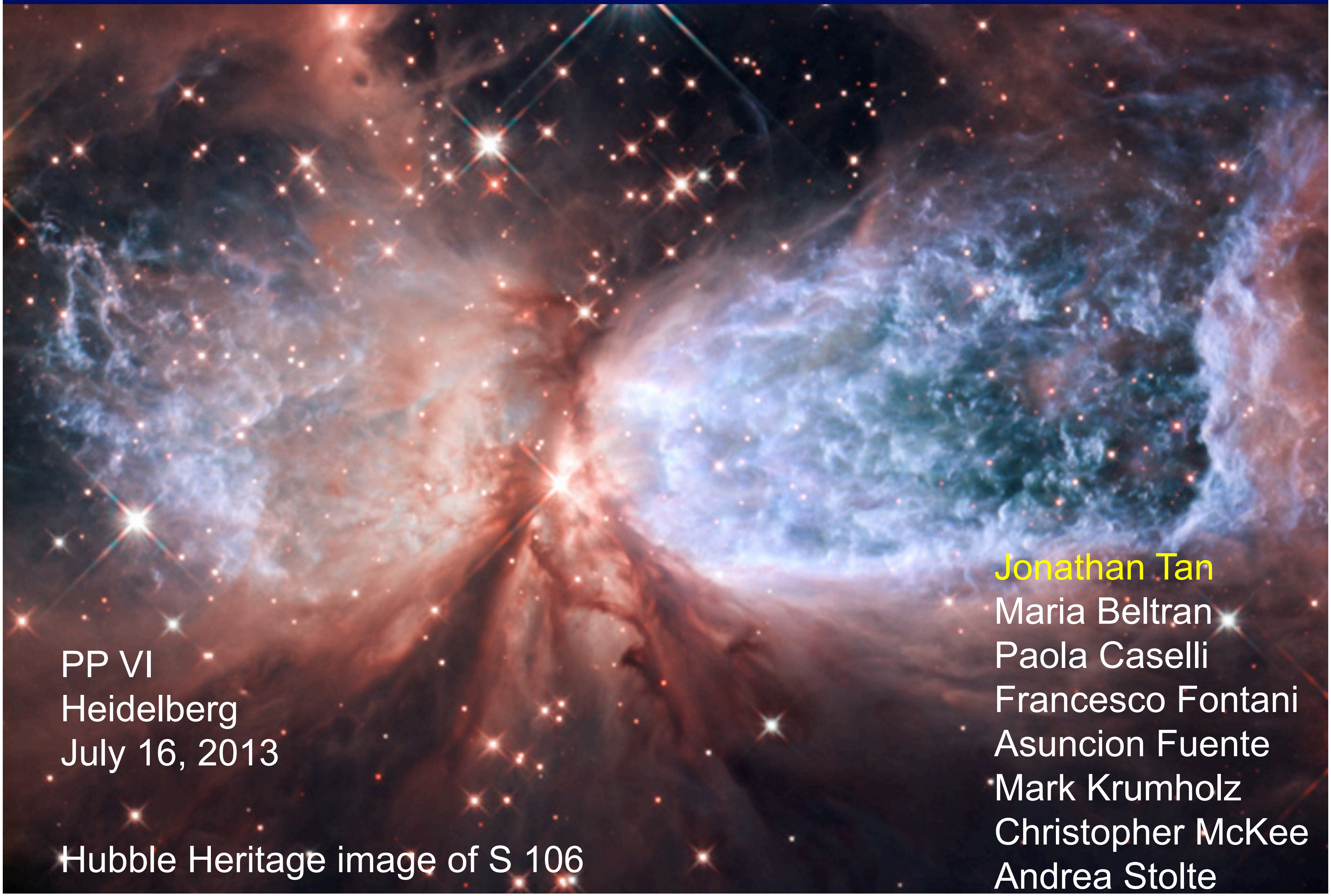
# MASSIVE STAR FORMATION



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PP VI
Heidelberg
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Hubble Heritage image of S 106

# MASSIVE STARS:

•Create most of the heavy elements

•Energize the interstellar medium (ISM)

–UV emission heats via photoelectric effect (~$10^2$ K)

–Ionizing luminosity creates ionized gas (~$10^4$ K)

–Stellar winds and supernovae create hot gas (~$10^6$ K)

•Regulate star formation

•Govern the evolution of galaxies

-Radiation pressure drives outflows

•May have re-ionized the universe

# OUTLINE

## Observation

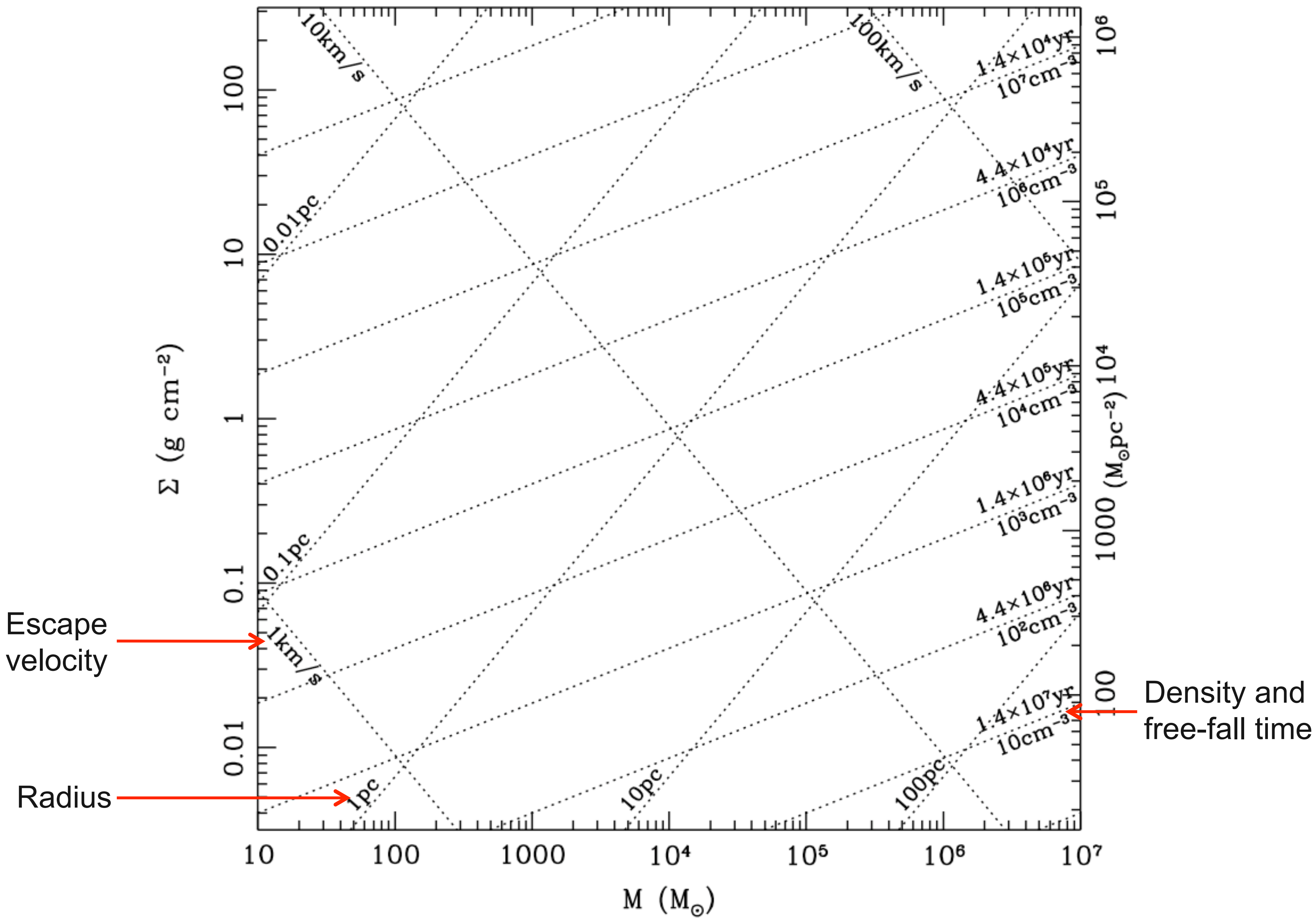
- The environments of massive star formation
- Turbulent motions
- Chemical identification of high-mass starless cores
- Protostellar accretion
- Circumstellar disks, jets and magnetic fields

## Theory

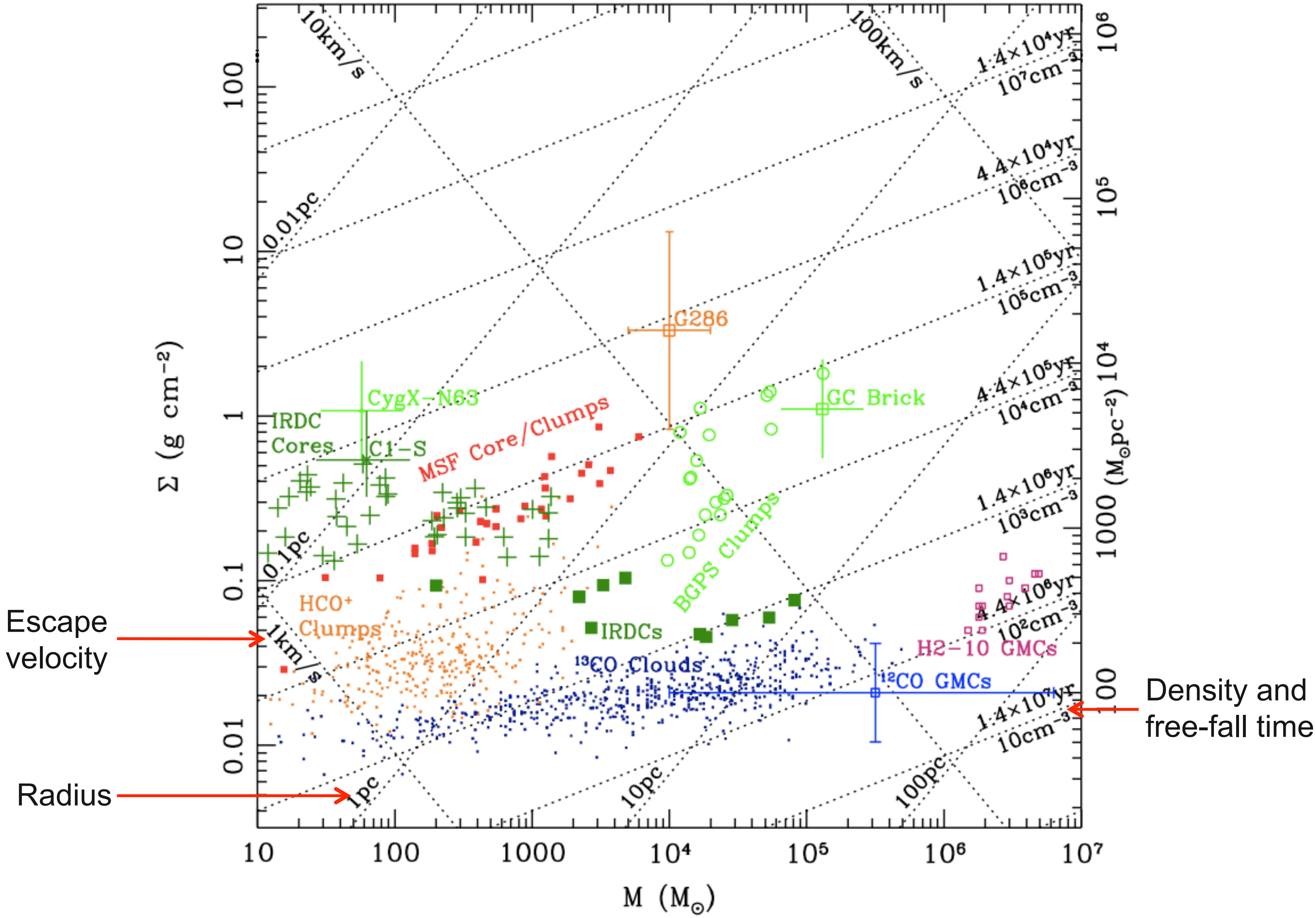
- High-mass vs. low-mass star formation
- Theories: Core accretion, competitive accretion, stellar collisions
- Suppressing fragmentation
- Overcoming radiation pressure

## The Future

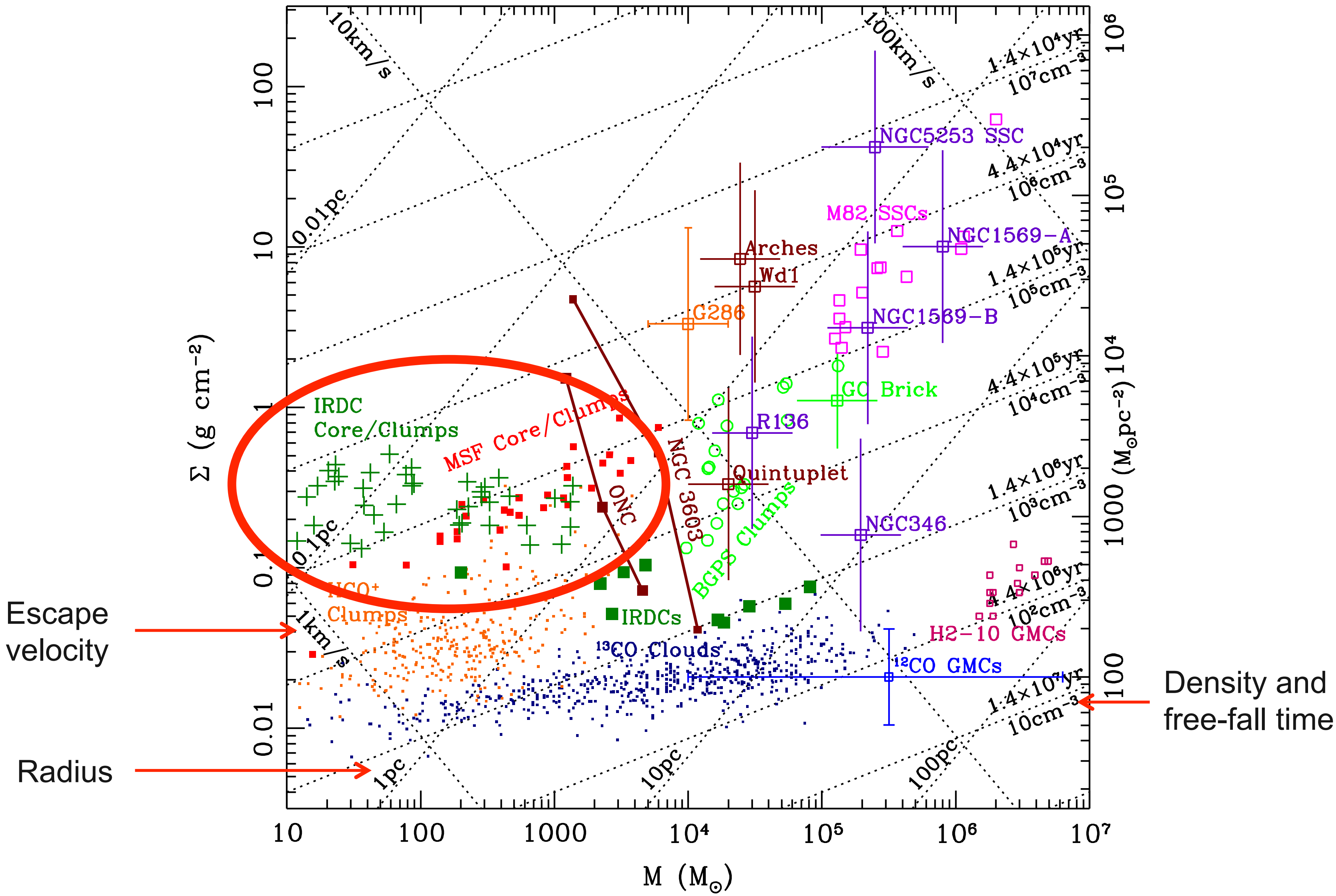
# The Environments of Massive Star Formation



