Forming Solar Mass Stars:
An Overview of Young Stellar Objects

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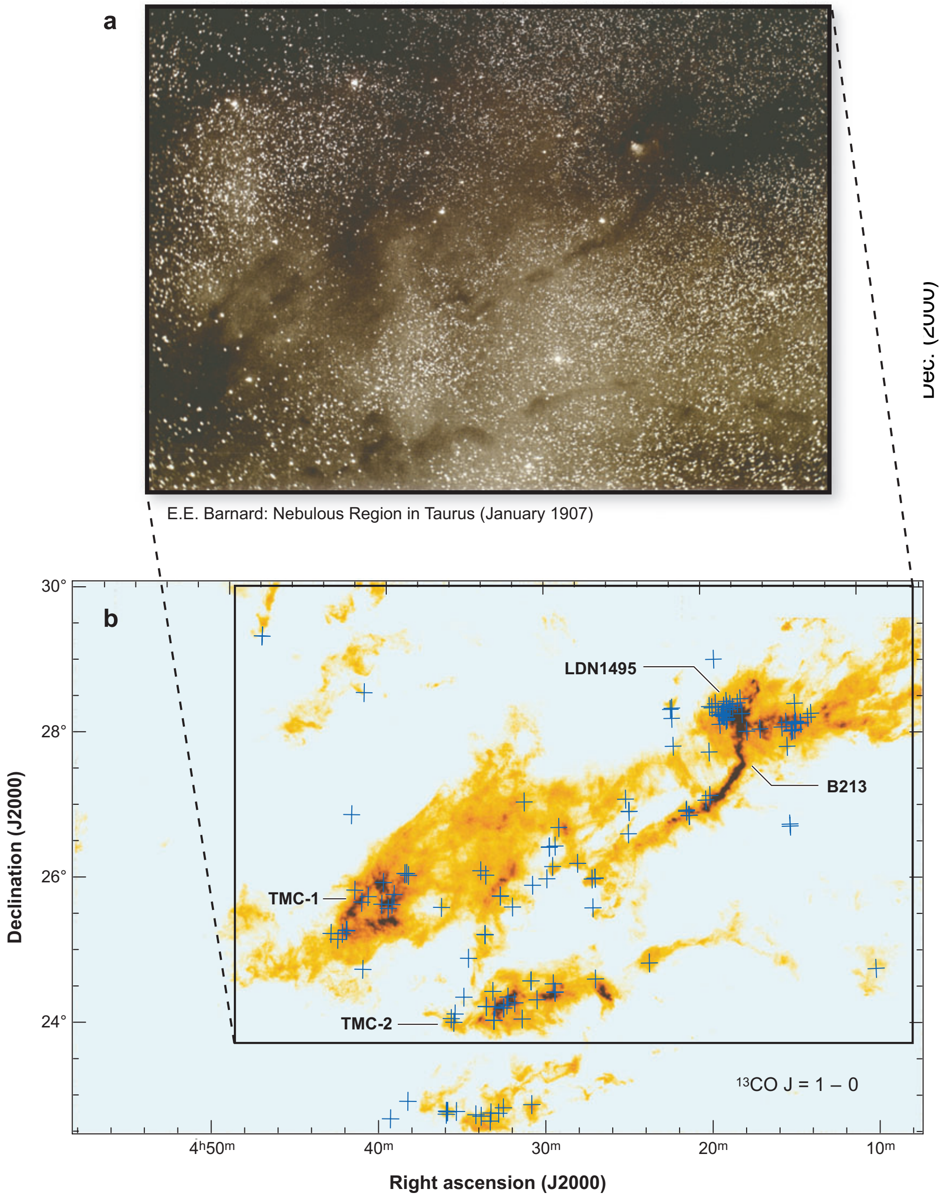
How do Solar Mass stars form?

- How do stars of ~1 M_{sun} form?
    - Masses from 0.08 M_{sun} to ~8 M_{sun}
    - Range of birth environments
    - Prospects for planet formation
- How did the Sun form?
    - Relics of the specific birth environment of the Sun
    - Imprint on the Solar System
- What can we learn from high angular resolution observations?

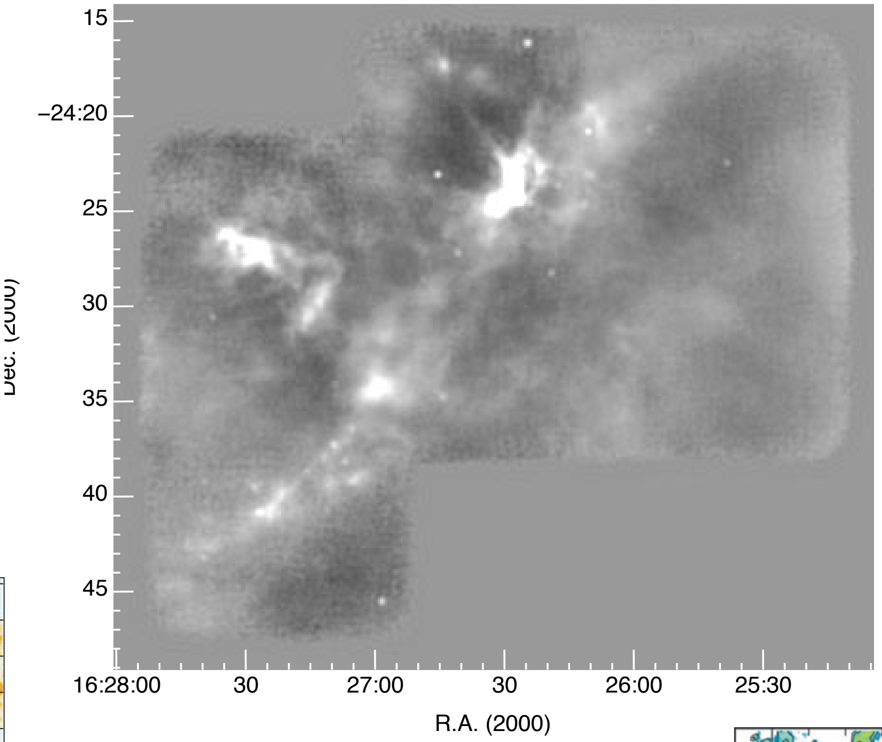
Route

- From interstellar clouds to the Initial Mass Function
- Properties of prestellar cores
- The standard picture of isolated, low-mass star formation
- Structure and classification of YSOs
- Protostellar feedback on YSOs: heating, shocks, and photo-processes
- Formation of accretion disks
- Characteristics and evolution of planet-forming disks
- Multiplicity and clustered star formation
- Conclusion: The formation of Solar Mass stars

From interstellar clouds to the Initial Mass Function

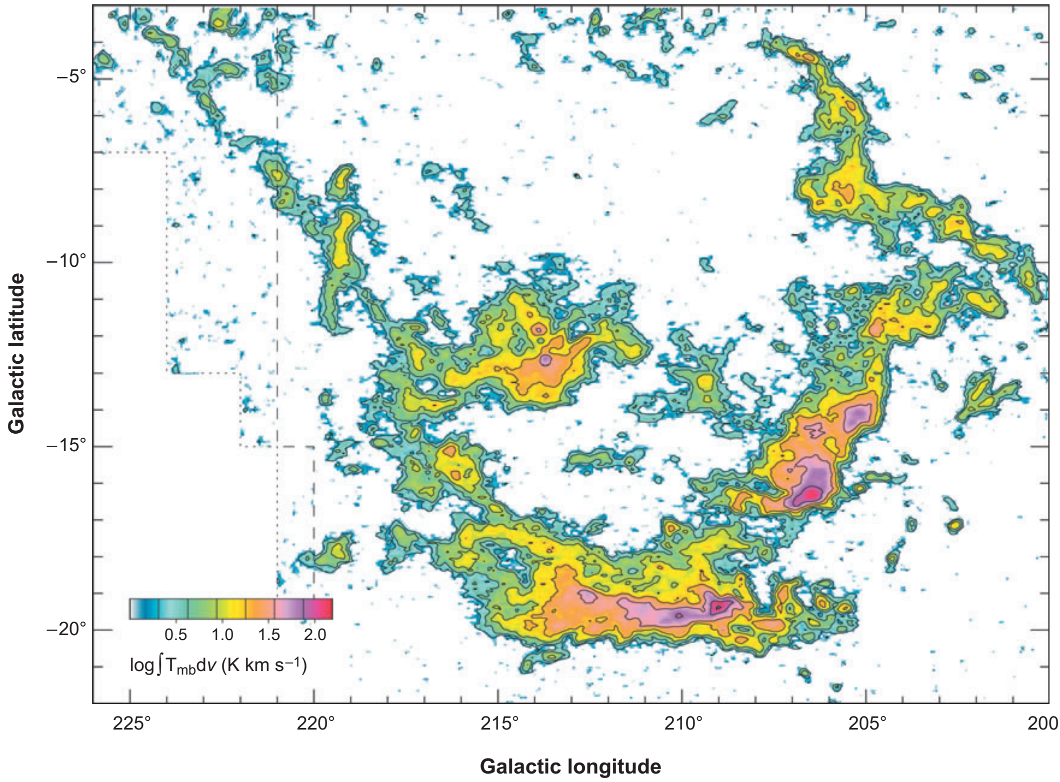


Taurus: extinction and ^{13}CO (from Bergin & Tafalla 2007)



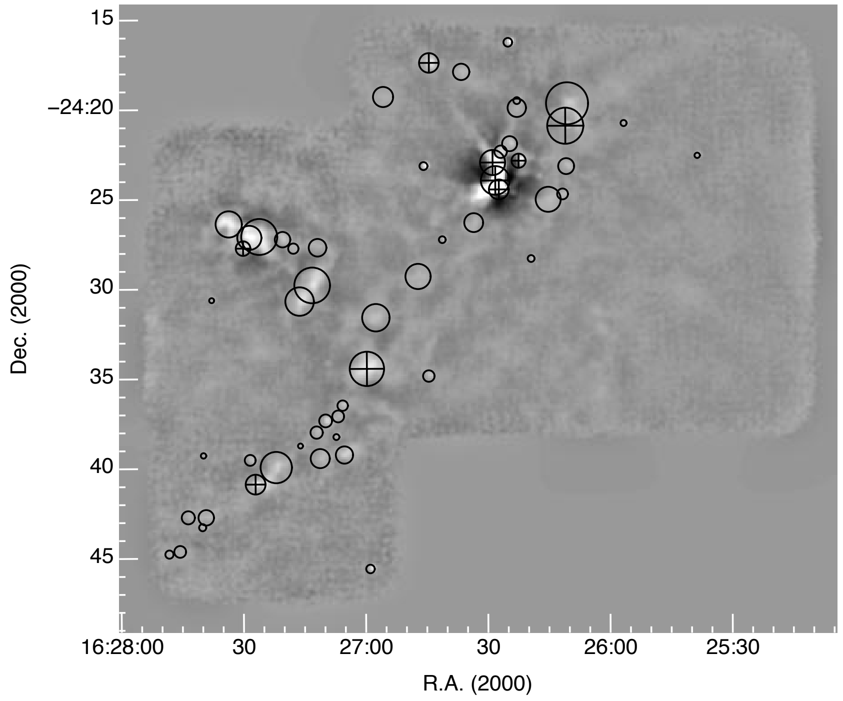
ρ Oph: 850 μm (Johnstone et al. 2000)

Orion and the Rosetta Nebula: ^{12}CO (from McKee & Ostriker 2007)

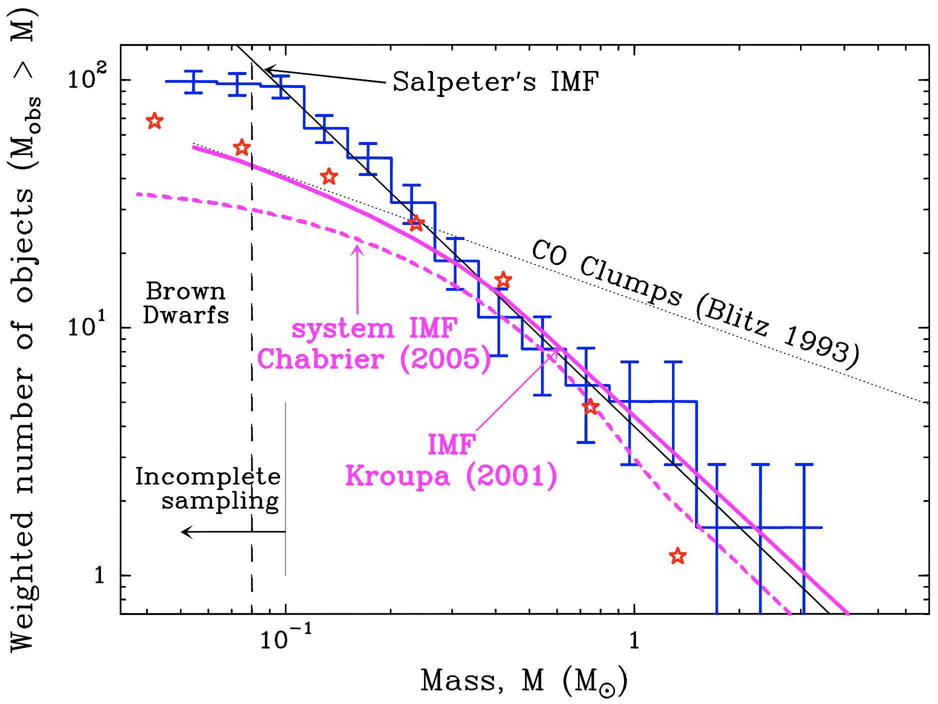


Hierarchical, filamentary cloud structure

From interstellar clouds to the Initial Mass Function

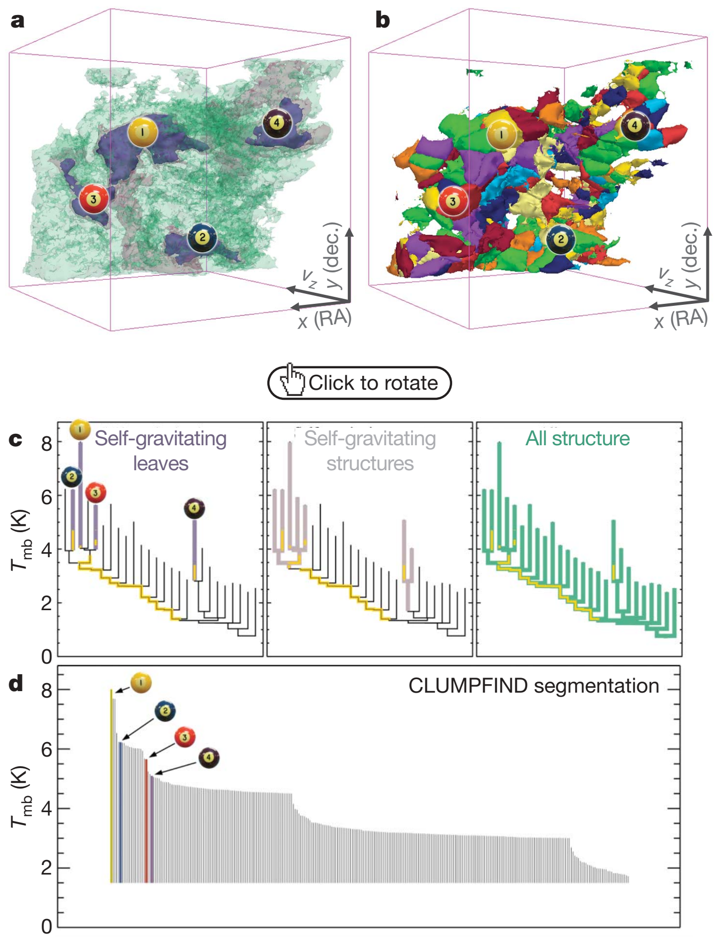


Johnstone et al. 2000



Motte et al. 1998; André et al. 2007

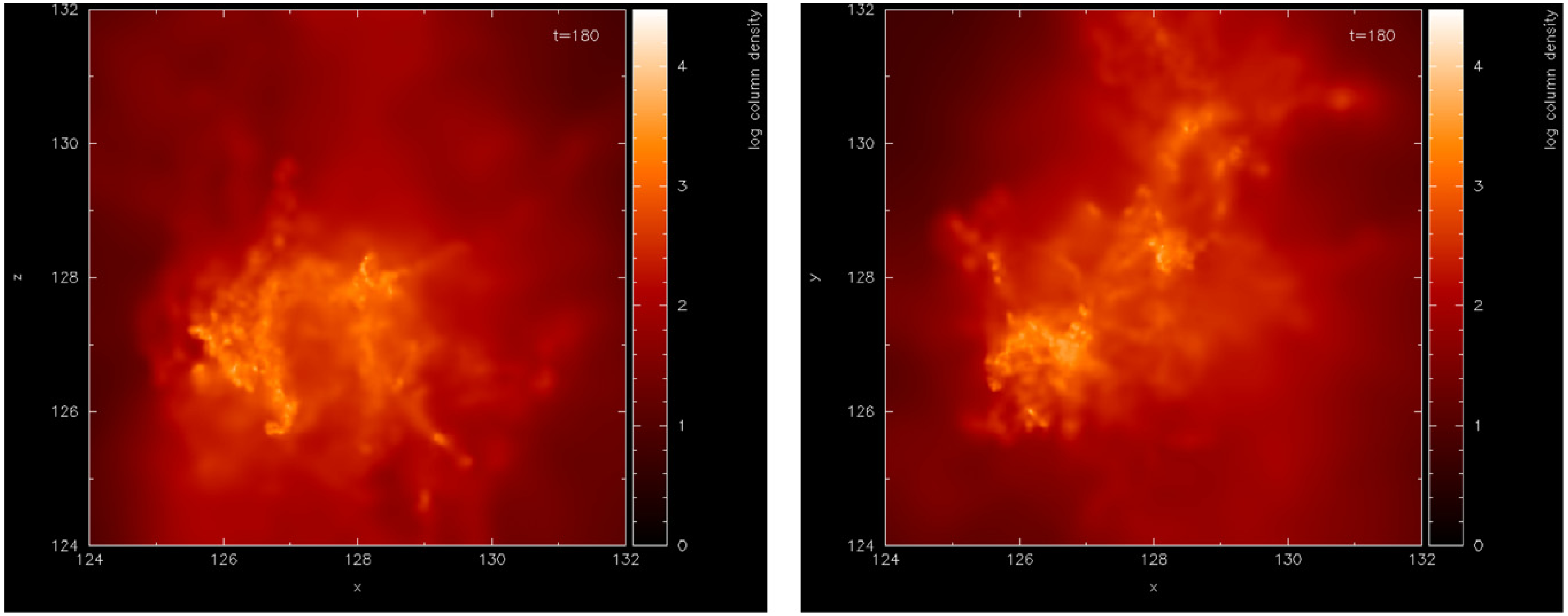
Goodman et al. 2009



Identify clumps (in three dimensions!) ➞
Clump Mass Function ~ Initial Mass Function

