Massive Star Formation Through The Universe

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Orion Nebula Cluster (VLT; JHK) (McCaughrean)

Primordial Mini-Halo (Abel, Bryan, Norman)
The Importance of Massive Stars
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**Planets form** from the crumbs left over from star formation. Planet & star formation in star clusters can be influenced by massive star feedback.
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Supermassive black hole formation may be via massive star clusters or Pop III stars. Supermassive black hole accretion is likely to be regulated by star formation.
The Physics of Massive Star Formation
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- A complicated, nonlinear process
- Gravity vs pressure (thermal, magnetic, turbulence, radiation, cosmic rays) and shear.
- Heating and cooling, generation and decay of turbulence, generation (dynamo) and diffusion of B-fields.
- Chemical evolution of dust and gas.
- Stellar structure and evolution
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- Stellar structure and evolution

- Wide range of scales (~12 dex in space, time) and multidimensional.

- Uncertain/unconstrained initial conditions/boundary conditions.
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Notation for the gas structures:
Core -> star or close binary
Clump -> star cluster
(Massive) Star Formation: Open Questions

- **Causation**: external triggering or spontaneous gravitational instability?
- **Initial conditions**: how close to equilibrium?
- **Accretion mechanism**: [turbulent/magnetic/thermal-pressure]-regulated fragmentation to form **cores** vs **competitive accretion / mergers**
- **Timescale**: fast or slow (# of dynamical times)?

$N \sim m^{2.35}$

Salpeter (1955)
(Massive) Star Formation: Open Questions

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- **Accretion mechanism:** [turbulent/magnetic/thermal-pressure]-regulated fragmentation to form **cores** vs competitive accretion / mergers
- **Timescale:** fast or slow (# of dynamical times)?
- **End result**
  - Initial mass function (IMF)
  - Binary fraction and properties

\[
dN^*/dm^* = A \, m^*^{-2.35}
\]

How do these properties vary with environment?
**Σ - M Diagram**

Physical Properties of Star-Forming Regions

\[
\Sigma \equiv \frac{M}{\pi R^2}
\]

\[
\bar{P} \sim G \Sigma^2
\]

\[
\bar{P}/k = 4.3 \times 10^{9} \Sigma^2 \text{K} \text{ cm}^{-3}
\]

\[
t_{ff} = \left( \frac{3\pi}{32G\rho} \right)^{1/2}
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- \(A_V = 1.4\)
- \(N_H = 3.0 \times 10^{21} \text{ cm}^{-2}\)
- \(\Sigma = 34 \, M_\odot \, \text{pc}^{-2}\)
- \(\Sigma \sim 10 \, M_\odot \, \text{pc}^{-2}\)

Local Galactic Disk
**CO GMCs and Clumps**
Solomon et al. (1987)
Roman-Duval et al. (2010)

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\[ A_V = 7.5 \]
\[ A_{8\mu m} = 0.30 \]
\[ N_H = 1.6 \times 10^{22} \text{cm}^{-2} \]
\[ \Sigma = 180 \text{ M}_\odot \text{ pc}^{-2} \]

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Santangelo et al. (2009)

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Simulated GMCs and Clumps
Tasker & Tan (2009)
Van Loo, Butler & Tan (2013)

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Physical Properties of Star-Forming Regions

$\Sigma \equiv \frac{M}{\pi R^2}$

$\frac{\dot{P}}{\pi} \approx G\Sigma^2$

$\frac{\dot{P}}{\pi} = 4.3 \times 10^5 \Sigma^2 K \text{cm}^{-3}$

$\Sigma = 34 M_\odot \text{pc}^{-2}$

$A_V = 7.5$
$A_{8\mu m} = 0.30$
$N_H = 1.6 \times 10^{22} \text{cm}^{-2}$

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Physical Properties of Star-Forming Regions

Σ ≈ 10 M⊙ pc⁻²
Local Galactic Disk

Σ ≈ 34 M⊙ pc⁻²

Σ ≈ 180 M⊙ pc⁻²

A_v = 7.5
N_H = 1.6x10^{22} cm⁻²

A_v = 1.4
N_H = 3.0x10^{21} cm⁻²

Σ ≈ 10 M⊙ pc⁻²

CHaMP HCO⁺ Clumps
Barnes et al. (2010, 2011)
Ma, Tan, Barnes (2013)
Physical Properties of Star-Forming Regions

- Local Galactic Disk
  - $A_V = 1.4$
  - $A_{8\mu m} = 0.30$
  - $N_H = 1.6 \times 10^{22} \text{ cm}^{-2}$
  - $\Sigma = 34 \ M_\odot \text{ pc}^{-2}$

- $\Sigma \sim 10 \ M_\odot \text{ pc}^{-2}$

- CHaMP HCO$^+$ Clumps
  - Barnes et al. (2010, 2011)
  - Ma, Tan, Barnes (2013)

- $\Sigma \equiv \frac{M}{\pi R^2}$
- $\overline{P} \sim G \Sigma^2$
- $\overline{P}/k = 4.3 \times 10^{8} \Sigma^2 \text{ K cm}^{-3}$
- $t_{ff} = \left( \frac{3\pi}{32G\rho} \right)^{1/2}$
Physical Properties of Star-Forming Regions

