# THE FORMATION OF MASSIVE STARS

$\eta$ Carina (NASA, ESA, N. Smith)

# THE FORMATION OF MASSIVE STARS

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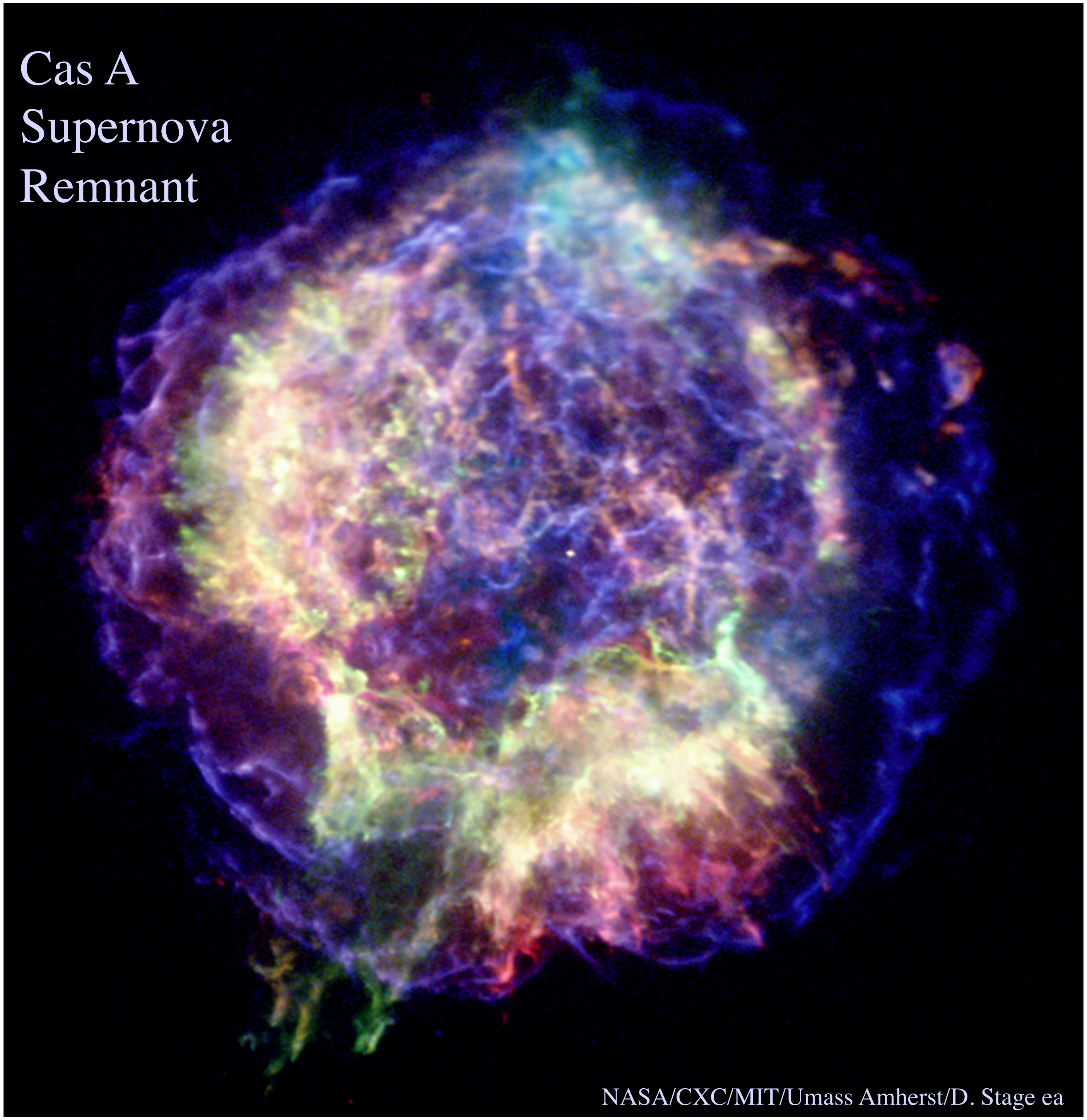
# MASSIVE STARS:

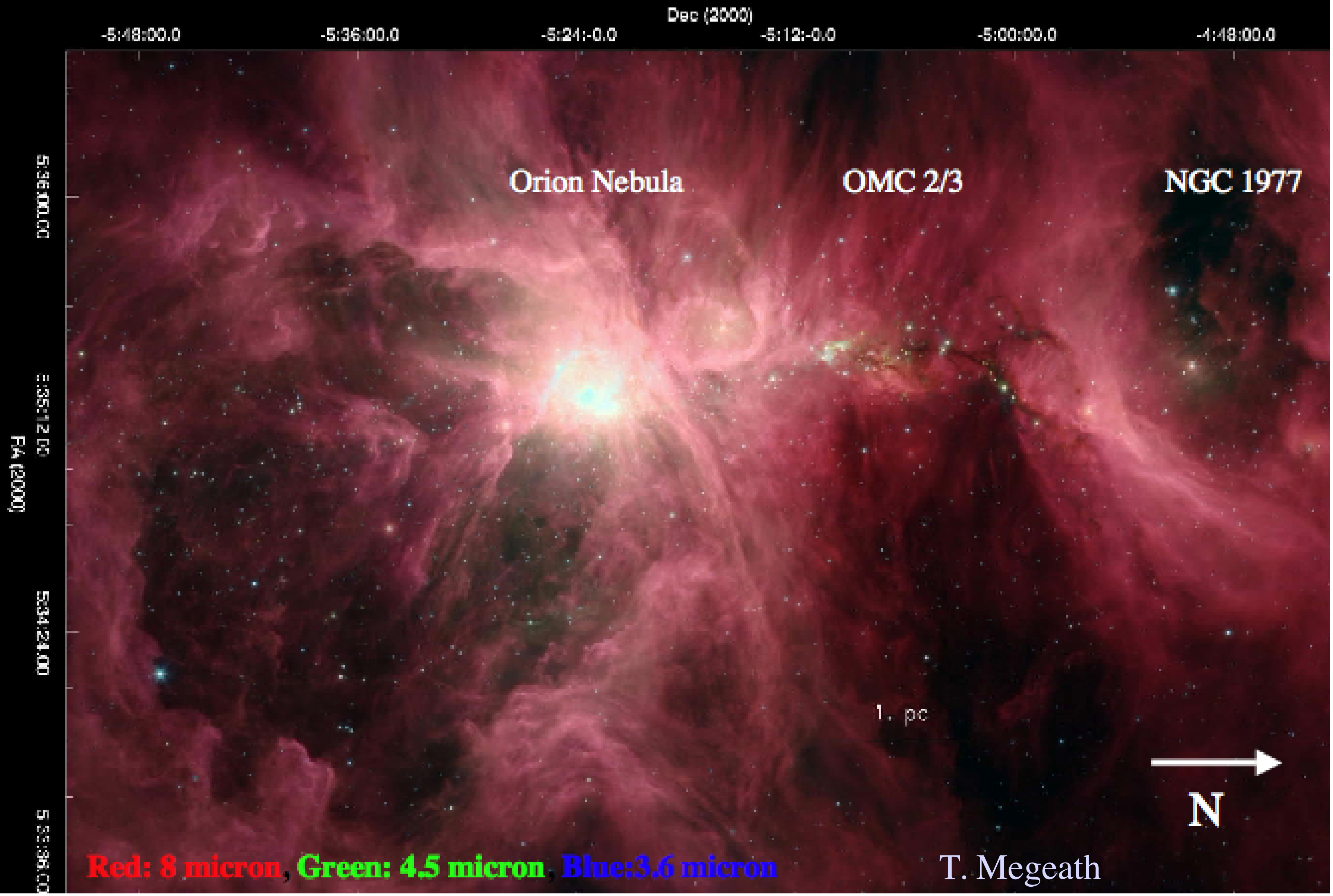
- Create most of the heavy elements


Cas A
Supernova
Remnant
NASA/CXC/MIT/Umass Amherst/D. Stage ea

# 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)

# The Orion Nebula Cluster



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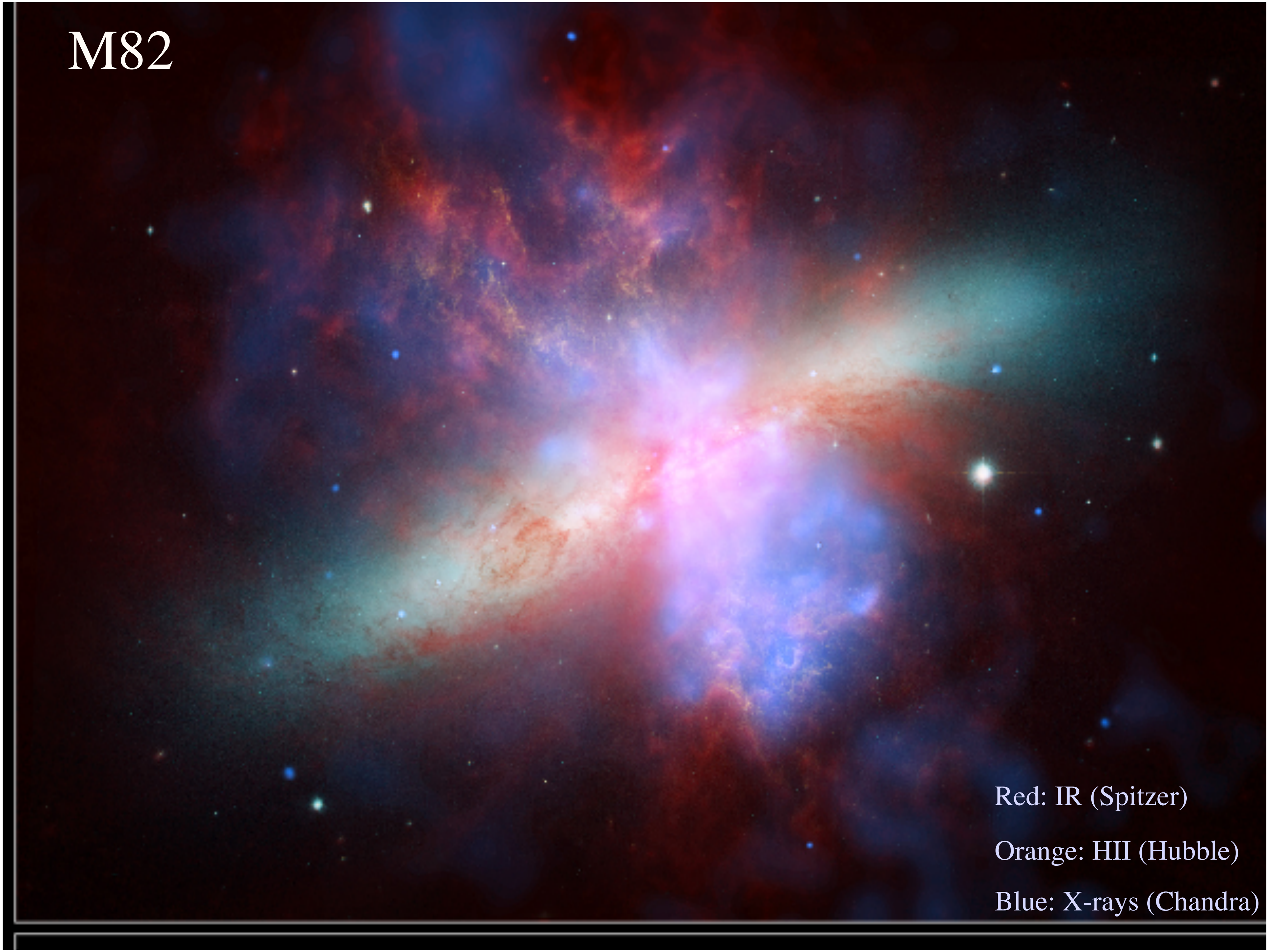
- Govern the evolution of galaxies
  - Radiation pressure drives outflows


M82
Red: IR (Spitzer)
Orange: HII (Hubble)
Blue: X-rays (Chandra)