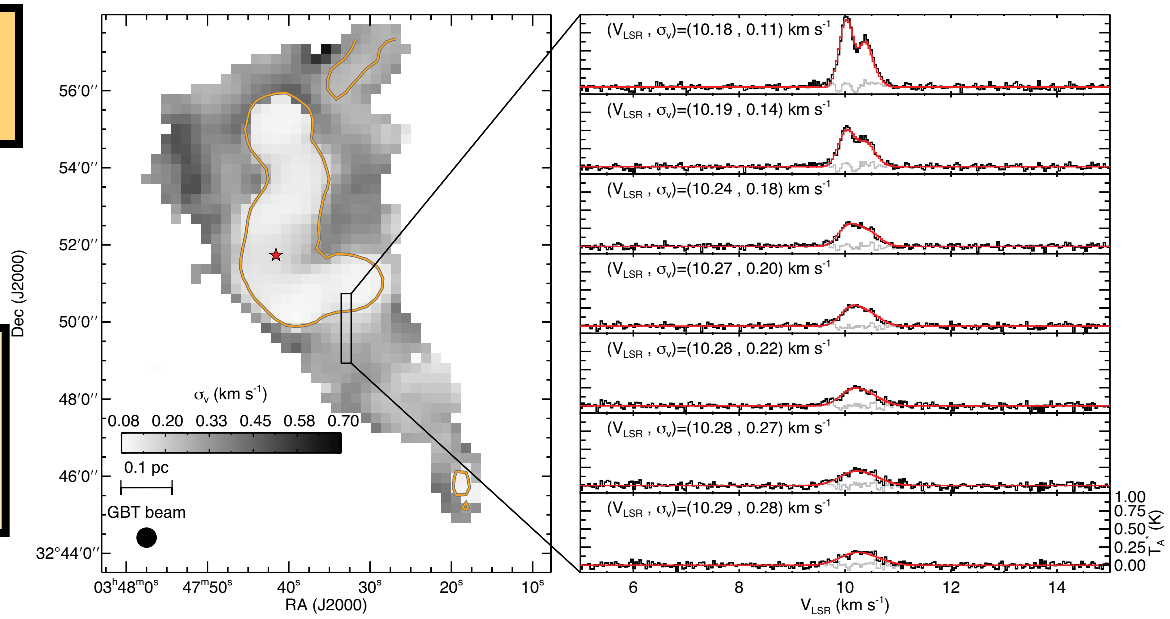
Is this the right way to get structure? (cf dendograms)

From interstellar clouds to the Initial Mass Function



Vázquez-Semadeni et al. 2009

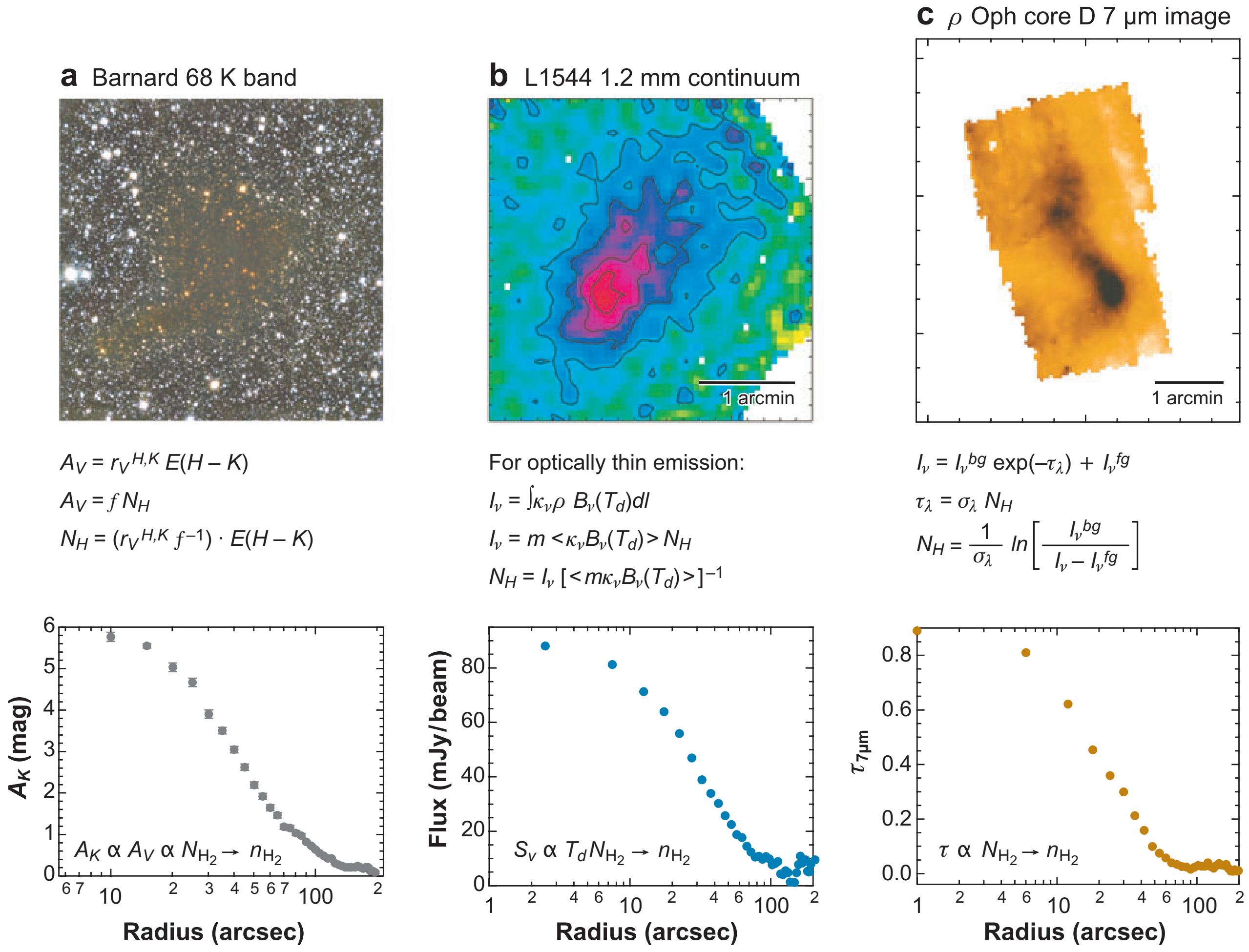
NH$_3$ Perseus B5:
Pineda et al. 2010



Cloud structure ↔ MHD turbulence

Transition to ‘coherence’ around 0.1-0.5 pc: prestellar core

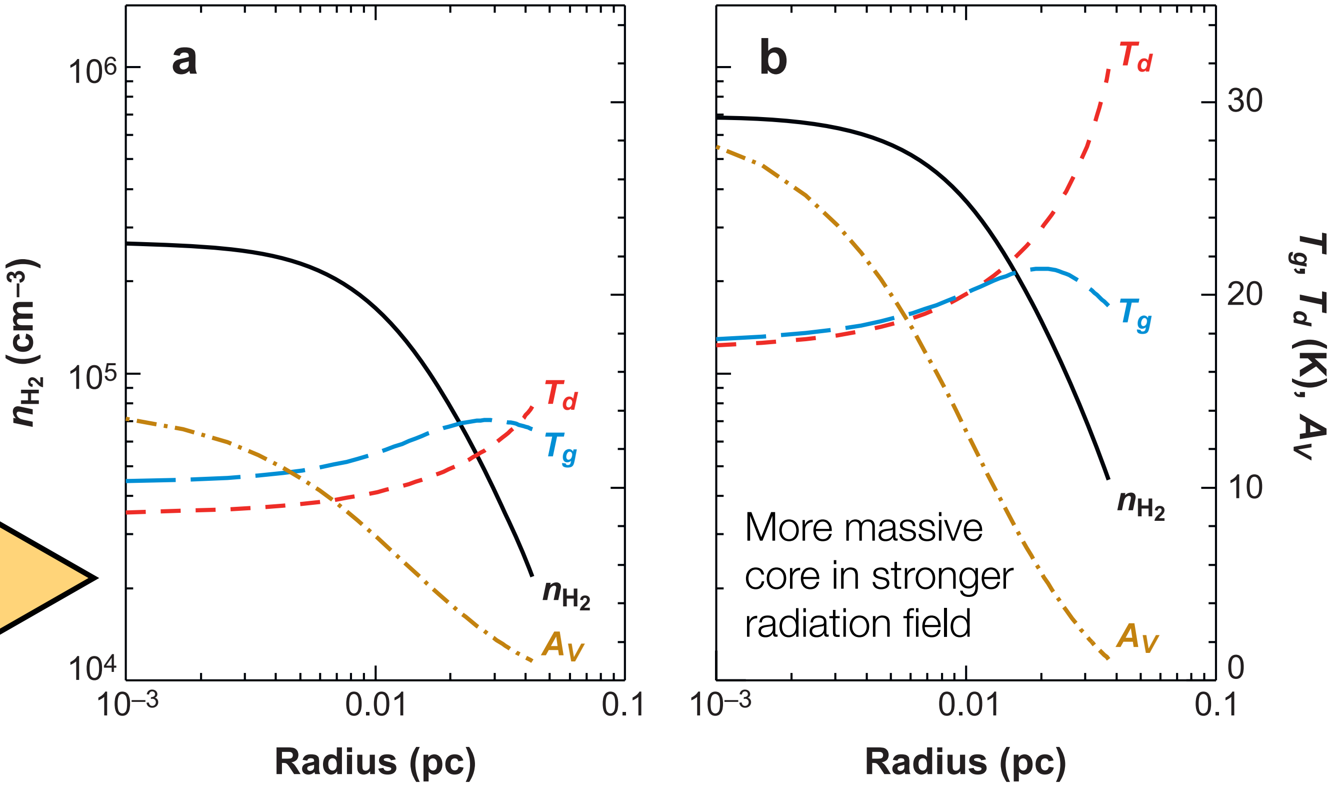
Properties of prestellar cores: density, temperature



Density follows Bonner-Ebert sphere*: unstable equilibrium of an isothermal presure-bounded sphere

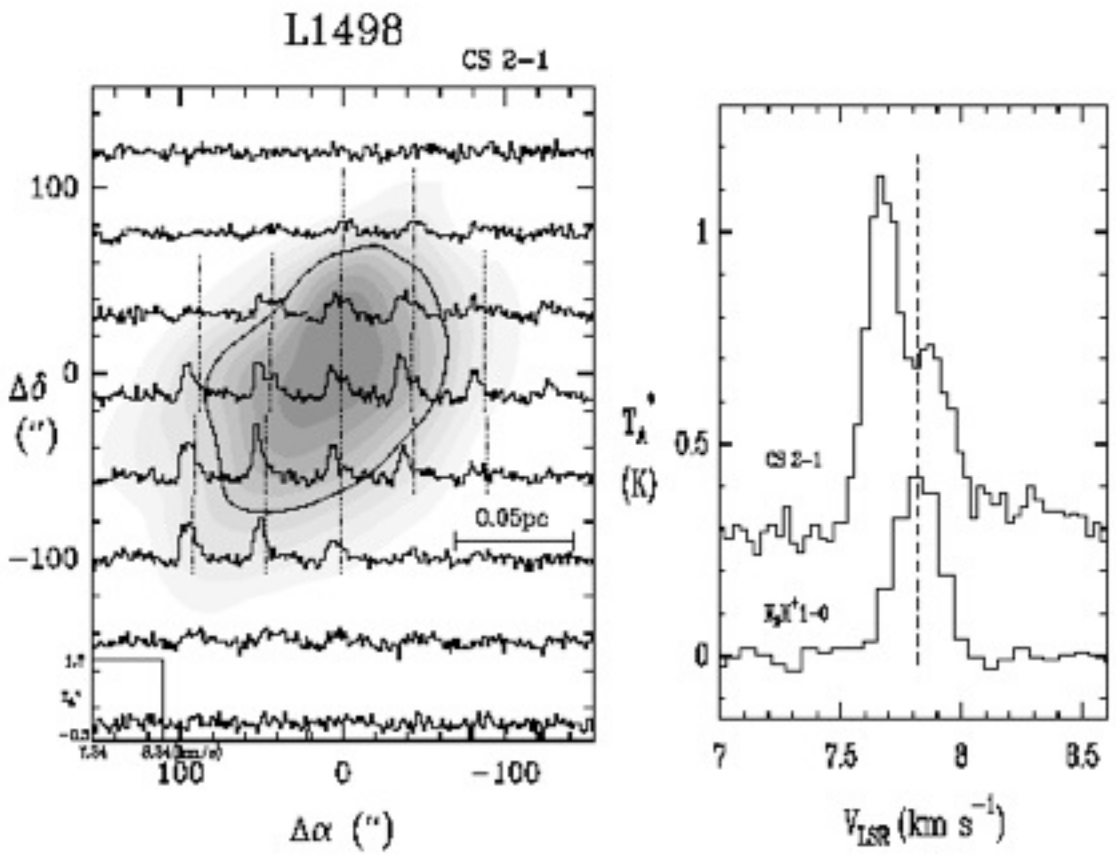
* Not a unique solution: *dynamic* structures can look the same (Ballesteros-Paredes et al. 2003; Myers 2005; Kandori et al. 2005)

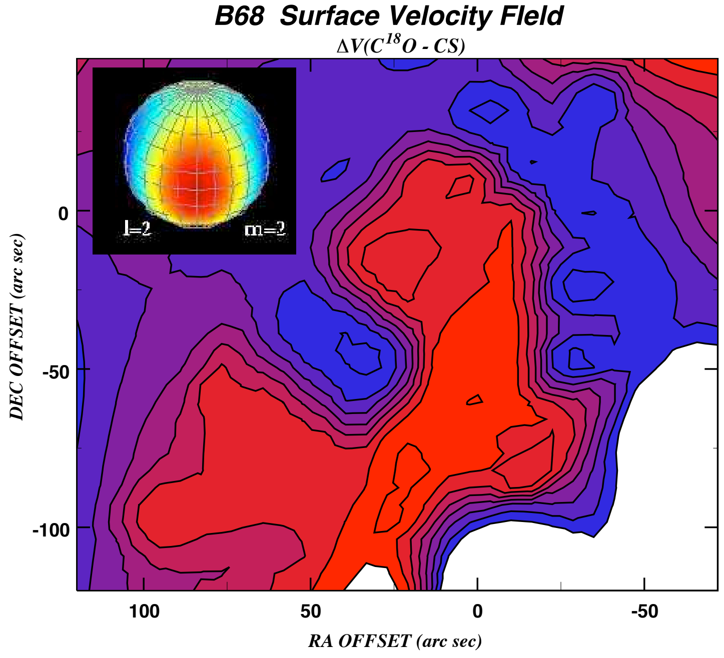
Invert to density & temperature



Bergin & Tafalla 2009; based on Alves et al. 2001; Ward-Thompson et al. 1999; Tafalla et al. 2002; Bacmann et al. 2000; Galli et al. 2002

Properties of prestellar cores: dynamics





Near-thermal line widths

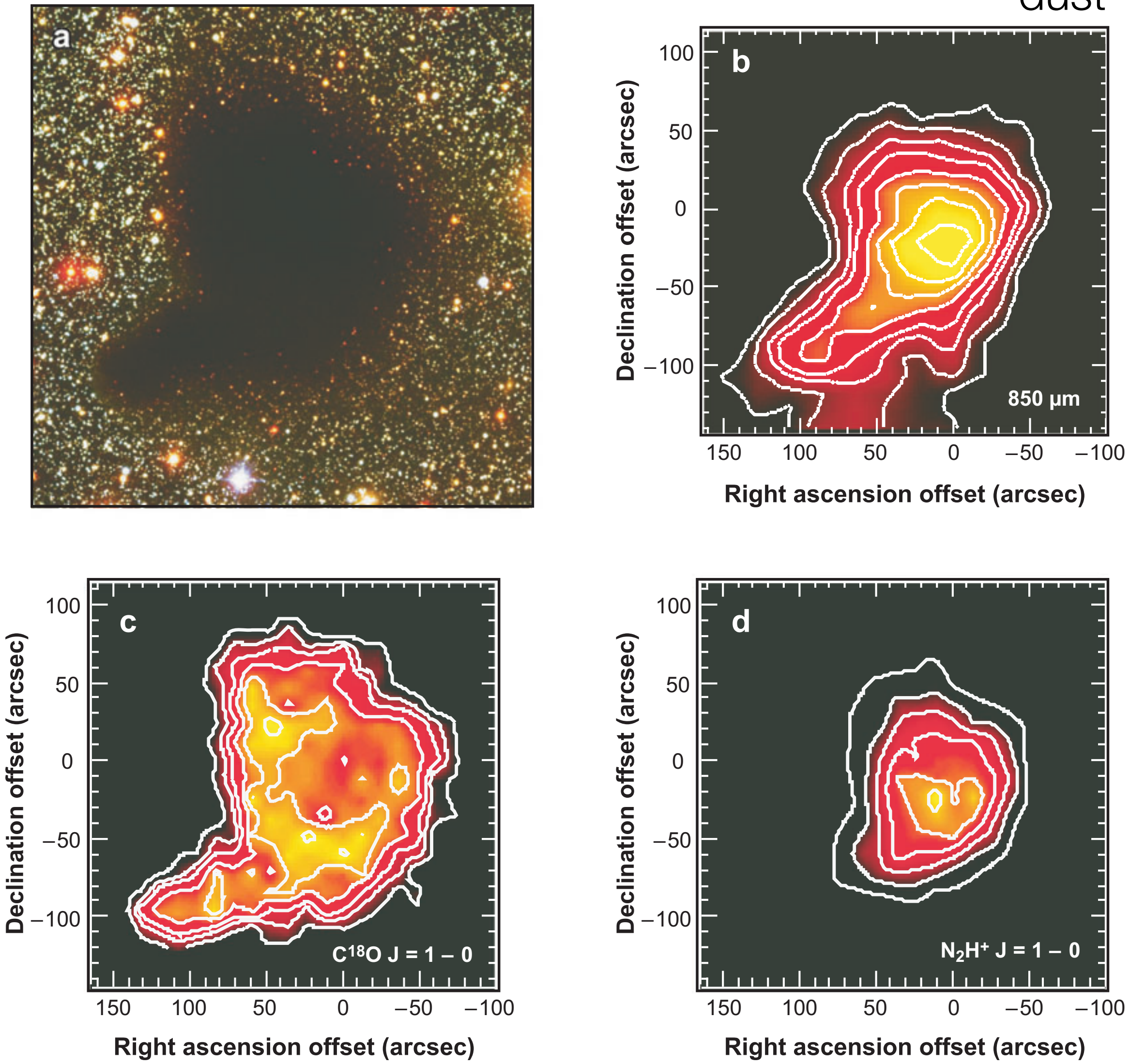
Little / no rotation

Extended inward motions
0.05-0.1 km s^{-1}: contraction

Oscillations?

Lee et al. 2001; Lada et al 2003; Bergin & Tafalla 2007

Properties of prestellar cores: chemistry



dust

$C^{18}O$

N_2H^+

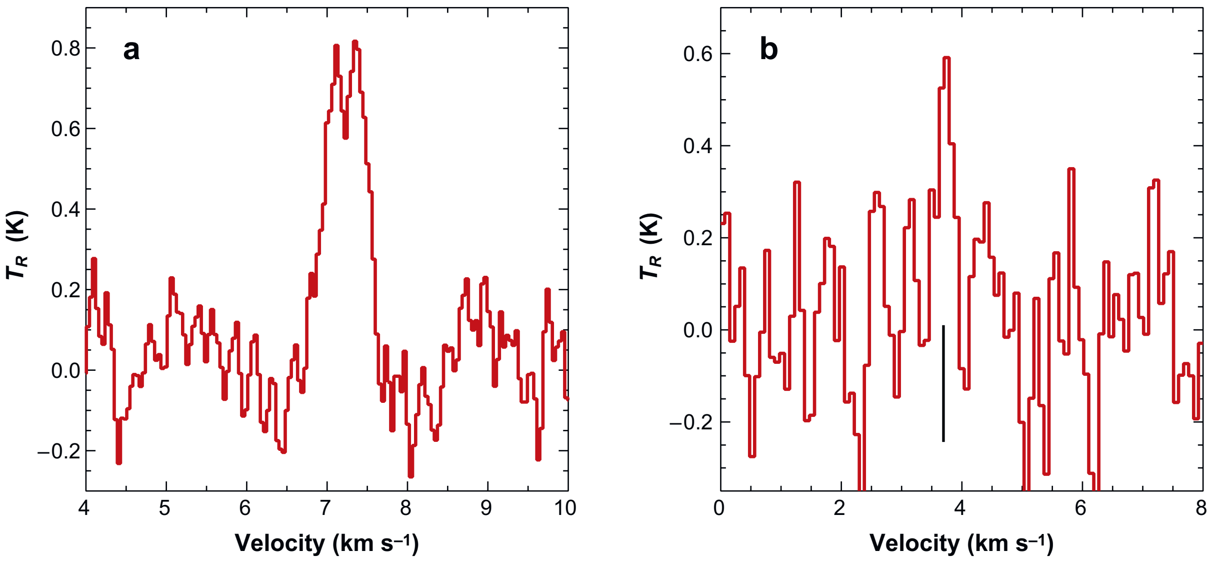
Molecules freeze out in dense and cold interior.