Local Galactic Disk

\[ A_V = 7.5 \]
\[ A_{8\mu m} = 0.30 \]
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CHaMP HCO\(^+\) Clumps

Barnes et al. (2010, 2011)
Ma, Tan, Barnes (2013)

Andersen et al., in prep.
Physical Properties of Star-Forming Regions

\[ \Sigma \equiv \frac{M}{\pi R^2} \]

Local Galactic Disk

\[ \Sigma \approx 34 \text{ M}_\odot \text{ pc}^{-2} \]

Ma, Tan, Barnes (2013)

CHaMP HCO\(^+\) Clumps

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VLBT13 GMCs

\[ \Sigma \approx 10 \text{ M}_\odot \text{ pc}^{-2} \]

\[ \frac{\dot{P}}{k} = 4.3 \times 10^{8} \Sigma^2 \text{ cm}^{-3} \]

\[ t_{ff} = \left( \frac{3\pi}{32G\rho} \right)^{1/2} \]
Massive Star Forming Clumps
Mueller et al. (2002)

Physical Properties of Star-Forming Regions

\[ \Sigma \equiv \frac{M}{\pi R^2} \]

\[ \rho \sim G \Sigma^2 \]

\[ \rho / k = 4.3 \times 10^8 \Sigma^2 \text{K} \text{cm}^{-3} \]

\[ t_{ff} = \left( \frac{3\pi}{32G\rho} \right)^{1/2} \]

- \( A_v = 230 \)
- \( N_H = 4.2 \times 10^{23} \text{cm}^{-2} \)
- \( \Sigma = 4800 \text{M}_\odot \text{pc}^{-2} \)

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Massive Sub-mm Clumps
Ginsburg et al. (2012)
Longmore et al. (2012)
Embedded Star Clusters
Orion Nebula Cluster
Hillenbrand & Hartmann (1998)
Da Rio et al. (2009, 2010)

\[ \Sigma \equiv \frac{M}{\pi R^2} \]
\[ \dot{P} \sim \frac{G \Sigma^2}{\dot{P}/k} = 4.3 \times 10^8 \Sigma^2 \text{K cm}^{-3} \]
\[ t_{ff} = \left( \frac{3\pi}{32G\rho} \right)^{1/2} \]
Massive Young Star Clusters

Physical Properties of Star-Forming Regions

\[ \Sigma \equiv \frac{M}{\pi R^2} \]
\[ \dot{P} \sim \frac{G \Sigma}{R} \]
\[ \dot{P}/k = 4.3 \times 10^8 \Sigma^2 K \text{cm}^{-3} \]
\[ t_{ff} = \left( \frac{3 \pi}{32 G \rho} \right)^{1/2} \]

- Local Galactic Disk: \( \Sigma \sim 10 M_\odot \text{ pc}^{-2} \)
- AV = 1.4
  - \( N_H = 3.0 \times 10^{21} \text{ cm}^{-2} \)
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Local Galactic Disk

- \( A_V = 230 \)
- \( A_{8 \mu m} = 8.1 \)
- \( N_H = 4.2 \times 10^{23} \text{cm}^{-2} \)
- \( \Sigma = 4800 \text{ M}_\odot \text{ pc}^{-2} \)

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- \( \Sigma = 34 \text{ M}_\odot \text{ pc}^{-2} \)

- \( \Sigma \approx 10 \text{ M}_\odot \text{ pc}^{-2} \)
Super Star Clusters
e.g. Anders et al. (2004)
McCrady & Graham (2007)

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Local Galactic Disk
**Σ - M Diagram**

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\[
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\]

\[
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**Local Galactic Disk**

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- \(A_{8\mu m} = 8.1\)
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- \(\Sigma = 4800\) M\(_{\odot}\) pc\(^{-2}\)

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- \(A_V = 1.4\)
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- \(\Sigma = 34\) M\(_{\odot}\) pc\(^{-2}\)

- \(\Sigma \sim 10\) M\(_{\odot}\) pc\(^{-2}\)
These are the (local) environments where massive stars form: can we scale-up low-mass SF theory?
Standard model of isolated low-mass star formation

Shu, Adams, Lizano (1987)
Standard model of isolated low-mass star formation

Many observed examples of this for low-mass star formation.

1. Molecular Cloud
   
   **Physical Conditions:**
   
   $L \sim 1 - 100 \text{ pc}$
   
   $n_H \sim 100 - 1000 \text{ cm}^{-3}$
   
   $T \sim 10 - 20 \text{ K}$
   
   **Astrophysical processes:**
   
   Converging flows in Galactic potential; stellar feedback; gravitational fragmentation
   
