Structure Formation and Evolution in Warm Dark Matter Cosmologies -Numerical Simulations-

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In memoriam Hector de Vega

Motivation

- ΛCDM fails to explain observed properties of galaxies and cluster of galaxies
- Missing Satellites Problem
- Cores vs Cusps
- Pure Disk Galaxies
- Where is the WIMP?

Motivation

- Warm dark matter (WDM) provides the best alternative to cold dark matter (CDM) candidates since it can be tested with astrophysical observations on small scales where the CDM model is challenged.

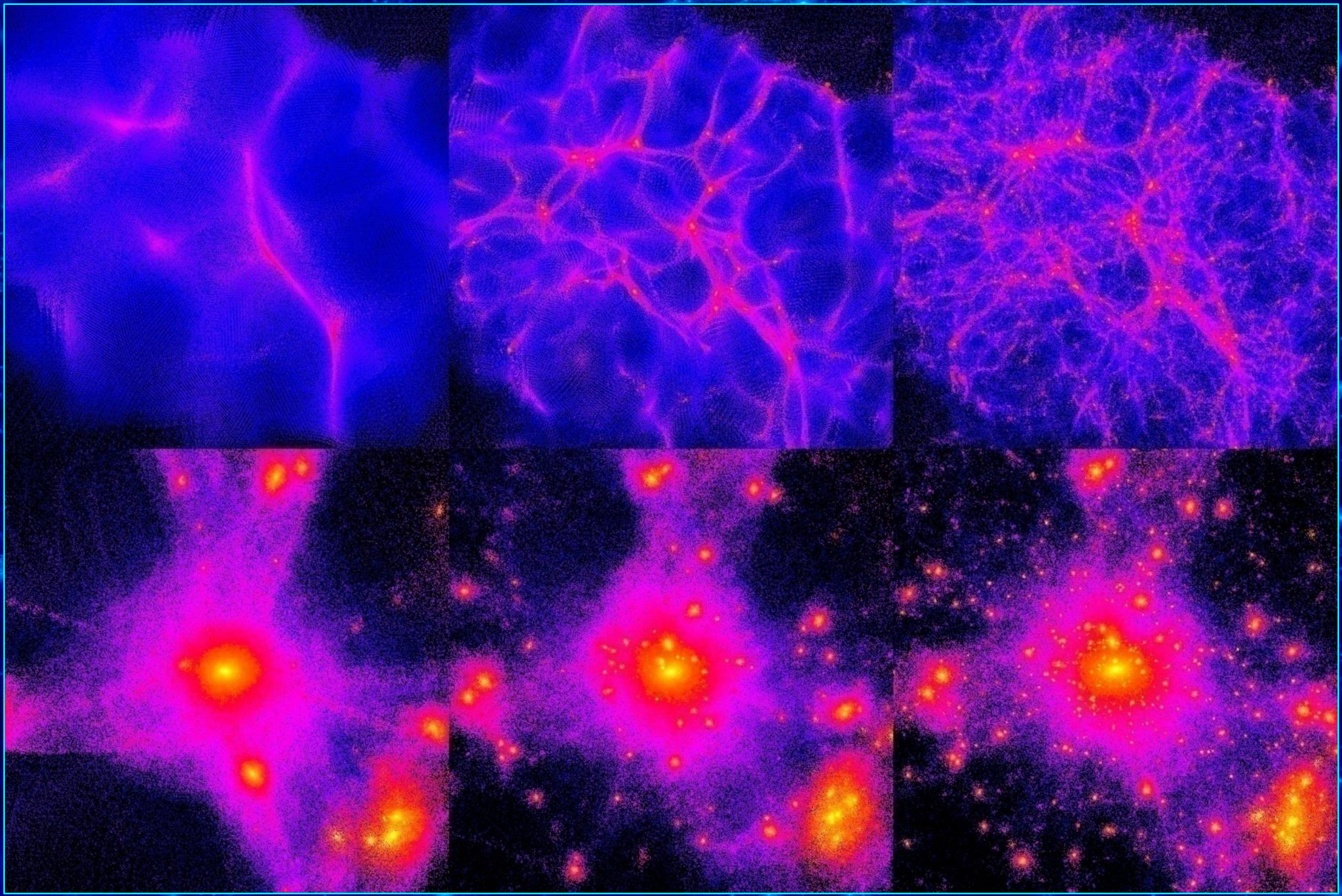
- WDM has a non-negligible velocity dispersion which dampens the small scale fluctuation spectrum and sets a phase space limit to cosmic structures.

- More recently we have seen renewed interest in warm dark matter since a candidate may occur naturally within extensions to the standard model of particle physics.

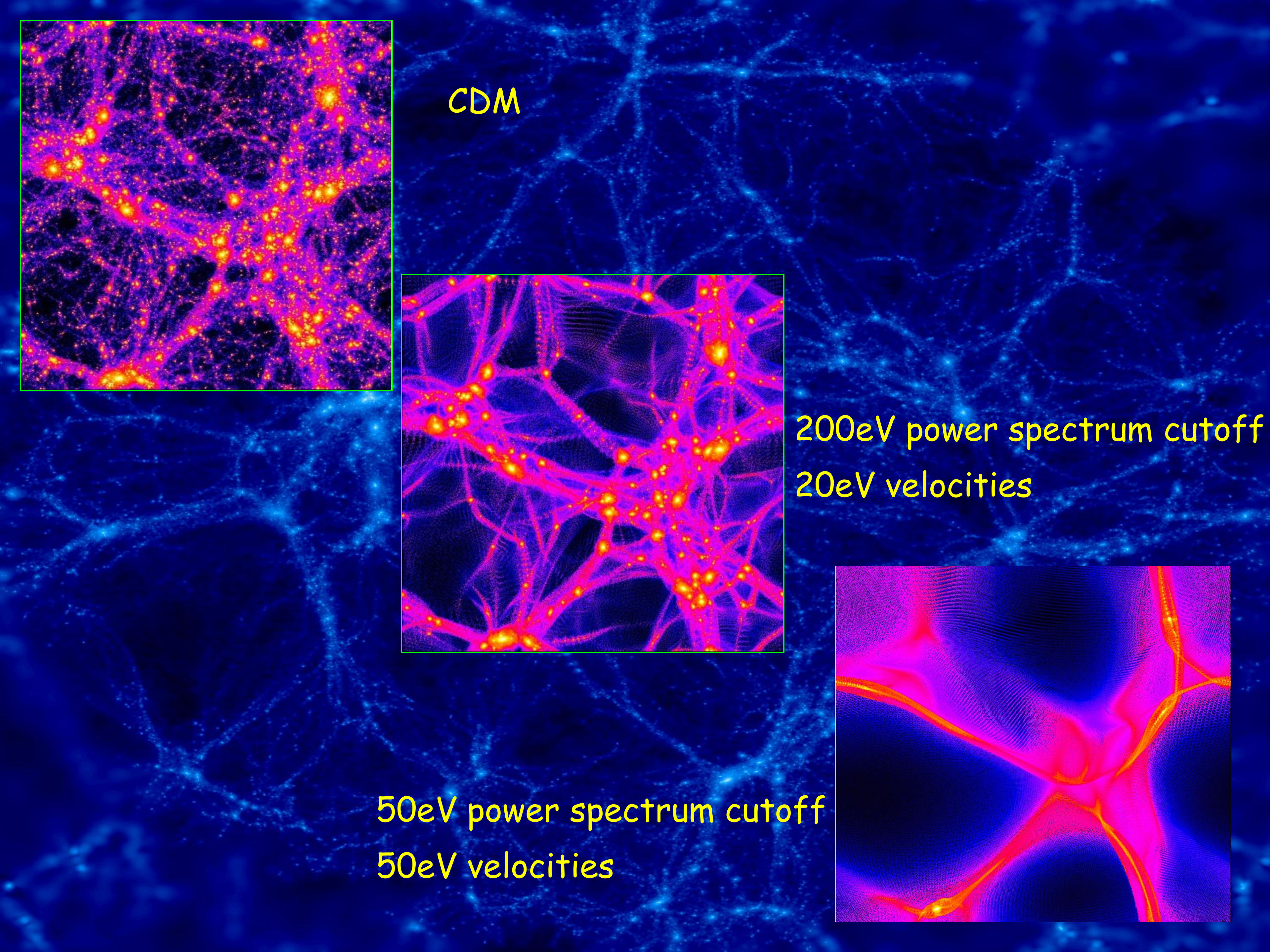
- The sterile neutrino can explain some key physical phenomena including neutrino oscillations, the dark matter and the baryon asymmetry of the universe.

Simulating the Warm Dark Matter - The Challenges

- How to treat the particles?
- How to cut the power spectrum?
- What about velocities ? The impact of velocity disperson.
- How to compare WDM sims with CDM sims and observations
- Resolution and softening
- Fragmentation
- Structure formation and its hidden treasures
- Halo internal structure
- The trustworthy factor and the catch 22



<1 kev DM | >1 kev DM | CDM


CDM
200eV power spectrum cutoff
20eV velocities
50eV power spectrum cutoff
50eV velocities

1 ~ 10

'or the unexpected virtue of ignorance'

Bode, Ostriker & Turok 2001

Assumptions: entropy production & negigible chemical potential

$$\frac{n_X}{n_\gamma} = \left(\frac{43/4}{g_{\rm dec}}\right)\left(\frac{4}{11}\right)\frac{g_X}{2}$$

$$\Omega_X h^2 \approx \frac{115}{g_{\rm dec}}\frac{g_X}{1.5}\frac{m_X}{\rm keV} .$$

$$\frac{v_0(z)}{1+z} = .012\left(\frac{\Omega_X}{0.3}\right)^{\frac{1}{3}}\left(\frac{h}{0.65}\right)^{\frac{2}{3}}\left(\frac{1.5}{g_X}\right)^{\frac{1}{3}}\left(\frac{keV}{m_X}\right)^{\frac{4}{3}} \,\mathrm{km\,s^{-1}}$$

$$(\exp(v/v_0)+1)^{-1}$$

$$\frac{v_0(z)}{1+z} \approx 0.12\left(\frac{1}{g_{\rm dec}}\right)^{1/3}\frac{\rm keV}{m_X}\,\mathrm{km\,s^{-1}}$$

$$g_{\rm dec} = 1000\,(g_X/1.5)^{1/3}$$

Different Assumptions:

- **number conservation**
- **non-entropy production**
- **quantum pression**
- **Thermalization caused by an exchange potential**

