Star Formation at Different Metallicities

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Star Formation
what can we learn from present-days about the primordial universe?

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**selected open questions**

- what processes determine the initial mass function (IMF) of stars?
- what are the initial conditions for star cluster formation?  
  how does cloud structure translate into cluster structure?
- how do molecular clouds form?
- what drives turbulence?
- what triggers / regulates star formation on galactic scales?
- how does star formation depend on metallicity?
selected open questions

- what processes determine the initial mass function (IMF) of stars?
  - what are the initial conditions for star cluster formation?
    how does cloud structure translate into cluster structure?
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  - what drives turbulence?
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  - how does star formation depend on metallicity?
stellar mass function
stars seem to follow a universal mass function at birth $\rightarrow$ IMF

(Kroupa 2002)

Orion, NGC 3603, 30 Doradus
(Zinnecker & Yorke 2007)
stellar masses

• distribution of stellar masses depends on
  - initial conditions
    --> statistical properties of star-forming cores
  - collapse and interaction of prestellar cores
    --> accretion and $N$-body effects
  - thermodynamic properties of gas
    --> balance between heating and cooling
    --> EOS (determines which cores go into collapse)
  - (proto) stellar feedback terminates star formation
    ionizing radiation, bipolar outflows, winds, SN

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ICs of star cluster formation

key question:

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Observers answer:

"this is not really well known . . ."

Fig. B.2. Same image layout as Figure B.1 but for IRDC 310.39-0.30. Cyan contours on the SPIRE panels (d, e, and f) show ATLASGAL 870 µm: 0.3, 0.45, 0.6, 0.75, 0.9, 1.05, 1.2, 1.35, 1.5 Jy beam

Fig. B.3. Same image layout as Figure B.1 but for IRDC 316.72+0.07. Cyan contours on the SPIRE panels (d, e, and f) show ATLASGAL 870 µm: 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0 Jy beam

Fig. B.6. Same image layout as Figure B.1 but for IRDC 004.36-0.06. Cyan contours on the SPIRE panels (d, e, and f) show ATLASGAL 870 µm: 0.07, 0.11, 0.14, 0.18, 0.21, 0.25, 0.28, 0.32, 0.35 Jy beam

Fig. B.7. Same image layout as Figure B.1 but for IRDC 009.86-0.04. Cyan contours on the SPIRE panels (d, e, and f) show ATLASGAL 870 µm: 0.08, 0.13, 0.168, 0.21, 0.25, 0.29, 0.34, 0.38, 0.42 Jy beam

Fig. B.14. Same image layout as Figure B.1 but for IRDC 18182. Cyan contours on the SPIRE panels (d, e, and f) show ATLASGAL 870 µm: 0.6, 0.9, 1.2, 1.5, 1.8, 2.1, 2.4, 2.7, 3.0 Jy beam

Fig. B.23. Same image layout as Figure B.1 but for IRDC 18437. Cyan contours on the SPIRE panels (d, e, and f) show ATLASGAL 870 µm: 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0 Jy beam

ICs of star cluster formation

key question:

what is the initial density profile of cluster forming cores? how does it compare low-mass cores?

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ICs of star cluster formation

key question:

- what is the initial density profile of cluster forming cores? how does it compare low-mass cores?

theorists answer:

“this is easy, I know exactly the right answer . . .”
ICs of star cluster formation

Key question:
- What is the initial density profile of cluster forming cores? How does it compare to low-mass cores?

Theorists answer:
- Top hat (Larson Penston)
- Bonnor Ebert (like low-mass cores)
- Power law \( \rho \propto r^{-1} \) (logotrop)
- Power law \( \rho \propto r^{-3/2} \) (Krumholz, McKee, etc)
- Power law \( \rho \propto r^{-2} \) (Shu)
- And many more
different density profiles

more precisely: does the density profile matter?

in comparison to
- turbulence ...
- radiative feedback ...
- magnetic fields ...
- thermodynamics ...
different density profiles

answer: **YES! it matters big time!**

approach: extensive parameter study

- different profiles (top hat, BE, $r^{-3/2}$, $r^{-3}$)
- different turbulence fields
  - different realizations
  - different Mach numbers
  - solenoidal turbulence
  - dilatational turbulence
  - both modes
- no net rotation, no B-fields
  (at the moment)

