PRESENTATION LOAD

# Local (Low-Mass) Star Formation:

## A few issues for contemplation and discussion


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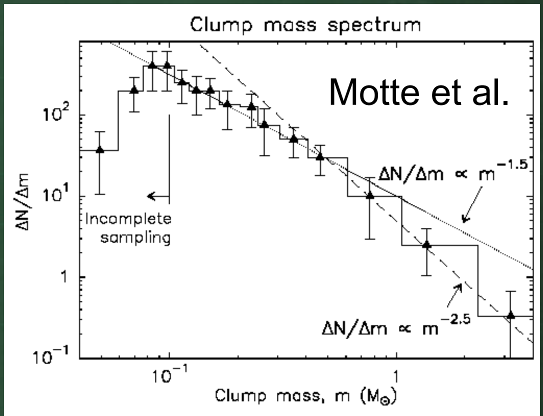
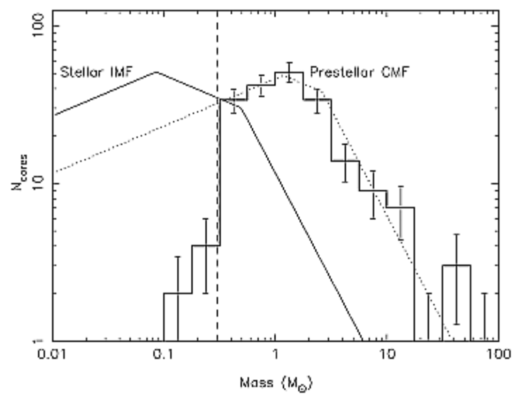
Scott Schnee, Melissa Enoch, et al.

# What We Think We Know About Cores …

- Distribution of core mass is steep
  - Similarity to IMF intriguing
    - Result indep. of structure analysis form
    - Totals to small fraction of the cloud
- Found in localized regions of cloud
  - Highest $A_v$ zones (highest column density)
  - Clustered together
- Thermal size vs. mass relation
  - Sub-Jeans $M \propto R^3$ (Pressure-confined objects?)
  - Largest objects are Grav. Unstable




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

# 1) Consider the Pre-Stellar Core …

$M, R, T, \sigma_{NT}$

(single dish observations)

$M(r), T(r), \sigma_{NT}(r)$

(Interferometer observations)

$$R_J \propto \left(\frac{T}{\rho}\right)^{1/2}$$

$$M_J \propto \left(\frac{T^3}{\rho}\right)^{1/2}$$

$$\rho(r) \propto r^{-\alpha}$$

$\alpha$ ~ importance of self-gravity

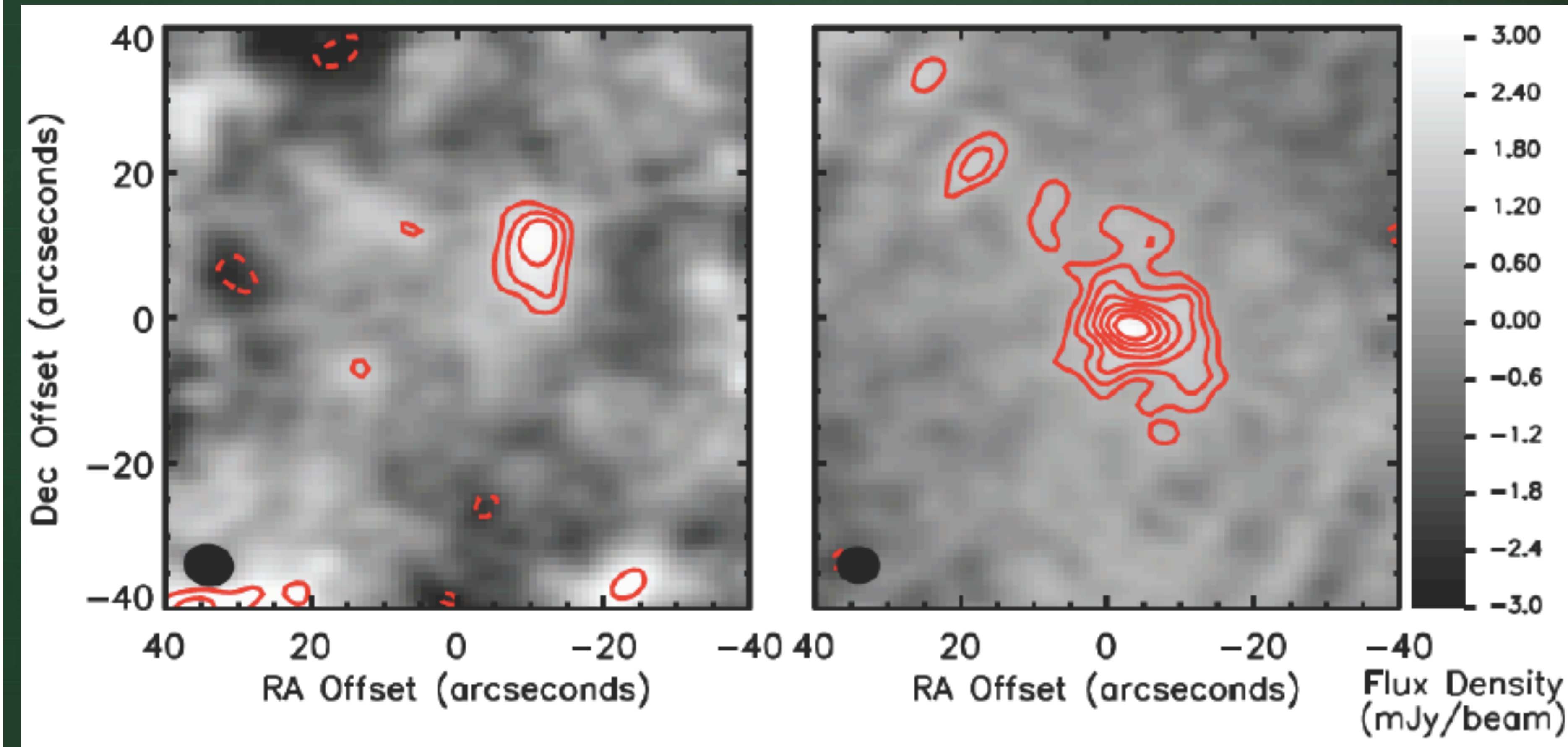
Is this a reasonable model?

Are pre-stellar cores simple or complex?

# Search for Substructure in 11 Perseus Starless Cores

with an interferometer, we only detected two cores and no multiples

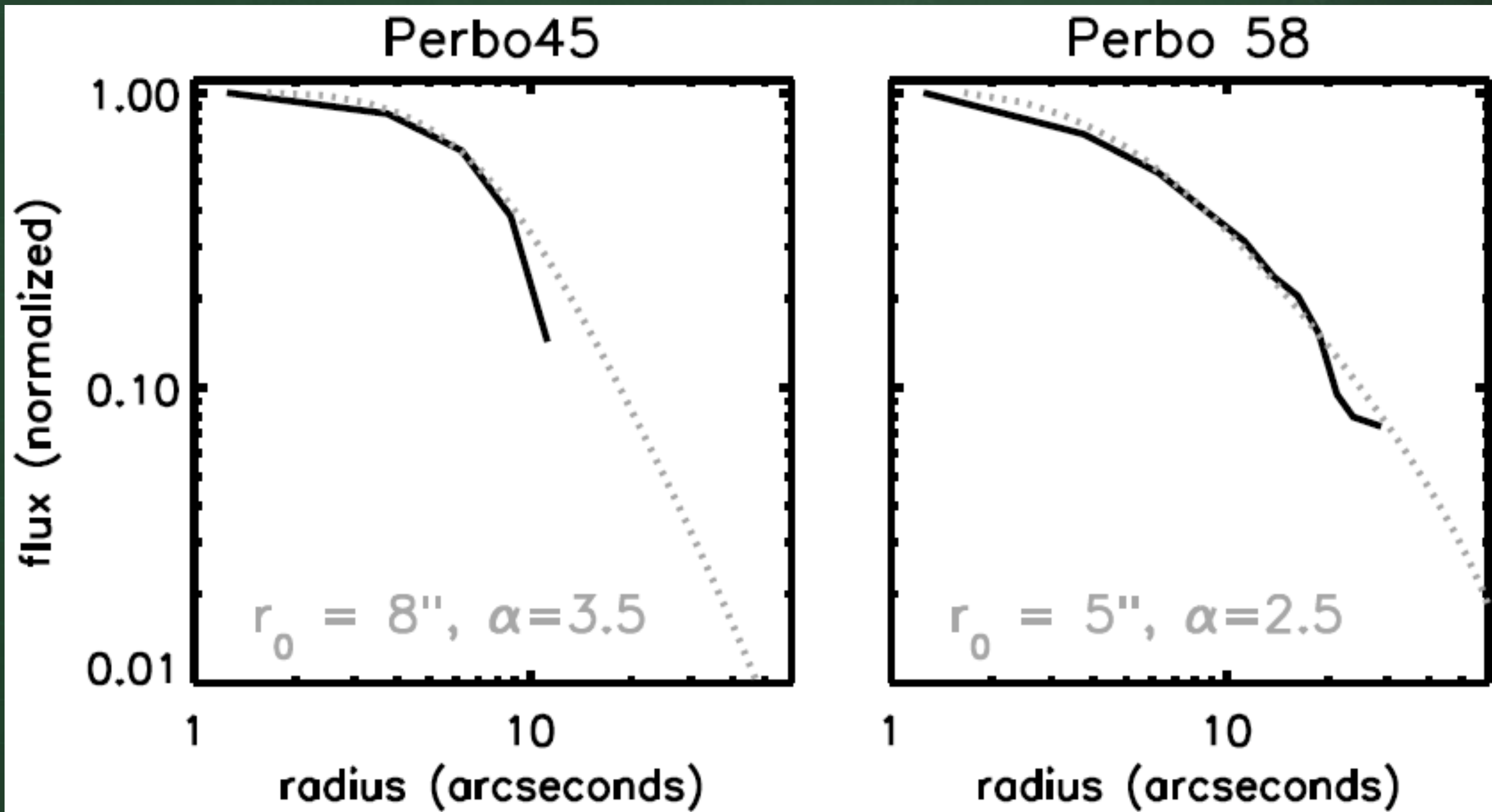
CARMA D+E array 7-point mosaics & SZA single pointing




(Schnee et al. accepted to ApJ)

# Modeling the density profile

$$n(r) = n_0/[1 + (r/r_0)^\alpha]$$




(Schnee et al. accepted to ApJ)

# Search for Fragmentation Reveals Little Substructure

## 3mm-derived Properties of Starless Cores

| Name | RA offset[1] ($''$) | Dec offset[1] ($''$) | Peak Flux[2] (mJy/beam) | Total Flux[2] (mJy) | Axes[3] ($''$) | $\theta_{PA}$[3] (degrees) | Mass[4] ($M_\odot$) | density ($cm^{-3}$) |
|---|---|---|---|---|---|---|---|---|
| Perbo11 | | | | | | | <0.11 | |
| Perbo13 | | | | | | | <0.29 | |
| Perbo14 | | | | | | | <0.20 | |
| Perbo44 | | | | | | | <0.14 | |
| Perbo45[5] | $-10.3 \pm 0.5$ | $8.8 \pm 0.7$ | $2.4 \pm 0.3$ | $11 \pm 0.5$ | $14 \times 9$ | -14 | 0.8 | $1.1 \times 10^7$ |
| Perbo50 | | | | | | | <0.16 | |
| Perbo51 | | | | | | | <0.62 | |
| Perbo58 | $-4.3 \pm 0.8$ | $-1.1 \pm 0.9$ | $2.0 \pm 0.3$ | $33 \pm 1$ | $26 \times 18$ | 35 | 2.4 | $4.5 \times 10^6$ |
| Perbo74 | | | | | | | <0.07 | |
| Perbo105 | | | | | | | <0.20 | |
| Perbo107 | | | | | | | <0.24 | |

1. Offset from (0,0) position given in Enoch et al. (2006)
2. Derived from Gaussian fit to flux distribution
3. Deconvolved using the synthesized beam
4. For non-detections, $3\sigma$ upper limits to a point source are given
5. Does not include SZA data, so some 3mm emission is resolved out

(Schnee et al. accepted to ApJ)

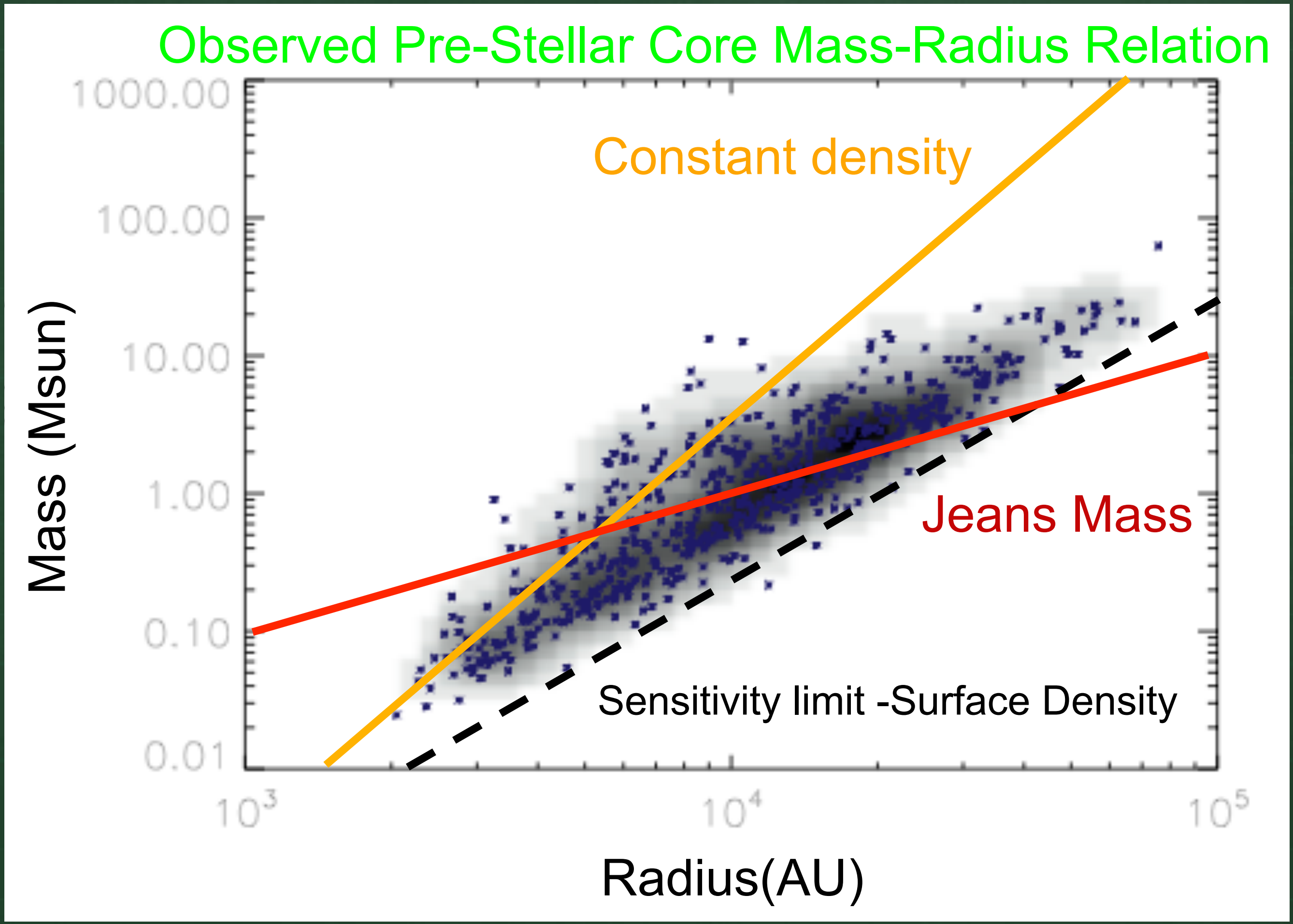
# 2) Consider the Pre-Stellar Core Again…


