Toward a New Paradigm of Star Formation:

Does Nature Abhor a Singular Isothermal Sphere?

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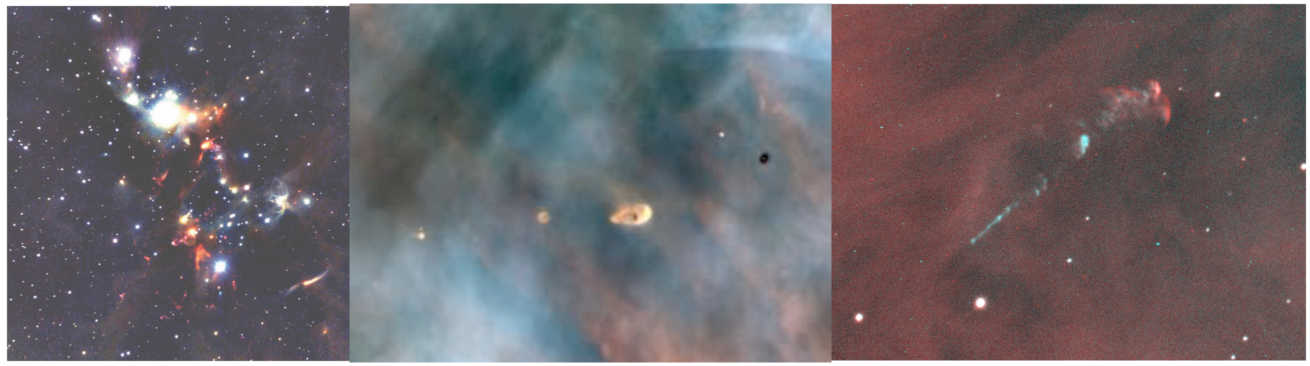
Outline



- Star Formation is Rapid
- Understanding cluster formation = understanding star formation
  - IMF
  - Turbulence simulations
- Cloud/Core structure
  - Magnetic fields: critical or subcritical?
  - Starless/pre-stellar cores
- The Next Decade
  - Surveys = large scale
  - Interferometers = high resolution

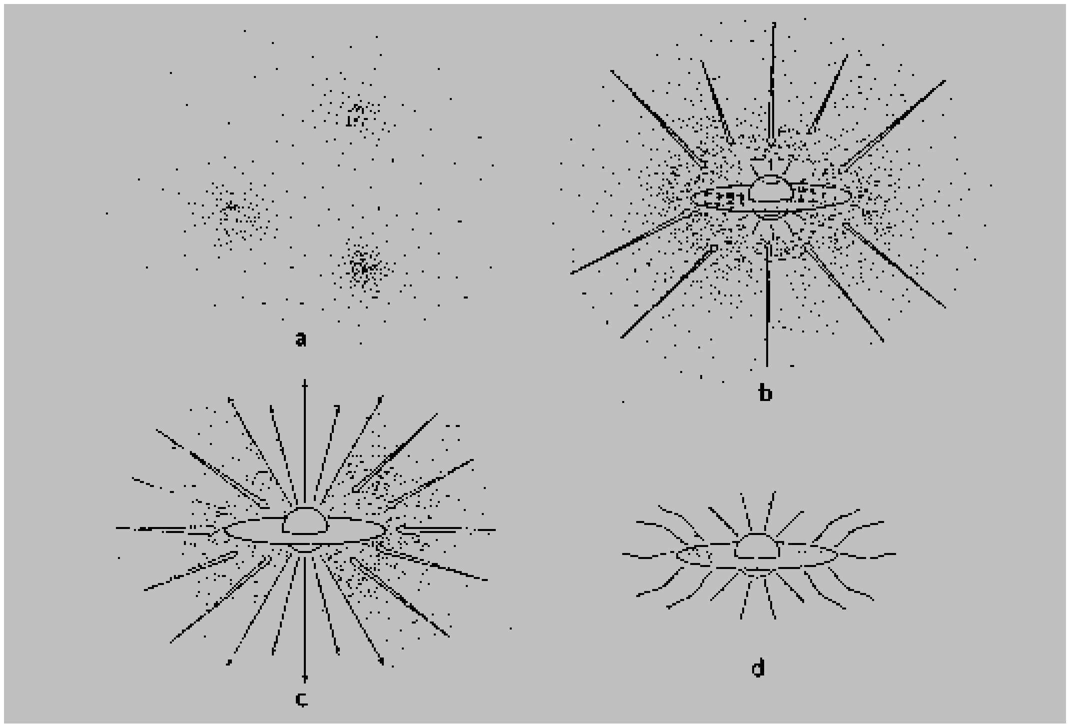
The Jeans Mass and SFE

- Jeans mass of GMCs: how much mass could the thermal motion support?
  - 25 K → 0.2 km/s → a few solar masses!
  - Orion is $10^6 M_{\odot}$!
- Molecular clouds are not globally collapsing
  - Support needed on cloud scales?
    - Magnetic fields and/or turbulence
- Star Formation Efficiency is Low (1-5 %)
  - Need to slow down collapse: magnetic fields and ambipolar diffusion
  - Are all regions “star-forming”? In turbulent star-forming scenario, not all “cores” will collapse; re-expansion is possible (Vasquez-Semadeni et al. 2003)

Evidence for Additional Support

- On Large Scales: good observations
  - Measured linewidths are much wider than thermal values (Myers et al.)
    - Turbulence (magnetic or non-magnetic?)
  - Measurements of Zeeman splitting of OH reveals magnetic fields are present at levels of several μG - mG (Troland, Heiles et al.)
  - Magnetic-kinetic-gravitational equipartion (Myers & Goodman 1988)
- On Small Scales: good theory
  - Ambipolar diffusion

The "Standard Model"



a. Core formation
b. Infall
c. Infall + outflow
d. T-Tauri

Ambipolar diffusion supports cloud to delay star formation (Shu & collaborators)

2 Myr to form a 1 $M_{\odot}$ star in Taurus

- isolated, low mass cores forming sun-like stars
- core formation? close multiples?

Star Formation is Rapid

Region	$\langle t \rangle$[a] (Myr)	Molecular Gas?
Coalsack	...	Yes
Orion Nebula......	1	Yes
Taurus..............	2	Yes
Oph.................	1	Yes
Cha I, II...........	2	Yes
Lupus...............	2	Yes
MBM 12A	2	Yes
IC 348	1–3	Yes
NGC 2264	3	Yes
Upper Sco	2–5	No
Sco OB2	5–15	No
TWA	~10	No
η Cha	~10	No

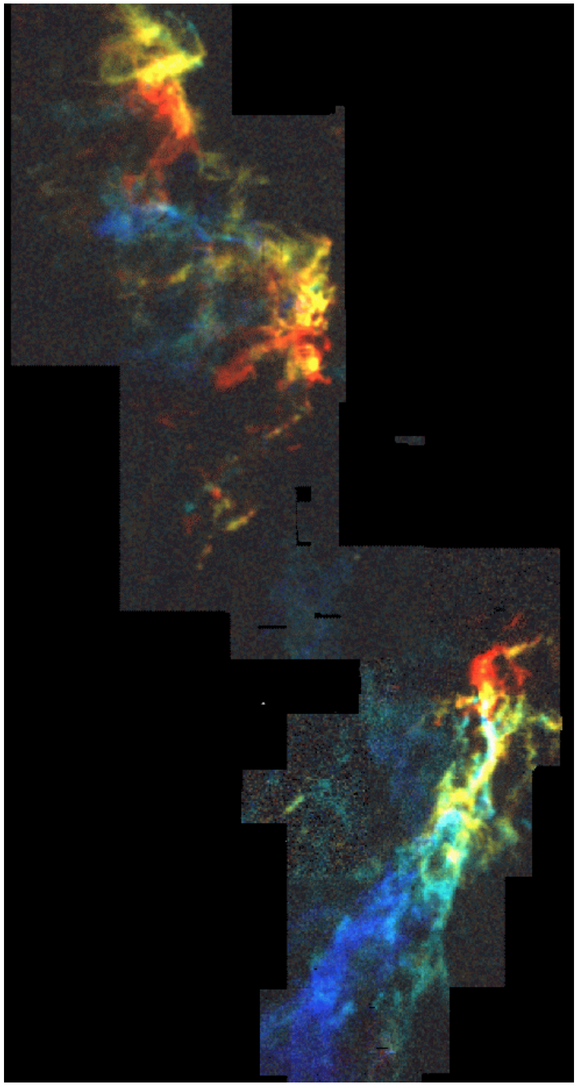
Hartmann et al. 2001

- Only one known cloud without any stellar population at all
- Stellar populations in embedded clouds are 1-3 Myr
- Older associations (5-10 Myr) have no remaining molecular gas (e.g. Leisawitz, Bash & Thaddeus 1989)

Implications of Short GMC lifetimes

- MHD turbulence decays rapidly (e.g. Stone et al. 1998)
  - Don't need to regenerate it if cloud lifetimes are comparable to or less than a crossing time
- Turbulence could just be leftover from cloud formation
  - Removes difficulty of requiring regeneration with stellar sources which are more likely to disrupt a cloud than stabilize it
- Low SFE is a result of global turbulent support, not slow cloud contraction under ambipolar diffusion (Hartmann 1998)
  - If ambipolar diffusion has no time to operate, large amounts of magnetic flux must not need to be removed from these cores (cannot be strongly magnetically subcritical)

Embedded Clusters & Molecular Gas

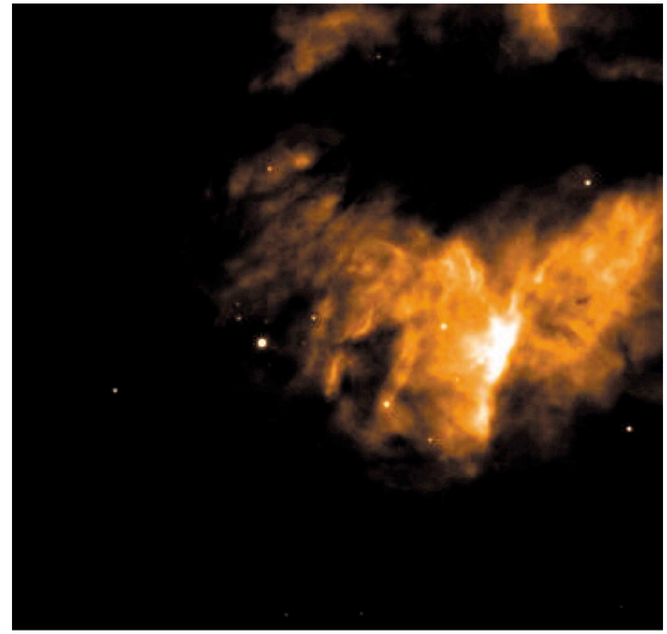


Bally 1986

- Less than 10% of the area and mass of a GMC is in the form of dense gas which is non-uniformly distributed
- Star formation efficiencies 10-30% within these dense cores, which are associated (naturally) with embedded clusters
- Globally SFE in molecular clouds only 1-5% (Duerr et al. 1982)

Embedded Clusters

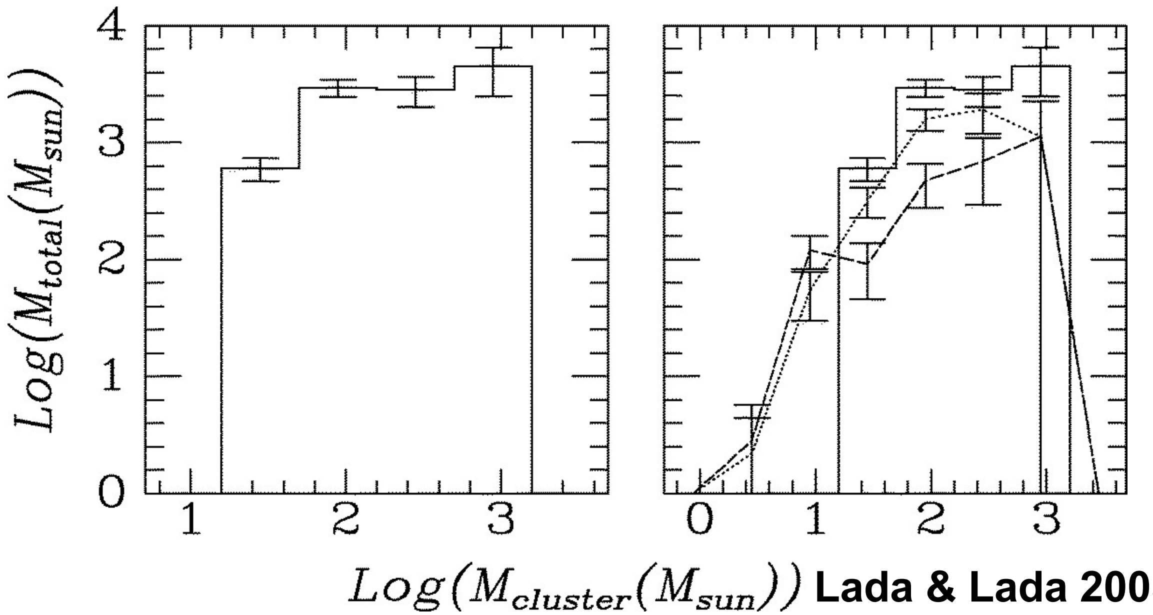
- discovered 30 yrs ago in a near-IR survey of Ophiuchus (Grasdalen et al. 1974; Wilking & Lada 1983)
- required infrared telescopes
- > 100 Galactic clusters known (pre-2MASS)
- 2MASS has recently increased population by 50% (Bica et al. 2003; Dutra et al. 2003)