   **Astrochemical processes:**
   
   Formation and destruction of $H_2$ and CO molecules; water-ice formation on dust

2. Starless Core
   
   **Physical Conditions:**
   
   $L \sim 0.1 \text{ pc}$
   
   $n_H \sim 10^4 - 10^5 \text{ cm}^{-3}$
   
   $T \sim 10 - 15 \text{ K}$
   
   **Astrophysical processes:**
   
   Gravitational fragmentation from turbulent, magnetized molecular cloud
   
   **Astrochemical processes:**
   
   Freeze-out of CO onto dust grain ice mantles; grain coagulation

3. Prestellar Core
   
   **Physical Conditions:**
   
   $L \sim 0.1 \text{ pc}$
   
   $n_H \sim 10^5 - 10^7 \text{ cm}^{-3}$
   
   $T \sim 5 - 15 \text{ K}$
   
   **Astrophysical processes:**
   
   Gravitational infall; angular momentum transfer
   
   **Astrochemical processes:**
   
   Deuteration; near-complete molecular freeze-out; surface chemistry

4. Protostellar Core
   
   **Physical Conditions:**
   
   $L \sim 0.1 \text{ pc}$
   
   $n_H \sim 10^5 - 10^{12} \text{ cm}^{-3}$
   
   $T \sim 10 - 100 \text{ K}$
   
   **Astrophysical processes:**
   
   Gravitational infall; accretion via disk; outflow; shocks; core disruption
   
   **Astrochemical processes:**
   
   Ice mantle sputtering and evaporation; high T chemistry; x-ray ionization

5. Protoplanetary Disk
   
   **Physical Conditions:**
   
   $L \sim 100 \text{ AU} \sim 0.0005 \text{ pc}$
   
   $n_H \sim 10^8 - 10^{12} \text{ cm}^{-3}$
   
   $T \sim 10 - 1000 \text{ K}$
   
   **Astrophysical processes:**
   
   Disk accretion & photoevaporation; grain growth, planetesimal & planet formation
   
   **Astrochemical processes:**
   
   High T chemistry; x-ray ionization

Shu, Adams, Lizano (1987)
Many observed examples of this for low-mass star formation.

Can we find the equivalent stages for massive star formation?

Does the fact that massive stars tend to form in crowded cluster environments preclude this model?
Massive Star Formation Theories

Core Accretion:
wide range of $\frac{dm}{dt} \sim 10^{-5} - 10^{-2} \, M_\odot \, yr^{-1}$
(e.g. Myers & Fuller 1992; Caselli & Myers 1995; McLaughlin & Pudritz 1997; Osorio+ 1999; Nakano+ 2000; Behrend & Maeder 2001)
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Turbulent Core Model:
(Mckee & Tan 2002, 2003)
Stars form from “cores” that fragment from the “clump”.

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\[ \bar{P} = \phi G \Sigma^2 \]
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If in equilibrium, then self-gravity is balanced by internal pressure:
B-field, turbulence, radiation pressure (thermal $P$ is small)

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Cores form from this turbulent medium: at any given time there is a small mass fraction in unstable cores. These cores collapse quickly to a central disk to form individual stars or binaries.

\[ \dot{m}_* \sim \frac{M_{\text{core}}}{t_{\text{ff}}} \]
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Competitive Accretion:
(Bonnell, Clarke, Bate, Pringle 2001; Bonnell, Vine, & Bate 2004; Schmeja & Klessen 2004; Wang, Li, Abel, Nakamura 2010)
Stars, especially massive stars, gain most mass by Bondi-Hoyle accretion of ambient clump gas.

If in equilibrium, then self-gravity is balanced by internal pressure: $B$-field, turbulence, radiation pressure (thermal $P$ is small)

Cores form from this turbulent medium: at any given time there is a small mass fraction in unstable cores. These cores collapse quickly to a central disk to form individual stars or binaries.

\[ \bar{P} = \phi_p G \Sigma^2 \]

\[ \dot{m}_* \sim M_{\text{core}} / t_{\text{ff}} \]
**Massive Star Formation Theories**

**Core Accretion:**
wide range of $\dot{m} \sim 10^{-5}$ - $10^{-2}$ $M_\odot$ yr$^{-1}$
(e.g. Myers & Fuller 1992; Caselli & Myers 1995; McLaughlin & Pudritz 1997; Osorio+ 1999; Nakano+ 2000; Behrend & Maeder 2001)

**Turbulent Core Model:**
(McKee & Tan 2002, 2003)
Stars form from “cores” that fragment from the “clump”.

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(Bonnell, Clarke, Bate, Pringle 2001; Bonnell, Vine, & Bate 2004; Schmeja & Klessen 2004; Wang, Li, Abel, Nakamura 2010)
Stars, especially massive stars, gain most mass by Bondi-Hoyle accretion of ambient clump gas.

Originally based on simulations including only thermal pressure.

Requires global collapse of clump (Krumholz, McKee & Klein 2005)
Massive Star Formation Theories

Core Accretion:
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Can we find these massive starless cores and clumps?
Physical Properties of Star-Forming Regions

Can we find these massive starless cores and clumps?

Are the cores & clumps in virial & pressure equilibrium?

\[ \Sigma = \frac{M}{\pi R^2} \]

\[ \frac{\dot{P}}{k} = 4.3 \times 10^8 \Sigma^2 \text{ K cm}^{-3} \]

\[ t_{ff} = \left( \frac{3\pi}{32G\rho} \right)^{1/2} \]

\[ A_V = 230 \]

\[ A_{8\mu m} = 8.1 \]

\[ N_H = 4.2 \times 10^{23} \text{ cm}^{-2} \]

\[ \Sigma = 4800 \text{ M}_\odot \text{ pc}^{-2} \]

\[ A_V = 7.5 \]

\[ A_{8\mu m} = 0.30 \]

\[ N_H = 1.6 \times 10^{22} \text{ cm}^{-2} \]

\[ \Sigma = 180 \text{ M}_\odot \text{ pc}^{-2} \]

\[ A_V = 1.4 \]

\[ N_H = 3.0 \times 10^{21} \text{ cm}^{-2} \]

\[ \Sigma = 34 \text{ M}_\odot \text{ pc}^{-2} \]

\[ \Sigma \sim 10 \text{ M}_\odot \text{ pc}^{-2} \]
Can we find these massive starless cores and clumps?

