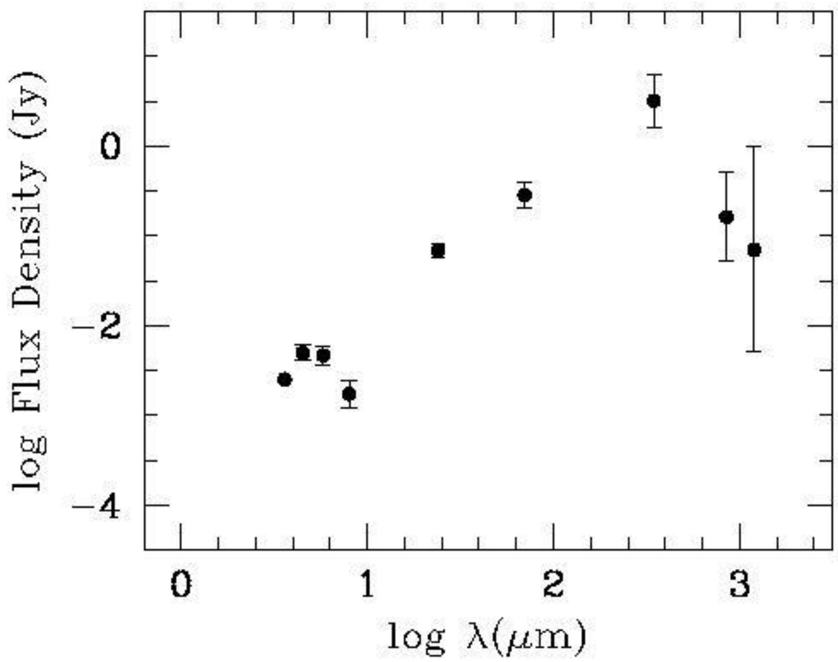
Physical Properties of L328-IRS

- Infrared slope
  $\alpha_{IR} = d\log(\lambda F_\lambda) / d\log \lambda$ between 3.6 ~ 24 μm (Lada ad Wilking 1984, Lada 1987)
  ; $\alpha_{L328IRS} = 0.61(+-0.63)$
  → Class I protostar

- T_{bol} ~ 44 K (< 70 K)
  → Class 0

- $L_{\geq 350\,\mu m} / L_{bol}$ ~0.72 (>> 0.02)
  → Class 0
  $L_{bol} \sim 0.22\, L_\odot$ (at d ~ 217 pc)

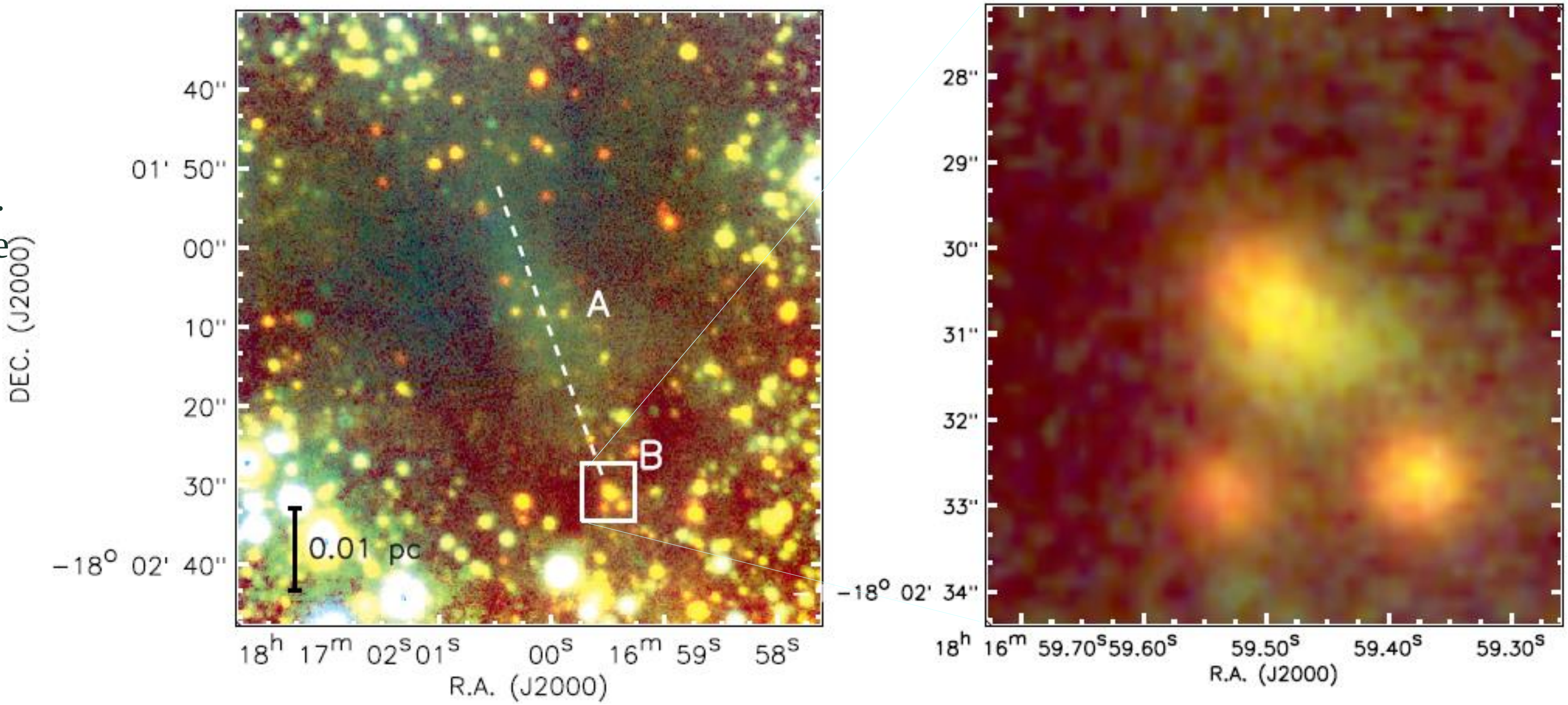
- $L_{int} = 0.04 - 0.06\, L_\odot$



→ *A Class 0 type Protostar or Proto-brown dwarf ?* (Lee + 2009)

Hints for Outflow Activity in NIR

JHKs Obs. with Baade 6.5m telescope (Lee et al. 2009)



- Fan shaped nebulosity of L328-IRS
- Elongated cavity of 30 arc-second size
- A line bisecting the elongated cavity and L328-IRS also passes through the nebulosity of L328-IRS
- Broad line widths of N_2H^+ toward the cavity structure (Crapsi et al. 2005); some turbulent effects produced by the outflow activity ?