$$R_J \propto \left(\frac{T}{\rho}\right)^{1/2}$$

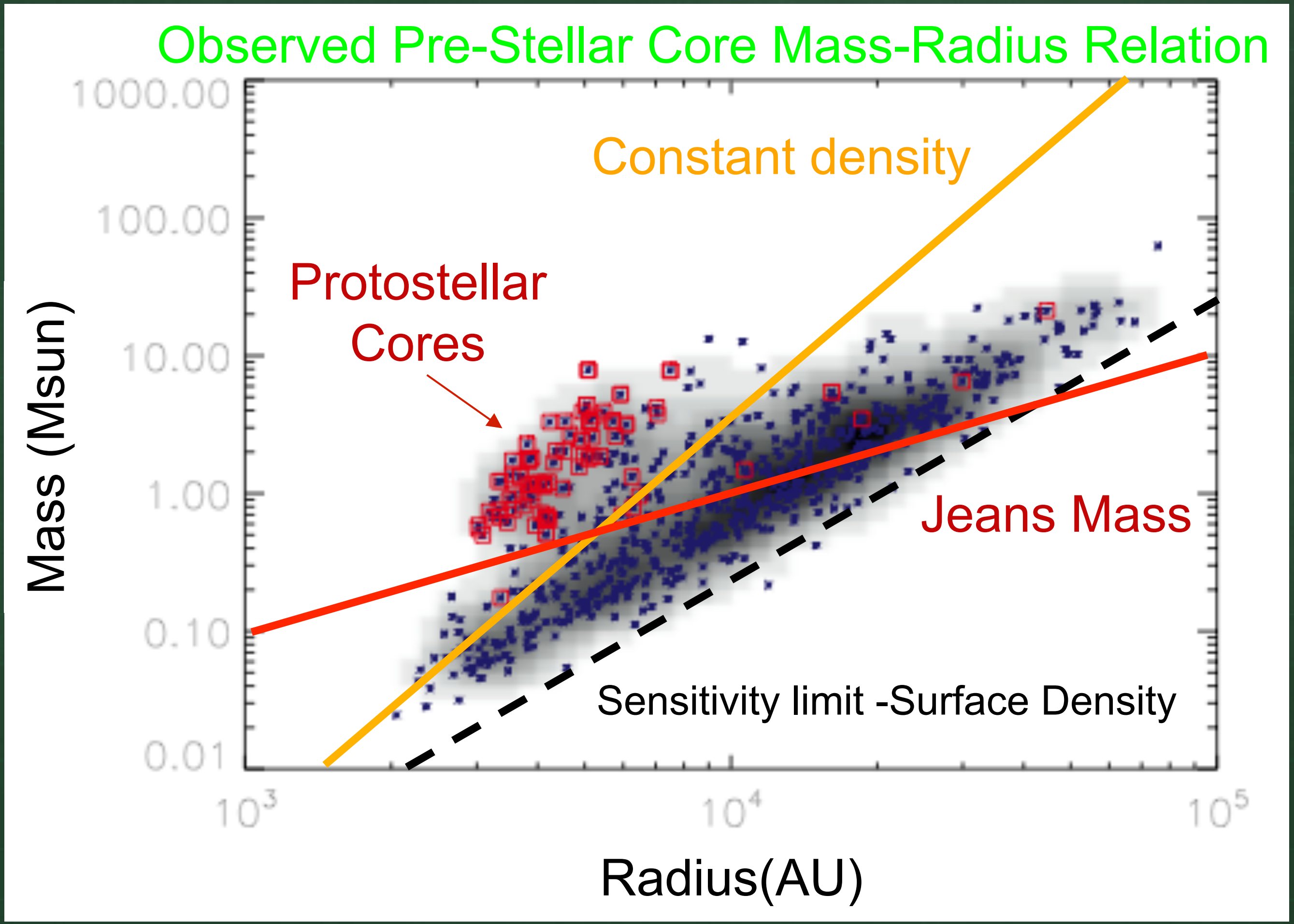
$$M_J \propto \left(\frac{T^3}{\rho}\right)^{1/2}$$

But, shouldn't the environment determine the core properties?!?

# An Enlightening Example …



# An Enlightening Example …



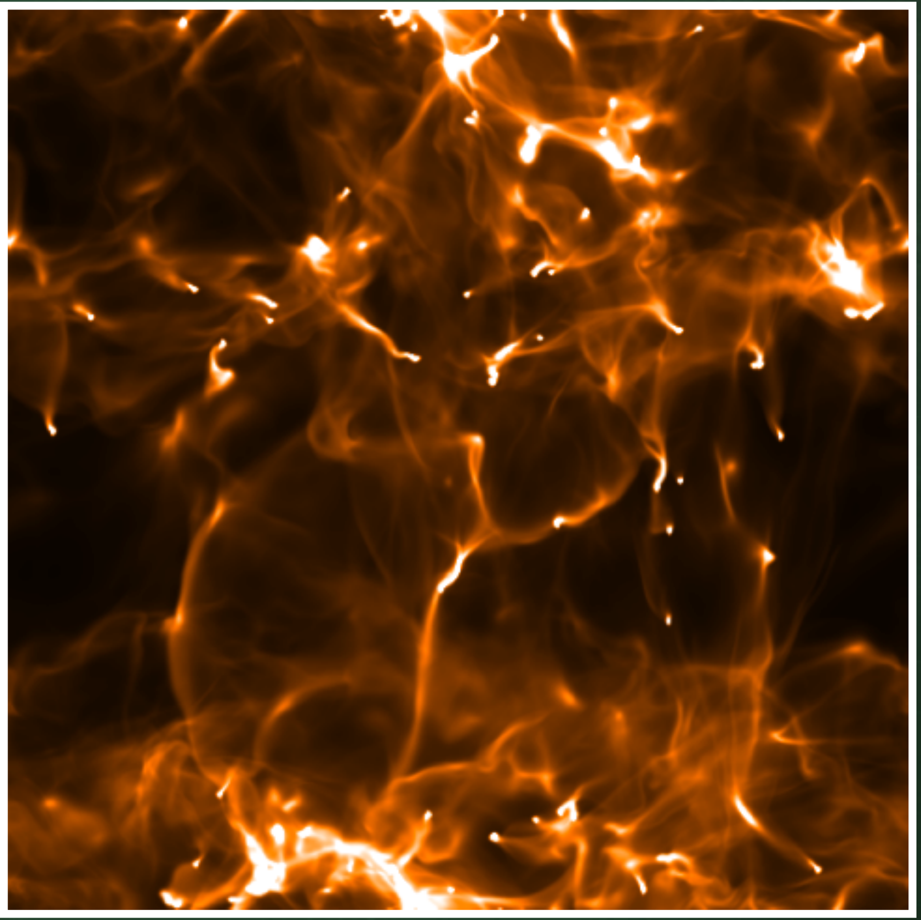
# An Enlightening Example …

Padoan & Nordlund simulation
(turbulence with self-gravity)

- mach 9 turbulence, with many initial Jeans masses

- observed density barrier due to ram pressure from turbulence
  - $\rho_{max} \sim M^2 \rho_{init} \sim 80\ \rho_{init}$

- requirement of observational high spatial and dynamic range
  - Herschel!



Note: this analysis only reveals that the environment can set core conditions

# 3) Consider the Pre-Stellar Core Again…

$$R_J \propto \left(\frac{T}{\rho}\right)^{1/2}$$

$$M_J \propto \left(\frac{T^3}{\rho}\right)^{1/2}$$

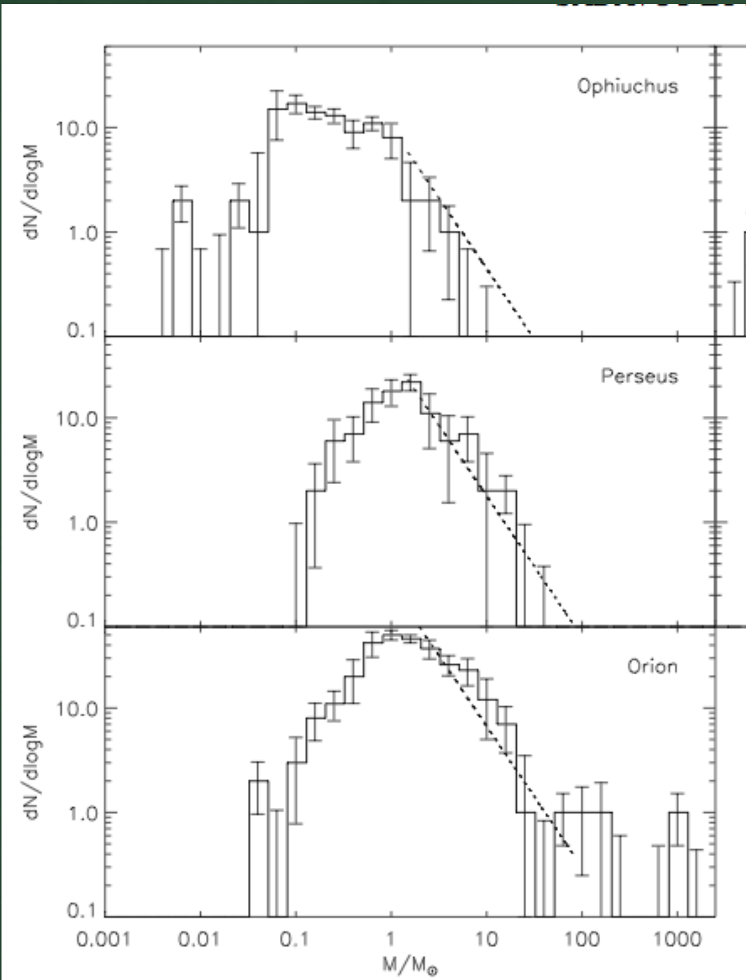

But, shouldn't gravitationally unstable cores collapse?

# How are Cores and Star Formation Related?

- Look for IR emission coincident with cores
  - Protostars will heat their environment and glow
- Fraction of cores with embedded IR is ~50% (Perseus)
  - Lifetime of observed cores is short
    - ~ lifetime of deeply embedded protostars
  - Usually only one embedded source per core (~5")!
    - little fragmentation inside cores
- Embedded source centrally located in cores
  - No evidence of dynamics between core and protostar

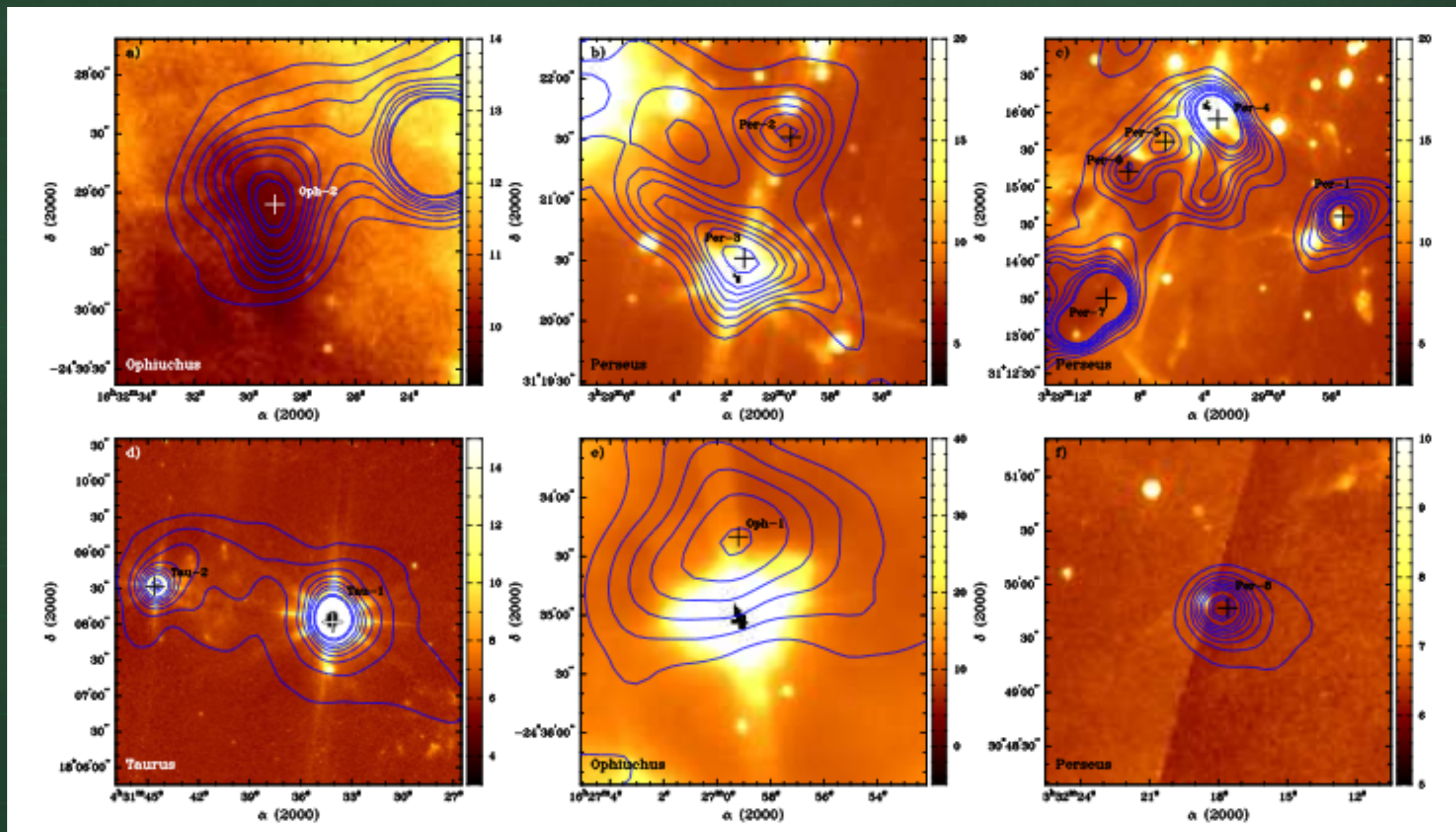

Dense cores appear highly correlated with star formation.
Dense core formation relatively quick and efficient.

