Dark Matter Halo Environment for Primordial Star Formation

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Outline

* Comprehensive analysis of the properties of high-z halos, such as spin and shape, with an unprecedented inclusion of detailed gas physics.
* First attempt to make such study in the low-end of the halo mass function ($\approx 10^{4-7} M_\odot$) including gas physics
* We provide useful fits for all quantities of interest, and their dependences with mass and redshifts, which can easily be inserted as input for analytical and semi-analytical models.
* Connection with PopIII stars IMF

Motivation

- The formation of first, metal-free (often referred to as **PopIII**) stars in the Universe represents a milestone during cosmic evolution, marking the **end of the Dark Ages** and producing the first heavy elements

- Thus, a key problem in physical cosmology is to understand the origin and evolution of such objects, born out of the pristine conditions leftover by the Big Bang. More specifically, the most urgent question concerns their **Initial Mass Function (IMF)**, which, despite its relevance, remains at best a poorly known quantity due to the lack of direct observations.

- Until recently, studies based on the standard ΛCDM cosmological model for structure formation predicted that the first stars **were predominantly massive**

- Even **more recently** results found that that instead of forming a single massive object, the gas typically fragments into a number of protostars with a **range of different masses**.

- In spite of this unsettled situation, a broad consensus exists on the fact that **rotation of the protogalactic cloud** is the **key factor** in determining the final outcome of the collapse.

- The angular momentum of the gas is probably linked to that of the parent halo. Hence, it is important to turn our attention to the properties of the dark matter halos that host the first stars to put the entire problem on a solid basis.

- Our purpose is to explore the properties (such as **spin and shape**) of the high-z halos likely to **host the first stars**, with an **unprecedented inclusion** of detailed **gas physics**.

Simulation

Modified version of Gadget-2 code. Initial conditions samples in $z = 100$, within a cubic volume of comoving side 1 Mpc h^{-1} and 320^3 particles per gas and dark matter species, corresponding to masses of 116 $M_{\odot}h^{-1}$ and 755 $M_{\odot}h^{-1}$, respectively. Snapshots in the range $11 < z < 16$, identification of halos by FoF and substructures by SubFind.

Follows the evolution of: e^-, H, H^+, H^-, He, He^+, He^{++}, H_2, H_2^+, D, D^+, HD, HeH^+

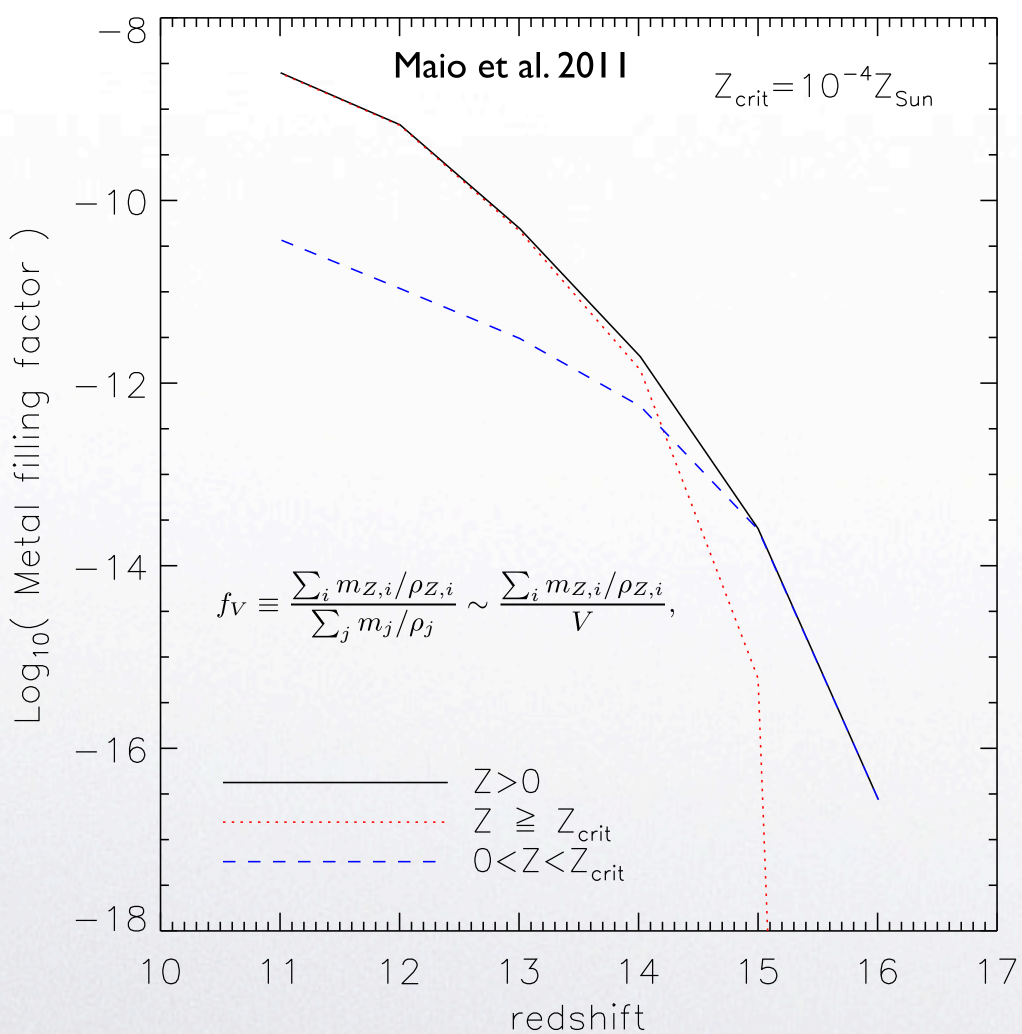
PopIII and PopII/I star formation, metal pollution C, O, Si, Fe, Mg, S, Ca, (Tornatore et al. 2007)

Gas cooling from resonant and fine-structure lines (Maio et al. 2007, 2009)

Feedback effects (Springel & Hernquist 2003)

More details in Maio et al. (2010), The simulations were performed by using the machines of the Max Planck Society computing center, Garching (Rechenzentrum-Garching).

Metal pollution



- metal pollution is a very efficient process and the critical metallicity is easily reached in less than $\sim 10^8$ yr;
- the population II regime is, in general, the dominant regime of star formation;
- the population III regime is expected to survive in isolated environments or in the outskirts of star forming haloes;
- metal pollution follows an "inside-out" mode and early metals are spread far away from their birth sites, even outside the virial radius;
- the inside-out mode leads metal pollution in closeby star forming haloes, inducing "gravitational enrichment", while self-enrichment is a negligeble process;
- the coexistence of cold, pristine-gas inflows and of hot, enriched-gas outflows determines turbulence with $R \sim 10^8 - 10^{10}$ and hydro instabilities;
- different Z_{crit} or popIII IMF alter only slightly these findings.

Halo properties derivation

Shape Tensor

$$\mathcal{S}_{jk} = \frac{1}{N}\sum_{i=1}^{N} r_{i,j} r_{i,k}.$$

Semi-axis a, b, c

$p = c/b$, $q = b/a$ and $s = c/a$.

Triaxiallity measures if halo is prolate (T =1) or oblate (T = 0).

$$\mathcal{T} = \frac{1-q^2}{1-s^2},$$

Spin Parameter

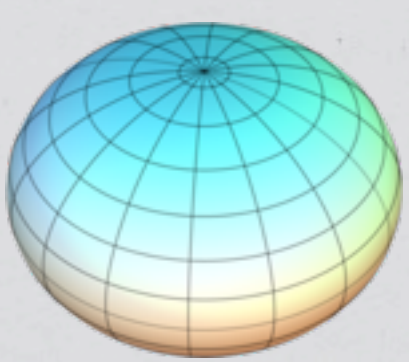
The spin parameter is a measure of the amount of coherent rotation in a system compared to random motions.

