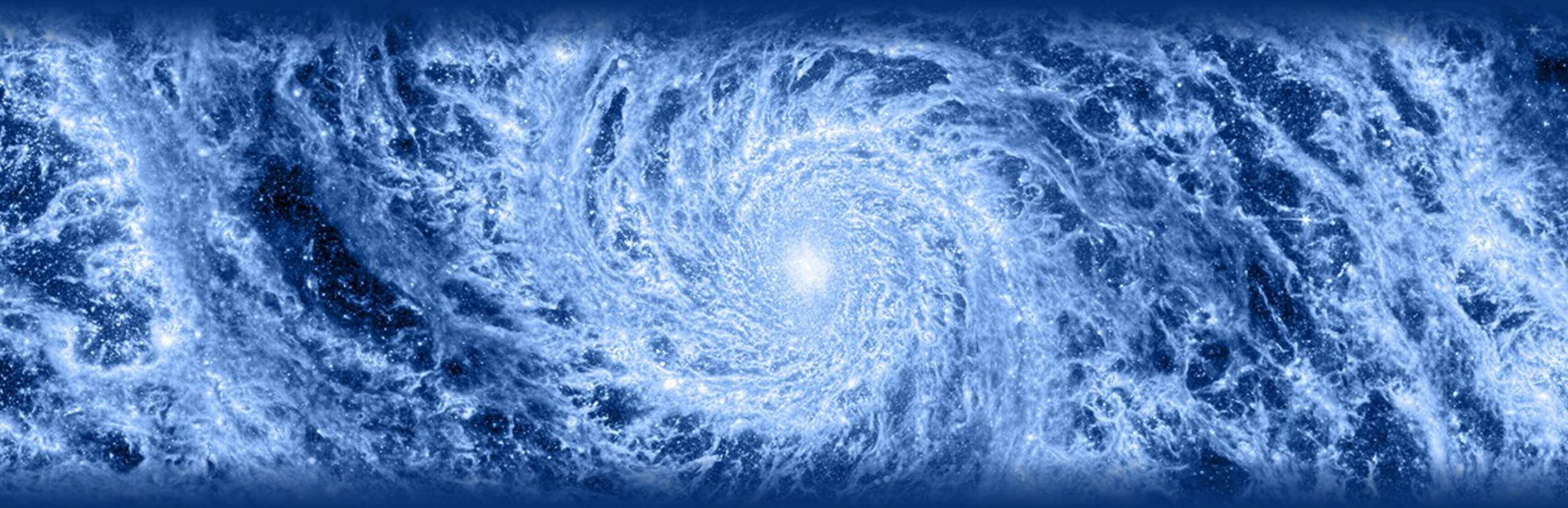
Galaxies

Prof. Benedikt Diemer



Chapter 4 • The formation of dark matter halos

§4.1 • Non-linear growth and halo collapse

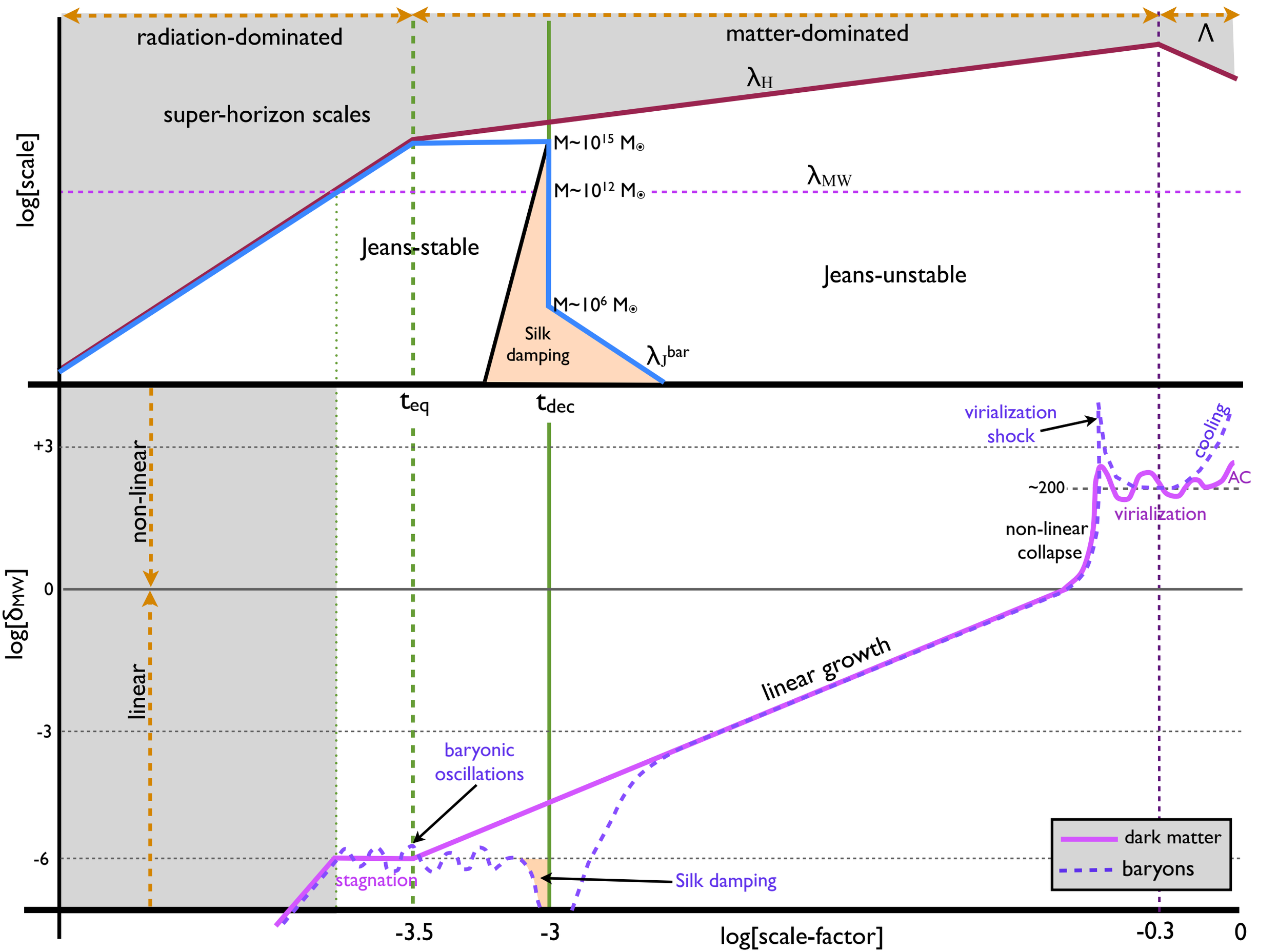
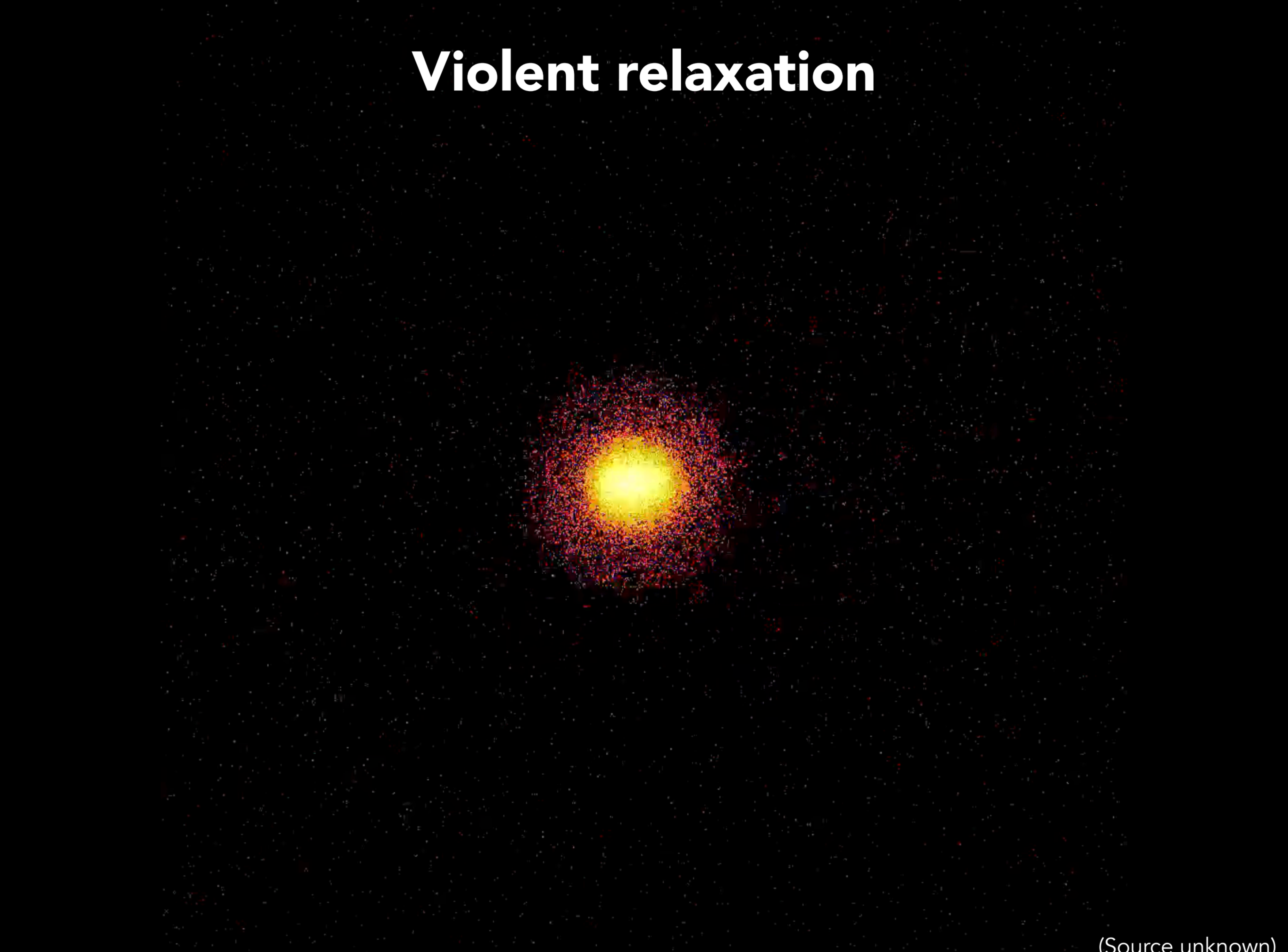


Figure by Frank van den Bosch

Violent relaxation



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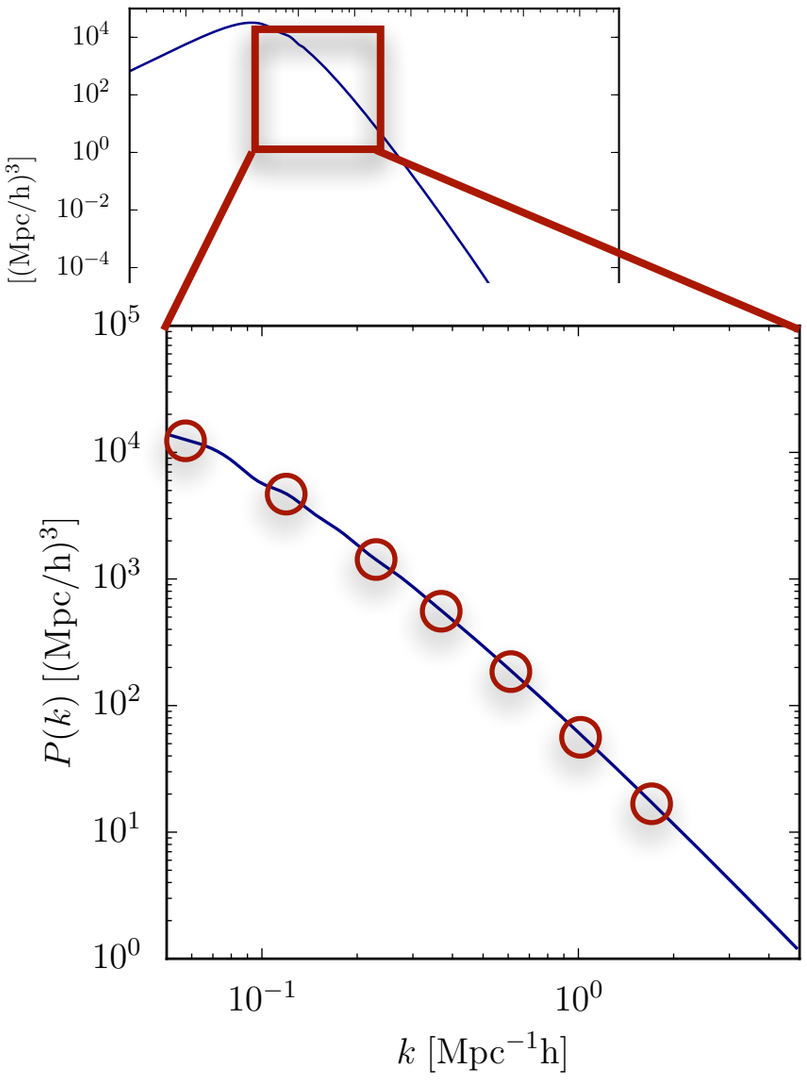
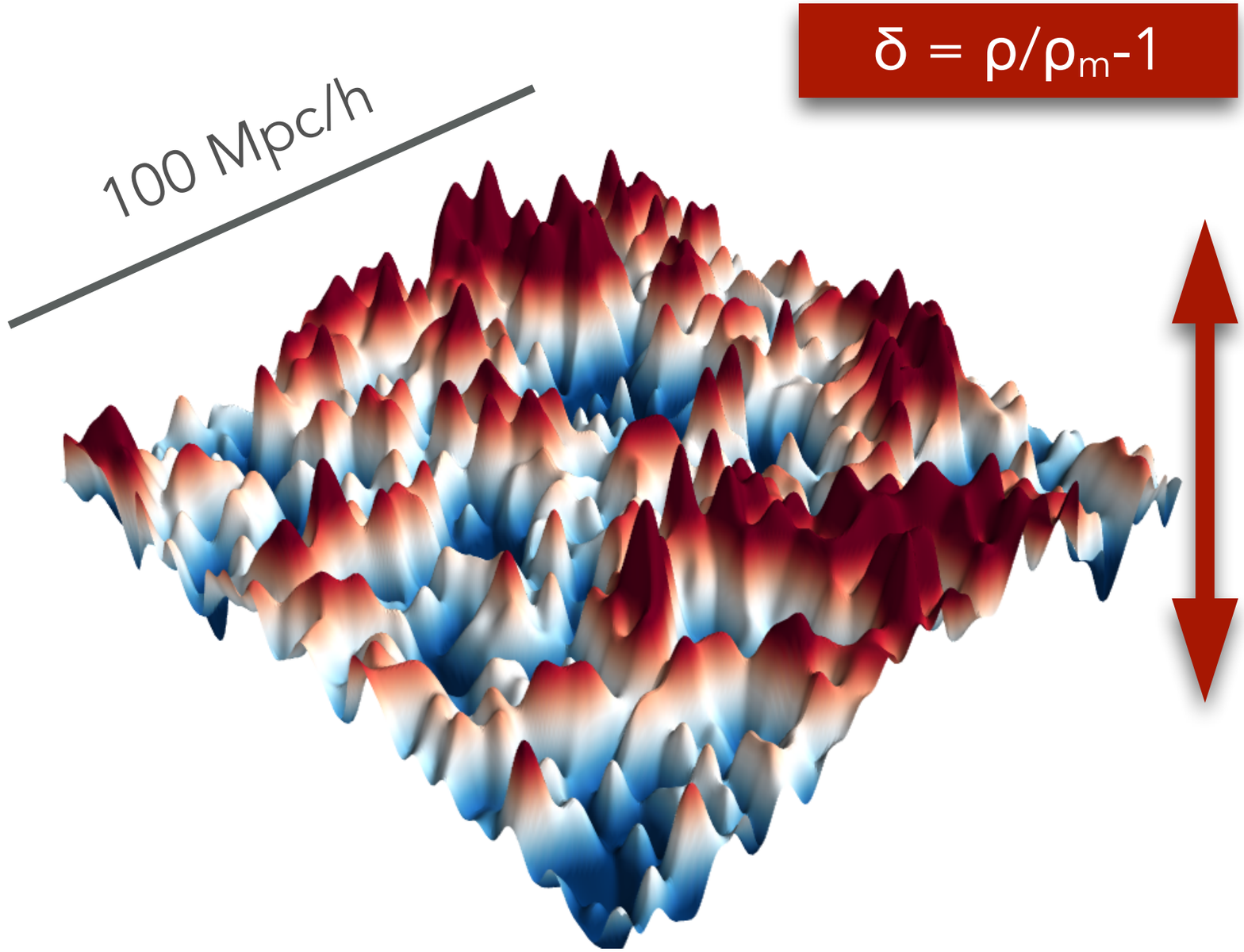
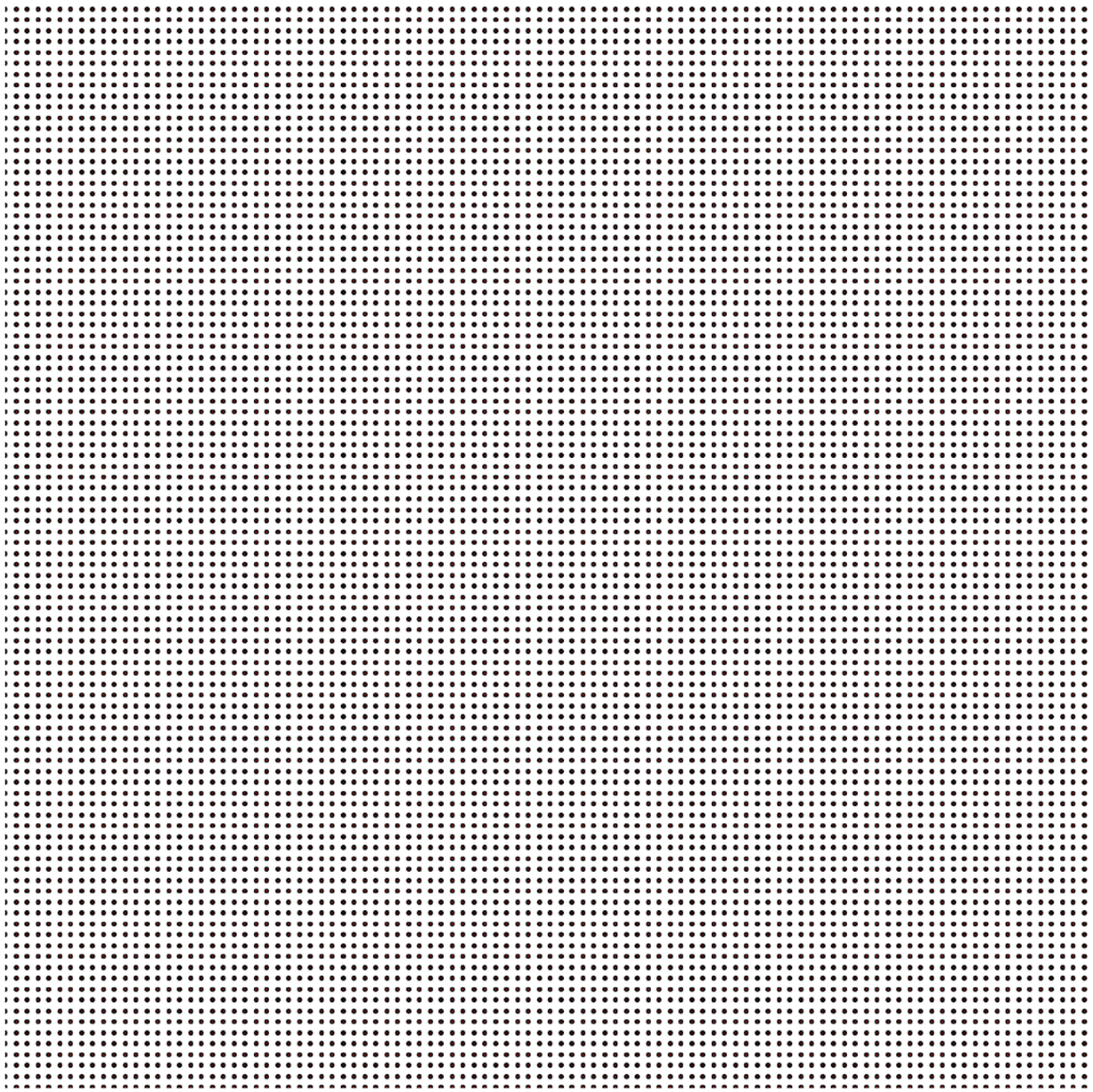
Gaussian random field