Are the cores & clumps in virial & pressure equilibrium?

Σ - M Diagram
Physical Properties of Star-Forming Regions

\[ \Sigma = \frac{M}{\pi R^2} \]
\[ \Sigma \approx 10 M_\odot \text{ pc}^{-2} \]

A\textsubscript{V} = 1.4
A\textsubscript{8\mu m} = 1.6x10\textsuperscript{22} cm\textsuperscript{-2}
N\textsubscript{H} = 3.0x10\textsuperscript{21} cm\textsuperscript{-2}
Σ = 34 M\textsubscript{\odot} pc\textsuperscript{-2}

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Infrared Dark Clouds: Probes of Initial Conditions
Pérault et al. 1996; Egan et al. 1998; Carey et al. 1998
Infrared Dark Clouds: Probes of Initial Conditions

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MSX
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

Spitzer IRAC 8µm (GLIMPSE)
Mid-IR Extinction Mapping of Infrared Dark Clouds
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G28.37+00.07

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

Correct for foreground

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![Schematic of simple 1D model of radiative transfer through an IRDC, assuming negligible emission from the IRDC at frequency $\nu$. If independent cores (i.e. localized density maxima) A and B are both of sufficient $\Sigma$, then $I_{\nu,1,\text{obs}} \ll I_{\nu,\text{fore}}$, so $I_{\nu,\text{1,obs}} \simeq I_{\nu,1}$, providing an accurate, empirical estimate of the foreground intensity to the IRDC.](Spitzer IRAC 8$\mu$m (GLIMPSE))

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

Correct for foreground

$\mathbf{I_{\nu,1,\text{obs}} = I_{\nu,\text{fore}} + I_{\nu,1}}$

$\mathbf{I_{\nu,0,\text{obs}} = I_{\nu,\text{fore}} + I_{\nu,0}}$

MJy sr$^{-1}$
Mid-IR Extinction Mapping of Infrared Dark Clouds
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G28.37+00.07

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

Correct for foreground

~Arcsecond scale maps of regions up to \( \Sigma \sim 0.5 \text{ g cm}^{-2} \); independent of dust temp.

Distance from molecular line velocities \( \rightarrow M(\Sigma) \)

Spitzer IRAC 8\(\mu\)m (GLIMPSE)
Can we find these massive starless cores and clumps?
Can we find these massive starless cores and clumps?

Kainulainen & Tan (2013)
Can we find these massive starless cores and clumps? Yes! And resolve their structure!

Kainulainen & Tan (2013)

Butler & Tan (2012)
Dynamical State of Massive Starless Cores
Four IRDC core/clumps selected to be dark at 8, 24, 70 μm
Four IRDC core/clumps selected to be dark at 8, 24, 70 μm

C1

F1

F2

G2

IRAM 30m
Four IRDC core/clumps selected to be dark at 8, 24, 70 μm

High Deuterium Fraction [N$_2$D$^+$/][N$_2$H$^+$]

(Fontani et al. 2011)
Four IRDC core/clumps selected to be dark at 8, 24, 70 μm

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High Deuterium Fraction \([N_2D^+] / [N_2H^+]\)
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\[ \text{H}_3^+ + \text{CO} \rightarrow \text{HCO}^+ + \text{H}_2 \]

\[ \text{H}_3^+ + \text{HD} \rightarrow \text{H}_2\text{D}^+ + \text{H}_2 \]

\[ \text{H}_2\text{D}^+ + \text{N}_2 \rightarrow \text{H}_2 + \text{N}_2\text{D}^+ \]

Astrochemical indicator that these are starless cores
(Caselli et al. 2002)
Four IRDC core/clumps selected to be dark at 8, 24, 70 μm

High Deuterium Fraction \([\text{N}_2\text{D}^+]/[\text{N}_2\text{H}^+]\) (Fontani et al. 2011)

**CO freeze-out**  
e.g. Hernandez et. al (2011)

\[ \text{H}_3^+ + \text{CO} \rightarrow \text{HCO}^+ + \text{H}_2 \]  
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\[ \text{H}_2\text{D}^+ + \text{N}_2 \rightarrow \text{H}_2 + \text{N}_2\text{D}^+ \]

Astrochemical indicator that these are starless cores (Caselli et al. 2002)
So use high angular resolution observations of $N_2D^+(3-2)$ to:

1. Identify exact location of (massive) starless cores
2. Measure core velocity dispersion, $\sigma$. 

**High Deuterium Fraction $[N_2D^+]/[N_2H^+]$**

(Fontani et al. 2011)

**CO freeze-out**

e.g. Hernandez et. al (2011)

\[
\begin{align*}
H_3^+ + CO & \not\rightarrow \ HCO^+ + H_2 \\
H_3^+ + HD & \rightarrow \ H_2D^+ + H_2 \\
H_2D^+ + N_2 & \rightarrow \ H_2 + N_2D^+
\end{align*}
\]

**Astrochemical indicator that these are starless cores**

(Caselli et al. 2002)
“Massive” “Starless” “Cores” with ALMA

Fig. 1.—The four massive starless core/clumps observed by ALMA: columns from left to right show C1, F1, F2, G2.

