Scalar Fields in Cosmology

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The LCDM

Some Problems of the LCDM

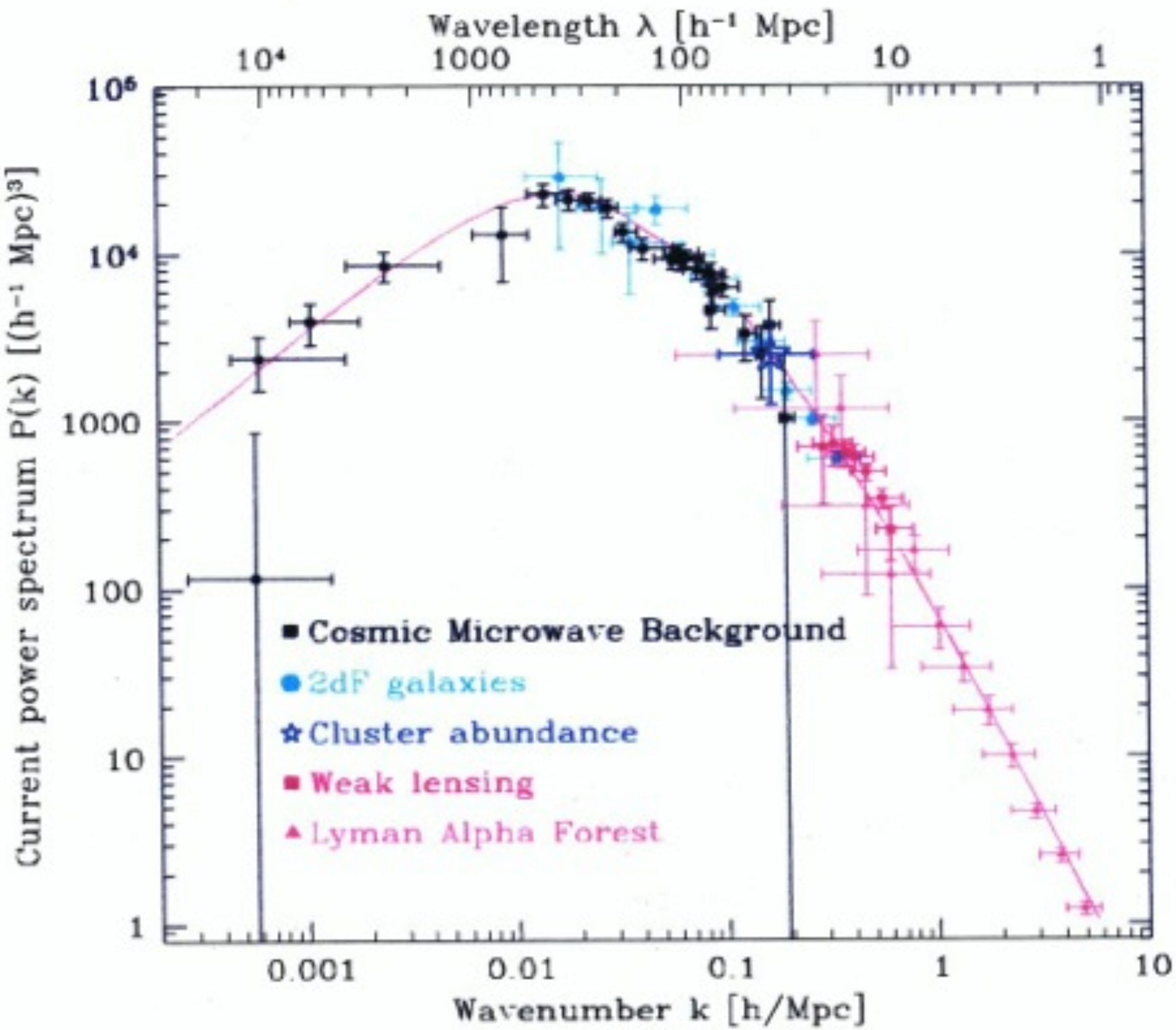
The SFDM Alternative

The Standard Model of Cosmology: LCDM

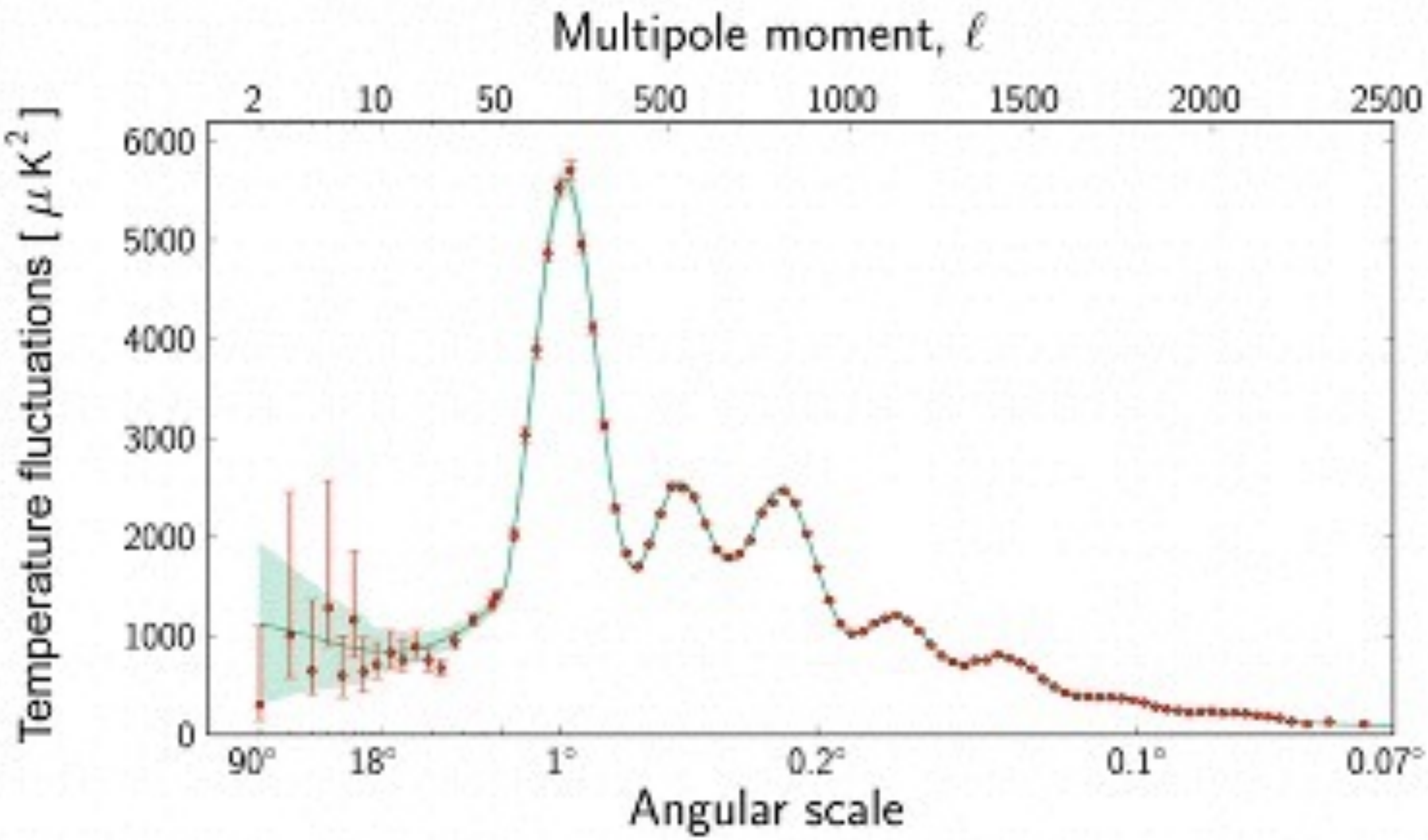
CDM Paradigme

- 1.- The DM fluctuation spectrum at recombination is detemined by a small number of physical paramenters.
- 2.- After recombination, the amplitude of the baryonic fluctuations rapidly grows to match that of the DM fluctuations.
- 3.- Smaller-mass fluctutions grow to nonlineartity and virialize and then are hirarchically clustered within successively larger bound systems.
- 4.- Ordinary matter in bound systems of total mass $10^{8-12} M_{\odot}$ cools rapidly enough within the DM halos to form galaxies, while larger mass fluctutations form clusters

The Standard Model of Cosmology: LCDM



The Standard Model of Cosmology: LCDM



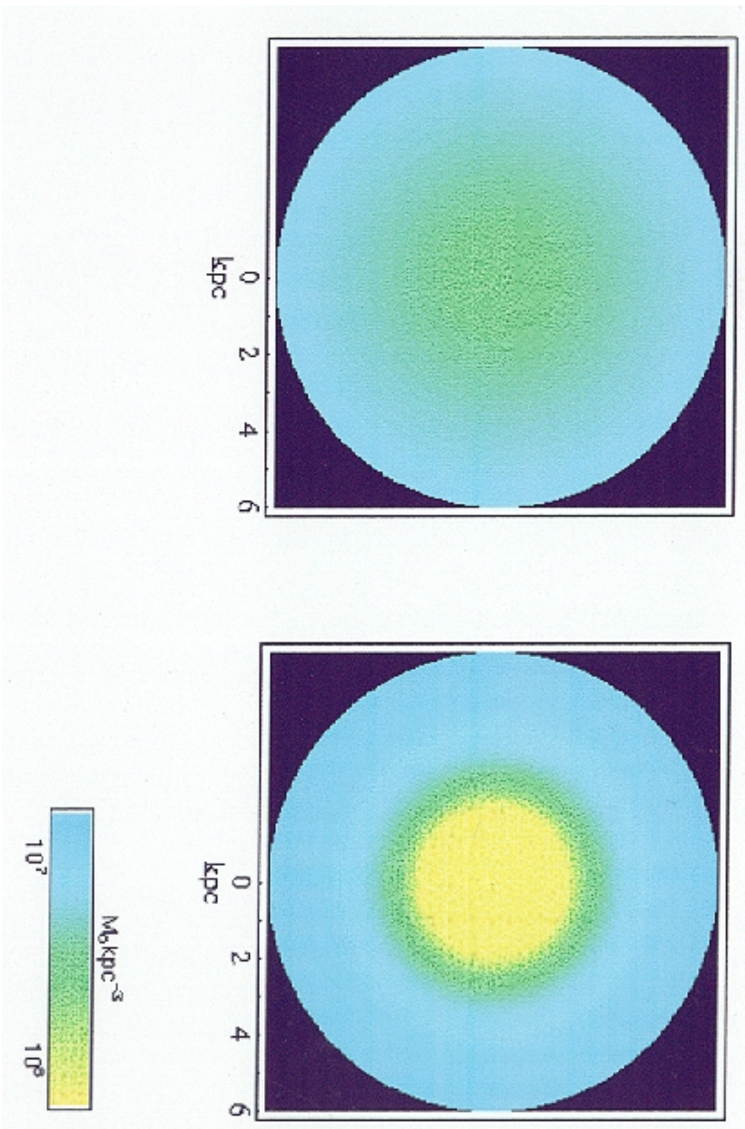
The Standard Model of Cosmology: Problems

- Extreme fine tuning
- Coincidence
- Cuspy central density profiles
- Missing Satellites Problem
- No-fit of the early assembly of galaxies
- Galaxies seems to be simpler
- Voids are too empty
- No-detection of DM
- etc.