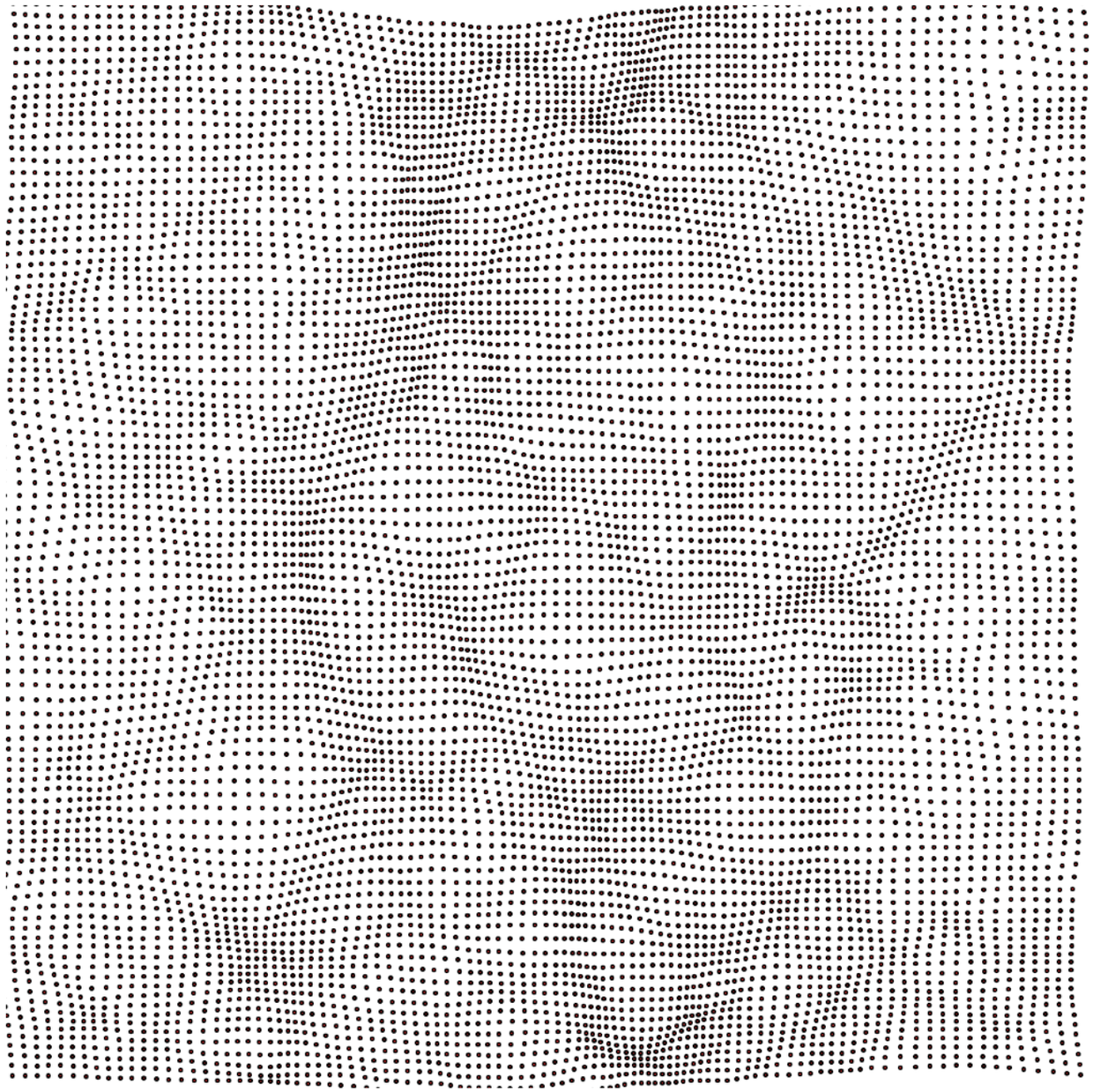




N-body simulations

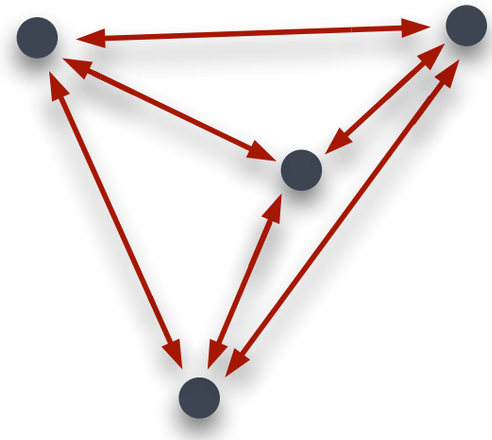


N-body simulations



Simulations of dark matter

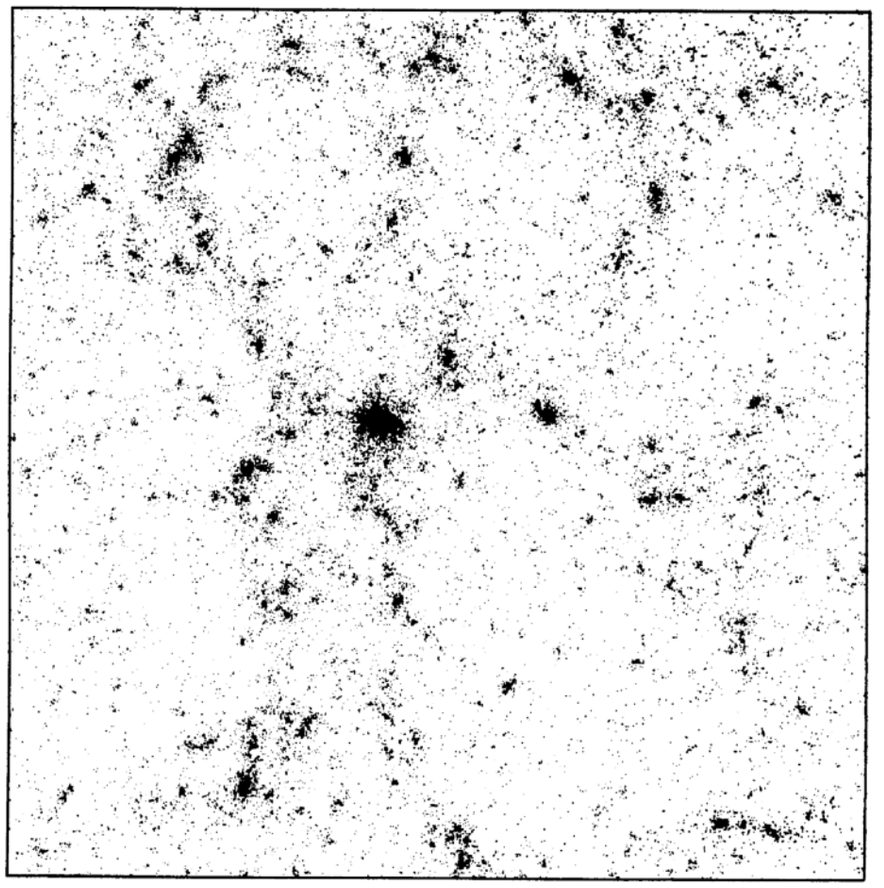
- Simulate the evolution of dark matter in a large **cube of space**
- Start at a time…
  - A while **after recombination**
  - Early enough that **initial fluctuations are still small**
- Physics in equations includes:
  - **Expansion** of Universe, including dark energy
  - **Gravity** of dark matter
  - **No collisions** between dark matter particles
- Solve Newton's law between N particles (**N-body simulation**)
- Compute gravitational force, move particles a bit, and so on



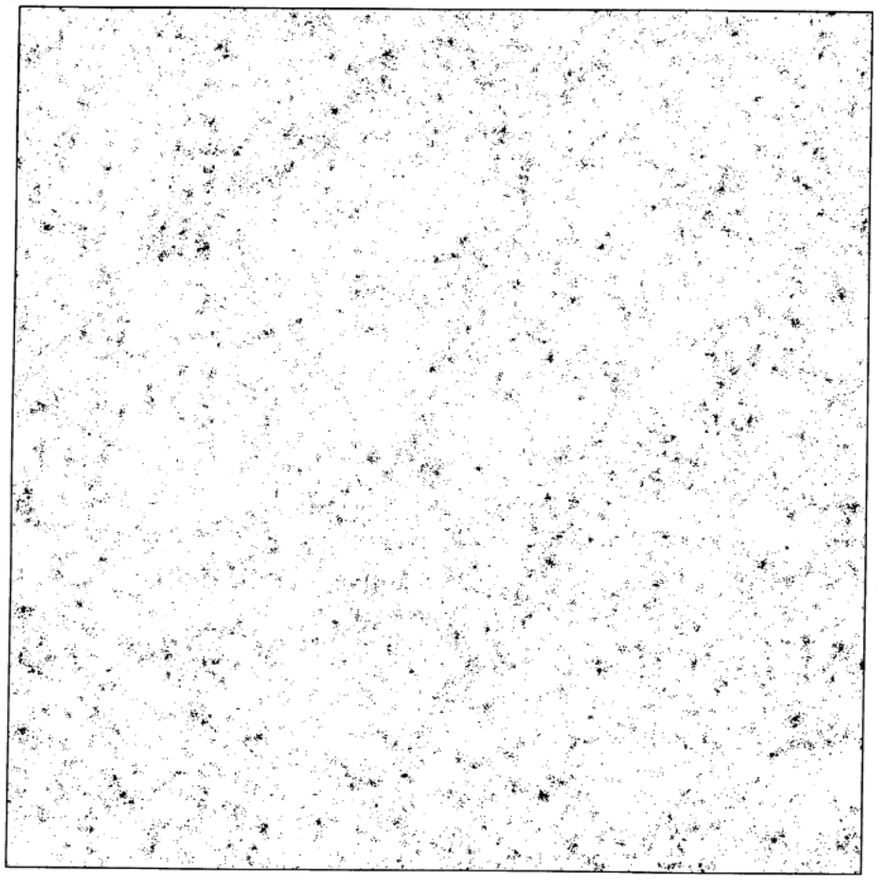
$$F = \frac{Gm_1m_2}{r^2}$$

Efstathiou et al. 1981/1985/1988 • Klypin & Shandarin 1983 • Frenk et al. 1983/1985/1988 • Davis et al. 1985

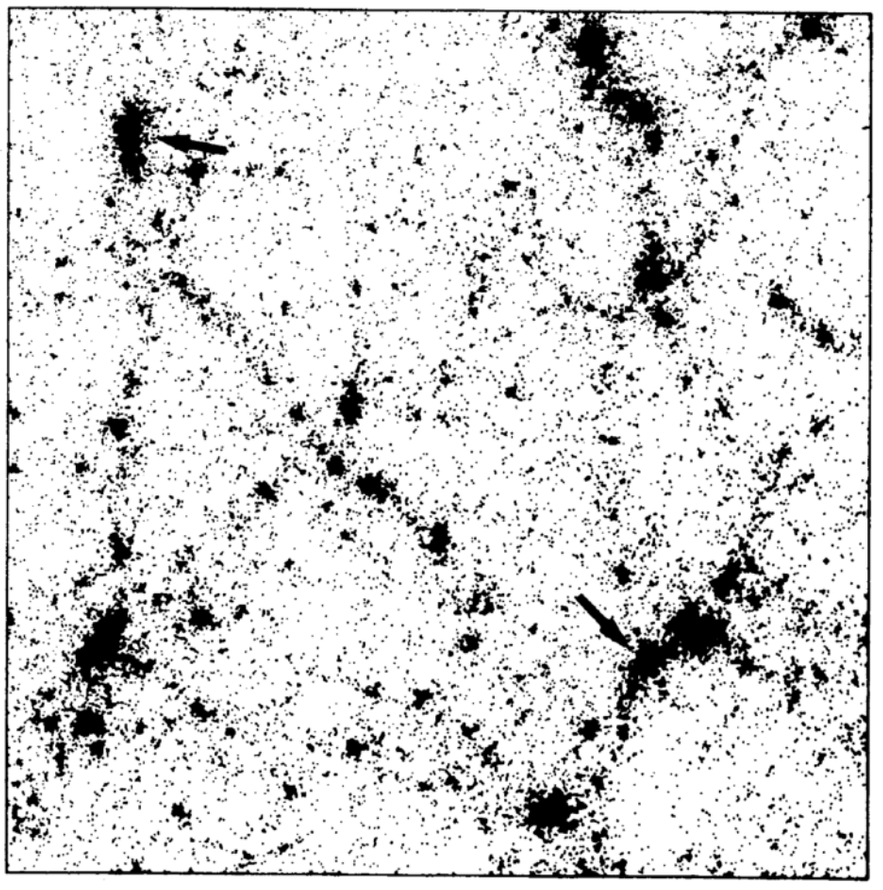
Davis et al. 1985



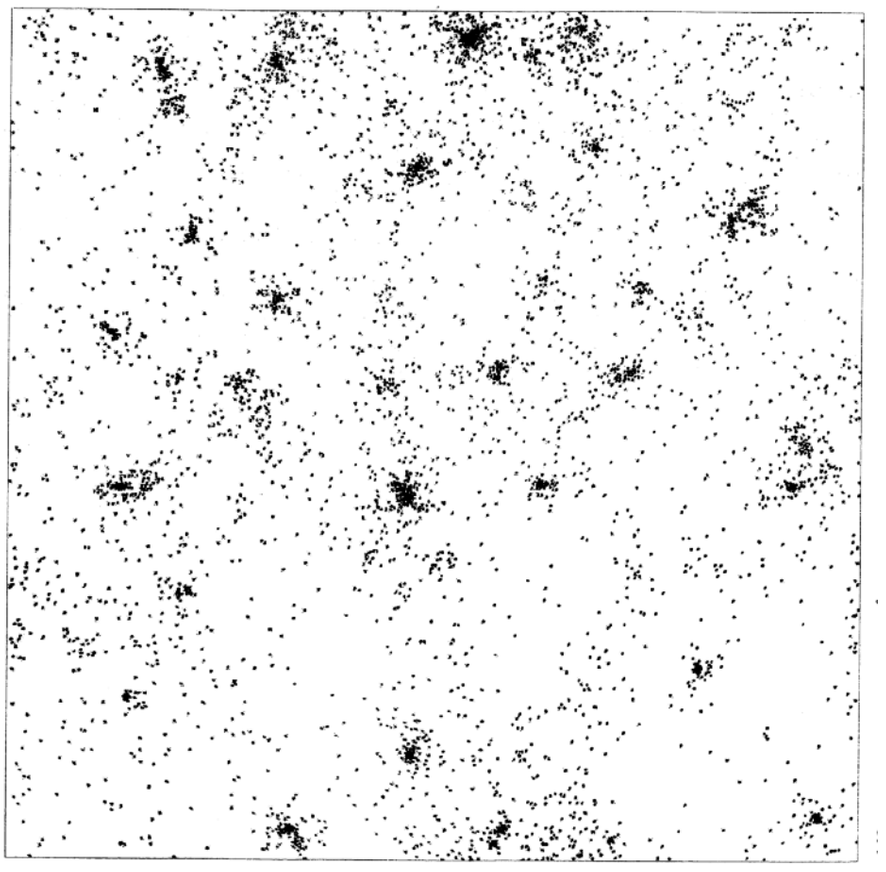
Efstathiou et al. 1981

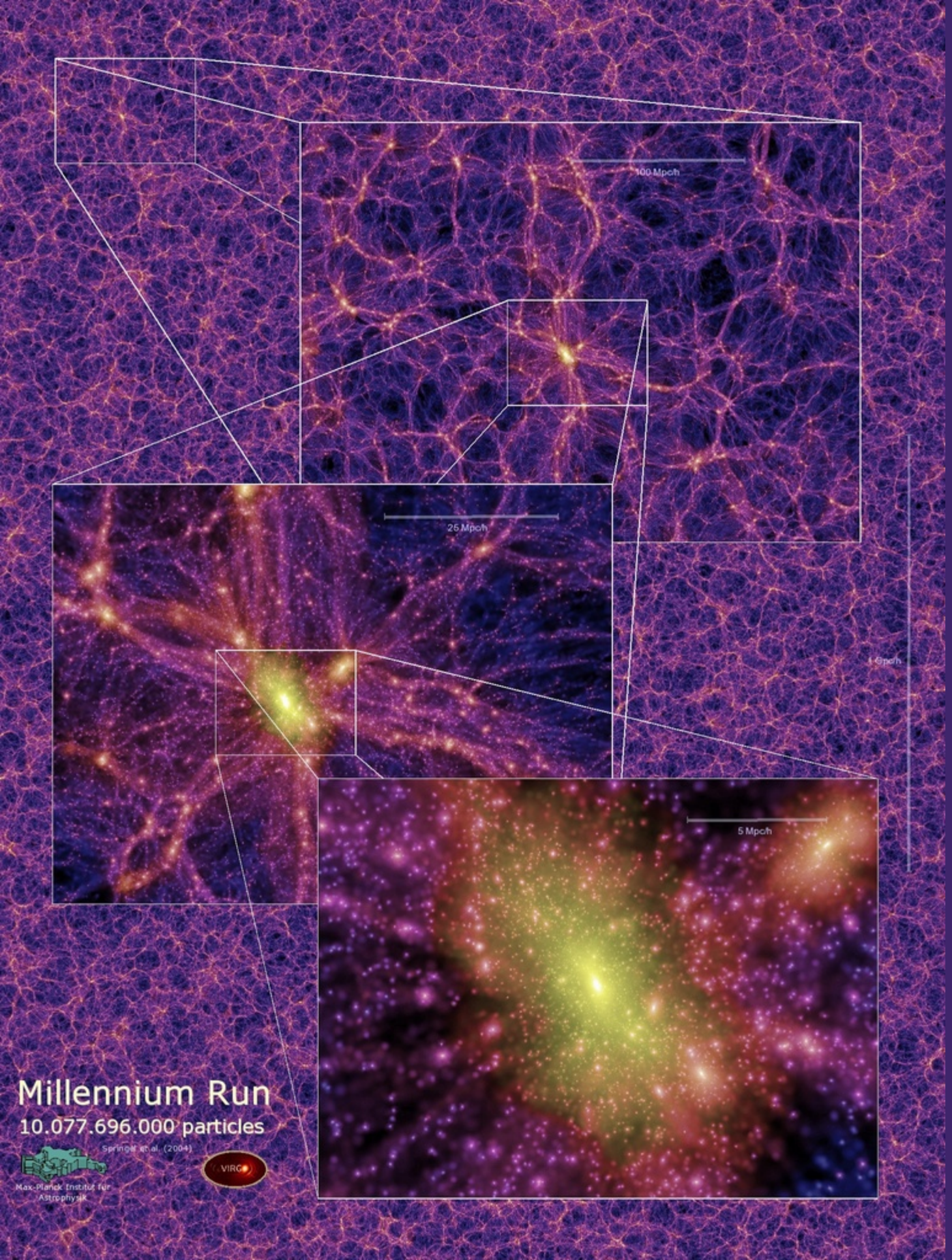


Frenk et al. 1988



Klypin & Shandarin 1983



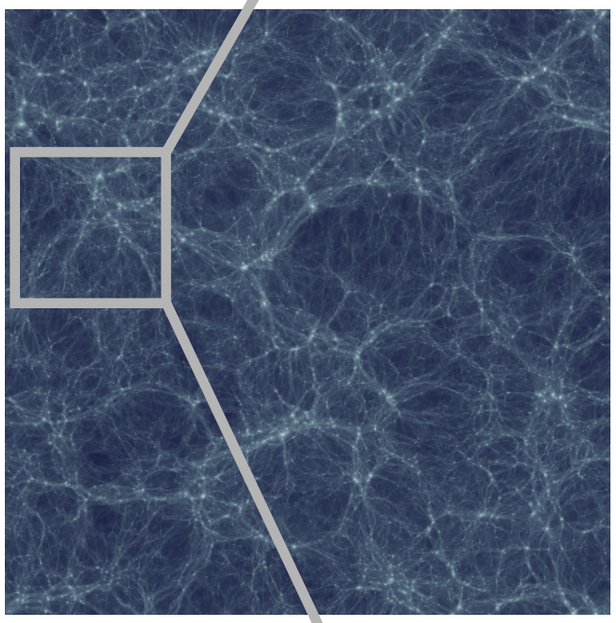


- Millennium Simulation (10 billion particles) was largest for a while
- Today reach **1 trillion** particles

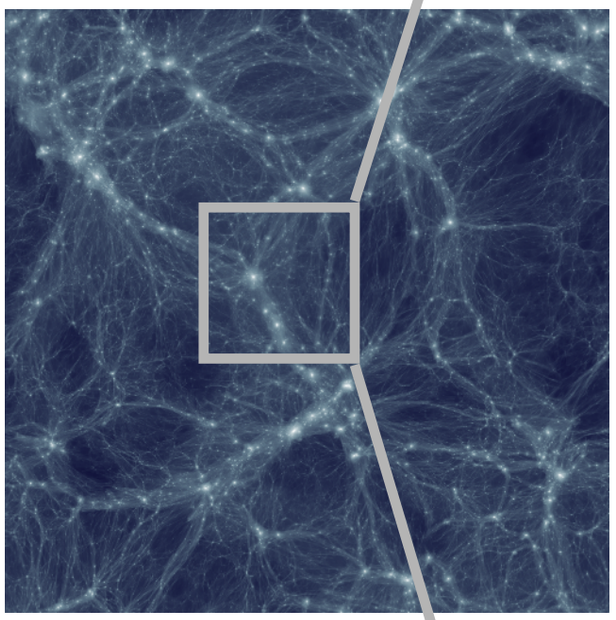
Springel et al. 2005/2008

(movie page)

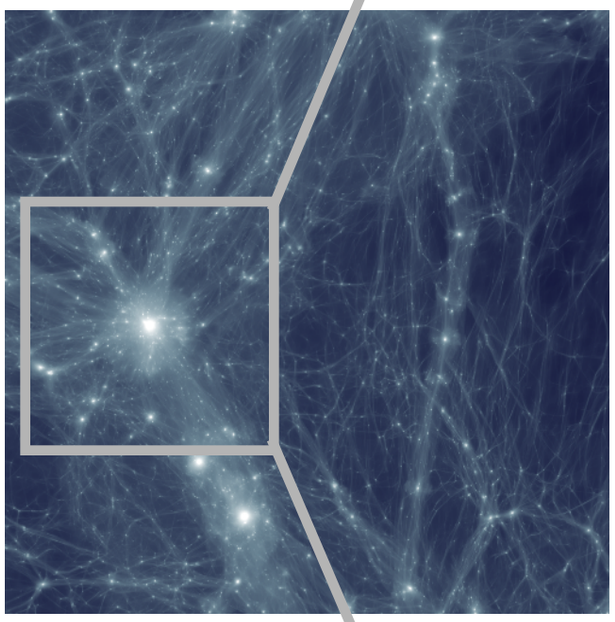
$a = 0.1$
$t = 0.6\ \mathrm{Gyr}$



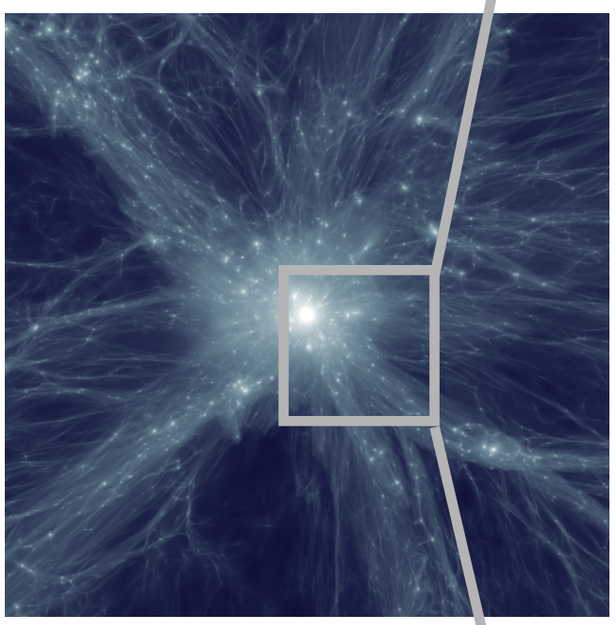
Visualization code:
Phil Mansfield



Visualization code:
Phil Mansfield



Visualization code:
Phil Mansfield



Visualization code:
Phil Mansfield

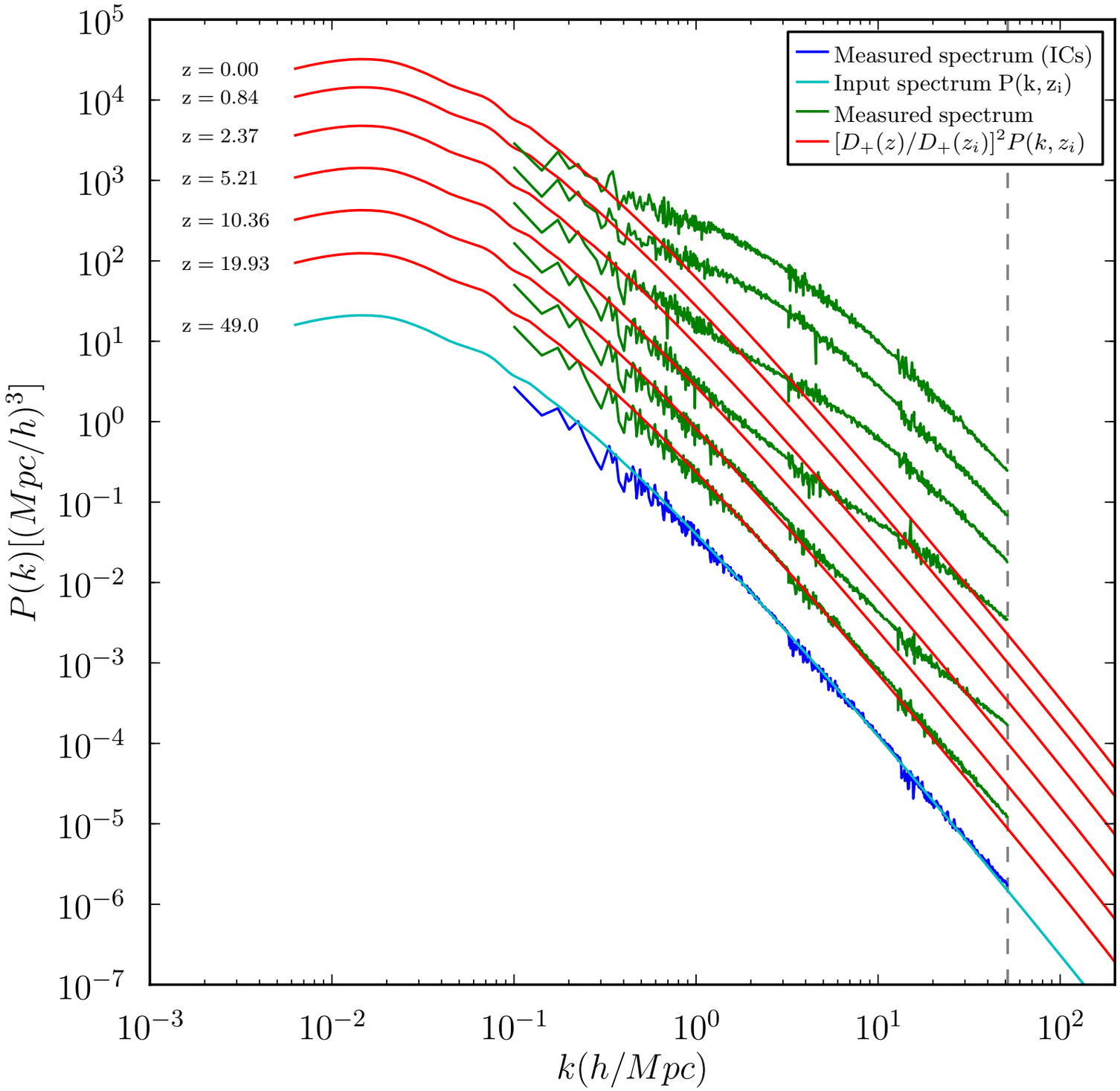
Formation of halos

- Could occur…
  - Top-down: Form big structures first, which fragment to make smaller structures
  - Bottom-up: Form small structures first, which merge into big structures