Paduroiu et. al 2015

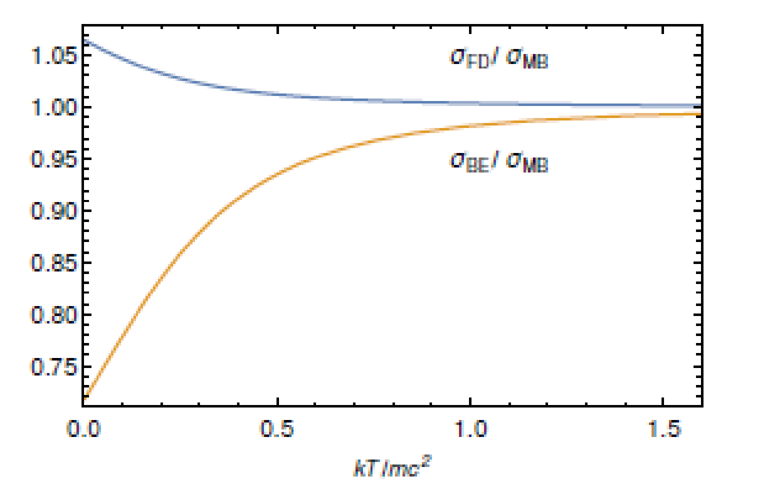
$$f(\mathbf{p}) = \frac{g}{(2\pi\hbar)^3}\frac{1}{\exp((\epsilon-\mu)/kT)\pm 1}$$

$$n(T,\mu) = \frac{4\pi g}{h^3}\int_0^\infty \frac{p^2}{\exp((\epsilon-\mu)/kT)\pm 1}\,dp$$

$$\epsilon(T,\mu) = \frac{4\pi g}{h^3}\int_0^\infty \frac{p^2\epsilon}{\exp((\epsilon-\mu)/kT)\pm 1}\,dp$$

$$P(T,\mu) = \frac{4\pi g}{h^3}\int_0^\infty \frac{p^2}{\exp((\epsilon-\mu)/kT)\pm 1}\frac{1}{3}\frac{c^2p^2}{\epsilon+mc^2}\,dp$$

$$v = 0.2226\left(\frac{n}{115\,\mathrm{cm}^{-3}}\frac{1}{g}\right)^{1/3}\left(\frac{mc^2}{\mathrm{keV}}\right)^{-1}\mathrm{km\,s}^{-1}$$



CAVEAT EMPTOR

$$\frac{v_0(z)}{1+z} = .012 \left(\frac{\Omega_X}{0.3}\right)^{\frac{1}{3}} \left(\frac{h}{0.65}\right)^{\frac{2}{3}} \left(\frac{1.5}{g_X}\right)^{\frac{1}{3}} \left(\frac{keV}{m_X}\right)^{\frac{4}{3}} \mathrm{km\,s^{-1}}$$

Bode et. al 2001

$$\Omega_X h^2 \approx \frac{115}{g_{\rm dec}} \frac{g_X}{1.5} \frac{m_X}{\rm keV} .$$

'valid' only for the case in which the full dark matter content is made up by only one type of particles

$$v = 0.2226 \left(\frac{n}{115\,\mathrm{cm^{-3}}} \frac{1}{g}\right)^{1/3} \left(\frac{mc^2}{\rm keV}\right)^{-1} \mathrm{km\,s^{-1}}$$

Paduroiu et. al 2015

Mass	Bode et al. Eq. (11)×3.571	Pierpaoli et al.	This work Eq. (25)
keV/c^2	km/s	km/s	km/s
0.2	0.366	0.4032	1.113
1.0	0.0429	0.0225	0.223
3.5	0.00806	0.0230	0.0636

Simulating the WDM…

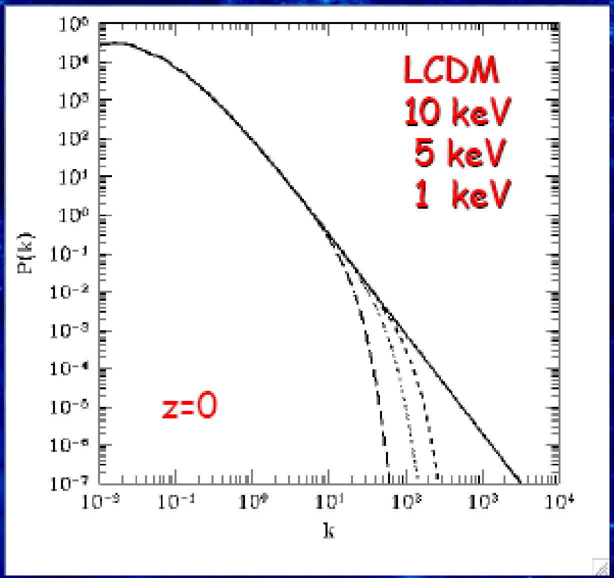
$$\frac{v_0(z)}{1+z} = .012\left(\frac{\Omega_X}{0.3}\right)^{\frac{1}{3}}\left(\frac{h}{0.65}\right)^{\frac{2}{3}}\left(\frac{1.5}{g_X}\right)^{\frac{1}{3}}\left(\frac{keV}{m_X}\right)^{\frac{4}{3}} \mathrm{km\,s^{-1}}$$

Bode, Turok, and Ostriker (2001)

$$T^2(k) = \frac{P^{WDM}}{P^{CDM}} = [1 + (\alpha k)^{2\nu}]^{-10/\nu}$$

$$\alpha = 0.049 \cdot \left(\frac{m_x}{1keV}\right)^{-1.11} \cdot \left(\frac{\Omega_\nu}{0.25}\right)^{0.11} \cdot \left(\frac{h}{0.7}\right)^{1.22} h^{-1}\mathrm{Mpc}.$$

Viel et. Al 2005



$$k_S \approx \left(\frac{0.3}{\Omega_X}\right)^{0.15}\left(\frac{m_X}{keV}\right)^{1.15} Mpc^{-1}$$

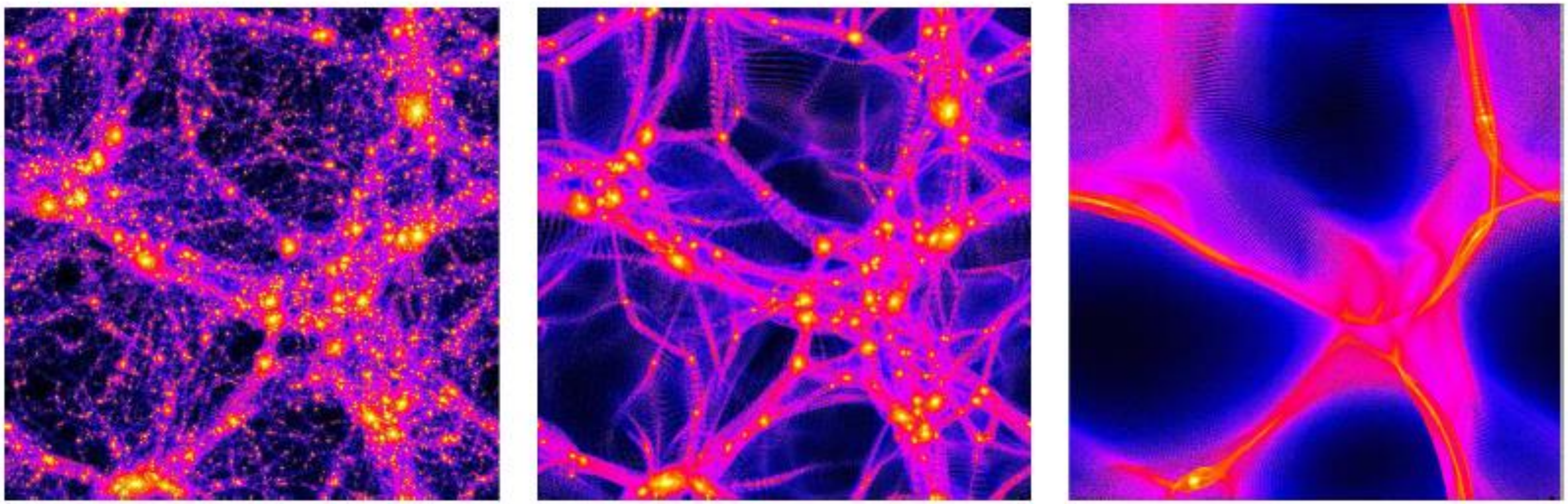


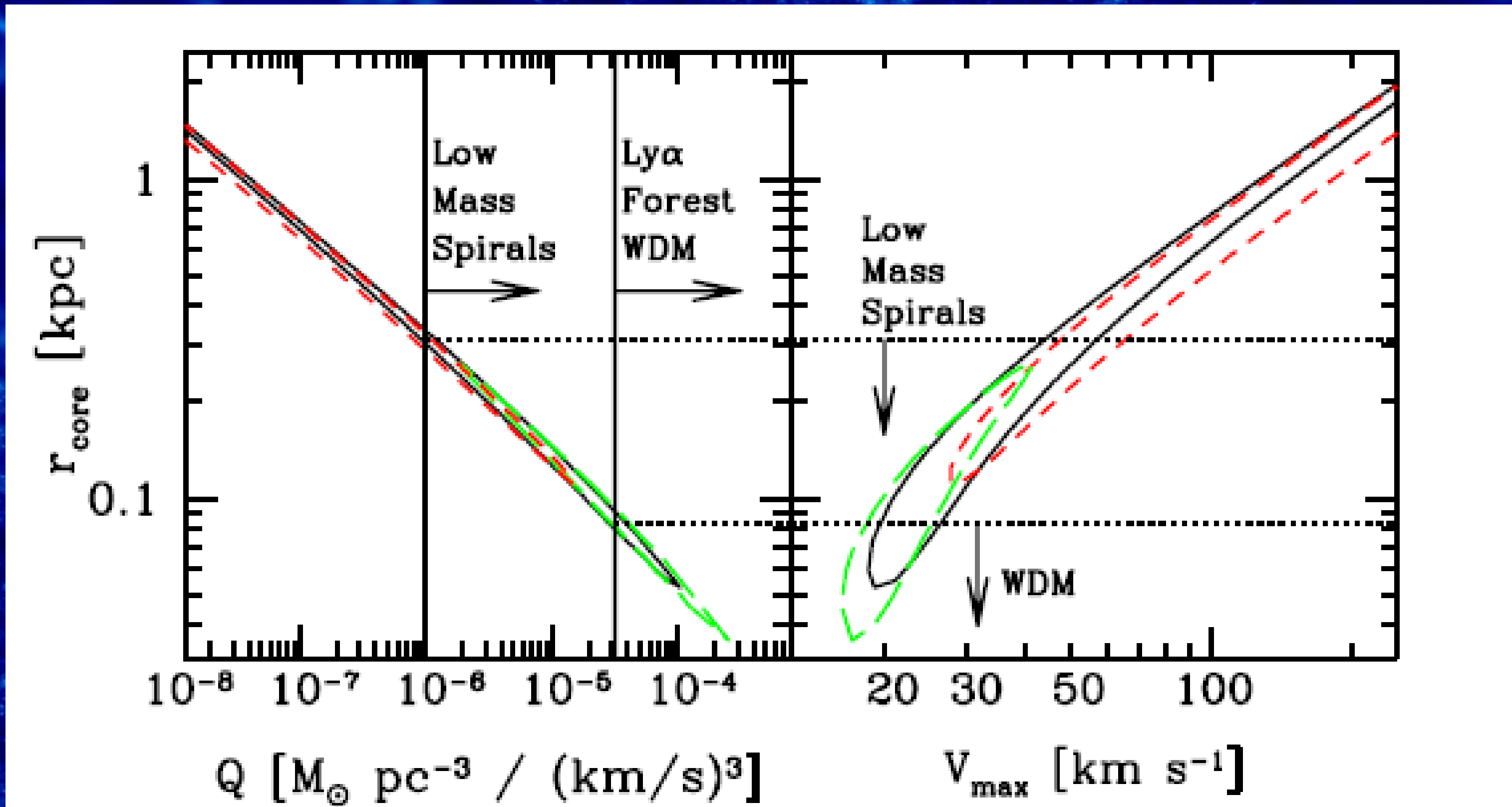
Figure 1. Three snapshots of different simulations at redshift $z = 0$. CDM, WDM3 and WDM4 are shown from left to right.