The Standard Model of Cosmology: Problems

- Cuspy central density profiles
- Missing Satellites Problem

Galaxy's Density



Galaxy´s density $\rho \sim \frac{1}{x^\alpha}$

Observed $0 < \alpha < 1$

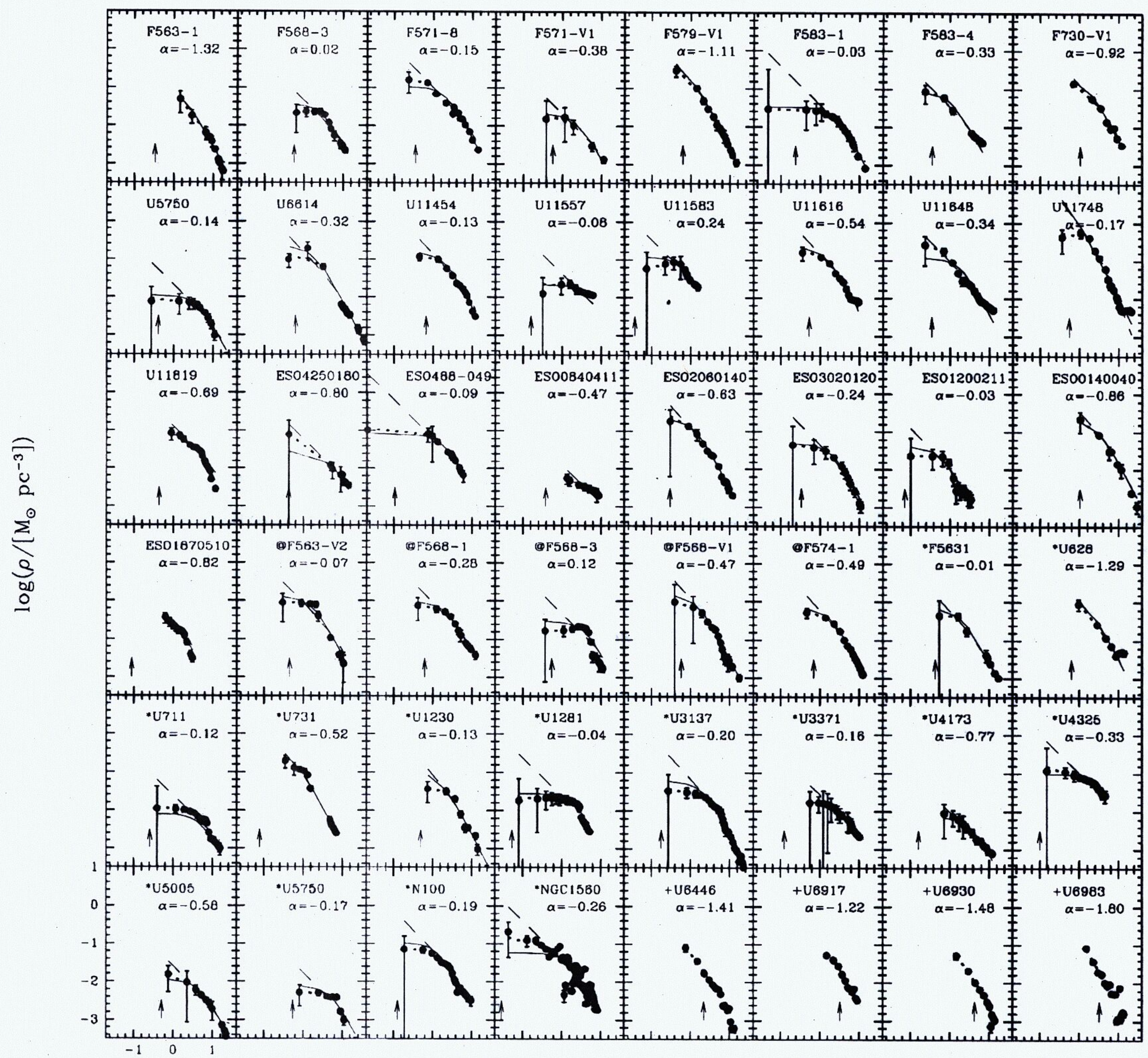
Theory

$$\rho_{NFW} = \frac{1}{x}\frac{\delta_0 \rho_0}{(1+x)^2}$$

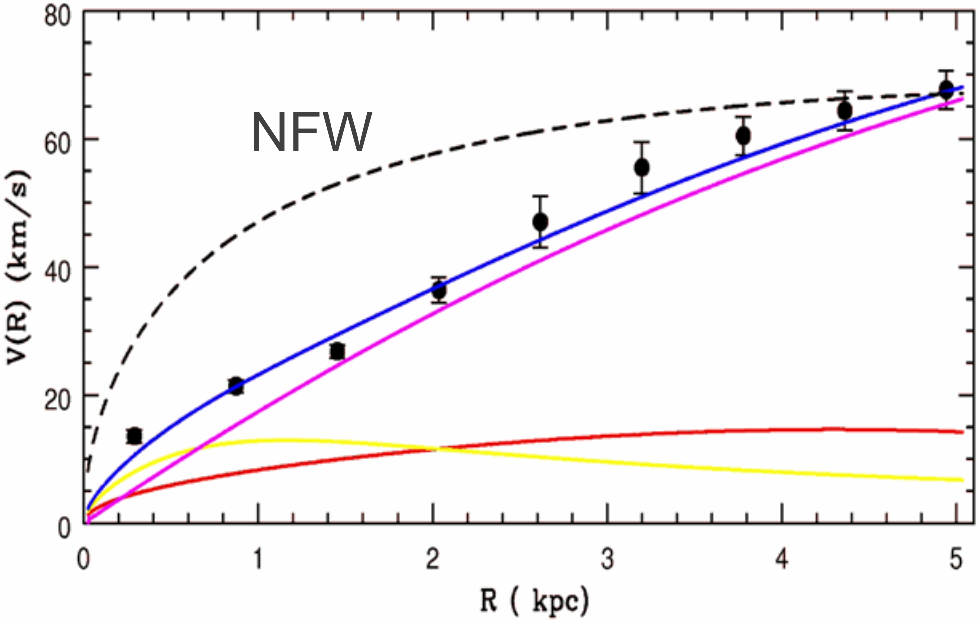
$$\rho_{NFW} \sim \frac{1}{x}$$