# Initial Determination of Starless Cores in JCMT Legacy Catalogue



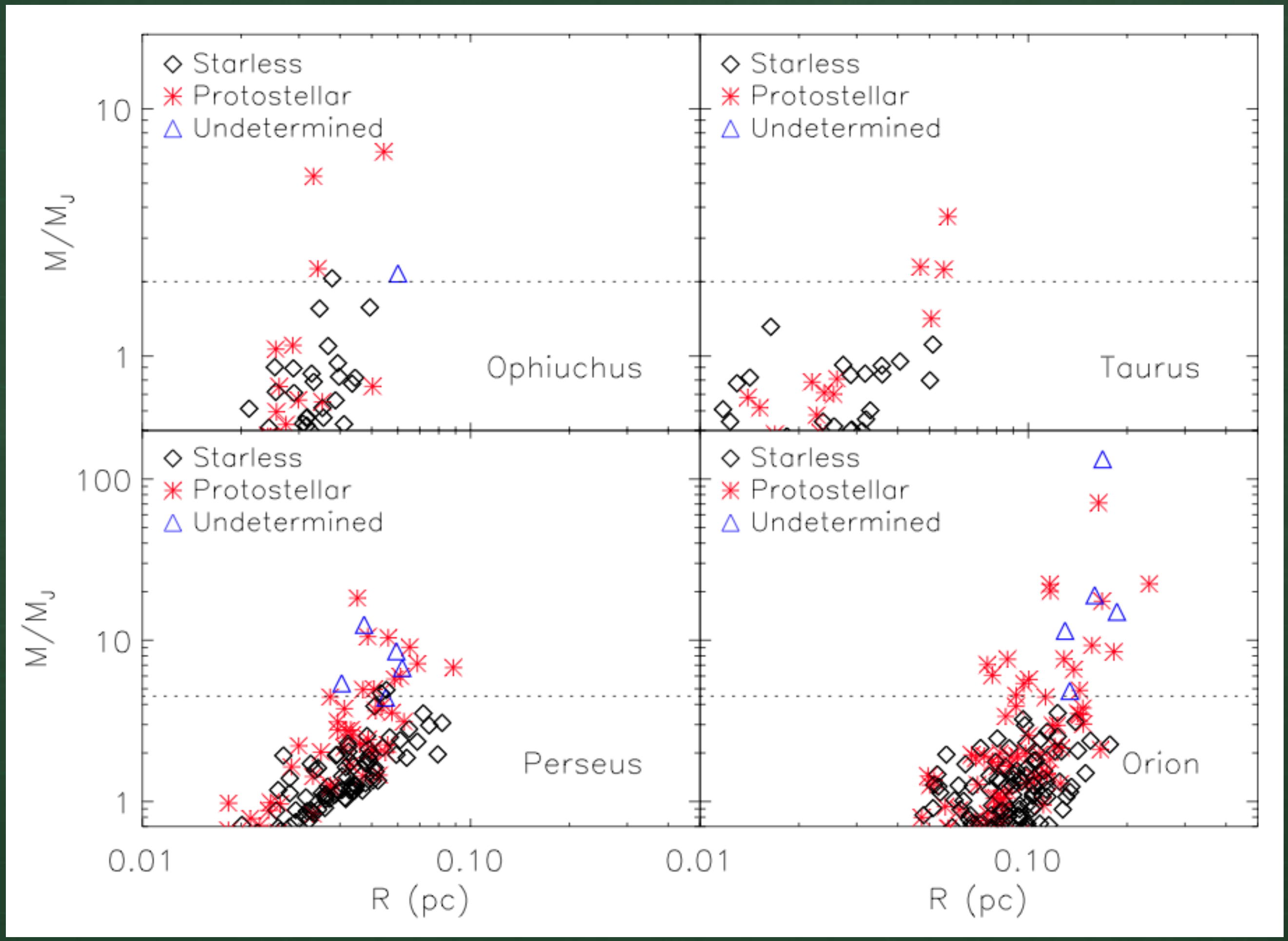

Sadavoy, Di Francesco, et al. 2010

# Careful re-analysis of the 17 most 'unstable' pre-stellar cores.




Sadavoy, Di Francesco, Johnstone 2010

# Most are ambiguous, only three excellent pre-stellar candidates.




Sadavoy, Di Francesco, Johnstone 2010

# 4) Consider the Pre-Stellar Core … (Yet Again)

$M, R, T, \sigma_{NT}$

(single dish observations)

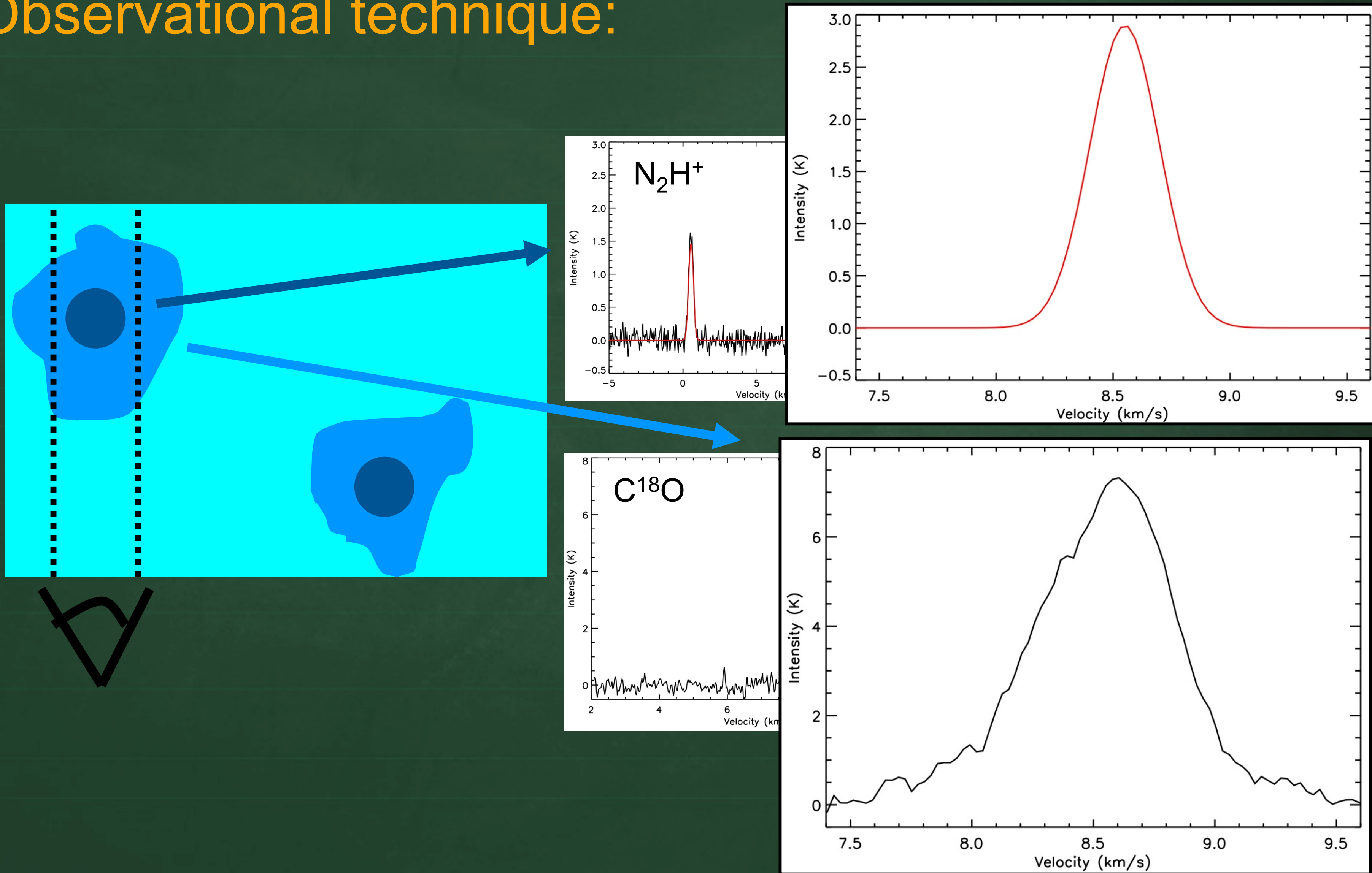
Transition Zone: Structure, Chemistry, and Kinematics!

How is the pre-stellar core assmbled?

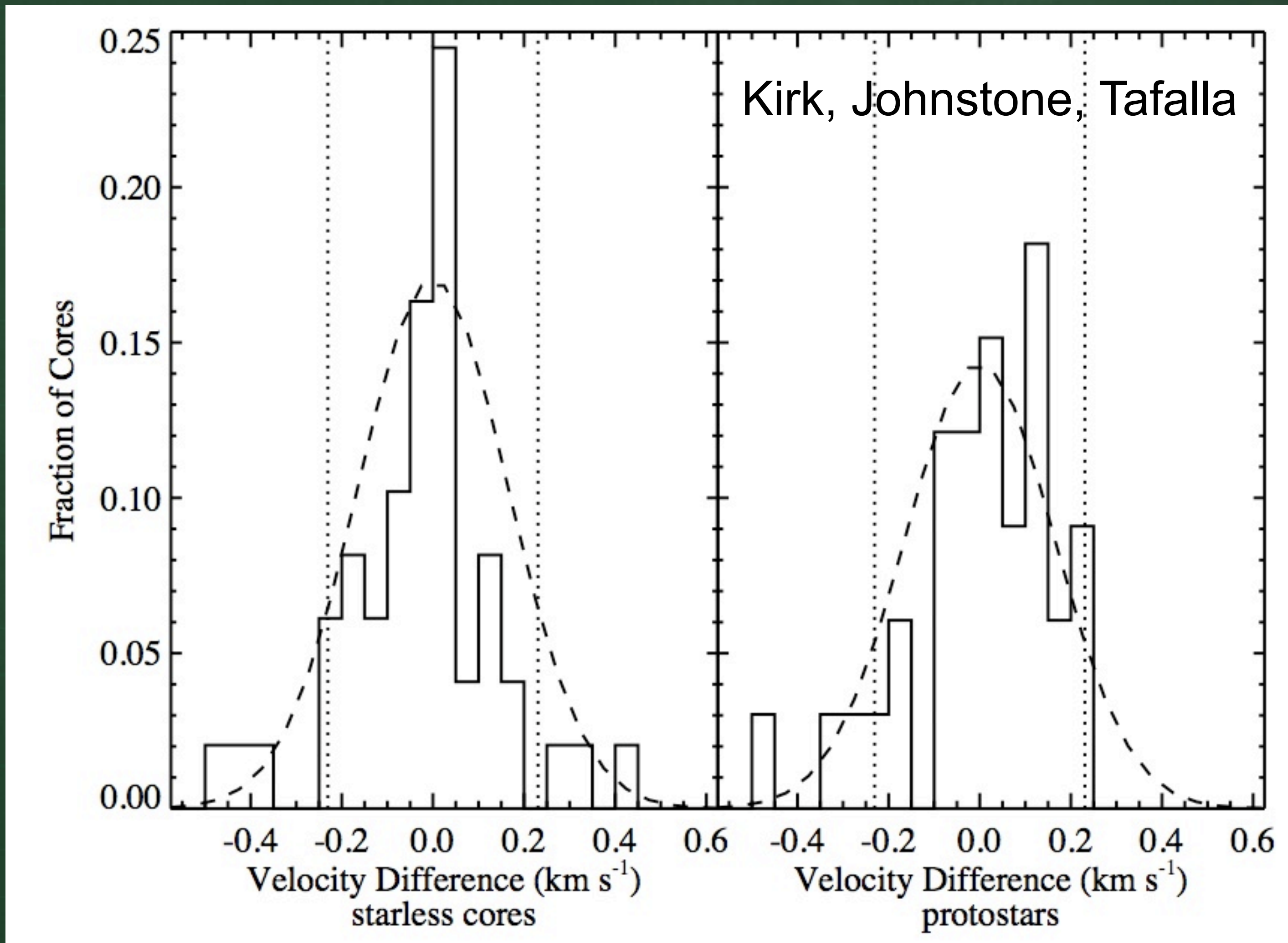
# How are Cores and Cloud Related?

- Compare the kinematical properties
  - Cloud - use CO isotopologues as tracer
  - Core - use $N_2H^+$ (or $NH_3$) as tracer
- 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
- Core to cloud motions
  - Much tighter relation than expected
    - Core formation is not dynamic?

# Observational technique:



# $C^{18}0$ and $N_2H^+$ have quite similar line centroids!!



# 5) Consider the Pre-Stellar Core One Last Time


$$R_J \propto \left(\frac{T}{\rho}\right)^{1/2}$$

$$M_J \propto \left(\frac{T^3}{\rho}\right)^{1/2}$$

Do all dense gas tracers tell the same story?