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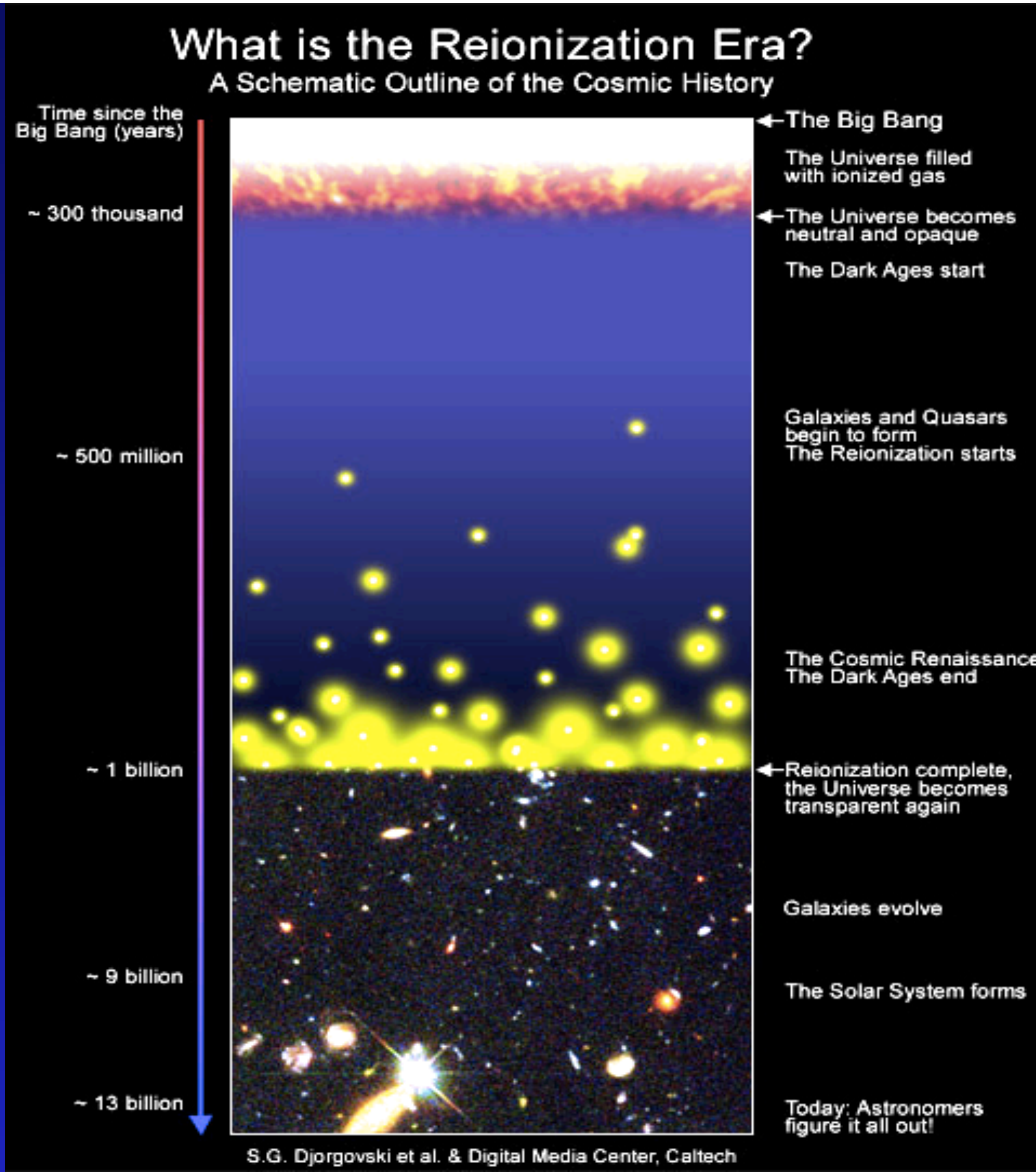
- Regulate star formation
- Govern the evolution of galaxies
  - Radiation pressure drives outflows
- May have re-ionized the universe


What is the Reionization Era?
A Schematic Outline of the Cosmic History
Time since the Big Bang (years)
~ 300 thousand
~ 500 million
~ 1 billion
~ 9 billion
~ 13 billion
The Big Bang
The Universe filled with ionized gas
The Universe becomes neutral and opaque
The Dark Ages start
Galaxies and Quasars begin to form
The Reionization starts
The Cosmic Renaissance
The Dark Ages end
Reionization complete, the Universe becomes transparent again
Galaxies evolve
The Solar System forms
Today: Astronomers figure it all out!
S.G. Djorgovski et al. & Digital Media Center, Caltech

# WHY DO WE KNOW SO LITTLE ABOUT MASSIVE STAR FORMATION?

- OBSERVATION:
  - Highly obscured ($A_V \sim 100\text{-}1000$)
  - Far away ($D \gtrsim 2$ kpc)
  - Crowded ($10^4$ stars $pc^{-3}$ at the center of Orion)

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- THEORY:
  - Wide range of length and time scales (like low-mass star formation)
  - Radiation dynamically important (unlike low-mass star formation)

# OUTLINE

*Characteristics of regions of high-mass star formation

*Basics

I. Star Formation in Isothermal Gas:
Everything you ever wanted to know about star formation in three slides

II. Properties of Turbulent Gas

* Theoretical models of massive star formation

* Challenges in massive star formation: Radiation pressure

* Observational predictions

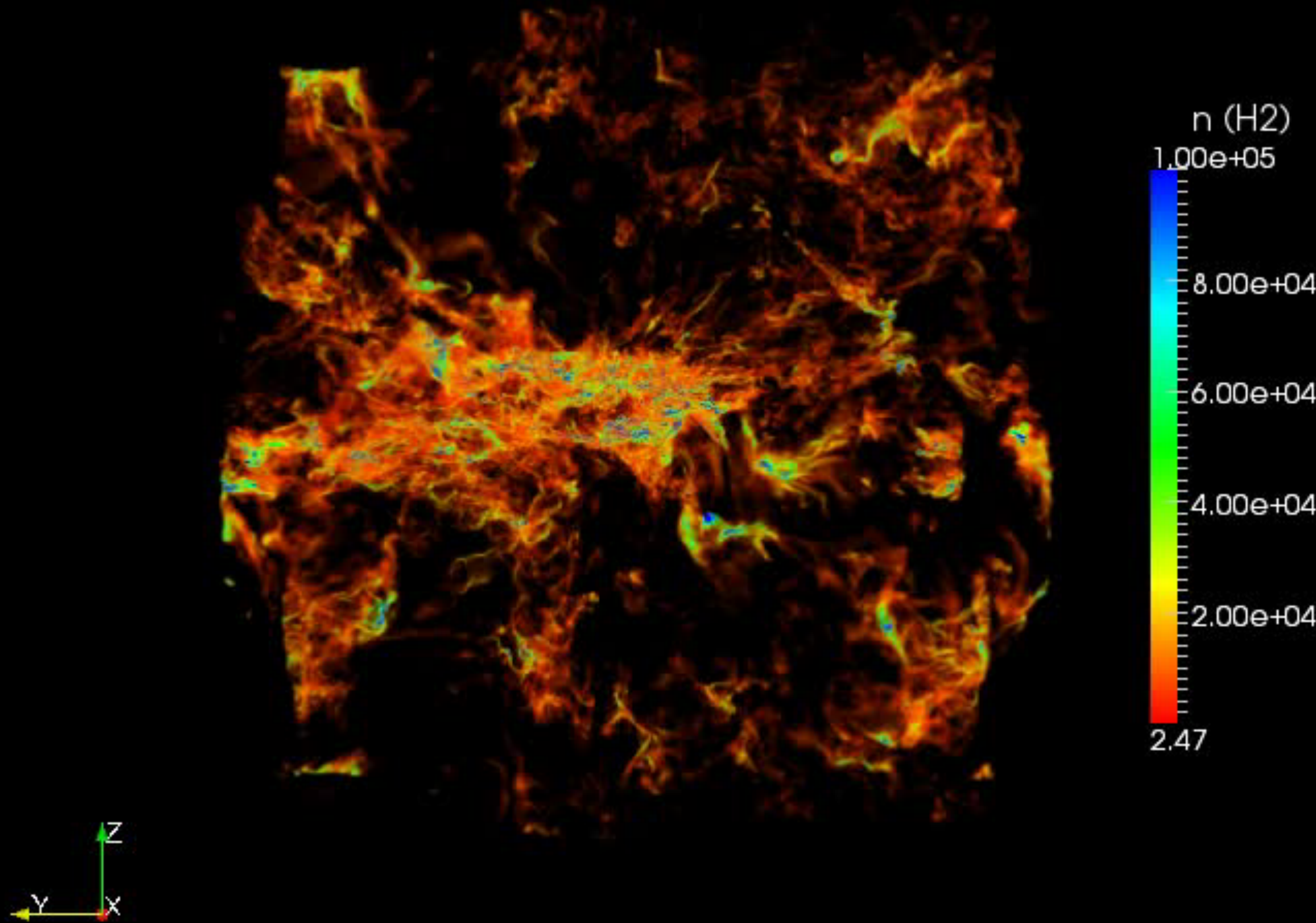
# Characteristics of Regions of Massive Star Formation

An Infrared Dark Cloud (IRDC) that is so dense and opaque that it blocks infrared radiation: the likely birthplace of a massive star

Blue & cyan: starlight
Red & green: dust emission

NASA/JPL-Caltech/WISE

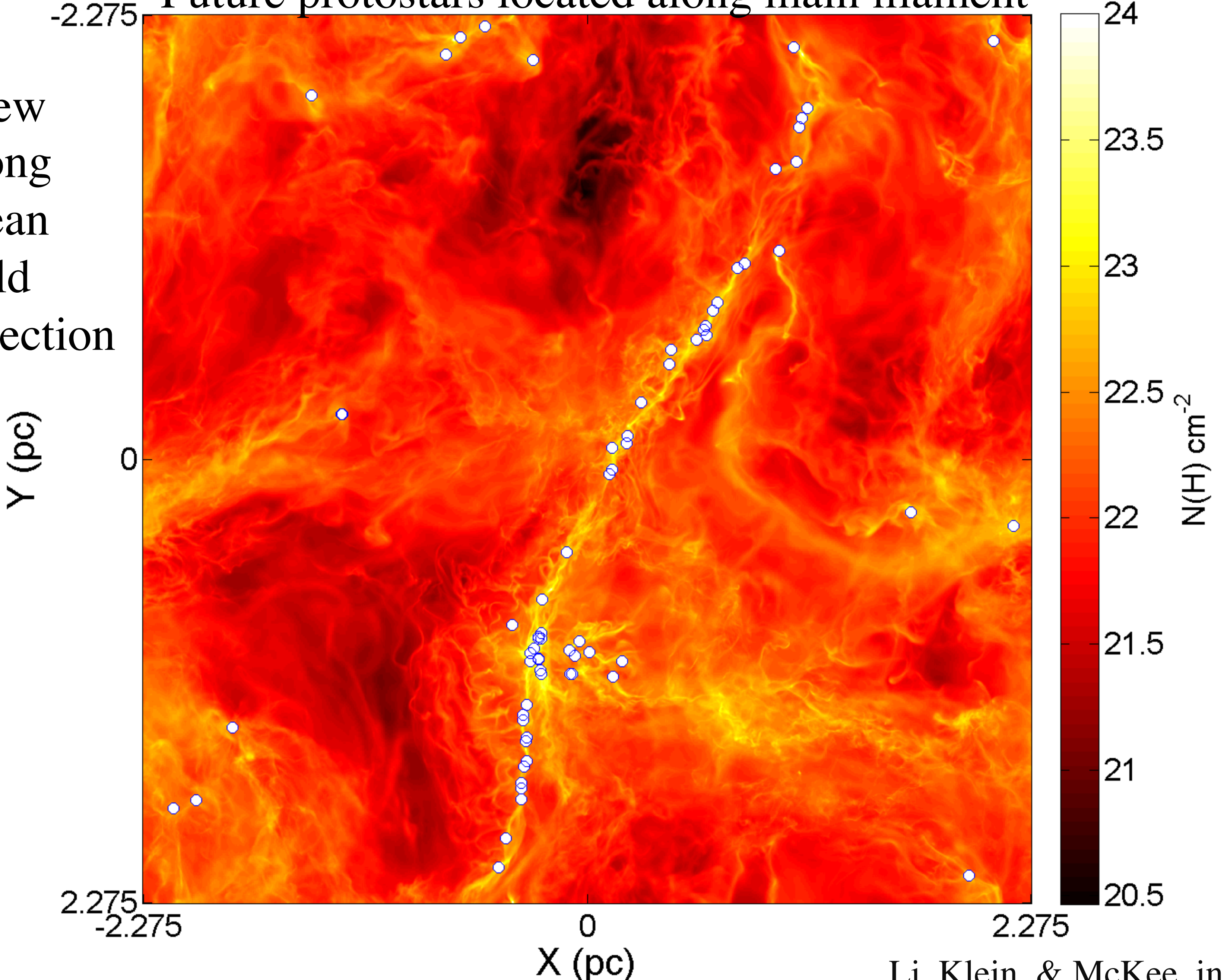
# Simulation of an IRDC in a turbulent, magnetized cloud




