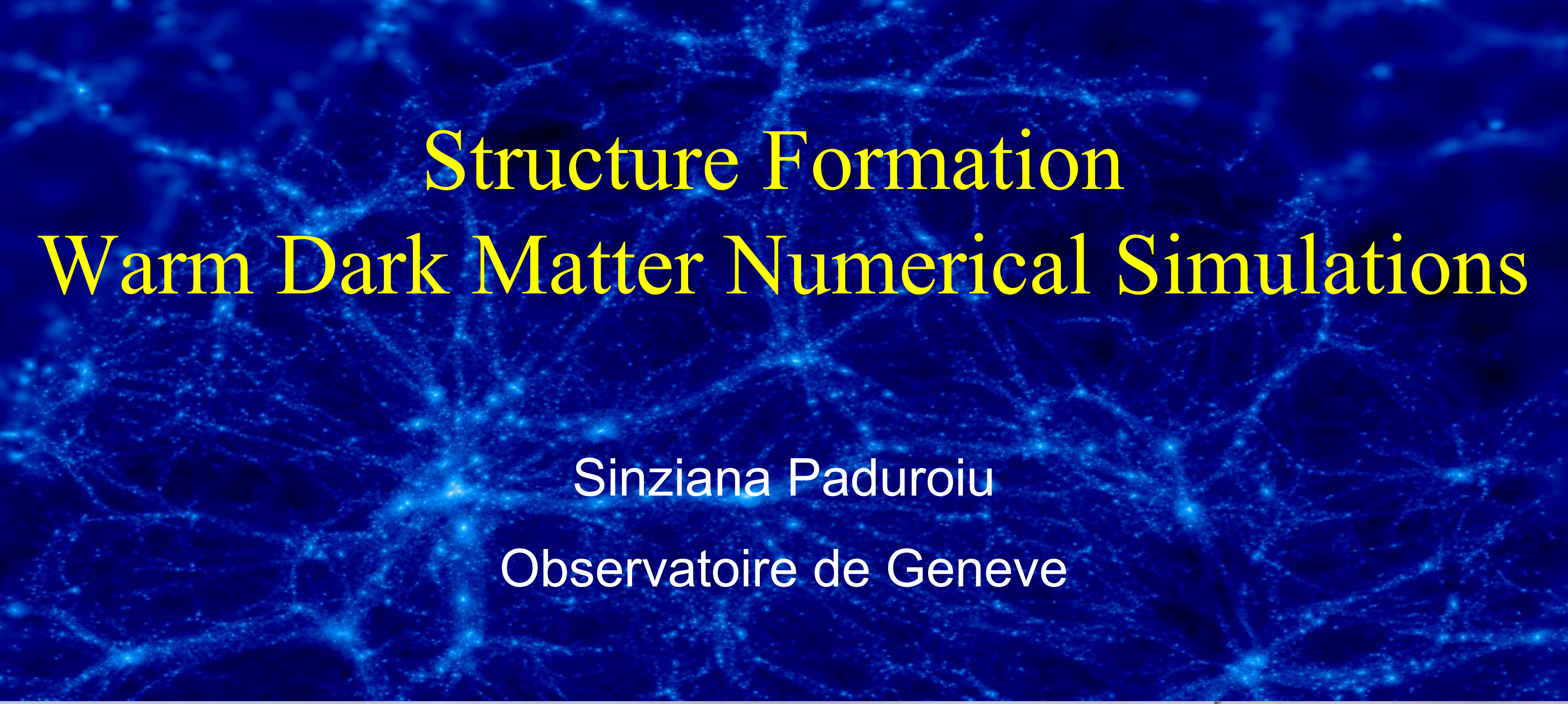
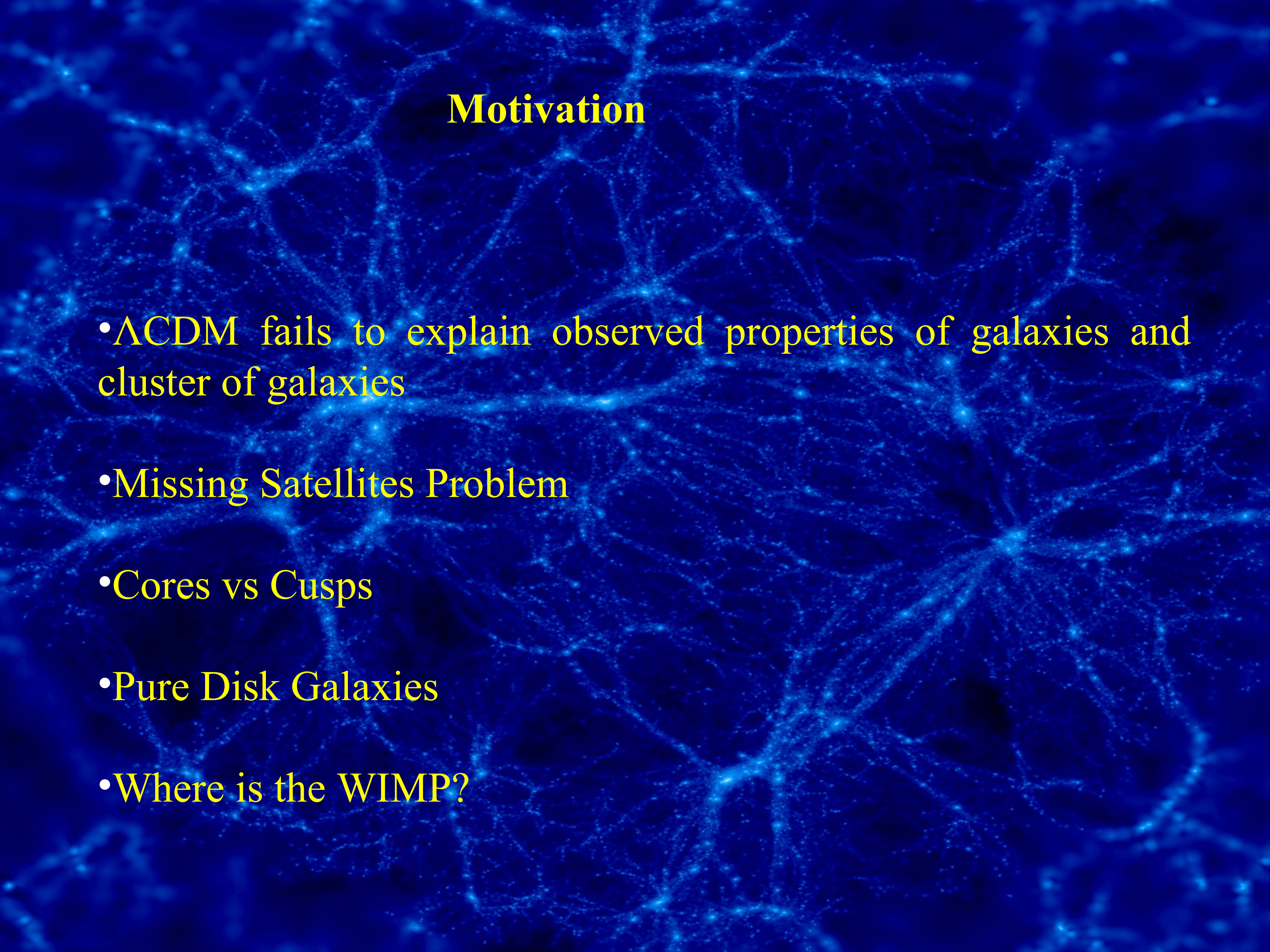


Structure Formation
Warm Dark Matter Numerical Simulations

Sinziana Paduroiu

Observatoire de Geneve

In collaboration with Yves Revaz, Daniel Pfenniger, Andrea Maccio, Joachim Stadel, Doug Potter, Ben Moore



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.

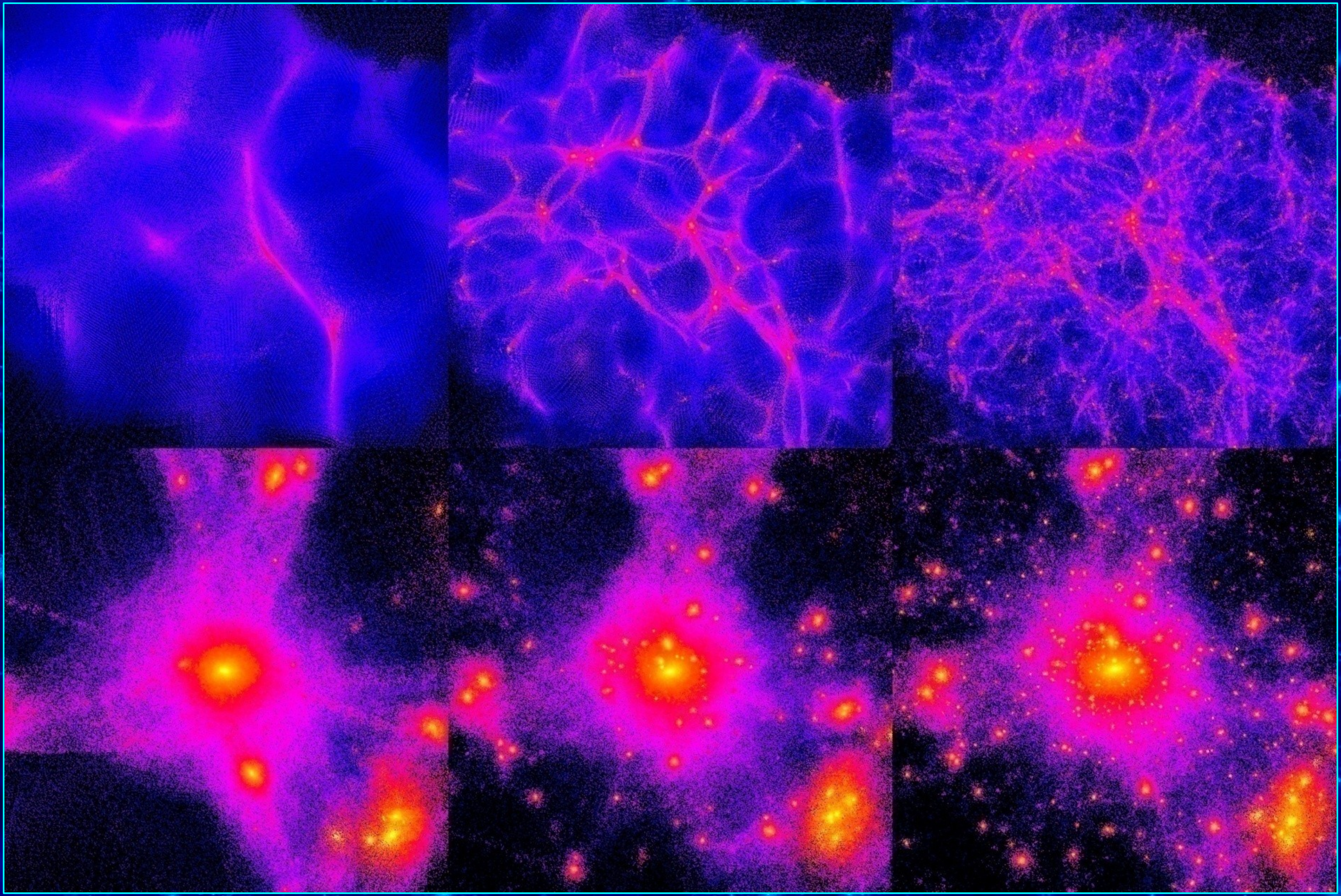
- WDM has a non-negligible velocity dispersion which dampens the small scale fluctuation spectrum and sets a phase space limit to cosmic structures.