# How reliable are the dense gas tracers?

(Johnstone, Rosolowsky, Tafalla, Kirk 2010)

- Compare three traditional dense gas tracers across 74 dense cores in Perseus
  - Dust ($H_2$), $N_2H^+$, and $NH_3$
- Compare the kinematical properties
  - $N_2H^+$ and $NH_3$
- Compare column density properties
  - $N_2H^+$ versus $NH_3$ (Nitrogen chemistry)
  - $N_2H^+$ and $NH_3$ versus $H_2$ (abundance)

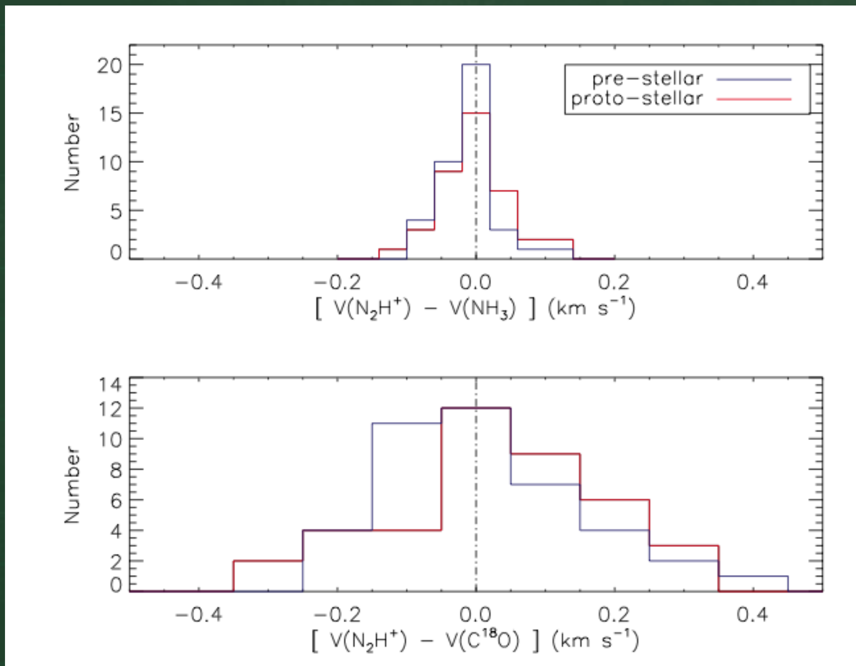
$NH_3$ is an excellent temperature probe

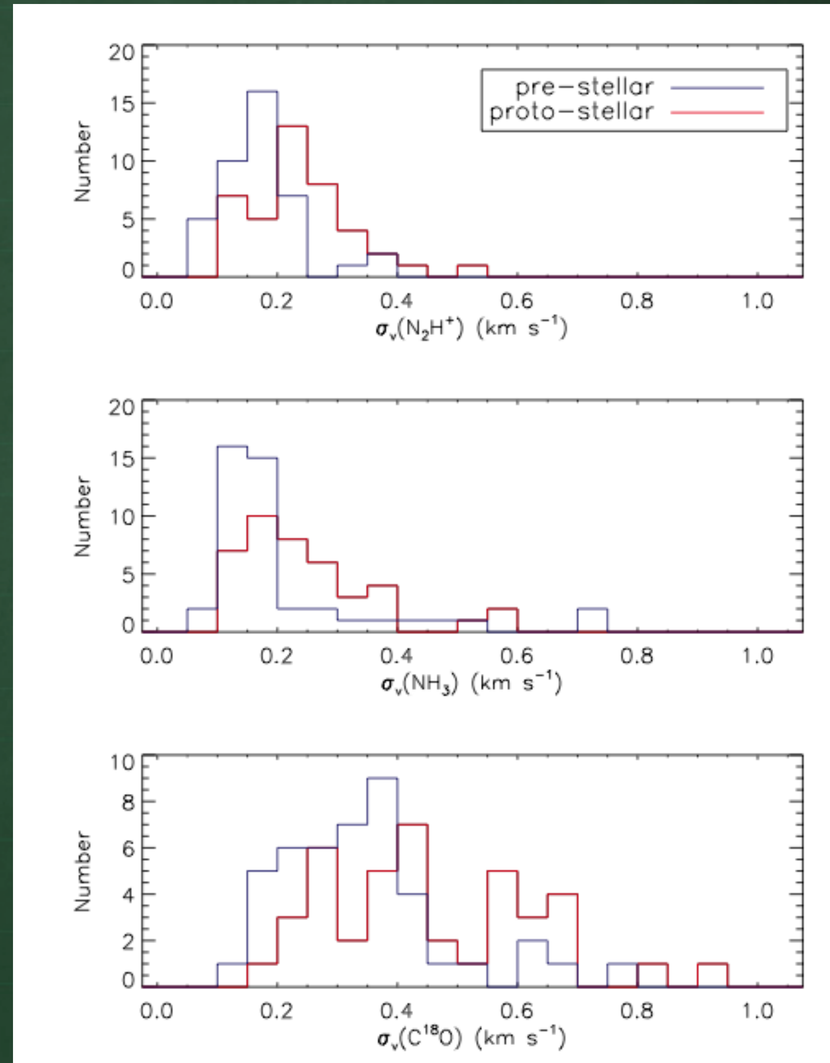
- $T_K \sim 11$ K for all Perseus cores (Rosolowsky et al. 2009)

# How reliable are the dense gas tracers?

## Kinematics:

(37 protostellar cores) (37 prestellar cores)




$N_2H^+$ and $NH_3$ have identical kinematic Signatures, unlike $C^{18}O$ [despite $NH_3$(1,1) and $C^{18}O$ 2-1 having similar critical density].

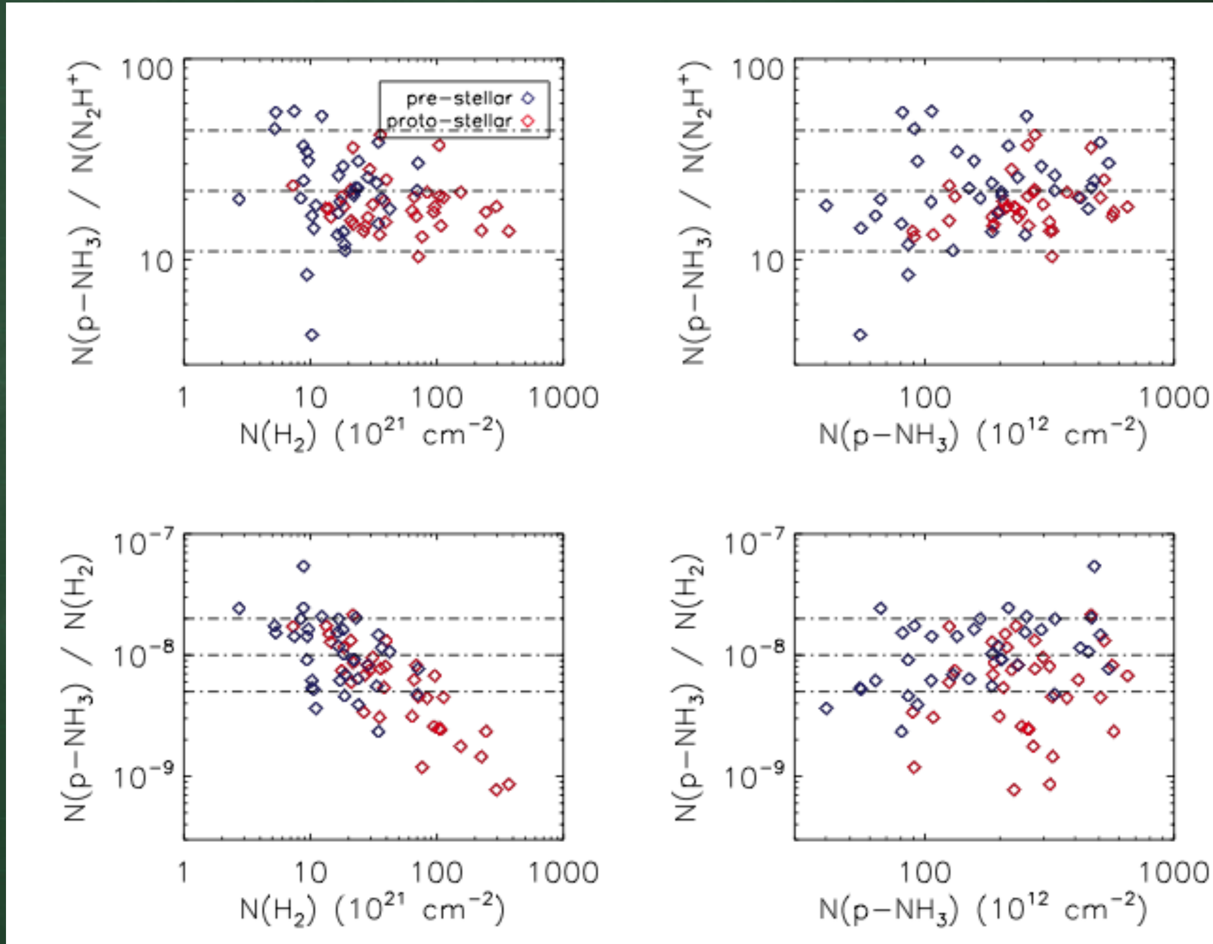
# How reliable are the dense gas tracers?

## Abundances: (37 protostellar cores) (37 prestellar cores)

$N_2H^+$ and p-$NH_3$ show a constant abundance ratio of ~ 20, for both prestellar and protostellar cores.

The abundance of the nitrogen-bearing species compared with $H_2$ appears to be lower within the highest column density protostellar cores.

Chemical evolution as a physical diagnostic? Clock?






1 2 3

# Summary and Discussion Points:

1. Observed Pre-Stellar Cores appear smooth and devoid of significant sub-structure
   - Does this imply a quiescent phase between assembly and collapse?
   - When does binary formation take place?
2. Pre-Stellar Cores physical properties should be determined by their environment
   - Can we use this information to infer molecular cloud conditions?
   - Should this not also work for the filaments seen by Herschel
3. Are there really lots of Pre-Stellar Cores with mass greater than Jeans?
   - All 'observed' objects should be studied very carefully (e.g. infall!) – interesting physics
   - How do 'massive pre-stellar cores' connect with our low-mass environment notions?
4. Pre-Stellar Cores and the Clump kinematics are well coupled
   - Is this a useful constraint for the theories of core formation?
5. Dense Gas Tracers are not all alike …
   - $NH_3$ and $N_2H^+$ show very similar kinematics and abundance ratios – chemistry?
   - The molecules and the dust on the other hand can differ greatly – who's right?

# Environmental 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

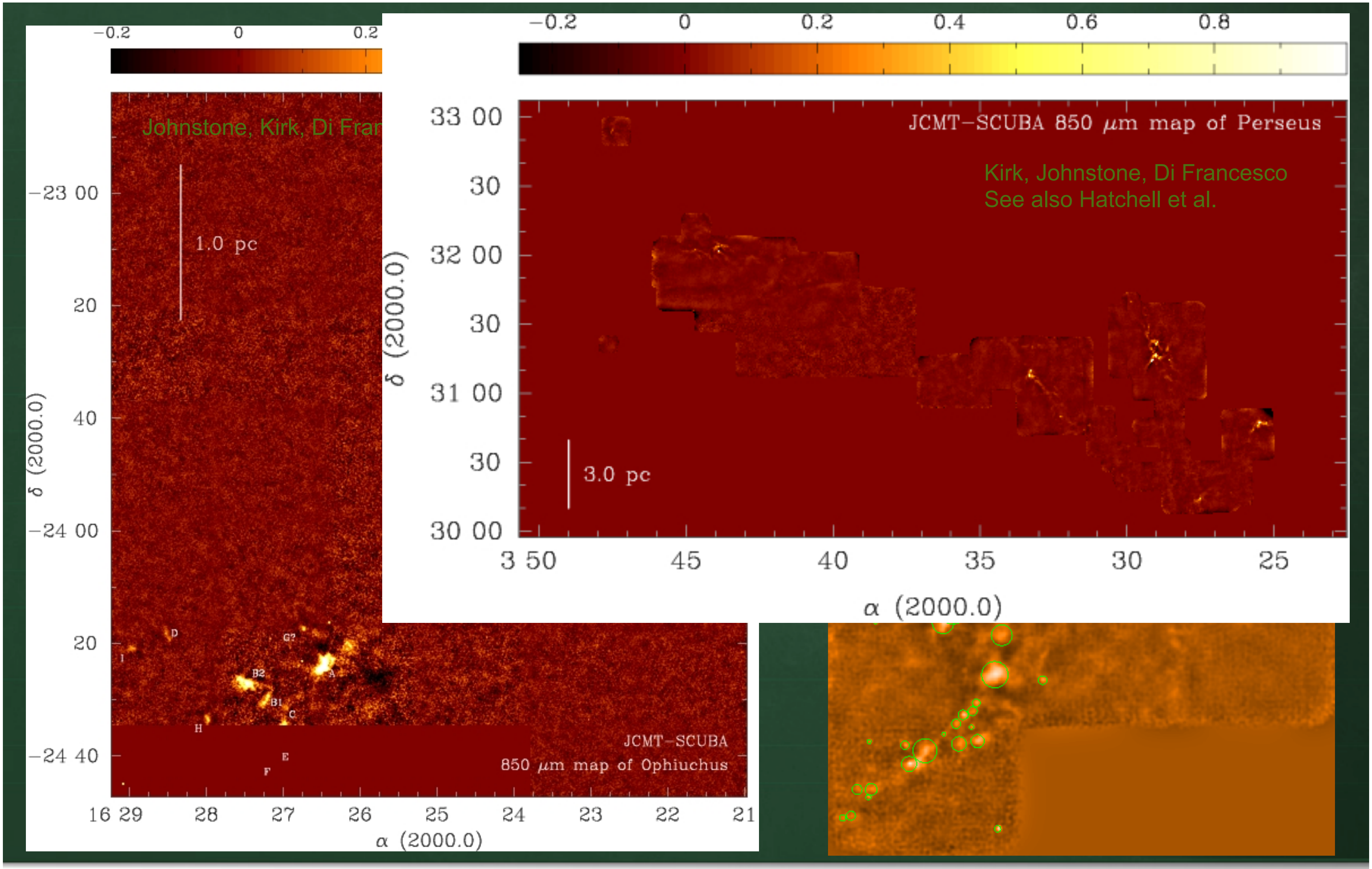
Kinematic Information - CO, $N_2H^+$ line widths, velocity centroids

Chemical Differentiation - CO, $N_2H^+$,$NH_3$, $H_2$ abundance

Polarization Angle - Magnetic Field Orientation

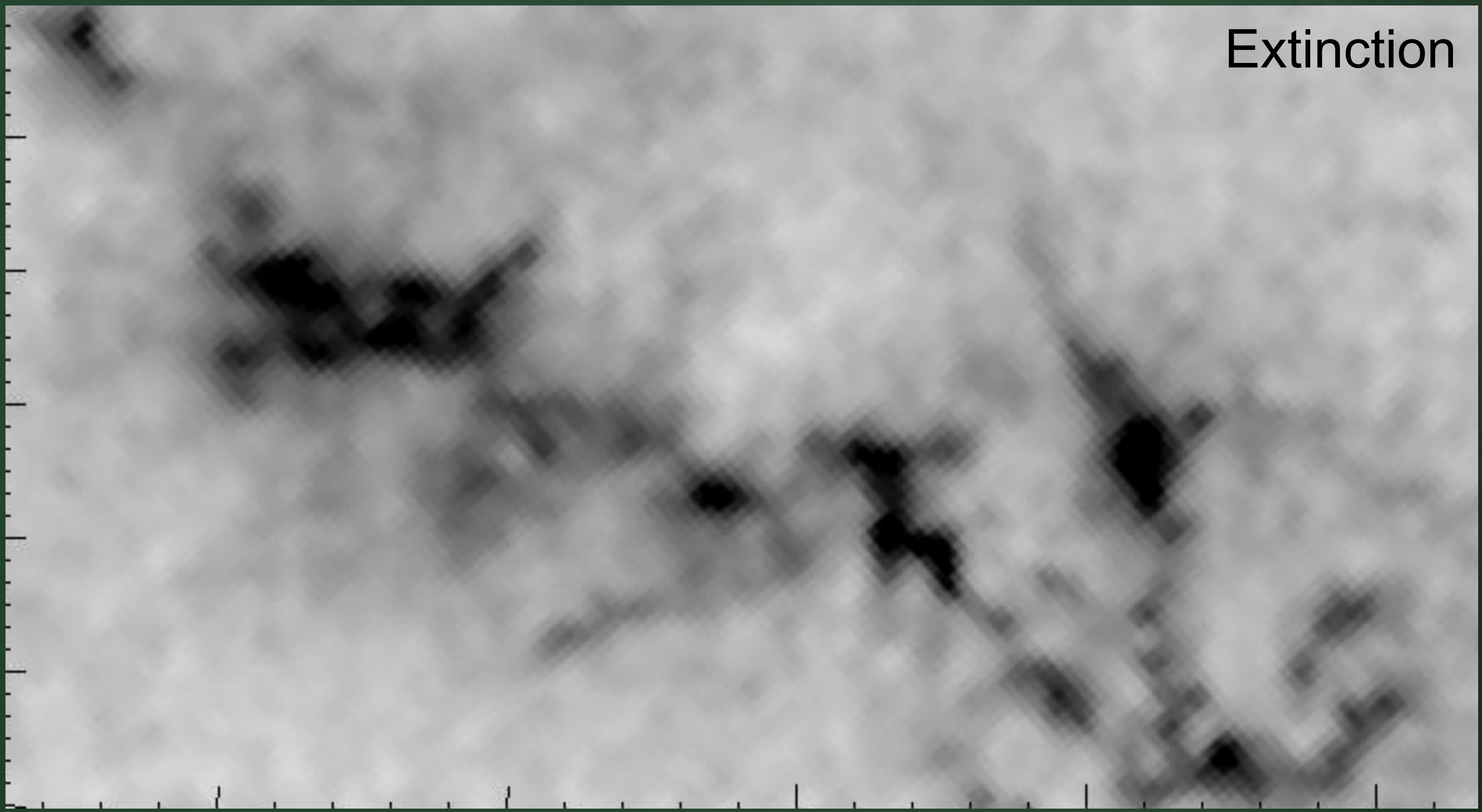
**Context for understanding low-mass core observations.**