# The Environments of Massive Star Formation



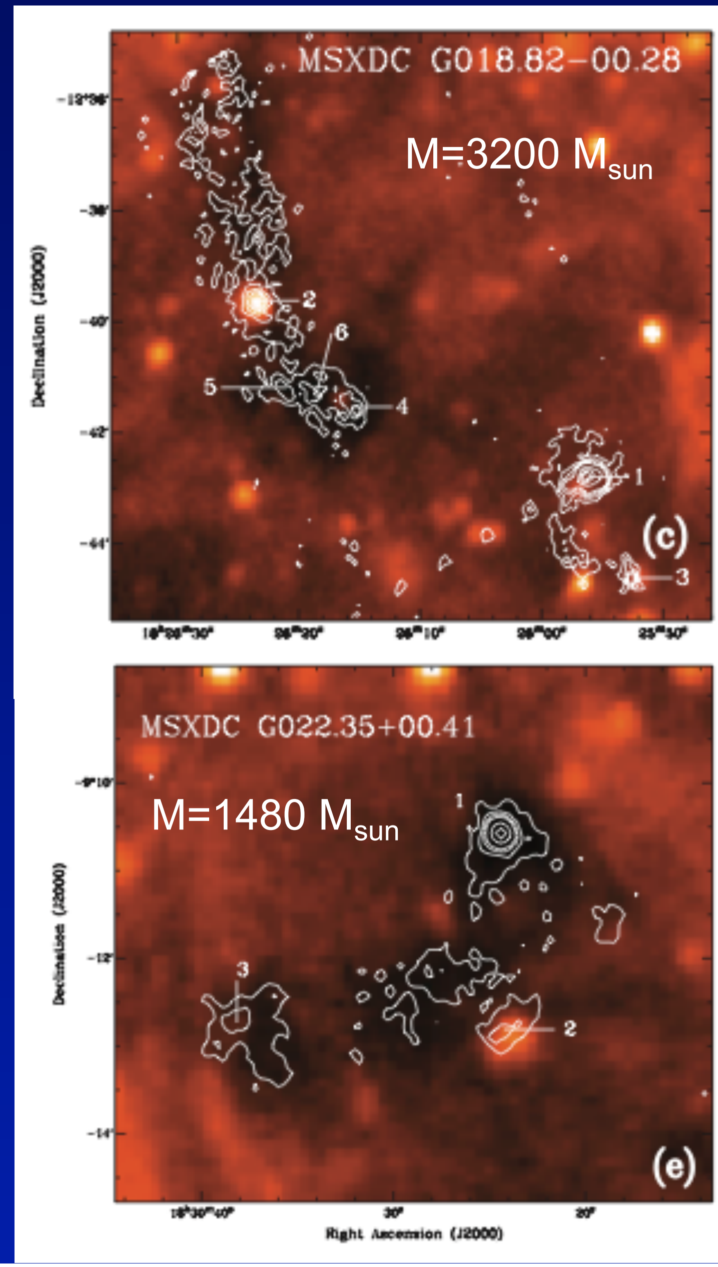
# The Environments of Massive Star Formation



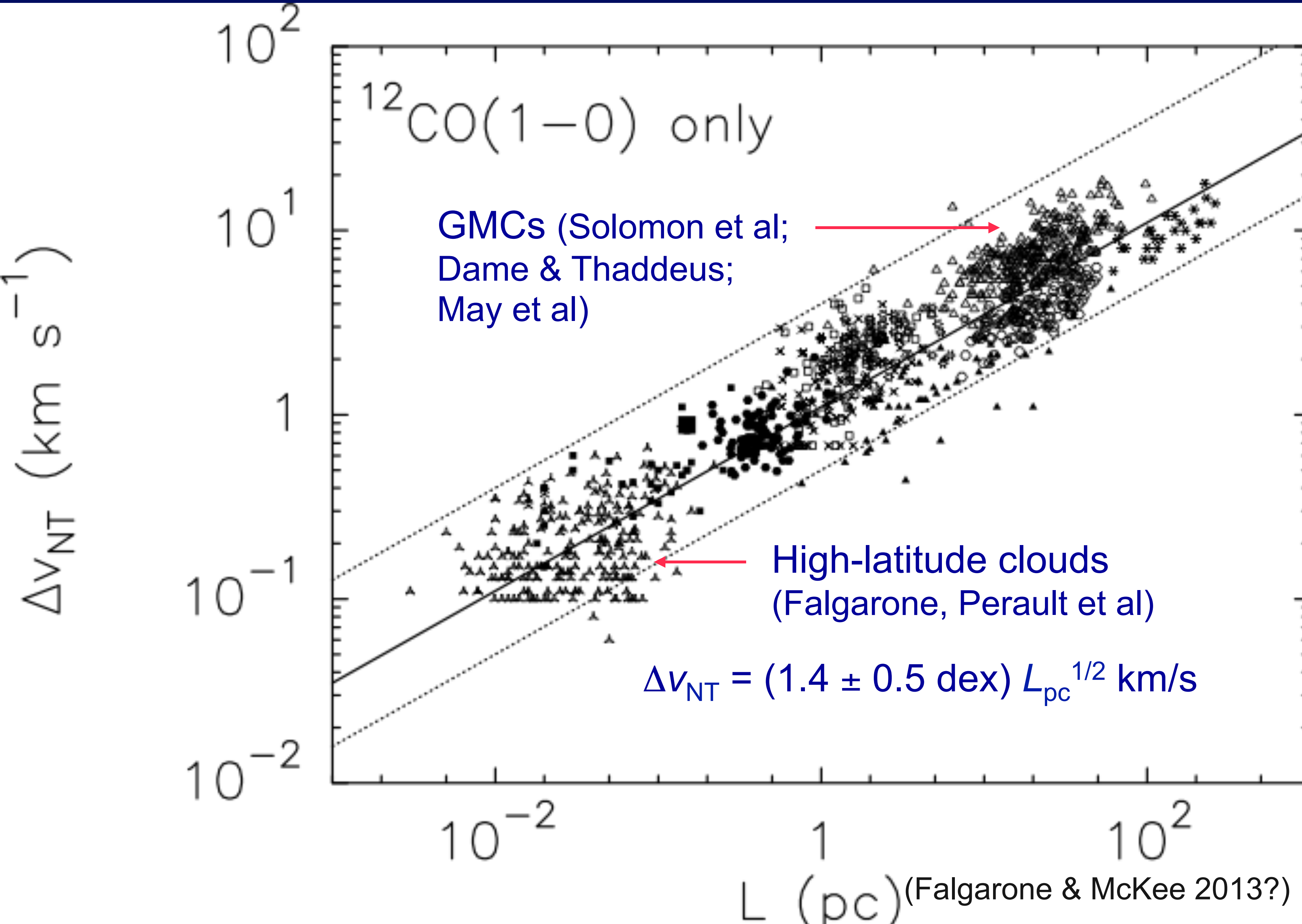
# Infrared Dark Clouds: Probes of Initial Conditions

Pérault et al. 1996; Egan et al. 1998; Carey et al. 1998; Rathborne et al. 2006

MSX

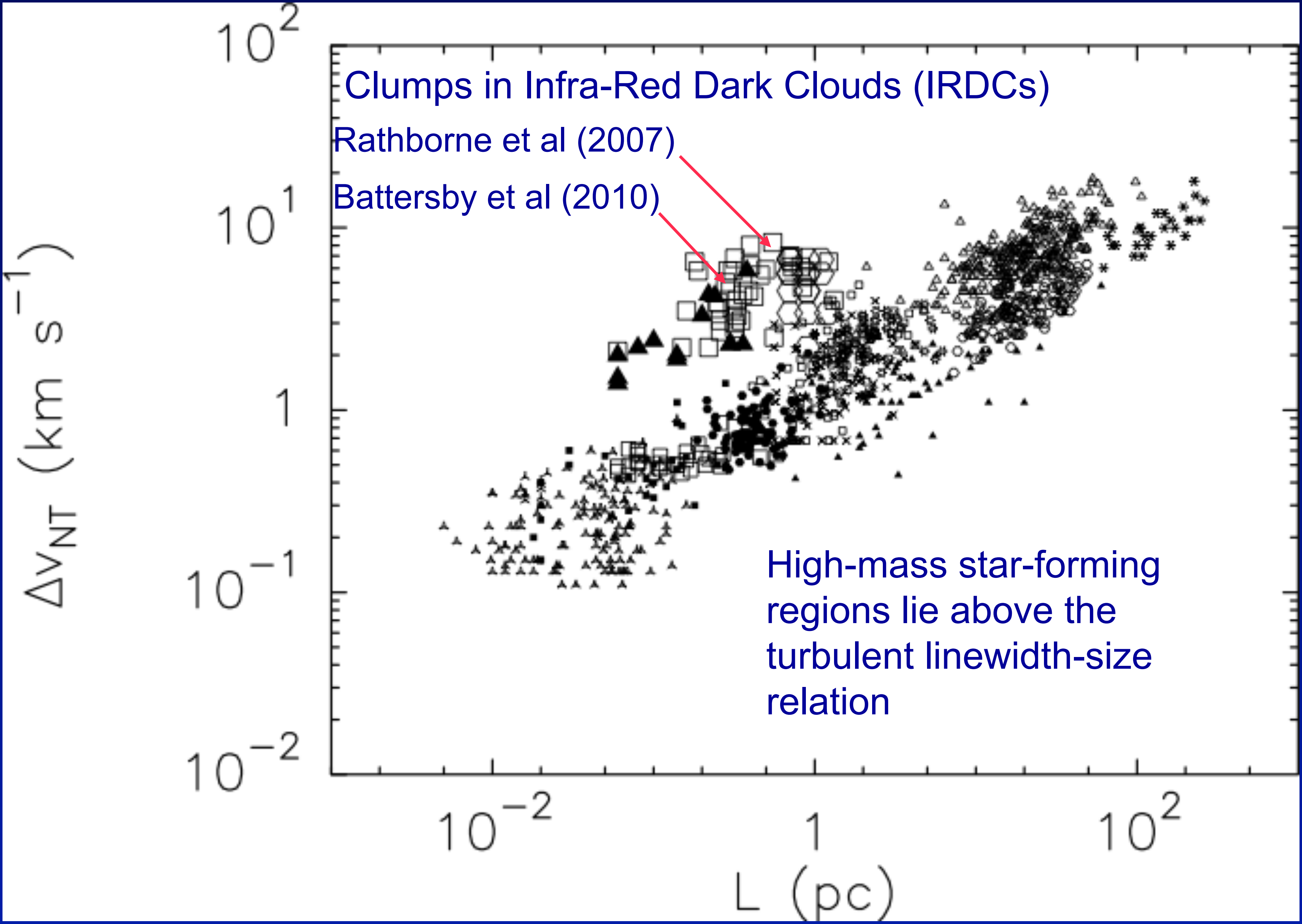


# Turbulent Linewidth-Size Relation for Galactic Molecular Gas




(Falgarone & McKee 2013?)

# Linewidth-Size Relation including Clumps in IRDCs



# Line-Width Size Relations for Bound and Unbound Gas

Turbulent linewidth-size relation for gravitationally unbound gas:

$$\Delta v \simeq (1.4 \pm 0.5\,\mathrm{dex})\, L_{\mathrm{pc}}^{1/2} \qquad \mathrm{km\ s^{-1}}$$

Virialized linewidth-size relation for gravitationally bound gas:

$$\alpha_{\mathrm{vir}} \equiv \frac{5\sigma^2 R}{GM} = \frac{5\sigma^2}{\pi G \Sigma R} \simeq \frac{\text{Kinetic energy}}{\text{Gravitational energy}} \qquad \left(\Sigma = \frac{M}{\pi R^2}\right)$$

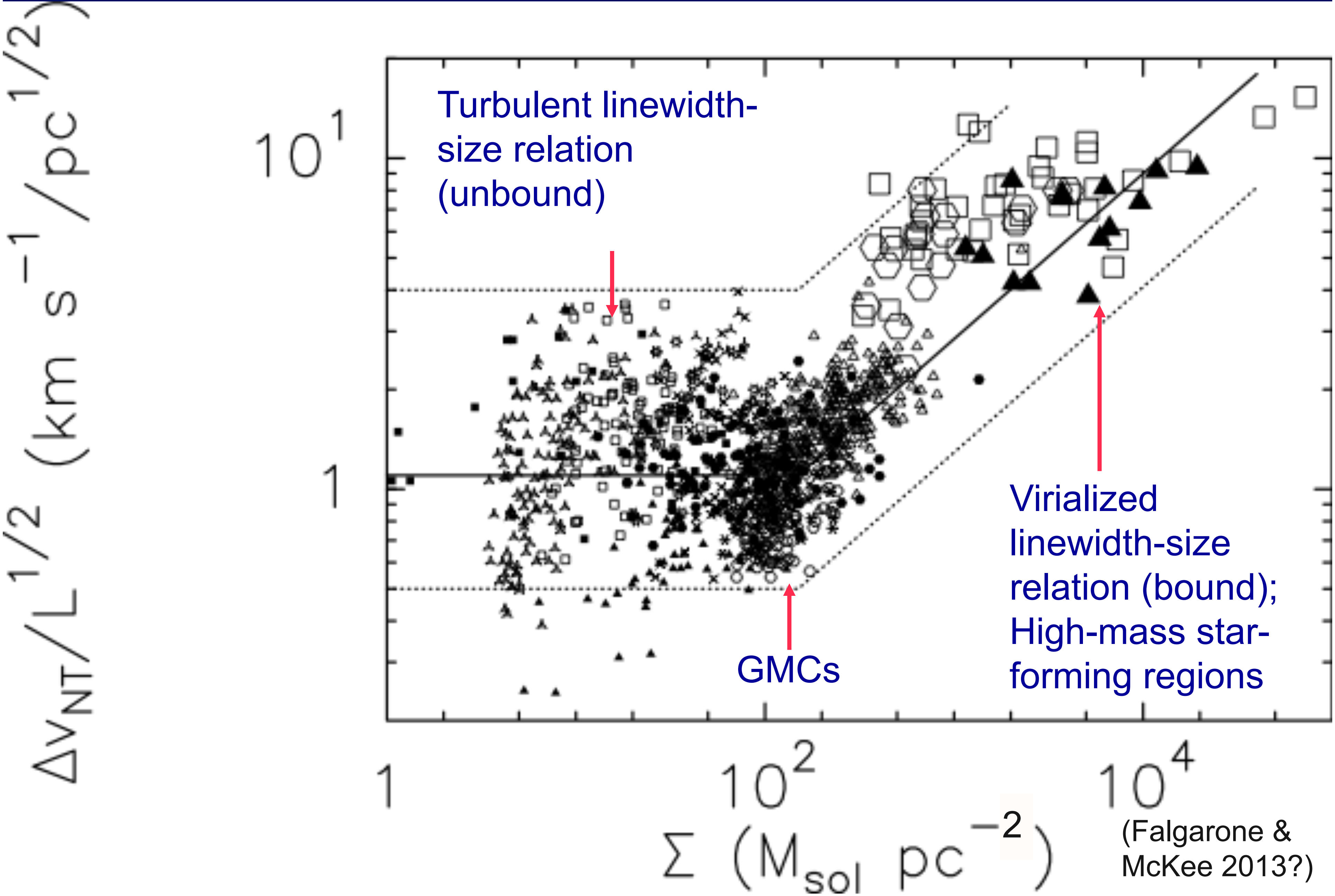
$$\Rightarrow \sigma \equiv \left(\frac{\pi}{5}\alpha_{\mathrm{vir}} G \Sigma R\right)^{1/2} \rightarrow \left(\frac{\pi}{5} G \Sigma R\right)^{1/2}$$

for bound clouds with $\alpha_{\mathrm{vir}} \sim 1$ (Heyer ea 2009)

Converting to FWHM, $\Delta v = 2.355\ \sigma$ :

$$\Delta v \simeq 0.9 \left[\left(\frac{\Sigma}{100\, M_{\mathrm{sun}}\,\mathrm{pc}^{-2}}\right) L_{\mathrm{pc}}\right]^{1/2} \qquad \mathrm{km\ s^{-1}}$$

# Generalized Linewidth-Size Relation Including IRDCs




(Falgarone & McKee 2013?)

