NRC · CNRC HERZBERG INSTITUTE of ASTROPHYSICS

UNIVERSITY OF VICTORIA ASTRONOMY Department of Physics and Astronomy

Constraining How Star Formation Proceeds

Through observations in Perseus and Ophiuchus

Doug Johnstone: NRC/UVic
Helen Kirk: UVic/NRC
James Di Francesco,
Jes Jorgensen, Phil Myers
COMPLETE & C2D

Observational Surveys Provide

Significant Statistical Information.

Clump mass and size distribution - large scales

Core mass and size distribution – small scales

Core locations - environment and clustering

Frequency of protostellar stages - Class -I, 0, I, II, III

Structure - filamentary, elipticity, directionality

Kinematic Information - CO and N_2H^+ widths, dist'n

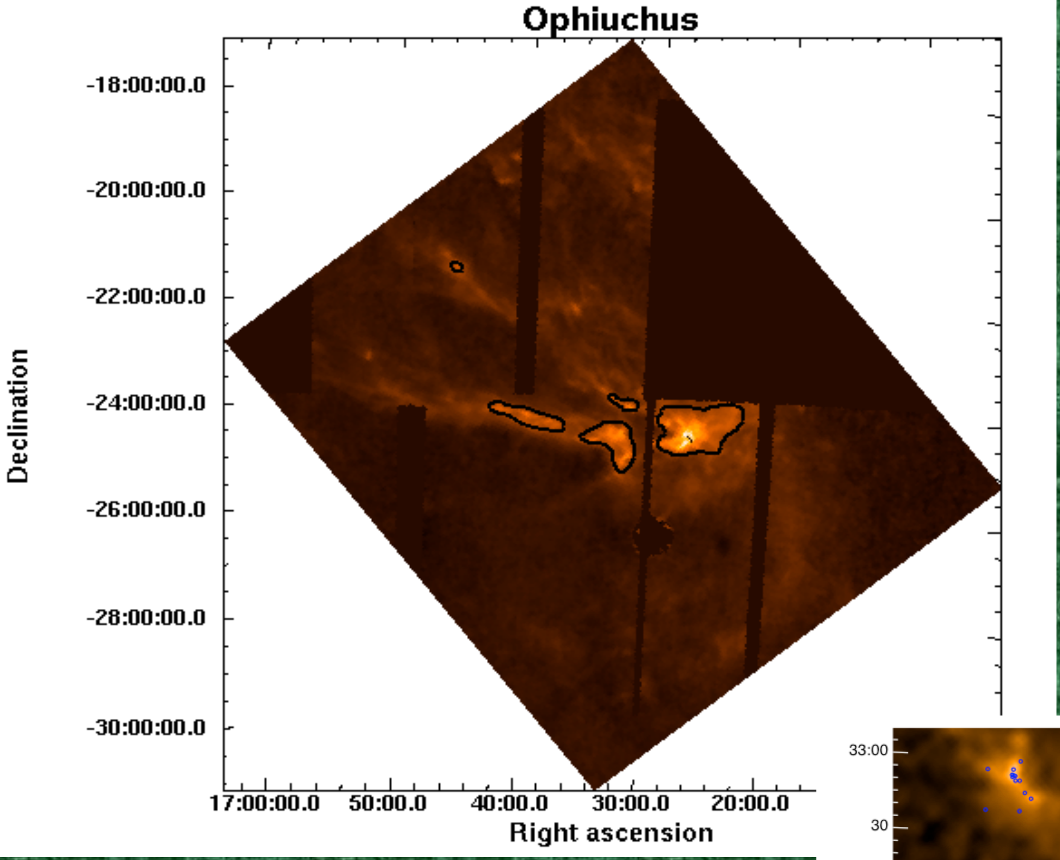
Polarization Angle - Magnetic Field Orientation

Reasonable theories must reproduce each of these conditions!

1) Clump Structure in Clouds

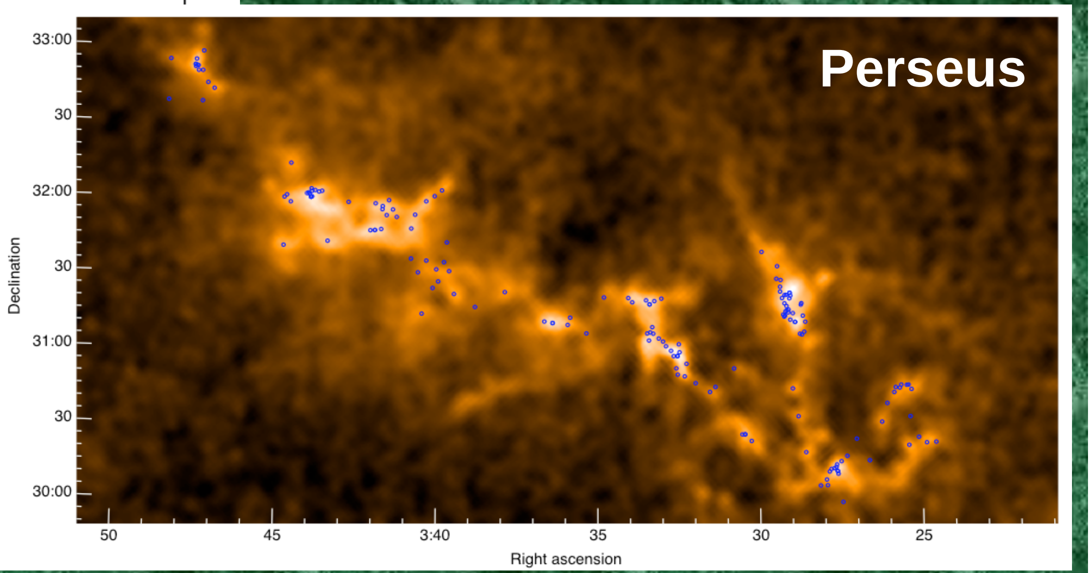
- Distribution of mass is shallow
  - $N \propto M^{-1/2}$: mass resides in massive objects
    - Result independent of structure analysis form
    - Totals to the entire mass of the cloud
- Non-thermal size versus mass relation
  - σ(linewidth)$\propto R^{0.5}$ (Larson's Law)
    - Larger objects require more support
    - Constant column density Av ~ a few
      - $M \propto R^2$

Large-scales dominate the molecular cloud.
Non-thermal support required and observed.



COMPLETE

Extinction Mapping
- 2mass colours
- ~arcminute resolution
- Column density proxy
  - A_V ~ 1 - 20



Technique:
NICER (Alves, Lombardi)

Ophiuchus

A_V Range	Cloud Area (%)	Cloud Mass ($M_\odot$)	Cloud Mass (%)
0–36	100	2020	100
0–7	88	1380	68
7–15	9	400	20
15–36	3	240	12

Mean A_v ~ 4

Perseus

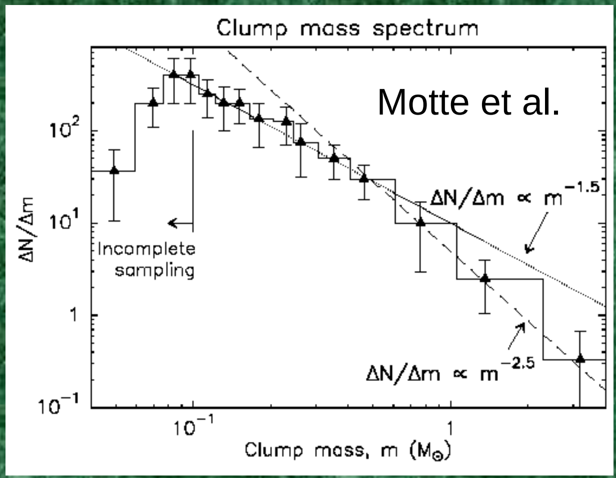
A_V Range	Cloud Area [a] (%)	Cloud Mass [a] $M_\odot$	Cloud Mass [a] %
0-12	100	18552	100
0-5	95.5	15982	86.1
5-10	4.4	2537	13.7
10-12	0.04	33	0.2

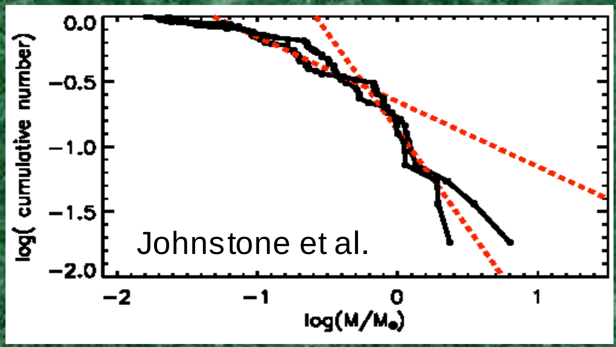
Mean A_v ~ 2

Large-scales dominate the molecular cloud.
Non-thermal support required and observed.

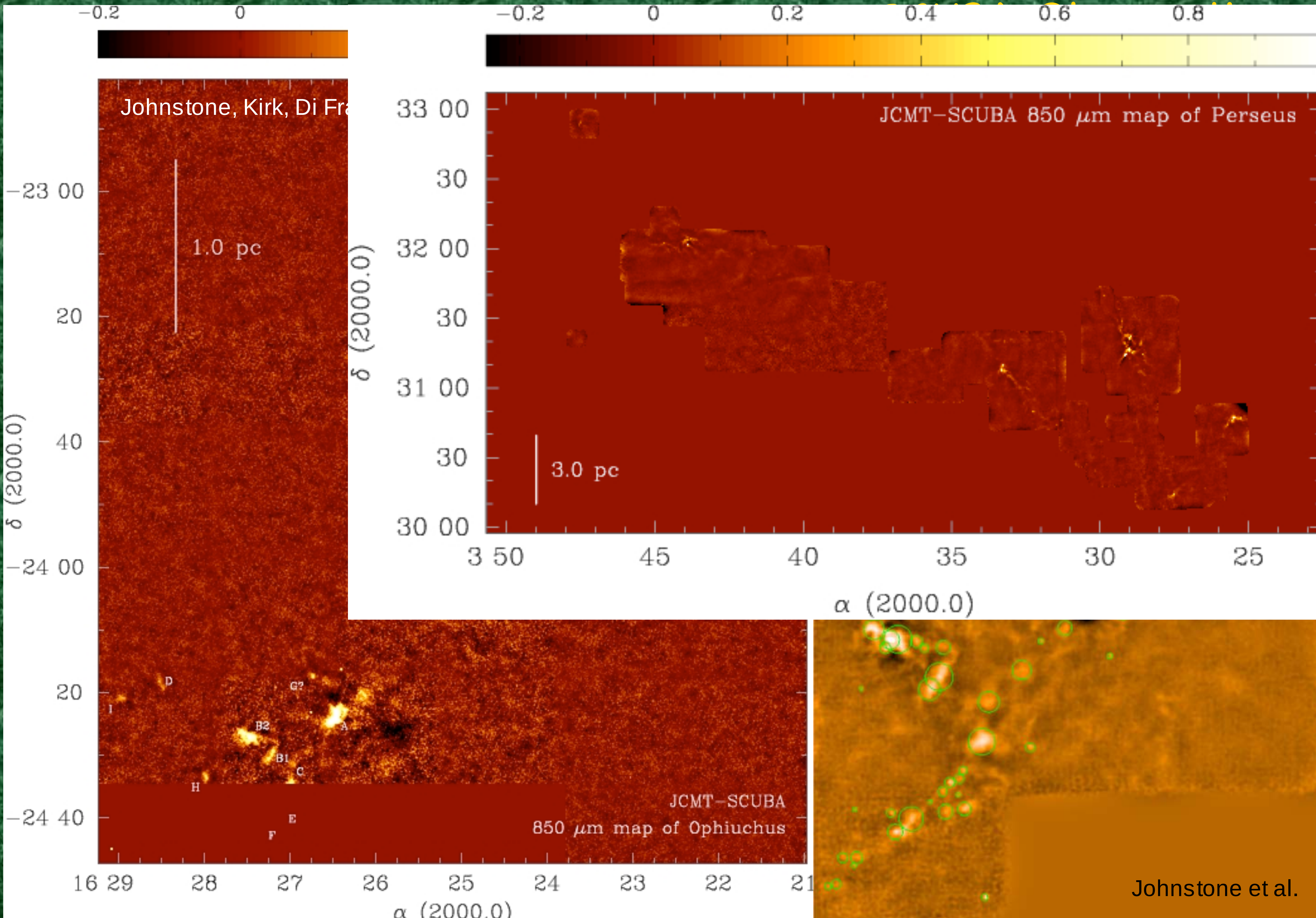
2) Core Structure in Clouds

- Distribution of mass is steep
  - $N \propto M^{-3/2}$: mass resides in small objects
    - Similarity to IMF intriguing
    - Result indep. of structure analysis form
    - Totals to small fraction of the cloud
- Thermal size vs. mass relation?
  - $M \propto R^3$ (Pressure-confined objects)
    - Largest objects are grav. Unstable
    - $M \propto R$ (Critical BE sphere/Jeans Mass)
- Found in localized regions of cloud
  - Highest A_V zones
  - Clustered



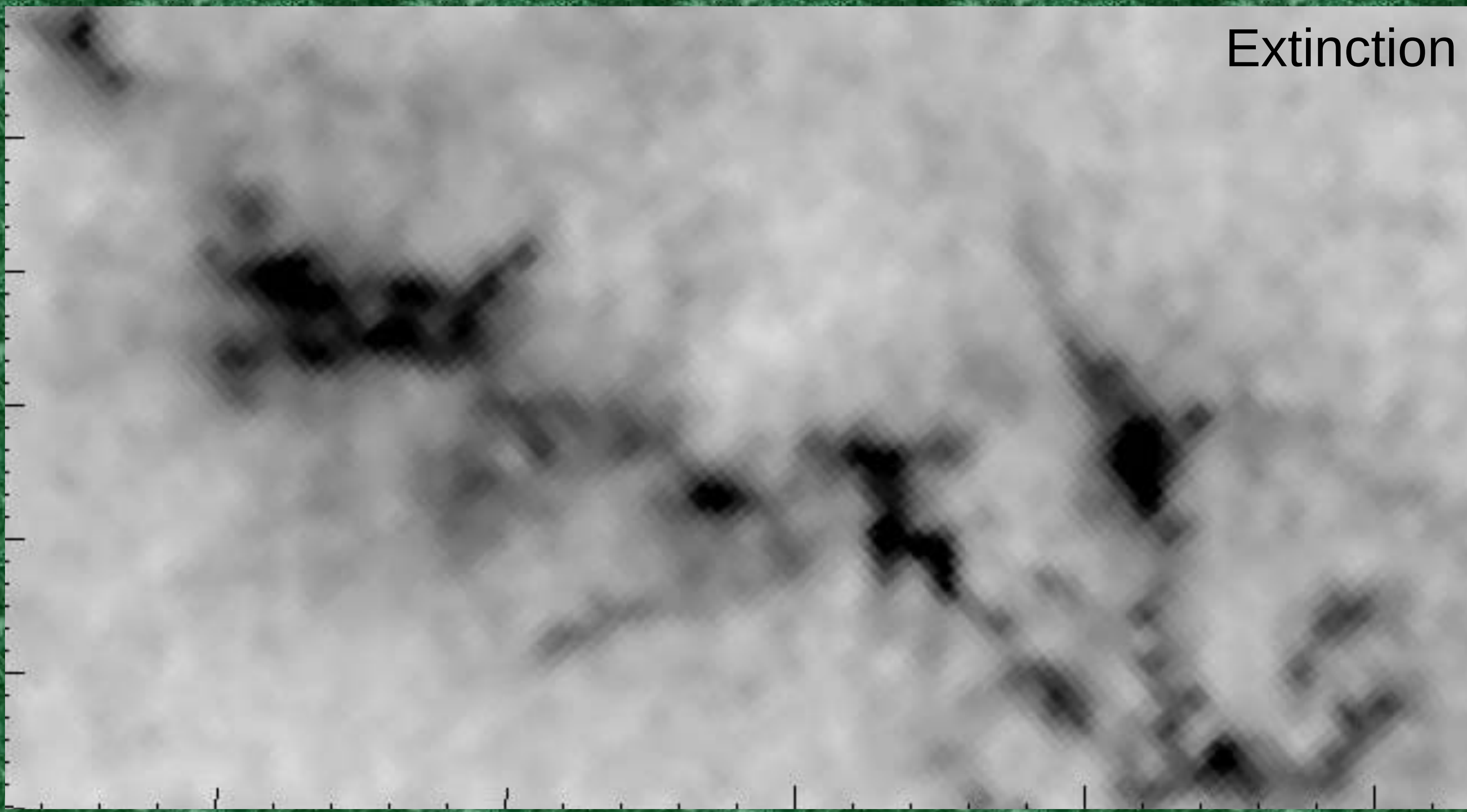


Dense material has different properties than bulk cloud.
No requirement for non-thermal support.