Table 1. Details of the simulations

Label	particle mass	velocities	box size	no.of particles	softening (r_{200})	halo mass	r_{200} (kpc)	N($< r_{200}$)
CDM	-	no	40 Mpc	160^3	2.6×10^{-3}	7×10^{11}	160	3.6×10^6
WDM1	200 eV	no	40 Mpc	160^3	2.6×10^{-3}	7×10^{11}	140	2.7×10^6
WDM2	200 eV	100 eV	40 Mpc	160^3	2.6×10^{-3}	7×10^{11}	140	1.7×10^6
WDM3	200 eV	20 eV	40 Mpc	160^3	2.6×10^{-3}	7×10^{11}	132	2.7×10^6
WDM4	50 eV	no	40 Mpc	160^3	2.6×10^{-3}	-	-	-
WDM5	200 eV	no	42.51 Mpc	300^3	0.66×10^{-3}	10^{13}	425	18.67×10^6
WDM6	200 eV	200 eV	42.51 Mpc	300^3	0.66×10^{-3}	10^{13}	425	18.66×10^6

Assumptions in determining the core radius:

- Isothermal spheres
- Liouville – Phase space density (PSD) is conserved
- Pauli exclusion principle
- PSD constant as mixing occurs
- Velocity dispersion in central halo = constant
- Density profile in central halo = constant

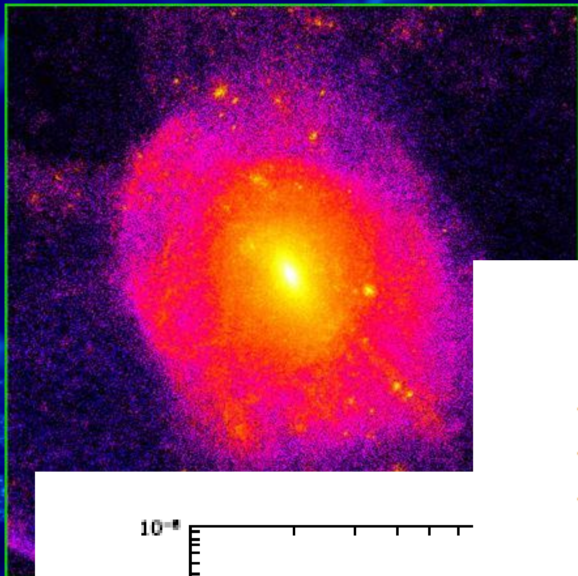


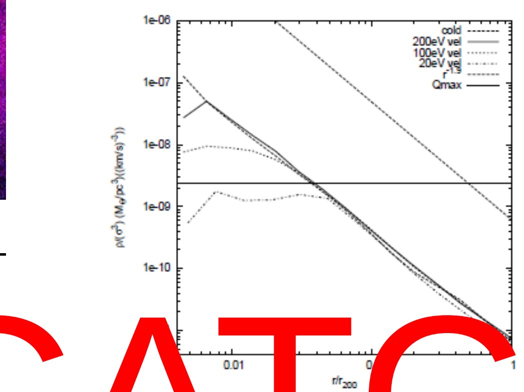
Constraints on the core radius of Fornax as a function of the central phase-space density and maximum circular velocity derived from the velocity dispersion profile

Strigari et al 2006

$$\rho(r) = \frac{\rho_0}{\left[1+(r/r_0)^\alpha\right]^{3/\alpha}}$$

CATCH 22





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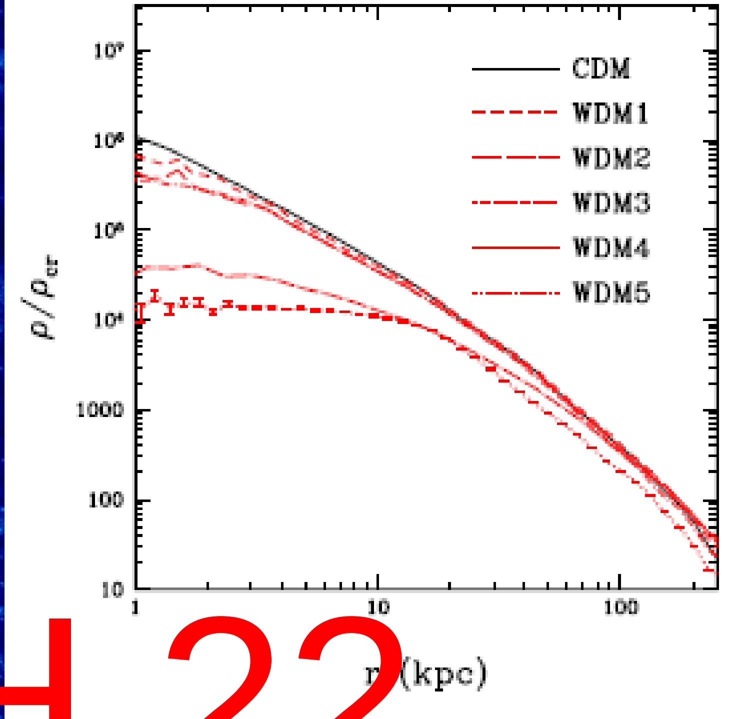

Fi... re 2. Th... sphericall... averaged density profiles for CDM, W... M1-5 halos.

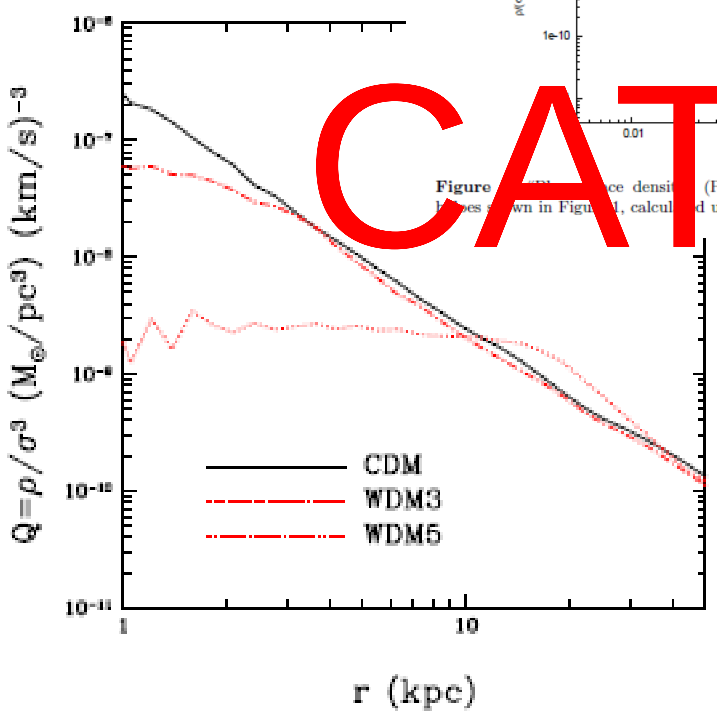

Figure 4. Phase space density profile for the CDM, WDM3 and WDM5 models at $z = 0$.

Label	m_ν (keV)	$m_{\nu,vel}$ (keV)	N_{vir} (10^6)	M_{vir} $(10^{12} M_\odot)$
CDM	∞	–	10.2	1.42
WDM1	2.0	1.32	8.6	1.22
WDM2	2.0	0.33	8.4	1.20
WDM3	2.0	0.13	8.5	1.21
WDM4	2.0	0.15	6.7	0.93
WDM5-N	2.0	0.05	4.9	0.71
WDM5	2.0	0.03	5.1	0.82

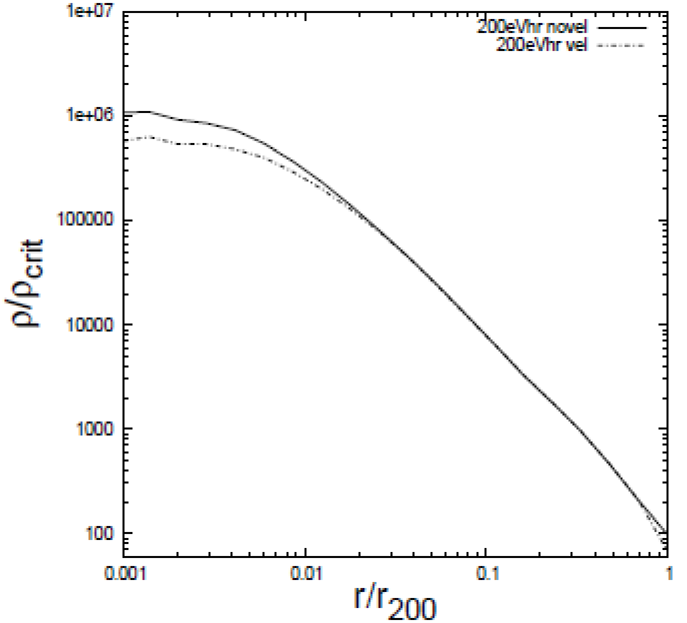

Figure 4. The density profiles for a high resolution halo in the 200 eV simulation WDM5 and WDM6

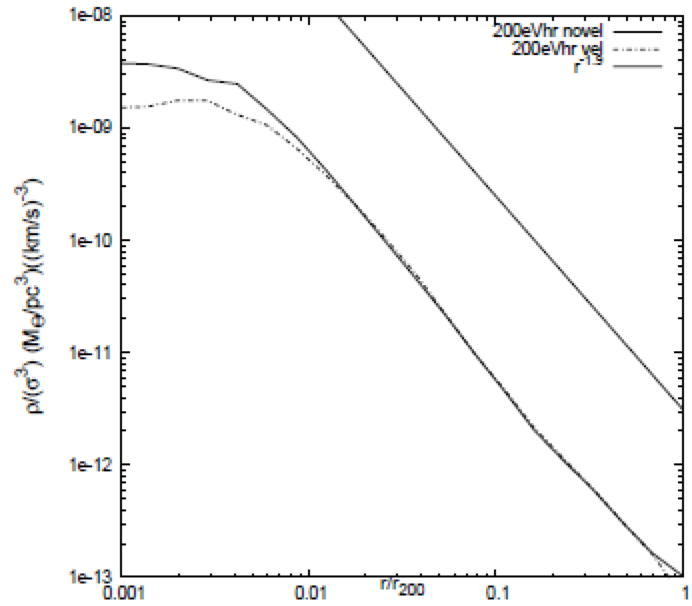

Figure 5. The PSD profiles for the 200eV halo from WDM5 and WDM6. A power law line of slope $r^{-1.9}$ is shown for reference.