Girichids et al. (2011, 2012a,b)
for the $r^{-2}$ profile you need to crank up turbulence a lot to get some fragmentation!
number of fragments depends on initial profile:
flat profiles ---> lots of (low-mass) fragments
steep profiles ---> bias to single (high-mass) objects

Girichids et al. (2011, 2012a,b)
however, the real situation is more complex: for example, $r^{-1.5}$ is a limiting case where tidal forces roughly balance self-gravity of perturbation.

Girichids et al. (in prep)
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stellar masses

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application to early star formation
degree of fragmentation depends on EOS!

polytropic EOS: \( p \propto \rho^{\gamma} \)

\( \gamma < 1 \): dense cluster of low-mass stars

\( \gamma > 1 \): isolated high-mass stars

(see Li et al. 2003; also Kawachi & Hanawa 1998, Larson 2003)
dependency on EOS

for $\gamma < 1$ fragmentation is enhanced $\rightarrow$ cluster of low-mass stars
for $\gamma > 1$ it is suppressed $\rightarrow$ formation of isolated massive stars

(from Li, Klessen, & Mac Low 2003, ApJ, 592, 975)
how does that work?

(1) \( p \propto \rho^\gamma \rightarrow \rho \propto p^{1/\gamma} \)

(2) \( M_{\text{jeans}} \propto \gamma^{3/2} \rho^{(3\gamma-4)/2} \)

- \( \gamma < 1 \):
  - large density excursion for given pressure
  - \( \langle M_{\text{jeans}} \rangle \) becomes small
  - number of fluctuations with \( M > M_{\text{jeans}} \) is large

- \( \gamma > 1 \):
  - small density excursion for given pressure
  - \( \langle M_{\text{jeans}} \rangle \) is large
  - only few and massive clumps exceed \( M_{\text{jeans}} \)
EOS as function of metallicity

Figure 1.

A color version of this figure is available in the online journal.

The gas is assumed to be fully atomic (molecular) in drawing those lines.

We defer detailed discussion on these differences to later in Section 3.4.

Let us summarize here the formation processes of H_2.

In the case of metallicity [M/H] ≳ −4, the clouds easily fragment as long as they exceed the gravity, and a hydrostatic object is formed. In the case of metallicity [M/H] < −4, fragmentation is strongly prohibited for most until 10^3 cm^−3, because the abundance of molecular hydrogen is enhanced by the molecular cooling channel.

Next, let us see the cooling and heating processes in the channel.

After this plateau, the H_2 abundance begins to increase again at intervals around 10^5 cm^−3, but is above 1 in this period except for brief cases with metals. Below 10^5 cm^−3, the H_2 channel is quenched until 10^2 cm^−3, while fragmentation is strongly prohibited for low-metallicity cases.

In particular, at high densities and for low-metallicity cases, the effective ratio of specific heat is an important index to examine the variation of pressure in response to the density variation, which is calculated by one-zone models. The dashed lines compared with Figure 2 of O05, where similar plots for the cases with metals.
EOS as function of metallicity

The figure shows the evolution of temperatures at the center of cloud cores during the prestellar collapse as a function of number density, which is calculated by one-zone models. The dashed lines play a crucial role in the thermal evolution. The evolution of H is shown for different metallicities. This should be associated with the three-body reaction (Equation (a)). Until very high density, the heating is owing to the compression cooling and heating are always almost balanced, so equilibrium between the H remains below 4 orders of magnitude. The effective ratio of specific heat remains below unity (Figure 1(a)). The heating is owing to the compression cooling and heating are always almost balanced, so equilibrium between the H remains below 4 orders of magnitude. The effective ratio of specific heat remains below unity (Figure 1(a)).