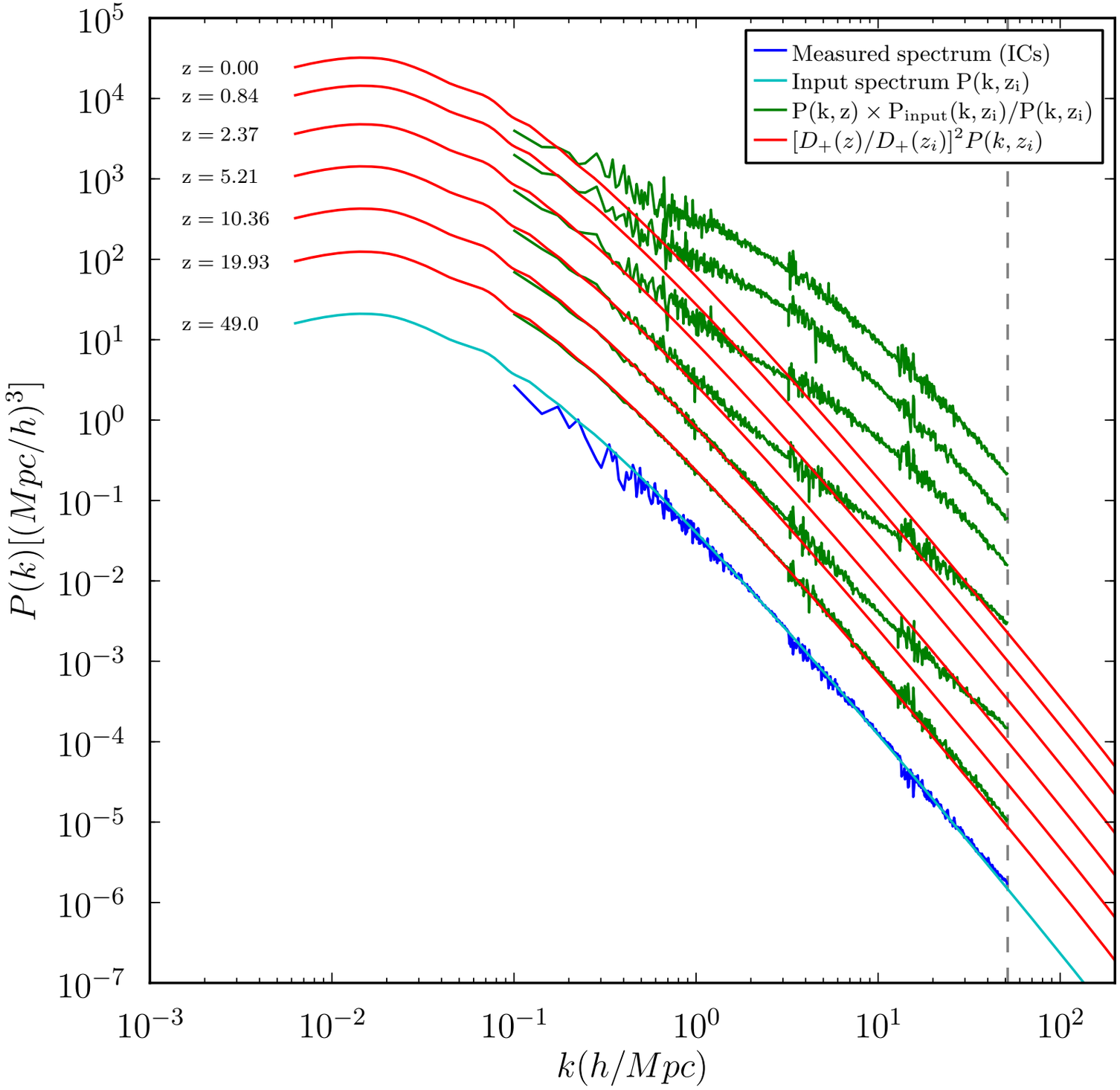
$t = 7.3$ Gyr

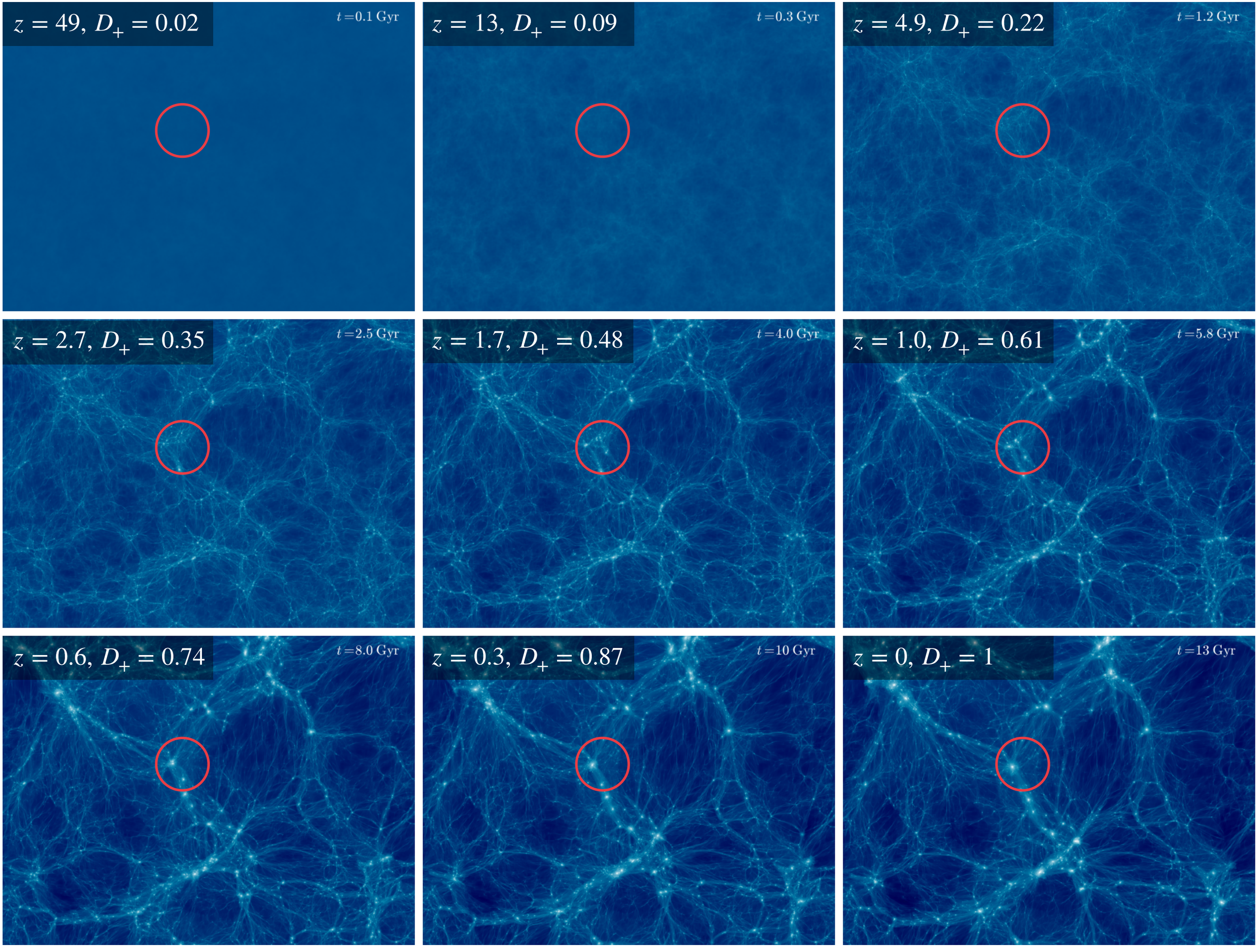
(movie page)

Evolution of power spectrum in simulation



Evolution of power spectrum in simulation




$z = 49$, $D_+ = 0.02$
$t = 0.1$ Gyr
$z = 13$, $D_+ = 0.09$
$t = 0.3$ Gyr
$z = 4.9$, $D_+ = 0.22$
$t = 1.2$ Gyr
$z = 2.7$, $D_+ = 0.35$
$t = 2.5$ Gyr
$z = 1.7$, $D_+ = 0.48$
$t = 4.0$ Gyr
$z = 1.0$, $D_+ = 0.61$
$t = 5.8$ Gyr
$z = 0.6$, $D_+ = 0.74$
$t = 8.0$ Gyr
$z = 0.3$, $D_+ = 0.87$
$t = 10$ Gyr
$z = 0$, $D_+ = 1$
$t = 13$ Gyr

§4.1.1 • The tophat collapse model

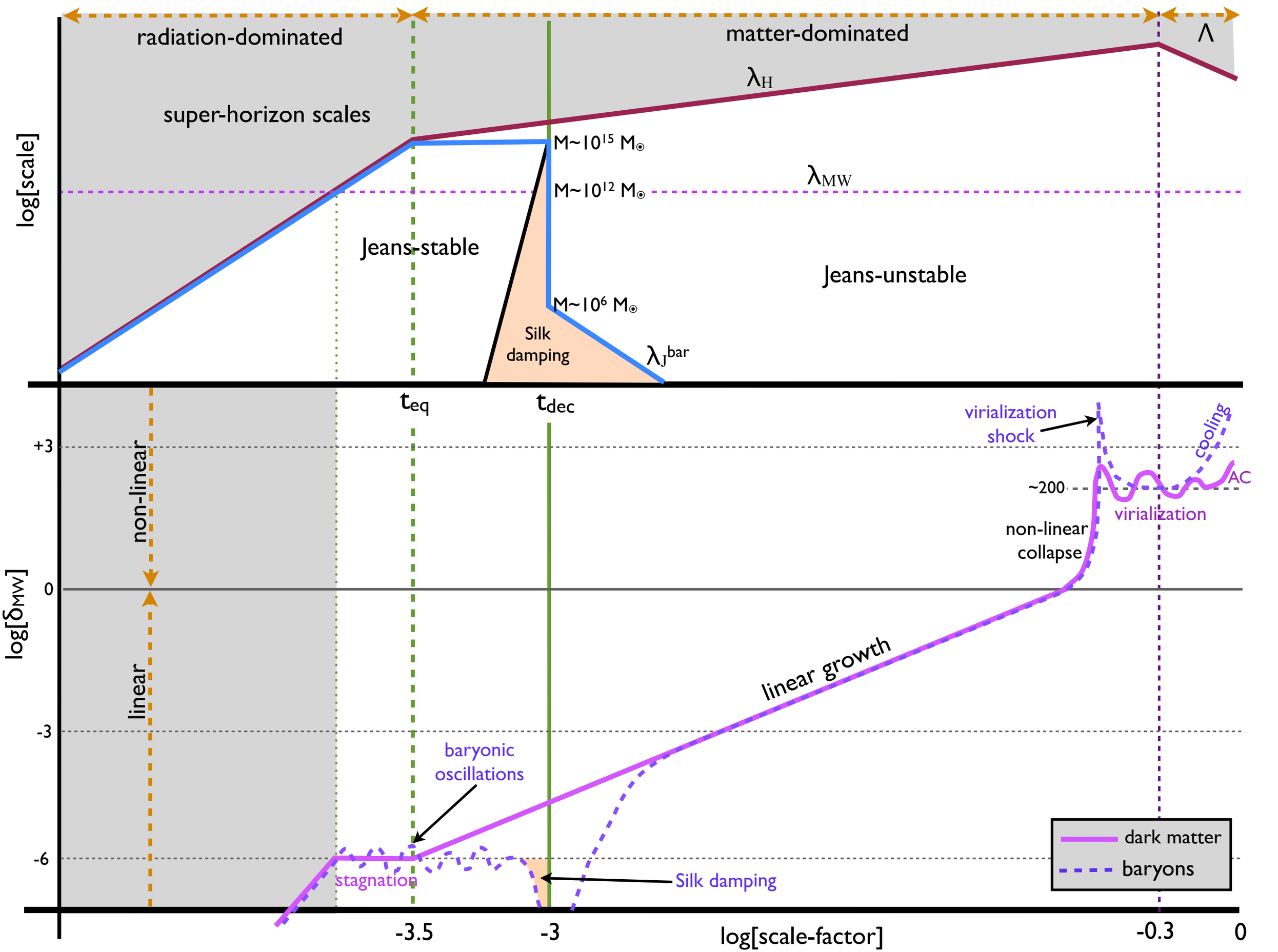
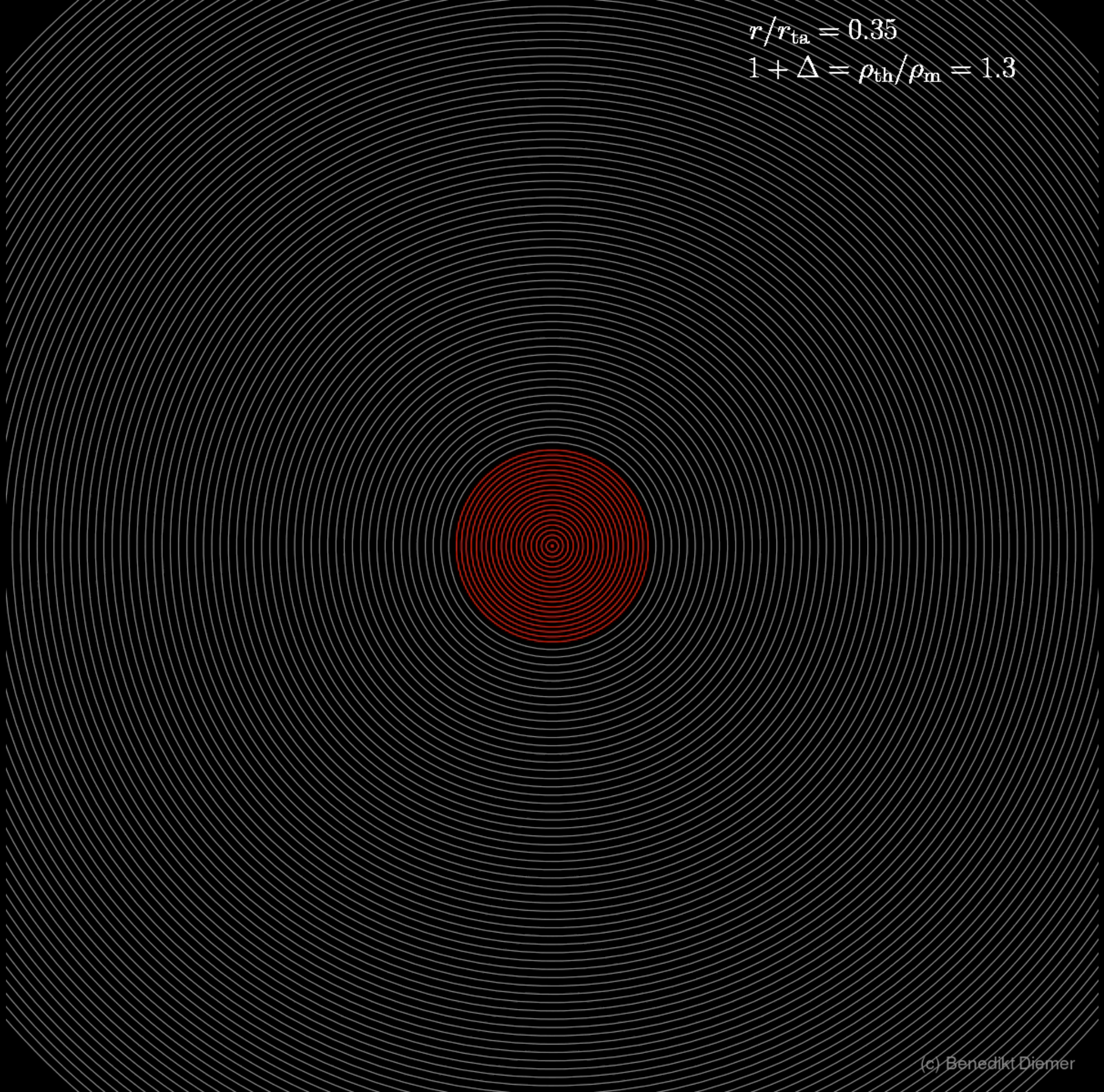


Figure by Frank van den Bosch



(movie page)

Tophat collapse model

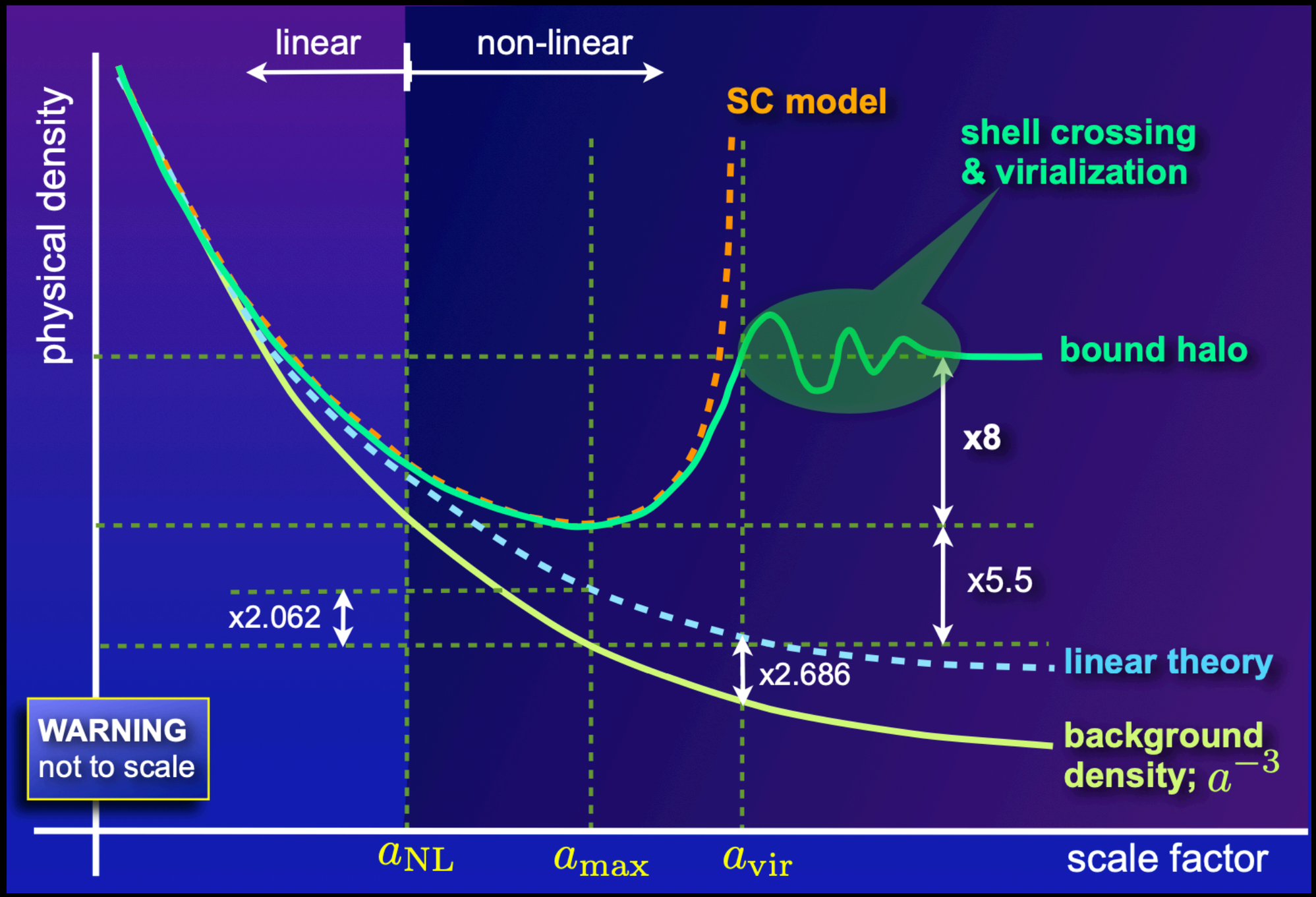
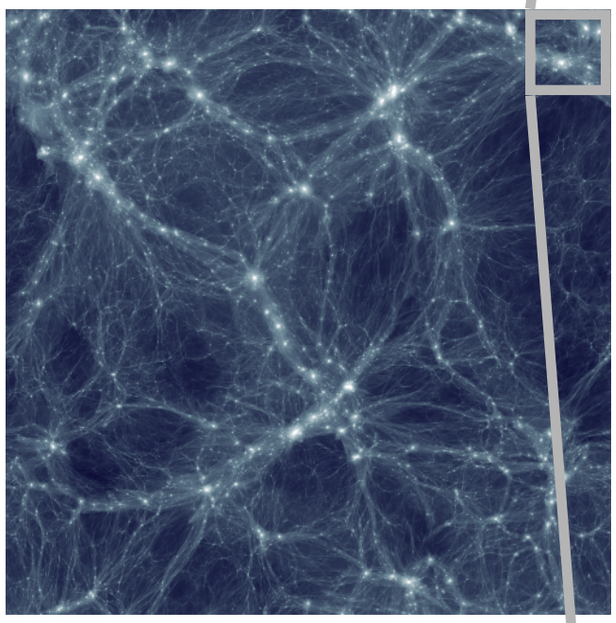
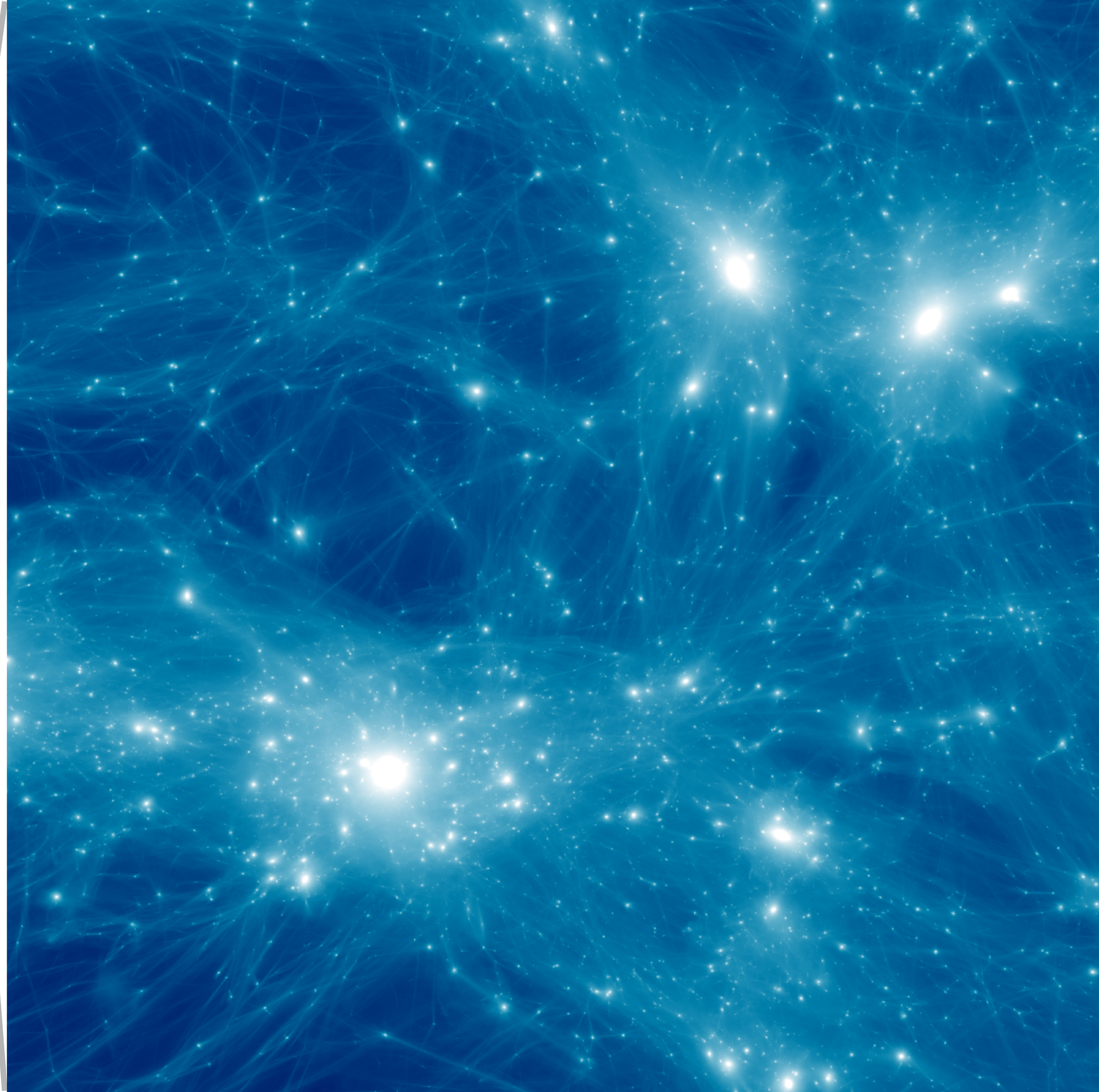