Alves, RCW 38
VLT

Embedded Cluster Mass Function

- flat from 50-1000 M◦_
- 1000 M◦ clusters contribute a significant fraction of total stellar mass
- > 90% of stars form in clusters exceeding 50 M◦_
- drop in lowest mass bin significant



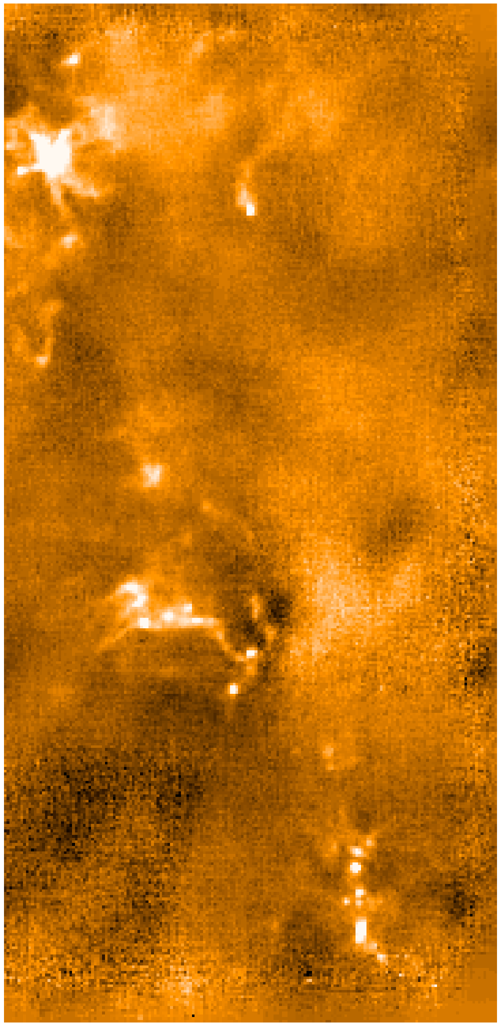
Lada & Lada 2003

There is a characteristic mass for star formation activity.

Embedded Clusters Dominate

- Fraction of stars born in embedded clusters is high based on observations in nearby regions
  - 60-90% forming stars in L1630 are in 3 clusters (Lada et al. 1991)
  - Similar results in 4 other clouds with 2MASS data (Carpenter 2000): 50-100%
  - Lower limits as field population is not removed!

- Clusters are the dominant mode of star formation for stars of all masses!



Orion B (L1630) JCMT
Johnstone et al. 2001

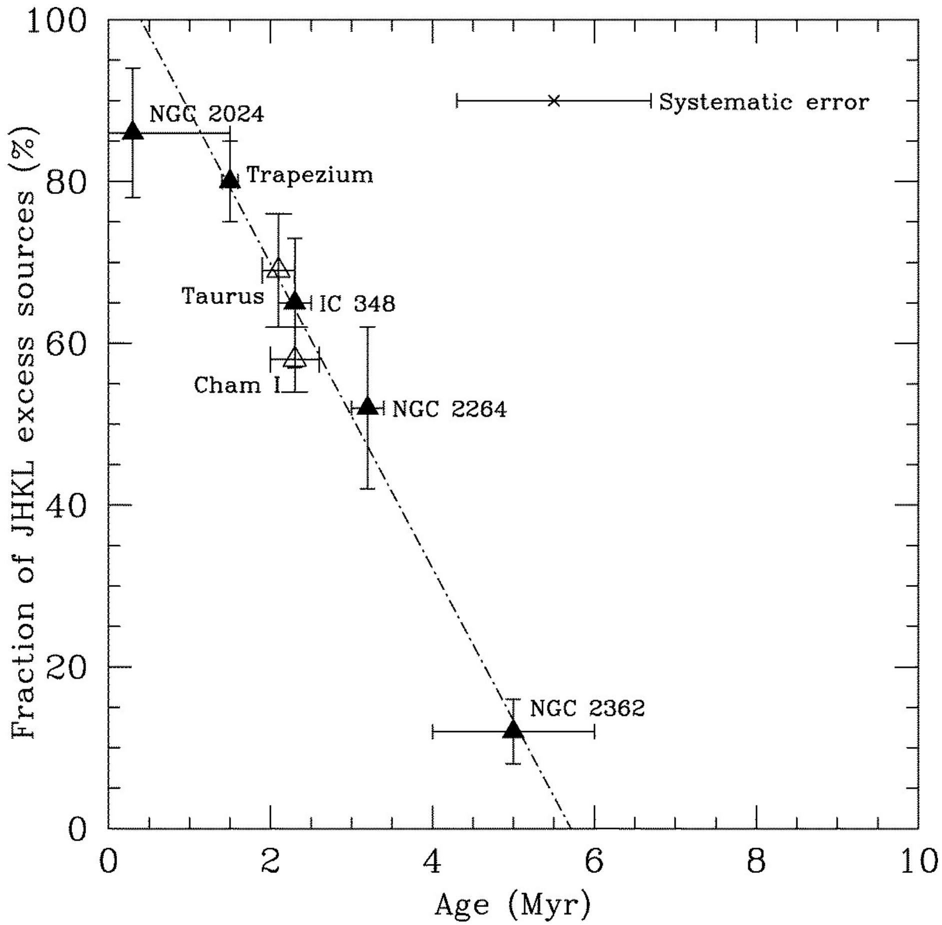
Observed Cluster Mortality

- Embedded cluster birthrate within 2 kpc:
  - 2-4 Myr^{-1} kpc^{-2} (Lada & Lada 2003)

- Open cluster birthrate within 2 kpc:
  - 5-9 times the rate of 0.45 Myr^{-1} kpc^{-2} (Battinelli & Capuzzo-Dolcetta 1991)

- → high infant mortality rate!
  - <10% survive beyond 10 Myr

Observed Disk Mortality Rates

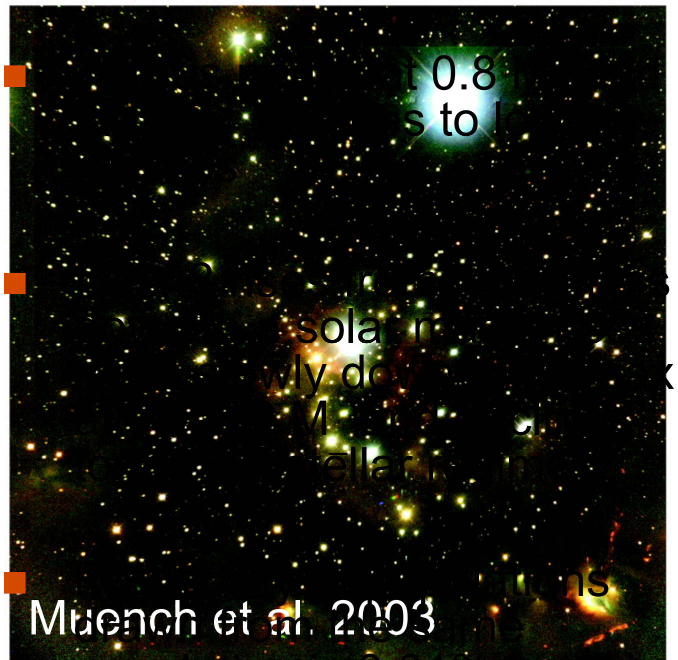


Disk Fraction vs. Cluster Age
(Haisch et al. 2001)

- all disks are lost in 6 Myr
  - need rapid planet formation
- outer disks? (mm mapping)
  - Taurus and _ Oph show a large fraction of sources have disks massive enough to form planets
  - Trapezium (BIMA and OVRO) at 3mm doesn't show disks over 0.015 M$_\odot$ (Mundy et al. 1995; Bally et al. 1998)
  - no massive disks in IC348 (outer disks dissipate in < 3 Myr; Carpenter 2000)
- difficult to form massive, planet forming disks in clusters or they are quickly destroyed in these environments

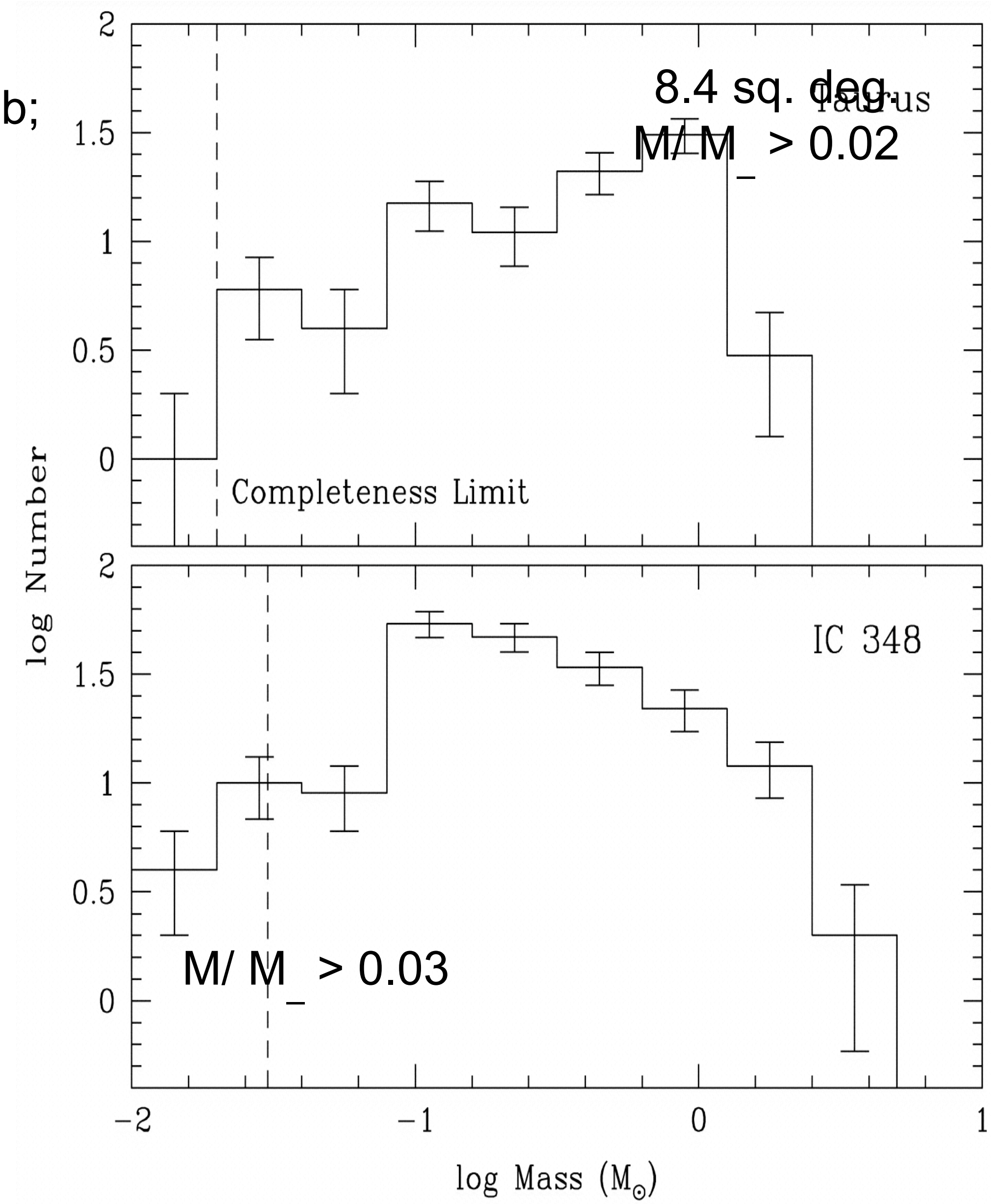
Variability in the Initial Mass Function