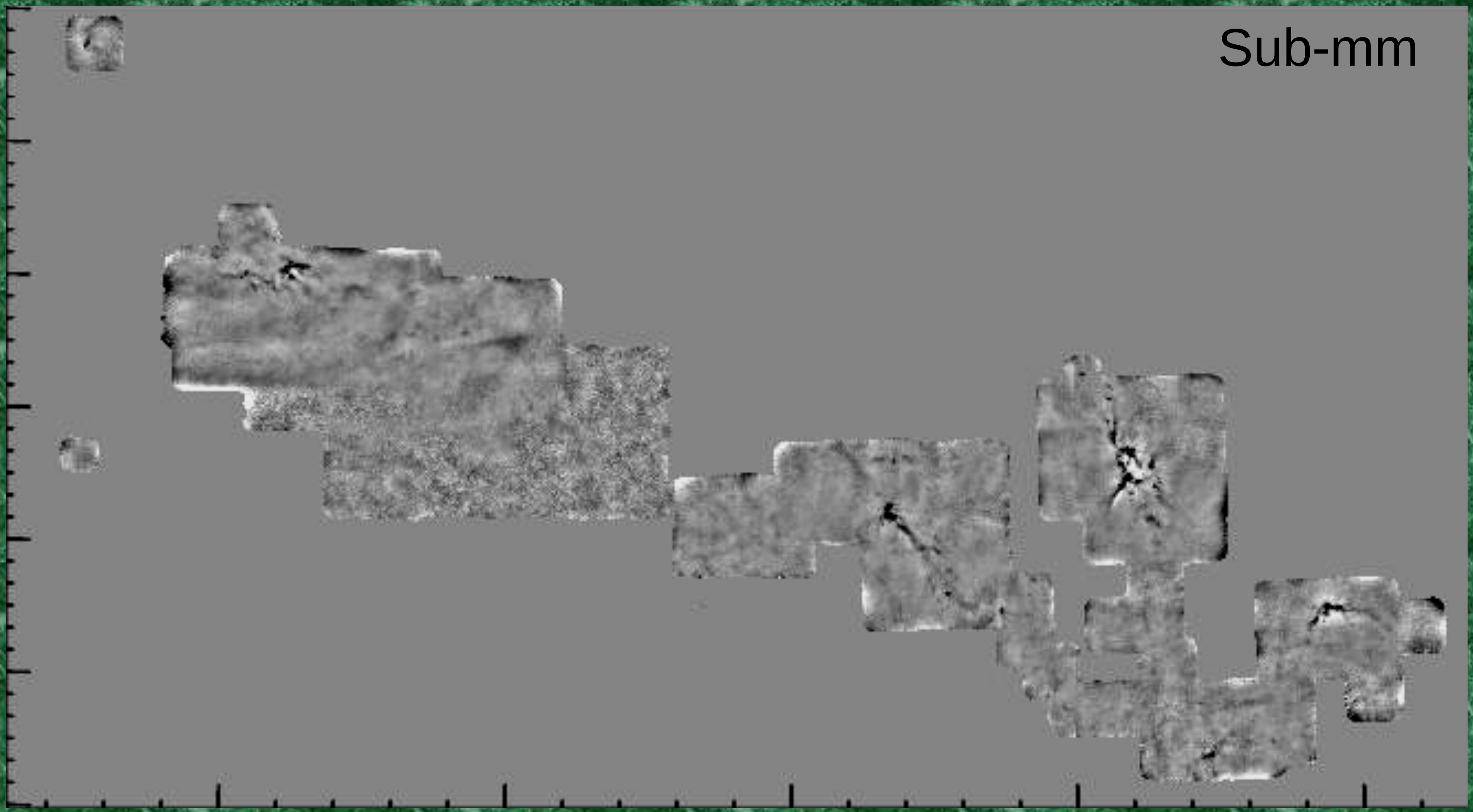


Johnstone, Kirk, Di Fra
1.0 pc
JCMT−SCUBA
850 μm map of Ophiuchus
α (2000.0)
δ (2000.0)
JCMT−SCUBA 850 μm map of Perseus
3.0 pc
α (2000.0)
δ (2000.0)
Johnstone et al.

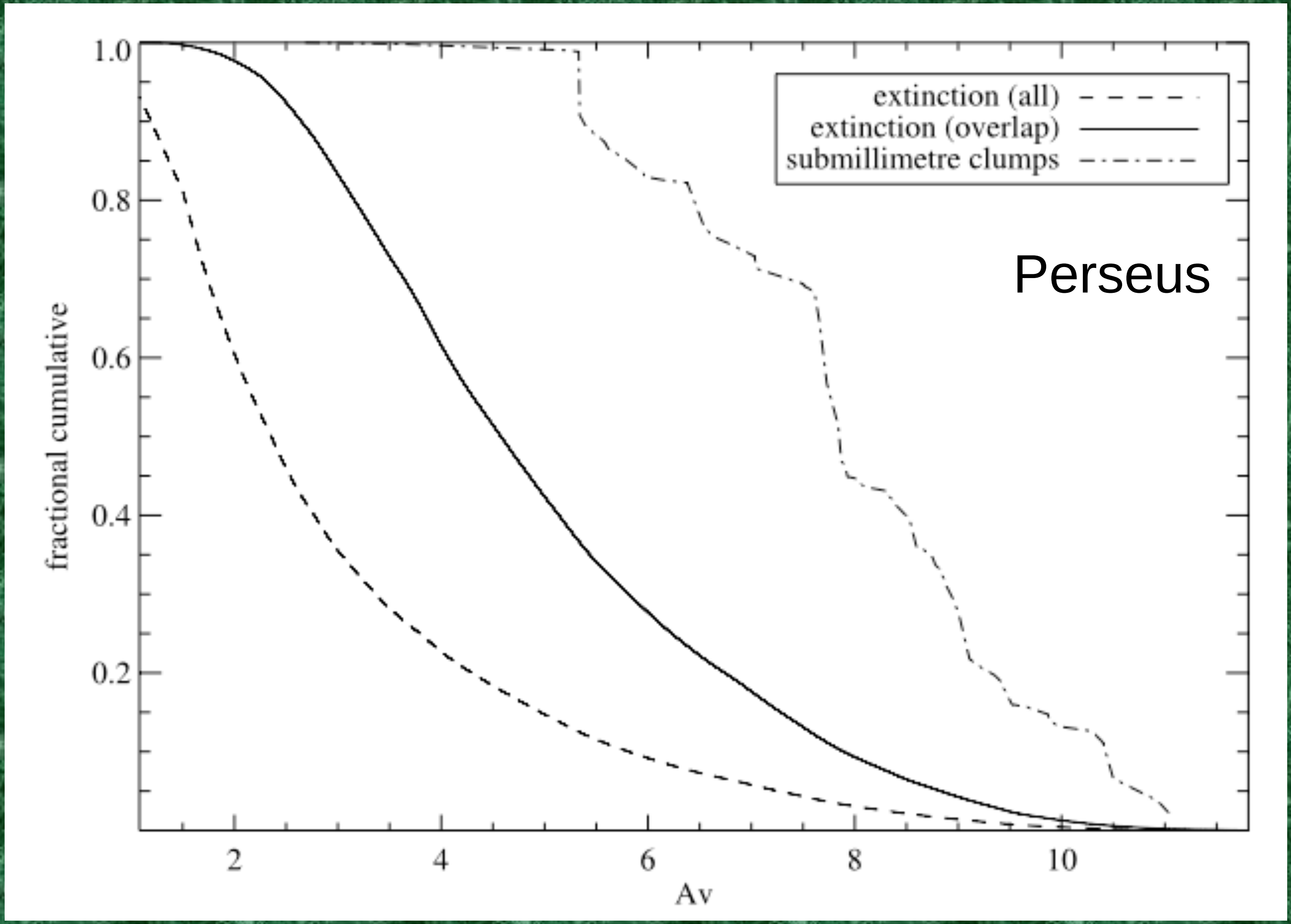
Extinction threshold



Extinction threshold



Cumulative Mass with A_v: Cloud vs. Cores



Ophiuchus

A_V Range	Cloud Area (%)	Cloud Mass ($M_\odot$)	Cloud Mass (%)	Clump Mass ($M_\odot$)	Clump Mass (%)	Mass Ratio (%)
0–36	100	2020	100	49.4	100	2.5
0–7	88	1380	68	0	0	0
7–15	9	400	20	3.1	6	0.8
15–36	3	240	12	46.3	94	19

Perseus

A_V Range	Cloud Area [a] (%)	Cloud Mass [a] $M_\odot$	Cloud Mass [a] %	Cloud Mass [b] $M_\odot$	Cloud Mass [b] %	Clump Mass $M_\odot$	Clump Mass %	Mass Ratio [b] (%)
0-12	100	18552	100	6074	100	51.2	100	0.8
0-5	95.5	15982	86.1	3611	59.5	0.5	1.0	0
5-10	4.4	2537	13.7	2429	40.0	45.5	88.9	4.7
10-12	0.04	33	0.2	33	0.5	5.2	10.1	30.3

Significance of these Cores?

Cores represent ~2% mass of cloud

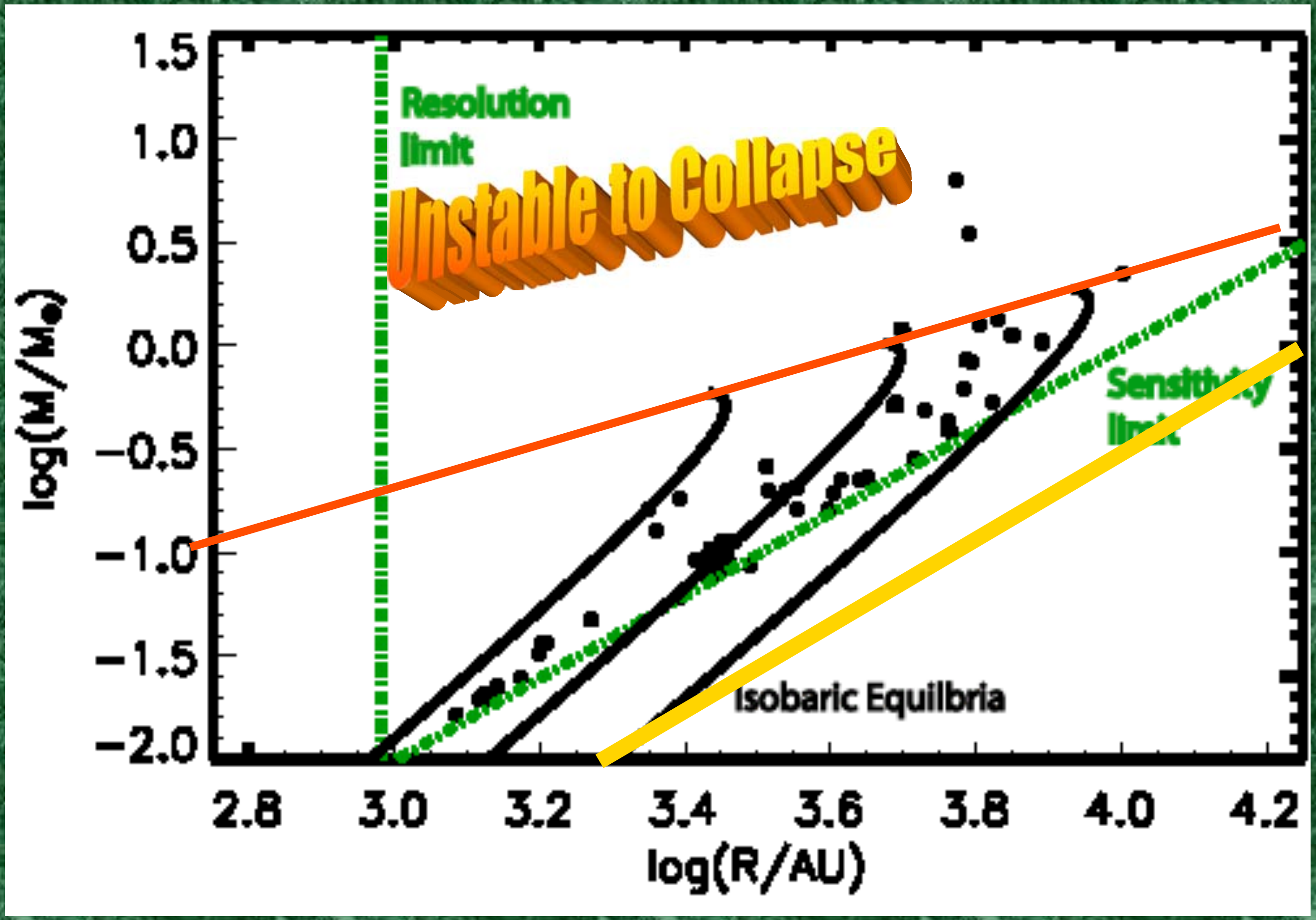
Cores represent ~20% mass of clump

Cores live primarily at high (>10) Av

Cores have stellar IMF-like mass f'n

Embedded stellar clusters have these same properties!

(Lada and Lada 2003)



(green lines: resolution & sensitivity limits)

(black lines: isobaric equilibria - unstable only above turn-over)

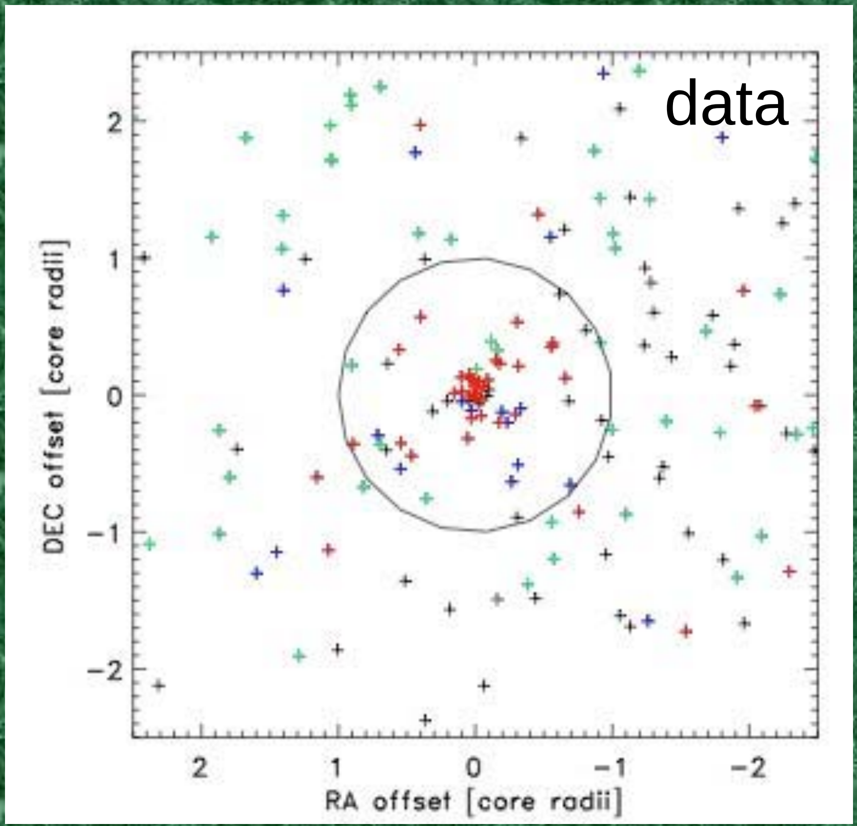
3) Embedded Protostellar Phase

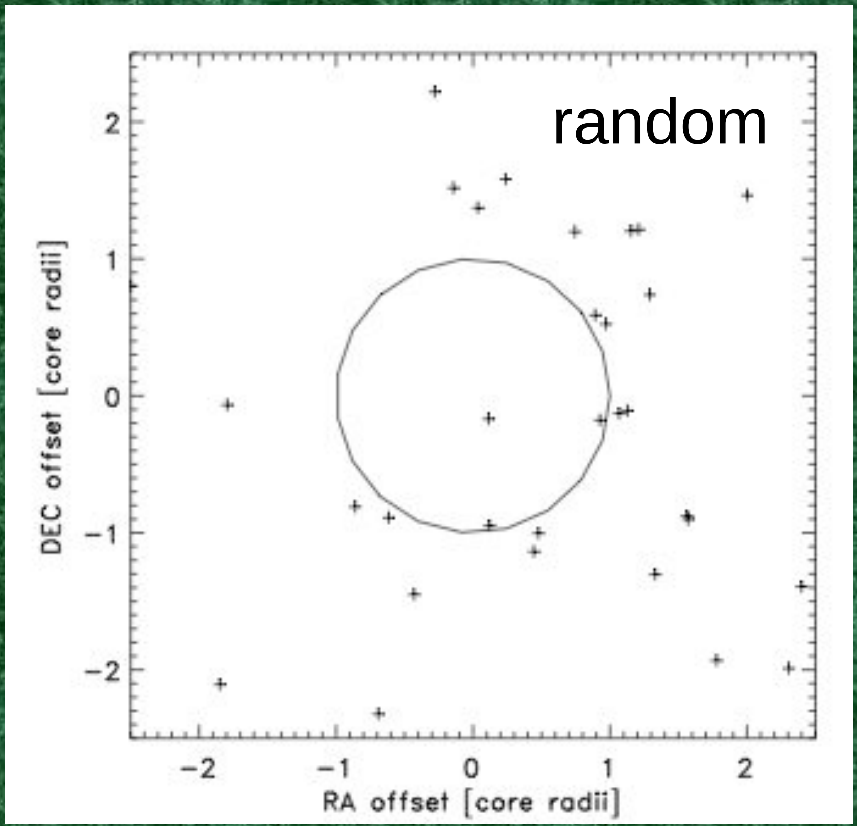
- Fraction of cores with embedded sources 50/50
  - Lifetime of cores is short
    - If all collapse then lifetime ~ Class 0 lifetime
  - Usually only one embedded source (~5")!
    - Fragmentation properties of cores
- 'Concentration' proxy for collapse
  - Related to Jeans' Mass (BE-analysis)?
  - Simply due to internal heating of envelope?
  - Observational clue only?
- Embedded sources centrally located in cores
  - Unlikely to be dynamical wrt envelope

Dense cores appear highly correlated with star formation.
Dense core formation relatively quick and efficient.