Figure by Frank van den Bosch

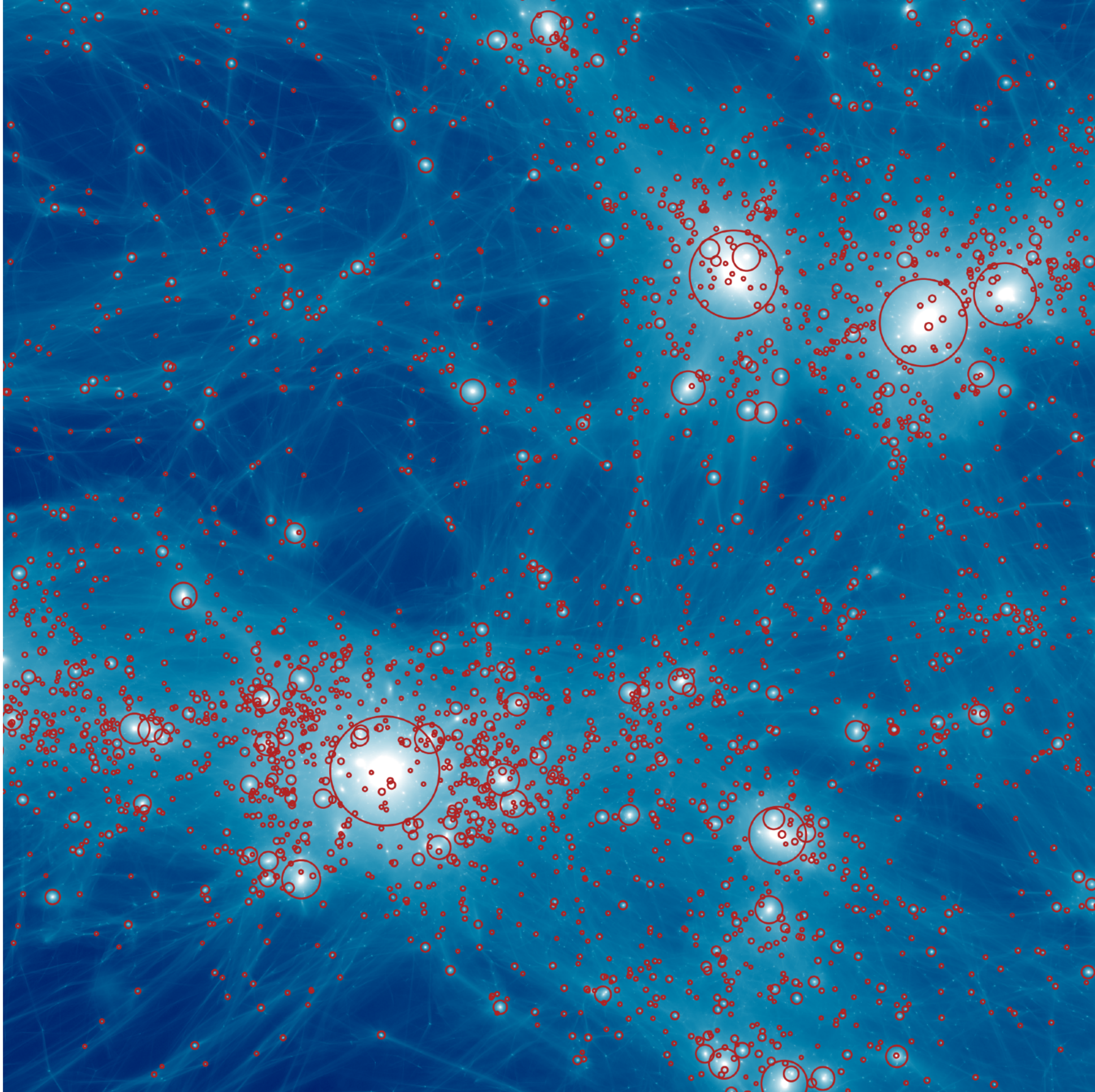
11 Mpc





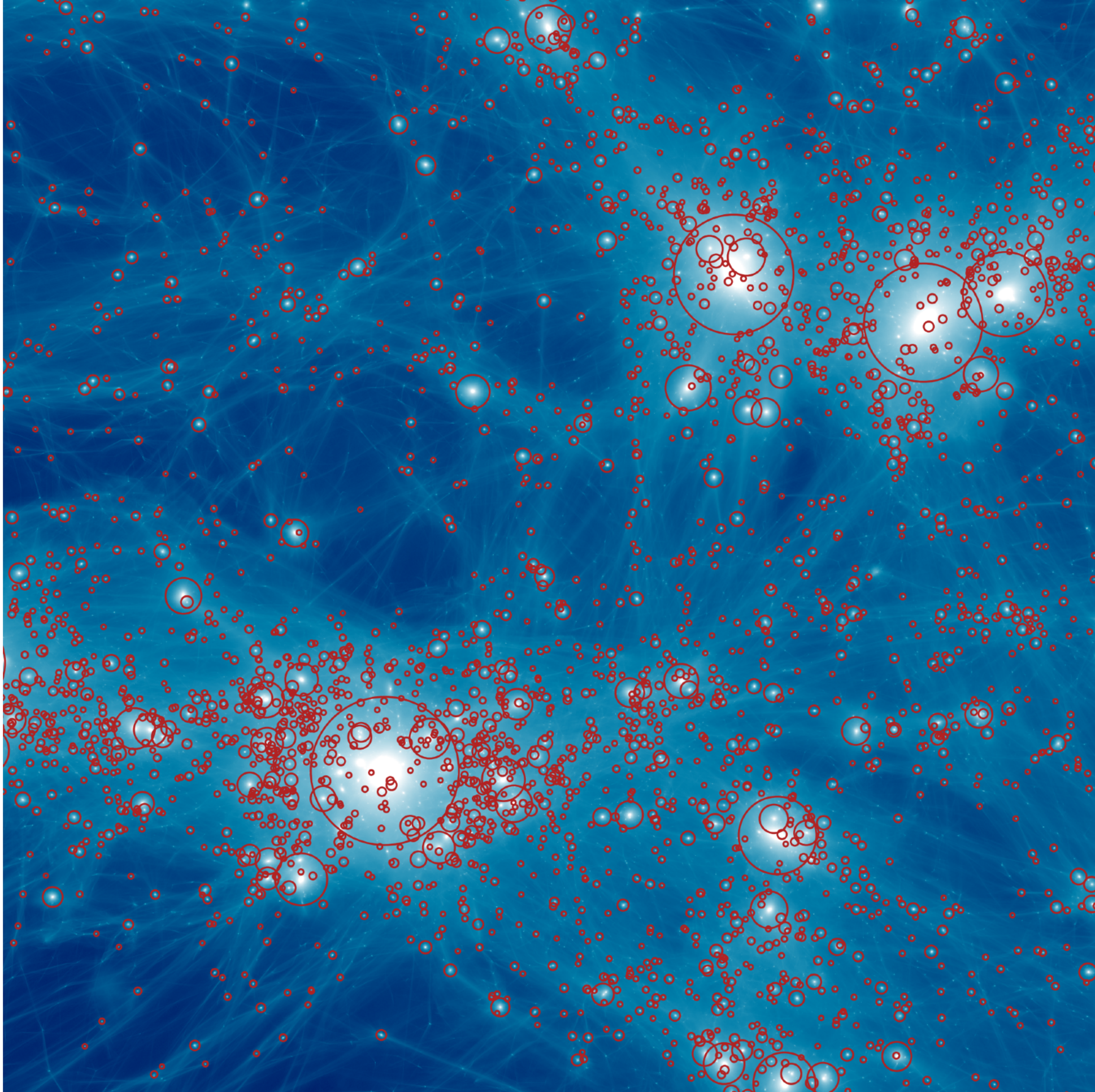
Visualization code:
Phil Mansfield

R_{500c}



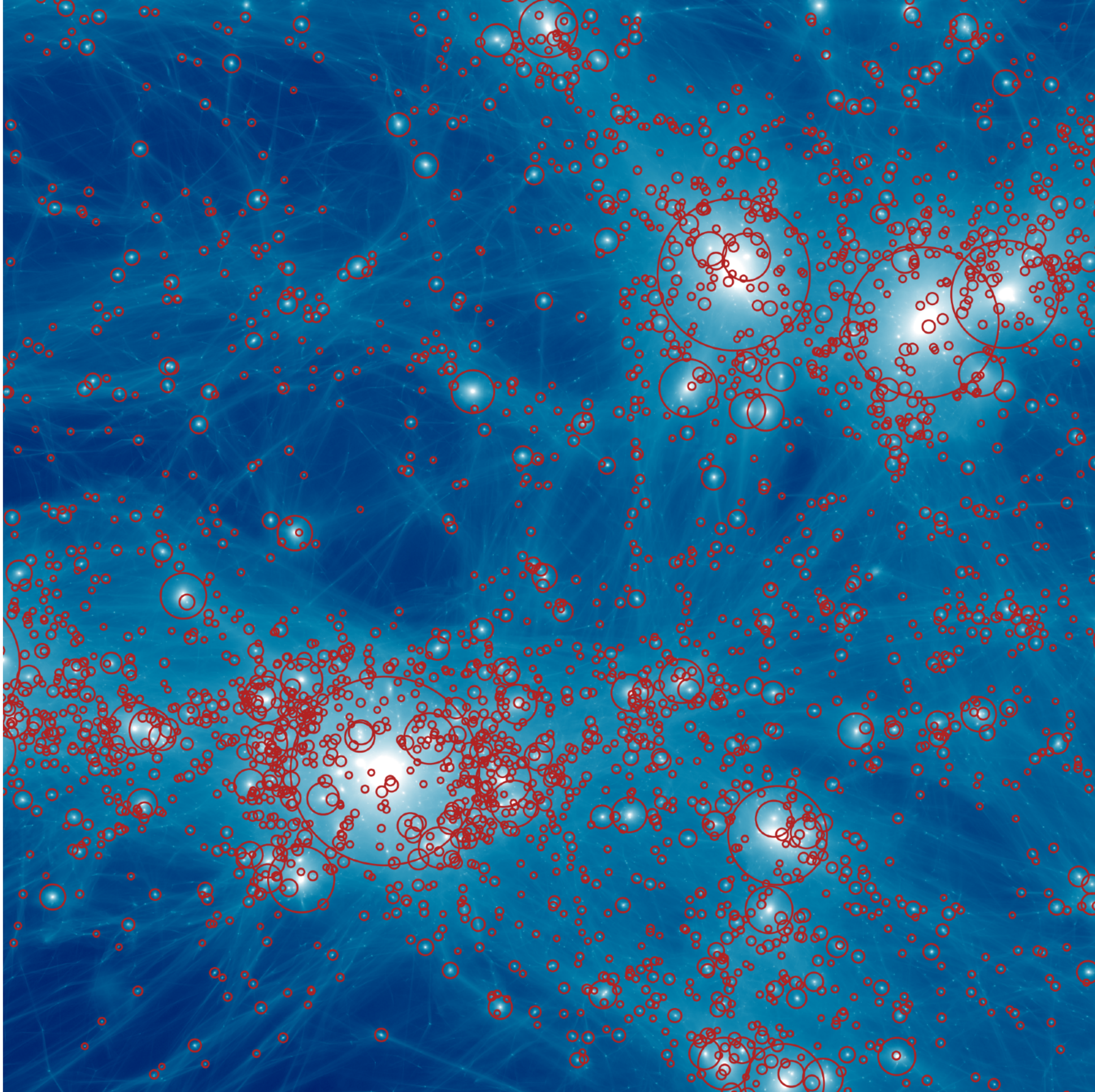
Halo finder: Rockstar
(Behroozi et al. 2013)

R_{200c}



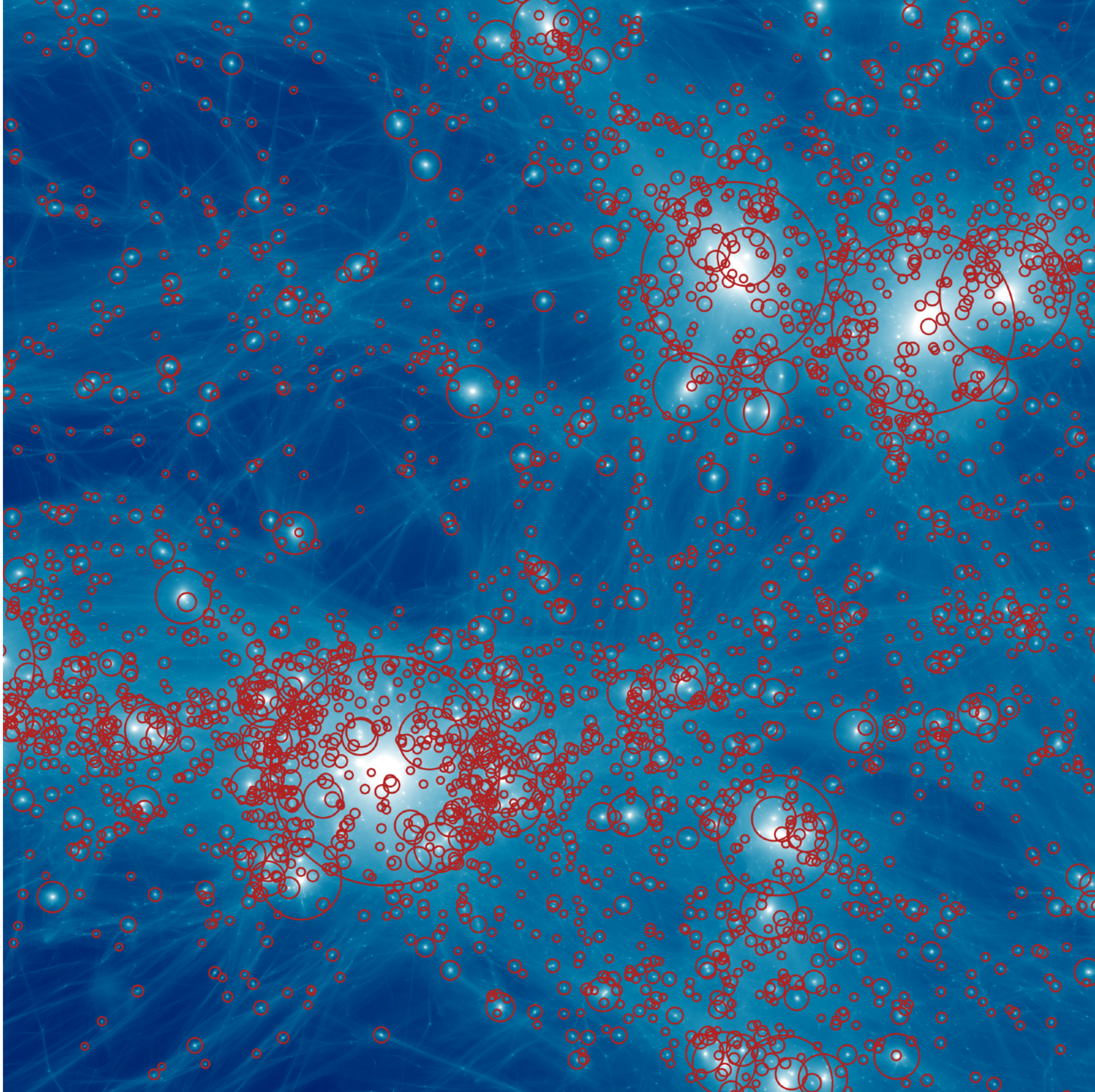
Halo finder: Rockstar
(Behroozi et al. 2013)

R_{vir}



Halo finder: Rockstar
(Behroozi et al. 2013)

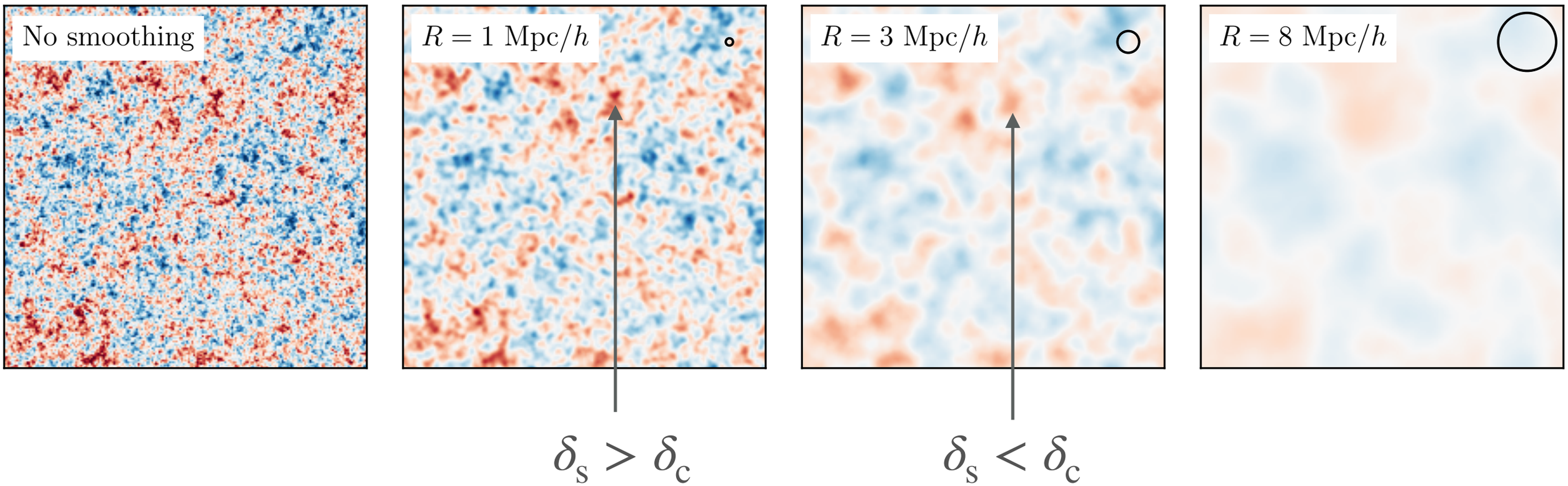
R_{200m}



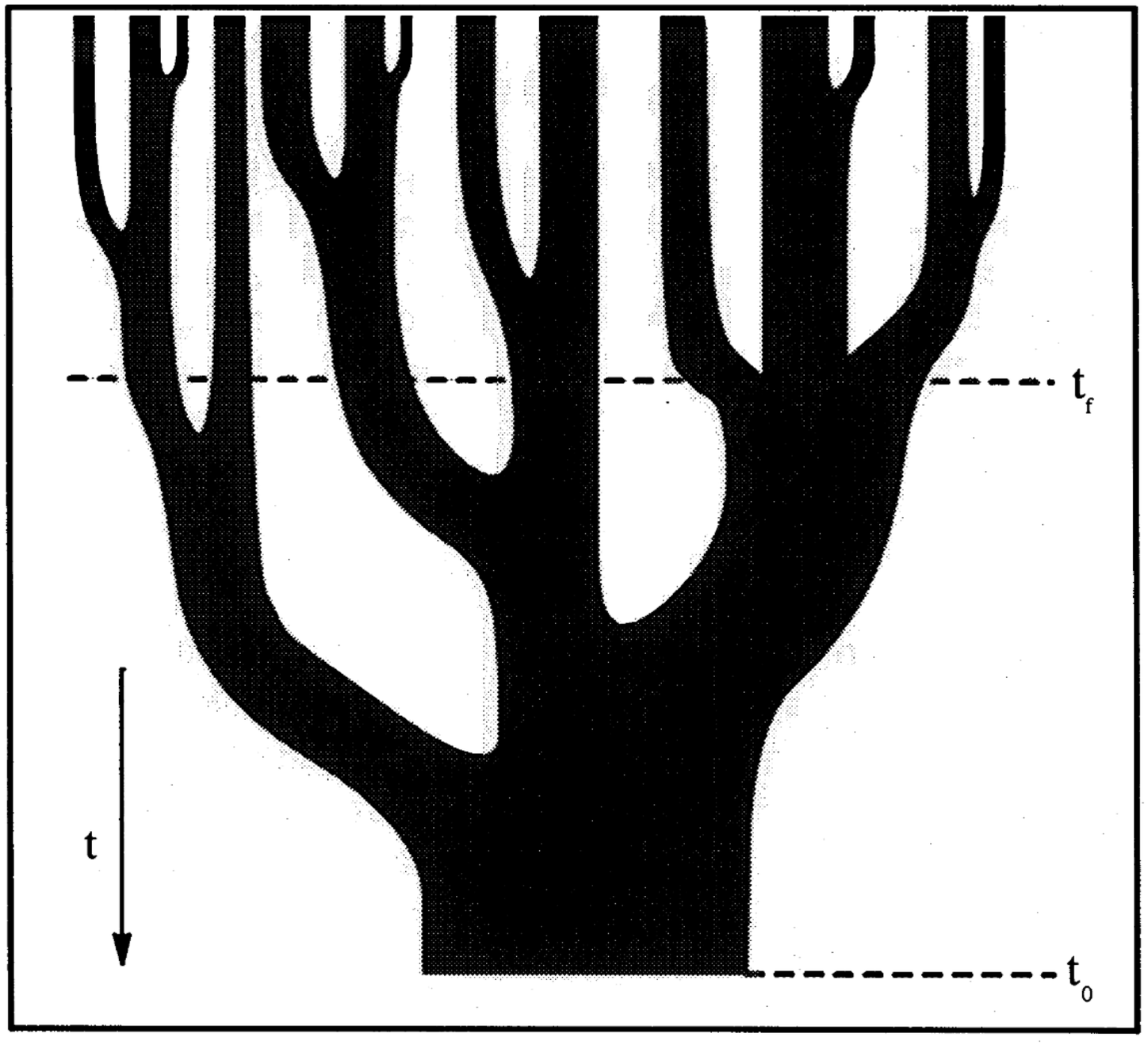
Halo finder: Rockstar
(Behroozi et al. 2013)