Luhman et al. 2003a,b;
Briceño et al. 2002

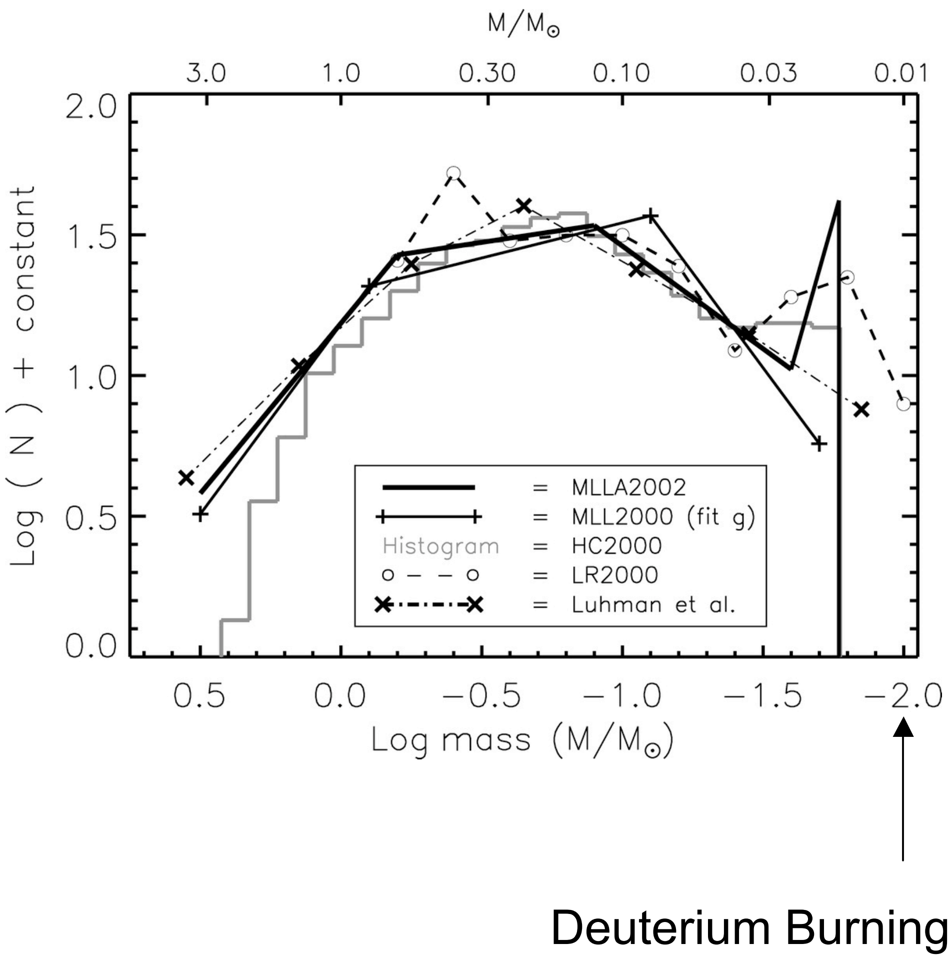


Muench et al. 2003

population is 0.01% based on a two sided K-S test.



IMF to the Deuterium Burning Limit



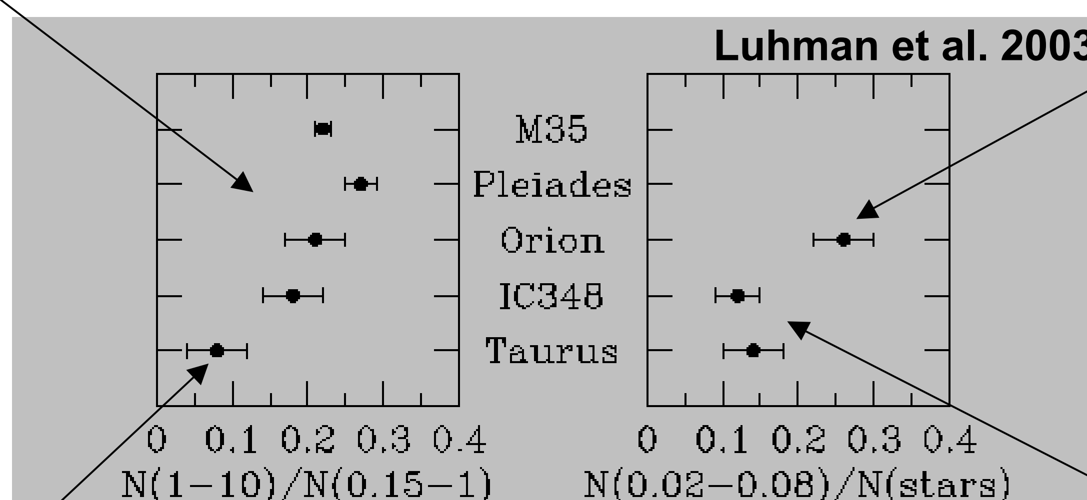
IMFs for Trapezium generated with different techniques all show a broad peak between 0.1-0.6 M_ with a clear decline in the substellar regime which is not an effect of incomplete sampling.

Lada & Lada 2003

Relative populations by mass

Four regions have comparable relative numbers of high-to-low mass stars

Frequency of BDs in Trapezium is 2x that in IC 348 or Taurus



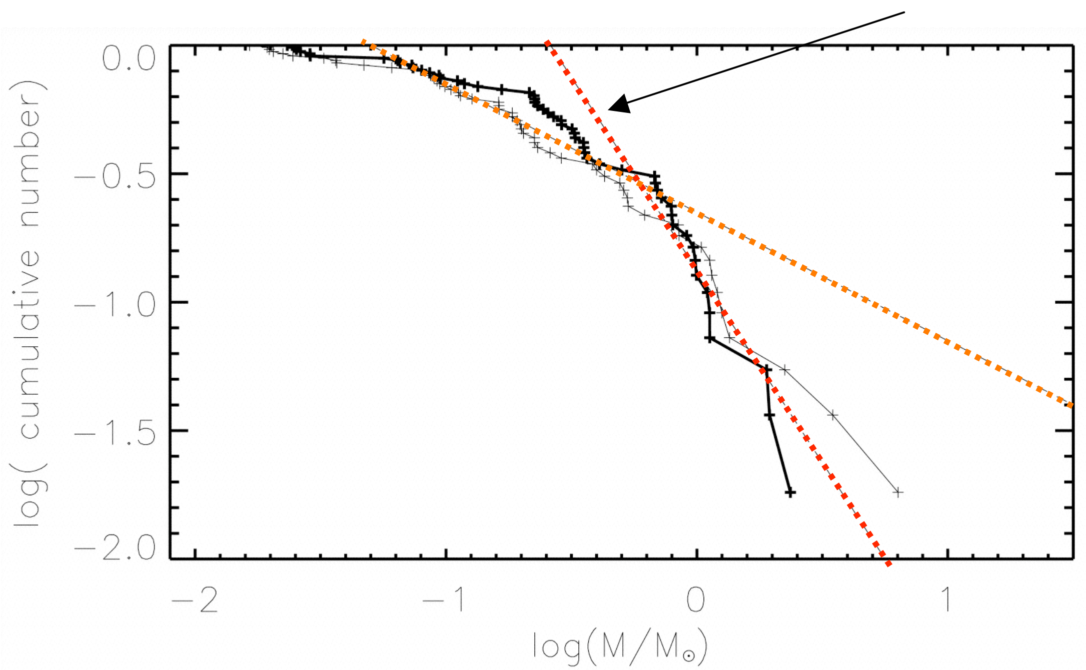
Taurus produces fewest high mass stars

Taurus actual favors intermediate mass stars over Orion

Taurus and IC 348 have comparable numbers of brown dwarfs

Except…

- Clump mass spectrum in Orion and Ophiuchus is Salpeter!

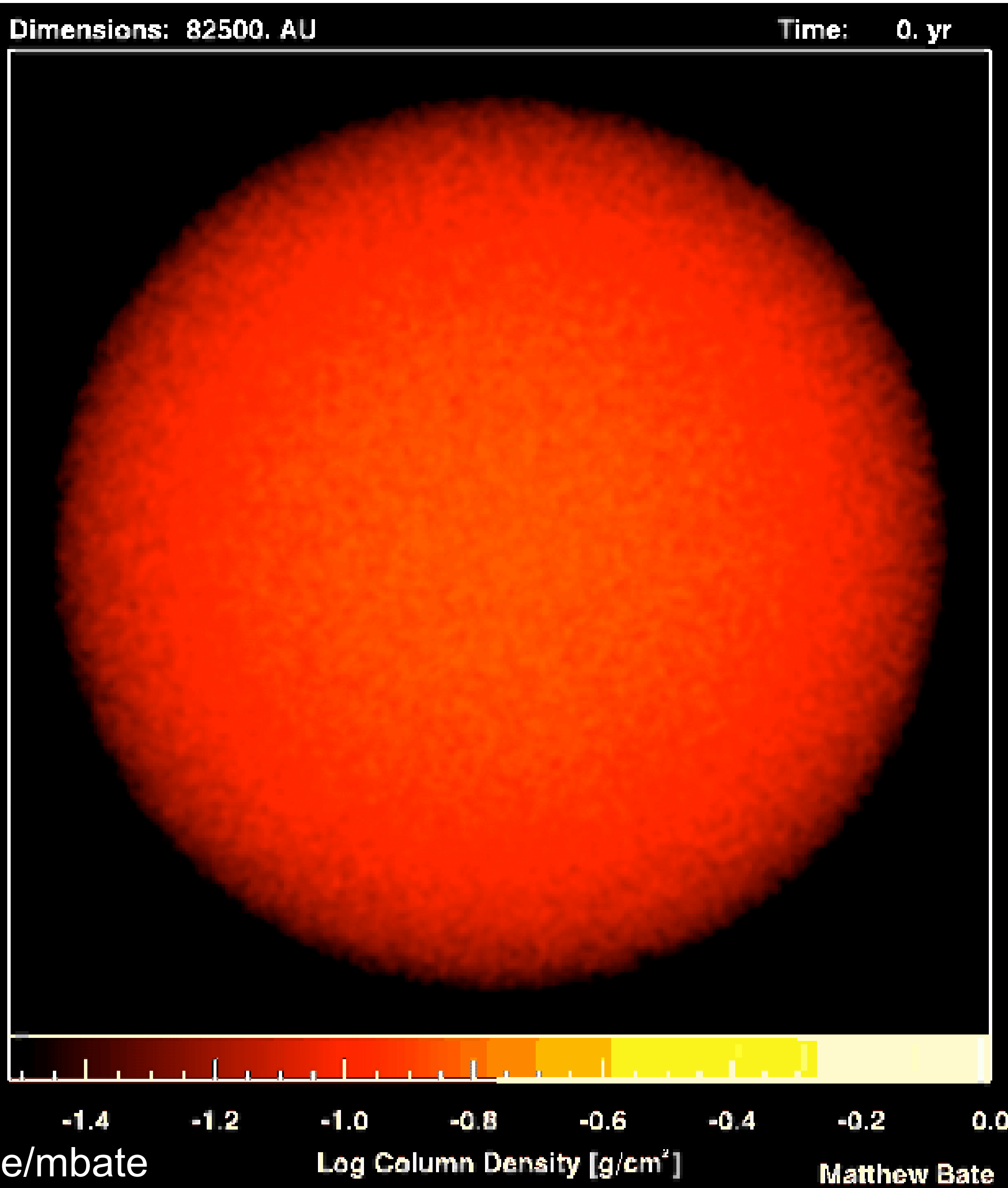


Johnstone et al. 2001
Motte et al. 2001

Theory of Embedded Clusters

- Numerical simulations required to follow evolution of a stellar cluster
  - turbulent hydrodynamical calculations to match observed properties of clouds
  - MHD?
- Simulations are challenging due to large range of scales involved (use of “sink” particles)
- Previous simulations just reach protostars or start after fragmentation to follow protostellar evolution

- Bate, Bonnell & Bromm (2003) turbulent hydrodynamic simulation
- Collapse of a 10 K, 50 M cloud with 3.5 million particles (!)
  - Minimum Jeans mass 1.1 M_J
  - Down to opacity limit of a few MJ (approx. 0.005 M)
  - Binaries as close as 10 AU
  - Resolved circumstellar disks down to 20 AU
- Roughly equal numbers of stars and brown dwarfs formed