Coincidence of 24 Micron source and Submm peak.

Jorgensen, Johnstone, Kirk, Myers 2007

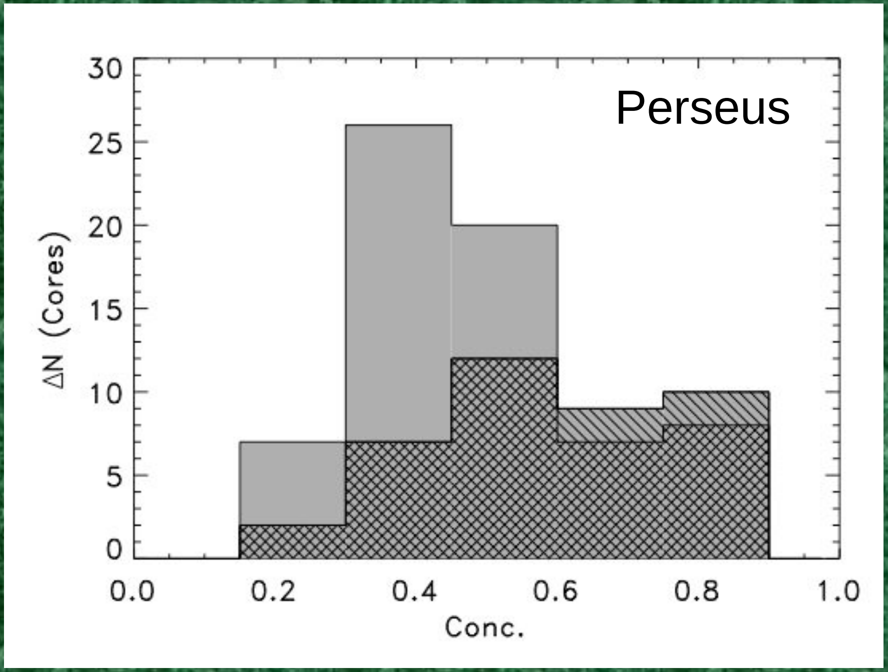


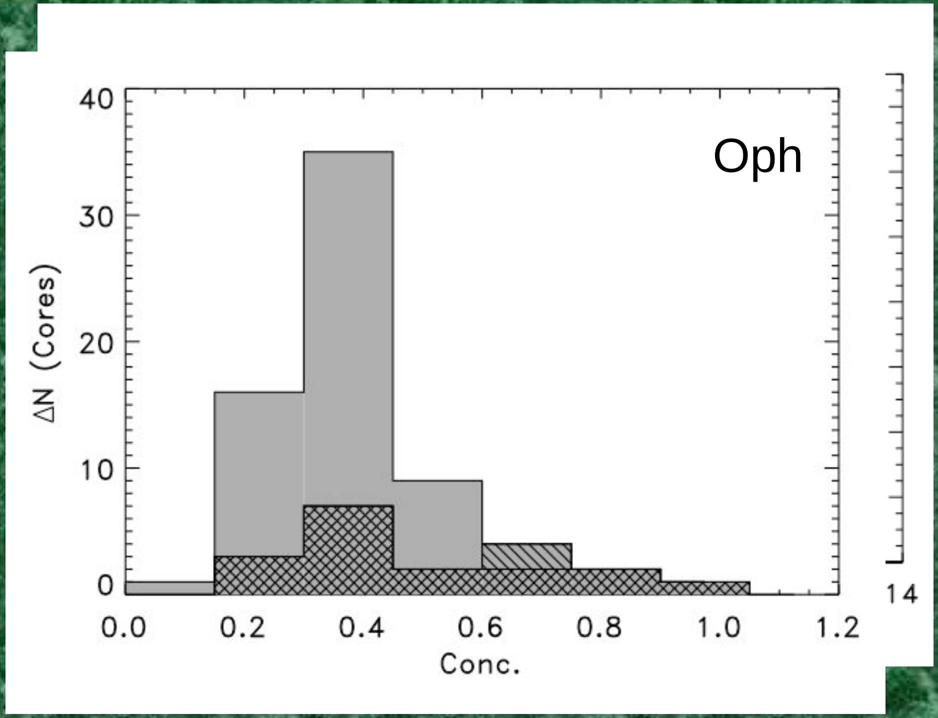


Protostars clustered around *and* within dense cores.

Correlation between protostars and core properties.

Jorgensen, Johnstone, Kirk, Myers

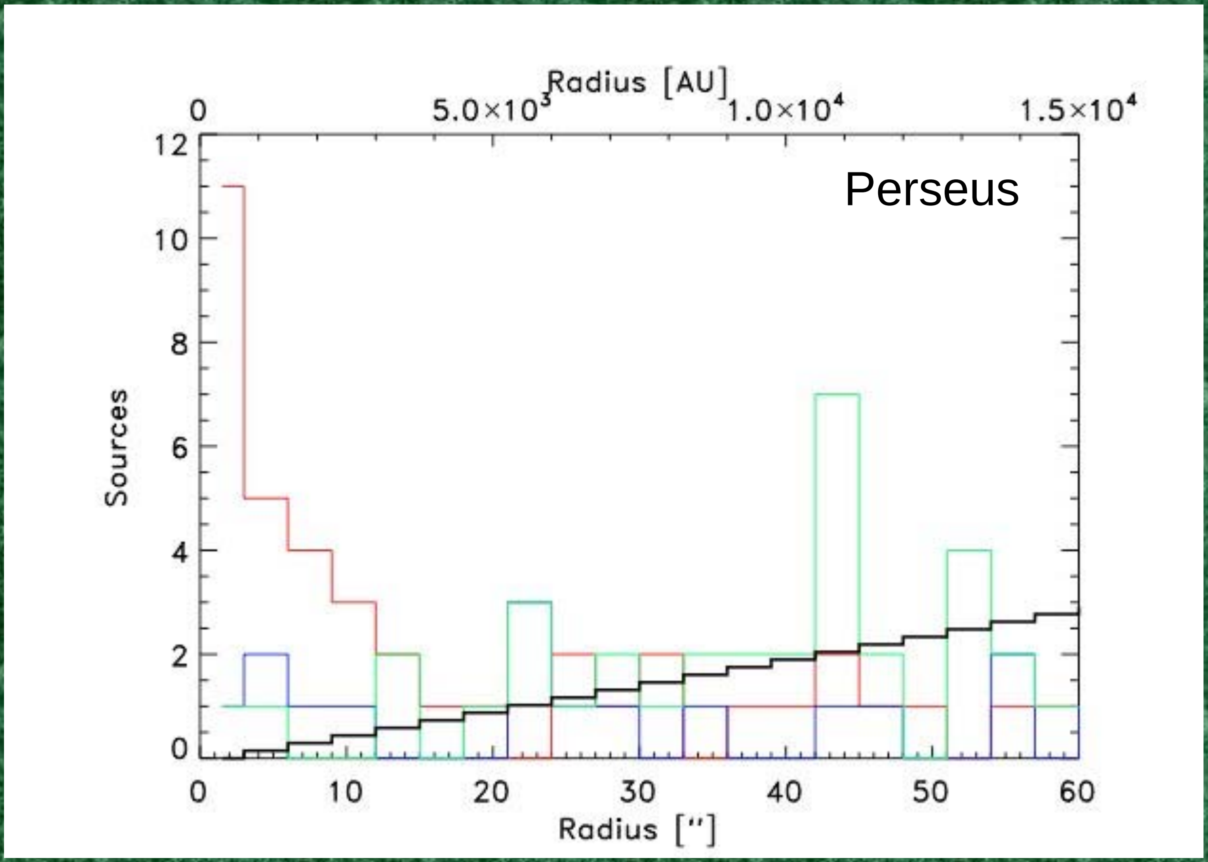




Brightest/most peaked sources contain protostars.
Does this negate the IMF-like core mass distribution?

Protostars in cores live near the center.

Jorgensen, Johnstone, Kirk, Myers



R < 10 arcseconds!
R < 2000 AU

For 0.1 km/s
τ =10^5 yrs
=life of Class0

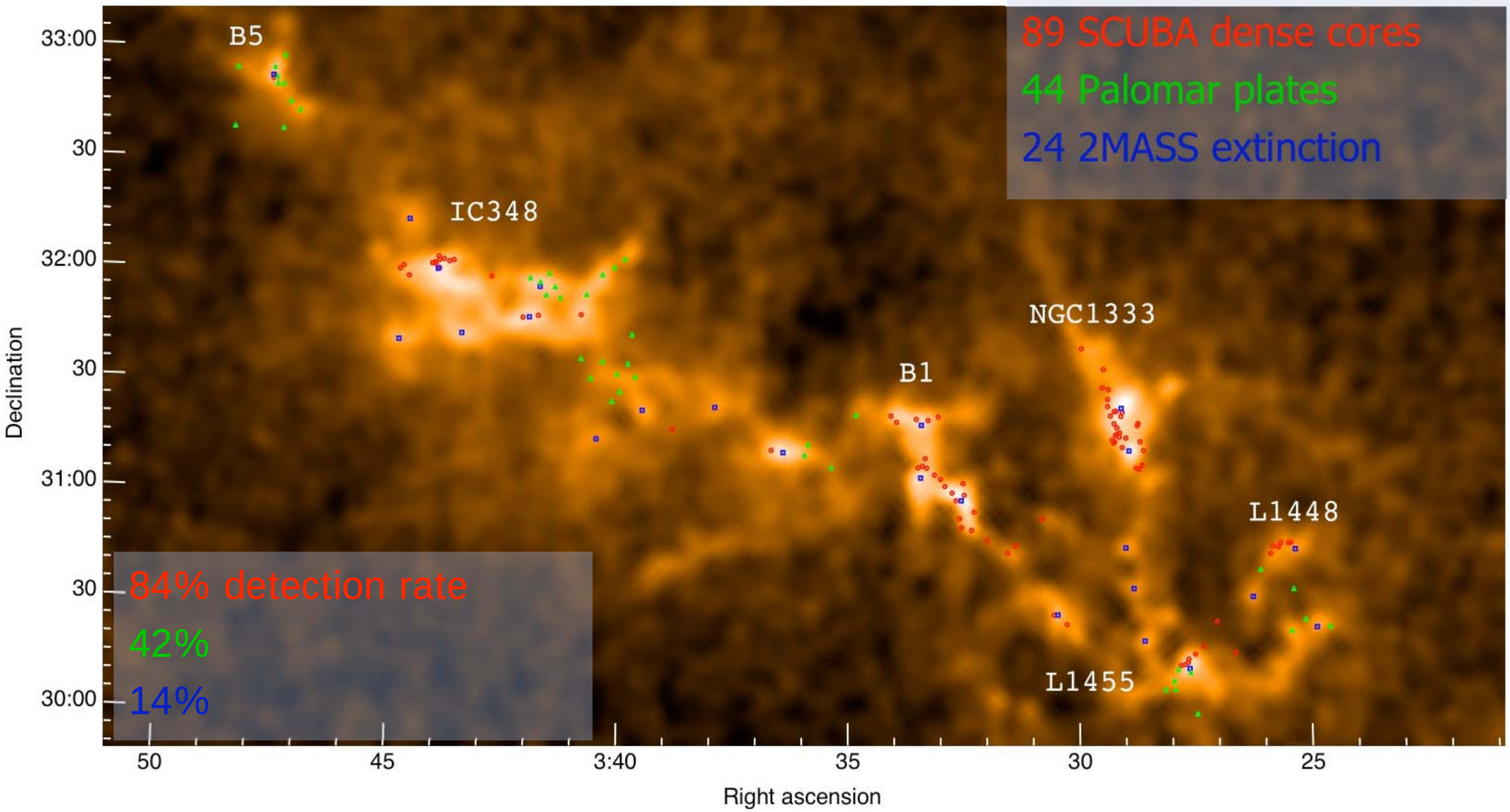
Protostars not moving with respect to core.

4) Kinematics of Cores

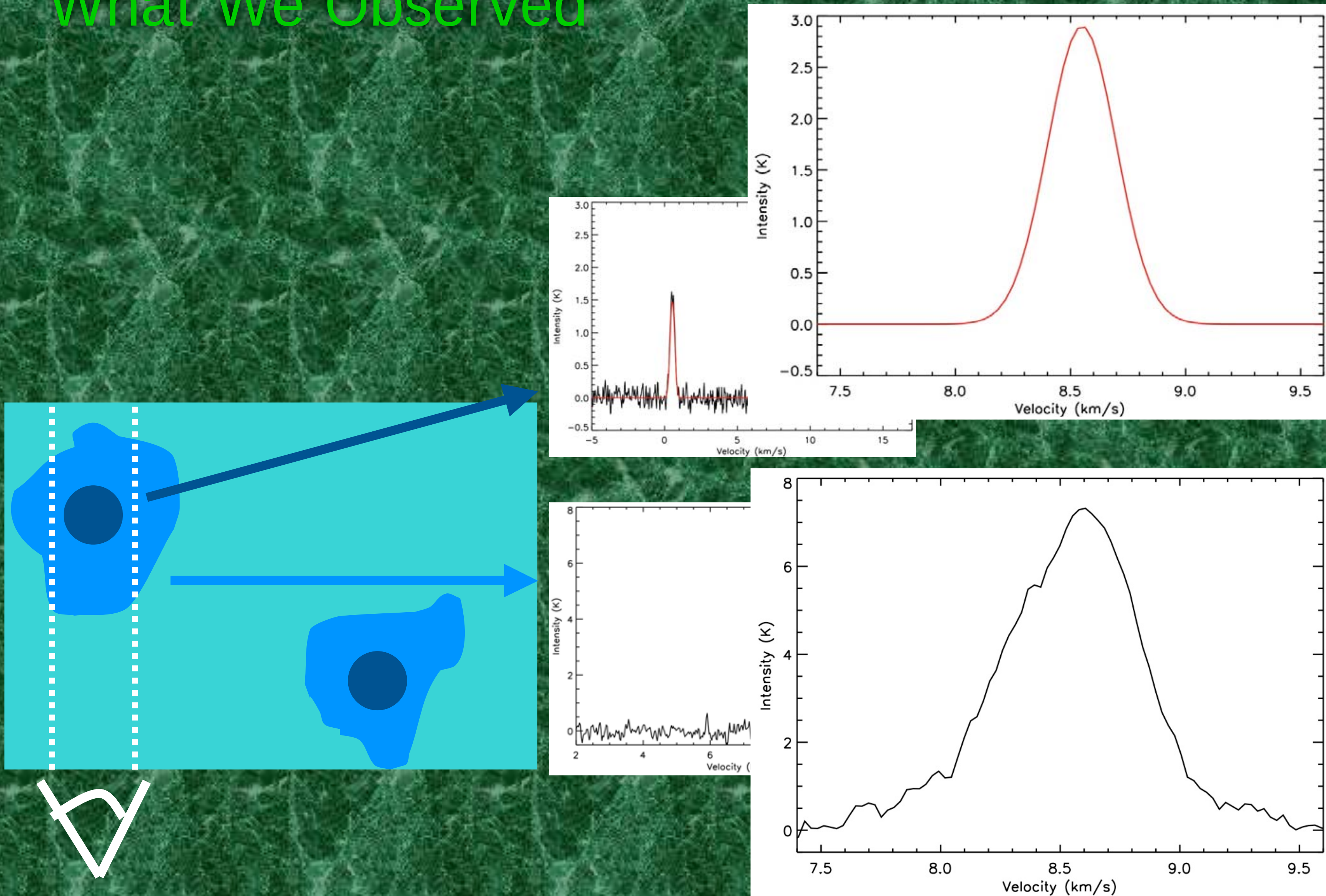
- Most cores appear thermal in N_2H^+
  - If quasi-static then pressure confined
    - ie gravity doesn't dominate
  - If transient then local stagnation point
    - ie not a shearing flow
  - CO observations are less obvious
    - Dominated by larger scales
- Core to core motions
  - Appear similar to virial
  - Insight into clump kinematics?