(a) First row: MIREX $\Sigma$ maps in g cm$^{-2}$ (BT12). The inner circles show the deconvolved extent of the N$_2$D$^+$ cores identified in row (b), while the outer circle has a radius large and shows the regions used to estimate the surrounding clump envelope.

(b) Second row: ALMA Cycle 0 observations of N$_2$D$^+$ (3-2) integrated intensity. Six cores, C1-N, C1-S, F1, F2, G2-N & G2-S, are defined by their 3$\sigma$ contours in position-velocity space. Note that not all high $\Sigma$ regions show strong N$_2$D$^+$ emission, but N$_2$D$^+$ cores do correlate well with structures seen in the MIREX maps.

(c) Third row: ALMA observations of DCO$^+$ (3-2) integrated intensity, which is generally more widespread than N$_2$D$^+$.

(d) Fourth row: ALMA observations of the 1.34 mm dust continuum emission. Core boundaries are defined using the projection of this 3$\sigma$ contour, after deconvolving with a Gaussian equivalent to the ALMA synthesized beam. The positions and average radial sizes, $R_c$, are listed in Table 2. The diameters of the cores are all larger than the angular resolution of the observations. Core C1-N appears to exhibit some substructure in its N$_2$D$^+$ (3-2) emission, whereas the other sources appear to be relatively monolithic.

The morphology of the continuum emission also generally matches that seen in the molecular line emission, especially that traced by N$_2$D$^+$ (3-2).

3.2. Core kinematics and velocity dispersion

The integrated N$_2$D$^+$ (3-2) spectra of the cores are shown in Fig. 2. These spectra are a blend of 47 hyperfine components. We fit model spectra to these data to derive the centroid velocity, $V_{\text{LSR}}$, N$_2$D$^+$, and the observed 1D velocity dispersion, $\sigma_{N_2D^+_{\text{obs}}}$, also listed in Table 2. This modeling allows for the possibility of optically thick parts of the hyperfine line complex, but we find all spectra can be well-modeled assuming optically thin line emission. We assume a gas temperature of $T = 10 \pm 3$ K (see §3.3.2) to remove the thermal component of the line to thus assess the nonthermal component of Noise.

Photo credit: Babak Tafreshi
Fig. 1.—The four massive starless core/clumps observed by ALMA: column from left to right show C1, F1, F2, G2.

(a) First row: MIREX $\Sigma$ maps in g cm$^{-2}$ (BT12). The inner circles show the deconvolved extent of the $N_2D^+$ cores identified in row (b), while the outer circle has a radius wide and shows the region used to estimate the surrounding clump envelope.

(b) Second row: ALMA Cycle 0 observations of $N_2D^+$ (3-2) integrated intensity. Six cores, C1-N, C1-S, F1, F2, G2-N & G2-S, are defined by their 3$\sigma$ contours in position-velocity space. Note that not all high $\Sigma$ regions show strong $N_2D^+$ emission, but $N_2D^+$ cores do correlate well with structures seen in the MIREX maps.

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“Massive”
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Starless
Massive

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Comparison to Turbulent Core Model

\[ \sigma_{c,\text{vir}} \rightarrow 1.09 \left( \frac{M_c}{60M_\odot} \right)^{1/4} \left( \frac{\Sigma_{cl}}{1\, \text{g cm}^{-2}} \right)^{1/4} \, \text{km s}^{-1} \]
Comparison to Turbulent Core Model

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Comparison to Turbulent Core Model

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

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

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

$M_{c,mm} = 62.5^{+129}_{-26.9} \, M_\odot$
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  \( m_A = \sqrt{3} \sigma_c / v_A = 1 \)

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<td>( M_c ) (M(_\odot))</td>
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- 1D velocity dispersion if virialized:
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  m_A = \sqrt{3} \sigma_c / v_A = 1
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\[ < \sigma_{\text{obs}} / \sigma_{\text{vir}} > = 0.81 \pm 0.13 \]
### Predictions from Virial Equilibrium

- 1D velocity dispersion if virialized: 
  \[ m_A = \sqrt{3} \sigma_c / v_A = 1 \]

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\sigma_{c,\text{vir}} \rightarrow 1.09 \left( \frac{M_c}{60 M_\odot} \right)^{1/4} \left( \frac{\Sigma_{\text{cl}}}{1 \text{ g cm}^{-2}} \right)^{1/4} \text{ km s}^{-1}
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\frac{\sigma_{obs}}{\sigma_{vir}} = 0.81 \pm 0.13
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\[
m_{A,vir} = 0.28 \rightarrow B_{vir} = 0.9\text{mG}
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Predictions from Virial Equilibrium

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\[ m_A = \sqrt[3]{3 \sigma_c/v_A} = 1 \]