- 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

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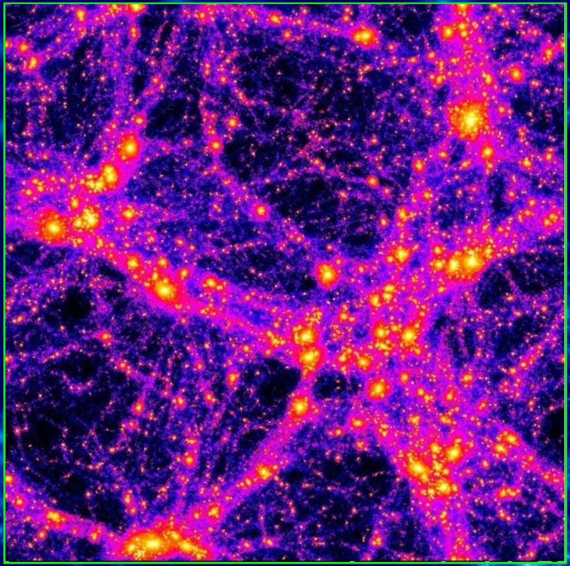
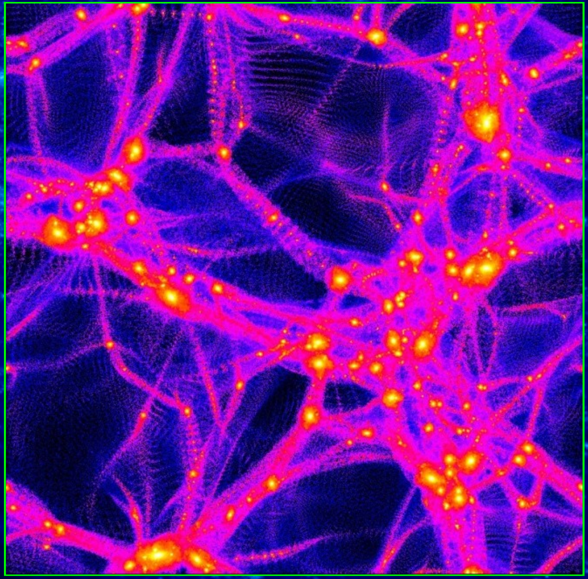
CDM



CDM

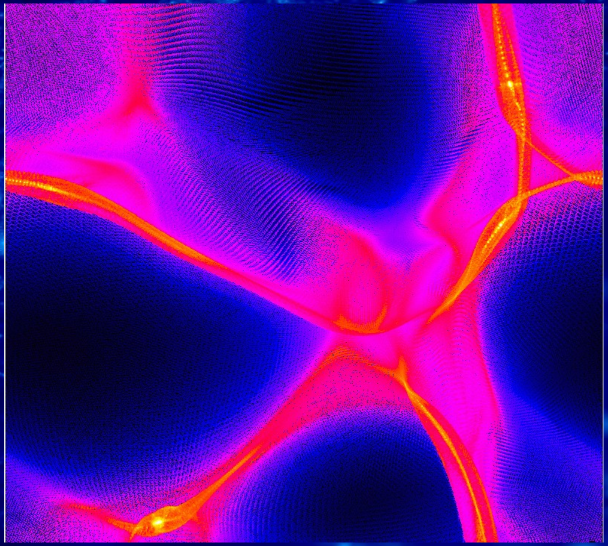


200eV power spectrum cutoff

20eV velocities

50eV power spectrum cutoff

50eV velocities



Simulating the WDM…

$P(k) = k^n * T^2(k,z) \quad n \sim 1$

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

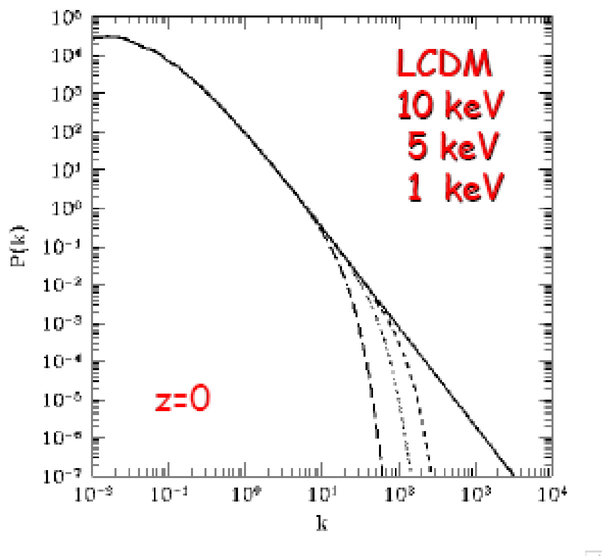
$$T^2(k) = \frac{P^{WDM}}{P^{CDM}} = [1 + (\alpha k)^{2\nu}]^{-10/\nu}$$

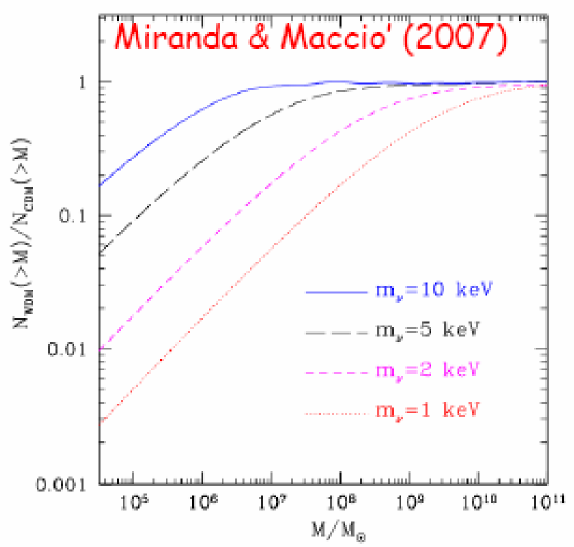
$$\alpha = 0.049 \cdot \left(\frac{m_x}{1keV}\right)^{-1.11} \cdot \left(\frac{\Omega_\nu}{0.25}\right)^{0.11} \cdot \left(\frac{h}{0.7}\right)^{1.22} h^{-1}\mathrm{Mpc}.$$

Bode, Turok, and Ostriker (2001)

Viel et. Al 2005

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





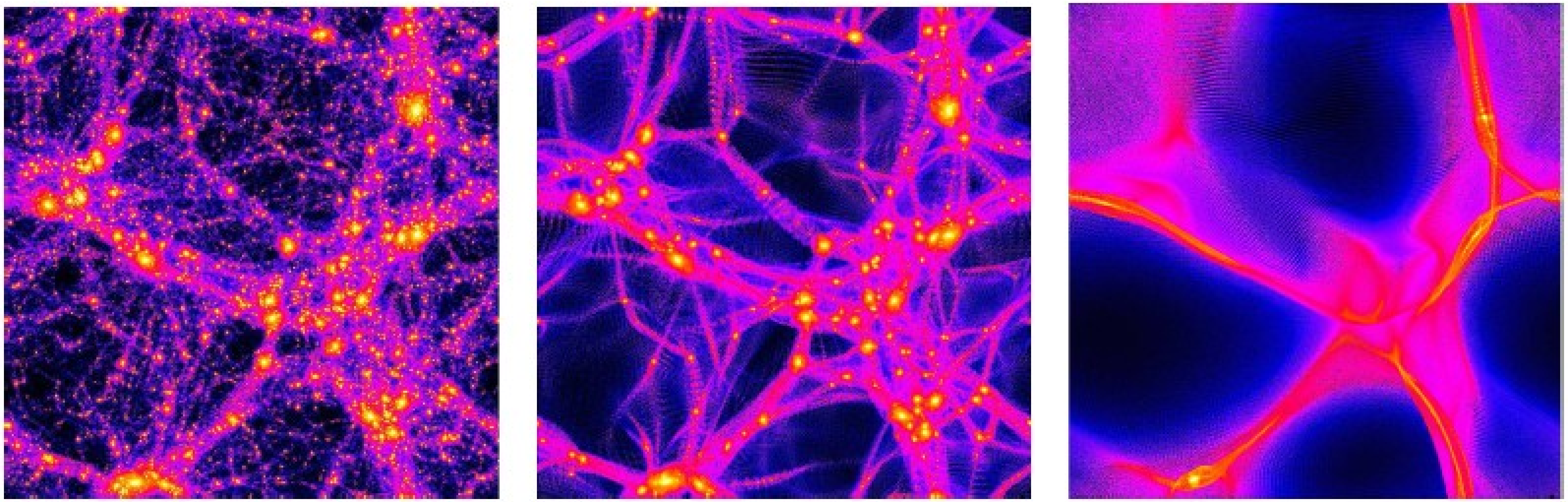


Figure 1. Three snapshots of different simulations at redshift $z = 0$. CDM, WDM3 and WDM4 are shown from left to right.

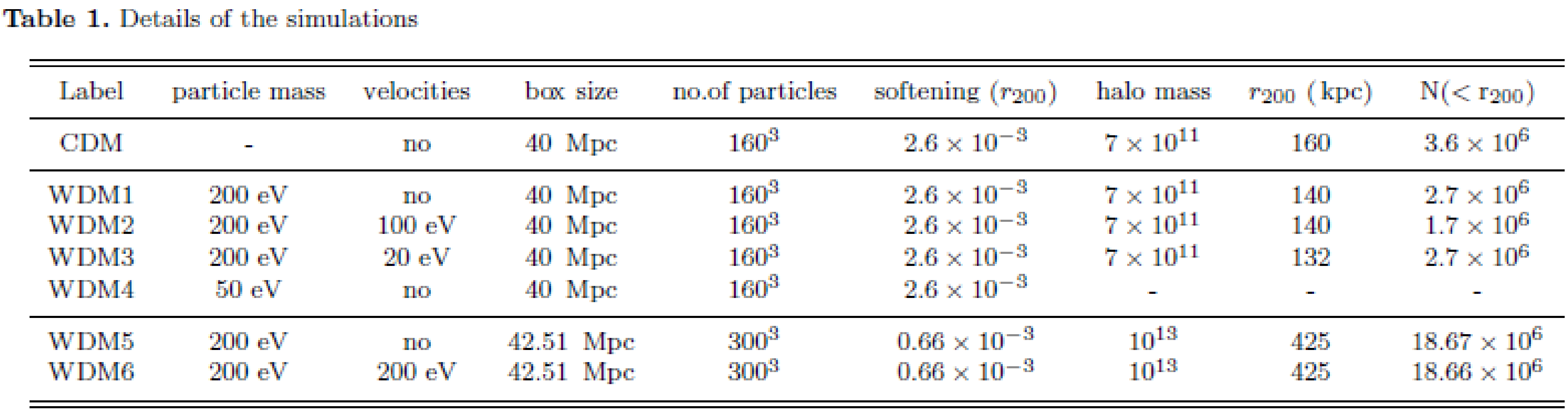
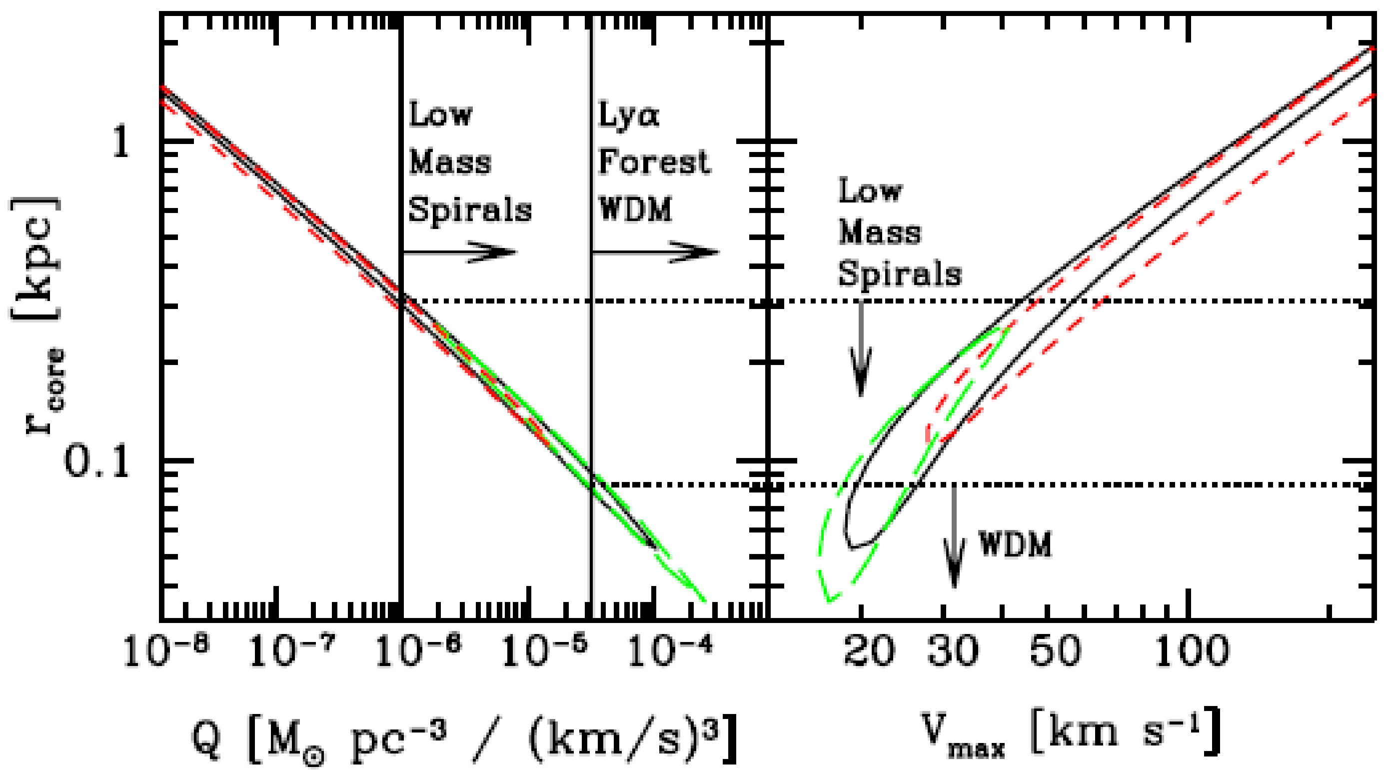