N_2H^+ may be a ‘late-depletor’.

Deuterated molecules are enhanced: e.g., H_2D^+

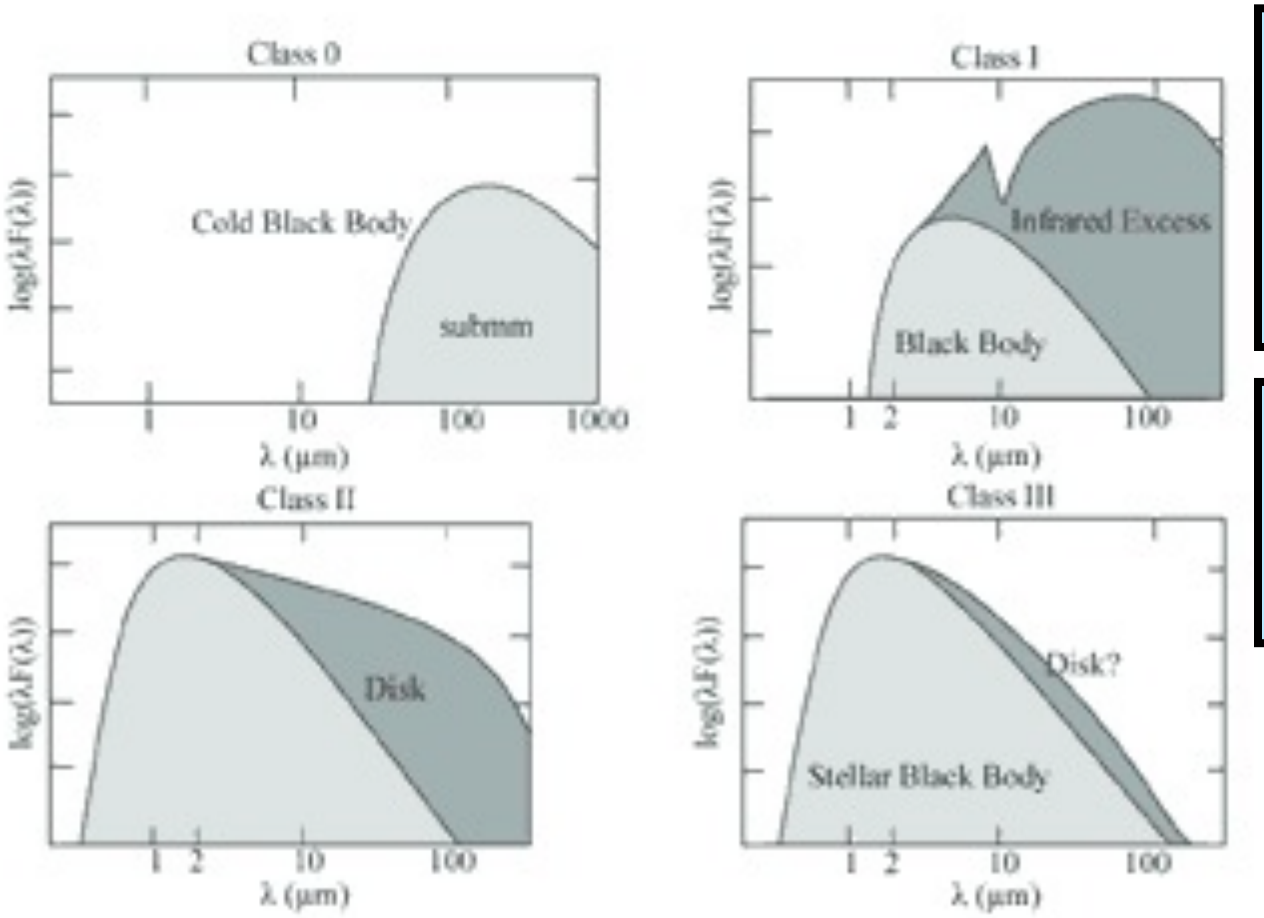
H_2D^+ in L1544

D_2H^+ in I16293E



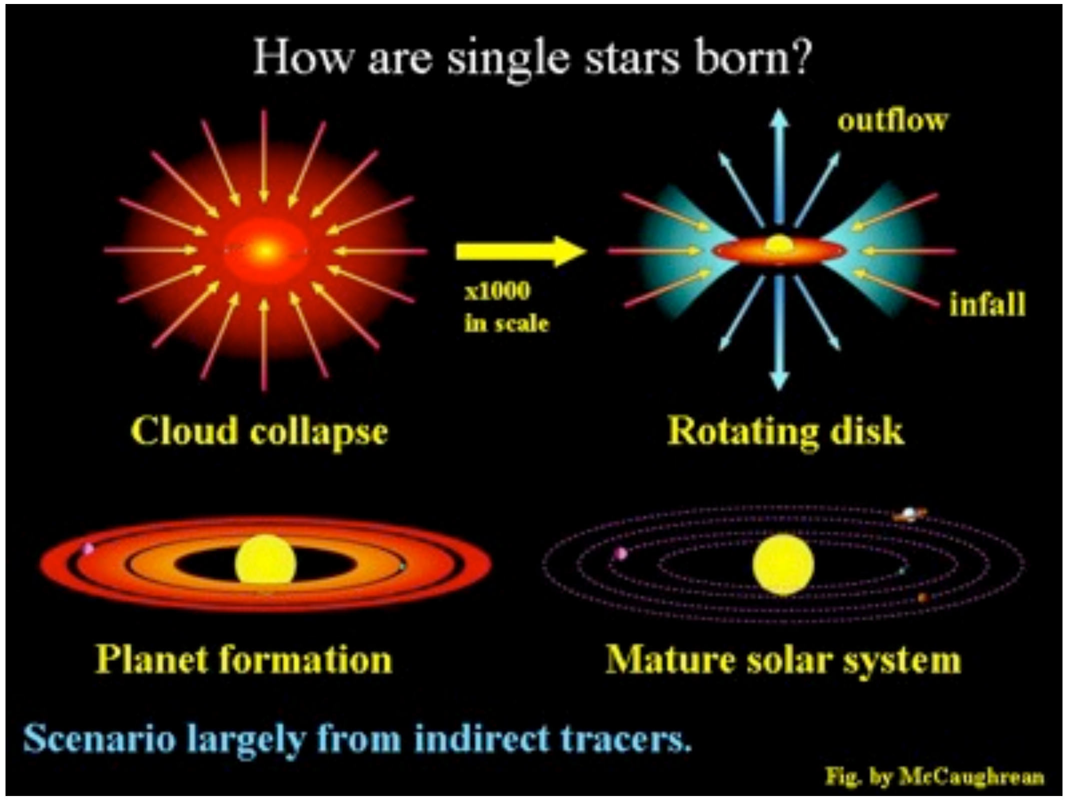
Bergin & Tafalla 2009; based on Bergin et al. 2002; Bianchi et al. 2003; Caselli et al. 2003; van der Tak et al. 2005; Vastel et al. 2004

The ‘standard’ model of isolated star formation



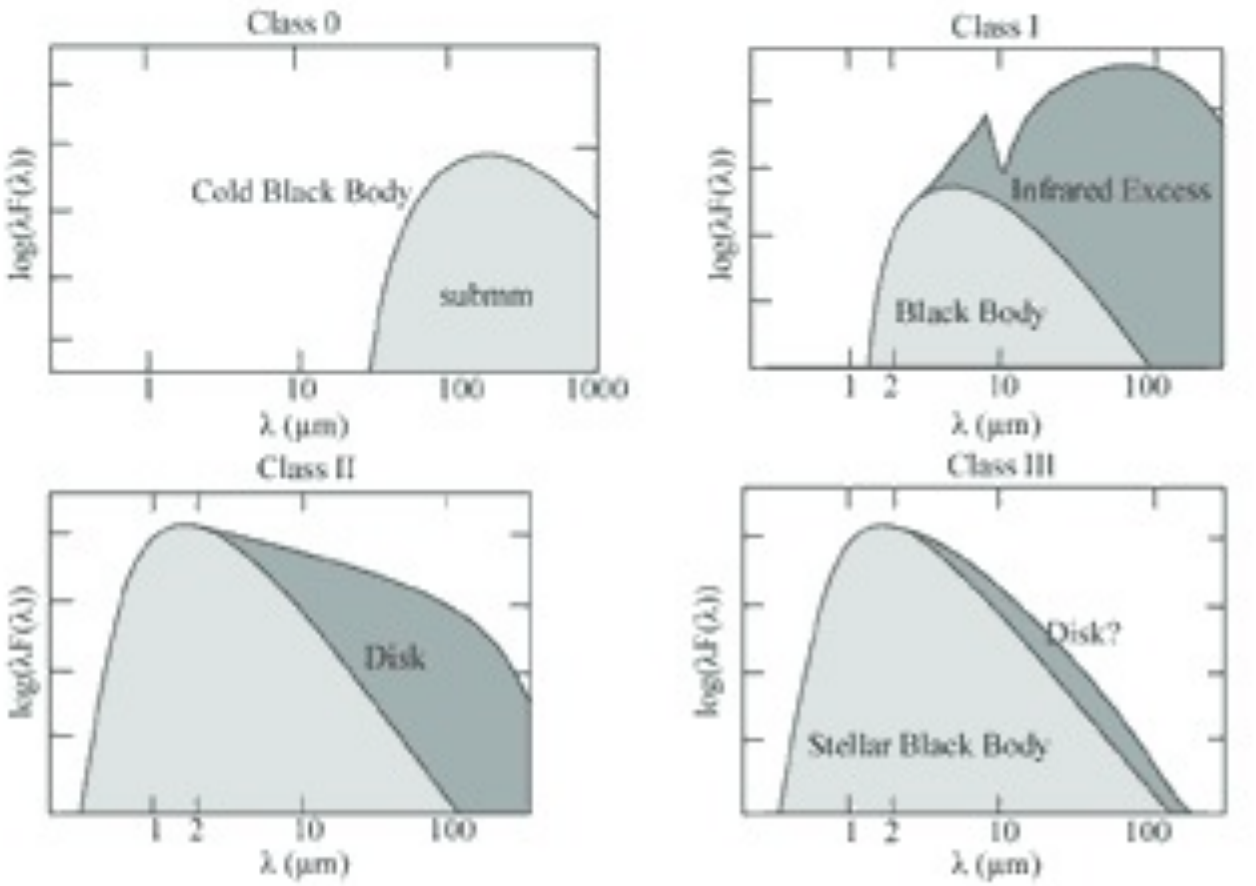
Lada (1987): pre-main sequence stars and infrared sources in star forming regions can be classified according to their 2.2–10/25 μm slope: Class I, II, III

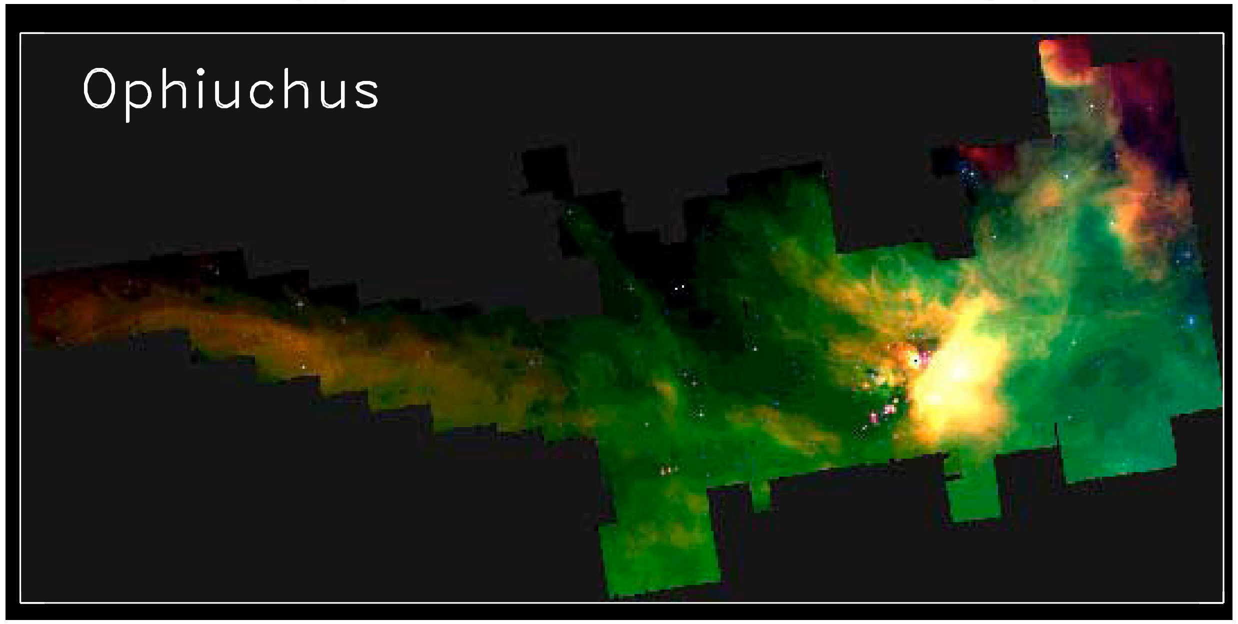
Later a Class 0 was added (André et al. 1993); sometimes a ‘Flat’ class is introduced between Classes I and II.



These classes can be placed in an intuitive evolutionary ordering.

Lifetimes and statistics of YSO classes





‘Cores to disks’ Spitzer Legacy survey:

- – Class 0 ~ 0.16 Myr (0.10 Myr)
- – Class I ~ 0.54 Myr (0.44 Myr)
- – Class II = 2±1 Myr

Numbers between brackets are corrected for extinction.

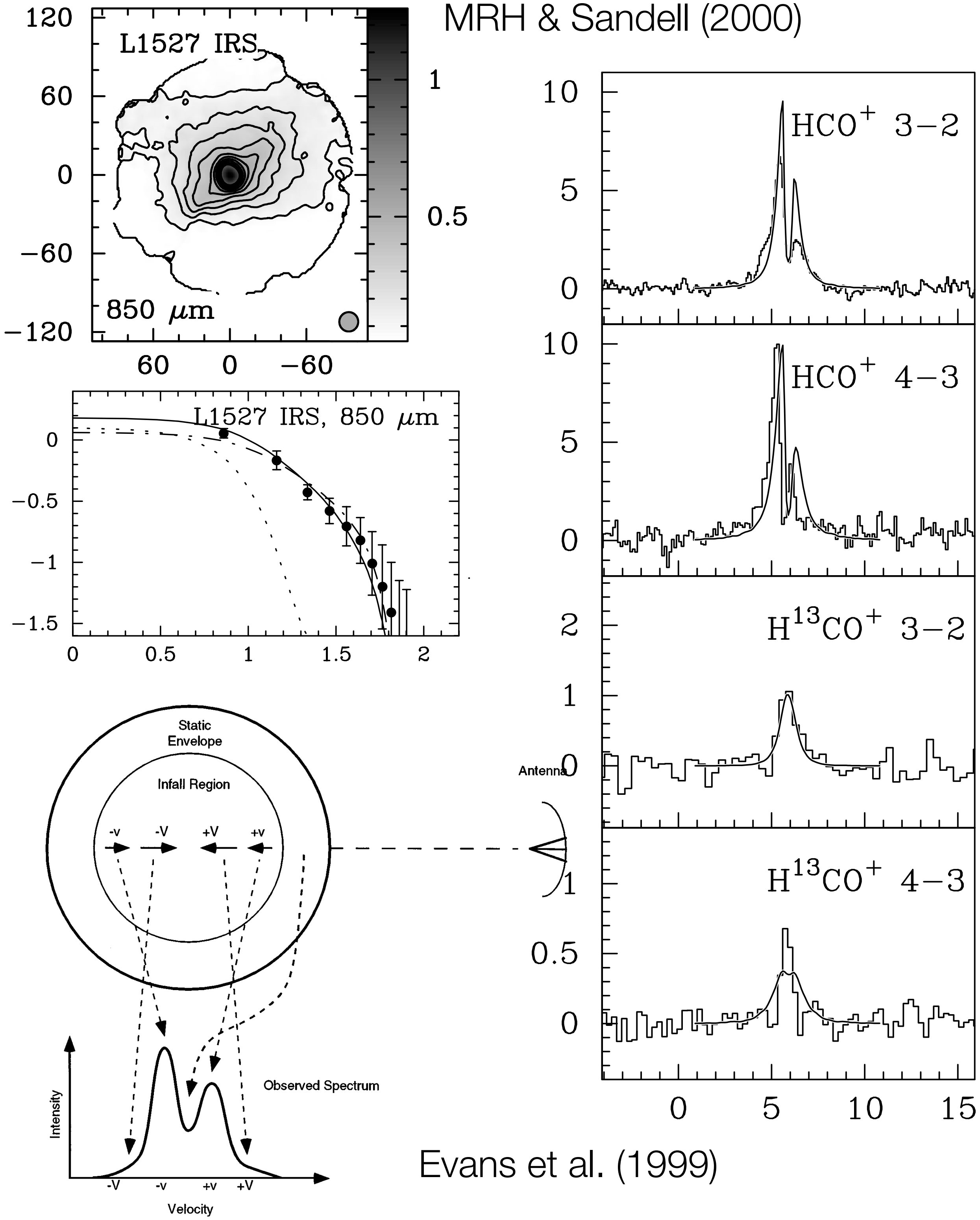
Median or half-lifetimes.

Distinguish (observational) *Class* from (physical) *Stage* (Robitaille et al. 2006)

Most youngest objects in clusters of >35 members and >1 M_{sun} pc^{-3}.

Evans et al. (2009)

The structure of Young Stellar Objects



MRH & Sandell (2000)

Evans et al. (1999)

Simple theoretical model: Shu (1977). Inside-out self-similar collapse of a singular isothermal sphere.

Family of solutions (Whitworth & Summers 1985).

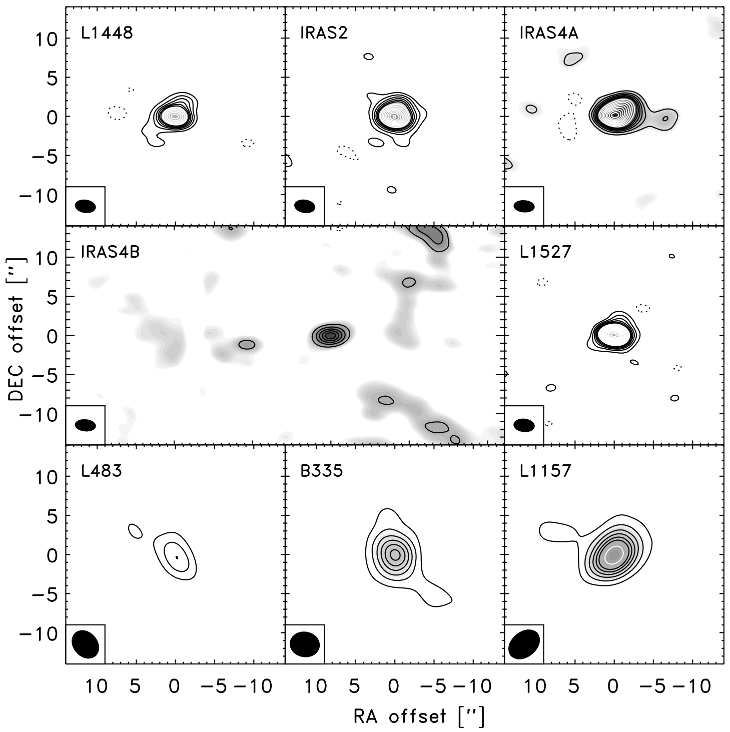
Refinements: slow rotation (Terebey et al. 1984); magnetic fields (Galli & Shu 1993; Allen et al. 2003).

