The formation of the first stars

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STScI | SPACE TELESCOPE SCIENCE INSTITUTE

Hubble Fellow

3rd of December 2018

Tokyo

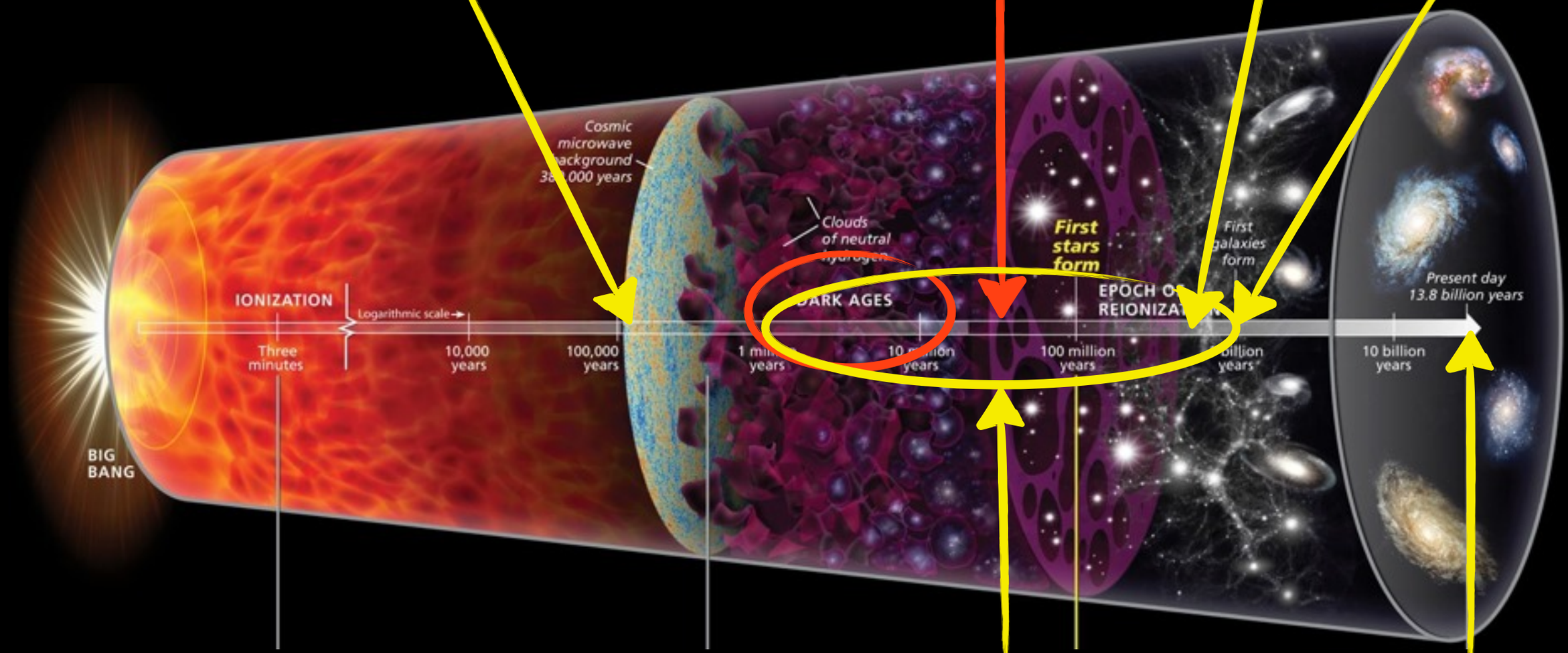
The dark ages

first galaxies z ~ 11

first stars z ~ 20

CMB z ~ 1100

quasars z ~ 7



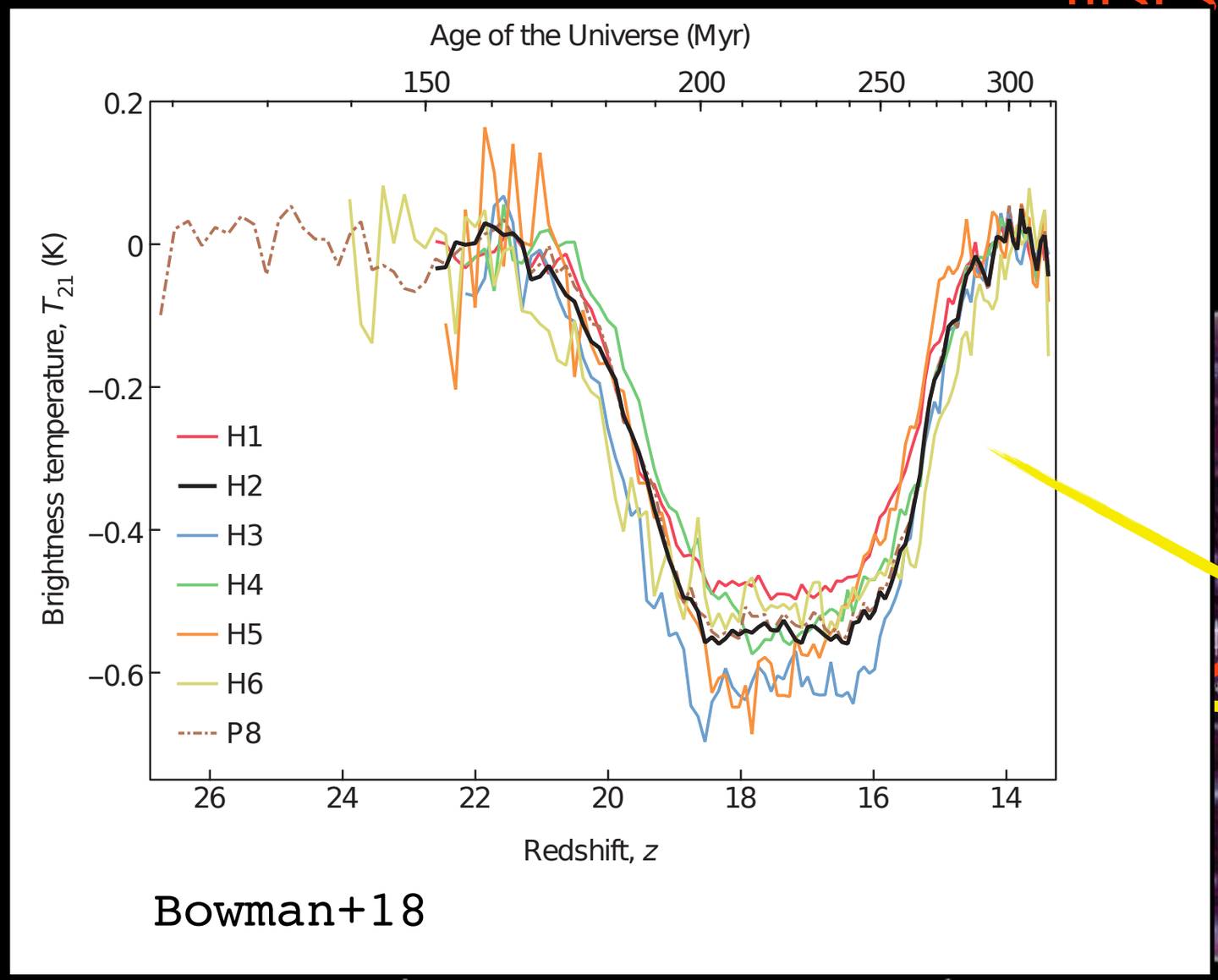
21cm signal: SKA

stellar archaeology

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

The dark ages

global 21cm signal: EDGES!