IRAM Observations

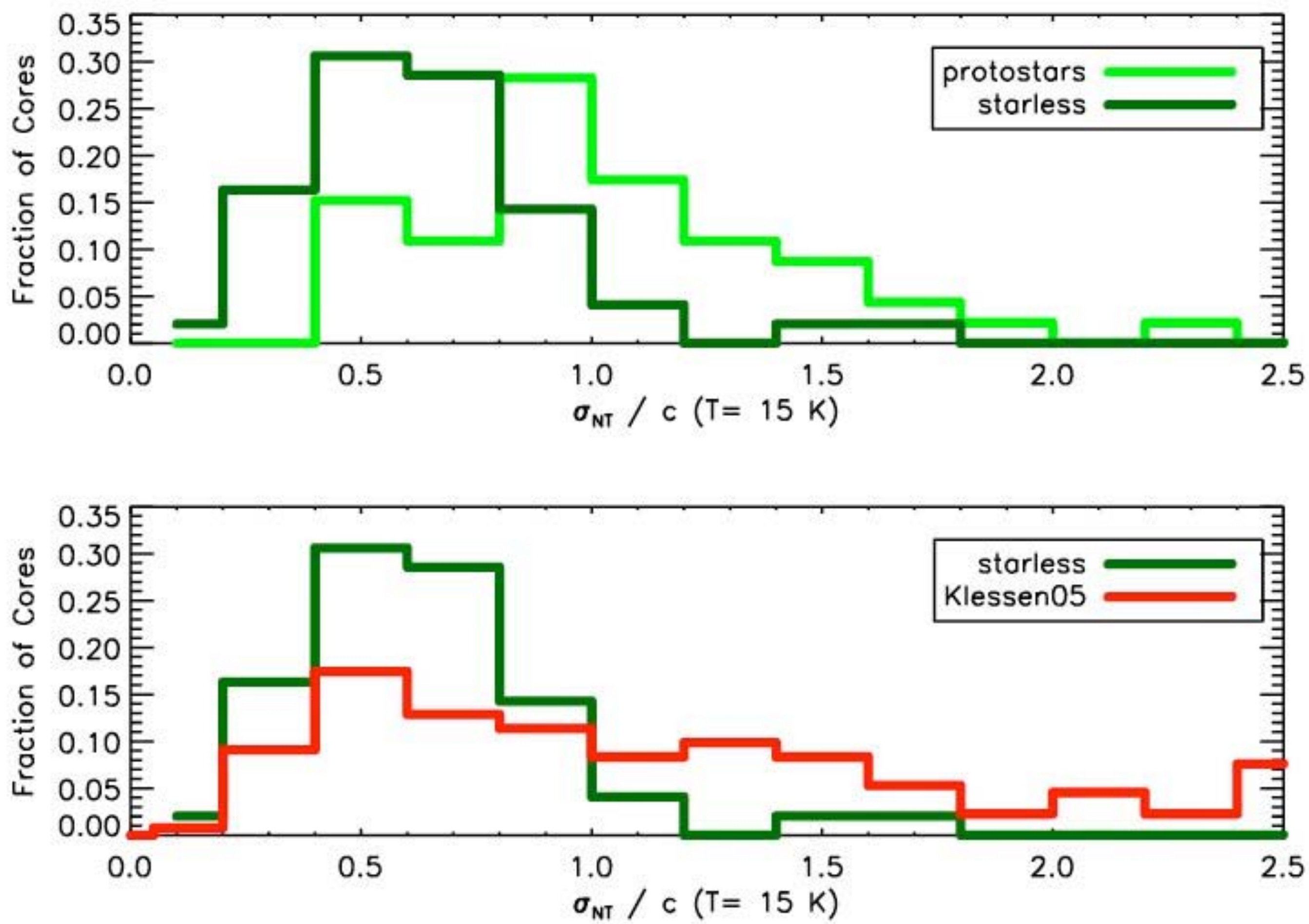
- N_2H^+ and $C^{18}O$
- 15 arcsecond res (~3000 AU)
- N_2H^+ dense gas tracer



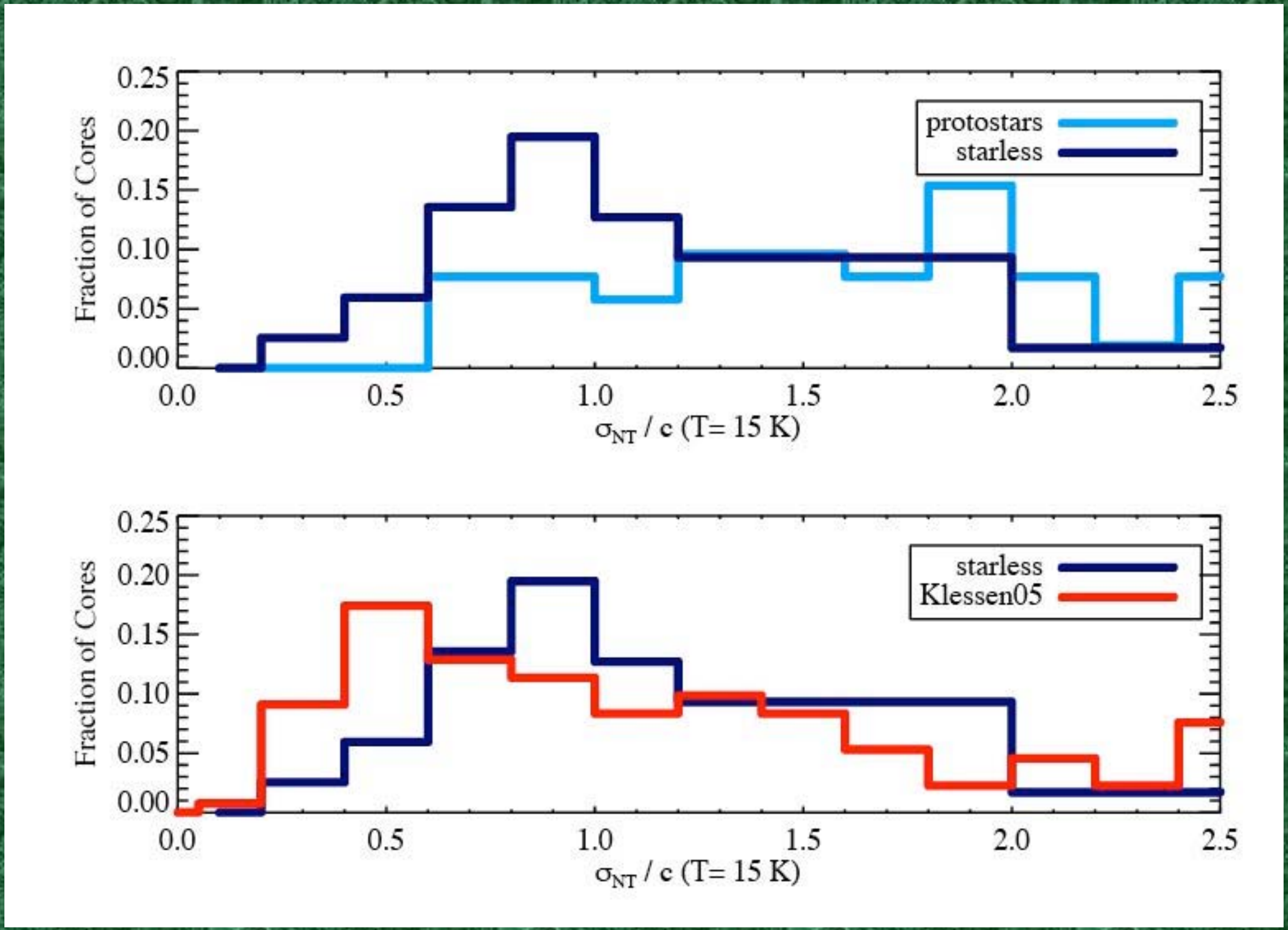
What We Observed



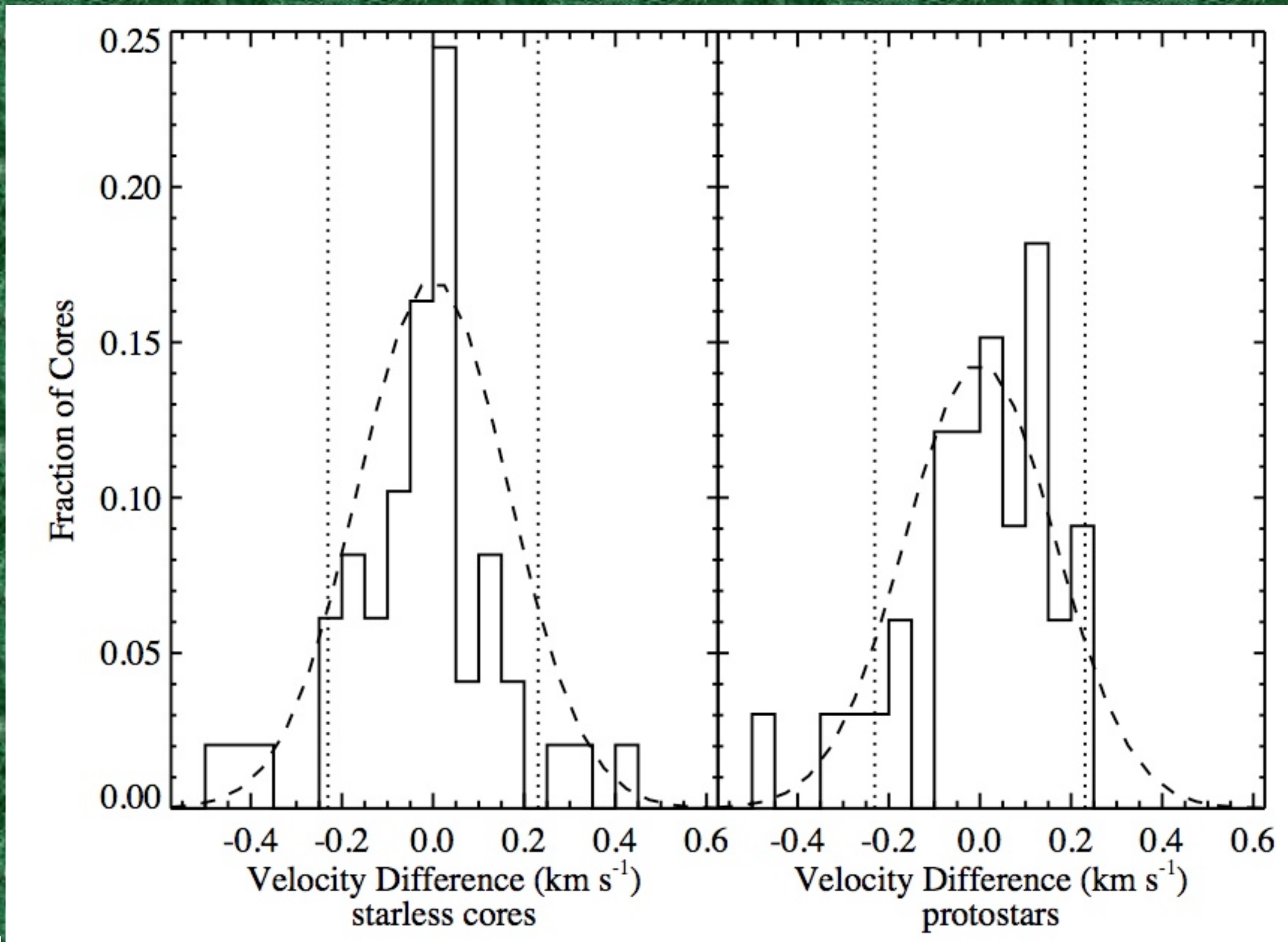
N_2H^+ linewidths of cores mostly thermal!



$C^{18}0$ linewidths of cores larger non-thermal component.

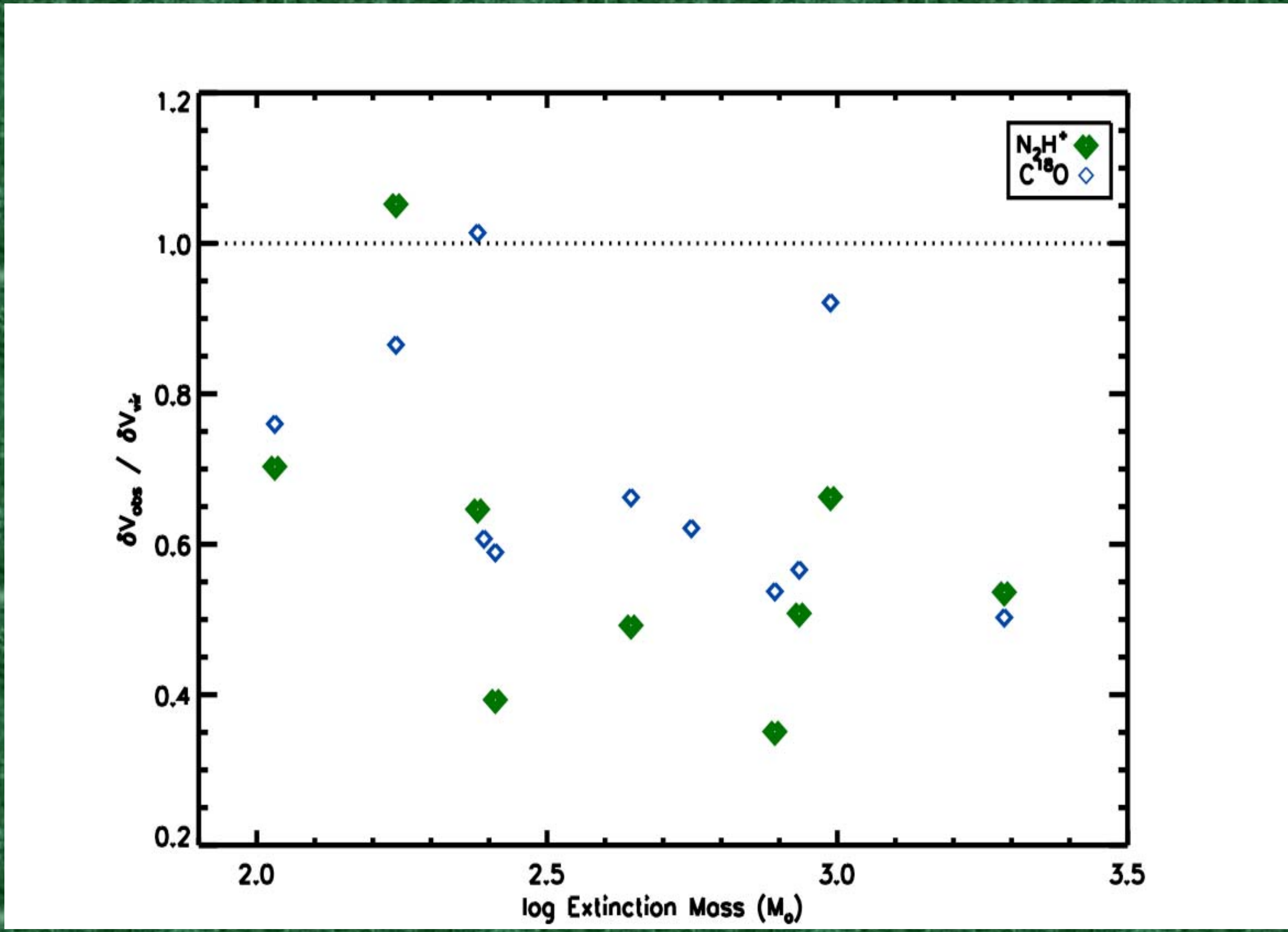


$C^{18}0$ and N_2H^+ have similar centroids.



