Minihaloes: hosts of the first stars influenced by large-scale effects

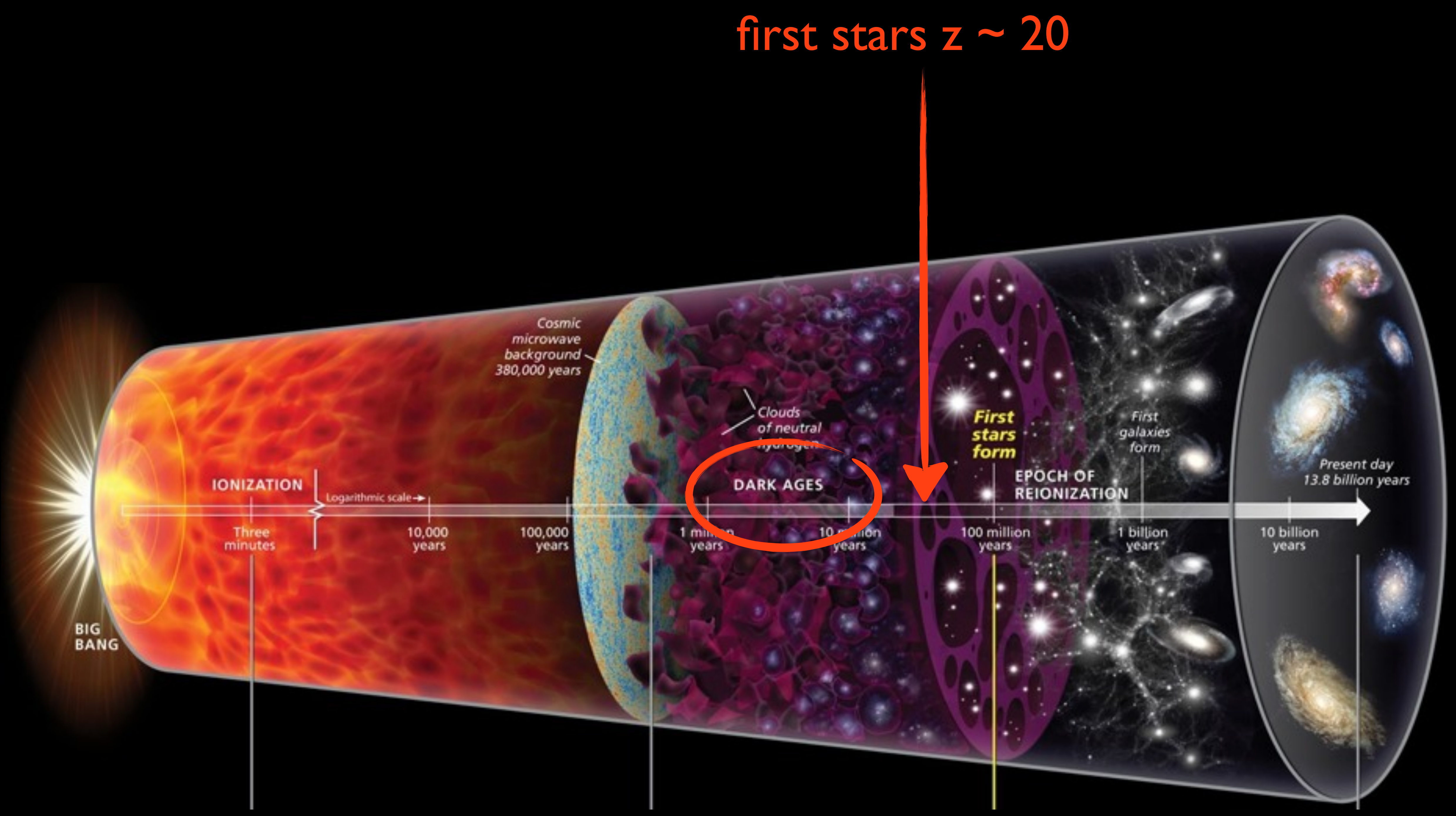
Anna T. P. Schauer

with Daniel Ceverino, Maik Drusche, Simon Glover, Ralf Klessen, Mattis Magg, et al.

10th of July 2018

Tokyo

The dark ages



http://discovermagazine.com/~/media/Images/Issues/2014/April/21-centimeter-cosmology.jpg

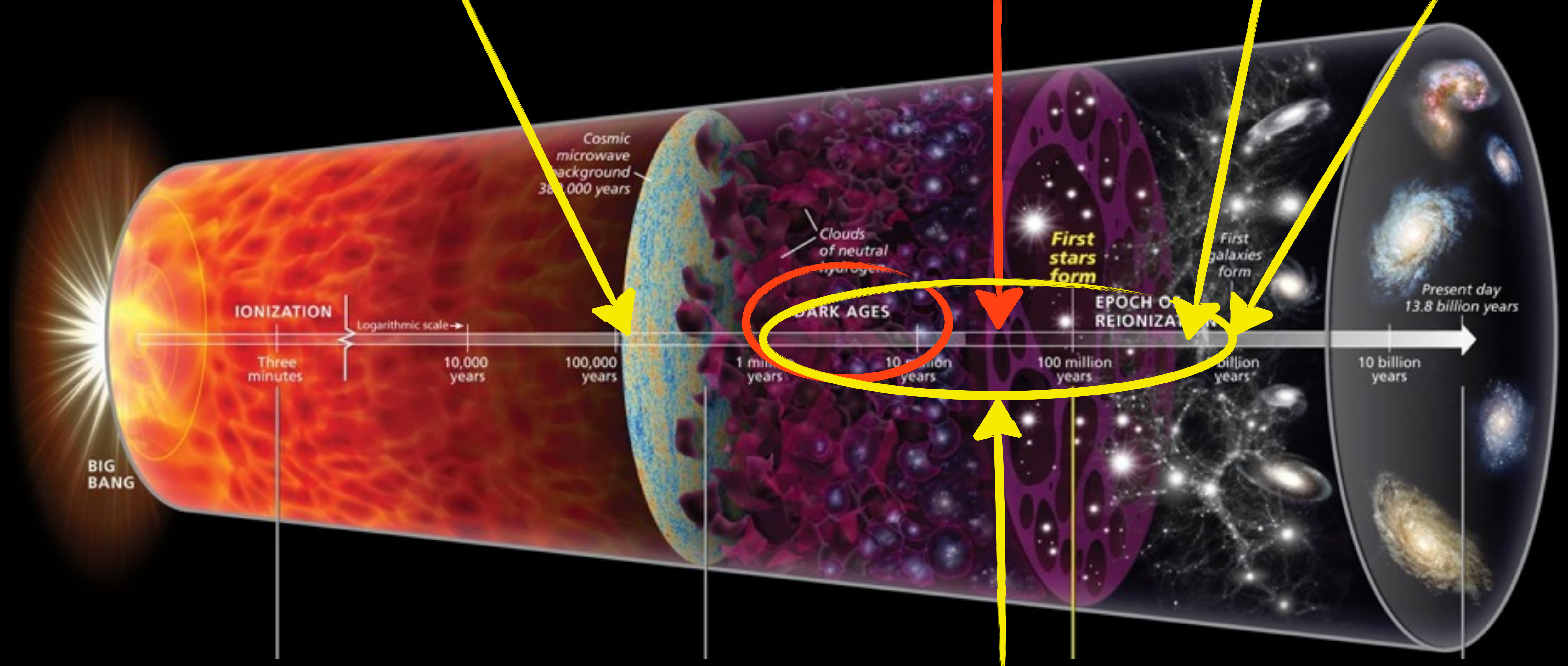
The dark ages

first galaxies z ~ 11

first stars z ~ 20

CMB z ~ 1100

quasars z ~ 7



21cm signal: SKA

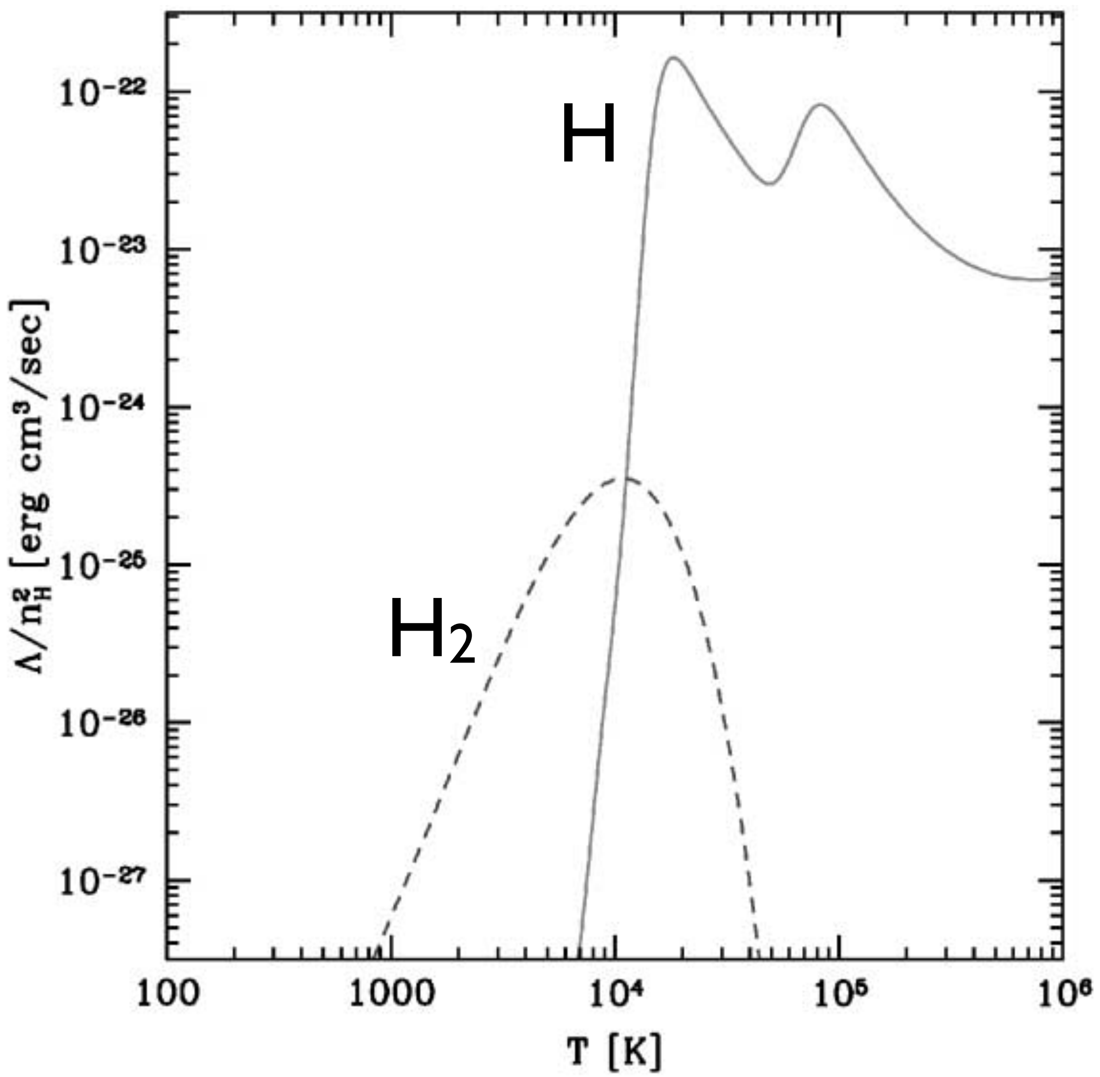
http://discovermagazine.com/~/media/Images/Issues/2014/April/21-centimeter-cosmology.jpg

First star formation

- Minihaloes / atomic cooling haloes: 10^5 - 10^7 $M_\odot$
- First stars form in minihaloes / atomic cooling haloes
- Cooling:
  - $T > 10^4$ K : atomic hydrogen
  - $T > 200$ K : molecular hydrogen
    - Direct formation: forbidden
    - Formation via H- channel:

$$H + e^- \rightarrow H^- + h\nu$$

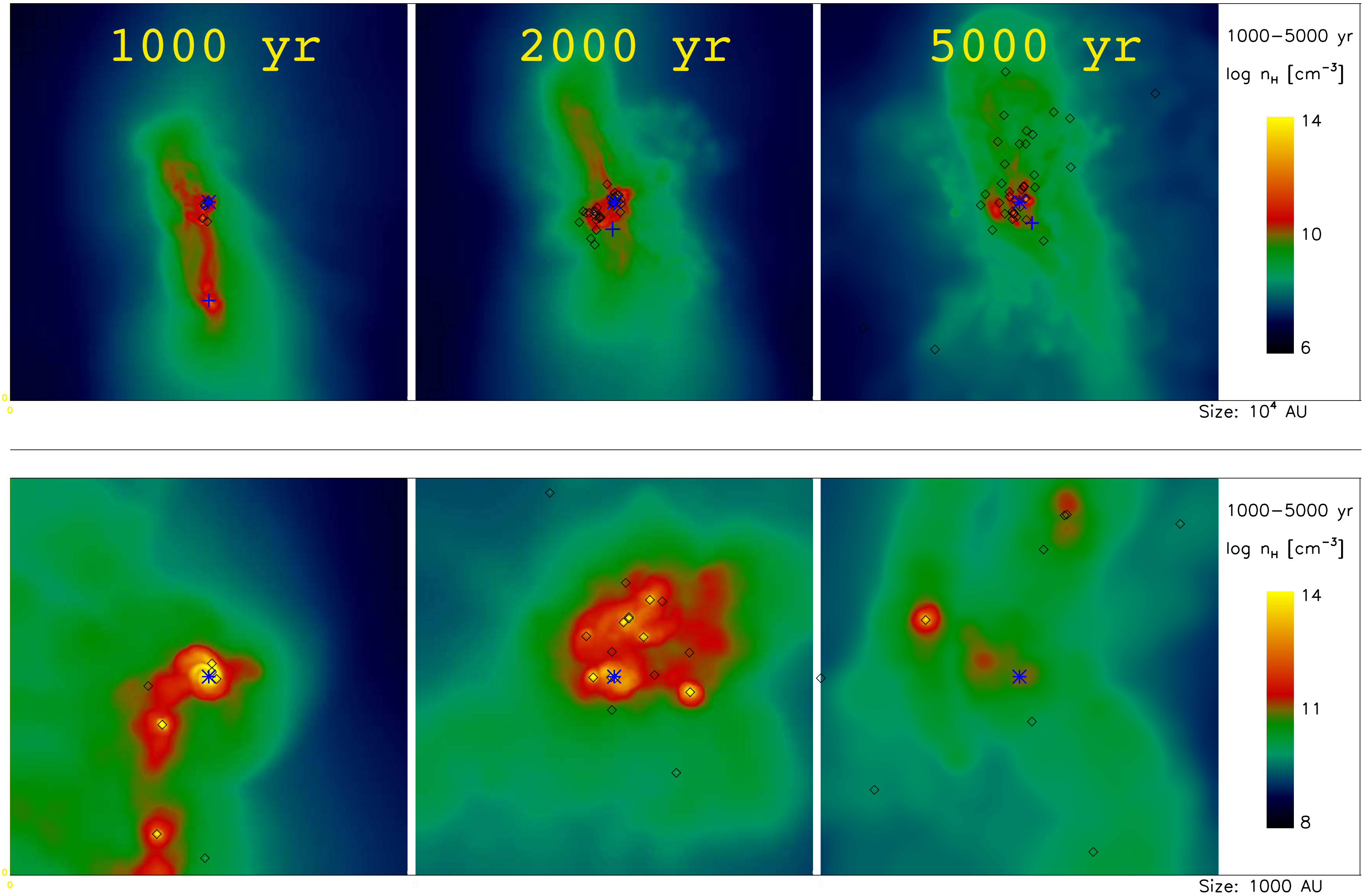
$$H^- + H \rightarrow H_2 + e^-$$



Barkana & Loeb 2001

Mass of first stars: uncertain

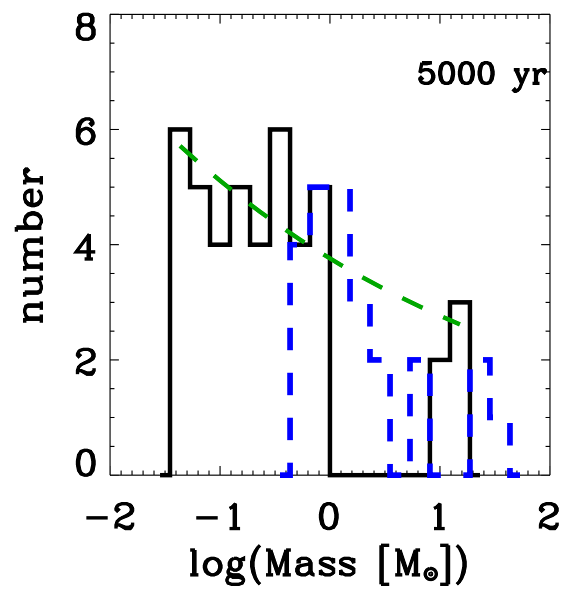
- First simulations: singe star with 100 - 1000 $M_\odot$ Abel+ 2002
- Resimulations with higher resolution: fragmentation!

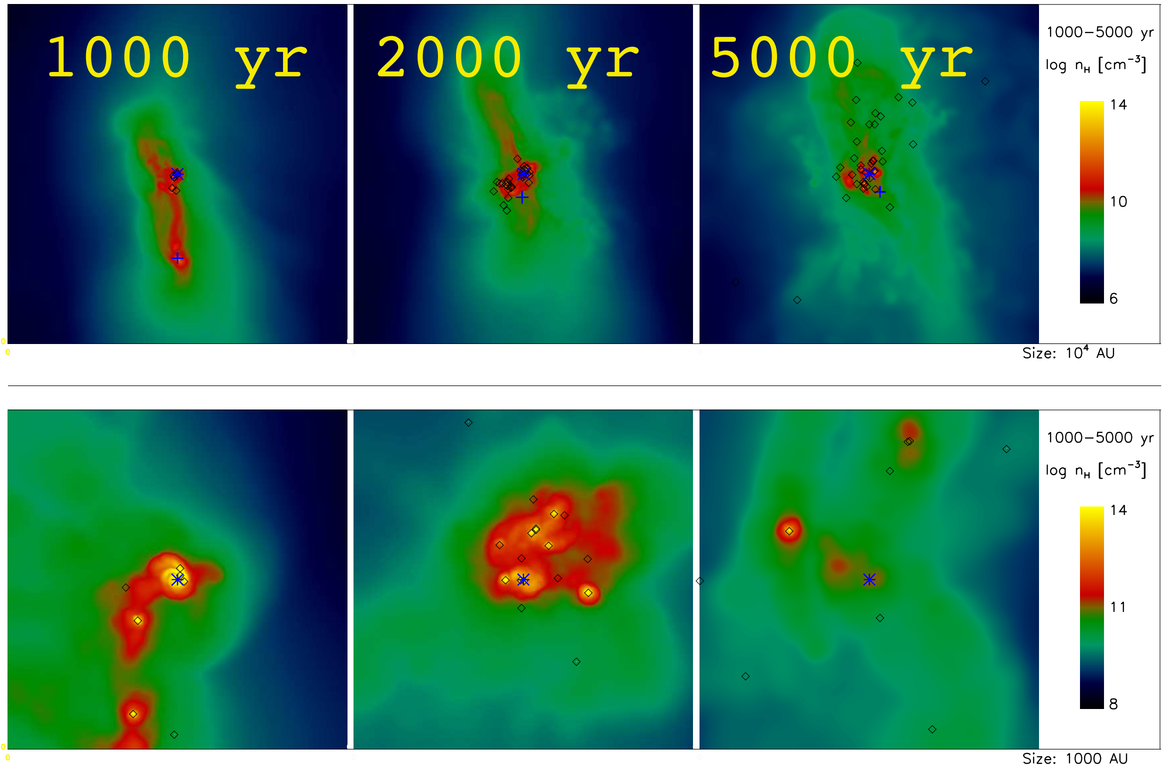


Stacy+ 2016

Mass of first stars: uncertain

- First simulations: singe star with 100 - 1000 $M_\odot$ Abel+ 2002
- Resimulations with higher resolution: fragmentation!
  - more than one star per minihalo
  - masses reach down to subsolar

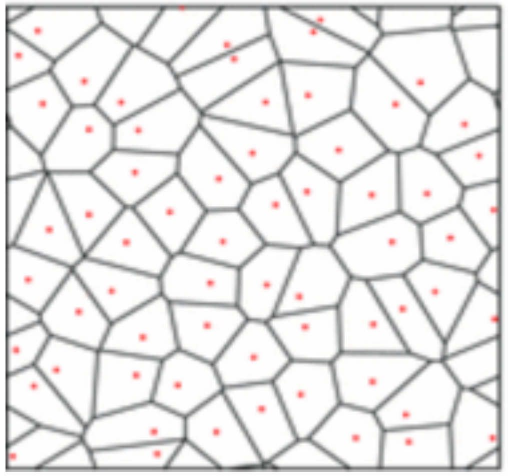




Stacy+ 2016

Author	d_{res} [AU]	No. Minialoes	t_{acc} [yr]	Feedback	M_{min} [$M_\odot$]	M_{max} [$M_\odot$]	M_{med} [$M_\odot$]
Stacy ea 2016	1.0	1	5000	LW+ion	0.05	20	0.5
Stacy & Bromm 2013	20	10	5000	–	0.5	40	2
Greif ea 2011	0.5	5	1000	Accr. heat	0.1	10	1
Susa ea 2014	30	59	$\sim 10^5$	LW	0.5	200	20
Hosokawa ea 2016	30	5	$\sim 10^5$	LW+ion	15	600	300
Hirano ea 2014*	25	100	$\sim 10^5$	LW+ion	10	2000	100

Our simulations



Springel 2013

code:	AREPO
dark matter:	SPH particles
gas:	Voronoi cells on moving mesh
chemistry:	primordial, including H_2, HD

Our simulations

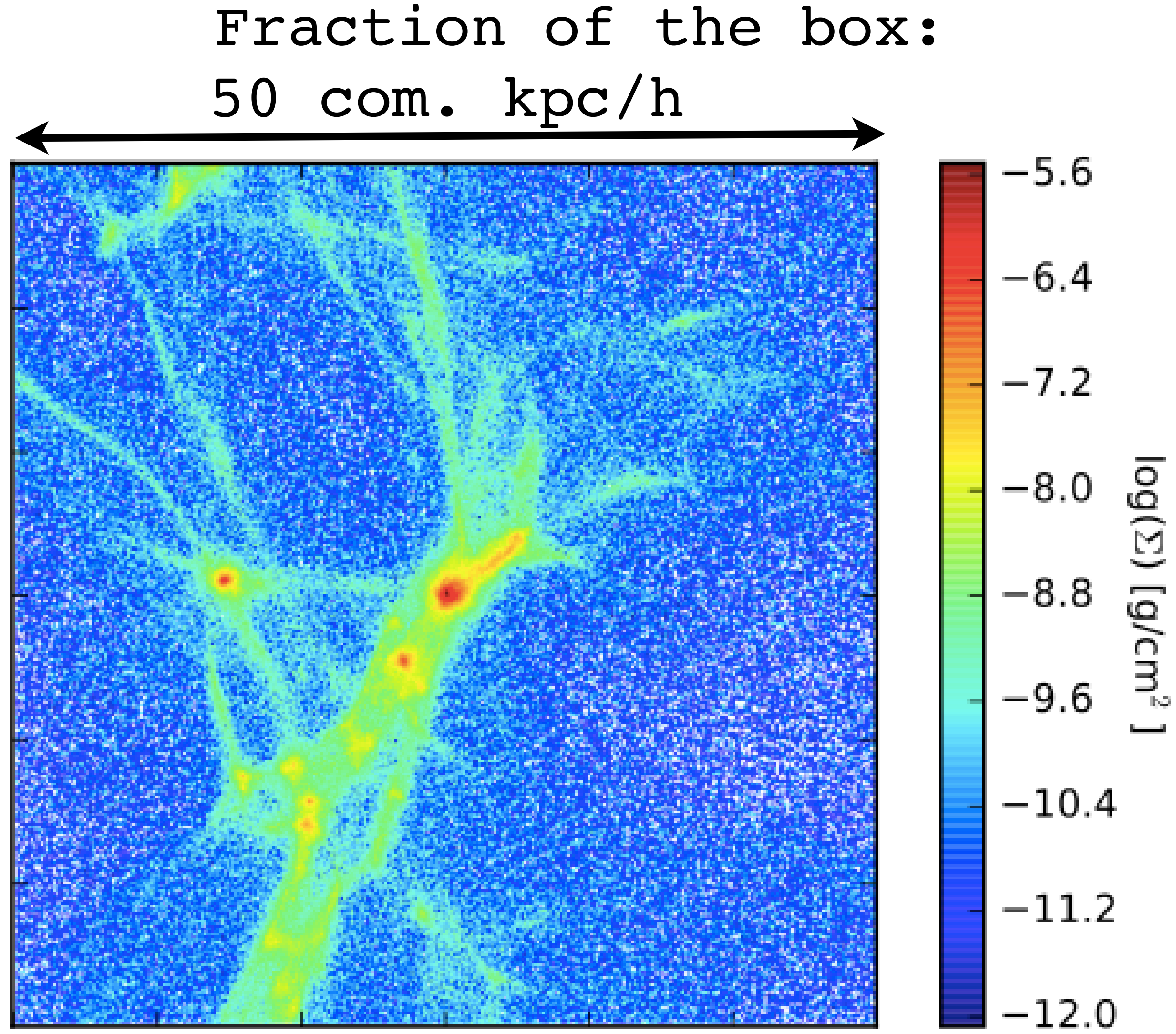
redshift range: z = 200 -> 14

box size: (1 cMpc/h)^3

DM particles / gas cells: 1024^3 each

mass resolution: 19 $M_\odot$ (gas)
99 $M_\odot$ (DM)

smoothing length: 20 cpc/h
(2 pc at z=15)

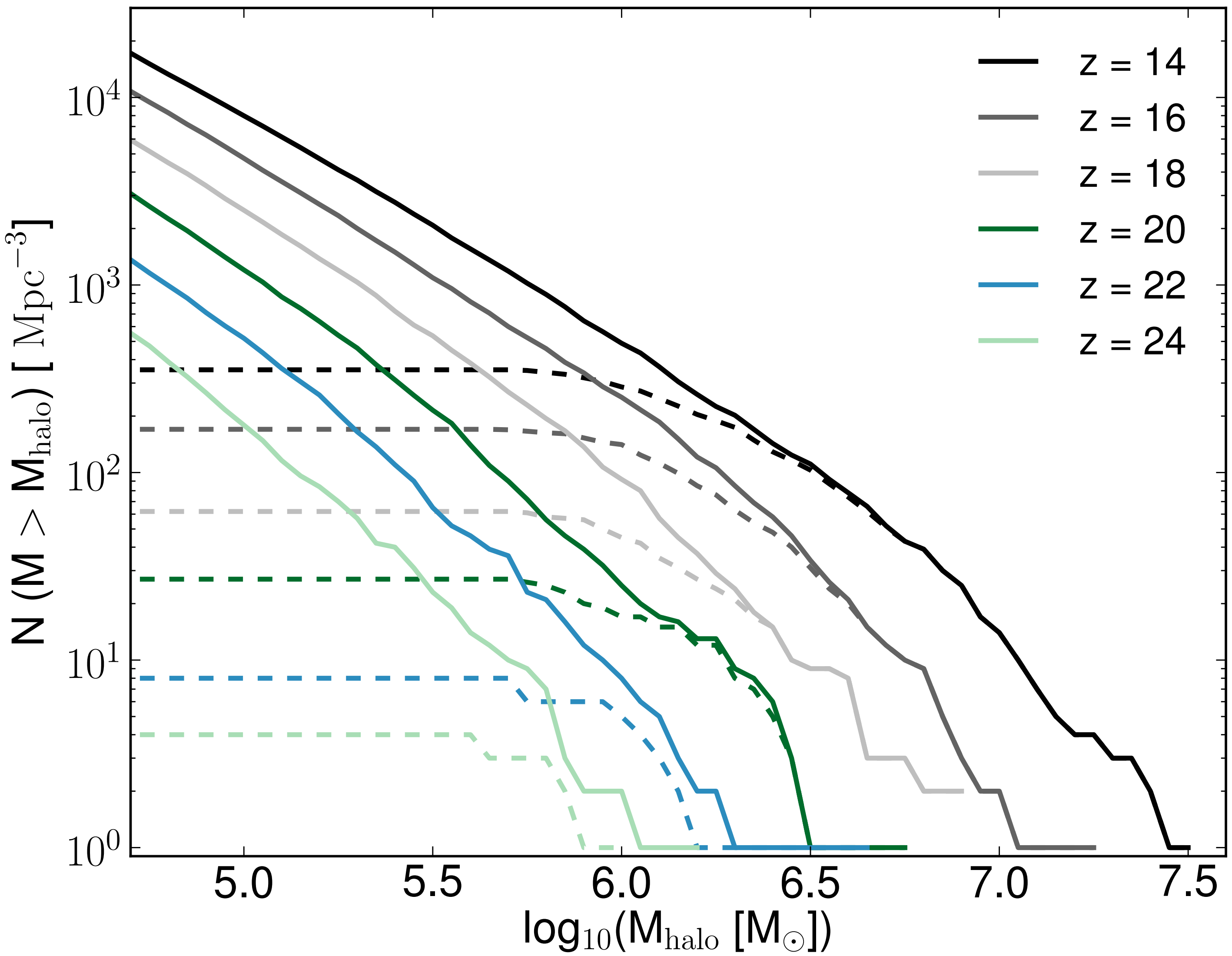


gas projection at z=15

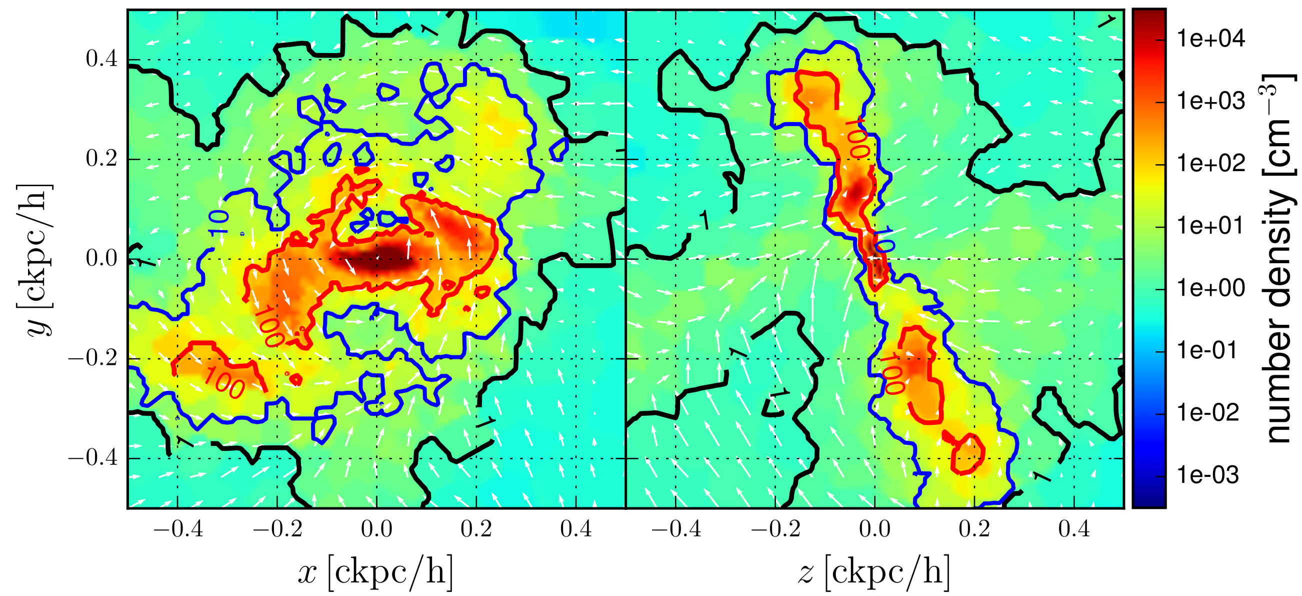
Picture from Bachelor Thesis of Maik Druschke

minihaloes

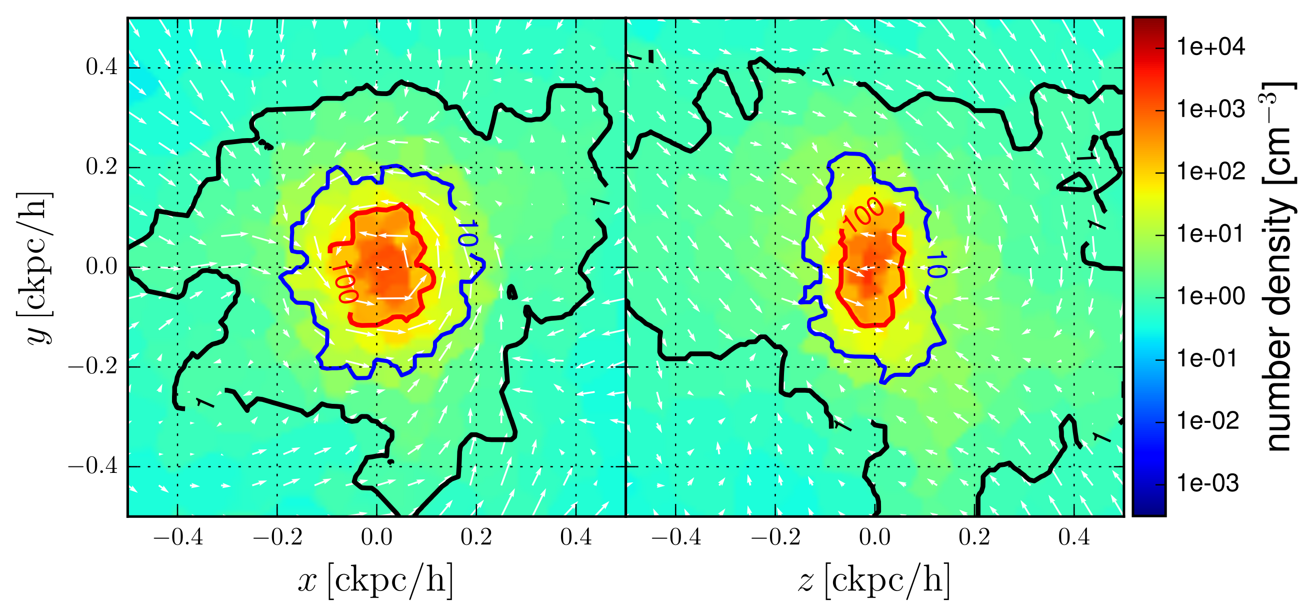
- halo mass function:



Schauer+ 2018 (submitted)



- density slices of single haloes



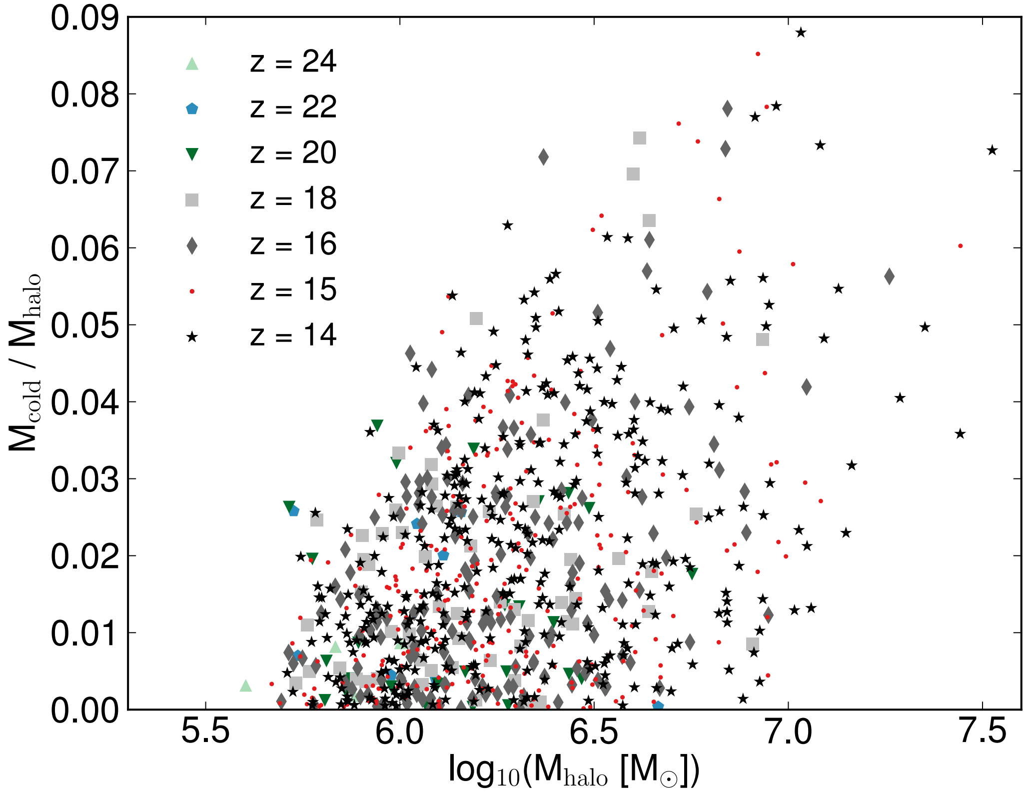
Druschke, Schauer+ 2018 (submitted)

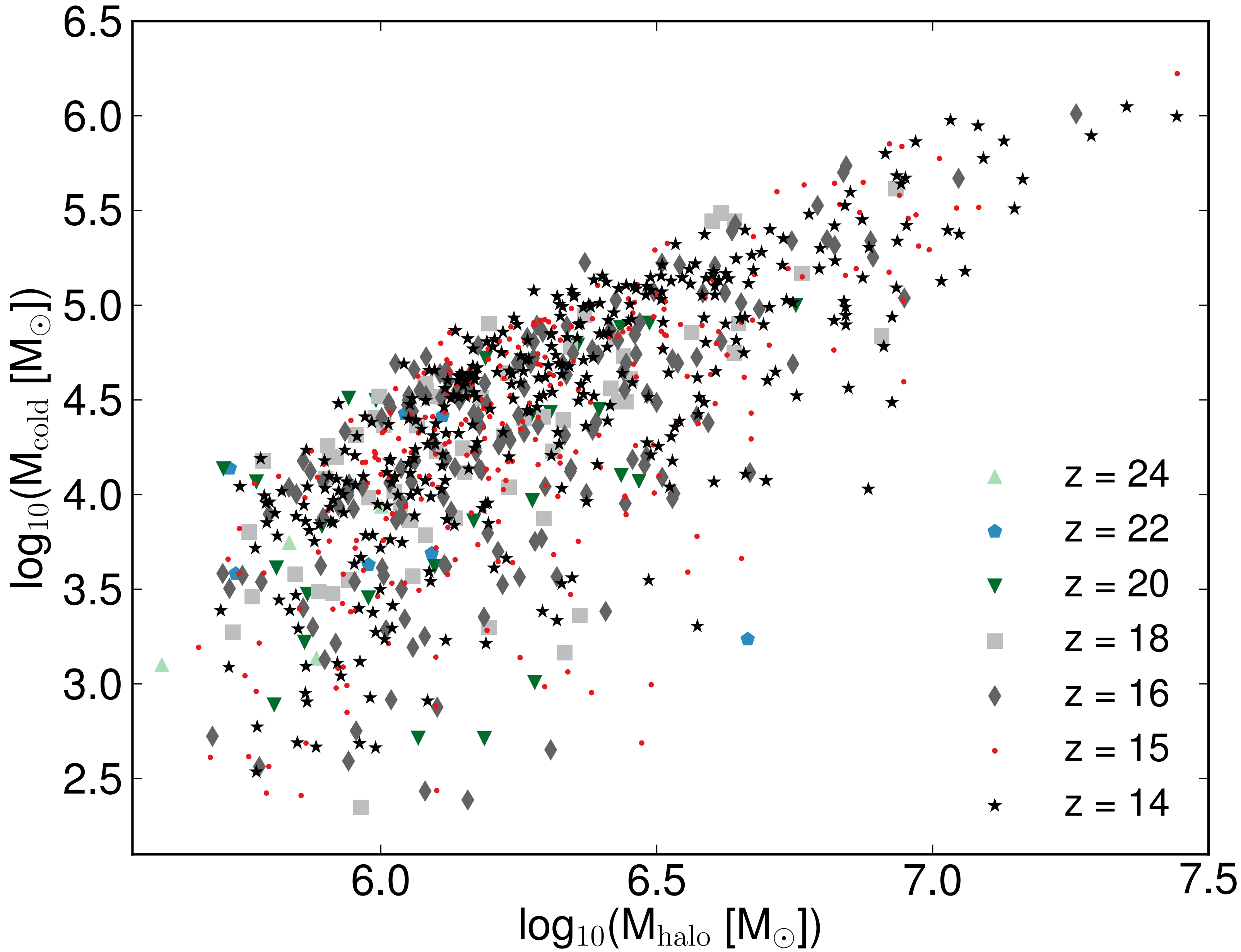
cold gas mass - halo mass relation

cold mass: sum of all cold, dense H_2 rich gas in halo

- $T < 500K$
- H_2 abundance $> 10^{-4}$
- $n > 100\ cm^{-3}$

Schauer+ 2018 (submitted)





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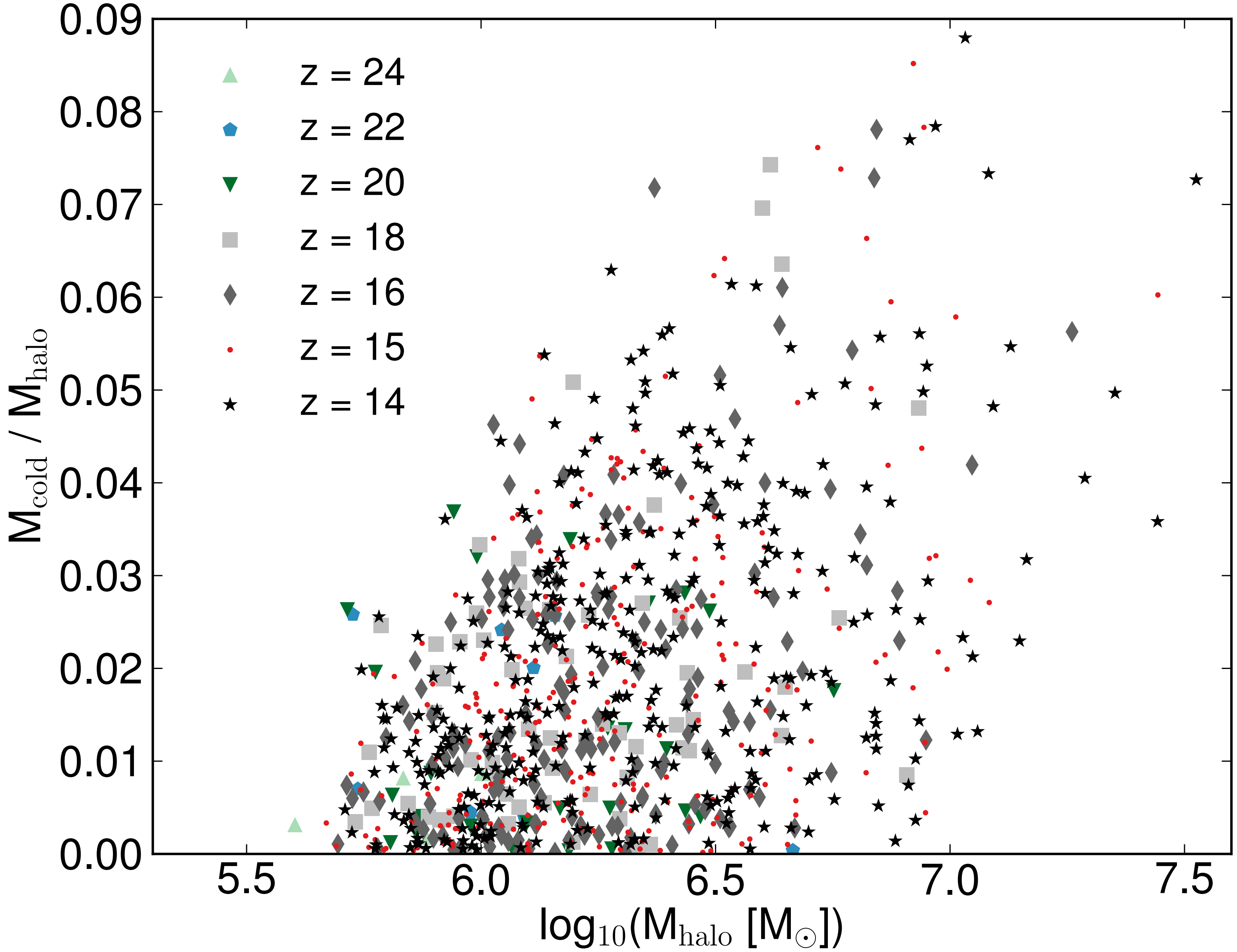
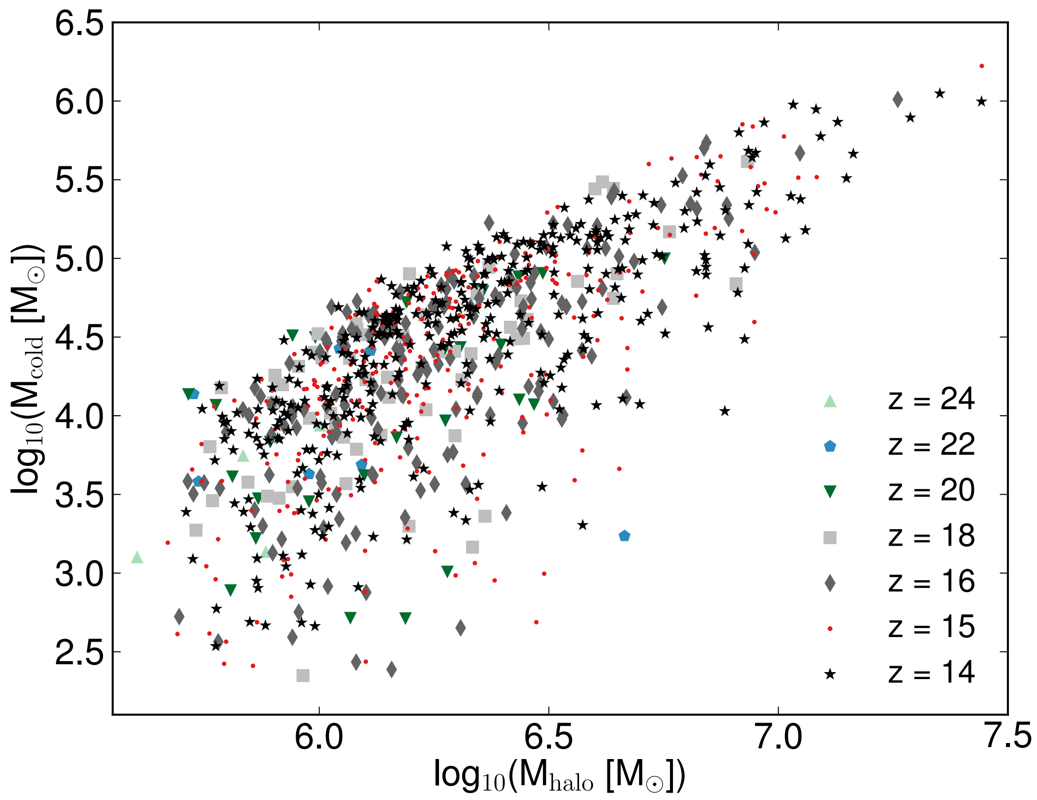
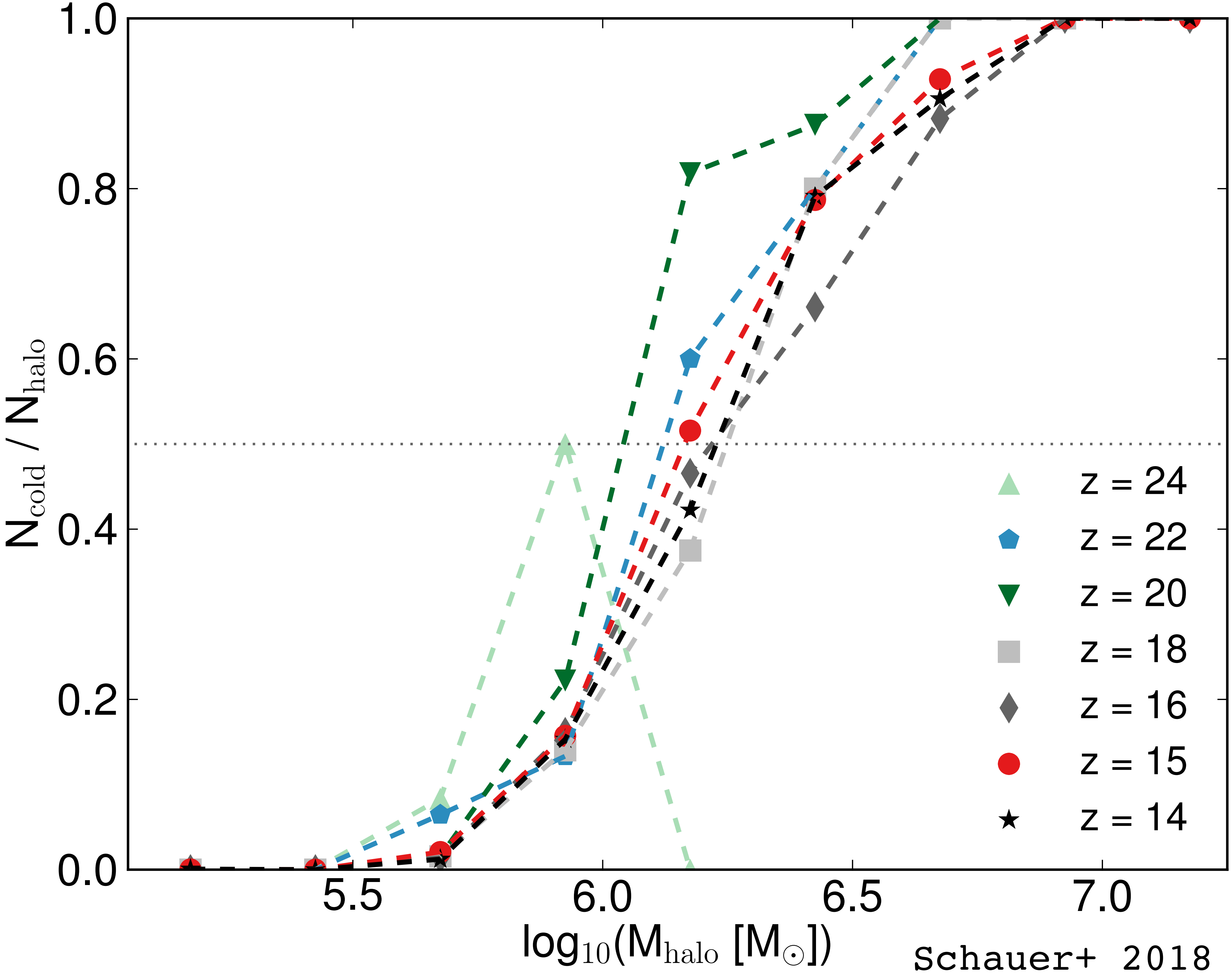


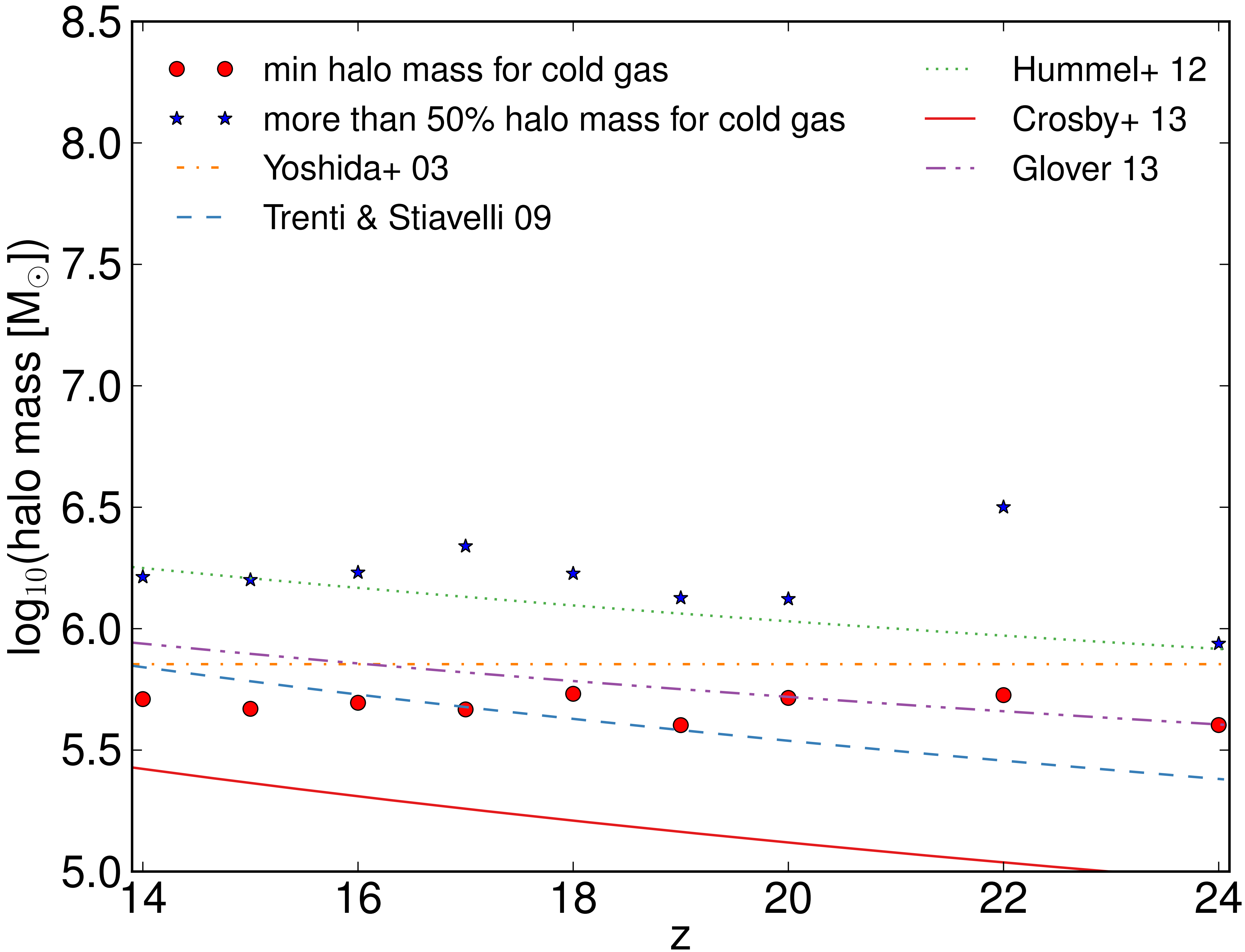


fraction of cold haloes



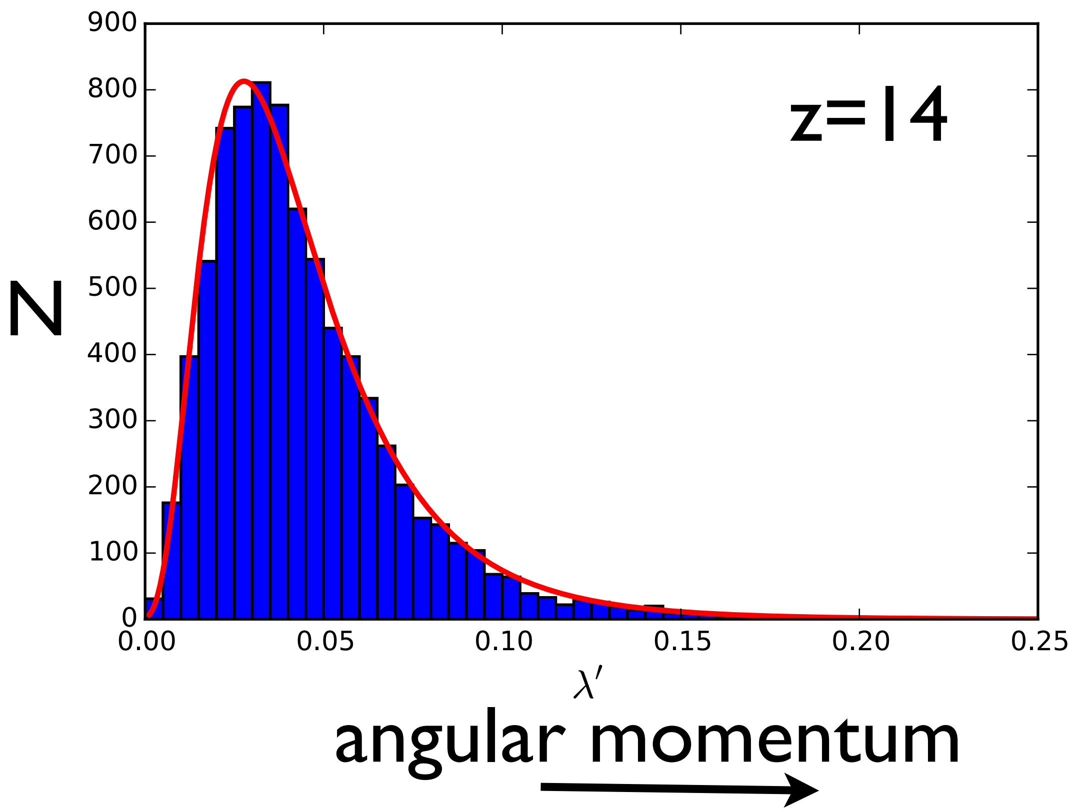
Schauer+ 2018 (submitted)

halo masses of cold haloes



Schauer+ 2018 (submitted)

spin parameter



- measure of angular momentum in galaxy

$$\lambda' = \frac{J}{\sqrt{2} M\, R\, v_{circ}}$$

Bullock+ 2001

- lognormal distribution

$$P(\lambda') = \frac{1}{\lambda\sqrt{2\pi}\sigma} \cdot \exp\left(-\frac{\ln^2\left(\frac{\lambda}{\lambda_0}\right)}{2\sigma^2}\right)$$

Druschke, Schauer+ 2018 (submitted)

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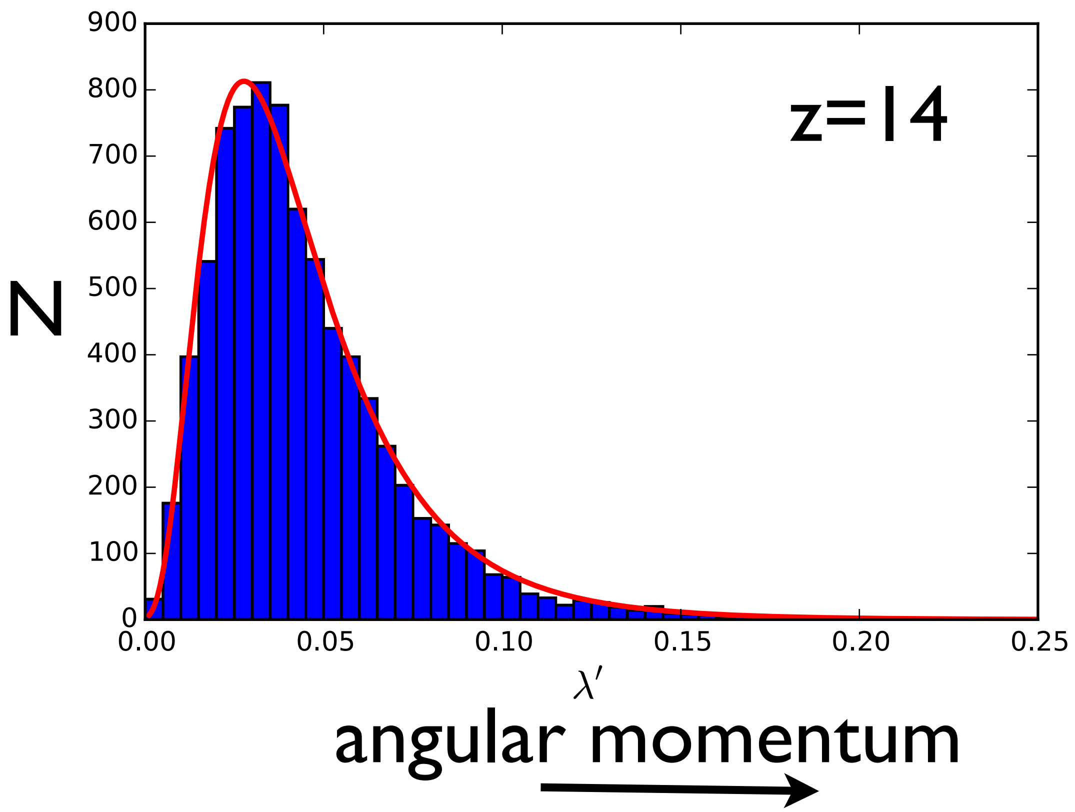