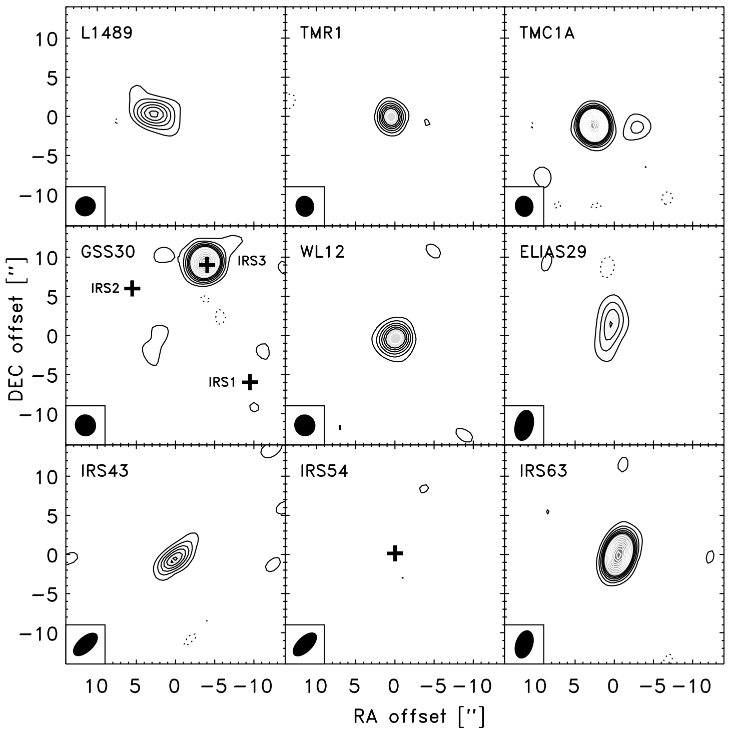
- density follows radial power law with index between -1 and -2.
- velocity tends toward free-fall; surrounded by static envelope.

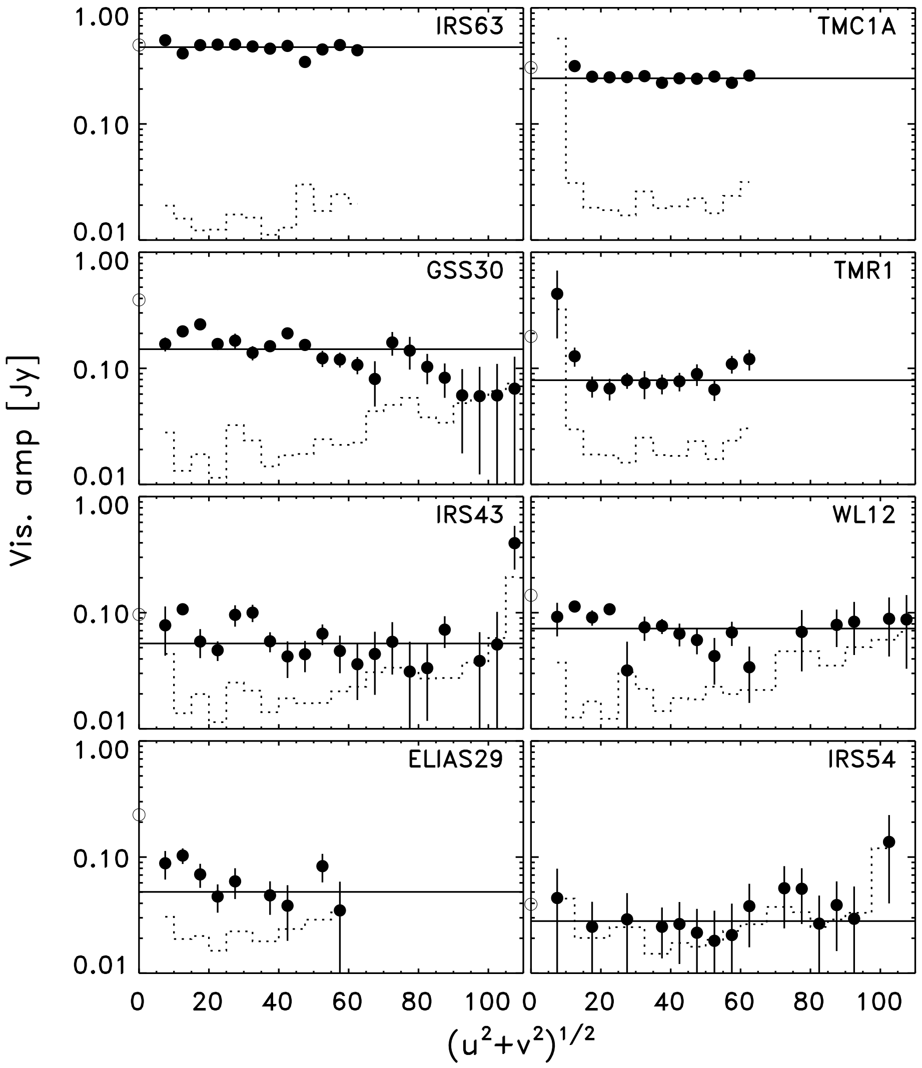
Dust continuum and molecular-line measurements well fit by Shu model (e.g., Hogerheijde & Sandell 2000)

The structure of Young Stellar Objects: envelope vs disk

Only millimeter interferometers can probe down to the few arcsec (several hundred AU) scale of embedded disks.







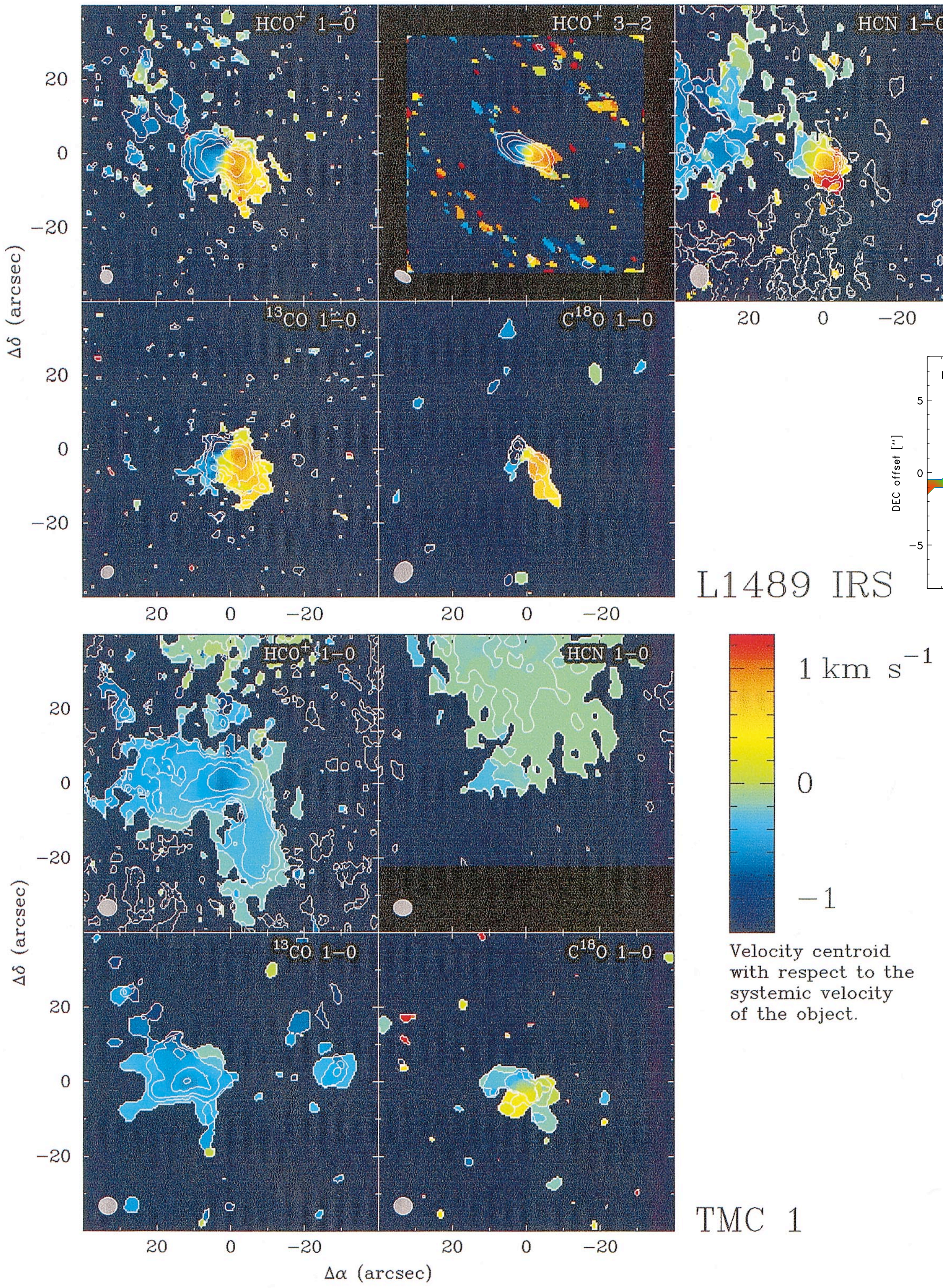
- compact mm emission toward ~all Class 0 and I objects
- M_{disk} = 0.05–0.1 M_{sun} (with scatter!)
- M_{disk} does not change with Class
- $M_{envelope}$ does change with Class from ~1 M_{sun} in Class 0 to ≲0.1 M_{sun} in Class I.

→ disks form early

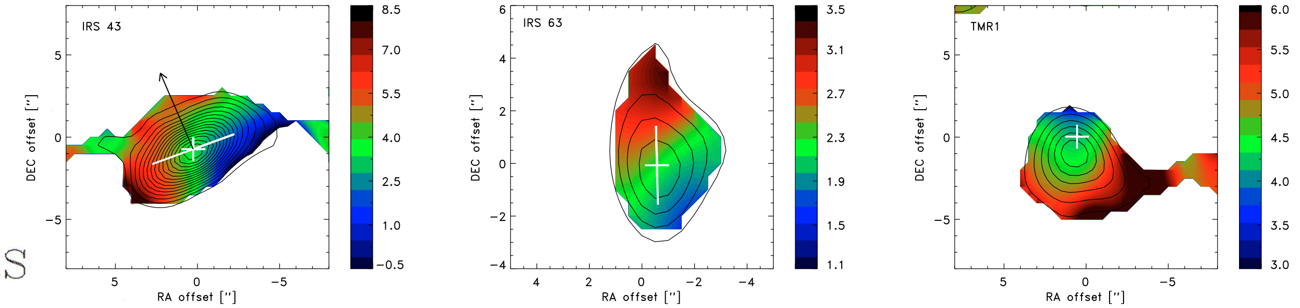
PROSAC: Jørgensen et al. (2007, 2009)

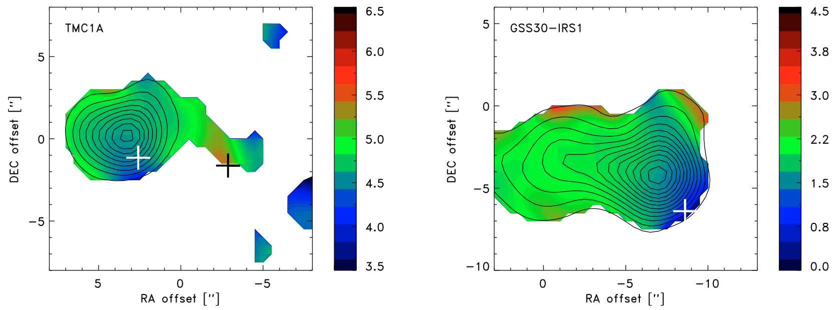
The structure of Young Stellar Objects: kinematics

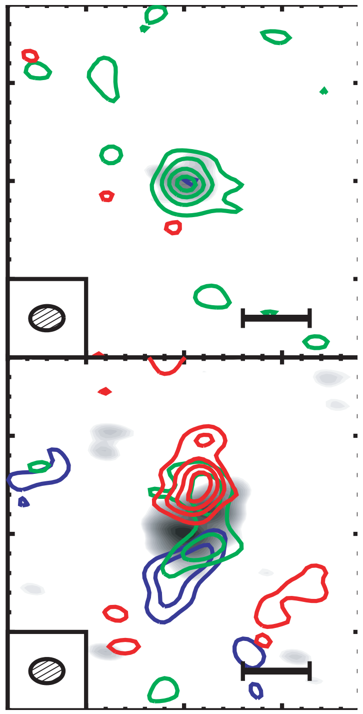
Velocity patterns show
- infall
- contributions from outflow(s)
- rotation (for Class I objects; star dominates mass)



Velocity centroid with respect to the systemic velocity of the object.



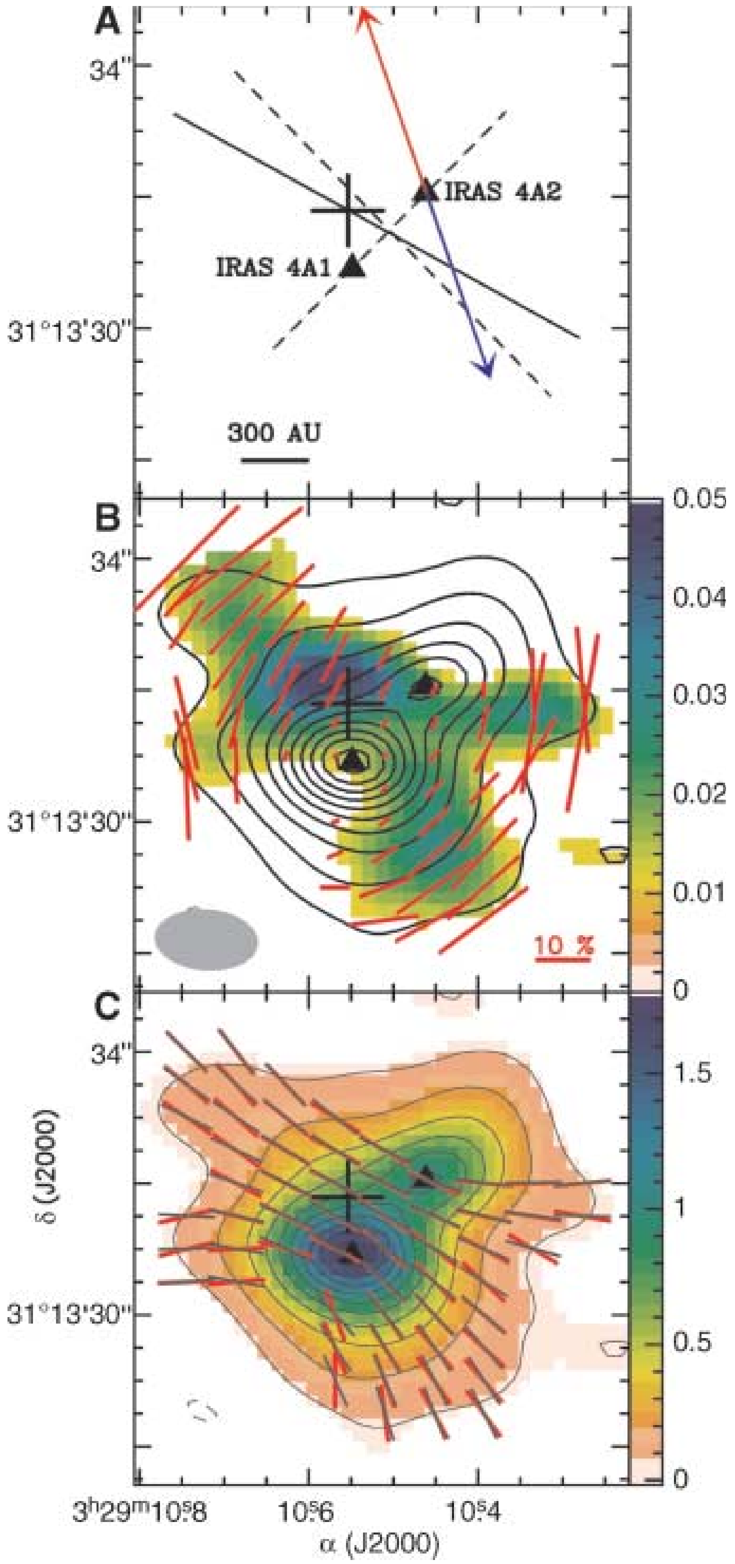




MRH (2001)

PROSAC: Jørgensen et al. (2007, 2009)

The structure of Young Stellar Objects: magnetic fields



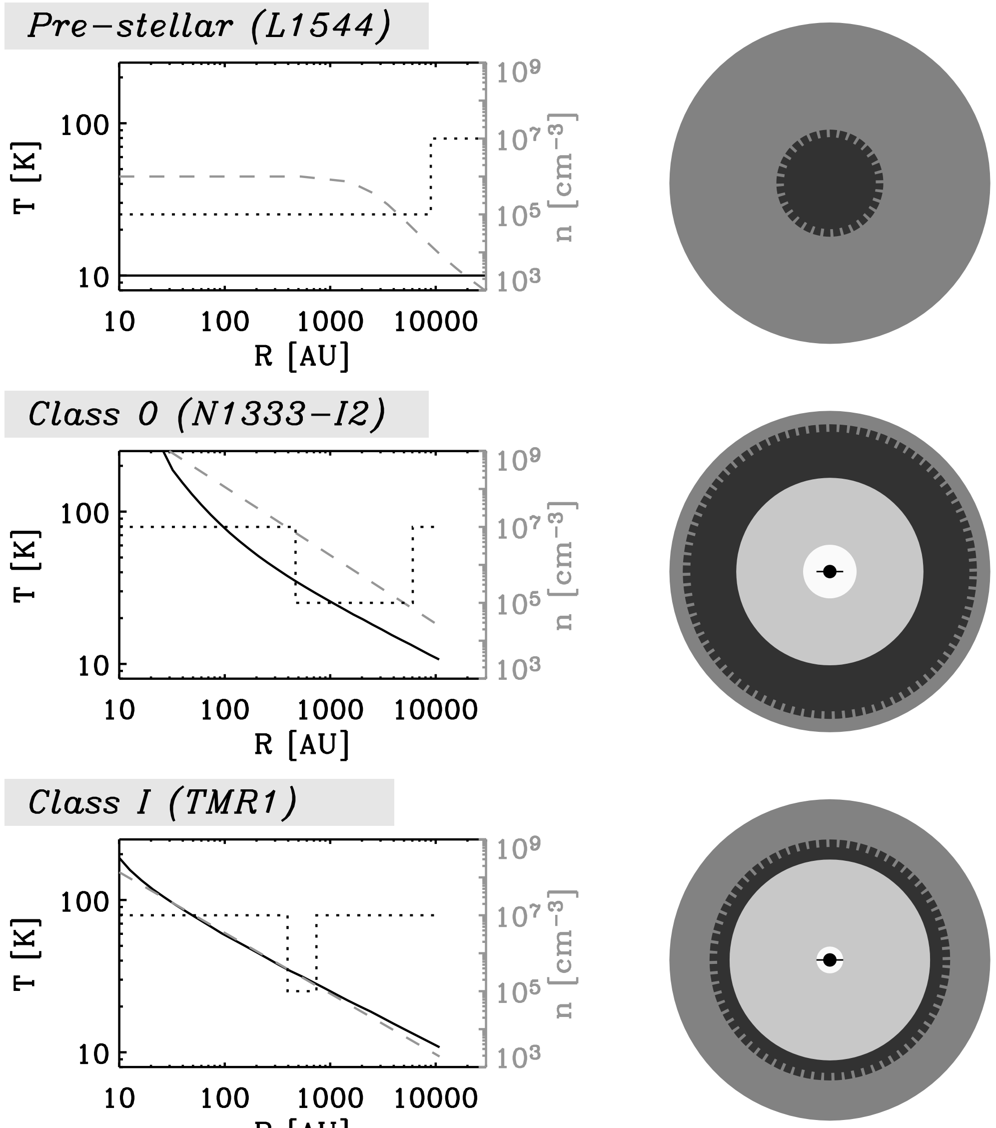
Polarization of thermal dust emission in NGC 1333 IRAS 4 matches theoretical expectations (e.g., Galli et al. 2006):