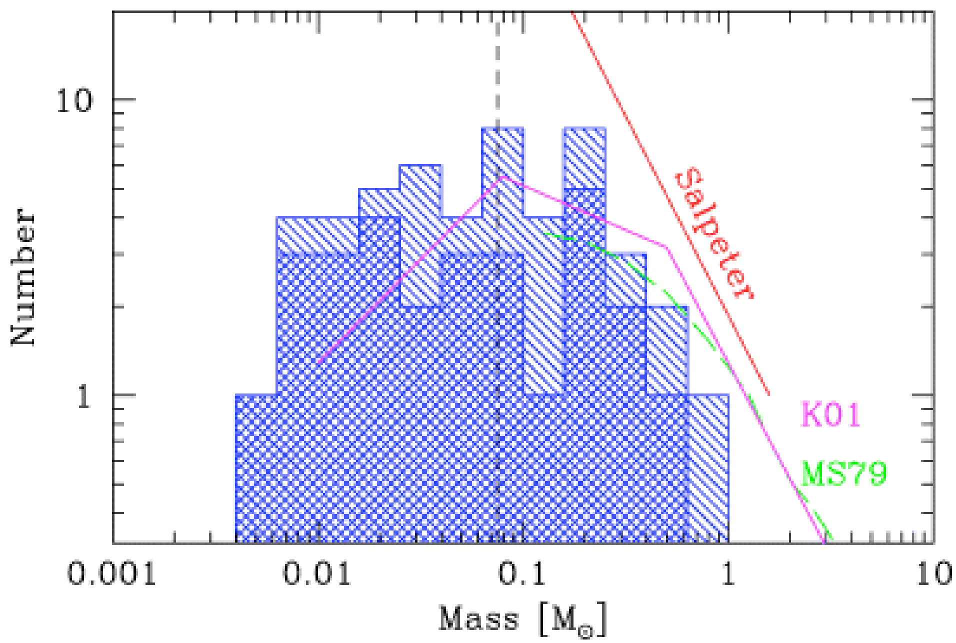


http://www.astro.ex.ac.uk/people/mbate

Outcome of the Simulation

	Simulation	Observation
Stars Brown Dwarfs	32 18	50:50 ratio (Reid et al. 1999)
Close Binaries (< 10 AU)	7 (16% of stars formed)	20% (Duquennoy & Mayor 1991)
Protoplanetary Disks (resolvable = 20 AU)	40% stars (20% ejected) 17% BDs (5% ejected)	80% in Trapezium by IR excess (Lada et al. 2000) 40/300 resolved by HST (Rodmann & McCaughrean, in prep)
Brown Dwarf Binaries	5%	15±7% (Close et al. 2003)

Predicted IMF



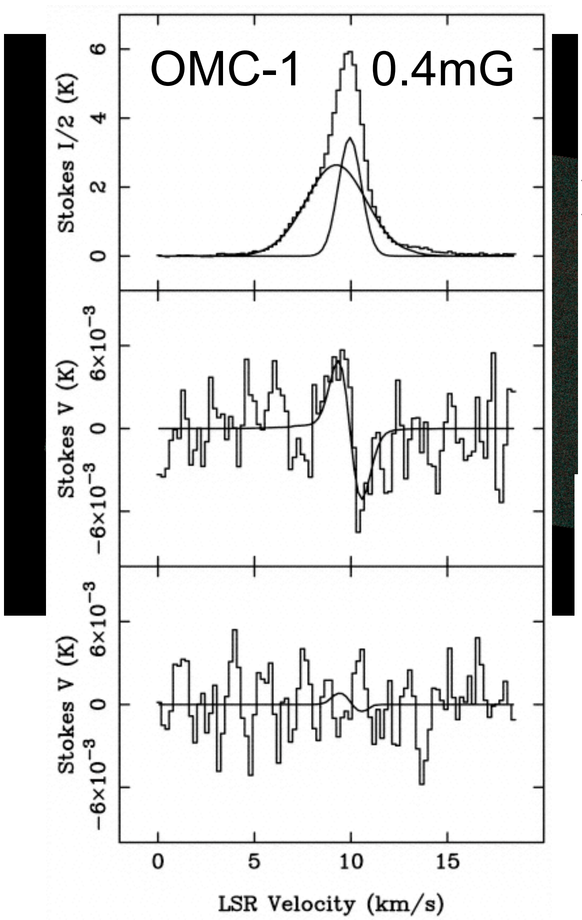
A characteristic mass is predicted by presence of turndown in substellar population.

→ Clearly seen in Trapezium data

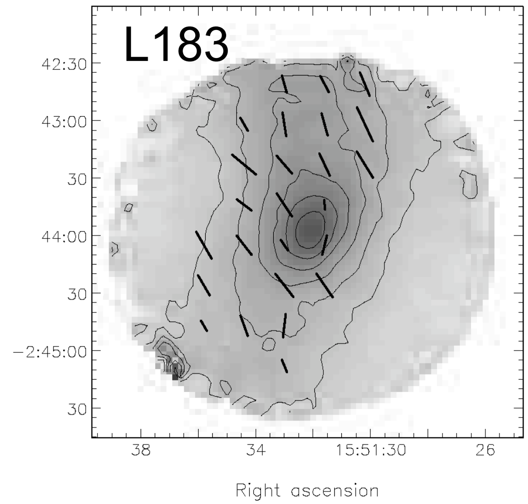
Salpeter (_ = -1.35) for M > 0.5 M_

_ = 0.0 for 0.006 < M < 0.5 M_

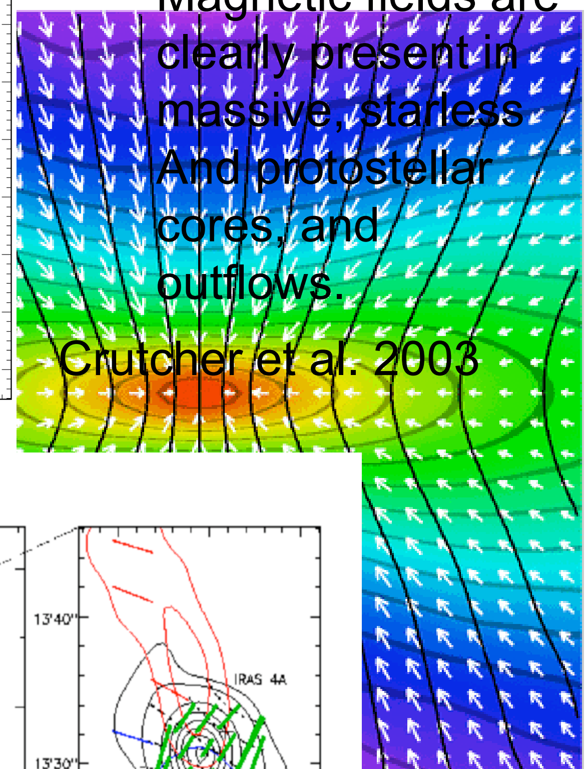
What about Magnetic Fields?



Crutcher et al. 1999

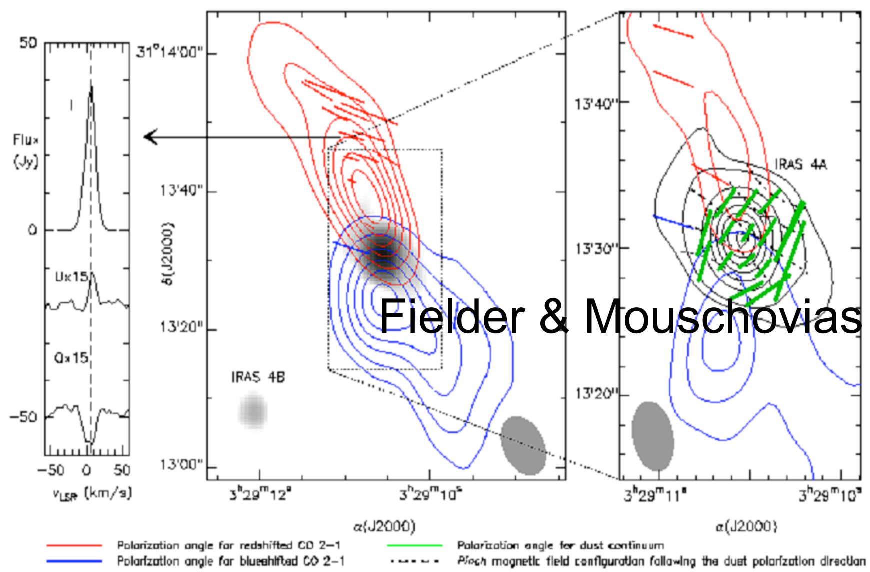


Magnetic fields are clearly present in massive, starless And protostellar cores, and outflows.