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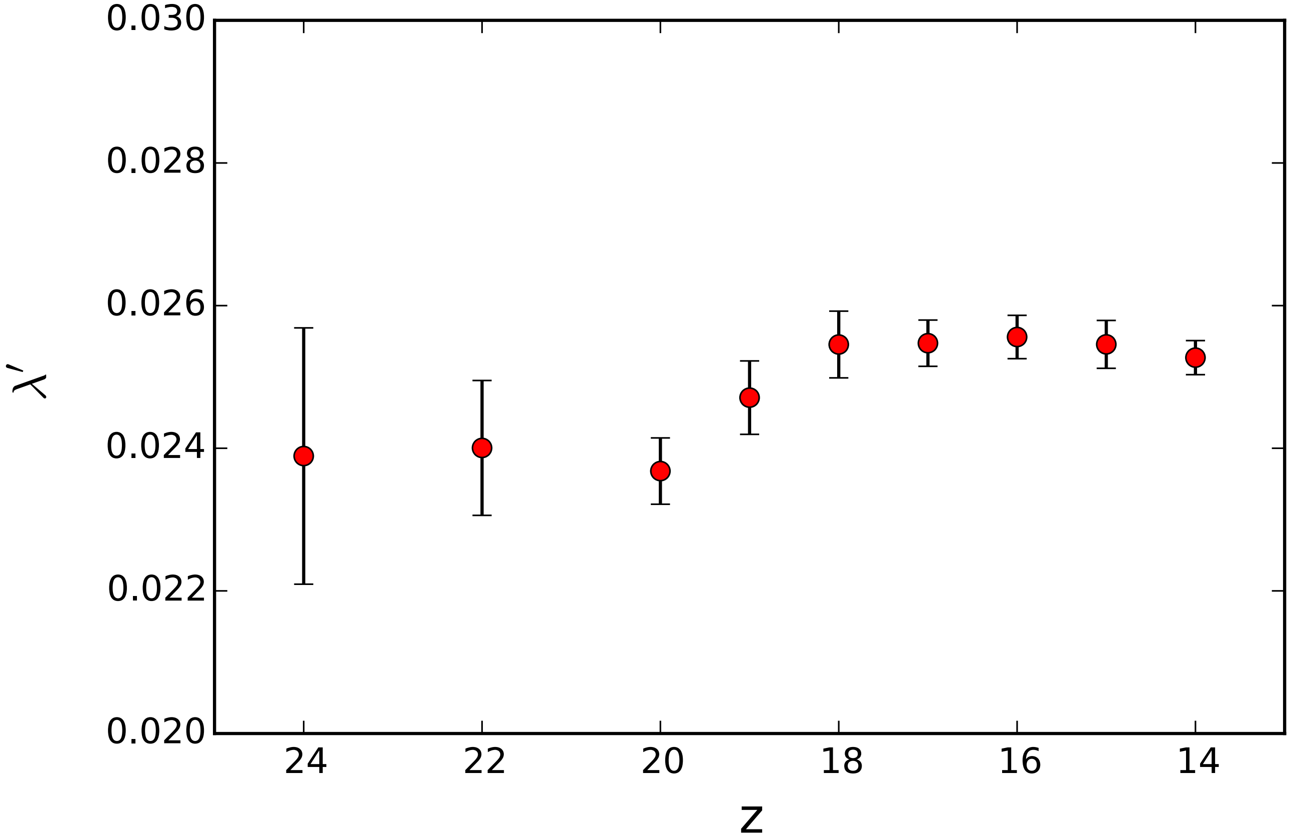
- (no) redshift evolution



Druschke, Schauer+ 2018 (submitted)

spin parameter

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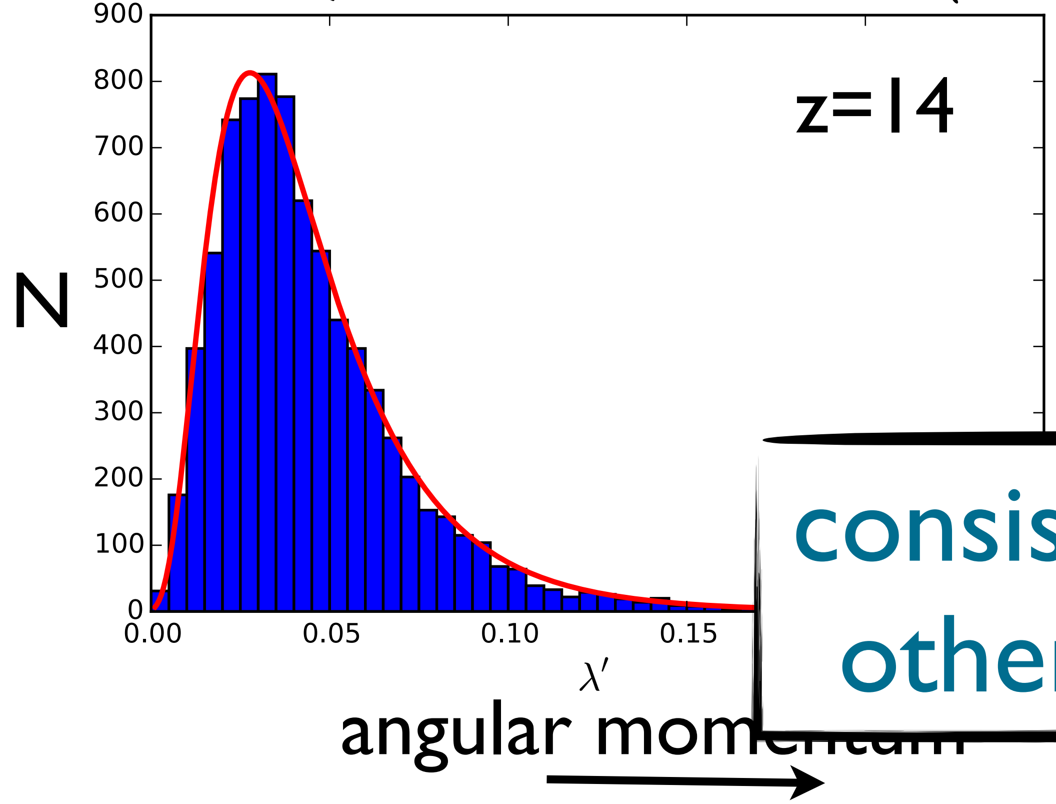
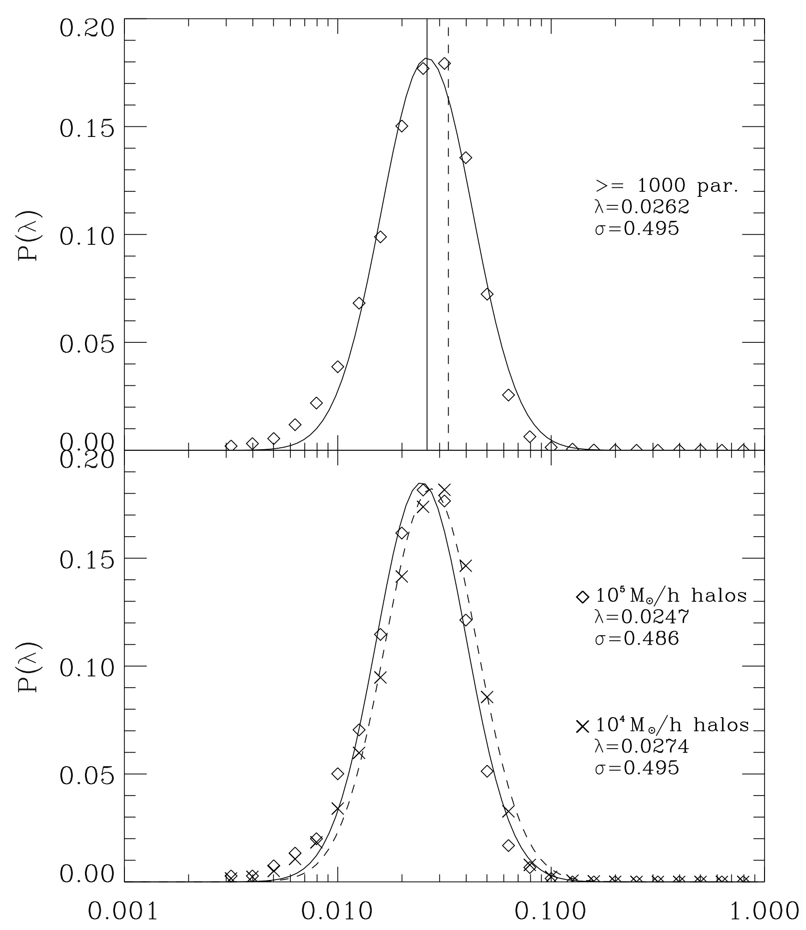
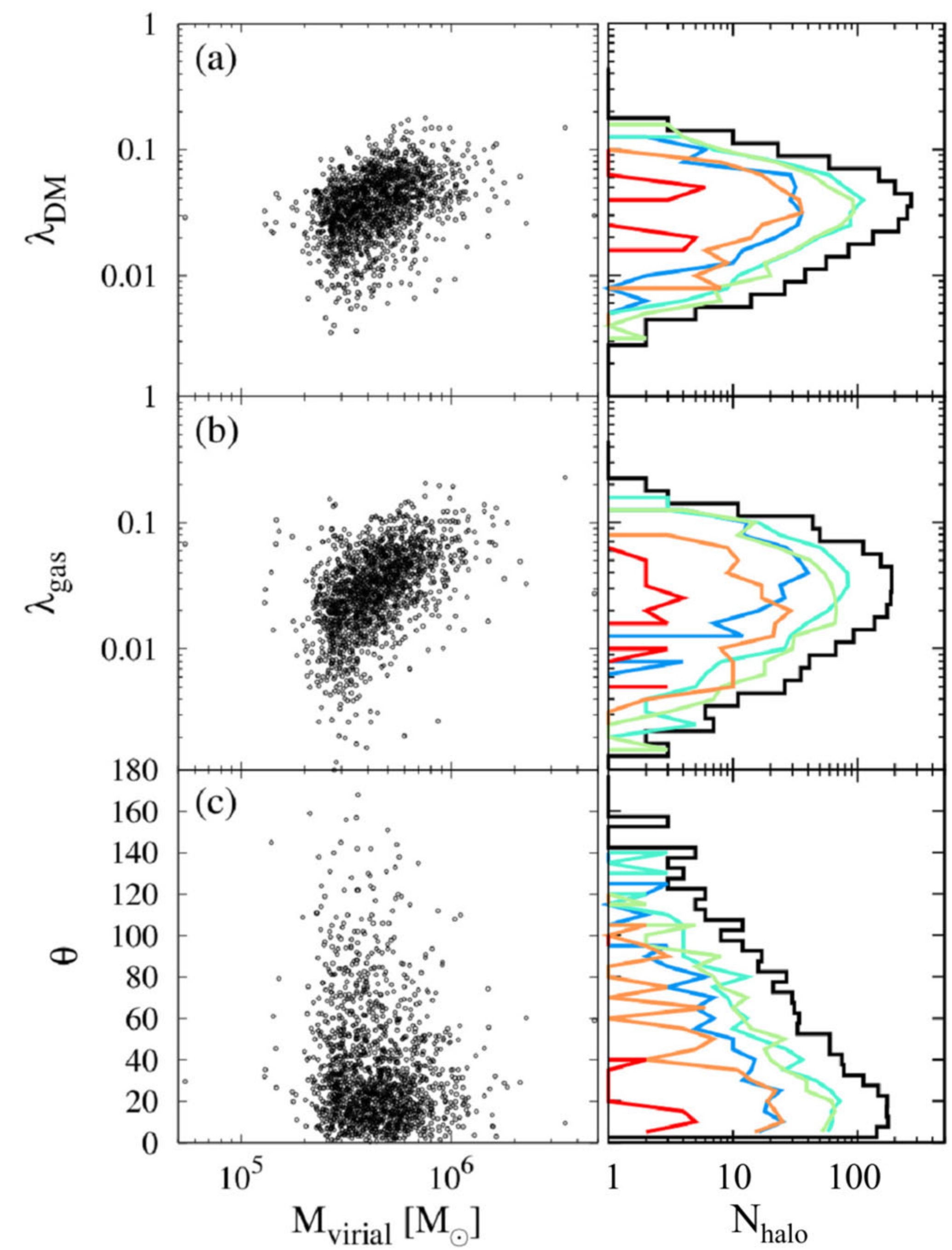


consistent with other studies



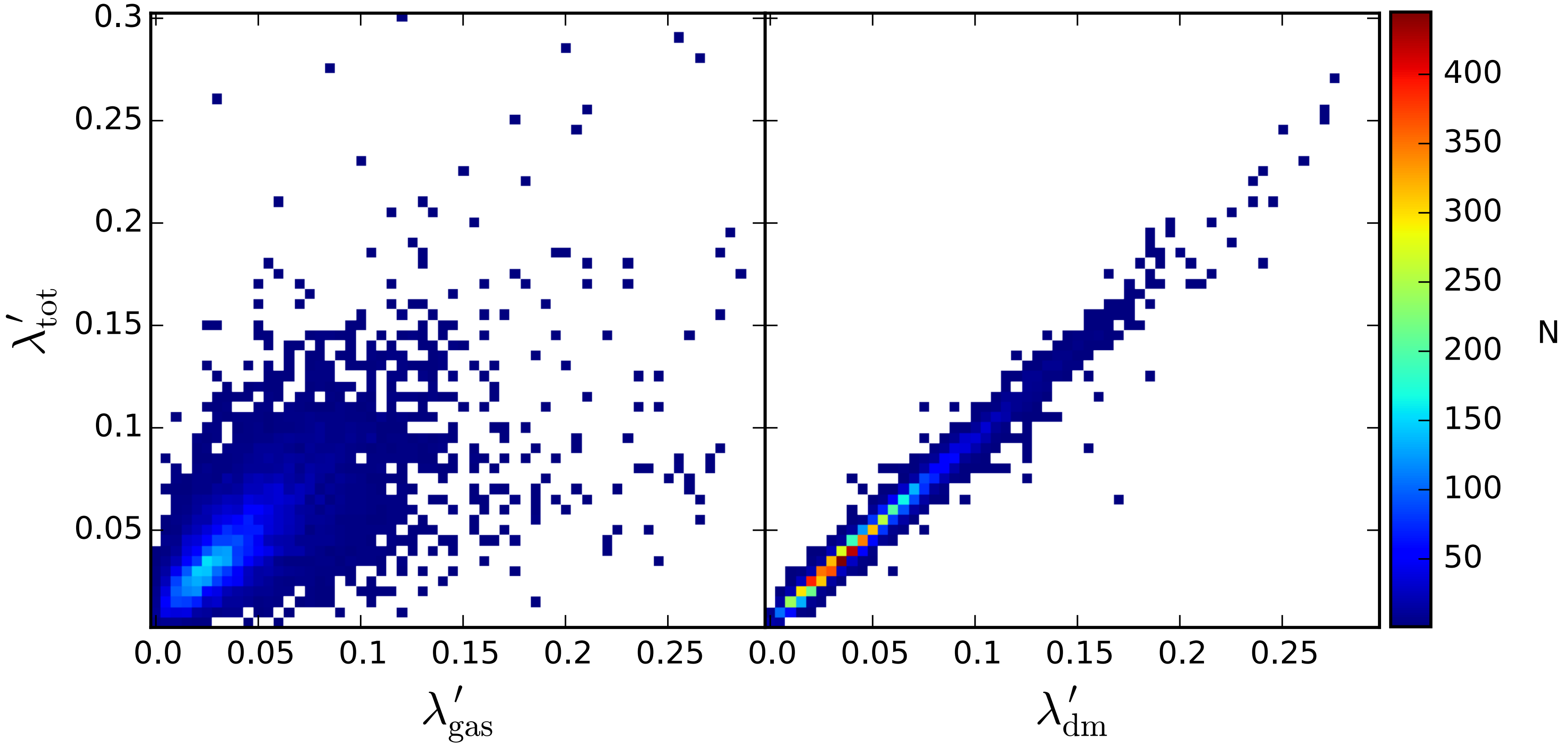
Sasaki+14



Hirano+15

spin parameter: dense centre

- weak correlation between the gas and the total spin



Druschke, Schauer+ 2018 (submitted)

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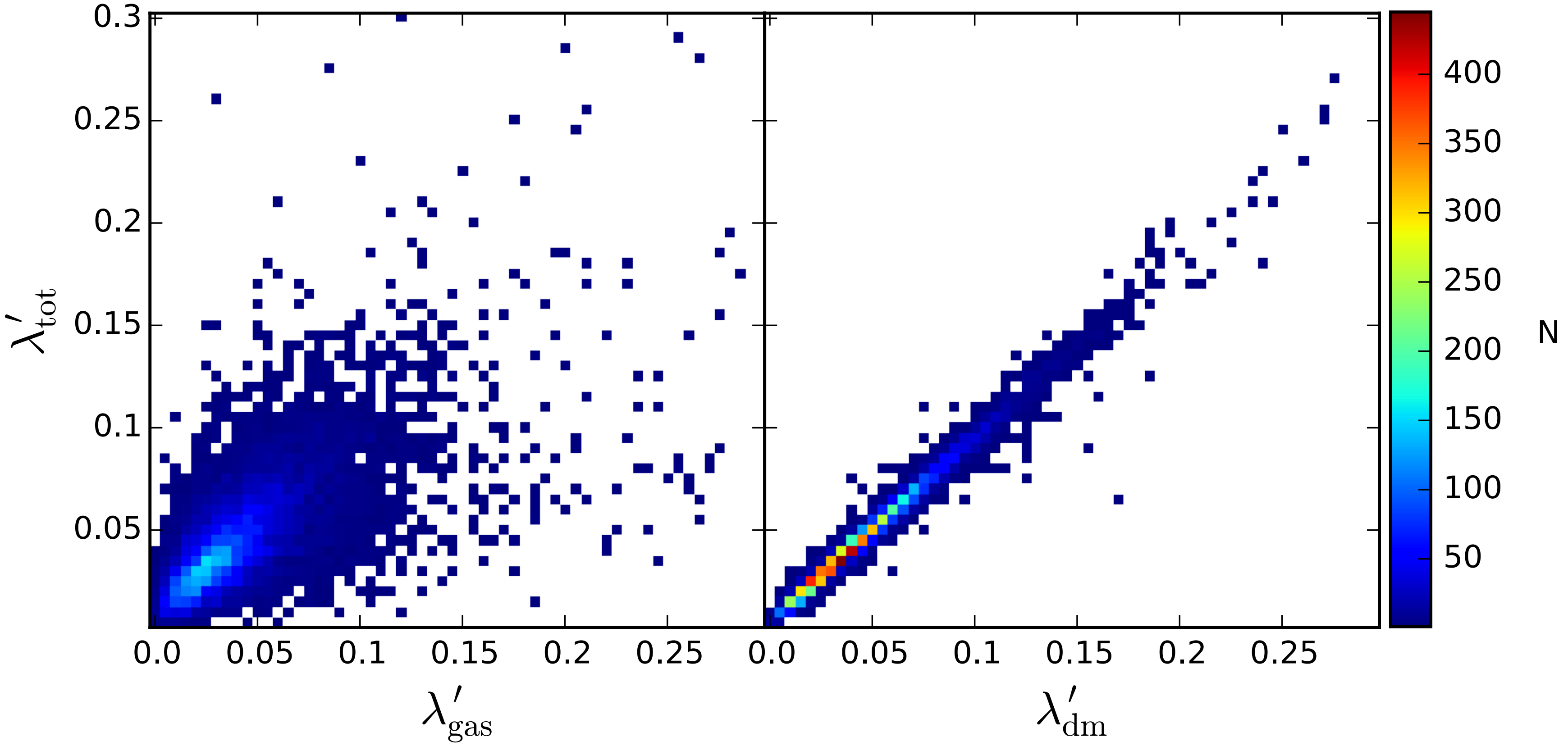
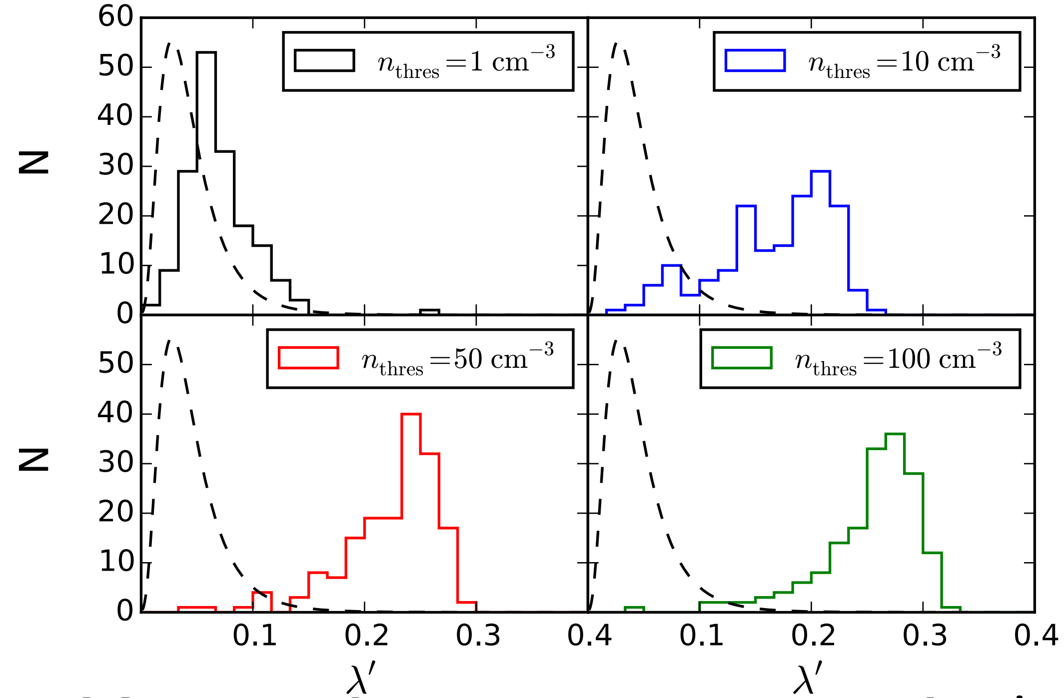


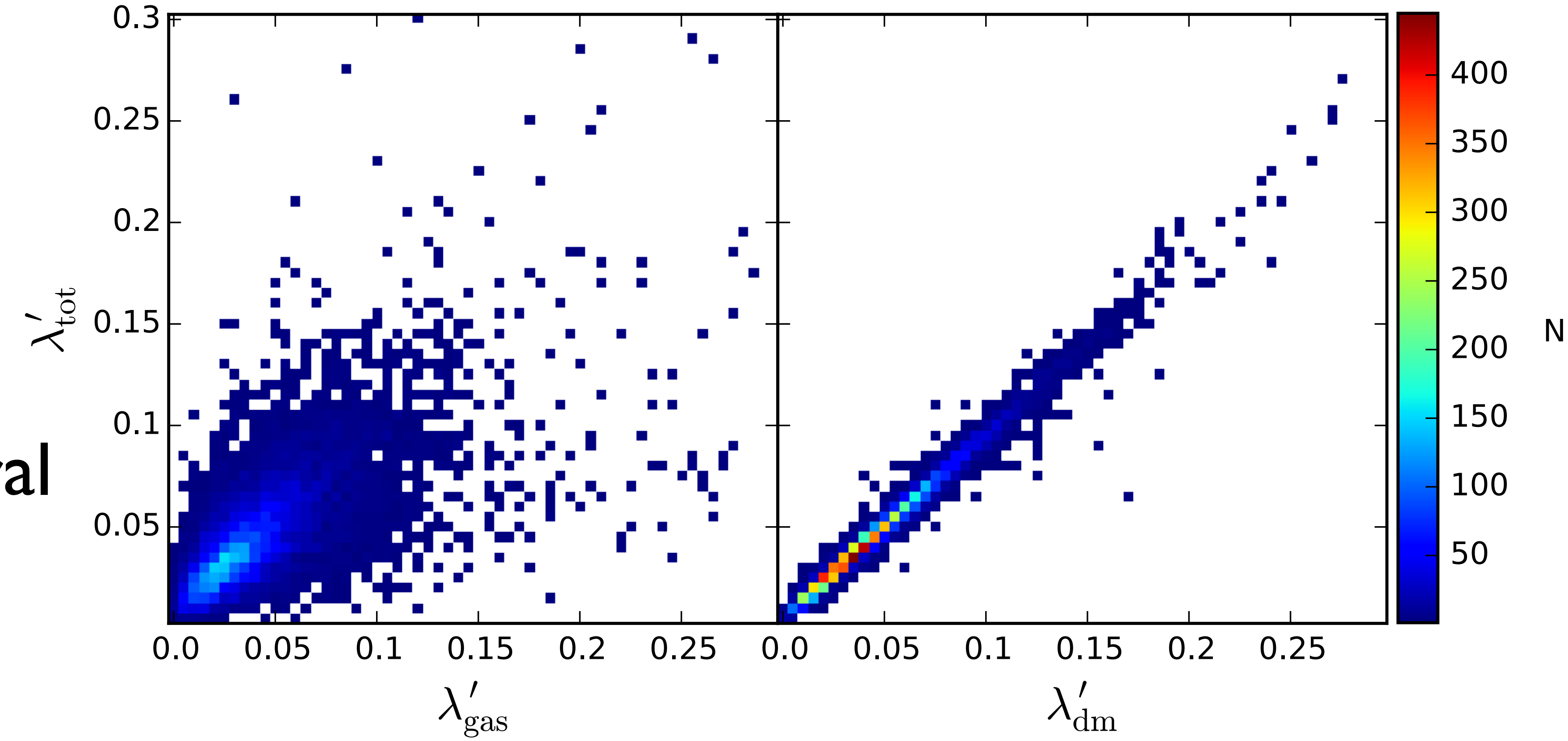
- high spin for high densities

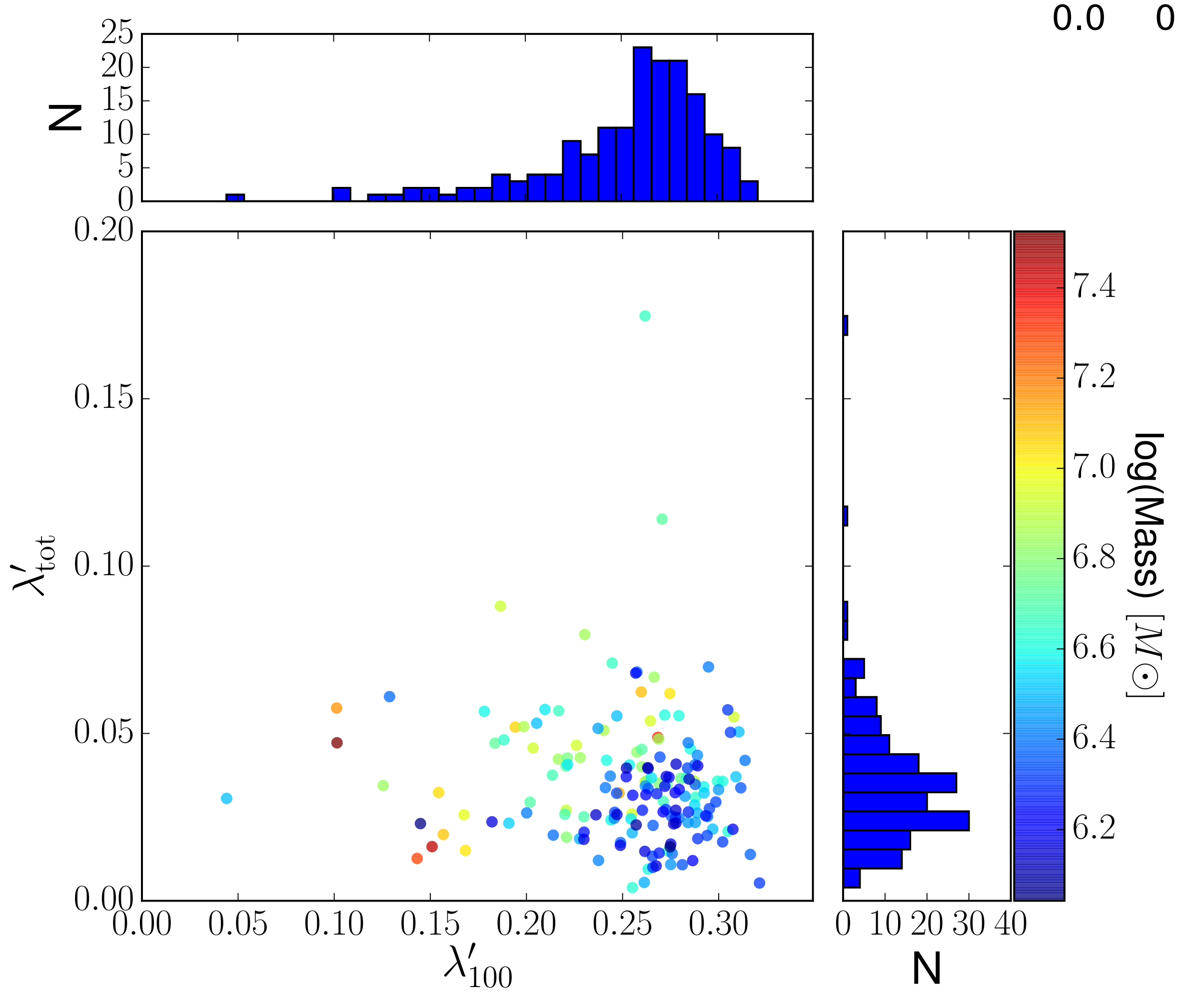


Druschke, Schauer+ 2018 (submitted)

spin parameter: dense centre

- weak correlation between the gas and the total spin
- no correlation between dense, central gas and total halo