Next, let us see the cooling and heating processes through the three-body H formation: 

\[ 2H + H \rightarrow H_2 + H \]

With gradual increase of temperature, the balance of chemical reaction:

\[ H_2 \rightarrow H + H \]

becomes optically thin (Figure 1(b)). The heating is owing to the compression cooling and heating are always almost balanced, so equilibrium between the H remains below 4 orders of magnitude. The effective ratio of specific heat remains below unity (Figure 1(a)).

If the metal-free one except for a slight offset at highest densities of a metal-free gas, we then describe the effects of metallicity on the core evolution. There are, however, small disagreements, (Omukai et al. 2005, 2010)

\[ \Gamma = 1 \times 10^{-4} M_{\odot} \]

\[ \tau = 1 \]

\[ [\text{M/H}] = -6 \]

\[ -5 \]

\[ -4 \]

\[ -3 \]

\[ -2 \]

\[ -1 \]

\[ 0 \]

Below (Z=0)

\[ Z = 0 \]

\[ [\text{M/H}] = -6 \]

\[ -5 \]

\[ -4 \]

\[ -3 \]

\[ -2 \]

\[ -1 \]

\[ 0 \]

\[ \times 10^{-4} M_{\odot} \]

(Omukai et al. 2005, 2010)
EOS as function of metallicity

The dashed lines are compared with Figure 2 of O05, where similar plots for the zone model (Figure 3.4) are shown for those cases. Note that the metal-free one except for a slight offset at highest densities are so small that the temperature evolution is almost identical to later in Section 3.2. We defer detailed discussion on these differences to later in Section 3.4. The effective ratio of specific heat is an important index to examine the temperature evolution at each metallicity. The contribution from the cooling and heating rates by individual processes are so small that the temperature evolution is almost identical to the metal-free one except for a slight offset at highest densities.
EOS as function of metallicity

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**EOS as function of metallicity**

![Graph showing the EOS as a function of metallicity](Image)

(Omukai et al. 2005, 2010)
present-day star formation

(Larson 1985, Larson 2005)

\( \gamma = 0.7 \)

\( \gamma = 1.1 \)
present-day star formation

real situation may be more complex and depend on flow properties, radiation field, total mass & size of cloud (extinction), etc.

(Clark et al. 2012)
IMF in nearby molecular clouds

with $\rho_{\text{crit}} \approx 2.5 \times 10^5 \text{ cm}^{-3}$

at SFE $\approx 50\%$

need appropriate EOS in order to get low mass IMF right

EOS as function of metallicity

In this section, we review thermal evolution of the cloud core for different metallicities. This should be compared with the case of metal-free gas, where HD plays an important role in cooling. The heating and cooling rates by individual processes are presented in Figure 1. In the case of metallicity $[\text{M/H}] = -6$, the evolution is nearly isothermal with temperature differences being small. At high densities and for low-metallicity cases, $\text{H}_2$ dominates. For the cooling, the $\text{H}_2$ collision-induced absorption line emission contributes significantly. After this plateau, the $\text{H}_2$ reaction is catalyzed by a small amount of remaining electrons. With gradual increase of temperature, the balance of chemical reactions shifts to higher energy.
The EOS (Equation of State) as a function of metallicity indicates the constant Jeans masses. For those above 10^4 M_{\odot}, the dynamical collapse is halted as the pressure overcomes the gravity, and a hydrostatic object is formed. Below 10^4 M_{\odot}, the Jeans mass decreases with decreasing metallicity, and the collapse becomes more efficient. The dashed lines correspond to the Jeans masses for different metallicities. This should be compared with Figure 2 of Omukai et al. (2005), where similar plots for the overall evolution are presented. In Figure 3, the evolution is nearly isothermal with temperature differences of a few Kelvin until the end of the collapse, justifying the one-zone treatment for the core evolution. There are, however, small disagreements, which are so small that the temperature evolution is almost identical to the case. In the case of metallicity [M/H] < -3, another critical value is (Omukai et al. 2005), justifying the one-zone treatment for cases with metals. Below 10^4 M_{\odot}, line cooling dominates. For the cooling, the H\alpha line is more effective in metal-free cases than in cases with metals. Below 10^4 M_{\odot}, the H\alpha cooling forms a plateau, which is due to the dominance of H\alpha cooling. After this plateau, the H\alpha cooling begins to decrease, and dust cooling becomes dominant. The effective ratio of specific heat at the center, (Equation (12)), is presented in Figure 1. The heating is owing to the compression and the amount of formed H\alpha, which is known to play an important role in cooling the free gas, HD, is known to play an important role in cooling the free gas, which contributes comparably to H\alpha cooling. The effective ratio of specific heat, \gamma, is presented in Figure 1. OMUKAI, HOSOKAWA, & YOSHIDA vol. 722.
transition: Pop III to Pop II.5