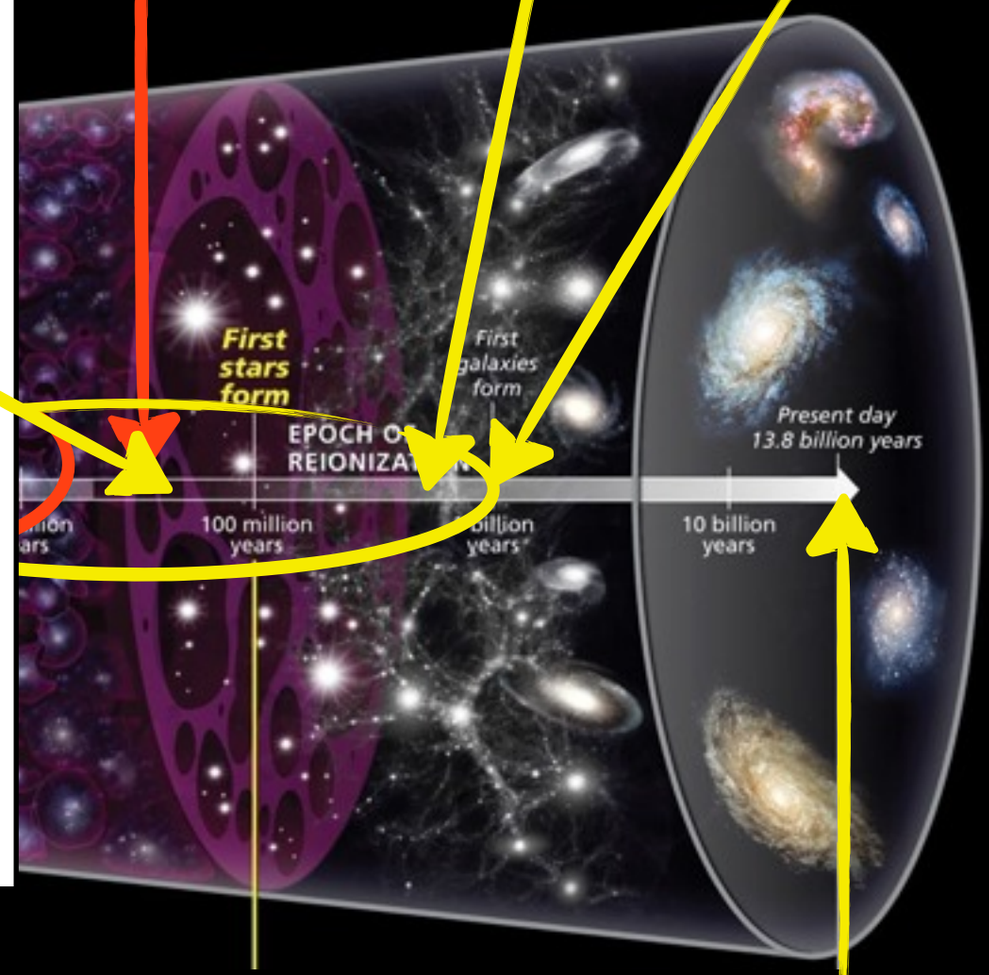


Bowman+18

first galaxies z ~ 11

first stars z ~ 20

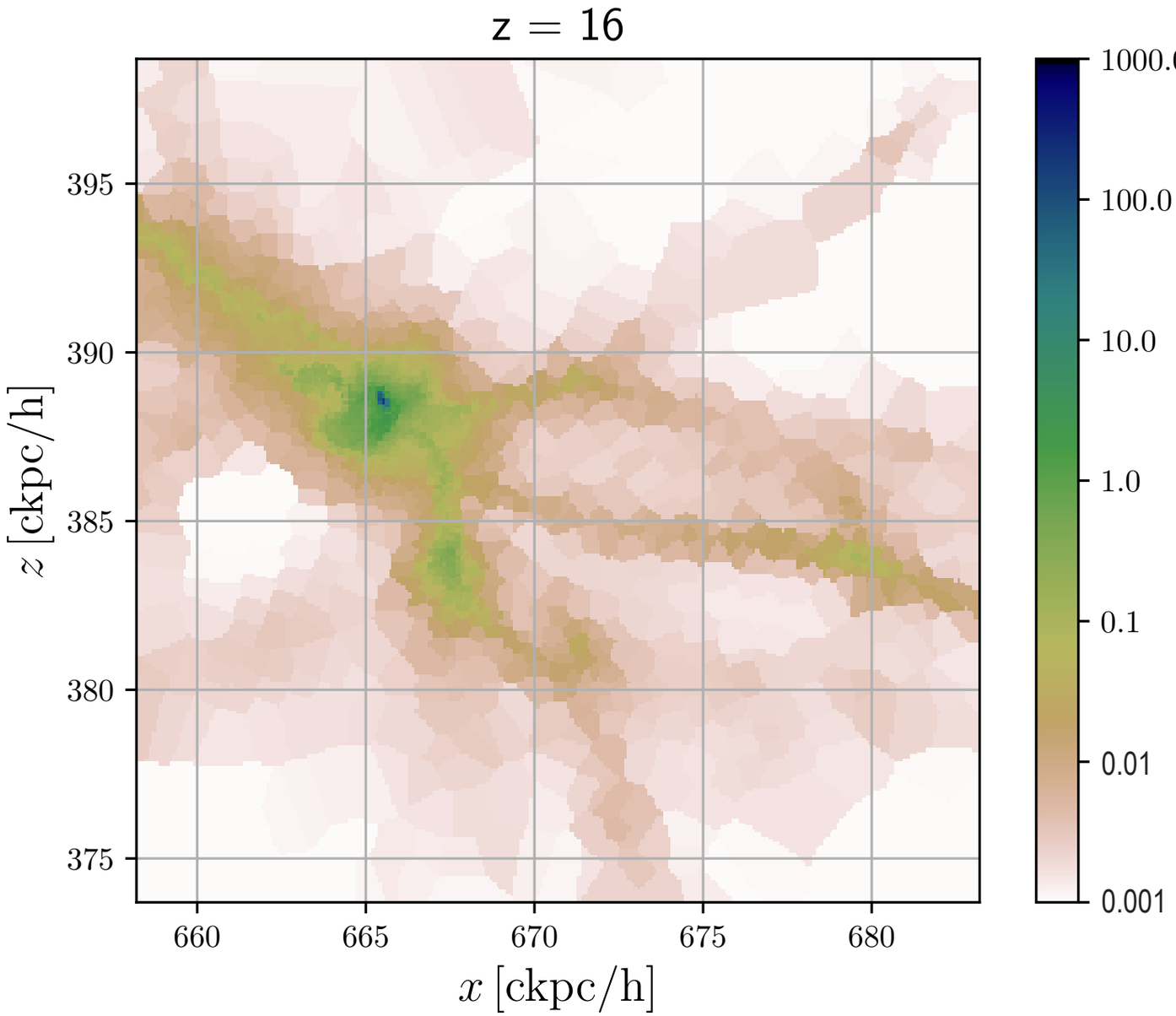
quasars z ~ 7



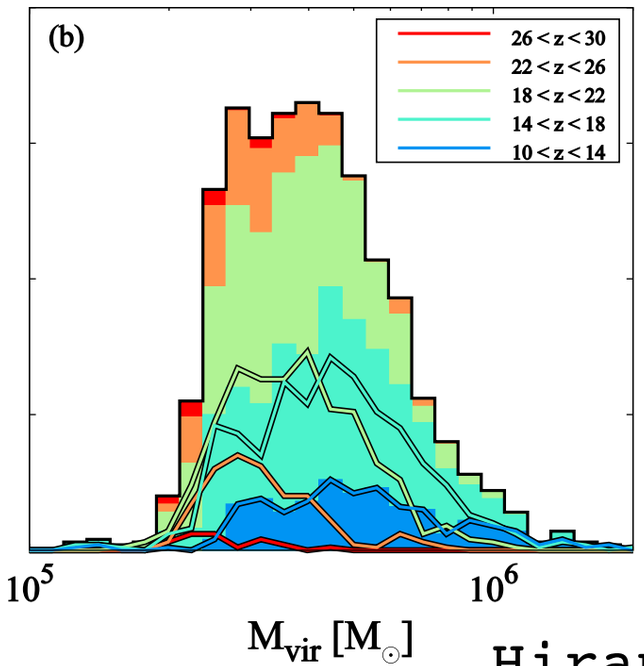
21cm signal: SKA stellar archaeology

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

Minihaloes

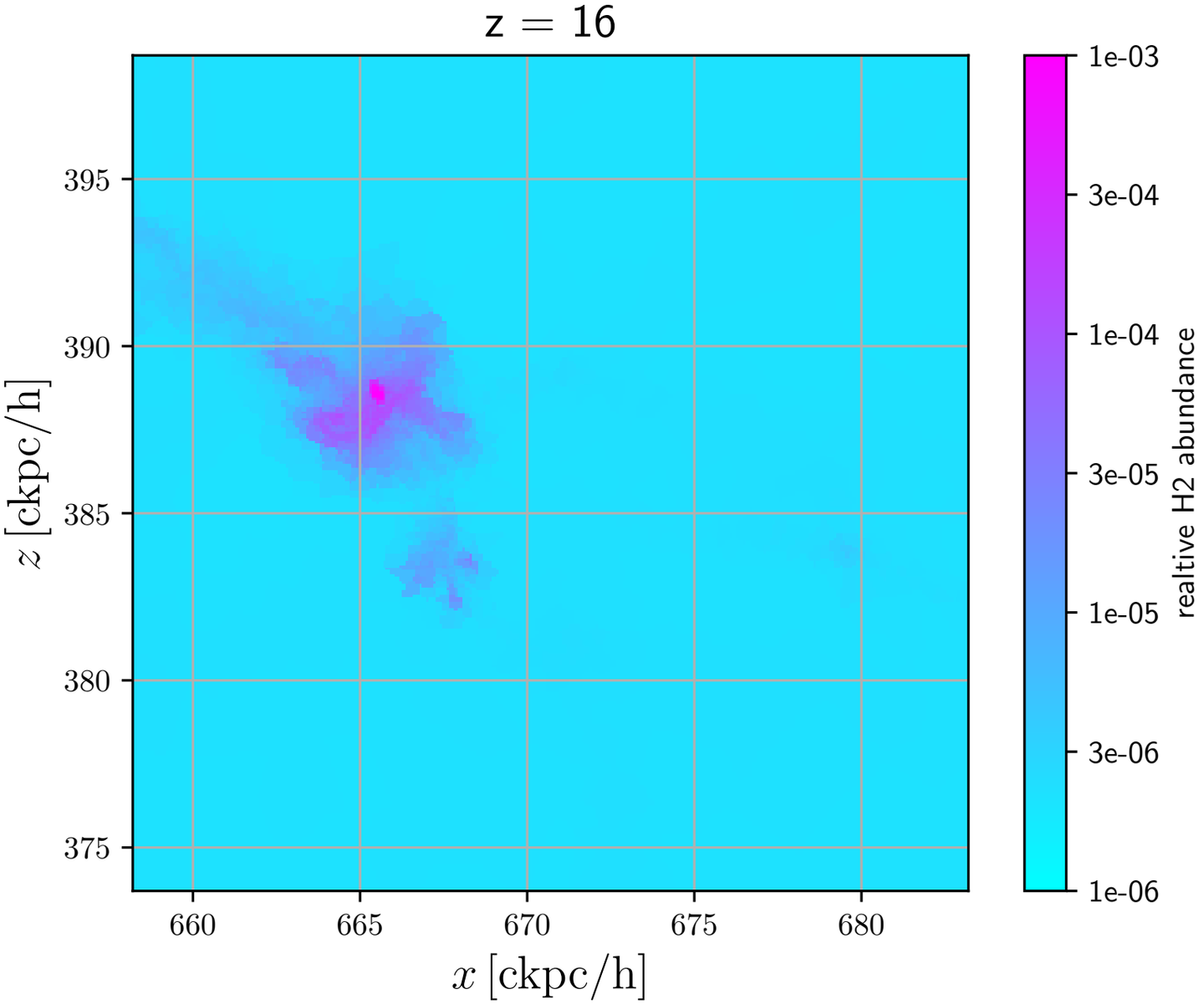


- high redshift: structure formation filamentary
- minihaloes / atomic cooling haloes: 10^5 - 10^7 $M_\odot$



Hirano+ 2015

Minihaloes



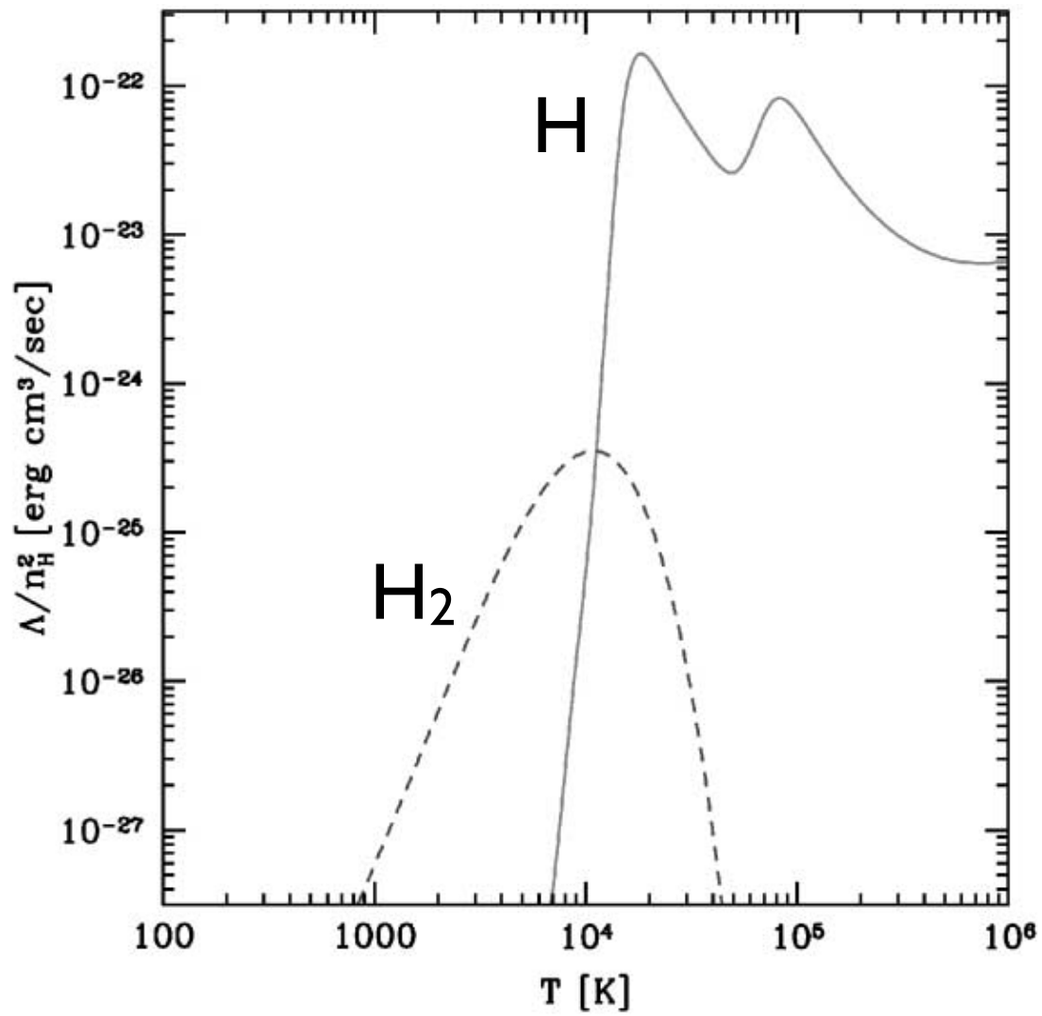
- high redshift: structure formation filamentary
- minihaloes / atomic cooling haloes: 10^5 - 10^7 $M_\odot$
- temperature: cold IGM, cool minihalo centres, 1000-10000 K haloes
- metal free
- molecular hydrogen rich

First star formation

- No metals or dust!
- Cooling:
  - $T > 10^4$ K : atomic hydrogen
  - $T > 200$ K : molecular hydrogen
    - Direct formation: forbidden
    - Formation via H- channel:

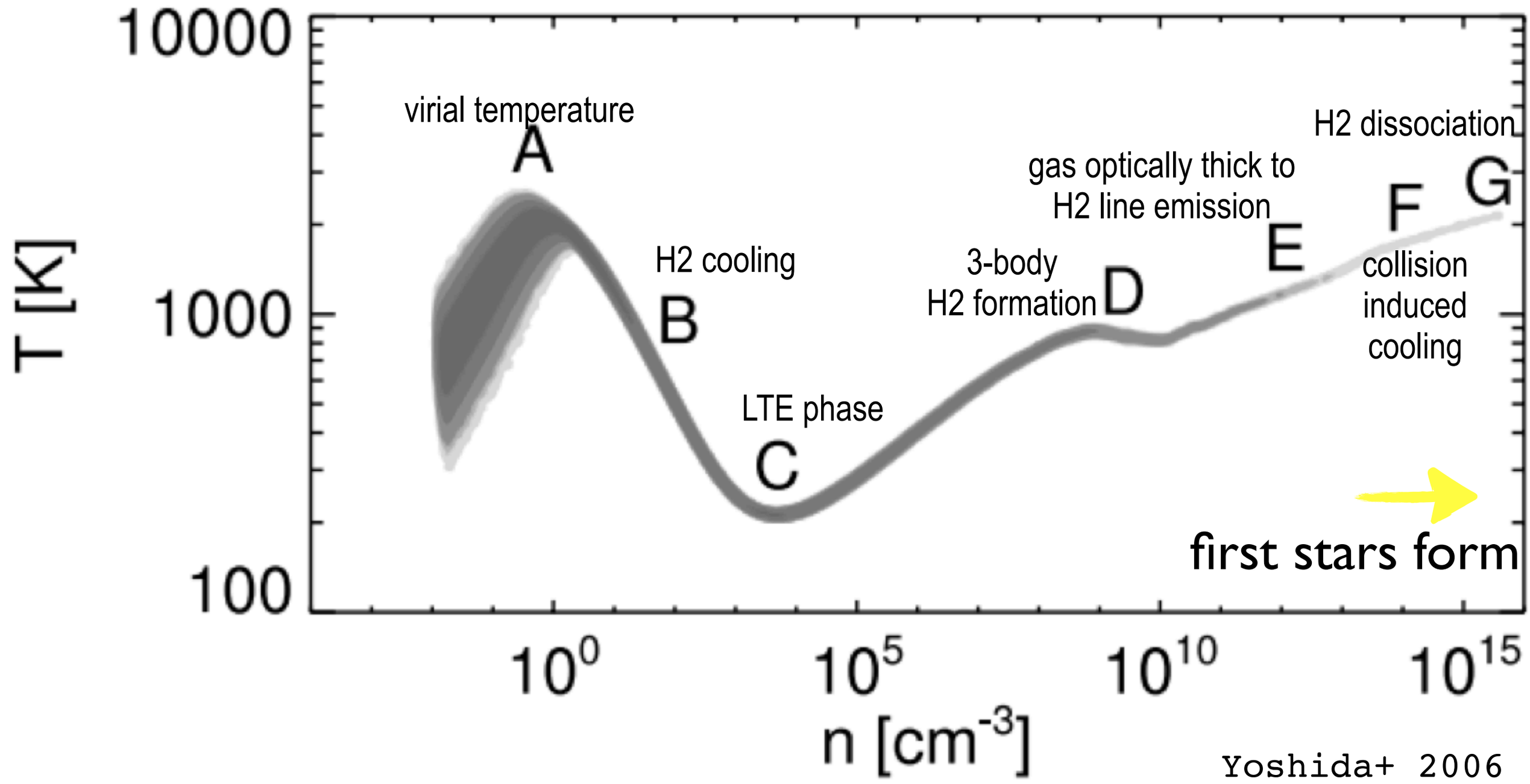
$$H + e^- \rightarrow H^- + h\nu$$

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



Barkana & Loeb 2001

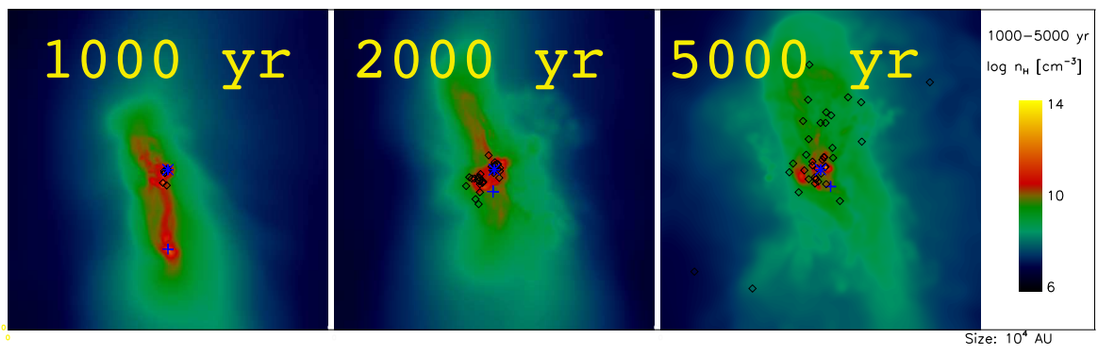
thermal evolution of gas cloud



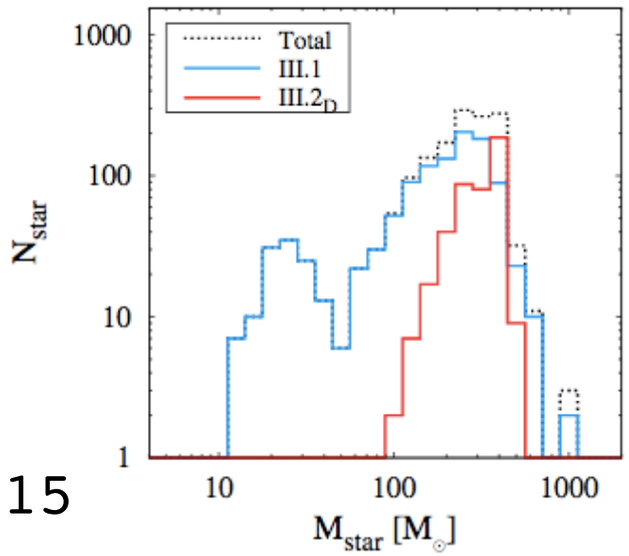
Yoshida+ 2006

Mass of first stars: uncertain

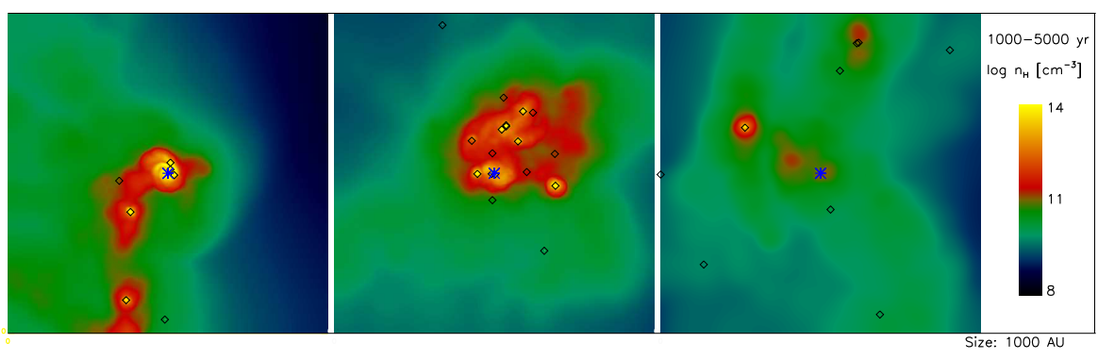
- First simulations: singe star with 100 - 1000 $M_\odot$ Abel+ 2002
- Resimulations with higher resolution: fragmentation!
  - more than one star per minihalo
  - masses reach down to subsolar



- However:



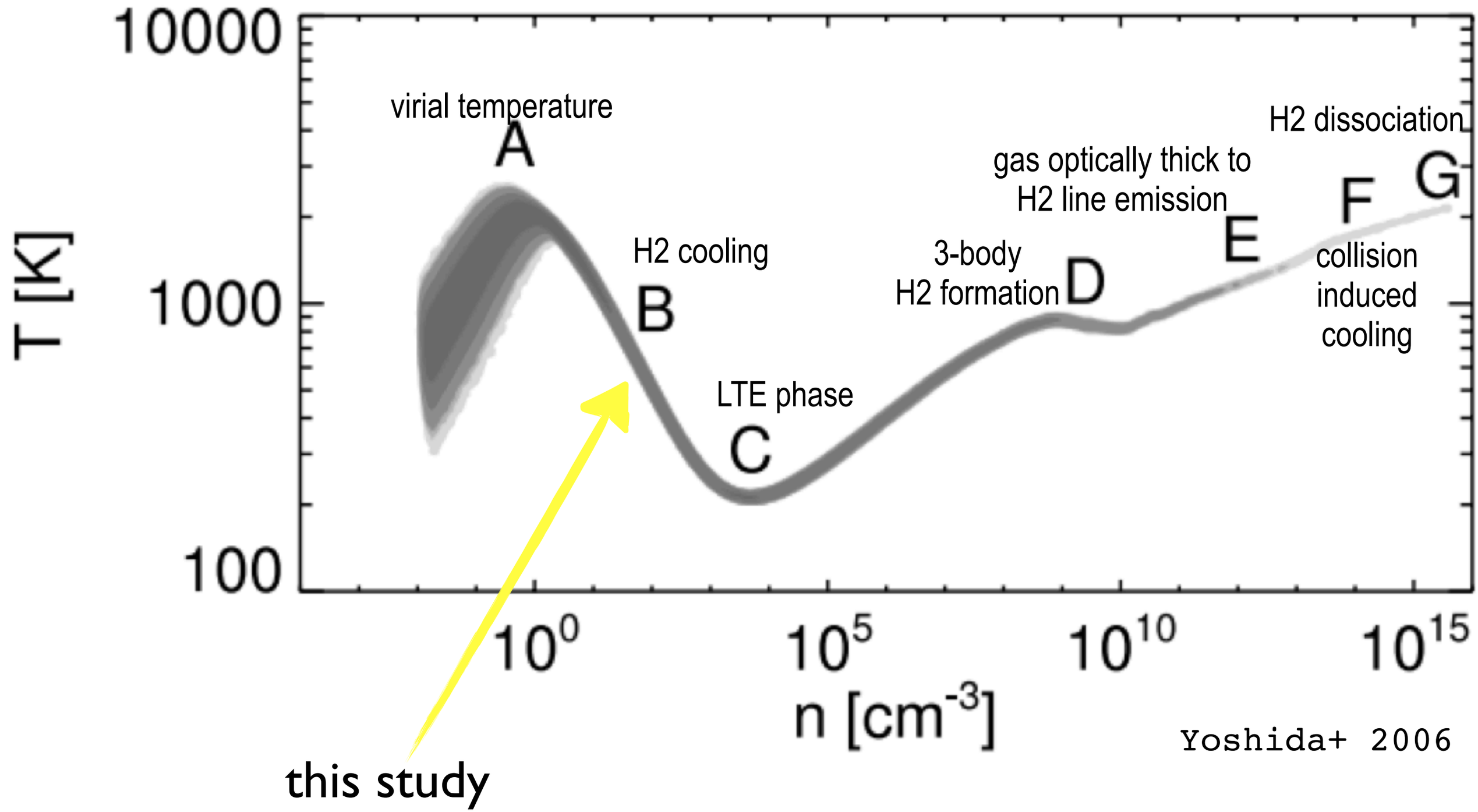
Hirano+ 2015



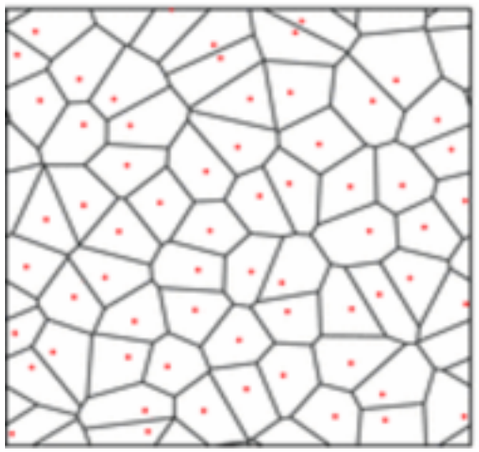
Stacy+ 2016

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

thermal evolution of gas cloud



Our simulations



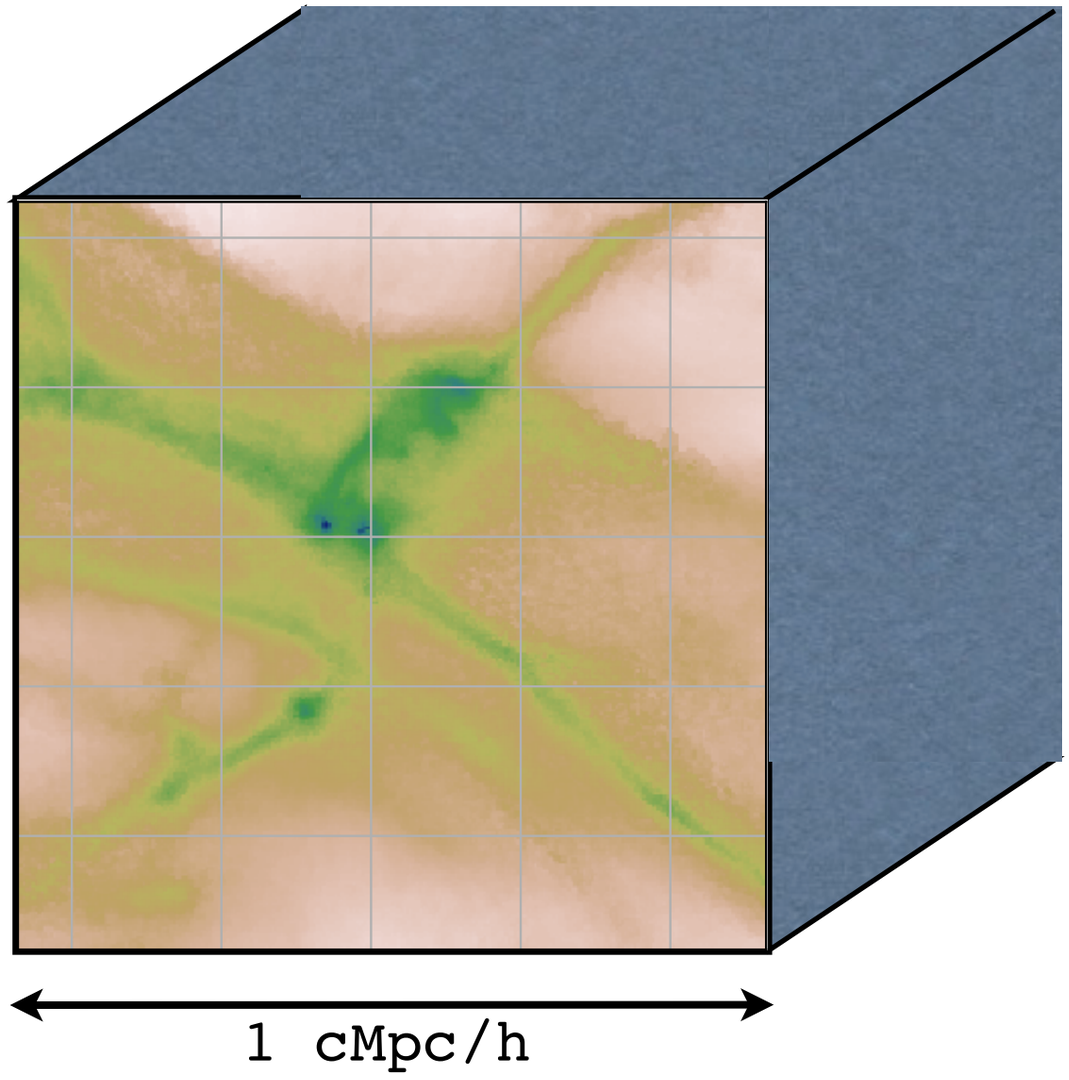
Springel 2013

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

Schauer+ 2018

Our simulations

redshift range:	z = 200 -> 14
box size:	$(1\ \mathrm{cMpc/h})^3$
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)

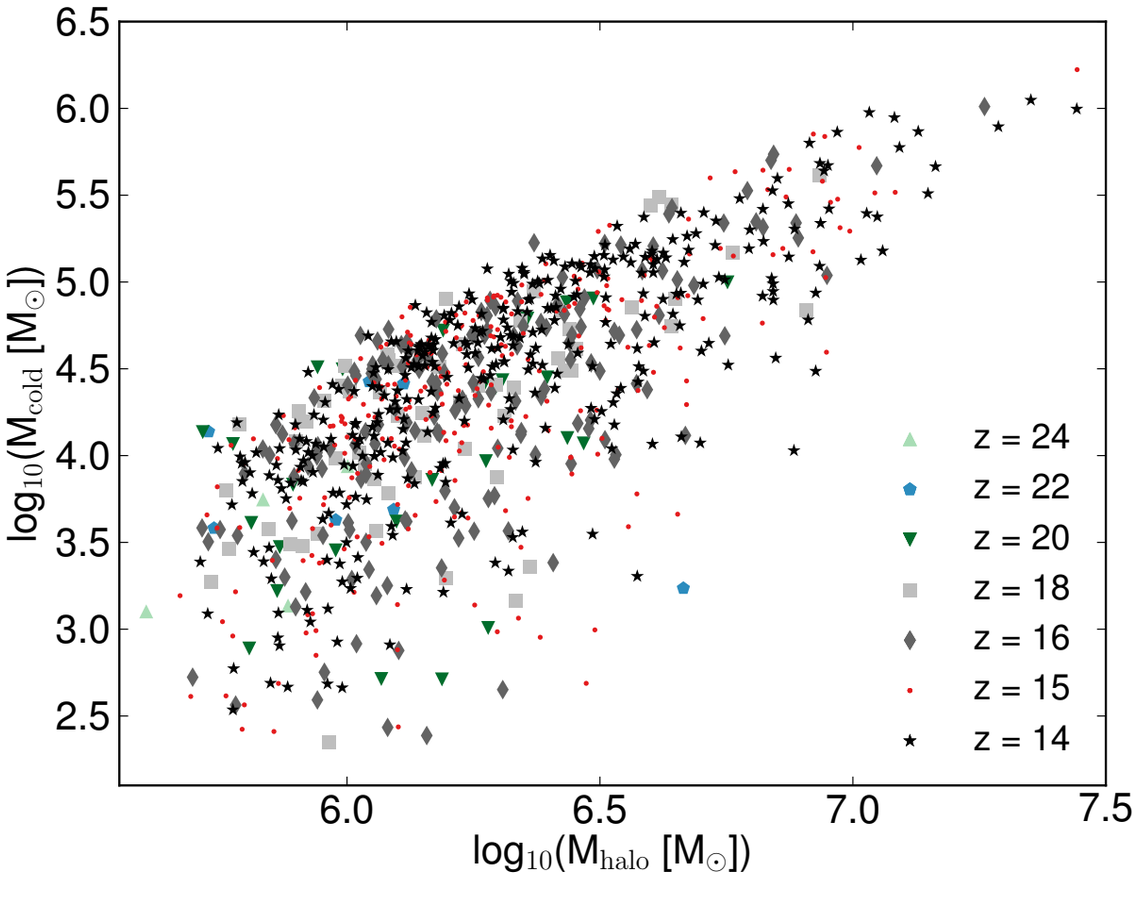


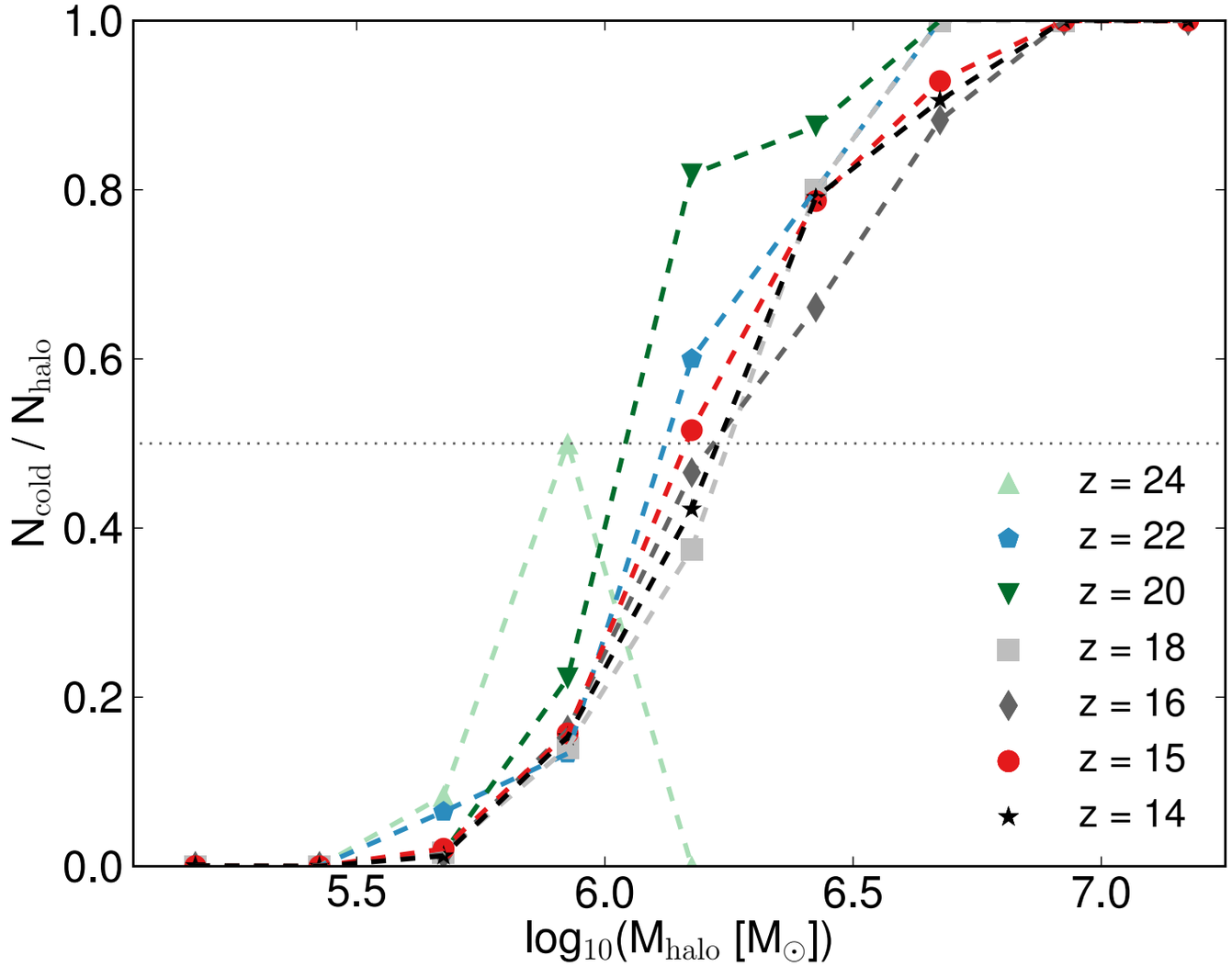
Schauer+ 2018

cold gas mass - halo mass relation

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

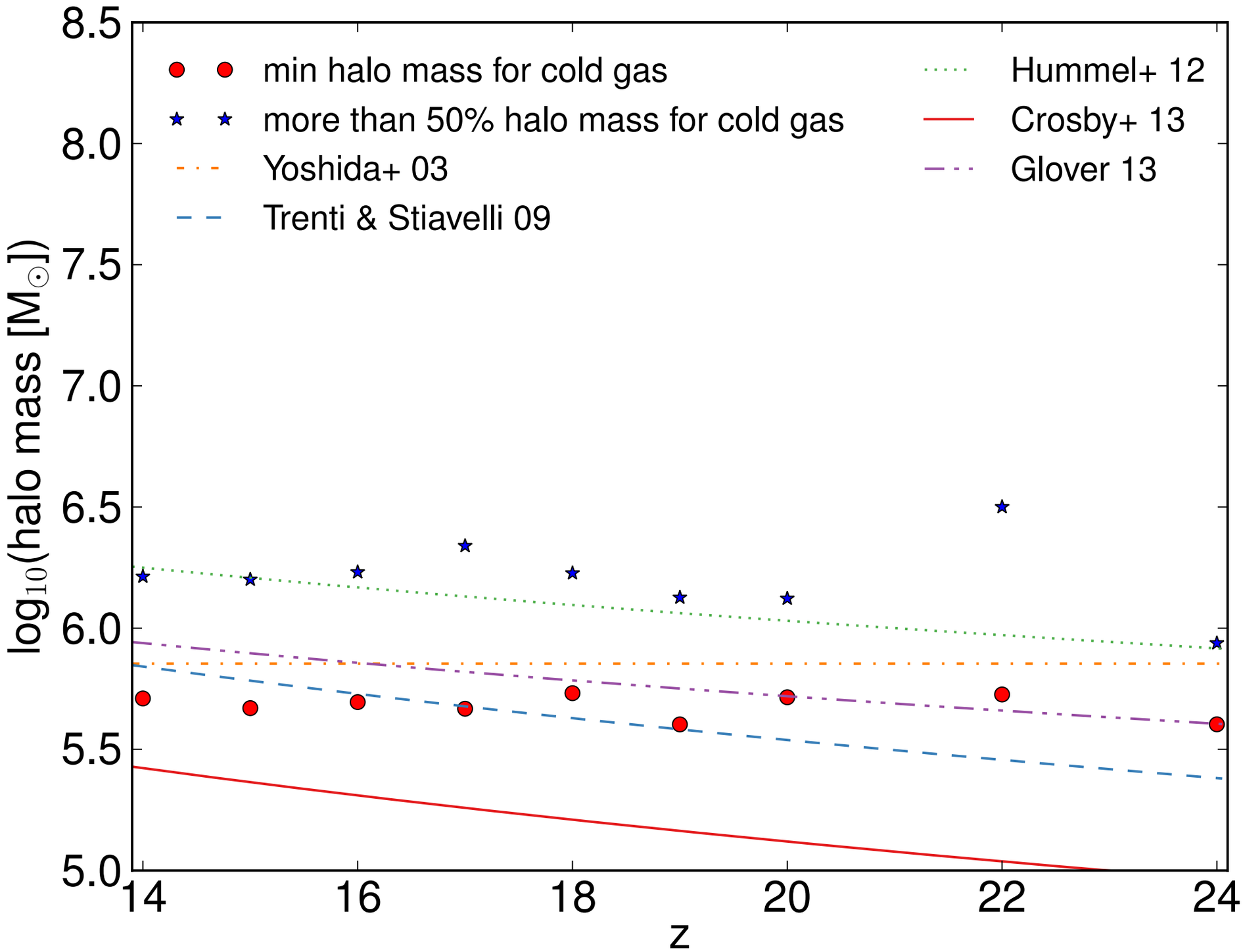
- T < 500K
- H_2 abundance > 10^{-4}
- n > 100 cm^{-3}