Li, Klein, & McKee, in prep

# Future protostars located along main filament

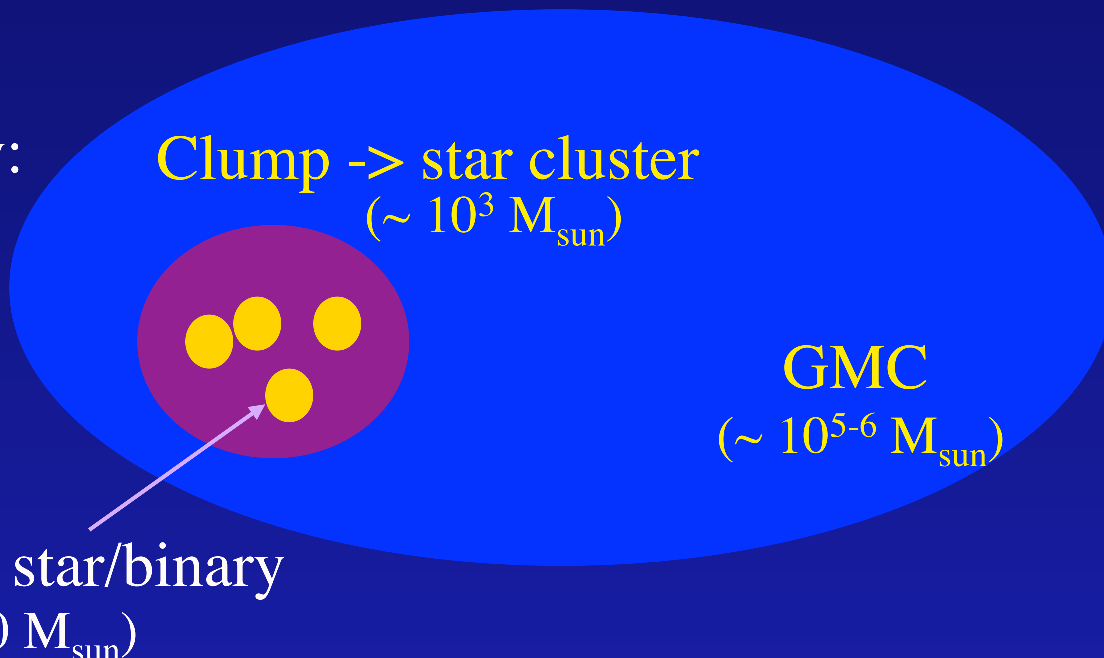
View along mean field direction




Li, Klein, & McKee, in prep

# Hierarchical Structure of Molecular Clouds

Terminology:




Structure self-similar from stellar mass to GMC mass

# High-Mass Star-Forming Clumps

(Plume et al. 1997; Shirley et al. 2003)

Sound speed $c_s \sim 0.3$ km s$^{-1}$ (Temperature ~ 30 K)

Supersonically turbulent: $\sigma \sim 2.5$ km s$^{-1}$

Radius ~ 0.5 pc

Mass ~ 4000 $M_{sun}$

$\Longrightarrow$ Density $\rho \sim 5 \times 10^{-19}$ g cm$^{-3}$ , $n_H \sim 2 \times 10^5$ cm$^{-3}$

Surface density $\Sigma \sim 1$ g cm$^{-2}$ ($A_V \sim 200$)

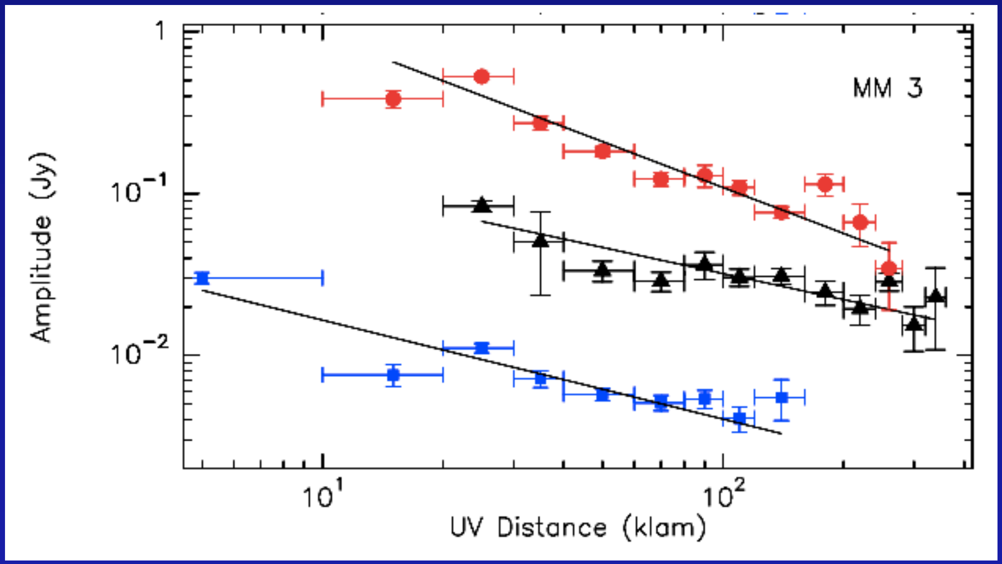
Compare typical Giant Molecular Cloud:

$n_H \sim 100$ cm$^{-3}$

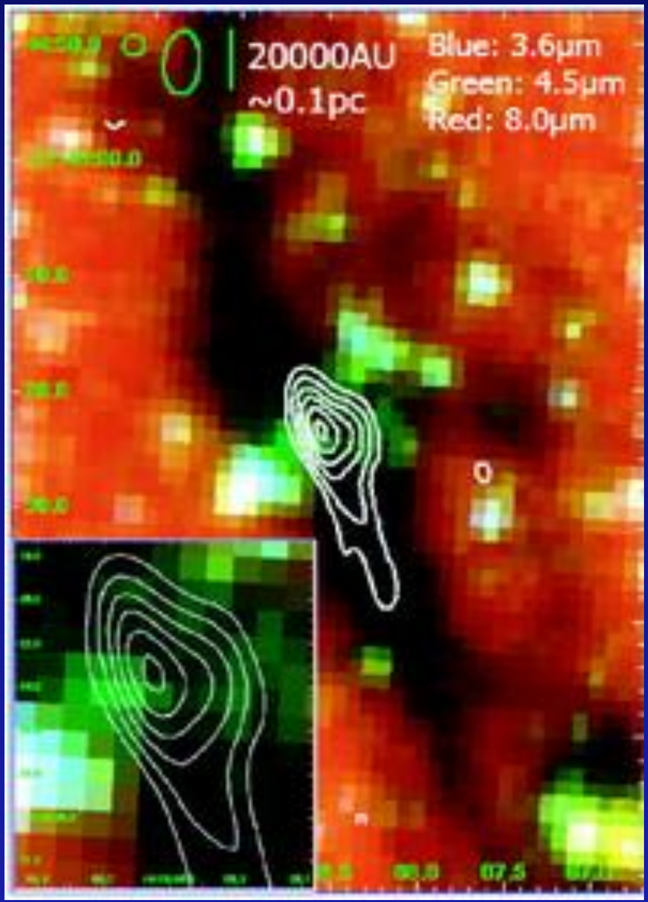
$\Sigma \sim 0.03$ g cm$^{-2}$

# Observation of Massive Cores inside Star-forming Clumps

- Largest cores in clumps: $M \sim 100\ M_\odot$, $R \sim 0.1$ pc
- Cores have power-law density profiles, index $k_\rho \approx 1.5$
- Some are starless now, but they are expected to form massive stars




Core density profile in 3 wavelengths, Beuther+ 07




Core in IRDC 18223-3, Spitzer/IRAC (color) and PdBI 93 GHz continuum (contours), Beuther et al. (2005, 2007)

But, it remains to be seen whether most high-mass stars form from cores, particularly in regions of clustered star formation.

# Evolutionary Sequence for High-Mass Star Formation

(Beuther+ 2007)

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

# BASICS: PART I

# Star Formation in Isothermal Gas

Pioneers:

Jeans, Bonnor, Ebert, Larson, Shu

# EVERYTHING YOU WANTED TO KNOW ABOUT STAR FORMATION: 1

Characteristic timescale set by self-gravity:

$$\frac{d^2R}{dt^2} \sim \frac{R}{t^2} \sim \frac{GM}{R^2}$$

$$\Longrightarrow \qquad t^2 \propto \frac{R^3}{GM} \sim \frac{1}{G\rho}$$

Free-fall time: $t_{ff} = (3\pi/32G\rho)^{1/2}$

$= 1.4 \times 10^5 \; (10^5 \; \mathrm{cm}^{-3}/n)^{1/2} \;\; \mathrm{yr}$

# EVERYTHING YOU WANTED TO KNOW ABOUT STAR FORMATION: 2

Characteristic mass:

Kinetic energy/mass ~ gravitational energy/mass

$$c_s^2 \equiv P/\rho \sim GM/R \implies M \sim Rc_s^2/G$$

Radius: $R \sim c_s t_{ff} \sim c_s/(G\rho)^{1/2}$

$\implies$ Mass $\sim Rc_s^2/G \sim c_s^3 t_{ff}/G \sim c_s^3/(G^3\rho)^{1/2}$

Bonnor-Ebert mass = maximum mass of stable isothermal sphere:

$$M_{\rm BE} = 1.18\, c_{\rm thermal}^3/(G^3\rho)^{1/2}$$

Gravity not important for masses $M << M_{\rm BE}$

EVERYTHING YOU WANTED TO KNOW ABOUT STAR FORMATION: 3

Characteristic accretion rate:

$$\dot{m}_* \sim m_{BE} / t_{ff} \sim c_s^3/(G^3\rho)^{1/2} \times (G\rho)^{1/2} \sim c_s^3/G$$

For a singular isothermal sphere (Shu 1977):

$$\dot{m}_* = 0.975\, c_s^3 / G$$

$$= 1.5 \times 10^{-6}\, (T/ 10\ \mathrm{K})^{3/2}\ \ M_{sun}\ \mathrm{yr}^{-1}$$

An isothermal gas at 10 K takes 6.5 x $10^5$ yr to form a 1 $M_{sun}$ star

6.5 x $10^7$ yr to form a 100 $M_{sun}$ star

>> age of star (~ 3 Myr)

NEED TO GENERALIZE THEORY

# BASICS: PART II

## Properties of Turbulent Gas

Pioneers in observation:

Larson, Falgarone, Solomon, Myers, Goodman

Pioneers in theory:

Gammie, Ostriker & Stone; MacLow; Padoan & Nordlund; Vazquez-Semadeni

# LINEWIDTH-SIZE RELATION IN TURBULENT GAS

Incompressible turbulence (Kolmogorov 1941)

Energy cascade from driving scale to dissipation scale:

$$\frac{v(\ell)^2}{t_{\rm flow}(\ell)} = \frac{v(\ell)^2}{\ell/v(\ell)} = \text{const} \Rightarrow v(\ell) \propto \ell^{1/3}$$