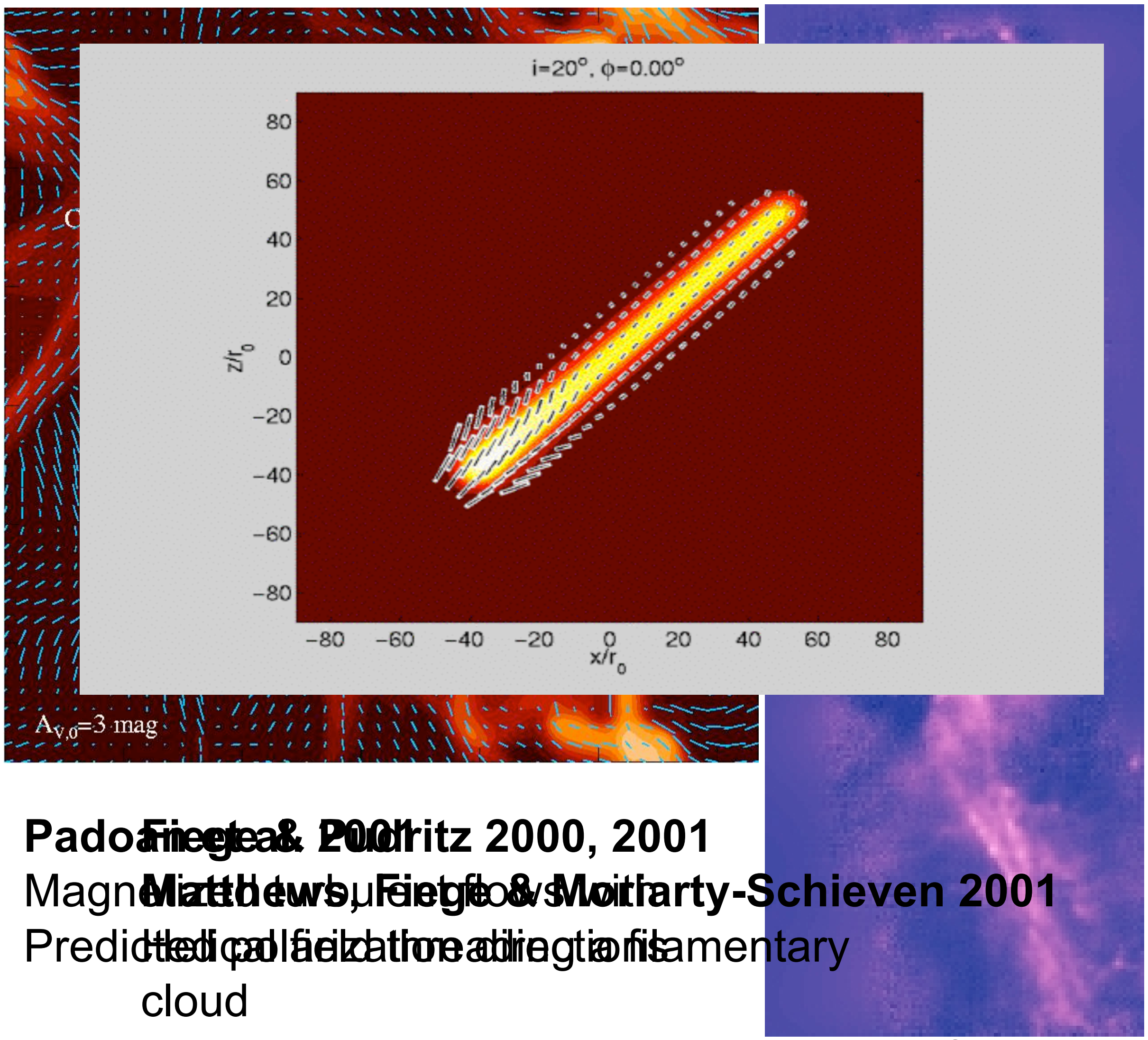
Crutcher et al. 2003

Fielder & Mouschovias 1993



Girart et al. 1999

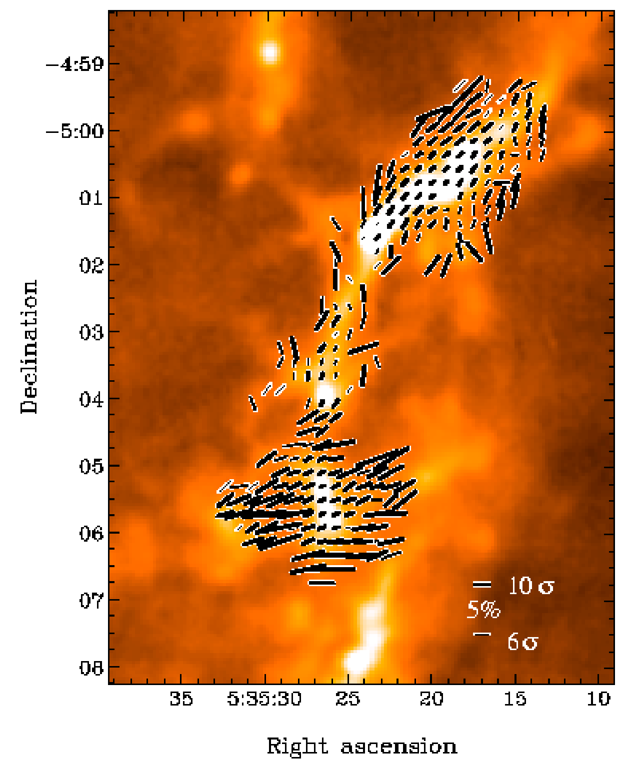
Magnetic Fields on Large Scales



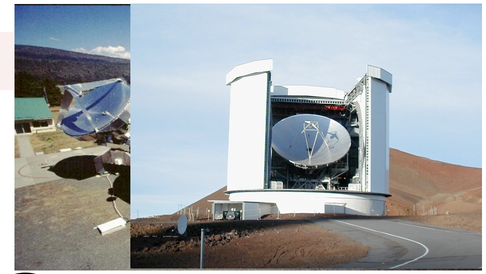
Padoan et al. 2001
Magnetized turbulent flows with
Predicted polarization directions

Fiege & Pudritz 2000, 2001
Matthews, Fiege & Moriarty-Schieven 2001
Helical field threading filamentary cloud

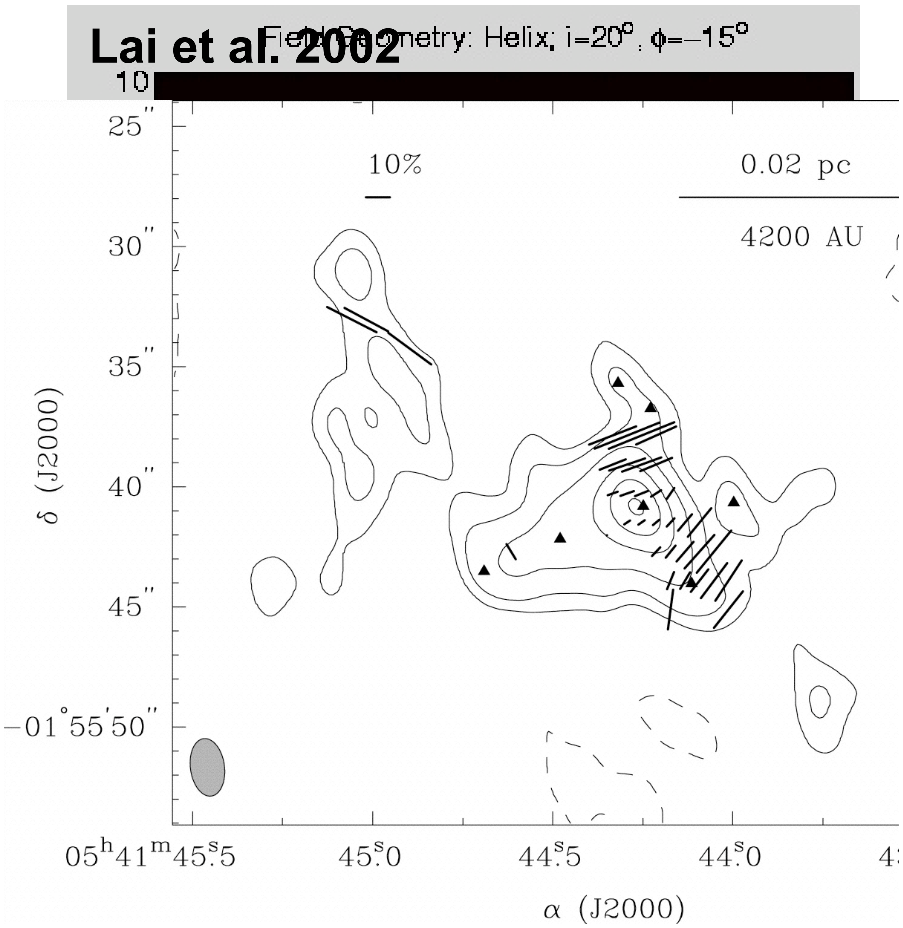
Johnstone & Bally

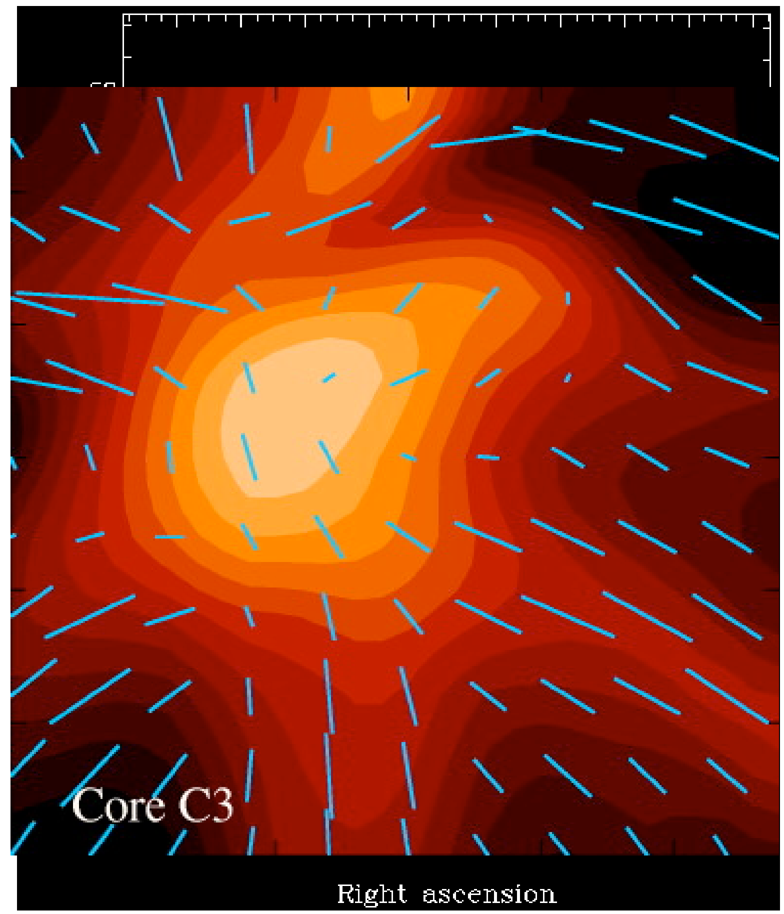


Matthews et al. 2001
Polarized emission along Orion's massive Integral-Shaped filament