§4.1.2 • The non-linear mass and hierarchical structure formation

Smoothed density fields

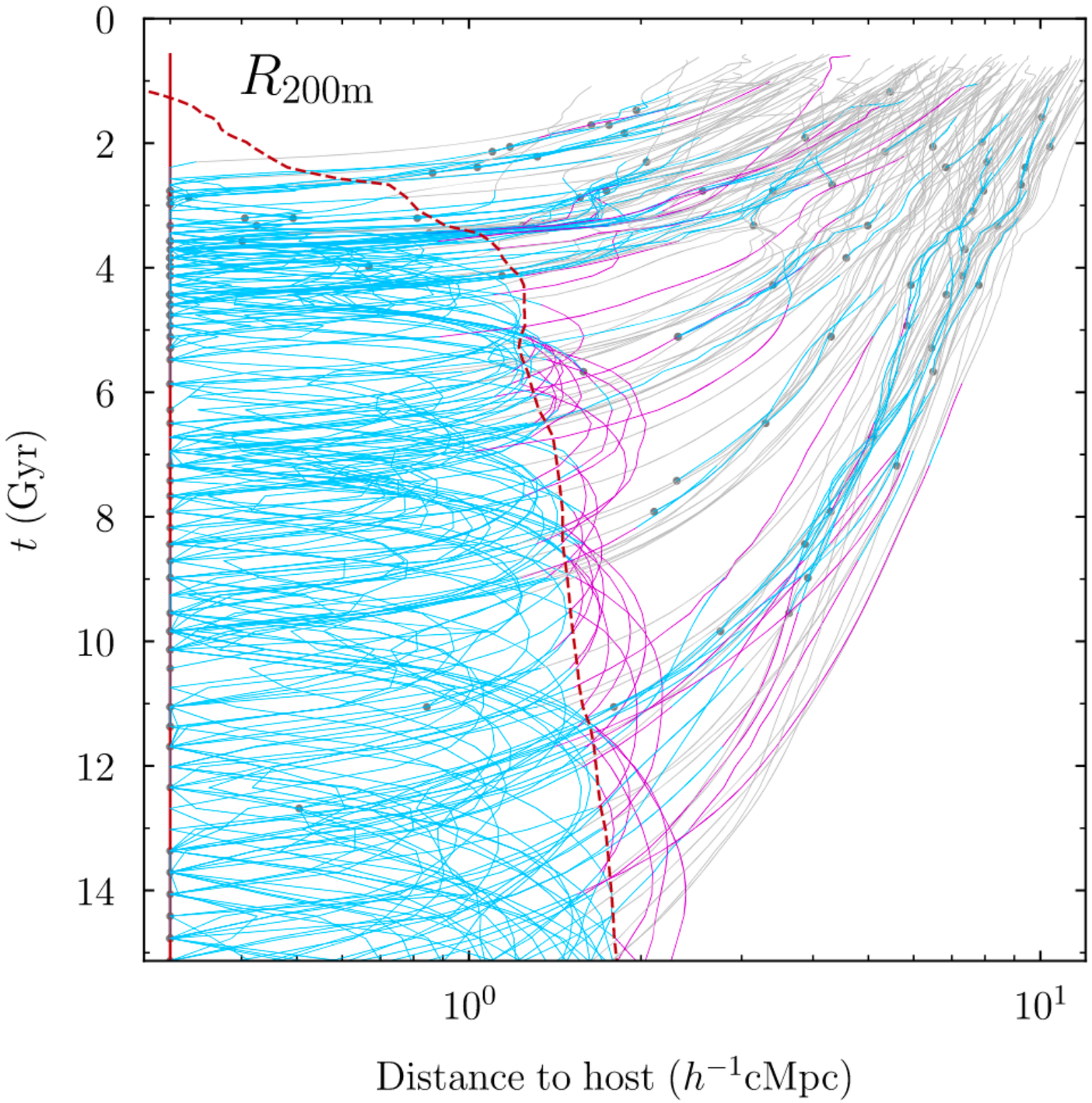


Merger tree



Lacey & Cole 1993

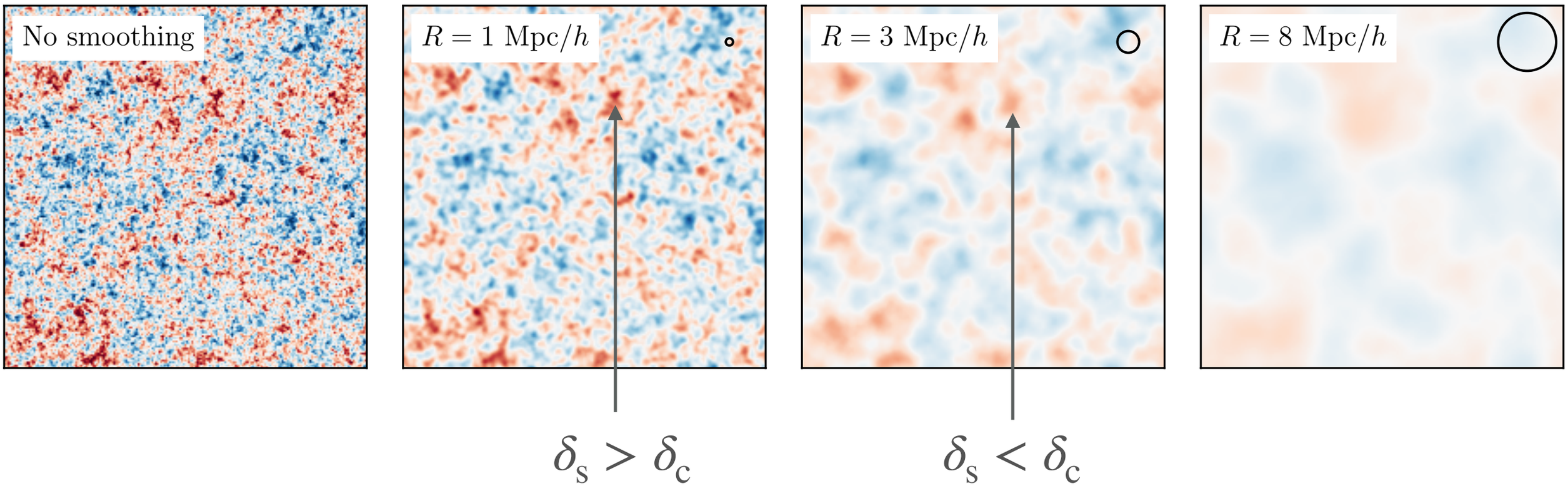
Merger tree



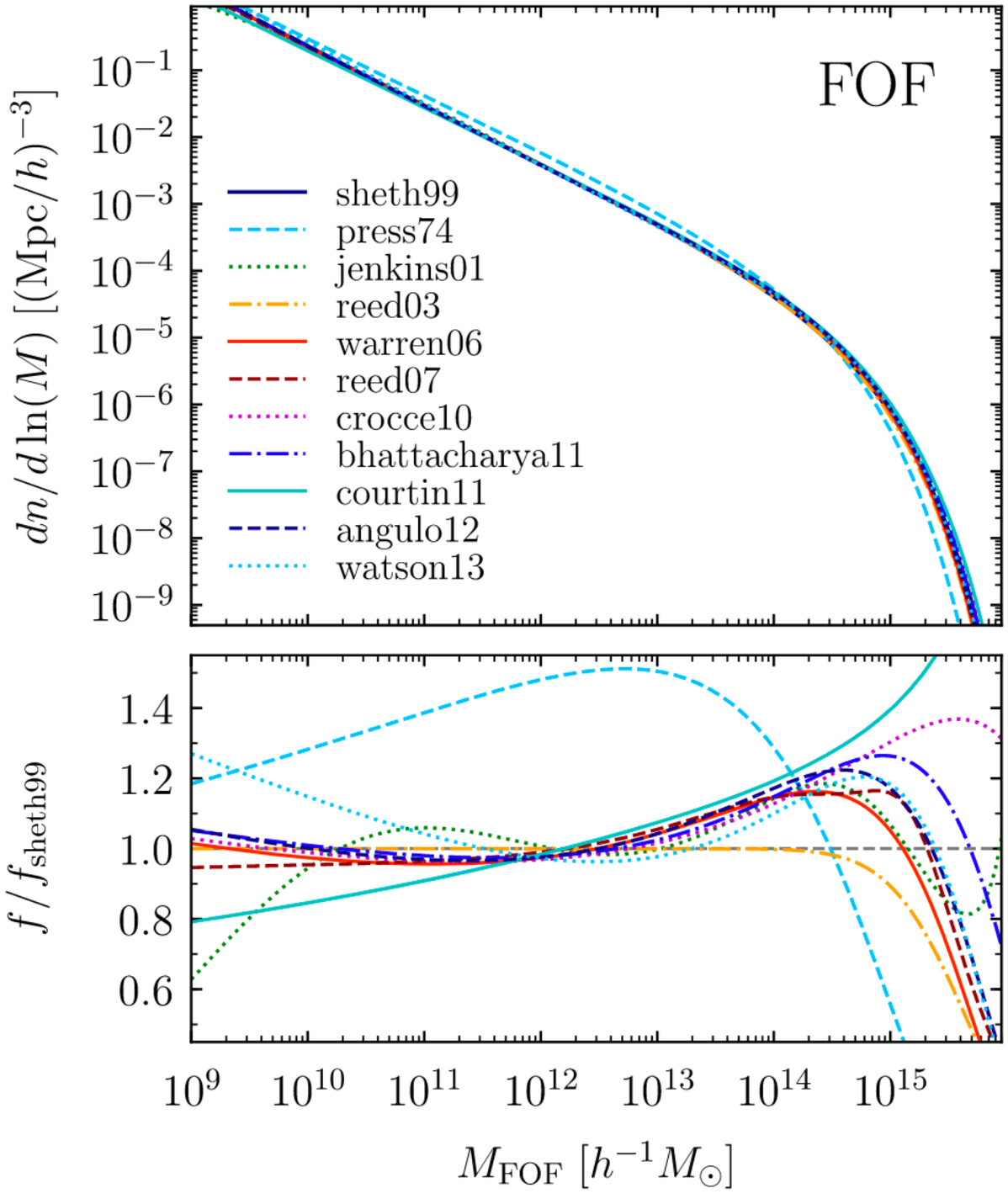
Diemer 2021

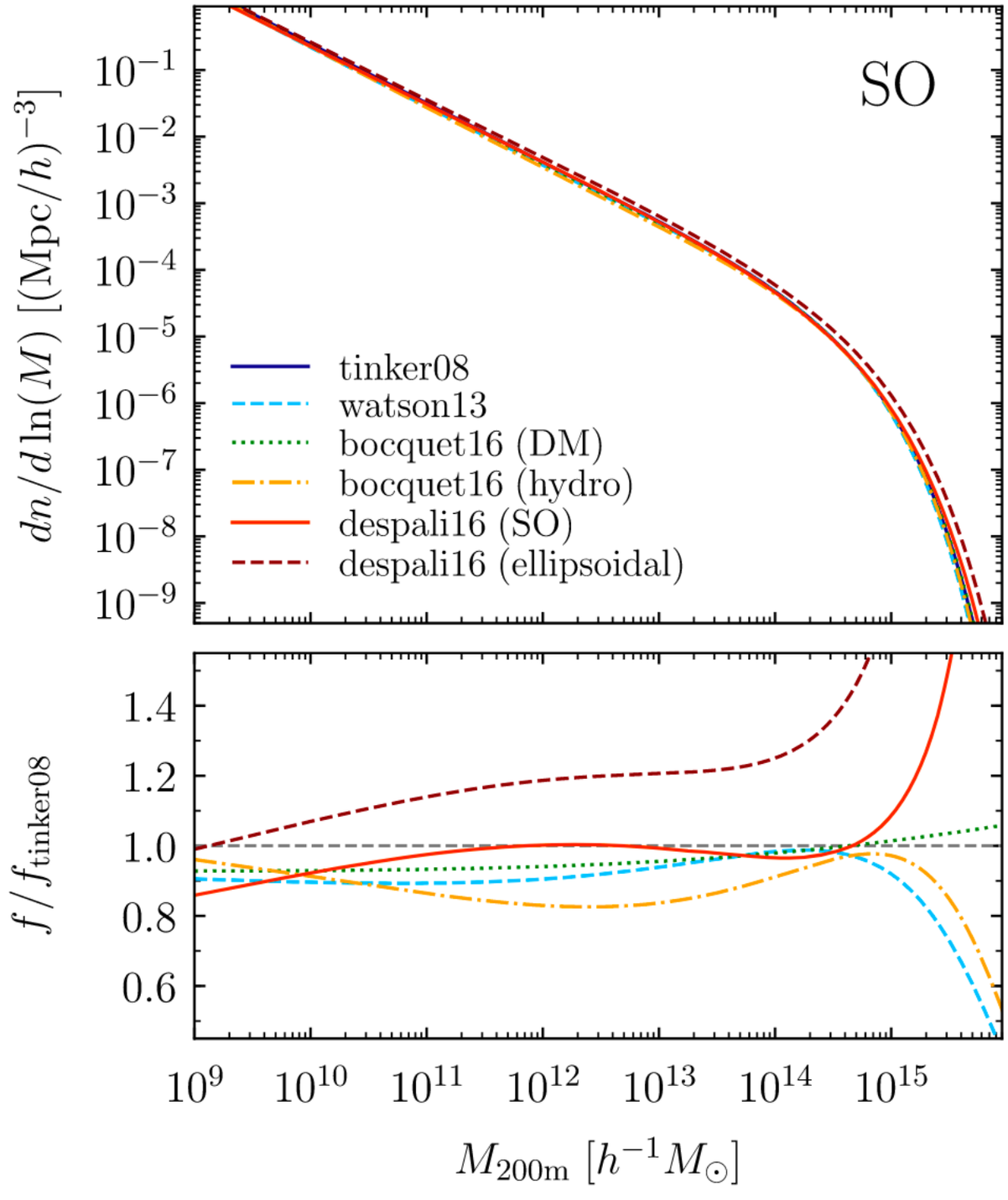
§4.2 • The halo mass function

Smoothed density fields



Mass function models



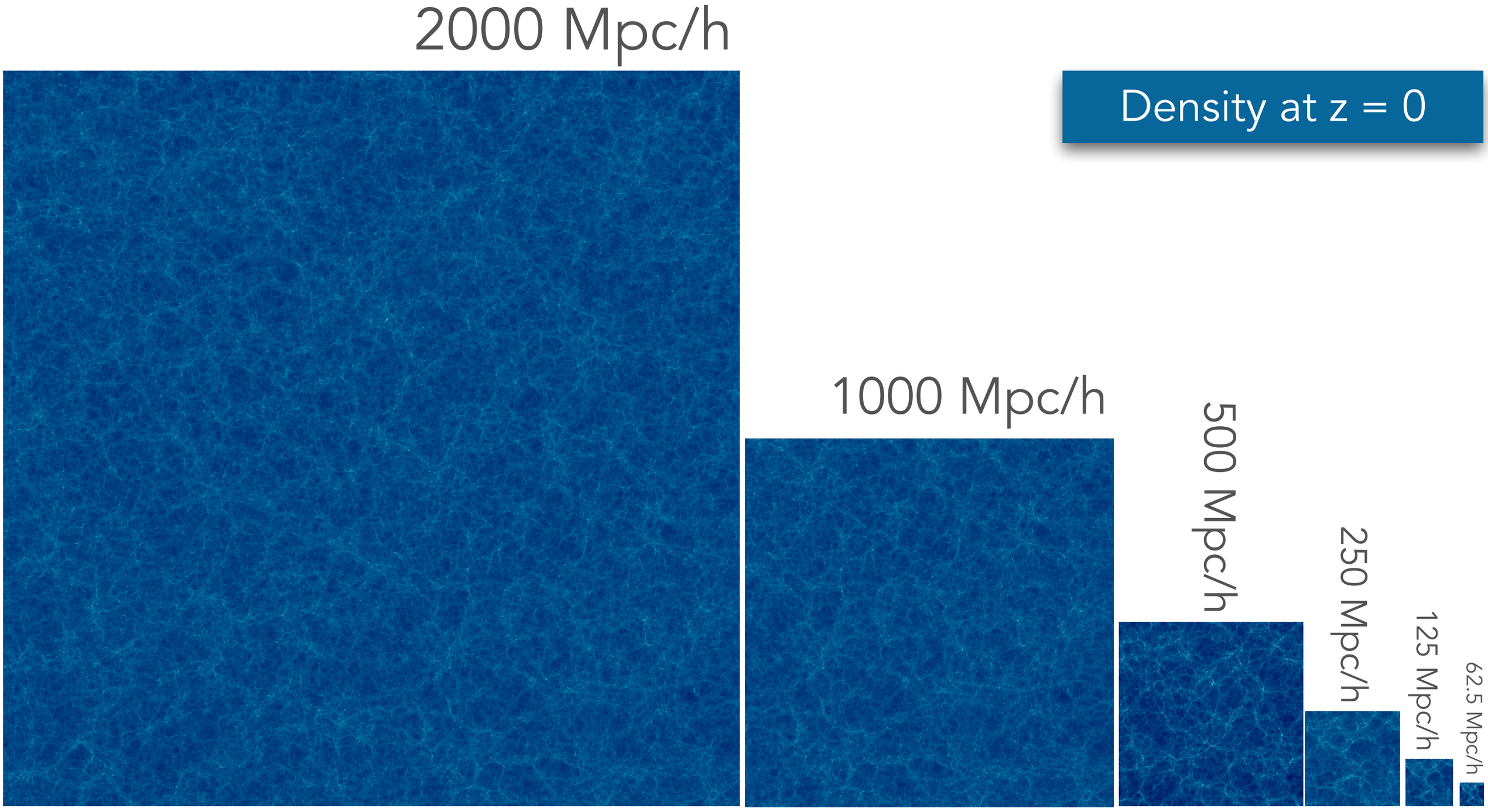


Diemer 2018

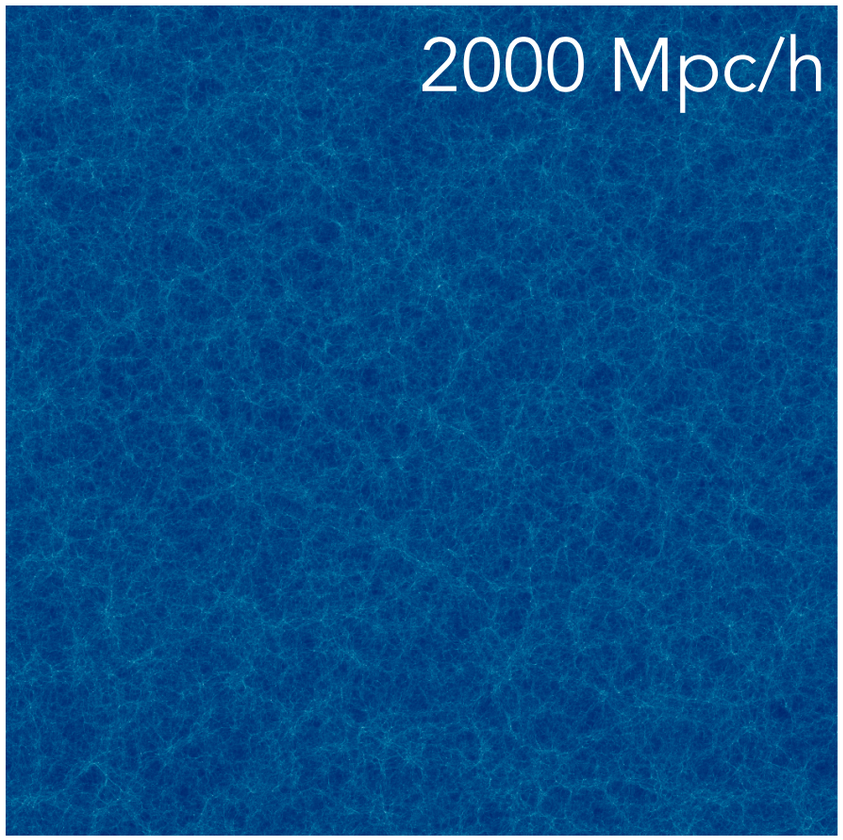
§4.3 • Halo structure

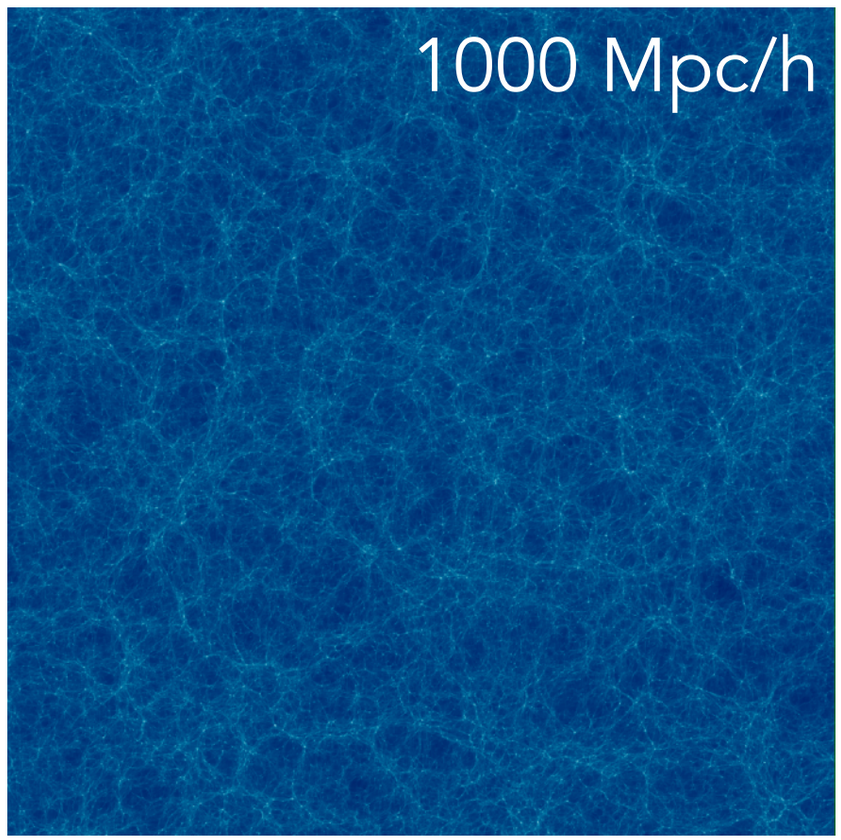
and its connection to formation history

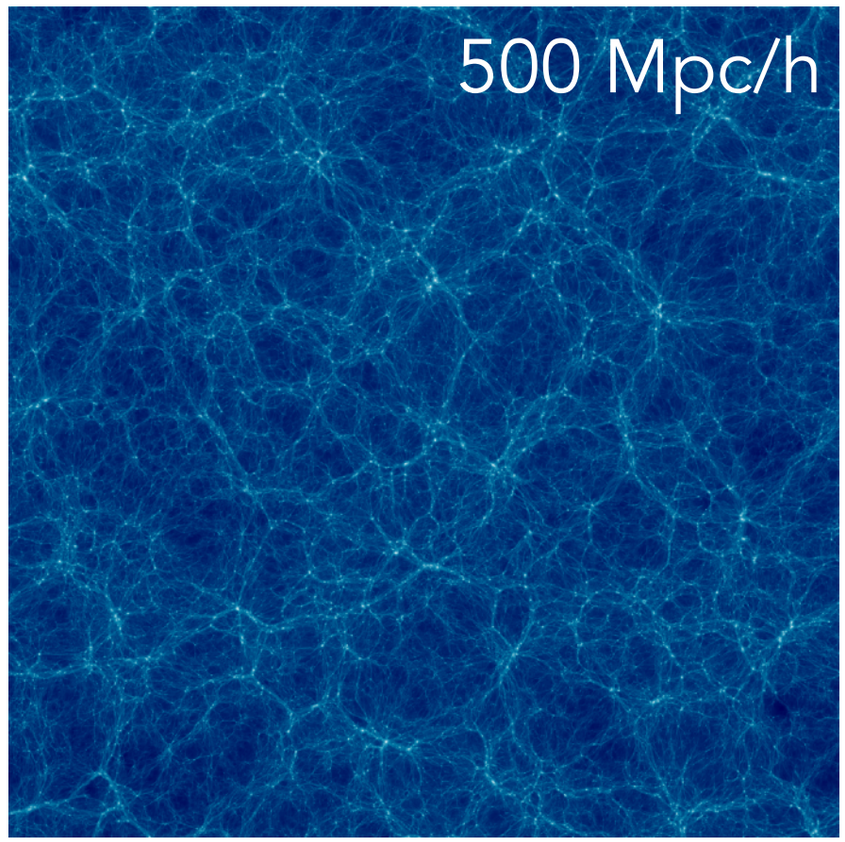
Erebos N-body simulations

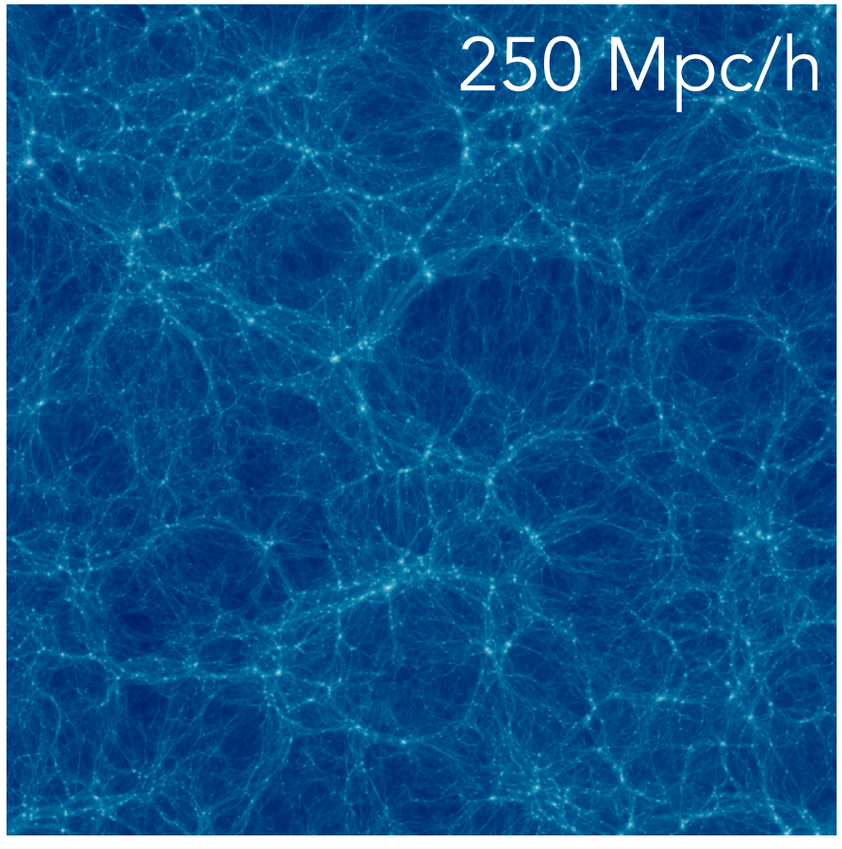


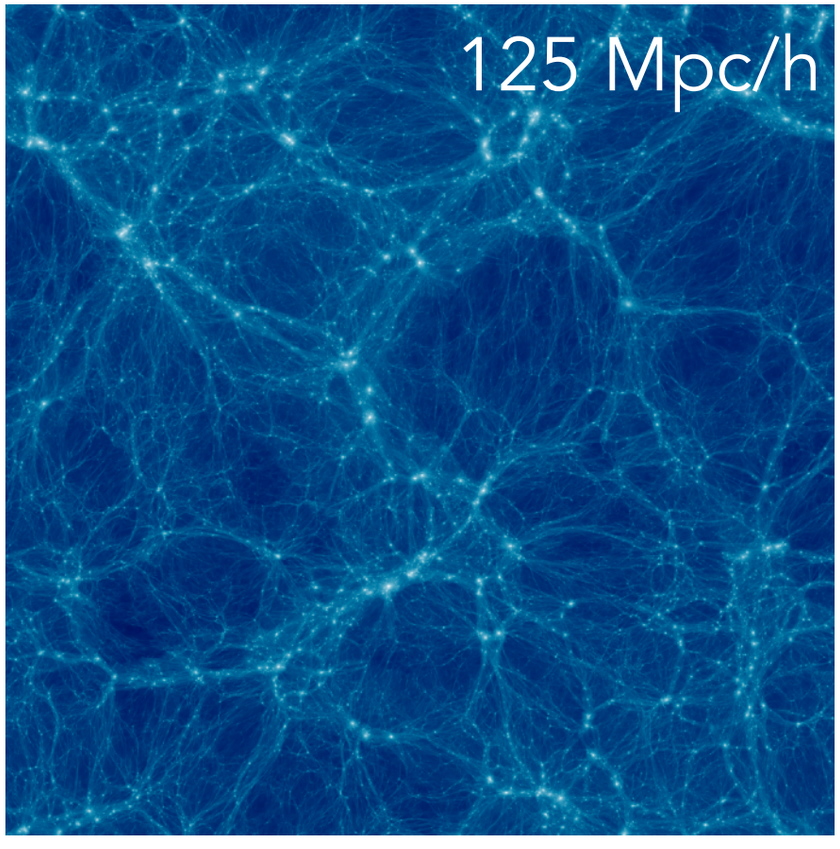
Diemer & Kravtsov 2014, 2015 • Springel 2005 • Crocce et al. 2006 • Behroozi et al. 2013ab