**And, all reasonable theories must reproduce each of these conditions!**

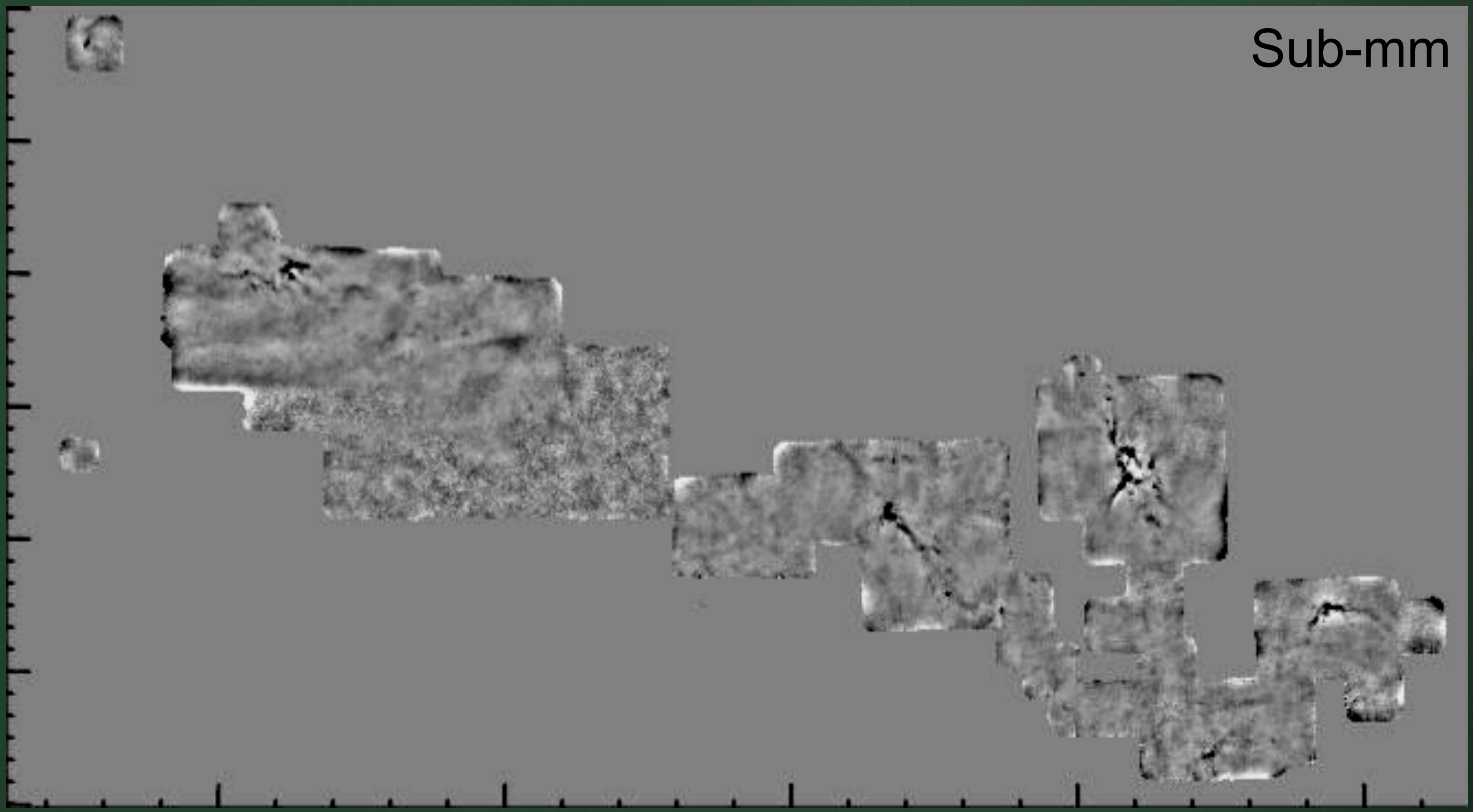



Johnstone et al.

# Extinction threshold



# Extinction threshold



## Ophiuchus

| $A_V$ Range | Cloud Area (%) | Cloud Mass ($M_\odot$) | Cloud Mass (%) | Core Mass ($M_\odot$) | Core 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] % | Core Mass $M_\odot$ | Core 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 Core Observations?*

Cores represent ~2% mass of cloud

Cores represent ~20% mass of clump

Cores live primarily at high (>10) Av

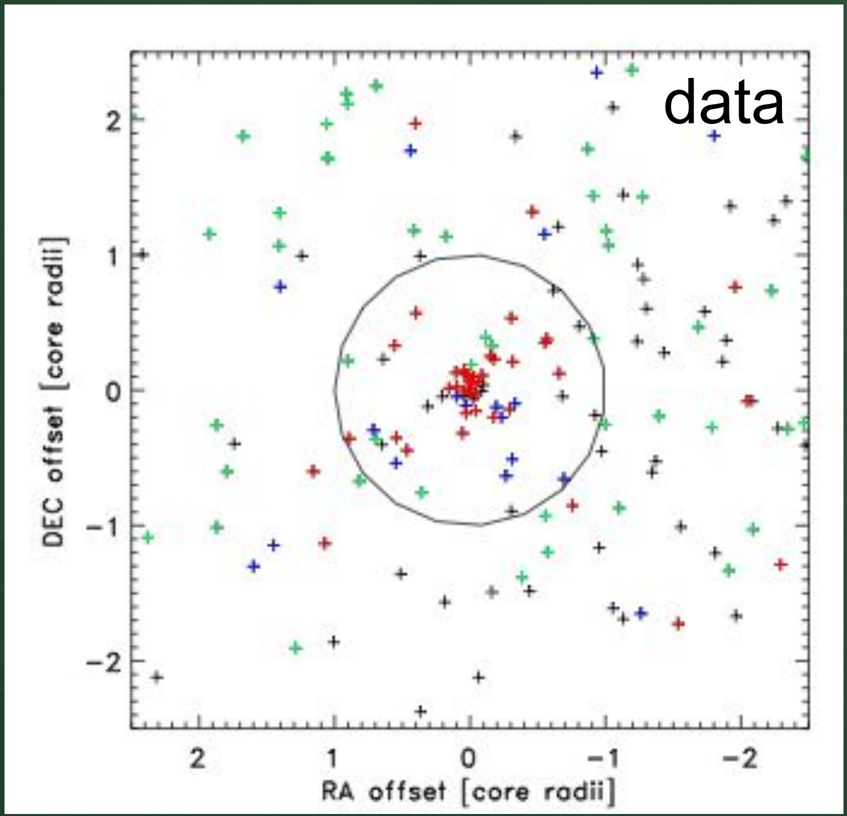
Cores have stellar IMF-like mass f'n

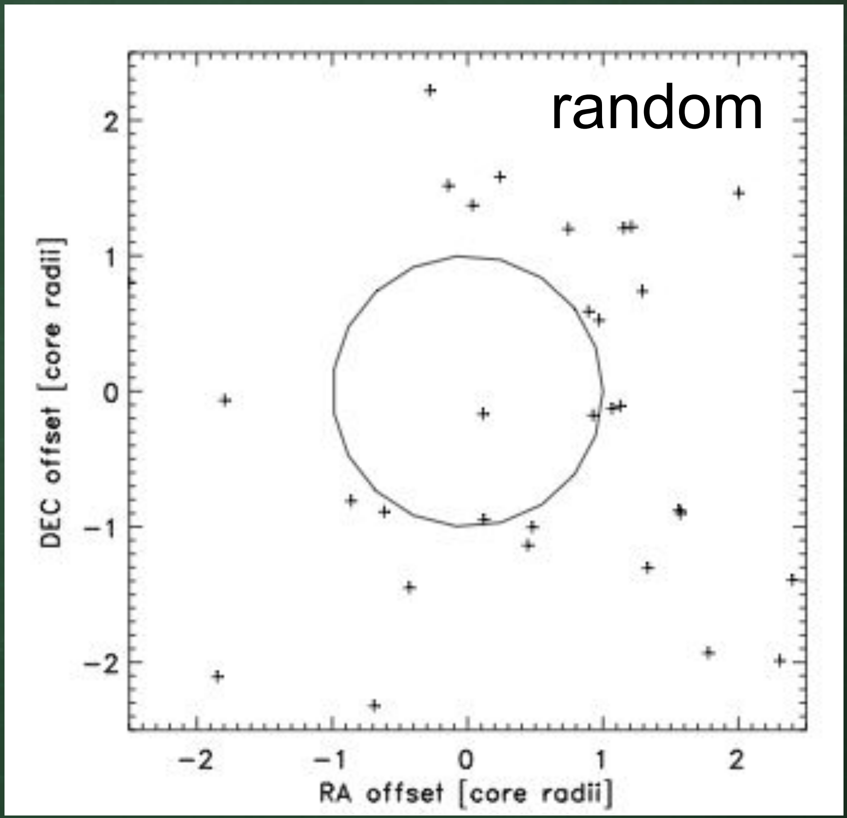
**Embedded stellar clusters have these same properties!**

**(Lada and Lada 2003)**

# Coincidence of 24 Micron source and Submm peak.

Jorgensen, Johnstone, Kirk, Myers 2007

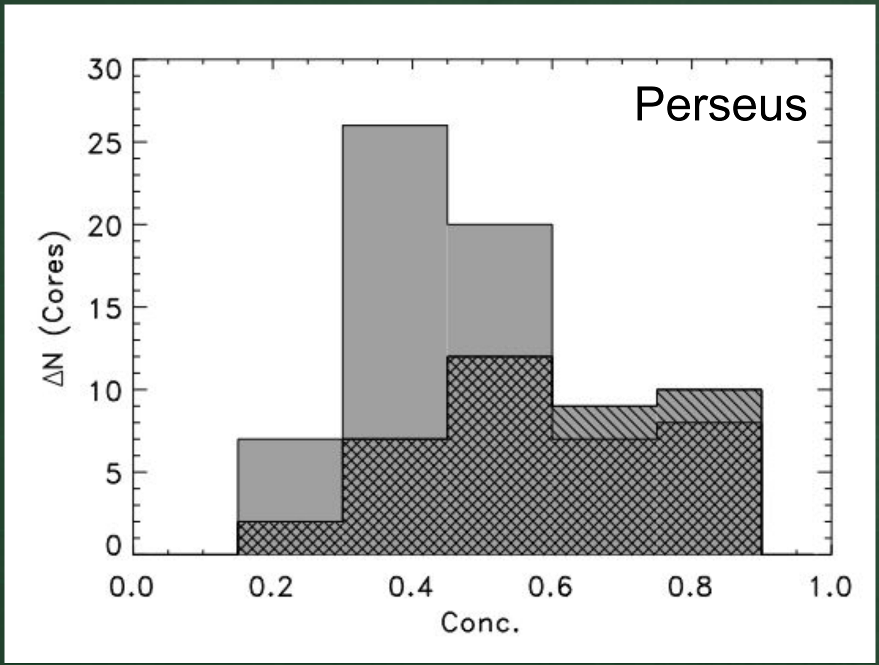


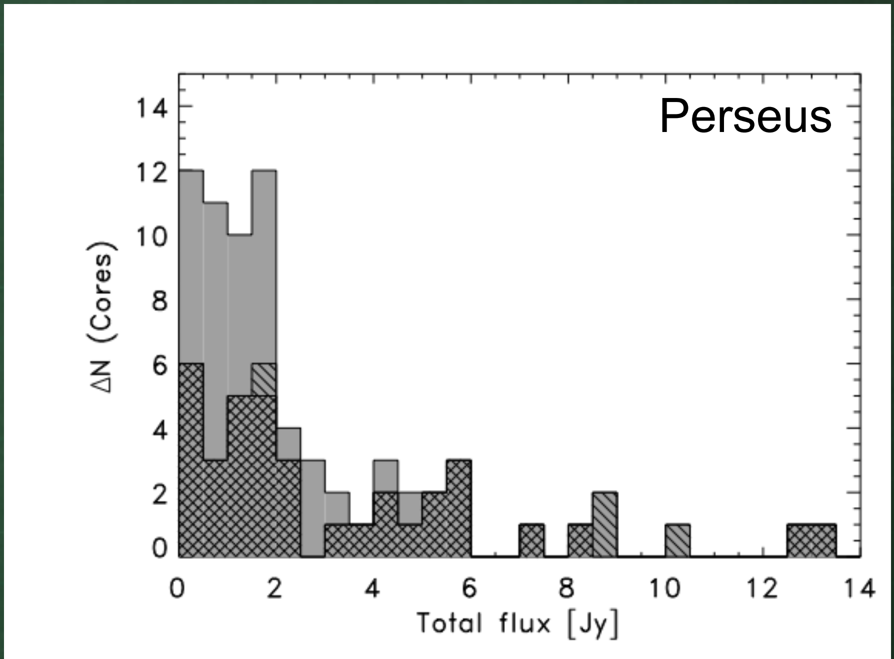




Protostars clustered around *and* within dense cores.