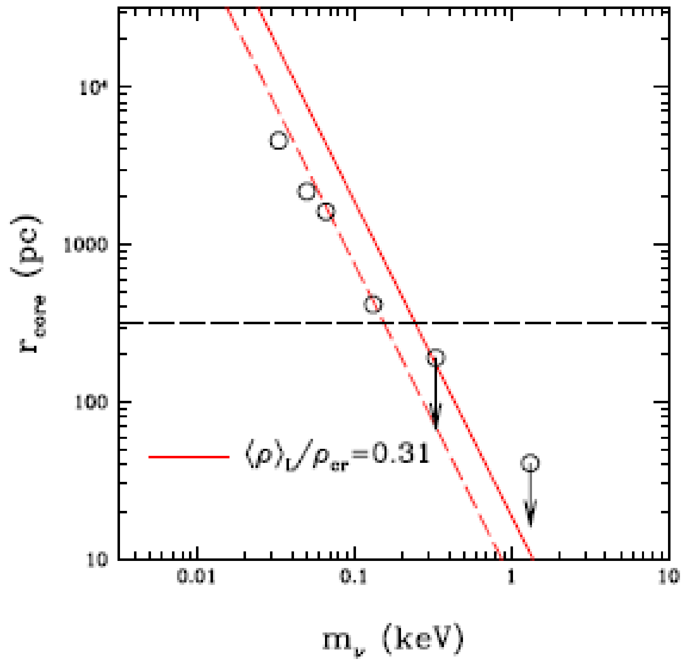

Figure 1. Comparison between core size in simulations (open symbols) and the theoretical expectation for a $M = 10^{12} M_\odot$ halo (solid line). The dashed horizontal line is the gravitational softening of our simulations. All points below this line should be considered as upper limits on the core size. The red dashed line is a linear fit to the simulation results.

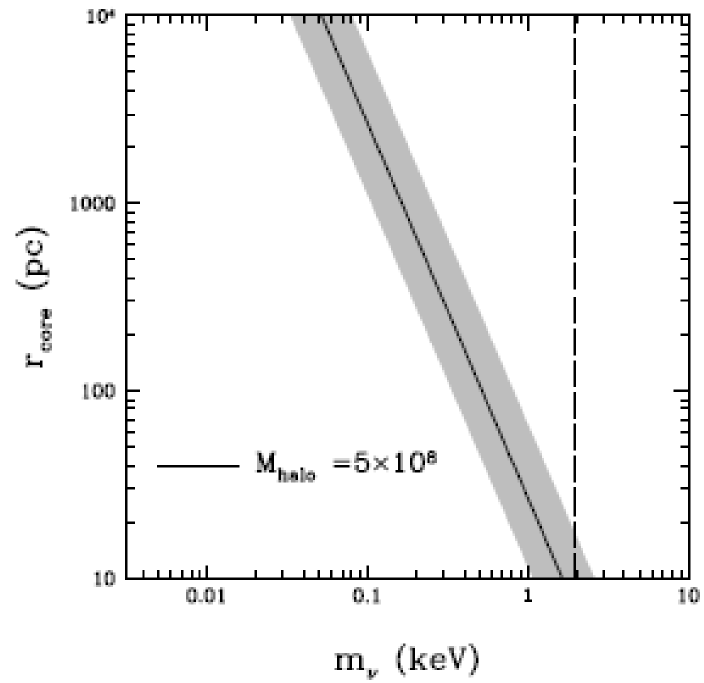

Figure 2. Expected core size for the typical dark matter mass of Milky Way satellites as a function of the WDM mass m_ν. The shaded area takes into account possible different values of the local density parameter $0.15 < \Omega_m < 0.6$. The vertical dashed line shows the current limits on the WDM mass from large scale structure observations.

Label	m_ν (keV)	$m_{\nu,\mathrm{vel}}$ (keV)	N_{vir} (10^6)	M_{vir} ($10^{12} M_\odot$)
CDM	∞	–	10.2	1.42
WDM1	2.0	1.32	8.6	1.22
WDM2	2.0	0.33	8.4	1.20
WDM3	2.0	0.13	8.5	1.21
WDM4	2.0	0.15	6.7	0.93
WDM5-N	2.0	0.05	4.9	0.71
WDM5	2.0	0.03	5.1	0.82

How to cook a big core...

Simulations of CDM+gas+AGN feedback+star formation fine-tuned

If one tunes it for solving the missing satellites problem looses the core

and vice-versa

Another Catch 22

Unfortunately, proper KeV simulations+baryons haven‘t been performed yet.

The formation of disc galaxies in high resolution moving-mesh cosmological simulations

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<<There is no evidence for any dark matter core formation in our simulations, even so they include repeated baryonic outflows by supernova-driven winds and black hole quasar feedback >>

Fermionic warm dark matter produces galaxy cores in the observed scales because of quantum mechanics

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Abstract

We derive the main physical galaxy properties: mass, halo radius, phase space density and velocity dispersion from a semiclassical gravitational approach in which fermionic WDM is treated quantum mechanically. They turn out to be fully compatible with observations. The Pauli Principle implies for the fermionic DM phase-space density $Q(\vec{r}) = \rho(\vec{r})/\sigma^3(\vec{r})$ the quantum bound $Q(\vec{r}) \leq K\ m^4/\hbar^3$, where m is the DM particle mass, $\sigma(\vec{r})$ is the DM velocity dispersion and K is a pure number of order one which we estimate. Cusped profiles from N-body galaxy simulations produce a divergent $Q(r)$ at $r = 0$ violating this quantum bound. The combination of this quantum bound with the behaviour of $Q(r)$ from simulations, the virial theorem and galaxy observational data on Q implies lower bounds on the halo radius and a minimal distance r_{min} from the centre at which classical galaxy dynamics for DM fermions breaks down. For WDM, r_{min} turns to be in the parsec scale. For cold dark matter (CDM), r_{min} is between dozens of kilometers and a few meters, astronomically compatible with zero. For hot dark matter (HDM), r_{min} is from the kpc to the Mpc. In summary, this quantum bound rules out the presence of galaxy cusps for fermionic WDM, in agreement with astronomical observations, which show that the DM halos are cored. We show that compact dwarf galaxies are natural quantum macroscopic objects supported against gravity by the fermionic WDM quantum pressure (quantum degenerate fermions) with a minimal galaxy mass and minimal velocity dispersion. Quantum mechanical calculations which fulfil the Pauli principle become necessary to compute galaxy structures at kpc scales and below. Classical N-body simulations are not valid at scales below r_{min}. We apply the Thomas-Fermi semiclassical approach to fermionic WDM galaxies, we resolve it numerically and find the physical galaxy magnitudes: mass, halo radius, phase-space density, velocity

Structure formation in warm dark matter cosmologies Top-Bottom Upside-Down

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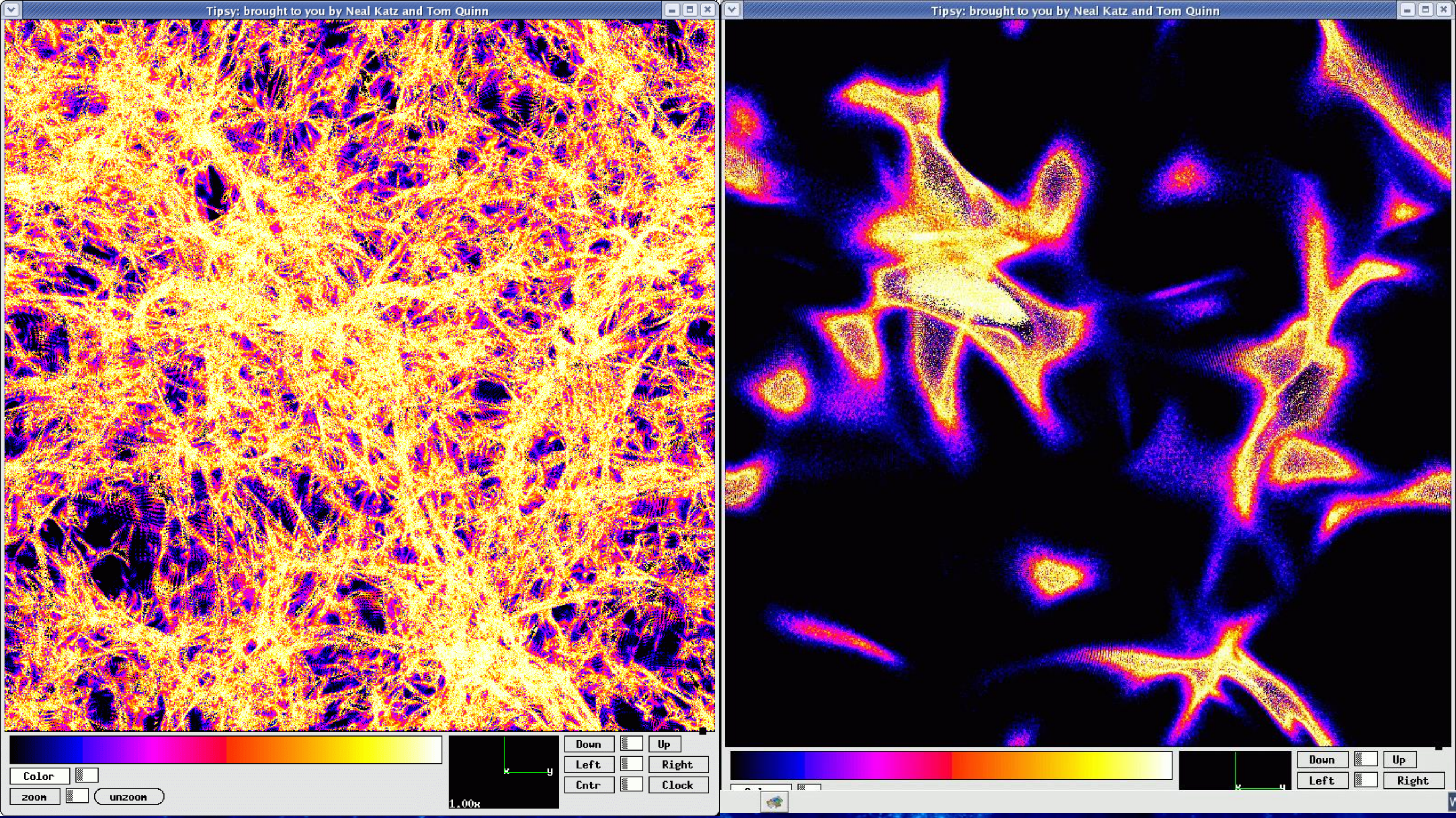
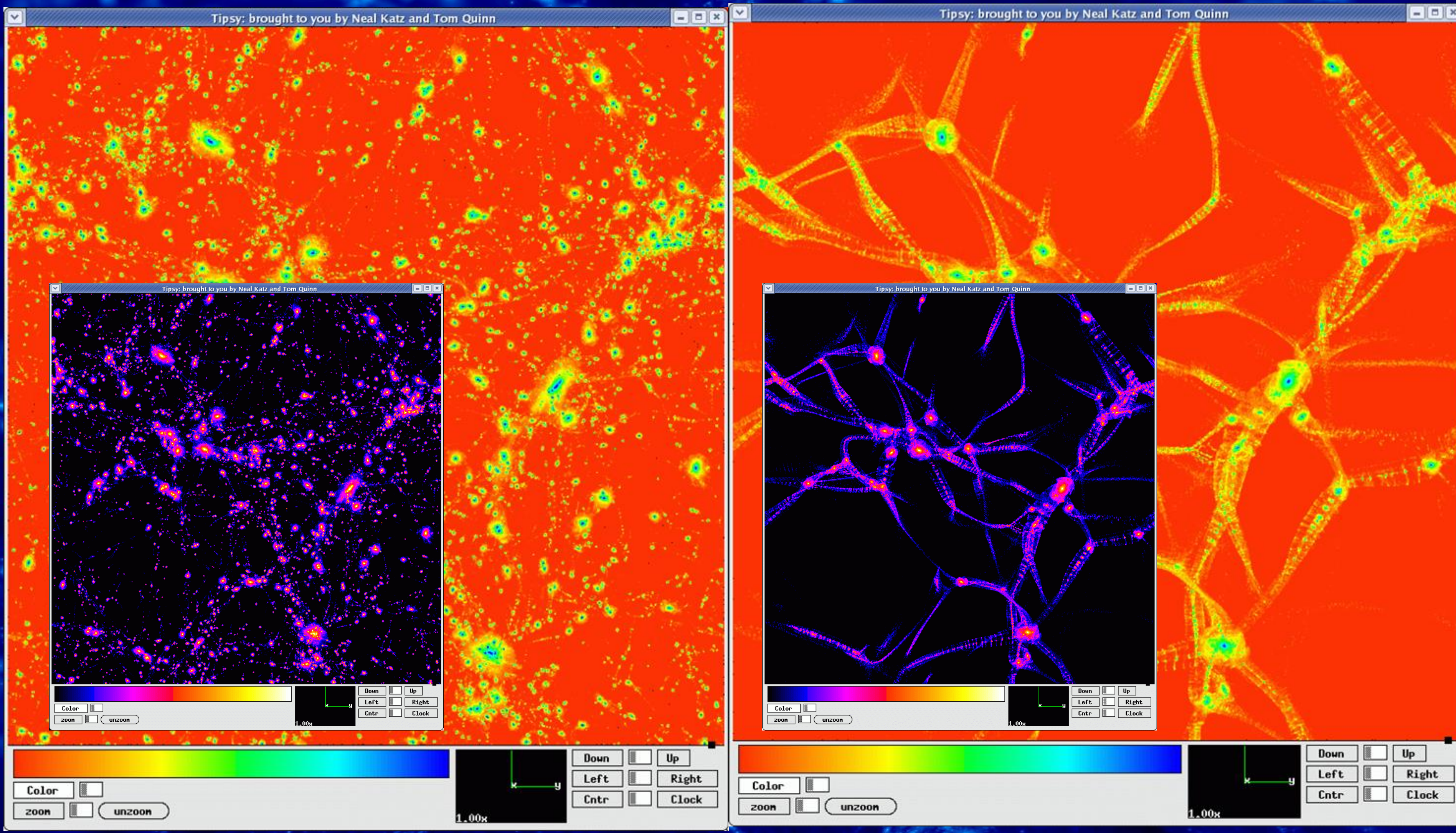
ABSTRACT
The damping on the fluctuation spectrum and the presence of thermal velocities as properties of warm dark matter particles like sterile neutrinos imprint a distinct signature found from the structure formation mechanisms to the internal structures of halos. Using warm dark matter simulations we explore these effects on the structure formation for different particle energies and we find that the formation of structure is more complex than originally assumed, a combination of top-down collapse and hierarchical (bottom-up) clustering on multiple scales. The degree on which one scenario is more prominent with respect to the other depends globally on the energy of the particle and locally on the morphology and architecture of the anayzed region. The presence of shells and caustics in warm dark matter haloes is another important effect seen in simulations. Furthermore we discuss the impact of thermal velocities on the structure formation from theoretical considerations as well as from the analysis of the simulations. We re-examine the assumptions considered when estimating the velocity dispersion for warm dark matter particles that have been adopted in previous works for more than a decade and we give an independent estimation for the velocities. We identify some inconsistencies in previous published results. The relation between the warm dark matter particle mass and its corresponding velocity dispersion is strongly model dependent, hence the constraints on particle mass from simulation results are weak. Finally, we review the technical difficulties that arise in warm dark matter simulations along with possible improvements of the methods.