# Evolutionary Sequence for High-Mass Star Formation

(Beuther+ 2007)

Terminology: Clumps form clusters, cores form stars

Core evolution:

* High-mass starless cores (HMSCs)
* High-mass cores harboring precursors to high-mass stars
* High-mass protostellar objects (HMPOs)
* Final stars

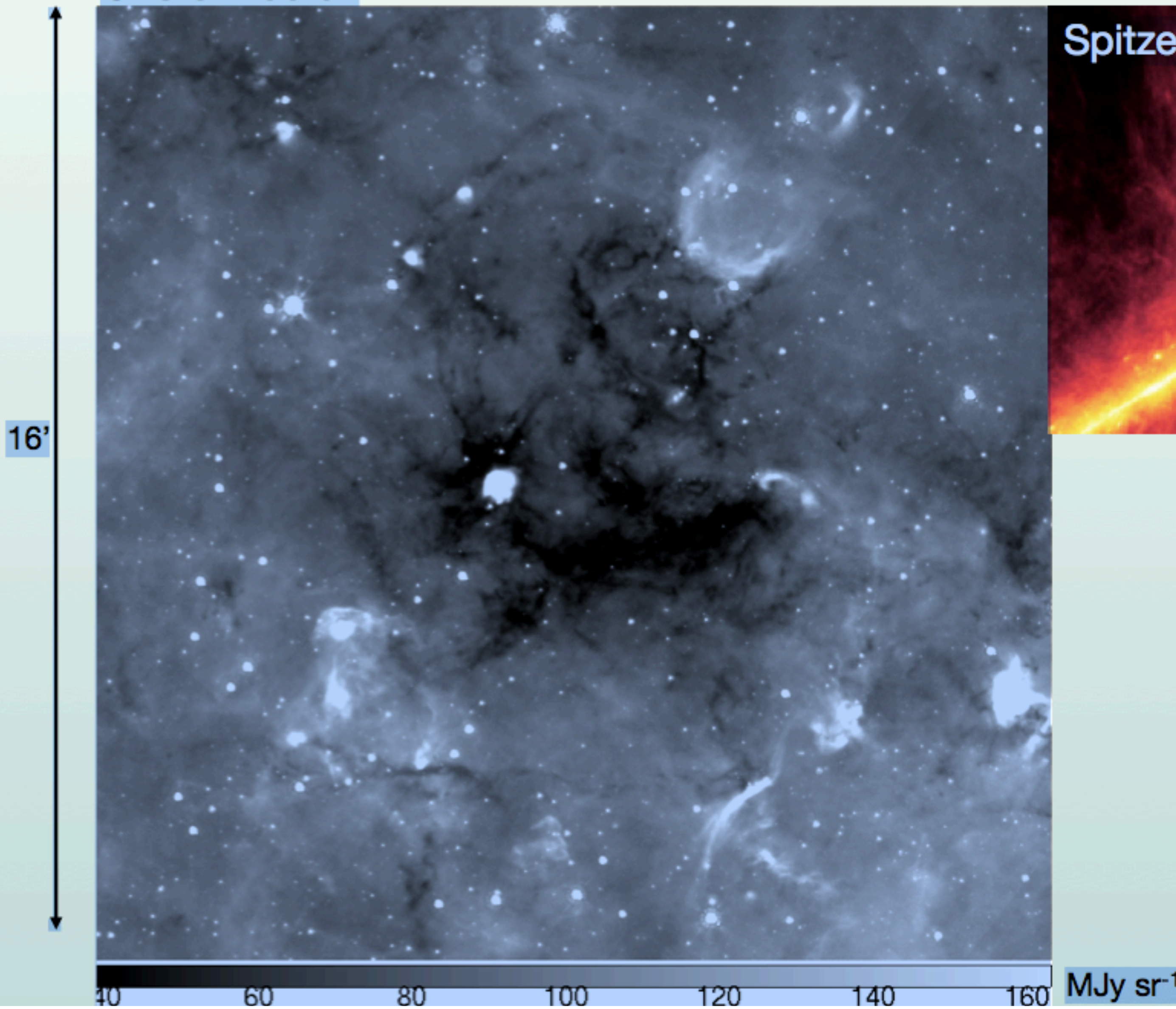
Clump evolution:

* Massive starless clumps (but none $>10^4\ M_{sun}$ with $\Sigma > 0.1$ g cm$^{-2}$ in 1st quadrant--Ginsburg+12)
* Protoclusters
* Stellar clusters

# Mid-IR Extinction Mapping of Infrared Dark Clouds

(Butler & Tan 2009, 2012; see also Peretto & Fuller 2009; Ragan et al. 2009; Battersby et al. 2010)

G28.37+00.07

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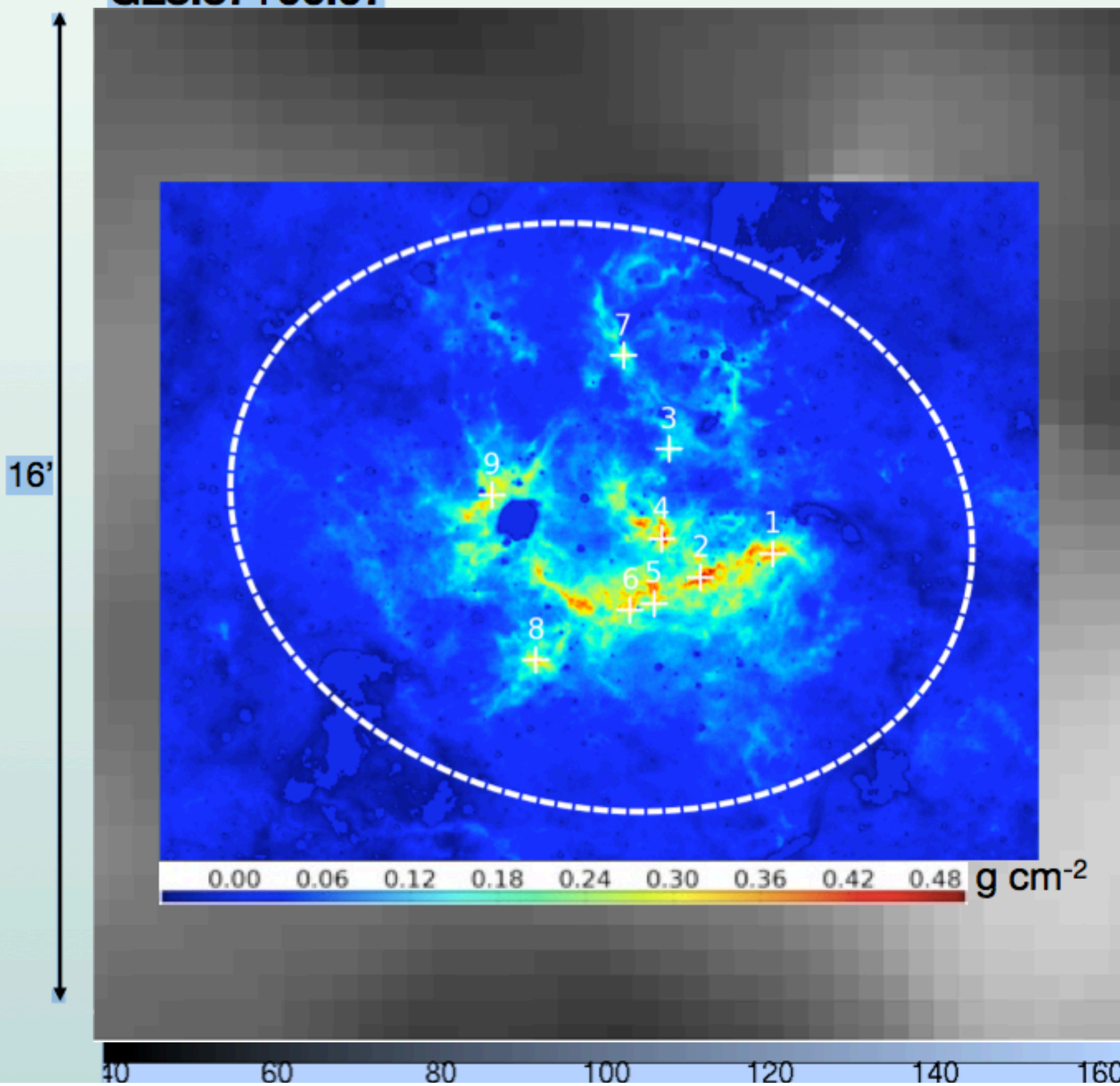




Median filter for background around IRDC; interpolate for region behind the IRDC

Correct for foreground

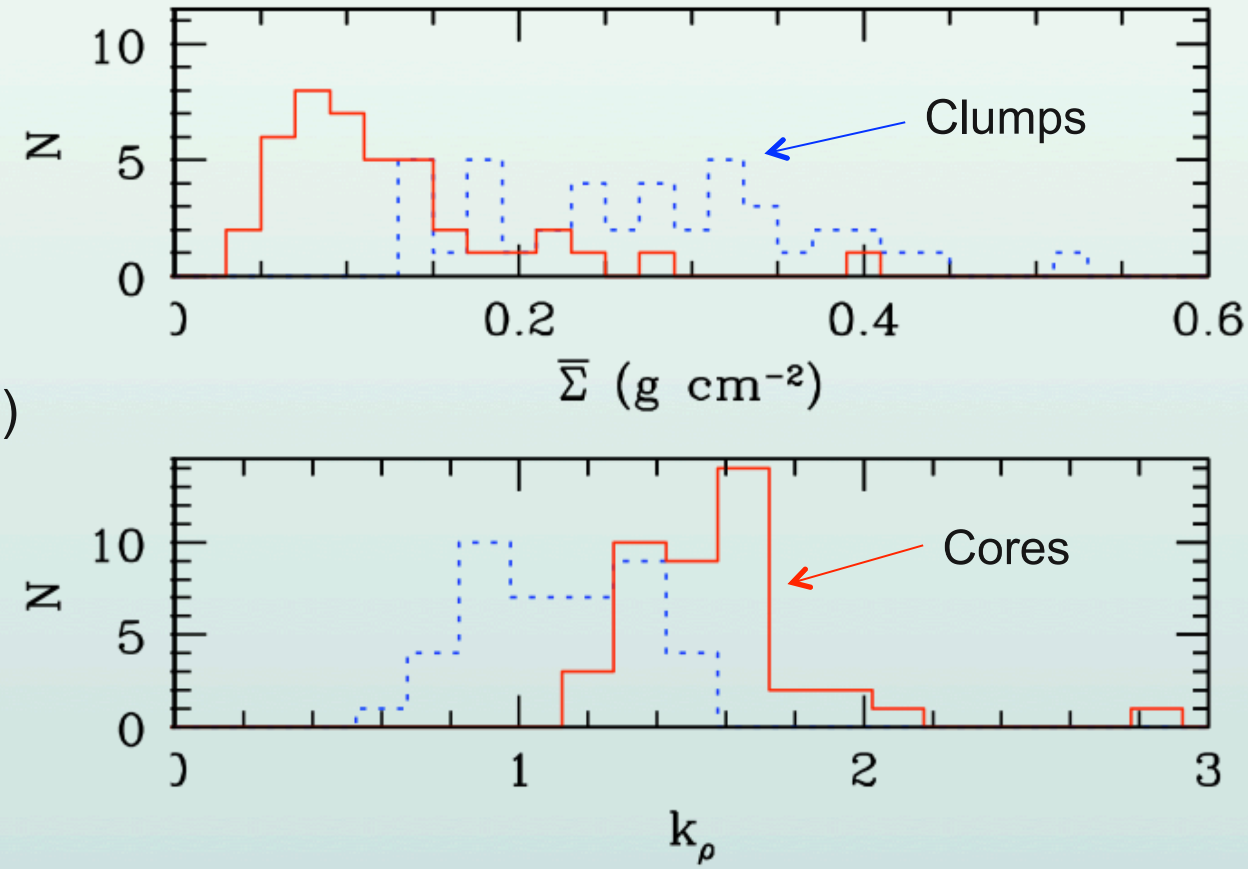
**~Arcsecond scale maps of regions up to $\Sigma$ ~0.5 g cm$^{-2}$; independent of dust temp.**

Distance from molecular line velocities -> M($\Sigma$)

## IRDC Core/Clump Structural Properties

Cores show central concentration; power law radial volume density profiles with index ~ -1.6. (see also Beuther+ 02)