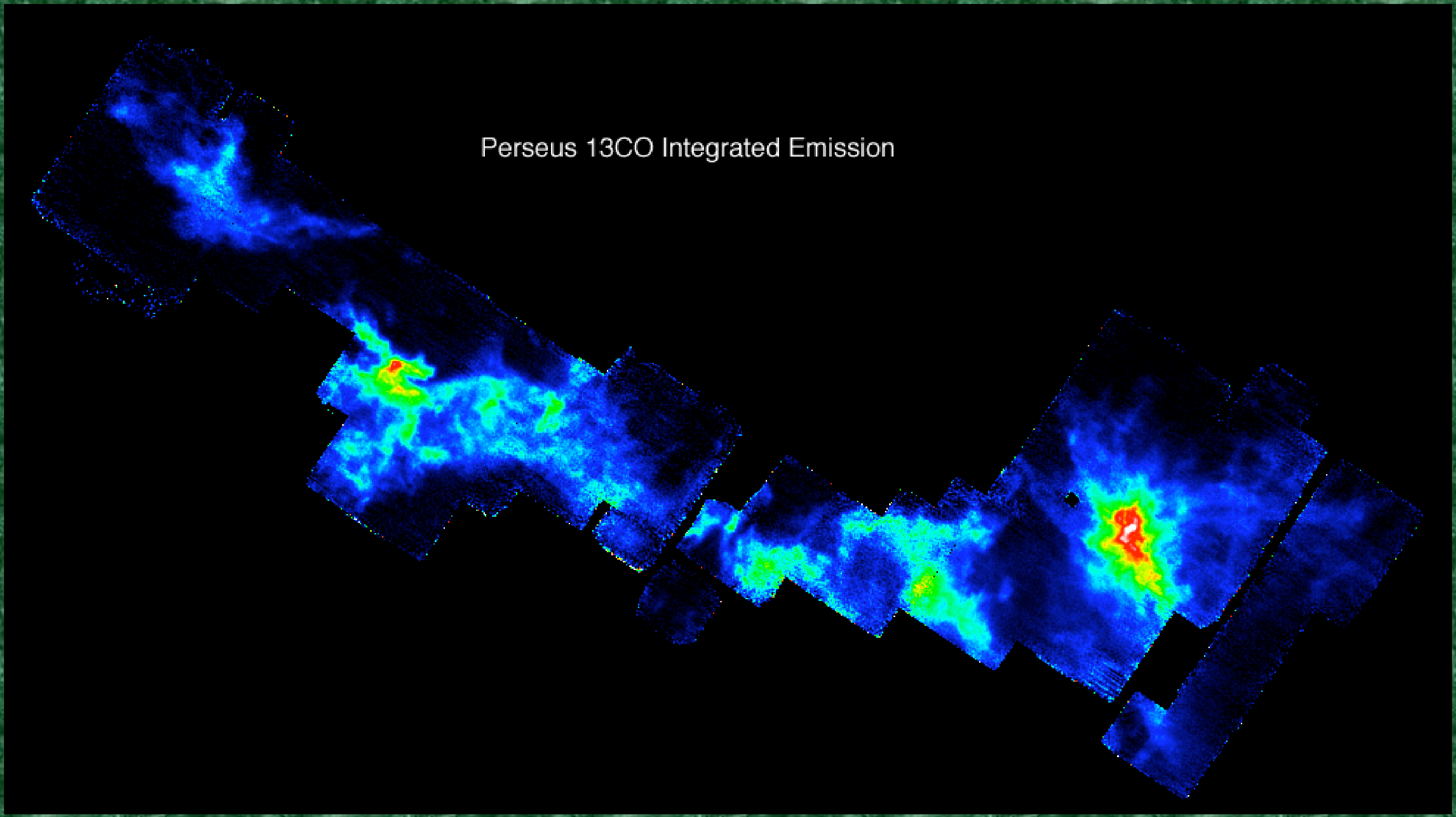
Motions of Cores within Clumps appear < Virial

Velocity Dispersion Versus Virial Measure



Extinction Mass of Clump

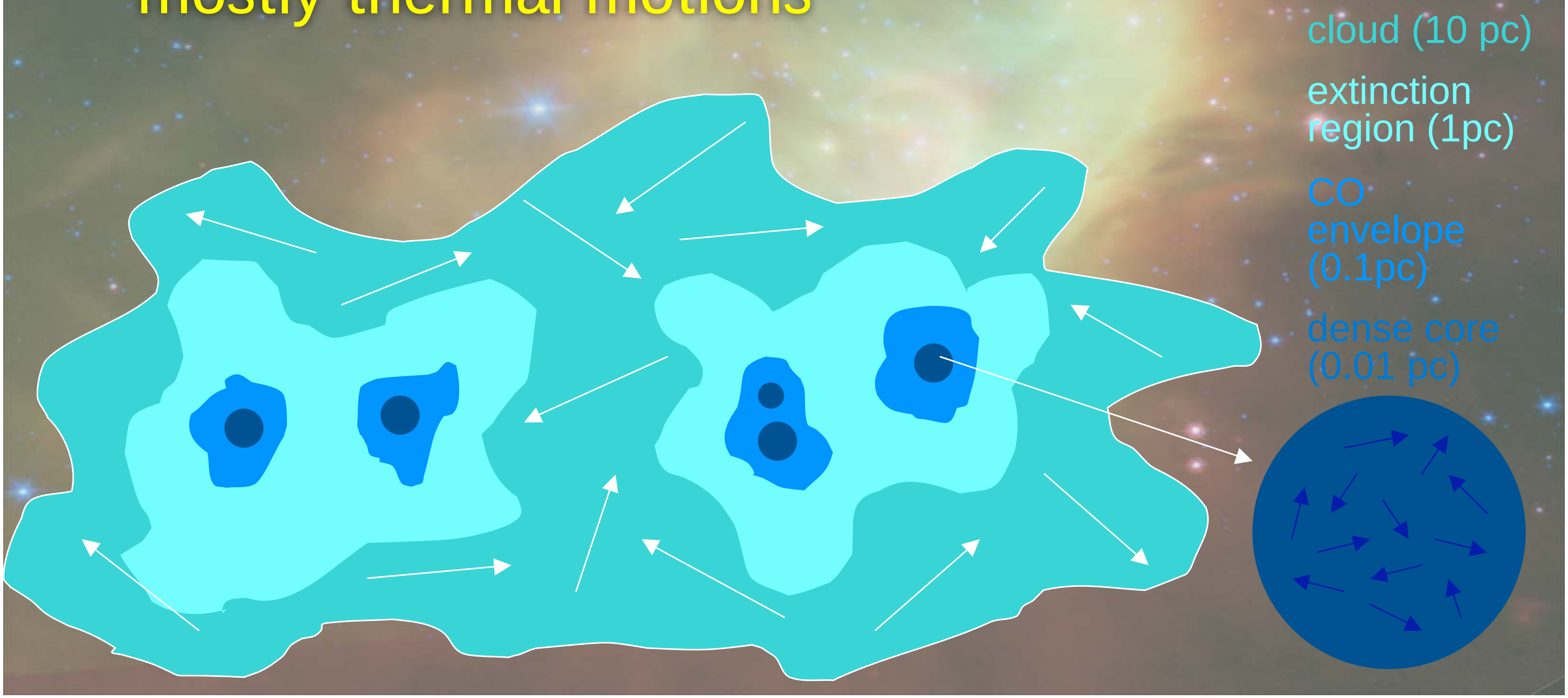
5) Kinematics of the Cloud

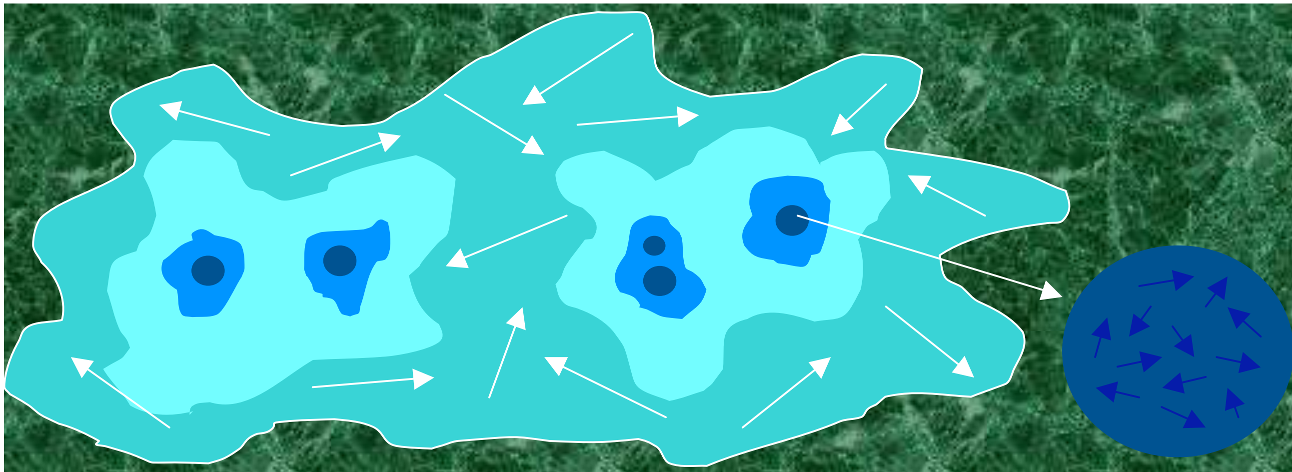


This image was constructed from ~140,000 individual ^{13}CO Spectra, obtained during the 2002-2003 season at FCRAO. Emission is integrated between 0 and 20 km/s. The entire data cube is nearly 4Gb in size! (HARP will play important role in this regard)

Star Formation & Dynamics

- On large scales, clouds exhibit supersonic turbulent motions
- On the smallest scales, dense cores have mostly thermal motions

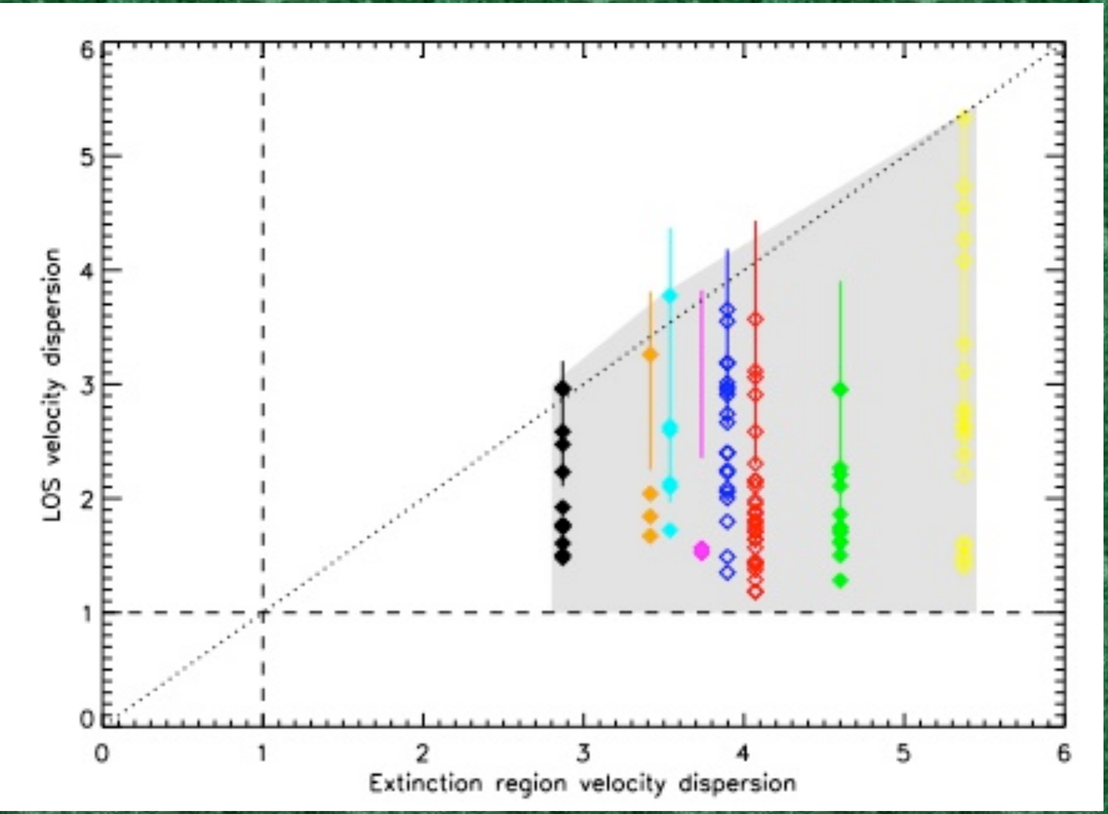


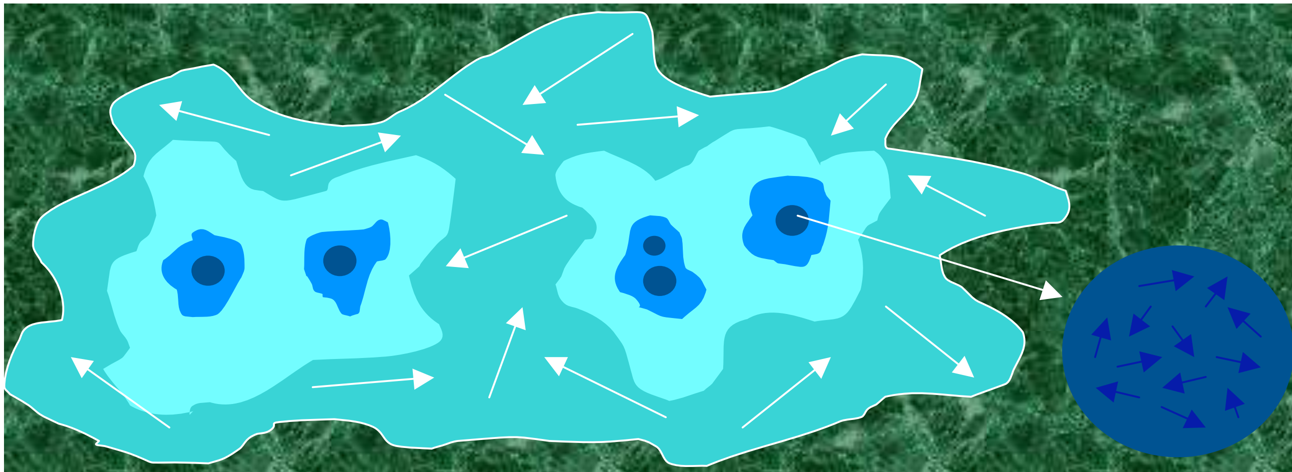


LOS velocity dispersion versus the dispersion of the entire region.