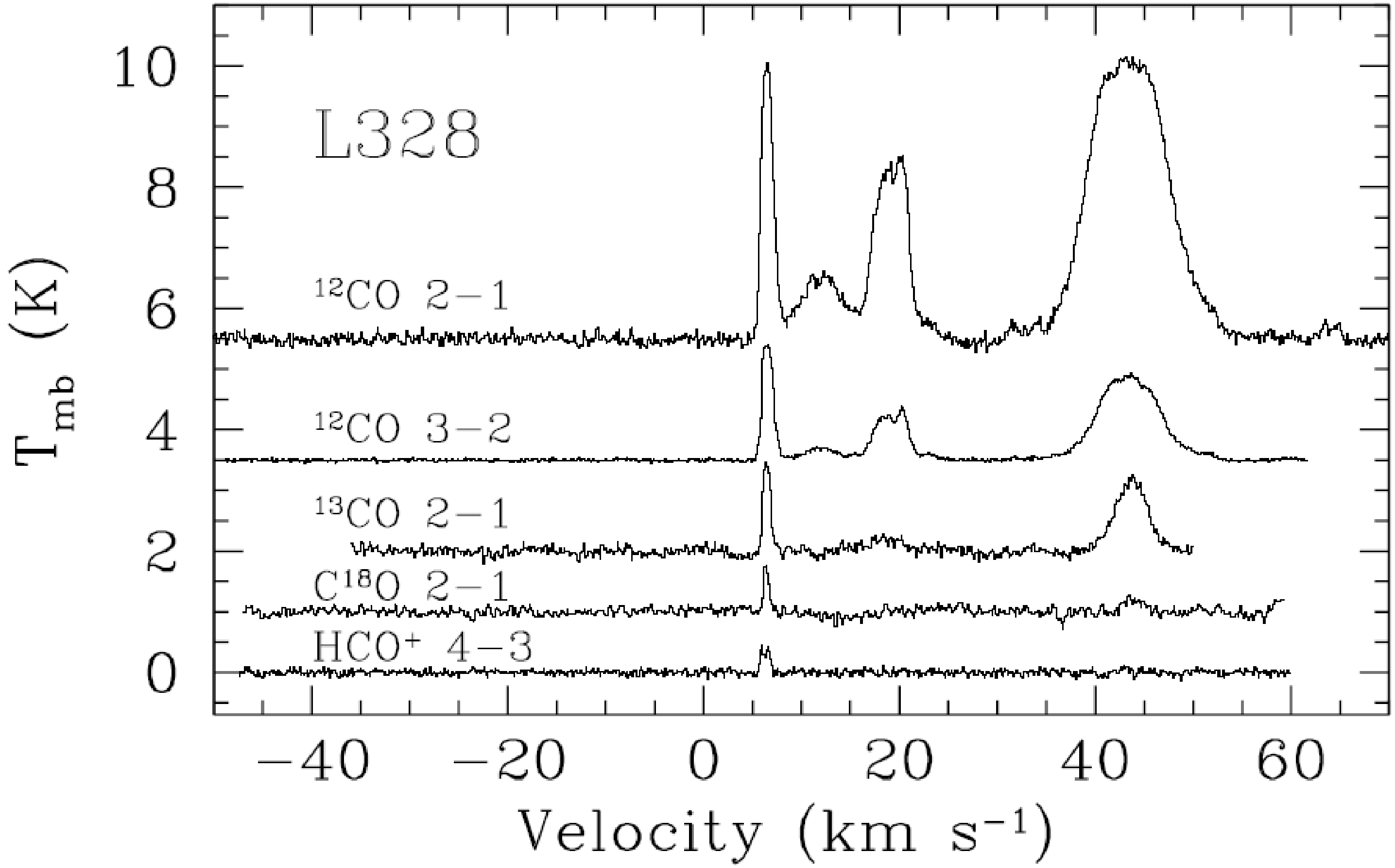
Molecular Line Observations of L328

CO, 13CO, C18O 2-1 lines with SRAO 6m, ~48” beam at 230 GHz (Dec. 2008 - May 2009)

CO 3-2, HCO+ 4-3 lines with ASTE 10m, 22” beam at 350 GHz (June 9th, 2011)

HCN 1-0, N2H+ 1-0 lines with KVN 21m, 30” beam at 100 GHz (Jan. 2012 -March 2013)