- gravity overcomes magnetic support
- field lines drawn in by collapsing gas

➔ hourglass shape

Girart et al. (2006)

The structure of Young Stellar Objects: chemistry



Jørgensen et al. (2005)

Pre-stellar cores:
– undepleted outer regions
– depletion in cold & dense interior

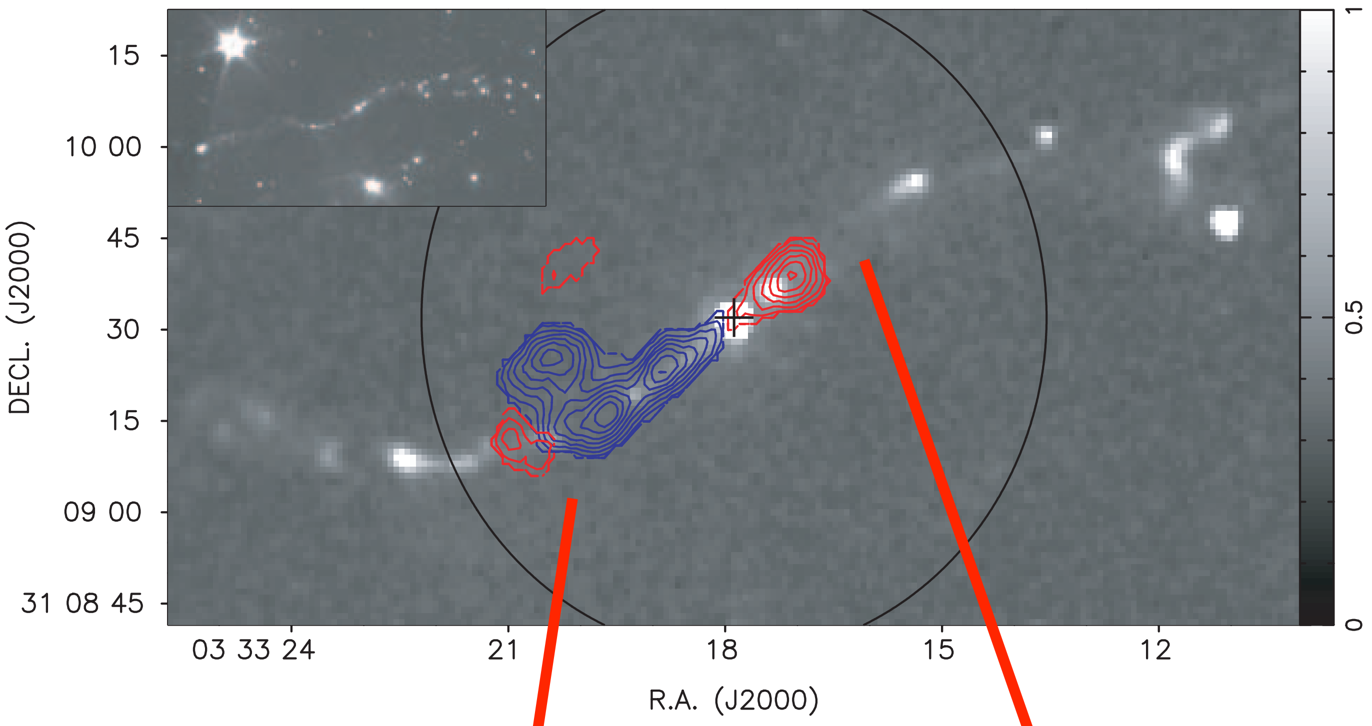
Class 0:
– undepleted outer skin
– depleted interior
– evaporation of (altered) species in small, warm central region: complex organics

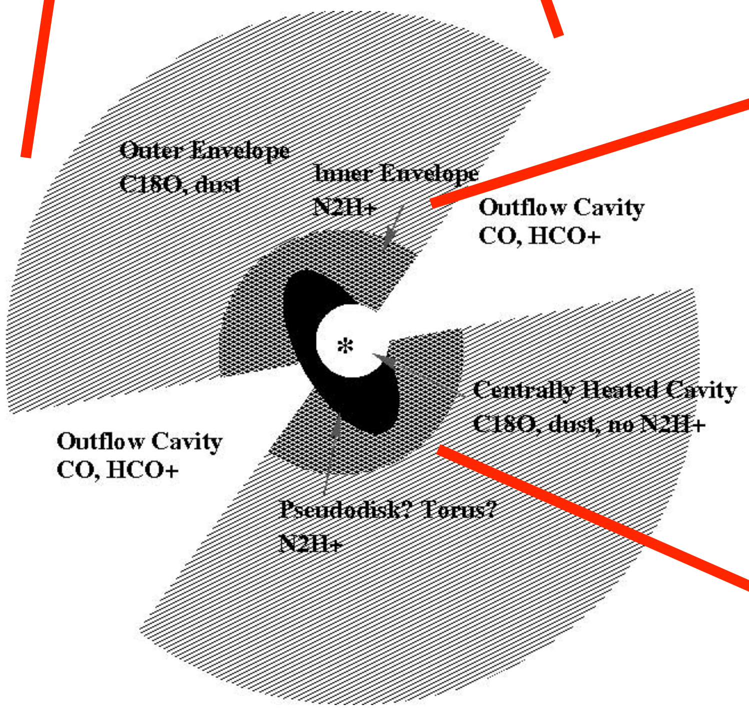
Class I:
– undepleted outer skin
– narrow shell with depletion
– undepleted in large, warm inner region

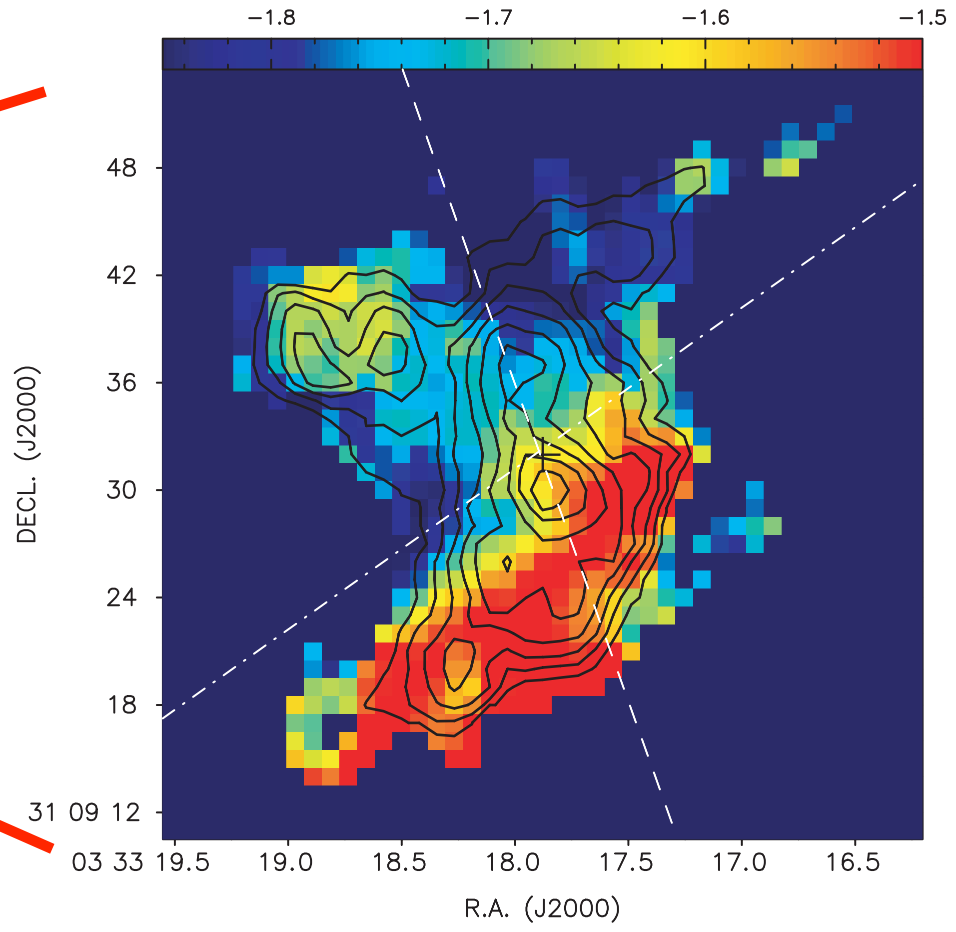
Protostellar feedback: outflows

All embedded young stars drive bipolar jets, which in their turn sweep up molecular outflows.

Responsible for clearing away remnant envelope

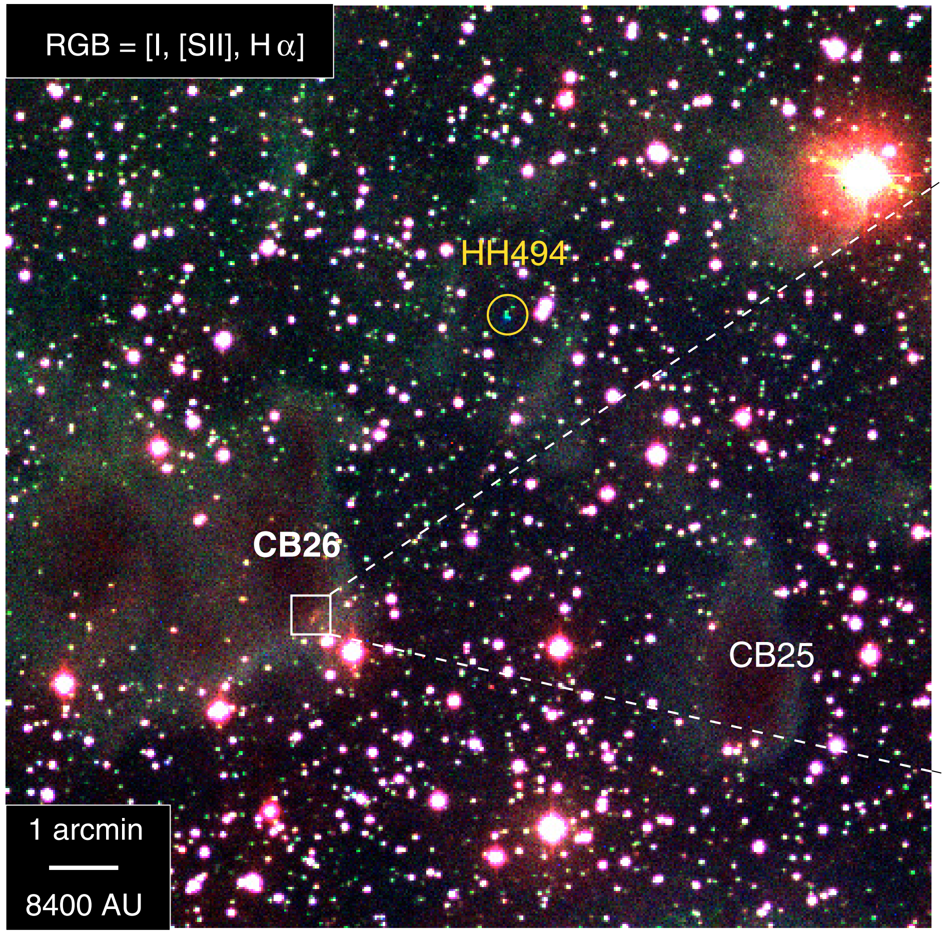


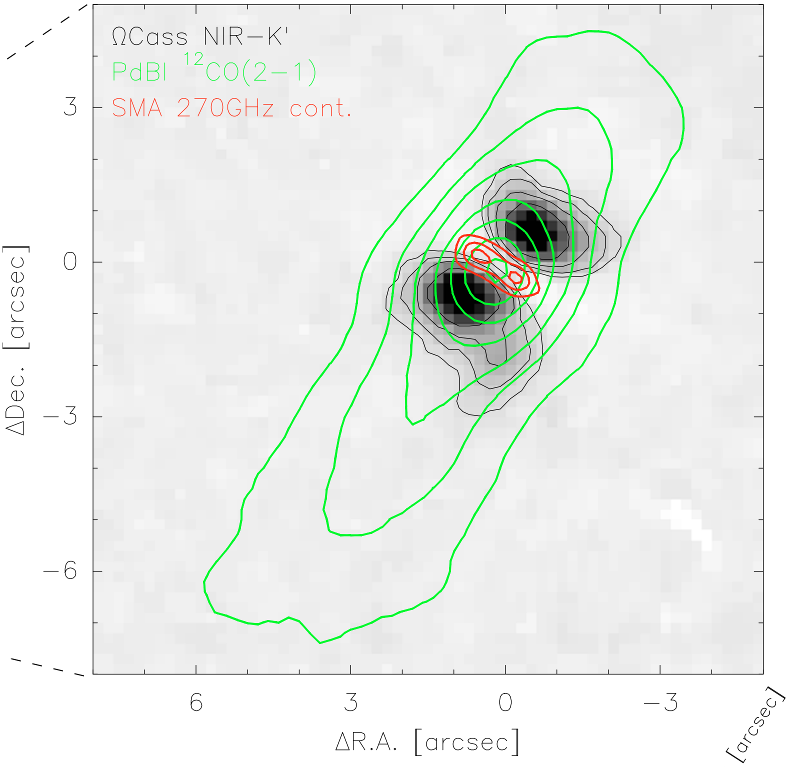


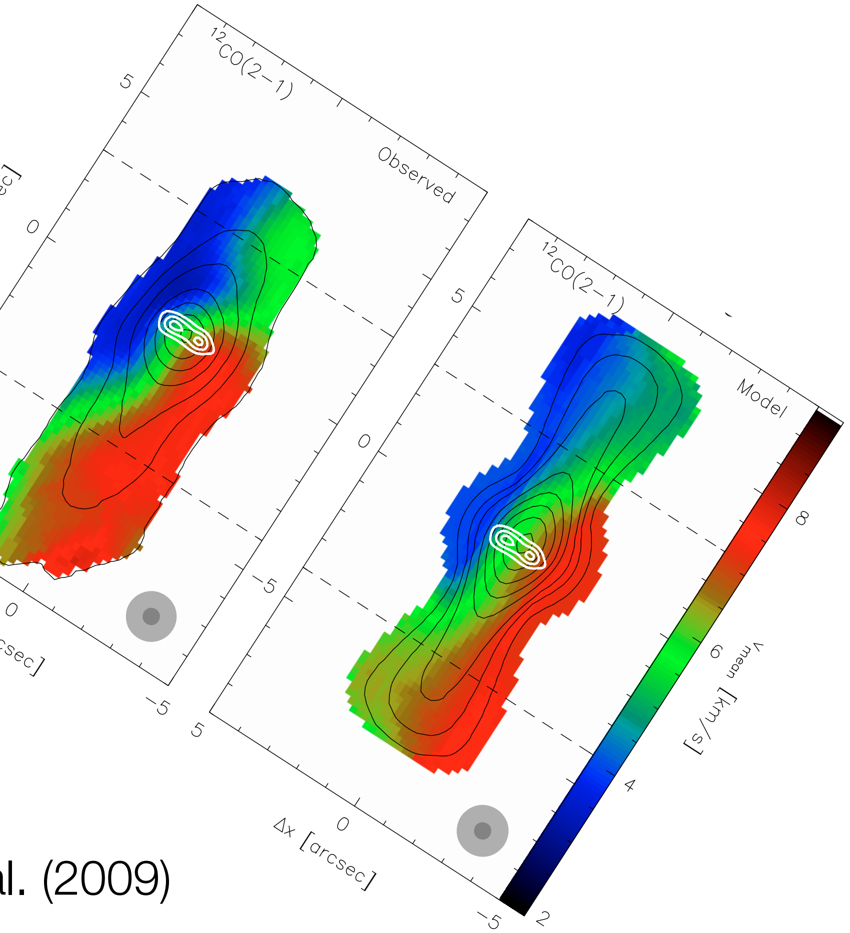


Matthews et al. (2006)

Protostellar feedback: outflows







Launched by stellar accretion flows or disk?
Carry away excess angular momentum.

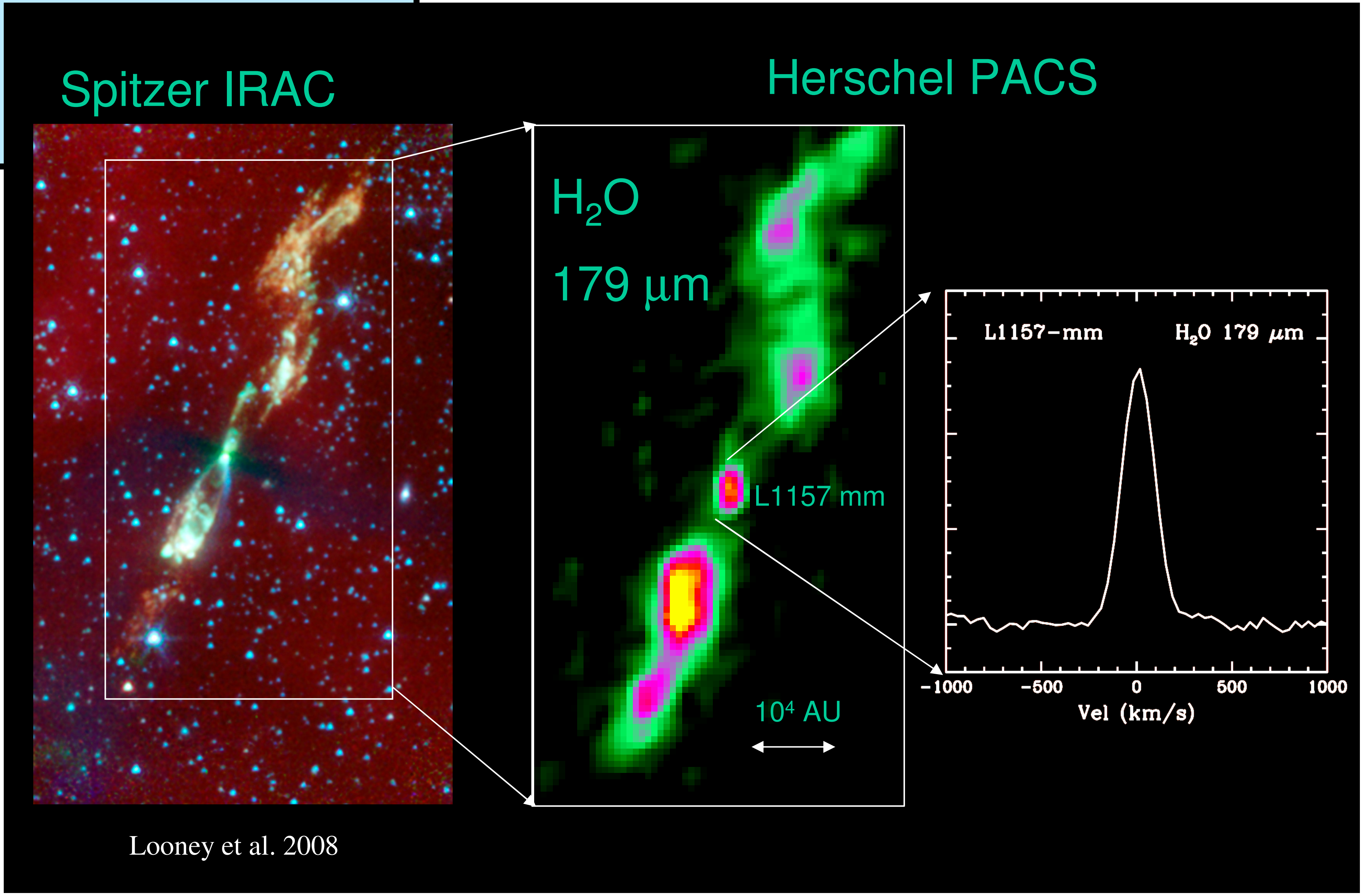
Launhardt et al. (2009)

Protostellar feedback: outflows

Inject turbulence into surrounding medium.