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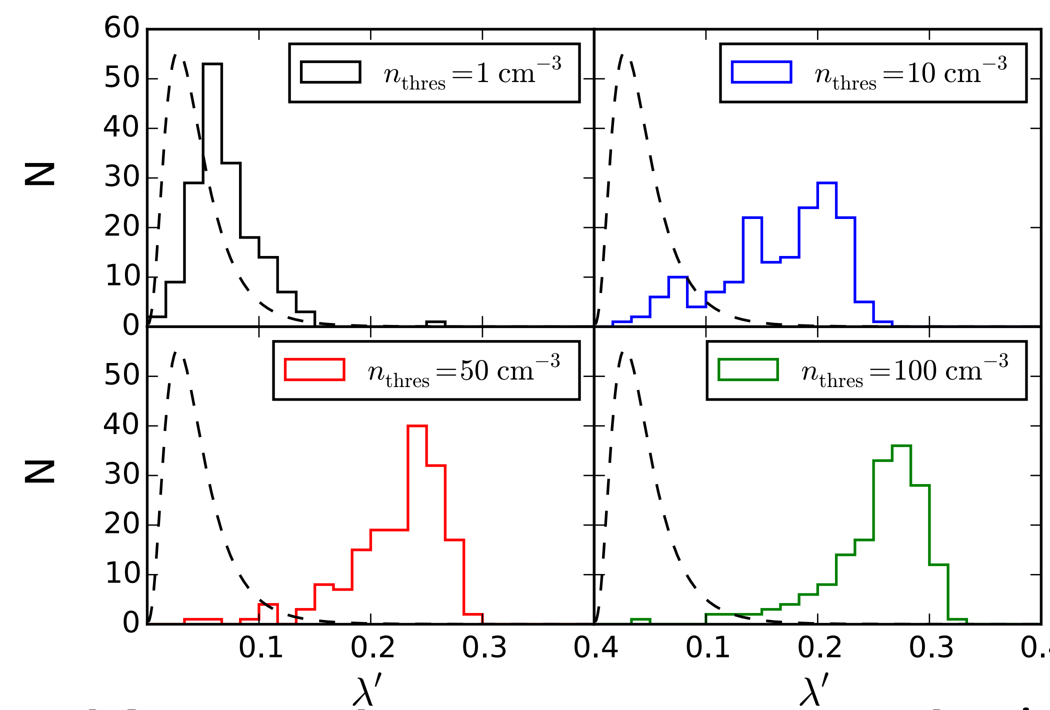
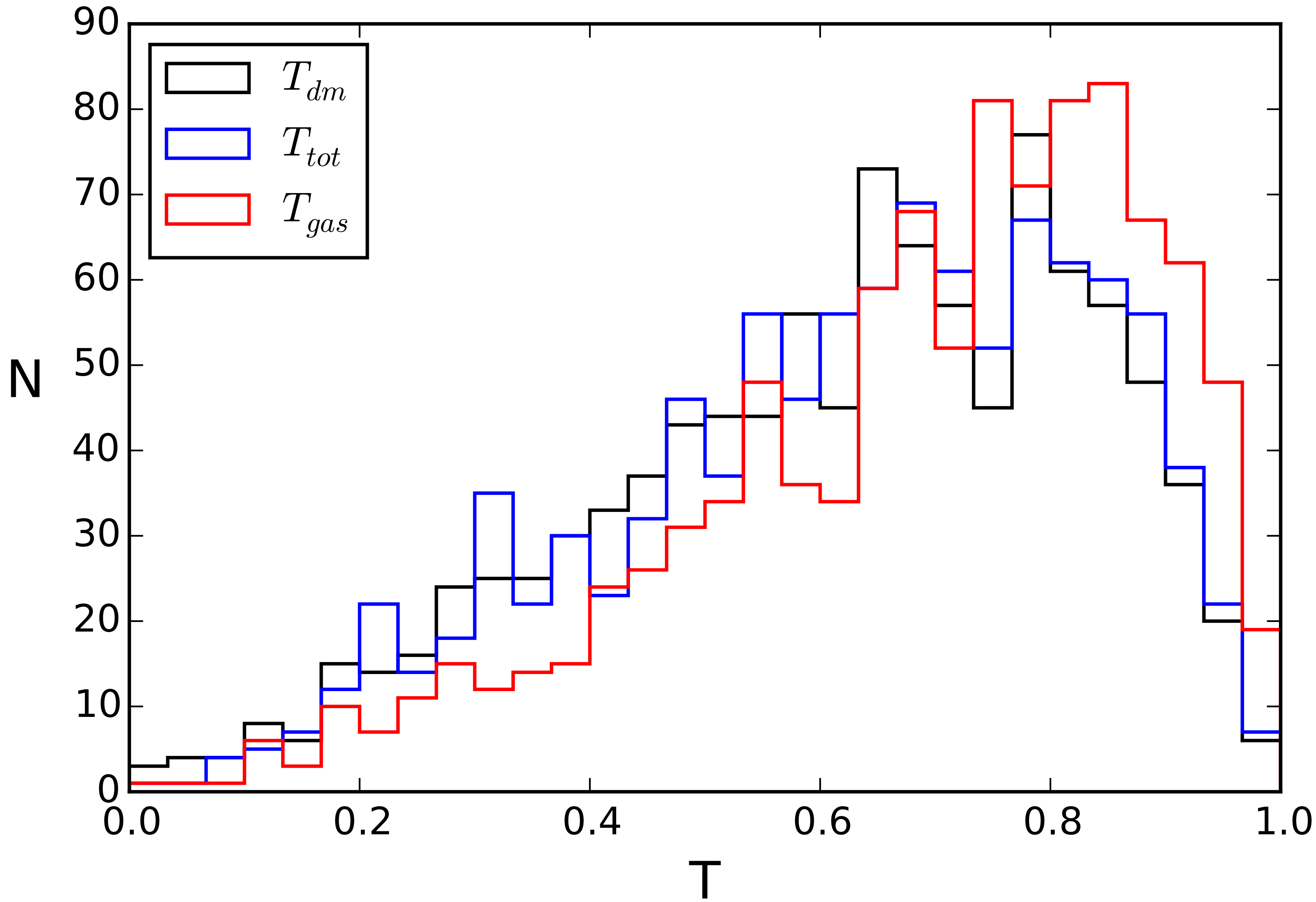


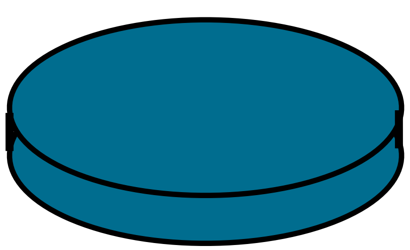
Druschke, Schauer+ 2018 (submitted)

triaxiality

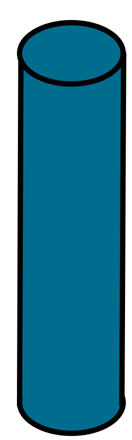


- for a > b > c (from inertia tensor): triaxiality T

$$T = \frac{a^2 - b^2}{a^2 - c^2}$$



T = 0: oblate



T = 1: prolate

Druschke, Schauer+ 2018 (submitted)

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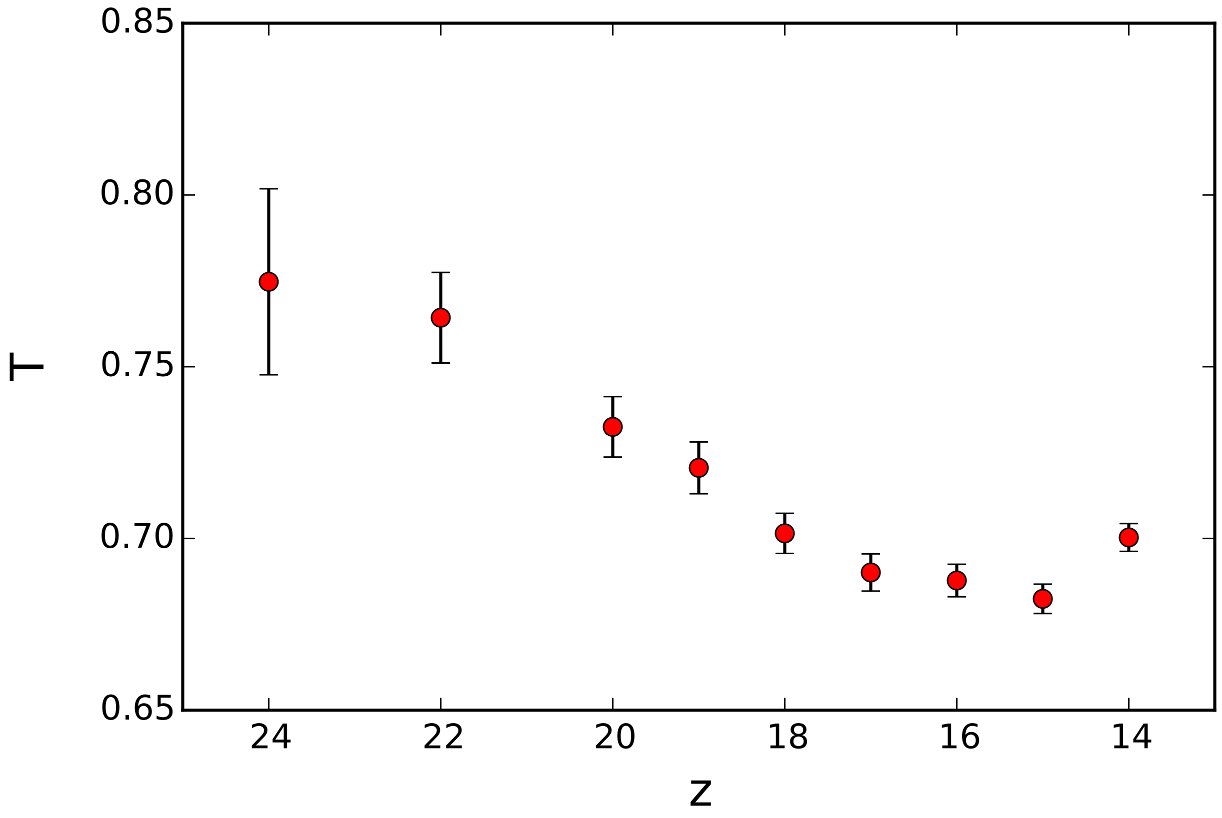
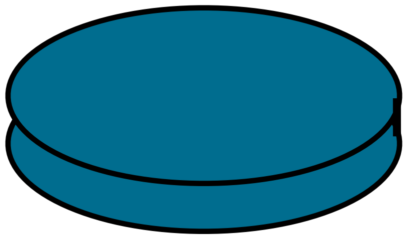


- redshift evolution



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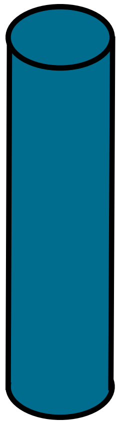

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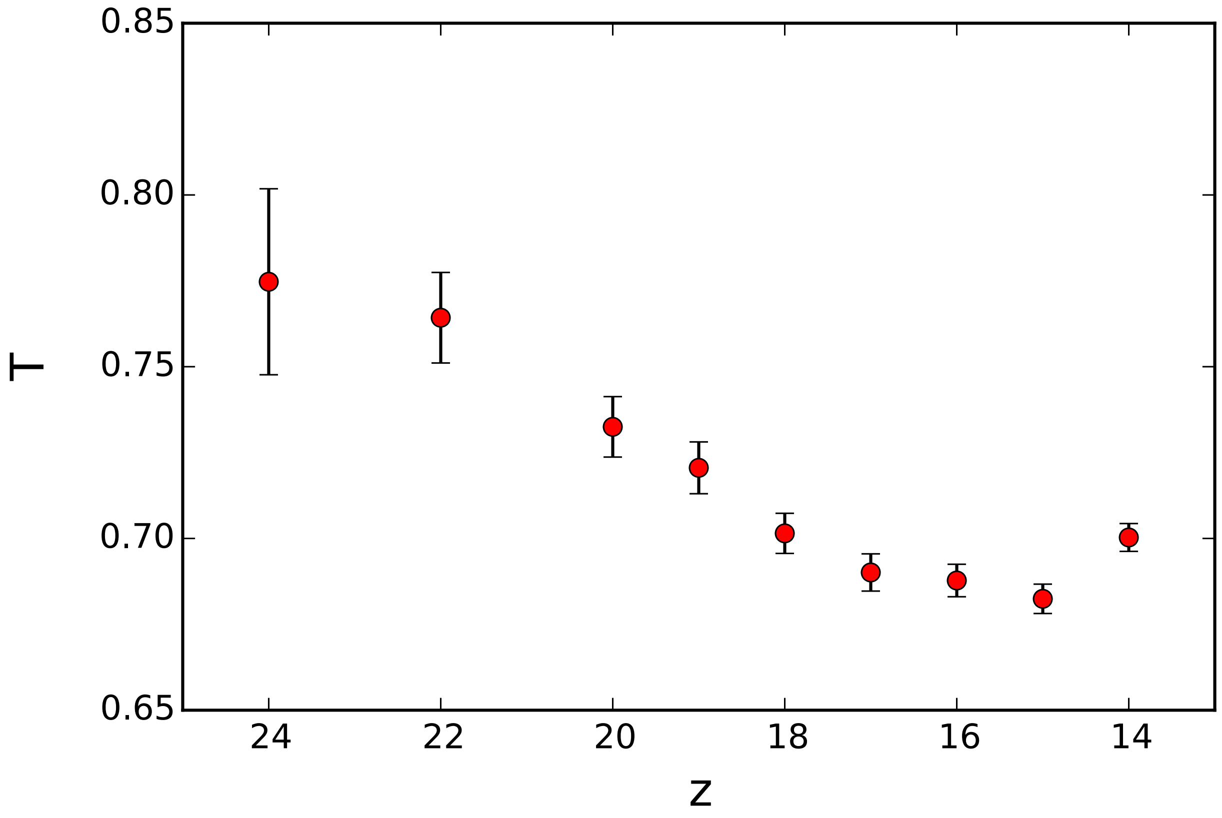
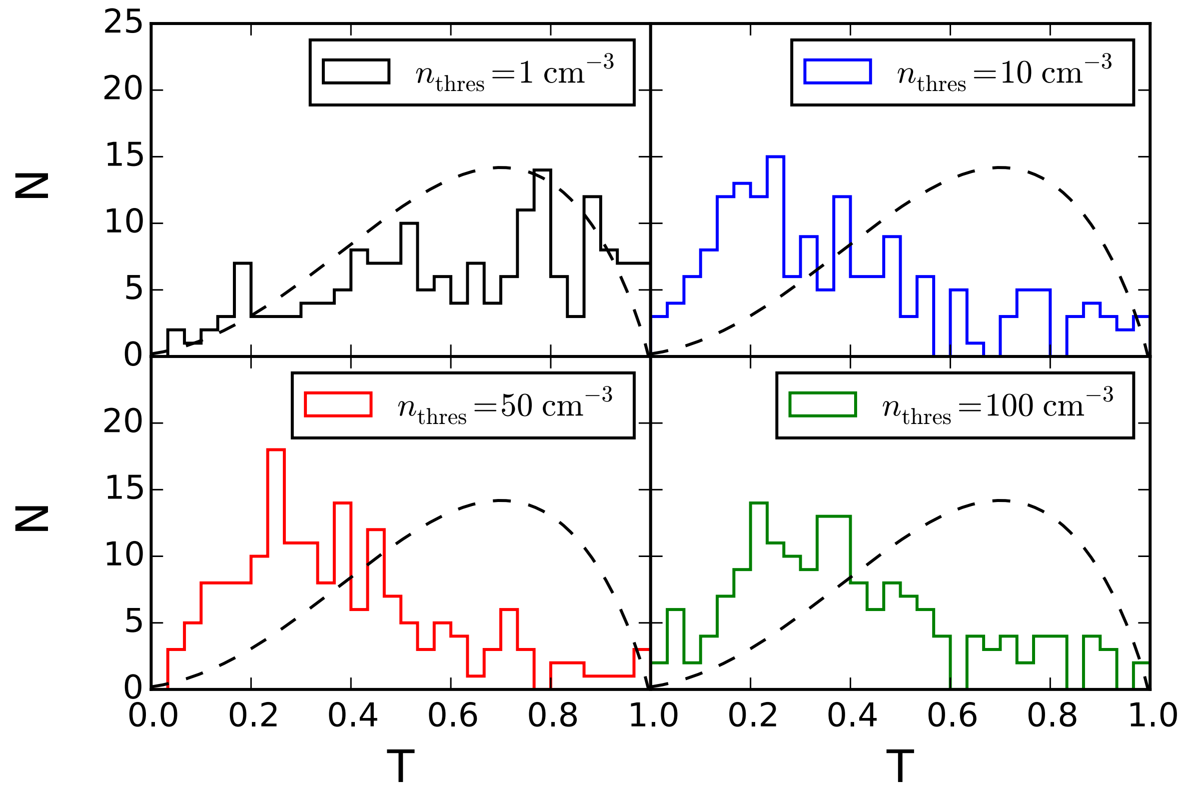
Druschke, Schauer+ 2018 (submitted)

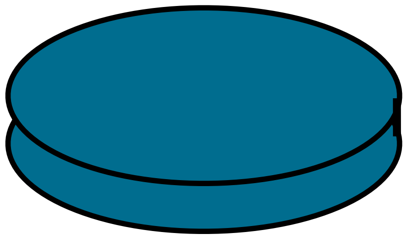
triaxiality: dense centre



- redshift evolution

- more oblate for high densities





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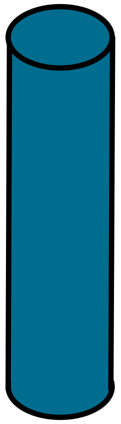

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Druschke, Schauer+ 2018 (submitted)

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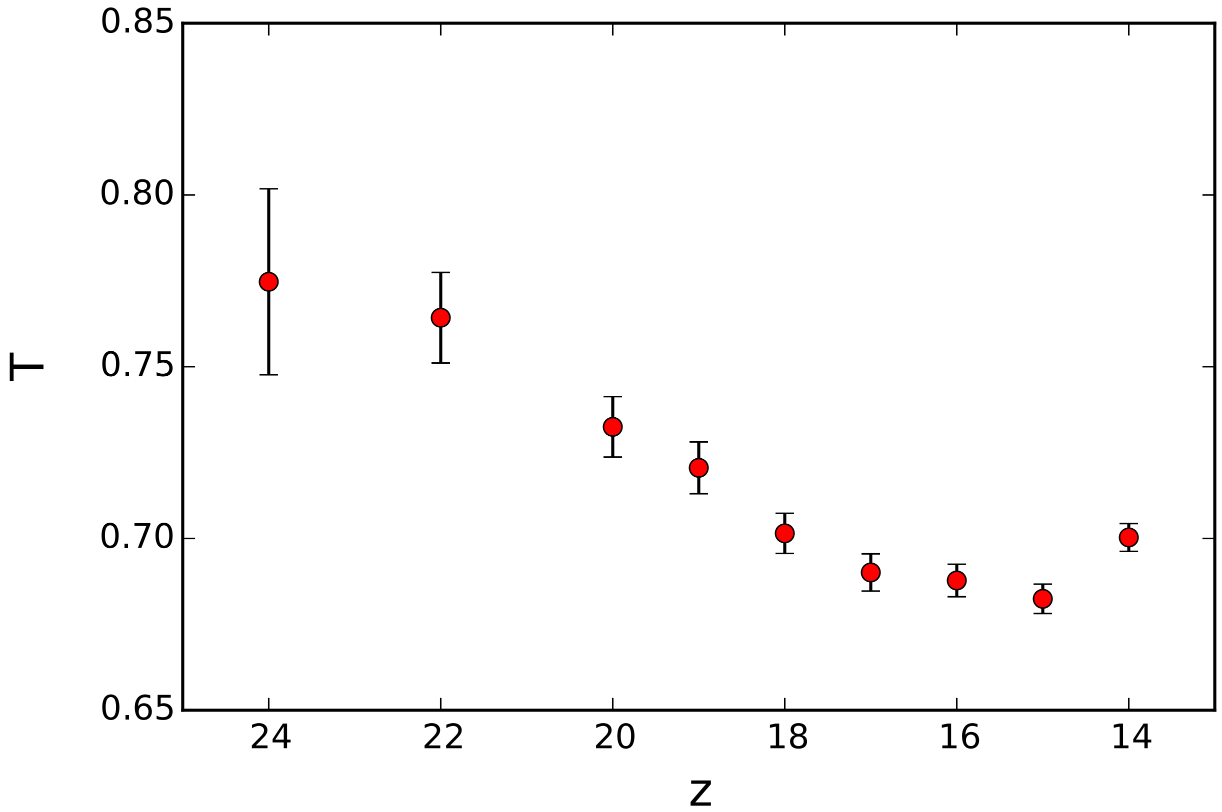

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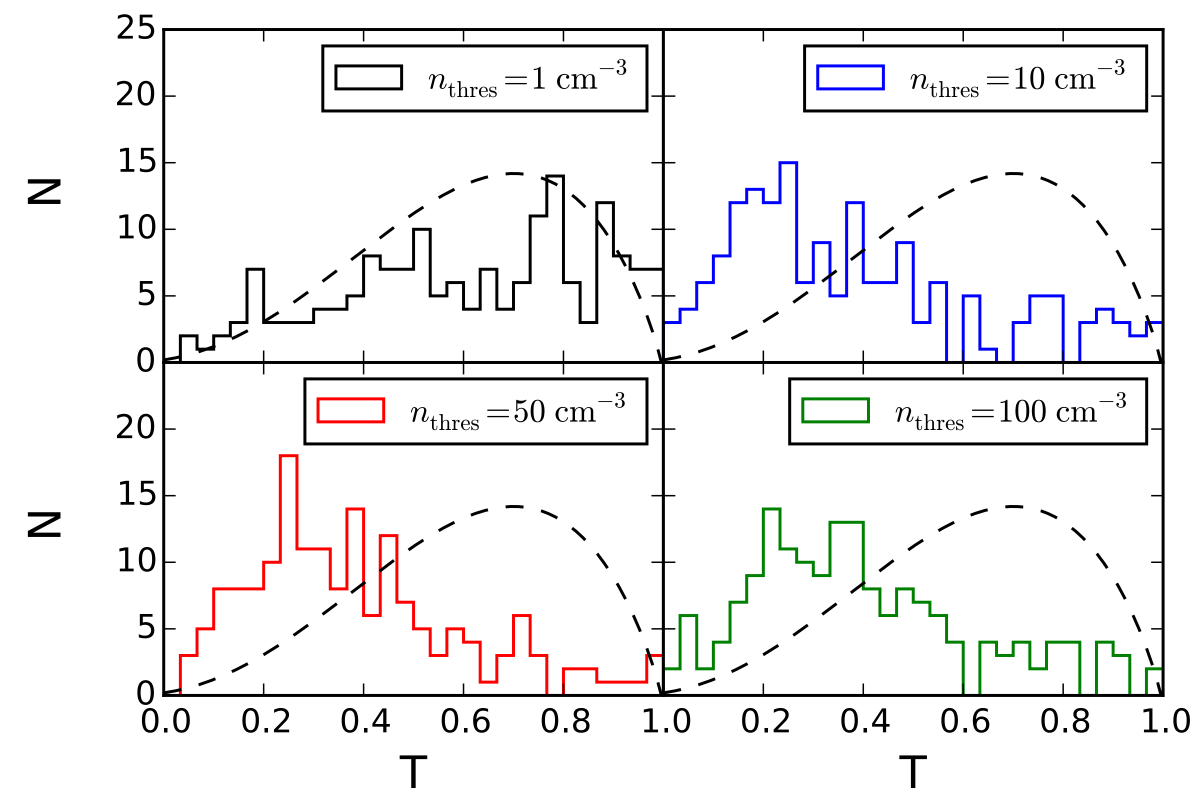
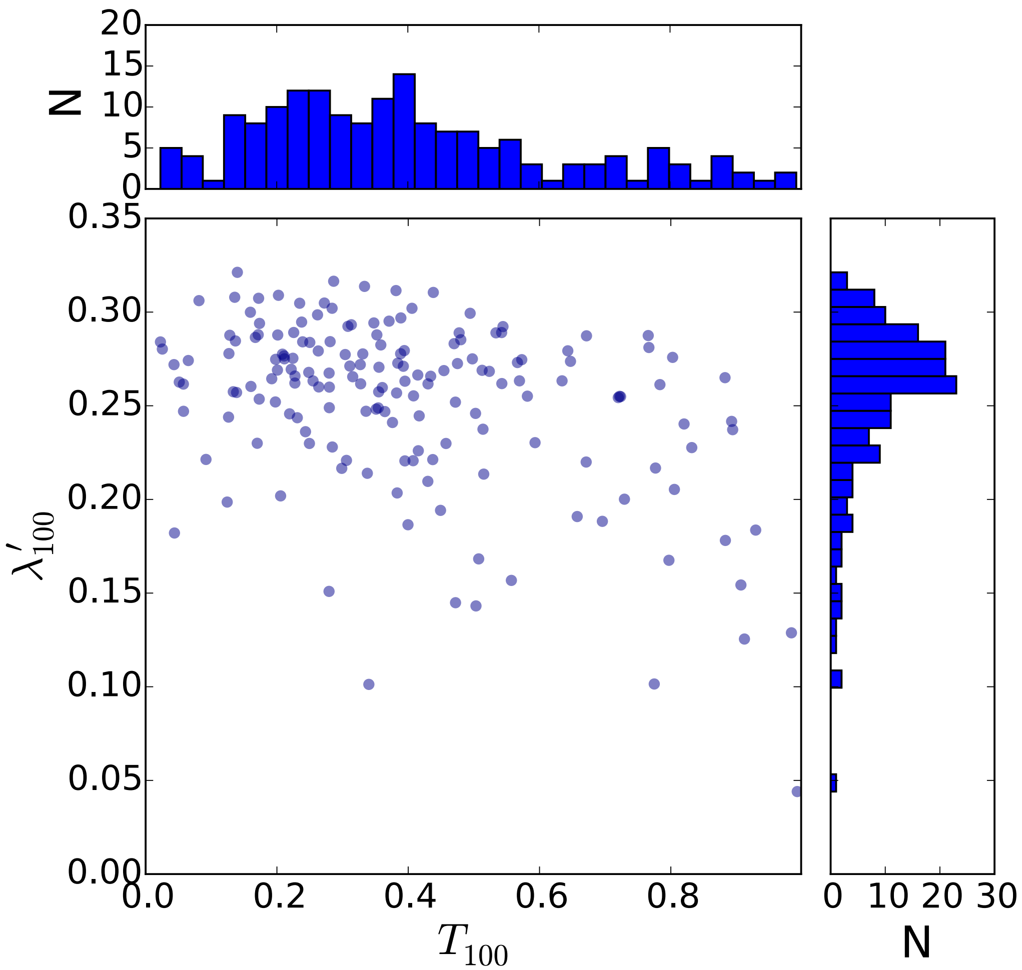
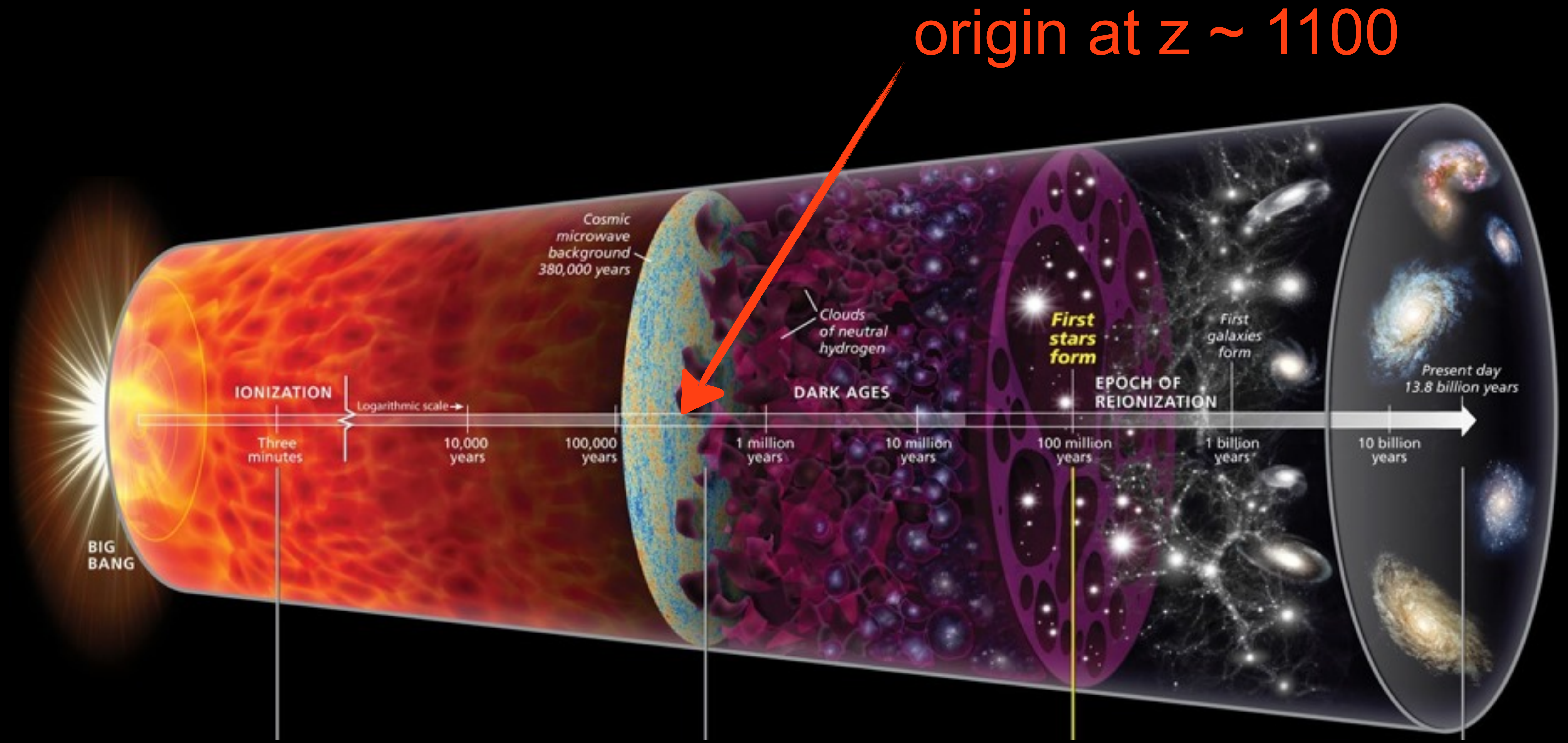