# Correlation between protostars and core properties.

Jorgensen, Johnstone, Kirk, Myers

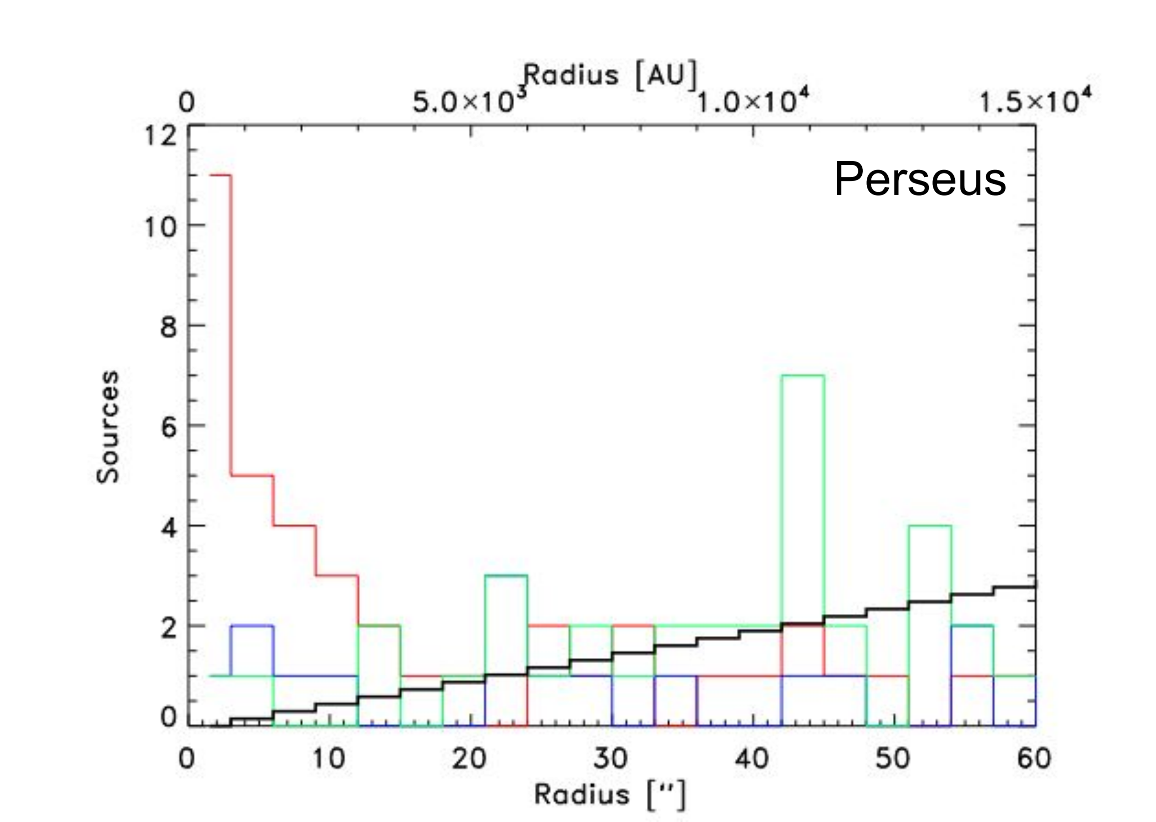



Brightest/most peaked sources contain protostars.
Does this negate the IMF-like core mass distribution?

# Protostars in cores live near the core center.

Jorgensen, Johnstone, Kirk, Myers



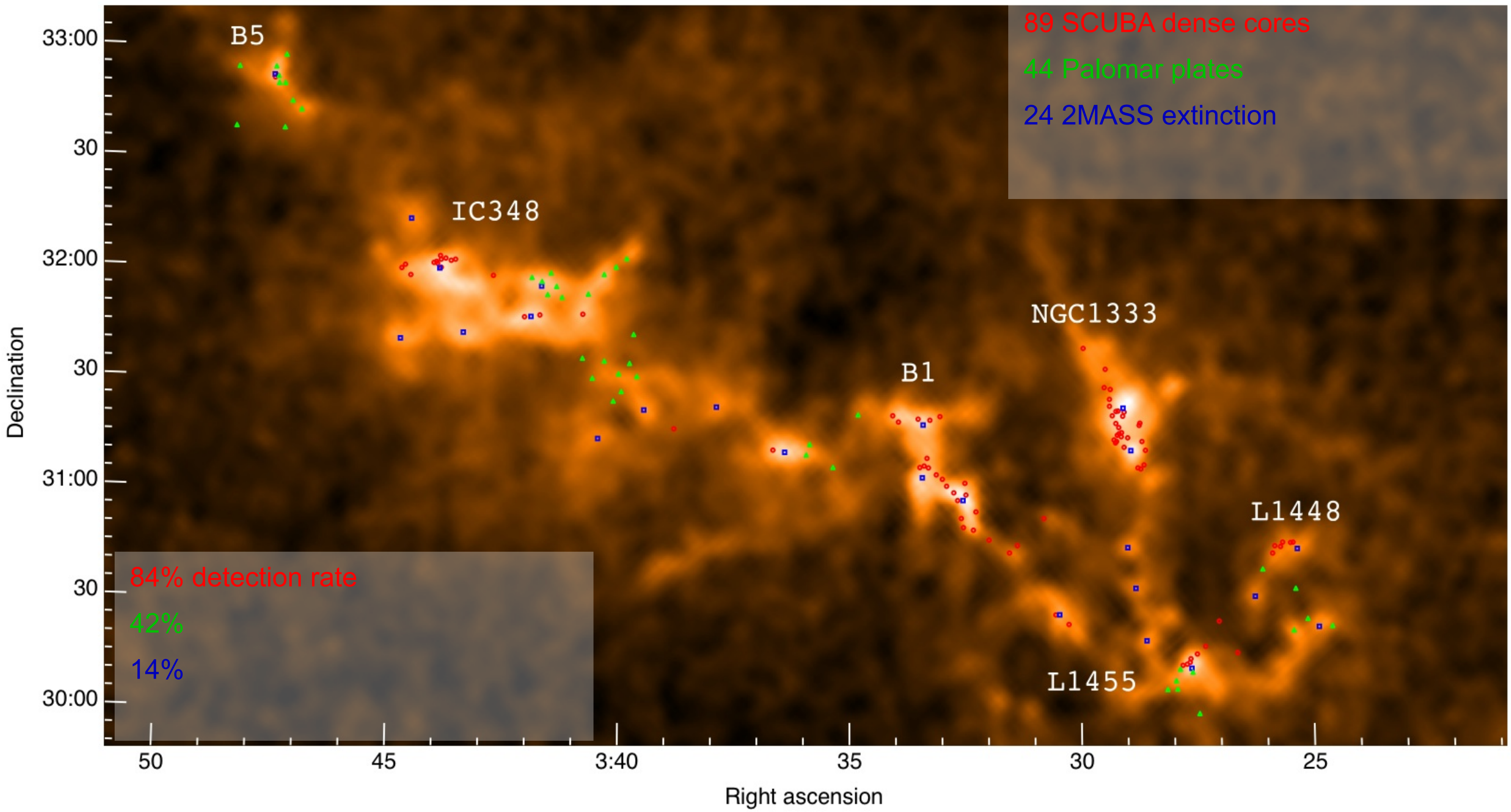

R < 10 arcseconds!
R < 2000 AU

For 0.1 km/s
$\tau = 10^5$ yrs
~lifetime of embedded protostar

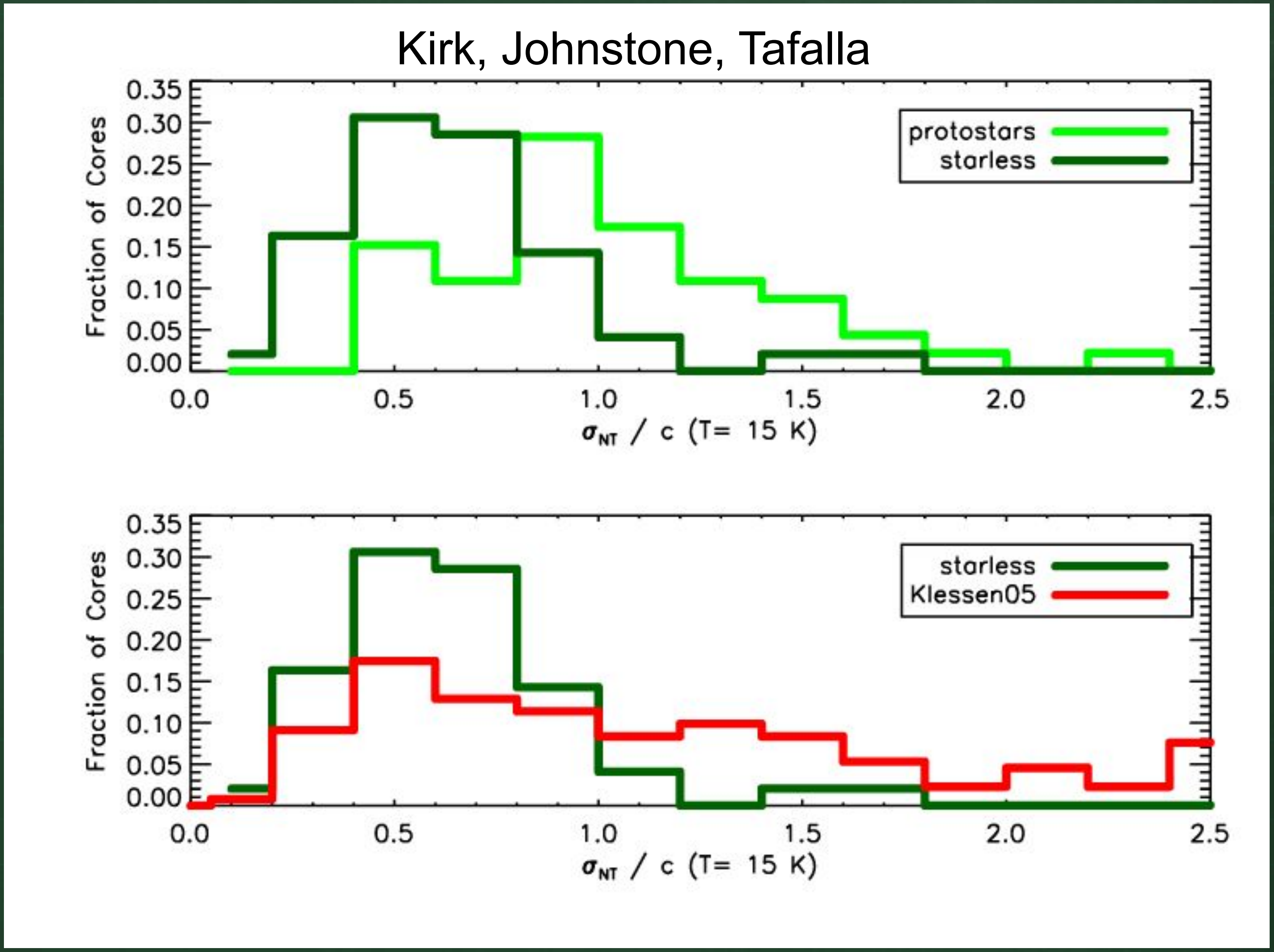
Protostars do not appear to be moving with respect to the core.

# IRAM Observations (Kirk, Johnstone, Tafalla 2007)

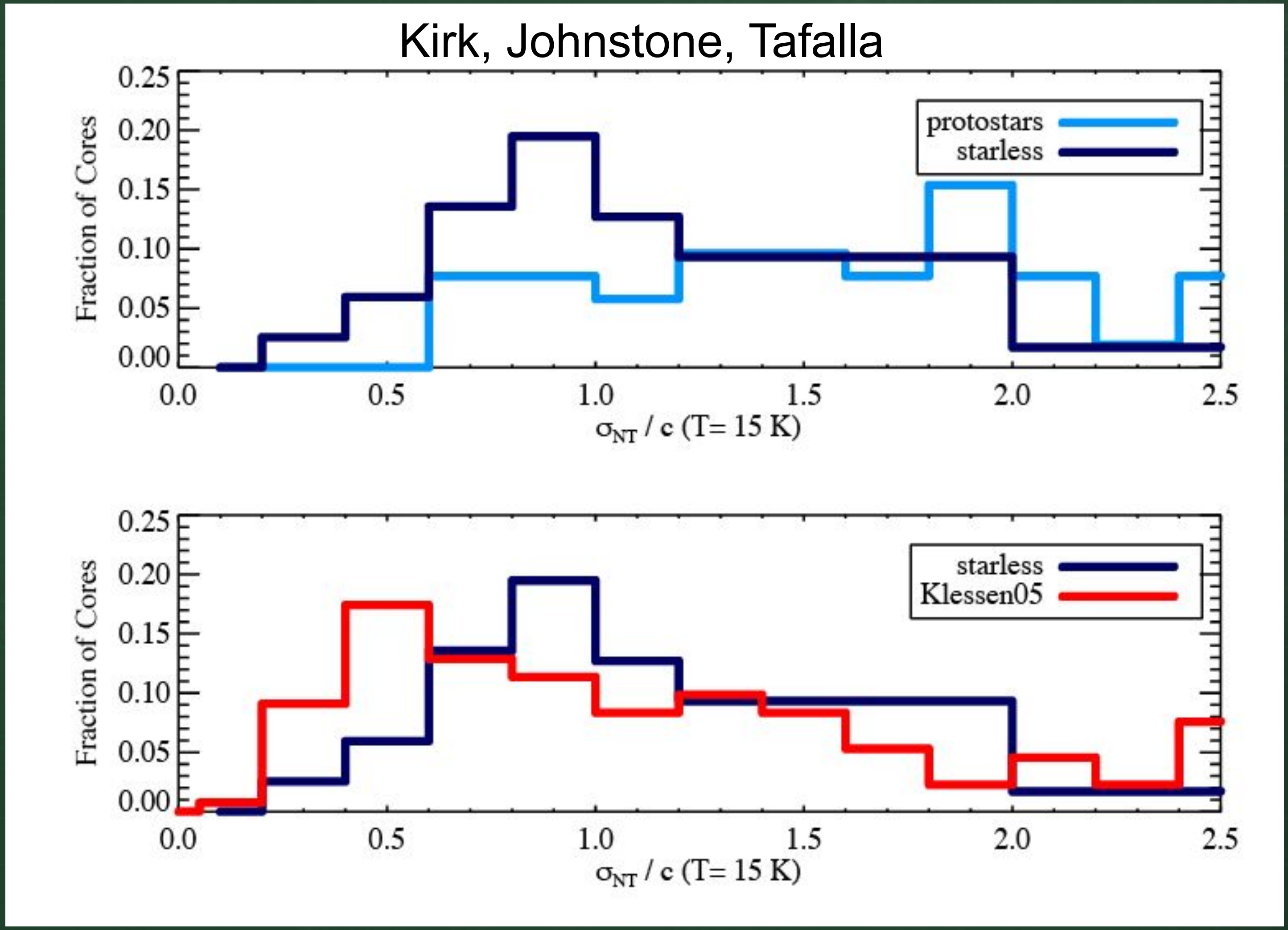
- $N_2H^+$ and $C^{18}O$
- 15 arcsecond resolution (~3000 AU)
- $N_2H^+$ a proxy for dense gas



