Star Formation

Ralf Klessen

Zentrum für Astronomie der Universität Heidelberg
Institut für Theoretische Astrophysik
thanks to ...

... people in the group in Heidelberg:

Richard Allison, Christian Baczynski, Erik Bertram, Frank Bigiel, Roxana Chira, Paul Clark, Gustavo Dopcke, Jayanta Dutta, Volker Gaibler, Simon Glover, Lukas Konstandin, Faviola Molina, Mei Sasaki, Jennifer Schober, Rahul Shetty, Rowan Smith, László Szűcs

... former group members:

Robi Banerjee, Ingo Berentzen, Christoph Federrath, Philipp Girichidis, Thomas Greif, Milica Micic, Thomas Peters, Dominik Schleicher, Stefan Schmeja, Sharanya Sur

... many collaborators abroad!
agenda

• star formation theory
  - phenomenology
  - historic remarks
  - our current understanding and its limitations

• application
  - the stellar mass function at birth (IMF)
• star formation sets in very early after the big bang
• stars always form in galaxies and protogalaxies
• we cannot see the first generation of stars, but maybe the second one
- correlation between stellar birth and large-scale dynamics
- spiral arms
- tidal perturbation from neighboring galaxy
HI gas more extended
• H2 and SF well correlated

galaxies from THINGS and HERACLES survey
(images from Frank Bigiel, ZAH/ITA)
Orion Nebula Cluster (ESO, VLT, M. McCaughrean)

data from T. Dame (CfA Harvard)
• stars form in molecular clouds
• stars form in clusters
• stars form on ~ dynamical time
• (protostellar) feedback is very important

Orion Nebula Cluster (ESO, VLT, M. McCaughrean)
Ionizing radiation from central star Θ1C Orionis

• strong feedback: UV radiation from Θ1C Orionis affects star formation on all cluster scales

Trapezium stars in the center of the ONC (HST, Johnstone et al. 1998)
eventually, clusters like the ONC (1 Myr) will evolve into clusters like the Pleiades (100 Myr)
• density
  - density of ISM: few particles per cm$^3$
  - density of molecular cloud: few 100 particles per cm$^3$
  - density of Sun: 1.4 g/cm$^3$

• spatial scale
  - size of molecular cloud: few 10s of pc
  - size of young cluster: $\sim 1$ pc
  - size of Sun: $1.4 \times 10^{10}$ cm
- contracting force
  - only force that can do this compression is **GRAVITY**

- opposing forces
  - there are several processes that can oppose gravity
  - **GAS PRESSURE**
  - **TURBULENCE**
  - **MAGNETIC FIELDS**
  - **RADIATION PRESSURE**

Modern star formation theory is based on the complex interplay between all these processes.
early theoretical models

**Jeans (1902):** Interplay between self-gravity and thermal pressure

- stability of homogeneous spherical density enhancements against gravitational collapse
- dispersion relation:

\[
\omega^2 = c_s^2 k^2 - 4\pi G \rho_0
\]

- instability when \( \omega^2 < 0 \)
- minimal mass:

\[
M_J = \frac{1}{6} \pi^{-5/2} G^{-3/2} \rho_0^{-1/2} c_s^3 \propto \rho_0^{-1/2} T^{-3/2}
\]

Sir James Jeans, 1877 - 1946
von Weizsäcker (1943, 1951) and Chandrasekhar (1951): concept of MICROTURBULENCE

- BASIC ASSUMPTION: separation of scales between dynamics and turbulence

\[ \ell_{\text{turb}} \ll \ell_{\text{dyn}} \]

- then turbulent velocity dispersion contributes to effective sound speed:

\[ C_c^2 \rightarrow C_c^2 + \sigma_{\text{rms}}^2 \]

- Larger effective Jeans masses \( \rightarrow \) more stability

- BUT: (1) turbulence depends on \( k \):

\[ \sigma_{\text{rms}}^2(k) \]

(2) supersonic turbulence \( \rightarrow \sigma_{\text{rms}}^2(k) \gg c_s^2 \) usually
problems of early dynamical theory

- molecular clouds are *highly Jeans-unstable*, yet, they do *NOT* form stars at high rate and with high efficiency (the observed global SFE in molecular clouds is ~5%)
  \[\Rightarrow \text{ something prevents large-scale collapse.}\]

- all throughout the early 1990’s, molecular clouds had been thought to be long-lived quasi-equilibrium entities.