Shock molecular gas
Heat dust
Evaporate ice mantles
Destroy dust

WISH (van Dishoeck, PI)
Nisini, Liseau et al.

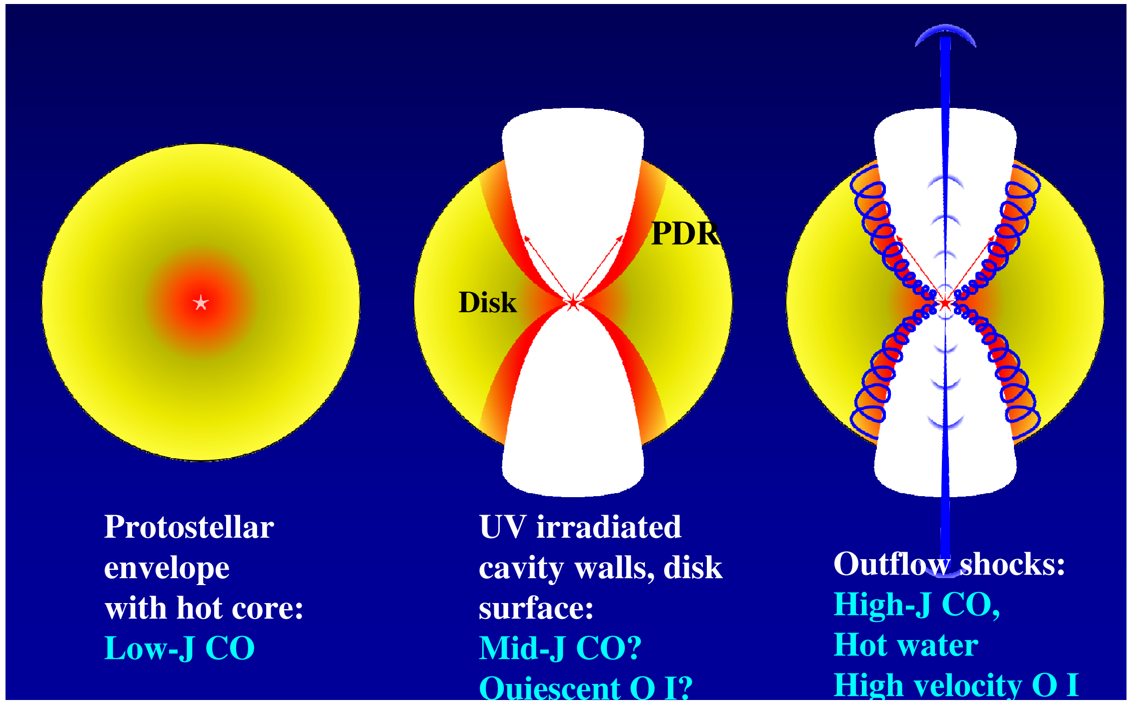


Looney et al. 2008

Protostellar feedback: outflows

WISH (van Dishoeck, PI)

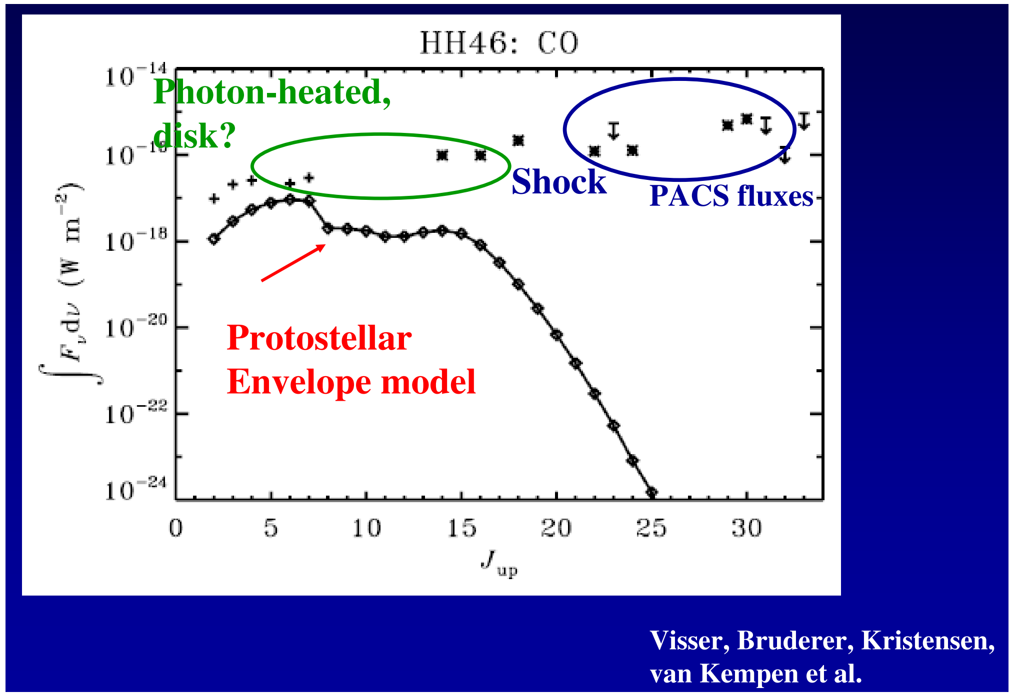
...and provide a path for ultraviolet photons to reach into the envelope...
(Spaans et al. 1995)



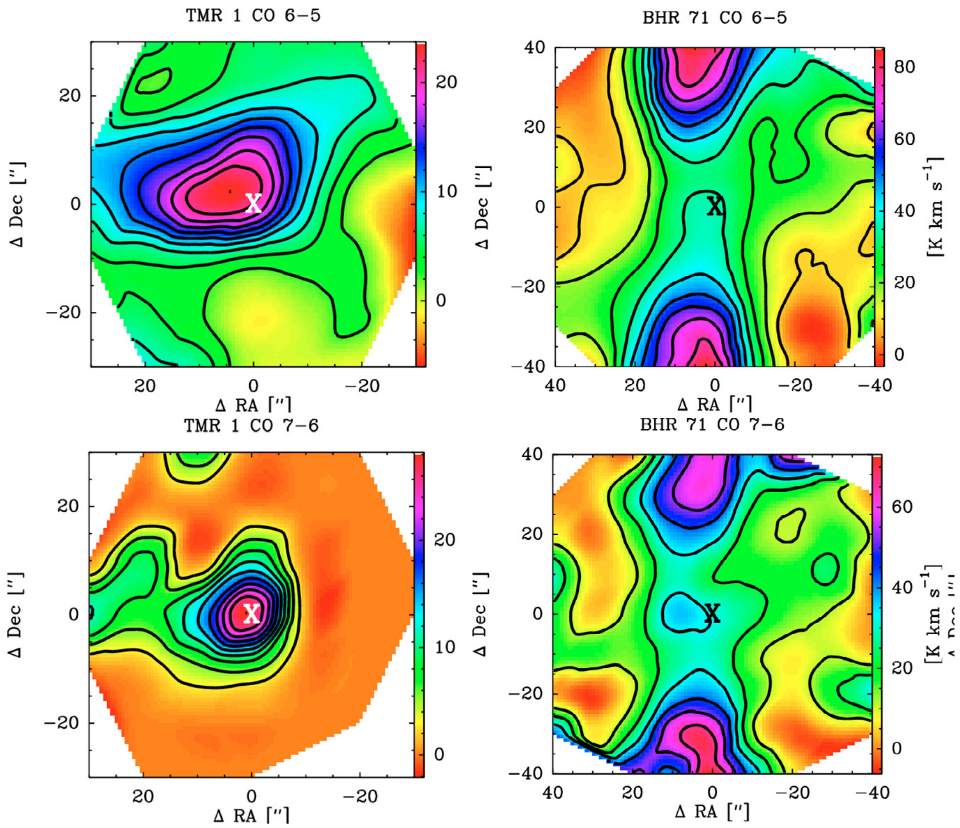
Protostellar envelope with hot core:
Low-J CO

UV irradiated cavity walls, disk surface:
Mid-J CO?
Quiescent O I?

Outflow shocks:
High-J CO,
Hot water
High velocity O I

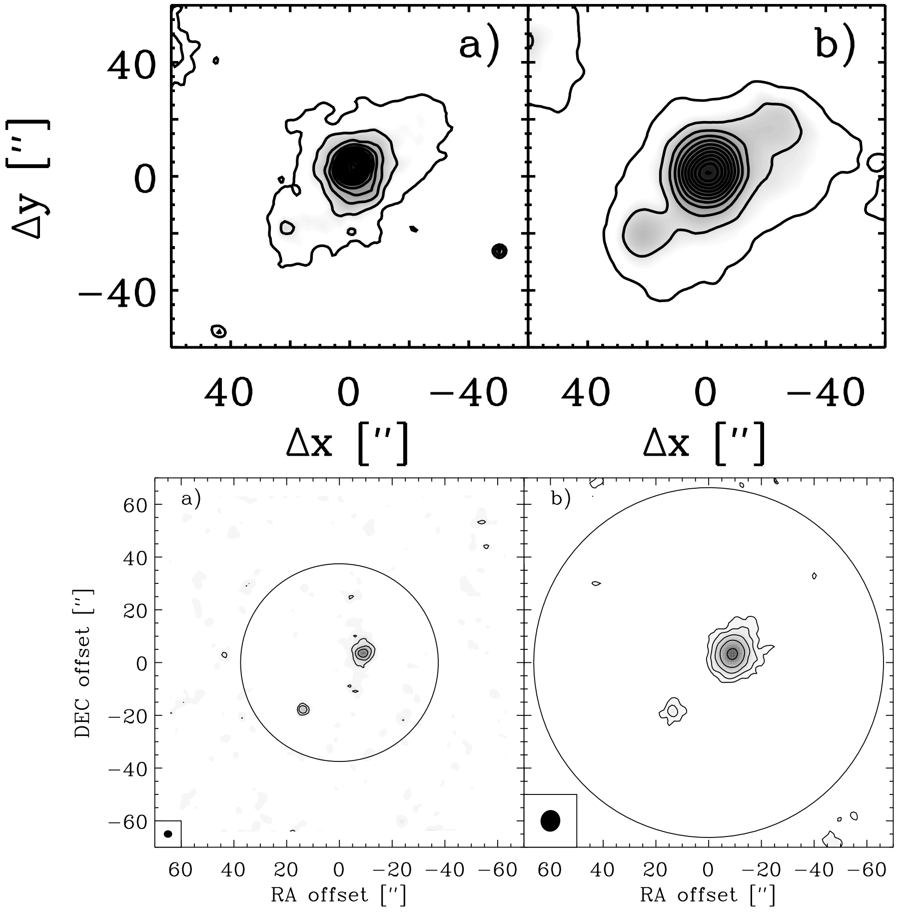


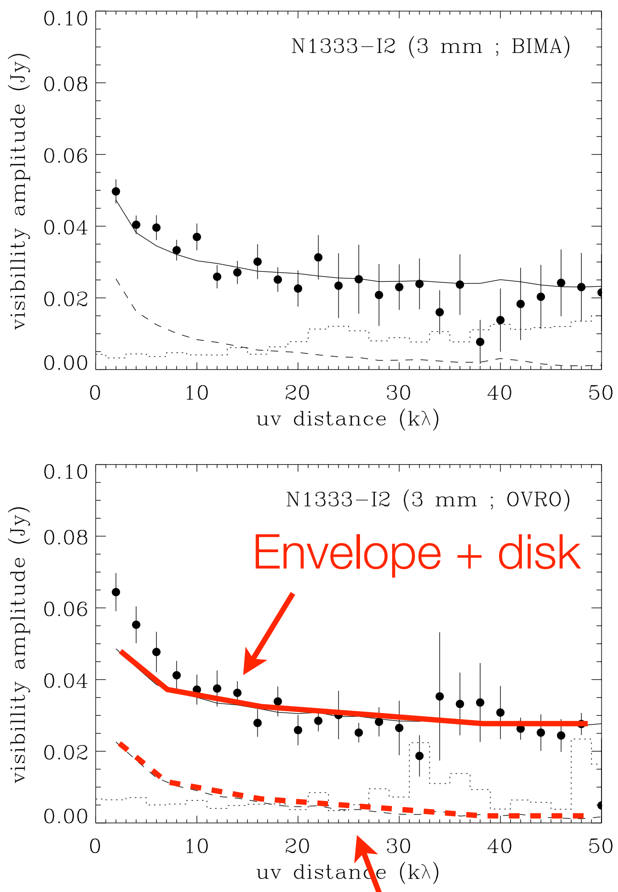
Visser, Bruderer, Kristensen, van Kempen et al.



van Kempen et al. (2009)

The formation of accretion disks





Envelope + disk

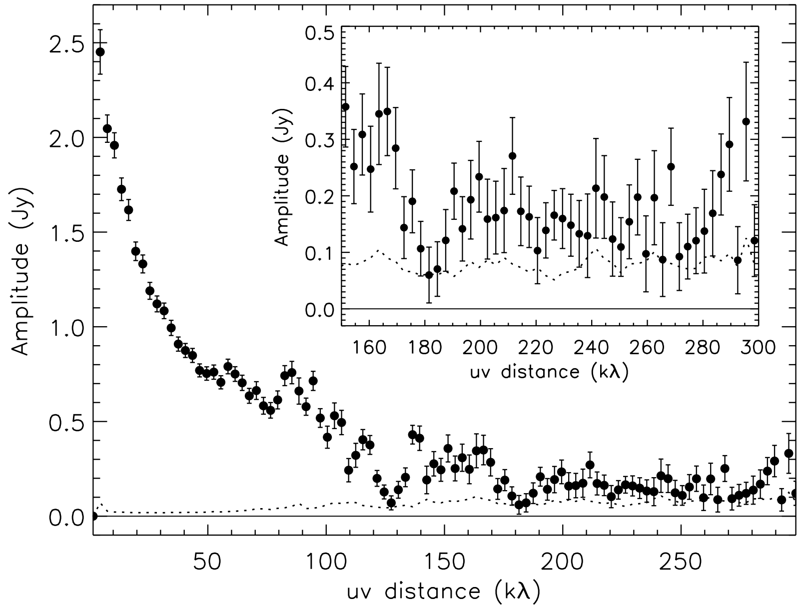
Envelope only

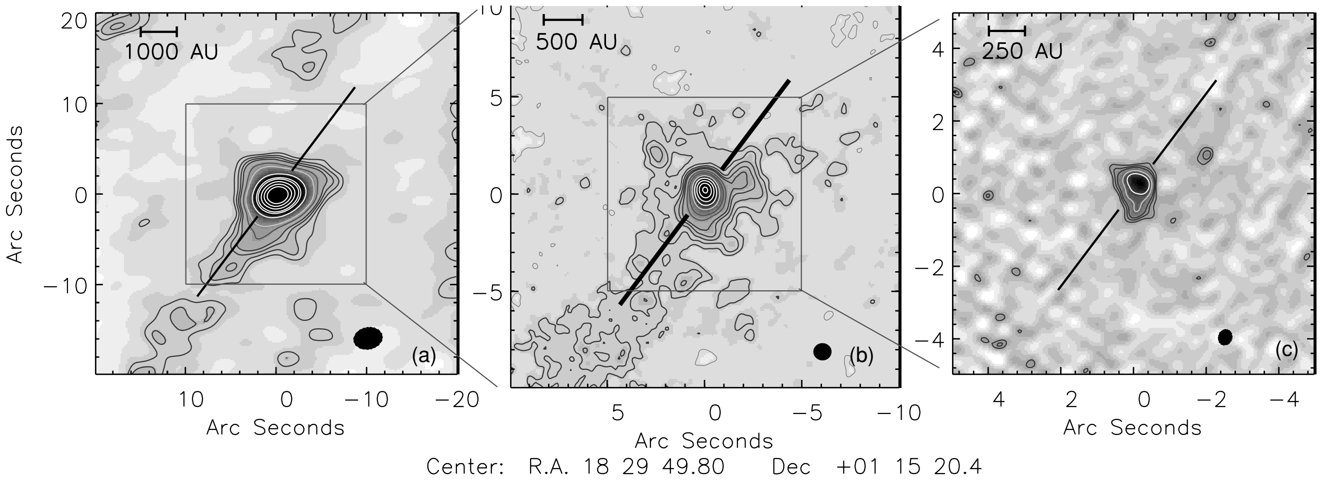
NGC 1333 IRAS2A: Jørgensen et al. (2004)

Need interferometers to separate growing disk from the envelope.

Disks form early (Class 0 phase) and M_{disk} stays ~constant throughout Class 0 and Class I phases. (Jørgensen et al. 2009)

Serpens SMM1: Enoch et al. (2009)





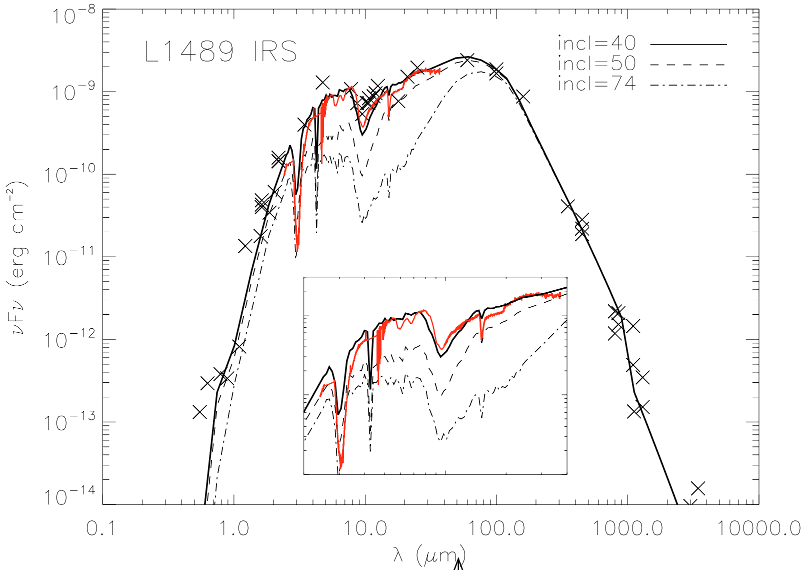
The formation of accretion disks

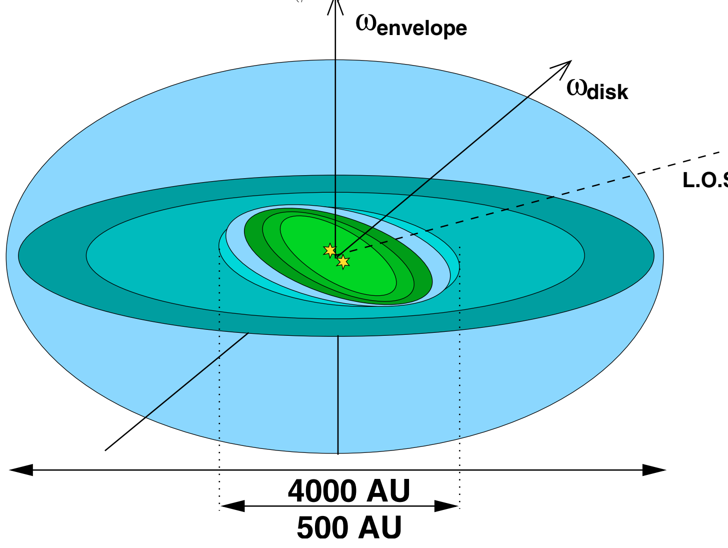
Brinch et al. (2007a,b)

How do we know this is a real disk?