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

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<td>( M_c ) (M(_\odot))</td>
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<td>63</td>
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<td>4.7</td>
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<td>( \sigma_{\text{vir}} ) (km/s)</td>
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<td>0.88±0.30</td>
<td>0.43±0.15</td>
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<td>0.25±0.09</td>
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<td>( \sigma_{\text{obs}} ) (km/s)</td>
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<td>0.25±0.02</td>
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\[ < \frac{\sigma_{\text{obs}}}{\sigma_{\text{vir}}} > = 0.81 \pm 0.13 \]

\[ < \frac{R_{\text{obs}}}{R_{\text{vir}}} > = 1.48 \pm 0.34 \]

\[ m_{A,\text{vir}} = 0.28 \rightarrow B_{\text{vir}}=0.9 \text{ mG} \]

\[ B_{\text{med}} \approx 0.12 n_H^{0.65} \mu \text{G} \] (for \( n_H > 300 \text{ cm}^{-3} \)) (Crutcher et al. 2010)

\[ n_{H,c}=6.4 \times 10^5 \text{ cm}^{-3} \rightarrow B_{\text{med}} = 0.7 \text{ mG} \]
Predictions from Virial Equilibrium

- 1D velocity dispersion if virialized:
  \( m_A = \sqrt{3} \sigma_c/v_A = 1 \)

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

<table>
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Tentative Conclusion: Cores appear to be near virial equilibrium, after accounting for clump envelope. Possibly slightly sub-virial; or have stronger B-fields. But we need a larger sample - massive starless cores are rare!
Deuteration Fraction as a Chemical Clock

\[ D_{\text{frac,N}_2\text{D}^+} = \frac{[N_2\text{D}^+]}{[N_2\text{H}^+]} \rightarrow \sim 1 \text{ in core C1-S (Kong+, in prep.)} \]

Results from CARMA

3 mm, \(N_2\text{H}^+\) (1-0), D config. ~ 6" beam, channel width ~ 0.08 km s

\(N_2\text{D}^+(3-2)\) \hspace{2cm} \(N_2\text{H}^+(1-0)\)

ALMA \hspace{2cm} CARMA
Deuteration Fraction as a Chemical Clock

\[ D_{\text{frac}, N_2D^+} = \frac{[N_2D^+]}{[N_2H^+]} \rightarrow \sim 1 \text{ in core C1-S (Kong+, in prep.)} \]

Astrochemical modeling implies \( t_{\text{deuteration}} \sim 5 \times t_{\text{ff}} \sim t_{\text{ambipolar}} \)

Nahoon + KIDA (Wakelam et al. 2012)
Massive Protostars: scaled-up versions of low-mass protostars?
Massive Protostars: scaled-up versions of low-mass protostars?
Protostellar Evolution

\begin{figure}
\centering
\includegraphics[width=\textwidth]{protostellar_evolution.png}
\caption{Protostellar Evolution Diagram with various conditions: \( \Sigma_{cl} = 0.316 \text{ g cm}^{-2} \), \( \Sigma_{cl} = 1 \text{ g cm}^{-2} \), \( \Sigma_{cl} = 3.16 \text{ g cm}^{-2} \), and ZAMS models.}
\end{figure}

\begin{itemize}
\item e.g. Hosokawa et al. (2010); Zhang et al. (2013)
\end{itemize}
Continuum Radiative Transfer Modeling
Adams & Shu (1985), Chakrabarti & McKee (2005), Robitaille et al. (2006+); Molinari et al. (2008)

Zhang & Tan (2011), Zhang, Tan, McKee (2013)

- hydrostatic core
- expansion wave
- rotating infall
- active accretion disk
- disk wind
- dust destruct. front
- gas + dust opacities
- protostellar evolution

Parameters:
\( \Sigma_{\text{clump}} = 1 \text{ g cm}^{-2} \)
\( M_{\text{core}} = 60 \text{ M}_{\odot} \)
\( \beta = 0.02 \)
\( m^* = 8 \text{ M}_{\odot} \)
\( L_{\text{bol}} = 6x10^3 \text{ L}_{\odot} \)
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Fig. 2.— The density and temperature profiles for the fiducial model (Model 13) at different scales.

\(n_\text{H} = 0.1\). He is assumed here. The white contours divide the disk, the envelope and the outflow. The dotted lines show the streamlines of the disk wind. Each interval contains 10% of the wind material. The black contour in the temperature profile is the dust destruction front (\(T = 2000\) K).

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Zhang & Tan (2011), Zhang, Tan, McKee (2013)
NIR to FIR morphologies
Zhang & Tan (2011); Zhang et al. (2013).

Rotation and outflow axis inclined at 60° to line of sight.

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Massive Protostar G35.2N: d=2.3kpc; L~$10^5L_\odot$

De Buizer (2006)
Massive Protostar G35.2N: $d=2.3\,\text{kpc}; L\sim10^5L_\odot$

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Gemini-T-ReCS

SOFIA-FORCAST

De Buizer (2006)

Zhang, Tan, De Buizer et al. (2013)
MIR SED requires high $\Sigma$ core/clump

$\Sigma_{\text{clump}} = 1 \text{ g cm}^{-2}$

$M_{\text{core}} = 240 \text{ M}_\odot$

$m^- = 34 \text{ M}_\odot$
Spectral energy distribution

The figure shows the spectral energy distribution (SED) for different models, with Model 1 being the black line, Model 2 in blue, Model 3 in green, and Model 4 in red. The SED is presented in units of ergs s\(^{-1}\) cm\(^{-2}\) for various wavelengths.