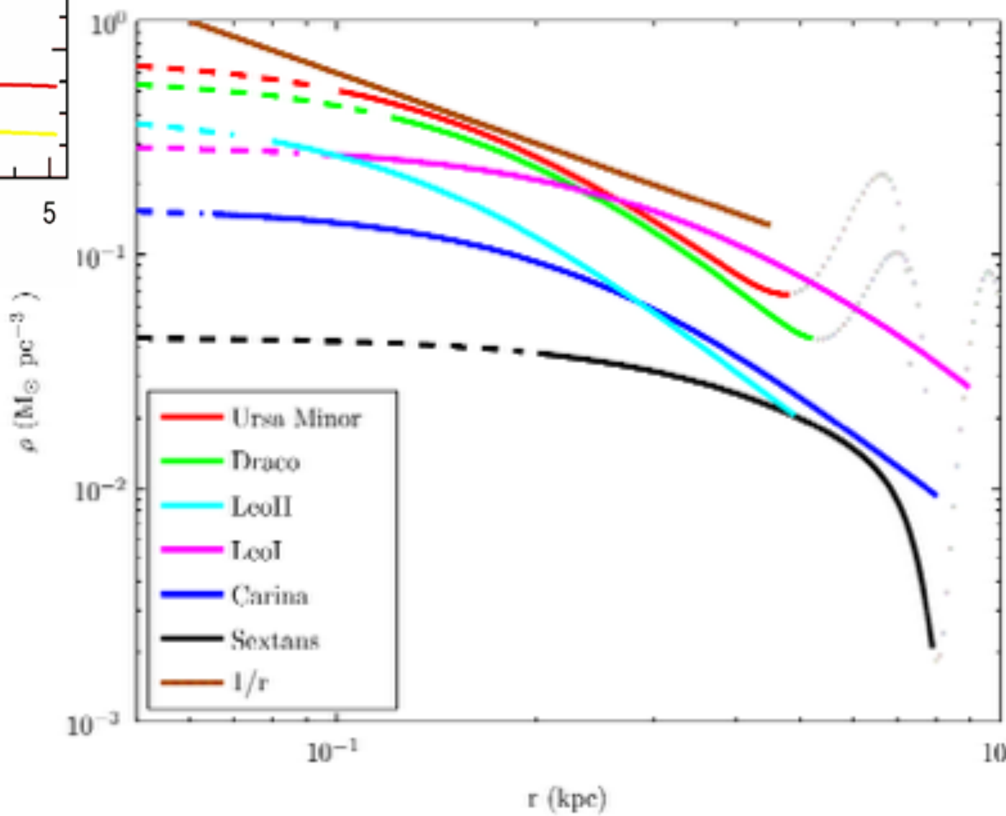
Galaxy's Center: Observations

W. J. G. de Blok, Stacy S. McGaugh, Albert Bosma, and Vera C. Rubin. ApJ Letters 552(2001)L24



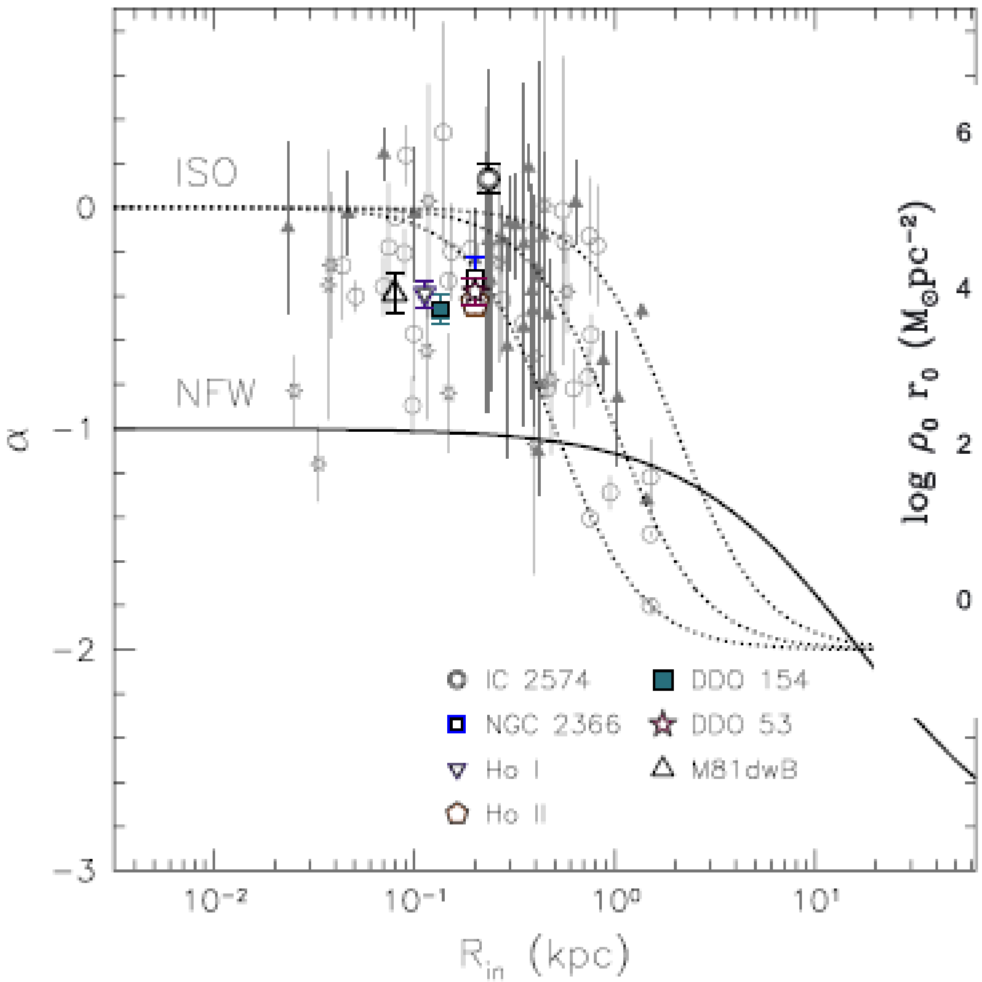
Galaxy's Center: Observations

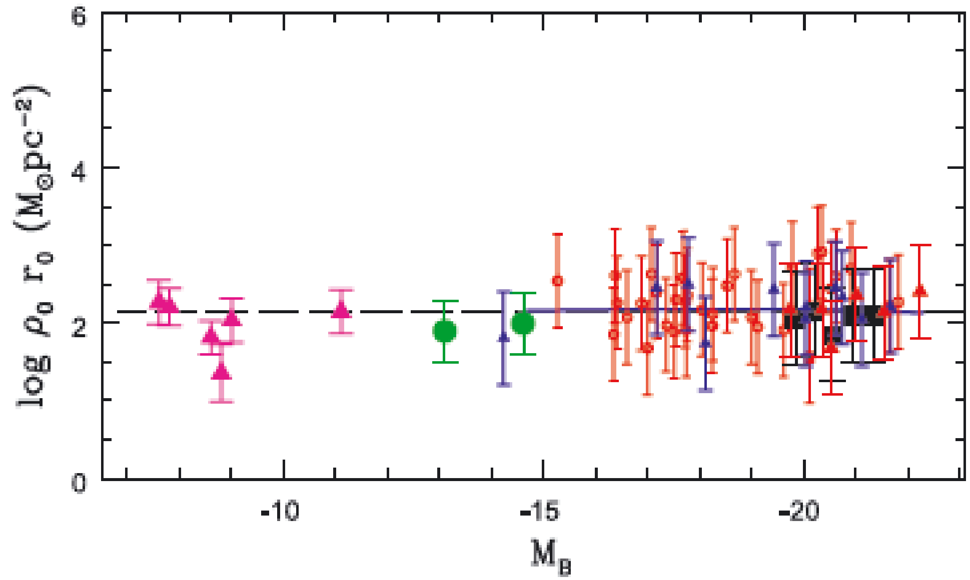




Galaxy's Center: Observations

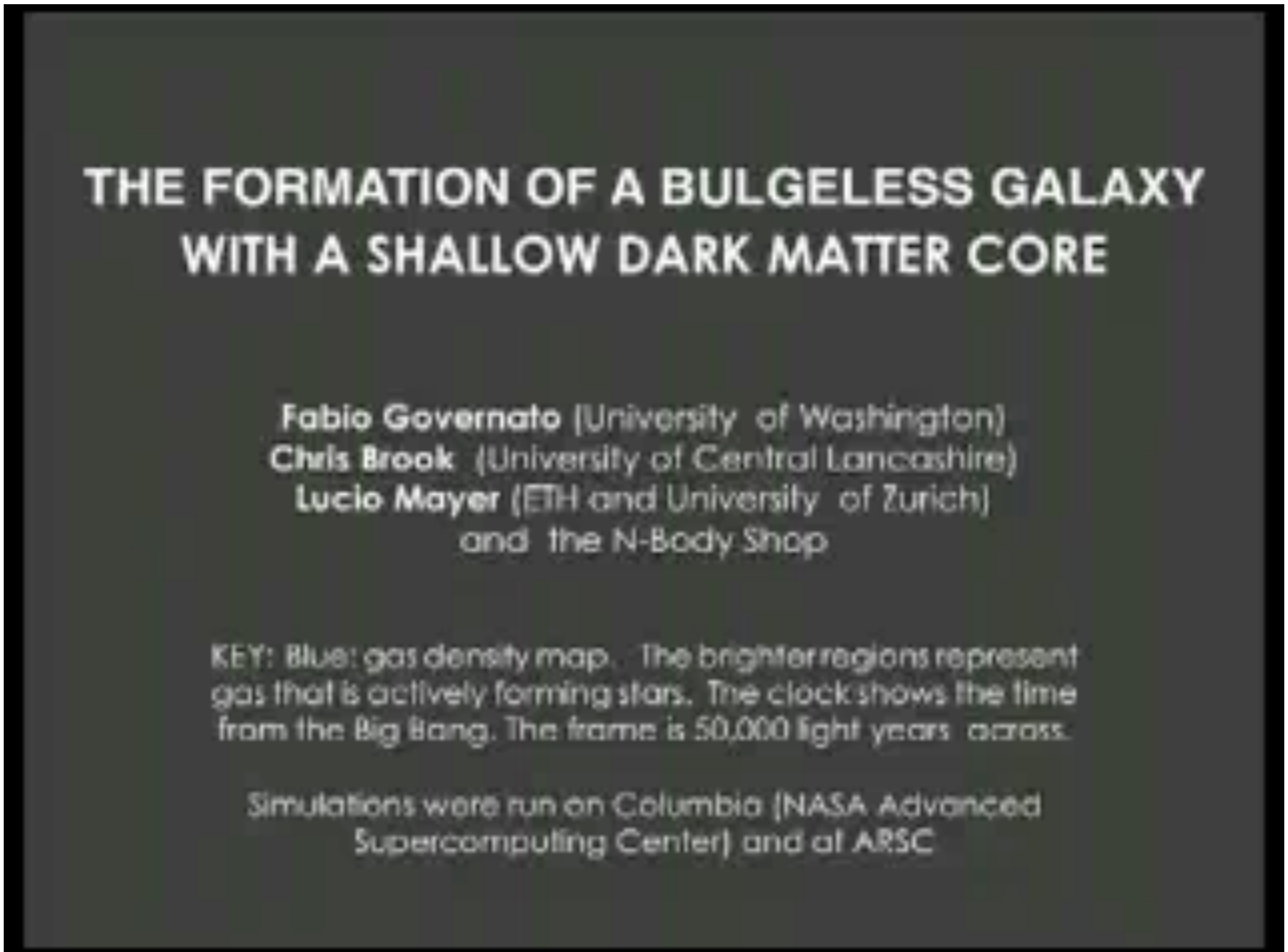
Gentile G., Tonini C. and Salucci P., A&A, 467, 925-931 (2007).