two competing models:
- cooling due to atomic fine-structure lines ($Z > 10^{-3.5} Z_{\text{sun}}$)
- cooling due to coupling between gas and dust ($Z > 10^{-5\ldots-6} Z_{\text{sun}}$)

**NB:** line cooling would only make very massive stars, with $M > $ few $\times 10 M_{\text{sun}}$. 

(Omukai et al. 2005, 2010)
### transition: Pop III to Pop II.5

**SDSS J1029151+172927**
- is first ultra metal-poor star with $Z \sim 10^{-4.5} Z_{\odot}$ for all metals seen (Fe, C, N, etc.)
  - [see Caffau et al. 2011]
- this is in regime, where metal-lines cannot provide cooling
  - [e.g. Schneider et al. 2011, 2012, Klessen et al. 2012]

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<table>
<thead>
<tr>
<th>Element</th>
<th>$[\text{X}/\text{H}]_{\text{ID}}$ (NLTE)</th>
<th>$N_{\text{lines}}$</th>
<th>$S_{\text{I}}$</th>
<th>$A(\text{X})_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>$-3.8 \leq -3.8 \leq -5.0$</td>
<td>G-band</td>
<td>8.50</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>$-4.1 \leq -5.0$</td>
<td>NH-band</td>
<td>7.86</td>
<td></td>
</tr>
<tr>
<td>Mg i</td>
<td>$-4.71 \pm 0.11 \leq -4.68 \pm 0.11 \leq -4.52 \pm 0.11 \leq -4.49 \pm 0.12$</td>
<td>5</td>
<td>0.1</td>
<td>7.54</td>
</tr>
<tr>
<td>Si i</td>
<td>$-4.27 \leq -4.30 \leq -3.93 \leq -3.96$</td>
<td>1</td>
<td>0.1</td>
<td>7.52</td>
</tr>
<tr>
<td>Ca i</td>
<td>$-4.72 \leq -4.82 \leq -4.44 \leq -4.54$</td>
<td>1</td>
<td>0.1</td>
<td>6.33</td>
</tr>
<tr>
<td>Ca ii</td>
<td>$-4.81 \pm 0.11 \leq -4.93 \pm 0.03 \leq -5.02 \pm 0.02 \leq -5.15 \pm 0.09$</td>
<td>3</td>
<td>0.1</td>
<td>6.33</td>
</tr>
<tr>
<td>Ti ii</td>
<td>$-4.75 \pm 0.18 \leq -4.83 \pm 0.16 \leq -4.76 \pm 0.18 \leq -4.84 \pm 0.16$</td>
<td>6</td>
<td>1.0</td>
<td>4.90</td>
</tr>
<tr>
<td>Fe i</td>
<td>$-4.73 \pm 0.13 \leq -5.02 \pm 0.10 \leq -4.60 \pm 0.13 \leq -4.89 \pm 0.10$</td>
<td>43</td>
<td>1.0</td>
<td>7.52</td>
</tr>
<tr>
<td>Ni i</td>
<td>$-4.55 \pm 0.14 \leq -4.90 \pm 0.11$</td>
<td>10</td>
<td>6.23</td>
<td></td>
</tr>
<tr>
<td>Sr ii</td>
<td>$-5.10 \leq -5.25 \leq -4.94 \leq -5.09$</td>
<td>1</td>
<td>0.01</td>
<td>2.92</td>
</tr>
</tbody>
</table>

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*(Caffau et al. 2011, 2012)*