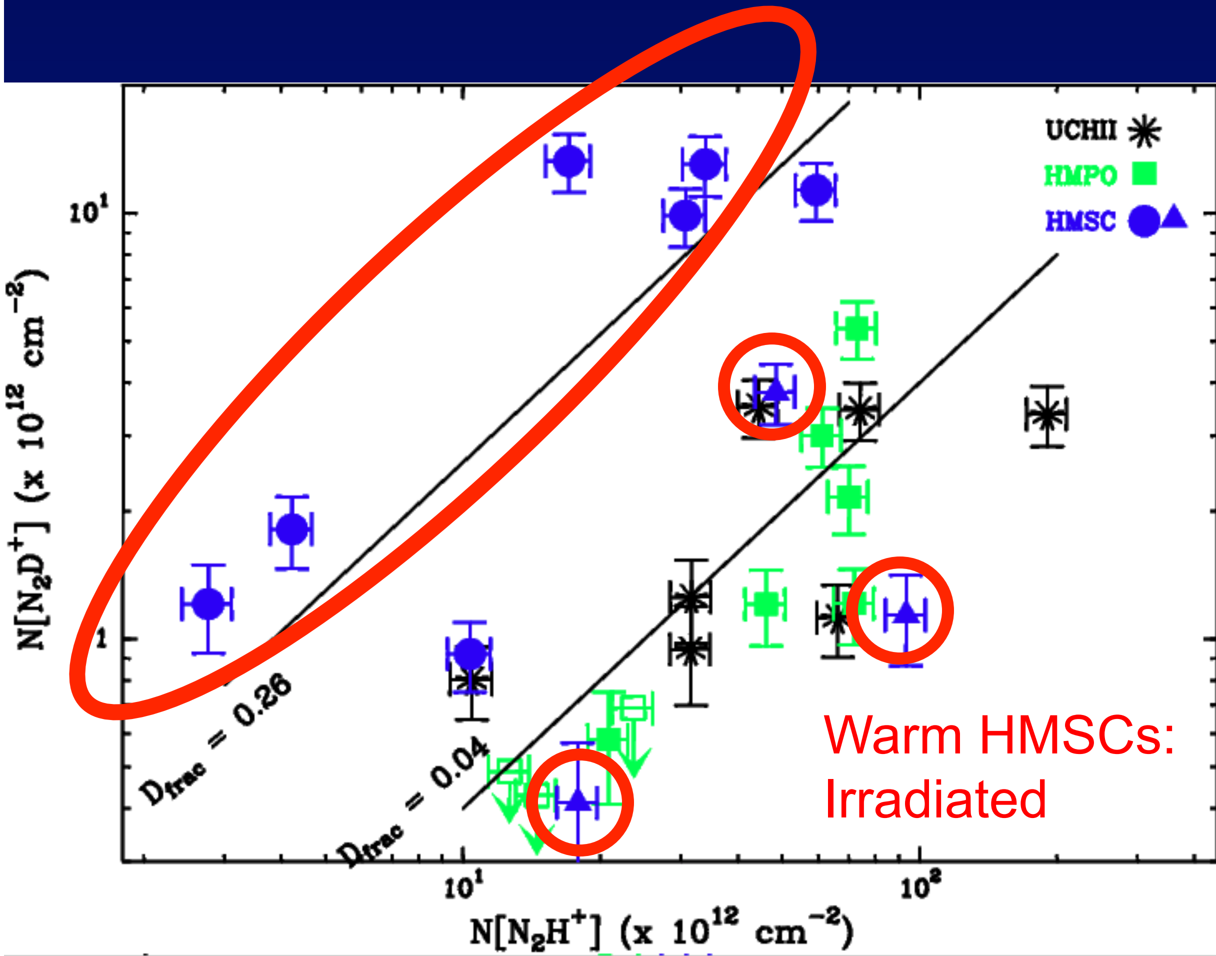
They contain many thermal Jeans masses.

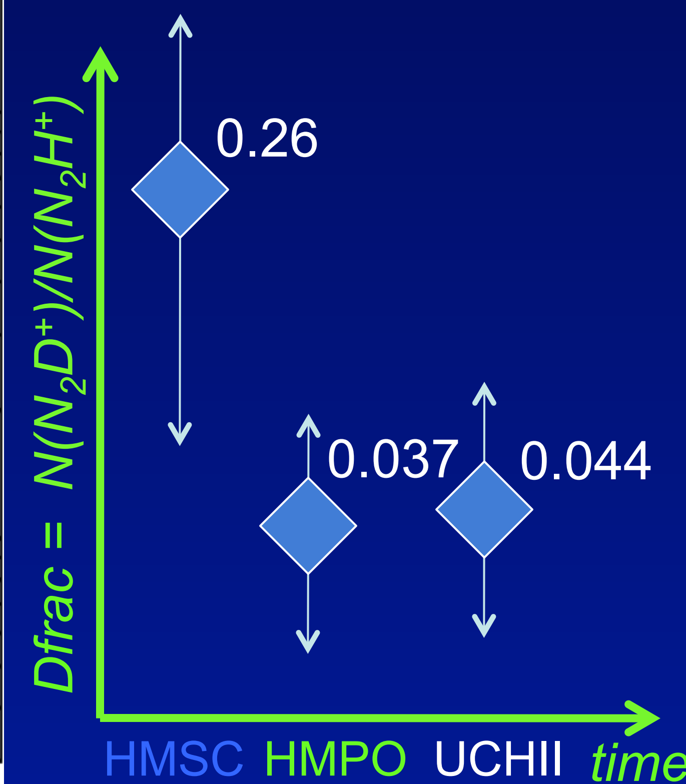



(Butler & Tan 12)

Separating HMSCs from HMPOs: $N(N_2D^+)$ versus $N(N_2H^+)$

(Fontani+ 11)



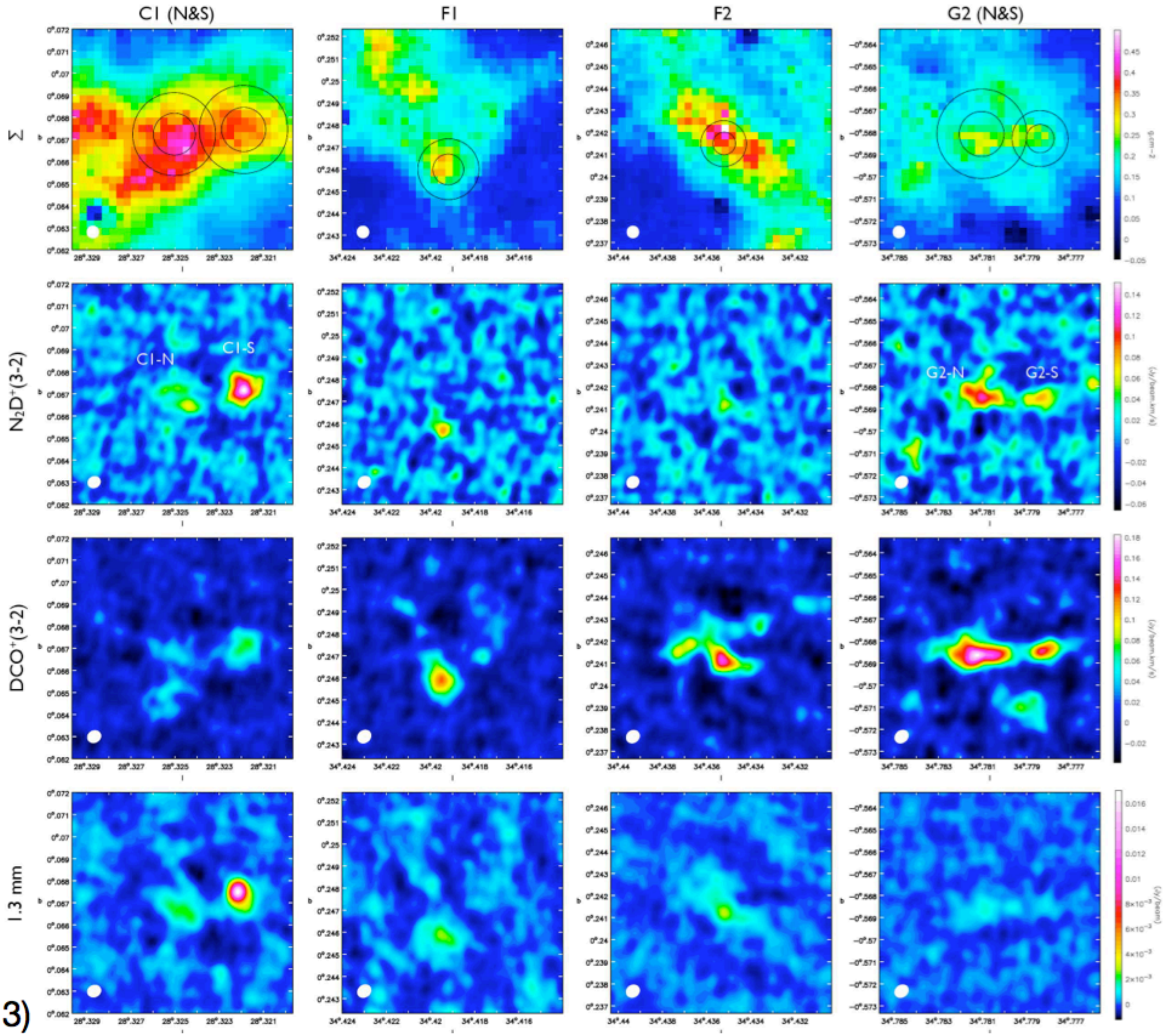




Statistical separation between HMSCs and HMPOs/UCHIIs:
Kolmogorov-Smirnov test: P ~ 0.004

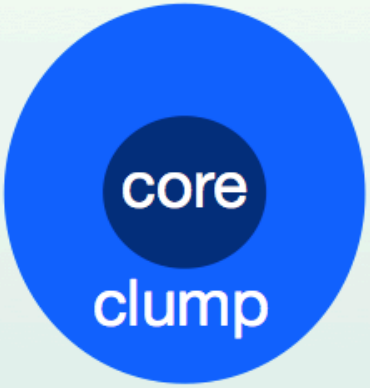
**The best targets to study the initial conditions of MSF**

**“Massive” “Starless” “Cores” with ALMA**

Selected for high $N_2D+/N_2H^+$




Tan et al. (2013)



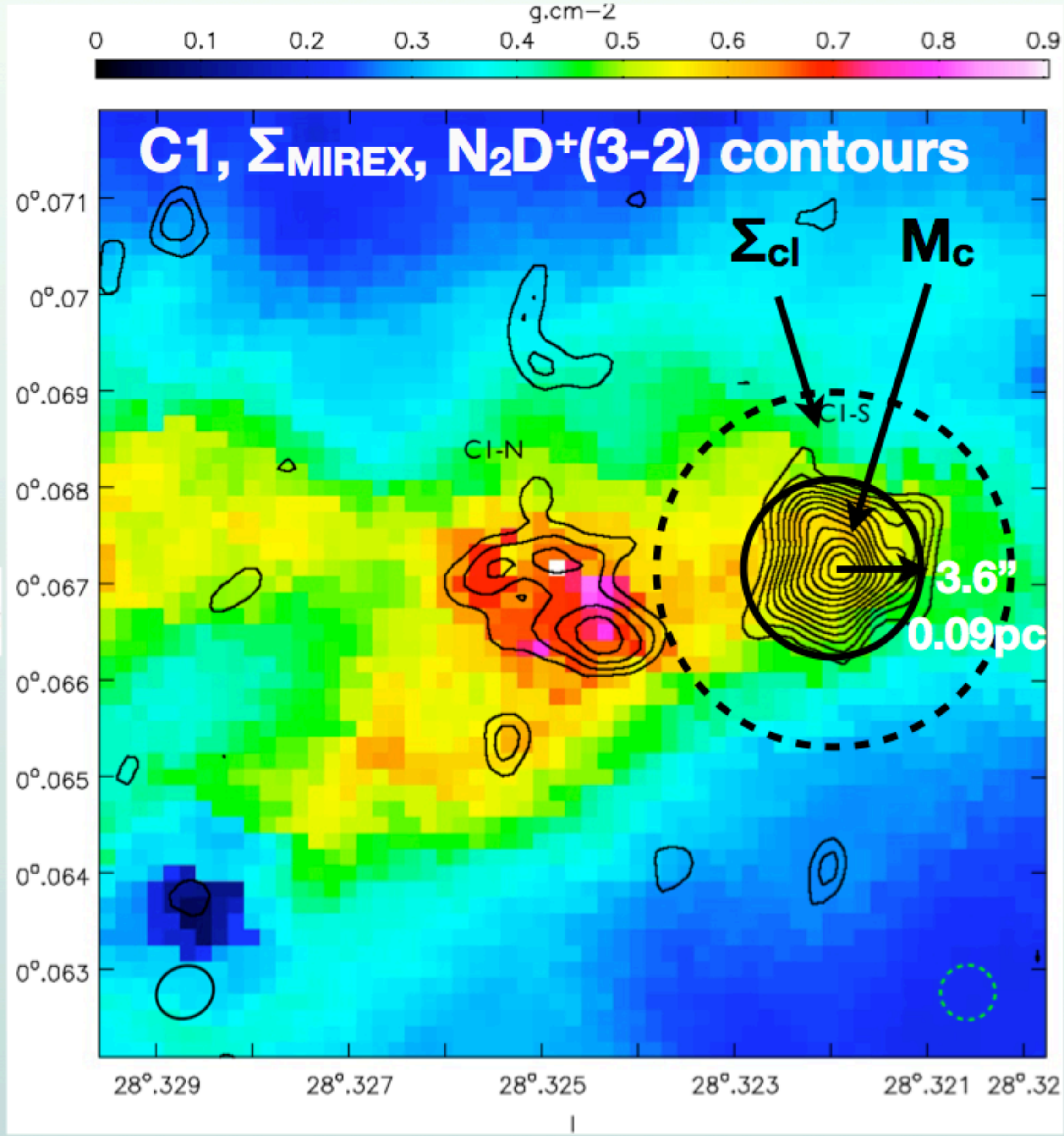

$$\sigma_{c,\mathrm{vir}} \rightarrow 1.09 \left(\frac{M_c}{60 M_\odot}\right)^{1/4} \left(\frac{\Sigma_{\mathrm{cl}}}{1\ \mathrm{g\ cm^{-2}}}\right)^{1/4} \mathrm{km\ s^{-1}}$$

Core masses inside 3σ $N_2D^+$ contour:

**$\Sigma_{cl}$ = 0.36 g cm$^{-2}$**

**$M_{c,MIREX}$ = 55.2 ± 25 $M_\odot$**

**$M_{c,mm}$ = 62.5 $^{129}_{26.9}$ $M_\odot$**




(Tan+ 13)

## These cores are close to virial equilibrium:

- 1D velocity dispersion if virialized:

( $m_A = \sqrt{3}\sigma_c/v_A$ = 1)

$$\sigma_{c,\mathrm{vir}} \to 1.09 \left(\frac{M_c}{60 M_\odot}\right)^{1/4} \left(\frac{\Sigma_{\mathrm{cl}}}{1\ \mathrm{g\ cm^{-2}}}\right)^{1/4} \mathrm{km\ s^{-1}}$$

| Core | C1-N | C1-S | F1 | F2 | G2-N | G2-S |
|---|---|---|---|---|---|---|
| $\Sigma_{cl}$ (g cm$^{-2}$) | 0.48 | 0.40 | 0.22 | 0.32 | 0.21 | 0.19 |
| $M_c$ ($M_\odot$) | 16 | 63 | 6.5 | 4.7 | 2.4 | 0.83 |
| $\sigma_{vir}$ (km/s) | 0.66±0.22 | 0.88±0.30 | 0.43±0.15 | 0.44±0.15 | 0.33±0.11 | 0.25±0.09 |
| $\sigma_{obs}$ (km/s) | 0.41±0.03 | 0.41±0.02 | 0.25±0.02 | 0.42±0.04 | 0.34±0.02 | 0.30±0.02 |