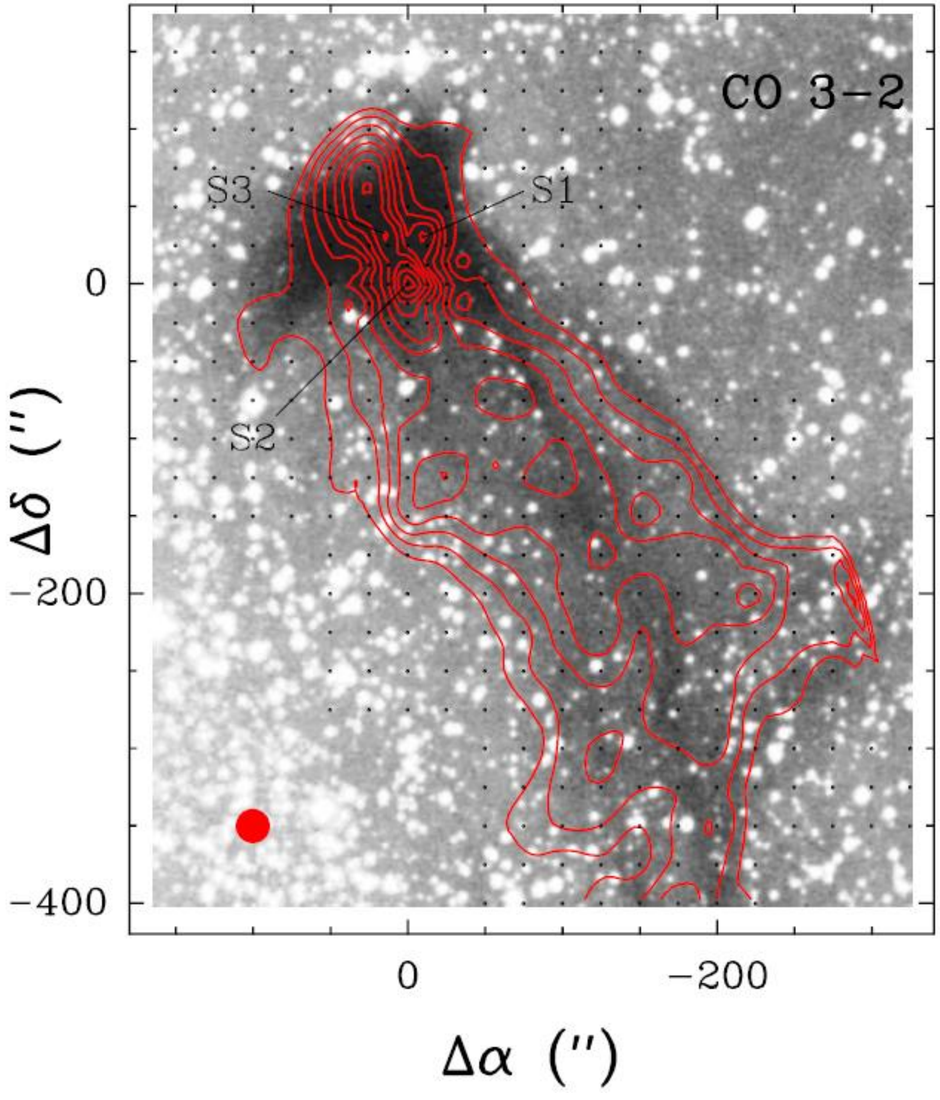
Average Line Spectra toward L328



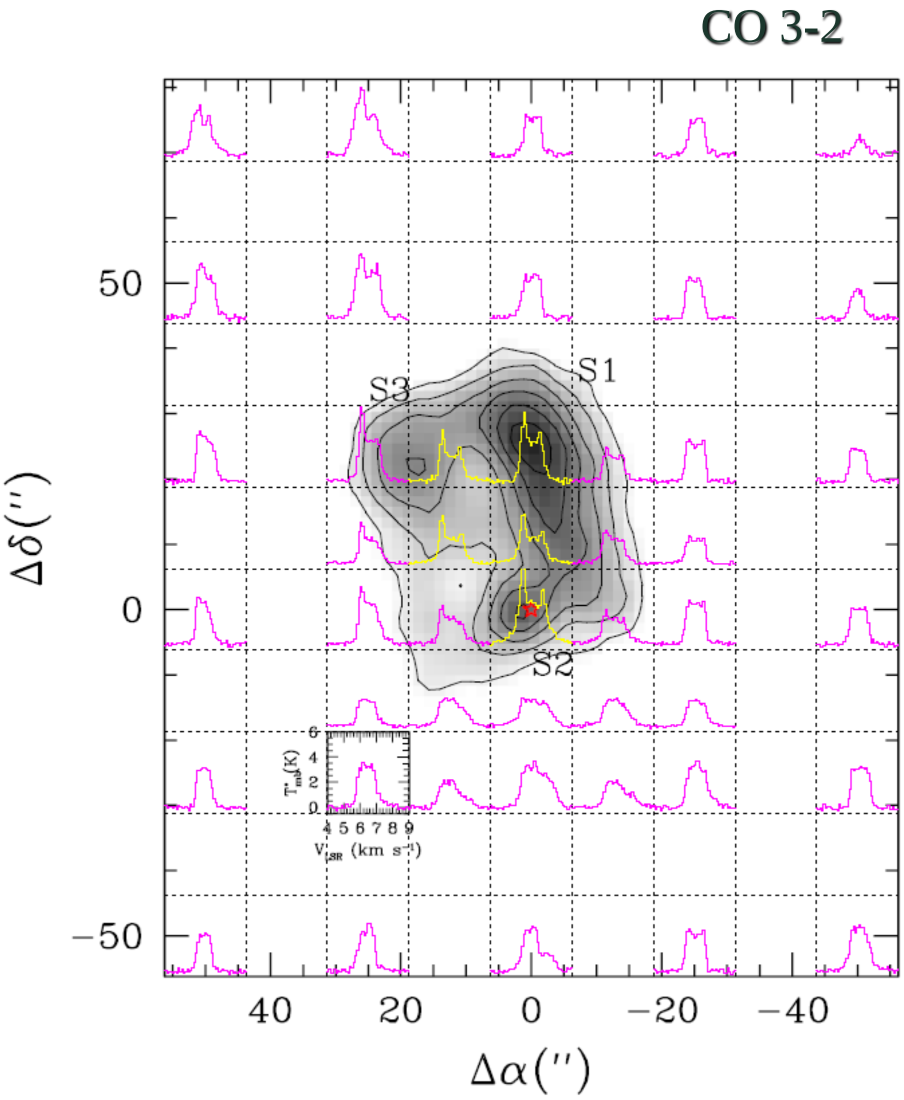
- Multi components over Galactic plane
- L328 core ~6.5 km/s component