Linewidth-size relations

Supersonic turbulence: $v(\ell) \propto \ell^{1/2}$

Larson (1981) discovered the linewidth-size relation in the ISM

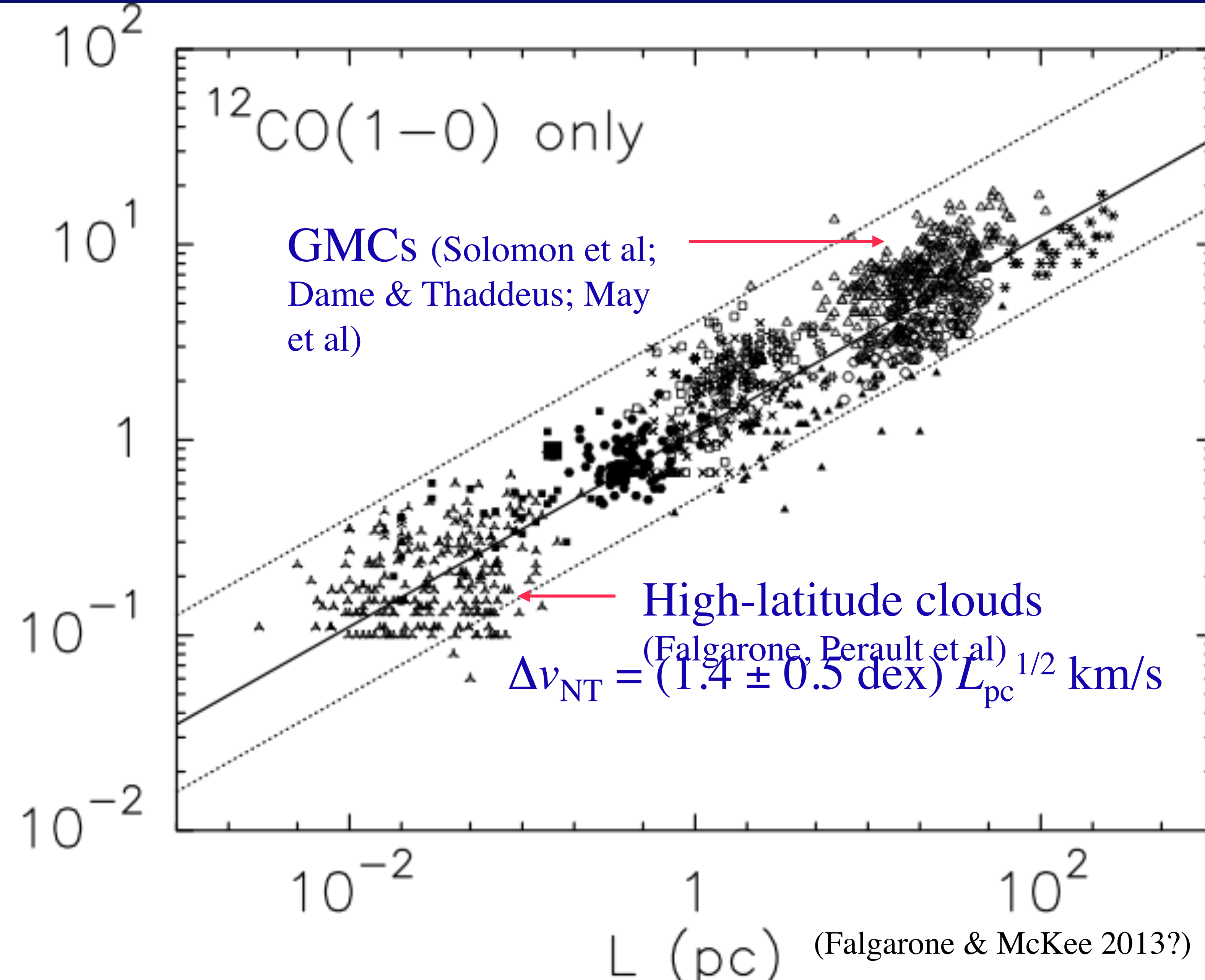
What drives the turbulence in molecular gas?

Supernovae (Mac Low et al)

Star formation (Norman & Silk 1980; McKee 1989; Matzner 2002; Nakamura & Li 2005)

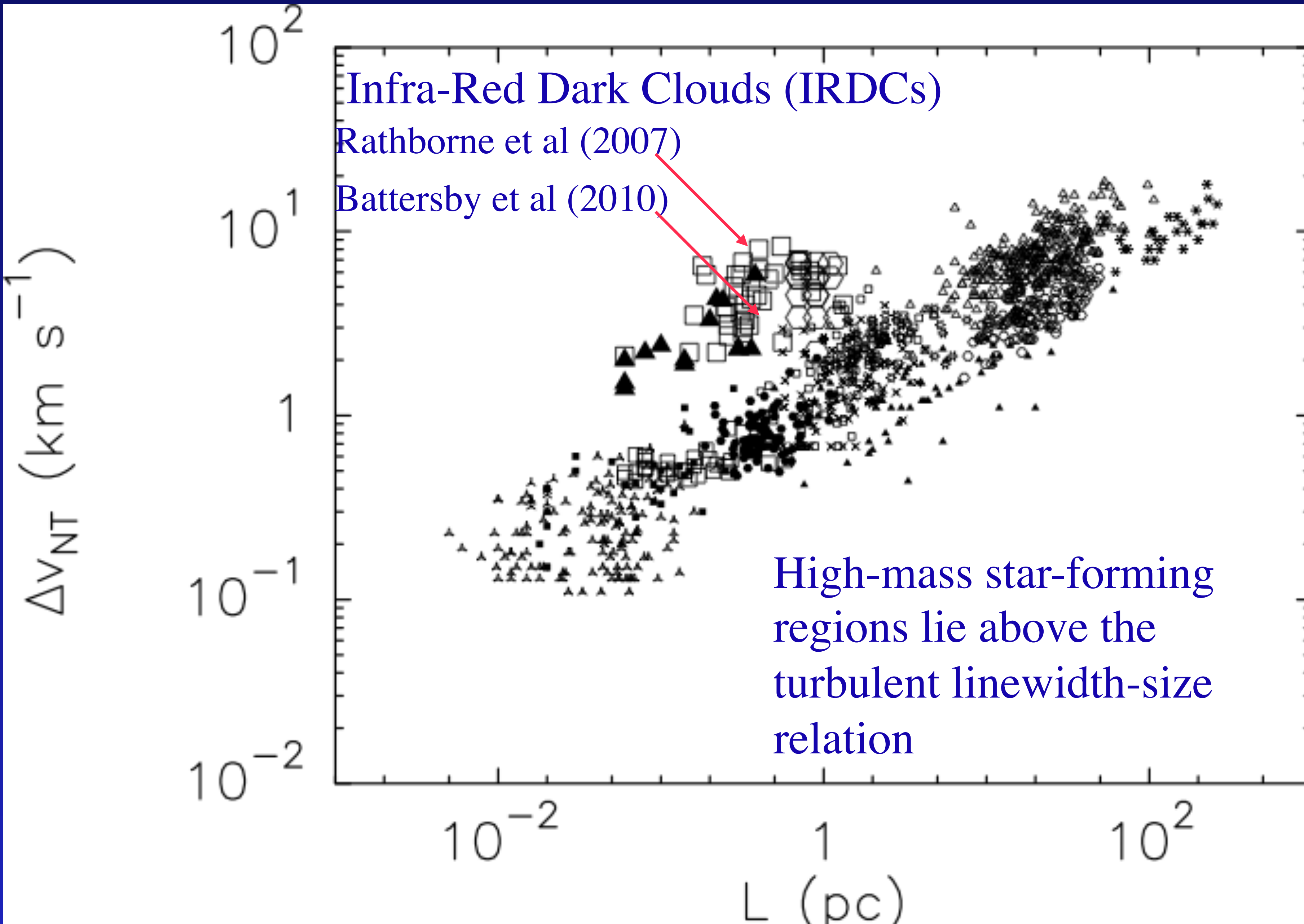
Self-gravity (Field et al. 2008), gravitational accretion (Klessen & Hennebelle 2010; Goldbaum, Krumholz, Matzner, & McKee 2011)

# Turbulent Linewidth-Size Relation for Galactic Molecular Gas




(Falgarone & McKee 2013?)

# Linewidth-Size Relation including High-Mass Star-Forming Regions



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:

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

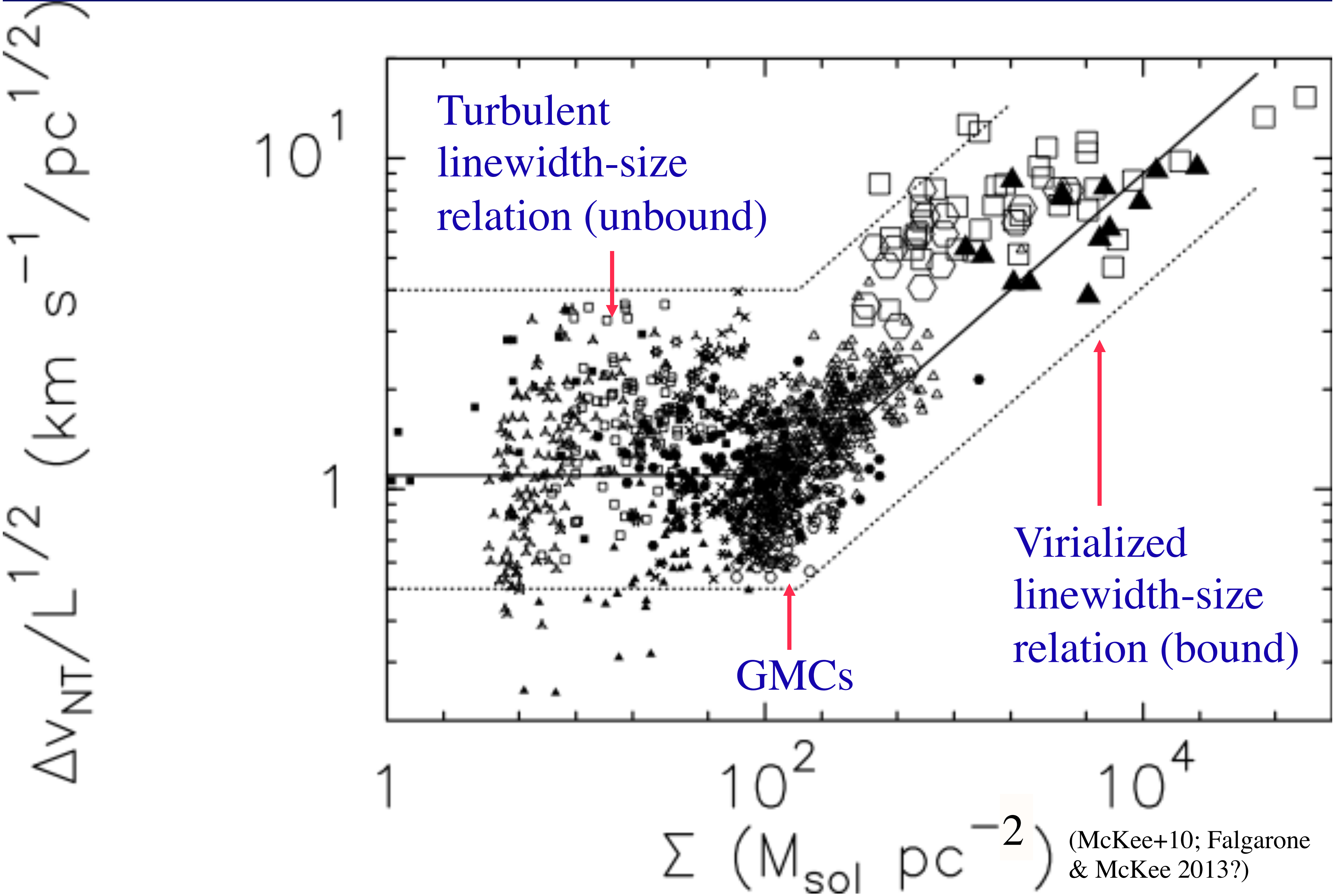
$$\Rightarrow \sigma \equiv \left(\frac{\pi}{5}\alpha_{\mathrm{vir}} G\Sigma R\right)^{1/2} \rightarrow \left(\frac{\pi}{5} G\Sigma R\right)^{1/2}$$