Flux profiles along outflow cavity axis

The figure displays flux profiles along the outflow cavity axis for different wavelengths: 37 μm, 31 μm, 18 μm, and 10 μm. The profiles are shown for far-facing and near-facing positions. The models are differentiated by different colors: Model 1 in black, Model 2 in blue, Model 3 in green, and Model 4 in red. The x-axis represents the position offset in arcsec, ranging from -30 to 30 arcsec.

Text:

- Spectral energy distribution
- MIR SED requires high Σ core/clump

Mathematical expressions:

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\[ \Sigma_{\text{clump}} \]
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MIR SED requires high \( \Sigma \) core/clump

Flux profiles along outflow cavity axis

\[ L_{\text{bol}} \sim (0.66 - 2.2) \times 10^5 \text{ L}_\odot \]
\[ M_{\text{core}} \sim 240 \text{ M}_\odot \]
\[ \Sigma_{\text{cl}} \sim 0.4 - 1 \text{ g/cm}^2 \]
\[ \theta_w \sim 35 - 51^\circ \]
\[ \theta_{\text{view}} \sim 43 - 58^\circ \]
\[ m^* \sim 20 - 34 \text{ M}_\odot \]
Towards more realistic density structures
(Staff et al. 2010; Staff & Tan, in prep.)
Feedback During Massive Star Formation

Is there a maximum stellar mass set by formation processes?

Salpeter (1955)

\[ \frac{dN^*}{dm^*} = A m^{*-2.35} \]

\( m^*_{\text{max}}? \)
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Is there a maximum stellar mass set by formation processes?

A number of studies have found $m_{\text{max}} \approx 150 \, M_\odot$ (e.g. Figer 2005). However, Crowther et al. (2010) claim the most massive star to form was initially $\sim 300 M_\odot$, which is consistent with statistical sampling of a Salpeter IMF with no maximum cutoff mass.

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$30 \text{ Doradus - LMC}$
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Feedback processes:
1. Protostellar outflows
2. Ionization
3. Stellar winds
4. Radiation pressure
5. Supernovae

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Currently unclear what sets the shape of the massive star IMF

Salpeter (1955)
\[ \frac{dN^*}{dm^*} = A \cdot m^{* -2.35} \]

\[ m^{*\text{max}}? \]

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The First Stars:
Can we apply massive star formation theory to predict their mass?
### Importance of First Stars and their Mass

**Astrophysical Effects**

- **Reionization** (H, He)
- **Metal Enrichment**
  - proto-galaxies and IGM
- **Illumination**
  - SN & GRBs?

**Observations**

- **CMB polarization** (WMAP Page et al. 07)
- **H 21cm** (LOFAR Morales & Hewitt 04)
- **Z of low Z halo stars** (Beers & Christlieb 05, Scannapieco et al. 2006; Meynet, Hirschi ea. 10)
- **Z of Lya forest?** (Schaye et al. 03 Norman et al. 04)
- **NIR bkg. intensity** (Santos et al. 02; Fernandez & Komatsu 06; Matsumoto ea. 10)
- **NIR bkg. fluctuations** (Kashlinsky et al. 04)
- **JWST** (Weinmann & Lilly 05)
- **SWIFT** (Bromm & Loeb 02; Tanvir ea 09)
- **ULXs** (Mii & Totani 2005)
- **Quasars** (Fan et al. 03; Willott et al. 03)
- **NIR counts** (Stark et al. 07)

**Progenitors of IMBHs/SMBHs?**

**Early Galaxies?**

**Influence on structure formation:**

Supermassive Black Holes, Globular Clusters, Galaxies?

Critical Z

$Z \approx 10^{-6}$ (Omukai ea. 05) to $10^{-3.5}$

Astrophysical Effects
1. Form pre-galactic minihalo \( \sim 10^6 M_\odot \) by \( z \sim 20 \).
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2. Form quasi-hydrostatic gas core inside halo: at \( r \approx 10 \) pc: \( M \approx 4000 M_\odot, n_H \approx 10 \) cm\(^{-3}\), \( f_{H_2} \approx 10^{-3}, T \sim >200K \)

3. Rapid 3-body \( H_2 \) formation at \( n_H \sim >10^{10} \) cm\(^{-3}\). Strong cooling \( \rightarrow \) supersonic inflow.
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4. 1D simulations (Omukai & Nishi 1998): Form $\sim$hydrostatic protostar $n_H \approx 10^{17}$ cm$^{-3}$, $T \approx 2000$ K: optically thick, adiabatic contraction $\rightarrow$ protostar $m* \approx 0.005 M_\odot$, $r* \approx 14 R_\odot$
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   \( T \approx 2000 \) K: optically thick, adiabatic contraction \( \rightarrow \) protostar 
   \( m_* \approx 0.005M_\odot \), \( r_* \approx 14R_\odot \)

Recent 3D sims. (Turk, Yoshida, Abel, Bromm, Norman etc.) reach \( \sim \) stellar densities, 
but then grind to a halt (small dynamical timescales), still at small (\( << M_\odot \)) protostellar 
masses. Occasional signs of binary fragmentation on larger scales (Turk et al. 2009). 
**For next stages, we develop analytic models: when does accretion end?**
Physical Properties of Star-Forming Regions