Table 1. Details of the simulations

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

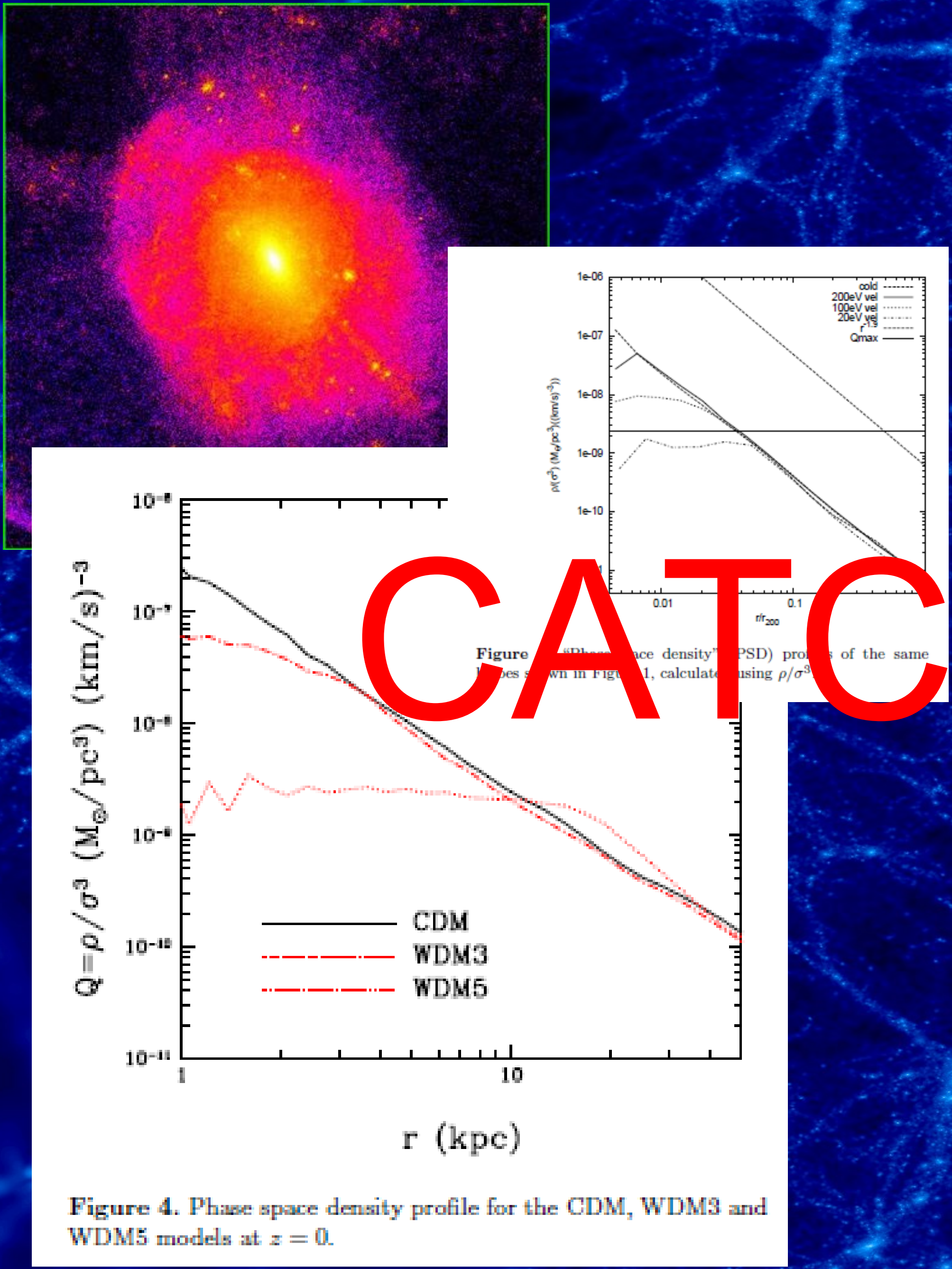


Figure “Pha ce density” PSD) pro s of the same es s wn in Fig 1, calculat using ρ/σ^3

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

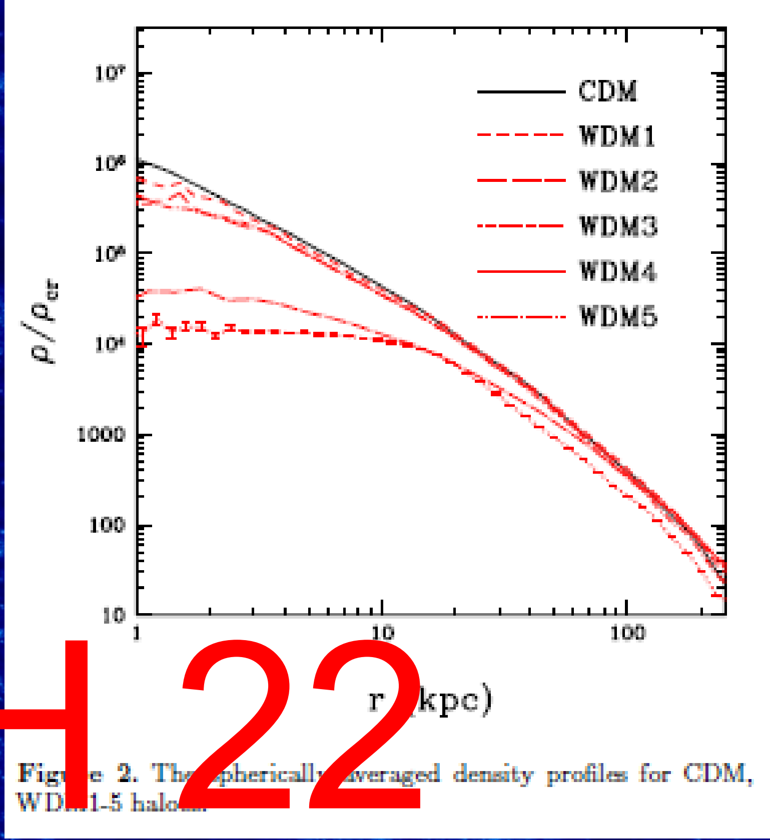
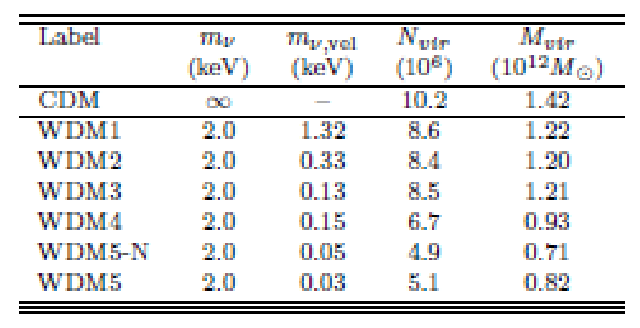


Fig e 2. The pherically veraged density profiles for CDM, WD 1-5 halo



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

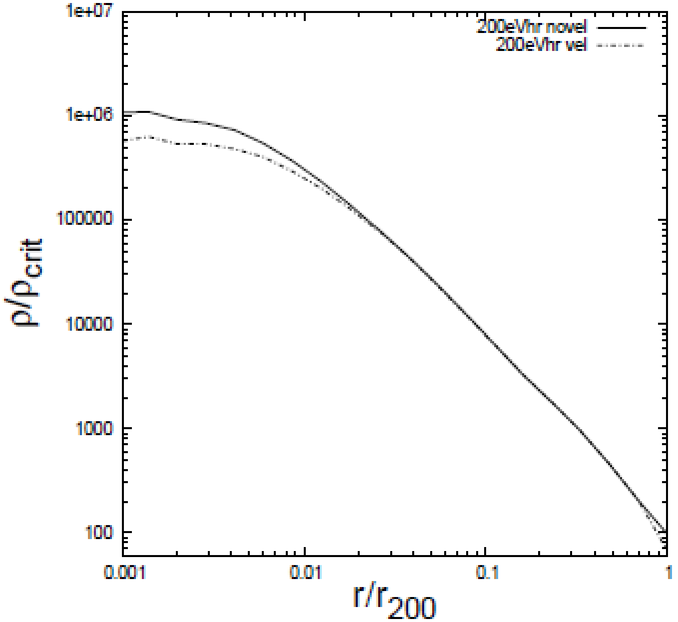


Figure 4. The density profiles for a high resolution halo in the 200 eV simulation WDM5 and WDM6

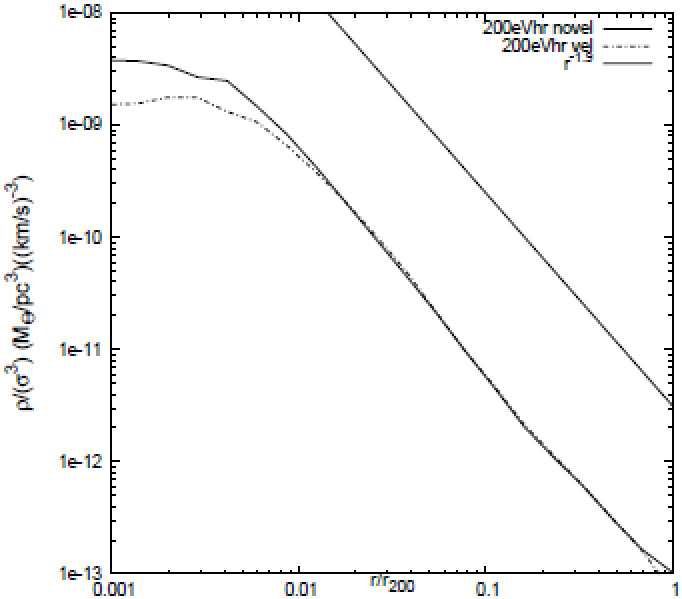


Figure 5. The PSD profiles for the 200eV halo from WDM5 and WDM6. A power law line of slope $r^{-1.9}$ is shown for reference.