- molecular clouds are *magnetized*
Magnetic star formation

- **Mestel & Spitzer (1956):** Magnetic fields can prevent collapse!!!
  - Critical mass for gravitational collapse in presence of B-field
    \[ M_{cr} = \frac{5^{3/2}}{48\pi^2} \frac{B^3}{G^{3/2} \rho^2} \]
  - Critical mass-to-flux ratio (Mouschovias & Spitzer 1976)
    \[ \left[ \frac{M}{\Phi} \right]_{cr} = \frac{\zeta}{3\pi} \left[ \frac{5}{G} \right]^{1/2} \]
  - Ambipolar diffusion can initiate collapse
“standard theory” of star formation

- BASIC ASSUMPTION: Stars form from magnetically highly subcritical cores

- Ambipolar diffusion slowly increases \( (M/\Phi) : \tau_{AD} \approx 10\tau_{ff} \)

- Once \( (M/\Phi) > (M/\Phi)_{\text{crit}} \):
  - dynamical collapse of SIS
    - Shu (1977) collapse solution
    - \( dM/dt = 0.975 \ c_s^3/G = \text{const.} \)

- Was (in principle) only intended for isolated, low-mass stars
problems of “standard theory”

- Observed B-fields are weak, at most marginally critical (Crutcher 1999, Bourke et al. 2001)


- Structure of prestellar cores (e.g. Bacman et al. 2000, Alves et al. 2001)

- Strongly time varying dM/dt (e.g. Hendriksen et al. 1997, André et al. 2000)

- More extended infall motions than predicted by the standard model (Williams & Myers 2000, Myers et al. 2000)

- Most stars form as binaries (e.g. Lada 2006)

- As many prestellar cores as protostellar cores in SF regions (e.g. André et al. 2002)

- Molecular cloud clumps are chemically young (Bergin & Langer 1997, Pratap et al 1997, Aikawa et al 2001)

- Stellar age distribution small ($\tau_{ff} << \tau_{AD}$) (Ballesteros-Paredes et al. 1999, Elmegreen 2000, Hartmann 2001)

- Strong theoretical criticism of the SIS as starting condition for gravitational collapse (e.g. Whitworth et al 1996, Nakano 1998, as summarized in Klessen & Mac Low 2004)

- Standard AD-dominated theory is incompatible with observations (Crutcher et al. 2009, 2010ab, Bertram et al. 2011)

(see e.g. Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194)
gravoturbulent star formation

- **BASIC ASSUMPTION:**
  
  star formation is controlled by interplay between supersonic turbulence and self-gravity

- turbulence plays a *dual role*:
  - on *large scales* it provides support
  - on *small scales* it can *trigger collapse*

- some predictions:
  - dynamical star formation timescale $\tau_{\text{ff}}$
  - high binary fraction
  - complex spatial structure of embedded star clusters
  - and many more . . .

Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194
McKee & Ostriker, 2007, ARAA, 45, 565
turbulent cascade in the ISM

- scale-free behavior of turbulence in the range
  \[ \frac{L}{\eta_K} \approx R^{3/4} \]
- slope between -5/3 ... -2
- energy “flows” from large to small scales, where it turns into heat

energy source & scale NOT known
(supernovae, winds, spiral density waves?)

dissipation scale not known
(ambipolar diffusion, molecular diffusion?)
molecular clouds
\[ \sigma_{\text{rms}} \approx \text{several km/s} \]
\[ M_{\text{rms}} > 10 \]
\[ L > 10 \text{ pc} \]

energy source & scale
\( \text{NOT known} \)
(supernovae, winds, spiral density waves?)

dense protostellar cores
\[ \sigma_{\text{rms}} << 1 \text{ km/s} \]
\[ M_{\text{rms}} \leq 1 \]
\[ L \approx 0.1 \text{ pc} \]

dissipation scale not known
(ambipolar diffusion, molecular diffusion?)
turbulence creates a hierarchy of clumps
as turbulence decays locally, contraction sets in
while region contracts, individual clumps collapse to form stars
while region contracts, individual clumps collapse to form stars
individual clumps collapse to form stars
individual clumps collapse to form stars
In dense clusters, clumps may merge while collapsing, then contain multiple protostars.