# $N_2H^+$ linewidths of cores dominated by thermal motion!

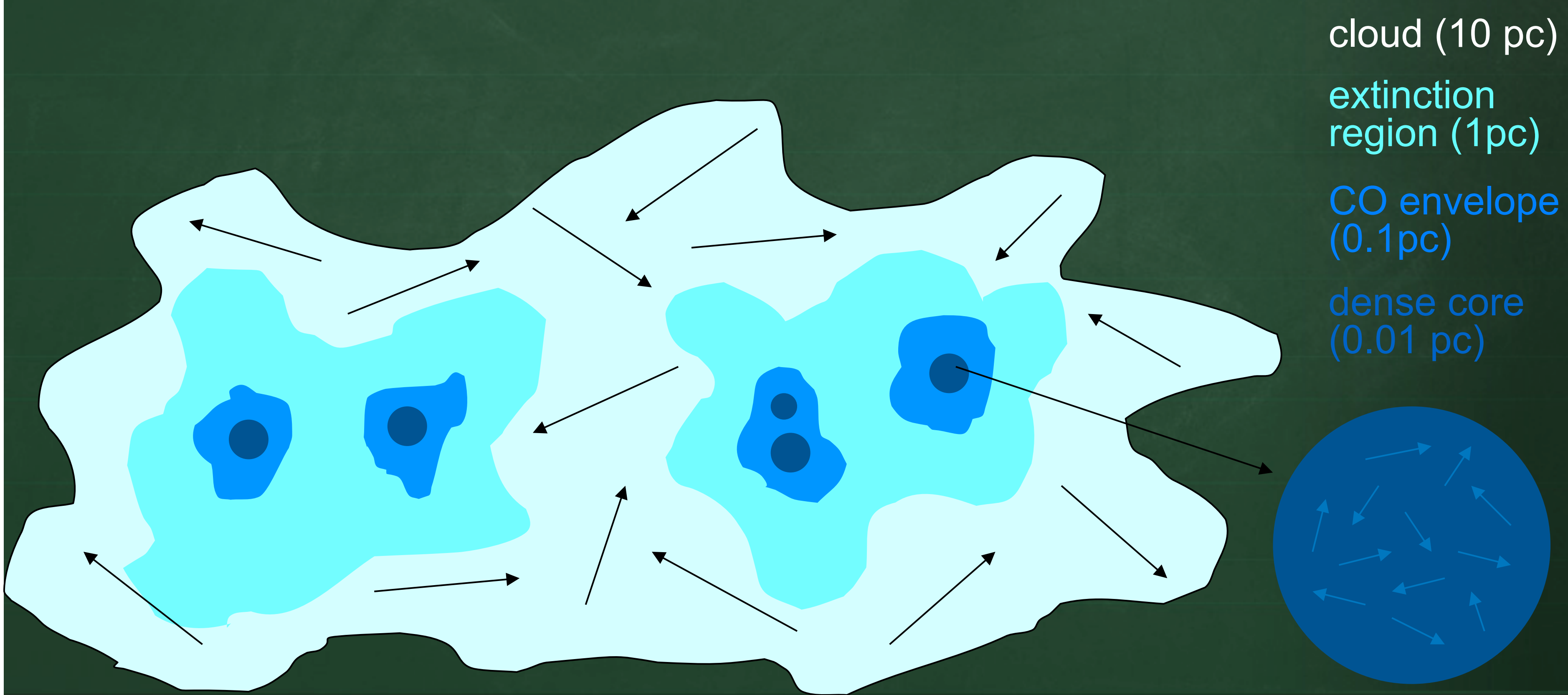


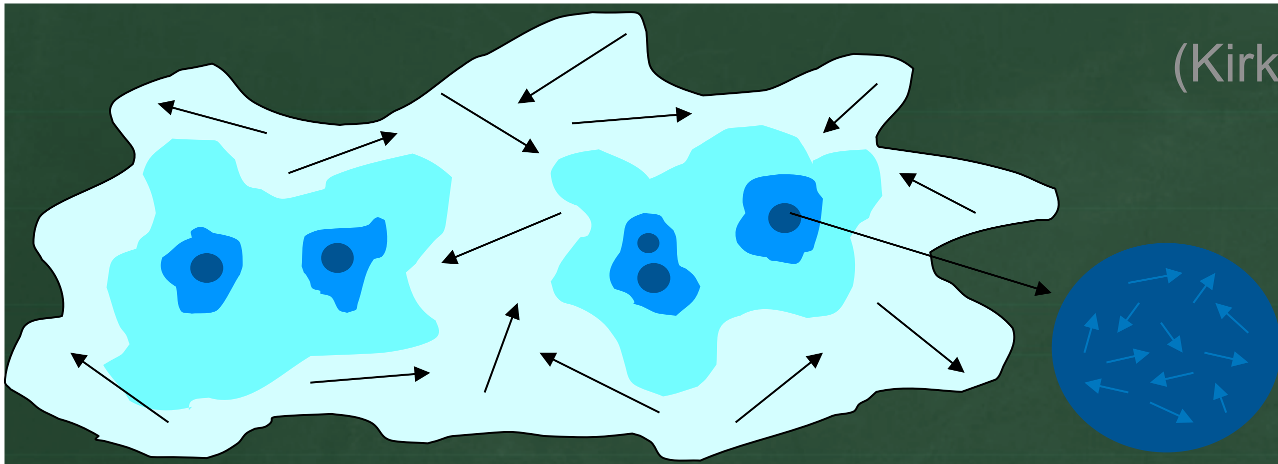
# $C^{18}0$ linewidths towards cores are non-thermal.



# Cores and Their Environments (Kirk, Johnstone, Basu 2009)

- On large scales, clouds exhibit supersonic turbulent motions
- On the smallest scales, dense cores have mostly thermal motions
- Time to compare the observations with simulations!



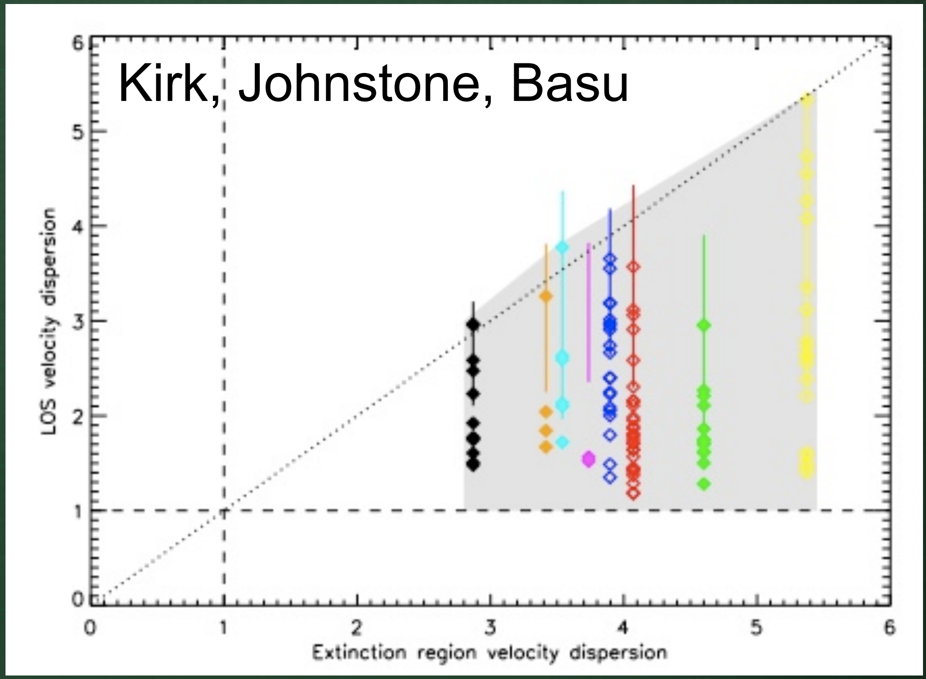


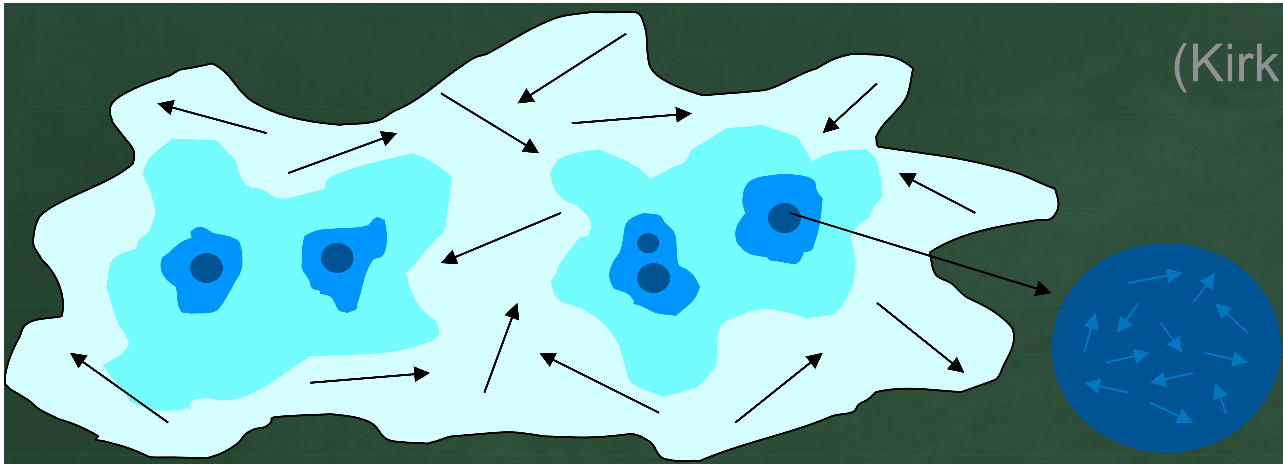
(Kirk, Johnstone, Basu 2009)

LOS Velocity dispersion.

Comparison between the region's total velocity dispersion and individual lines of sight.

Large linewidths observed in clouds not simply bulk motion.



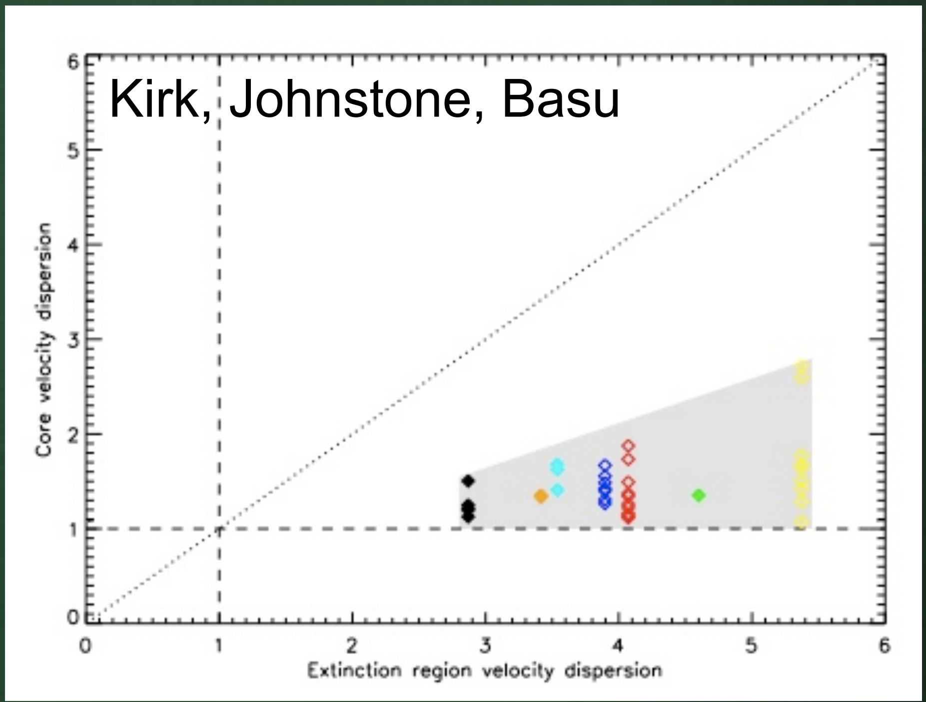


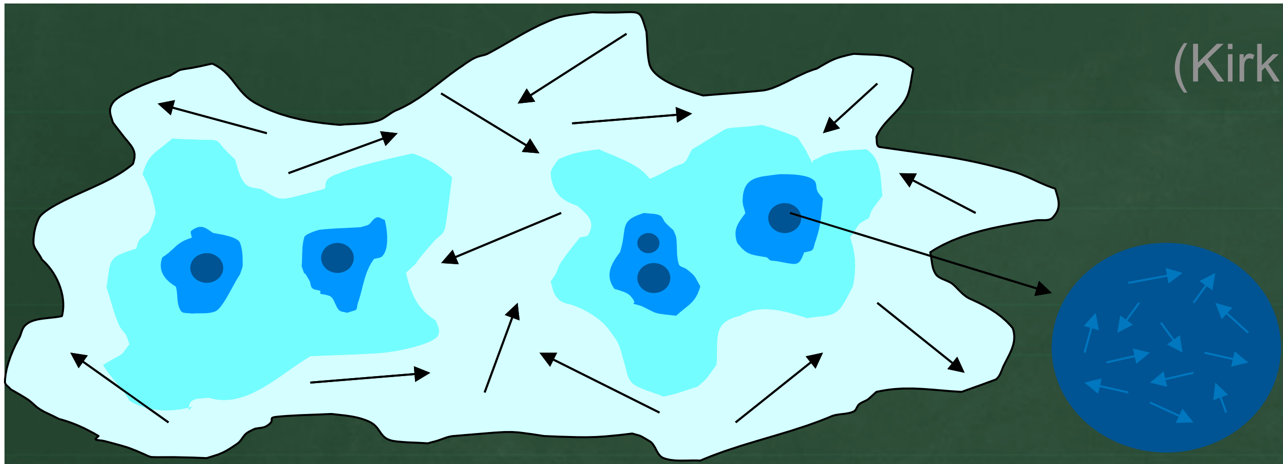
(Kirk, Johnstone, Basu 2009)

# Core Velocity Dispersion.

The velocity dispersion within individual cores.

Almost all simulations show this behaviour. Dense cores form where gas has lost its non-thermal support (if not, they'd be extremely over-pressured).