- oblate halo centres are fast rotators

Druschke, Schauer+ 2018 (submitted)

streaming velocities



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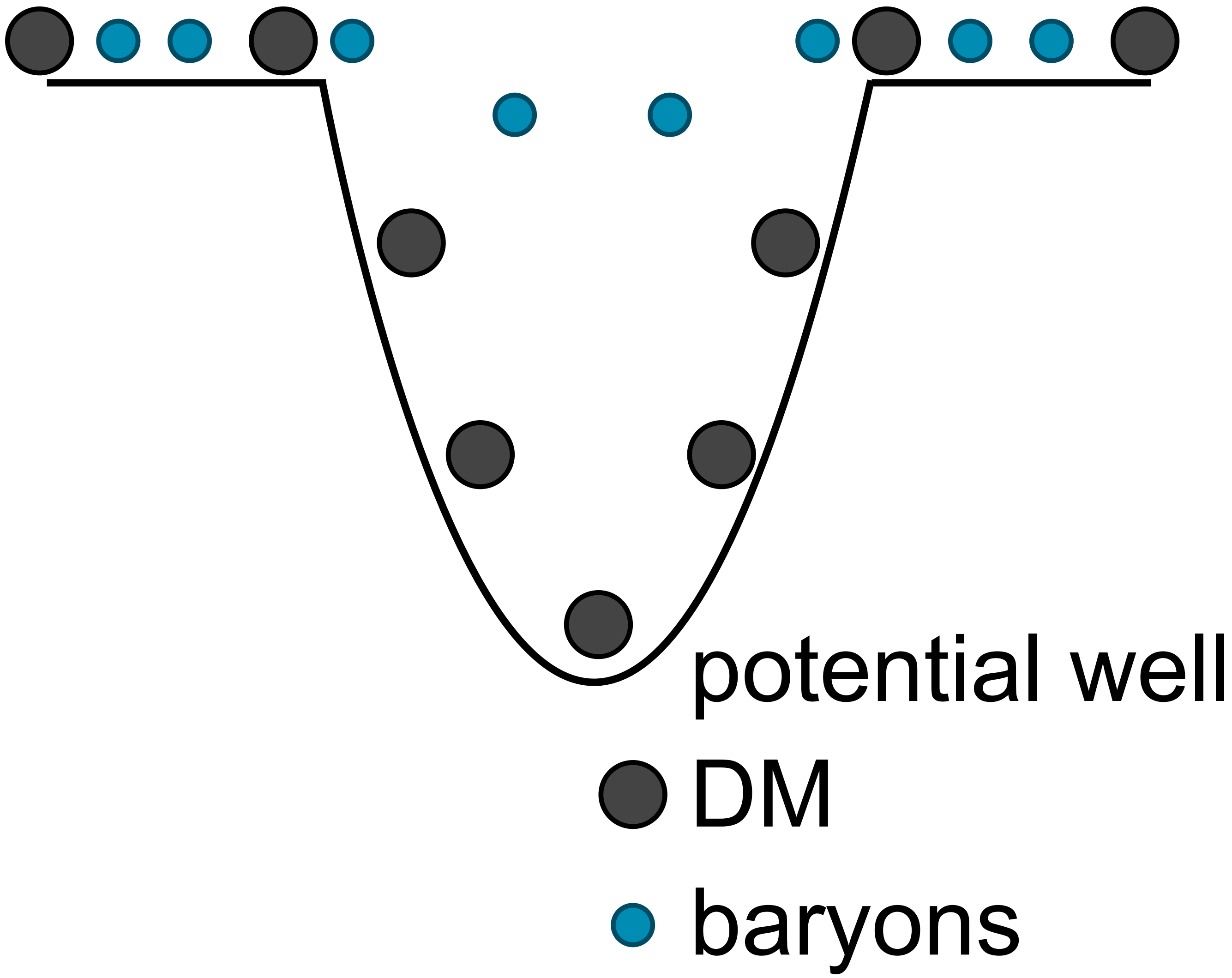
streaming velocities

- Before recombination: coupling of baryons and photons
- DM fluctuations increase
- baryon fluctuations are suppressed



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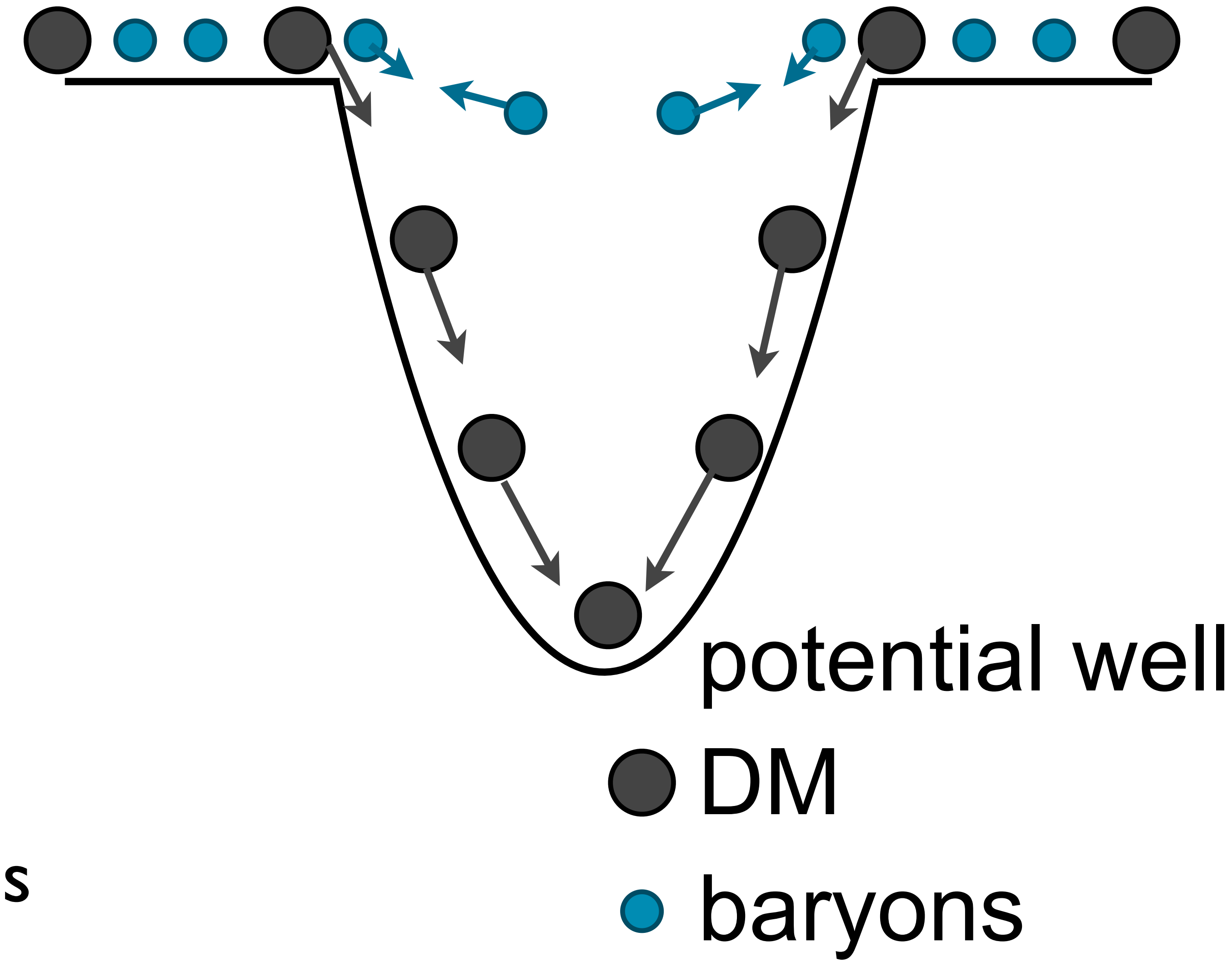


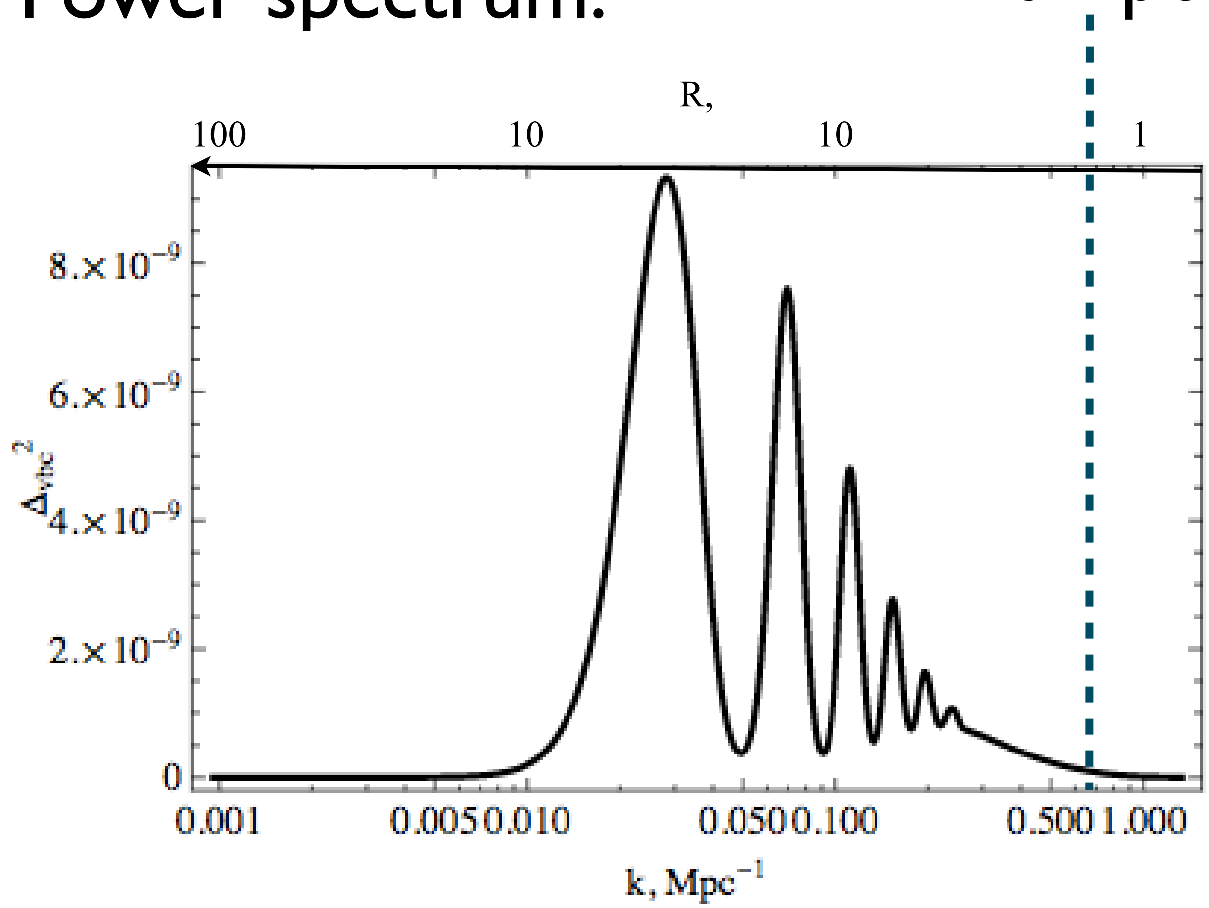
streaming velocity

=

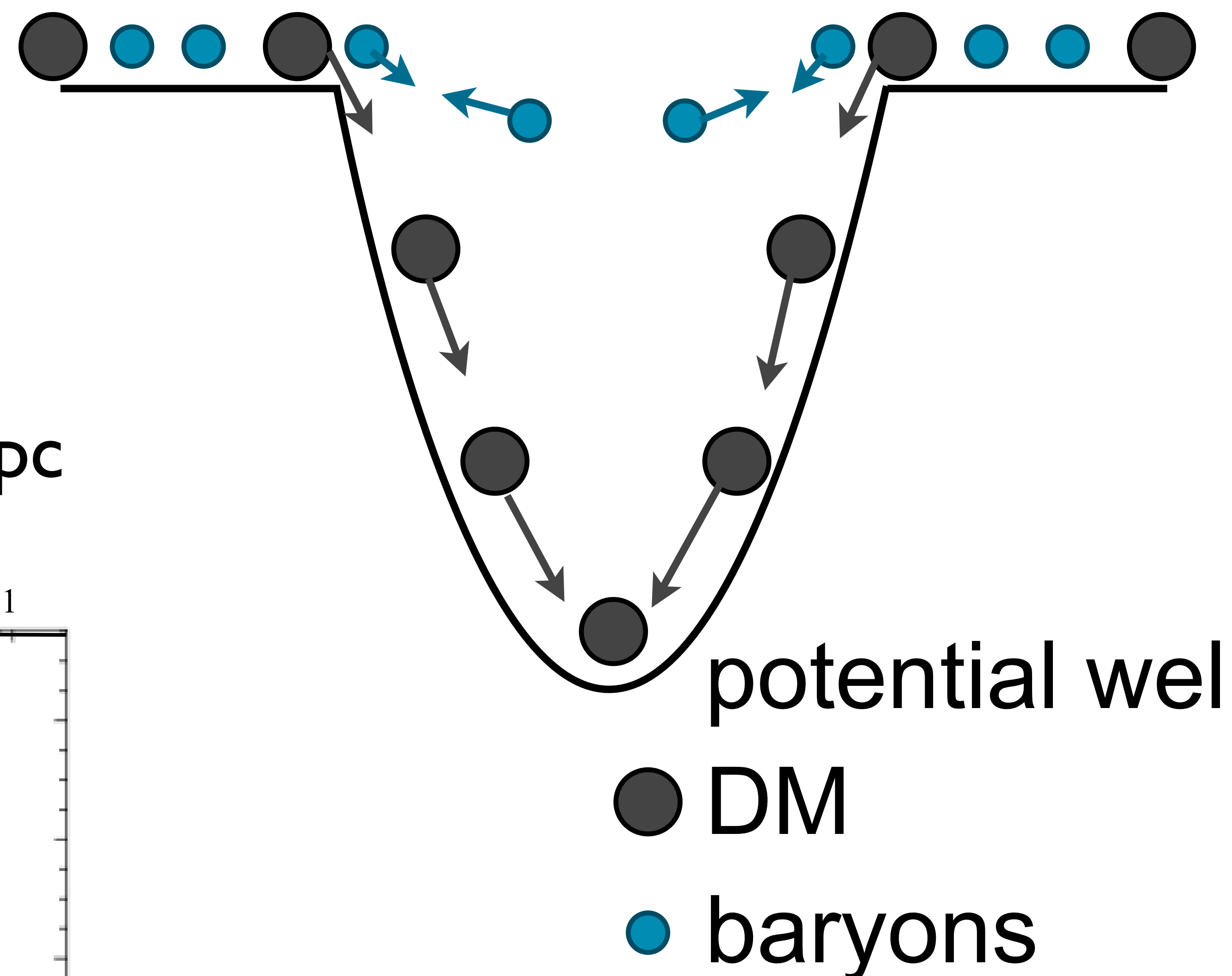
offset velocity between baryons and dark matter

streaming velocities

- coherent over large scales, ~3Mpc
- $1\sigma_{rms} \sim 30\ km\ s^{-1}$ value at recombination
- decaying as (1+z)
- Power spectrum:



Tseliakhovich & Hirata 10



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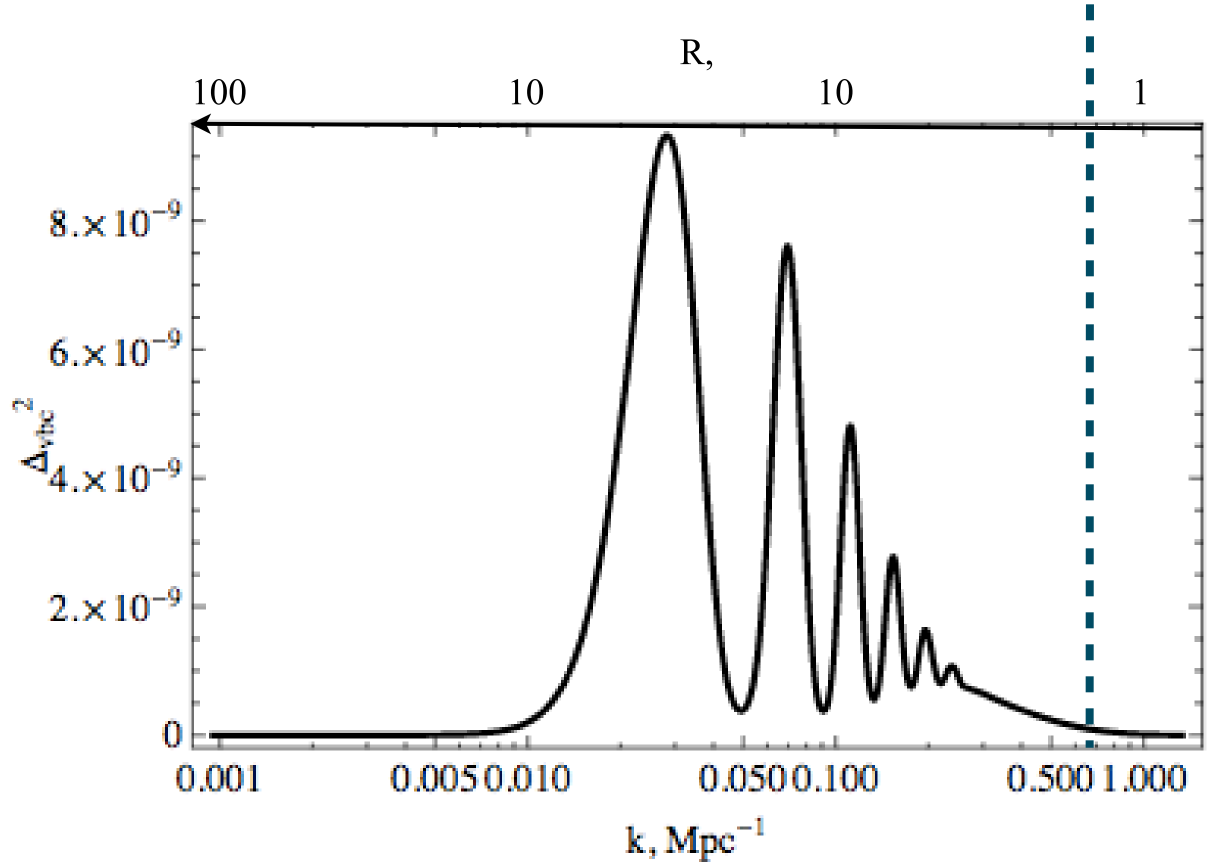
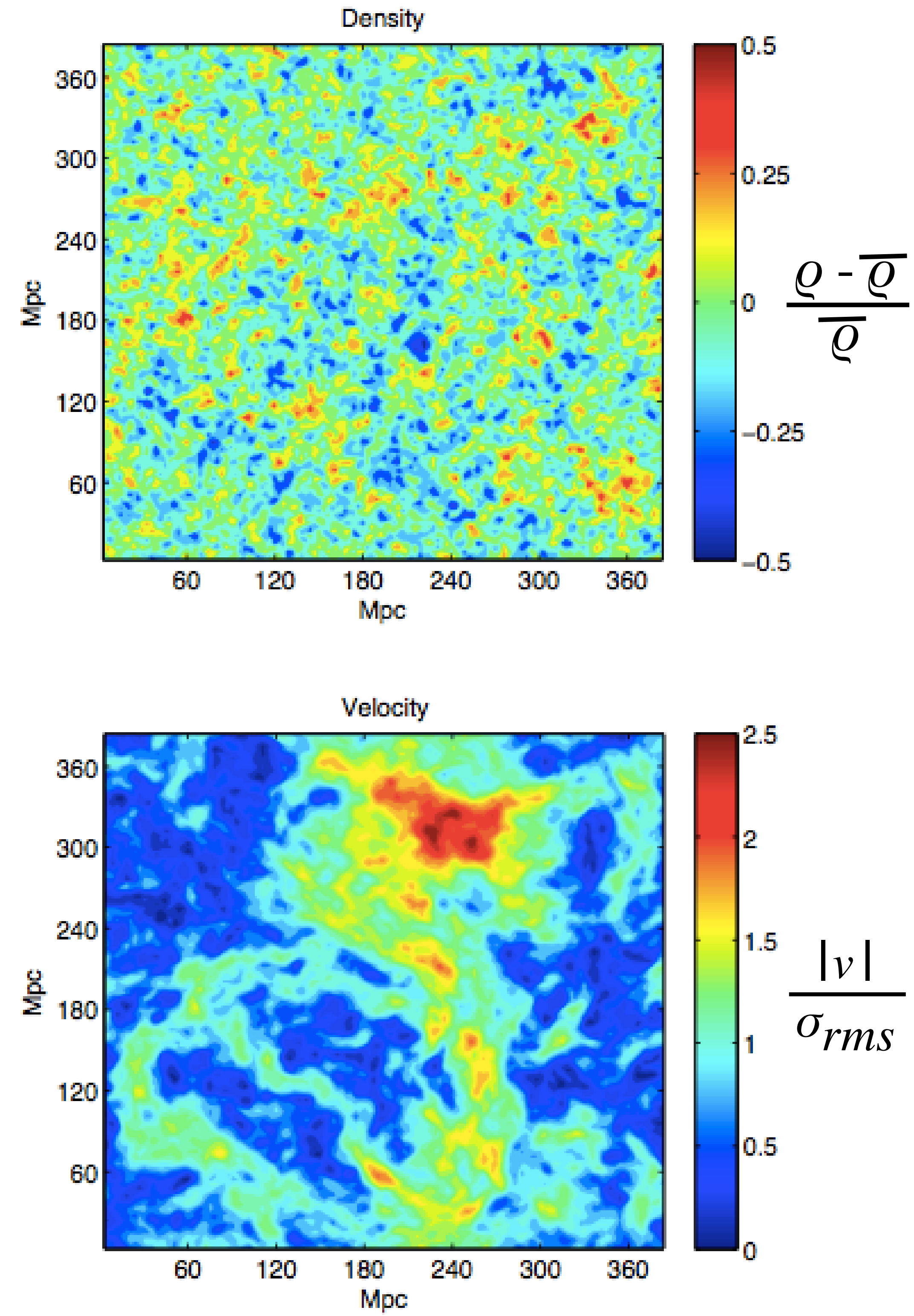


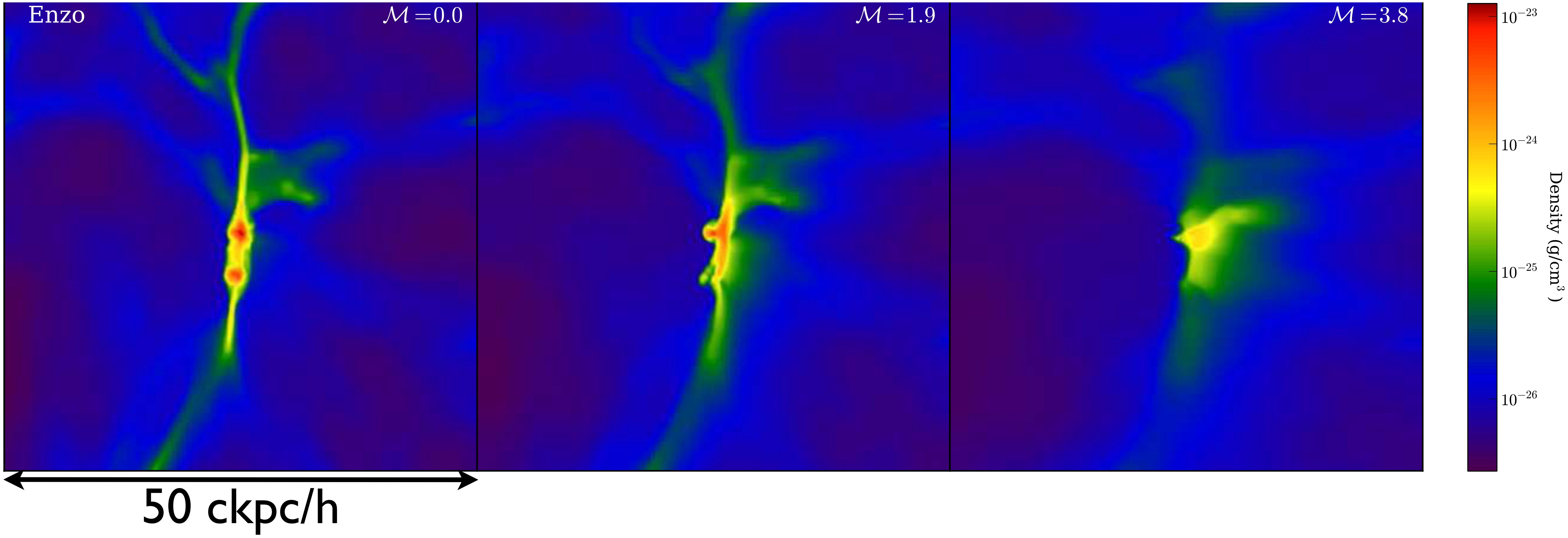
Tseliakhovich & Hirata 10



z=20, Fialkov+ 13

Effects of streaming velocities

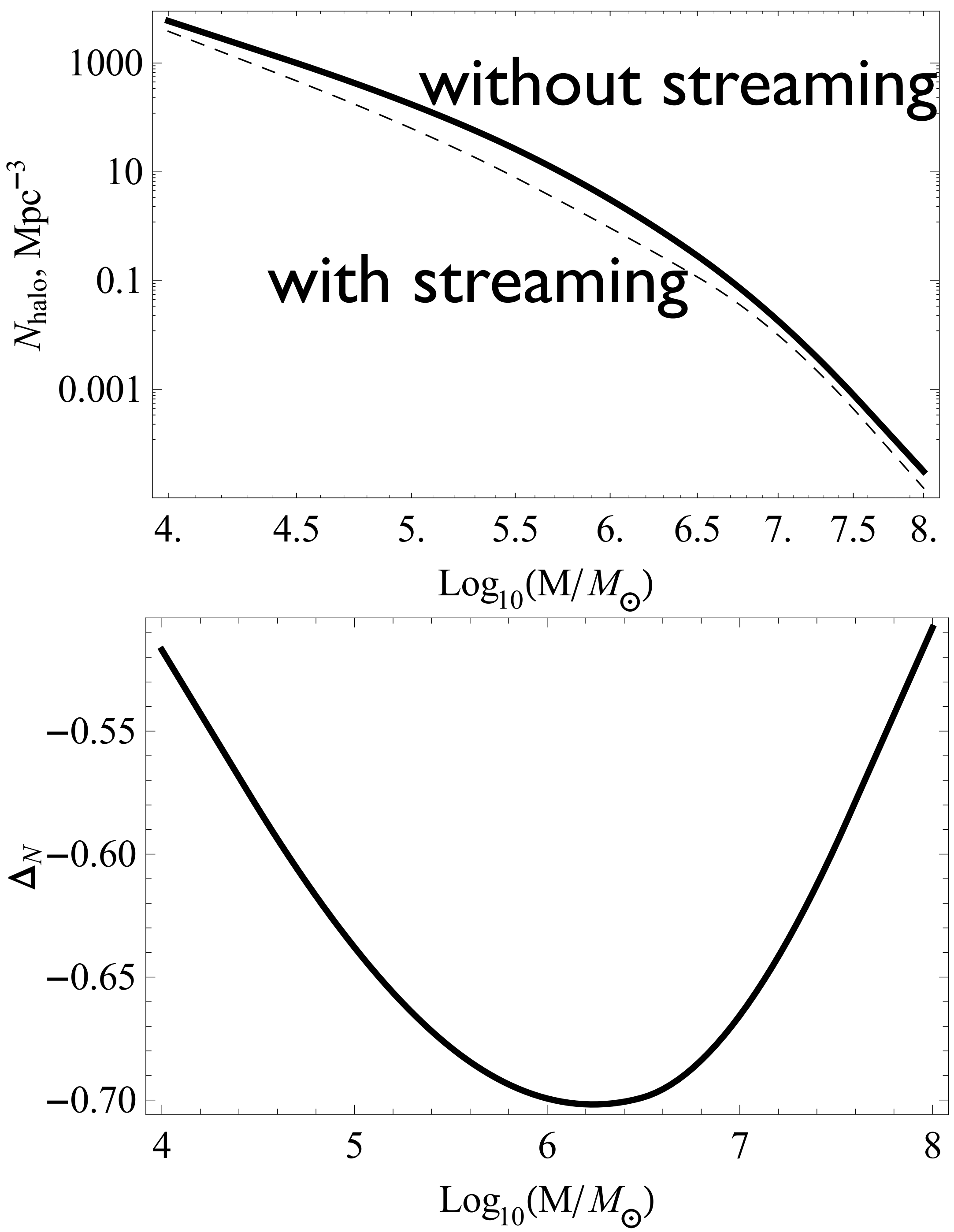
Minihalo at z = 20, M = 8 x 10^5 $M_\odot$