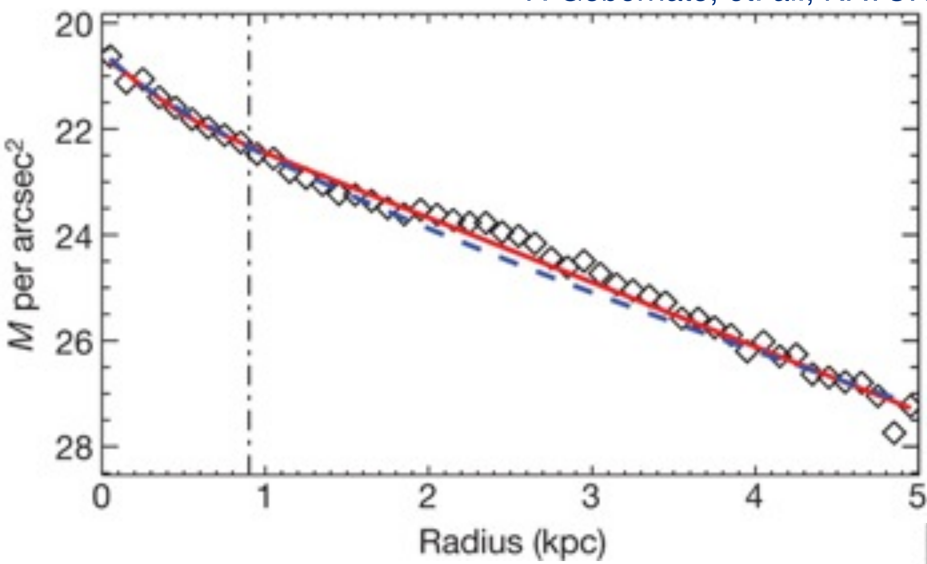
Galaxy’s Center: Simulations

F. Gobernato, et. al., NATURE, Vol 463, 14 January 2010



Galaxy's Center: Simulations

F. Gobernato, et. al., NATURE, Vol 463, 14 January 2010

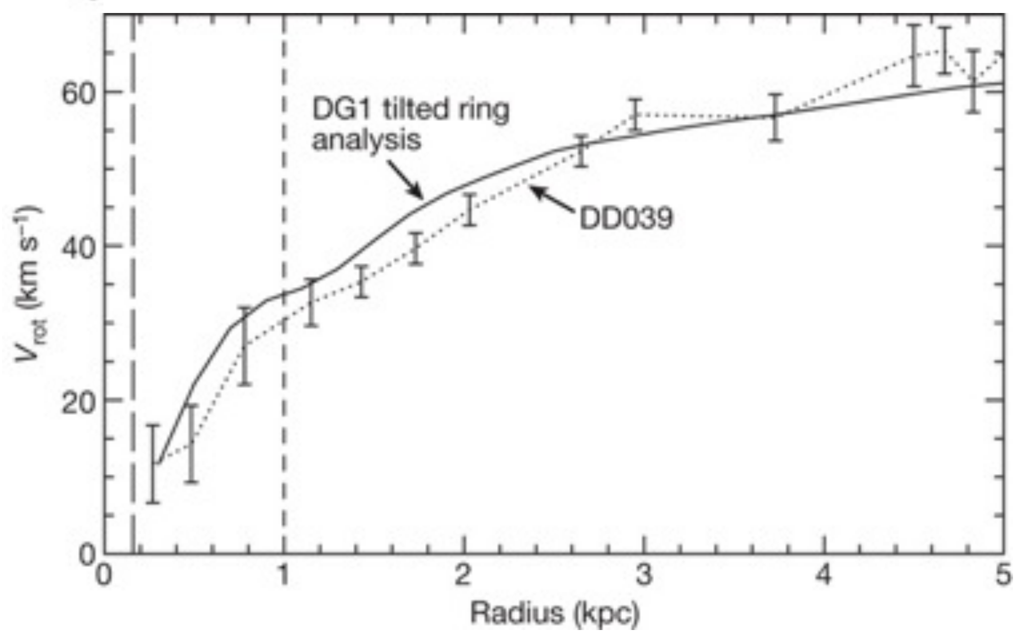


Einasto profile

$$\rho = \rho_0 e^{-A\, r^{\alpha}}$$

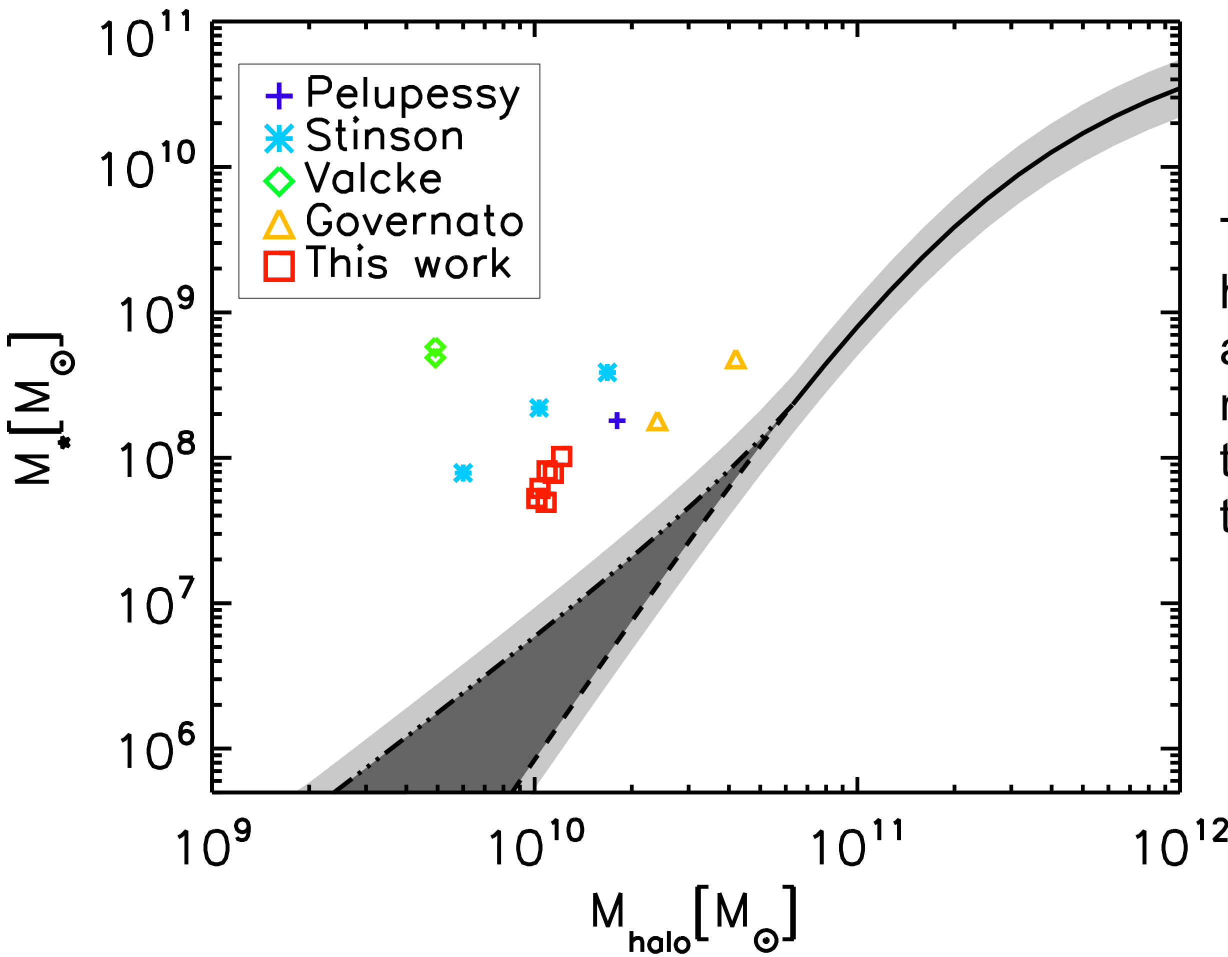
No evidence for internal features or star formation that could be the result of tidal processes or star formation induced by the cluster environment.

ej: Samantha J. Penny, Christopher J. Conselice, Sven De Rijcke and Enrico V. Held:
Mon. Not. R. Astron. Soc. 393, 1054–1062 (2009), etc.



Stellar Mass Predictions

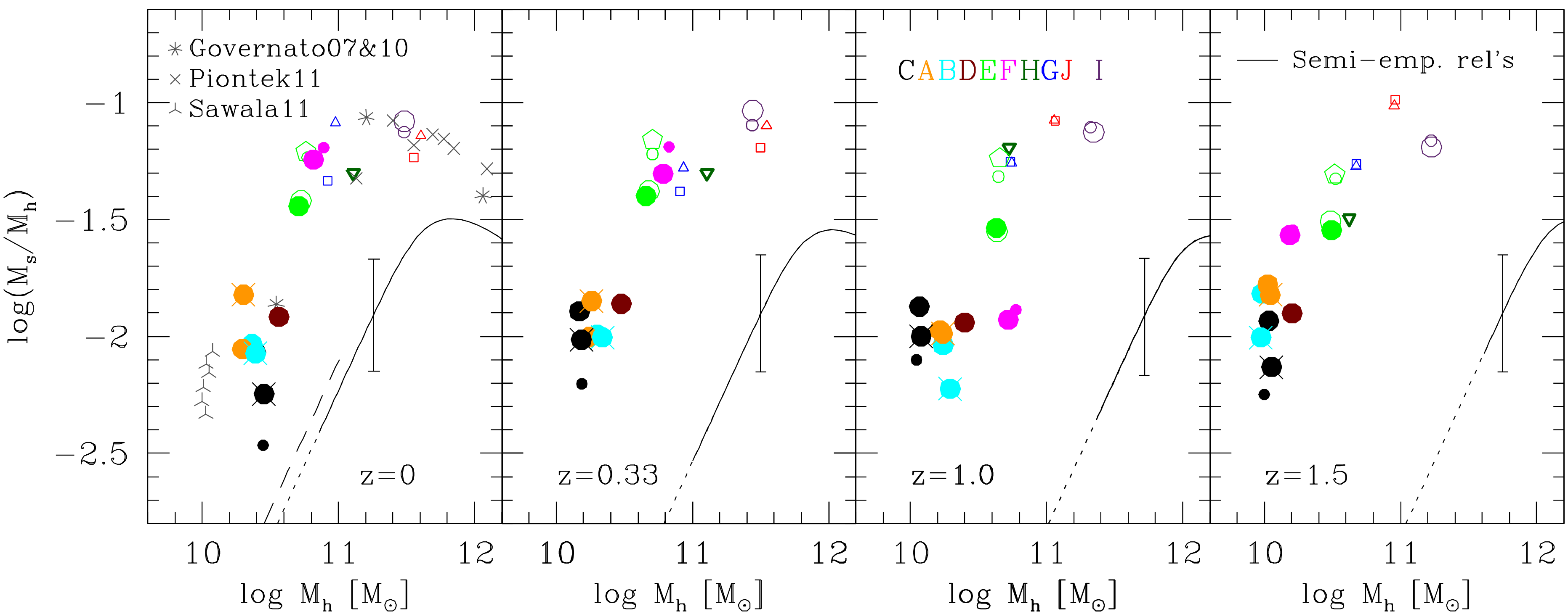
Till Sawala, Qi Guo, Cecilia Scannapieco, Adrian Jenkins and Simon White. Mon. Not. Roy. Astron. Soc. 413, (2011), 659



The dwarf galaxies formed in hydrodynamical simulations are almost two orders of magnitude more luminous than expected for haloes of this mass.

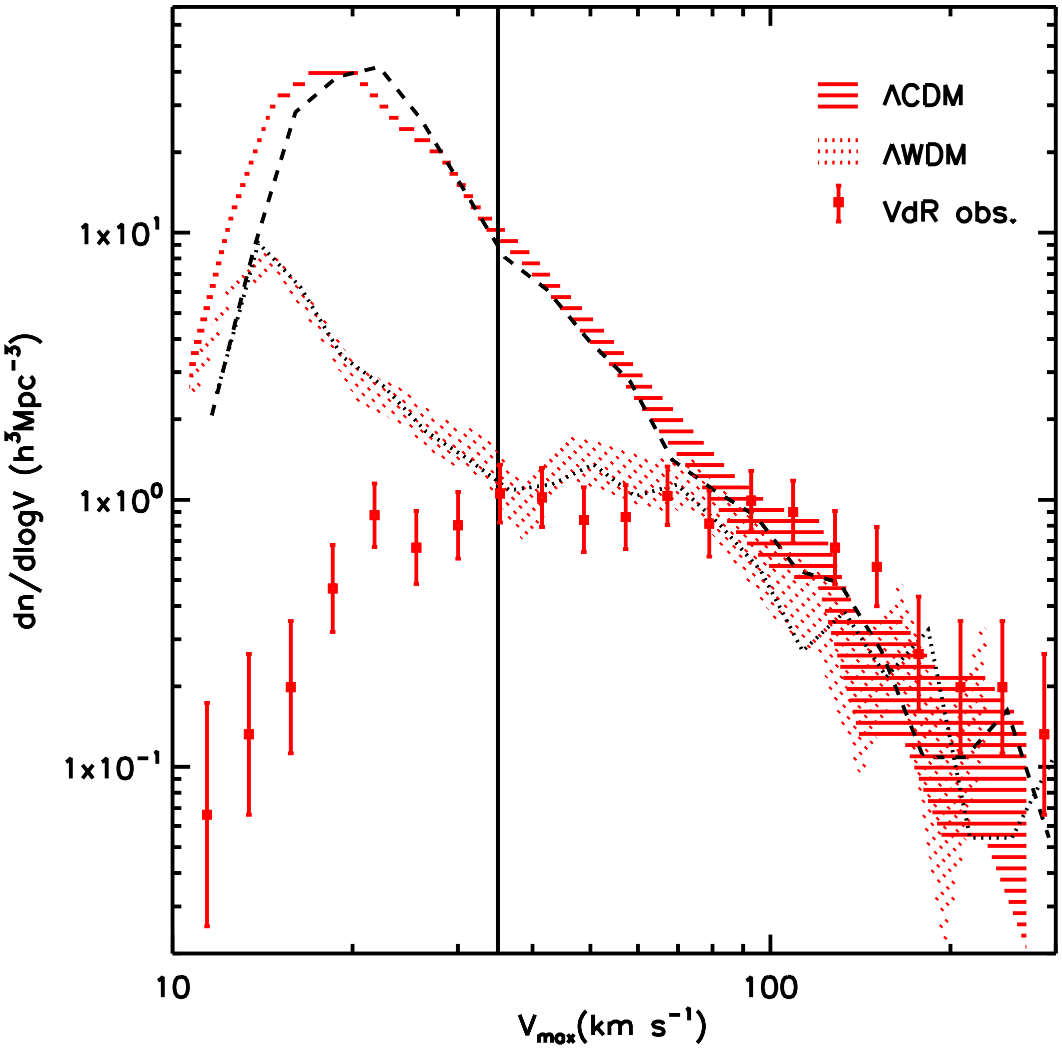
Stellar Mass Predictions

V. Avila-Reese, P. Colín, A. González-Samaniego, O. Valenzuela, C. Firmani, H. Velázquez, & D. Ceverino. ApJ, 736:134, (2011)