Preservation of Field Geometry from Clouds to Cores

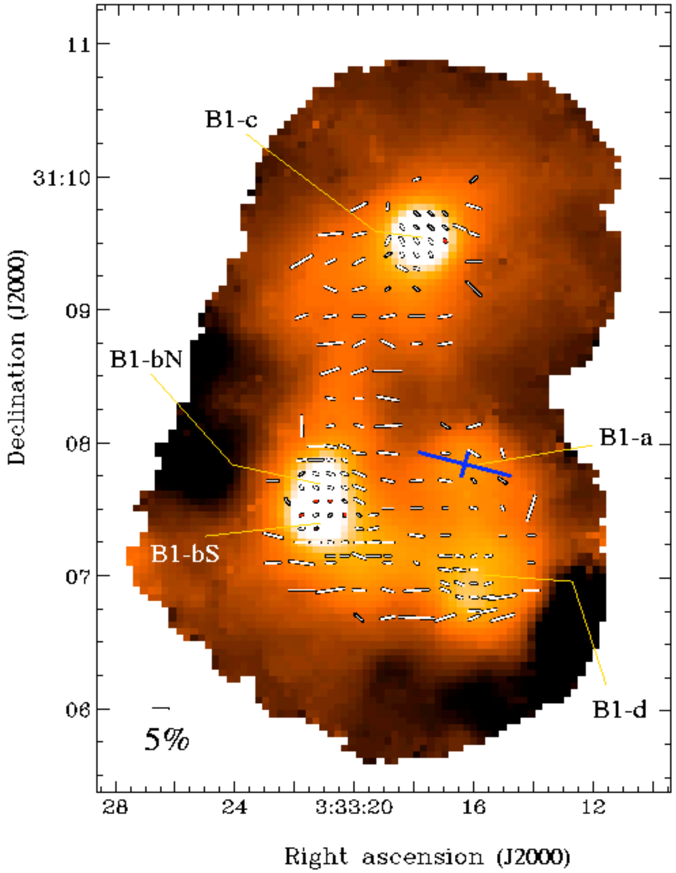




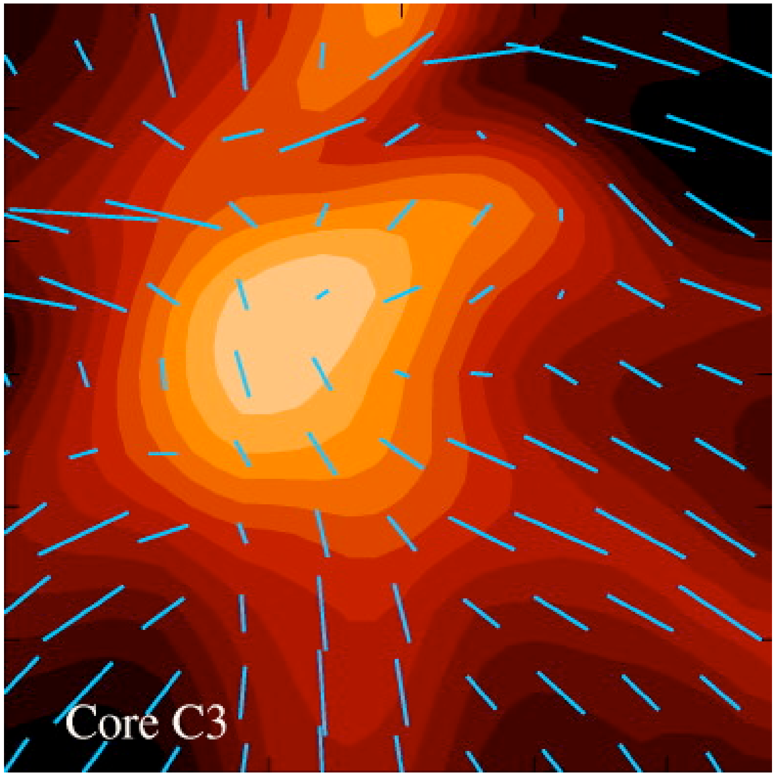
Dotson et al. 2000

Matthews, Fiege & Moriarty-Schieven 2002

Preservation of Field Geometry from Clouds to Cores



Matthews & Wilson 2002

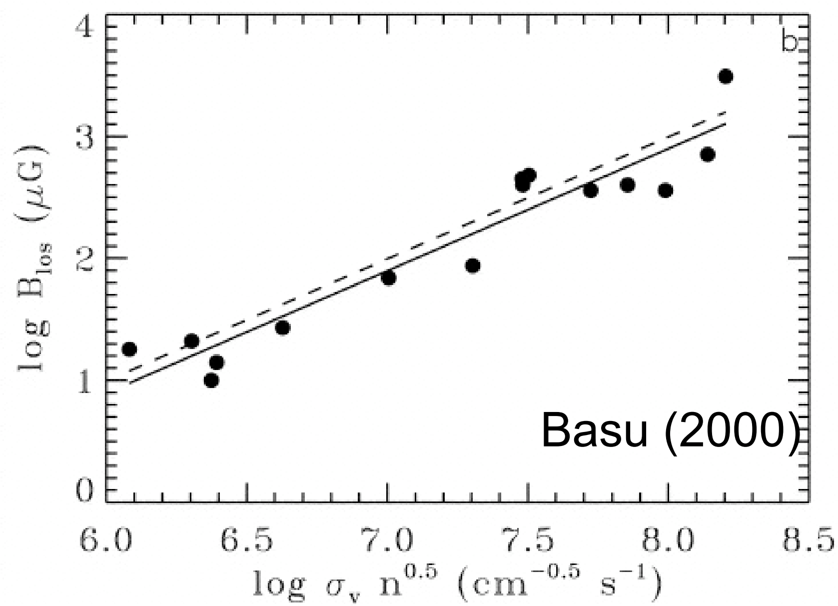


Padoan et al. 2001

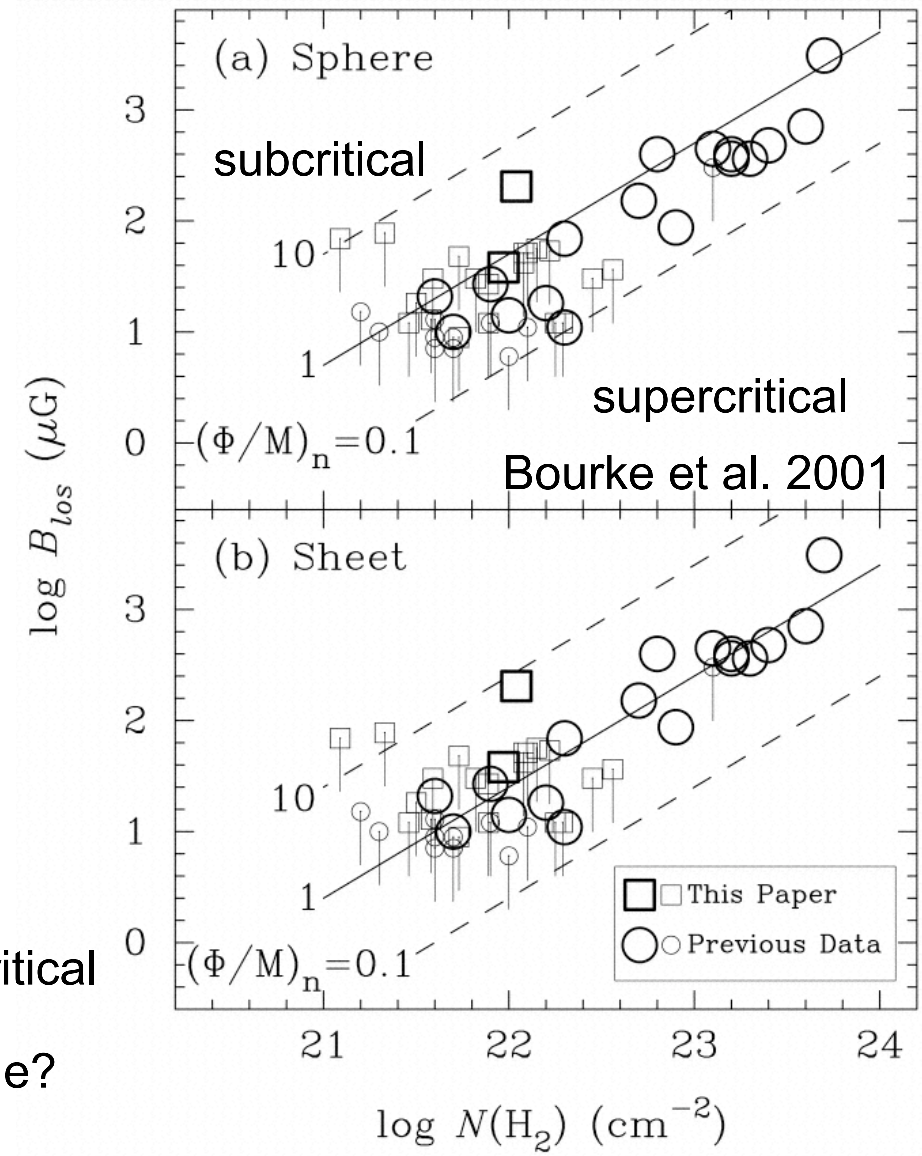
Magnetic Turbulence

- Virial equilibrium between gravity and turbulence →
- Flux freezing →
- Expect:

Observations of Magnetic Field Strengths

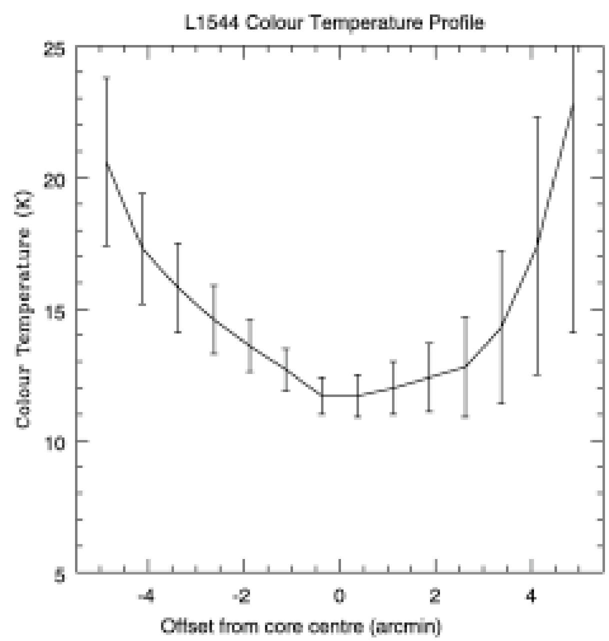


- McKee (1989) argued for GMCs being critical or supercritical
- Observations also show this supercritical condition in cores
- Is the magnetic field along for the ride? (Why does it look so ordered?)



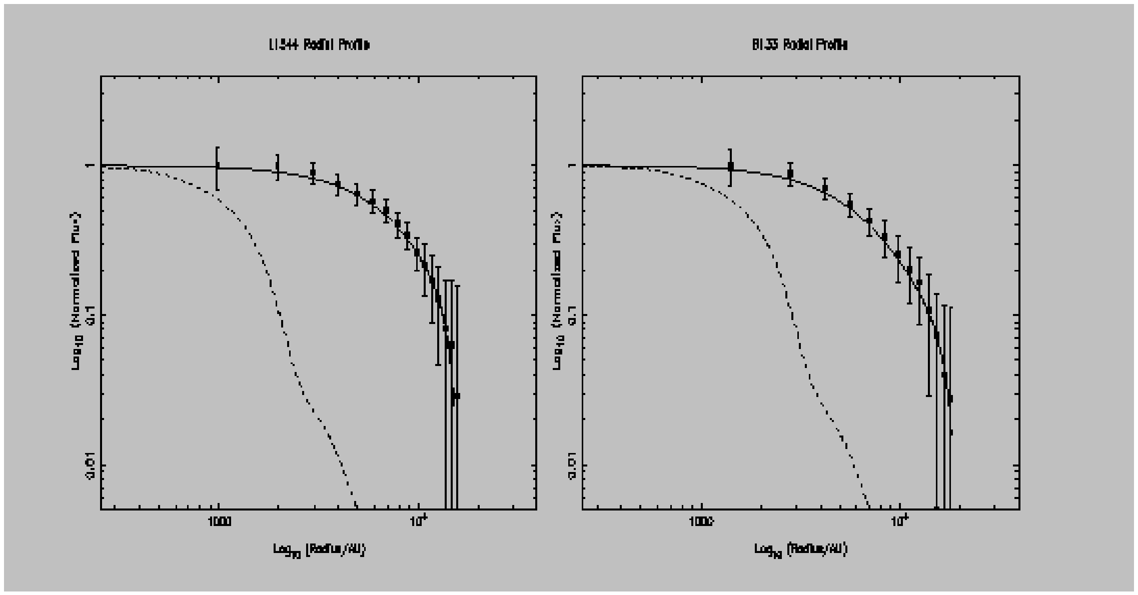
Starless and Pre-stellar "Cold" Cores:
Initial Conditions of Collapse

- Definitions:
  - Pre-stellar cores are sufficiently centrally condensed that they are likely to form stars in future (Ward-Thompson et al. 1994)
  - Starless cores will not
- Characteristics:
  - linewidths are thermal
  - Very asymmetrical
  - evidence of external heating



Ward-Thompson et al. 1999

Pre-stellar Cores



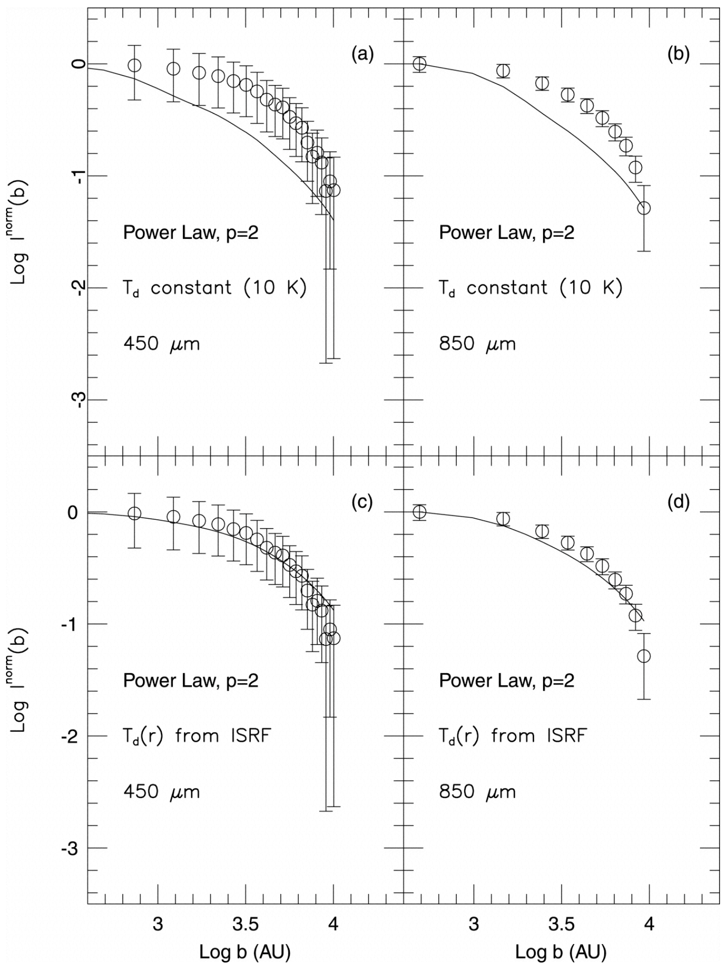
Ward-Thompson et al. 1994

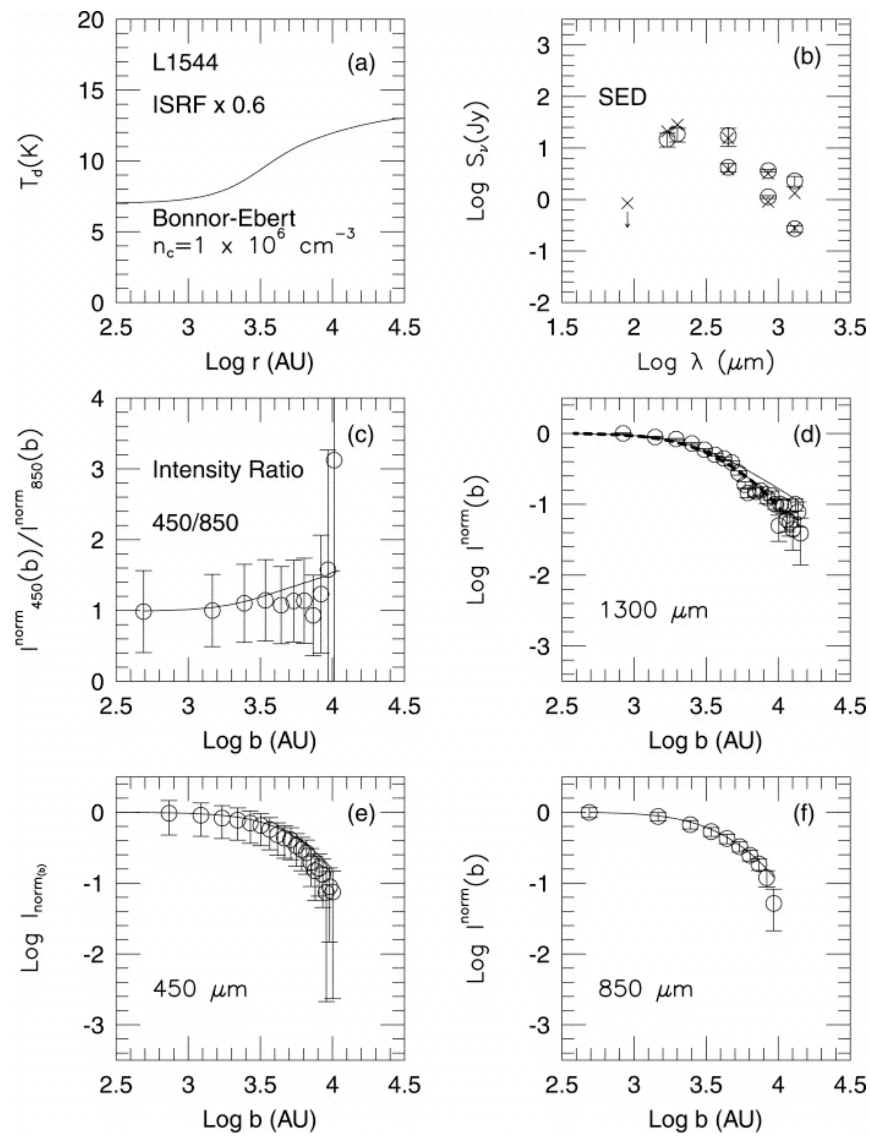
- Characterized by a density profile which is flat in the centre and steep toward the edge
- Is not solely a function of T(r) since the same profile is seen in MIR and NIR absorption surveys (e.g. Alves et al. 2001)