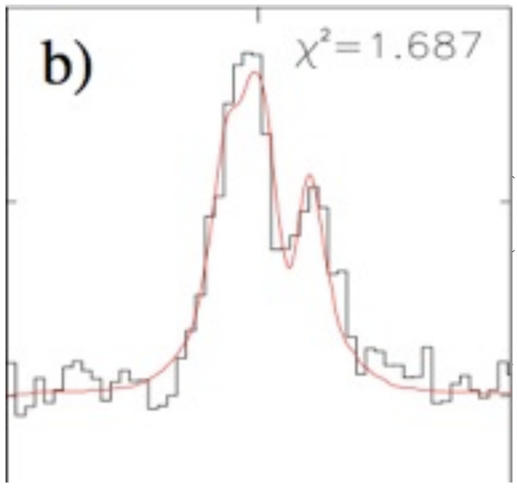
Find signature of Keplerian rotation.

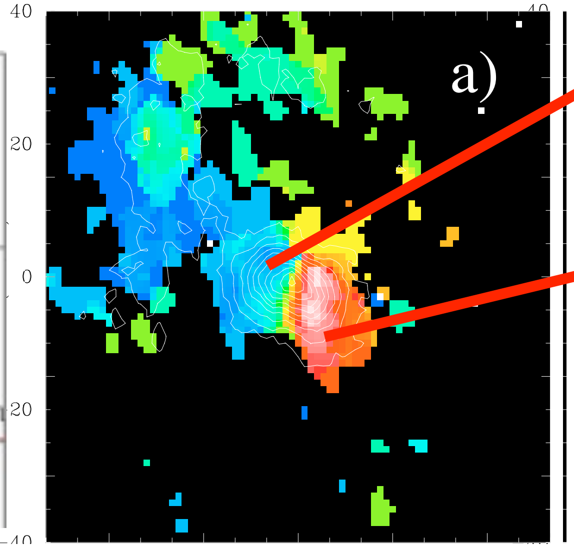
L1489 IRS: 35˚ angle between envelope and disk

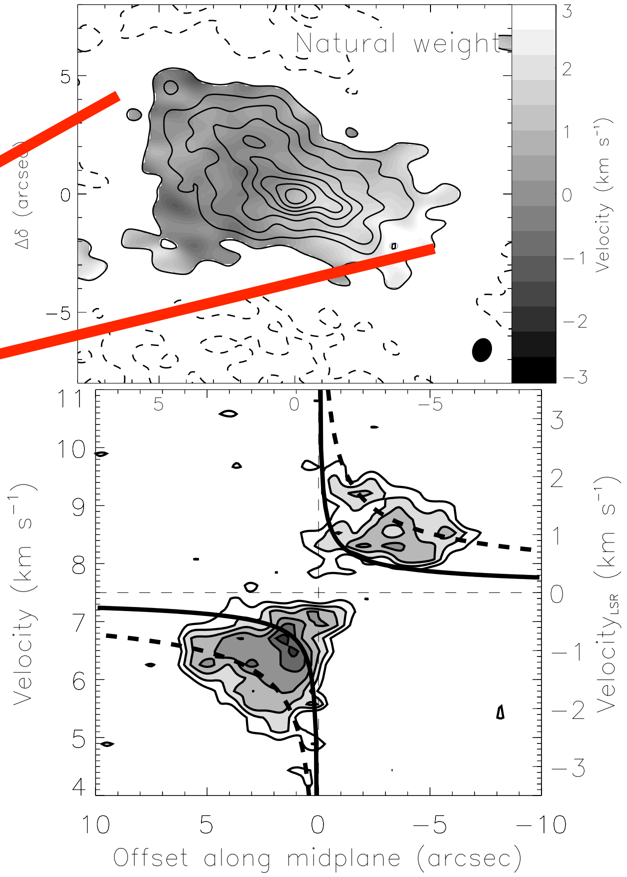




L1489 IRS: rotating disk, 200 AU







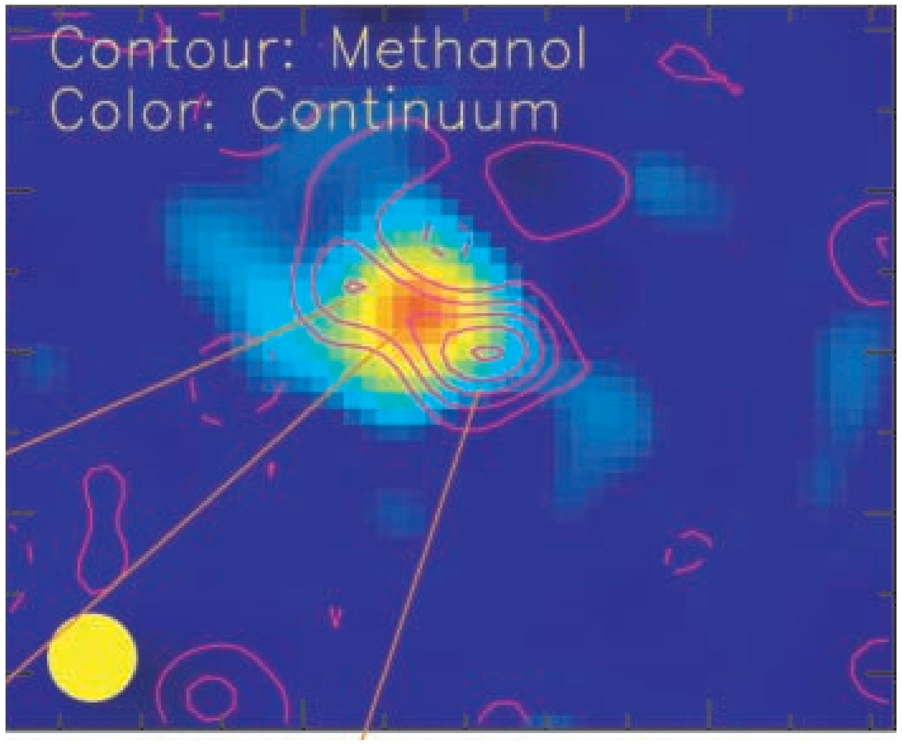
L1489 IRS: rotating + contracting envelope, 2000 AU

The formation of accretion disks

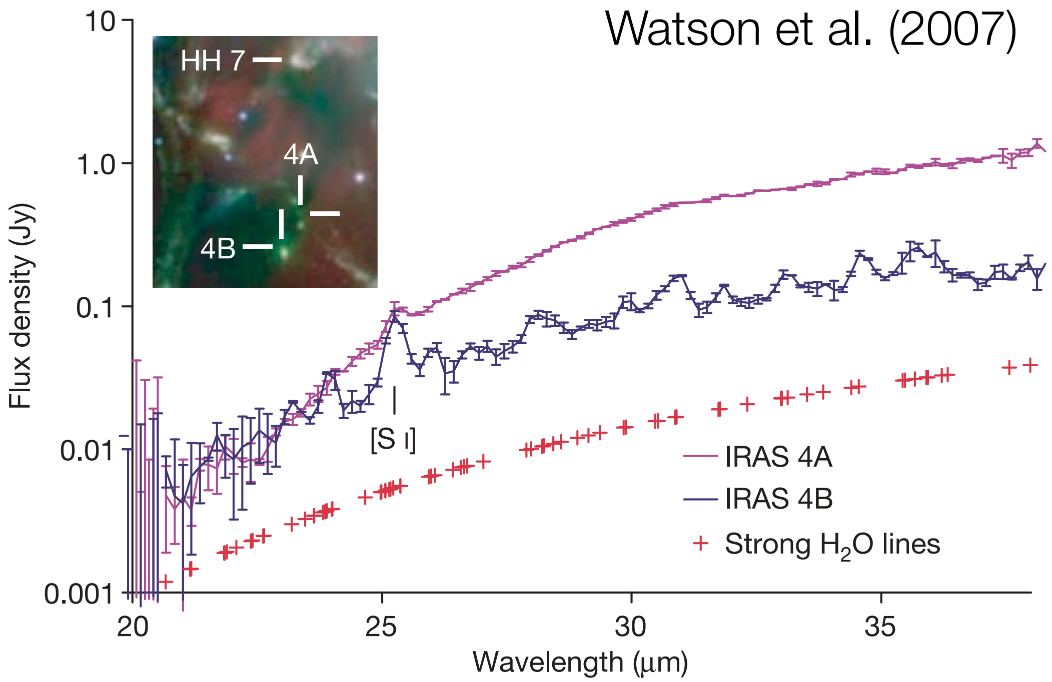
Chemical signatures of the disk/ envelope accretion shock.

Warm and cold water vapor around NGC1333 IRAS4B

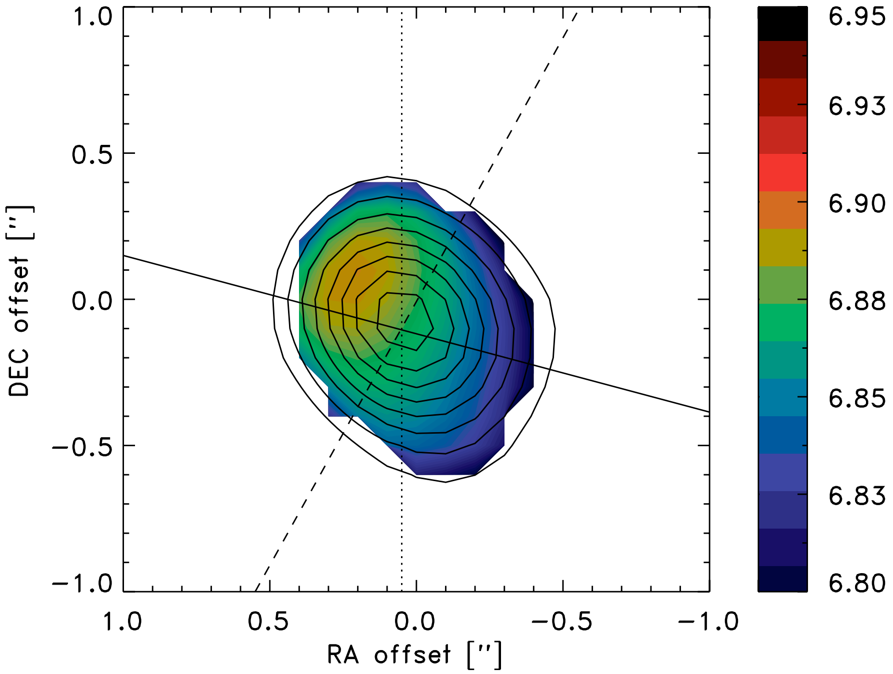
Methanol around L1157



Velusamy et al. (2002)



Watson et al. (2007)



Jørgensen et al. (2010)

Characteristics and evolution of protoplanetary disks

Majority of T Tauri* stars have a protoplanetary disk

Many disks are gas-rich

Disks often show Keplerian rotation

*Class II = T Tauri star

Simon et al. (2000)

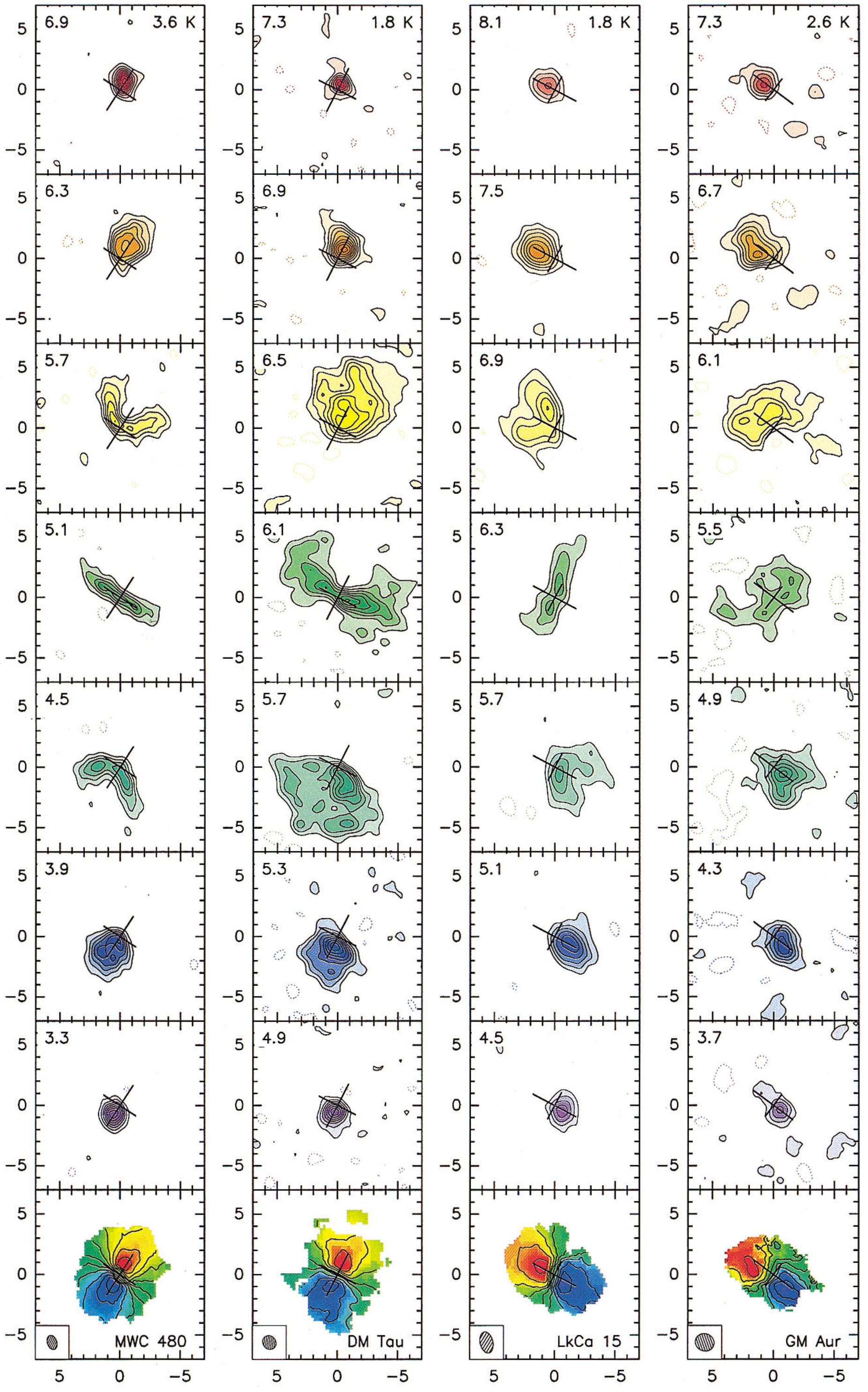


FIG. 1*a*

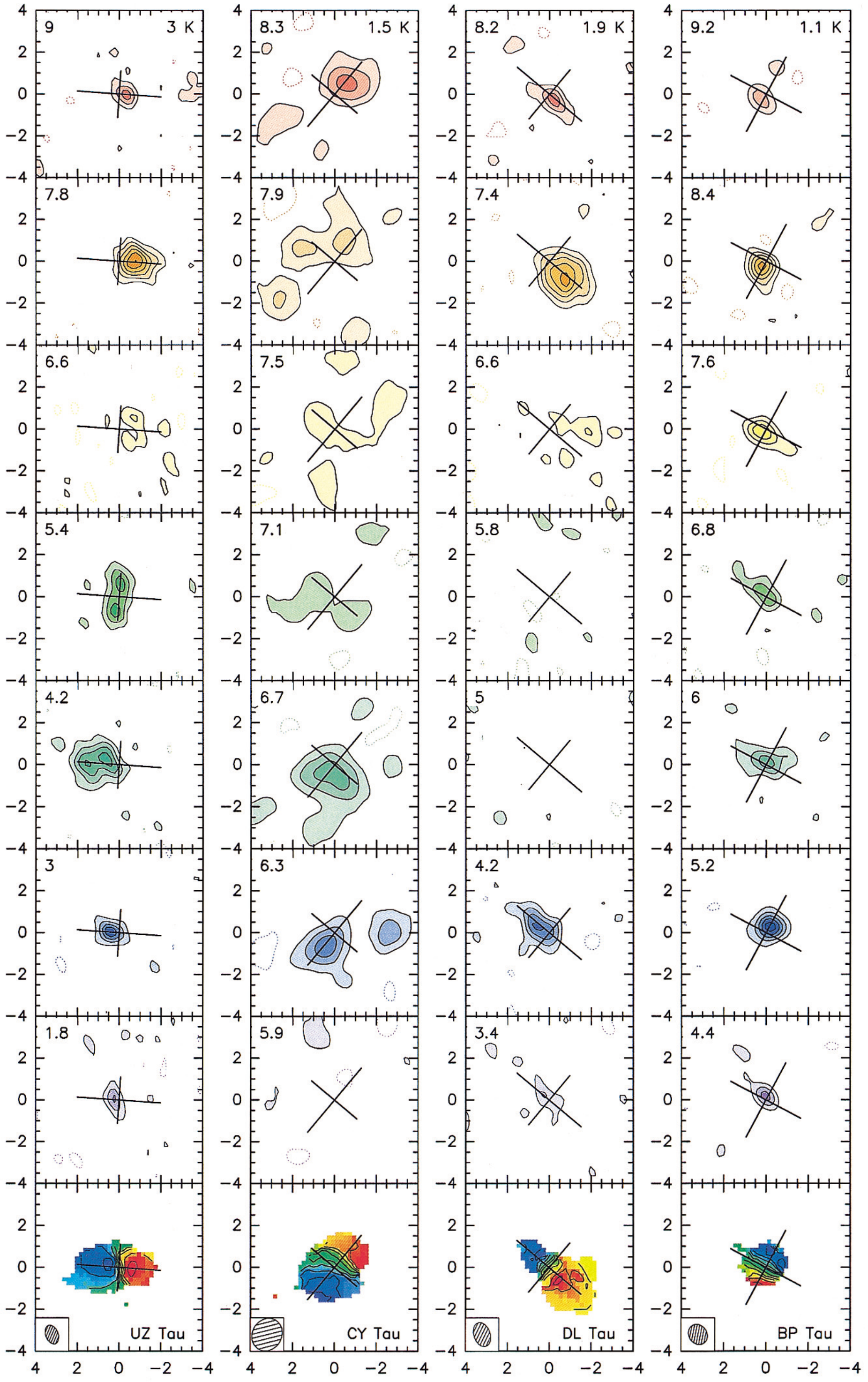
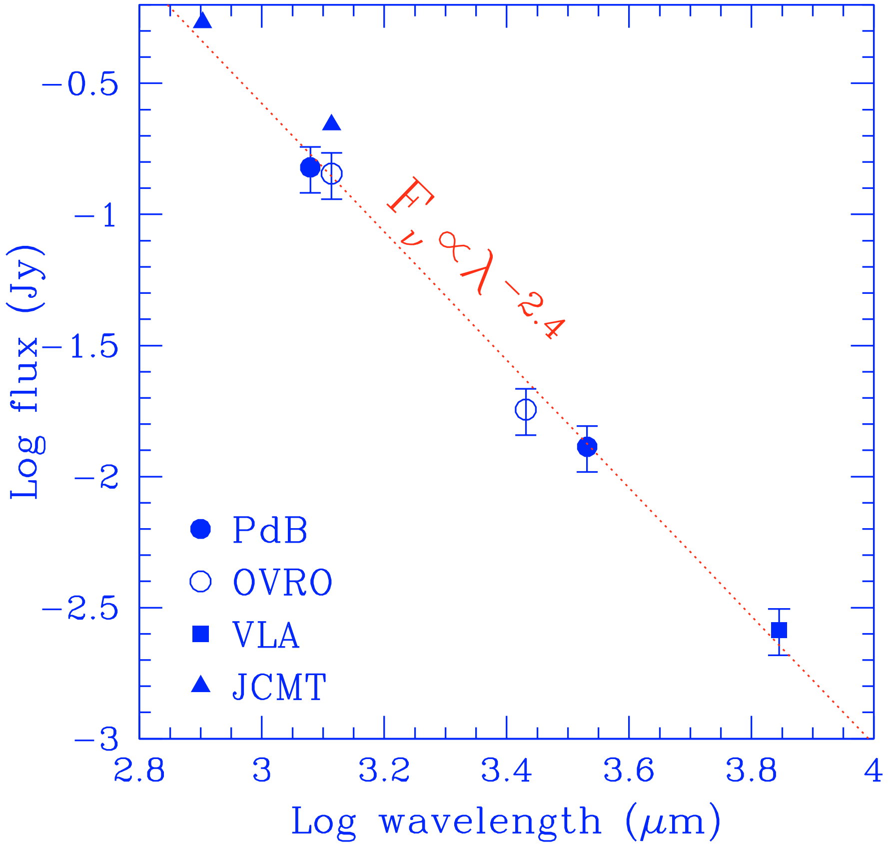