**$<\sigma_{obs}/\sigma_{vir}>$ = 0.81 ± 0.13**

(Tan+ 13)

Assumptions for predicted virial velocity:

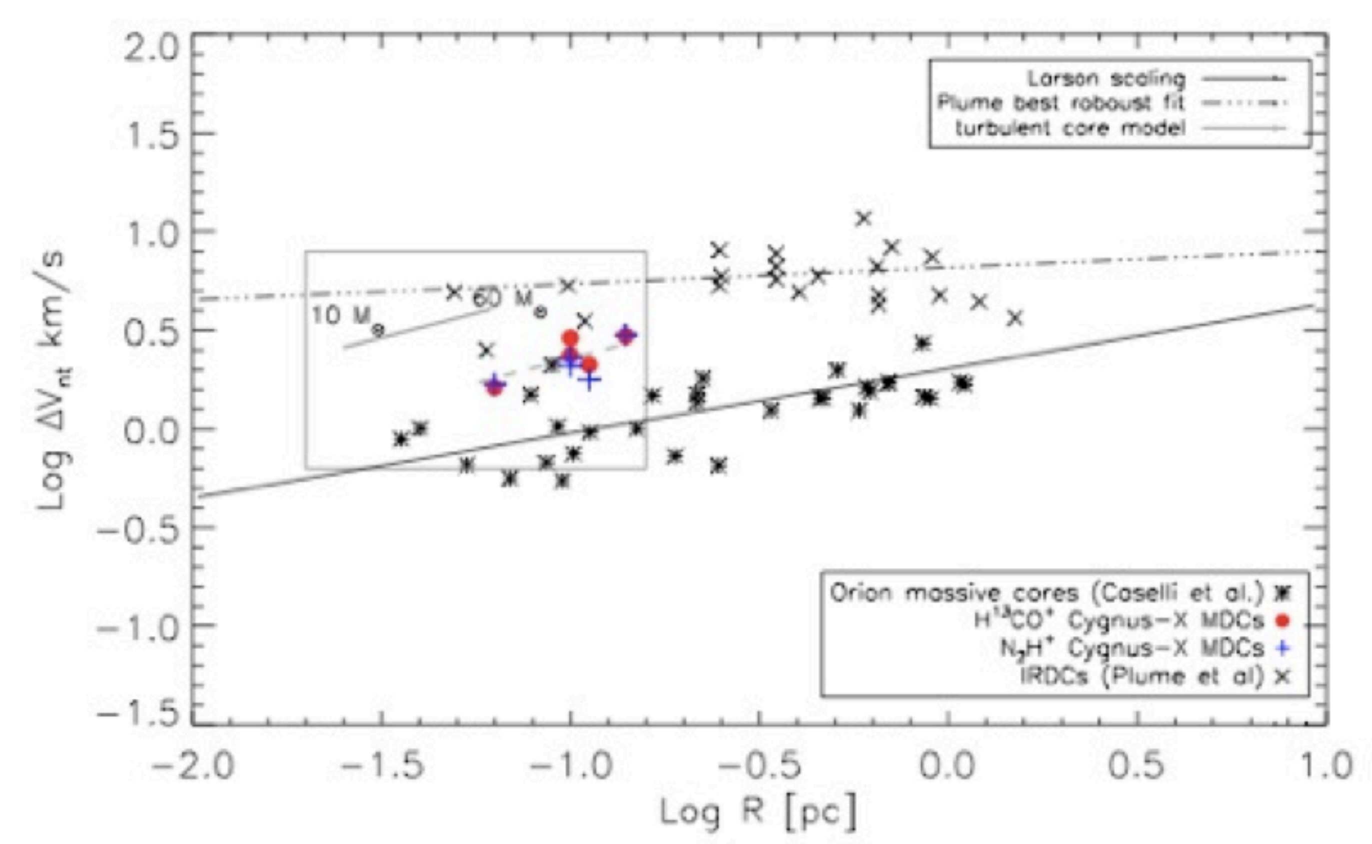
Core in pressure balance with weight of surrounding clump

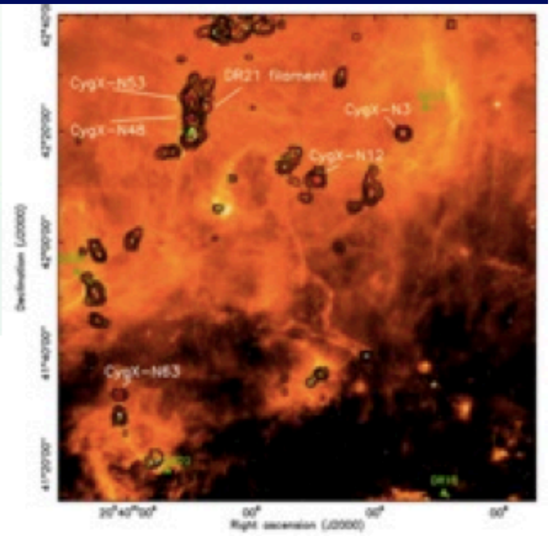
Includes magnetic pressure corresponding to Alfven Mach number = 1

$N_2D^+$ accurately measures σ though neutral lines broader (Houde+ 00)

# $H^{13}CO^+$ Cores in Cygnus-X

Csengeri et al. (2011)

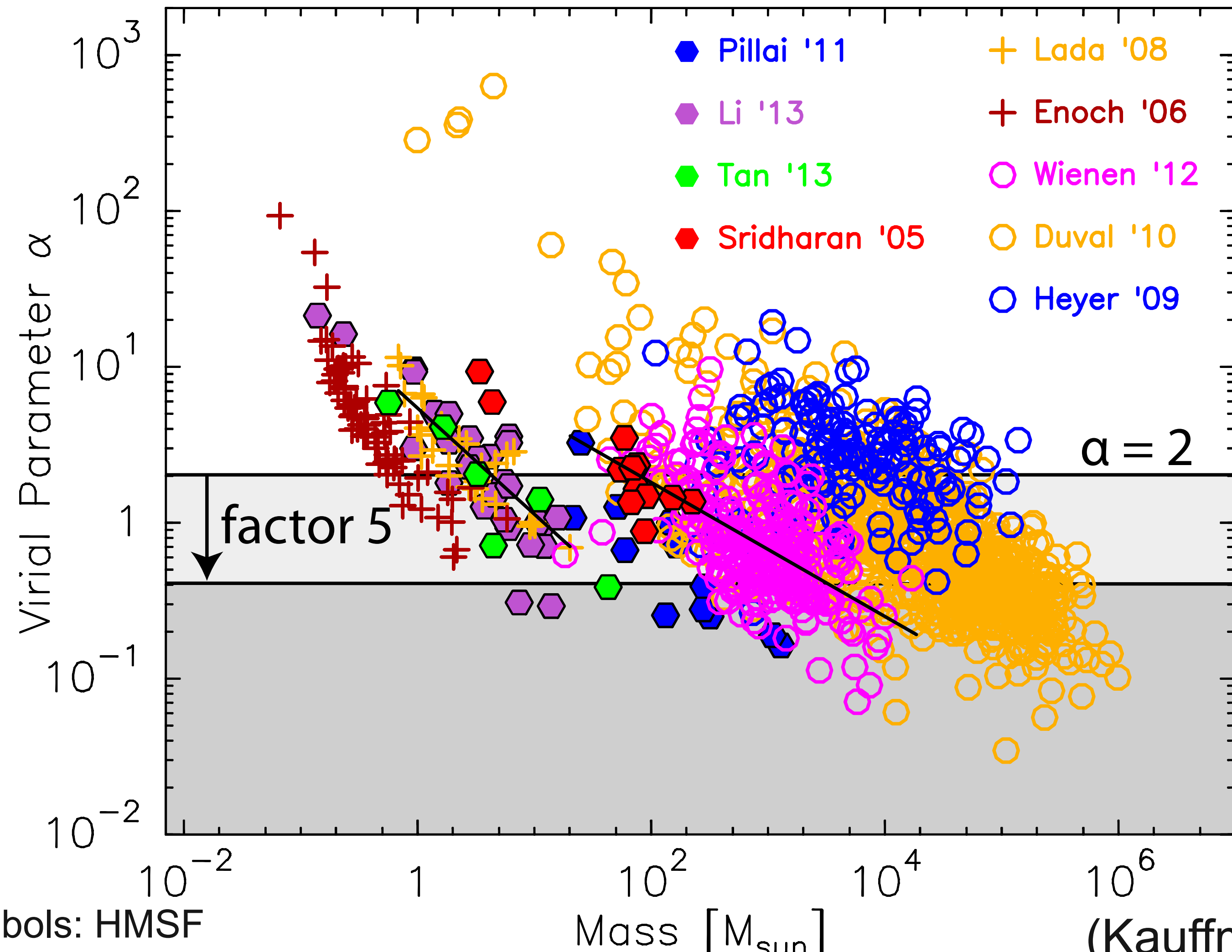



Orion cores fit TNT model of Myers & Fuller 92 => in virial equilibrium.

Cygnus X cores fit Turbulent Core model (McKee & Tan 02, 03) => in virial equilibrium

Not all cores are in virial equilibrium though:




Filled symbols: HMSF
Open symbols include non-HMSF

(Kauffmann+ 13)

Low $\alpha_{vir}$ could be due to strong field ($B_{max} = 1.95 n_6^{0.65}$ mG -- Crutcher+ 10), observational uncertainties (e.g., Duval assumed $CO/H_2 = 8 \times 10^{-5}$), or initial conditions, but not to free-fall collapse ($\alpha_{vir\text{ , free-fall}} = 10/3$)

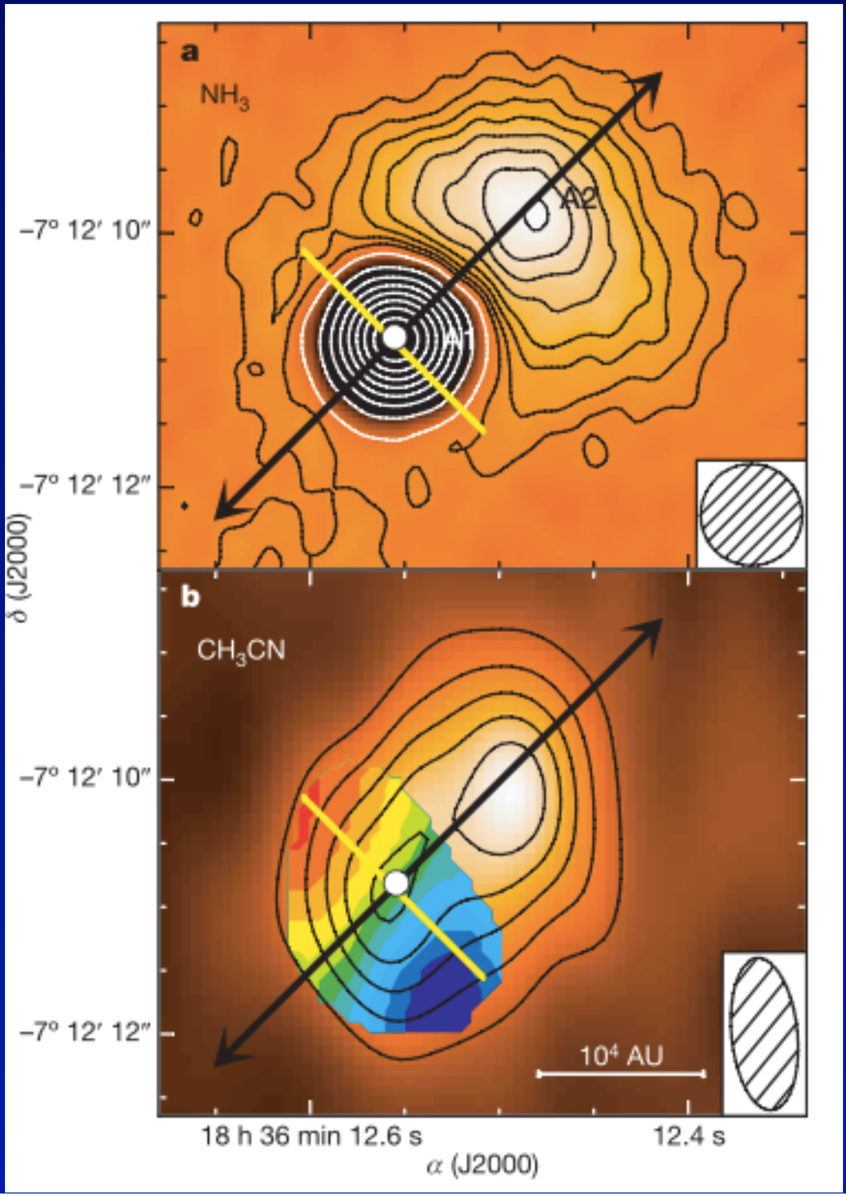
# Observations of Accretion onto Cores and Clumps--I

Accretion onto 20 $M_{sun}$ protostar (Beltran+ 06)

$NH_3$ absorption against 1500 AU hypercompact HII region (white contours; black contours are emission.