- SIS model can be ruled out (Bacmann et al. 2000)

- Purely thermal BE sphere central temp is much higher than the observed temp in some cases (e.g. Andre et al. 2003; Harvey et al. 2003)
  → Either cores are already collapsing or another support mechanism is operating

Radial Profiles

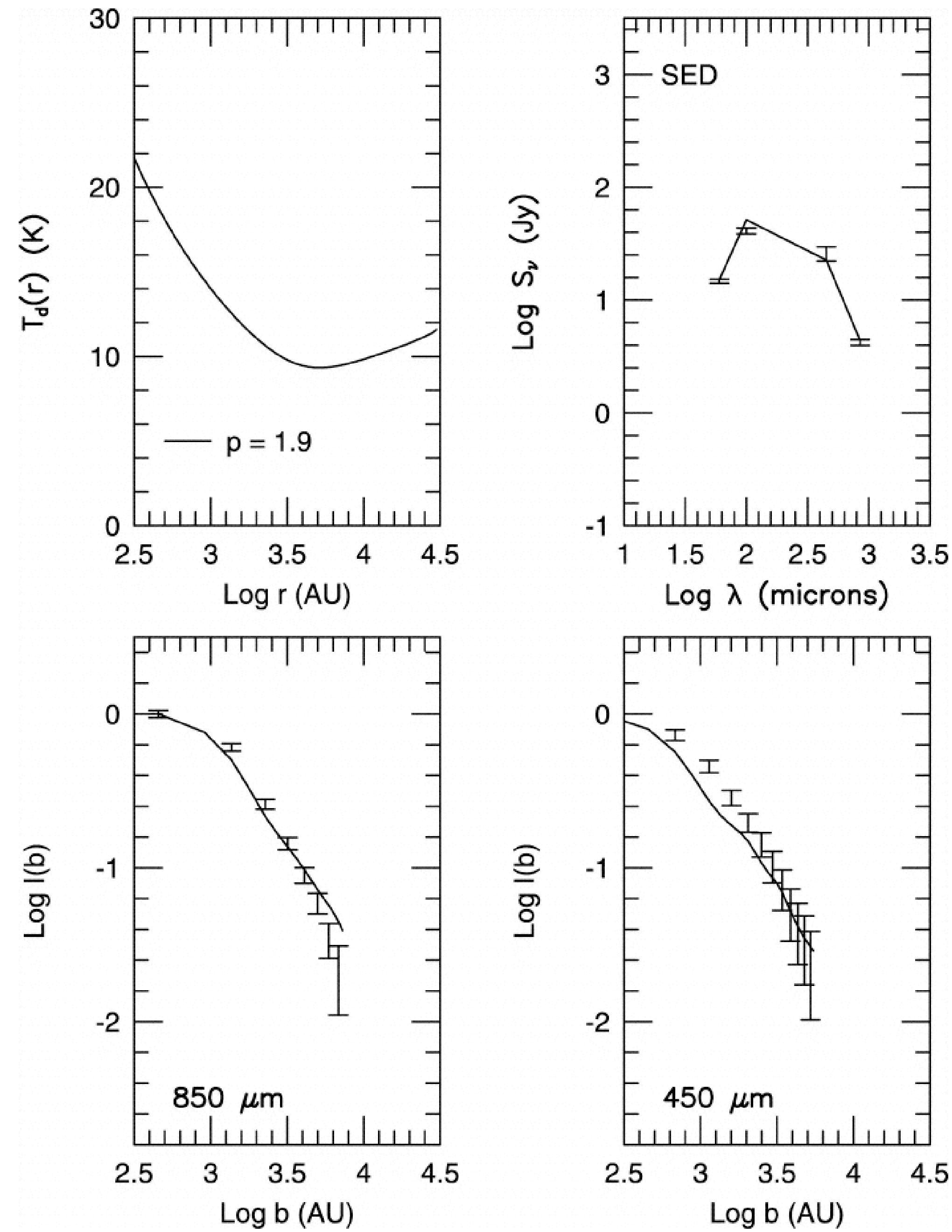




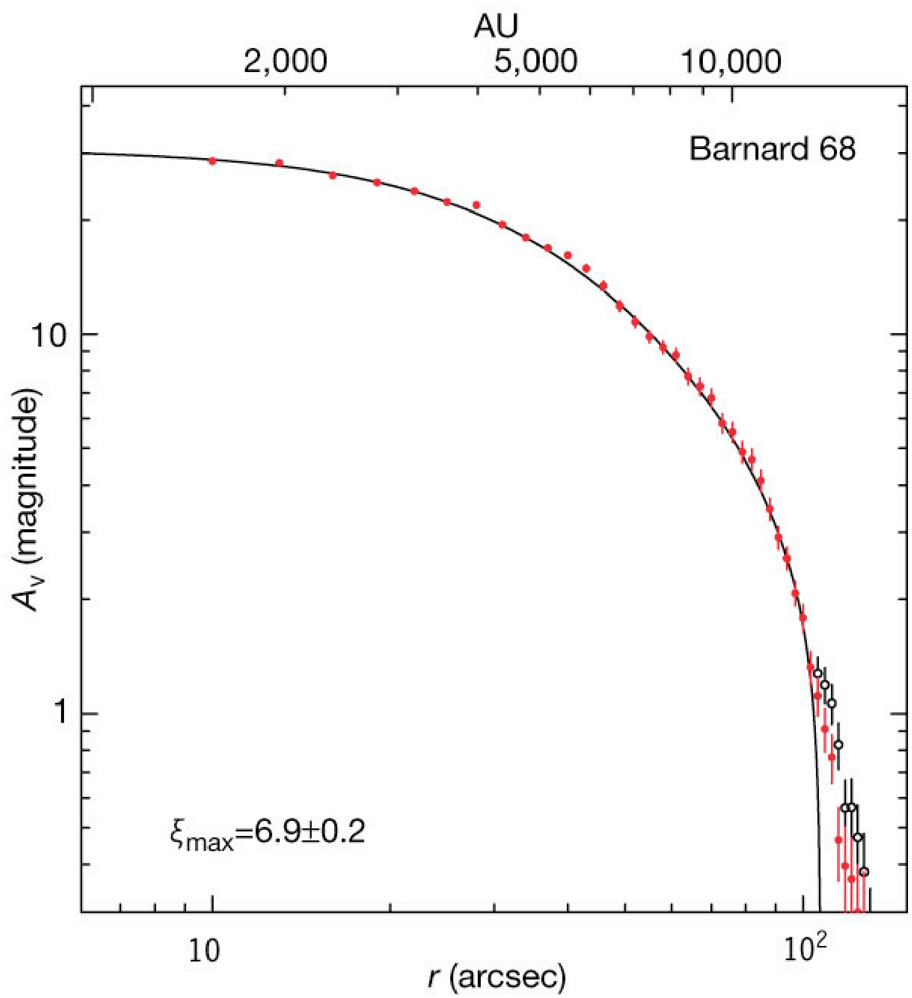
Pre-stellar core modeled by Evans et al. 2001 as best fit by a non-isothermal BE sphere

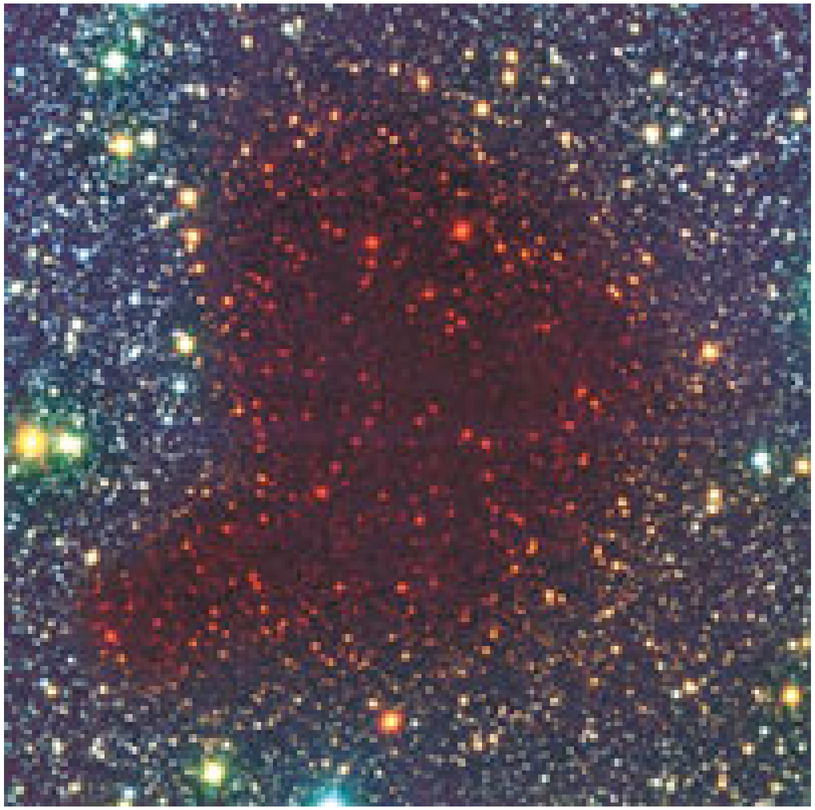
Radial Profiles

SIS does give the best fit to the radial density profile of B228, a Class 0 protostar (Shirley et al. 2002)