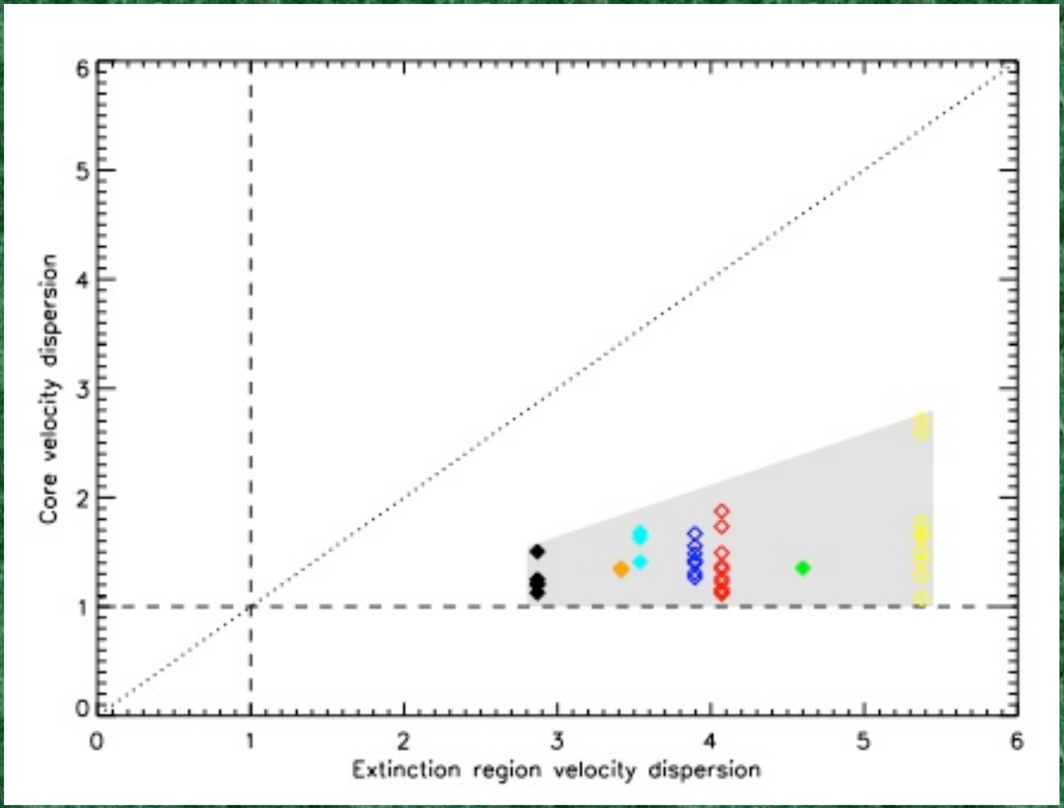
Sym- LOS toward cores
Line- random LOS

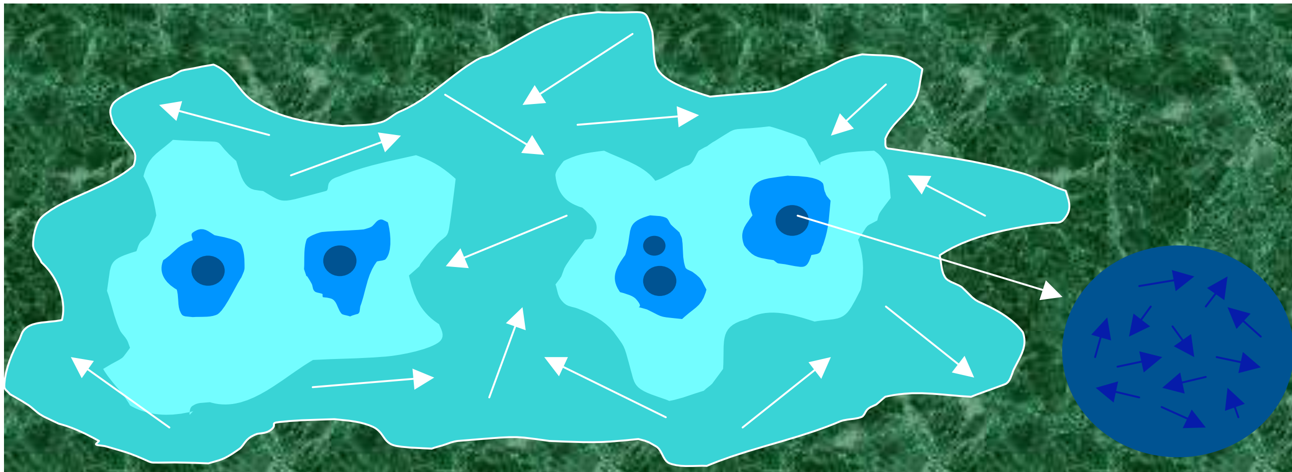
Units of sound speed.



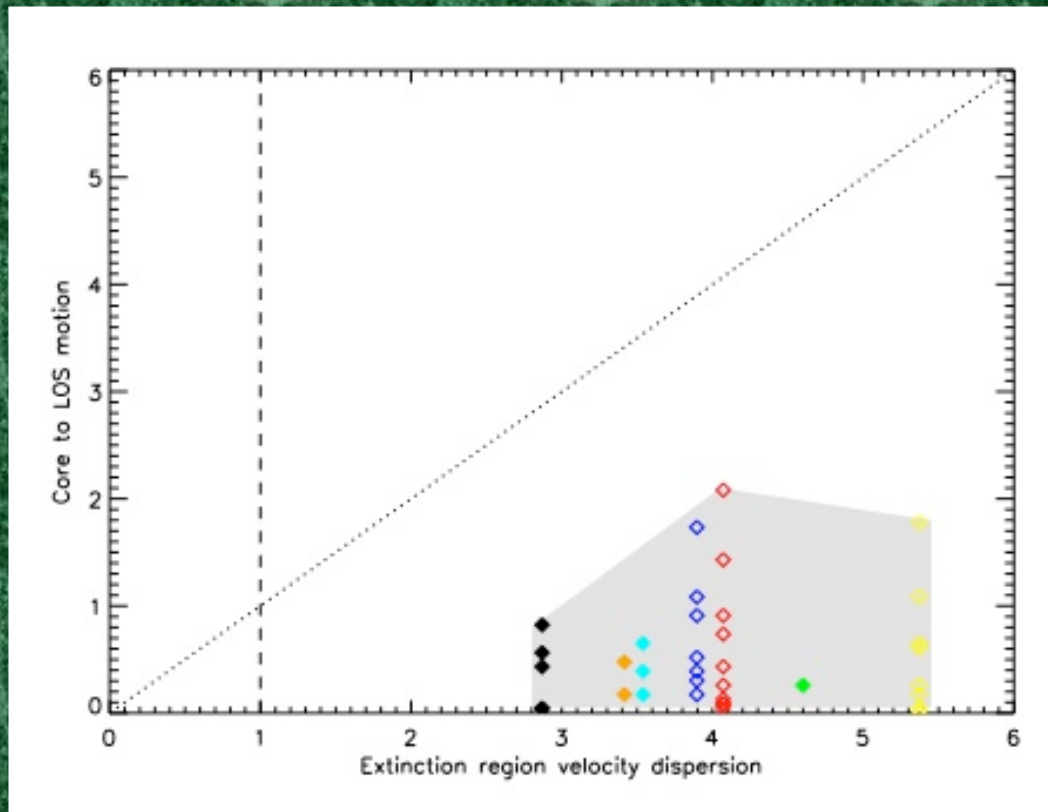


Core velocity dispersion versus the dispersion of the entire region.





Difference between core velocity & LOS velocity centroid versus the dispersion of the entire region.



Questions we hope to address

- How are clouds supported?
  - Long-lived? Magnetic fields, turbulent input
  - Short-lived? Turbulent dissipation, etc
  - Determines the initial conditions for structure
- How does material clump and make cores?
  - Quasi-static? Ambi-polar diffusion etc.
  - Dynamic? Turbulent flows, waves, etc
  - Determines the initial conditions for star formation
- How do cores collapse?
  - Regulated? Inside-out, smooth, etc.
  - Fragmented? Dynamical, fast loss of support
  - Determines the initial conditions for binaries, clusters

Observational Surveys Provide

Significant Statistical Information.

Clump mass and size distribution - large scales

Core mass and size distribution – small scales

Core locations - environment and clustering

Structure - filamentary, elipticity, directionality

Frequency of protostellar stages - Class -I, 0, I, II, III

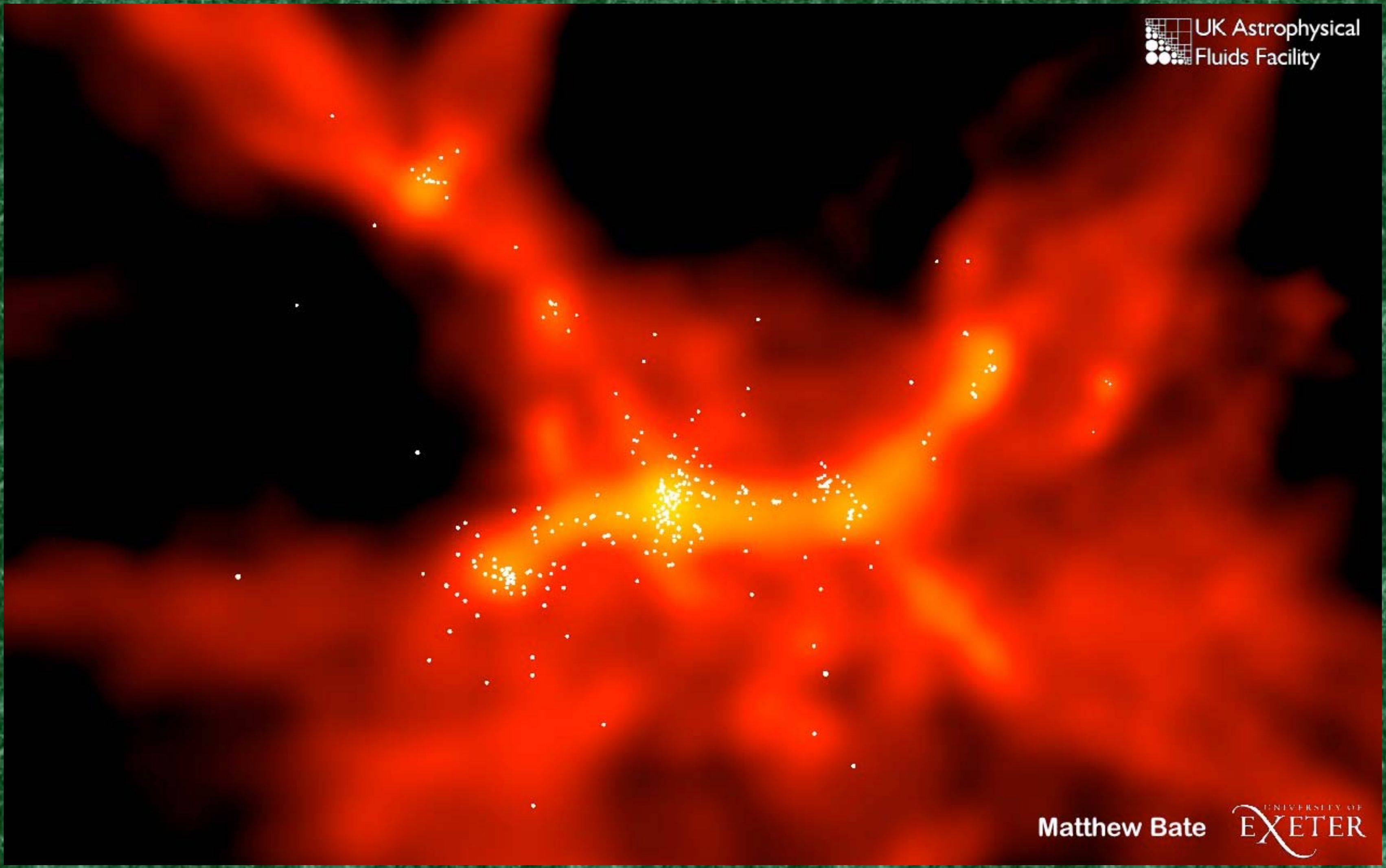
Kinematic Information – CO and N_2H^+ widths, dist'n

Polarization Angle - Magnetic Field Orientation

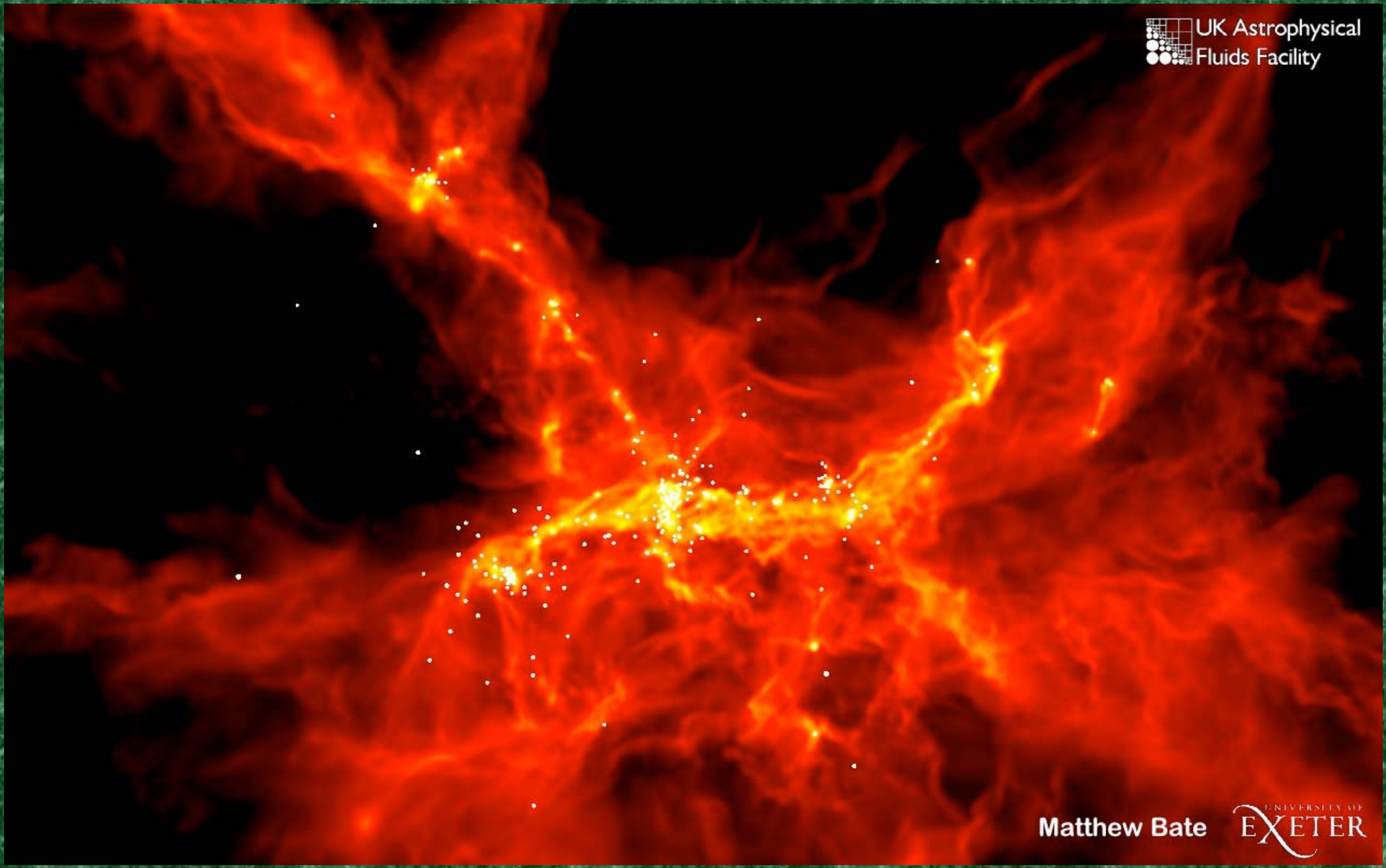
Reasonable theories must reproduce each of these conditions!