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

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

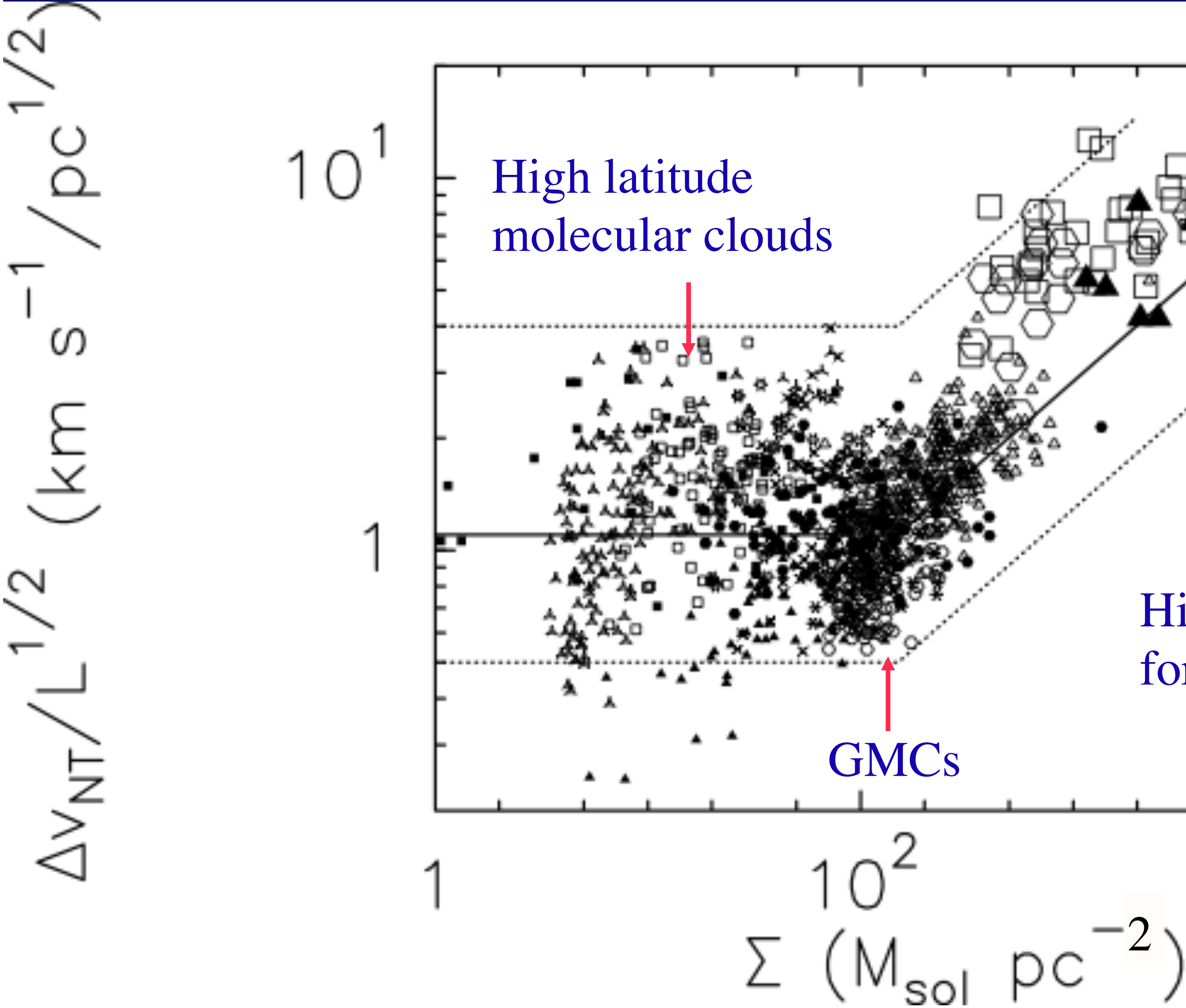
$$\Delta v \simeq 0.9 \left[\left(\frac{\Sigma}{100\, M_{\mathrm{sun}}\,\mathrm{pc}^{-2}}\right) L_{\mathrm{pc}}\right]^{1/2} \qquad \mathrm{km\ s^{-1}}$$

# Generalized Linewidth-Size Relation for Bound and Unbound Gas




(McKee+10; Falgarone & McKee 2013?)

# Generalized Linewidth-Size Relation for Bound and Unbound Gas




(McKee+10; Falgarone & McKee 2013?)

# How 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

1. Core accretion models

    The Turbulent Core Model

    Suppressing fragmentation

2. Competitive accretion model

3. Stellar collision model

# Theories of Massive Star Formation-I

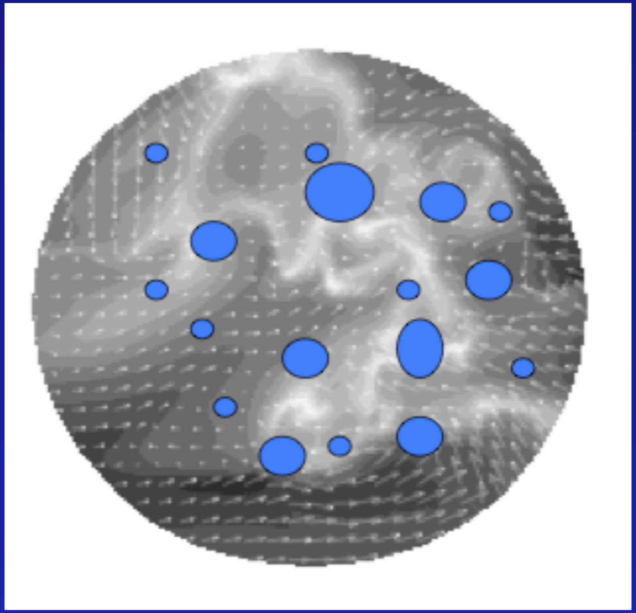
## Core Accretion Models

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? (Discussed later)

# The Turbulent Core Model for Massive Star Formation

(McKee & Tan 2002, 2003)
(Tan & McKee 2004)

Accretion rate $\dot{m}_* \sim \sigma^3/G$ (formation time ~ free-fall time)

However, for massive stars, $\sigma$ is highly supersonic; it depends on scale and must be determined self-consistently.

Virial equilibrium $\Rightarrow \sigma^2 \sim GM/R$

Surface density $\Sigma = M/\pi R^2$

$\Rightarrow \quad \dot{m}_* \propto G^{1/2} (M\,\Sigma)^{3/4}$

Accretion rate determined by core mass $M$ and surface density $\Sigma$: High $\Sigma \Rightarrow$ high accretion rate

Turbulent cores are scale-free $\Rightarrow$ model as singular polytropic spheres (McLaughlin & Pudritz 1996, 1997)

Numerical evaluation $\Rightarrow$ massive stars form in about $10^5$ yr:

$t_{*f} = 0.50 \times 10^5\ (m_{*f}/30\ M_{sun})^{1/4}\ \Sigma^{-3/4}$ yr

## HOW DO MASSIVE PROTOSTELLAR CORES AVOID FRAGMENTATION?

A 30 $M_{sun}$ star forms from a cloud of mass ~ 100 $M_{sun}$; the rest is ejected by the outflow

Recall that the maximum stable mass of an isothermal cloud is the Bonnor-Ebert mass, which is less than 1 $M_{sun}$

Why doesn't the massive protostellar core fragment into a hundred small stars instead of one large one? (Dobbs ea 2005)

High luminosity of accreting protostar raises temperature of gas to several hundred K within 1000 AU

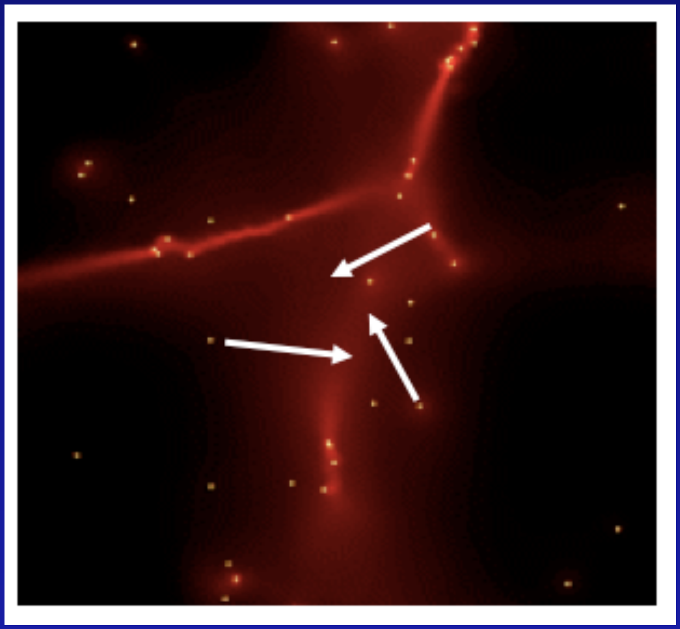
⇒ Jeans mass significantly increased and fragmentation is suppressed -- no fragmentation observed in our calculation.

(Krumholz 2006; Krumholz, Klein & McKee 2007)

# 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)

# THE FUNDAMENTAL PROBLEM IN MASSIVE STAR FORMATION: RADIATION PRESSURE

Force per particle due to radiation flux $F = L/4\pi\, r^2$:

$$\text{Force} = F\,\sigma/c = L\,\sigma/4\pi r^2 c \qquad \text{where here } c = \text{speed of light}$$

$\sigma$ = cross section

Eddington luminosity $L_E$: radiative force balances gravity:

$$L_E\,\sigma/4\pi r^2 c = GM\mu/r^2 \;\Rightarrow L_E = 4\pi GMc/(\sigma/\mu)$$

(where $\mu$ = mass/particle)

Typical infrared cross section per unit mass for dust in massive protostellar envelopes: $\sigma/\mu \approx 5\ \text{cm}^2\ \text{g}^{-1}$

$$\Rightarrow L_E = 4\pi GMc/(\sigma/\mu) = 2500\ (M/M_{sun})\ L_{sun}$$

# THE FUNDAMENTAL PROBLEM IN MASSIVE STAR FORMATION: RADIATION PRESSURE--II

Massive stars are very luminous:

$$L = 10\ (M/M_{sun})^3\ L_{sun} \text{ for } M \sim (7\text{-}20)\ M_{sun}$$

$$L \sim 10^6\ L_{sun} \text{ for } M = 100\ M_{sun}$$

Predict growth of protostar stops when radiative force exceeds gravity:

$$L = 10\ (M/M_{sun})^3\ L_{sun} > L_E = 2500\ (M/M_{sun})\ L_{sun}$$

$\Rightarrow$ Stars cannot grow past 16 $M_{sun}$

But stars are observed to exist with $M > 100\ M_{sun}$

HOW IS THIS POSSIBLE?