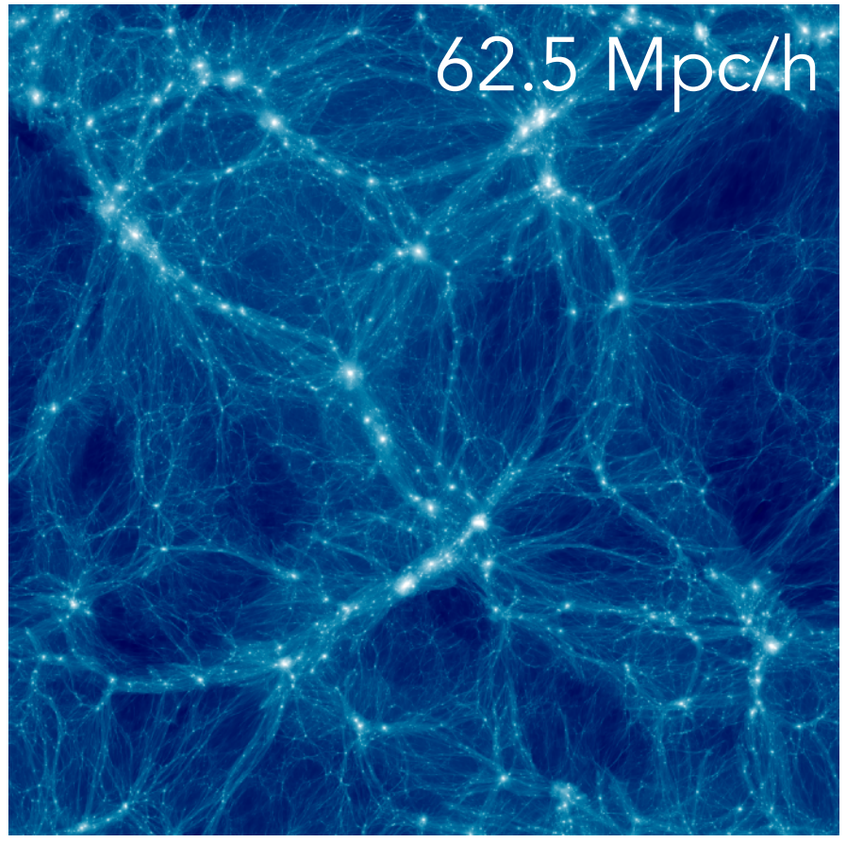






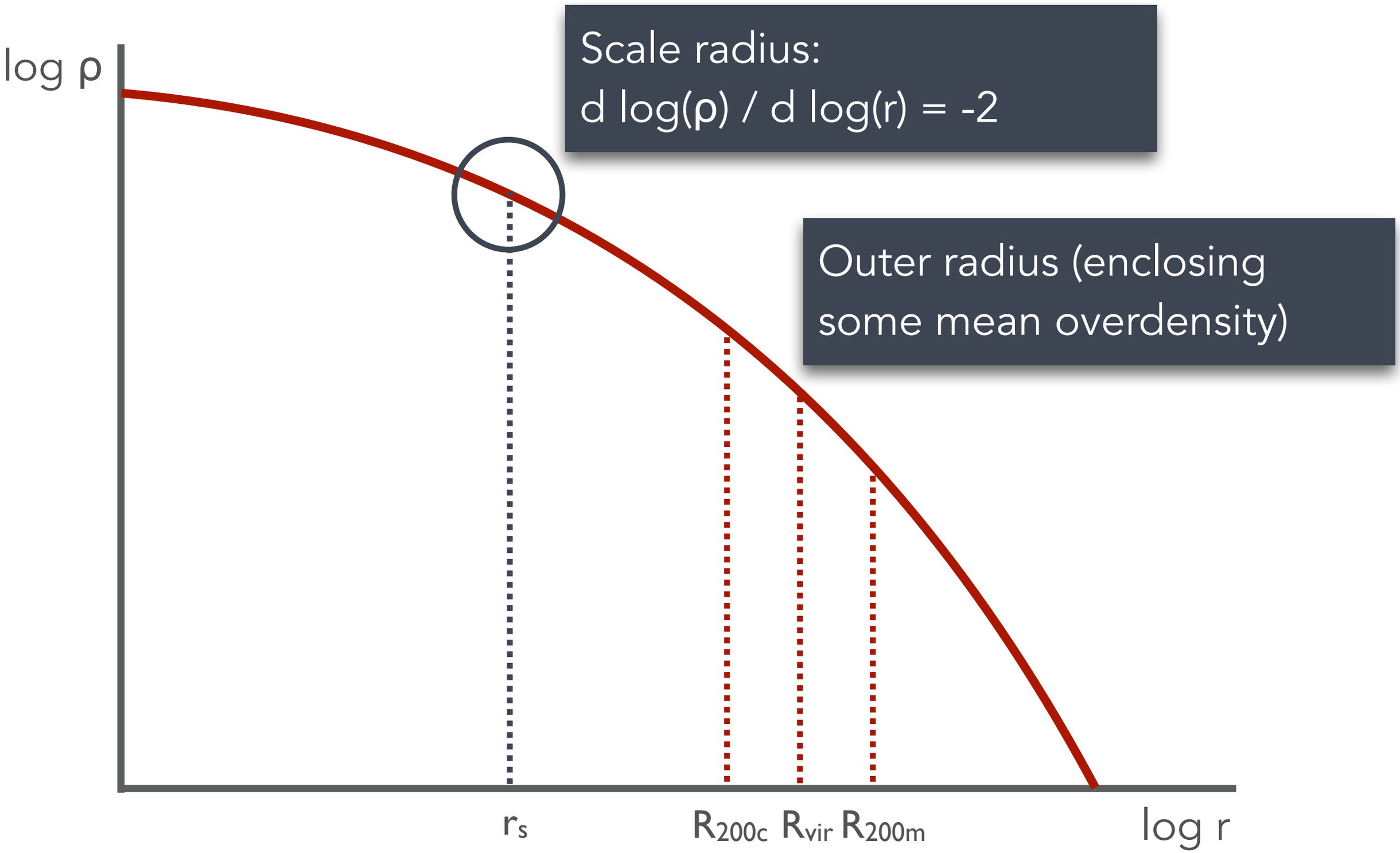






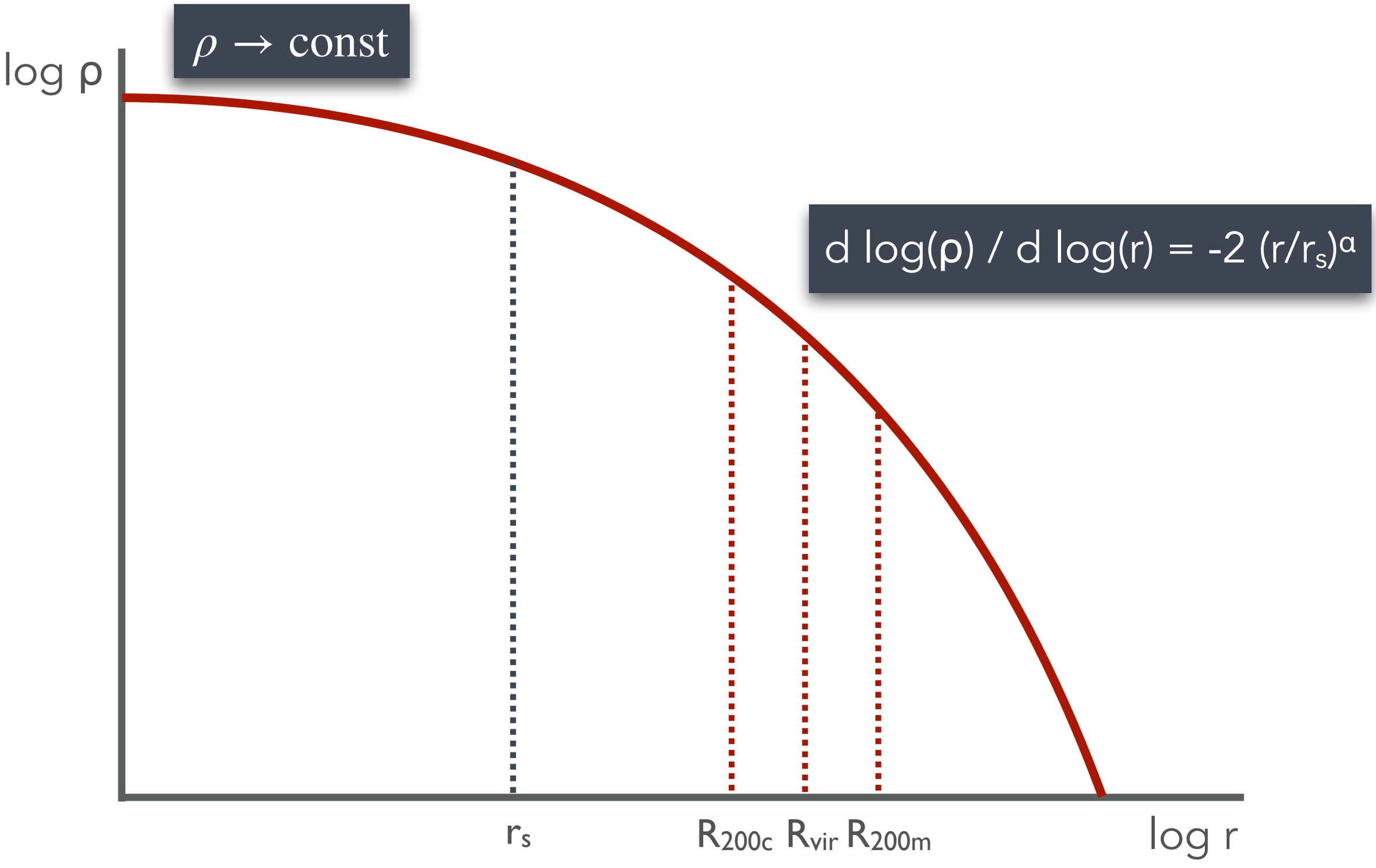
Diemer & Kravtsov 2014, 2015 • Springel 2005 • Crocce et al. 2006 • Behroozi et al. 2013ab

Density profile



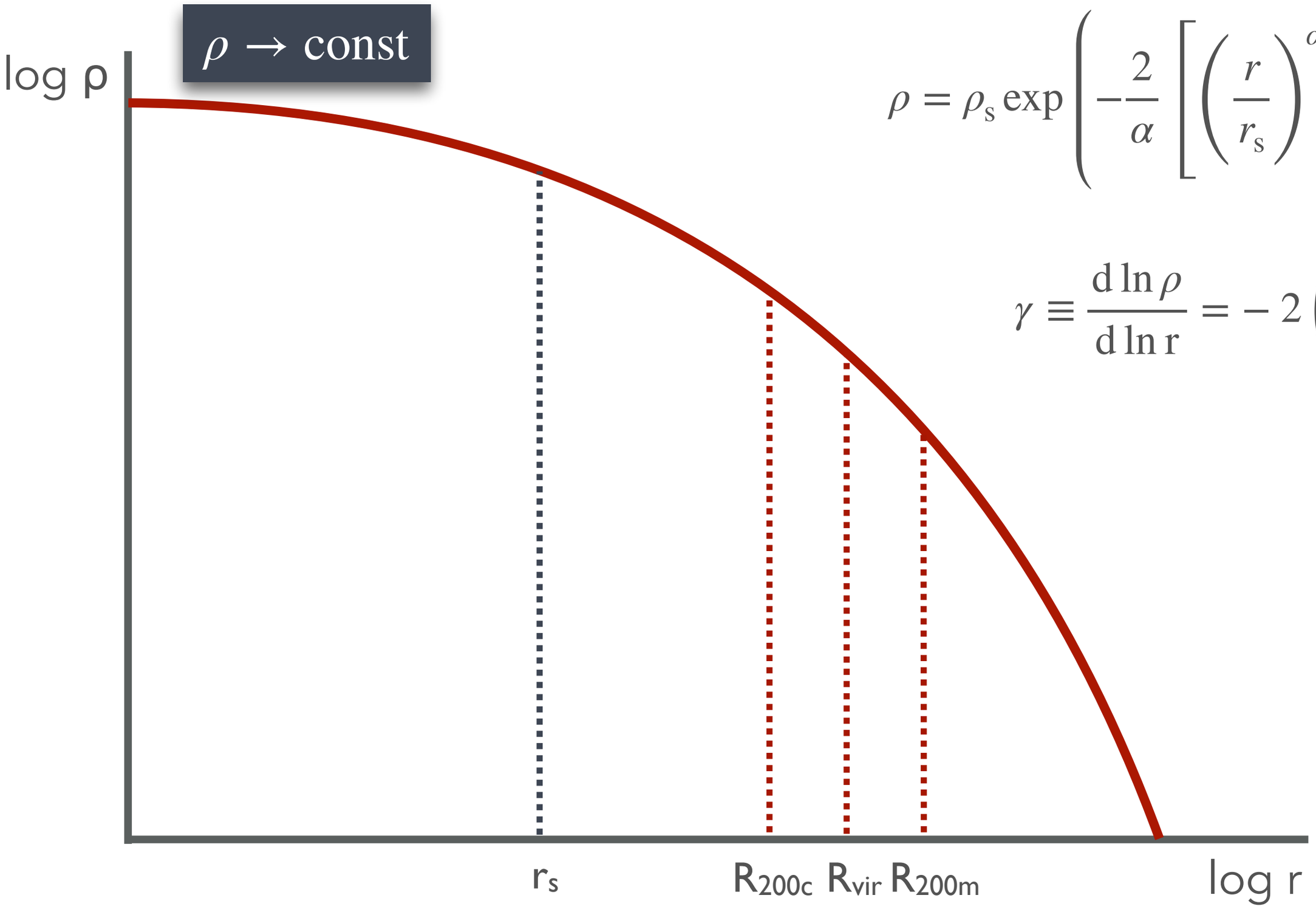
Einasto 1965 • Frenk et al. 1988 • Hernquist 1990 • Dubinski & Carlberg 1991
Navarro et al.1995/1996/1997/2004

Einasto profile



Einasto 1965

Einasto profile

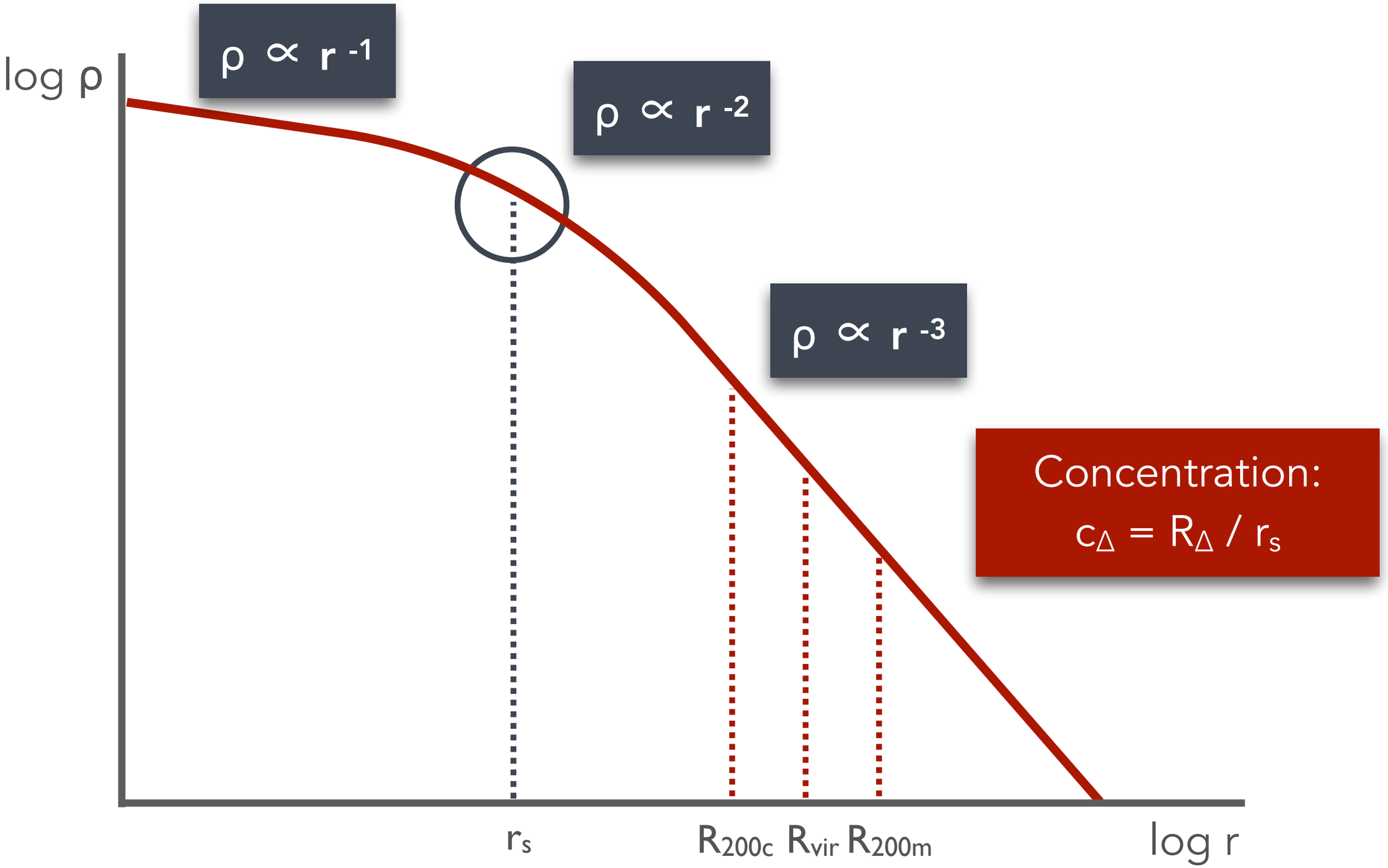


$$\rho = \rho_s \exp\left(-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha} - 1\right]\right)$$

$$\gamma \equiv \frac{\mathrm{d}\ln\rho}{\mathrm{d}\ln r} = -2\left(\frac{r}{r_s}\right)^{\alpha}$$