CO distribution of L328

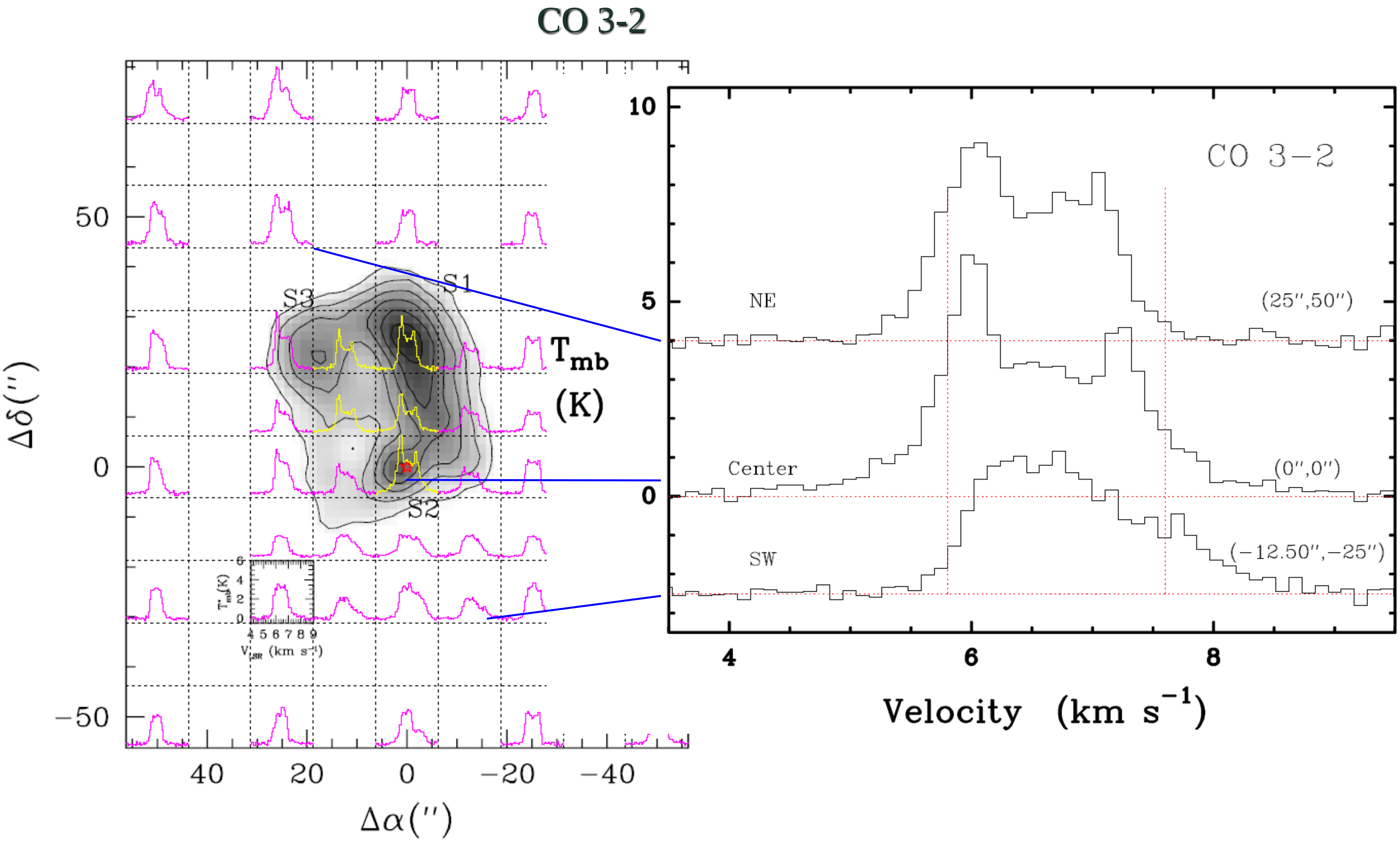
- Delineates optically obscured regions



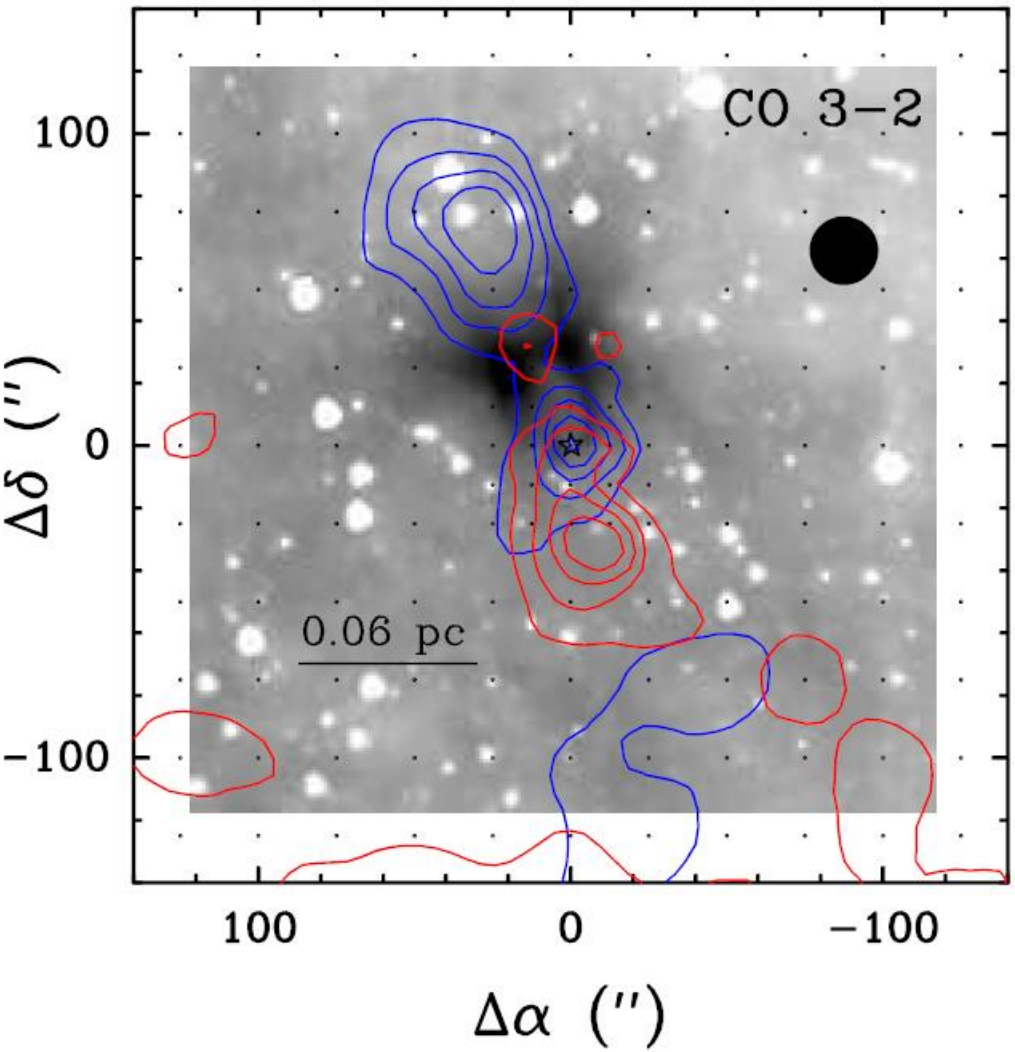
CO outflow of L328-IRS



CO outflow of L328-IRS



CO bipolar outflow from L328-IRS



Mass Accretion rate

Under assumption that jet/wind energy is due to the gravitational energy released by mass accretion onto L328-IRS

$$\dot{M}_{\rm acc} = \frac{1}{f_{\rm ent}} \frac{\dot{M}_{\rm acc}}{\dot{M}_W} \frac{1}{V_W} F_{\rm outflow} \sin i/\cos^2 i \ \ M_\odot \ {\rm yr}^{-1},$$

$$F_{\rm outflow} = (P_{\rm outflow}/\tau_d)$$

- $P_{outflow} = M_{outlow} \times V_{flow}$
- V_{flow_blue} ~ 1.2 km/s
- V_{flow_red} ~ 1.4 km/s
- T_d>~6.4 10^4 yrs

~3.6 10^{-7} $M_\odot$ yr^{-1}

- f_{ent} ~0.18 (0.1 - 0.25)
- $\dot{M}_w/\dot{M}_{\rm acc} \sim 0.1$
- V_w (jet/wind vel.) ~ 150 km/s (Bontemps et al. 1996)
- Optical depth correction of ~3.8
- T_{ex} ~ 100 K (van Kempen + 2009)
- i = 57°.3

Central Mass

- *A mass accreted* during the dynamical time of 6.4 10^4 years, with an assumption of about 10% mass loss through jet or wind (Bontemps et al. 1996) : ~0.02 $M_\odot$