*(Schneider et al. 2011, 2012, Klessen et al. 2012)*
inferring masses of previous generations of stars based on the Leo star abundance patterns (Heger et al., see also Tominaga et al. 2007, Izutani et al. 2009, Joggerst et al. 2009, 2010)

<table>
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<tr>
<th>Element</th>
<th>([X/H]_{3D})</th>
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<th>S(_H)</th>
<th>A((X)_{ho})</th>
</tr>
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<tr>
<td>C</td>
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<td></td>
</tr>
<tr>
<td>N</td>
<td>(\leq -4.1)</td>
<td>(\leq -5.0)</td>
<td></td>
<td></td>
<td></td>
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<td>Mg(_i)</td>
<td>(-4.71 \pm 0.11)</td>
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<td></td>
</tr>
<tr>
<td>Ca(_ii)</td>
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<td>(-4.93 \pm 0.03)</td>
<td>(-5.02 \pm 0.02)</td>
<td>(-5.15 \pm 0.09)</td>
<td>5</td>
</tr>
<tr>
<td>Ti(_i)</td>
<td>(-4.75 \pm 0.18)</td>
<td>(-4.83 \pm 0.16)</td>
<td>(-4.76 \pm 0.18)</td>
<td>(-4.84 \pm 0.16)</td>
<td>5</td>
</tr>
<tr>
<td>Fe(_i)</td>
<td>(-4.73 \pm 0.13)</td>
<td>(-5.02 \pm 0.10)</td>
<td>(-4.60 \pm 0.13)</td>
<td>(-4.89 \pm 0.10)</td>
<td>43</td>
</tr>
<tr>
<td>Ni(_i)</td>
<td>(-4.55 \pm 0.14)</td>
<td>(-4.90 \pm 0.11)</td>
<td></td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Sr(_ii)</td>
<td>(\leq -5.10)</td>
<td>(\leq -5.25)</td>
<td>(\leq -4.94)</td>
<td>(\leq -5.09)</td>
<td>1</td>
</tr>
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SDSS J1029151+172927

- is first ultra metal-poor star with Z ~ \(10^{-4.5}\) Z\(_\odot\) for all metals seen (Fe, C, N, etc.)
  [see Caffau et al. 2011]
- this is in regime, where metal-lines cannot provide cooling
  [e.g. Schneider et al. 2011, 2012, Klessen et al. 2012]

new ESO large program to find more of these stars
(120h x-shooter, 30h UVES)
[PI E. Caffau]
sions are more frequent for higher densities, we expect that its ...

...more efficient cooling of gas. When cooling and heating balance, for $10^4 < Z < 10^5 \, \text{M}_\odot$, heating dominates. For

...temperature as $Z$ varies from the CMB temperature in the low density region to 1000 K. For instance, the metal-free case reaches temperature $3000 \, \text{K}$ at the point of time just before the formation of the first sink particle (see Table 1). The dust temperature (shown in blue) is always lower than the gas temperature. In order to guide on the evaluation of the effect of dust on the thermodynamic evolution of the gas and dust, we take a closer look at the cooling and heating processes for the various metallicities tested in Figure 1.
Fig. 6.—Sink particle mass function at the point when 4.7 $M_\odot$ of gas had been accreted by the sink particles in each simulation. To resolve the fragmentation, the mass resolution is smaller than the Jeans mass at the point in the temperature-density diagram where dust and gas couple and the compressional heating starts to dominate over the dust cooling.

3.7. Mass accretion

The mass accreted by the sink particles varied within the different metallicities, and changed the final IMF. This different accretion can also influence the expected accretion luminosity. We did not take this thermal process into account during the calculations, but it is relevant to speculate if it is comparable to the other thermal processes, and necessary to include in future simulations.

In Figure 10 we present accretion properties for the newborn stellar systems. The top panel shows how the total mass in sinks evolve with time, and the comparison for different $Z$.

The accretion rate varies from 0.02 to 0.17 $M_\odot$ yr$^{-1}$, and it is on average lower for the $Z = 10^{-4} Z_\odot$ case. The $Z = 10^{-4} Z_\odot$ case accreted mass slower than the others, taking the longest time to accrete 4.7$M_\odot$.