$CH_3CN$ emission showing rotation in source A1

Accretion rate (0.4 – 10) x $10^{-3}$ ($\Omega/4\pi$) $M_{sun}$ $yr^{-1}$



# Observations of Accretion onto Cores and Clumps--II

## Accretion in high-mass cluster-forming clumps (Lopez-Sepulchre+ 10)

Only 13% of IR-loud and 32% of IR-dark clumps show infall

Outflows seen in 75% of sources, both IR-loud and IR-dark => active SF

Median infall rate ~ 5 x $10^{-3}$ $M_{sun}$ $yr^{-1}$

Estimate protostellar accretion rate ~ $10^{-5}$ $M_{sun}$ $yr^{-1}$ from protostellar jets

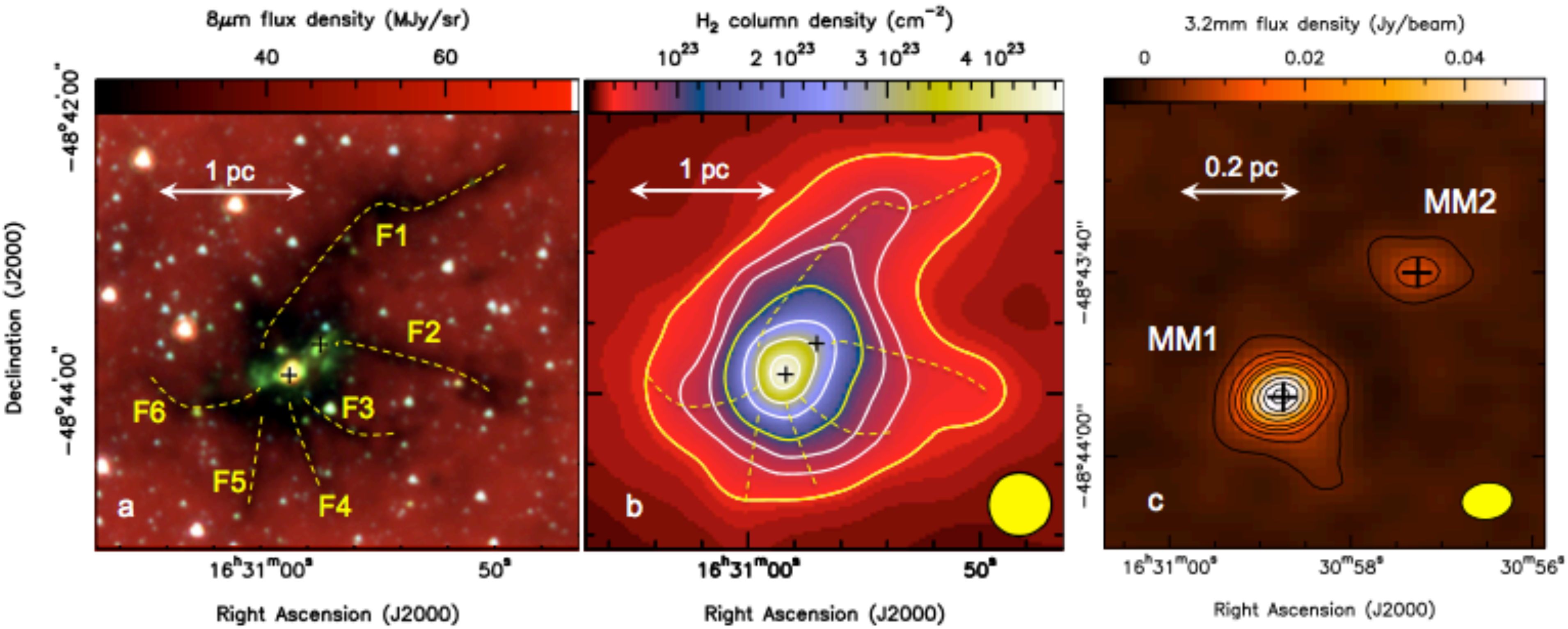
## Clump accretion at a fraction of the free-fall velocity (Wyrowski+ 12)

$NH_3$ absorption against dust continuum => $v_{in} = f\, v_{ff}$ , with f = 0.2-0.3

Can show characteristic accretion rate $M/t_{ff} = \pi^{-1}(v_{ff}^3 / G)$, similar to Shu (1977) rate, $0.975\, c^3 / G$.

They infer clump accretion rate ~ (3-10) x $10^{-3}$ $M_{sun}$ $yr^{-1}$

# A remarkable protocluster clump (Peretto+ 13)




SDC335: M=5500 $M_{sun}$ , R=1.2 pc, Σ = 0.3 g $cm^{-2}$; quasistatic contraction

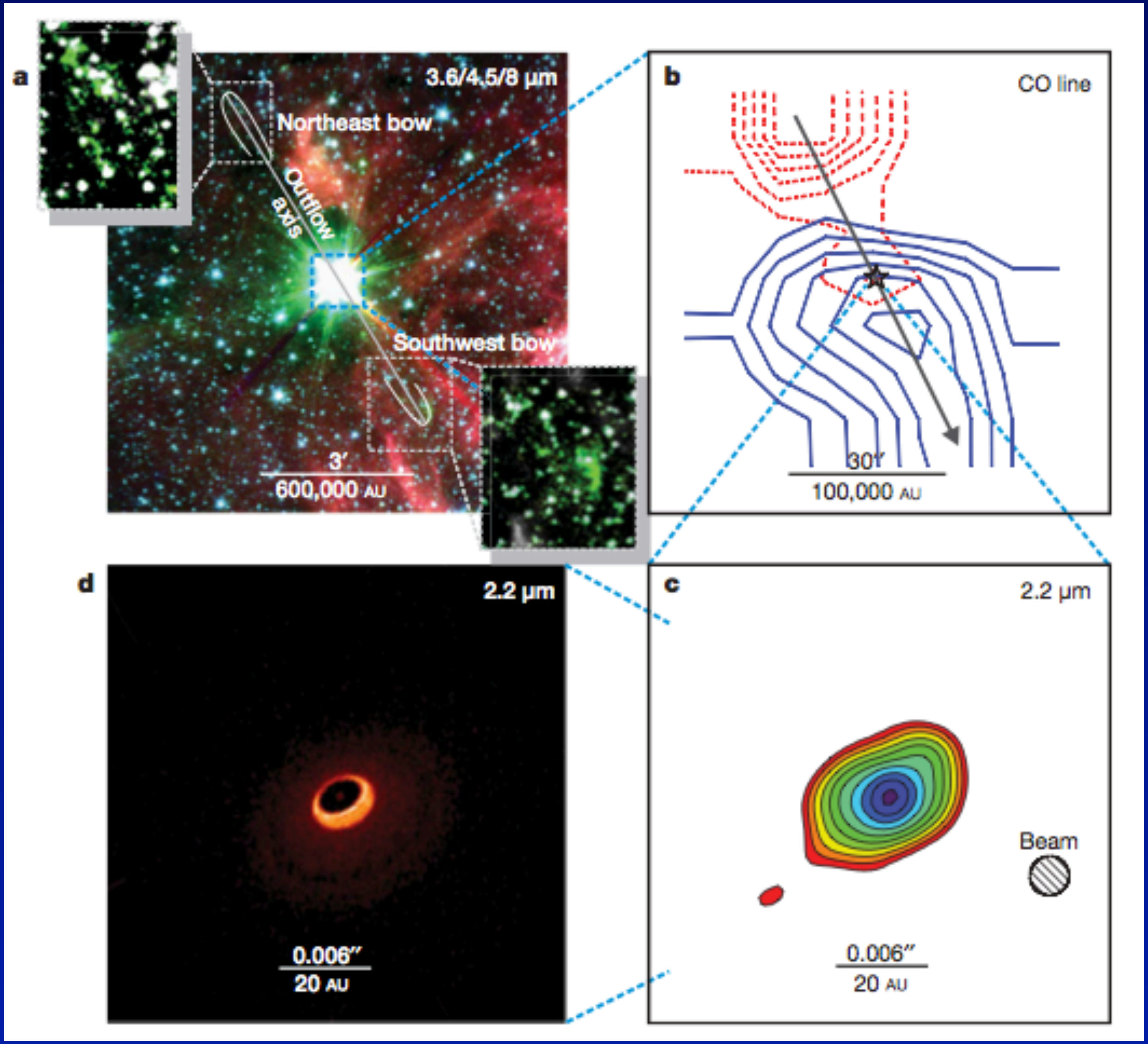
MM1: M=545 $M_{sun}$ , R=0.027 pc, $n_H$=2x$10^8$, Σ=52 g $cm^{-2}$

# Circumstellar disks around massive protostars-I

VLTI observations of IRAS 13481-6124 (Kraus+ 10)

13 x 19 AU disk with central 9.5 AU hole

Infer:
$M^* = 18\ M_{sun}$ ;
flared disk with
$M = 18 \pm 8\ M_{sun}$
$R_{disk} = 130$ AU



# Circumstellar disks around massive protostars-II

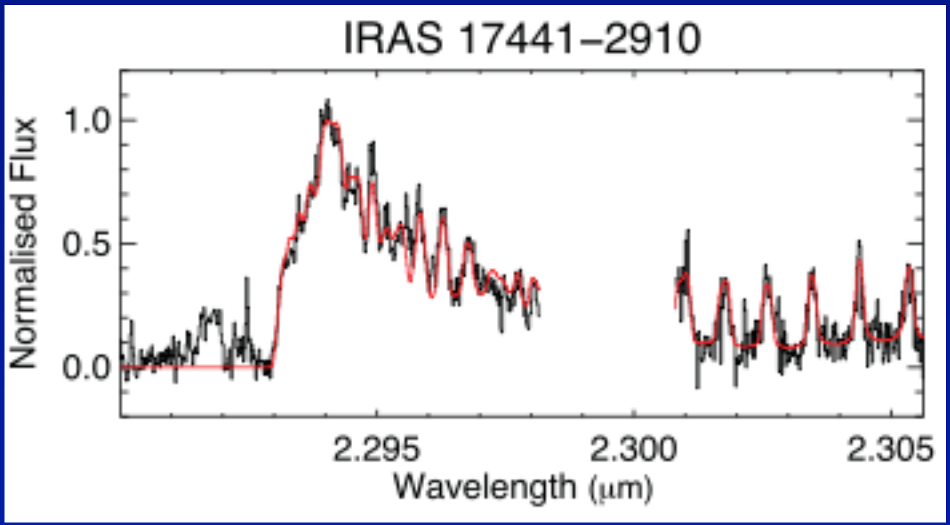
CO bandhead emission from massive YSOs (Ilee+ 13)

Presumably still accreting (Mottram+ 11) => probably HMPOs

25% of sample from Red MSX survey (Lumsden+ 02) show CO emission

All spectra consistent with Keplerian disks, mostly located near dust sublimation radius

Disks are detected around several O type stars, up to 57 $M_{sun}$ :



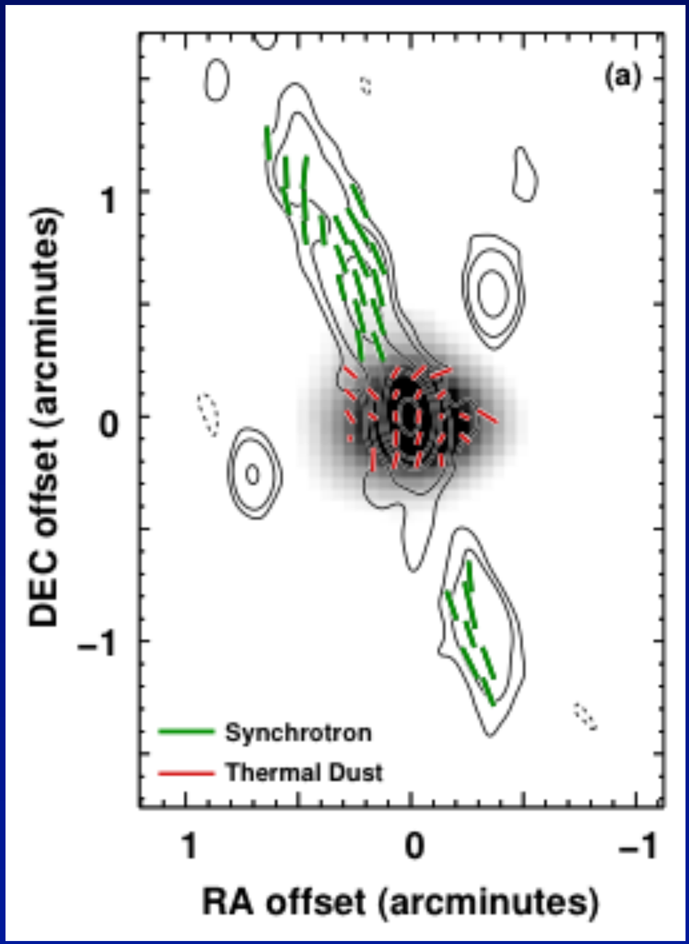
# Observation of magnetized jet from a high-mass protostar

IRAS 18162-2048

$L$=17,000 $L_{sun}$

$\Rightarrow M \approx 10\ M_{sun}$

if dominated by one star




6 cm (contours)

Synchrotron emission

850 μm (gray scale)

Thermal emission

(Carrasco-Gonzalez et al. 2010)

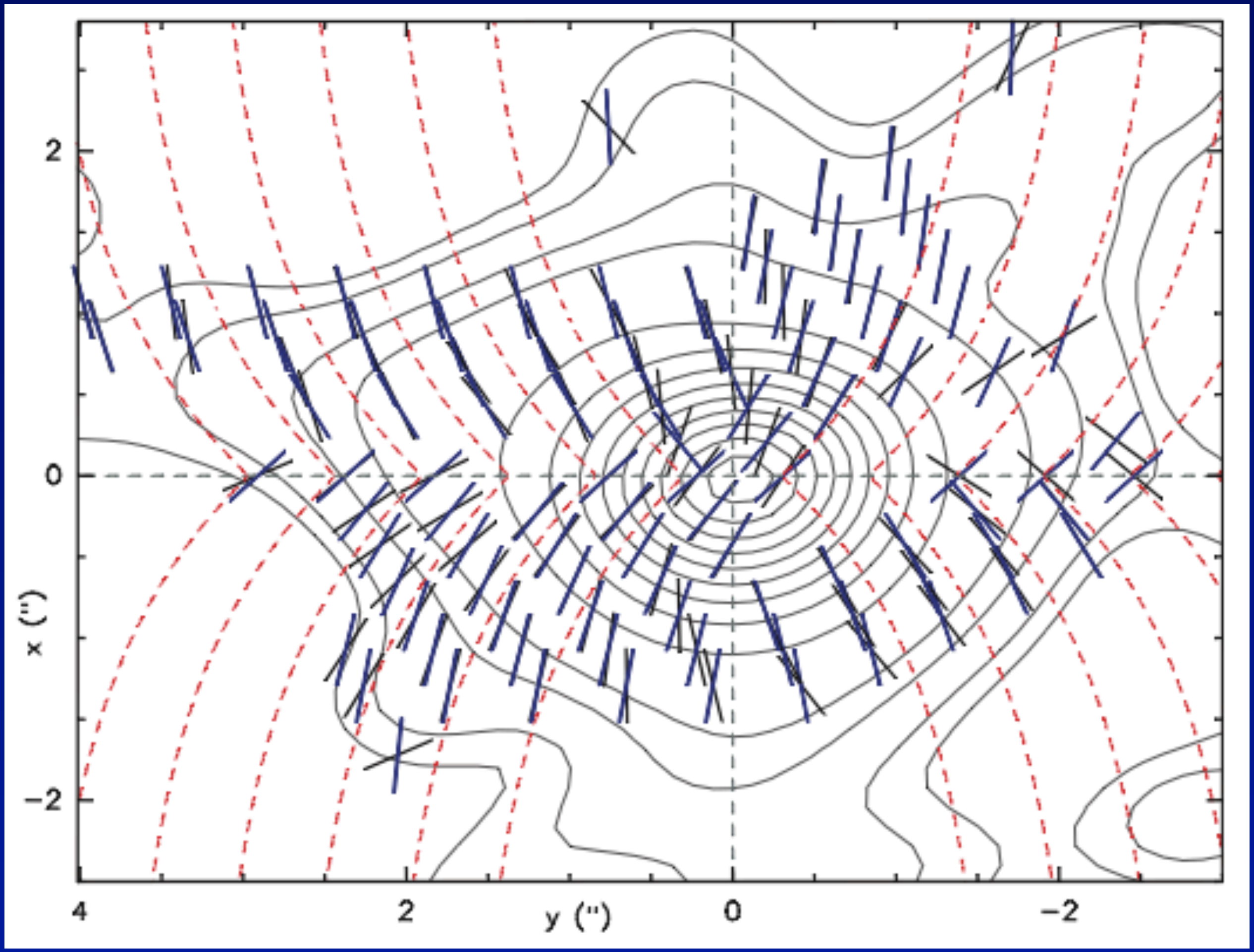
Suggests massive protostars have hydromagnetic outflows like low-mass stars

# A strong magnetic field in a high-mass star-forming clump

Polarization map of hot molecular core G31.41 with mass 577 $M_{sun}$

Classical hour-glass shape => strong field

Girart's estimate of 9.7 mG from Chandrasekhar-Fermi probably too high—magnetically subcritical




Girart+ 09

$B_{max}$ from Crutcher+ (2010) ~ 6 mG => mass/flux = 1.4

# Theoretical Considerations

Massive star formation differs from low-mass star formation:

*Protostellar core can contain many Jeans masses

*Correspondingly, turbulence can be significant in the core

*Magnetic fields *may* be less important

Magnetic critical mass inferred from median field from Crutcher+10 is ~ (4 – 32) $n_6^{-0.15}$ $M_{sun}$

* Radiative feedback can be significant (Kahn 74, Larson & Starrfield 71):

-The force due to radiation pressure can exceed that due to gravity

- Protostellar accretion can continue after star approaches main sequence and even after star begins to create an HII region

But, is high-mass SF basically a scaled up version of low-mass SF?