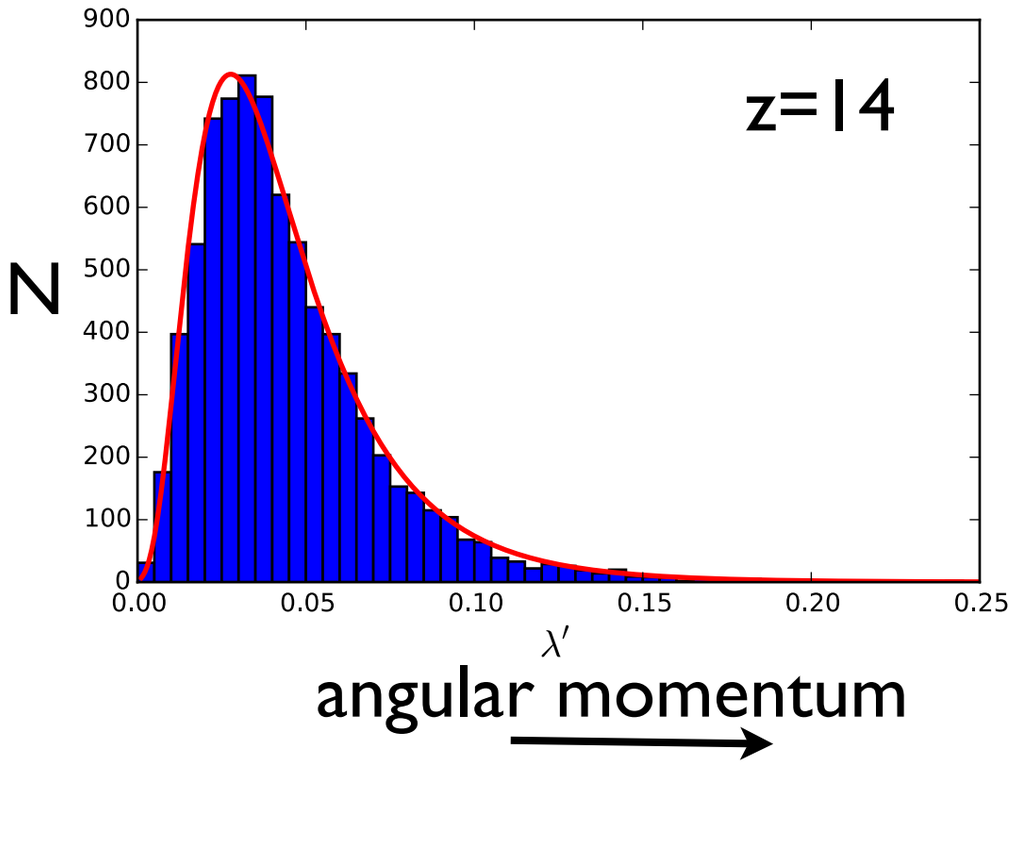
Schauer+ 2018

halo masses of cold haloes



Schauer+ 2018

spin parameter



- measure of angular momentum in galaxy

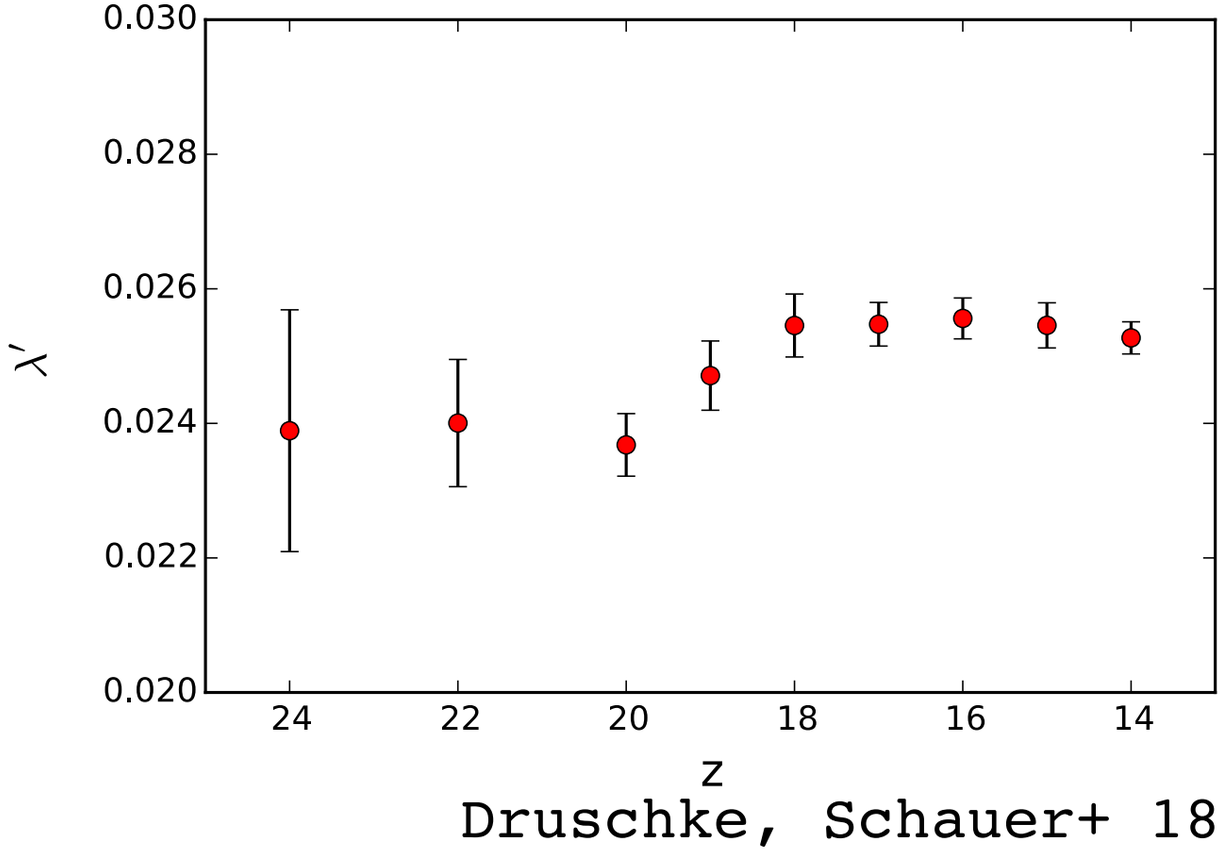
$$\lambda' = \frac{J}{\sqrt{2} M R v_{circ}}$$