FIG. 1*b*

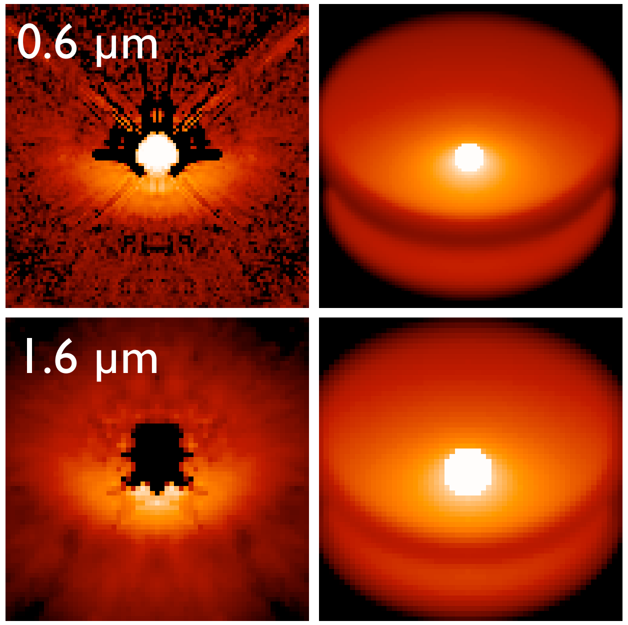
Characteristics and evolution of protoplanetary disks



Testi et al. (2003)

Dust grains grow and settle to the midplane

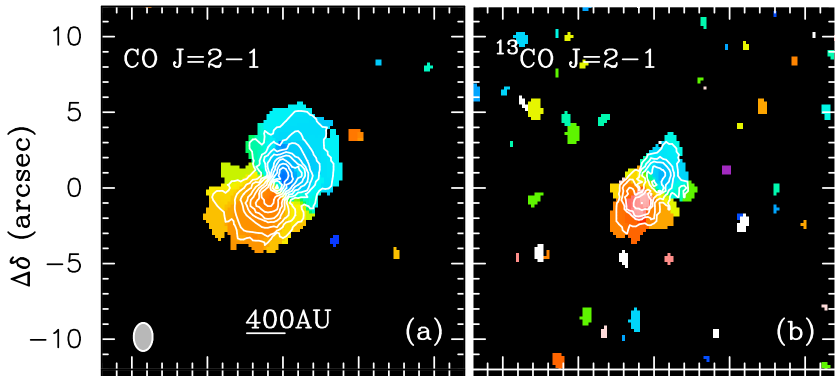
Beckwith & Sargent (1991)

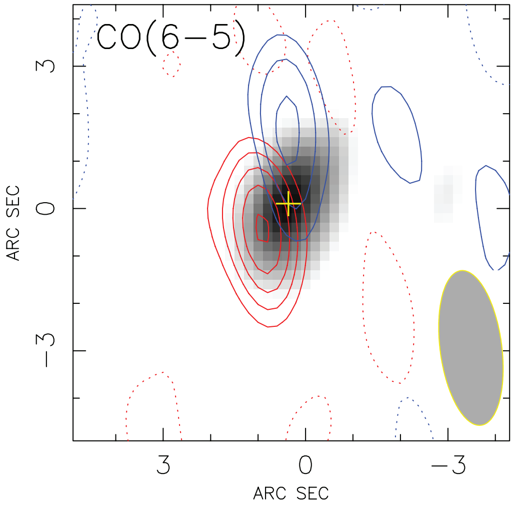


Pinte et al. (2008)

Gas affected by ultraviolet photons

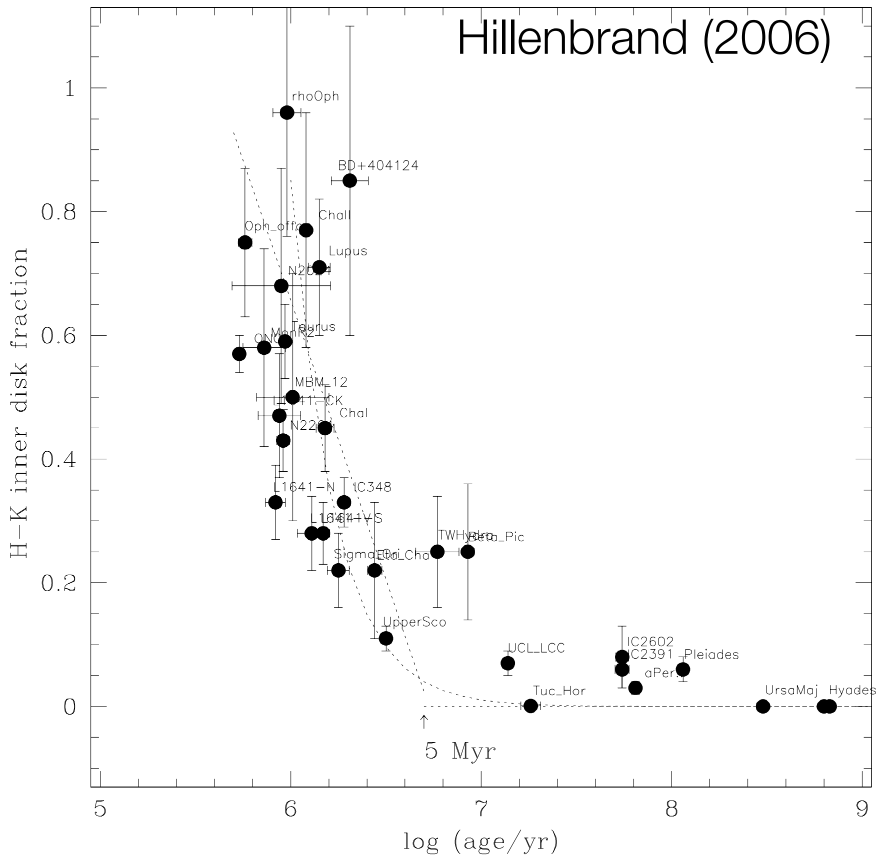
Panić et al. (2009)



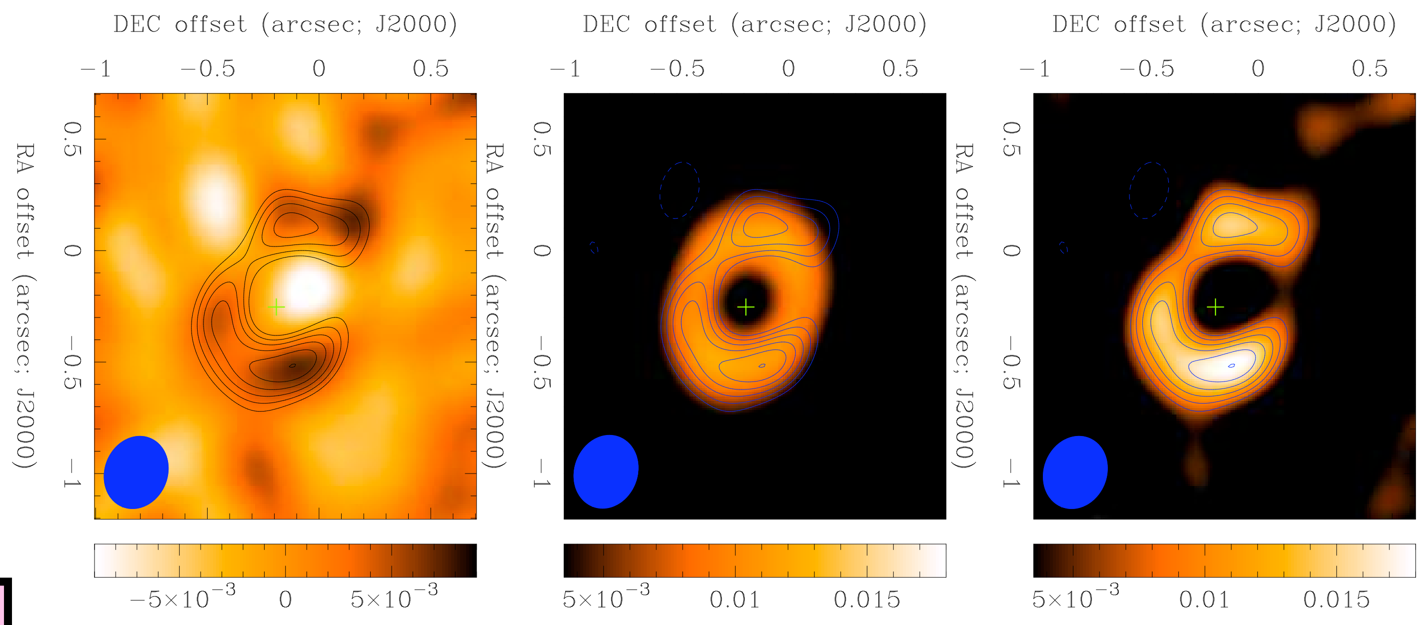


Qi et al. (2006)

Characteristics and evolution of protoplanetary disks


Hillenbrand (2006)

Median disk dispersal time 2–3 Myr


Brown et al. (2008)

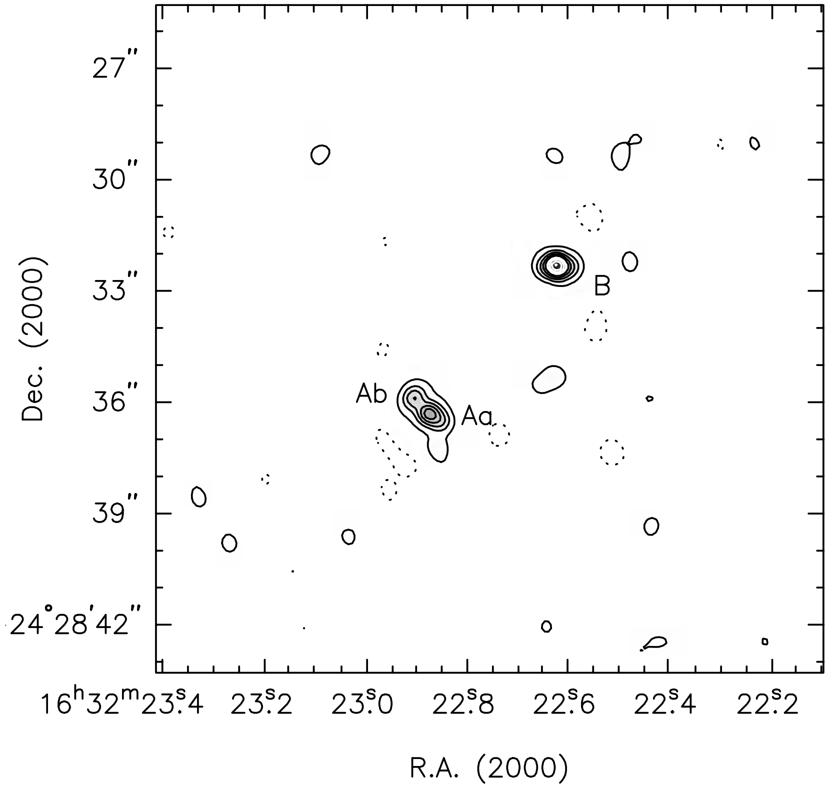
Small fraction of disks have inner cleared out gaps

photoevaporation
planets
(close stellar companions)

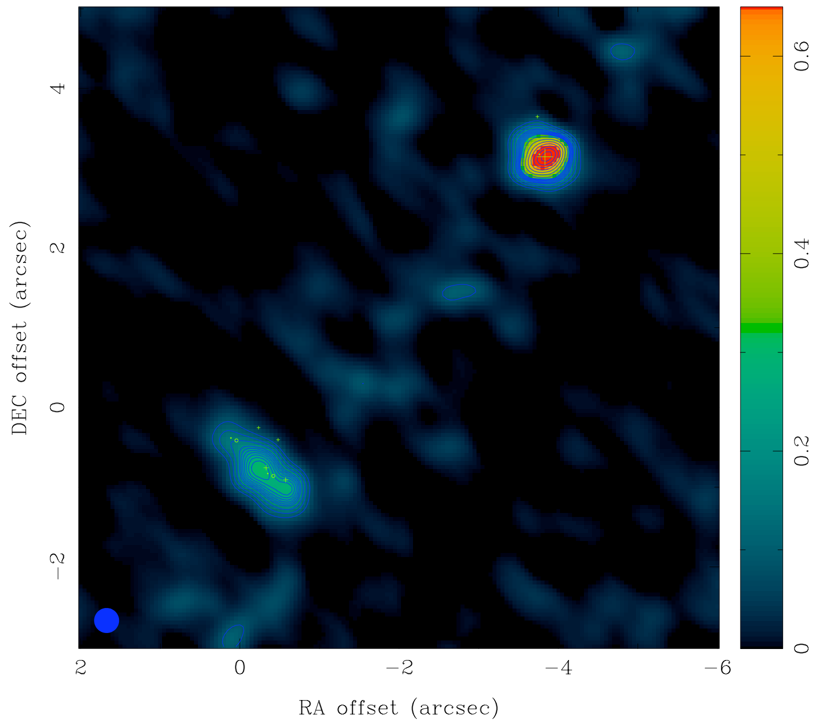
Multiplicity...

20-30% of T Tauri stars are in multiple systems
(e.g, Koehler 2001; Leinert et al. 1993; Ghez et al. 1993; Reipurth & Zinnecker 1993; Simon et al.1995)

Many YSOs also harbor multiple systems



SMA observations of IRAS16293-2422
Chandler et al. (2005)

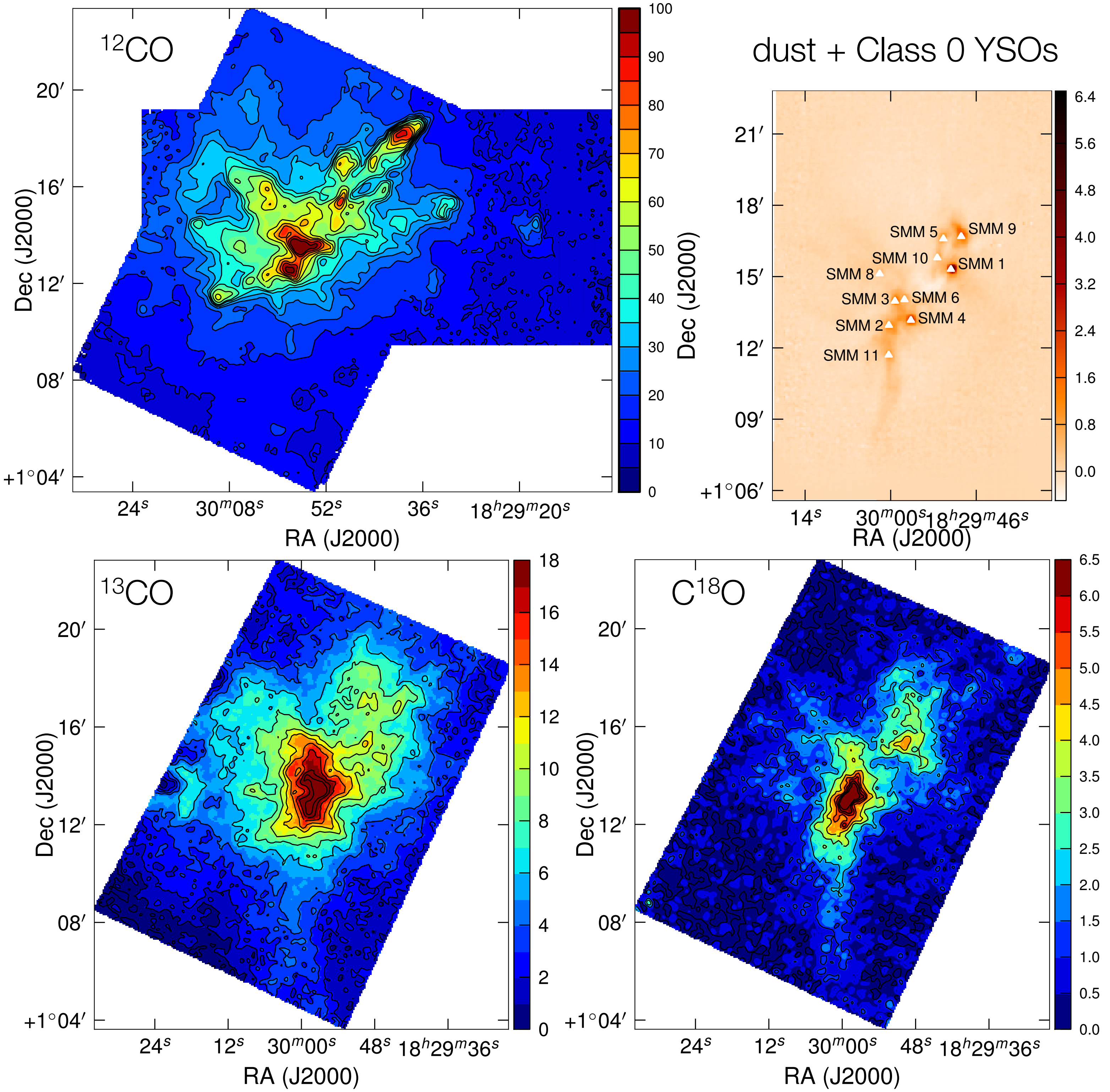


SMA+JCMT+CSO observations of IRAS16293-2422
Frieswijk et al. (in prep)

...and clustered star formation

Most (solar mass) stars form in clusters of ~hundreds of members (Lada & Lada 2003)

Competative accretion;
Outflows;
High-mass stars...



Serpens core
Graves et al. (in prep)

Conclusion: The formation of Solar Mass stars

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- Prestellar cores: ~Bonnor-Ebert spheres. Dynamics?

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Good picture of isolated star formation

Most stars form in multiple systems, clusters

Birth cluster of the Sun: $10^3<N<10^4$

Outlook

- ALMA
  - study YSOs in clustered regions like we have in isolation
  - separate disks from envelopes
- Herschel
  - access the FIR range, where key species have transitions: energetics
- E-ELT, JWST
  - MIR spectroscopy of gas close to the star (star/disk connection)

Major reviews

- Evans 1999 ARA&A, 37, 311
- McKee & Ostriker 2007 ARA&A, 45, 565
- Bergin & Tafalla 2007 ARA&A, 45, 339
- Reipurth, Jewitt & Keil 2006, Protostars & Planets V (Univ Arizona Press)
- Evans et al. 2009, ApJS, 181, 321