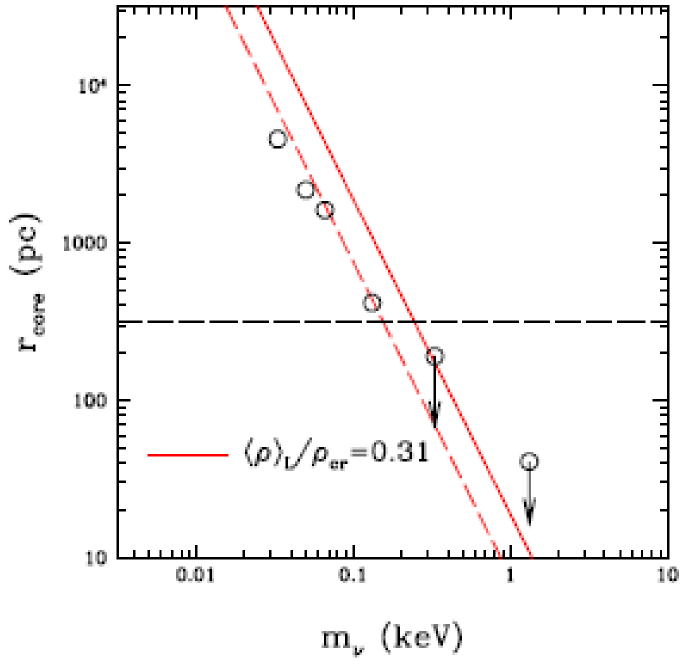


Figure 1. Comparison between core size in simulations (open symbols) and the theoretical expectation for a $M = 10^{12} M_\odot$ halo (solid line). The dashed horizontal line is the gravitational softening of our simulations. All points below this line should be considered as upper limits on the core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

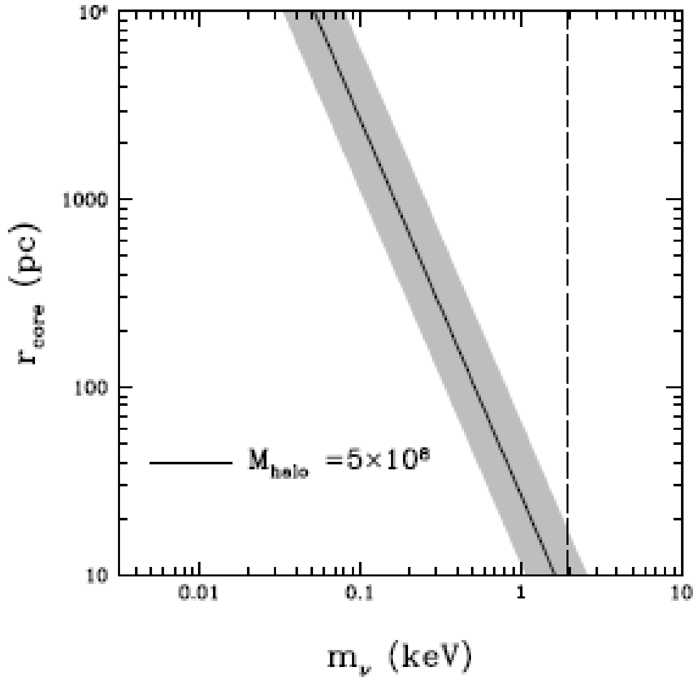
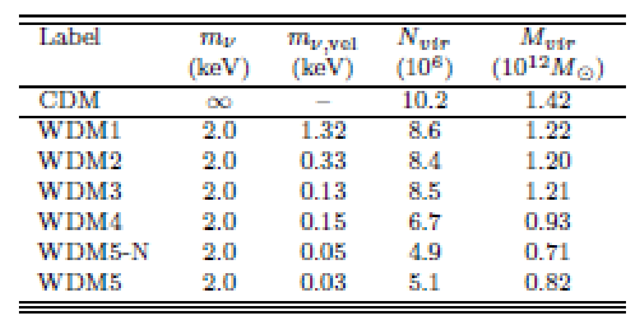


Figure 2. Expected core size for the typical dark matter mass of Milky Way satellites as a function of the WDM mass m_ν. The shaded area takes into account possible different values of the local density parameter $0.15 < \Omega_m < 0.6$. The vertical dashed line shows the current limits on the WDM mass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

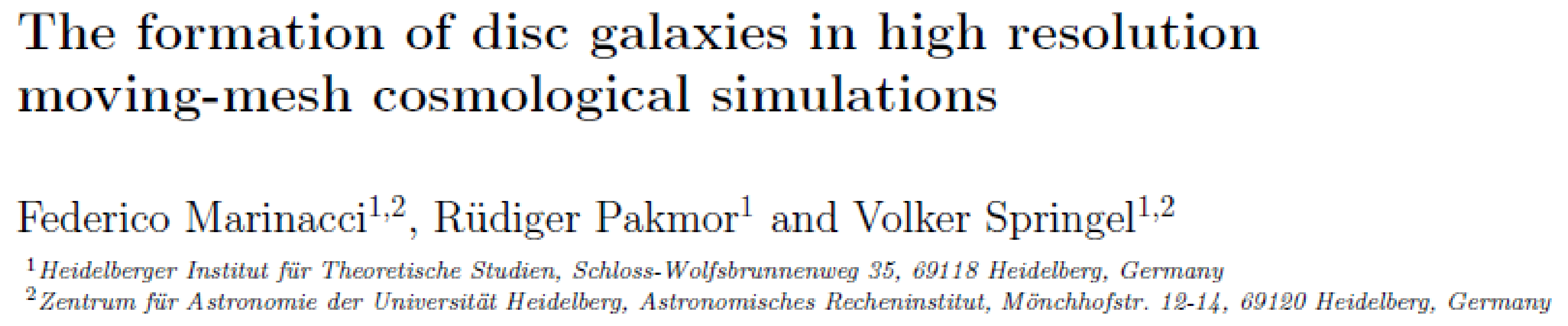
Simulations of CDM+gas+AGN feedback+star formation fine-tuned

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.

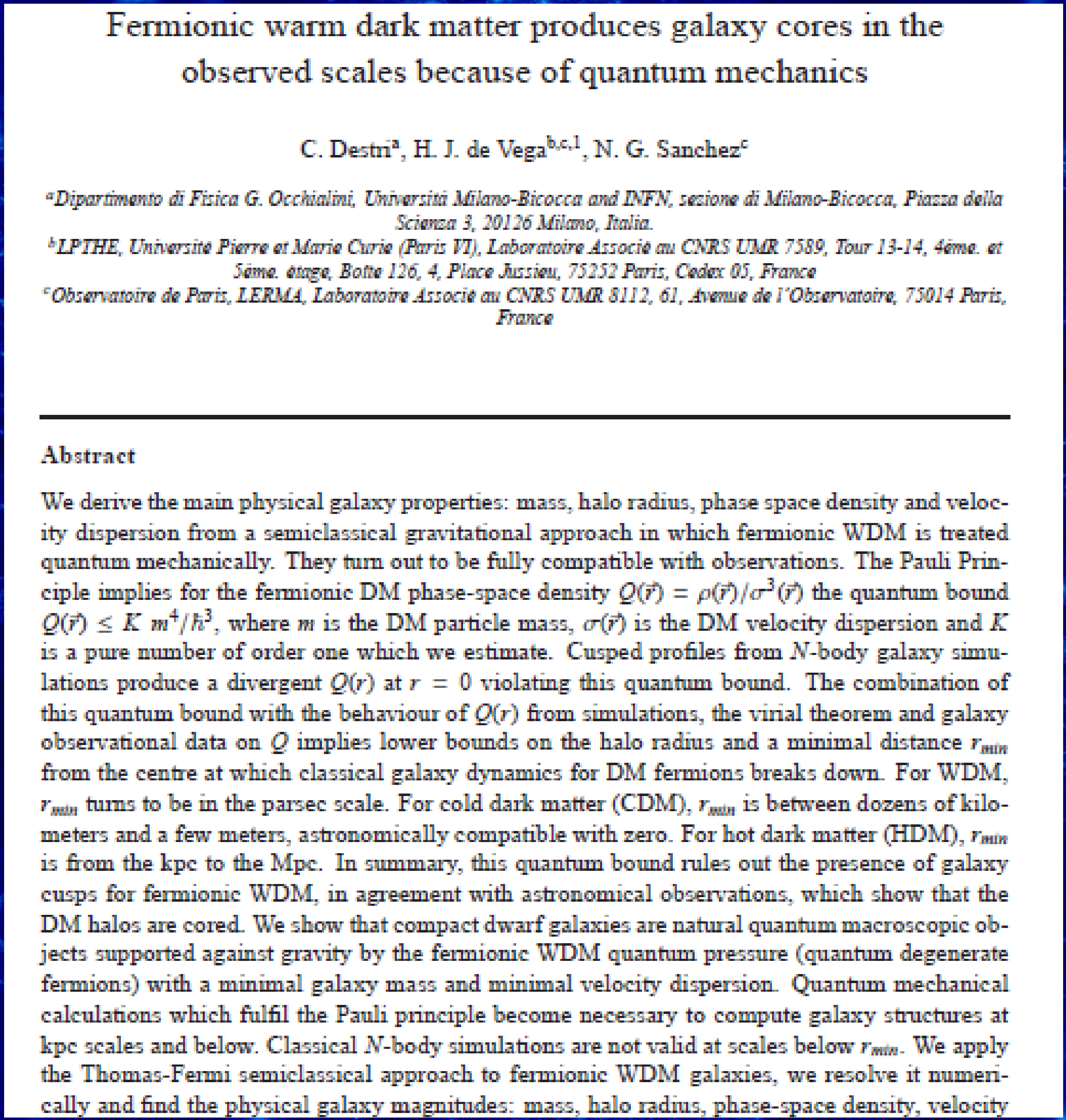


The formation of disc galaxies in high resolution moving-mesh cosmological simulations

Federico Marinacci[1,2], Rüdiger Pakmor[1] and Volker Springel[1,2]

[1] *Heidelberger Institut für Theoretische Studien, Schloss-Wolfsbrunnenweg 35, 69118 Heidelberg, Germany*
[2] *Zentrum für Astronomie der Universität Heidelberg, Astronomisches Recheninstitut, Mönchhofstr. 12-14, 69120 Heidelberg, Germany*