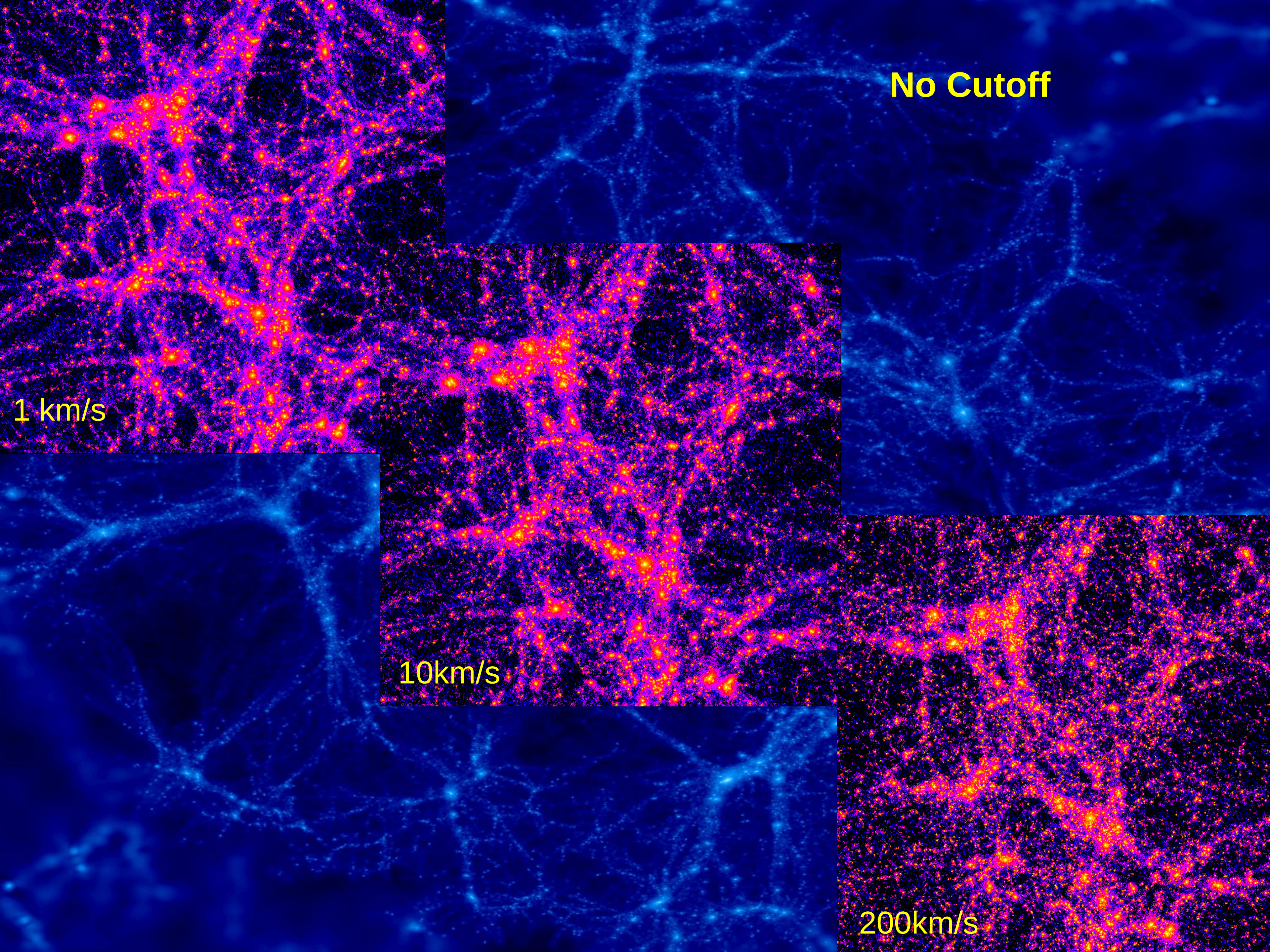
Mildly non-linear regions at z=3 in CDM and WDM