# Theories of Massive Star Formation-I

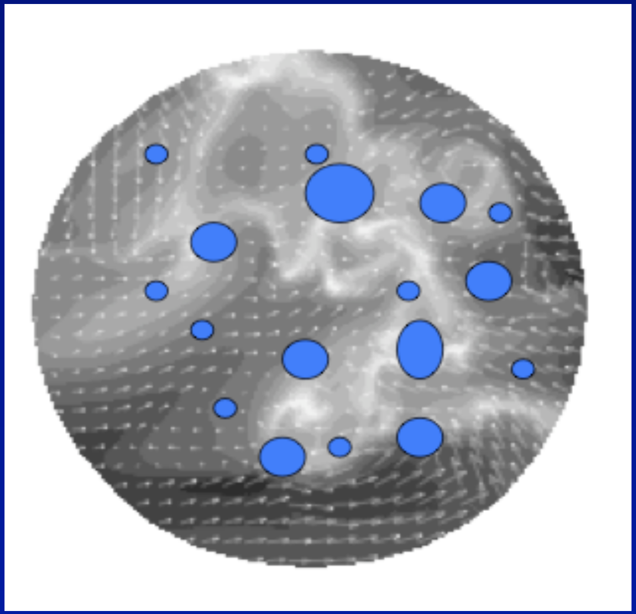
## Core Accretion Models

Star forms from core with a mass that is related to final mass of star:

Generalization of theory of low-mass star formation

Predicts that IMF is determined by the core mass function (CMF)

Basis of recent theories of IMF (Padoan & Nordlund 2007, Hennebelle & Chabrier 2008, Hopkins 2012)

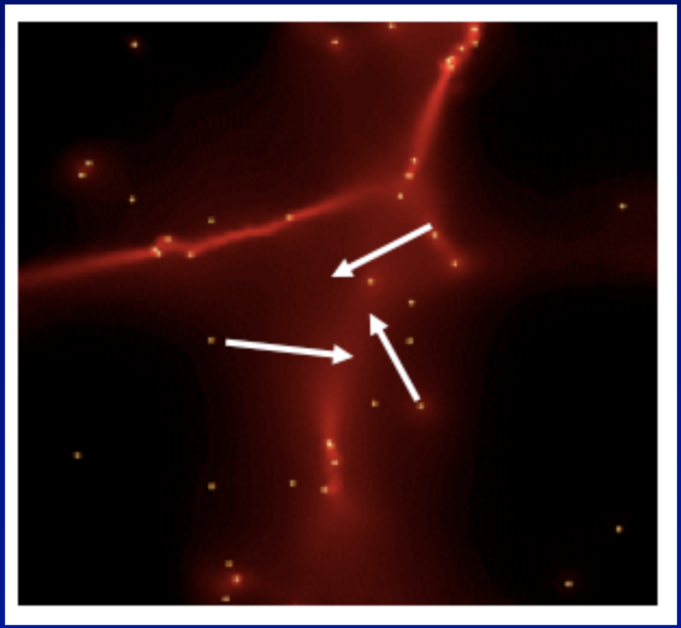


Challenges: Why doesn’t core fragment into small stars (Dobbs+ 05)?
Where are the protostellar accretion disks?

# Theories of Massive Star Formation-II

Competitive Accretion Model (Zinnecker 1982; Bonnell+ 97)

Massive stars form via (tidally modified) Bondi-Hoyle accretion onto small protostars formed by gravitational collapse



(Bonnell+ 01, 04)

Challenges:

Does not work in turbulent medium (Bonnell+ 01; Krumholz+ 05)

Magnetic fields (Cunningham+ 12; A. Lee+ 13) and wide-angle outflows reduce accretion, not yet included in simulations

Challenge to both theories: Why doesn't radiation pressure halt accretion?

# Theories of Massive Star Formation-III

Stellar collision model (Bonnell+ 98)

Massive stars form via direct collisions of lower mass stars, thereby overcoming the problem of radiation pressure

Distinct from collisions inferred to occur after formation in binaries (Sana+12—observation), triples (Moeckel & Bonnell 13—theory), and hierarchical clusters (Fujii & Portegies Zwart 13).

Simulations including gas accretion and N-body stellar dynamics show that stellar collisions not important in forming stars in either intermediate clusters like Orion or large clusters like the Arches (Moeckel & Clarke 11, Baumgardt & Klessen 11)

# Core accretion: Suppression of fragmentation-I

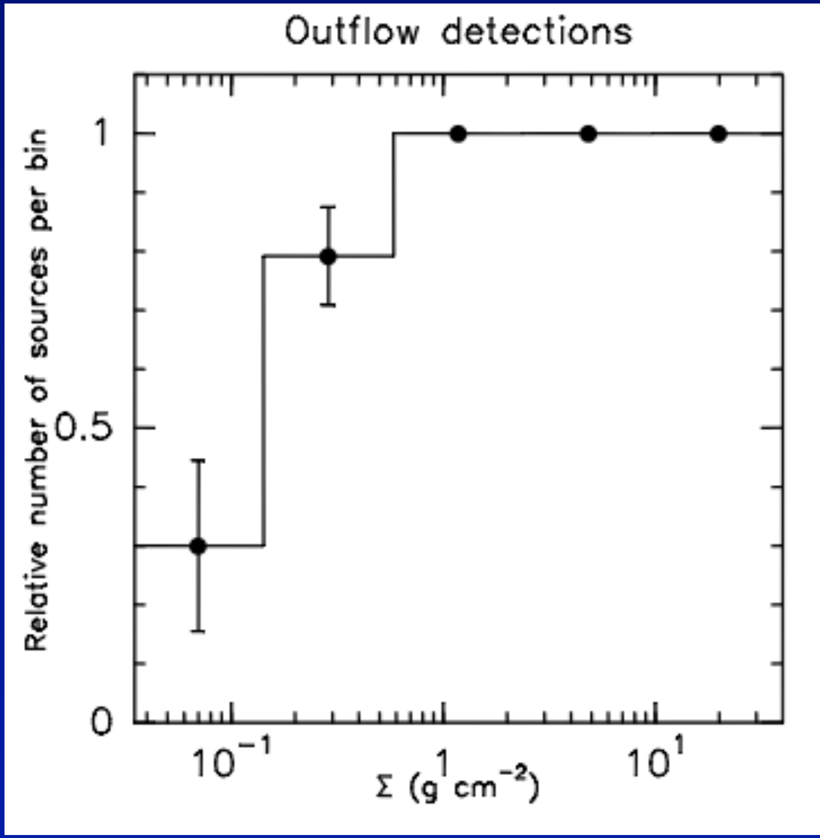
Radiation feedback suppresses fragmentation (Krumholz 06)

Confirmed by simulations (Krumholz+ 2007, 2010, 2011)

A threshold of ~ 1 g $cm^{-2}$ for massive SF? (Krumholz & McKee 08)

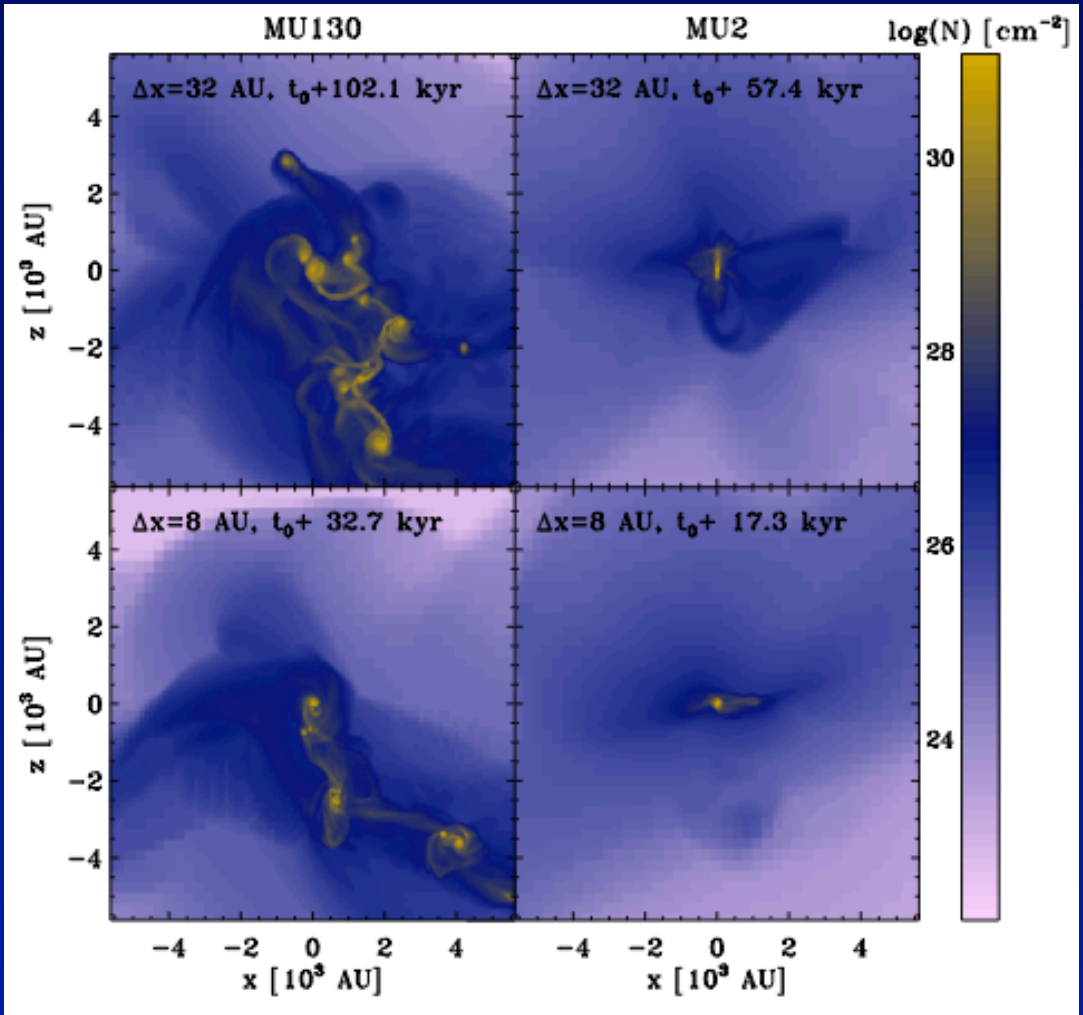
Observation shows frequency of outflows (=> protostars) increases for $\Sigma > 0.3$ g $cm^{-2}$

(Lopez-Sepulchre+ 10)



# Core accretion: Suppression of fragmentation-II

Magnetic fields + radiation more effective at suppressing fragmentation

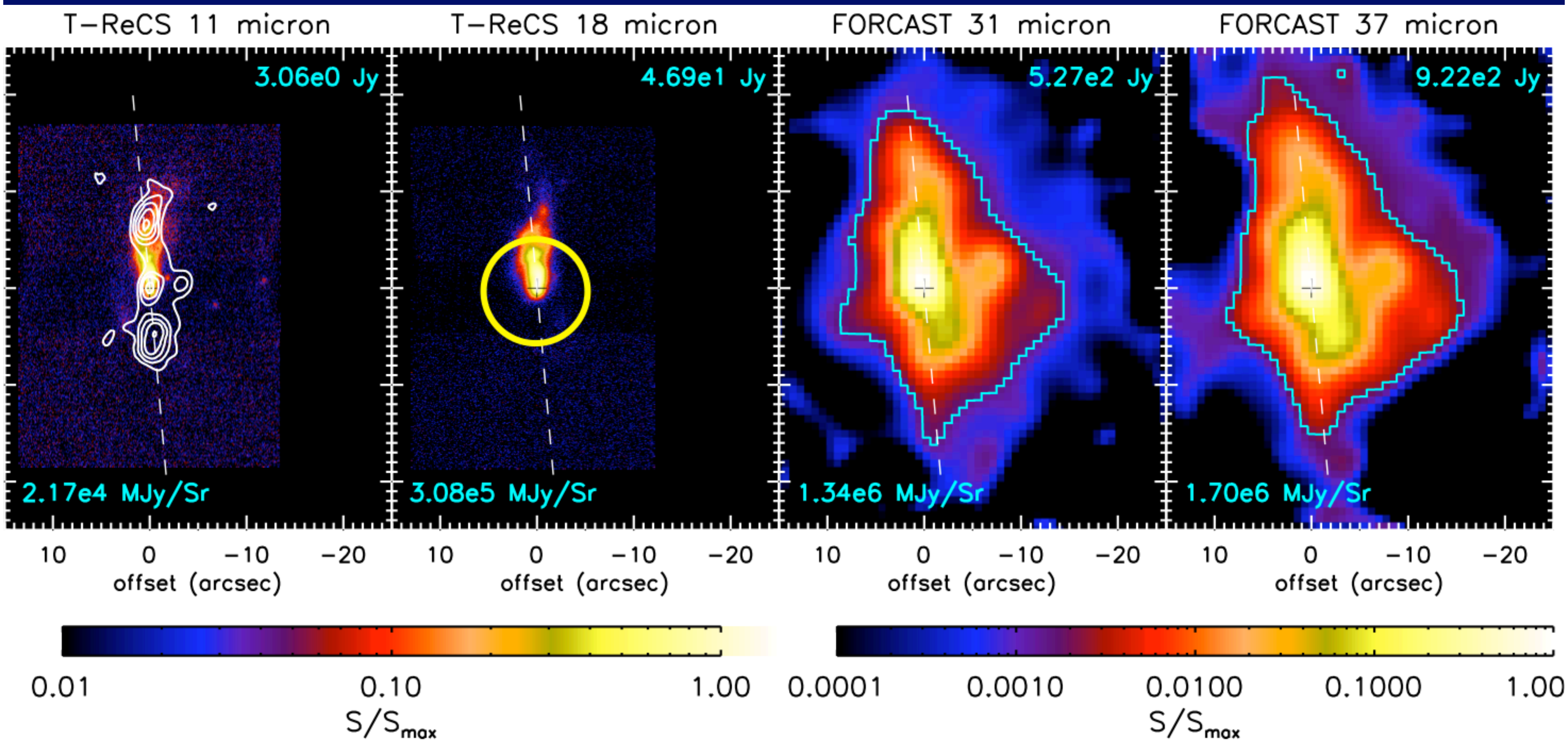



No fragmentation at observed mass/flux (MU2), but significant fragmentation at high mass/flux (MU130)