$$\lambda \equiv \frac{J|E|^{1/2}}{GM^{5/2}},$$

Specific angular momentum

$$\mathbf{j} = \frac{1}{N}\sum_{i=1}^{N} r_i \times v_i,$$

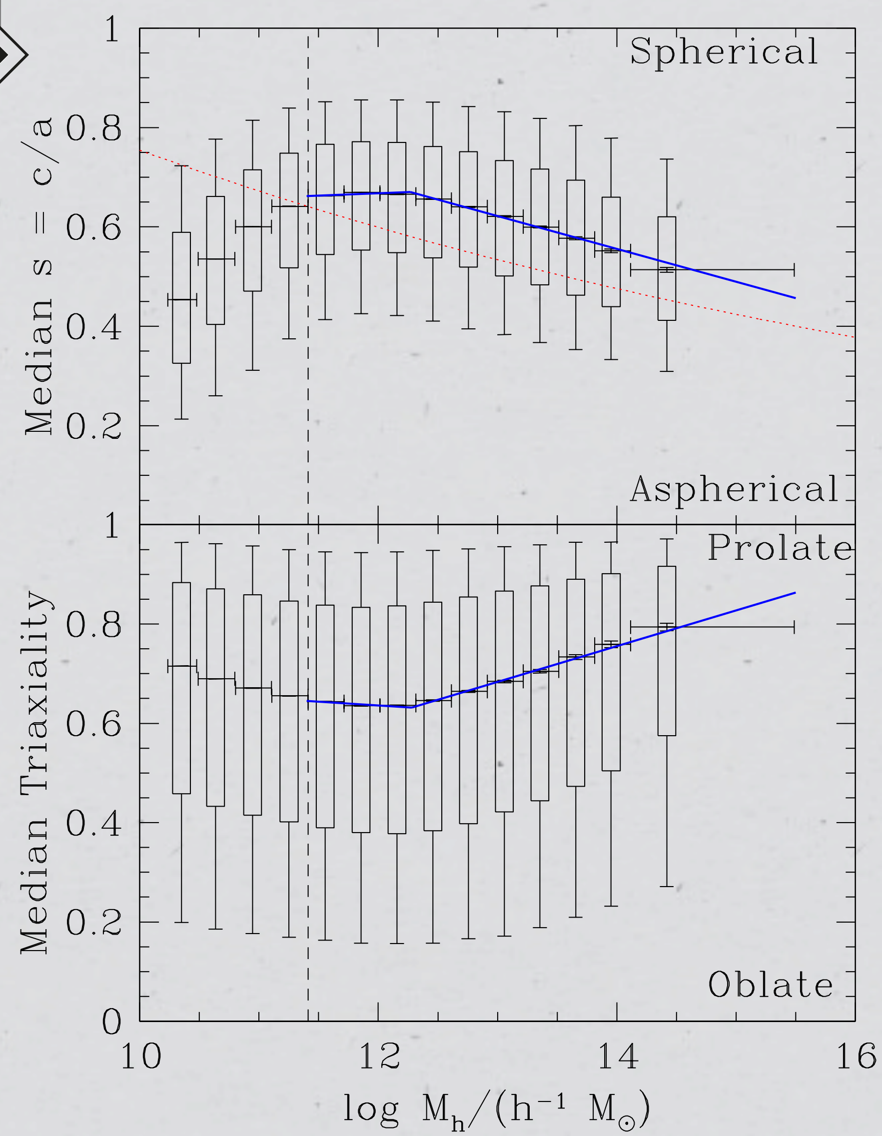
For a spherical object, it corresponds approximately to the ratio of its own angular velocity to the angular velocity needed for it to be supported against gravity solely by rotation