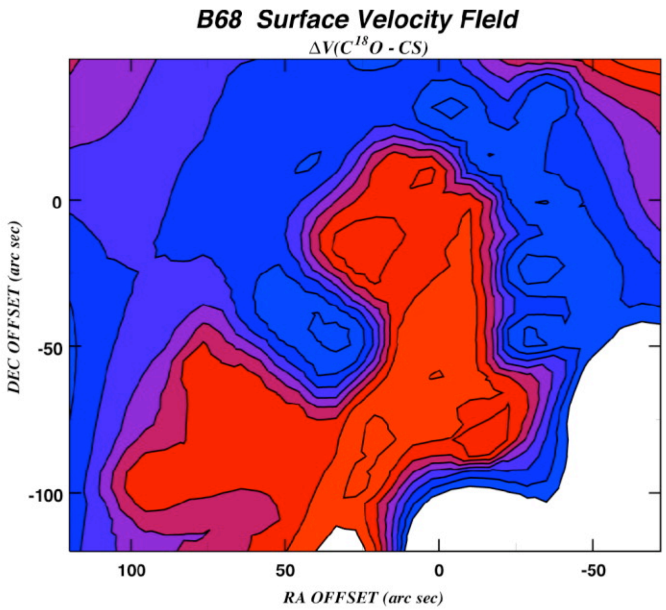
Cold Cores

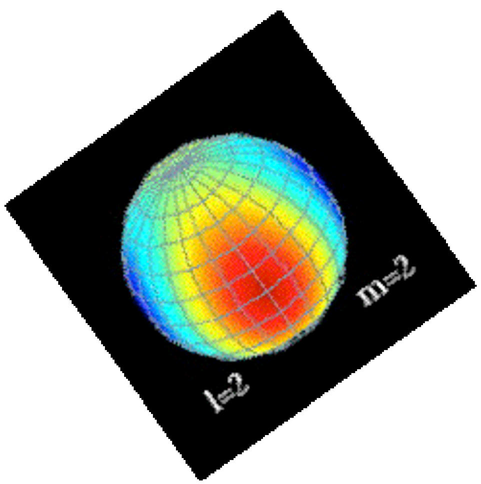


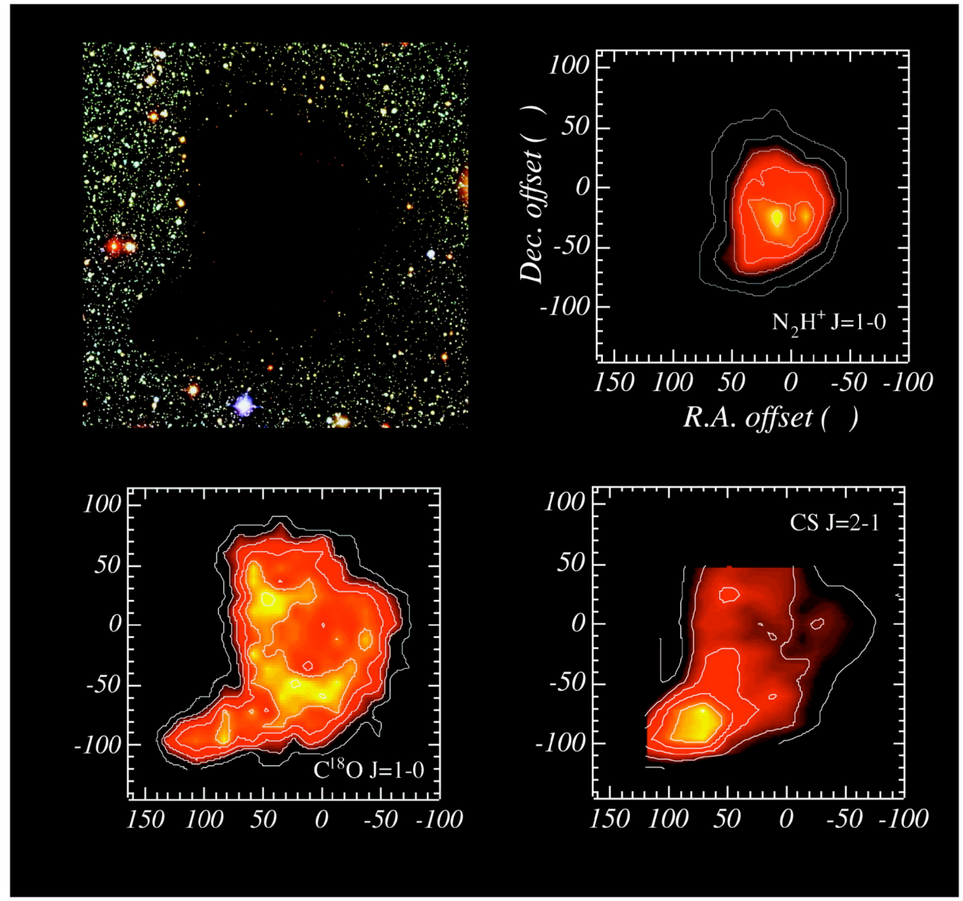


Barnard 68: The “Classic” Bonner-Ebert Sphere (Alves, Lada & Lada 2001)

Barnard 68







Alves et al. 2002 suggest that the velocity field of B68 is indicative of an l=2, m=2 vibrational mode

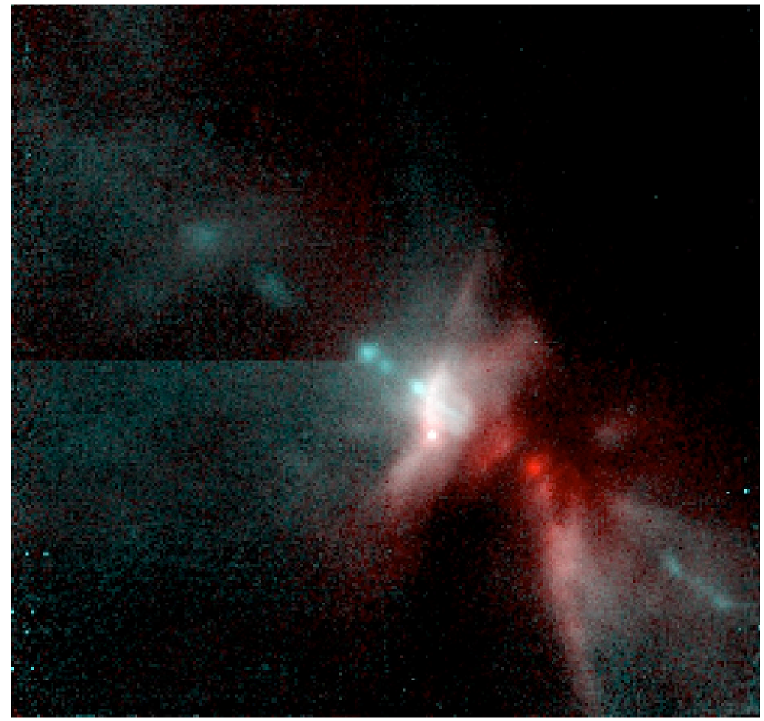
Summary

- Star Formation is rapid and cluster dominated
  - Cloud and star formation may have to be treated together
  - Both magnetic and non-magnetic turbulence simulations are promising
  - Observations of the large scale magnetic field strength are needed to judge its global support
- Initial Mass Function is Variable with a Characteristic Mass
- Magnetic Fields are present on core scales
  - Cores appear either critical or supercritical based on recent OH data
  - Ambipolar diffusion models predict cores to be subcritical
- Starless/Pre-stellar Cores are generally fit well by pressure bounded Bonner-Ebert spheres
- SIS works well for some Class 0 (more evolved) sources

What I haven't discussed

- Outflows/Jets
- Disks
  - X-Winds vs. Disk Winds
- Chemistry

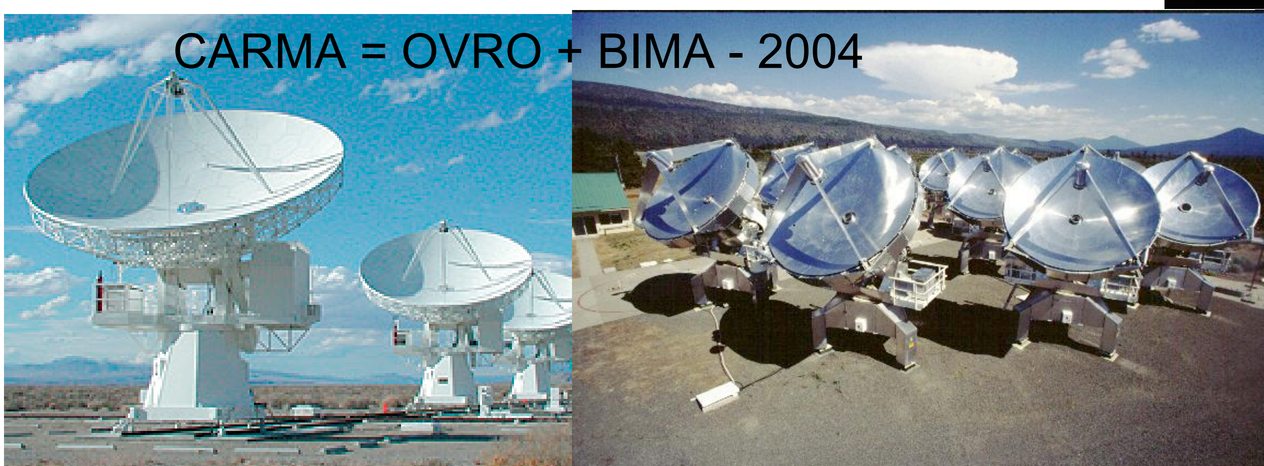
These topics all involve complex modeling by themselves;
We cannot yet simulate the full dynamic range of the problem.



HH111

Resolution is Imminent…


VLT interferometer - 2003


CARMA = OVRO + BIMA - 2004


ALMA - 2007

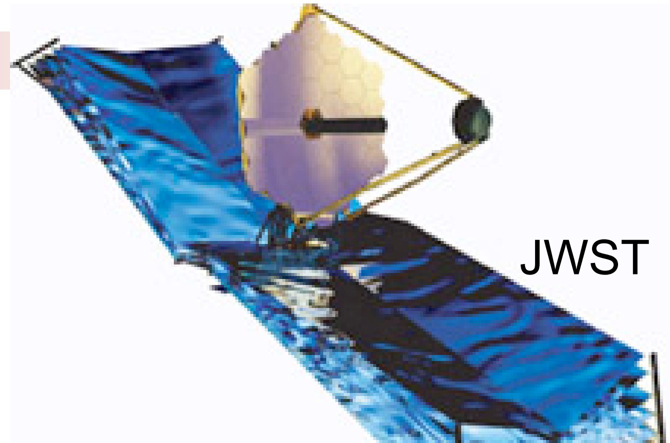
CARMA

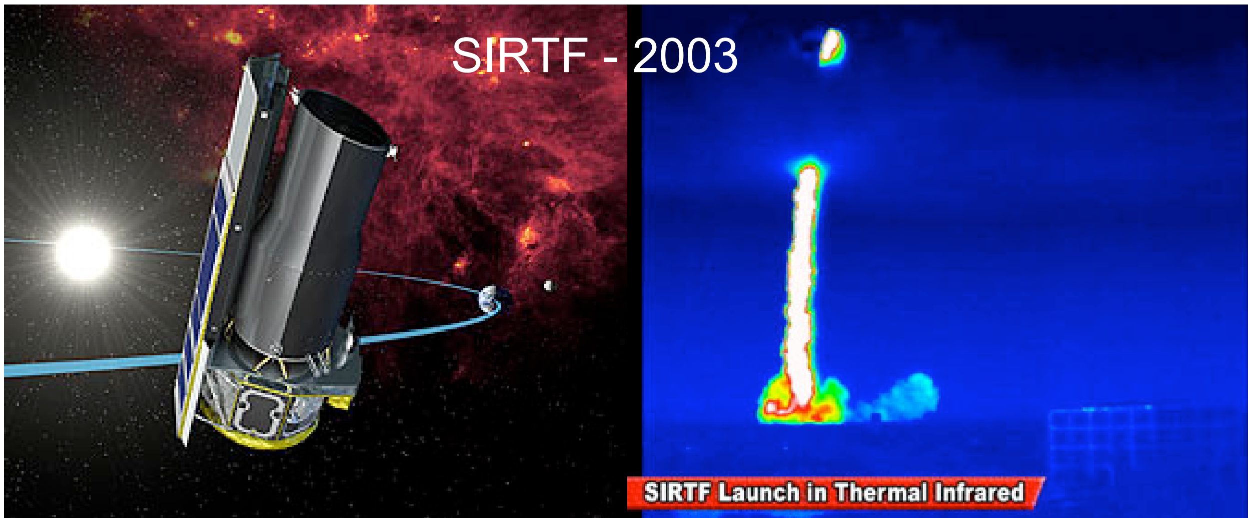
Combined Array for Research in Millimeter-Wave Astronomy

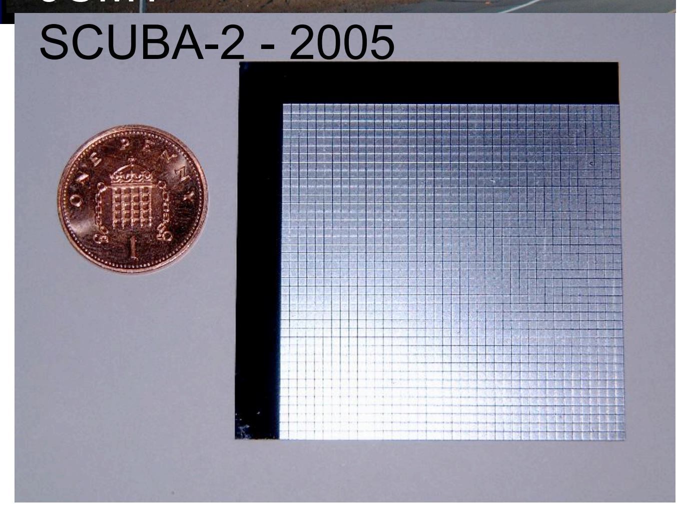

Keck Interferometer - 2003


SubMillimeter Array - 2003

The Big Picture is still required.







Plus:
LMT, CSO,
IRAM 30m,
APEX, GBT
can all contribute to star formation studies.

A Wish List for Star Formation

- A polarimeter on all instruments
  - Scientific dividends greatly outweigh fractional costs
- More computing power to combine nested grid simulations with input physics to follow:
  - Turbulence, fragmentation
  - Collapse, outflow, disk formation
  - Chemistry on appropriate scales