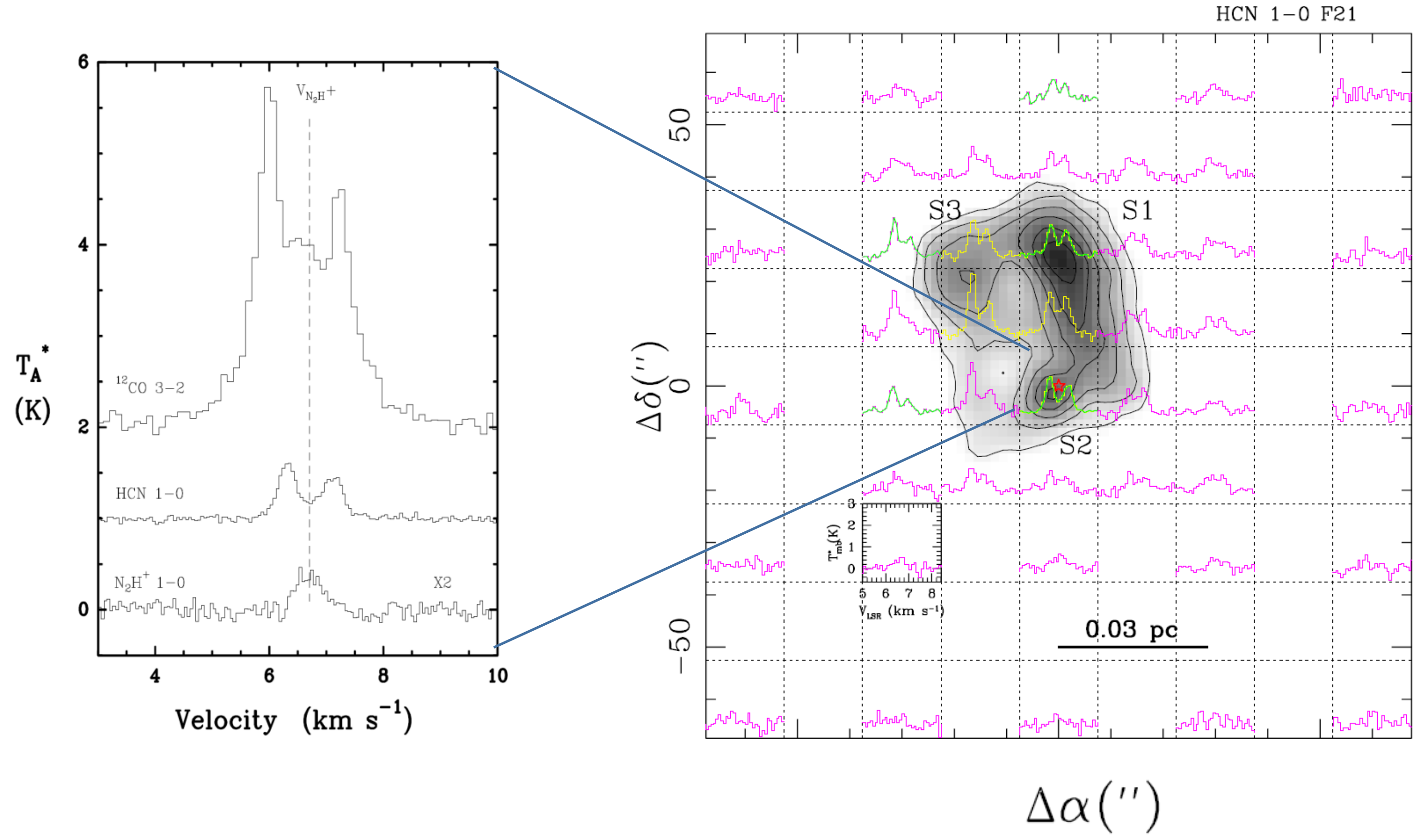
- *A mass to be accreted* during the Class 0 lifetime of ～0.16 Myr (Evans et al. 2009) : ~0.05 $M_\odot$

$$M_{\rm env} = \frac{S_\nu D^2}{B_\nu(T)\kappa_\nu} \sim 0.09\ M_\odot$$

- S_ν is the flux density at 350 μm
- B_ν (T) is the Planck function at temperature (T~16 K from a gray body least squares fit)
- κ_ν is the dust opacity of OH5

➔*L328-IRS may be hard to grow to a normal star as massive as 0.08 $M_\odot$ and is likely a good candidate of a proto-brown dwarf .*

Infall Signatures toward L328 and L328-IRS



- Extended infall asymmetry in HCN 1-0 and CO 3-2 in L328
- Infall asymmetry in various density tracers such as HCN 1-0, CO 3-2, and in N2H+ 1-0 toward L328-IRS

==> Global contracting motions, as do cores associated with normal stars.

Jeans Length

- Jeans length of L328

$$L_j \approx (15\,kT / 4\pi G \mu_{H_2} m_{\mathrm{H}} \rho_o)^{1/2}$$

$$\sim 0.027 \text{ pc}$$

~Similar to projected separation (0.02 ~0.03pc) among sub-cores in L328 !!

The proto-brown dwarf L328-IRS is being made through a very similar process to that of normal stars

Summary

L328-IRS is one of the best candidates for a proto-brown dwarf and the best example testing the idea that a brown dwarf forms like a normal star.

However, $\dot{M}_{acc}$ and M_* are very uncertain.

➔Inconclusive

➔***ALMA observations may help!***

ALMA Observations of L328+IRS

- Observations (Cycle 2)

- Continuum + 12CO, 13CO, C18O 2-1, and CH3OCHOA 17-16 lines
- Configuration: C34-6 &C34-2
- Resolution = 0.33´´ x 0.25´´ (87 AU x 37 AU) at 230 GHz
  1.51´´ x 0.84´´
- A maximum recoverable scale of 11.4´´
- Rms of combined data
  ~4.0 mJy/beam/0.096km/s for C18O2-1
  ~0.04mJy/beam for continuum (~7.5 GHz bandwidth)
- Data last delivered on August 2015

Alternative (indirect) mass estimation of the central source

1. Estimate M_* by assuming that $L_{acc} = G M_* \dot{M}_{acc}/2R$ is responsible for its internal luminosity of ~$0.05L_\odot$

2. Estimate M_{acc} (~$\tau \dot{M}_{acc}$) assuming that the mass accreted in a constant rate during the dynamical time.

Mass Accretion rate

Under assumption that jet/wind energy is due to the gravitational energy released by mass accretion onto L328-IRS

$$\dot{M}_{\rm acc} = \frac{1}{f_{\rm ent}} \frac{\dot{M}_{\rm acc}}{\dot{M}_W} \frac{1}{V_W} F_{\rm outflow} \quad \sin i / \cos^2 i \ \ M_\odot \ {\rm yr}^{-1},$$

$$F_{\rm outflow} = (P_{\rm outflow}/\tau_d)$$

- τ_d separately determined for each blob

- f_{ent} ~0.18 (0.1 - 0.25)
- $\dot{M}_w/\dot{M}_{\rm acc} \sim 0.1$
- V_w (jet/wind vel.) ~ 150 km/s (Bontemps et al. 1996)
- Optical depth corrected
- T_{ex} ~ 9.9 – 30K from CO2-1
- i = determined

Mass accretion rate and alternative mass estimation of the central source

- $\dot{M}_{acc} \sim 8.2\ 10^{-7}\ M_{\odot}\ yr^{-1}$ when $i=65^{o}$

  c.f.) Single dish value : $\dot{M}_{acc} \sim 6.3\ 10^{-7}\ M_{\odot}\ yr^{-1}$ when $i=65^{o}$

1. $M_{*} \sim 0.013\ M_{\odot}$ if the internal luminosity of $\sim 0.05 L_{\odot}$ is mainly from accretion process in L328-IRS (from $L_{acc} = G\ M_{*} \dot{M}_{acc}/2R$)
2. $M_{acc} (\sim \tau_{acc}\ \dot{M}_{acc}) \sim 0.023\ M_{\odot}$ if $\dot{M}_{acc}$ was constant accretion during $\tau_{acc} \sim 3\ 10^{4}$ yrs.