\[ \alpha = \frac{E_{\text{kin}}}{|E_{\text{pot}}|} < 1 \]
in *dense clusters*, clumps may merge while collapsing
---> then contain multiple protostars
in *dense clusters*, competitive mass growth becomes important
low-mass objects may become ejected --> accretion stops
feedback terminates star formation
result: *star cluster*, possibly with H II region
some concerns of simple model

- **energy balance**
  - in molecular clouds:
  
  kinetic energy ~ potential energy ~ magnetic energy > thermal energy
  - models based on HD turbulence misses important physics
  - in certain environments (Galactic Center, star bursts), energy density in *cosmic rays* and *radiation* is important as well

- **time scales**
  - star clusters form fast, but more slowly than predicted by HD only (feedback and magnetic fields do help)
  - initial conditions do matter (turbulence does not erase memory of past dynamics)

- **star formation efficiency (SFE)**
  - SFE in gravoturbulent models is too high (again more physics needed)
• stars form from the complex interplay of self-gravity and a large number of competing processes (such as turbulence, B-field, feedback, thermal pressure)

• the relative importance of these processes depends on the environment
  - prestellar cores --> thermal pressure is important
  - molecular clouds --> turbulence dominates

    \[ \sigma \propto L^{1/2} \] (Larson’s relation: \( \sigma \propto L^{1/2} \))

  - massive star forming regions (NGC602): radiative feedback is important
  - small clusters (Taurus): evolution maybe dominated by external turbulence

• star formation is regulated by various feedback processes

• star formation is closely linked to global galactic dynamics

Star formation is intrinsically a multi-scale and multi-physics problem, where it is difficult to single out individual processes. Simple theoretical approaches usually fail.
Star formation is intrinsically a multi-scale and multi-physics problem, where it is difficult to single out individual processes. Simple theoretical approaches usually fail.
Star formation is intrinsically a multi-scale and multi-physics problem, where it is difficult to single out individual processes. Simple theoretical approaches usually fail.
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? how do the first stars form?
Stars seem to follow a universal mass function at birth -\rightarrow\text{IMF}

(Kroupa 2002)

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

• distribution of stellar masses depends on
  - turbulent initial conditions
    --> mass spectrum of prestellar cloud 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

(Kroupa 2002)
example: model of Orion cloud

Bonnell et al. 2010

"model" of Orion cloud:
15,000,000 SPH particles,
$10^4 M_{\odot}$ in 10 pc, mass resolution
0.02 $M_{\odot}$, forms ~2,500 "stars" (sink particles)

MASSIVE STARS
- form early in high-density gas clumps (cluster center)
- high accretion rates, maintained for a long time

LOW-MASS STARS
- form later as gas falls into potential well
- high relative velocities
- little subsequent accretion
Dynamics of nascent star cluster

in dense clusters protostellar interaction may be come important!

Trajectories of protostars in a nascent dense cluster created by gravoturbulent fragmentation
Mass accretion rates vary with time and are strongly influenced by the cluster environment.

stellar masses

- Distribution of stellar masses depends on:
  - Turbulent initial conditions
    --> Mass spectrum of prestellar cloud 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

Application to early star formation

(Kroupa 2002)
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

\[ \gamma = 0.2 \quad \gamma = 1.0 \quad \gamma = 1.2 \]

- For \( \gamma < 1 \) fragmentation is enhanced → *cluster of low-mass stars*
- For \( \gamma > 1 \) it is suppressed → 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)  \[ M_{\text{jeans}} \propto \gamma^{3/2} \rho^{(3\gamma-4)/2} \]

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

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

Figure 3. Temperature evolution at the center for different metallicities. This should be compared with Figure 2 of O05, where similar plots for the one-zone model (Figure 3.2) are presented. The constant Jeans masses are indicated by the dashed lines. Until very high densities, the cooling is owing to the formation heating associated with the three-body reaction (Equation (10)). The heating is catalyzed by a small amount of remaining electrons. With increasing densities and the amount of formed $H_2$, the continuum absorption decreases. Another critical value is when $\frac{\Gamma_{\text{eff}}}{\Gamma_{\text{eff},\text{H}_2}} = 1$, while fragmentation is strongly prohibited for $\frac{\Gamma_{\text{eff}}}{\Gamma_{\text{eff},\text{H}_2}} < 1$, where $\Gamma_{\text{eff}}$ is an important index to examine the variation of pressure in response to the density variation.