## ADDRESSING THE PROBLEM OF RADIATION PRESSURE

- Effect of accretion disks

  Accreting gas has angular momentum and settles into a disk before accreting onto star

  Previous work has shown that disk shadow reduces the radiative force on the accreting gas

  (Nakano 1989; Jijina & Adams 1996; Yorke & Sonnhalter 2002)

- 3D simulation of massive star formation with adaptive mesh refinement (AMR):

  Effect of Rayleigh-Taylor instabilities

  (Krumholz et al. 2009)

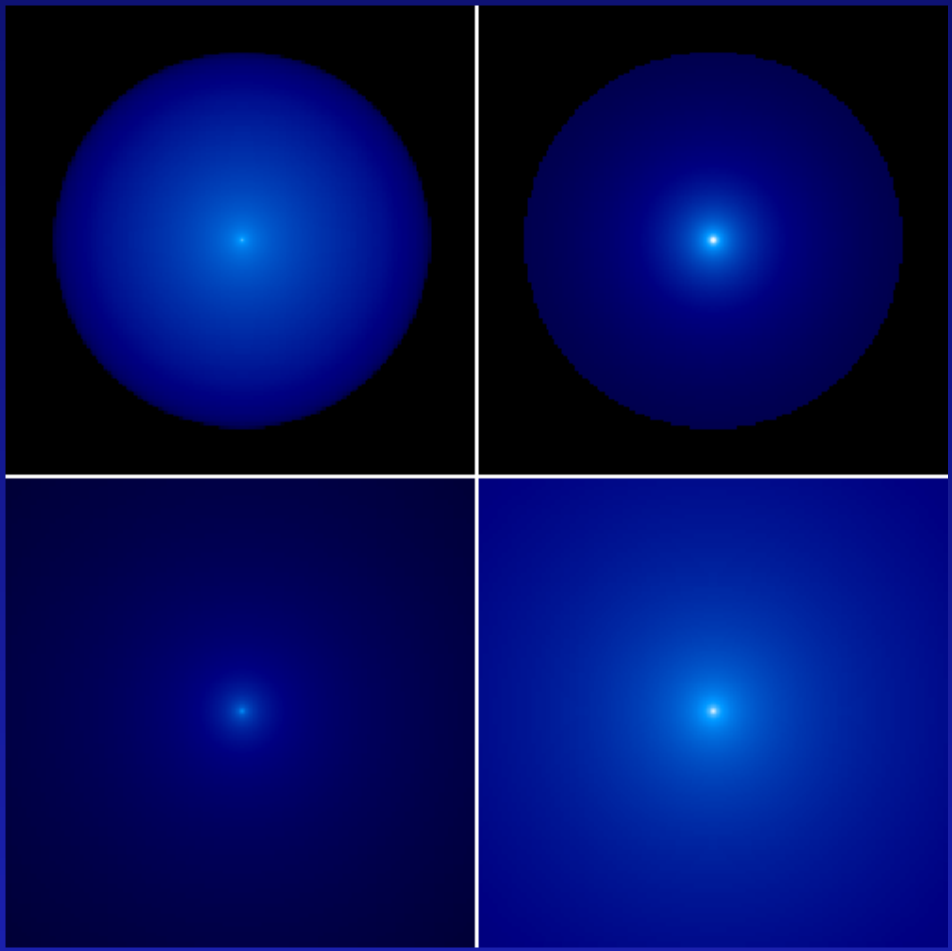
- Effect of bipolar outflows on radiation pressure

  (Krumholz et al. 2005; Cunningham et al 2011)

# Collapse of 100 $M_{sun}$ core to binary with $M_* = 39$ & 27 $M_{sun}$

L = 0.25 pc

L = 2000 AU



Column density along axis

Density in plane with axis

(Krumholz+ 09)

## Conclusion of simulation with radiation pressure but no outflows:

Rayleigh Taylor instability and disk formation allow accretion to overcome radiation pressure

But, the 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

# PROTOSTELLAR OUTFLOWS REDUCE RADIATION PRESSURE

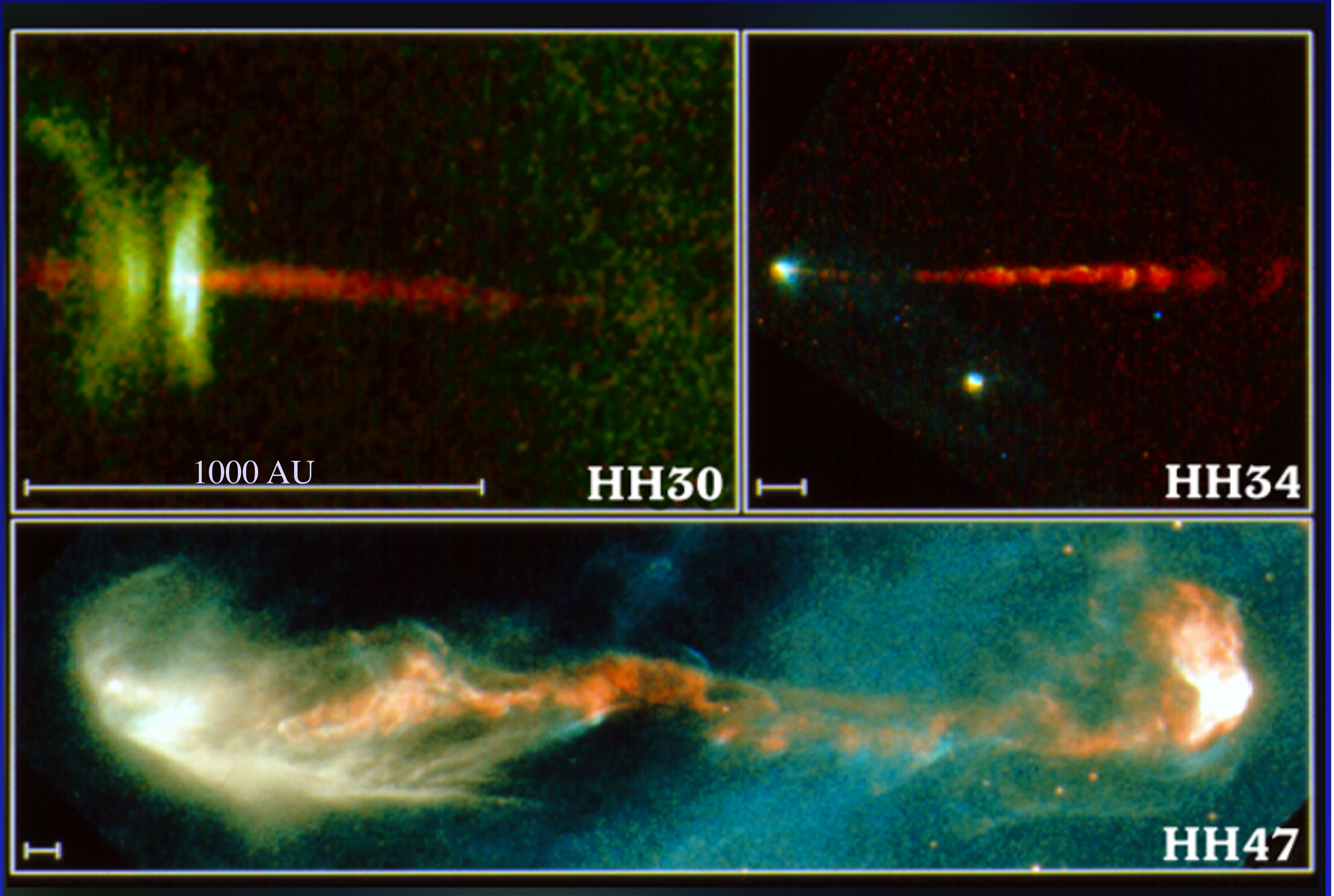
Protostars have powerful, collimated outflows

Mass ejection rate ~ (0.1-0.3) × accretion rate

Wind velocity ~ Keplerian velocity at stellar surface

Outflow is driven by magnetic forces associated with the rotating, magnetized disk

# Bipolar outflows from low-mass protostars



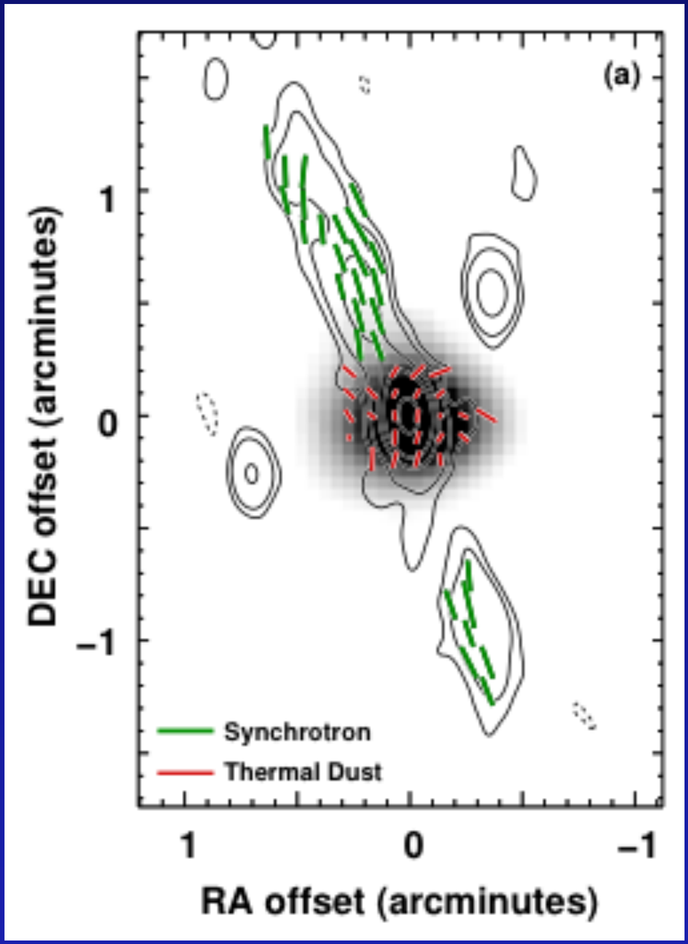

C. Burrows (STScI & ESA); J. Hester (Arizona St); J. Morse (STScI); NASA

# 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)

# PROTOSTELLAR OUTFLOWS REDUCE RADIATION PRESSURE

Protostars have powerful, collimated outflows

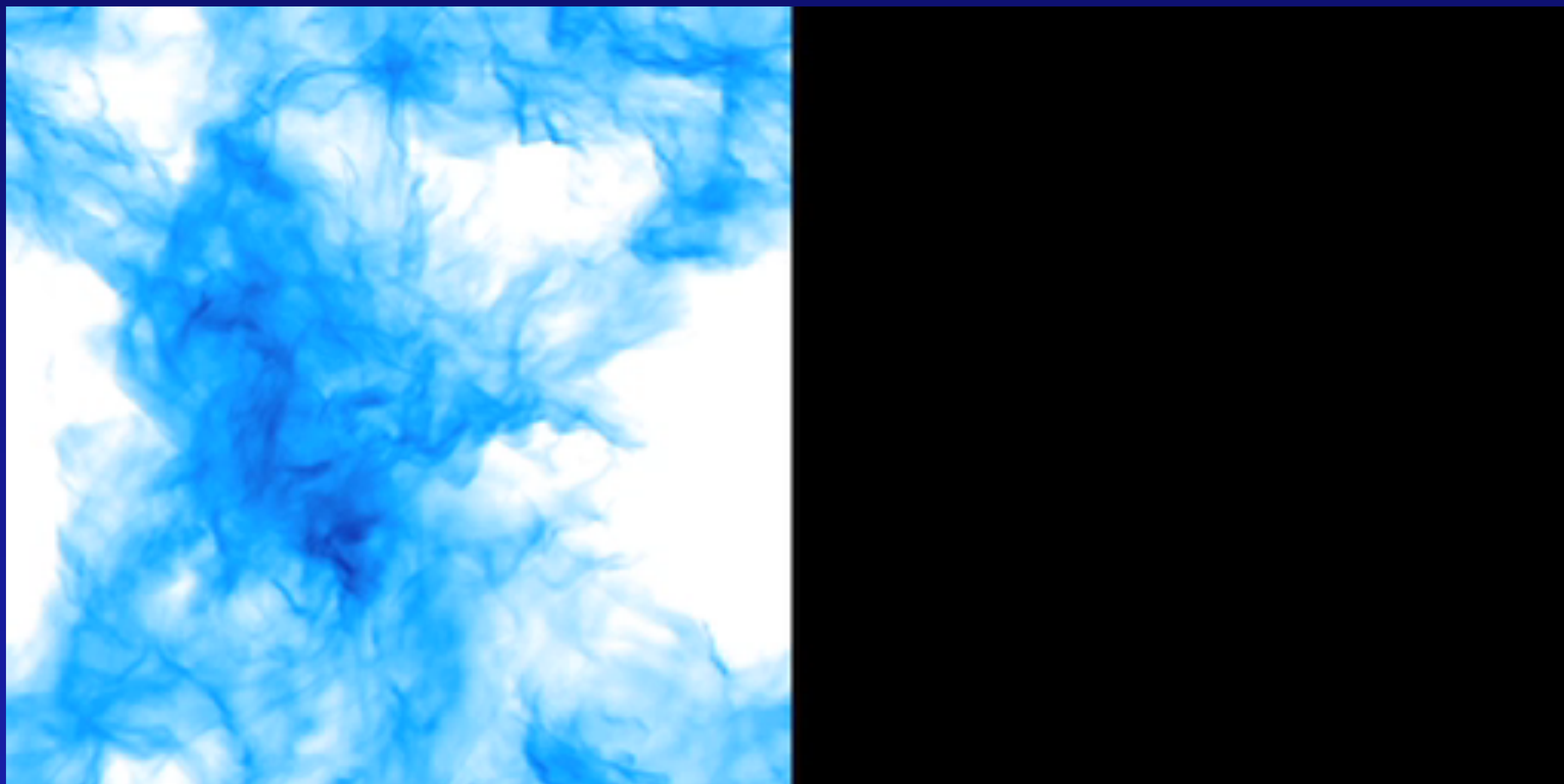
Mass ejection rate ~ (0.1-0.3) × accretion rate onto protostar