$\Sigma \equiv \frac{M}{\pi R^2}$

$\bar{P} \sim G \Sigma$

$\bar{P}/k = 4.3 \times 10^8 \Sigma^2 \text{K cm}^{-3}$

$t_{ff} = \left( \frac{3\pi}{32G\rho} \right)^{1/2}$

$A_V = 230$

$A_{8\mu m} = 8.1$

$N_H = 4.2 \times 10^{23} \text{cm}^{-2}$

$\Sigma = 4800 \text{ M}_\odot \text{ pc}^{-2}$

$A_V = 7.5$

$A_{8\mu m} = 0.30$

$N_H = 1.6 \times 10^{22} \text{cm}^{-2}$

$\Sigma = 180 \text{ M}_\odot \text{ pc}^{-2}$

$A_V = 1.4$

$N_H = 3.0 \times 10^{21} \text{cm}^{-2}$

$\Sigma = 34 \text{ M}_\odot \text{ pc}^{-2}$

$\Sigma \sim 10 \text{ M}_\odot \text{ pc}^{-2}$
Physical Properties of Star-Forming Regions

- Local Galactic Disk
  - $A_V = 1.4$
  - $N_H = 3.0 \times 10^{21} \text{ cm}^{-2}$
  - $\Sigma = 34 \text{ M}_\odot \text{ pc}^{-2}$

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Physical Processes in Pop III star formation

Dark Matter Annihilation Heating? (Spolyar et al. 2008; Natarajan, Tan, O'Shea 2009)

Accretion Rate

\[ \dot{m}_* = 0.026 K^{15/7} (m_*/M\odot)^{-3/7} M\odot \text{yr}^{-1} \] (Tan & McKee 2004)

Initial Conditions

polytropic structure: \[ P = K \rho^\gamma \] (Abel ea, Bromm ea, Yoshida ea, Omukai ea.)
Physical Processes in Pop III star formation

Radiative Feedback

Protostellar Evolution

Magnetic Field Generation?

Rotation & Disk Structure; Fragmentation?

Dark Matter Annihilation Heating?

Accretion Rate

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---

(McKee & Tan 2008)

(Omukai & Palla 2003; Tan & McKee 2004)

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Protostellar feedback (ionization) halts accretion at ~100-200 $M_\odot$

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Protostellar Evolution

Magnetic Field Generation?

Rotation & Disk Structure; Fragmentation?

Dark Matter Annihilation Heating?

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polytropic structure: $P=K\rho^\gamma$
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Analytic models for star formation, including effects of radiative and mechanical feedback

- Tan & McKee 2004: Accretion rate, disk structure, protostellar evolution
- Tan & Blackman 2004: Magnetic field growth, mechanical feedback from outflows
- McKee & Tan 2008: Radiative feedback (Ly-alpha radiation pressure, ionization)
- Natarajan, Tan, O'Shea, in prep: DM annihilation

Physical Processes in Pop III star formation

- Protostellar feedback (ionization) halts accretion at ~100-200 M_☉
- Rotation & Disk Structure; Fragmentation?
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  polytropic structure: \[ P = K ρ^γ \]

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- Protostellar Evolution

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- Protostellar Evolution

Schaerer 2002

(McKee & Tan 2008)

(Omukai & Palla 2003; Tan & McKee 2004)

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Overview of Radiative Feedback

See also Omukai & Inutsuka (2002); Hosokawa & Omukai (2009); Hosokawa et al. (2011)
Overview of Radiative Feedback

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Competition between disk photoevaporation and residual accretion

$\mathbf{m^*}$
Overview of Radiative Feedback

McKee & Tan (2008)

Competition between disk photoevaporation and residual accretion

Protostellar feedback (ionization) halts accretion at ~100-200 solar masses.

\[ m_{sf} = 145 K^{60/47} (f_{sh}/0.2)^{28/47} (\bar{\epsilon}_{sd}/0.25)^{12/47} M_\odot \]

See also Omukai & Inutsuka (2002); Hosokawa & Omukai (2009); Hosokawa et al. (2011)
Spolyar, Freese, Gondolo (2008) predict WIMP annihilation heating is important for $n > 10^{13}\text{cm}^{-3}$ or $r < 20\text{AU}$. Could delay or halt collapse: dark matter powered protostar. Main uncertainties: $\rho_{DM}(r<10^{-3}\text{pc})$, $m_\chi$, $<\sigma v>$, $f_{\text{trap}}$
Heating by WIMP Dark Matter Annihilation?

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Natarajan, Tan, O’Shea (2009) examined the \( \rho_{\text{DM}} \) profiles of 3 simulated minihalos, finding steepening for \( r<0.5 \text{pc} \), i.e. where baryons dominate. Here \( \rho_{\text{DM}} \propto r^{-2} \).
WIMP Annihilation Heating Rate / Baryonic Cooling Rate

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This may allow supermassive stars to form since they stay large and cool (little ionizing feedback)
Conclusions: Massive Star Formation Through the Universe

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The First Stars (Pop III): Well defined initial conditions from cosmology: massive, warm gas cores at centers of dark matter minihalos. Standard star formation theory predicts massive stars form with ~100-200 M☉. WIMP annihilation heating may allow supermassive star, then black hole, formation.