Bullock+ 2001

- lognormal distribution

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

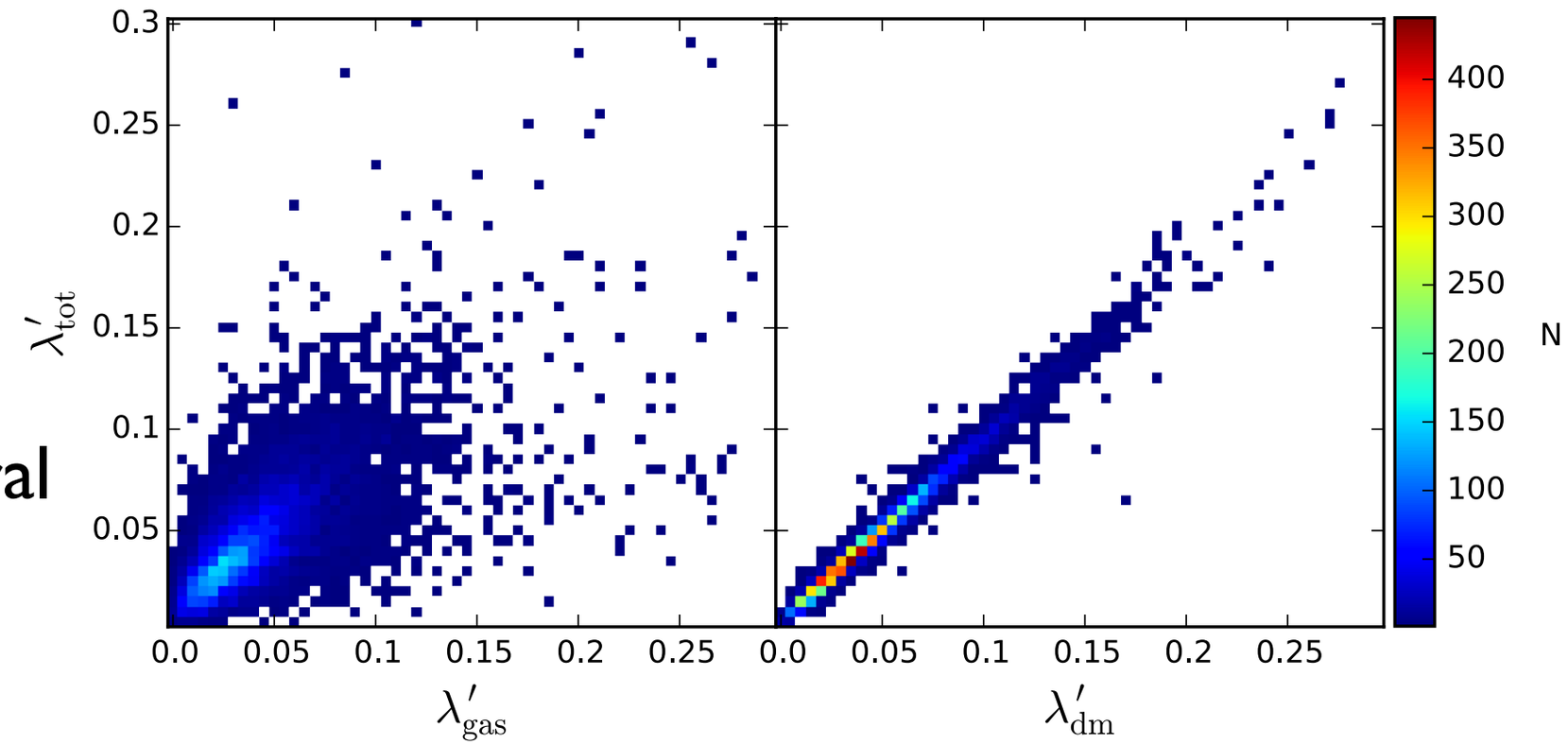
- (no) redshift evolution

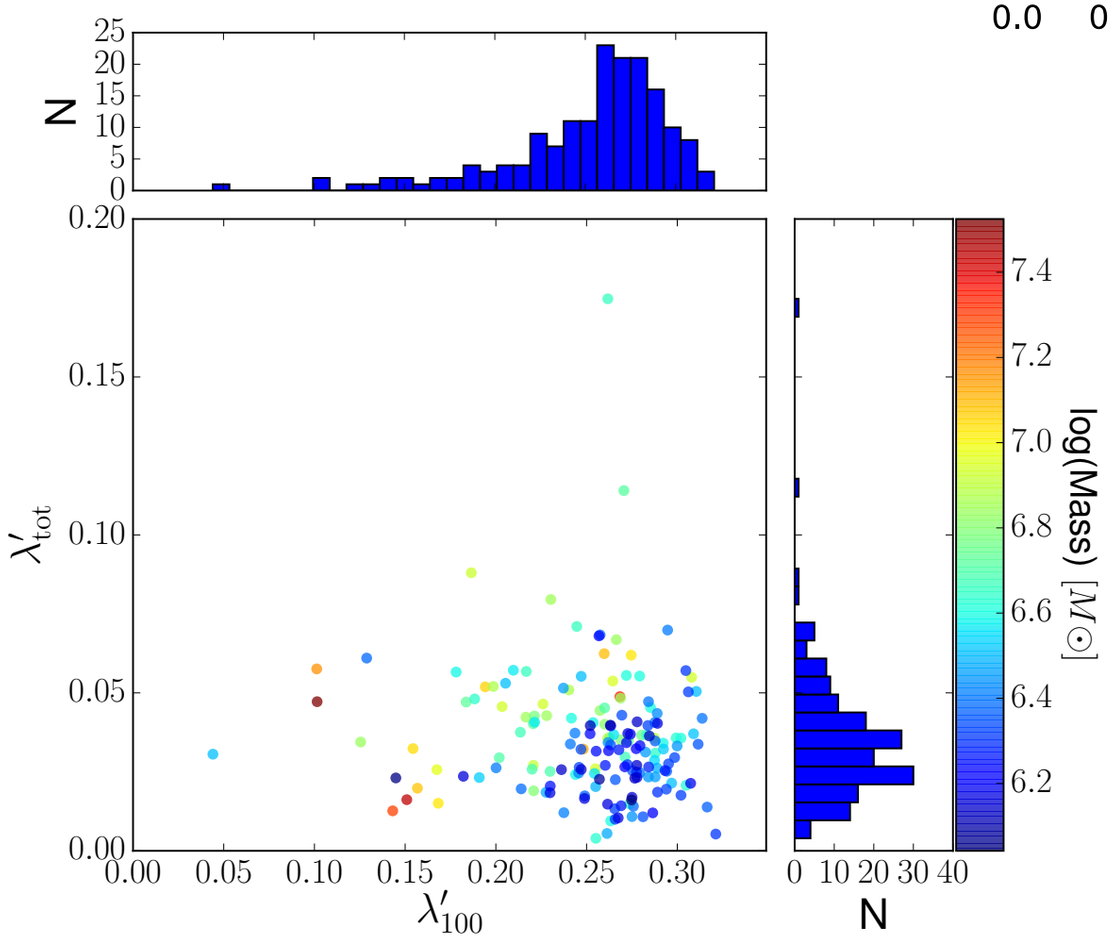


Druschke, Schauer+ 18

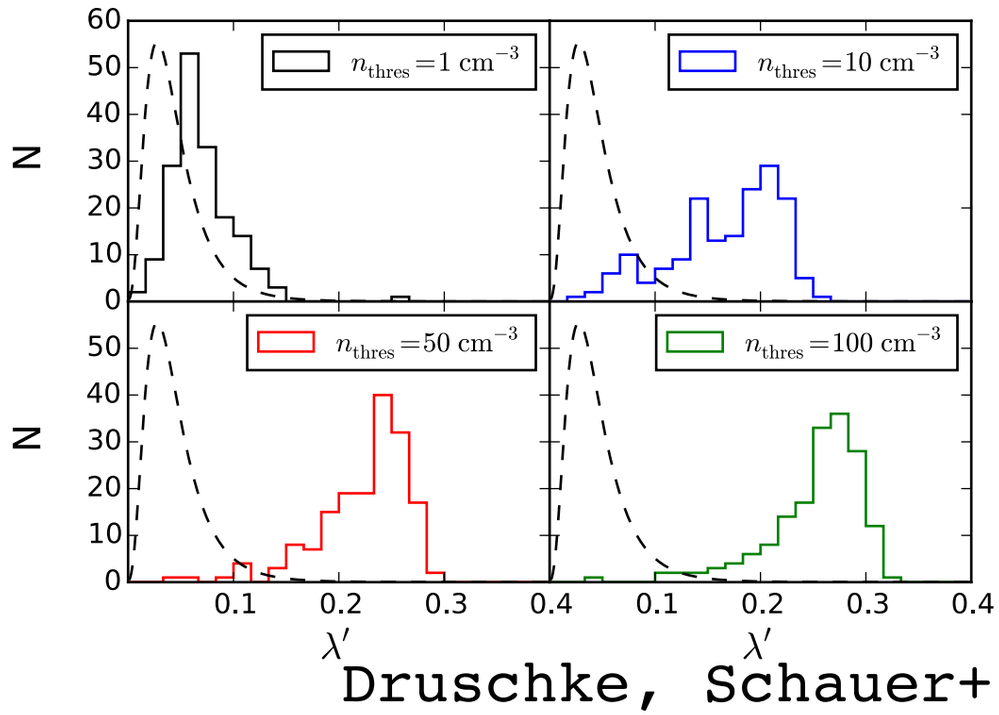
spin parameter: dense centre

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





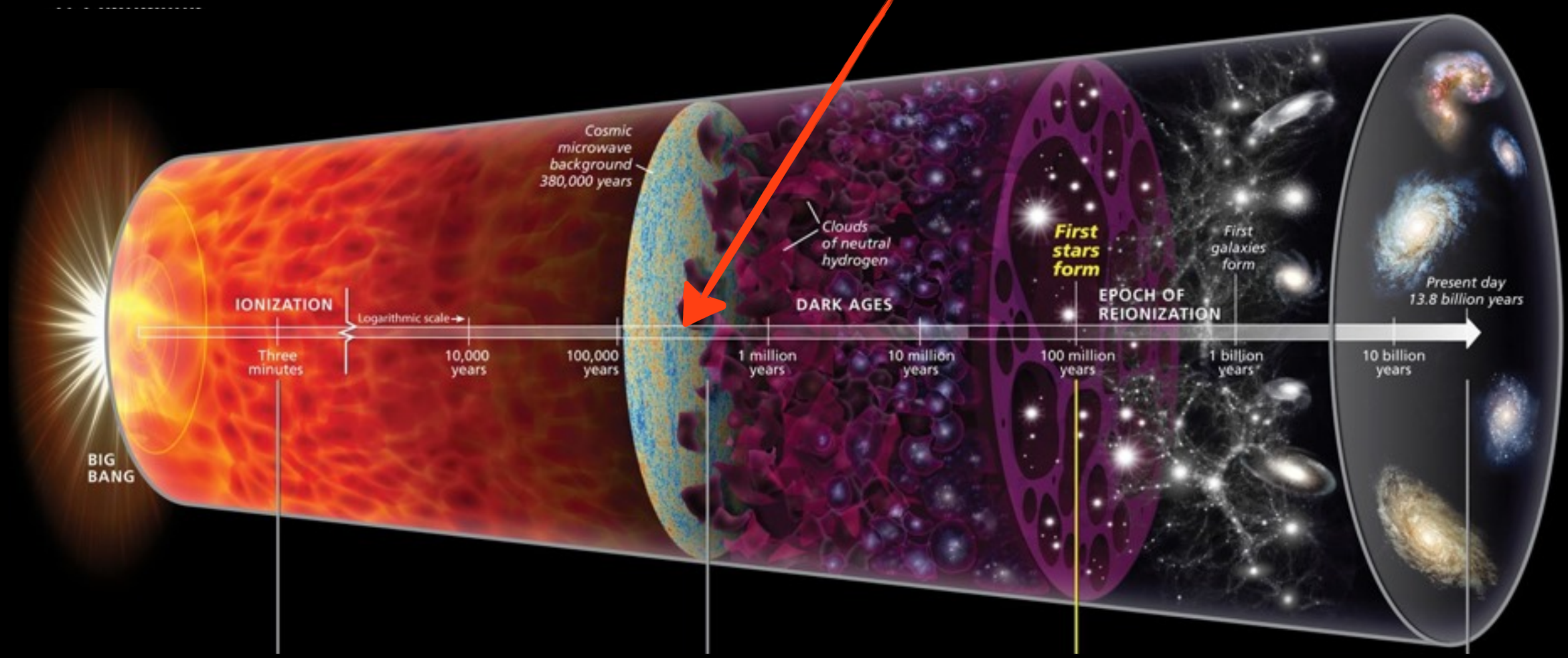
- high spin for high densities



Druschke, Schauer+ 18

streaming velocities

origin at z ~ 1100



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

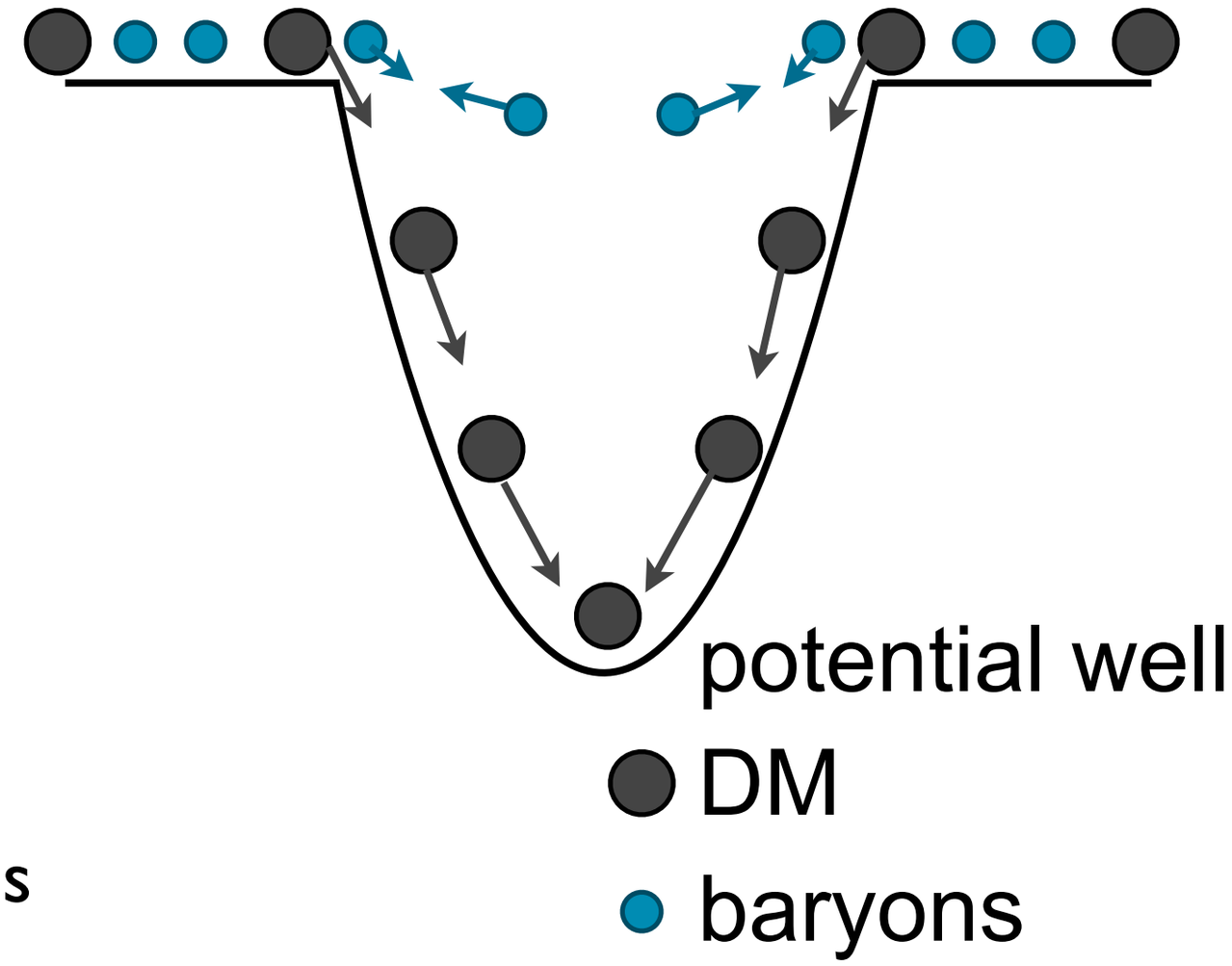
streaming velocities

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

streaming velocity

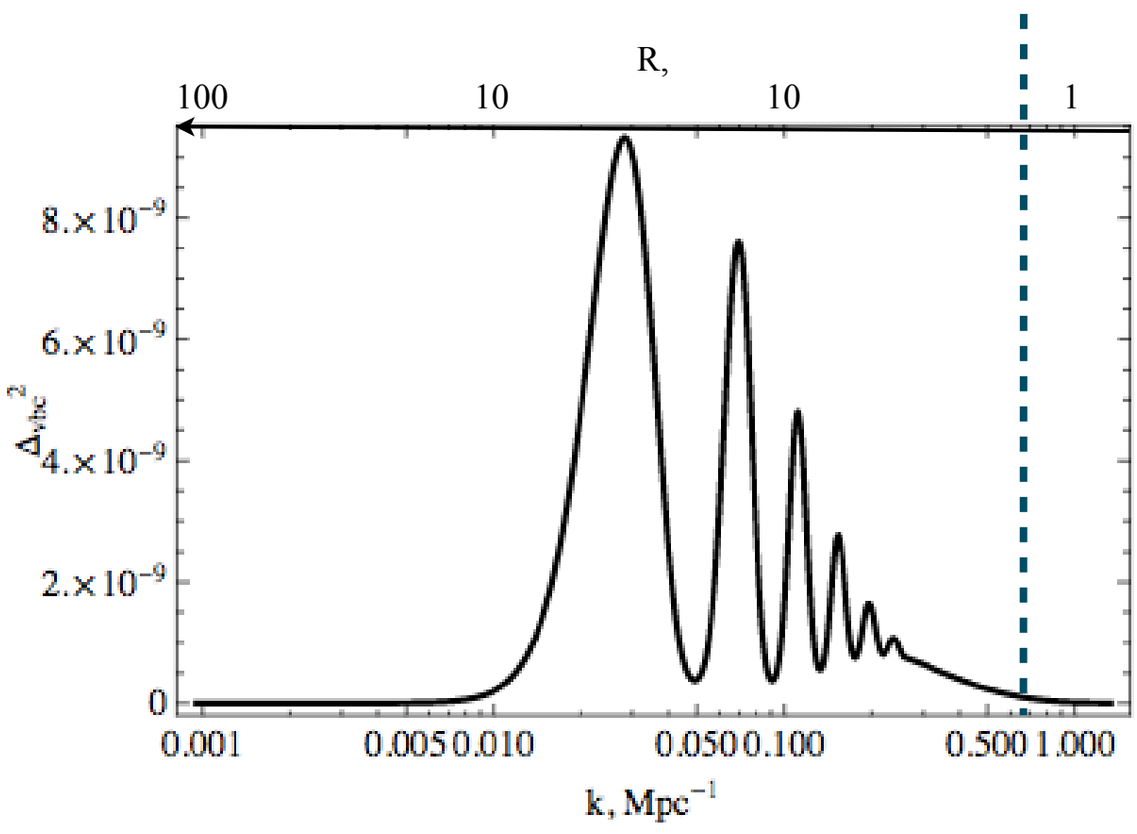
=

offset velocity between baryons and dark matter

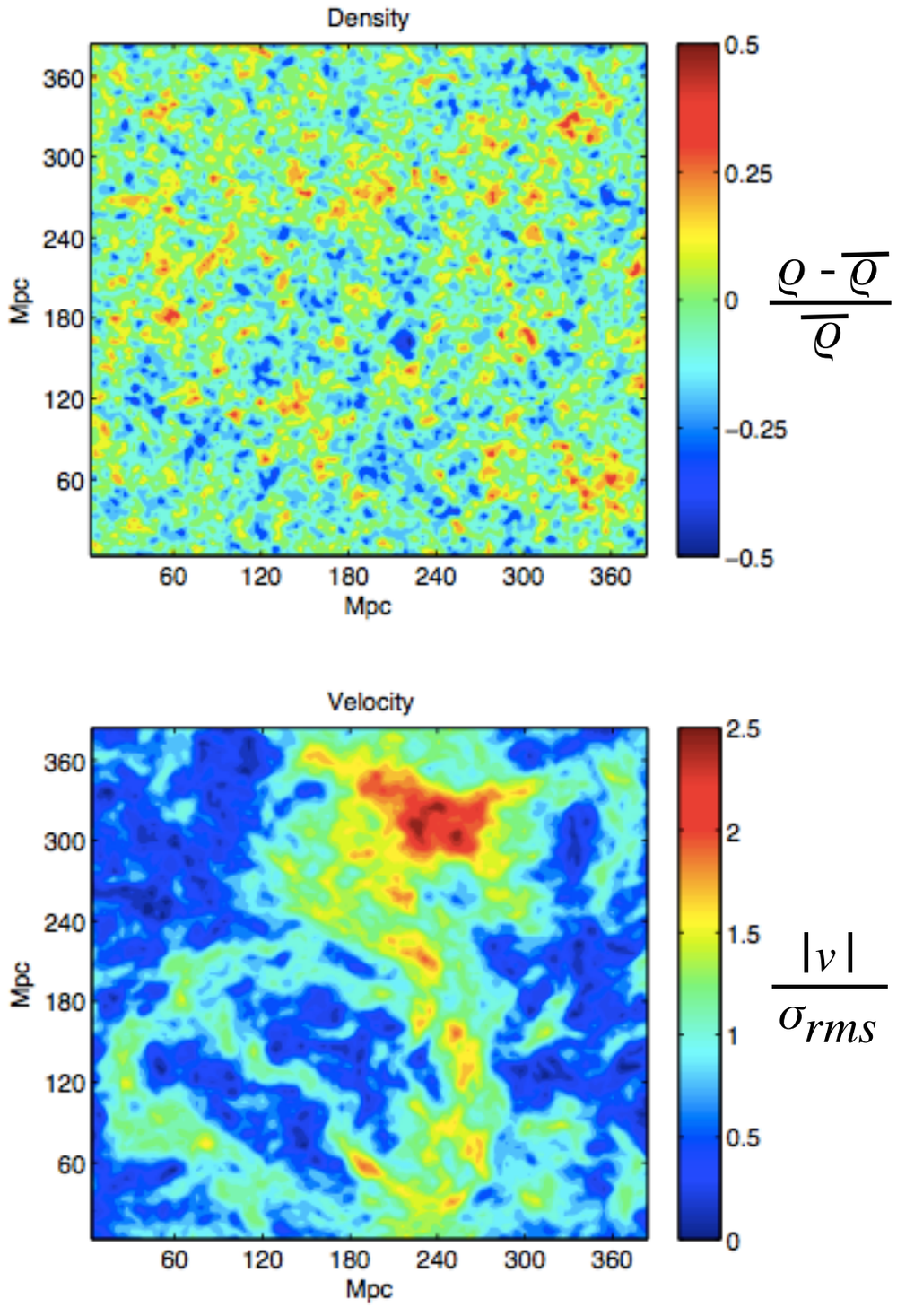


streaming velocities

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



Tseliakhovich & Hirata 10

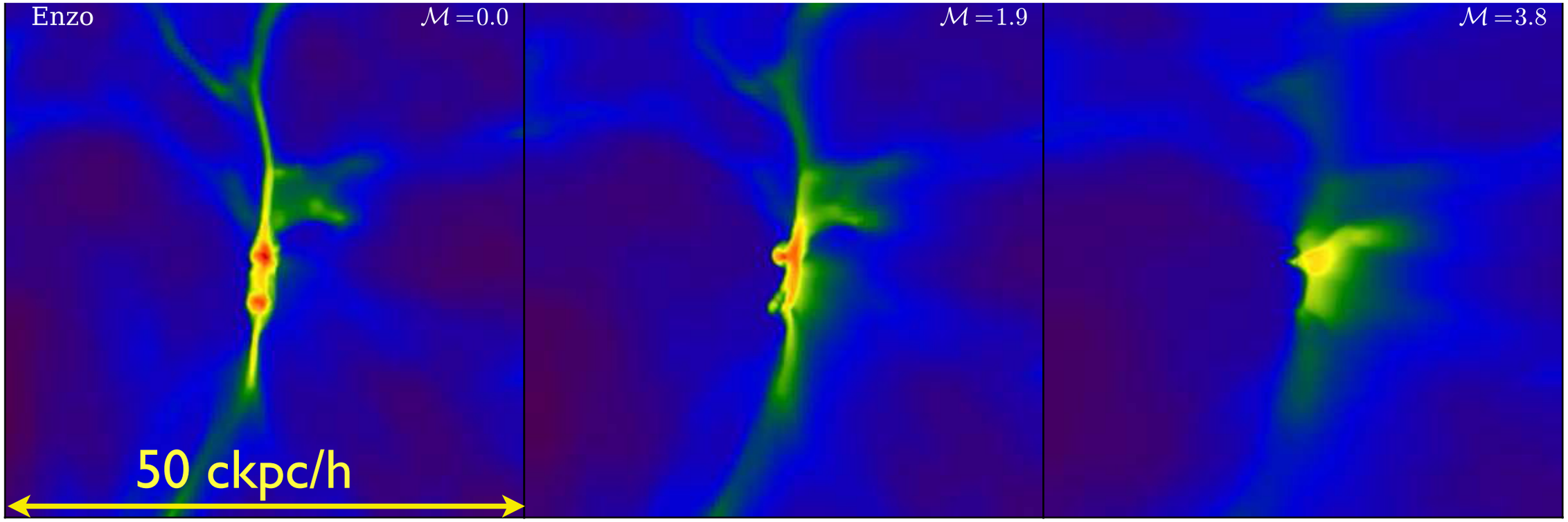


z=20, Fialkov+ 13

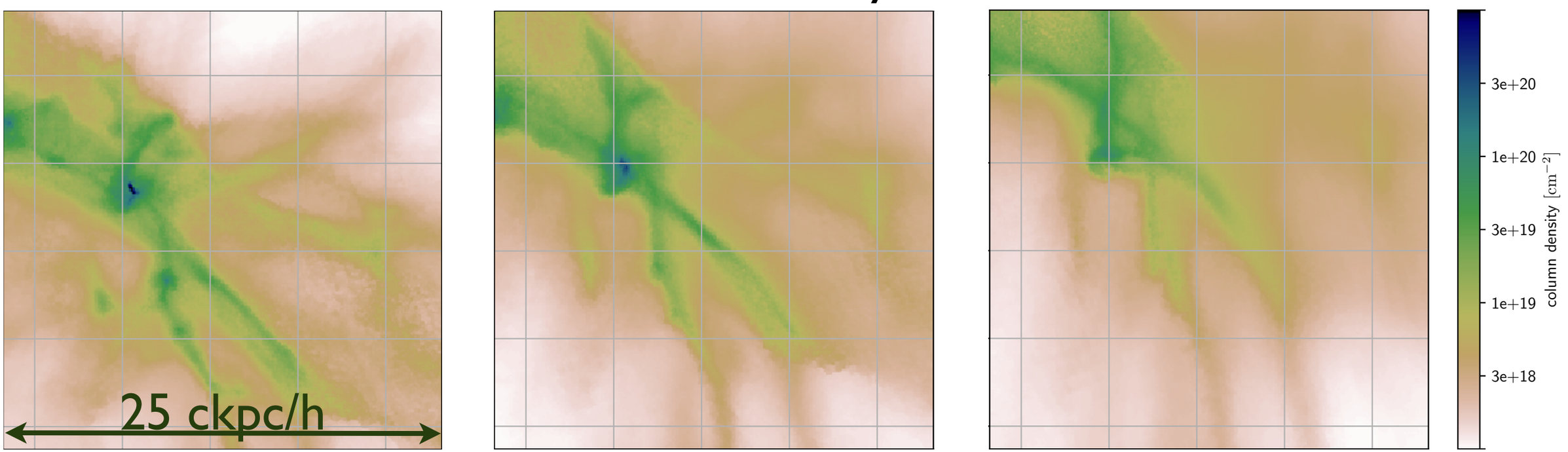
Effects of streaming velocities

density:

O'Leary & McQuinn 2012

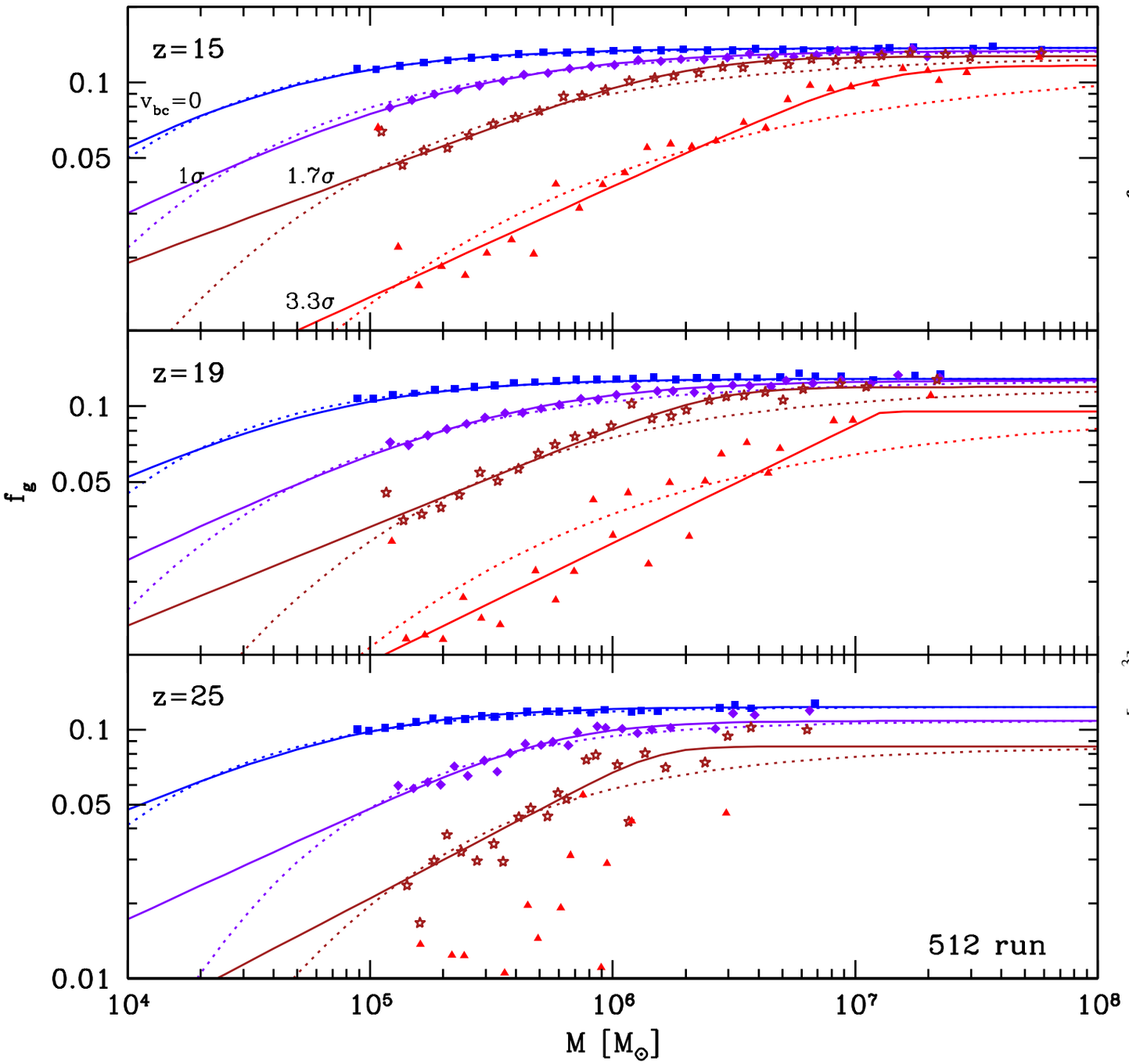


column density:



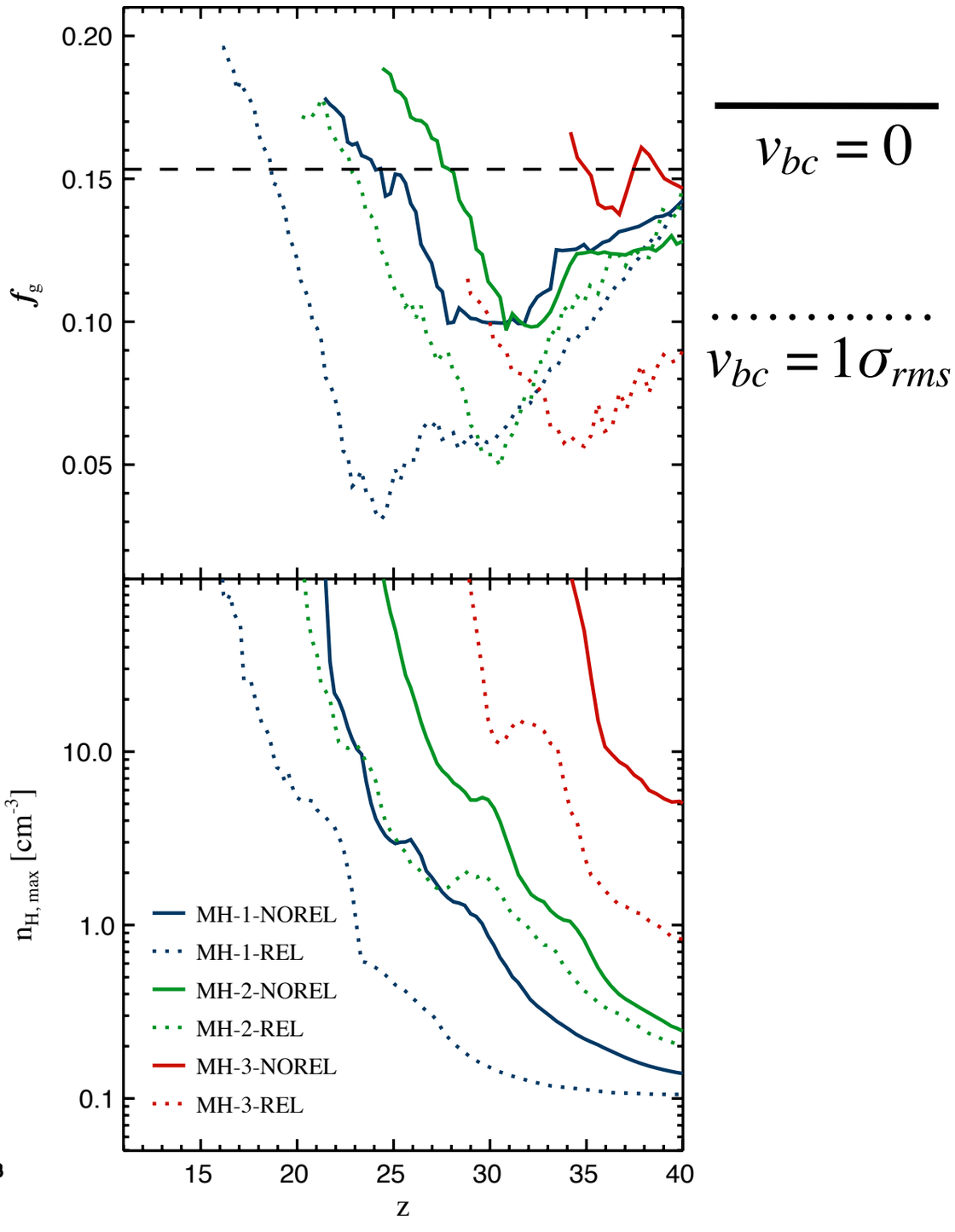
Decrease in baryon fraction

- simulations with gas, but no chemistry



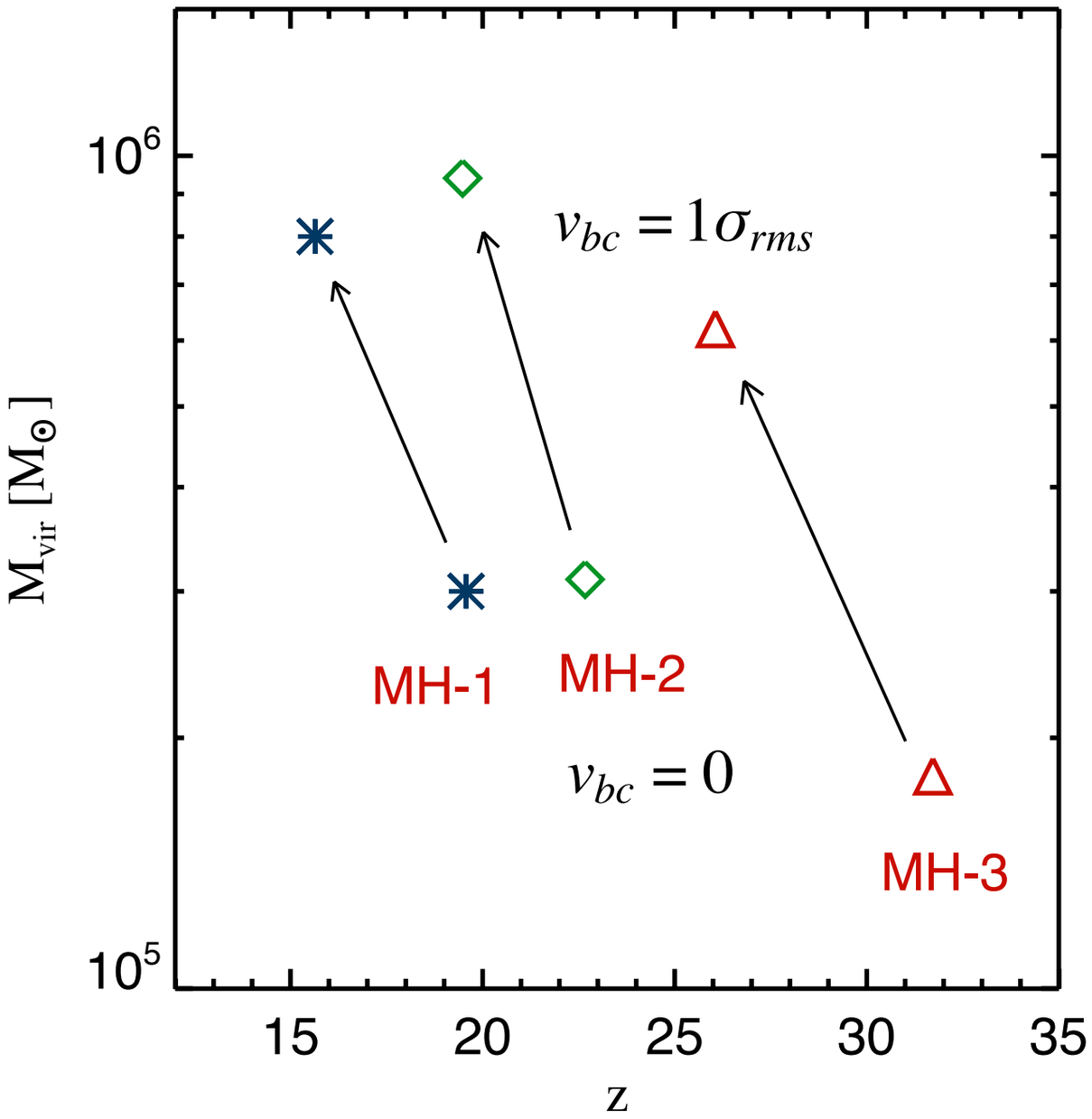
Naoz et al. 2013

- full hydrodynamics & chemistry

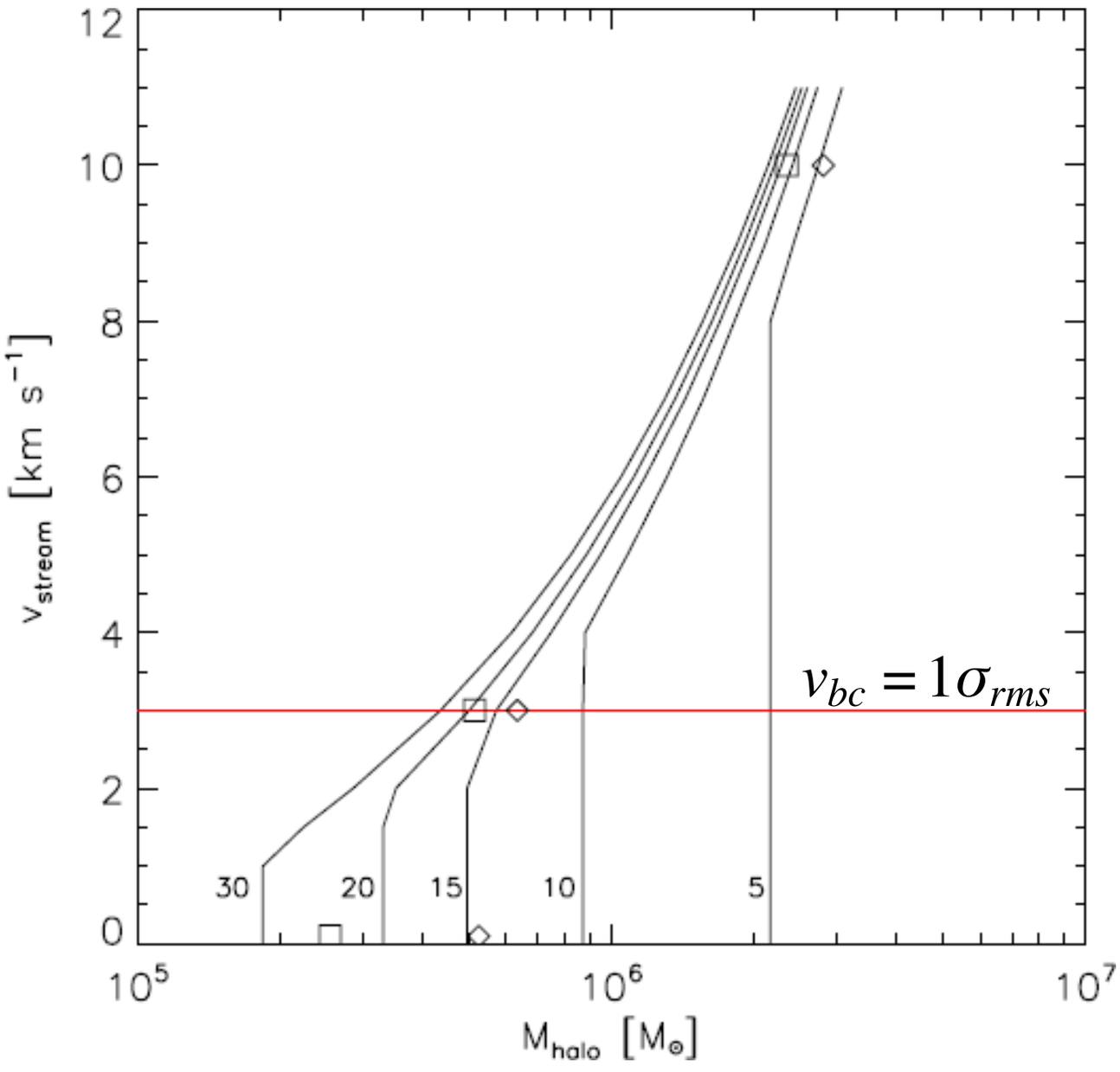


Greif et al. 2011

Increase in halo mass + SF delay



Greif+11

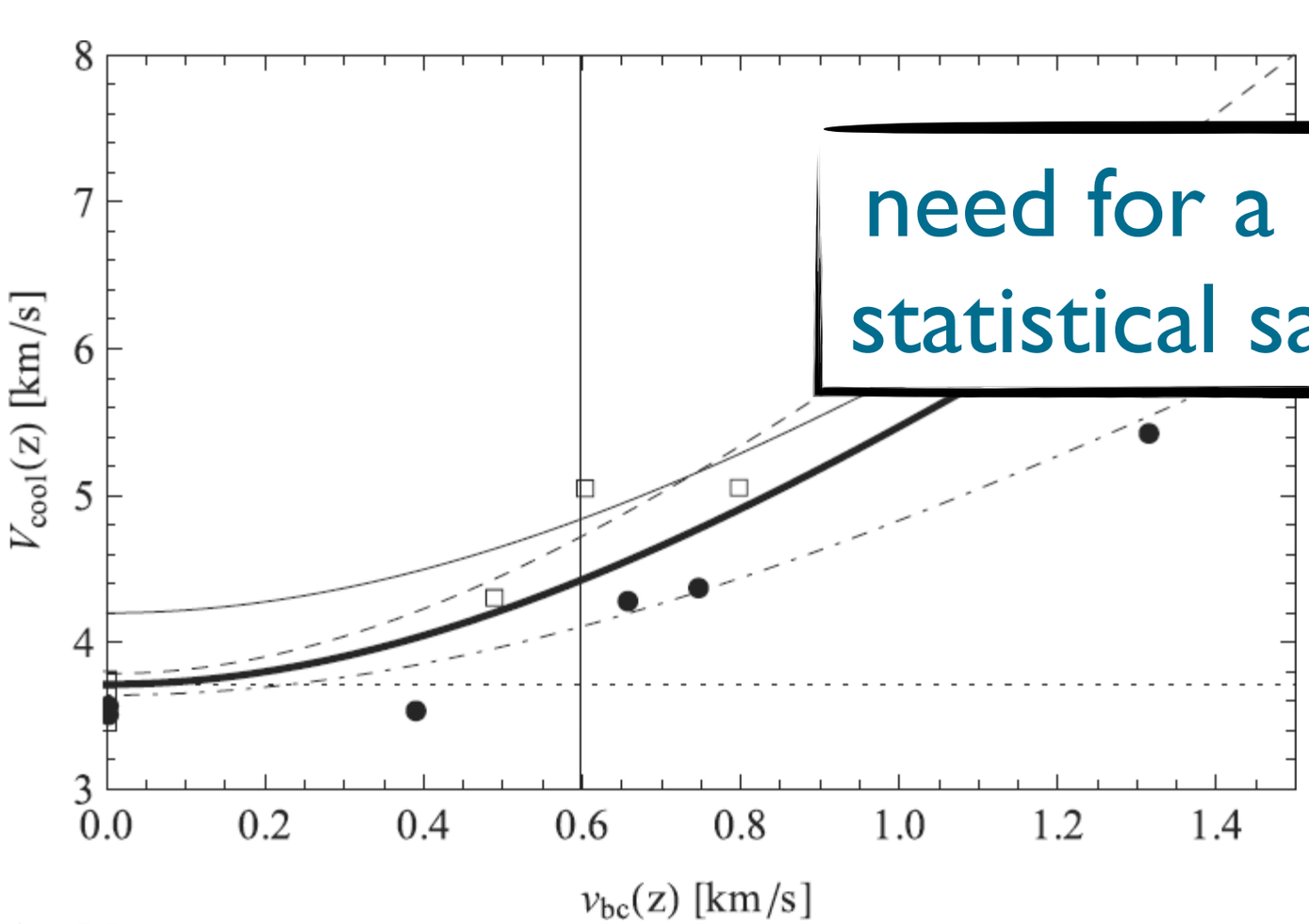


Stacy+11

Increase in halo mass + SF delay

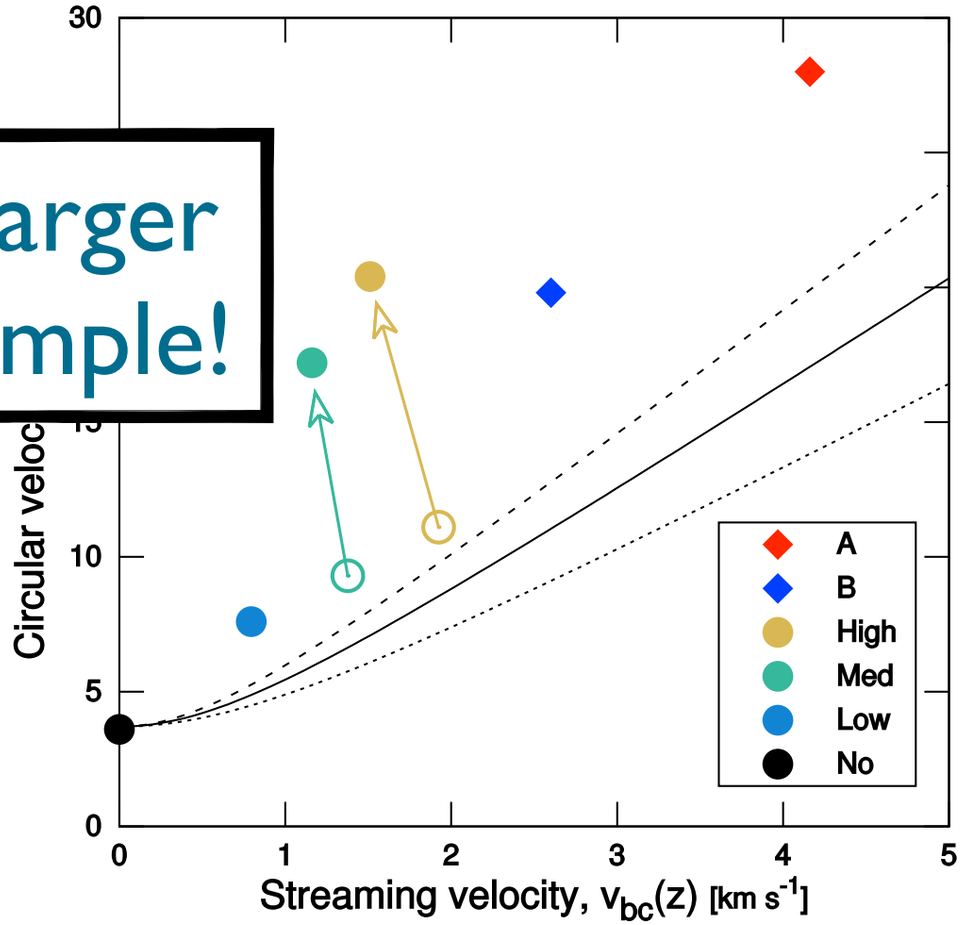
- quantification of the halo mass by its circular velocity: $v_{circ,0} = \sqrt{\frac{G\,M_{vir}}{R_{vir}}}$
- modification of circular velocity with streaming velocity:

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



Fialkov+12

need for a larger statistical sample!



Hirano+18

Our simulations

redshift range: z = 200 -> 14

box size: (1 cMpc/h)^3

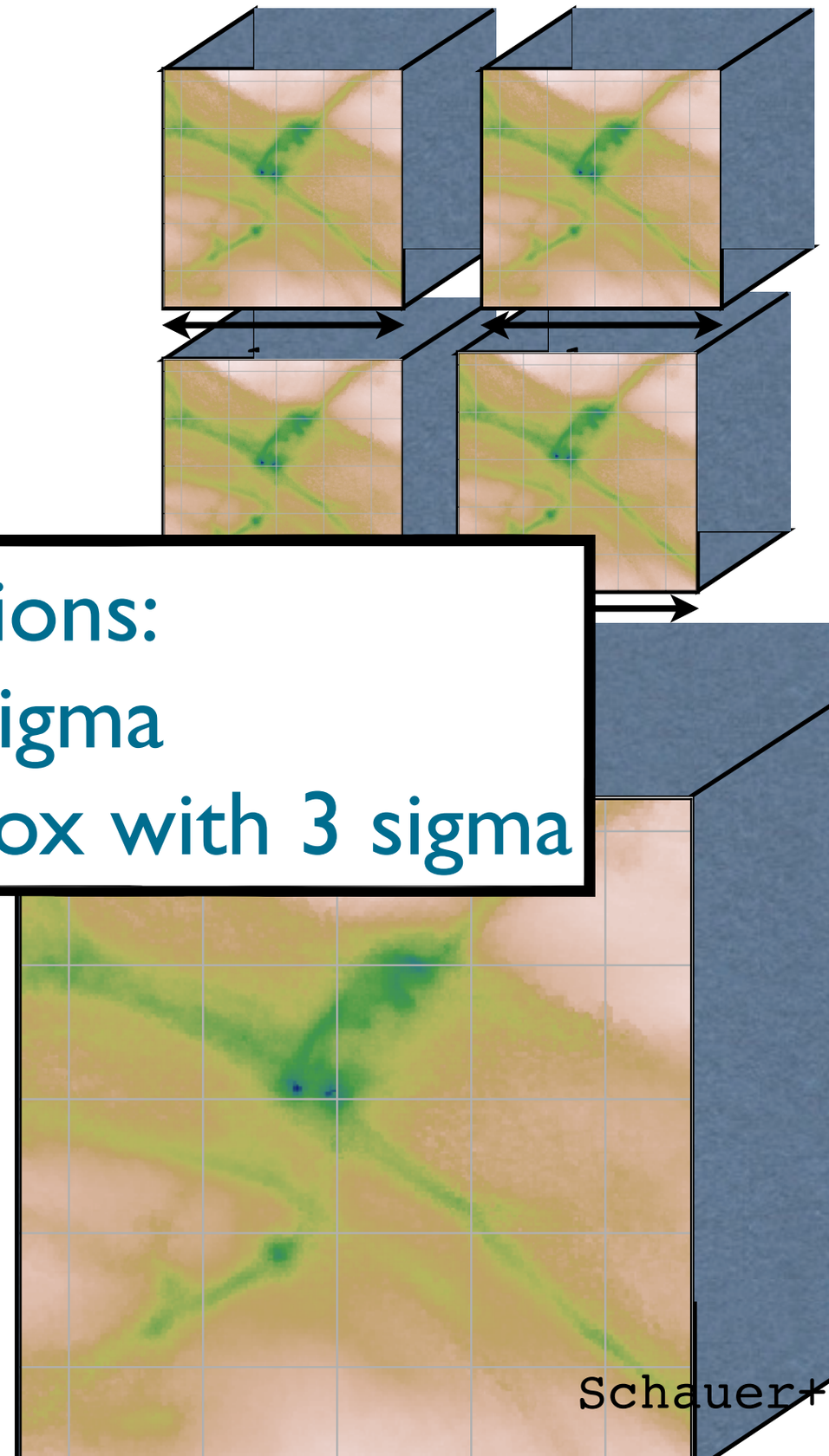
DM particle / cells:

mass resolu

99 $M_\odot$ (DM)

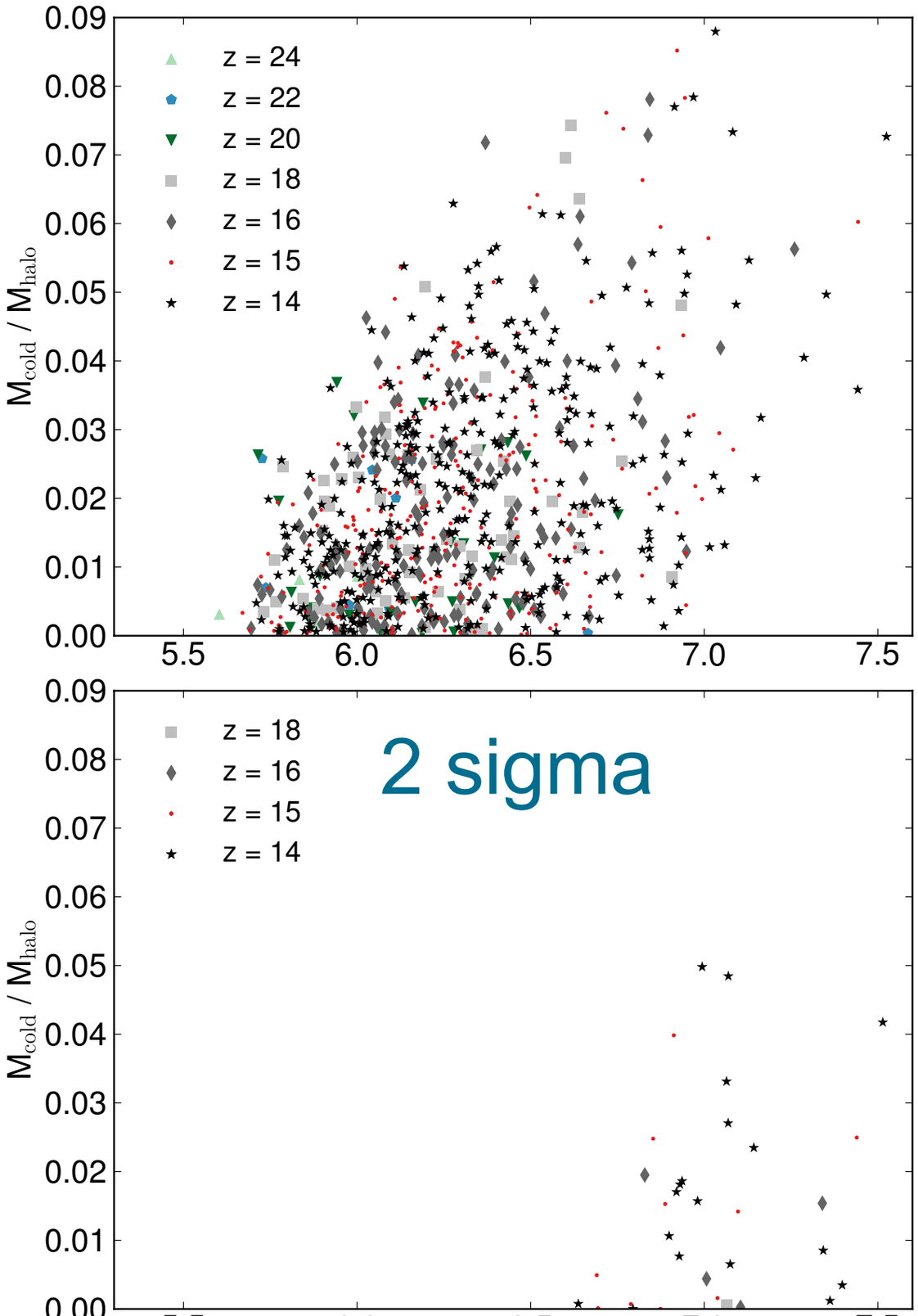
smoothing length: 20 cpc/h (2 pc at z=15)

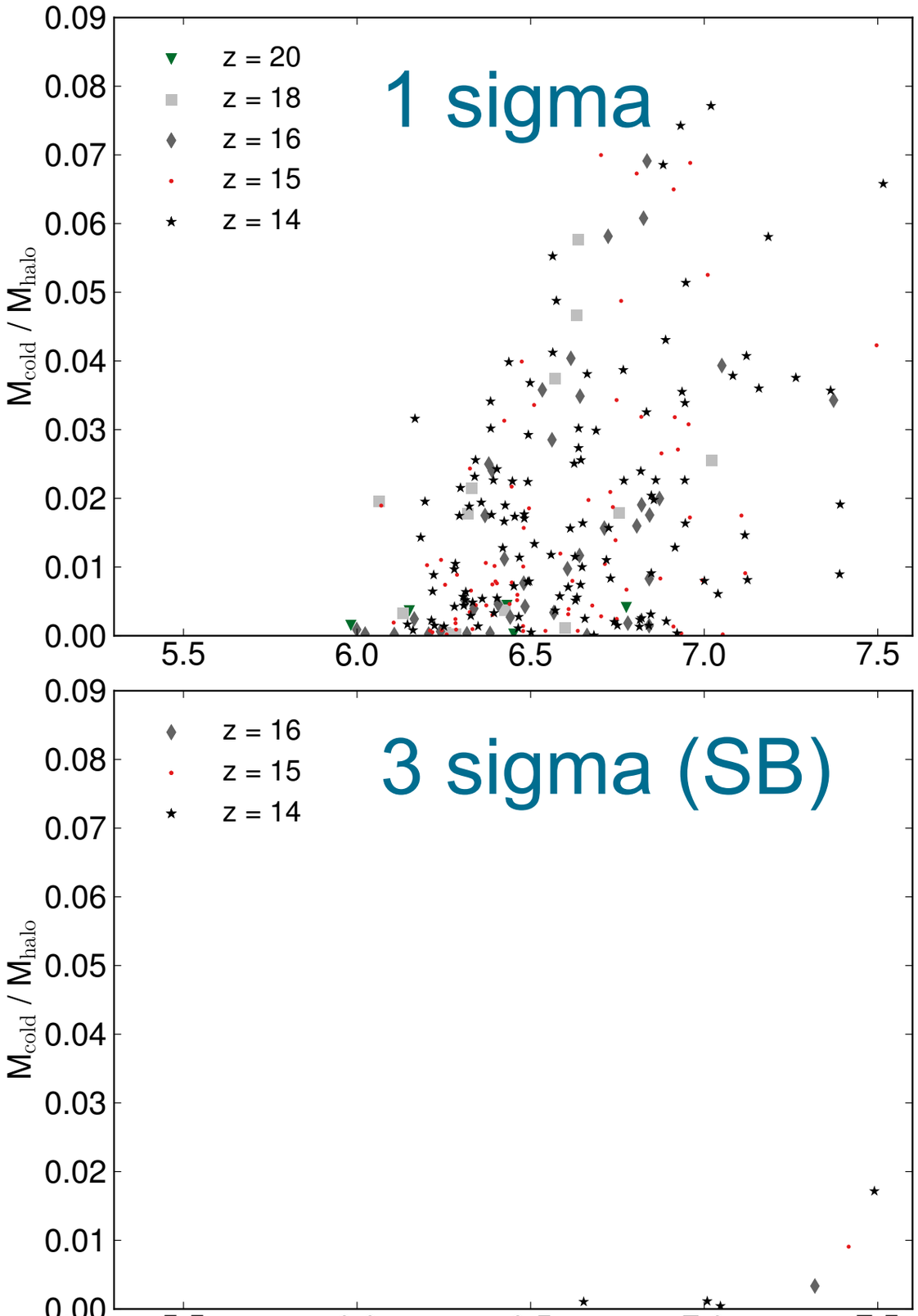
5 simulations:
0, 1, 2, 3 sigma
one large 4cMpc/h box with 3 sigma