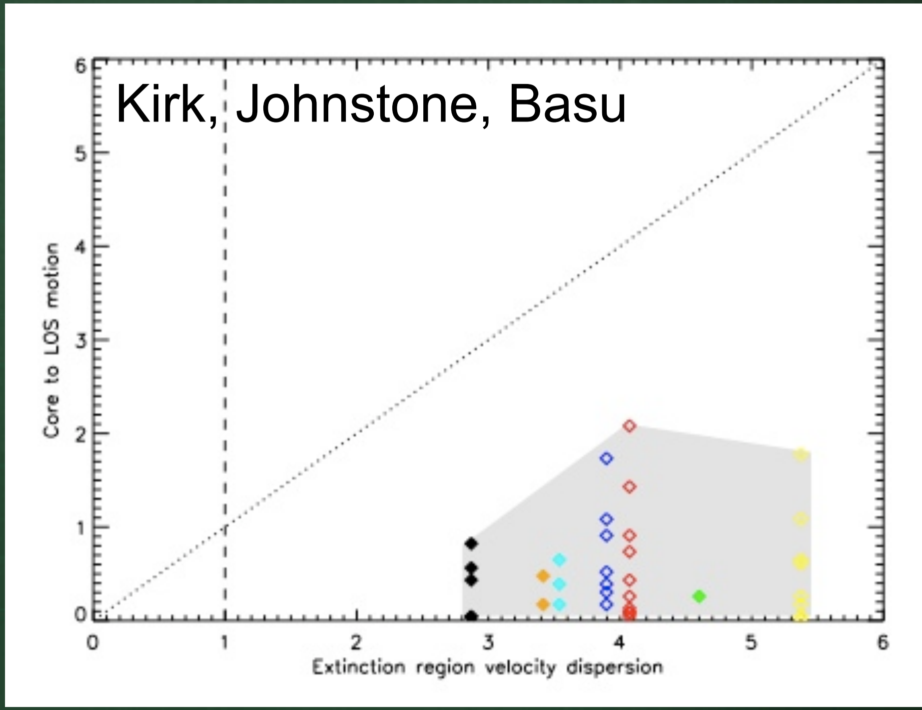


(Kirk, Johnstone, Basu 2009)

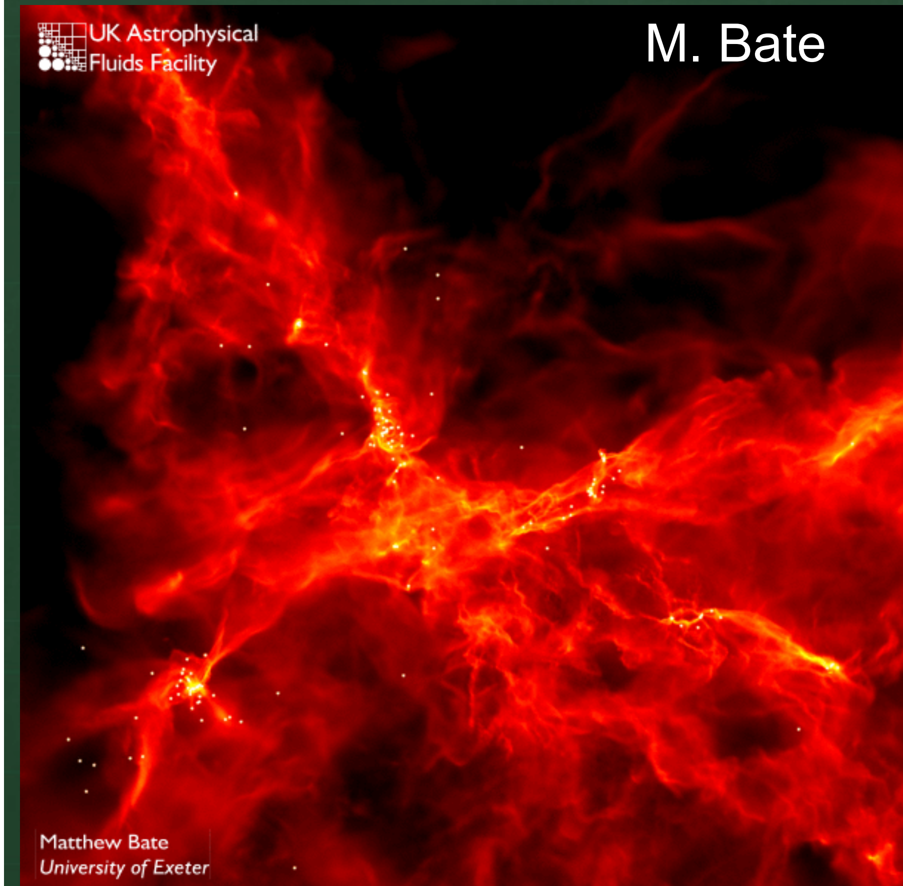
Core Versus LOS motion.

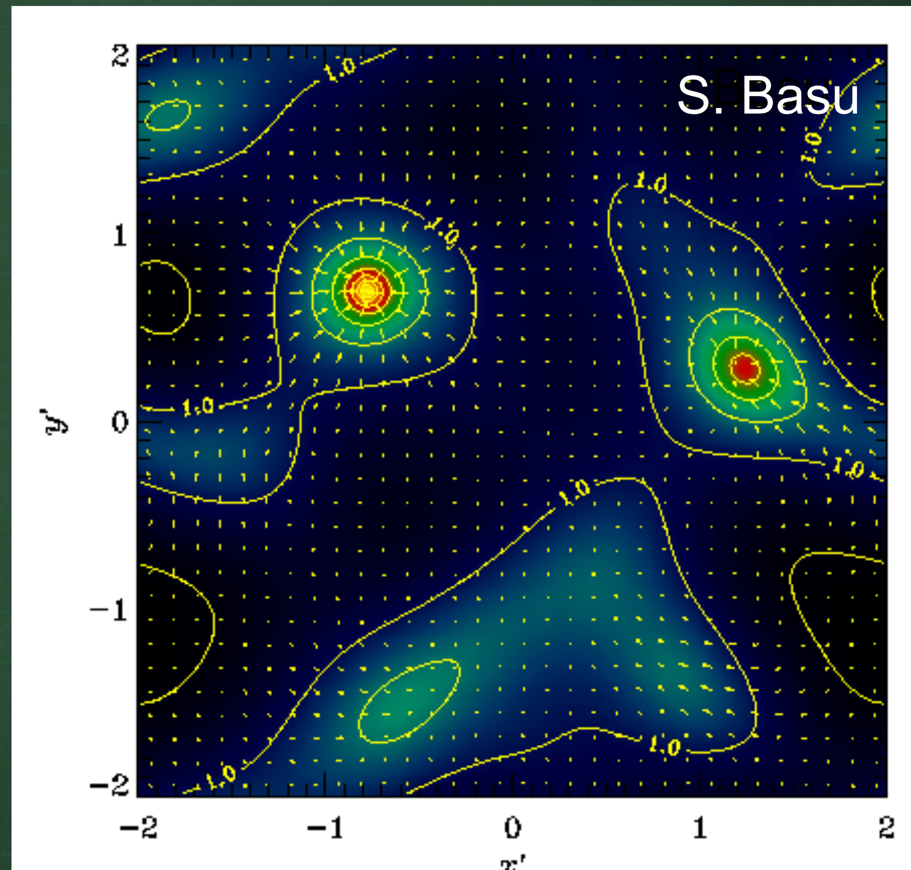
Comparison between the velocity centroid of the core and the bulk gas along the line of sight.

Present simulations have real trouble with this diagnostic!



# Two theorist's ideas about core environments.

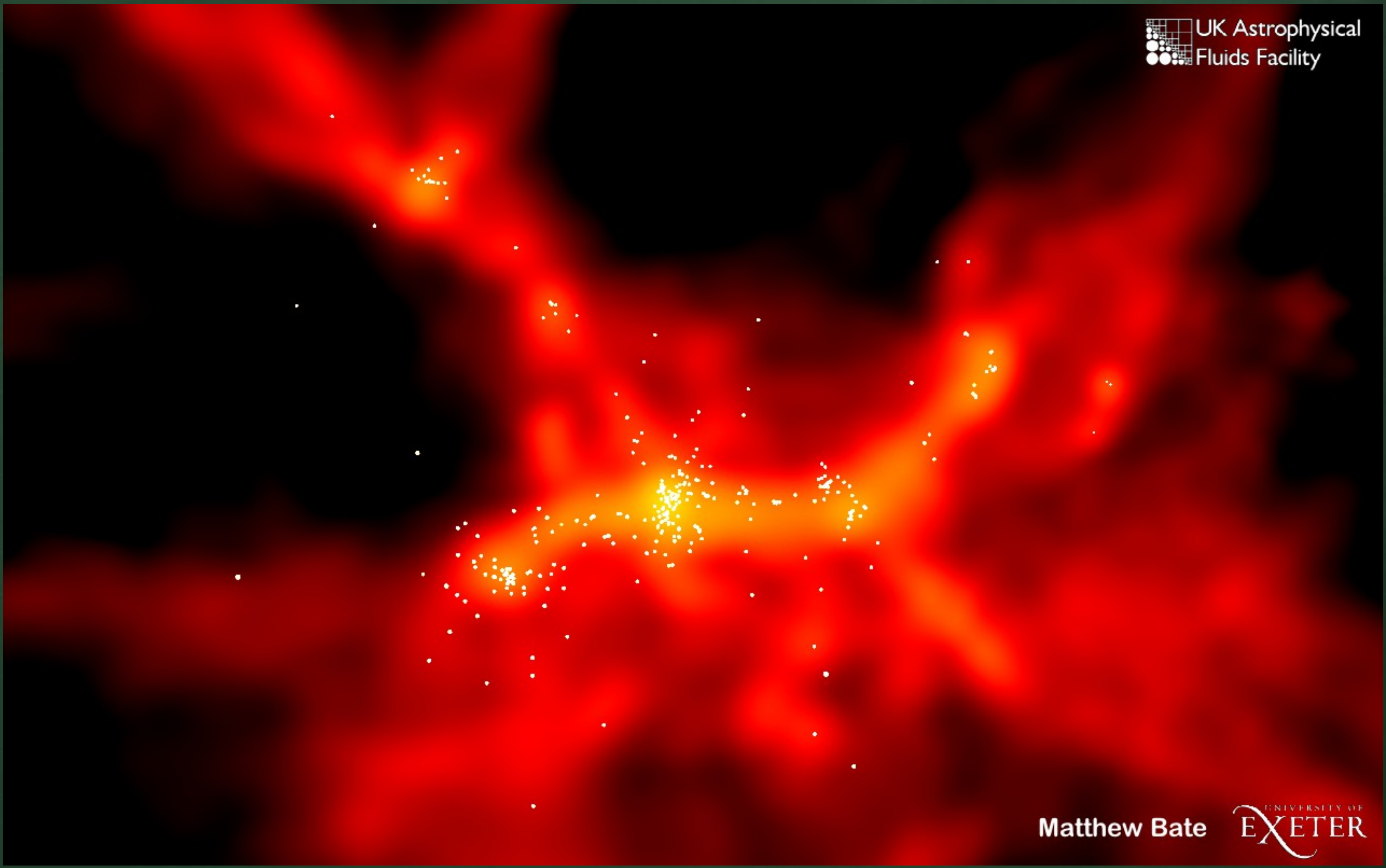



Gravo-Turb (dynamic)

Magnetic Fields (slow)

# Structure :The Need for Resolution!



# Structure :The Need for Resolution!

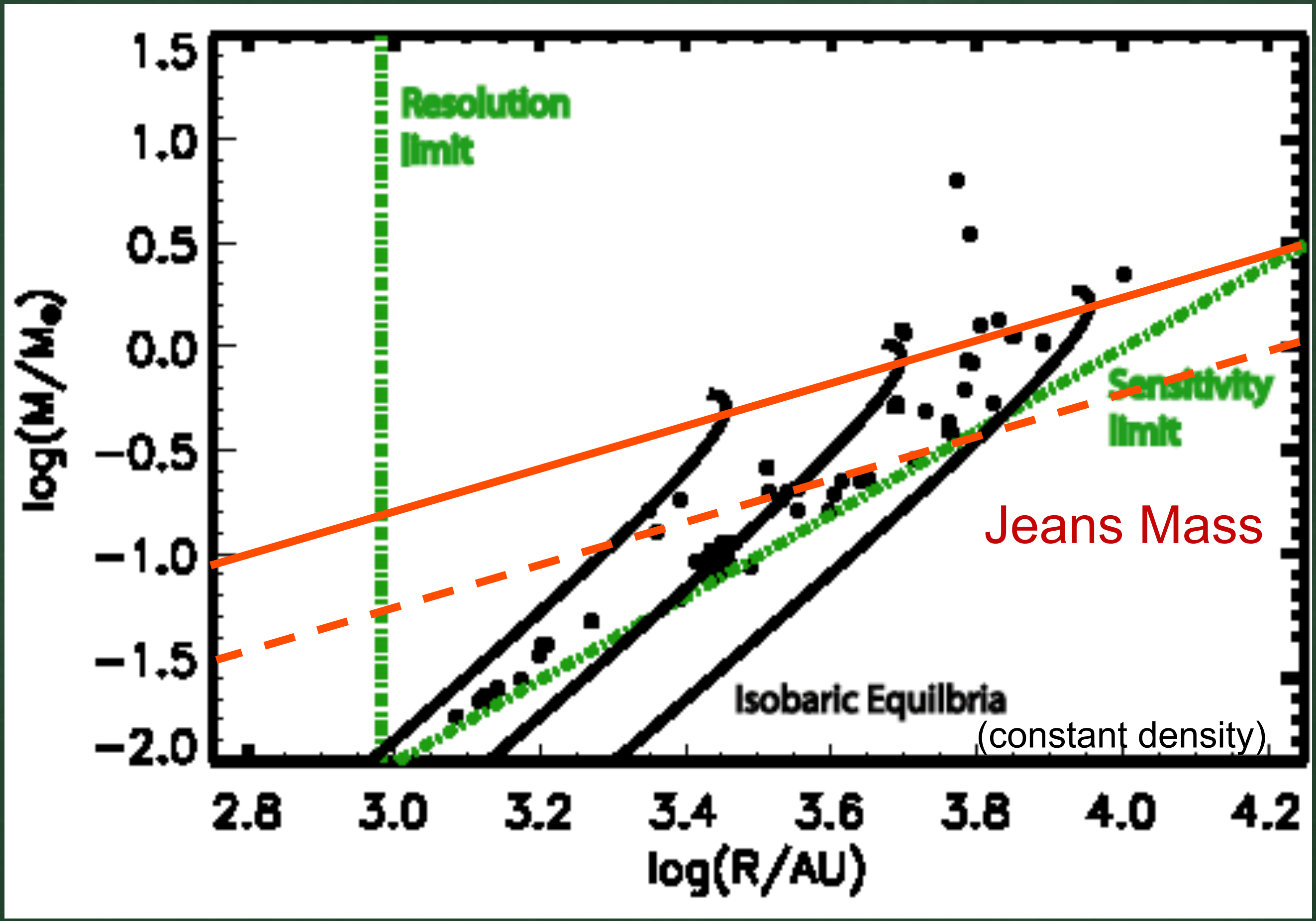

# NRC - HIA (Canada)

## Band 3 Receiver (3 mm)

Specifications:

- 84-116 GHz
  - CO (1-0), $N_2H^+$
- 8 GHz bandwidth
- T < 17 K
- always on!
- Primary bm ~ 60”

# An Observational Example … (Herschel should do better!)




Ophiuchus, observed with SCUBA at the JCMT (Johnstone et al.)