For example, the clouds easily fragment as long as $\frac{\Gamma_{\text{eff}}}{\Gamma_{\text{eff},\text{H}_2}} > 1$. Another critical value is $\frac{\Gamma_{\text{eff}}}{\Gamma_{\text{eff},\text{H}_2}} = 1$, which gives $T(\text{K}) \approx 10000$ and this suppresses the cooling rate gradient. The effective ratio of specific heat at the center, compared with Figure 2 of O05, where similar plots for the overall evolution is quite similar to that calculated by the one-zone model until $10^6 M_{\odot}$. For the cooling, the $H_2$ formation dominates. For the higher density, the $H_2$ formation heating contributes comparably to $H_2$ dissociation, but for $10^3 M_{\odot}$, another molecular species in the metal-poor gas contributes to $H_2$ dissociation. For the metallicity, the catalysis and $H_2$ formation (Equation (11)) are below $10^{-2}$, which contributes comparably to $H_2$ dissociation.

For the cooling rate, the $H_2$ formation and dissociation are associated with the three-body reaction (Equation (11)). In our case, however, it only contributes comparably to $H_2$ dissociation, but for $10^3 M_{\odot}$, which saturates at $\frac{\Gamma_{\text{eff}}}{\Gamma_{\text{eff},\text{H}_2}} = 1$. If a metal-free gas is once ionized (Uehara & Inutsuka 2006), the $H_2$ dissociation is very efficient ($\sim 80$% of the electron density). For the ionization, the $H_2$ formation and dissociation are associated with the three-body reaction (Equation (11)). The heating is caused by the compression, but for $10^3 M_{\odot}$, the $H_2$ formation heating dominates. For the ionization, the $H_2$ formation and dissociation are associated with the three-body reaction (Equation (11)).

In this section, we review thermal evolution of the cloud core in particular, at high densities and for low-metallicity cases. We then describe the effects of metallicity later in Section 3.2. We then describe the effects of metallicity.

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

The evolution of temperatures in prestellar cloud cores with metallicities is presented in Figure 1. The dashed lines indicate the constant Jeans masses. For those above 10^{-3} cm^{-3}, the dynamical response of self-gravitating clouds to thermal cooling and heating processes control the core evolution. There are, however, small disagreements, in particular, at high densities and for low-metallicity cases. Below 10^{-2} M_{\odot}, the clouds easily fragment as long as the dynamical response of self-gravitating clouds to thermal processes is quenched after the three-body reaction (Equation (11)).

For example, the clouds easily fragment as long as their recombination proceeding, the H\alpha line-emission contributes comparably to H\alpha radiation losses, and the H\alpha cooling rate at 10^{-2} M_{\odot} is above 1 in this period except for brief intervals.

After this plateau, the H\alpha channel is quenched below 10^{-2} M_{\odot}, which is associated with the three-body reaction (Equation (9)).

The effective ratio of specific heat increases only by a small factor whereas density increases by many orders of magnitudes. The effective ratio of specific heat is an important index to examine the variation of pressure in response to the density variation, giving only by a small factor whereas density increases by many orders of magnitudes. The effective ratio of specific heat is an important index to examine the variation of pressure in response to the density variation.

After this plateau, the H\alpha channel is quenched below 10^{-2} M_{\odot}, which is associated with the three-body reaction (Equation (9)).

We defer detailed discussion on these differences to later in Section 3.2.

(Omukai et al. 2005, 2010)

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

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

- which one is explains origin of extremely metal-poor stars

NB: lines would only make very massive stars, with $M > \text{few } x 10 \ M_{\odot}$.

(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]

- new ESO large program to find more of these stars (120h x-shooter, 30h UVES)
[PI E. Caffau]

(Caffau et al. 2011, 2012)
(Schneider et al. 2011,2012, Klessen et al. 2012)
transition: Pop III to Pop II.5

Fig. 2. — Number density maps for a slice through the high density region. The image shows a sequence of zooms in the density structure in the gas immediately before the formation of the first protostar.

Thermodynamical evolution of gas and dust

ANALYSIS

3. Fragmentation of star-forming clouds at very low metallicities

4. Dependence of gas and dust temperatures on gas density for metallicities $10^{-5}$, $10^{-4}$, $10^{-3}$, and $10^{-2}$.