i.e. overdensities between 1 and 5 w.r.t. mean

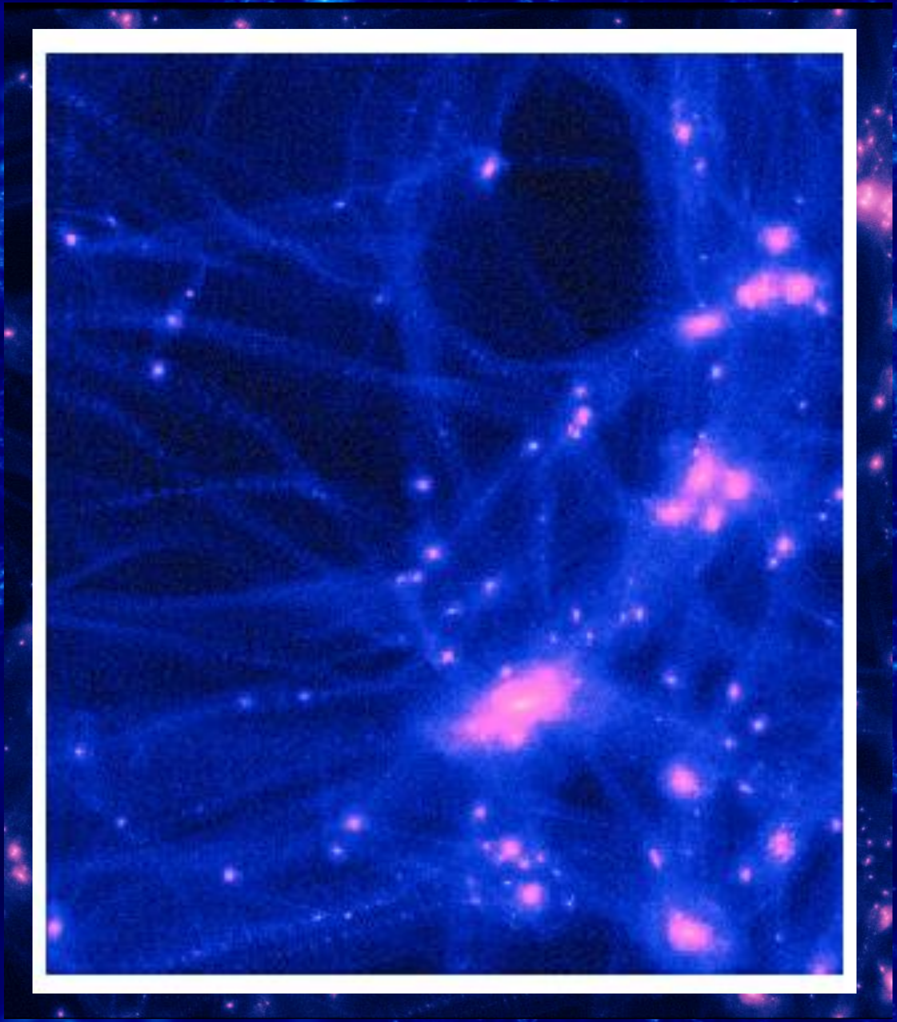


Virialised regions at z=3 in CDM and WDM

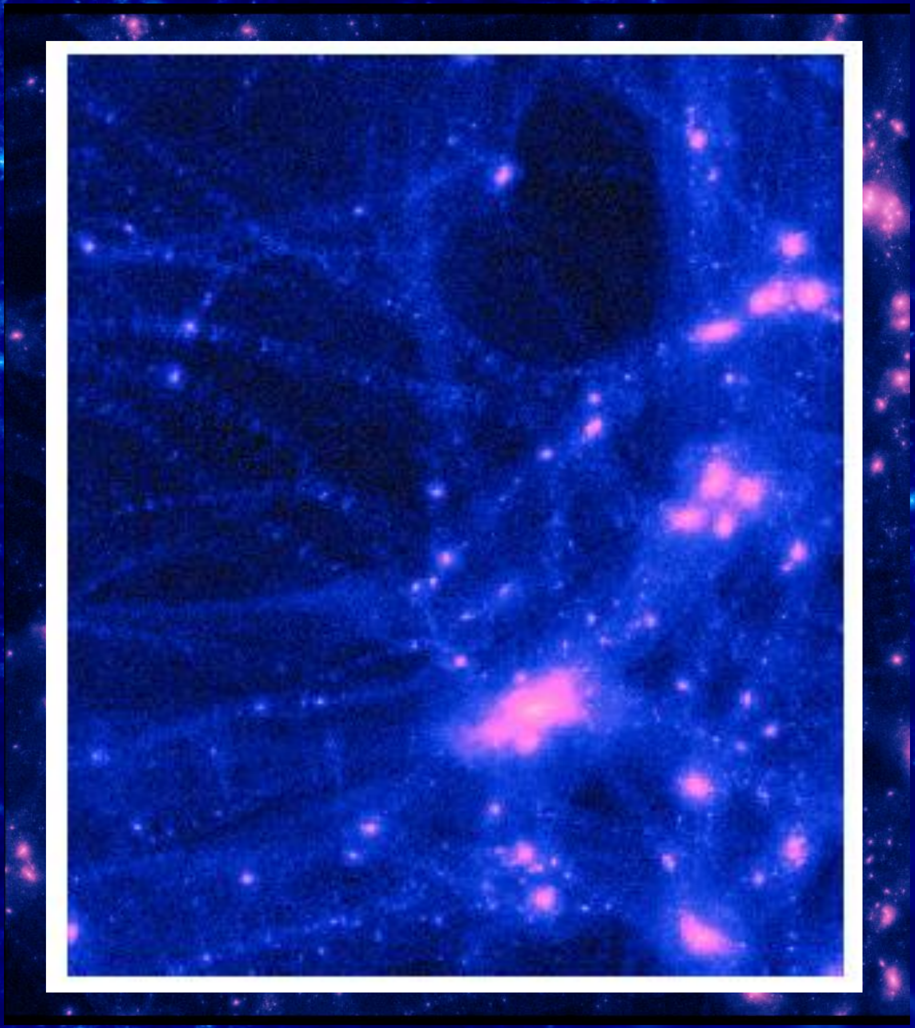
i.e. overdensities higher than 100 w.r.t. mean

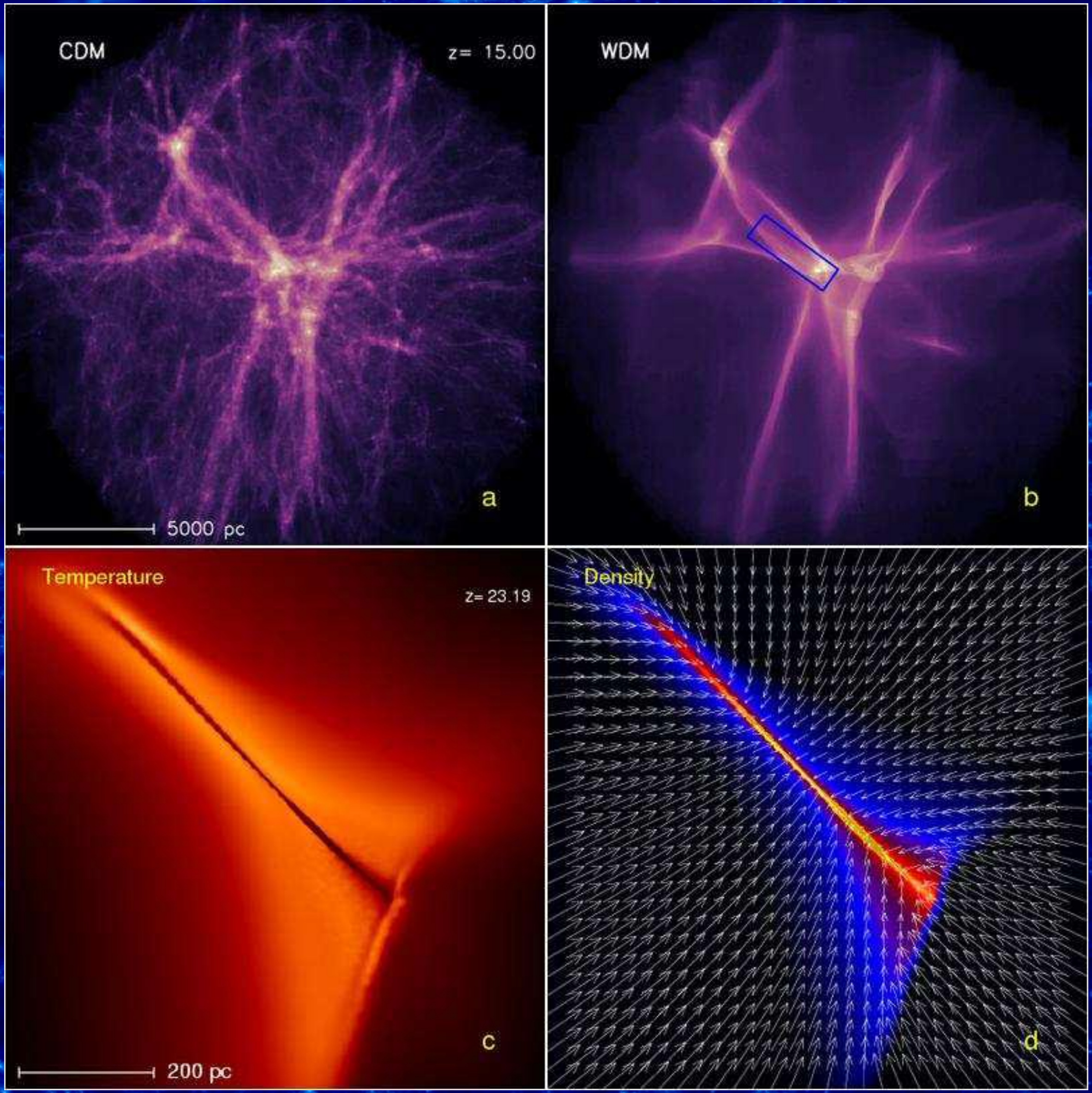

No Cutoff
1 km/s
10km/s
200km/s

Thermal Velocities



No Thermal Velocities





Liang Gao & Tom Theuns, Science sept 2007

Label	velocities z_i km/s	cutoff eV	box size Mpc/h	N	softening pc
CDM	no	-	40	300^3	50
WDM1	no	200	40	300^3	50
WDM2	36.6	200	40	300^3	50
WDM3	no	1000	40	300^3	50
WDM4	4.2	1000	40	300^3	50
WDM5	36.6	200	30	256^3	100

Simulations details: 2.72×10^5 M_o / particle
355 pc spline gravitational softening
WMAP7 cosmological parameters
z=100 initial redshift

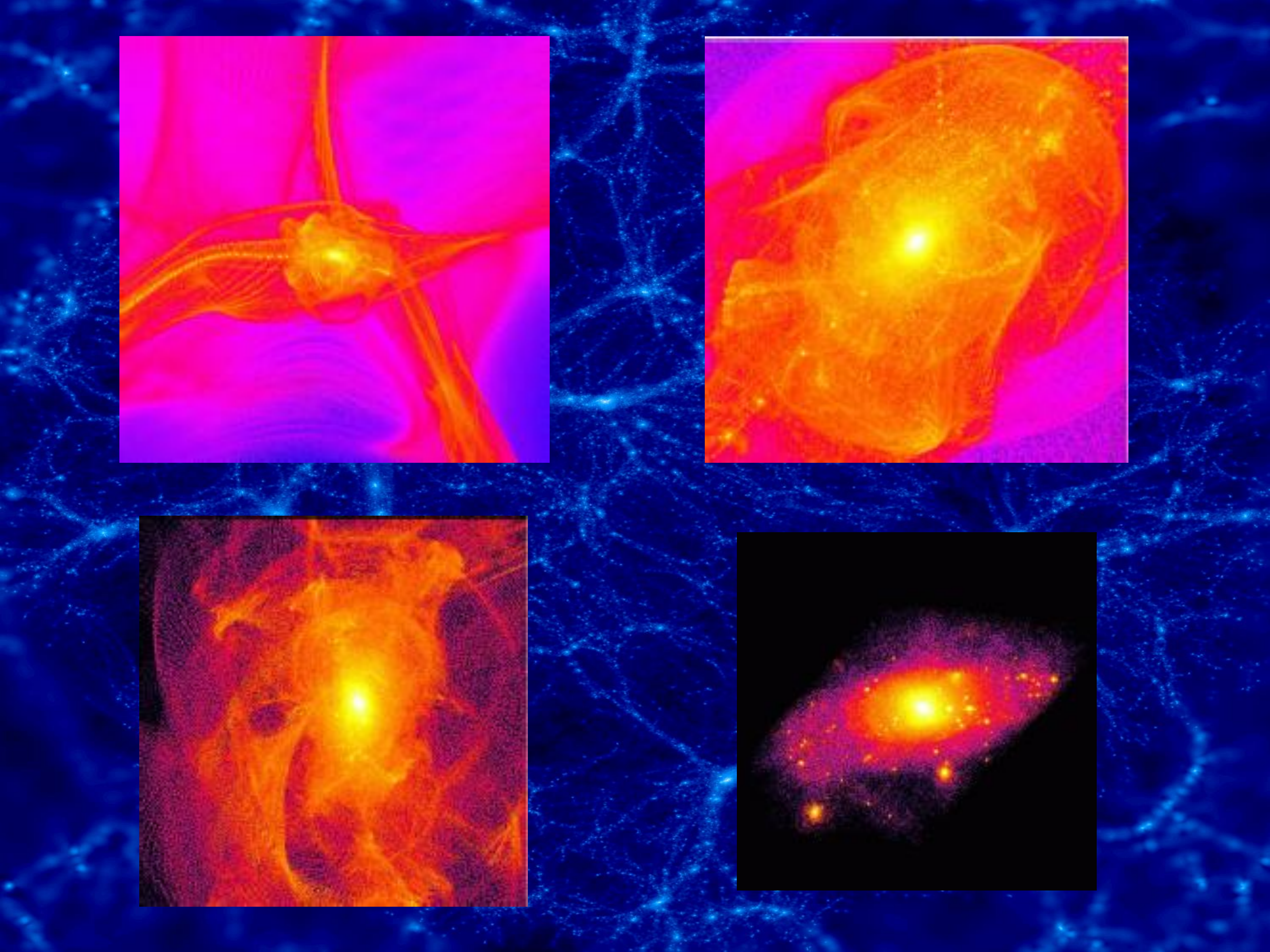
Label	size	first collapse	average density	highest density
-	box	z	critical	critical
lu.avi	1/4	10.88	0.264	477
ld.avi	1/4	10.18	0.258	481
ru.avi	1/4	10.18	0.268	480
rd.avi	1/4	10.64	0.258	474