Tempted to conclude that L328-IRS is likely a proto-BD, but…

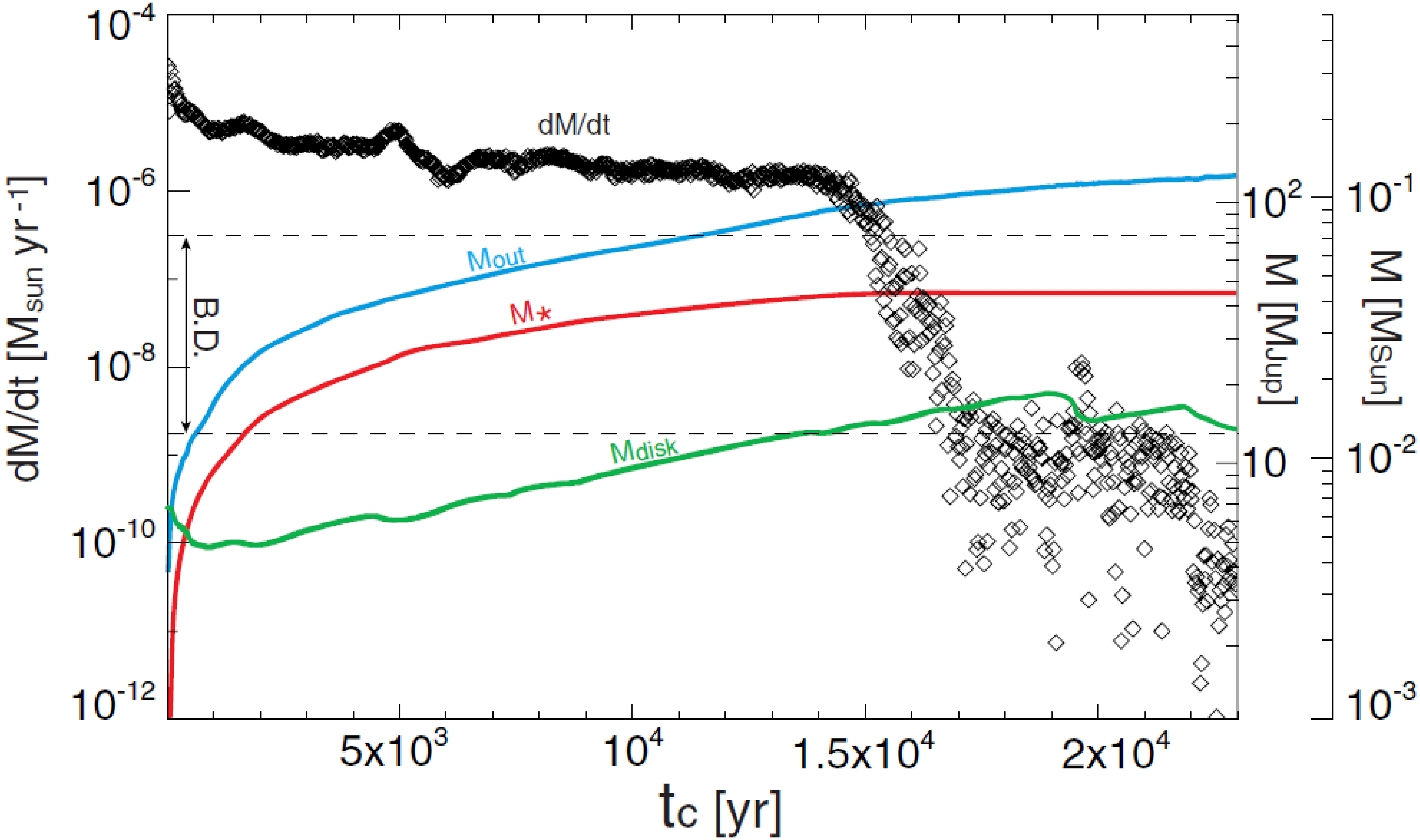
Our mass estimation can be very much subject to uncertainties

- Various uncertain parameters;

the entrainment efficiency (f_{ent}), the ratio of mass accretion rate to a wind/jet loss rate $\dot{M}_{acc}/\dot{M}_{V}$, jet/wind velocity ($V_w$), and other parameters involved in the blob mass estimation.

- $\dot{M}_{acc}$ may not be necessarily constant during the Class 0 phase (e.g., Machida + 2009, Machida and Hosokawa 2013)

➔ Direct kinematic estimation of M_* will be more helpful.



- Mass accretion rate during a model proto-BD phase from MHD (nested grid) simulation (Machida +2009)

Summary

- Conformation of L328-IRS as a bona fide proto-BD is inconclusive.

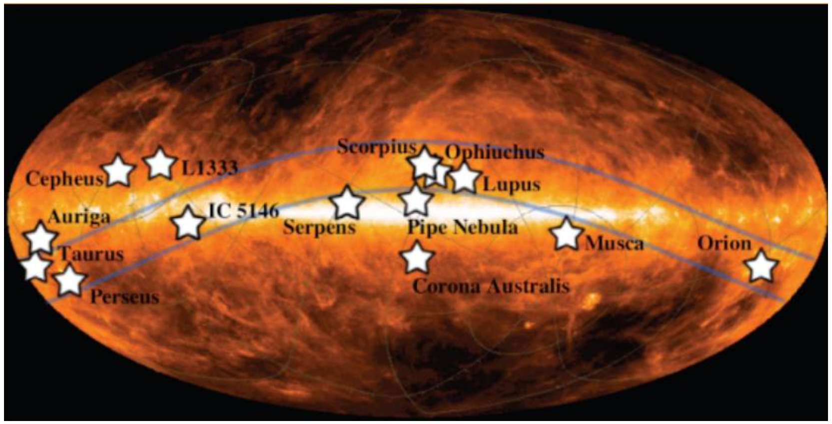
- ALMA observations of L328-IRS in other molecular lines which can trace inner most region within 60 AU will certainly help.

- A systematic ALMA survey of proto-BD candidates will be extremely useful for understanding the formation of the BDs.

Search for new VeLLOs

Works by M. Kim, Lee + 2016

The Spitzer, Herschel, and EAO-JCMT data for 18 clouds in Gould Belt (within d=500 pc)



- Spitzer's data from 3.6 to 70 μm

- c2d survey for Perseus; Serpens; Chamaeleon II; Lupus; Ophiuchus clouds
- The Spitzer Gould Belt Survey (GBS) for CMC, Chamaeleon I, Chamaeleon III, Musca, Lupus V, Lupus VI, Ophiuchus North, Aquila, CrA, Cepheus, and IC 5146 clouds
-Other Spitzer's surveys for the Taurus and the Orion clouds.