Commercon+ 11; see also Myers+13

# Core accretion: The Turbulent Core model (McKee & Tan 02, 03)

## Modeling the emission with comparison to G35.2N (Zhang+ 13)--I

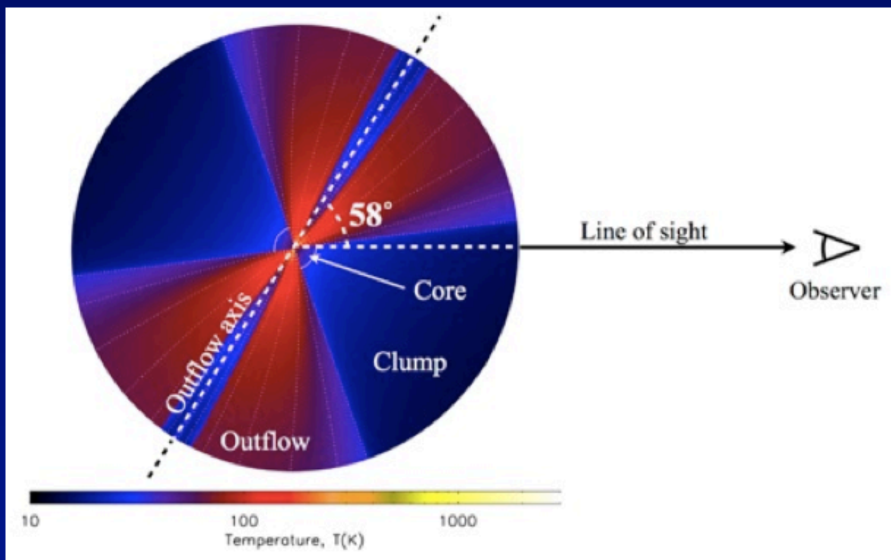


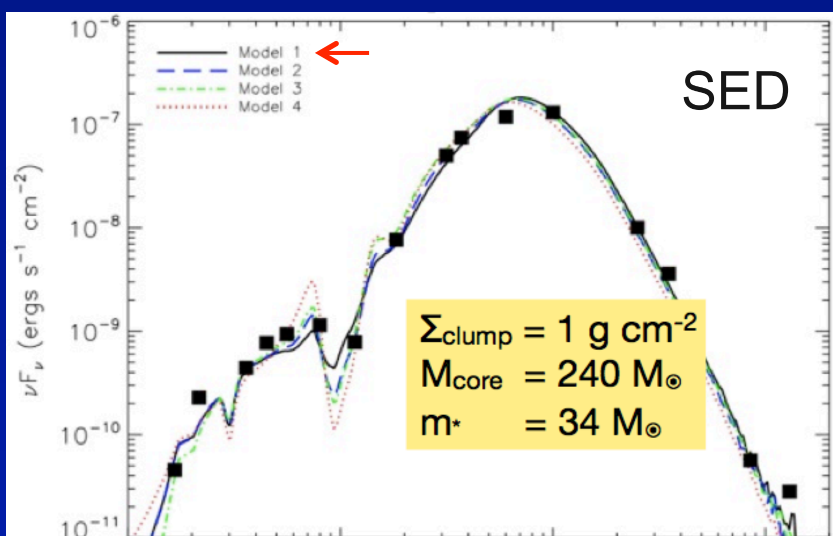

De Buizer (2006)

Zhang, Tan, De Buizer et al. (2013)

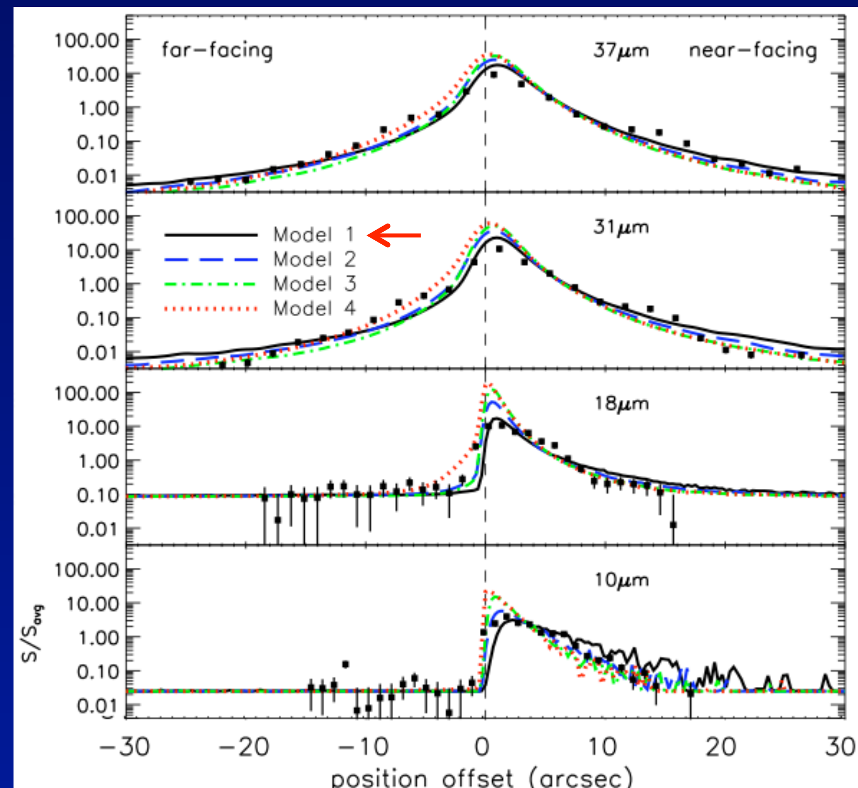
# Core accretion: The Turbulent Core model (McKee & Tan 02, 03)

## Modeling the emission with comparison to G35.2N (Zhang+ 13)--II




Flux profiles along outflow axis




$L_{bol} \sim (0.66 - 2.2)\times10^5 L_\odot$

$M_{core} \sim 240 M_\odot$

$\Sigma_{cl} \sim 0.4 - 1$ g/cm$^2$

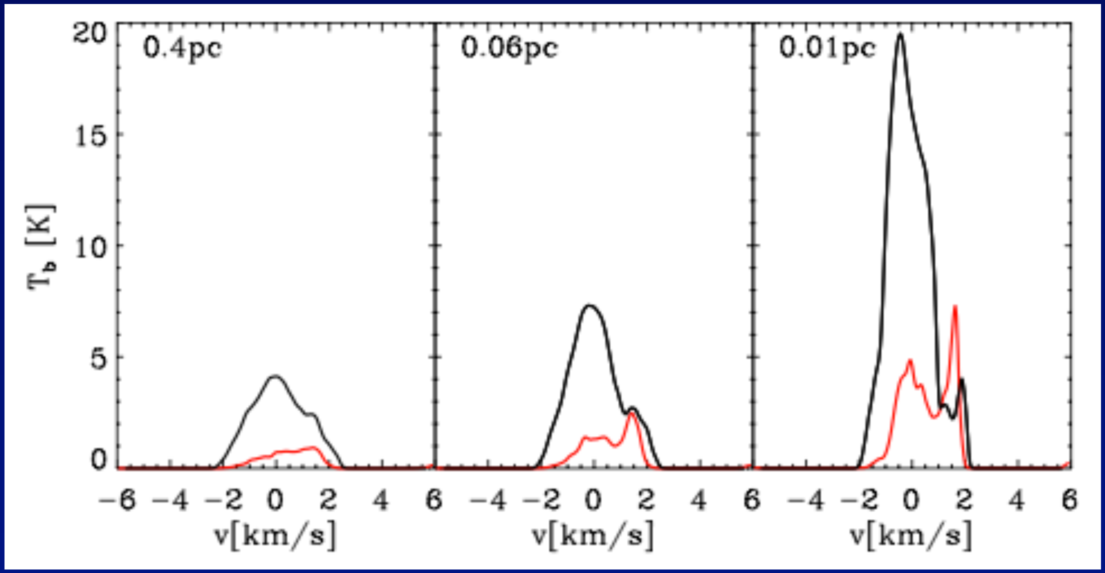
$\theta_w \sim 35 - 51^\circ$

$\theta_{view} \sim 43 - 58^\circ$

**$m_* \sim 20 - 34\ M_\odot$**

# Competitive Accretion

ALMA resolution




Predicted variation of $HCO^+$ (black) and 4 x $N_2H^+$ (red) with resolution

(R. Smith+ 13)

Related models:

Fragmentation-induced starvation (Peters+ 10): Accretion flow onto central massive stars fragments into stars, halting the accretion

Massive star formation via Bondi accretion, including photoionization feedback (Keto 2007)

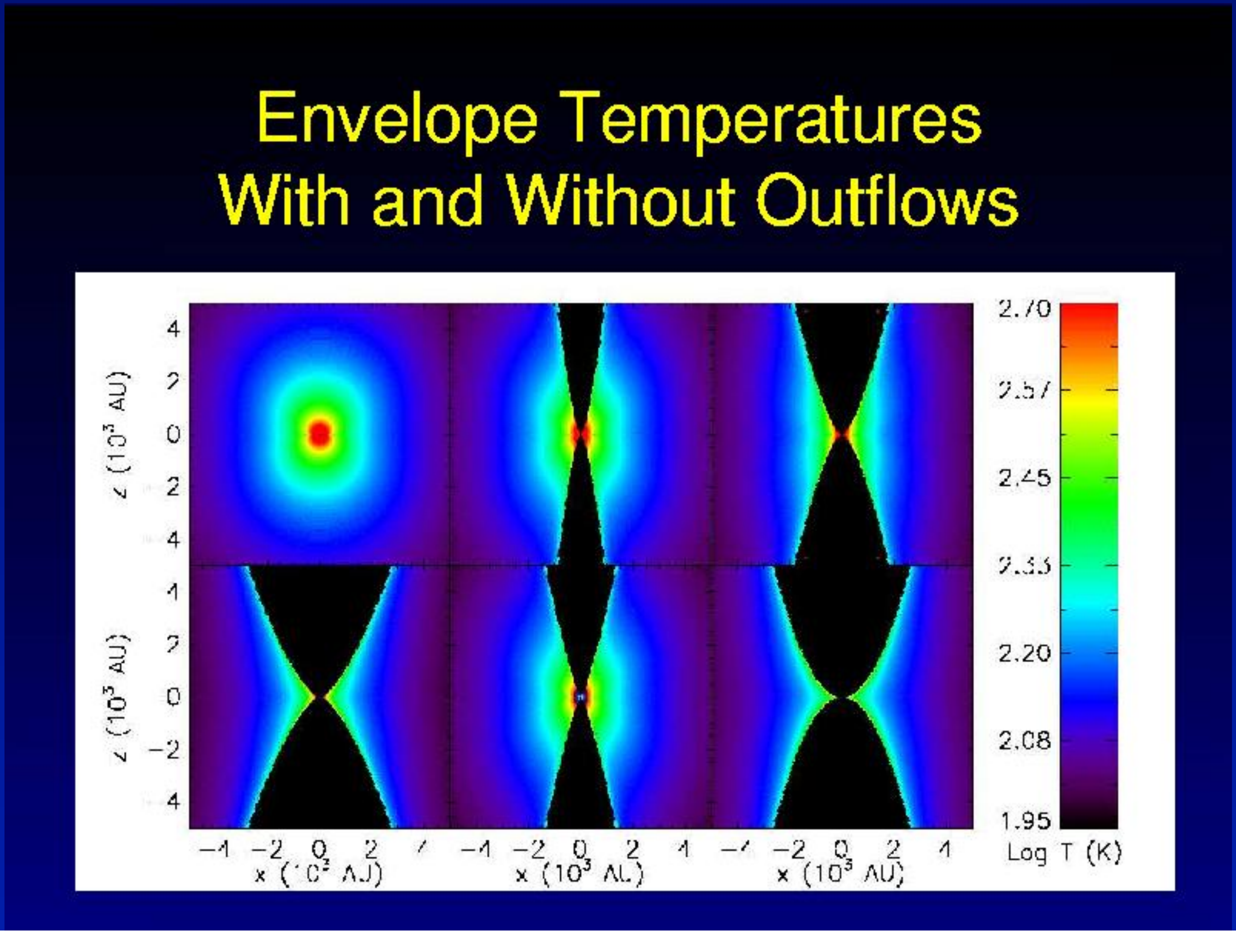
# Overcoming Radiation Pressure--I

Outward force due to radiation exceeds gravity for M* > 20 $M_{sun}$

Theoretical suggestions for overcoming radiation pressure

Disk formation (Nakano 89; Jijina + Adams 96)

Beaming of radiation (Nakano 1989) due to outflow cavity (Krumholz+ 05):



# Overcoming Radiation Pressure--II

Simulations show disks (Kuiper+ 10, 11; Kuiper & Yorke 13) and wind-blown outflow cavities (Cunningham+ 11) enable accretion to continue

Role of Rayleigh-Taylor instability in enabling accretion is disputed:

RTI effective: Krumholz+ 09, Jacquet & Krumholz 11, Jiang+ 13

RTI ineffective: Kuiper+ 10

Will be resolved by future simulations

# Core Accretion or Competitive Accretion or ??

Observation:

Does the IMF mirror the Core Mass Function at high mass?
(e.g., Beuther & Schilke 04)

Are disks always present in high-mass protostars? Ilee+ 13 find 25%

Comparison of high-spatial resolution observations of continuum and line emission with theory (Zhang+ 13; R. Smith+13)

Determine the protostellar luminosity function, which depends on the accretion history of protostars (Offner & McKee 2011)

Is the IMF at high mass universal? The IMF in SgrA* is only slightly flatter than Salpeter (Lu+ 13). What about the origin of very massive stars > 150 $M_{sun}$ (Crowther+ 10)?

Can massive stars form in isolation? Bressert+ 12 find 15 candidate isolated O stars near 30 Dor in the LMC

# Core Accretion or Competitive Accretion or ??

Simulation:

Self-consistent initial conditions: Include self-consistent feedback (Wang + 10) and allow turbulence to cascade down from large scales

Competitive accretion simulations generally begin with smooth initial conditions and do not form bound cores

Core accretion simulations begin with initial density structures, but these are formed before gravity is turned on (e.g., Krumholz+ 12)

Include complete physics:

Non-ideal magnetohydrodynamics

Multi-frequency radiation, beamed from star and diffuse

Ionizing radiation

Protostellar outflows (sub-grid scale for now)

With ALMA and more powerful simulations

THE FUTURE WILL BE REVOLUTIONARY!