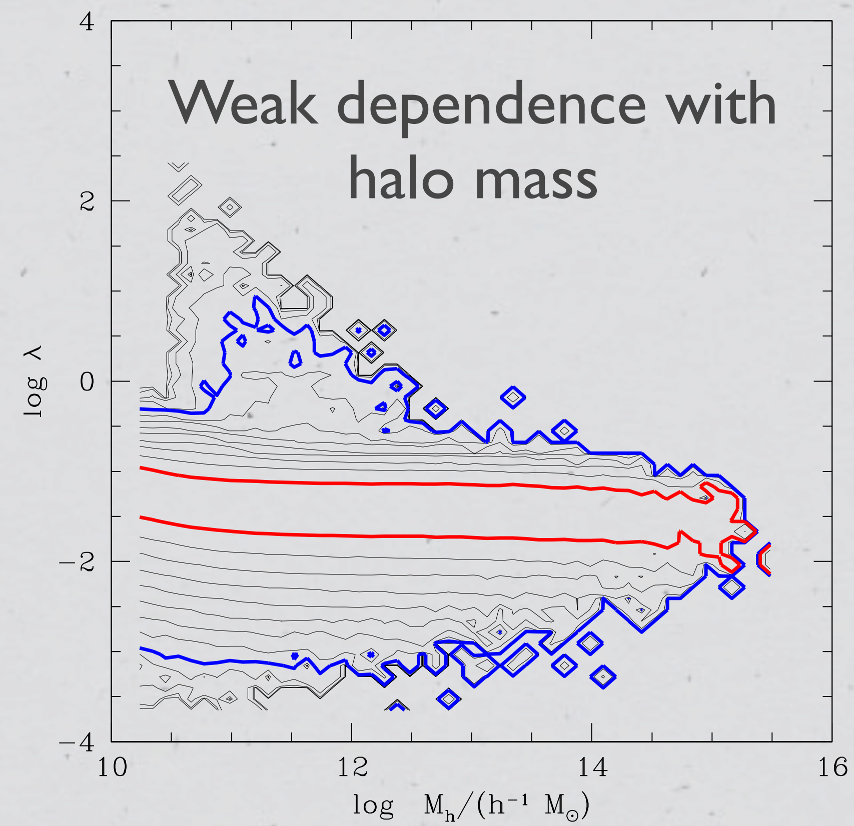
Oblate: *T=0*

Prolate: *T=1*

Low-z halos

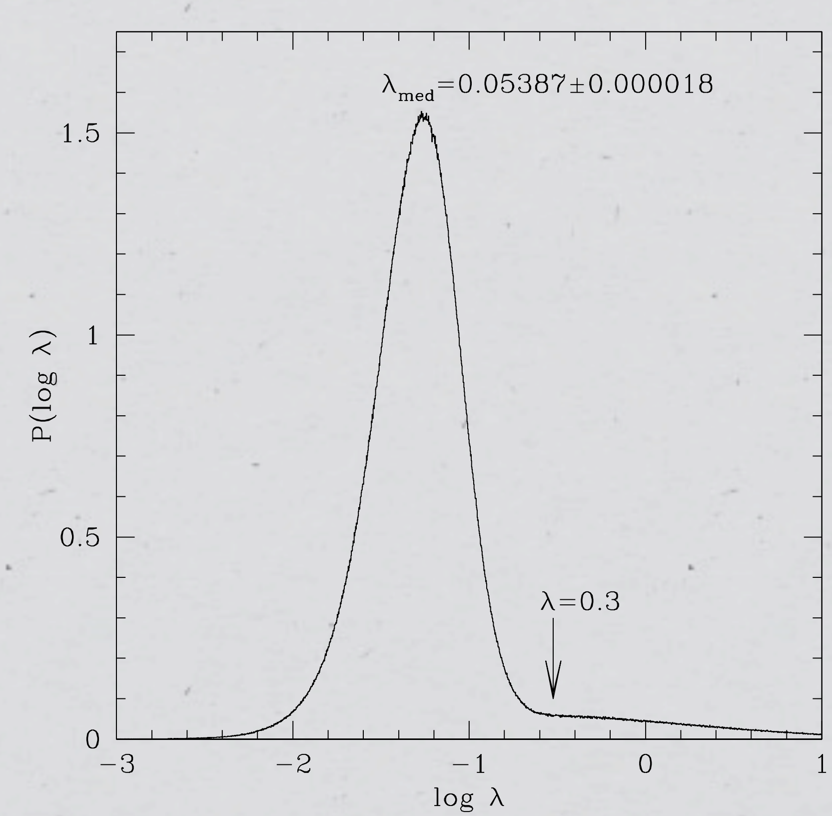


More spherical and prolate

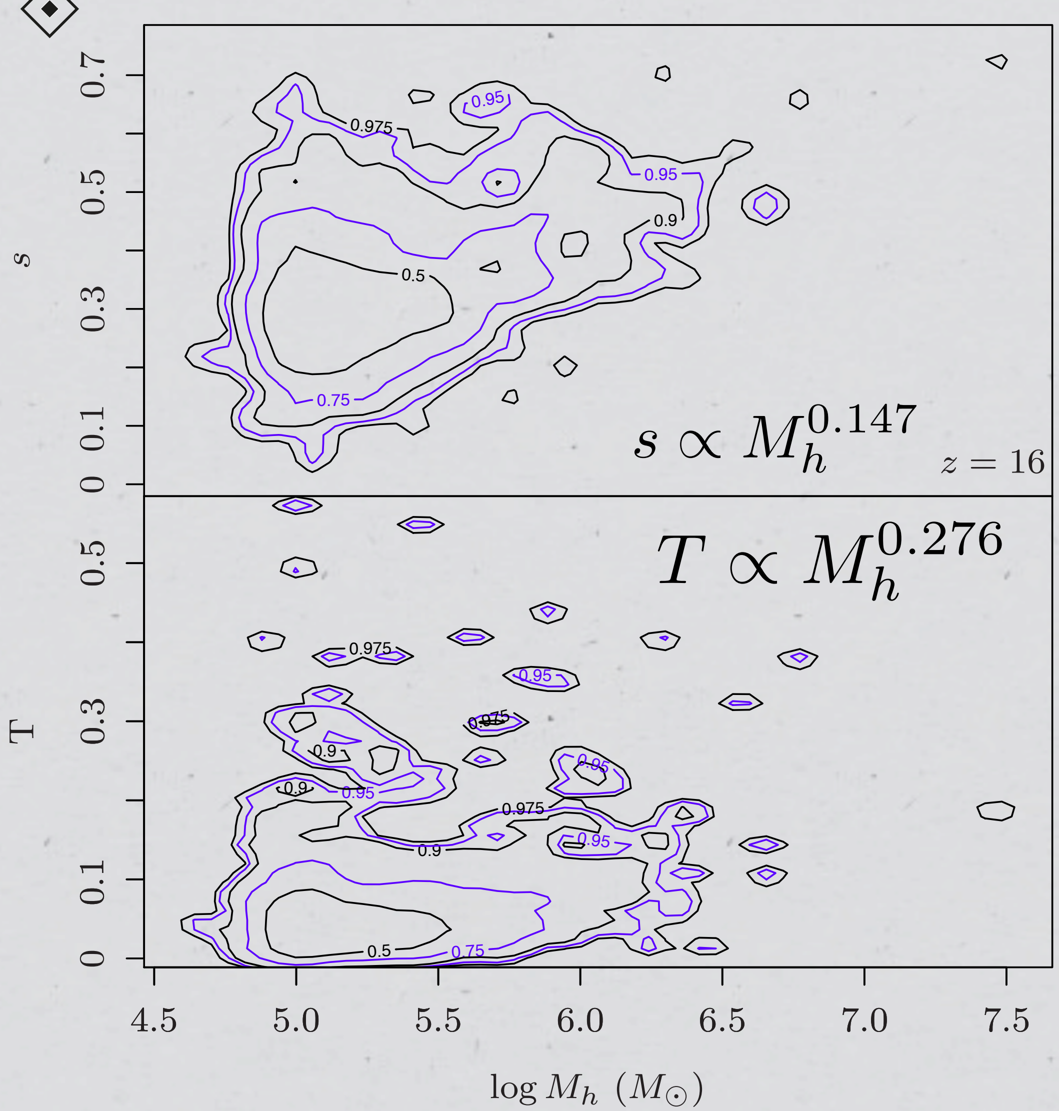


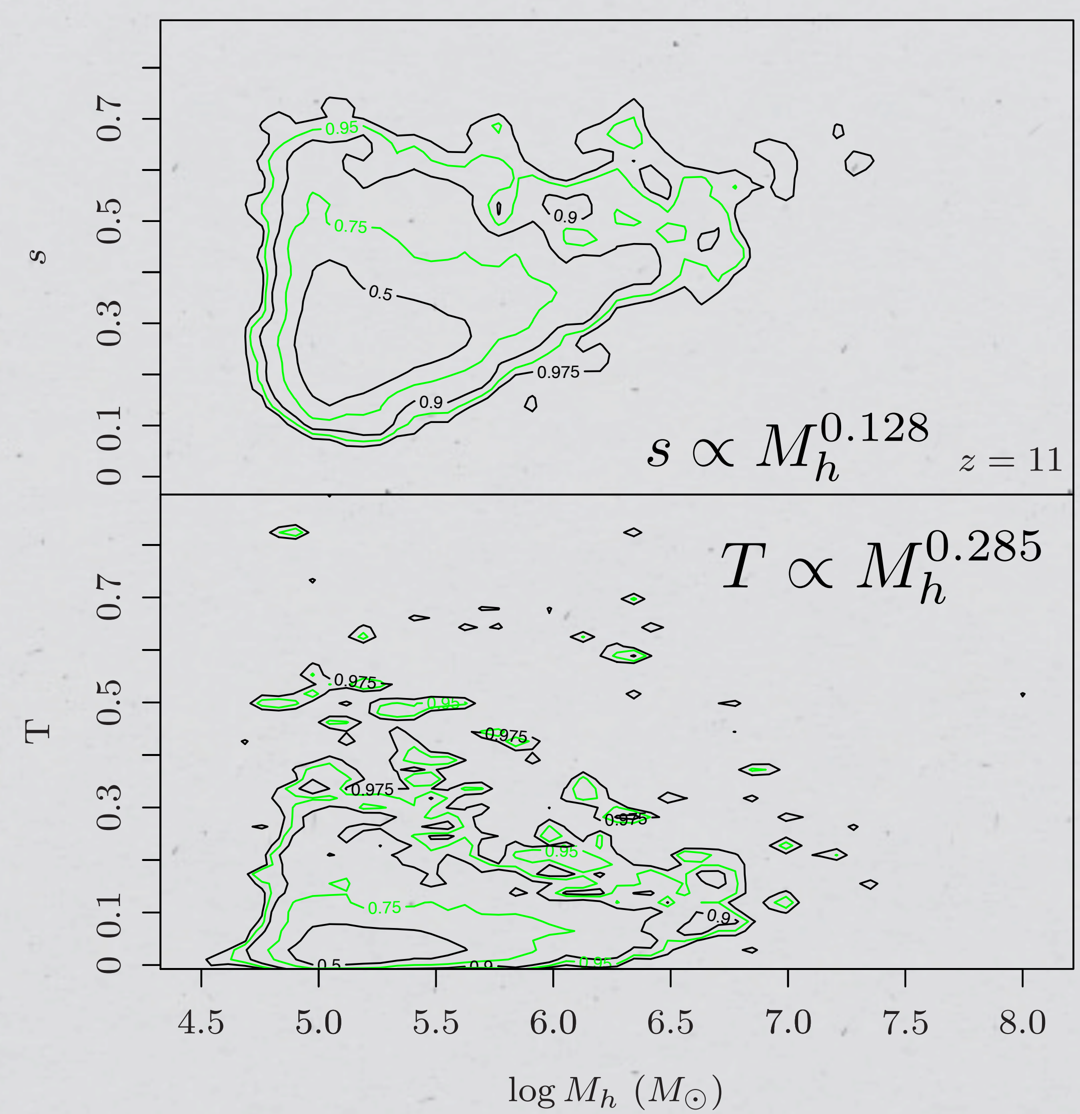
Well described by a lognormal, but best fit with a power-law

$$P(\log\lambda) = A\left(\frac{\lambda}{\lambda_0}\right)^3 \exp\left[-\alpha\left(\frac{\lambda}{\lambda_0}\right)^{3/\alpha}\right]$$