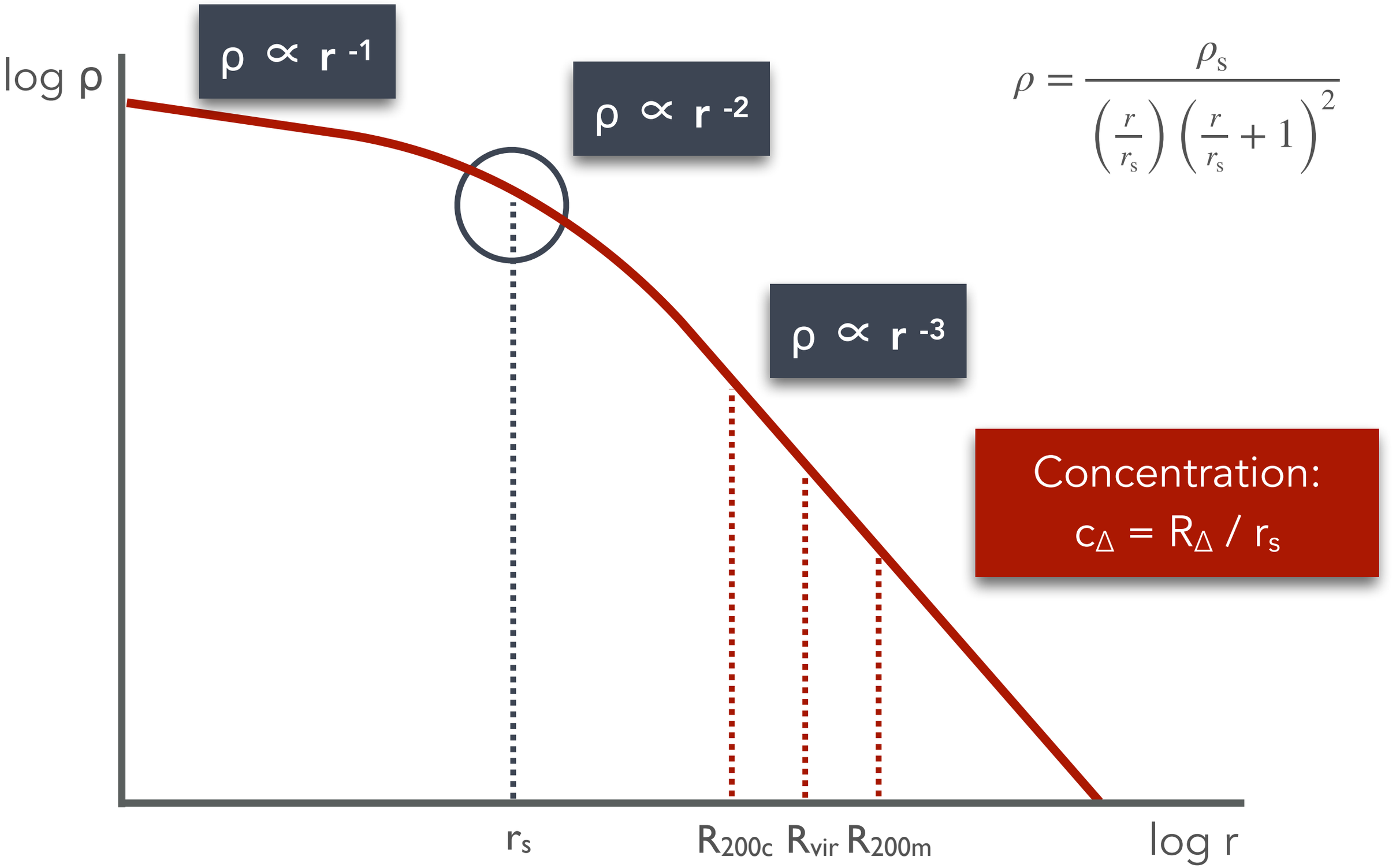
Einasto 1965, 1969

Navarro-Frenk-White profile



Navarro et al. 1995/1996/1997

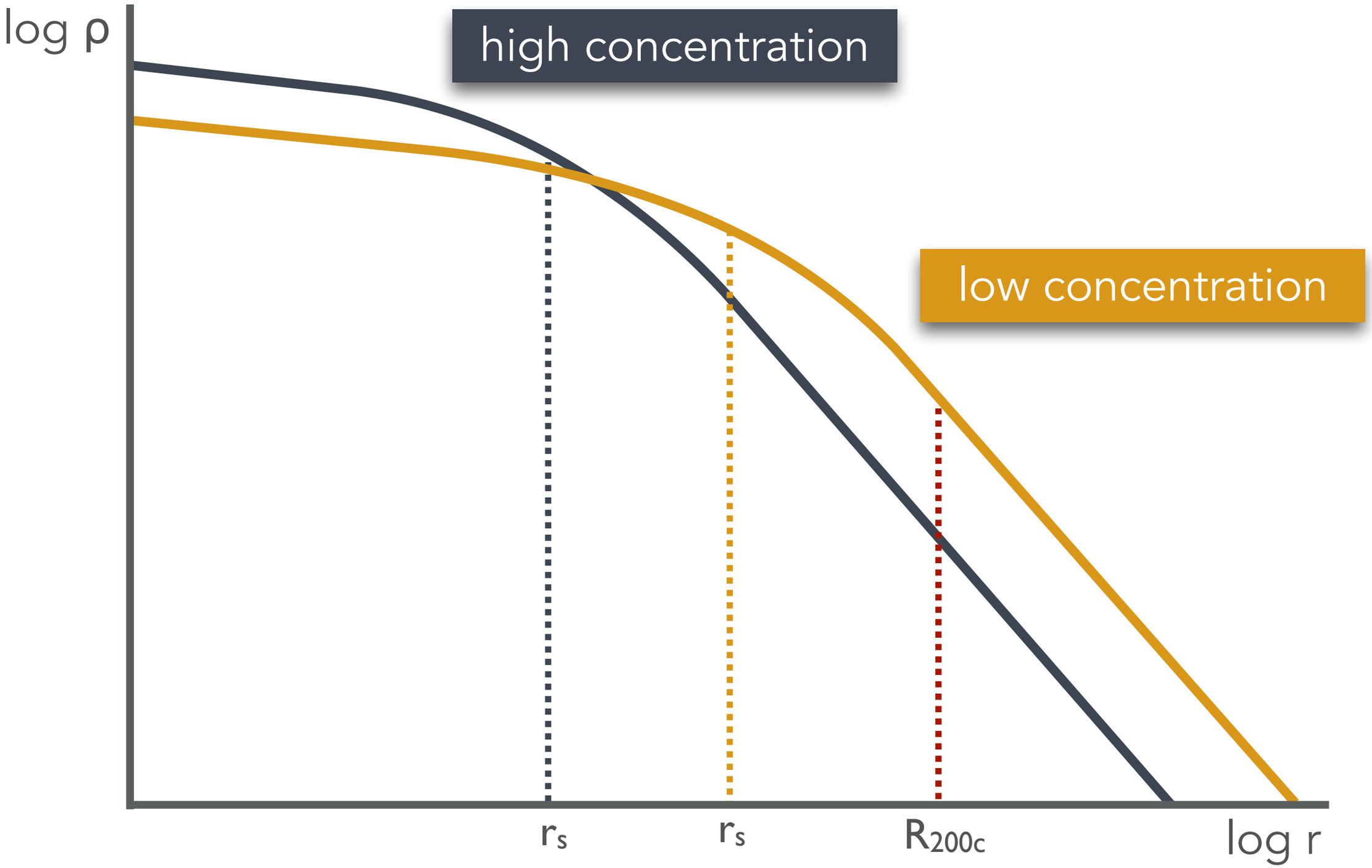
Navarro-Frenk-White profile



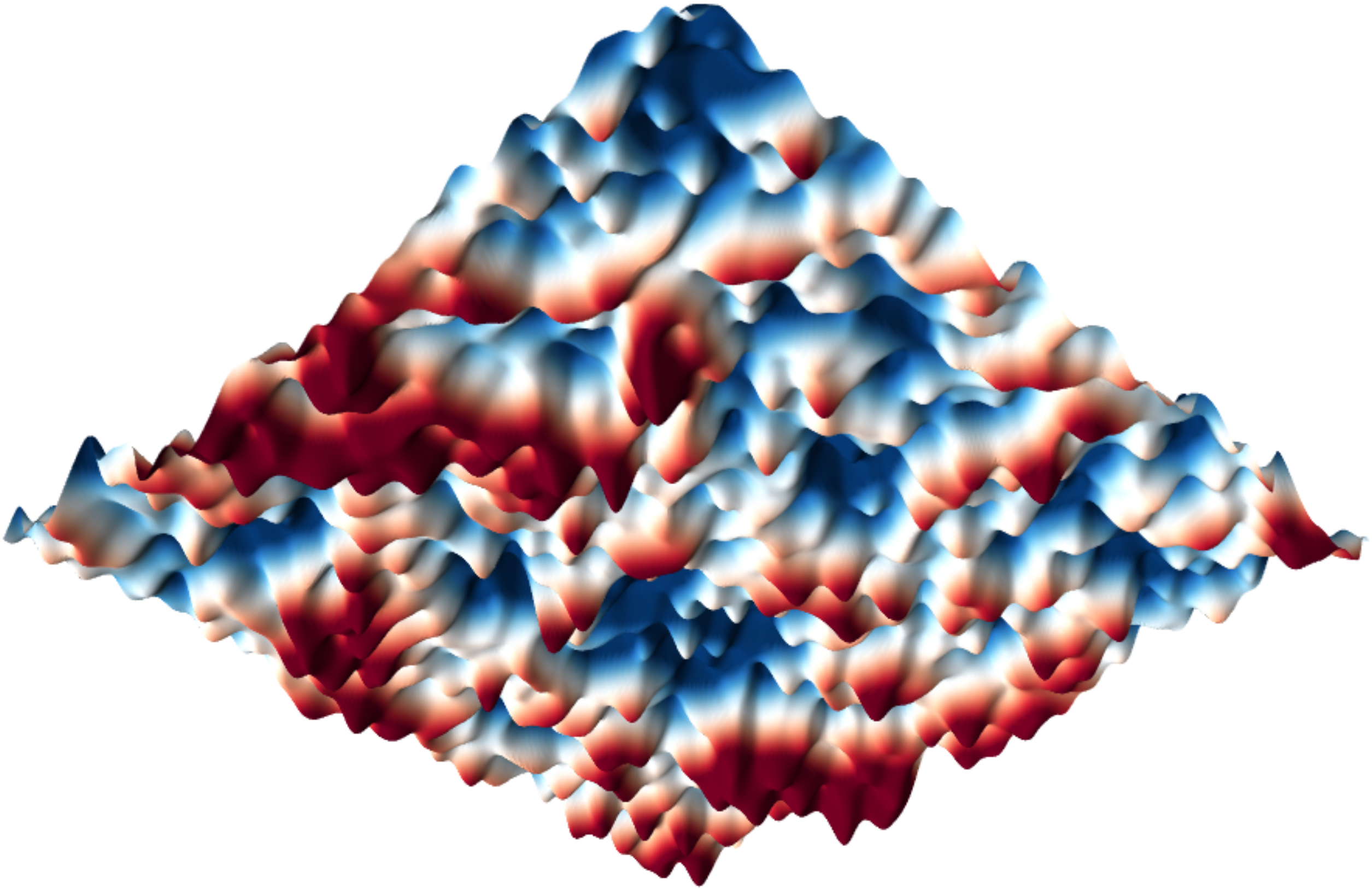
$$\rho = \frac{\rho_s}{\left(\frac{r}{r_s}\right)\left(\frac{r}{r_s}+1\right)^2}$$