Velocity predictions

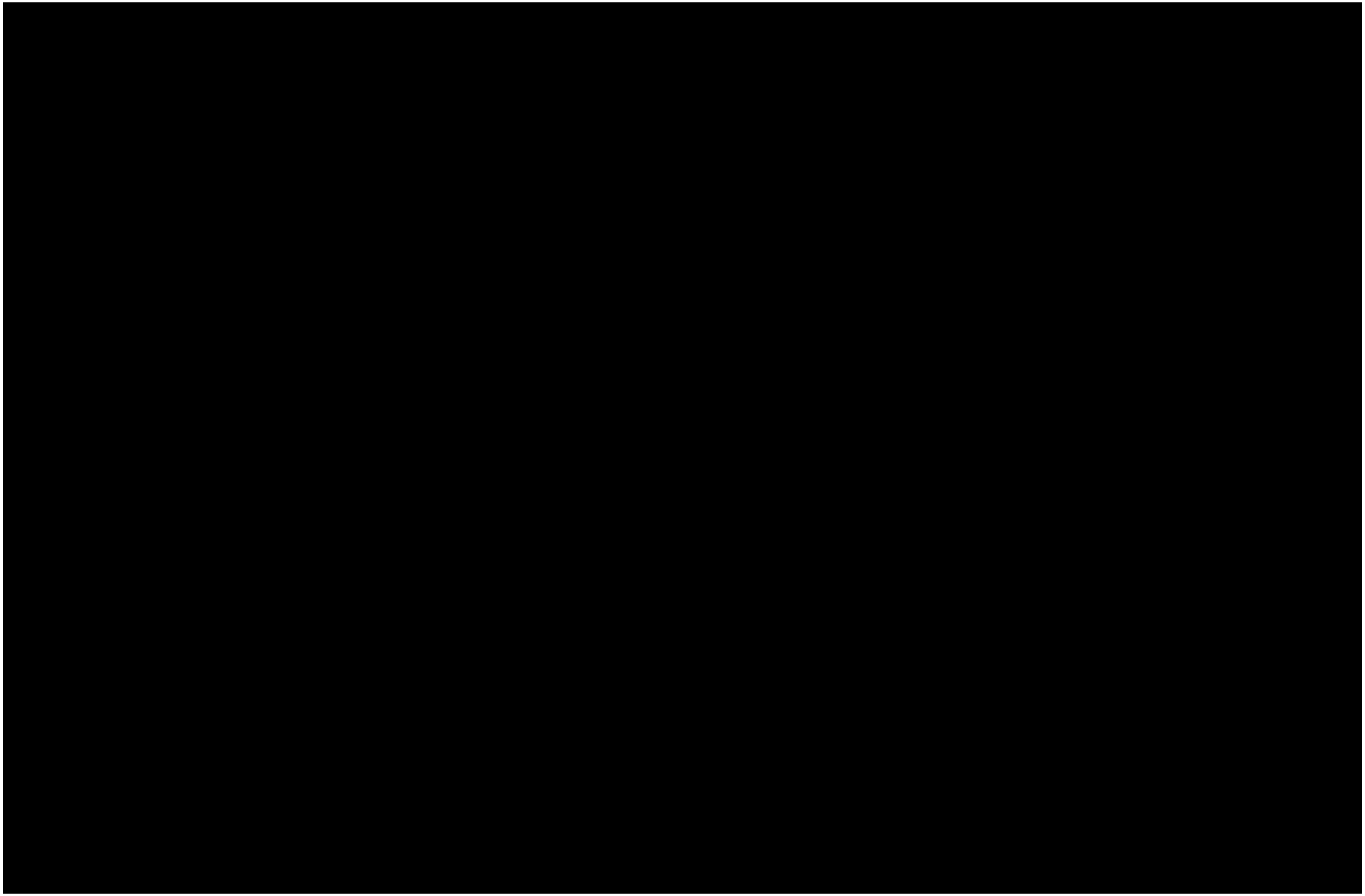
Jesús Zavala, et. al. ApJ, 700:1779–1793, 2009 August 1



The simulation with CDM predicts a steep rise in the VF toward lower velocities; for Vmax = 35 km/s, it forecasts ~10 times more sources than the ones observed. If confirmed by the complete ALFALFA survey, these results indicate a potential problem for the CDM paradigm

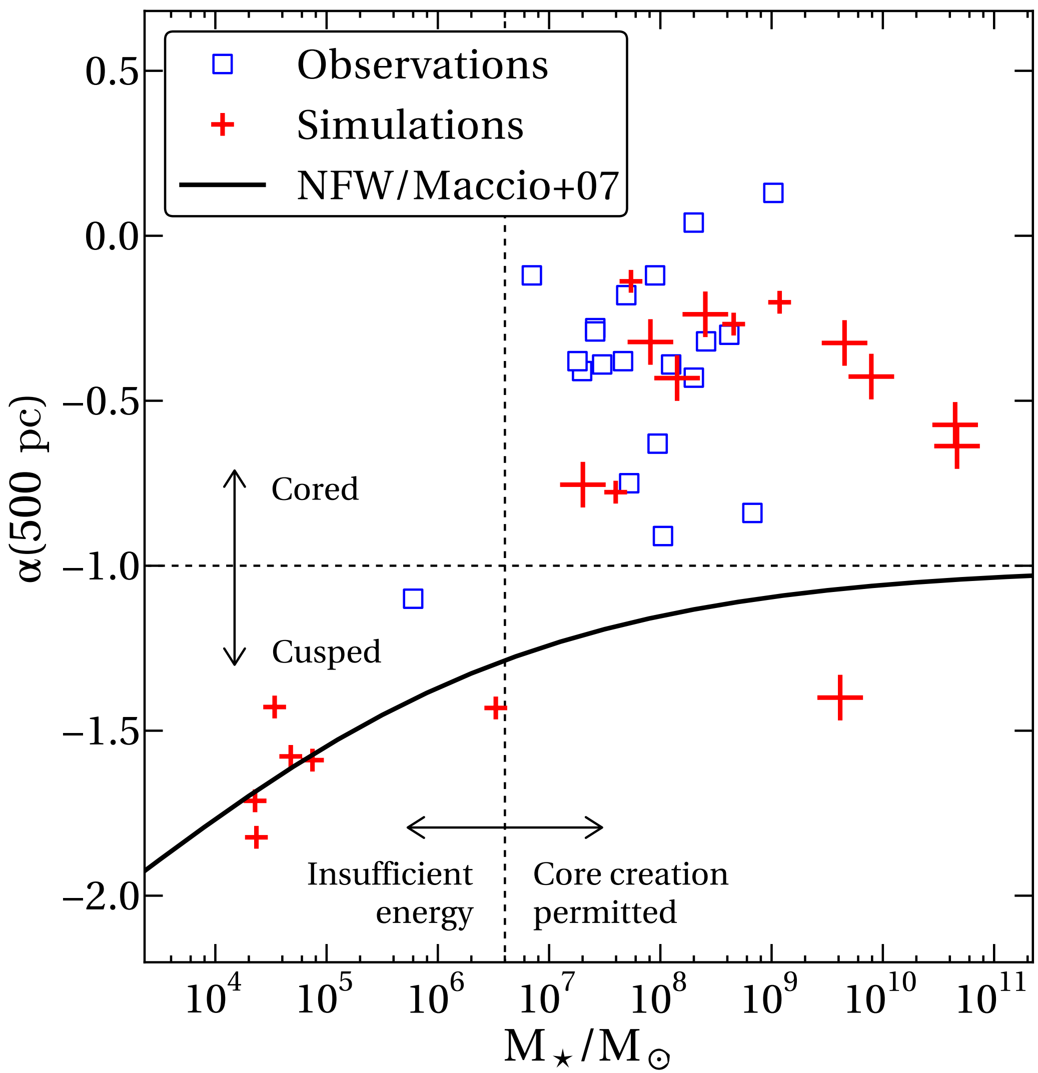
Numerical Simulations

M. Vogelsberger, S. Genel, V. Springel, P. Torrey, D. Sijacki, D. Xu, G. Snyder, S. Bird, D. Nelson & L. Hernquist. Nature 509 (2014) 177