FIN

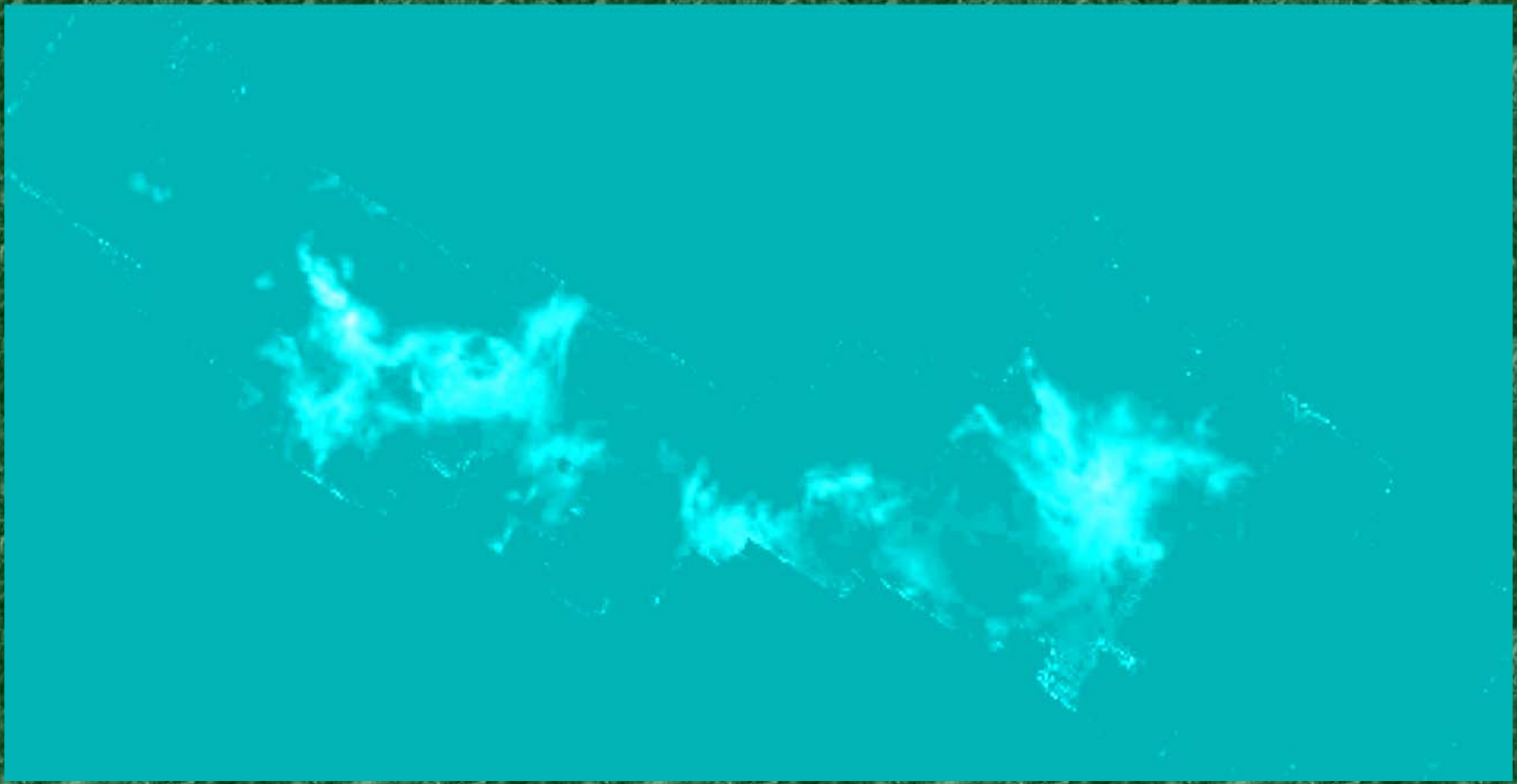
Structure :The Need for Resolution!



Structure :The Need for Resolution!

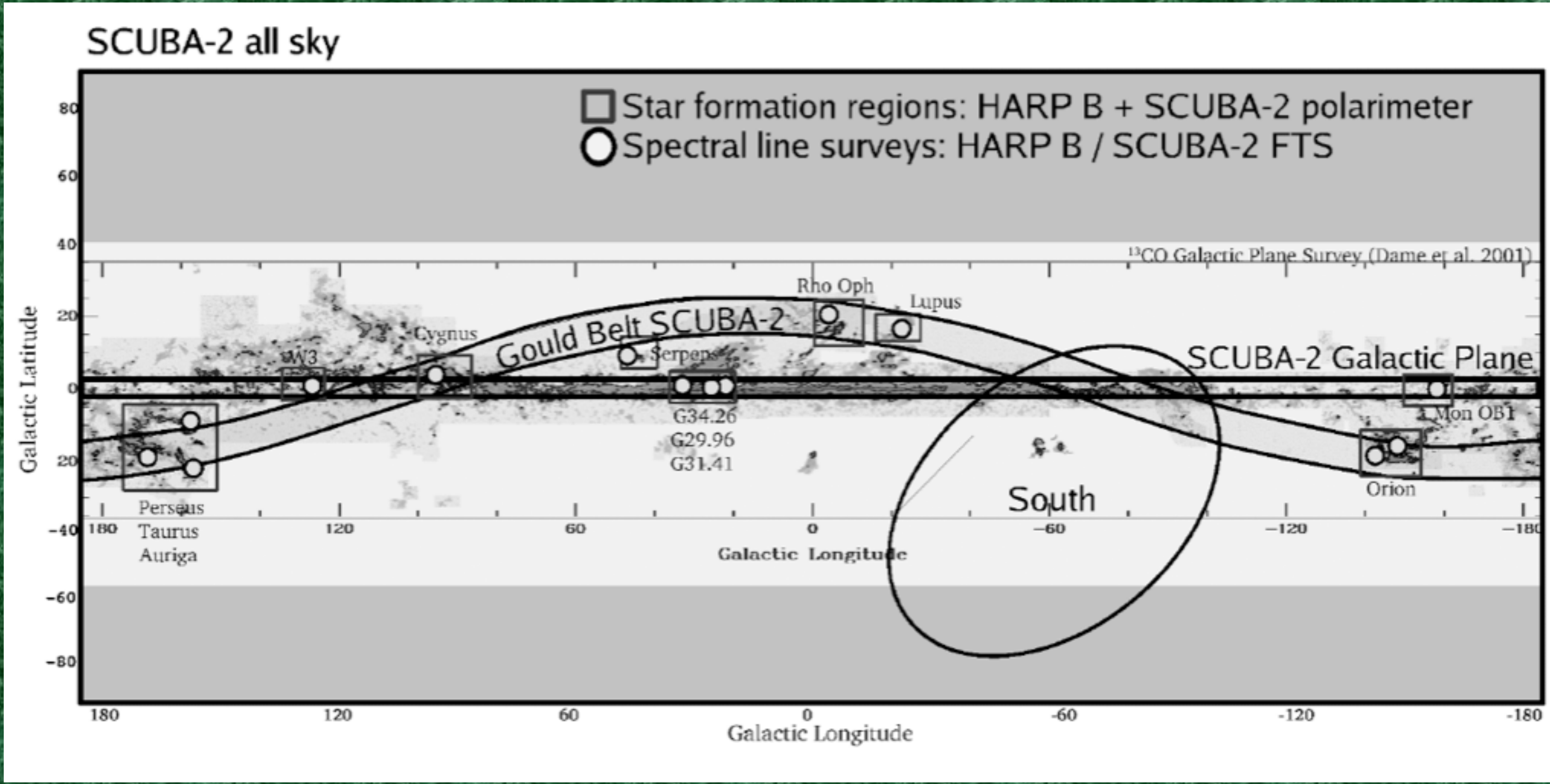


Molecular Cloud Mapping



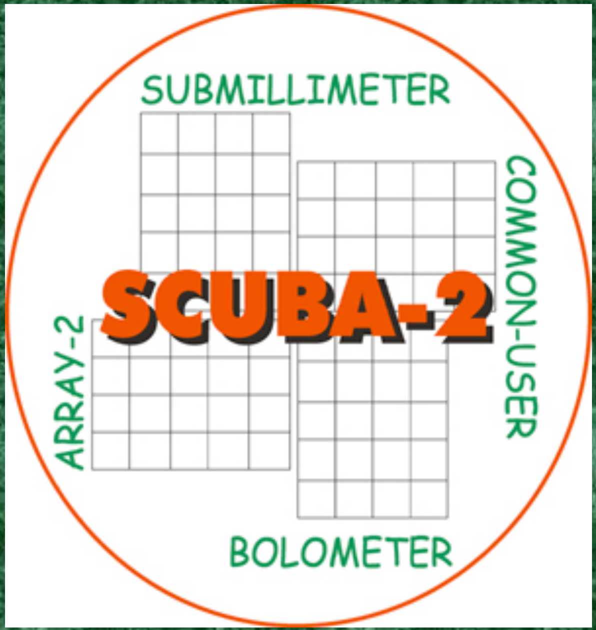
This image was constructed from ~140,000 individual ^{13}CO Spectra, obtained during the 2002-2003 season at FCRAO. Emission is integrated between 0 and 20 km/s. The entire data cube is nearly 4Gb in size! (HARP will play important role in this regard)

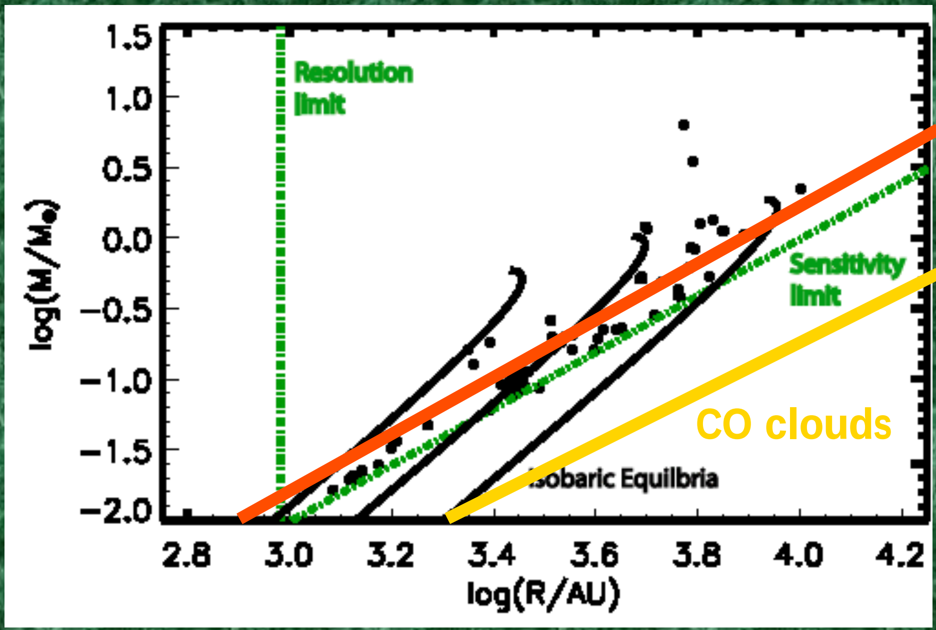
Gould's Belt - Nearby Star Formation Sites



SCUBA2 Legacy Project: Mapping most star formation in Gould's Belt, covering ~700 square degrees, and sensitive to every Class 0 & I protostar and every L1544-like pre-stellar core within 0.5 kpc!

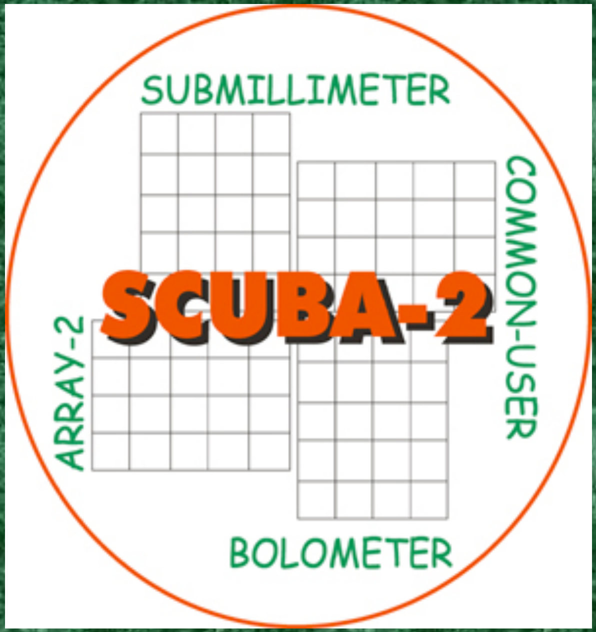
The Future of Sub-mm Mapping

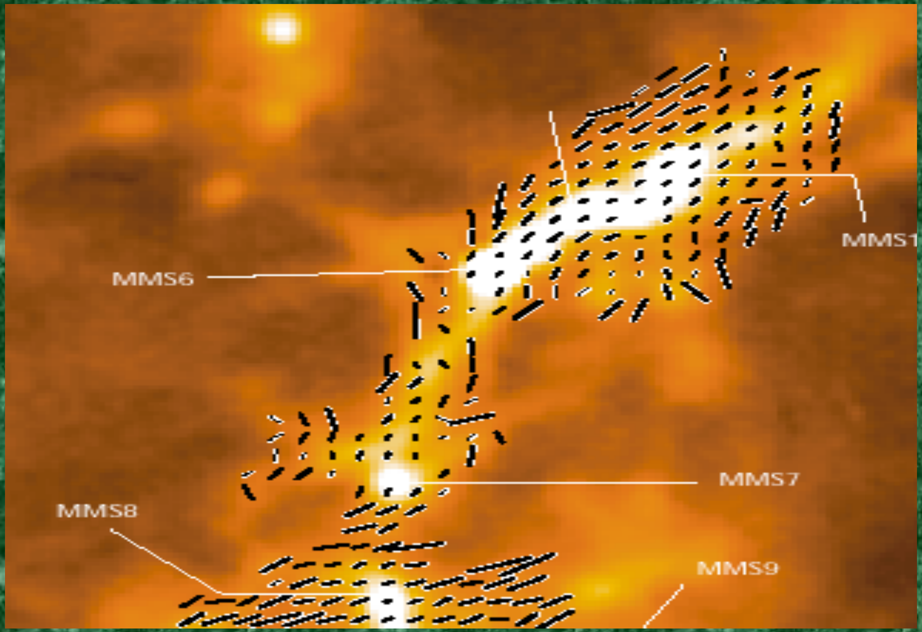




1. Imaging at 850 and 450 microns (>100 faster than SCUBA)
2. Covering 10 sq. deg. to 2mJy (CO clouds) in < 100 hrs
3. Deep, unbiased, structure surveys within molecular clouds
4. JCMT Legacy Surveys - Gould Belt, Galactic Plane, Debris Disks