<<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.>>



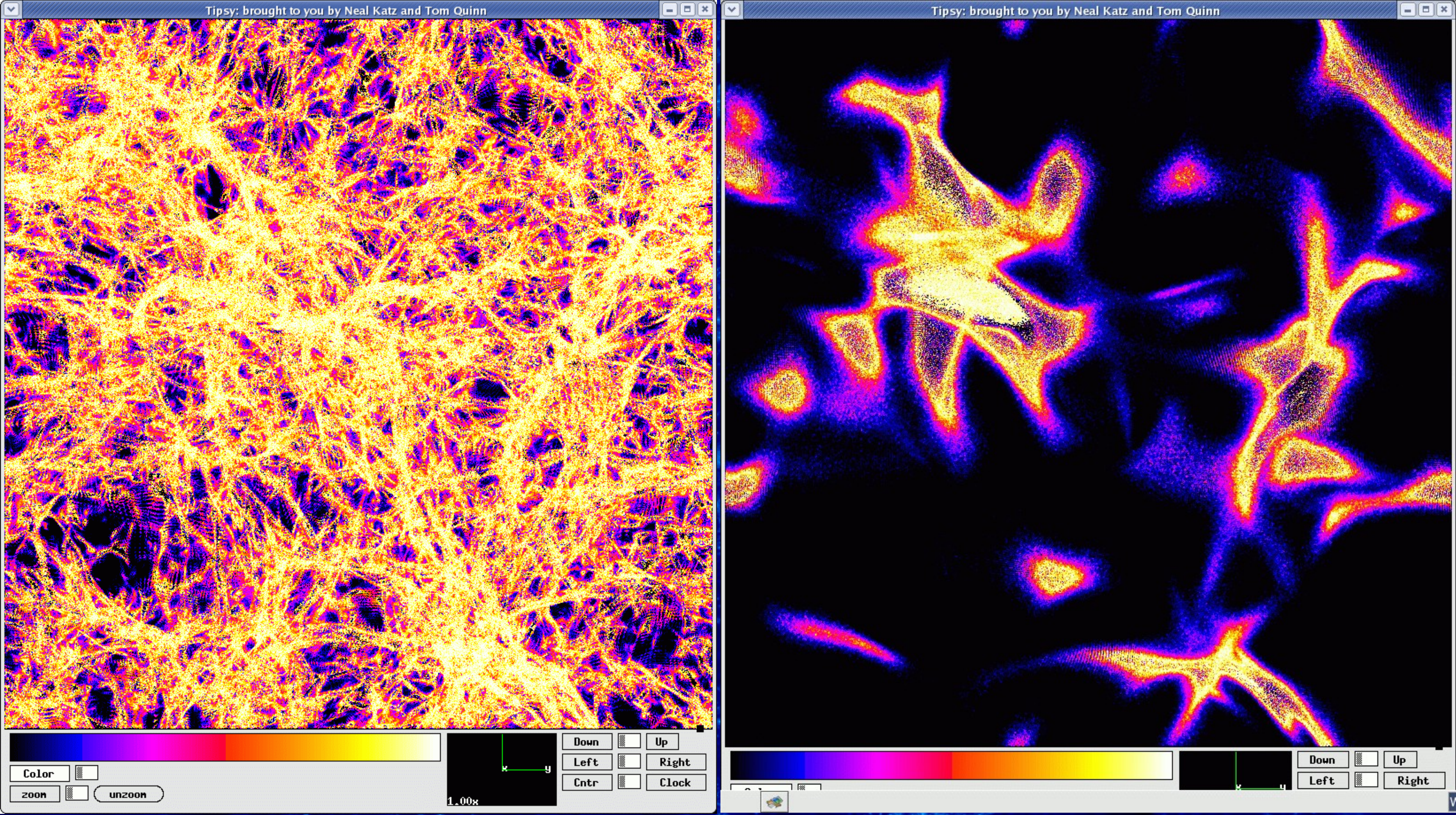
Fermionic warm dark matter produces galaxy cores in the observed scales because of quantum mechanics

C. Destri[a], H. J. de Vega[b,c,1], N. G. Sanchez[c]

[a]*Dipartimento di Fisica G. Occhialini, Università Milano-Bicocca and INFN, sezione di Milano-Bicocca, Piazza della Scienza 3, 20126 Milano, Italia.*
[b]*LPTHE, Université Pierre et Marie Curie (Paris VI), Laboratoire Associé au CNRS UMR 7589, Tour 13-14, 4ème. et 5ème. étage, Boite 126, 4, Place Jussieu, 75252 Paris, Cedex 05, France*
[c]*Observatoire de Paris, LERMA, Laboratoire Associé au CNRS UMR 8112, 61, Avenue de l'Observatoire, 75014 Paris, France*

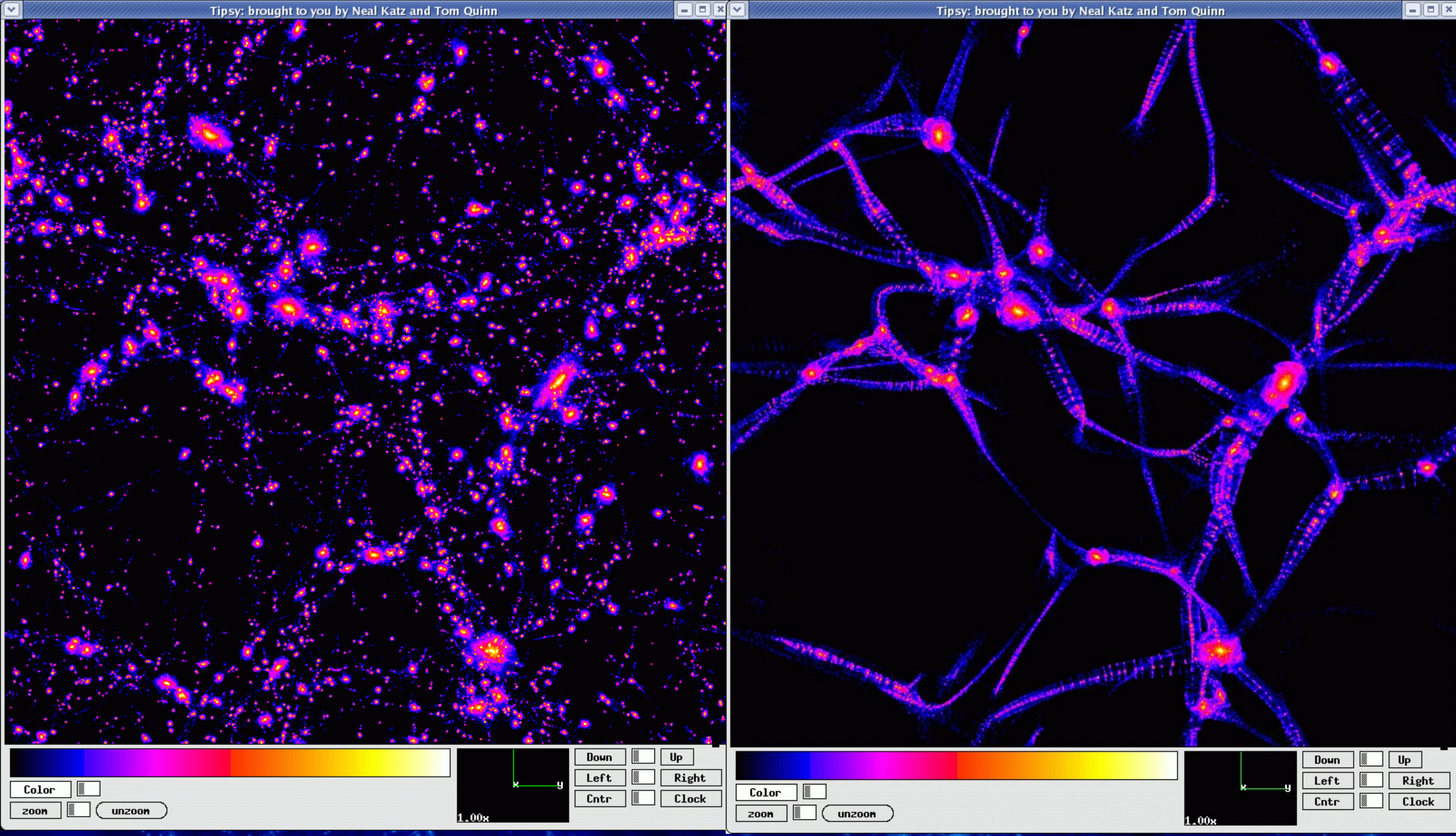
Abstract

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



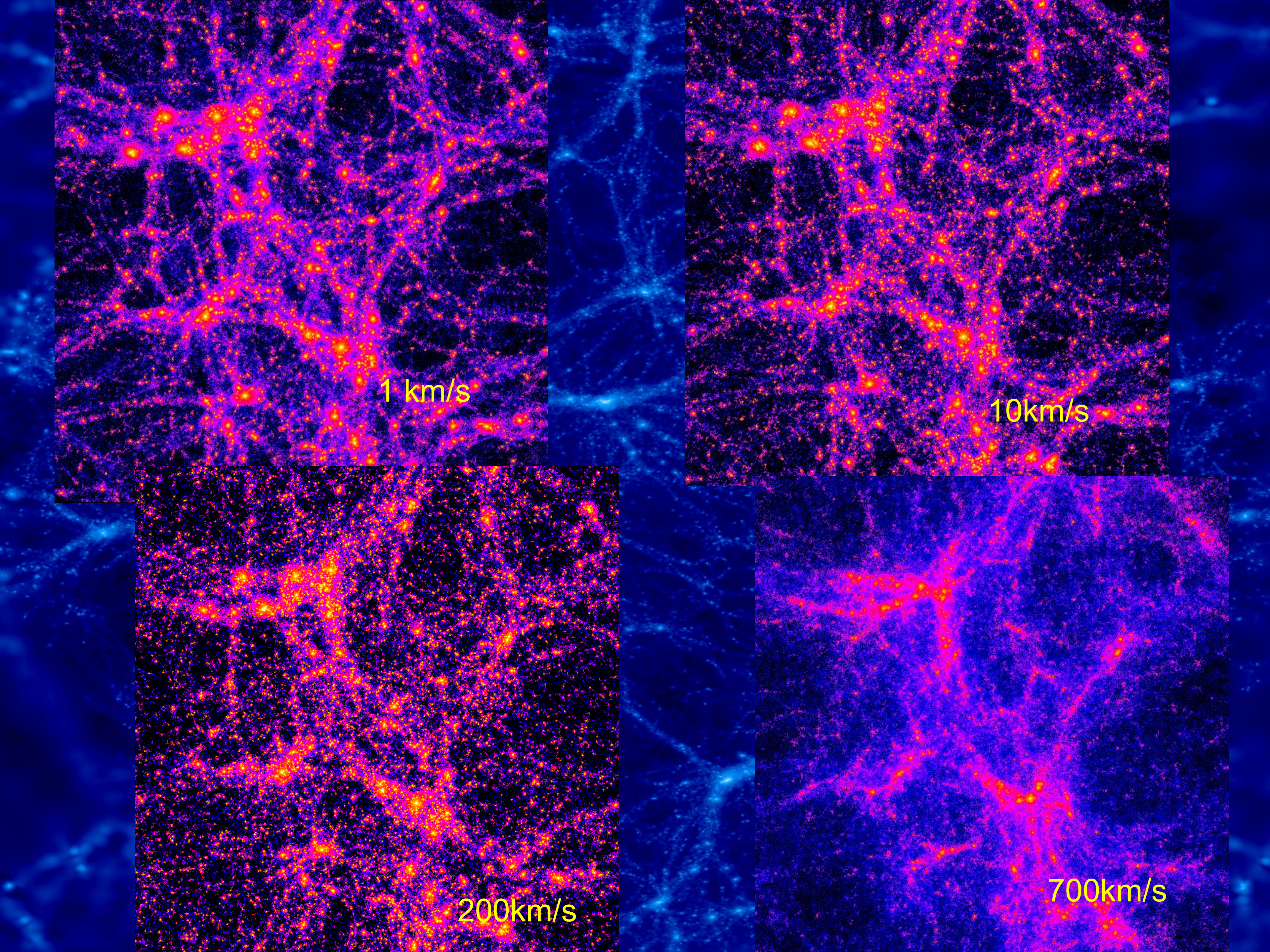
Mildly non-linear regions at z=3 in CDM and WDM (200ev)