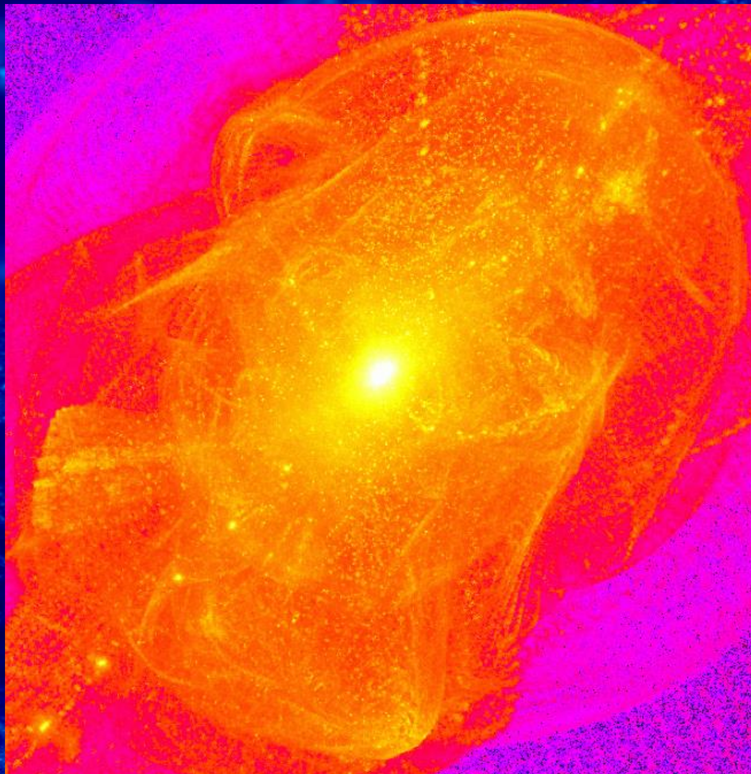
The movies…

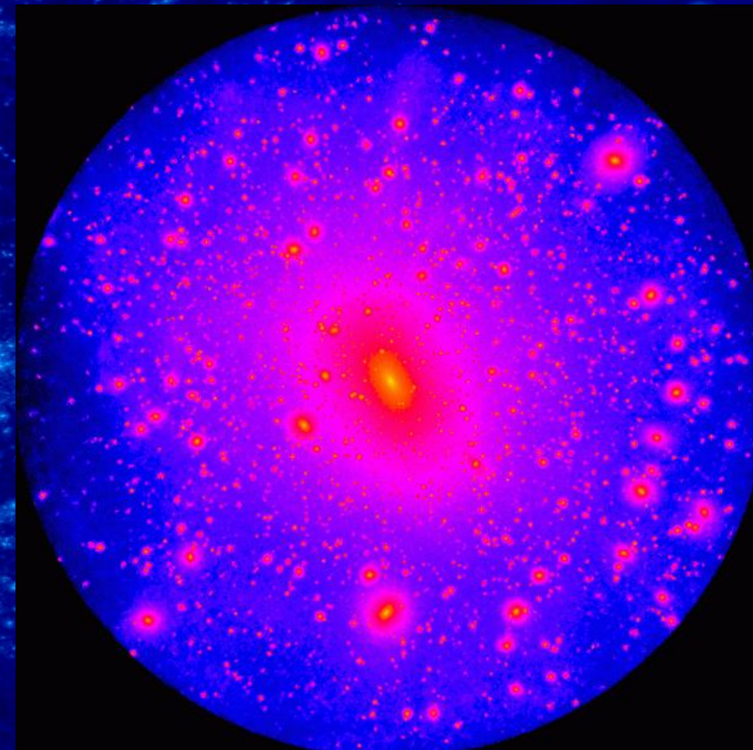
https://www.youtube.com/playlist?list=PLnGS4wkStJ1aqi3M9hTDaUzuZ-vs-Qg6i

or on demand ...

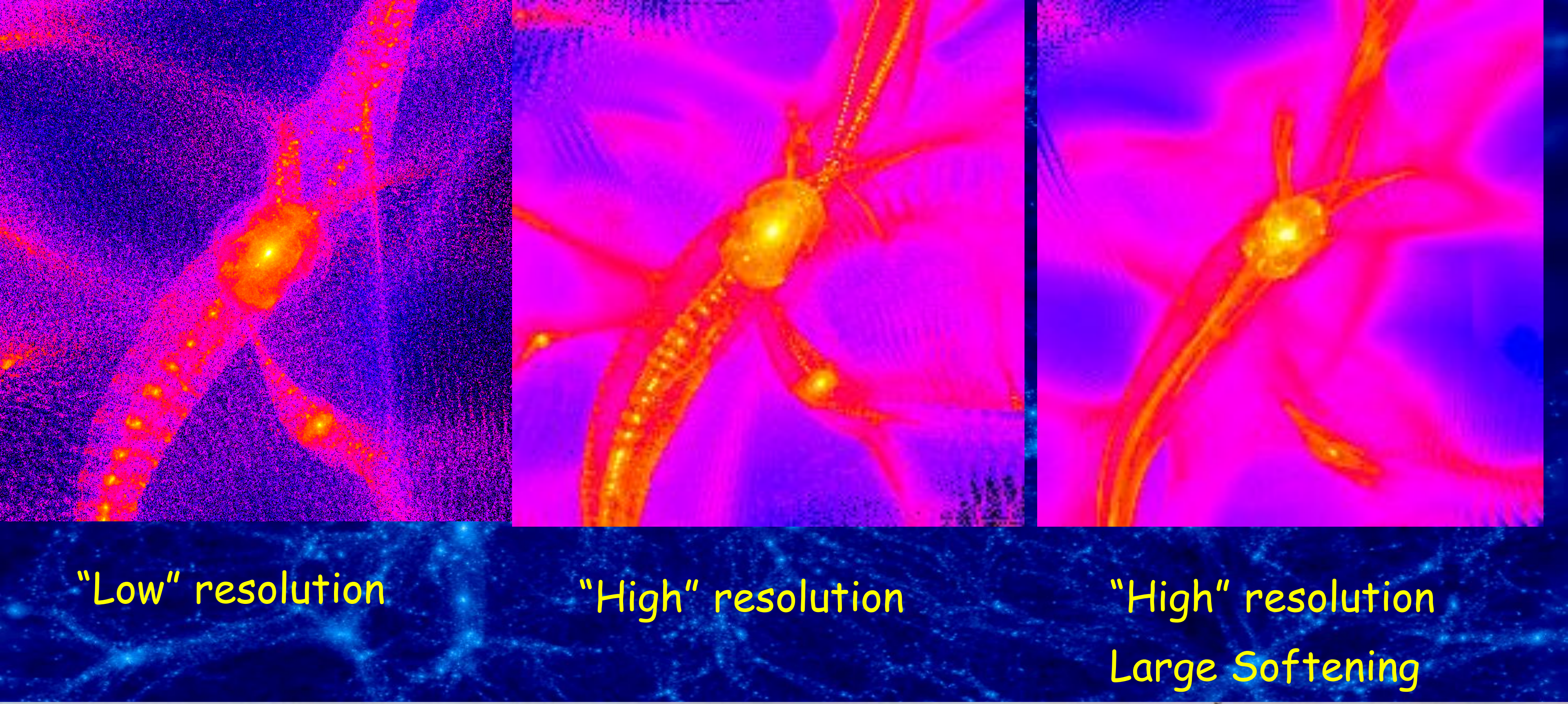
- During the early stages one sees the formation of well contoured filaments.
- In the higher density regions, usually situated at the intersection of such filaments, the first halos are formed through gravitational collapse. These halos continue growing into larger ones by accreting particles from the disrupted filaments.
- In medium density regions, haloes show a hierarchical formation trend. Small haloes collapse first and then merge into bigger haloes.
- In less dense regions, the ones isolated by voids and have a very slow evolution, we have observed filaments that collapse very late. The top down formed halo survives without any mergers until redshift zero.
- Finally there is the more complex scenario in which we observe large haloes formed earlier which merge together.