O'Leary & McQuinn 2012

Decrease in halo mass function

- prediction from a Press-Schechter formalism



Tseliakhovich & Hirata 2010

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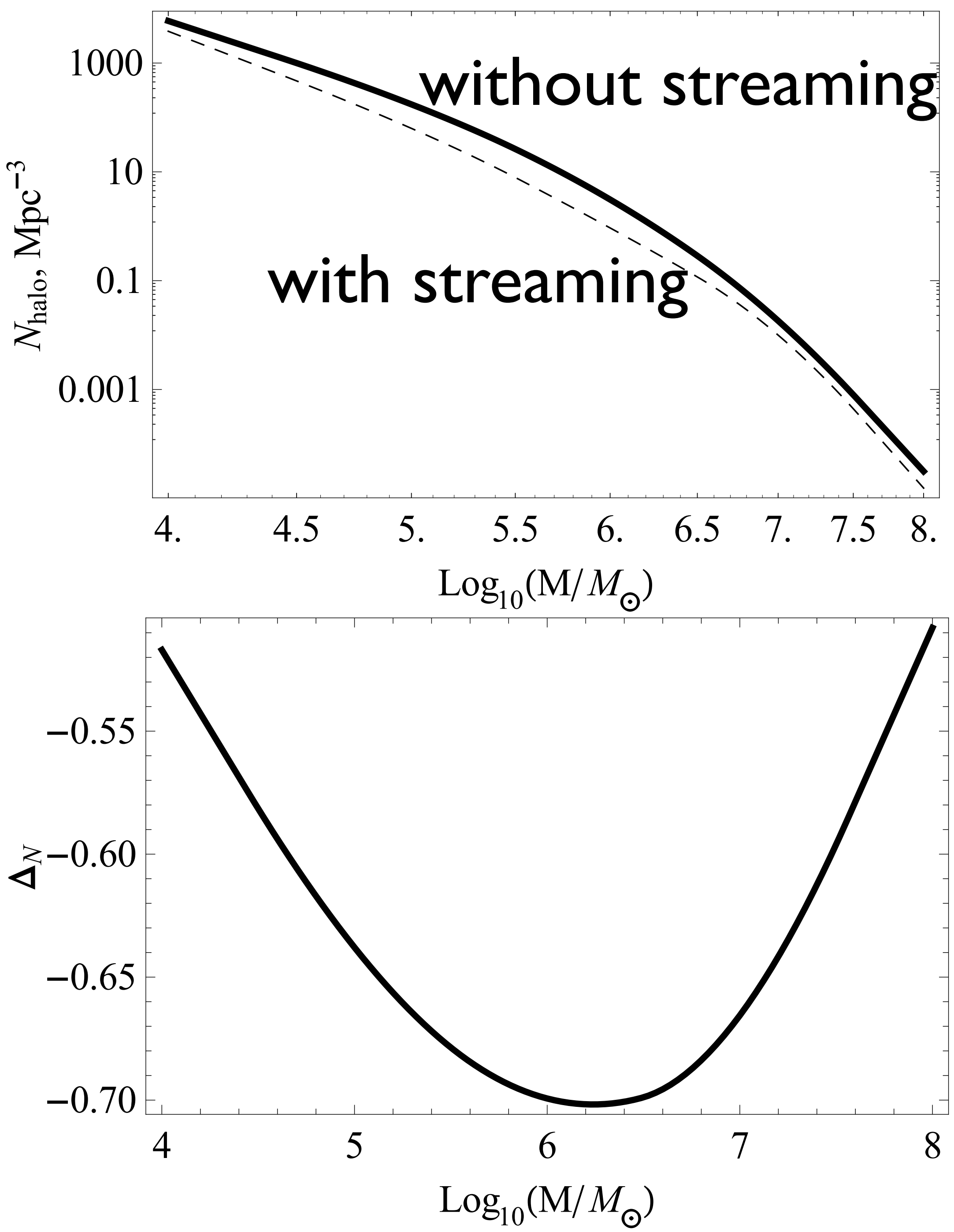
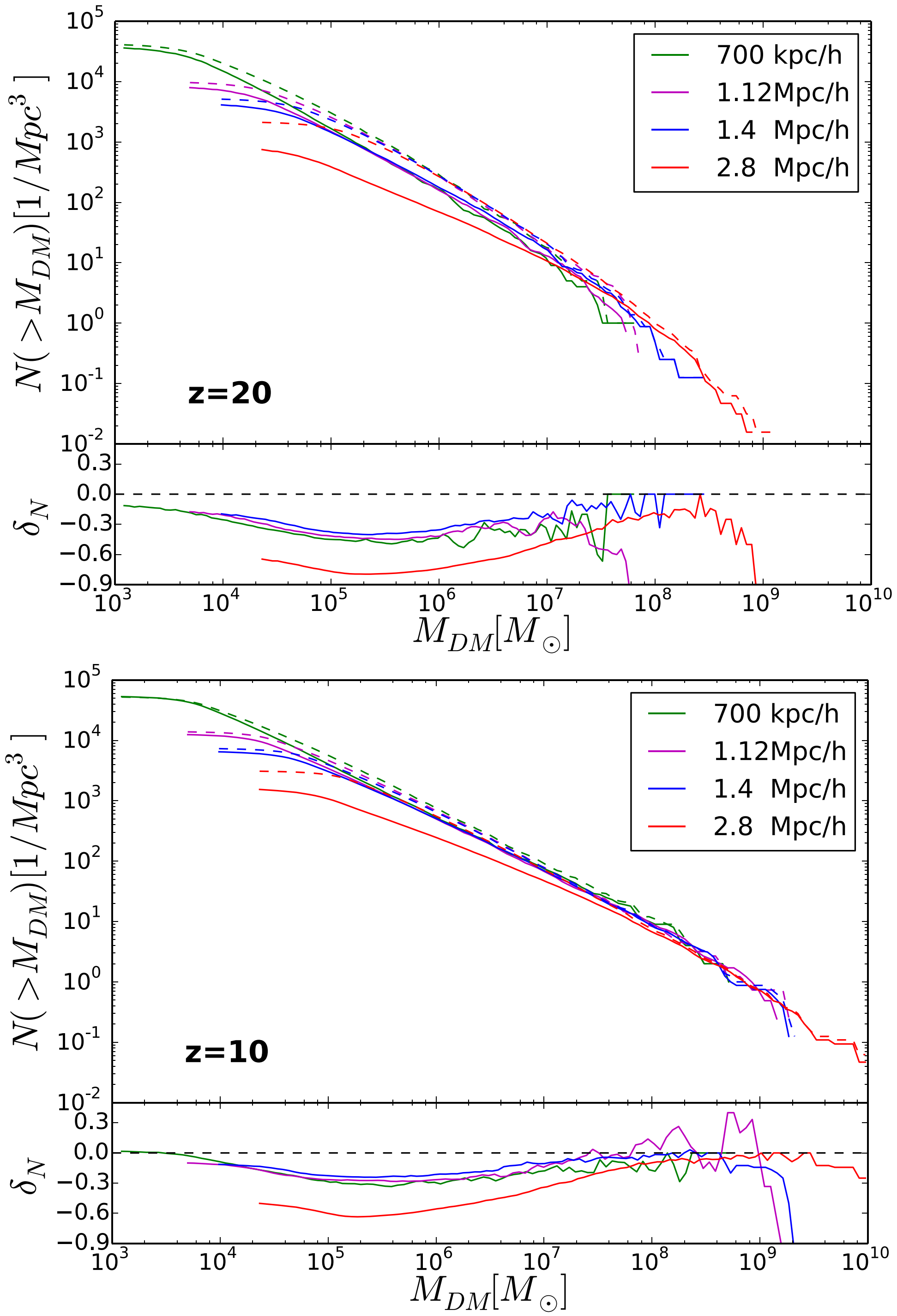


Tseliakhovich & Hirata 2010

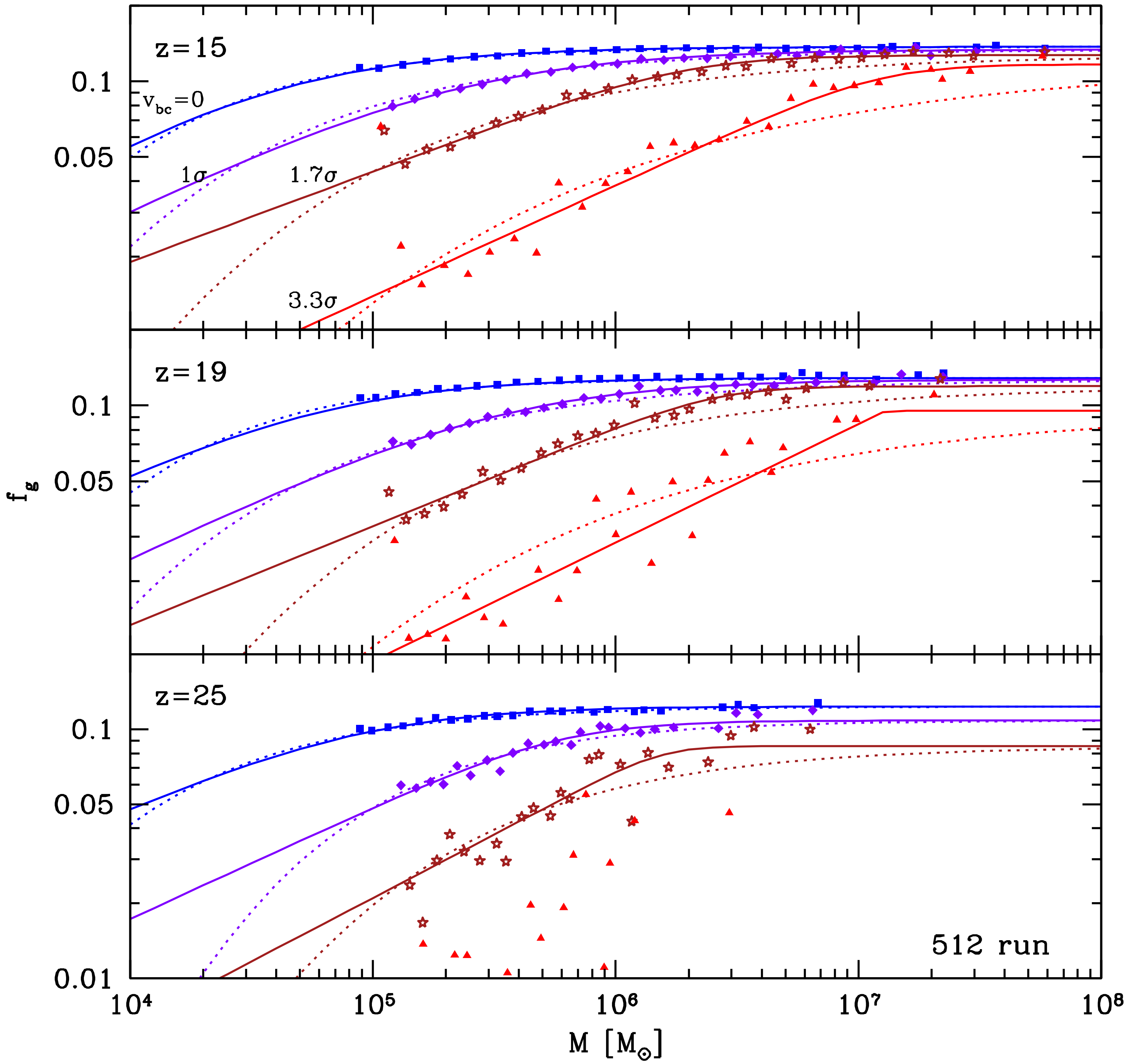
- numerical simulation



Popa+ 2016

Decrease in baryon fraction

- simulations with gas, but no chemistry



Naoz et al. 2013

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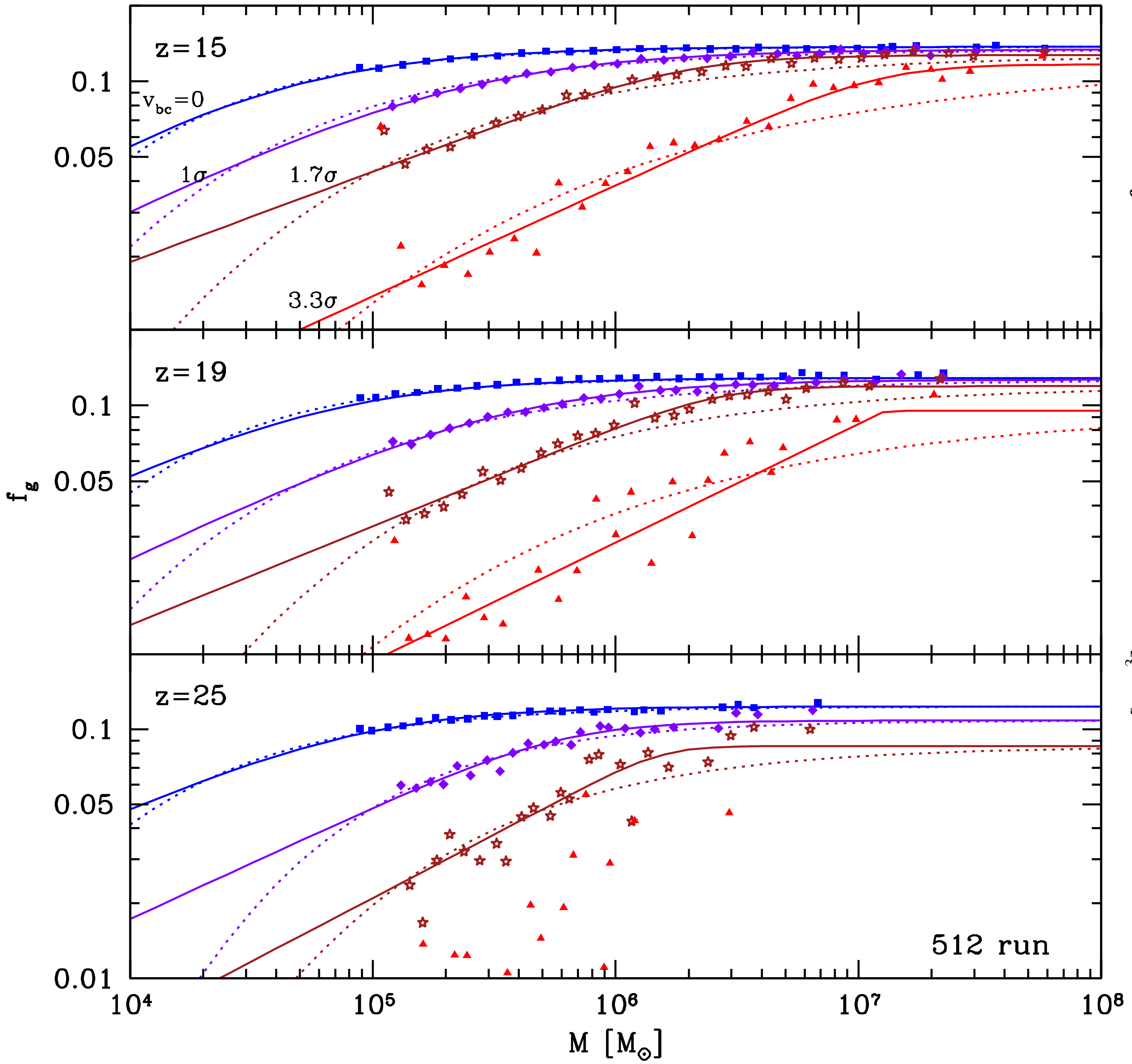
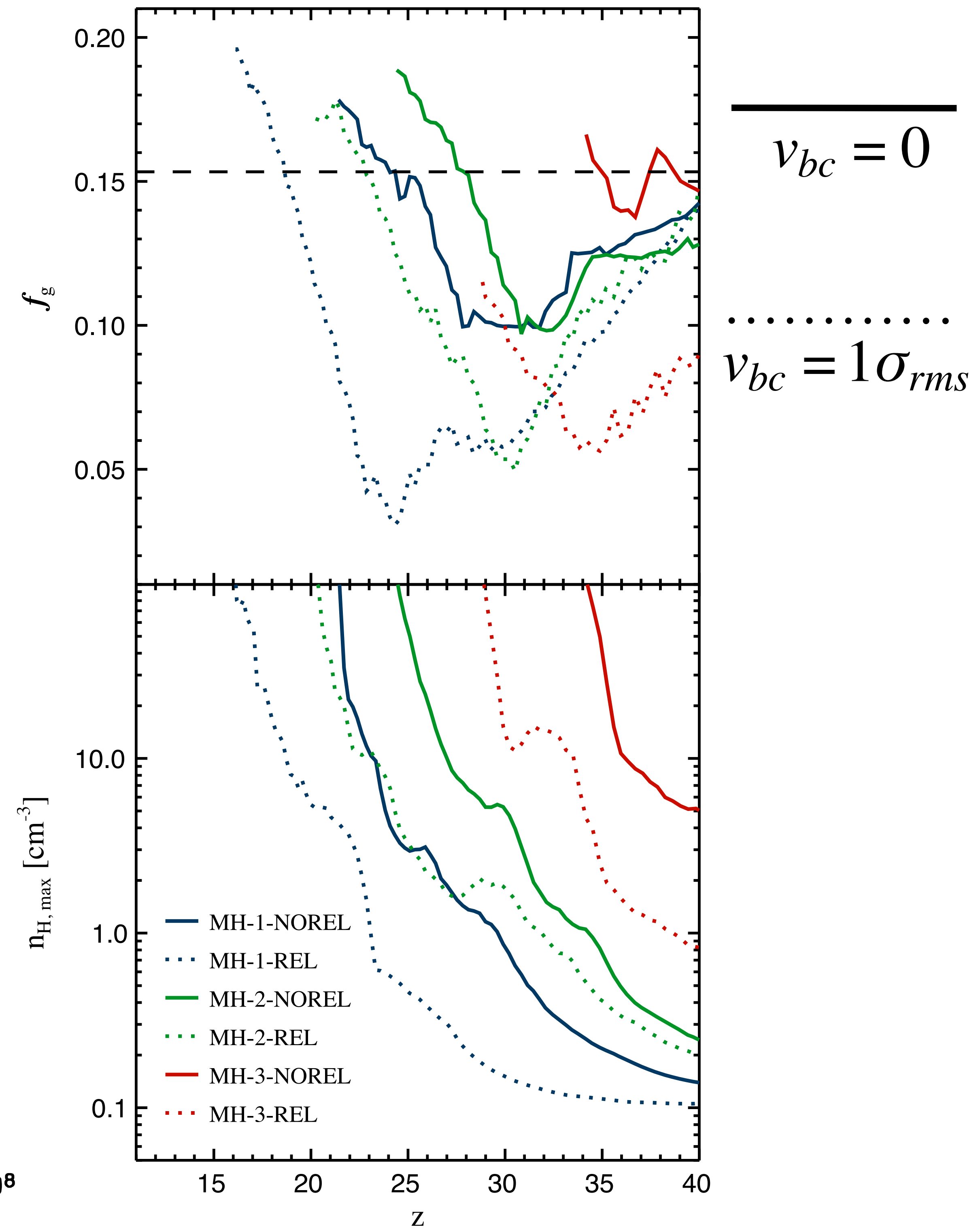


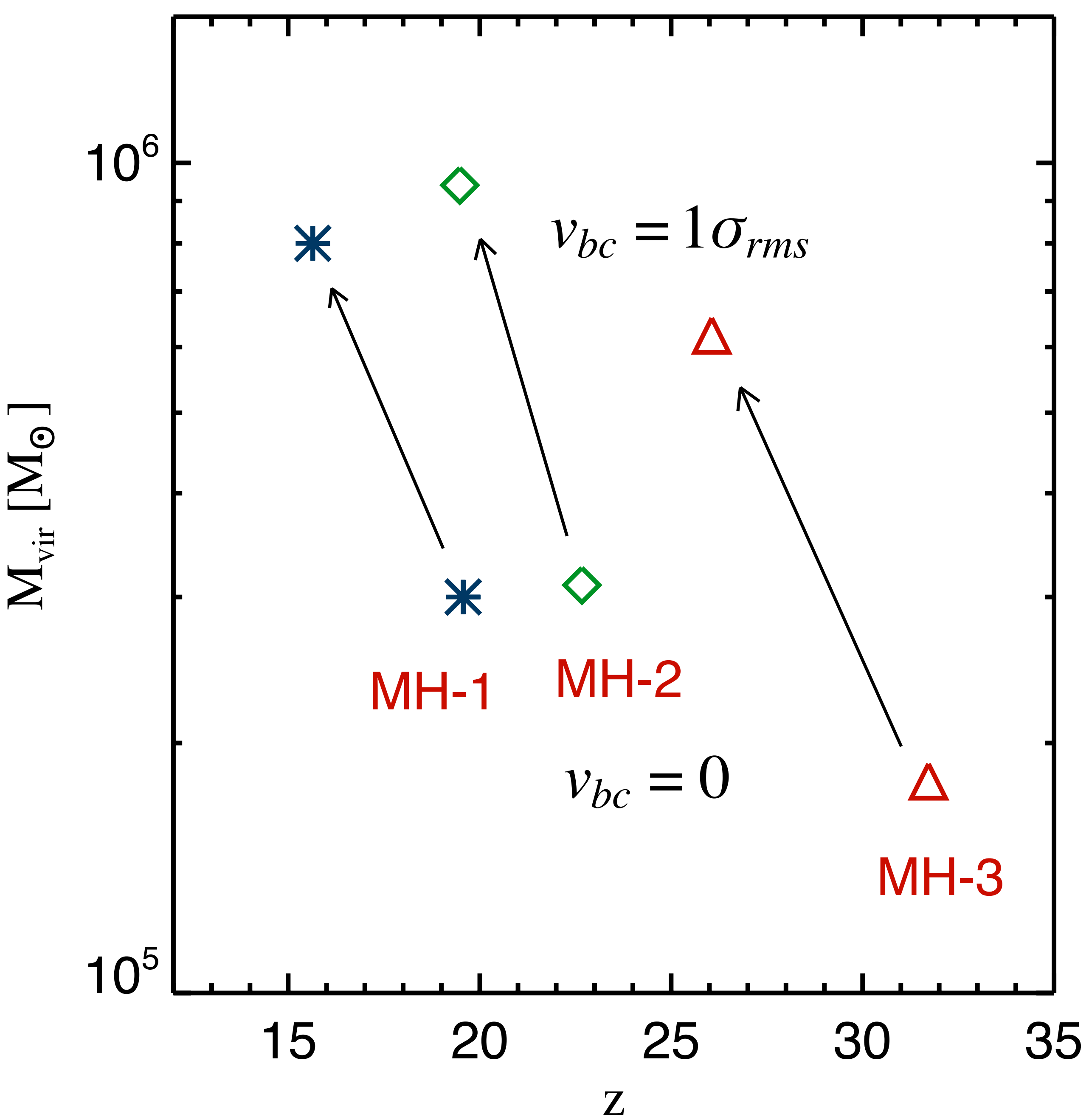
Naoz et al. 2013

- full hydrodynamics & chemistry



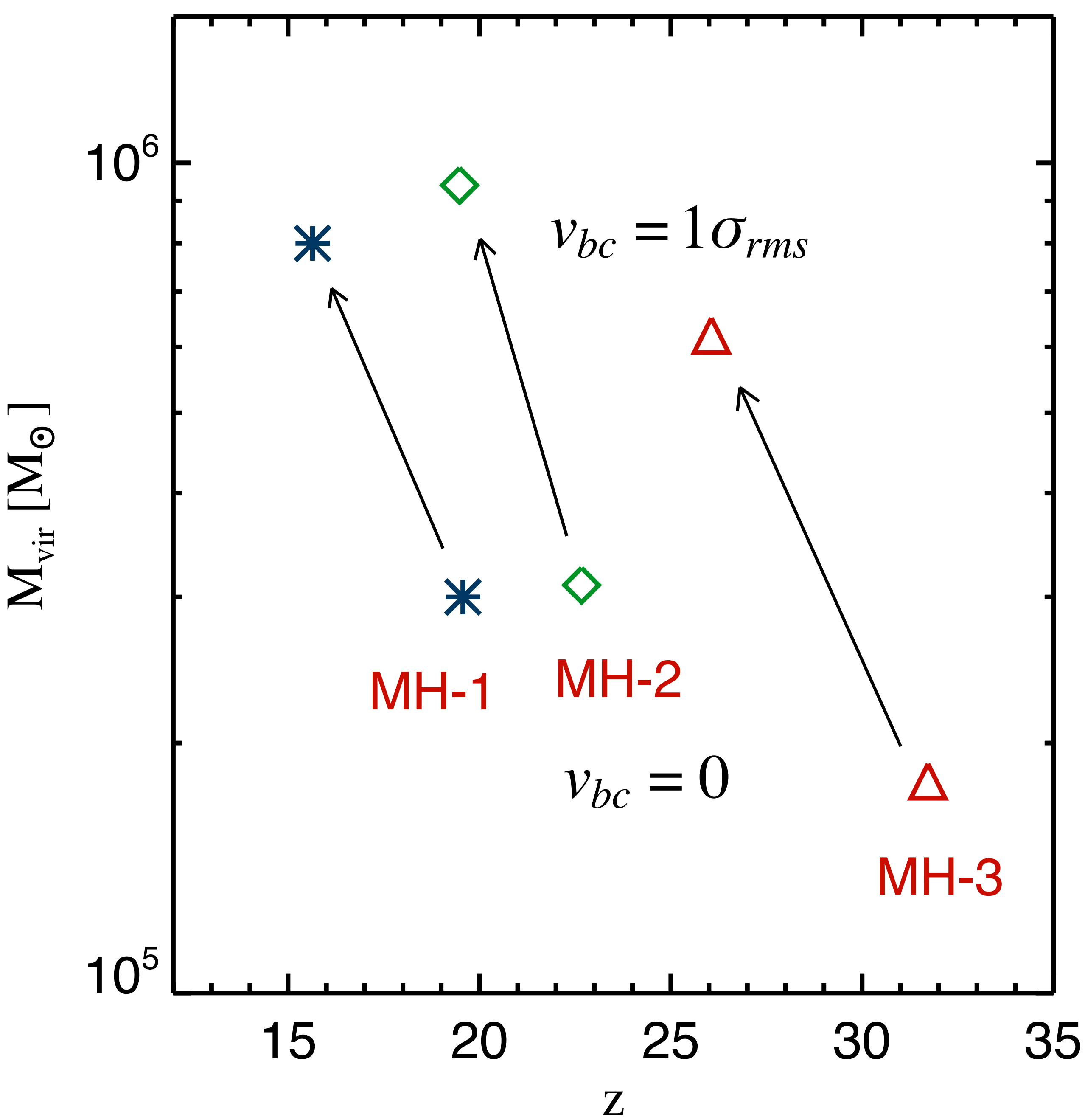
Greif et al. 2011

Increase in halo mass + SF delay

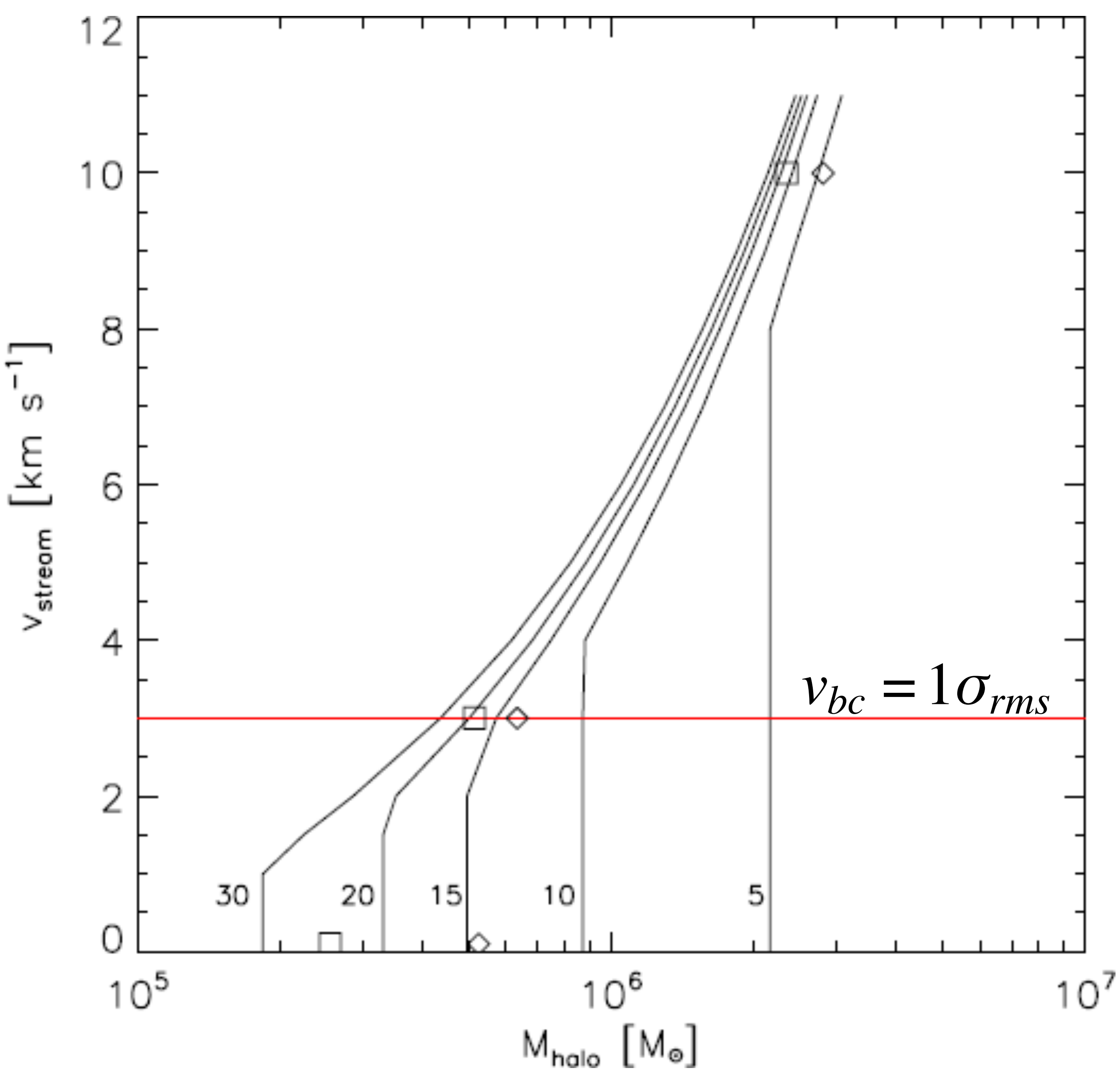


Greif+11

Increase in halo mass + SF delay



Greif+11



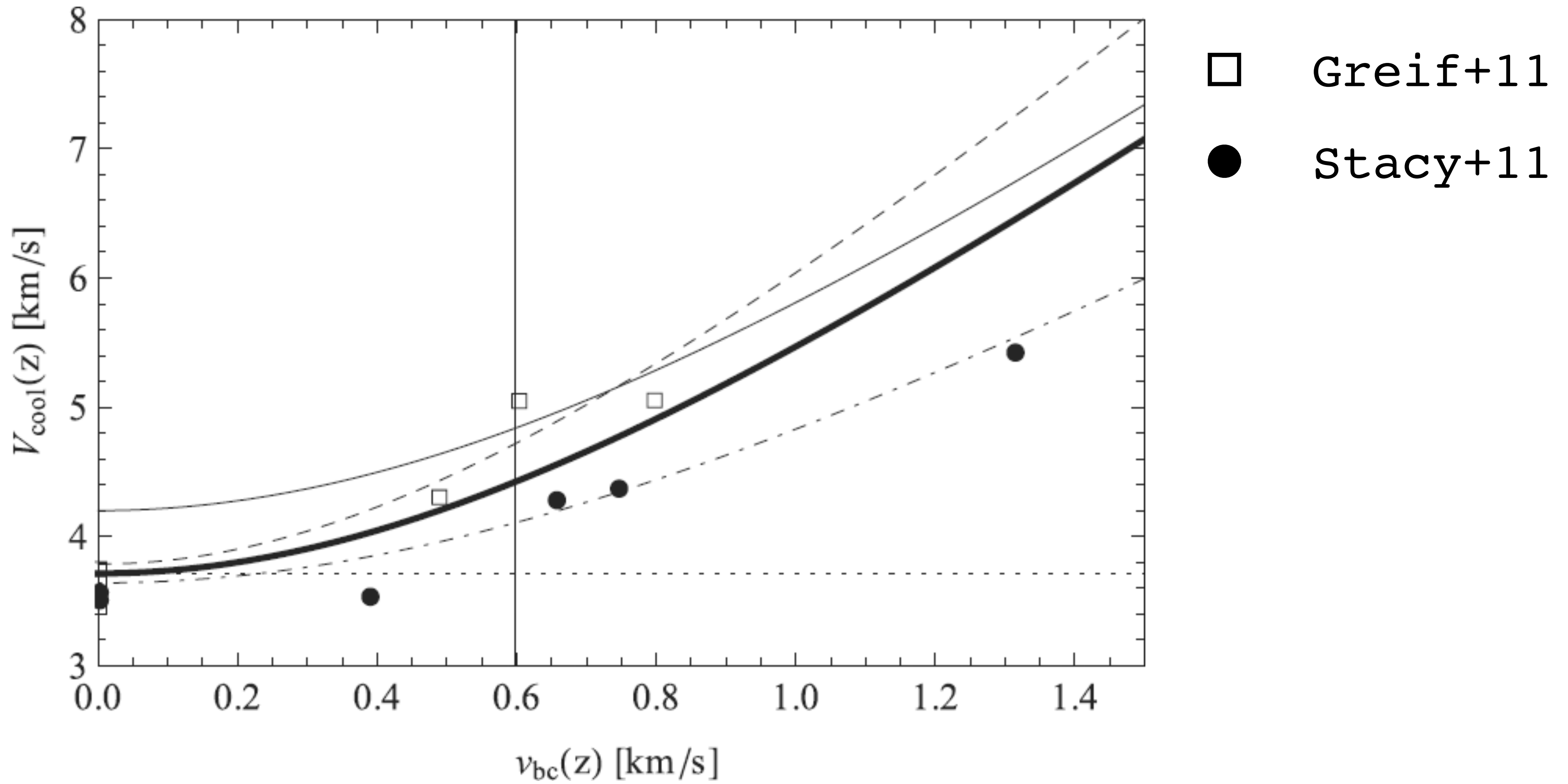
Stacy+11

Increase in halo mass + SF delay

- quantification of the halo mass by its circular velocity: $v_{circ,0} = \sqrt{\frac{G\,M_{vir}}{R_{vir}}}$