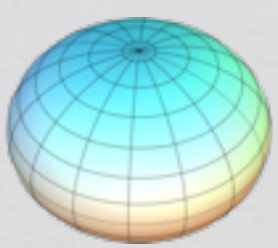
Shape-Mass Correlation





$$\langle s \rangle = 0.3 \pm 0.1$$

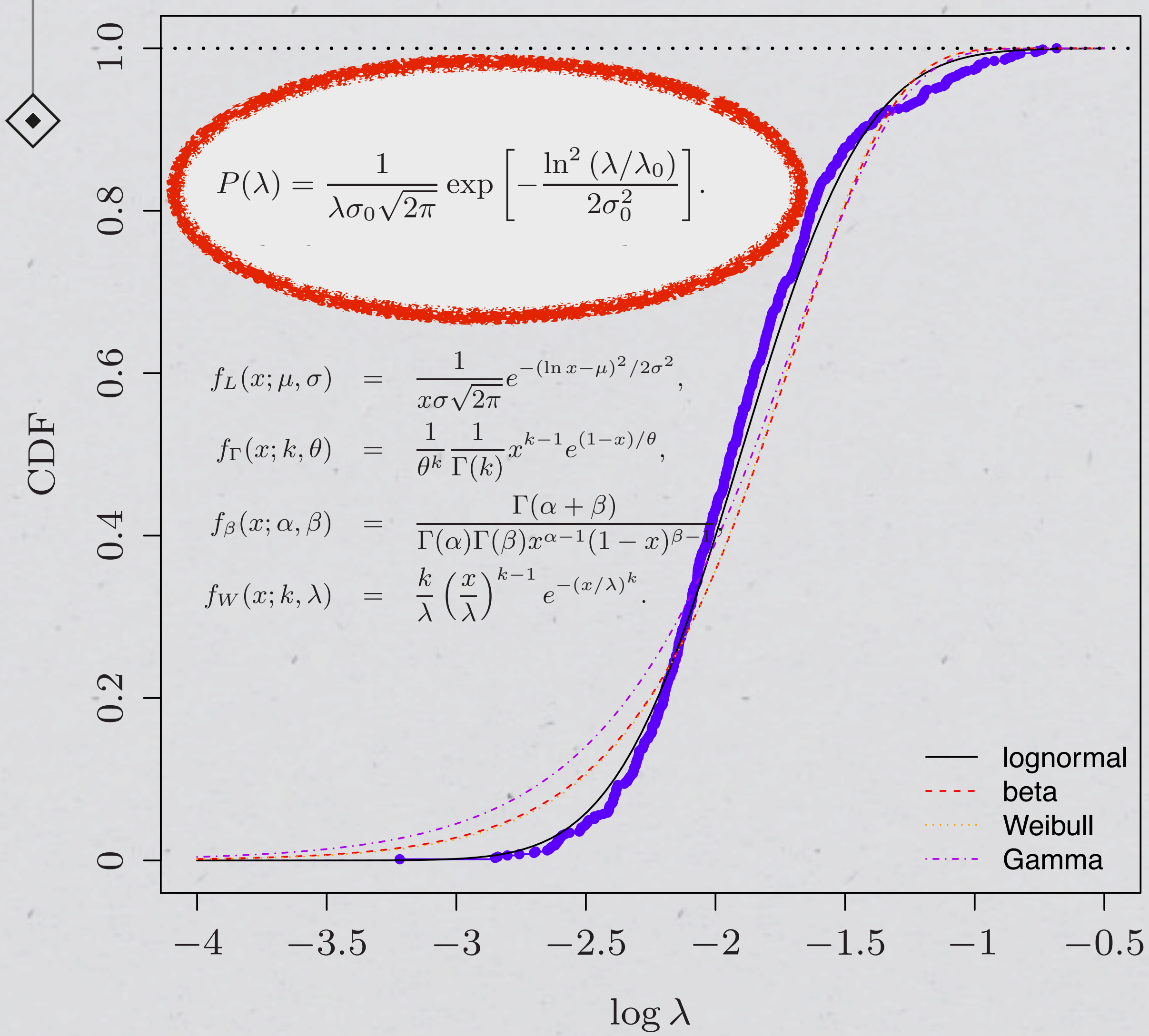
More than 90% of the halos T < 0.4



Oblate

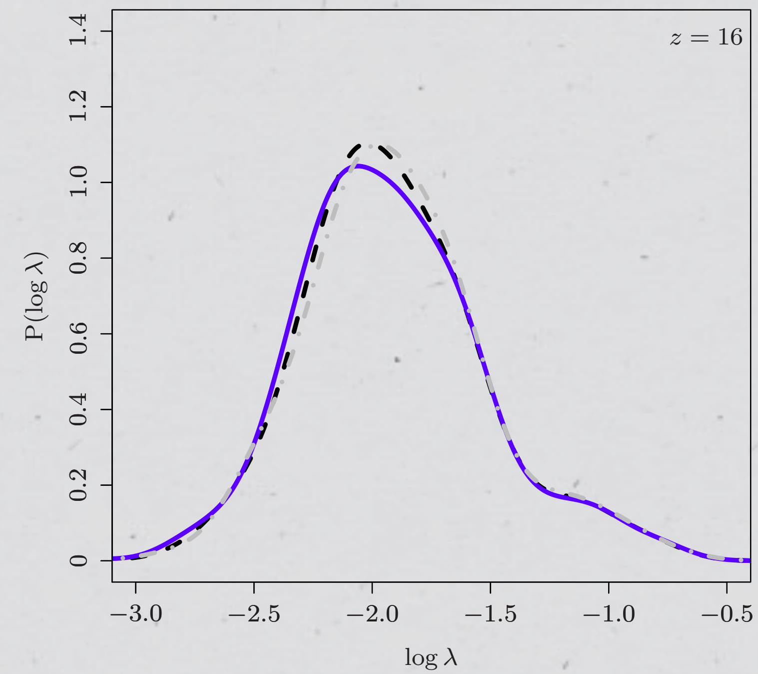
Spin distribution

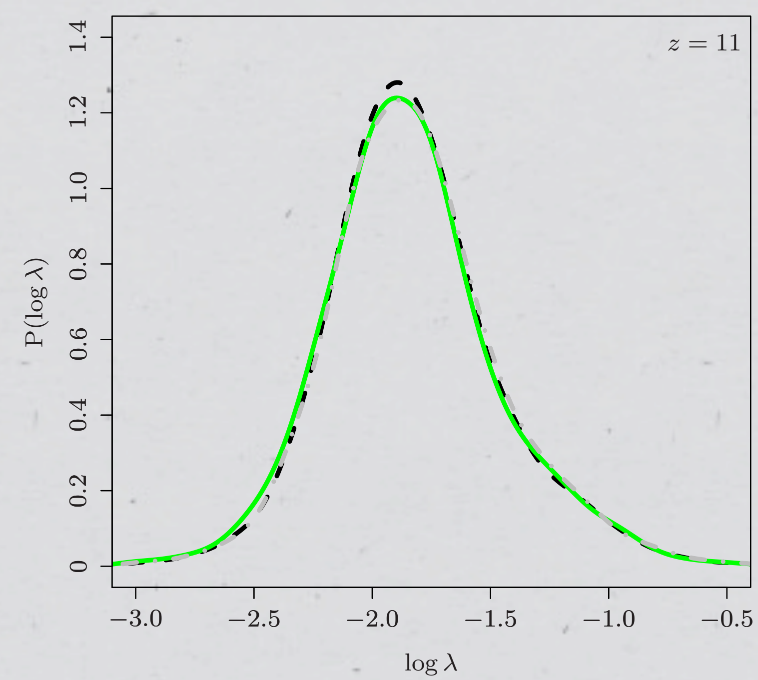
Well described by a lognormal distribution



$$P(\lambda) = \frac{1}{\lambda\sigma_0\sqrt{2\pi}} \exp\left[-\frac{\ln^2(\lambda/\lambda_0)}{2\sigma_0^2}\right].$$

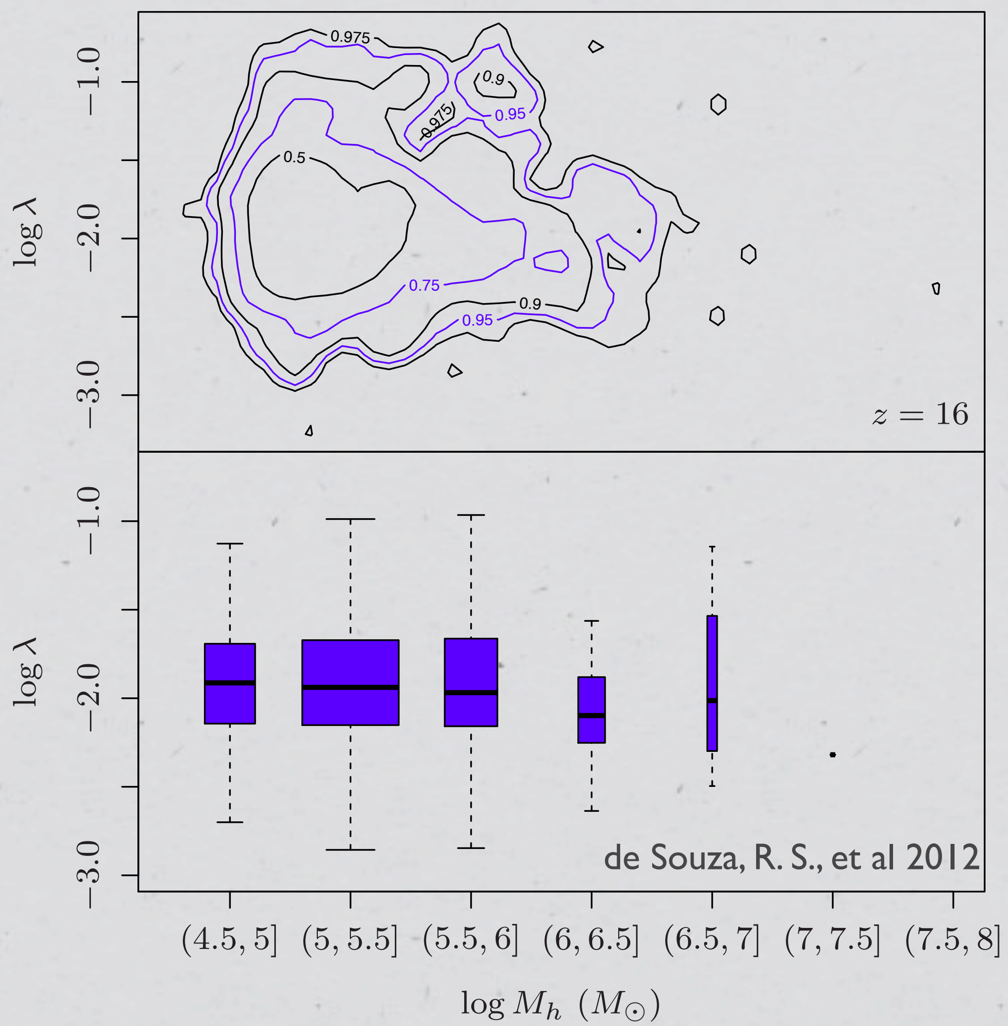
$$\begin{aligned}
f_L(x;\mu,\sigma) &= \frac{1}{x\sigma\sqrt{2\pi}} e^{-(\ln x-\mu)^2/2\sigma^2}, \\
f_\Gamma(x;k,\theta) &= \frac{1}{\theta^k}\frac{1}{\Gamma(k)} x^{k-1} e^{(1-x)/\theta}, \\
f_\beta(x;\alpha,\beta) &= \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)x^{\alpha-1}(1-x)^{\beta-}} \\
f_W(x;k,\lambda) &= \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-(x/\lambda)^k}.
\end{aligned}$$

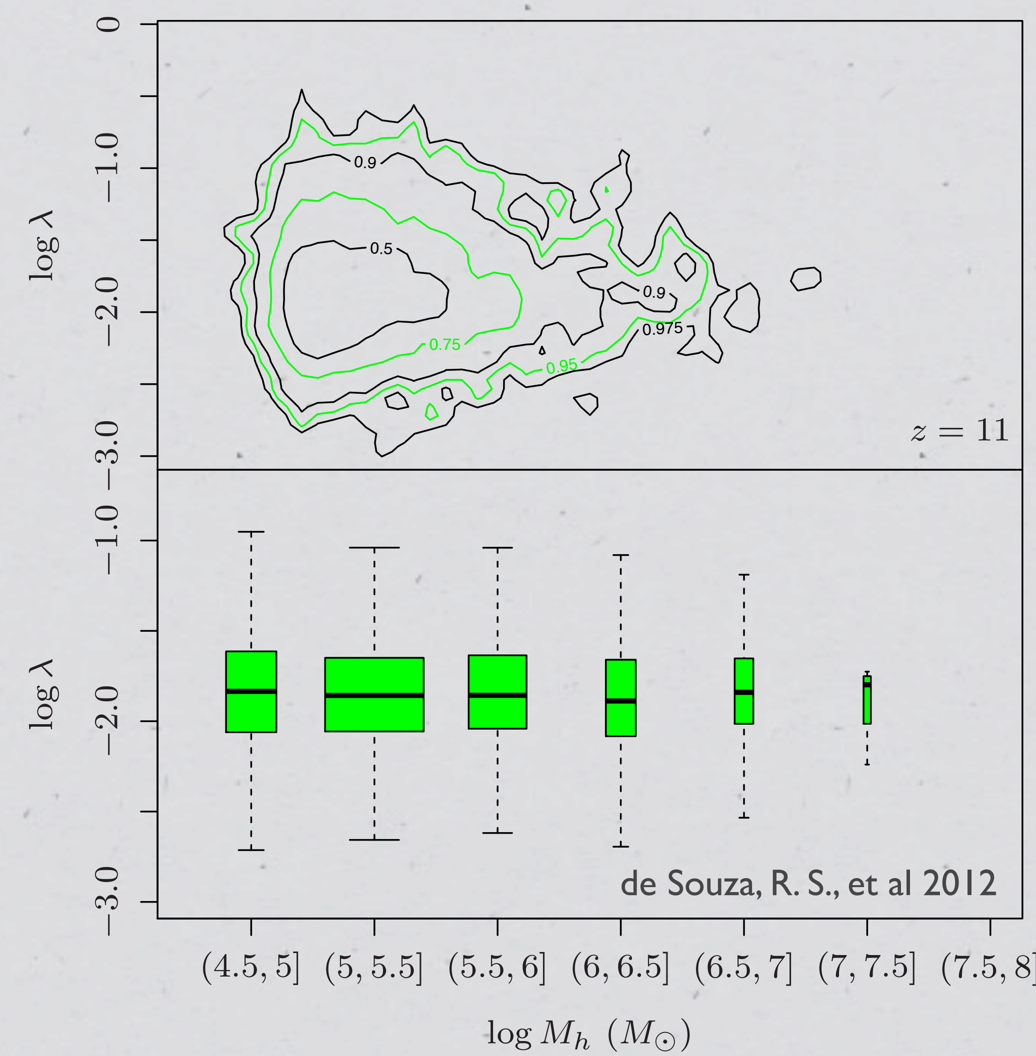




The spin distributions of dark matter and gas are considerably different at z = 16, with the baryons rotating slower than the dark matter. At z = 11, instead, they track each other almost perfectly, as a consequence of a longer time interval available for momentum redistribution between the two components.