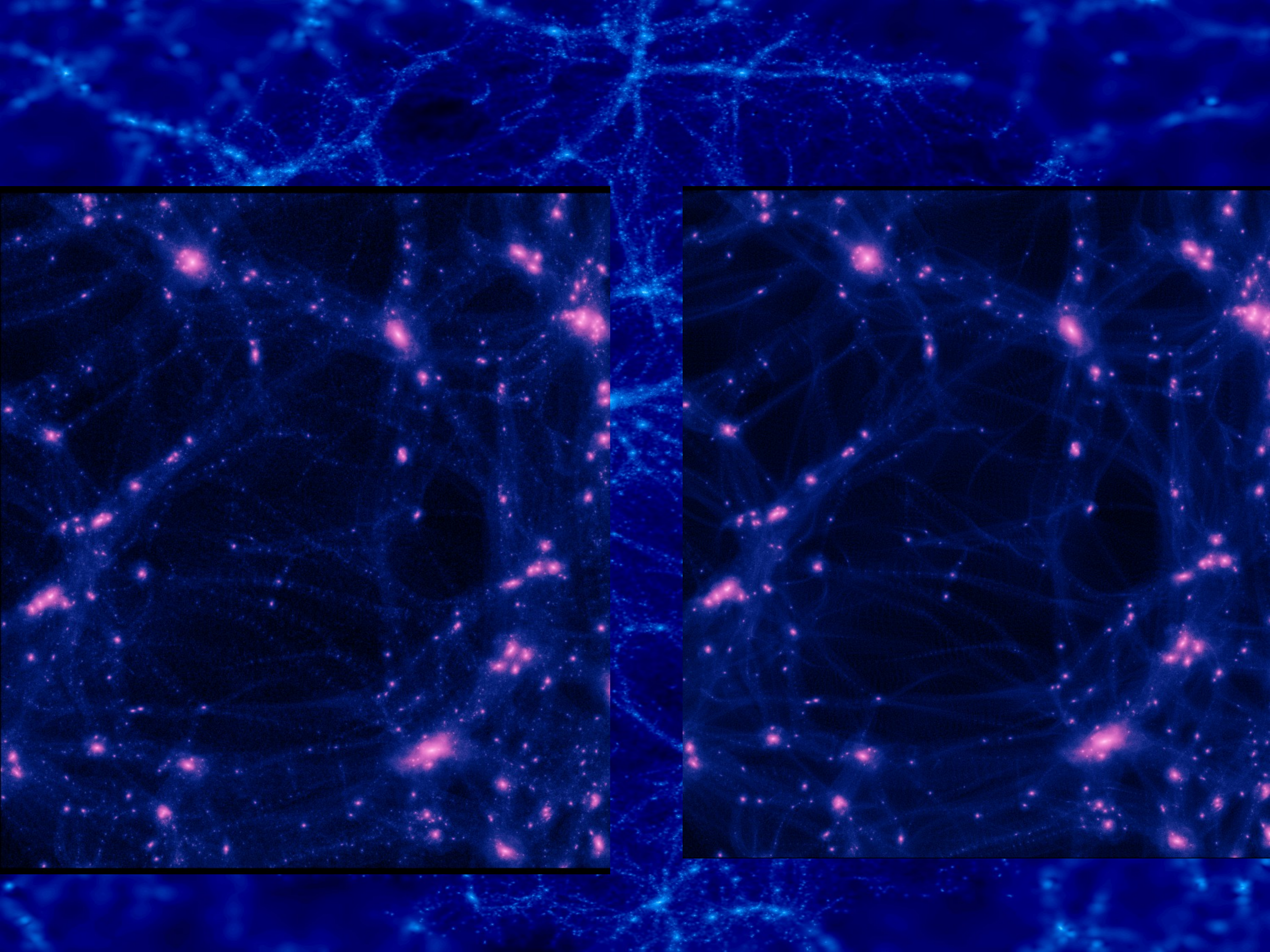
i.e. overdensities between 1 and 5 w.r.t. mean

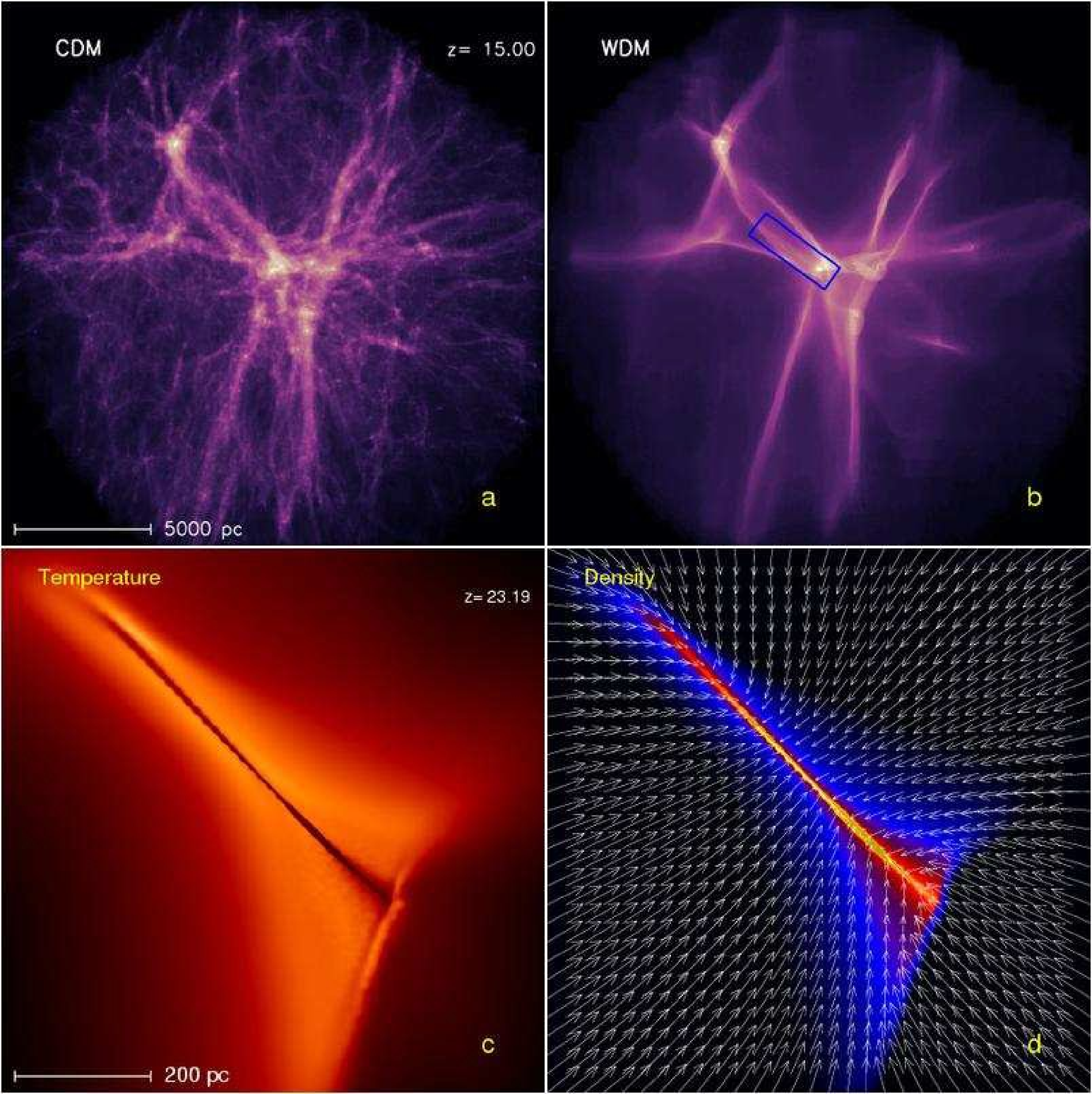


Virialised regions at z=3 in CDM and WDM (200ev)