We have performed a set of four simulations for different metallicities in order to test if dust can efficiently cool the gas. Metallicity affects the cooling of the gas, and changes the fragmentation behavior. Since dust cooling is important at very low metallicities ($[M/H] = -5$), the evolution is close to isothermal. Changes in metallicity influence the point in density-$n$ at which dust cooling becomes important. For metallicities ($Z = 0$), dust cooling begins to be important for $n > 10^4$ cm$^{-3}$, whereas dust cooling becomes important for $n > 10^5$ cm$^{-3}$ for $Z = 10^{-4}$.

For all cases where dust was present, its cooling became the most important e-folding time over the two main coolants (dust and H$^-$). The dust temperature (shown in blue) is shown in the figure just before the formation of the first sink particles (see Table 1). The dust temperature shows the effect of the evolution of the gas and dust temperatures, and the cooling and heating processes involved.

The evolution of the gas and dust temperatures are shown in Figure 1. The evolution of the gas and dust temperatures are shown in Figure 2. The main cooling and heating rates are shown in Figure 3.

The mass accreted by the sink particles varied within the mass resolution of the simulations. The mass accretion rate is defined as the variation of that number, or accretion in sinks evolve with time. The comparison for different metallicities shows that the mass accretion rate is lower for $Z = 10^{-4}$ cm$^{-3}$ than $Z = 10^{-3}$ cm$^{-3}$, and it is lower for $[M/H] = -5$ than $[M/H] = -6$.

For the $Z = 0$ case, dust cooling becomes important for $n > 10^4$ cm$^{-3}$, whereas dust cooling becomes important for $n > 10^5$ cm$^{-3}$ for $Z = 10^{-4}$.

The other thermal processes play a minor role during the heating. These thermal processes are not shown in the figure, but they are included in future simulations.

In Figure 2 we show the main cooling and heating rates. The cooling and heating rates are shown in Figure 3. The cooling and heating rates are shown in Figure 4. The cooling and heating rates are shown in Figure 5.

The gas thermal evolution during the collapse takes different paths depending on the metallicity, as expressed in the density-temperature diagram (Figure 1). In order to explain these different paths, we take a closer look at the cooling and heating processes involved.

While dust cooling becomes important for $n > 10^4$ cm$^{-3}$ in the $Z = 0$ case, dust cooling becomes important for $n > 10^5$ cm$^{-3}$ for $Z = 10^{-4}$.

Changes in metallicity influence the point in density-$n$ at which dust cooling becomes important e-folding time over the two main coolants (dust and H$^-$). The dust temperature (shown in blue) is shown in the figure just before the formation of the first sink particles (see Table 1). The dust temperature shows the effect of the evolution of the gas and dust temperatures, and the cooling and heating processes involved.

The values were calculated just before the first sink particle formation and the accretion in sinks evolve with time. The comparison for different metallicities shows that the mass accretion rate is lower for $Z = 10^{-4}$ cm$^{-3}$ than $Z = 10^{-3}$ cm$^{-3}$, and it is lower for $[M/H] = -5$ than $[M/H] = -6$.

For the $Z = 0$ case, dust cooling becomes important for $n > 10^4$ cm$^{-3}$, whereas dust cooling becomes important for $n > 10^5$ cm$^{-3}$ for $Z = 10^{-4}$.

The other thermal processes play a minor role during the heating. These thermal processes are not shown in the figure, but they are included in future simulations.


hints for differences in mass spectrum

disk fragmentation mode

grovoturbulent fragmentation mode

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

(Omukai 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)
A detailed look at accretion disk around first star

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


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.
important disk parameters

\[
Q = \frac{c_s \kappa}{\pi G \Sigma}
\]

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, \( Q = \frac{c_s}{\kappa G \Sigma} \), 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 \( \kappa \) 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)
similar study with very different numerical method (AREPO)

one out of five halos

expected mass spectrum

we see “flat” 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☉ (e.g. Tominaga et al. 2007, Izutani et al. 2009, Joggerst et al. 2009, 2010).
Star formation is intrinsically a multi-scale and multi-physics problem, where it is difficult to single out individual processes.

- stars form from the **complex interplay** of **self-gravity** and a large number of competing processes (such as **turbulence**, **B-field**, **feedback**, **thermal pressure**)
- **thermodynamic properties** of the gas (heating vs cooling) play a key role in the star formation process
- detailed studies require the **consistent treatment** of many **different physical and chemical processes** (theoretical and computational challenge)
- star formation is **regulated** by several **feedback loops**, which are still poorly understood
- **primordial star formation** shares the same **complexities** as present-day star formation