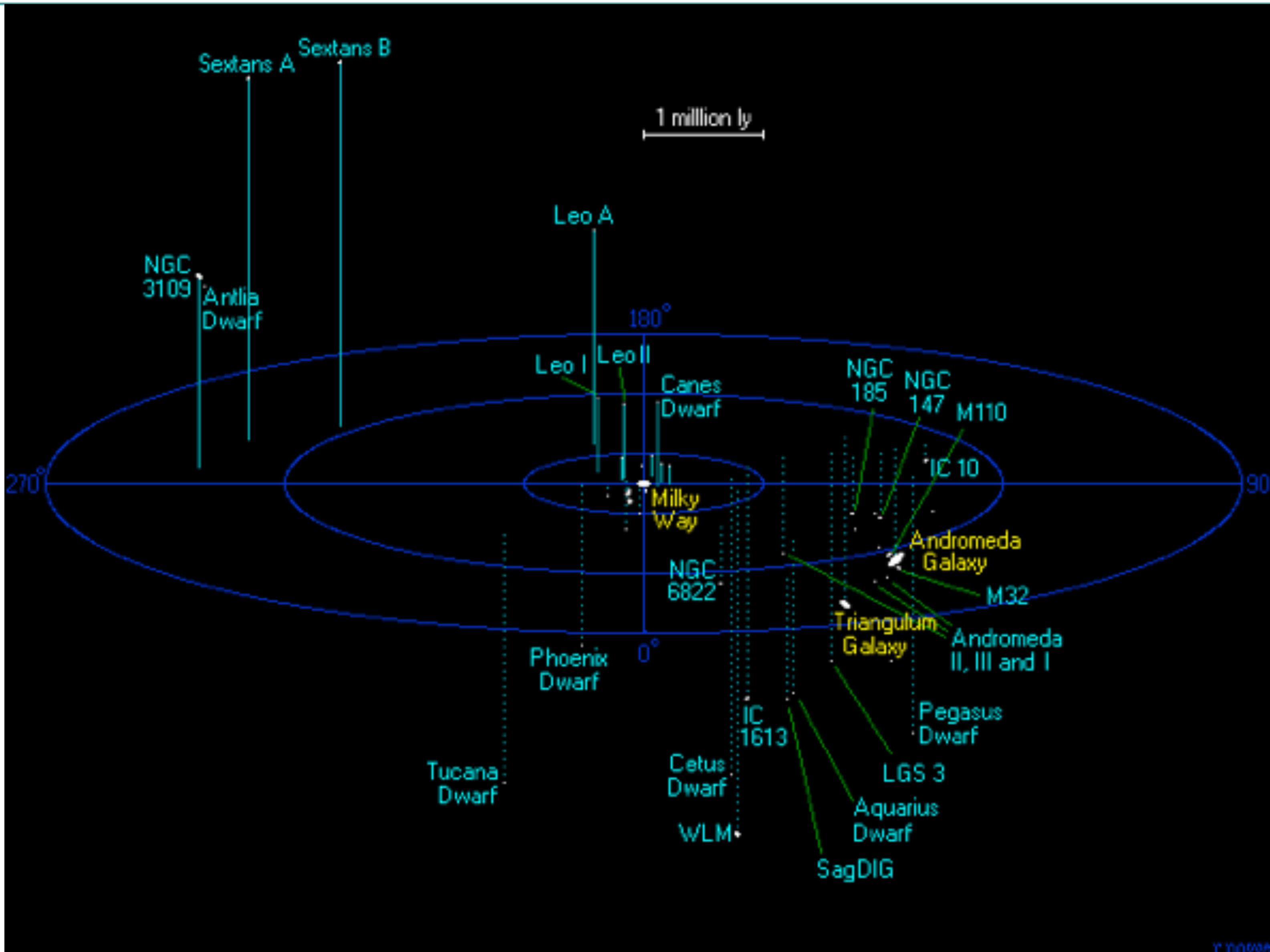


Metallicity

Andrew Pontzen & Fabio Governato. Nature 506 (2014) 171

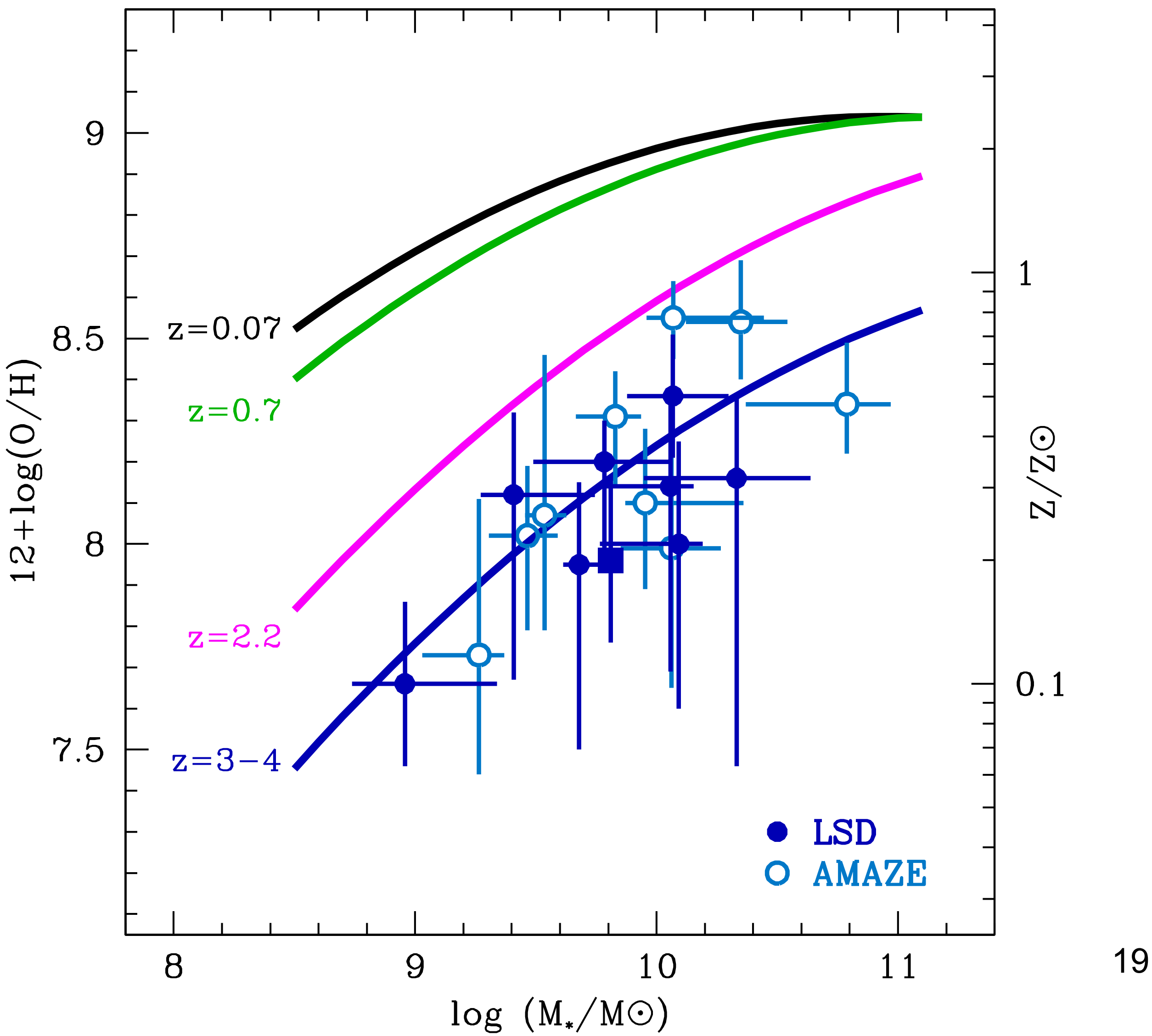


Galaxy Satellites



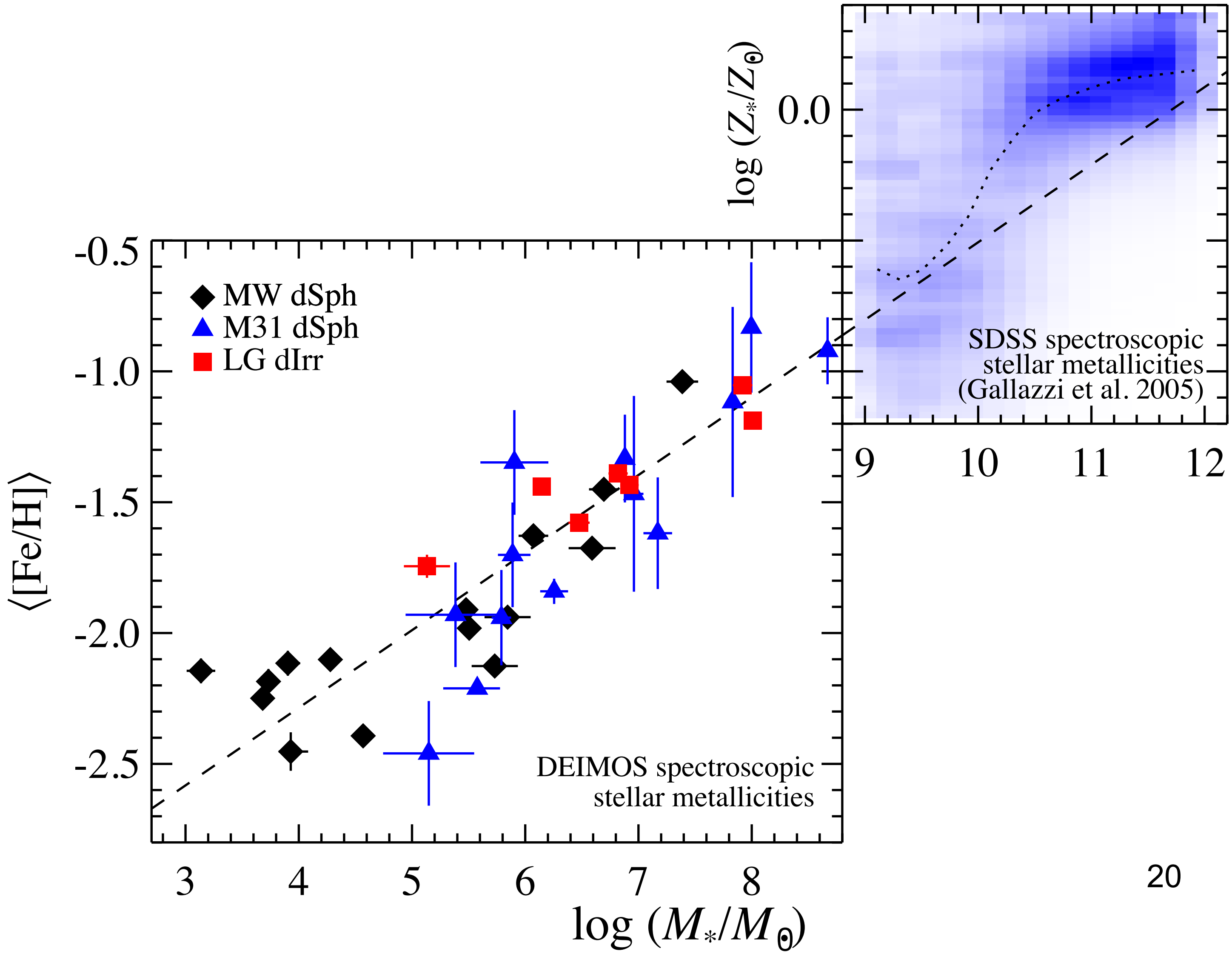
Metallicity

F. Mannucci and G. Cresci. arXiv:1011.0264



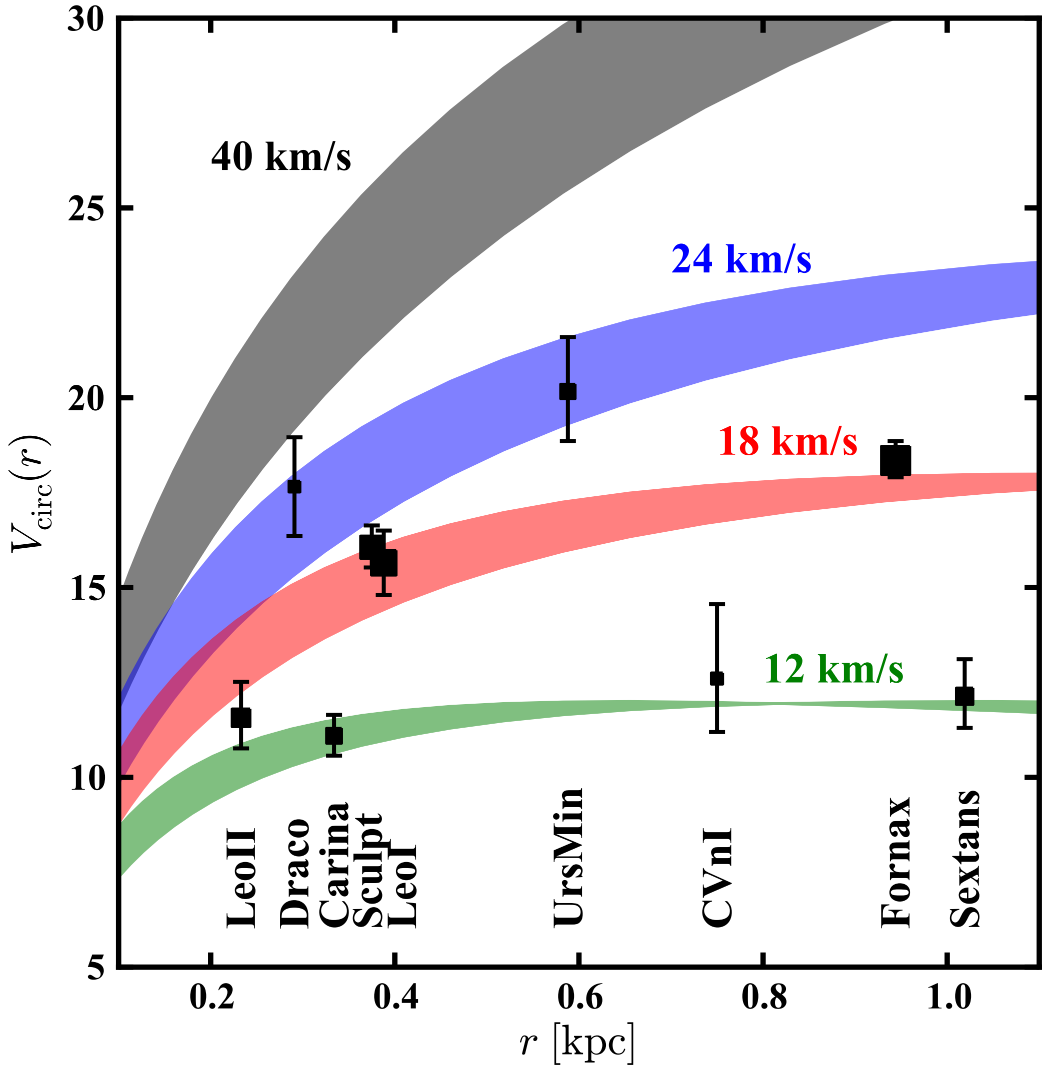
Metallicity

Evan N. Kirby, Judith G. Cohen, Puragra Guhathakurta, Lucy Cheng, James S. Bullock,Anna Gallazzi. ApJ (2013) 779 102