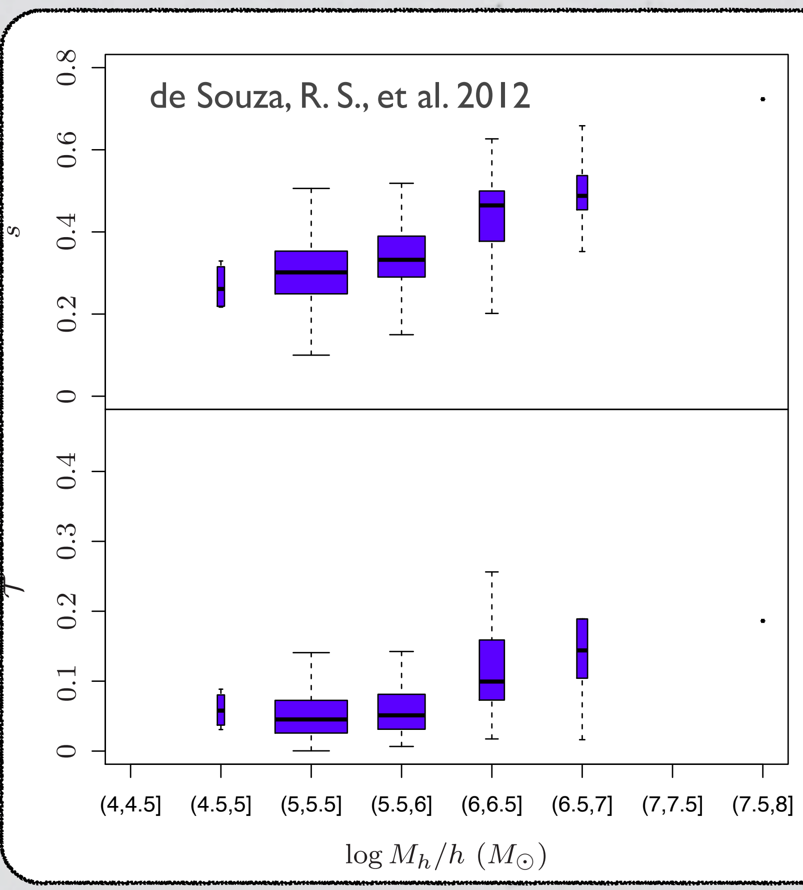
Spin-Mass Correlation

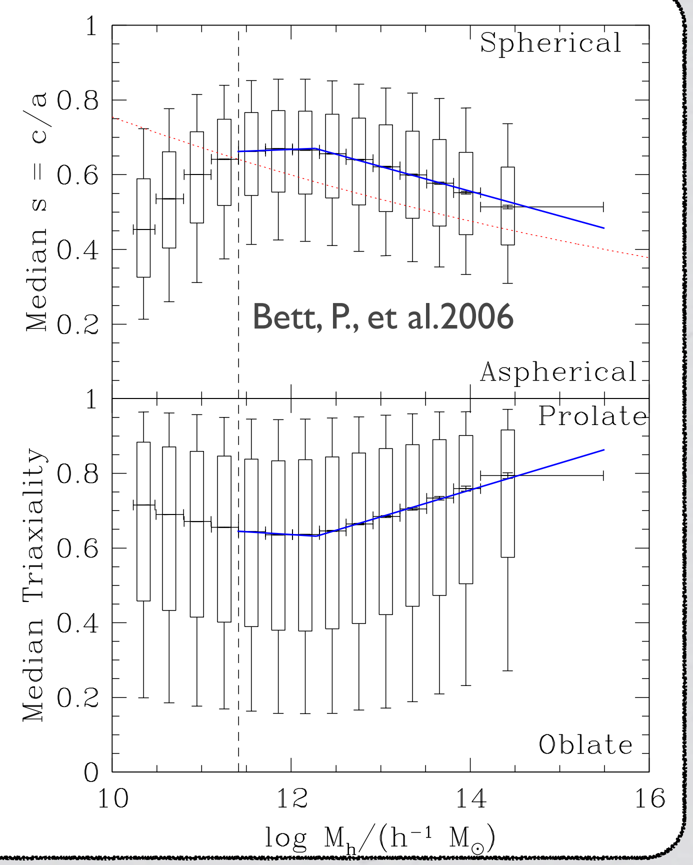


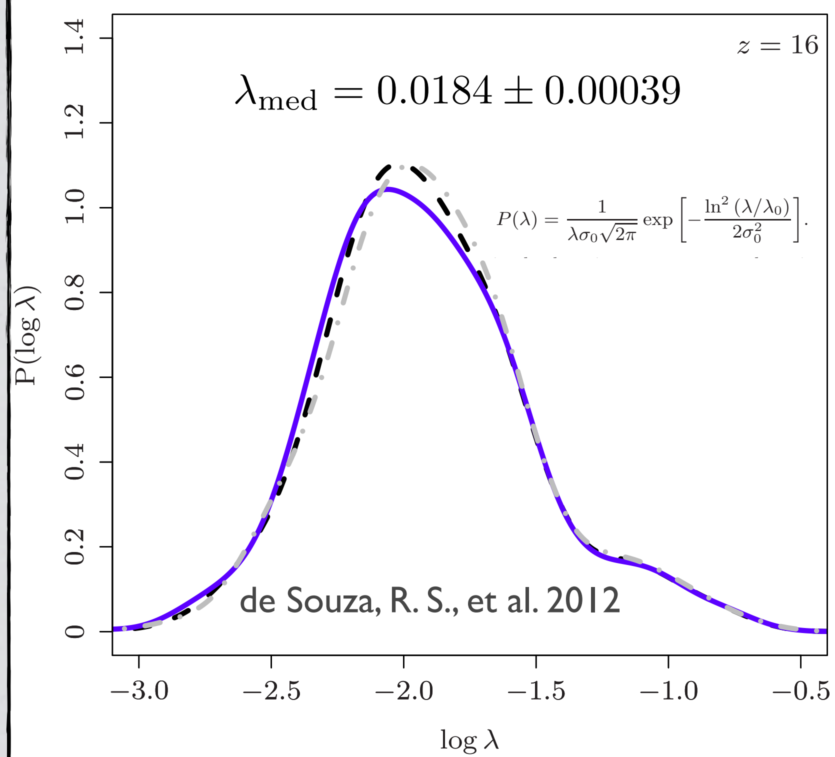


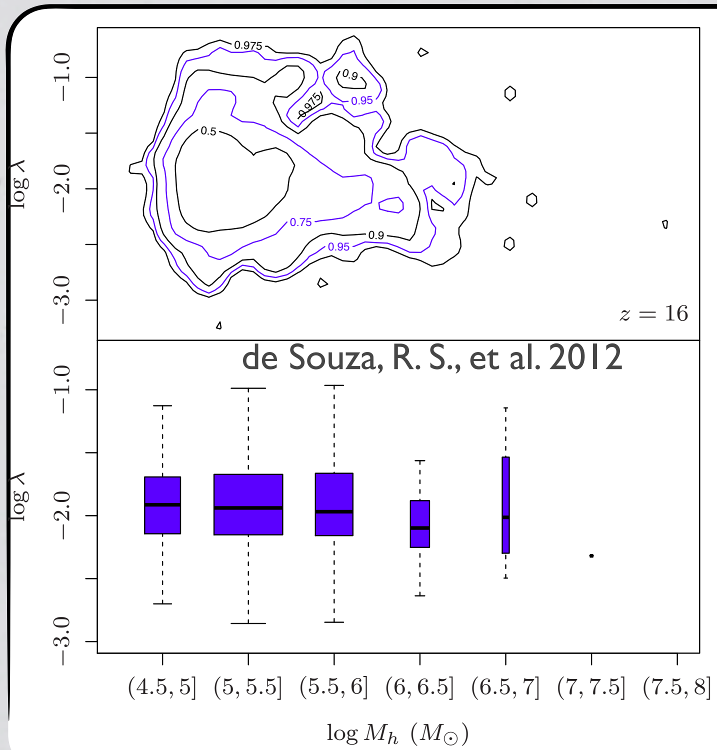
Halo Spin virtually independent of total halo mass