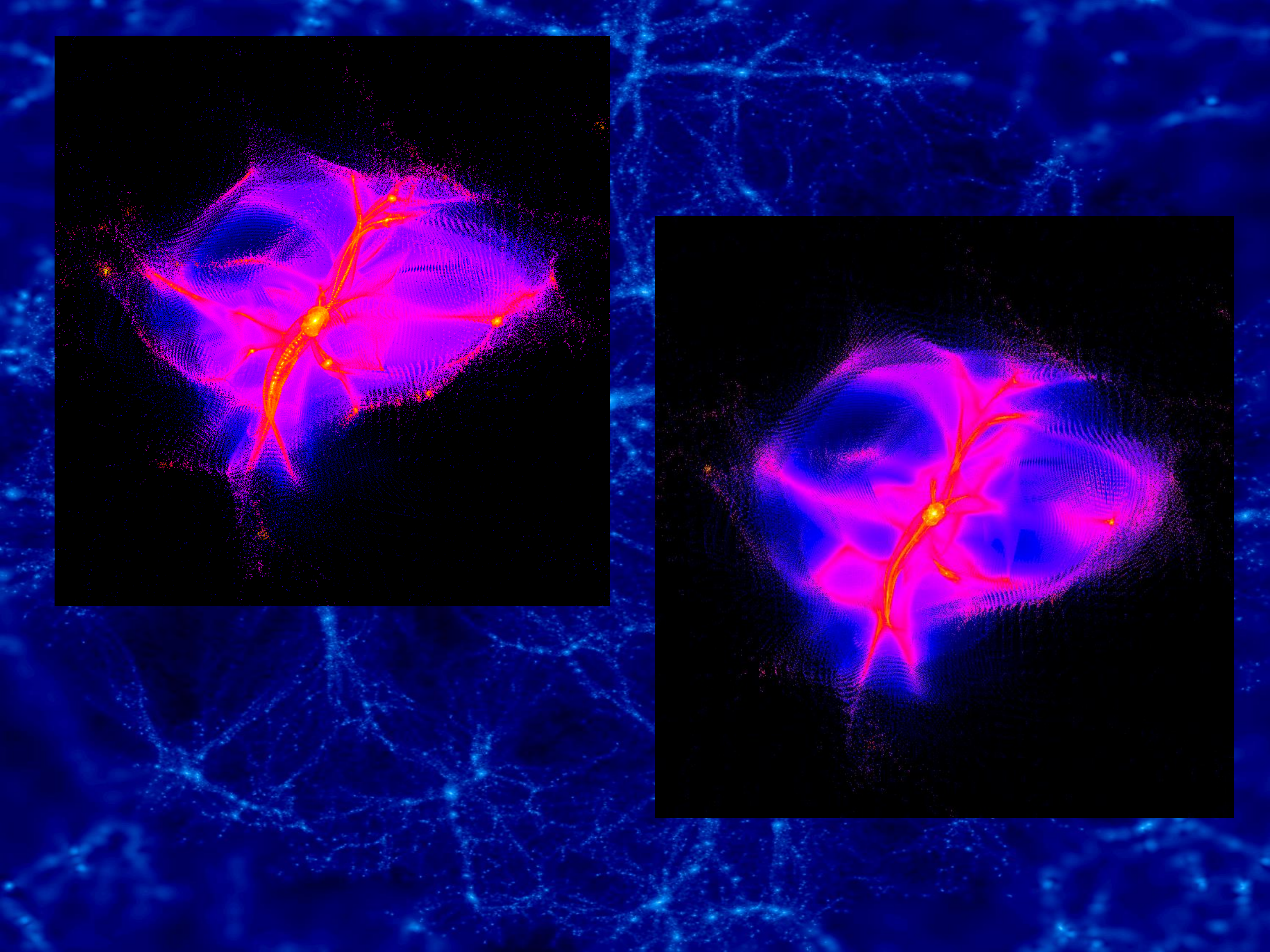


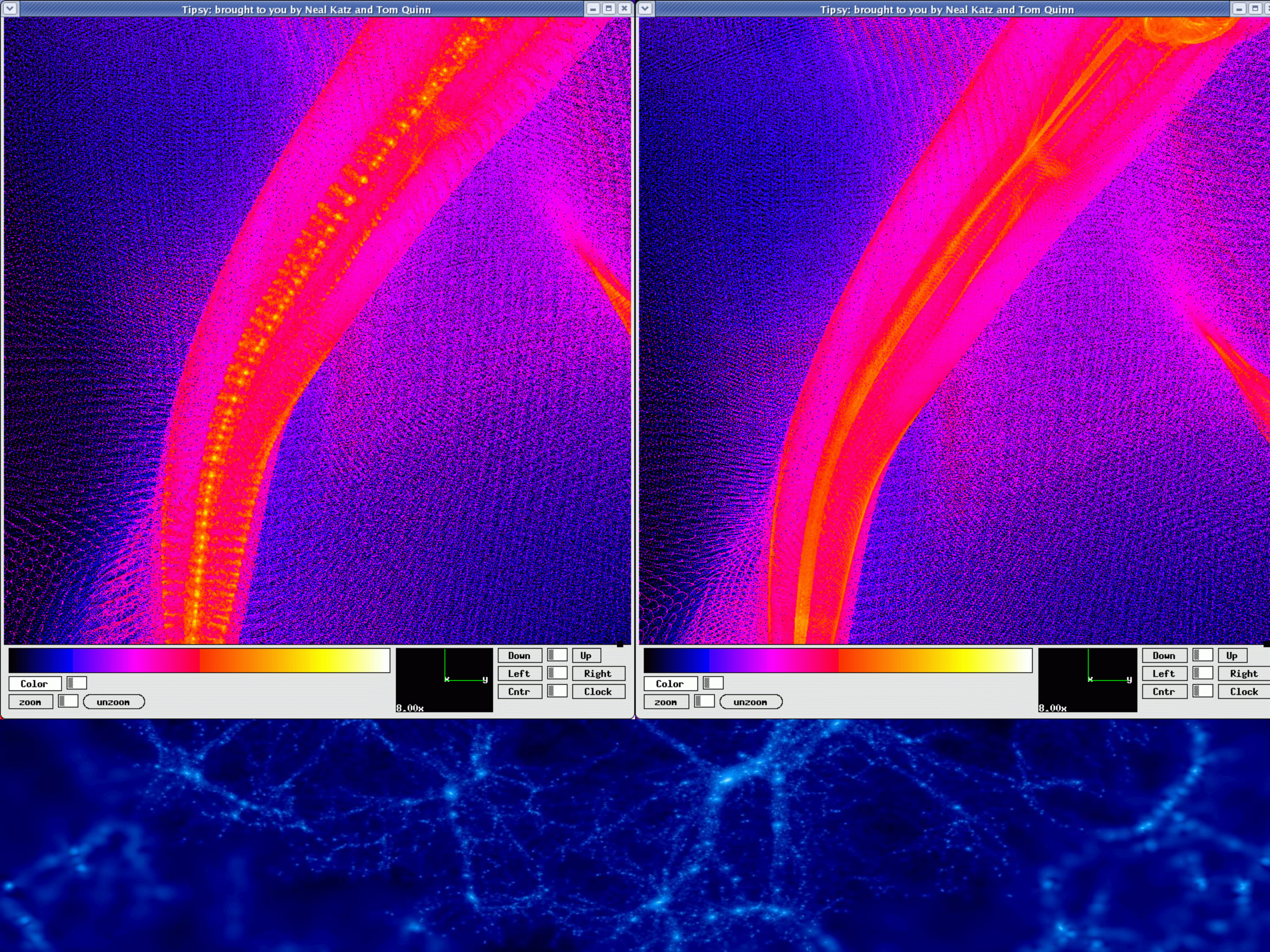




	Number of part.	r_{vir} [kpc]	mass p. part. [$M_\odot$]	boxsize [Mpc]
m<200eV	18 mil.	630	10^5	42.5
m>2keV	50 mil.	200	10^7	40


"Low" resolution
"High" resolution
"High" resolution
Large Softening




Tipsy: brought to you by Neal Katz and Tom Quinn
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zoom
unzoom
8.00x
Down
Up
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Clock
Tipsy: brought to you by Neal Katz and Tom Quinn
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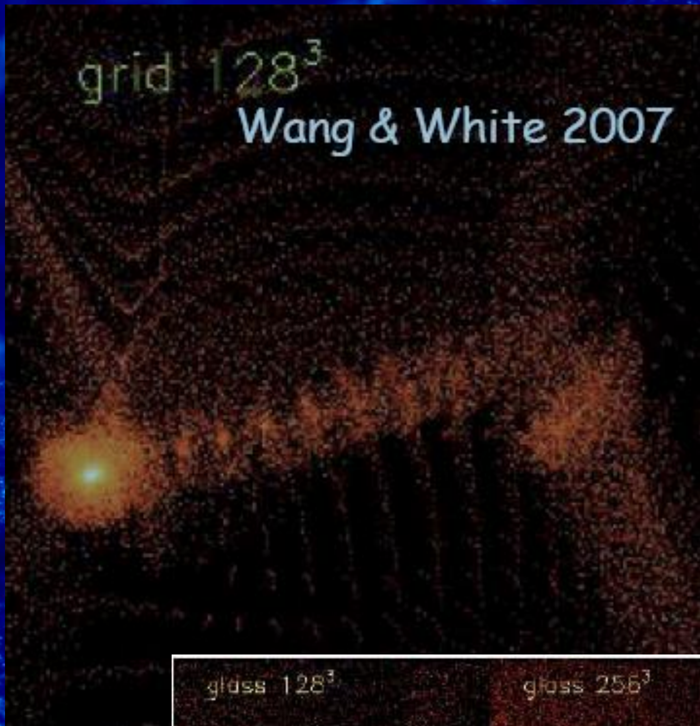
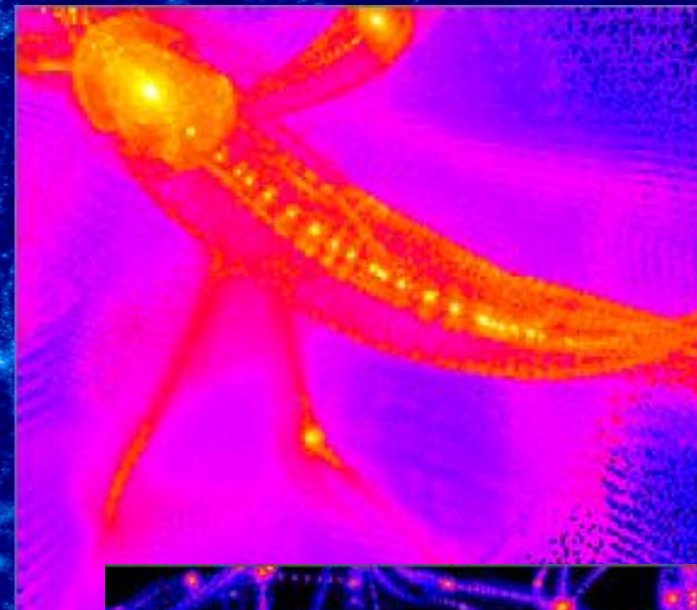
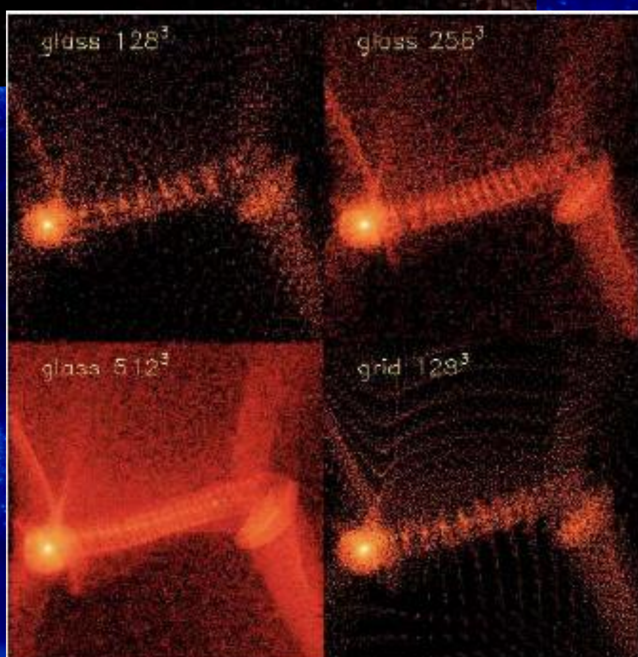
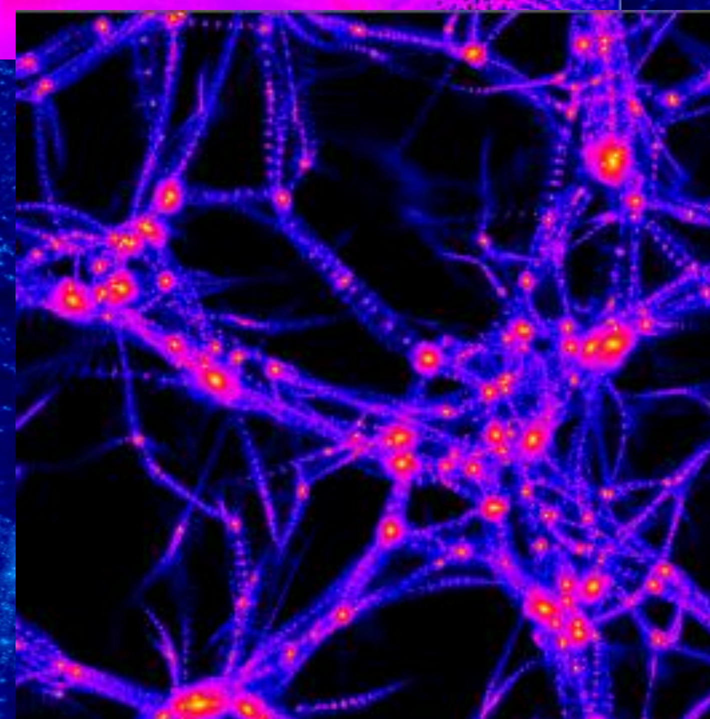

grid 128³
Wang & White 2007




glass 128³
glass 256³
glass 512³
grid 128³



CONCLUSIONS and COMPLICATIONS

- Formation of haloes in WDM models differs from CDM.
  Hybrid mechanism - Top-Down & Hierarchical; long distance & nearest neighbours
  Looking at high redshift galaxies for T-D memory.

- The exact recipe for structure formation seems to depend only on the morphology and architecture of the environment
- ☼ Quantum Pressure; Baryons and their physics

- Warm dark matter haloes contain visible caustics and shells.

- The finite initial fine grained PSD is also a maximum of coarse grained PSD.
  The turn over in PSD results in constant density core with characteristic size.

- Spurious fragmentation below the free streaming scale hard to overcome – in case of infinite resolution a filament collapses into a two dimensional line
  $$ Adaptive softening?

- The velocity dispersion is crucial in describing warm dark matter particles!
  There is no universal one to one correspondence between mass and thermal velocity
  Mass constraints on the particle's mass, are not accurate