Wind velocity ~ Keplerian velocity at stellar surface

Outflow is driven by magnetic forces associated with the rotating, magnetized disk

Wind cavity channels radiation away from infalling gas, reducing radiation pressure

Simulation of the formation of a cluster containing massive stars in a 1000 $M_{sun}$ cloud with surface density 1 g $cm^{-2}$ for 30,000 yr



Mass

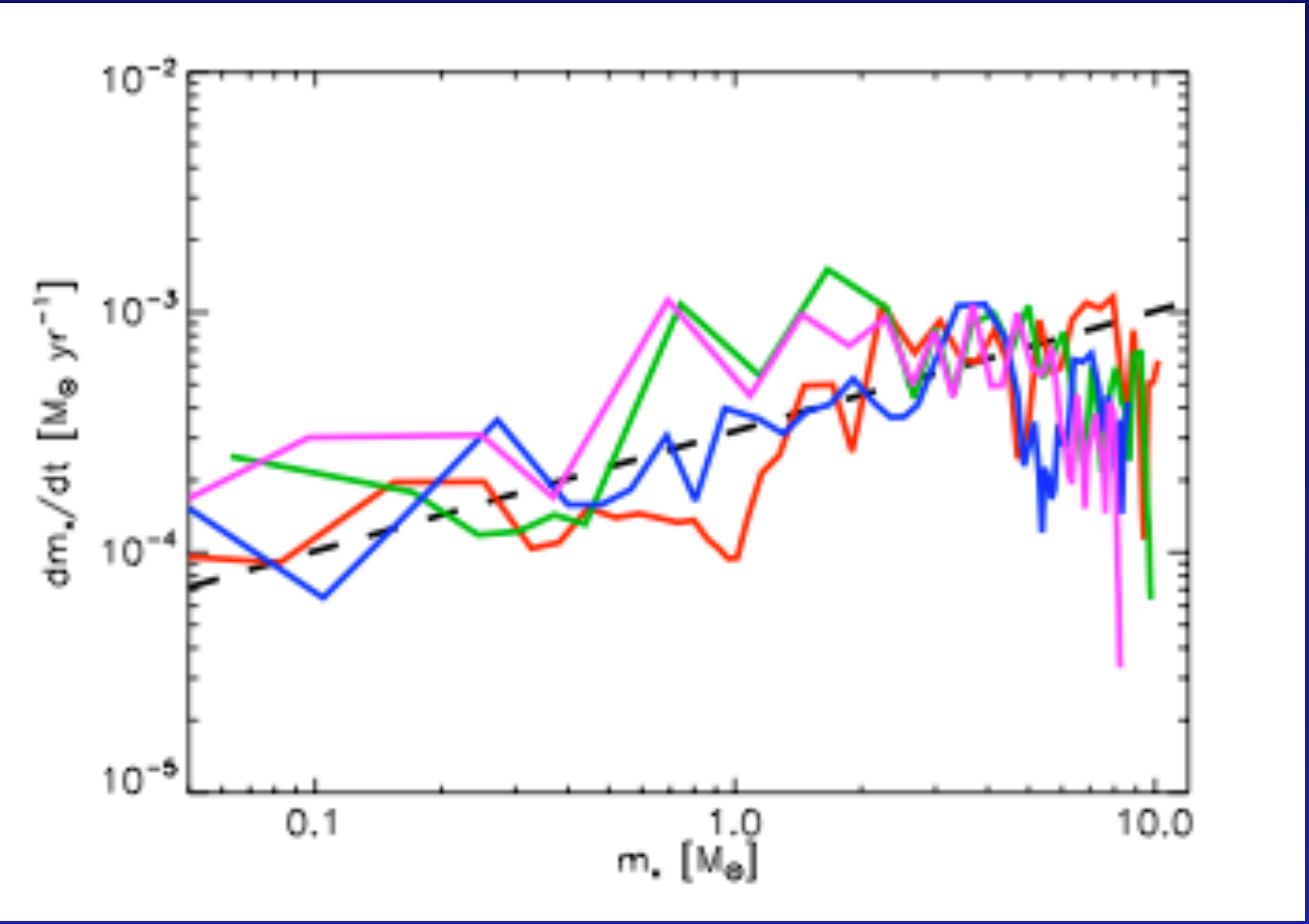
Temperature

First simulation to produce IMF with massive stars

Results consistent with core accretion models

Krumholz et al. (2012)

## Comparison of Theory and Simulation




Accretion rate of 4 most massive protostars in a turbulent 1000 $M_{sun}$ cloud consistent with Turbulent Core Model (McKee & Tan 02, 03; Tan & McKee 04)

(Simulation: Krumholz, Klein & McKee 2012)

# CONCLUSIONS ON RADIATION PRESSURE

Outward force due to radiation pressure can exceed the inward force of gravity during the formation of massive stars

Geometrical effects due to disks and outflow cavities reduce the radiation pressure on the accreting gas; also cool the gas, increasing fragmentation

Radiative Rayleigh-Taylor instabilities may allow continued accretion in absence of outflows; no evidence yet that radiation pressure affects stellar mass

Currently not known whether the maximum mass of a star is set by processes associated with its formation or with instabilities in the star itself

# OBSERVATIONAL PREDICTIONS

1. Massive stars form in cores with surface density $\Sigma \sim 1$ g cm$^{-2}$

# Observed Clusters with Massive Stars Have $\Sigma \sim 1$ g cm$^{-2}$

Table 1. Characteristic Surface Densities of Regions of High-Mass Star Formation

| Object [Ref.][a] | $M$ ($M_\odot$) | $R_{1/2}$ (pc) | $\Sigma$ (g cm$^{-2}$) | $\bar{P}_{\rm cl}/k$ (K cm$^{-3}$) |
|---|---|---|---|---|
| Galactic Star-forming Clumps [1] | 3800[b,c] | 0.5[c] | 1.0 | $4 \times 10^8$ |
| Orion Nebula Cluster [2] | 4600[b] | 0.8 | 0.24 | $2 \times 10^7$ |
| Arches Cluster [3,4] | $2 \times 10^4$ | 0.4 | 4 | $7 \times 10^9$ |
| Galactic Globular Clusters [5,6] | $2 \times 10^5$ [b] | 3.4 | 0.8 | $3 \times 10^8$ |
| NGC1569-A1,A2 [7,8] | $4 \times 10^5$ [b] | 2.2 | 2.7 | $3 \times 10^9$ |
| NGC5253 [9] | $0.6 - 1.5 \times 10^6$ [d] | 1.0 | 20-50 | $2 - 11 \times 10^{11}$ |

[a]References: (1) Plume et al. (1997); (2) Hillenbrand & Hartmann (1998); (3) Figer et al. (1999); (4) Kim et al. (2000); (5) Binney & Merrifield (1998); (6) van den Bergh et al. (1991); (7) Gilbert & Graham (2001); (8) DeMarchi et al. (1997); (9) Turner, Beck, & Ho (2000)

[b]Virial mass estimates

[c]The half-mass radius is not well-defined for the Plume et al. (1997) clouds, since the mass distribution on larger scales is not known. We therefore evaluate $\Sigma = M/\pi R^2$ using the typical radius and virial mass that they observe.

[d]Extrapolation from inferred LyC luminosity of H II region based on Salpeter IMF with a lower mass limit $m_l = 1, 0.1\ M_\odot$.

McKee & Tan (2003)

# OBSERVATIONAL PREDICTIONS

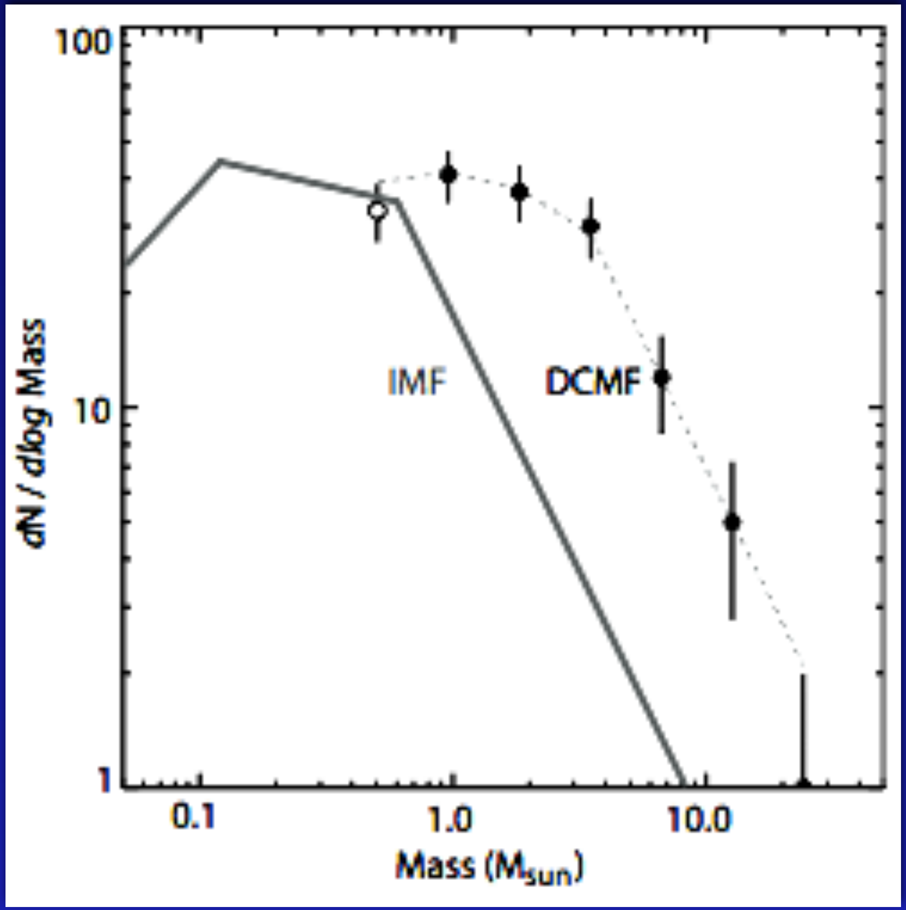
1. Massive stars form in cores with surface density $\Sigma \sim 1$ g cm$^{-2}$

2. The IMF should follow the Core Mass Function, scaled down by a factor of a few (Theory: Matzner & McKee 2000; McKee & Tan 2002, 2003)

# Observed Core Mass Function

(Motte, Andre, & Neri 1998, Testi & Sargent 1998, Johnstone et al. 2001, Reid & Wilson 2005, 2006, Lombardi et al. 2006, Alves et al. 2007)

- The core MF is similar to the stellar IMF, but shifted to higher mass a factor of a few
- Correspondence suggests a 1 to 1 mapping from core mass to star mass




Dense core mass function (DCMF) in Pipe Nebula vs. stellar IMF (gray) (Alves, Lombardi, & Lada 2007)

Predict similar result for massive cores (see Beuther & Schilke 2004; Bontemps et al 2010) --- ALMA observations will test this