Schauer+ 2018

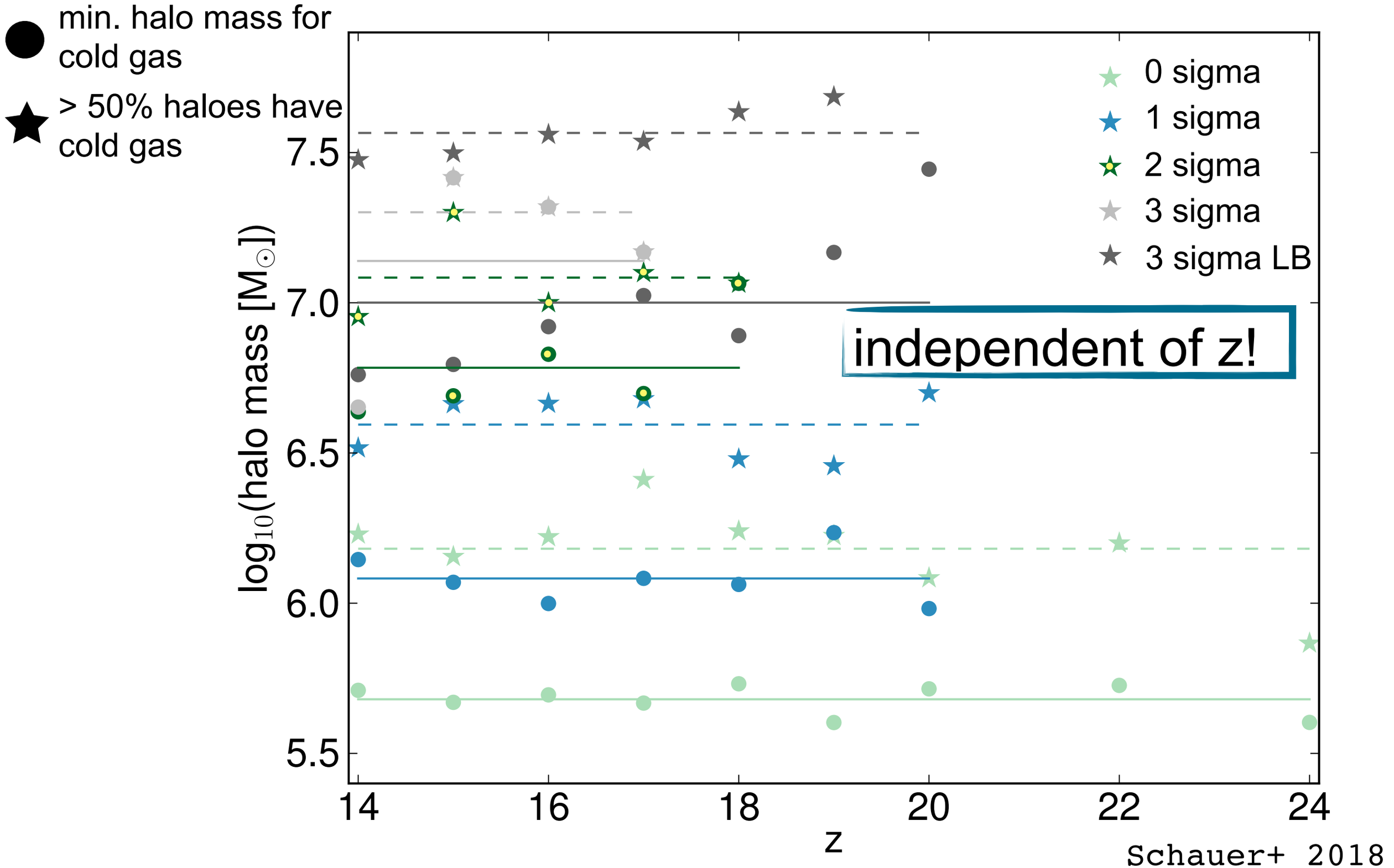
cold mass - halo mass: streaming



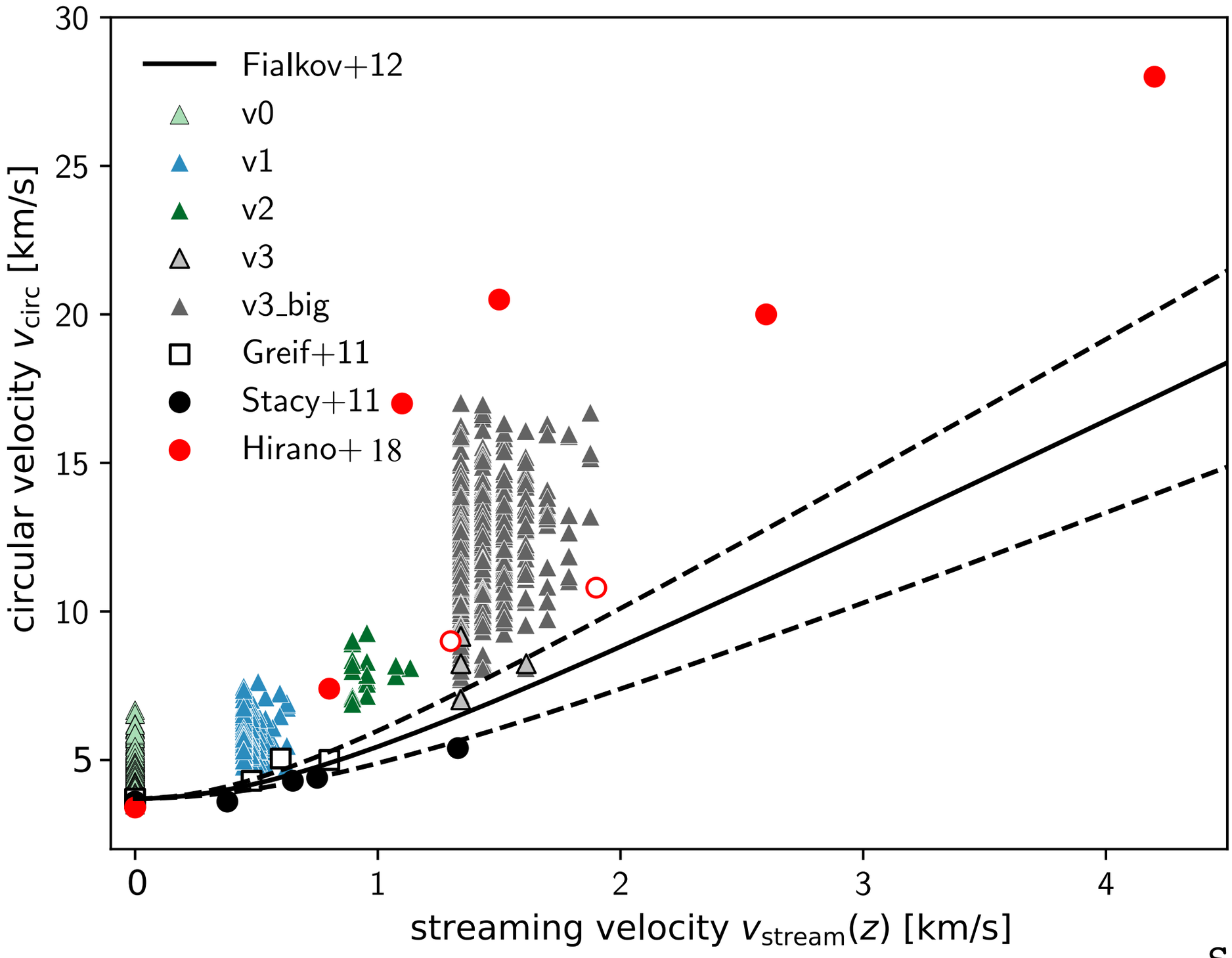


Schauer+ 2018

halo masses of cold halos: streaming

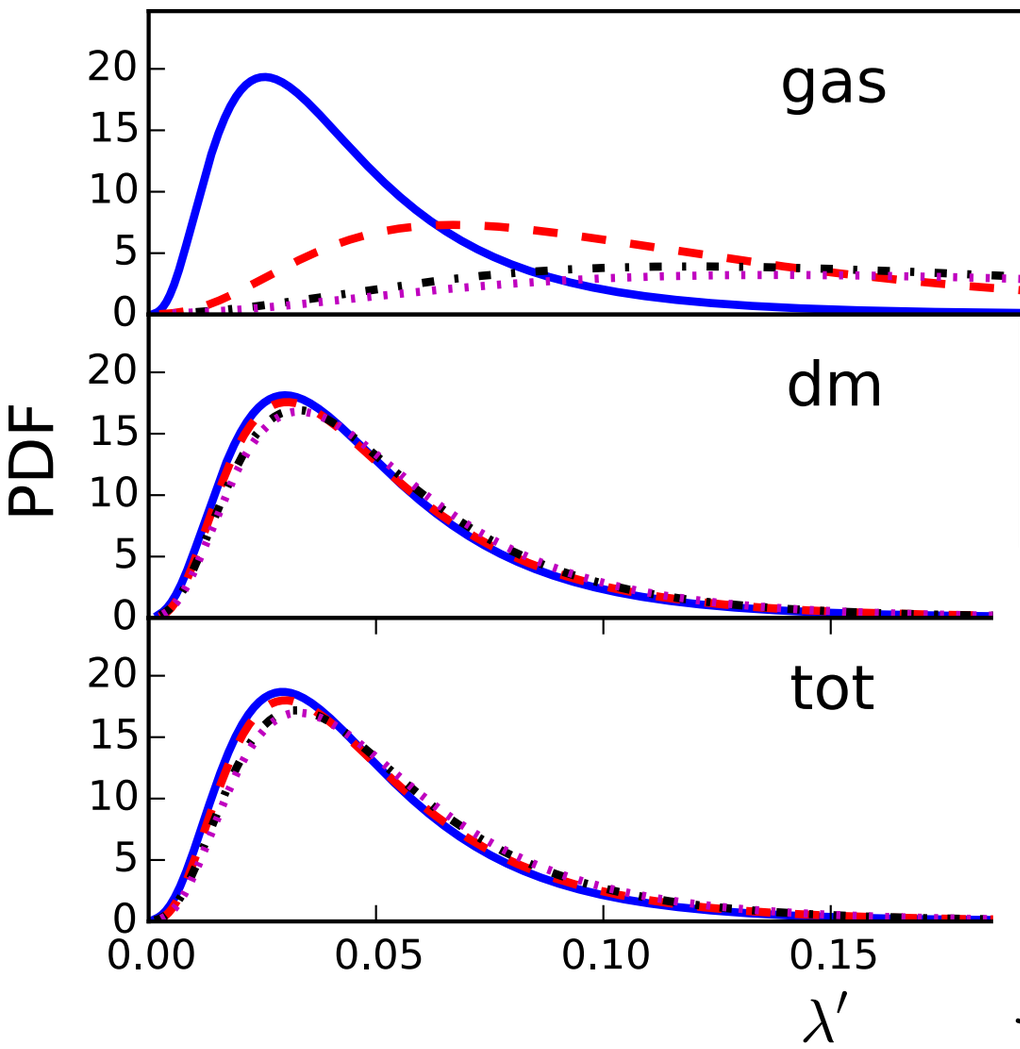


halo masses of cold halos: streaming

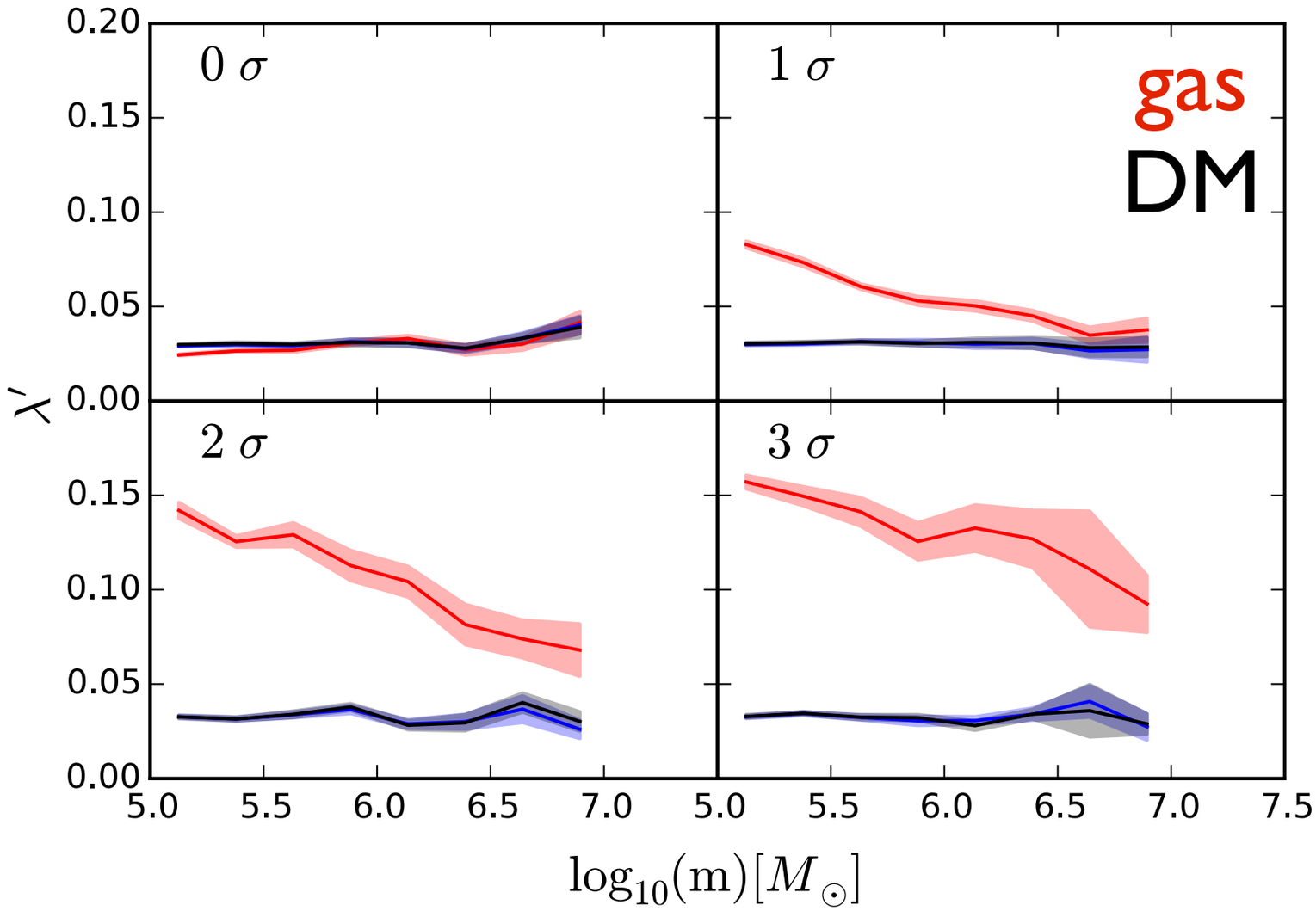


Schauer+ 2018

spin of minihaloes in streaming regions



- dark matter: spin follows log normal distribution
- spin parameter of gas gets larger with streaming motion



- mass dependence for streaming velocity regions: higher spin in smaller haloes

Druschke, Schauer+ in prep.

Conclusions

- Minimum minihalo mass for SF > $5 \times 10^5\ M_\odot$
- No correlation between the spin of entire halo and on the central gas cloud scale

  Druschke, Schauer+18
- 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, ArXiv 1811.12920
  - higher gas spin in streaming regions

    Druschke, Schauer+ in prep.
- LW radiation and streaming velocities: soon to come!