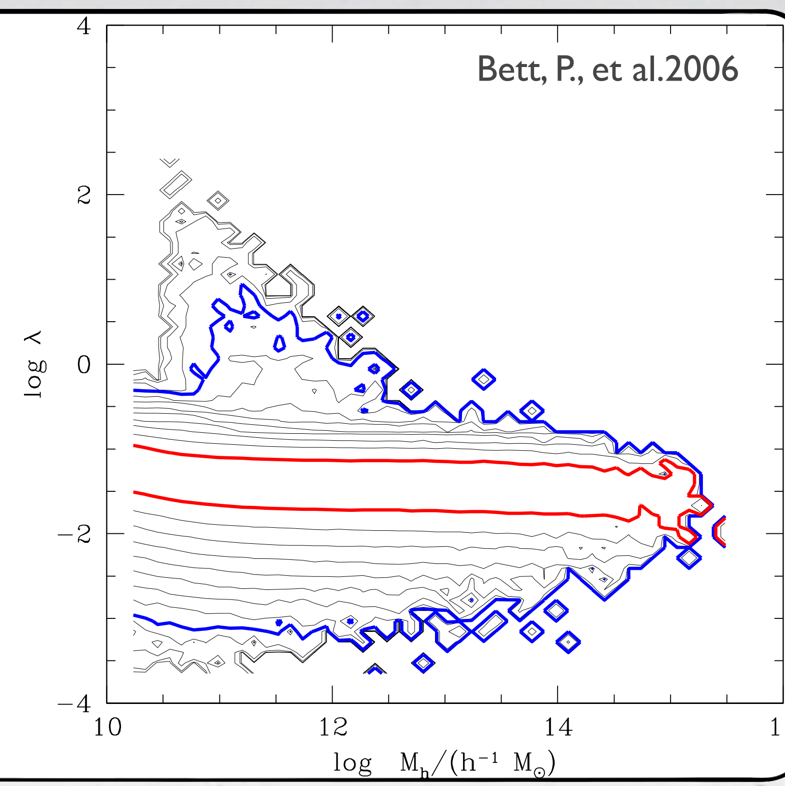
Comparison with low-z and massive halos

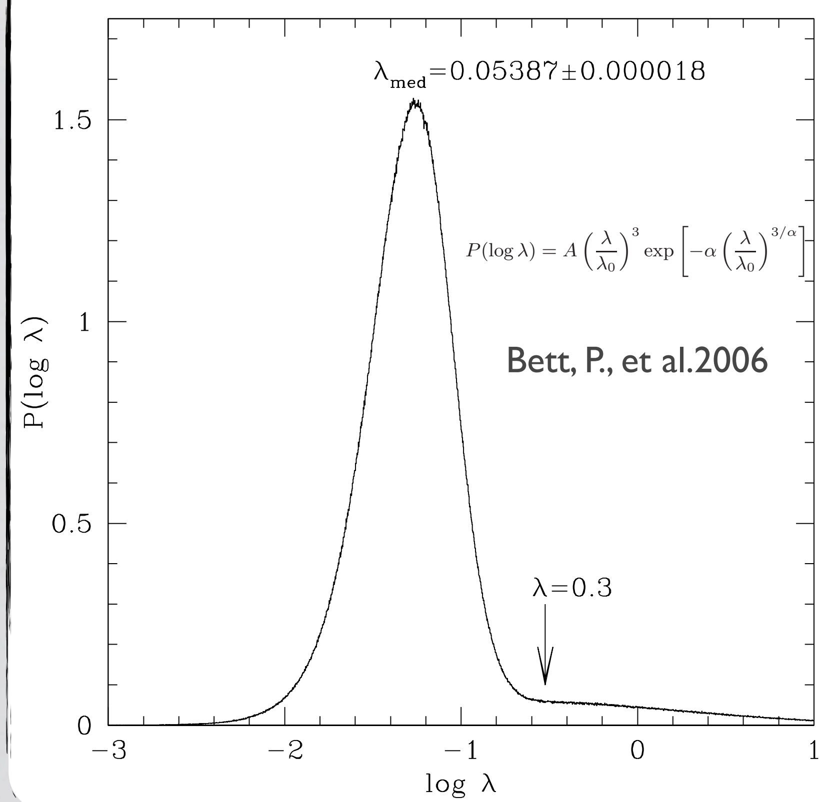








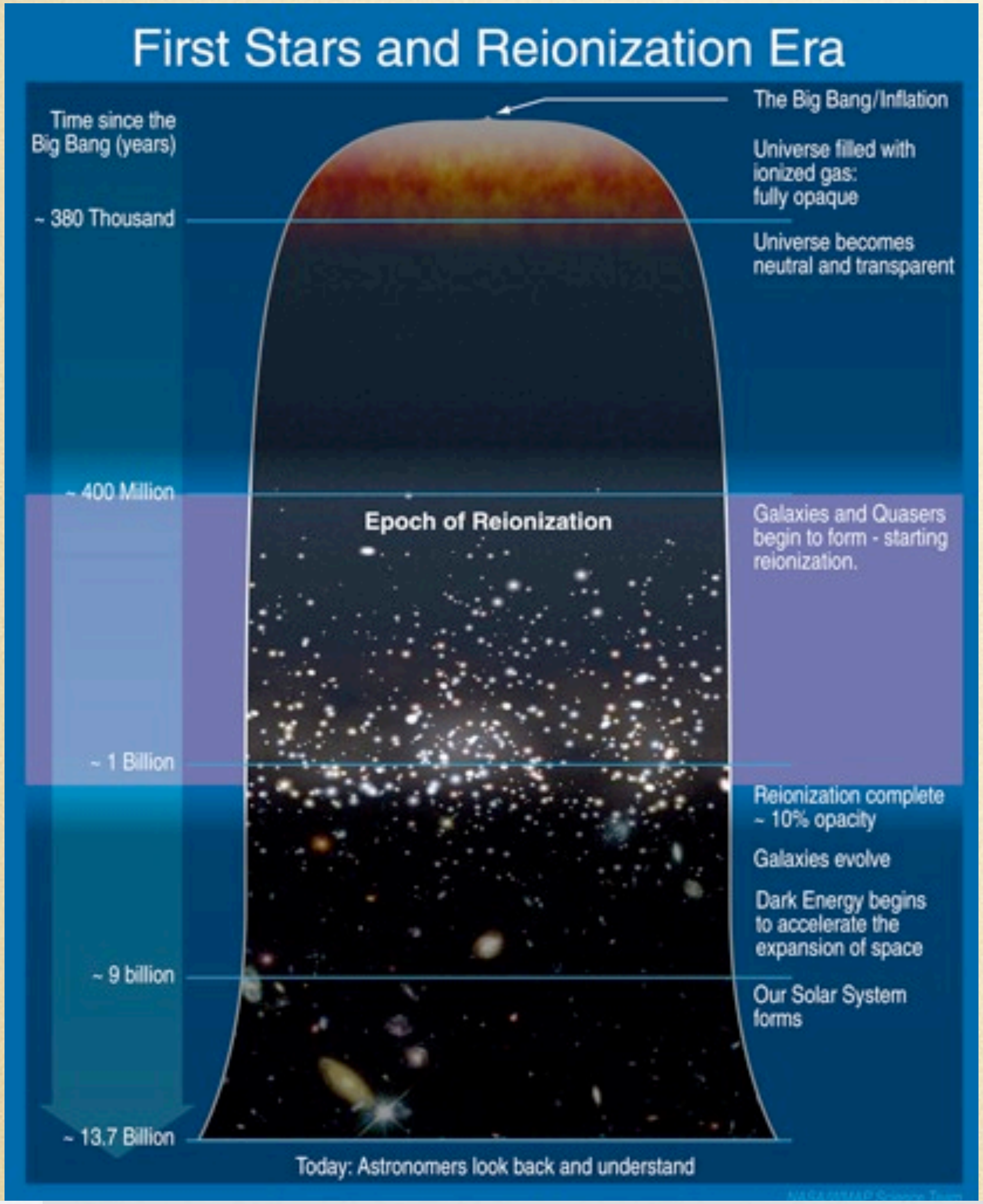




Connection with PopIII IMF

- In the following we discuss the possibility to connect the host halo properties to the typical mass scale of the collapsed protostar.
- It is important to keep in mind that all results presented hereafter rely on the best available semi-analytical model to translate the angular momentum distribution into a corresponding stellar IMF.
- Despite such limitation, our approach provides the best way to statistically analyze a large sample of simulated halos, which could not be performed otherwise.