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

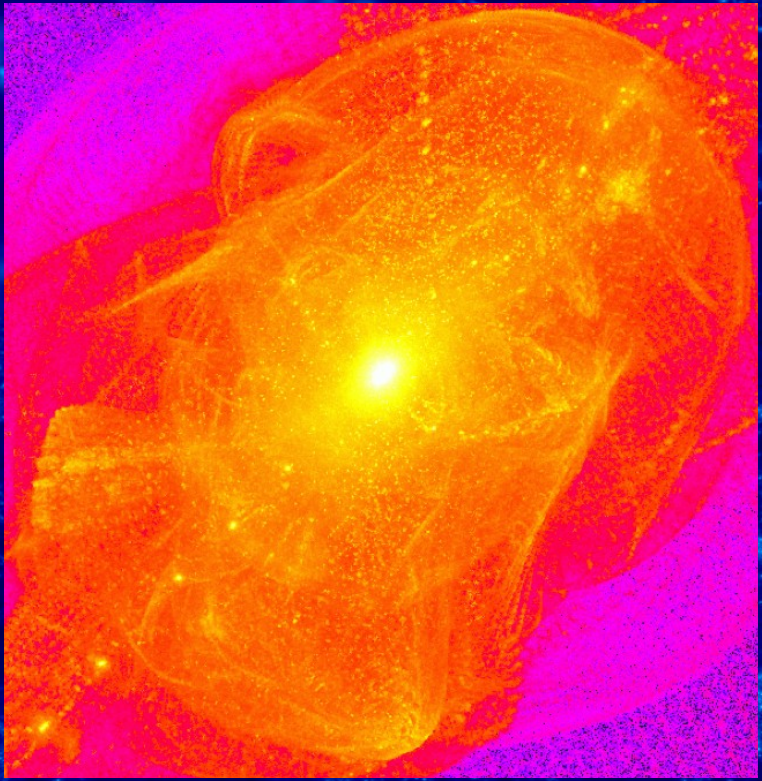

1 km/s
10km/s
200km/s
700km/s

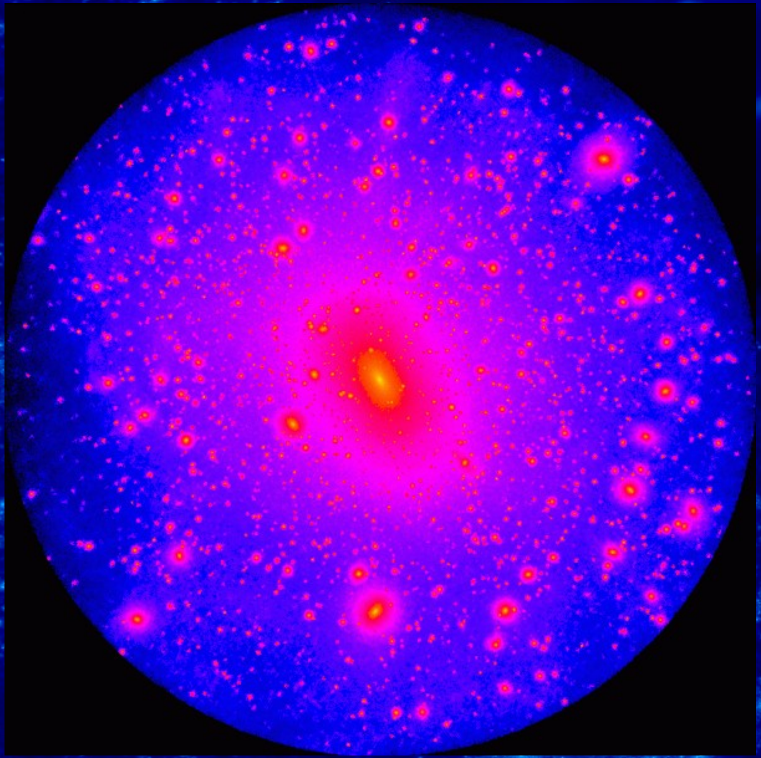




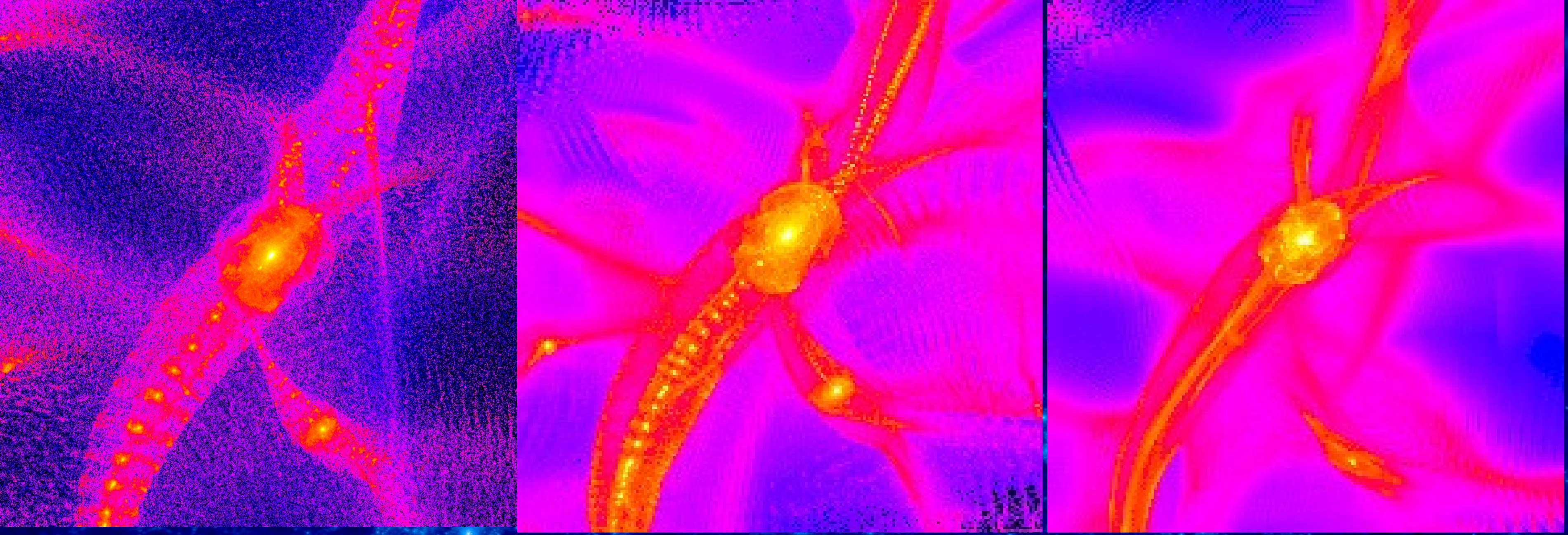
Liang Gao & Tom Theuns, Science sept 2007

The movies…





	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” resoluti n

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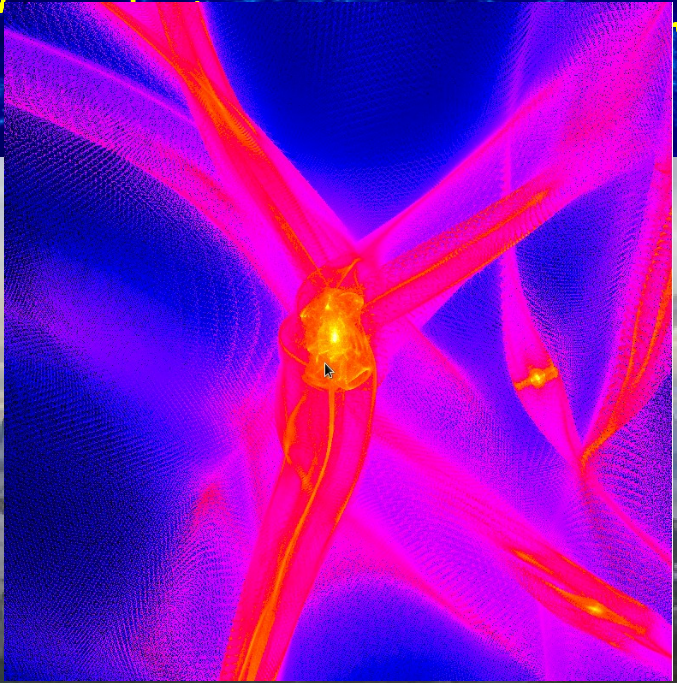