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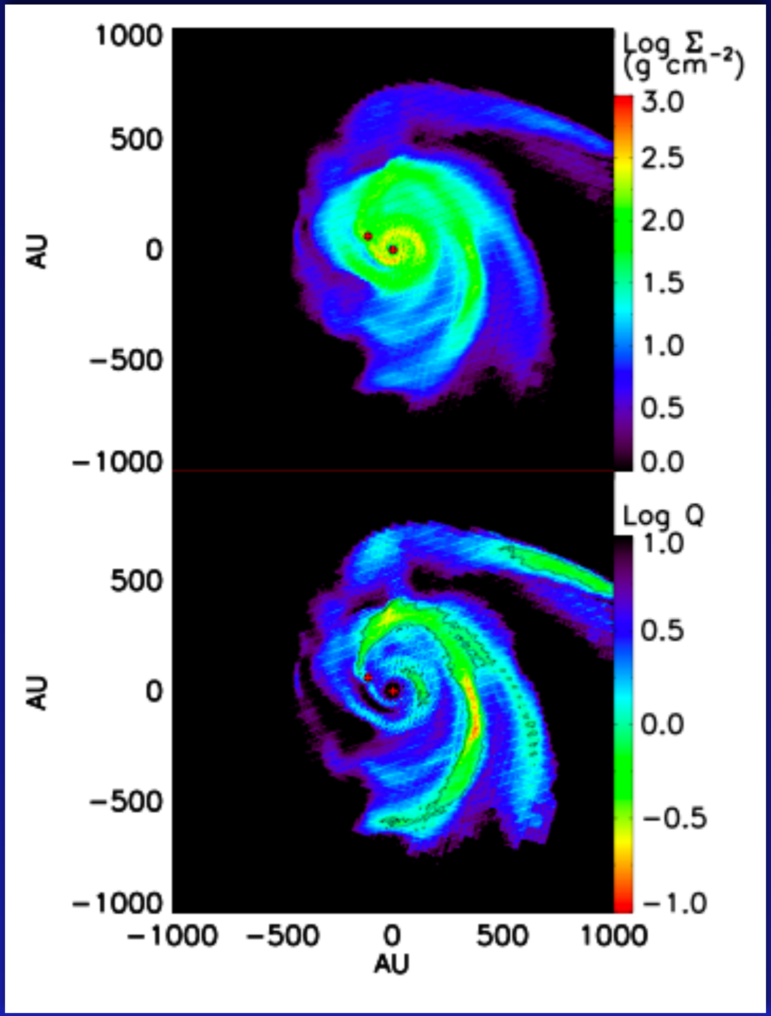
3. Massive disks should accompany massive protostars, in contrast with predictions of competitive accretion or stellar coalescence models

# Massive Disk Properties

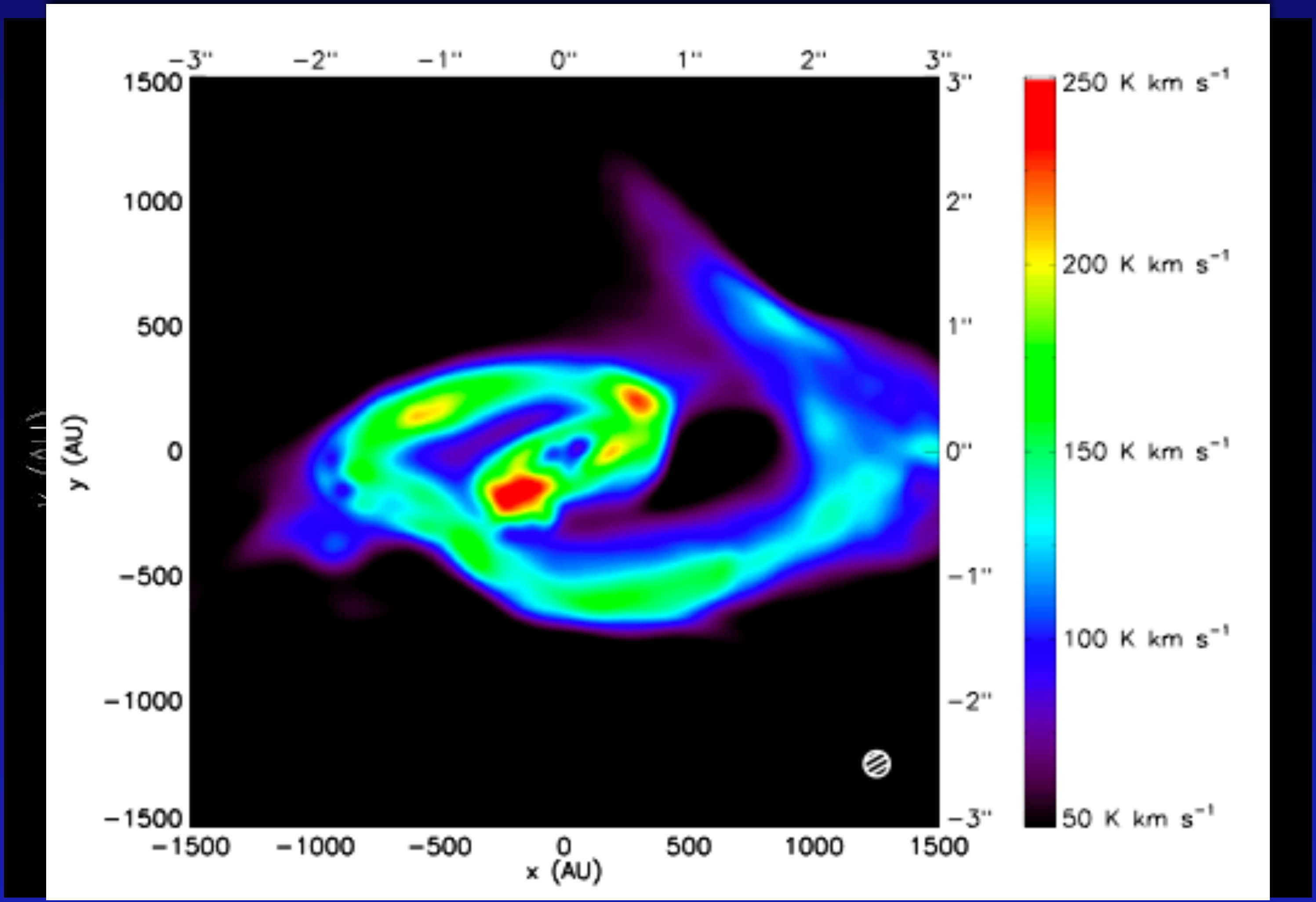
- $M_{\text{disk}} / M_* \approx 0.2 - 0.5$, $r_{\text{disk}} \sim 1000$ AU
- Global gravitational instability creates strong $m = 1$ spiral pattern
- Spiral waves drive rapid accretion; $\alpha_{\text{eff}} \sim 1$
- Disks reach $Q \sim 1$, form a few stellar fragments




Surface density (upper) and Toomre *Q* (lower)

(Krumholz, Klein, & McKee, 2007)

# Prediction for ALMA: Imaging spectroscopy of rotating $m = 1$ spiral



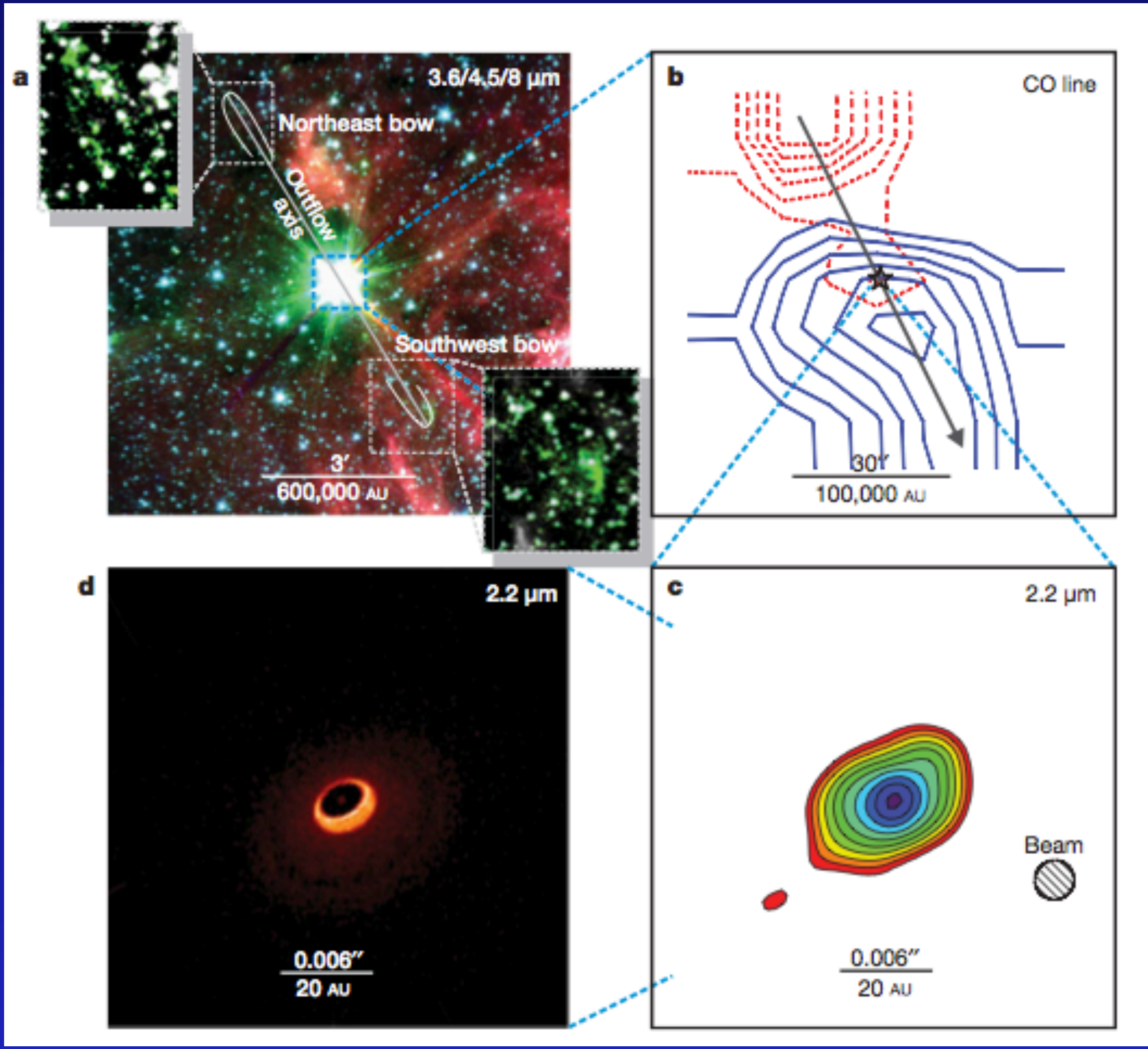

Simulated 1000 s / pointing ALMA observation of edge-on disk at 0.5 kpc in $CH_3CN$ (12-11) 220.7 GHz, $T_{up} = 69$ K (Krumholz, Klein & McKee 2007)

# Discovery of 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



# Discovery of circumstellar disks around massive protostars-II

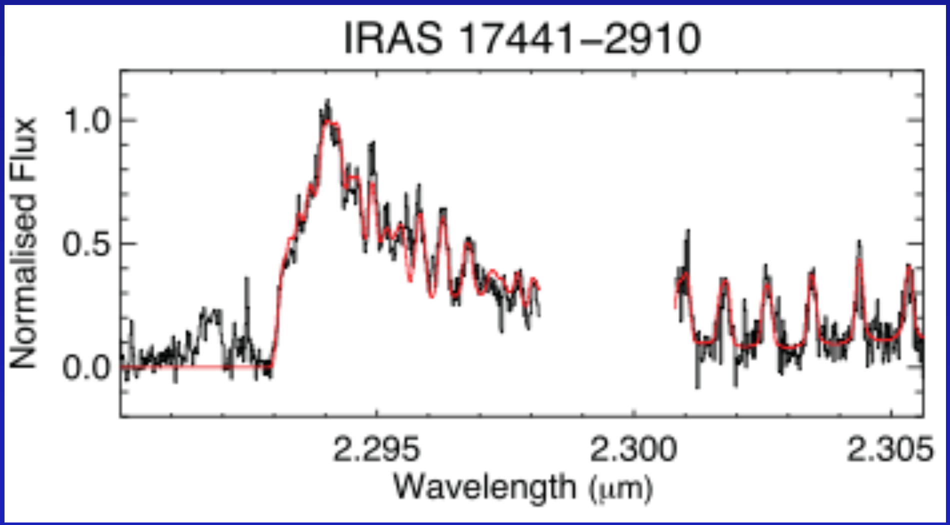
CO bandhead emission from massive YSOs (Ilee+ 13)

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 $M_{sun}$ :



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*Full understanding of massive star formation requires more observation, simulation and theory

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(Myers+ in prep include magnetic fields also)

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Our understanding of massive star formation should be transformed in the next 2-3 years—and you can contribute!