TBTF

Michael Boylan-Kolchin, James S. Bullock and Manoj Kaplinghat. Mon.Not.Roy.Astron.Soc.422:(2012)1203



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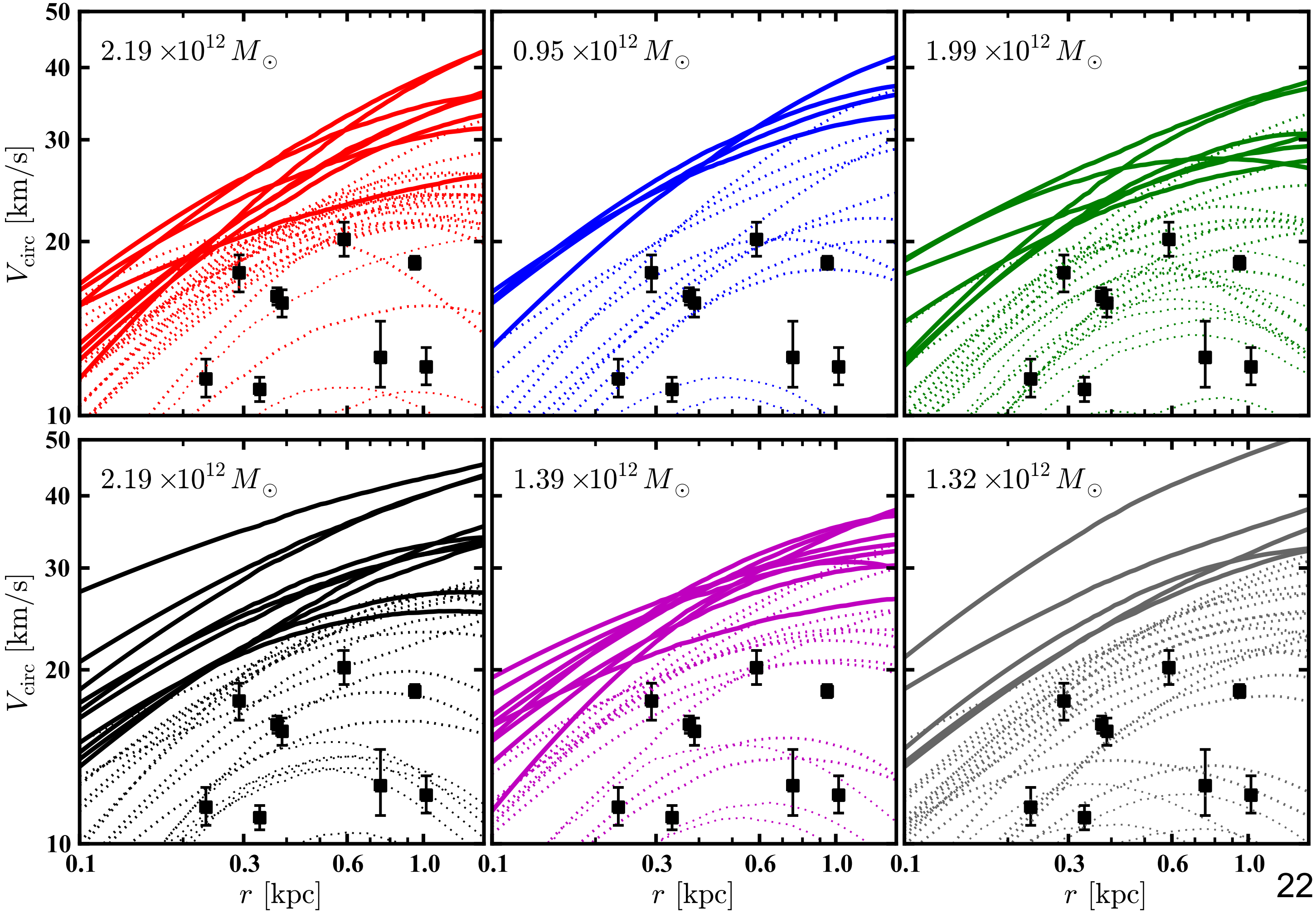
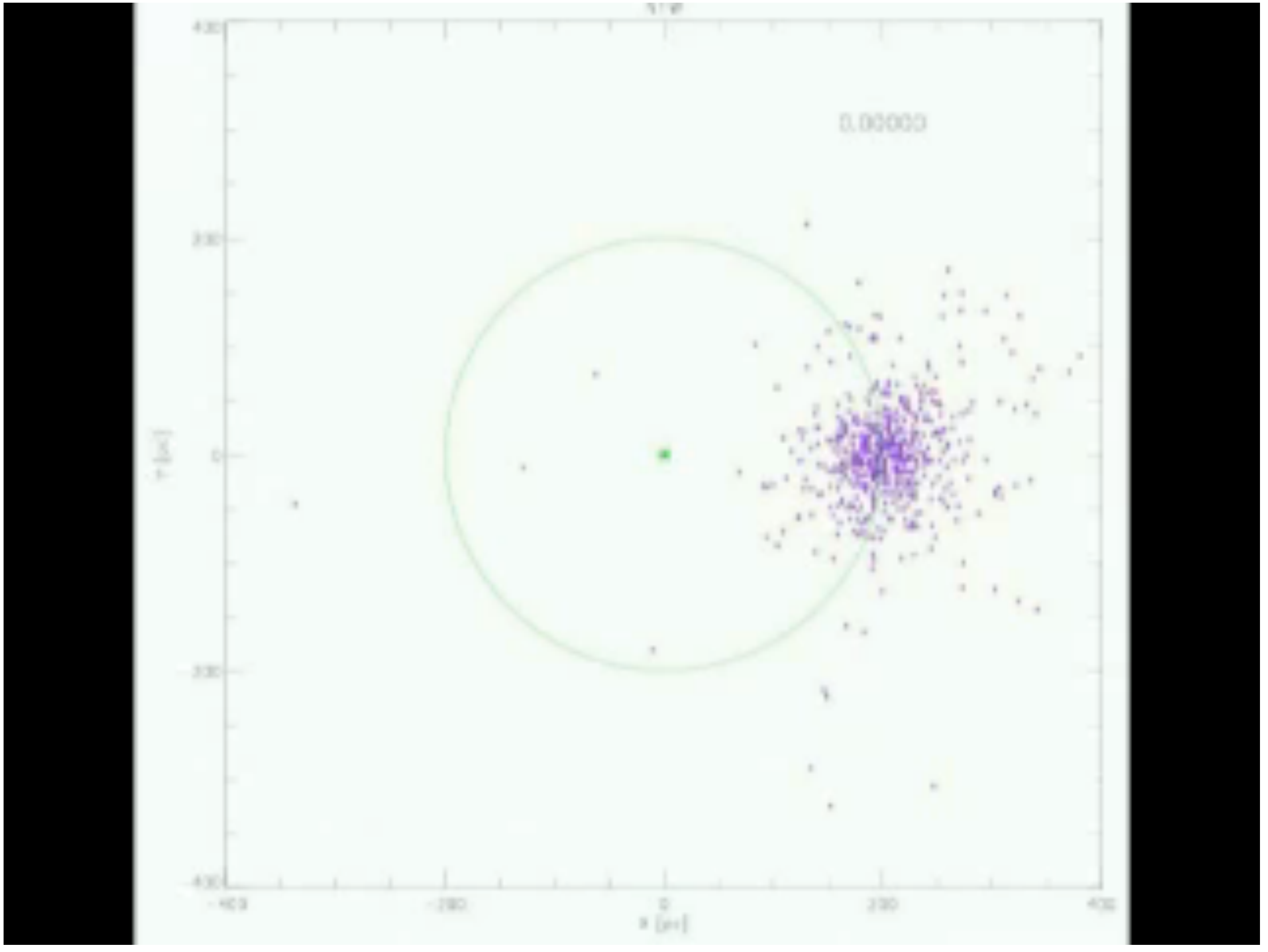
Michael Boylan-Kolchin, James S. Bullock and Manoj Kaplinghat. Mon.Not.Roy.Astron.Soc.422:(2012)1203



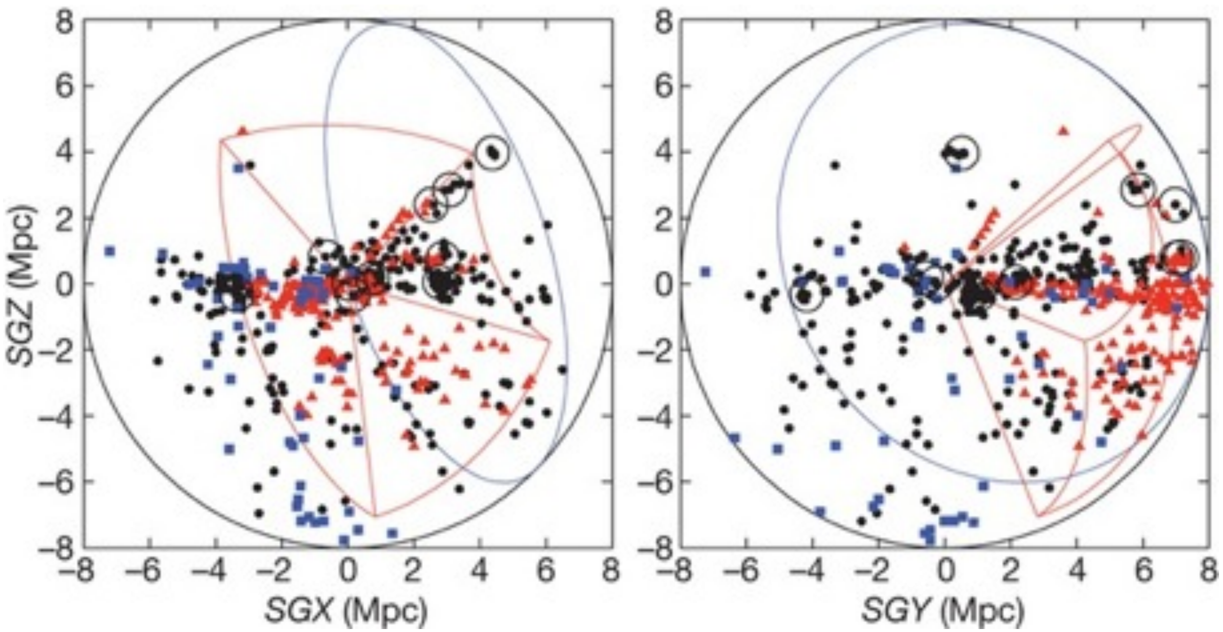
Galactic Dynamics

Jorge Peñarrubia, A. J. Benson, Matthew G. Walker, Gerard Gilmore, Alan W. McConnachie and Lucio Mayer. MNRAS 406, 1290–1305 (2010)