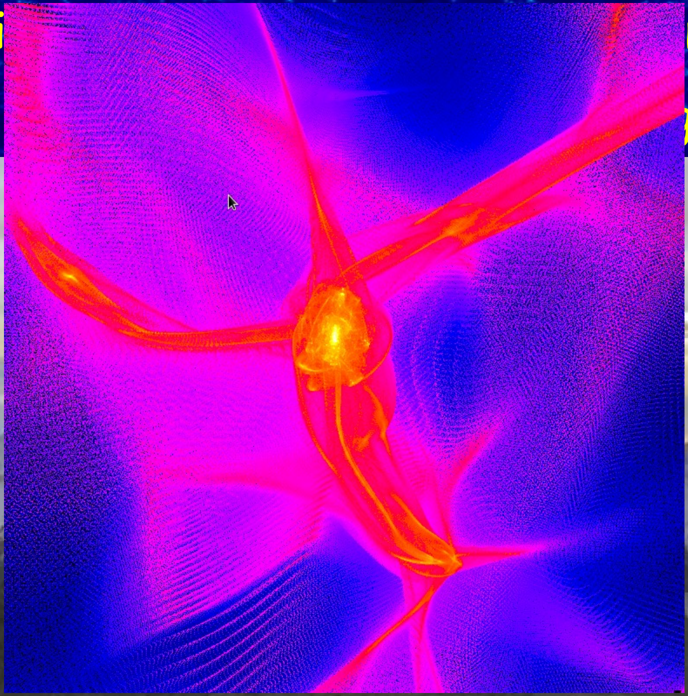

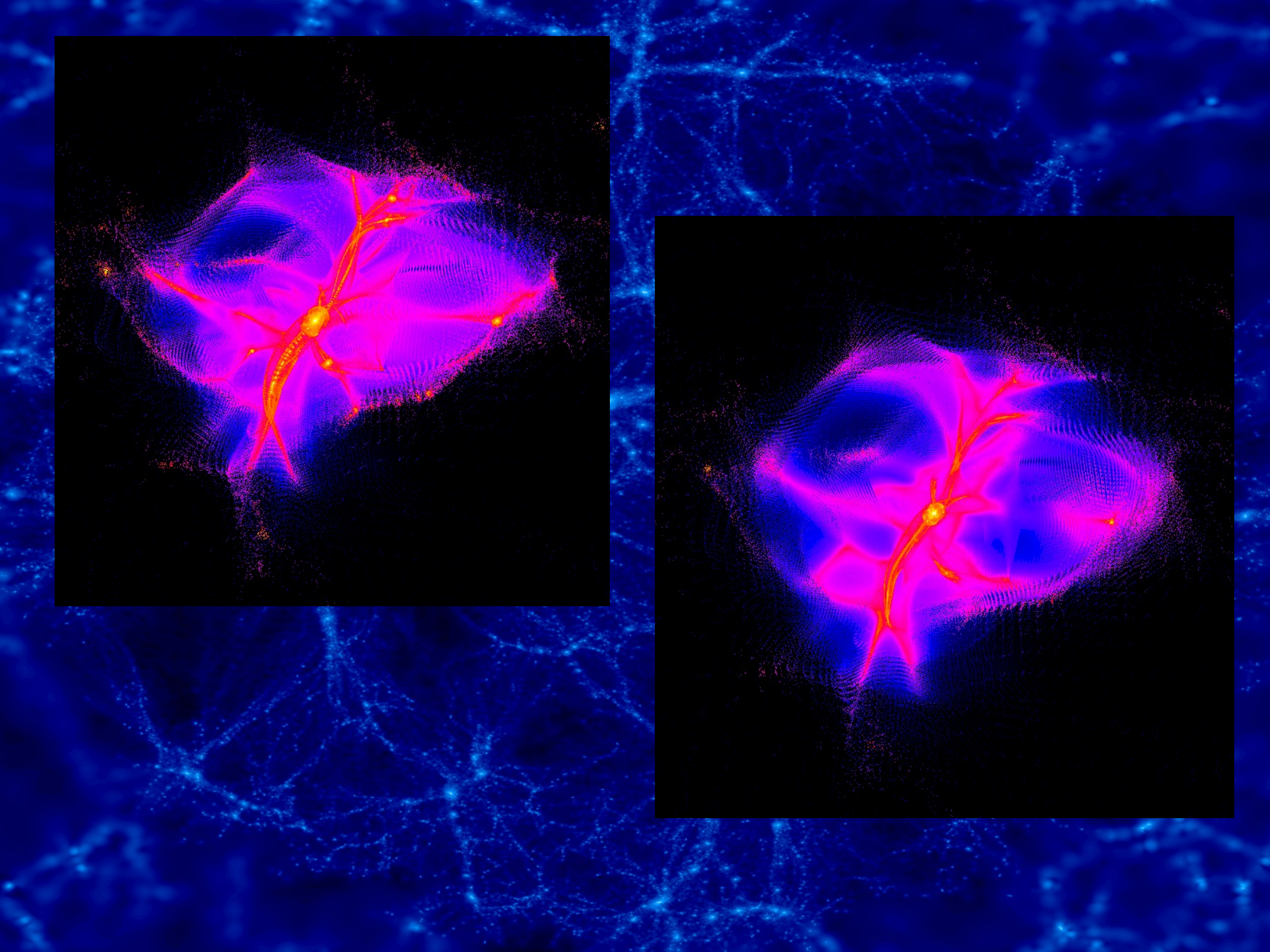

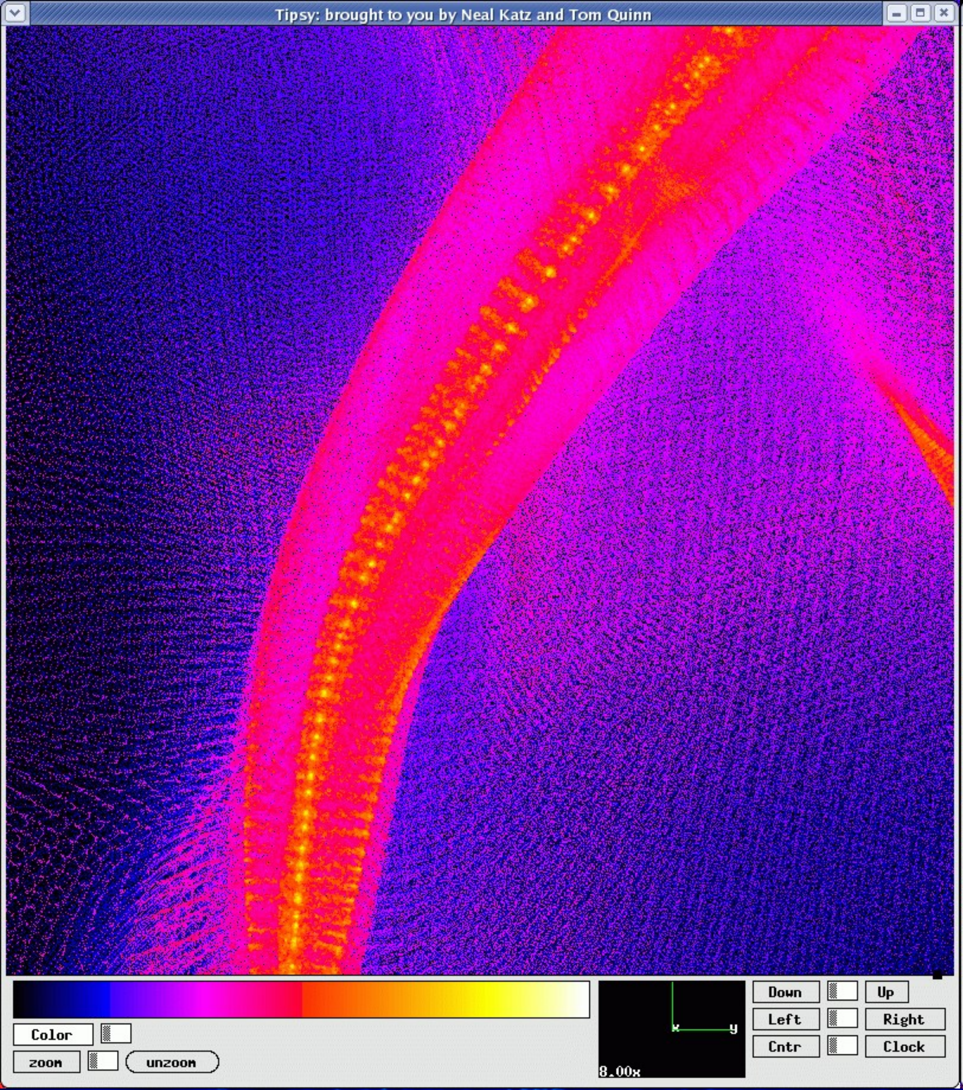
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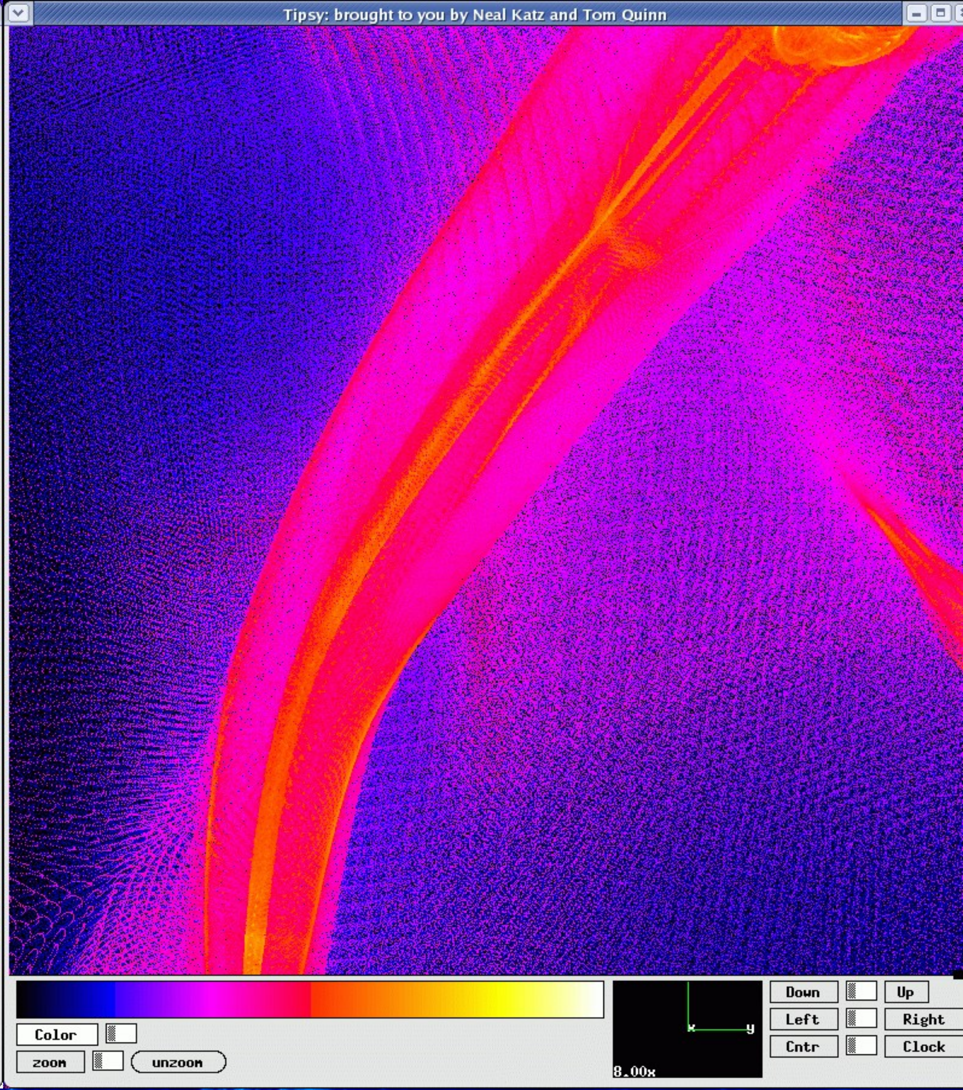
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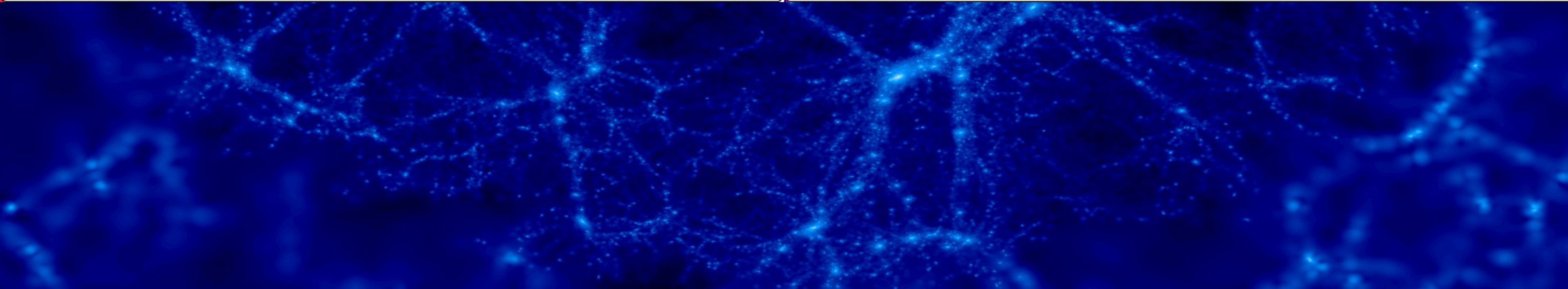
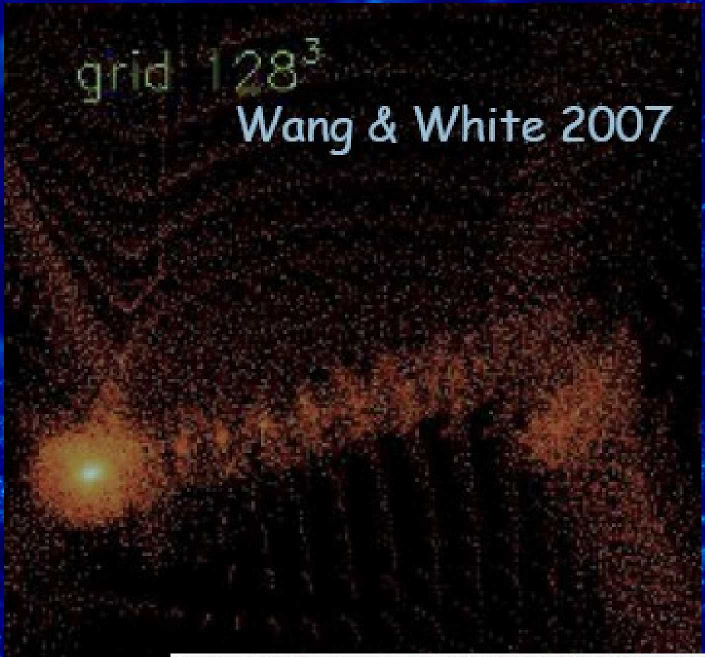
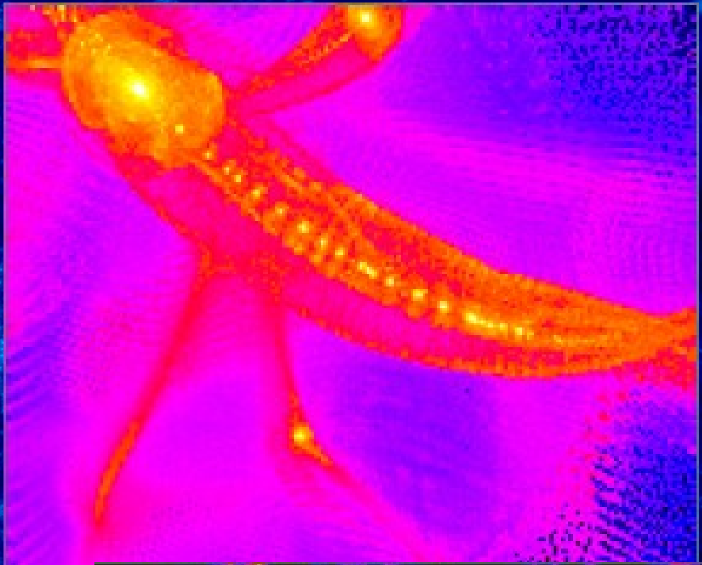
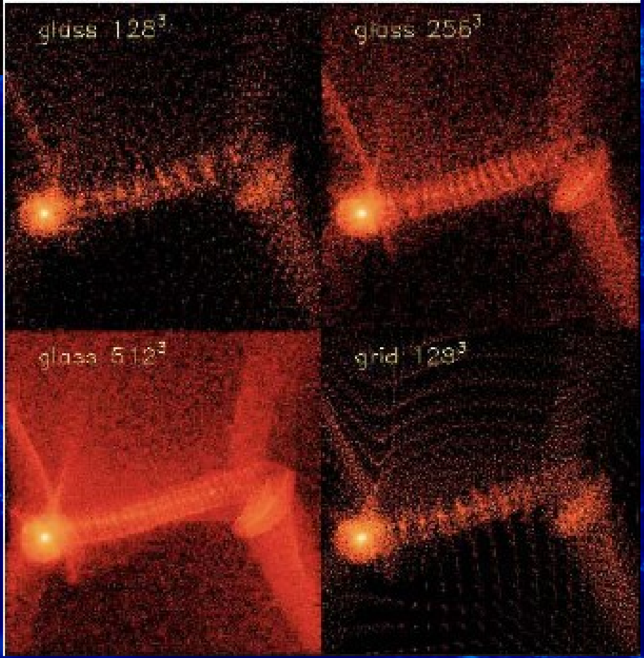
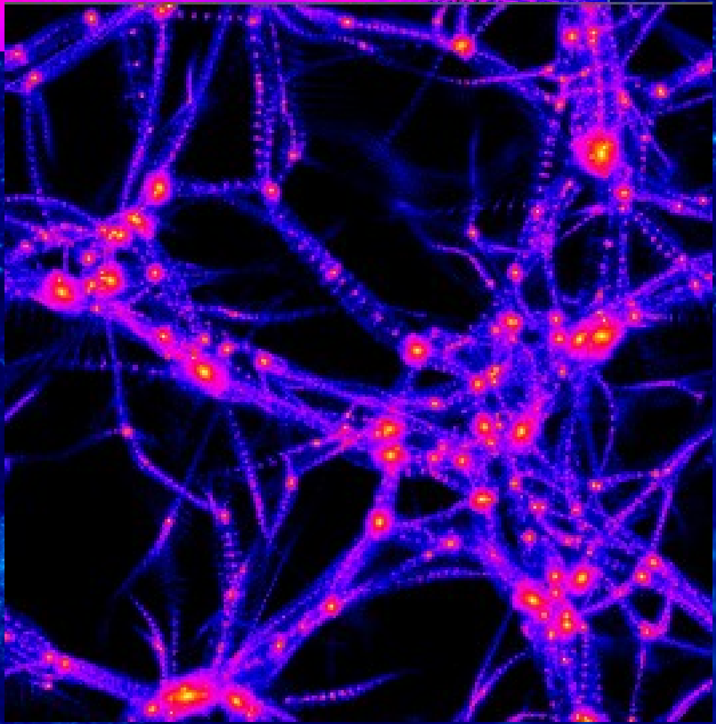




Wang & White 2007







CONCLUSIONS and COMPLICATIONS

- Formation of haloes in WDM models differs from CDM. Top-Down, Hierarchical, Grid Down. Looking at high redshift galaxies for T-D memory.

- The exact recipe for structure formation seems to depend only on the “topology”of the environment

☼ Q uantum Pressure; Baryons and their physics

- 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?

- Warm dark matter haloes contain visible caustics and shells.