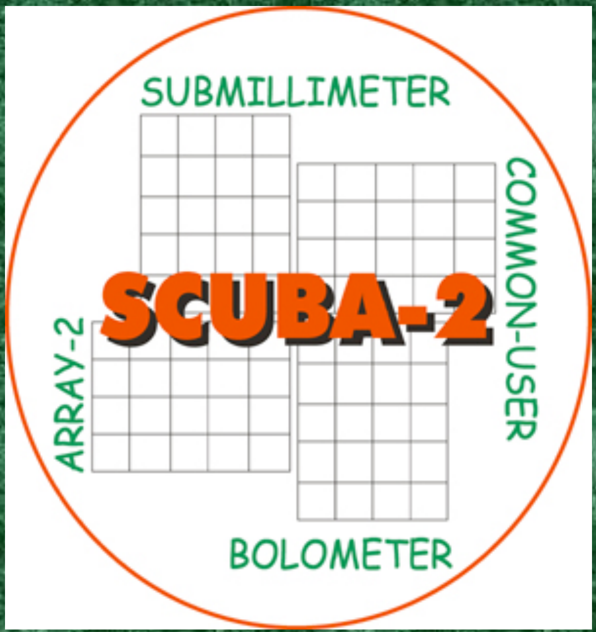
Polarimetry

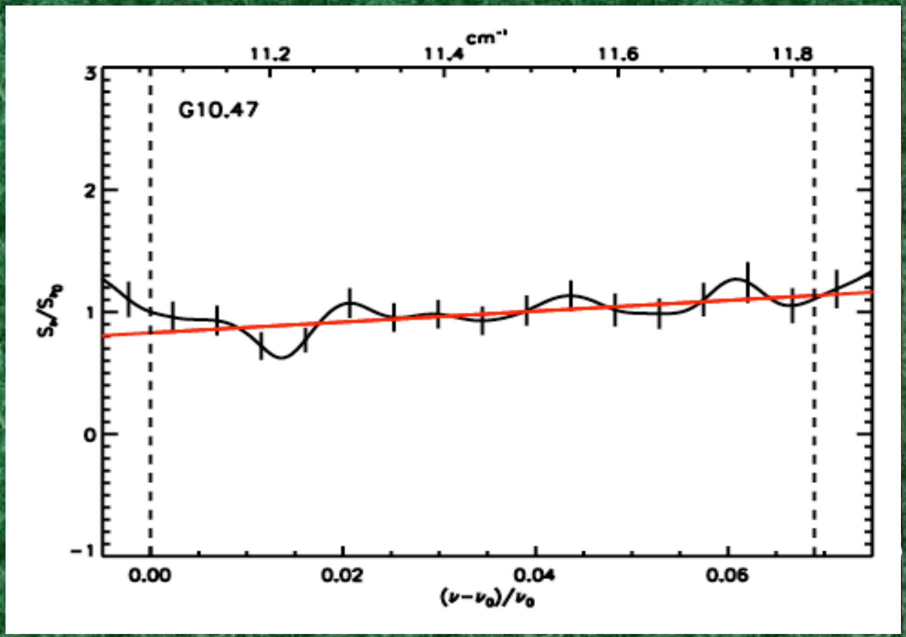




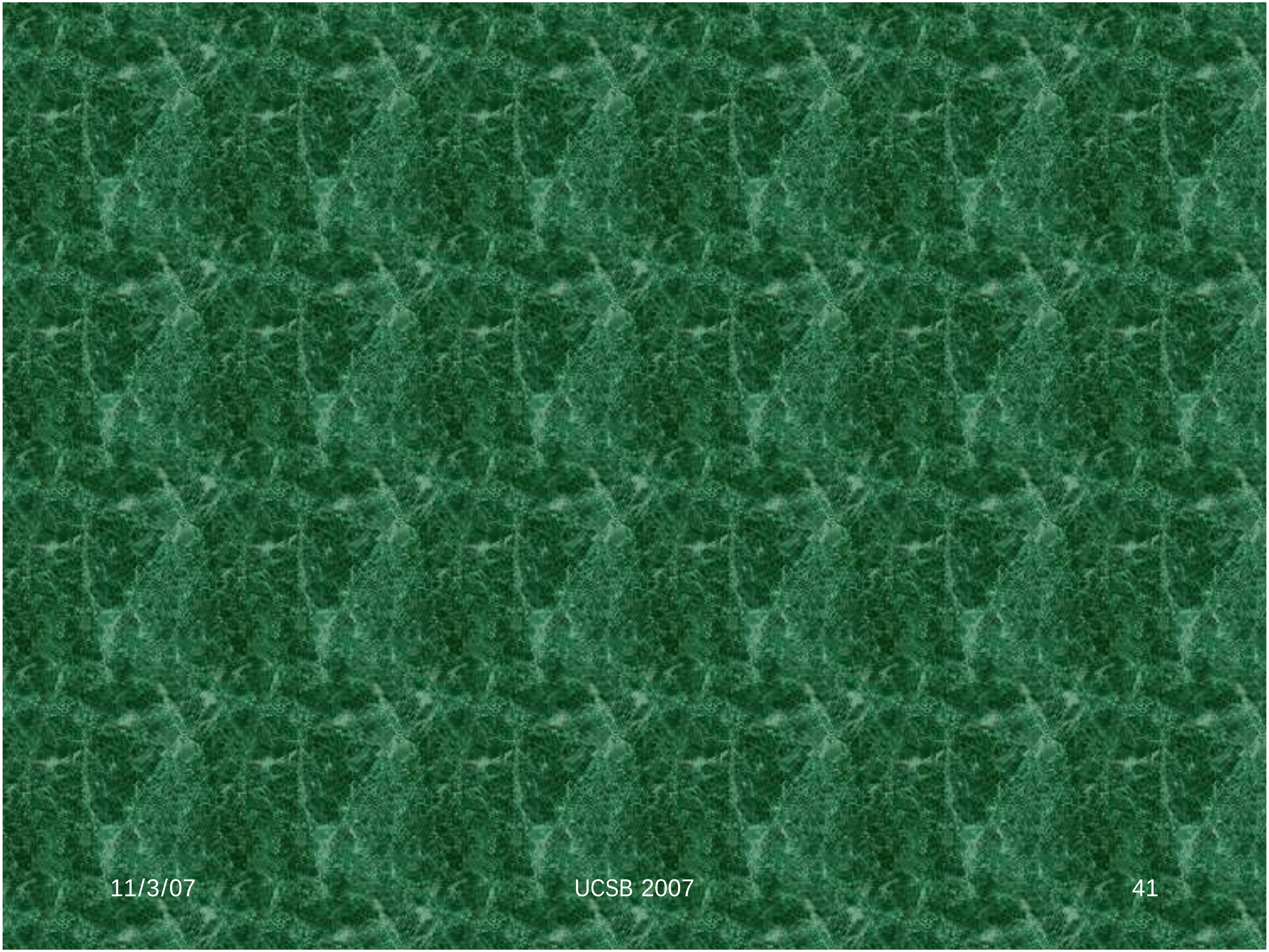
1. Polarimetry (>1000 faster than SCUBA)
2. Should detect magnetic geometry over much of cloud
3. Important observational constraint for theories/simulations
4. Further exploration of dust properties

Sub-mm Spectral Index

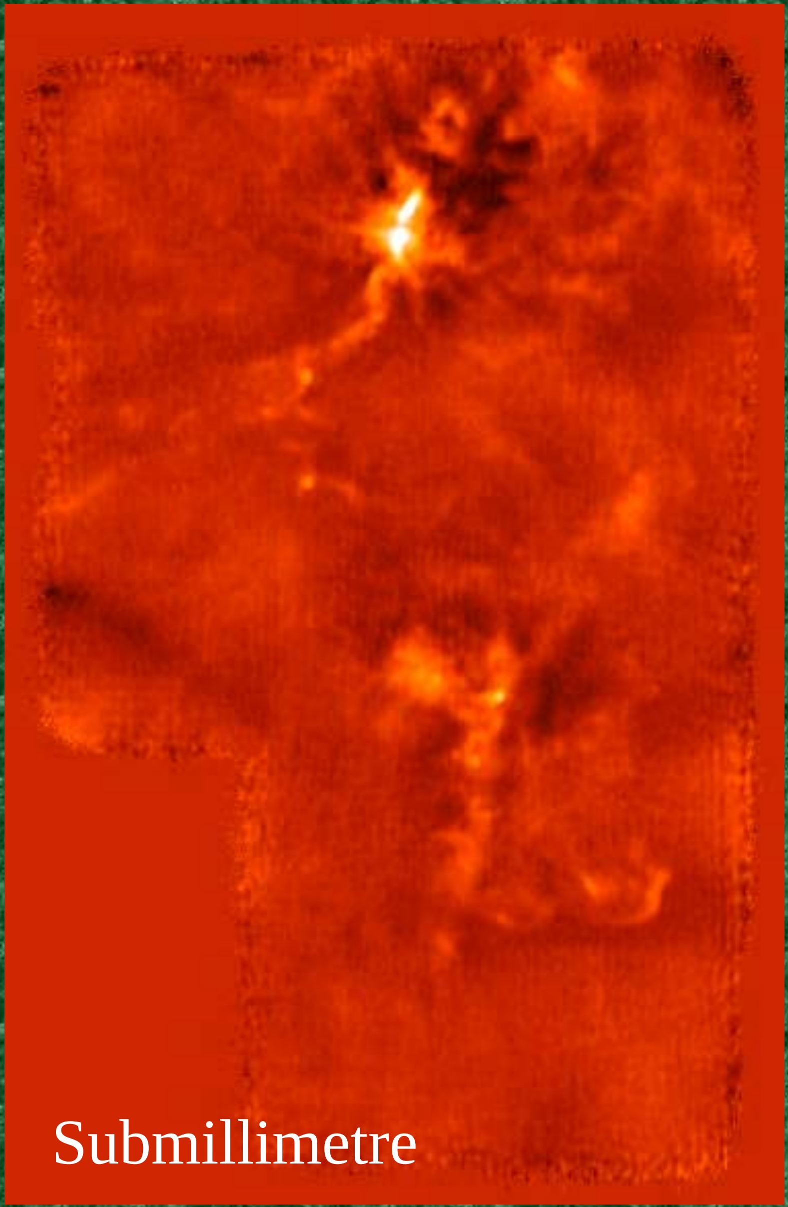




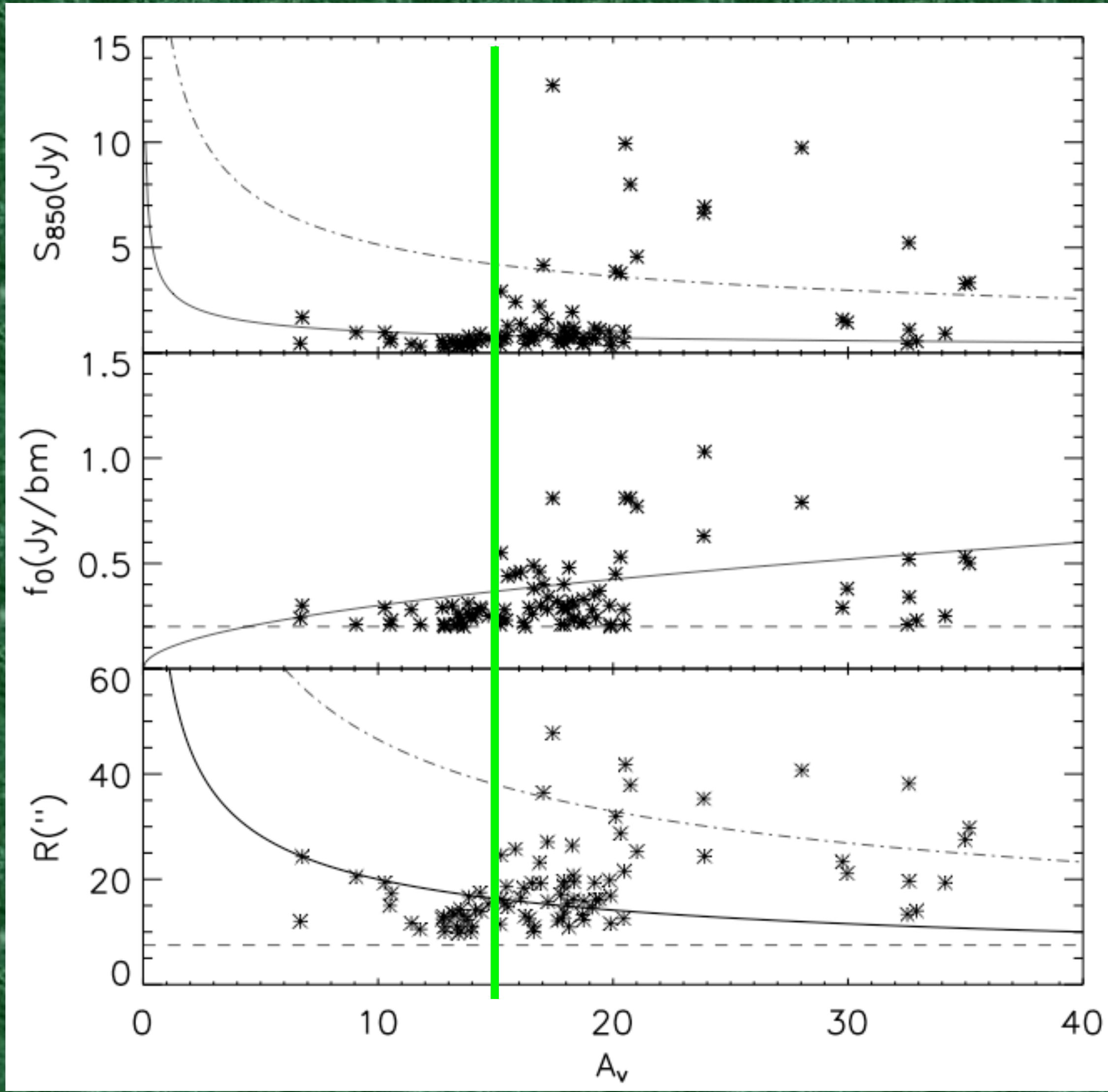
1. Fourier Transform Spectroscopy (>1000 faster than SCUBA)
2. High spectral resolution – survey strong molecular lines
3. Low spectral resolution – model SED through submillimetre
   - Determine dust properties (ß± 0.1) (Friesen et al. 2005)

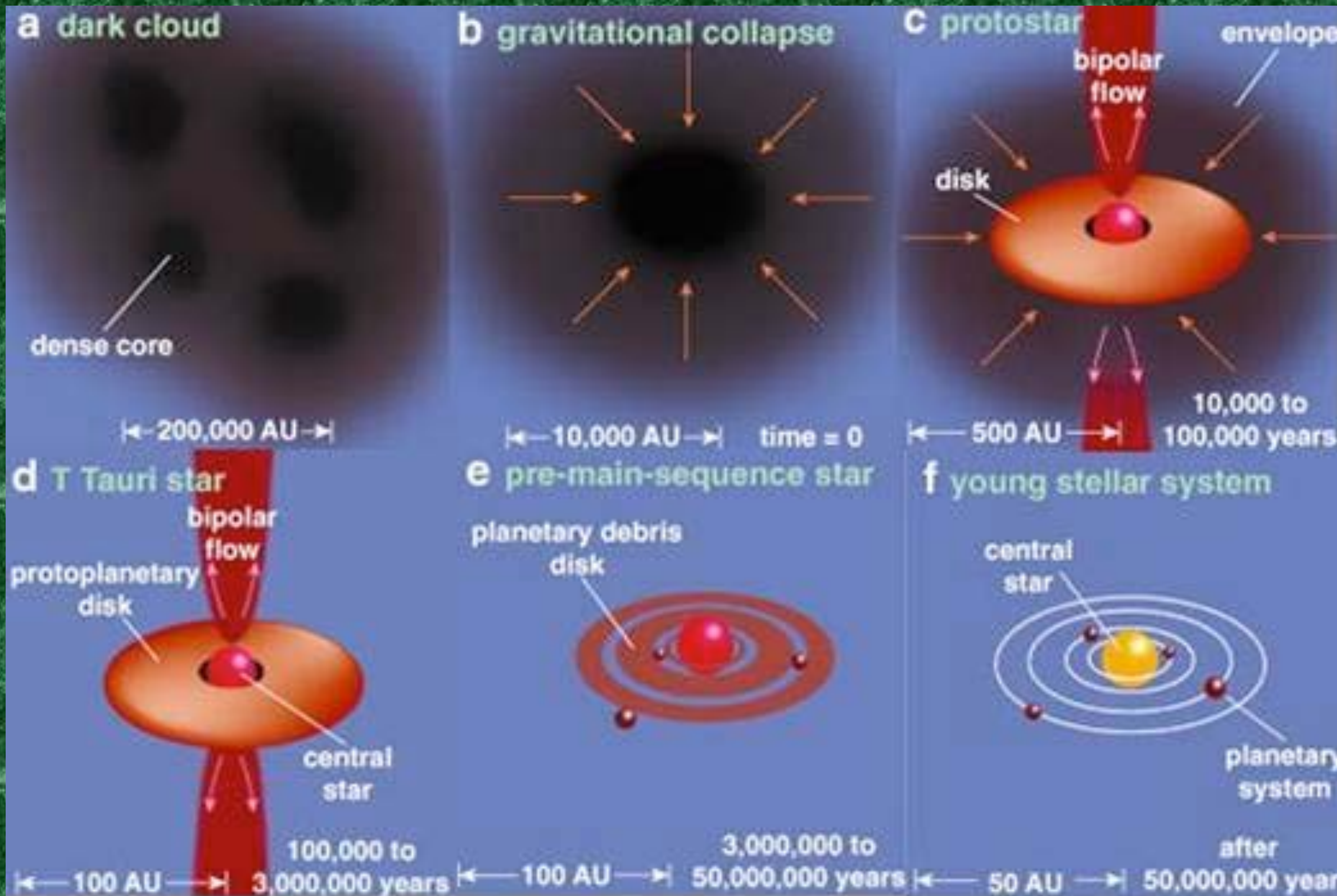


Observing Star Formation



Is this an Observational Issue?




a dark cloud
dense core
200,000 AU
b gravitational collapse
10,000 AU
time = 0
c protostar
bipolar flow
envelope
disk
500 AU
10,000 to 100,000 years
d T Tauri star
bipolar flow
protoplanetary disk
central star
100 AU
100,000 to 3,000,000 years
e pre-main-sequence star
planetary debris disk
100 AU
3,000,000 to 50,000,000 years
f young stellar system
central star
planetary system
50 AU
after 50,000,000 years