- modification of circular velocity with streaming velocity:

$v_{circ} = \sqrt{[\alpha\, v_{bc}]^2 + v_{circ,0}^2}$ with $\alpha = 4.015$ and $v_{circ,0} = 3.714$ km s^{-1} (fitted)



Fialkov+12

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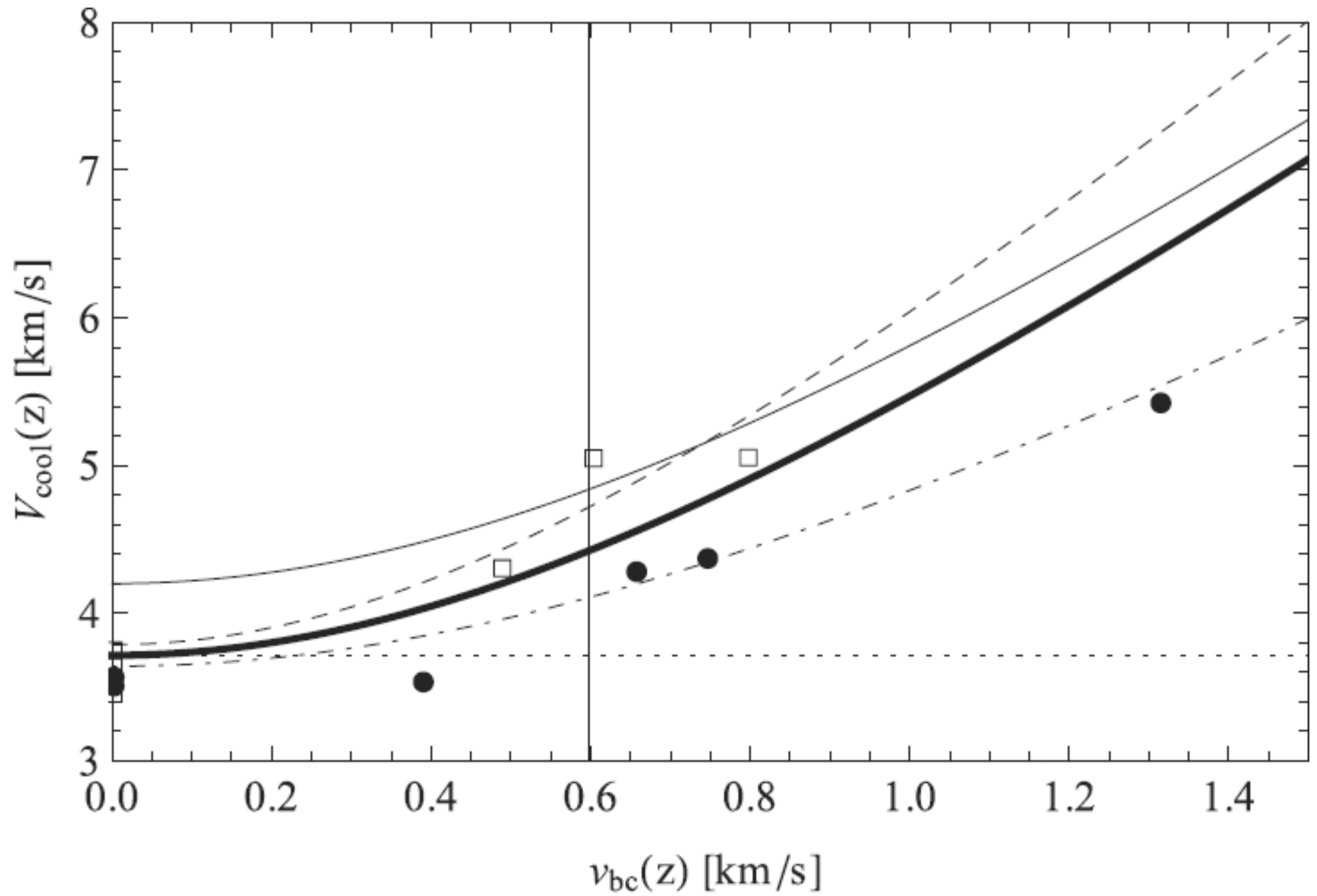
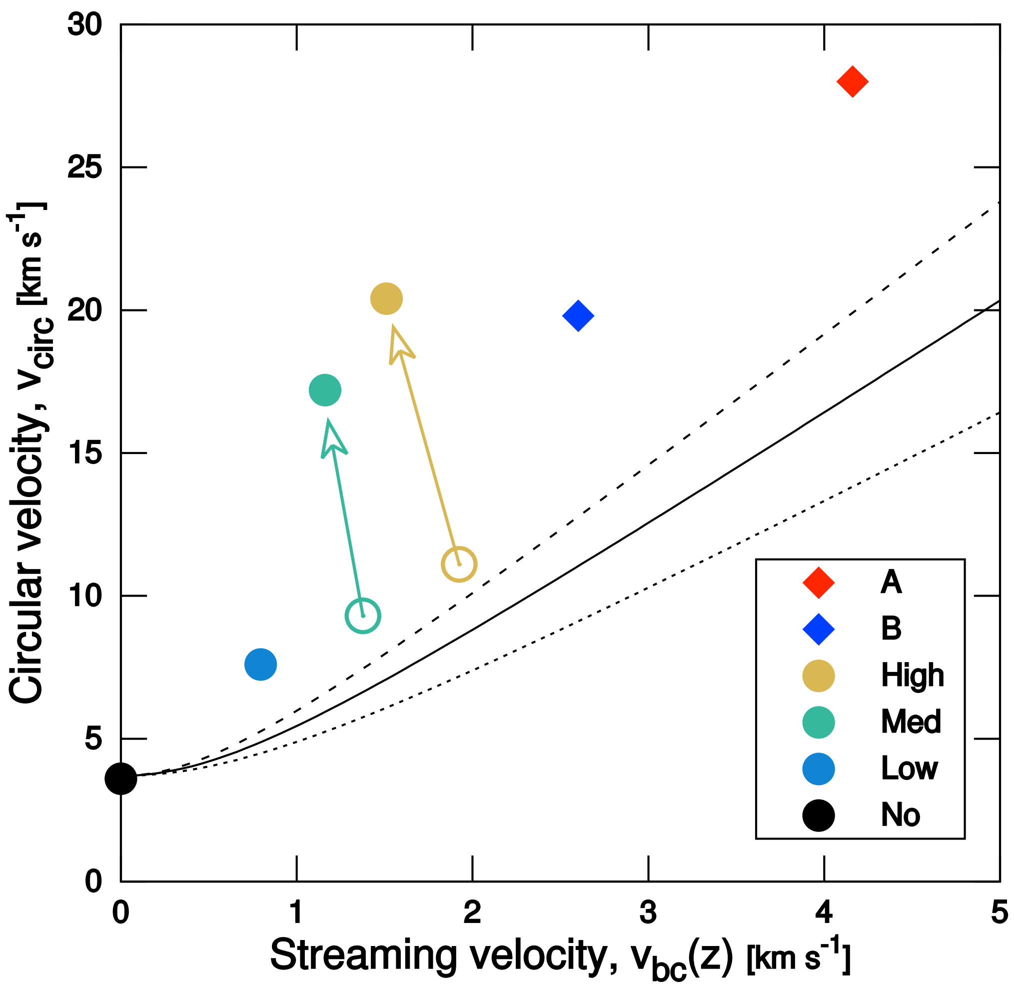


Fialkov+12



Hirano+18

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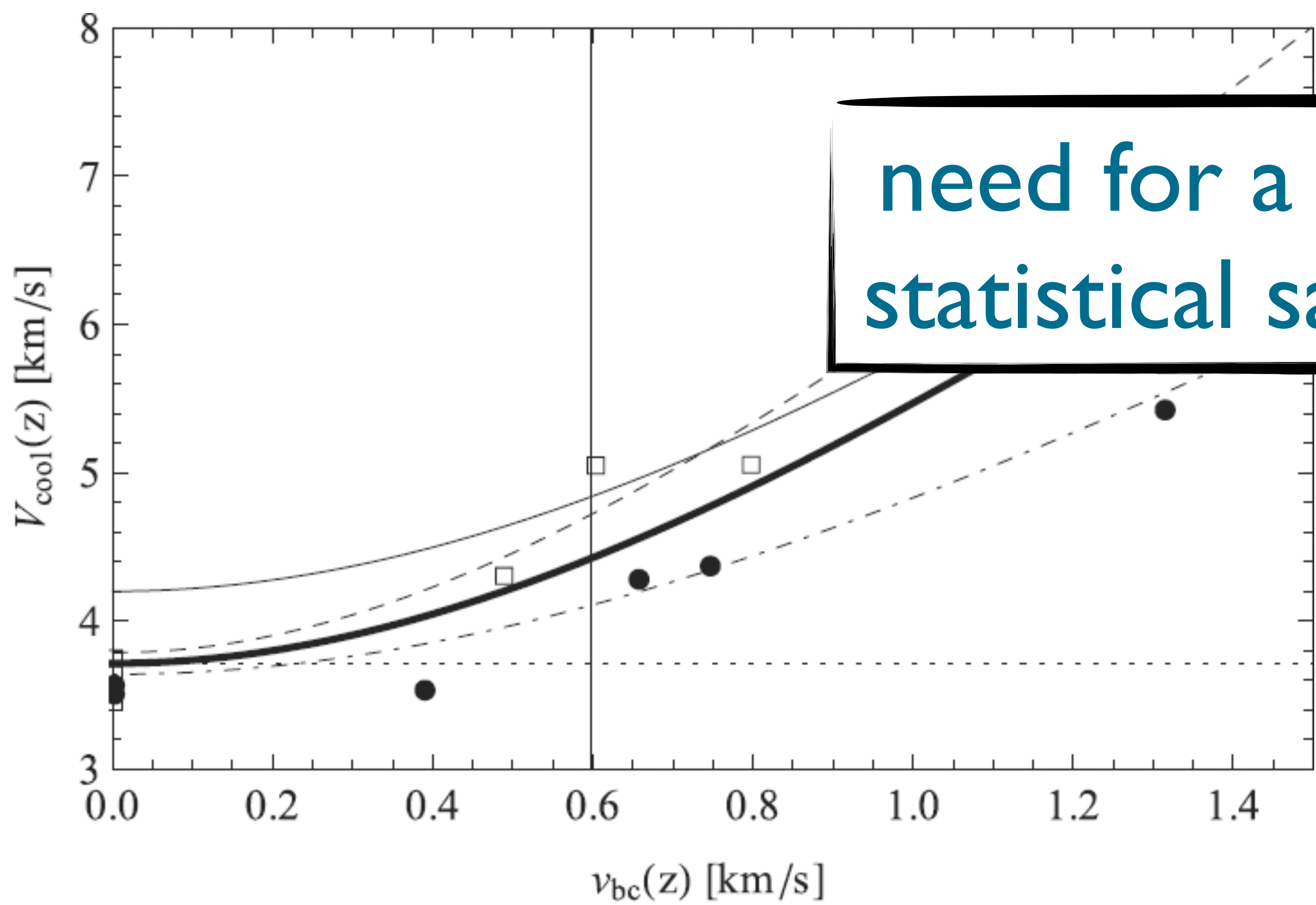
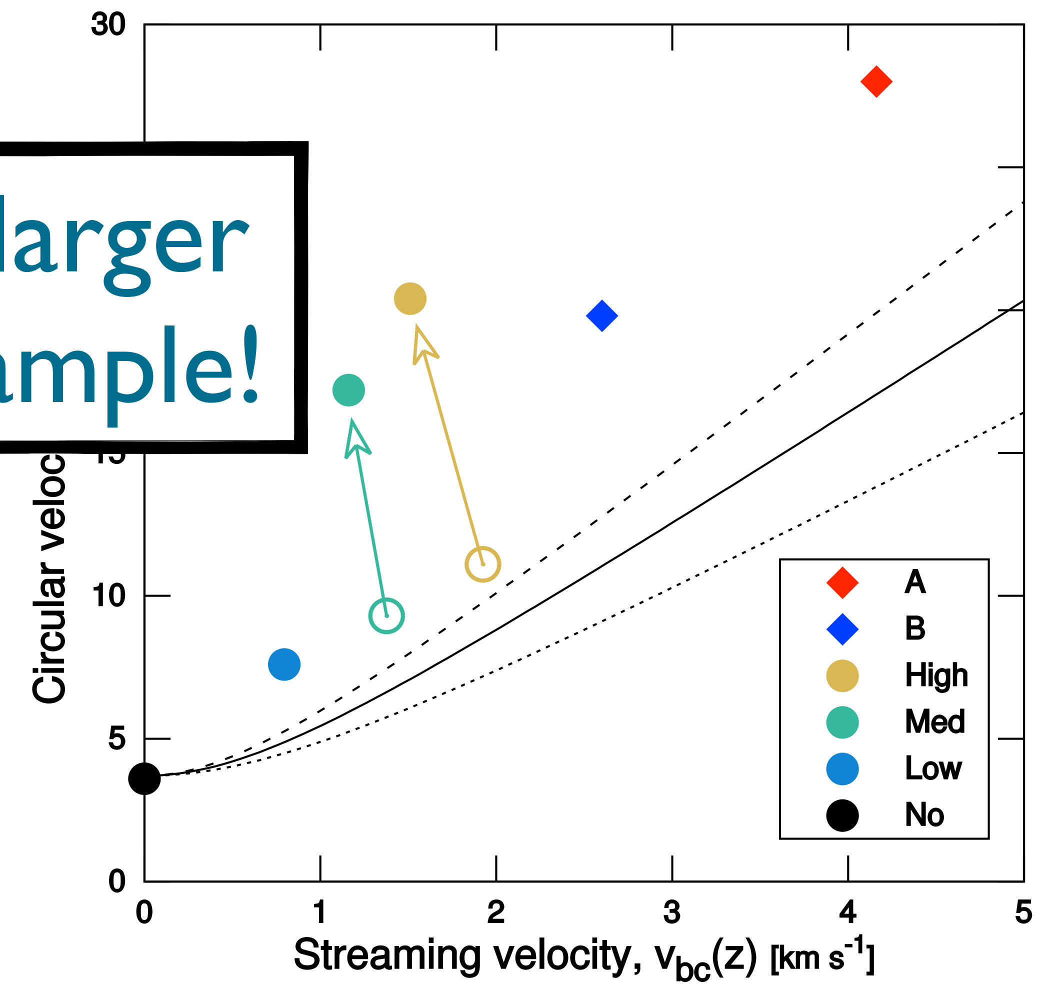


Fialkov+12

need for a larger statistical sample!



Hirano+18

Our simulations

redshift range: $z = 200 \rightarrow 14$

box size: $(1\ cMpc/h)^3$

DM particles / gas cells:

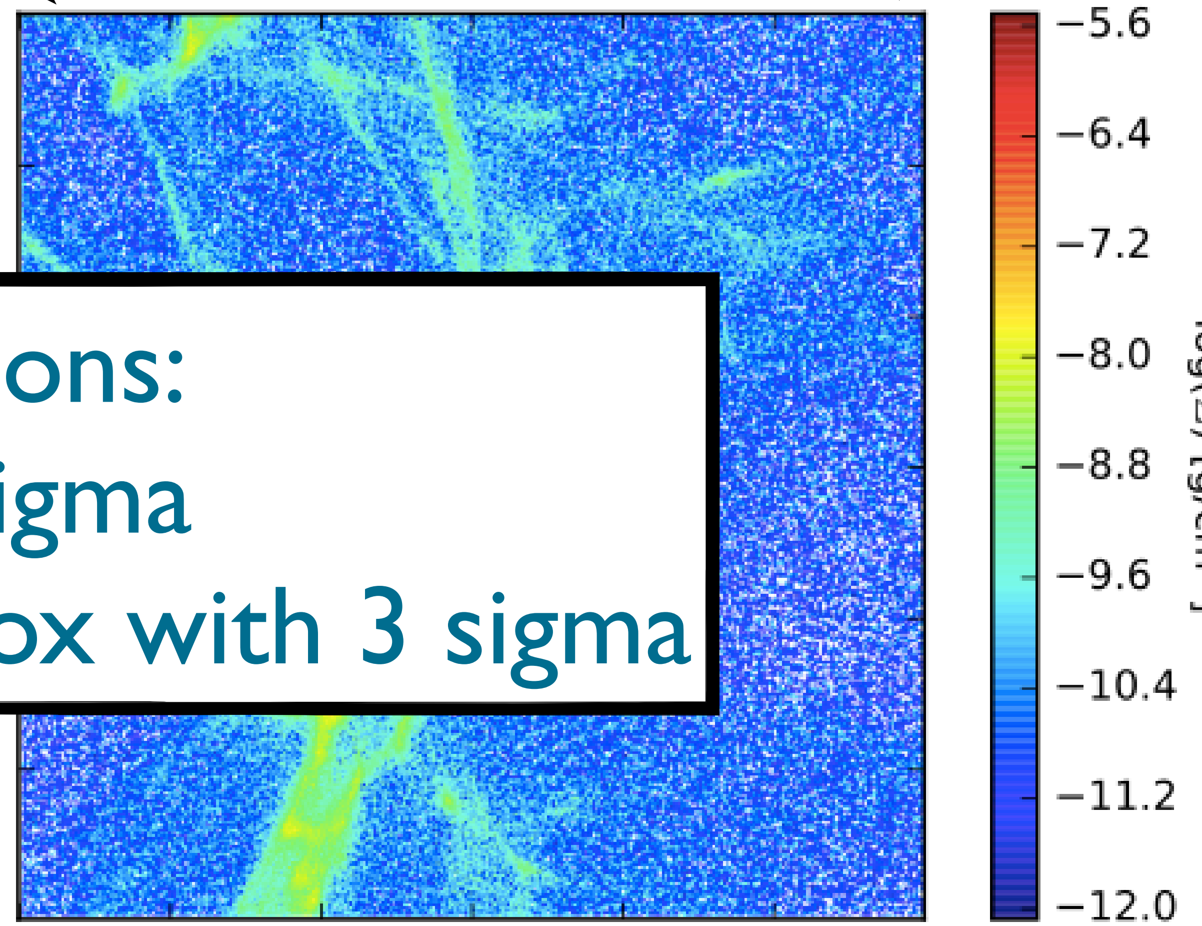
mass resolu…

… $M_\odot$ (DM)

smoothing length: 20 pc/h (2 pc at z=15)

5 simulations:
0, 1, 2, 3 sigma
one large 4cMpc/h box with 3 sigma

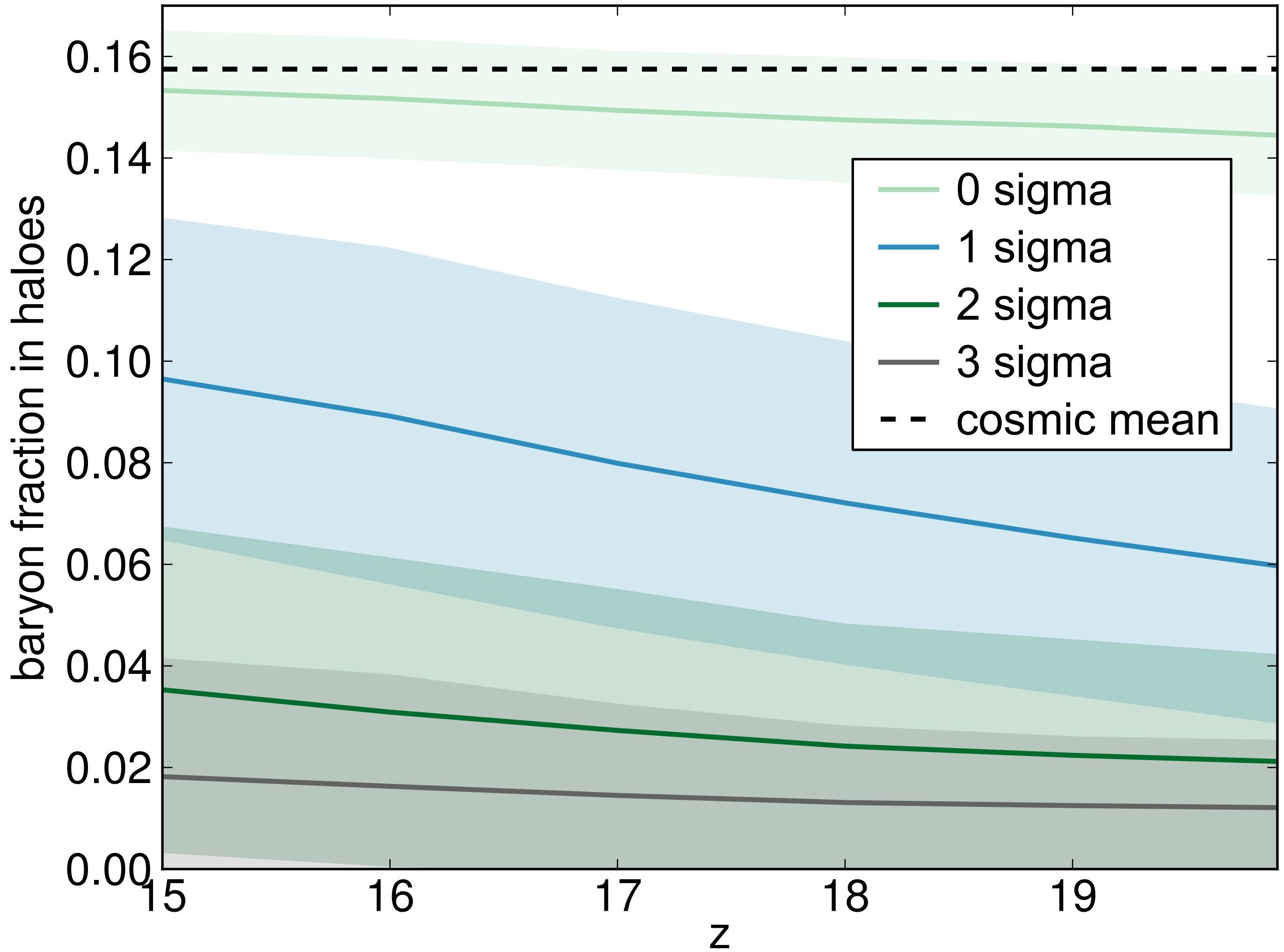
Fraction of the box:
50 com. kpc/h



gas projection at z=15

Picture from Bachelor Thesis of Maik Druschke

minihaloes with streaming velocity

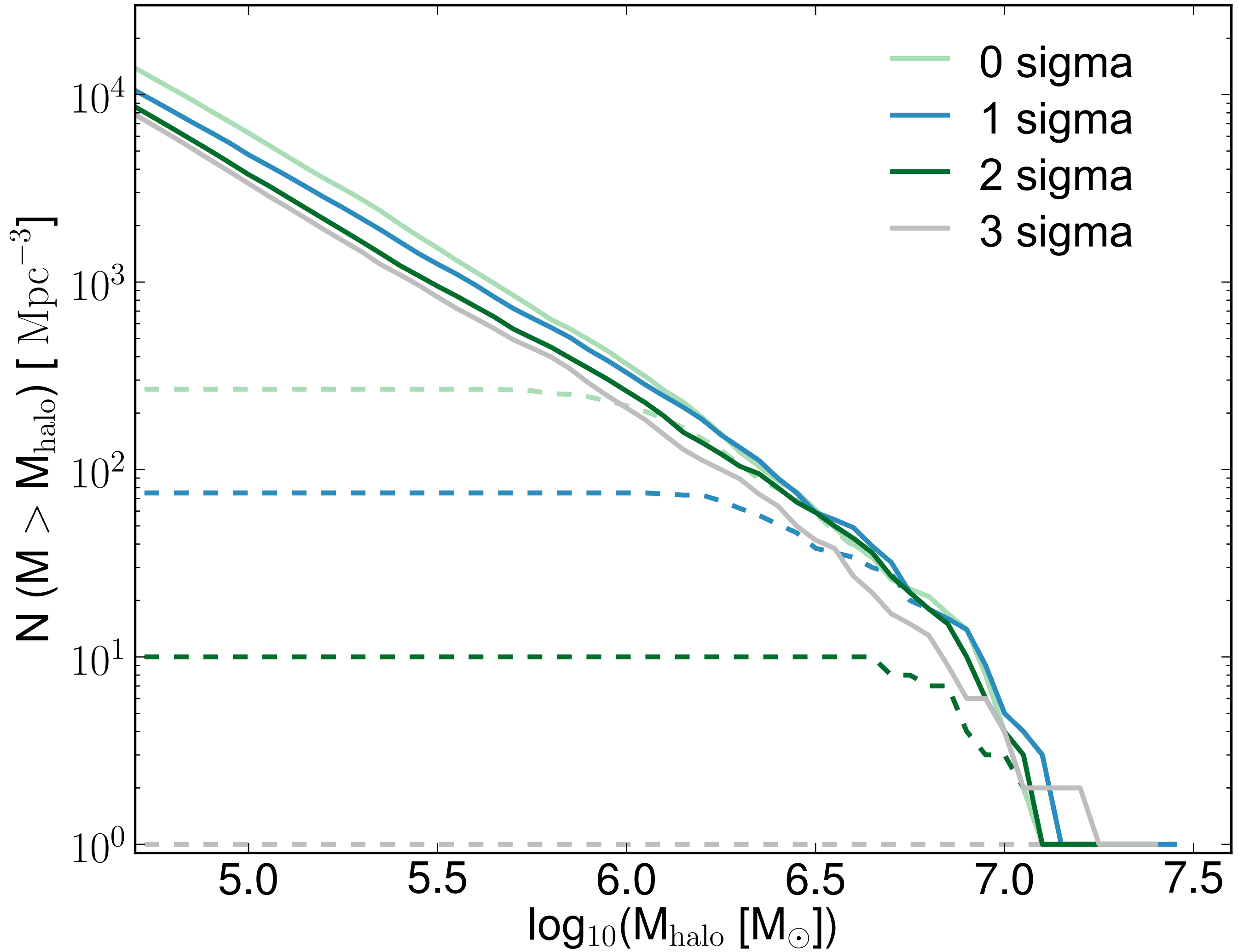


baryon fraction:

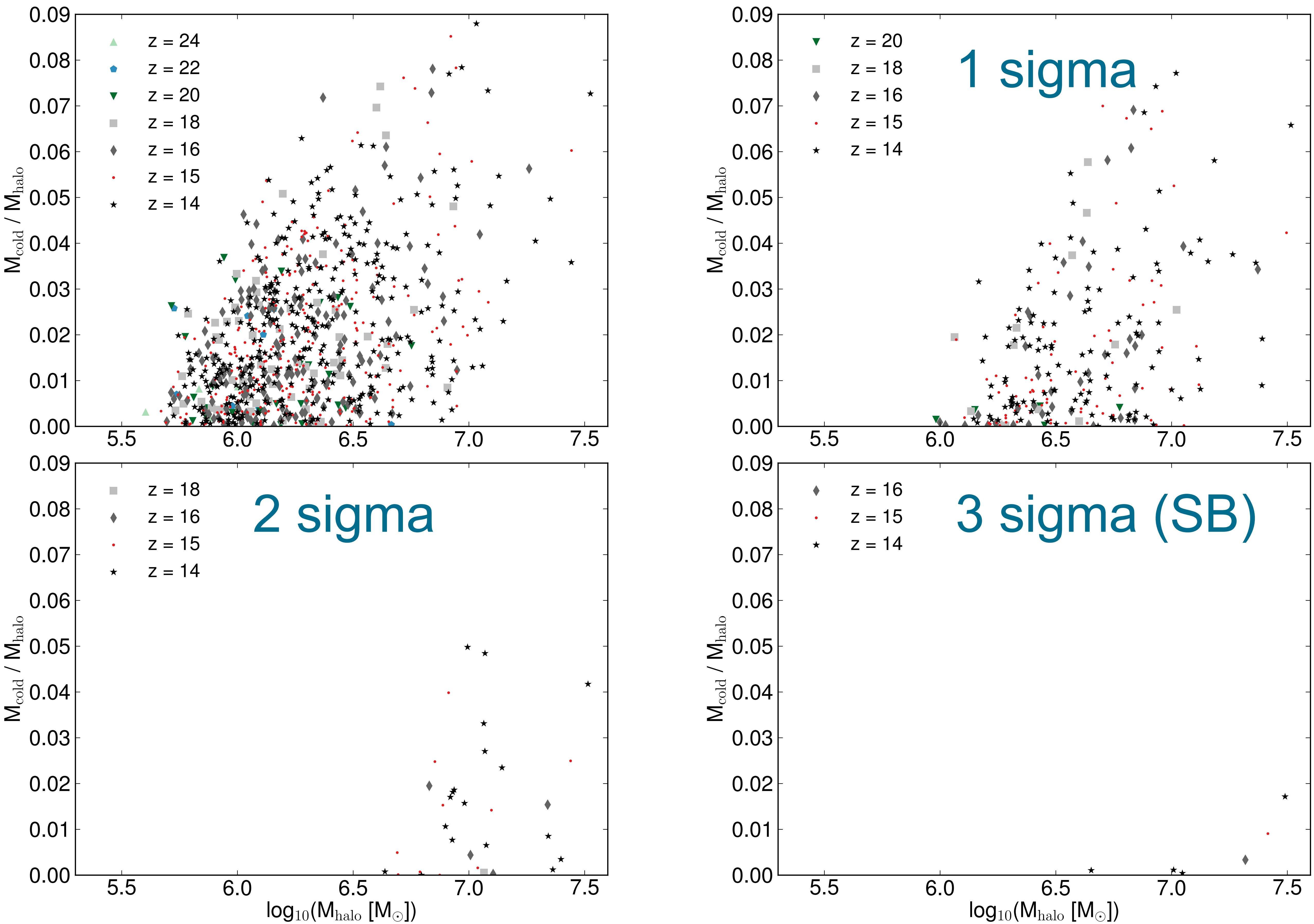
- increases with redshift
- for streaming velocities: far below cosmic mean

halo mass function:

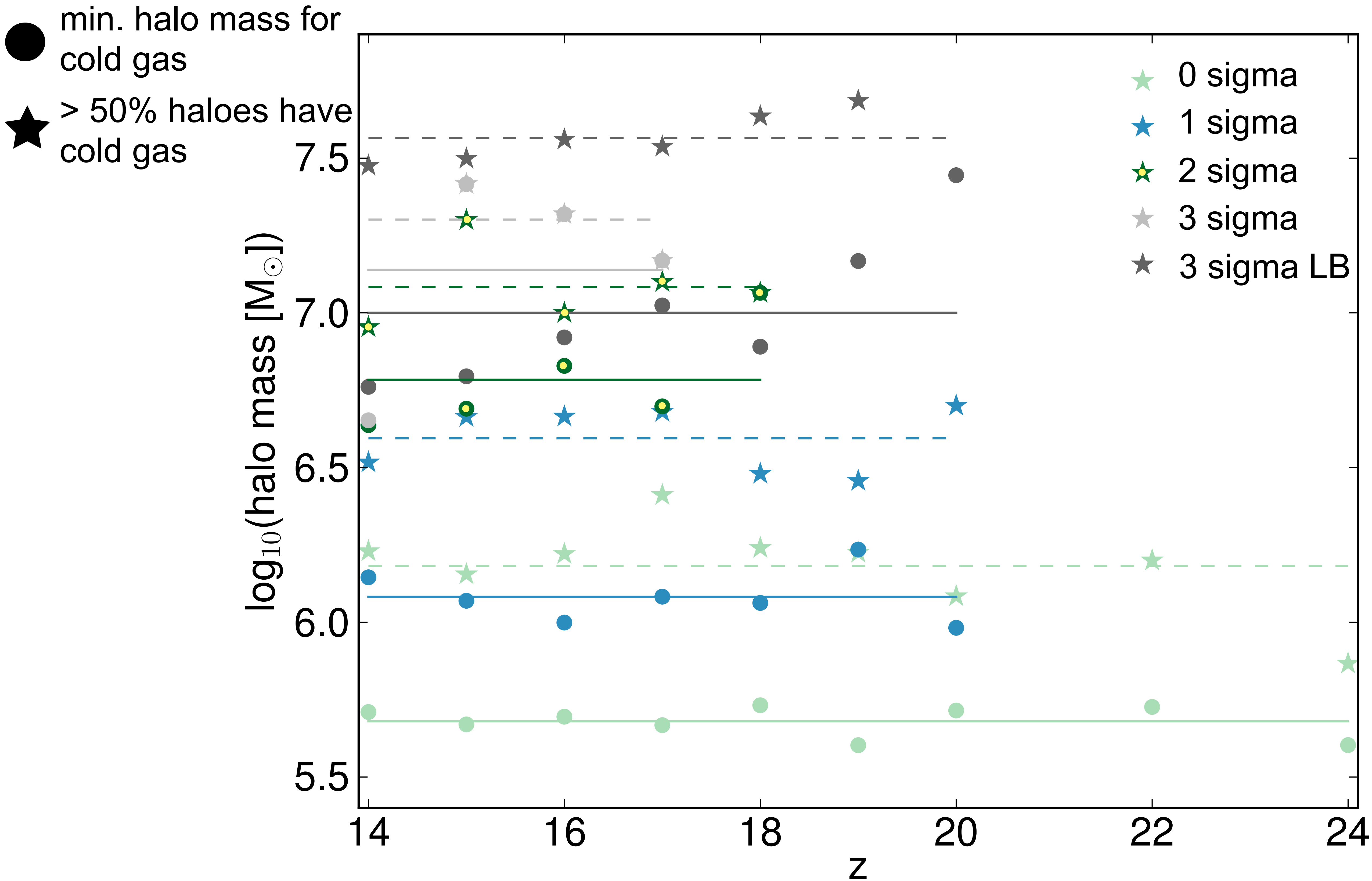
- number density decreases with streaming velocity



cold mass - halo mass: streaming



halo masses of cold halos: streaming



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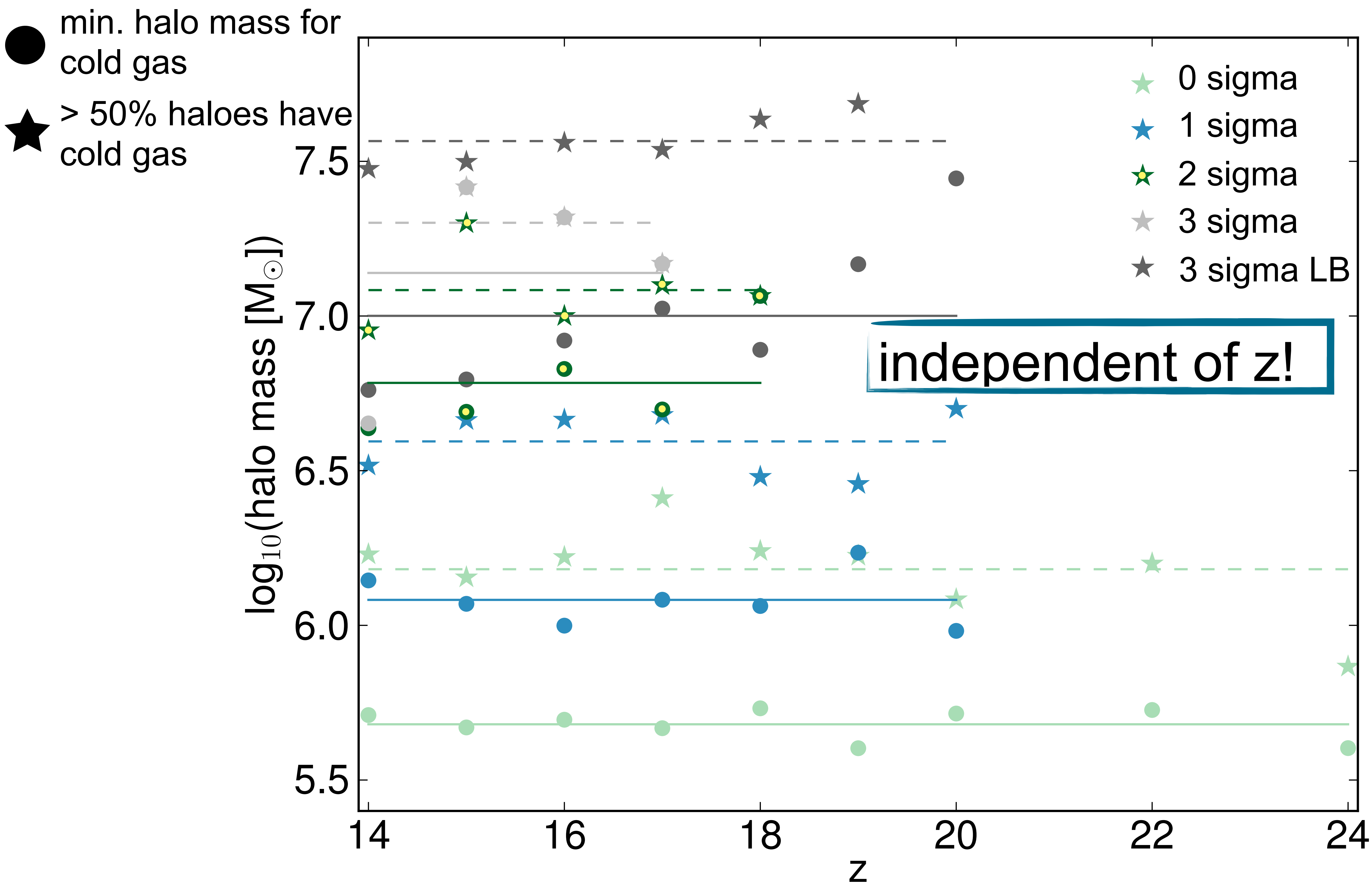

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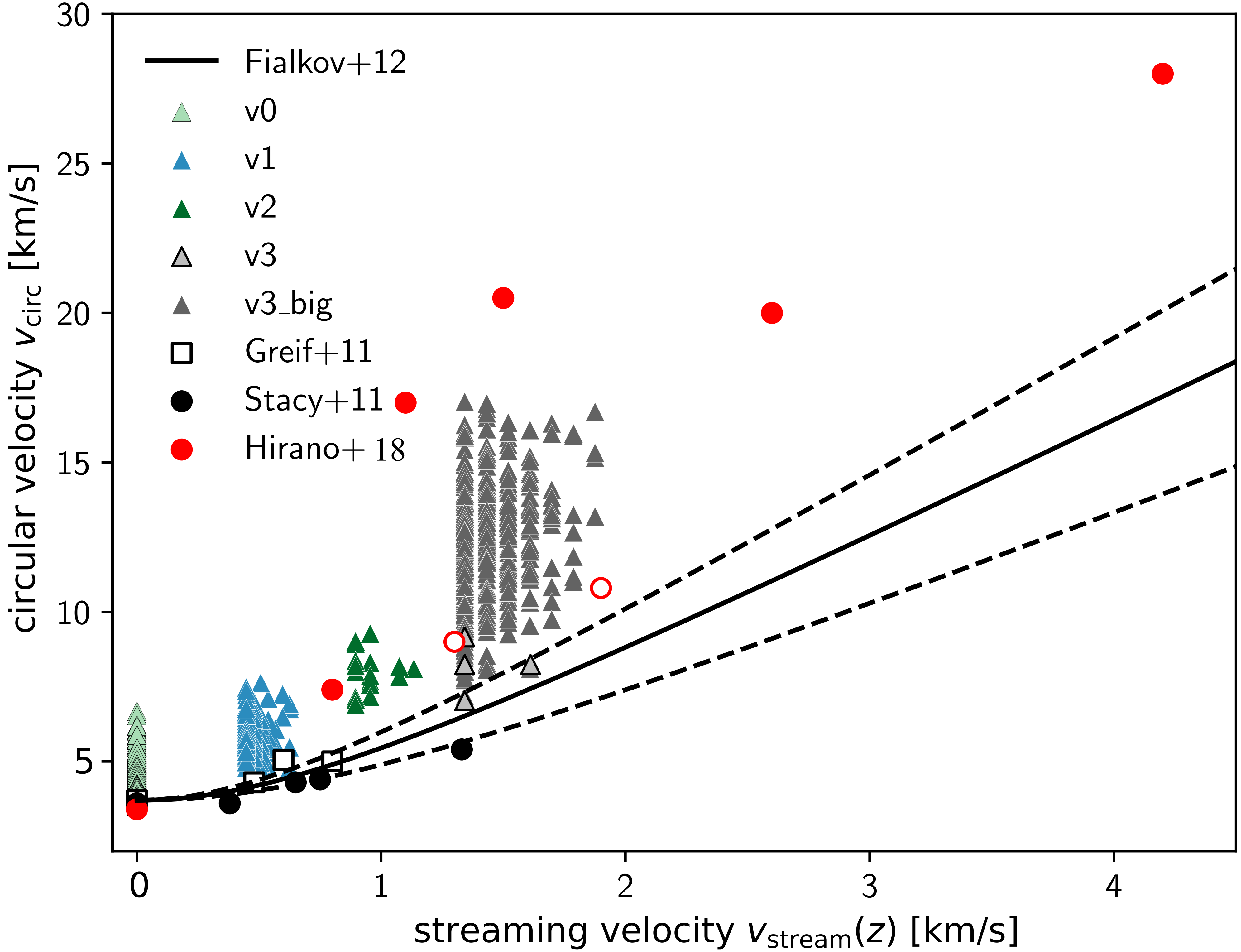
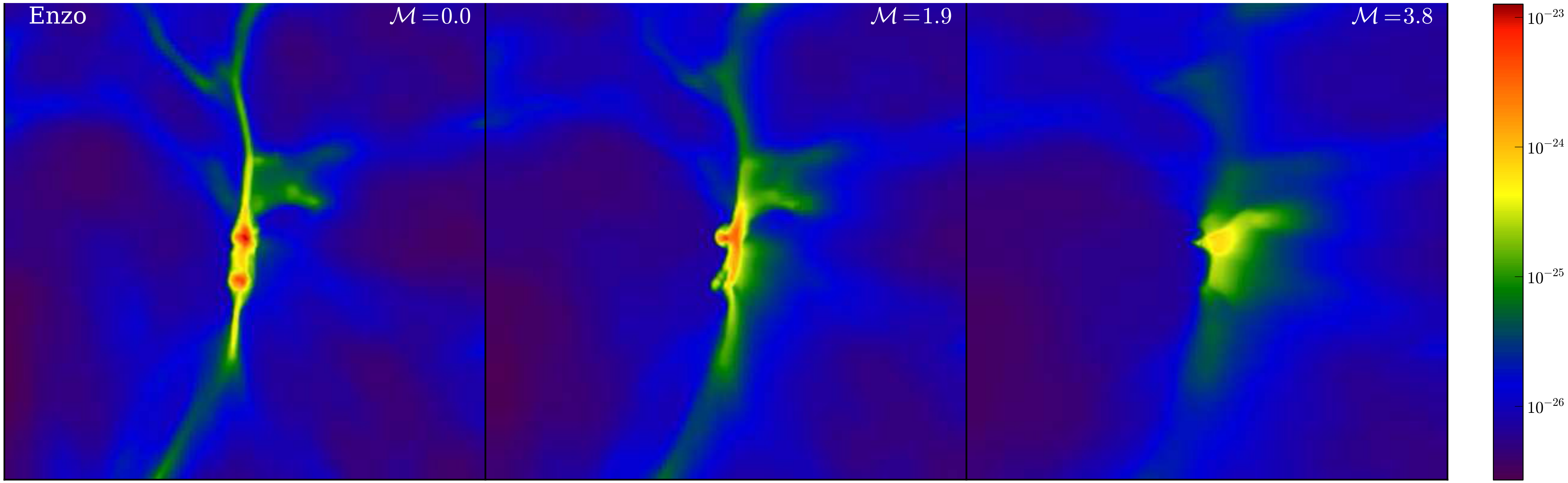


Effects of streaming velocities

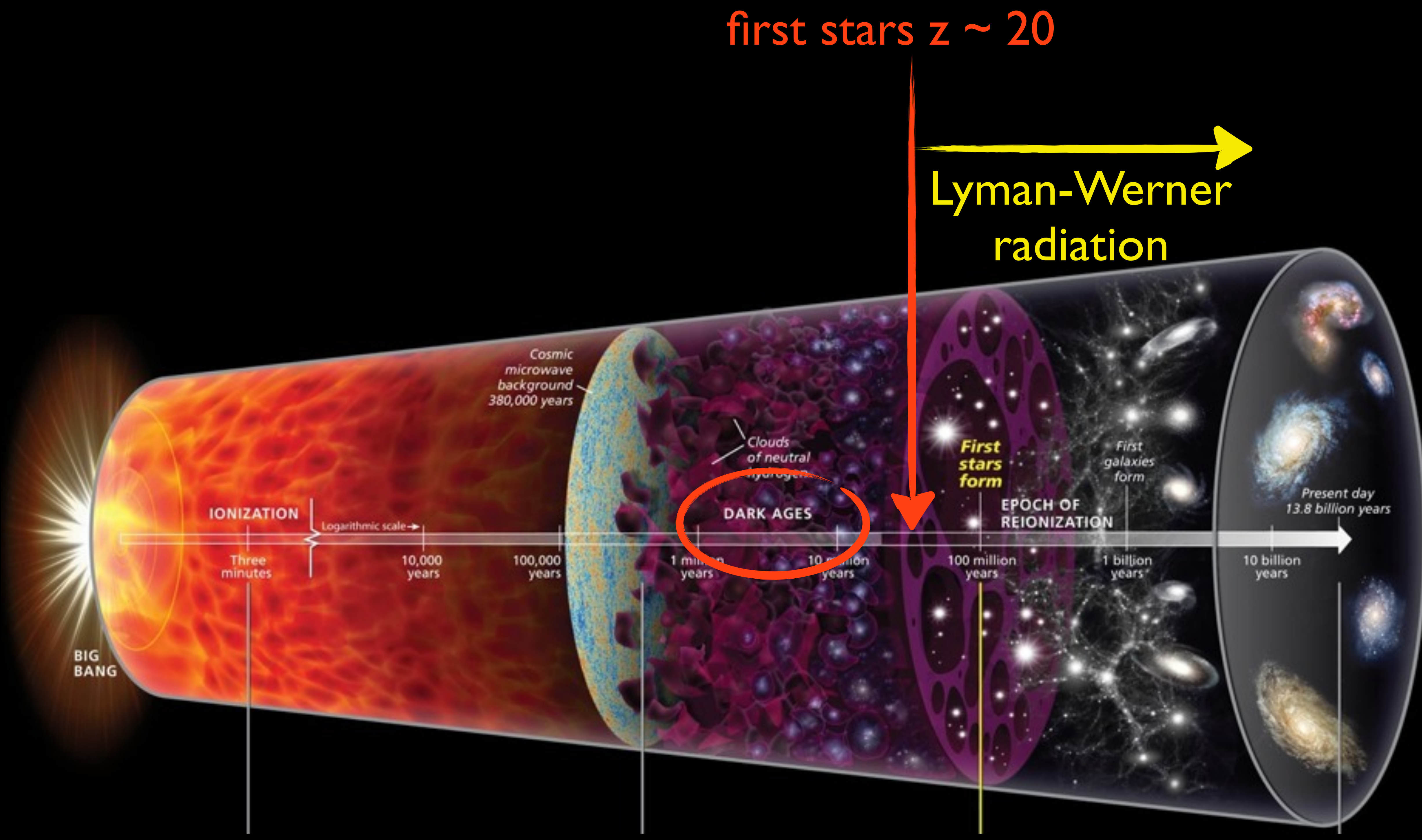


O'Leary & McQuinn 2012

- Decrease in halo mass function
- Decrease in baryon fraction
- Increase in critical halo mass for Pop III star formation
- Delay of Pop III star formation

Review: Fialkov 2014

Lyman-Werner radiation



http://discovermagazine.com/~/media/Images/Issues/2014/April/21-centimeter-cosmology.jpg

Lyman-Werner radiation

- Lyman-Werner radiation: UV radiation, 11.2 eV < E < 13.6eV
    - destroys molecular hydrogen
    - reduces star formation
- BUT: H_2 can self-shield and be shielded by neutral H
- LW radiation can travel large distances: Lyman-Werner background
- typical LWBG strength: 0.01-0.1 J_{21}
  $J_{21} = 10^{-21}$ erg s^{-1} cm^{-2} Hz^{-1} sr^{-1}

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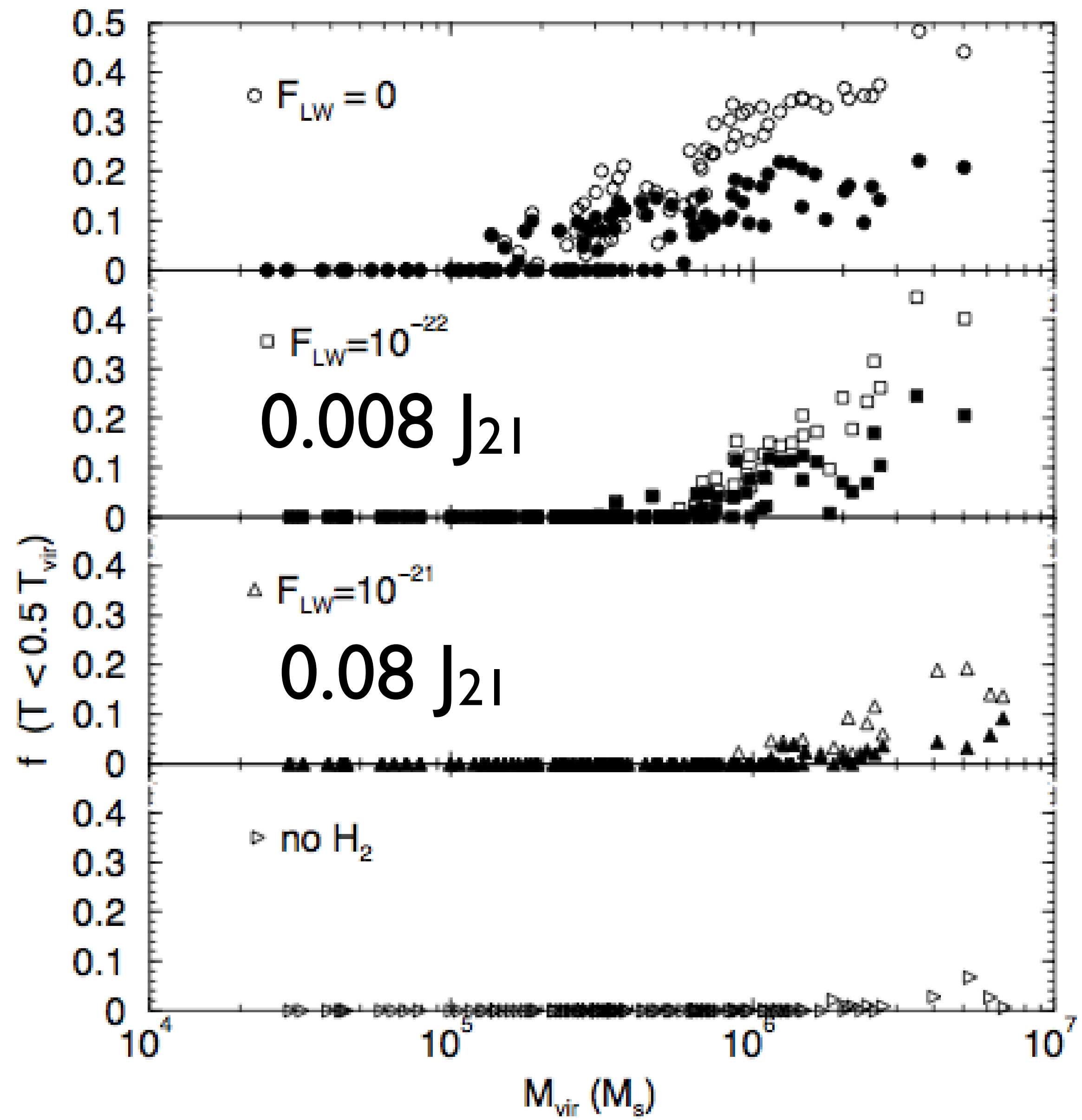
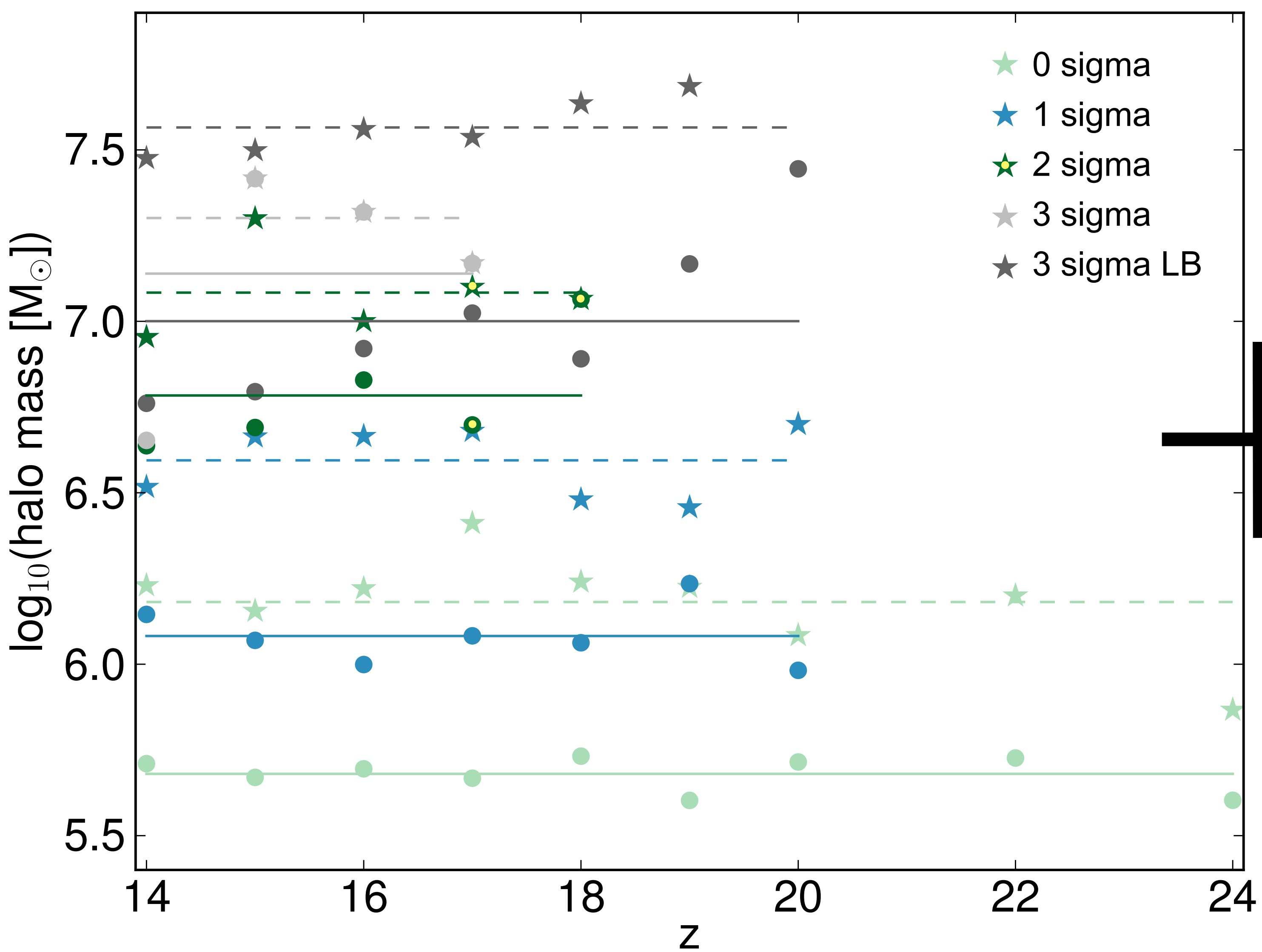


FIG. 3.—Fraction of cold gas within the virial radius as functions of cloud mass and soft-UV background flux F_{LW} in ergs^{-1} cm^{-2} Hz^{-1}. Open symbols represent f_c, the fraction of gas that has cooled via H_2 cooling ($T < 0.5\ T_{vir}$, $\rho > 1000\rho_{mean}$ with ρ_{mean} the mean baryonic density of the universe). Filled symbols represent f_{cd}, the fraction of cold, dense gas ($T < 0.5\ T_{vir}$, $\rho > 10^{19}\ M_\odot$ Mpc^{-3}) available for star formation.

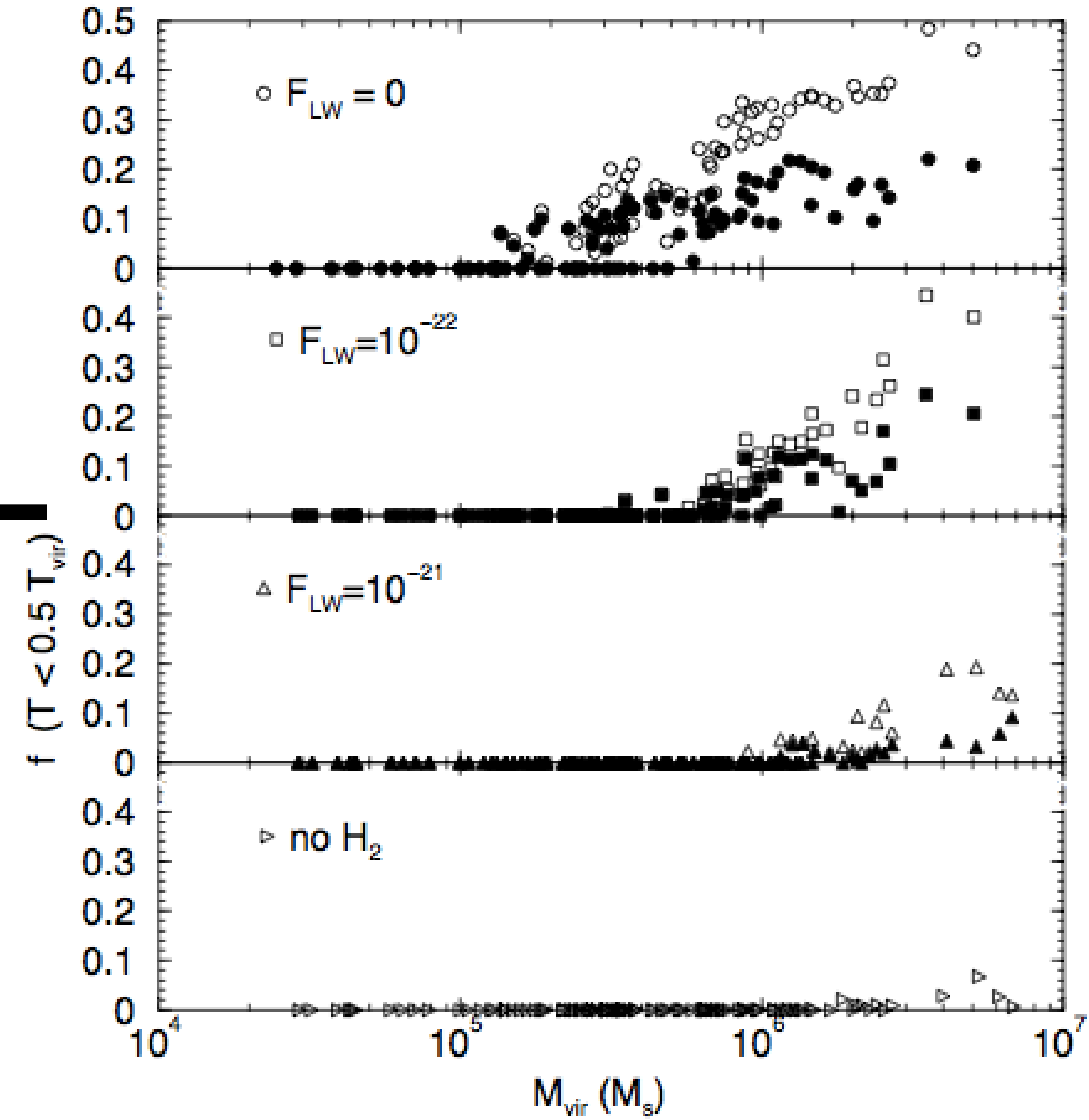
Machacek+ 2001

Outlook: Lyman-Werner radiation background + streaming velocities



+

Machacek+01



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Questions for discussion?

- What is your guess? Does Lyman-Werner radiation dominate or streaming velocities?
- Is a time-dependent Lyman-Werner background needed for my future simulations?
- What about X-rays? Do they stop star formation (heating) or enhance star formation (production of e- and therefore H_2)?
- How many subclasses of Pop III.2 stars do we need to account for all important effects?

Conclusions

- Minimum minihalo mass for SF > 5×10^5 $M_\odot$
- No correlation between the spin of entire halo and on the central gas cloud scale `Druschke, Schauer+18 (submitted)`
- Streaming velocities are offset velocities between DM and baryons. Impacts on first star formation:
  - Lower gas content in minihalos
  - Halos start containing cold gas at later redshift
  - The halo mass threshold moves to higher values, with masses > 10^7 $M_\odot$ for 3 sigma streaming `Schauer+18 (submitted)`
- Combination of LW radiation and streaming velocities: soon to come!

Thank you