In the bottom panel of Figure 10, we show the accretion luminosity calculated by considering that all gas was accreted.

Fig. 7.—Timescales for fragmentation (bottom panel) and accretion (middle panel), and also their fraction (top panel) versus enclosed gas mass ($M_{enc}$) for the metallicities tested. The values were calculated just before the first sink particle was formed.

Fig. 8.—Timescales for fragmentation and accretion for different metallicities.

t_{\text{frag}} (\langle N / (dN/dt) \rangle) indicates the average for the number of sink particles ($N$) divided by the time variation of that number, or the sink particle formation rate.

t_{\text{acc}} (\langle M / (dM/dt) \rangle) is the average accretion time, which is calculated by dividing the total mass in sink particles divided by the mass accretion rate.

EOS as function of metallicity

(Omukai et al. 2005, 2010)
EOS as function of metallicity

- slope of EOS in the density range $5 \text{ cm}^{-3} \leq n \leq 16 \text{ cm}^{-3}$ is $\gamma \approx 1.06$.
- with non-zero angular momentum, disk forms.
- disk is unstable against fragmentation at high density

(Okukai et al. 2005, 2010)
most current numerical simulations of Pop III star formation predict very massive objects
(e.g. Abel et al. 2002, Yoshida et al. 2008, Bromm et al. 2009)

similar for theoretical models (e.g. Tan & McKee 2004)

there are some first hints of fragmentation, however
(Turk et al. 2009, Stacy et al. 2010)
detailed look at accretion disk around first star

successive zoom-in calculation from cosmological initial conditions (using SPH and new grid-code AREPO)

Redshift:
$z = 21$

Boxsize:
$150/h$ kpc (comoving)

Slice Width:
$10/h$ kpc (comoving)

$\frac{\text{Enclosed gas mass}}{\text{Bonner-Ebert mass}}$:
$Z = \frac{\text{ig}}{\text{ig}}$

$Z = 0$

$10^5$ AU

$10^4$ AU

$10^2$ AU

$10^3$ AU


detailed look at accretion disk around first star

successive zoom-in calculation from cosmological initial conditions (using SPH and new grid-code AREPO)

what is the time evolution of accretion disk around first star to form?

Figure 1: Density evolution in a 120 AU region around the first protostar, showing the build-up of the protostellar disk and its eventual fragmentation. We also see ‘wakes’ in the low-density regions, produced by the previous passage of the spiral arms.
Figure 2: Radial profiles of the disk’s physical properties, centered on the first protostellar core to form. The quantities are mass-weighted and taken from a slice through the midplane of the disk. In the lower right-hand plot we show the radial distribution of the disk’s Toomre parameter, \( Q = \frac{c_s}{\kappa \pi G \Sigma} \), where \( c_s \) is the sound speed and \( \kappa \) is the epicyclic frequency. Because our disk is Keplerian, we adopted the standard simplification, and replaced \( \Omega \) with the orbital frequency.

The molecular fraction is defined as the number density of hydrogen molecules \( n_{H_2} \), divided by the number density of hydrogen nuclei \( n \), such that fully molecular gas has a value of 0.5 (Clark et al. 2011b, Science, 331, 1040).
Most recent calculations:

fully sink-less simulations, following the disk build-up over \( \sim 10 \) years
(resolving the protostars - first cores - down to \( 10^5 \) km)
expected mass spectrum

expected mass spectrum

• expected IMF is flat and covers a wide range of masses

• implications
  - because slope > -2, most mass is in massive objects as predicted by most previous calculations
  - most high-mass Pop III stars should be in binary systems --> source of high-redshift gamma-ray bursts
  - because of ejection, some low-mass objects (< 0.8 M☉) might have survived until today and could potentially be found in the Milky Way

• consistent with abundance patterns found in second generation stars
The metallicities of extremely metal-poor stars in the halo are consistent with the yields of core-collapse supernovae, i.e. progenitor stars with 20 - 40 M_{\odot}.

(Joggerst et al. 2009, 2010)

(Tominaga et al. 2007)
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- primordial star formation shares the same complexities as present-day star formation
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