Population III Stars



- First stars in the Universe
- Metal free
- End of ``Dark Age"
- Relation to reionization
- No observations so far
- *GRBs from Pop III stars are expected to be observable!*

de Souza, R. S., et al. 2011, 2012a, 2012b

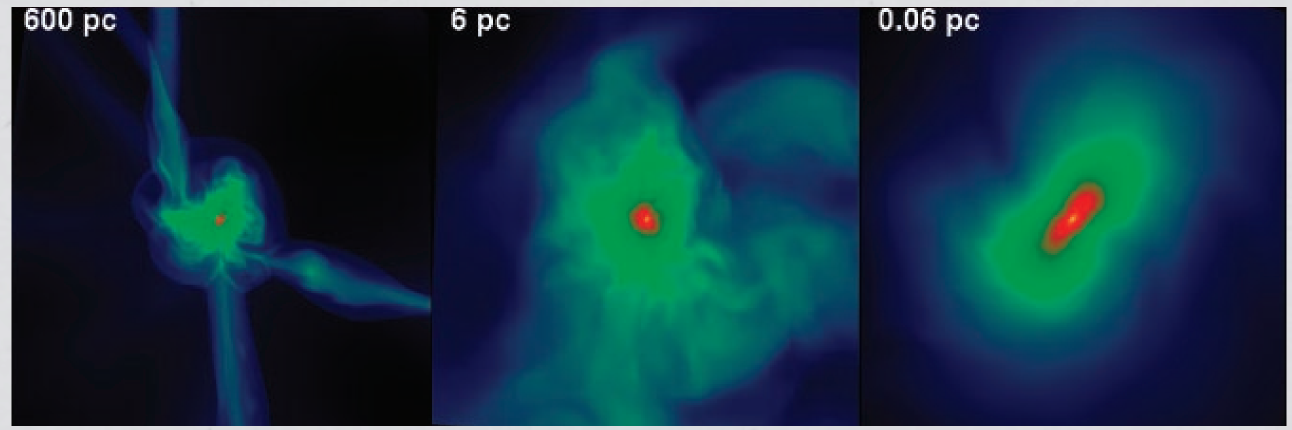
What do we know about Pop III IMF?

Until recently...

Abel et al. 2002
Omukai & Palla 2003
Yoshida et al. 2006

Predominantely massive:
> 100 solar masses

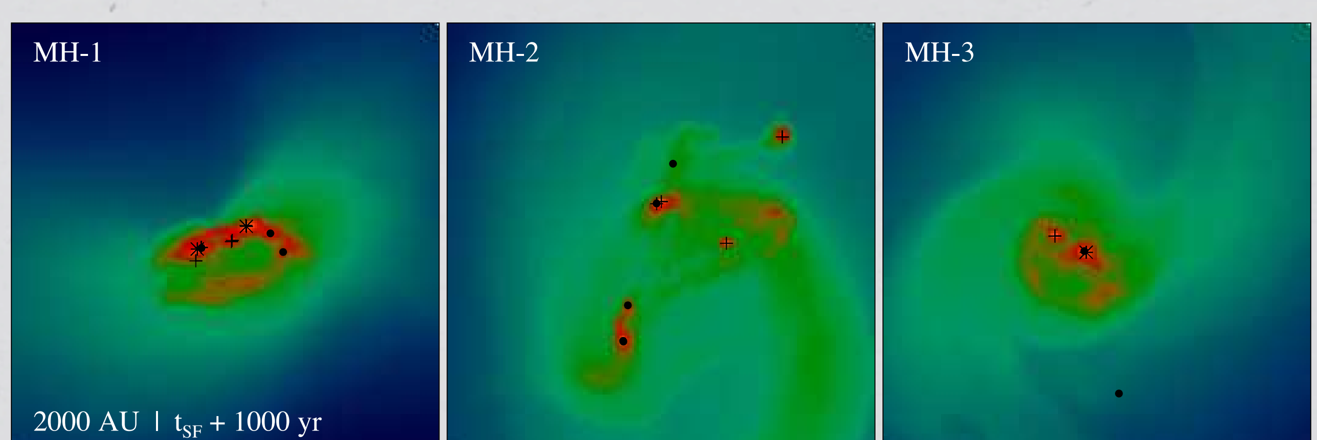
Abel et al. 2002



Even more recently...

Hosokawa et al., 2011,
Clark et al., 2011,
Stacy et al., 2012,
Greif et al., 2012

Greif et al., 2012

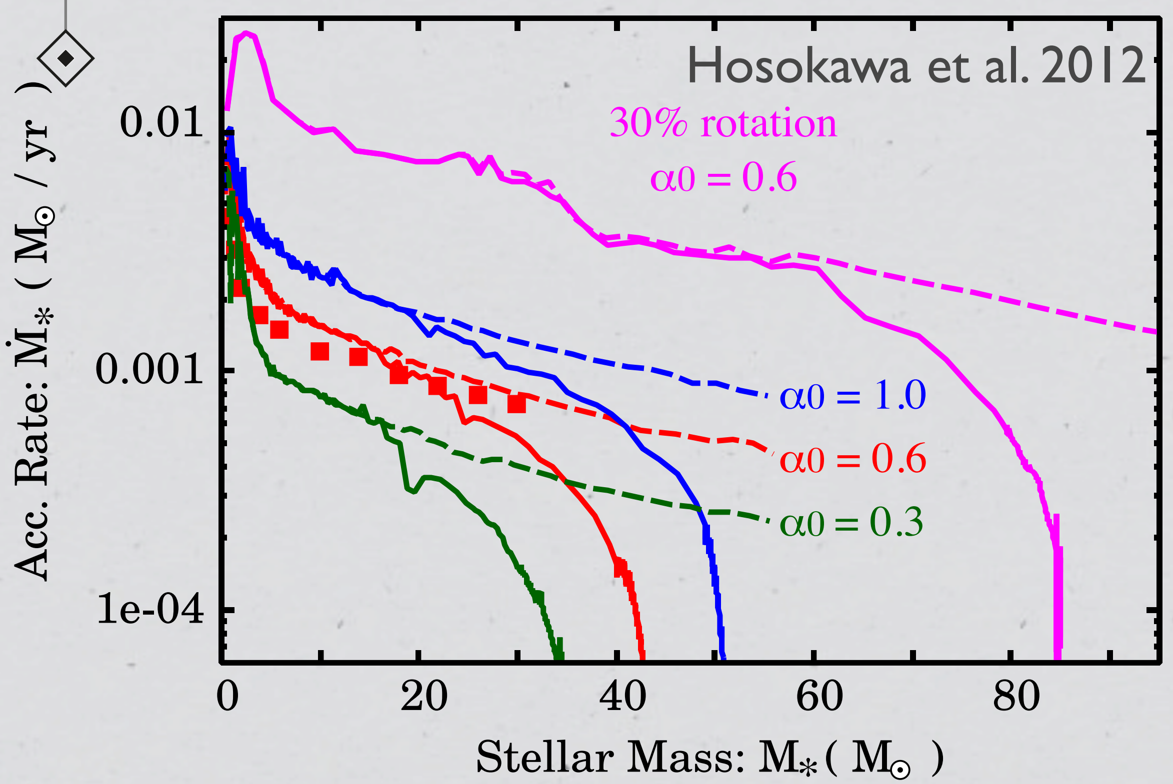


Accretion disks that build up around Population III stars are strongly susceptible to fragmentation and that the first stars should therefore form in clusters rather than in isolation.

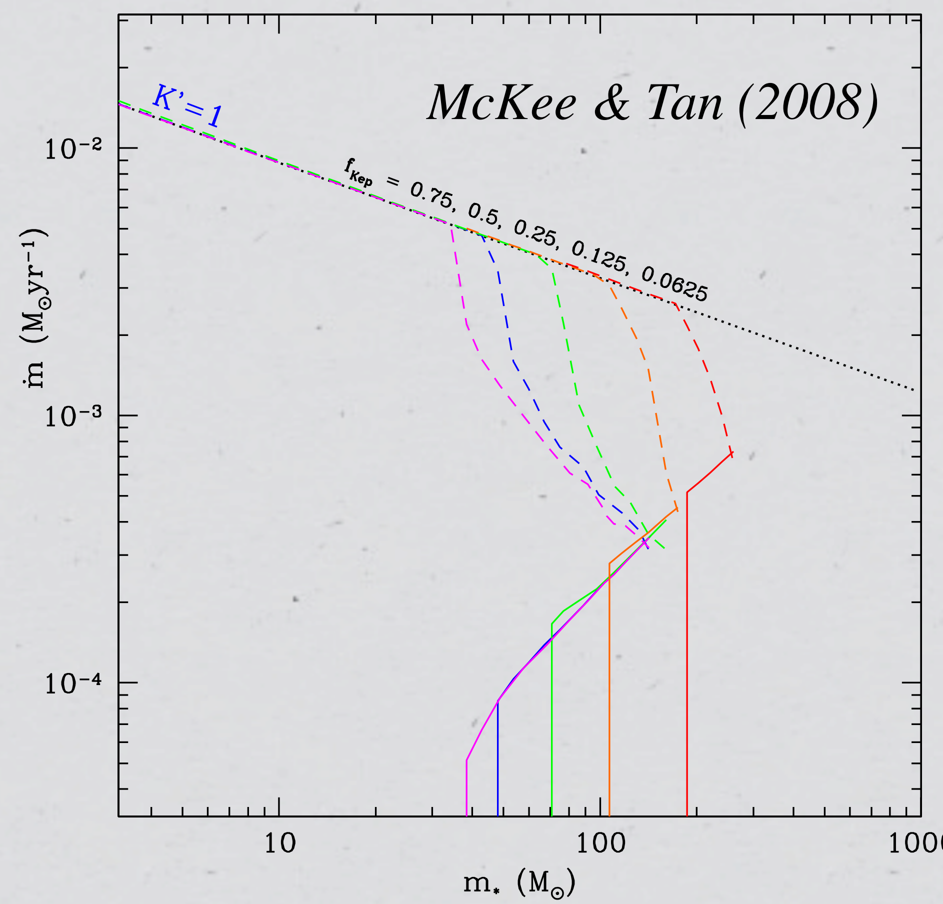
Results far from being conclusive

Population III stars mass

Radiation-hydrodynamics simulations



Semi-analytic model:

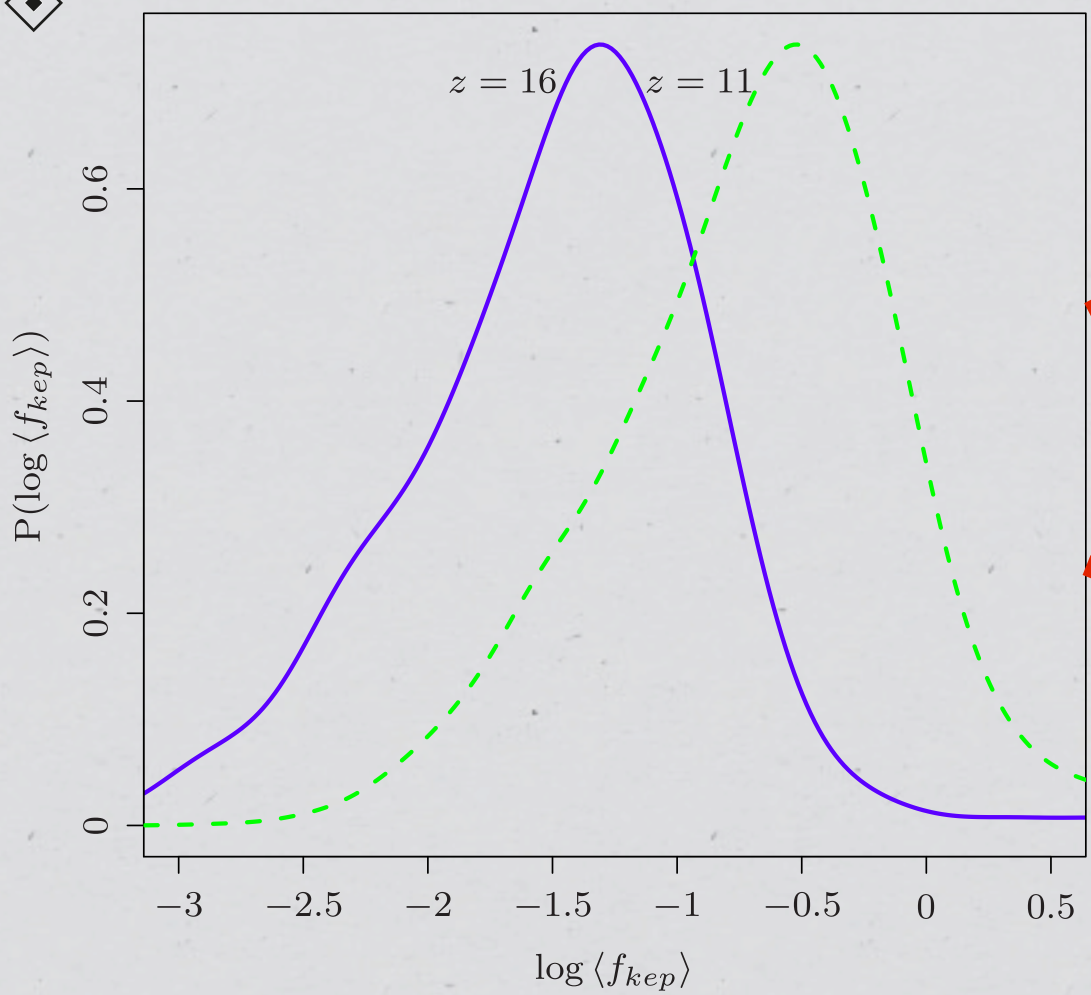


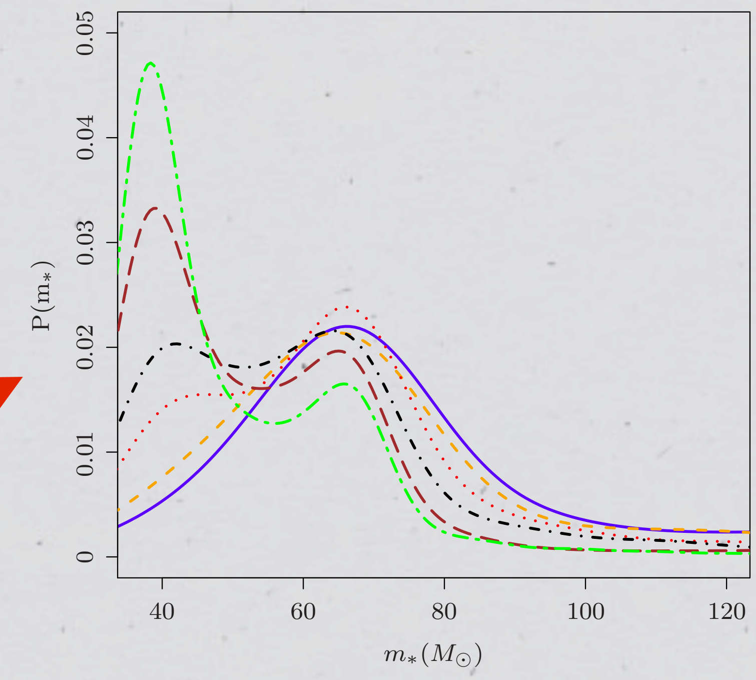
$$f_{\rm Kep}(M_r) \equiv \frac{V_{\phi,r}}{V_{\rm Kep,r}}, \qquad V_{\phi,r} = \frac{l_r}{r}, \; V_{{\rm Kep},r} = \sqrt{\frac{GM_r}{r}},$$

Key factor: rotation of the protostellar core

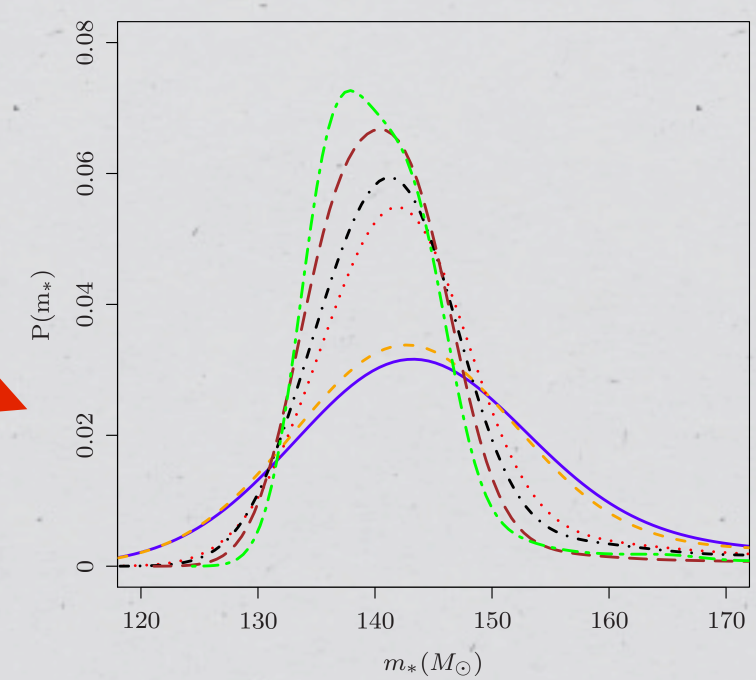
Typical rotation distribution and Pop III IMF

It is important to notice that the comparisons are done by collecting different dark matter and gas particles of the same halo, thus fully accounting for the back-reaction of baryons on the parent dark matter distribution.





Feedback model



At z= 16 the IMF tends to closely track the lognormal distribution imprinted by the rotation properties of the halos.

Depending on the feedback model, though, the distribution can be centered at $\approx 65 M_\odot$ or $\approx 140 M_\odot$

At later times, model MT1 tends to evolve into a bimodal distribution with a second prominent peak located at $35 - 40 M_\odot$ in addition to the initial one.

The bimodality comes from the non-linear connection between rotation and mass scale.

Summary

* **High-z haloes are less spherical**, with an average sphericity ⟨s⟩ ~ 0.3±0.1, and more oblate than low-z haloes.

* **Larger halos** in the simulation tend to be both **more spherical and prolate**.

* The **spin distribution** for both gas and dark matter inside these small haloes can be well represented by a **lognormal function**, in accordance with previous results. The dark matter component dominates the general behavior of total halo spin distribution for for higher-z, while for lower redshifts both components track each other almost perfectly, as a consequence of a longer time interval available for momentum redistribution between the two components.

* The **spin distribution** shows a **weak dependence with halo mass**. With a slightly stronger dependence for higher redshifts.

* According to most recent theories of PopIII star formation, **rotation** is the **key factor** in determining their **final mass**. Using the results of two feedback models (MT1 and MT2) by McKee & Tan (2008) and mapping our halo spin distribution into a PopIII IMF, we find that **at high-z** the **IMF** tends to **closely track** the **spin lognormal distribution**; depending on the **feedback model**, though, the distribution can be **centered at ≈ 65$M_\odot$** (MT1) or ≈ **140$M_\odot$** (MT2). At later times, model MT1 tends to evolve into a **bimodal distribution** with a **second** prominent **peak** located at **35 – 40$M_\odot$**, as a result of the non-linear relation between rotation and halo mass.

Message to take home

Although on a protostellar basis radiative feedback acting on baryons might be the key factor in determining the mass of the first stars, it is the angular momentum distribution of the dark matter halos that controls the build-up of the IMF

While the PopIII IMF is still highly debated the present study offers an intriguing indication that the IMF of the first stars might be tied and controlled by the properties of their parent halos, thus linking in a novel way large scale structure and early star formation.

If this is indeed the case, our suggestion could lead to clear and testable predictions (e.g. PISN rates, abundance of pure PopIII galaxies, metal abundance patterns in the IGM and low-mass stars to mention a few) for the number, properties and cosmic evolution of these pristine stellar systems.