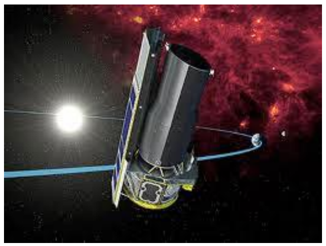
- Herschel's data at 70, 100,160, 250, 350, and 500 μm

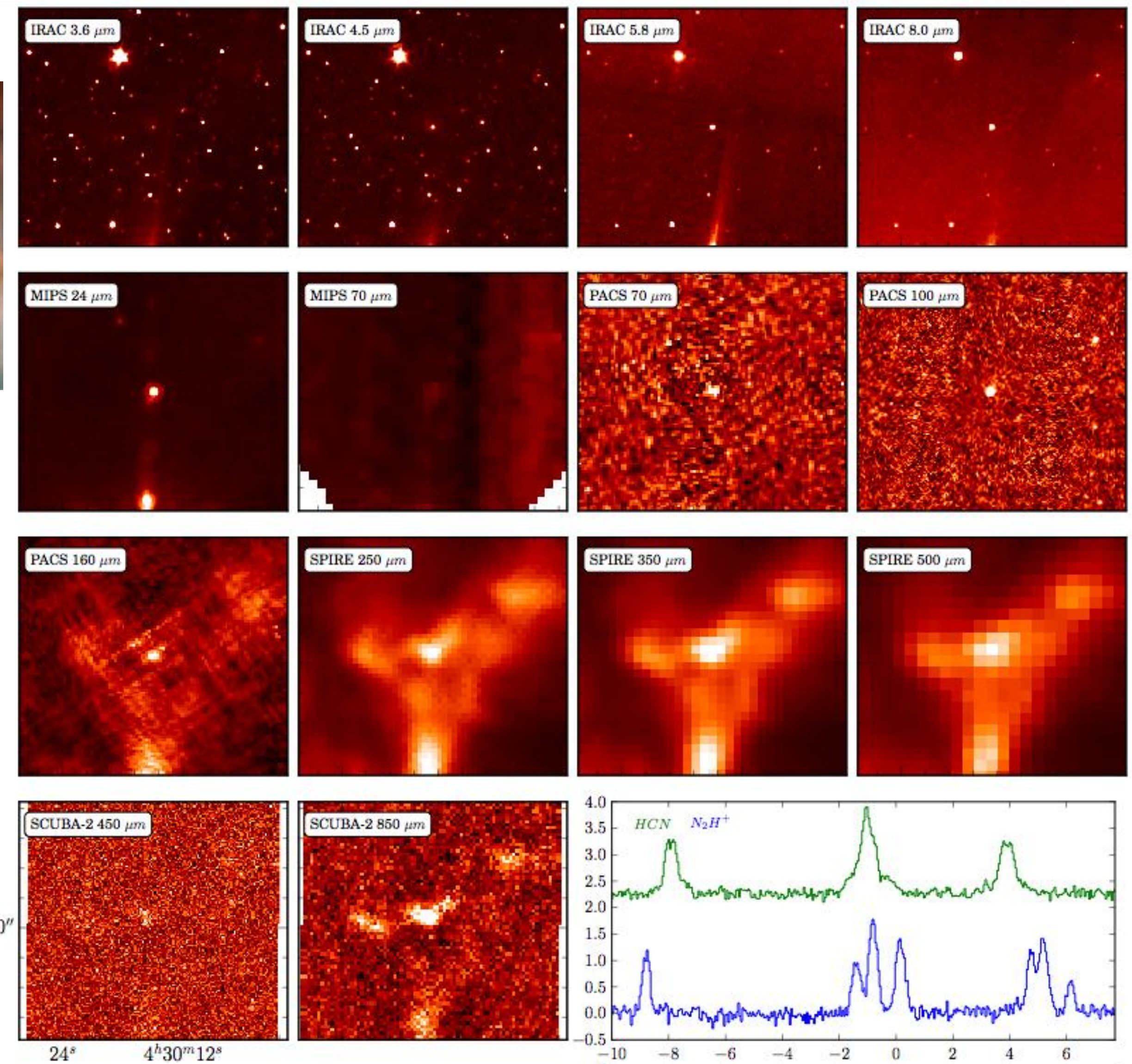
- Images from Herschel Science Archive for all GB clouds
  Photometry with CSAR (Cardiff Source-finding AlgoRithm)

- EAO-JCMT GBS SCUBA-2 data at 450 and 850 μm

- Images from JCMT Science Archive Archive for Perseus, Cepheus, IC 5146, Ophiuchus/Scorpius, Lupus, Serpens, Taurus-Auriga , Orion clouds
  Photometry with CSAR

79 New VeLLOs (In total 95 VeLLOs)!!





Outflow Survey of the VeLLOs with single dish telescopes (G.Kim, Lee + in prep.)