Navarro et al. 1995/1996/1997

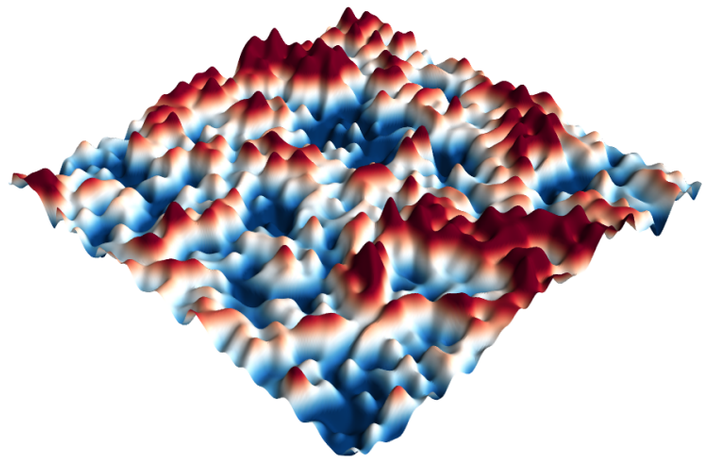
Navarro-Frenk-White profile



Navarro et al. 1995/1996/1997

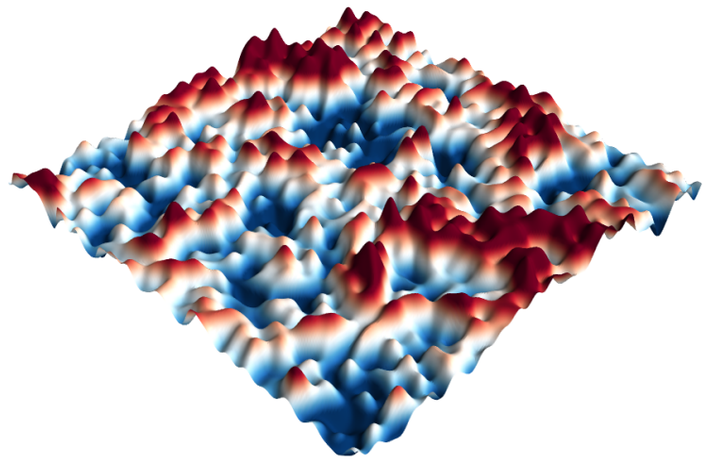


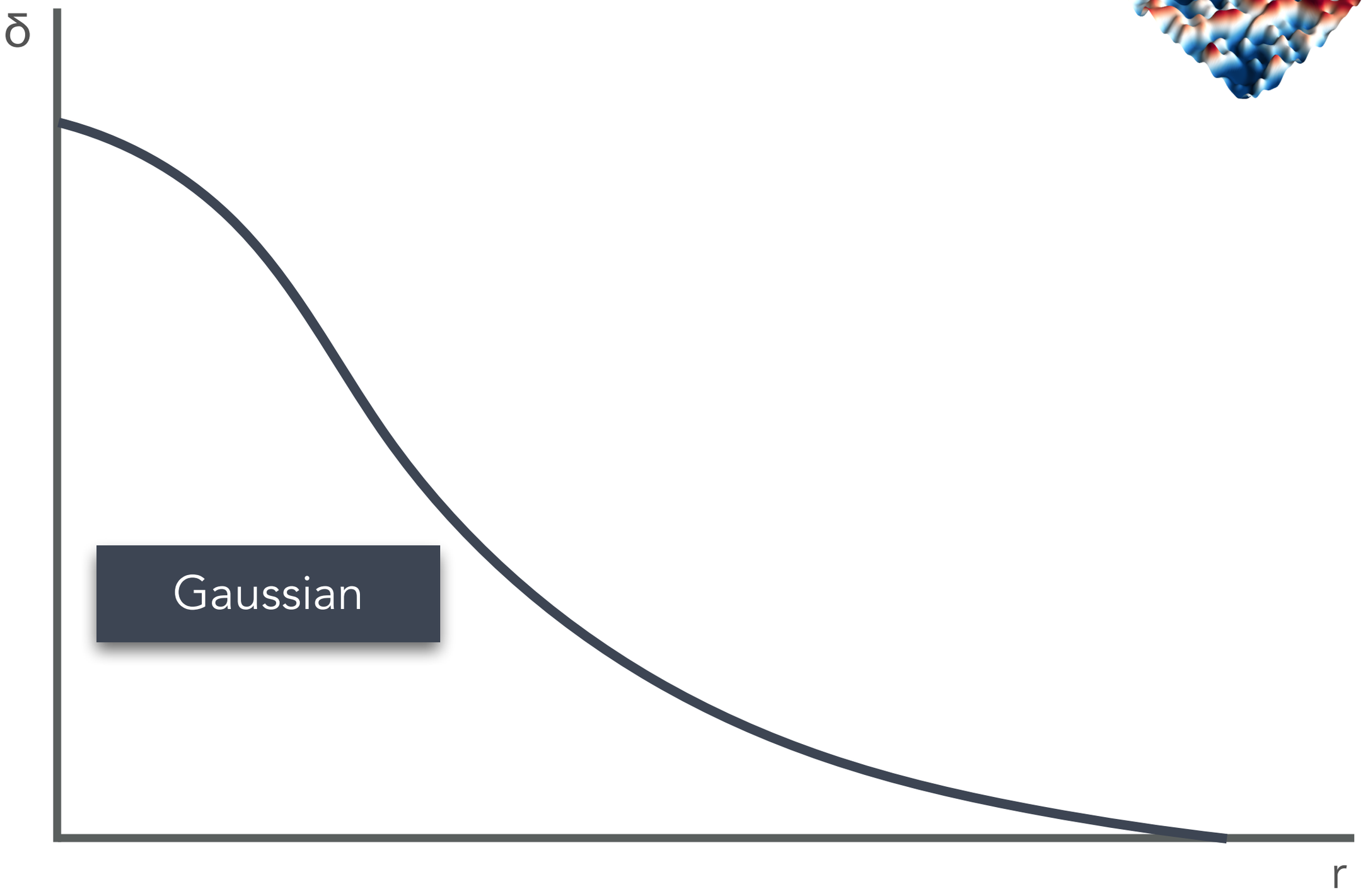
Initial peaks



Bardeen et al. 1986 • Dalal et al. 2010

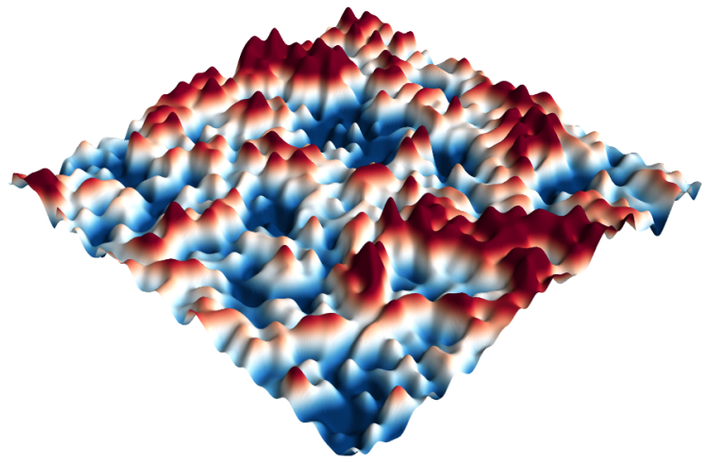
Initial peaks

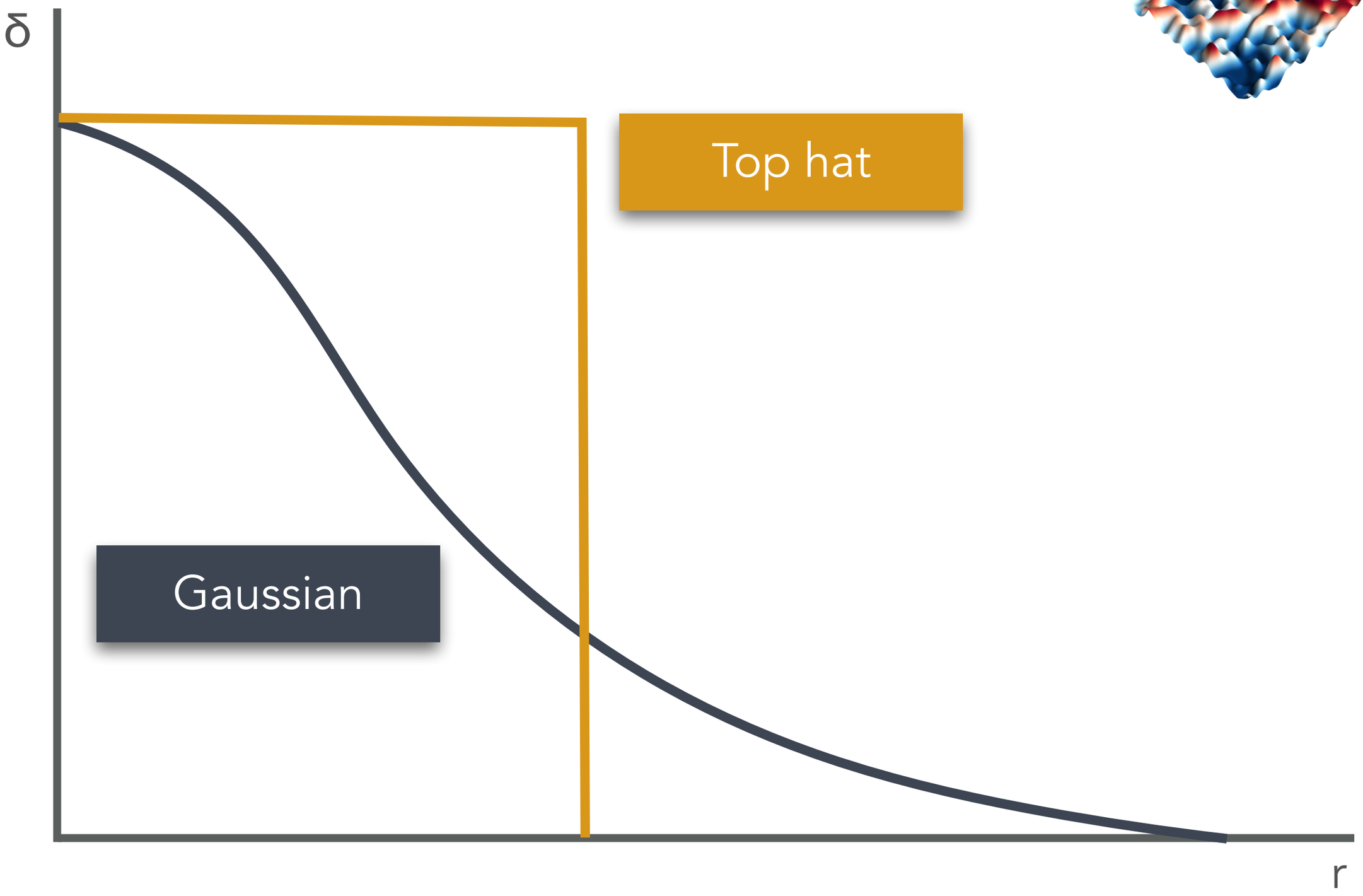




Bardeen et al. 1986 • Dalal et al. 2010

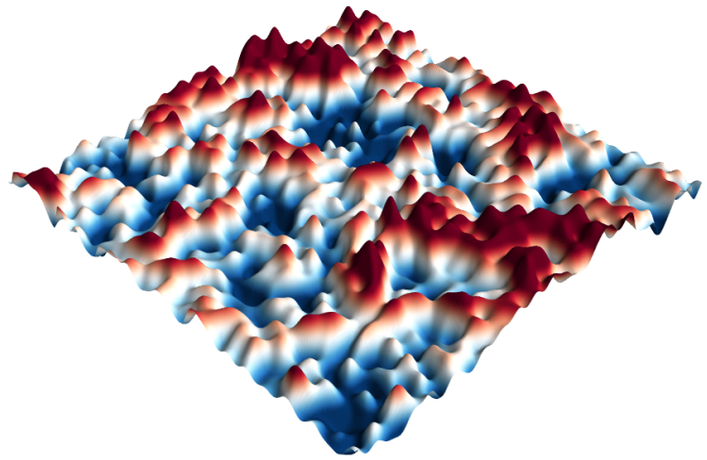
Initial peaks

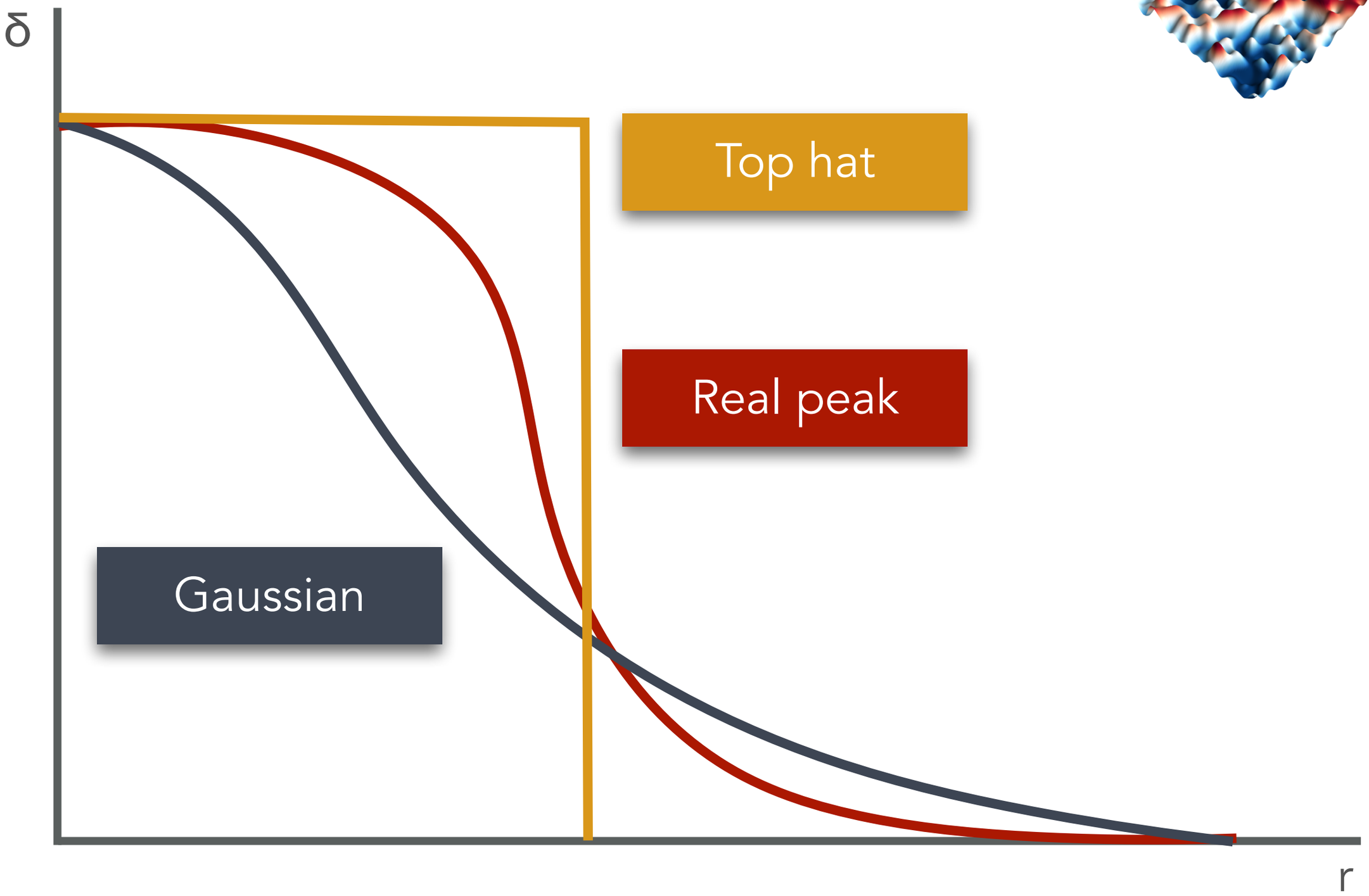




Bardeen et al. 1986 • Dalal et al. 2010

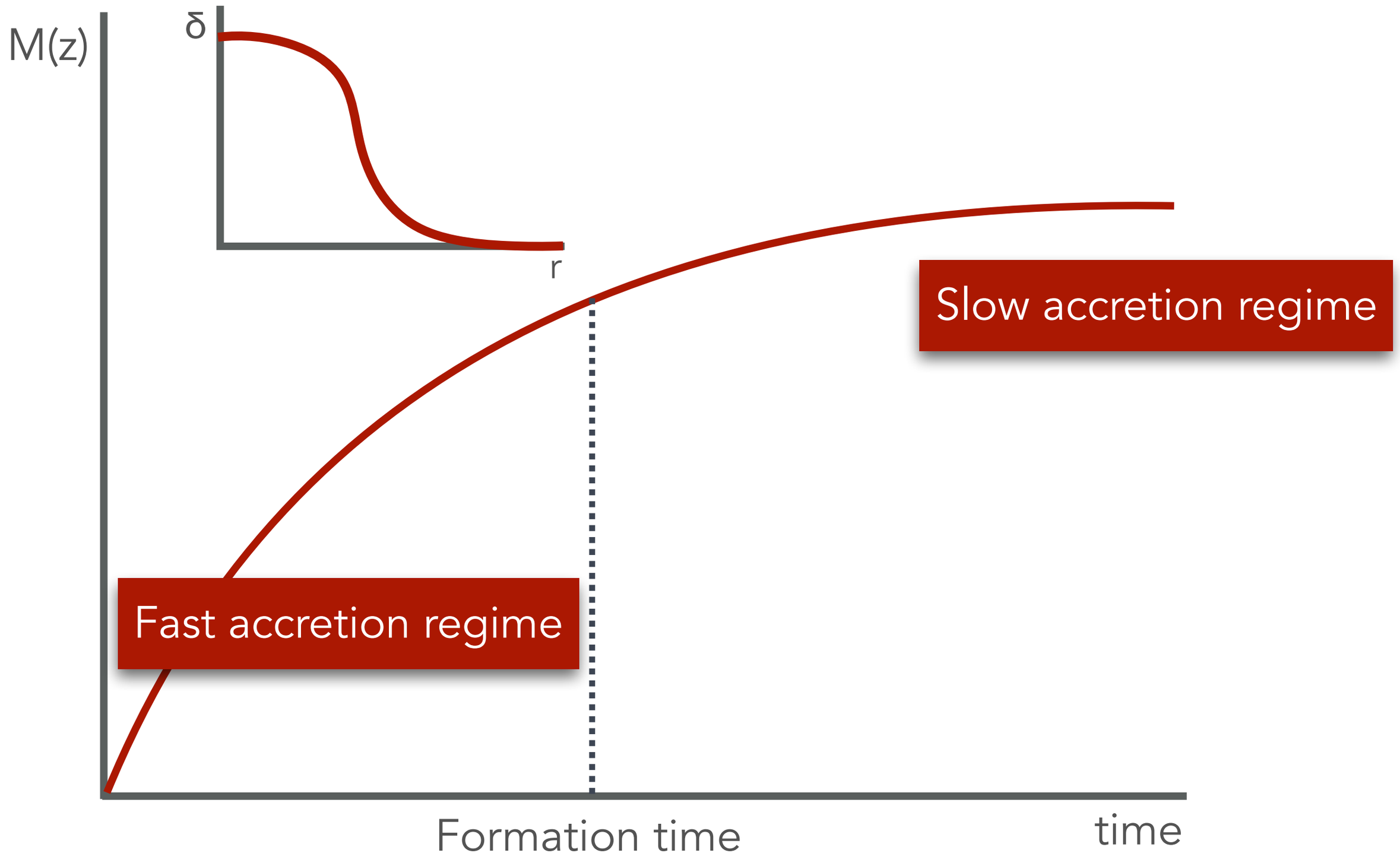
Initial peaks





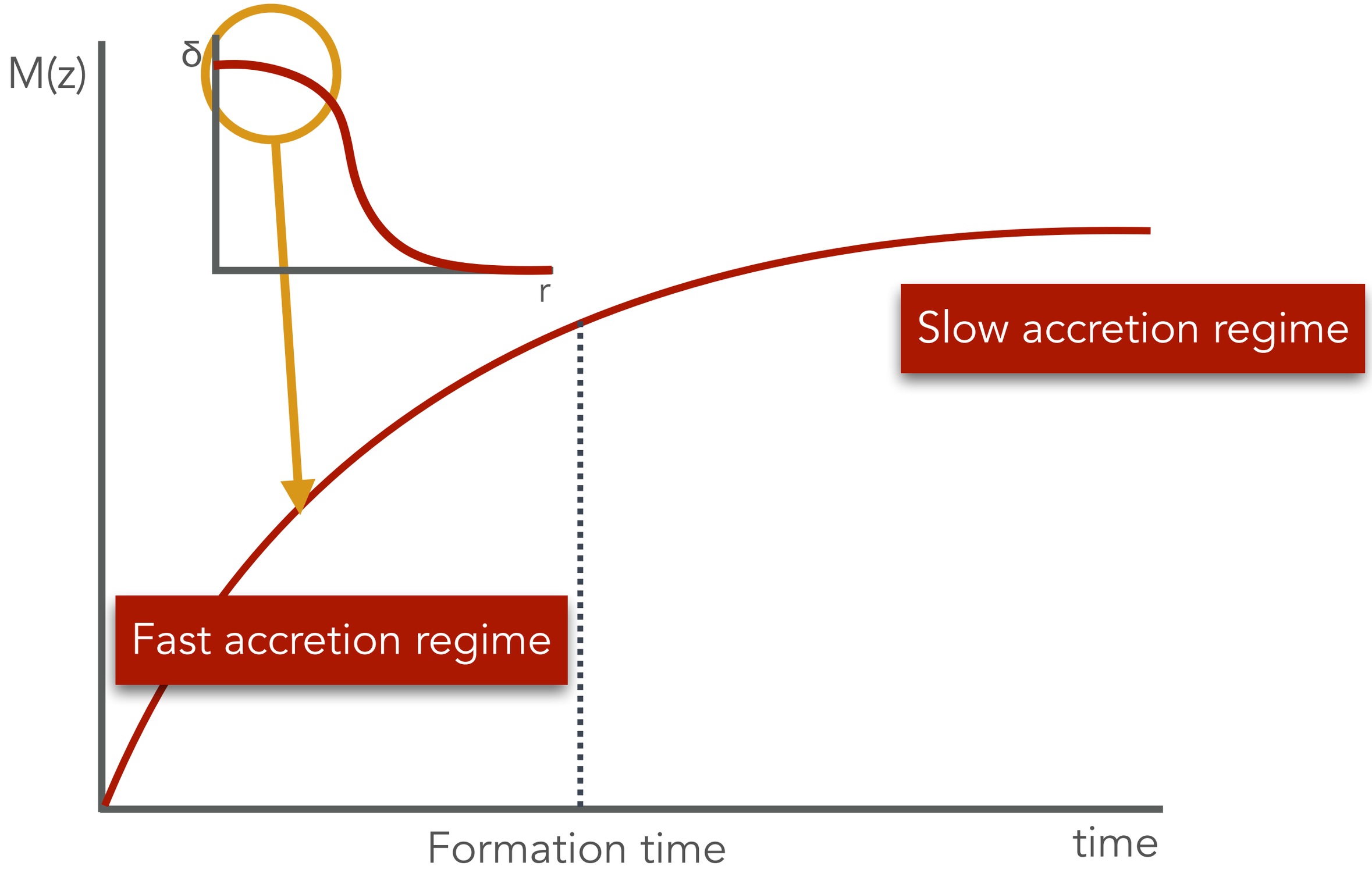
Bardeen et al. 1986 • Dalal et al. 2010

Mass accretion history



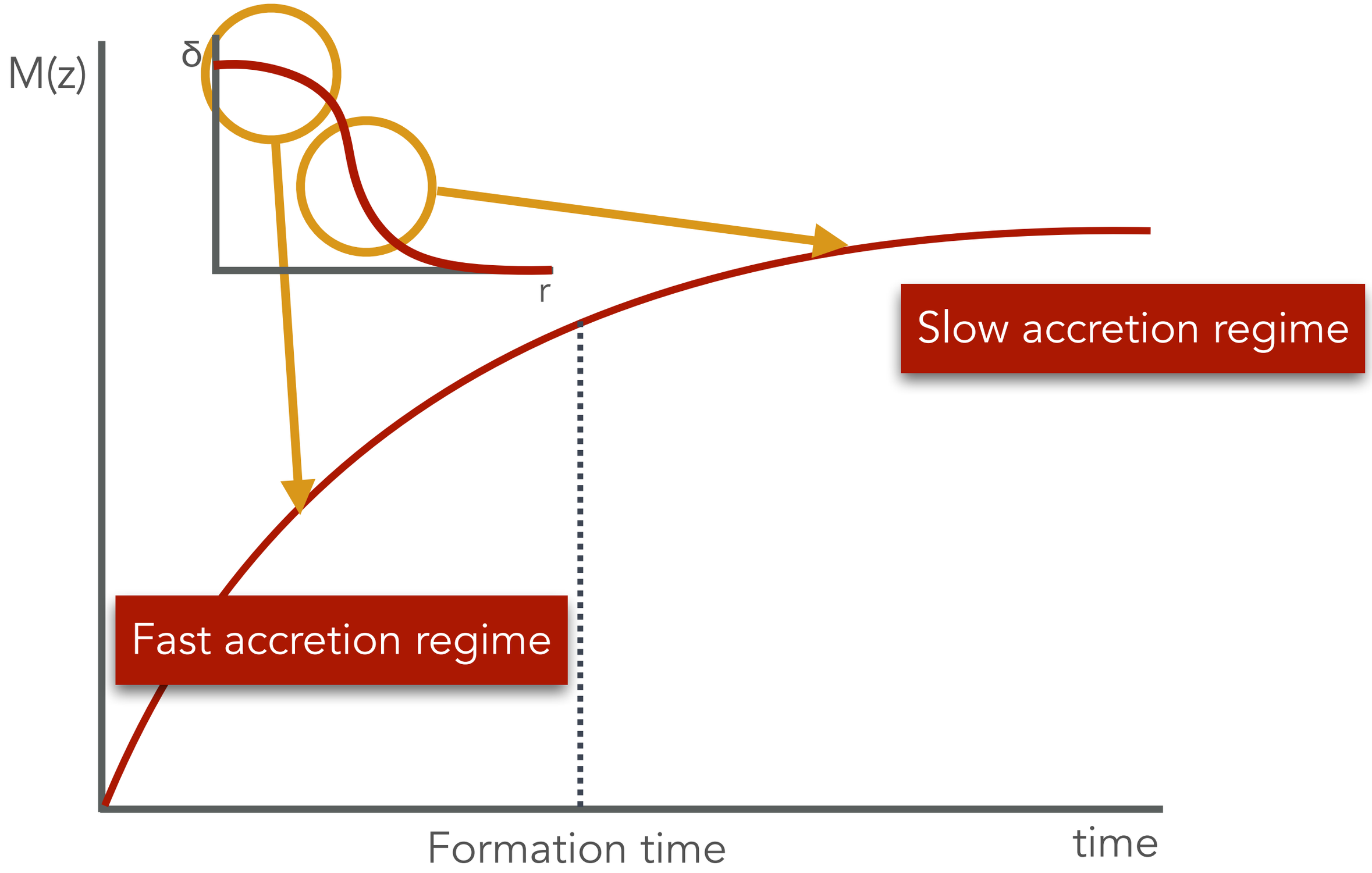
Wechsler et al. 2002 • van den Bosch 2002 • Zhao et al. 2003/2009 • Dalal et al. 2010

Mass accretion history



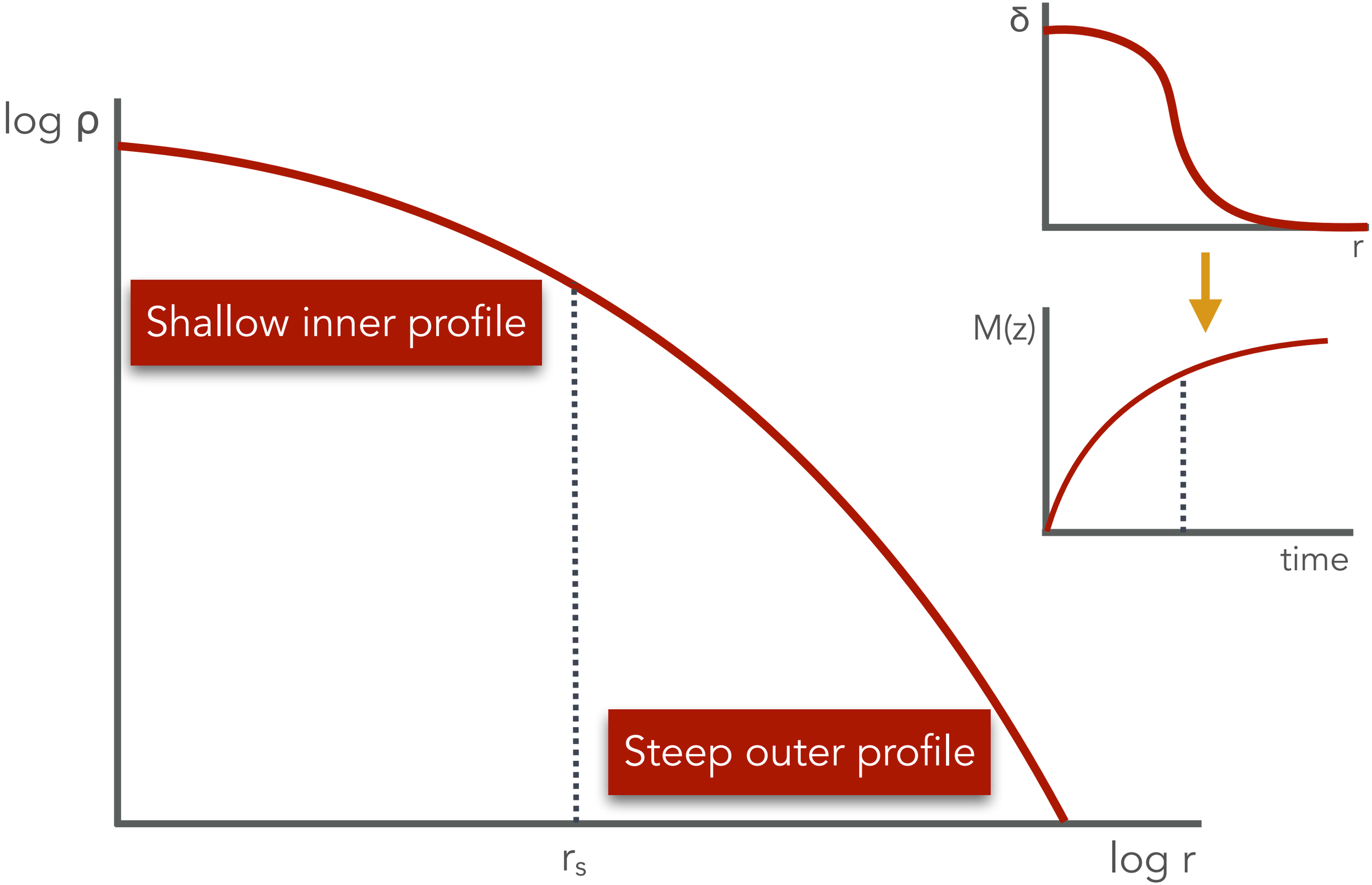
Wechsler et al. 2002 • van den Bosch 2002 • Zhao et al. 2003/2009 • Dalal et al. 2010

Mass accretion history



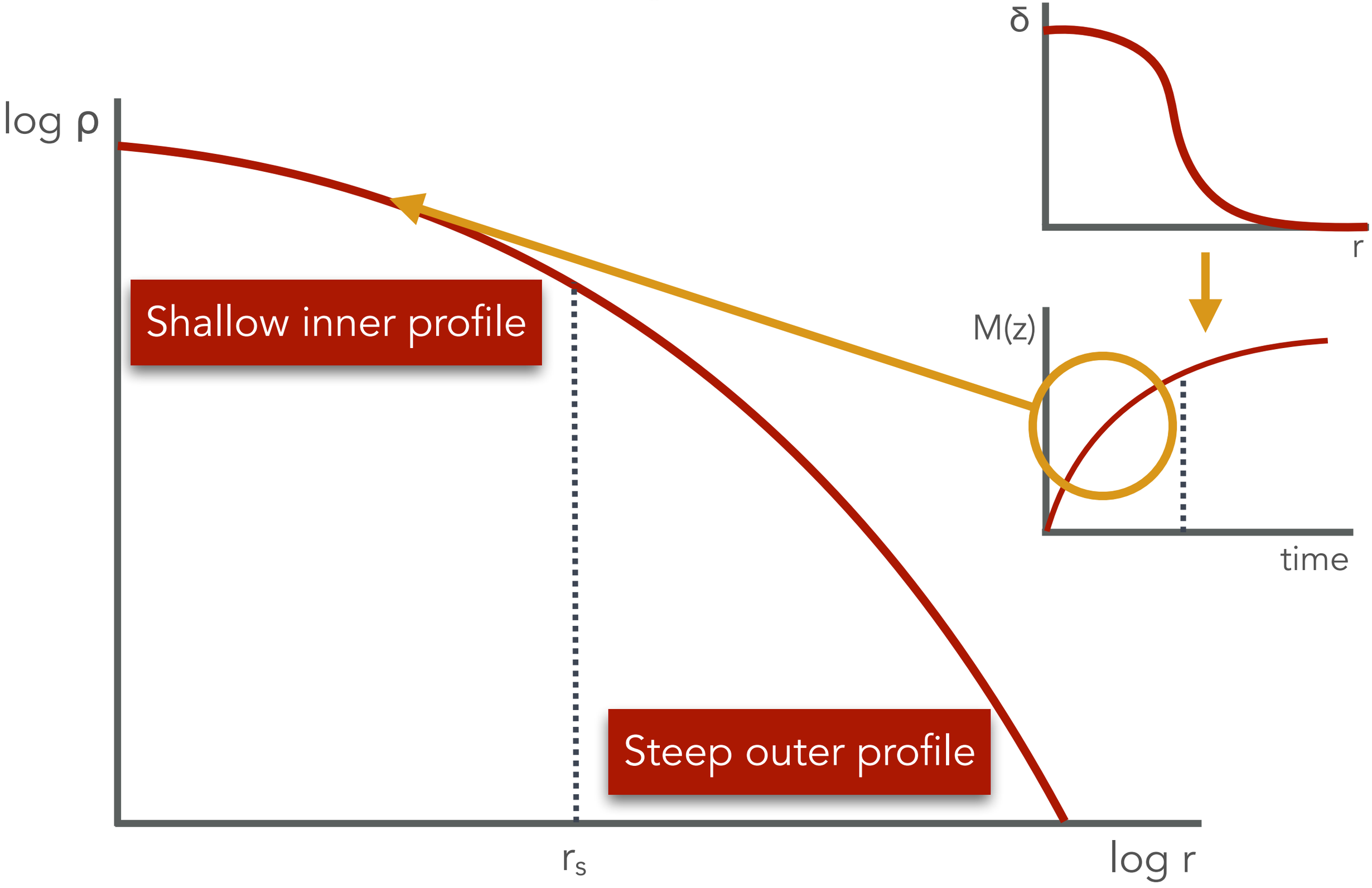
Wechsler et al. 2002 • van den Bosch 2002 • Zhao et al. 2003/2009 • Dalal et al. 2010

Density profile



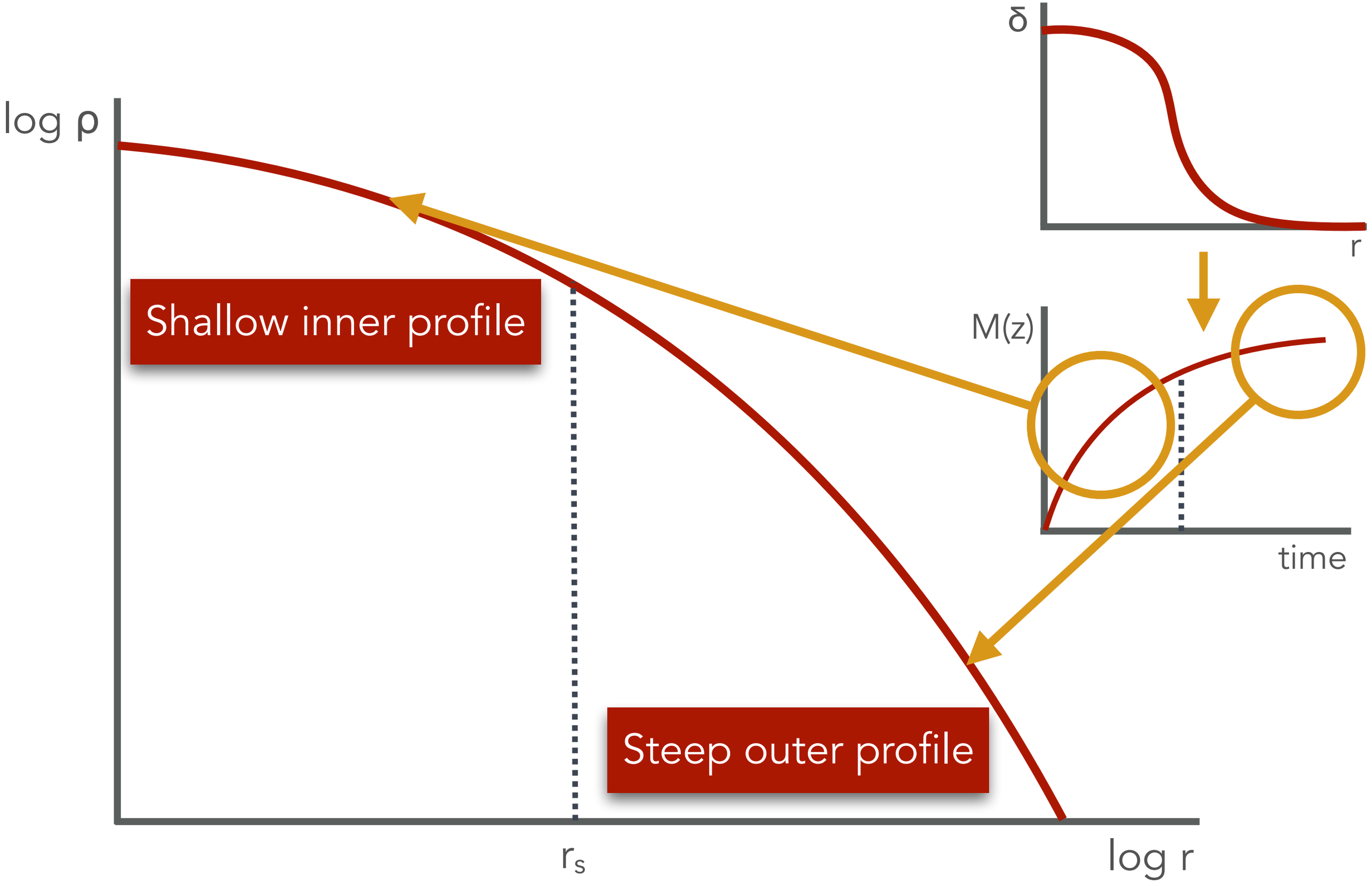
Navarro et al. 1997 • Wechsler et al. 2002 • Lu et al. 2006 • Dalal et al. 2010 • Ludlow et al. 2013

Density profile



Navarro et al. 1997 • Wechsler et al. 2002 • Lu et al. 2006 • Dalal et al. 2010 • Ludlow et al. 2013

Density profile



Navarro et al. 1997 • Wechsler et al. 2002 • Lu et al. 2006 • Dalal et al. 2010 • Ludlow et al. 2013

Reading

- CFN §7.3.2, §7.4.3-§7.4.4, §7.5.2
- MvdBW §5.1, §5.4.4, §7.2, §7.5.1