- Observations

- 68 VeLLOs in total
- 12CO, 13CO, C18O 2-1 lines

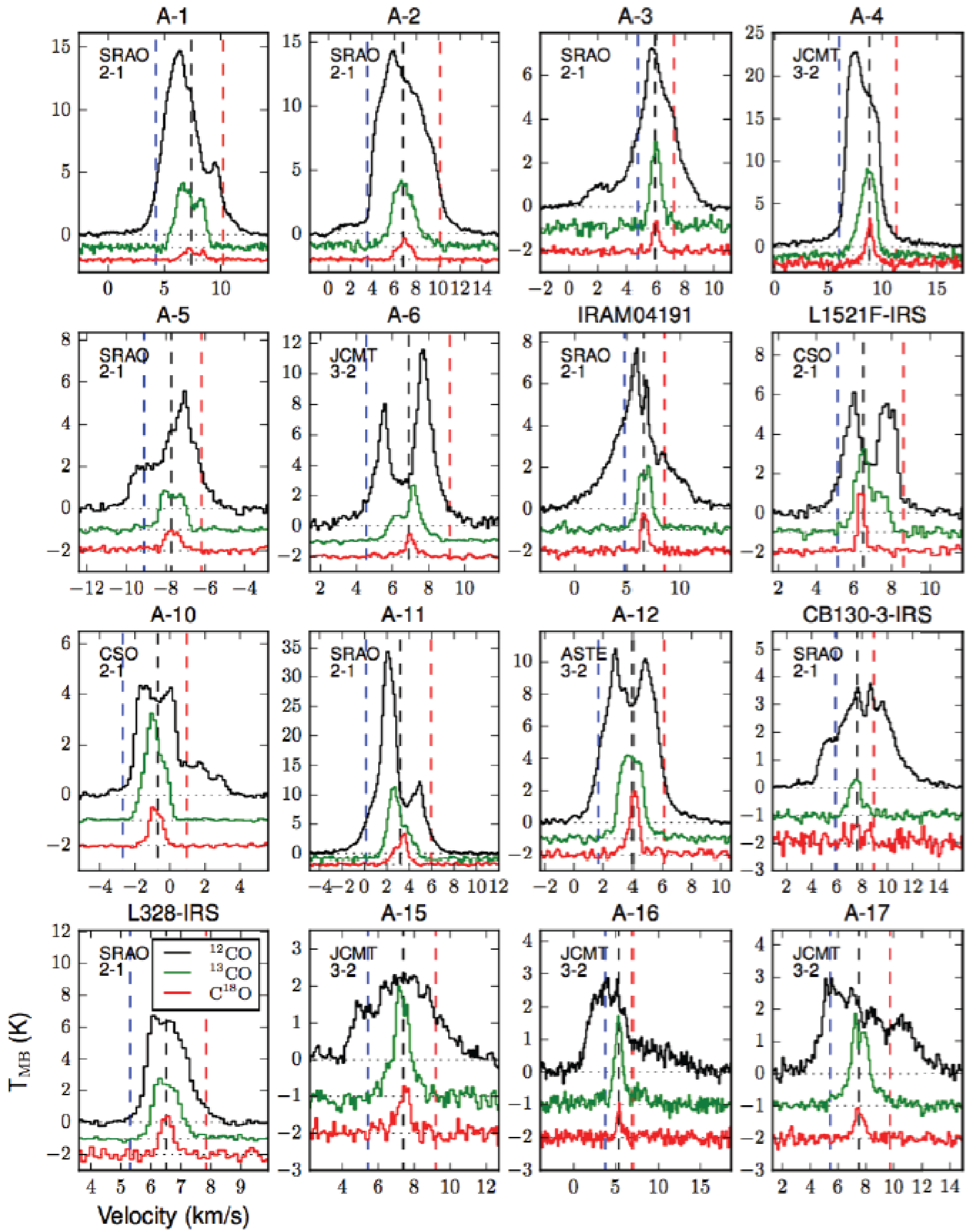
SRAO 6m Dec 2008 – April 2010

CSO 10.4m Oct., Nov. 2013, and Sept. 2014

- 12CO , 13CO, C18O 3-2 lines

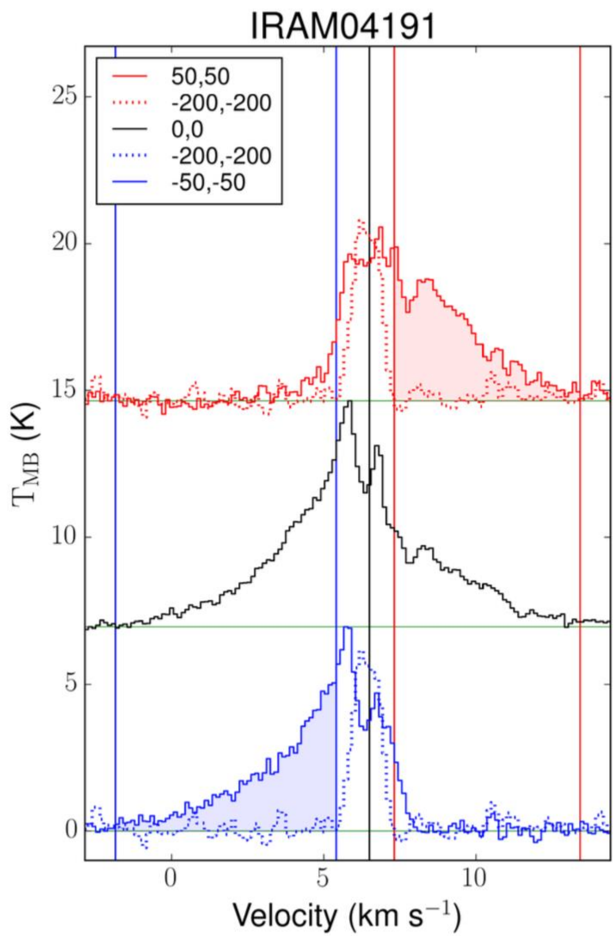
EAO-JCMT 15m Sept., Nov. 2015, March, April, June 2016

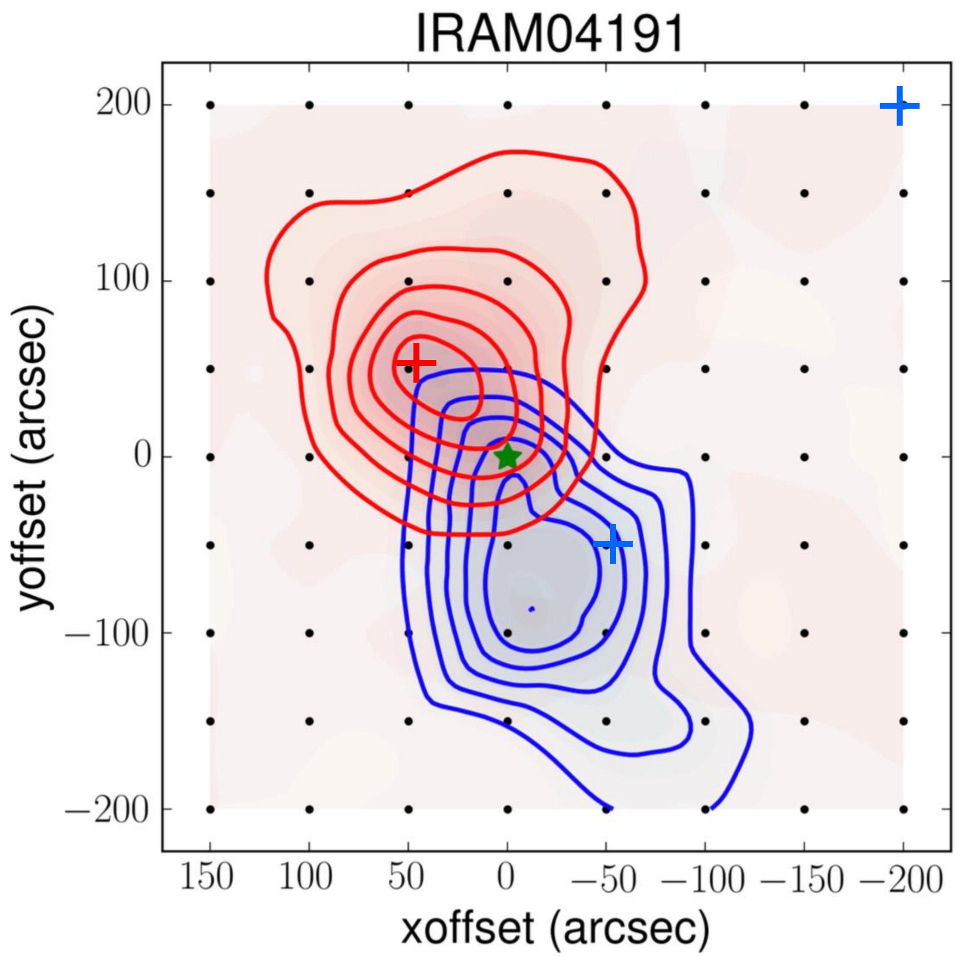
ASTE 10m Sept., June, Sept. 2014, Nov. 2015



56 of 68 VeLLOs show wing features !

Mapping Observations of 68VeLLOs





Conclusion

- Welcome to Astronomical world !

- Welcome to join our group for this adventurous study !