Voids are too empty

P. J. E. Peebles & A. Nusser, Nature 465(2010)565

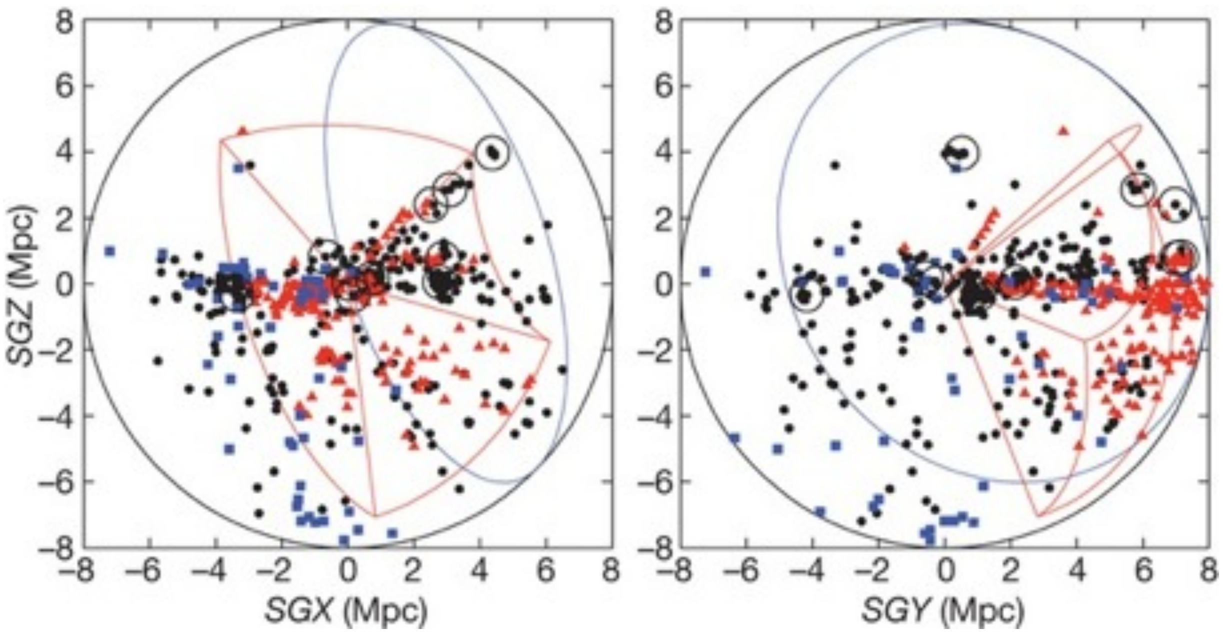


It is not clear why objects that might have been assembled in such very different ways, from different ancestral objects, should have had evolutionary tracks that converged to show small dispersions around simple power law forms for their size–luminosity relations.

Nair, P. B., van den Bergh, S. & Abraham, R. G. The environmental dependence of the luminosity-size relation for galaxies. Astrophys. J. 715, 606–622 (2010).

Voids are too empty

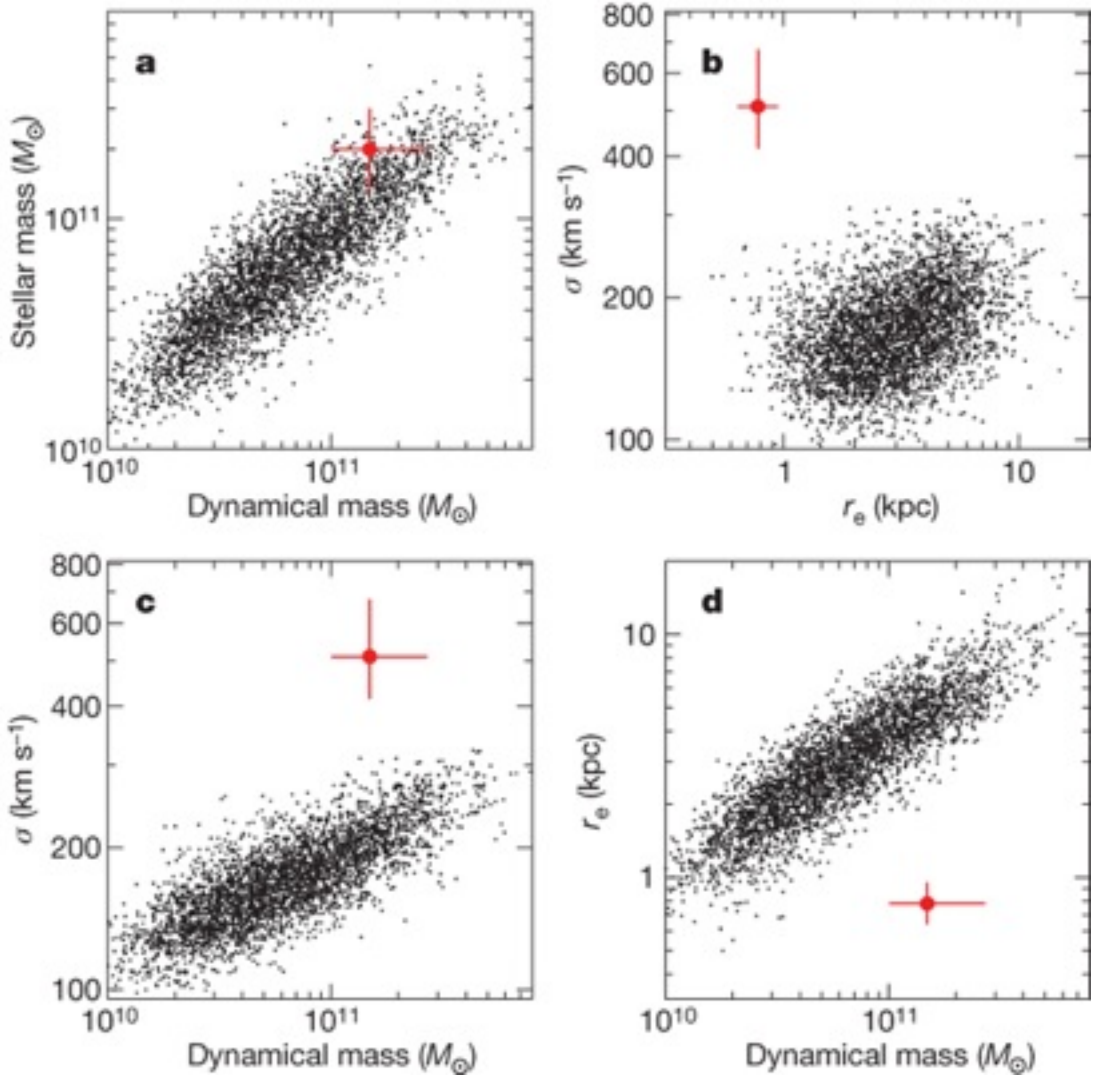
P. J. E. Peebles & A. Nusser, Nature 465(2010)565



In short, the general insensitivity of galaxies to their environments is not expected in standard ideas. It would help if galaxies were more rapidly assembled, as they could then evolve as more nearly isolated island universes.

Early Galaxies Compactness

Pieter G. van Dokkum et. al. NATURE, Vol 460, 6 August 2009. The Astrophysical Journal, 677:L5–L8, 2008 April 10



Early Galaxies Compactness

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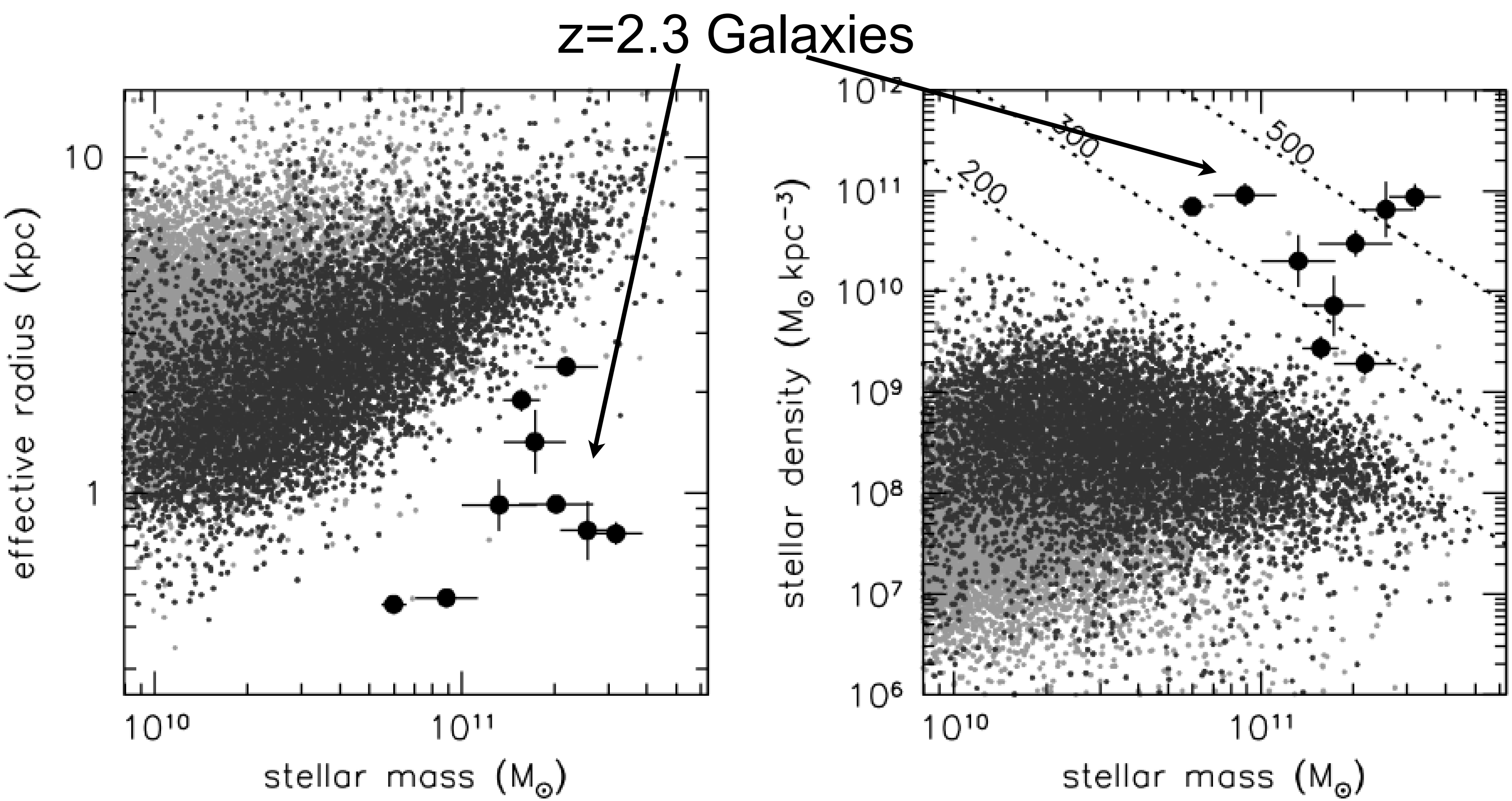

Some Alternatives

SM Extentions

- Self-Interacting DM
- Warm DM
- Super Heavy DM
- Self-Annihilating DM
- Decaying DM
- Extra Symmetries,
- Repulsive DM
- Fuzzy DM
- k-essence
- Scalar Field DM (BEC DM), etc.

GR Extentions

- Scalar Field DM (BEC DM)
- MOND -> MOND+
- f(R)
- Extra Dimensions
- etc.

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GR Extentions

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- etc.

Fuzzy, BEC, Ultra-light, Scalar Field DM

A brief Review of the Scalar Field Dark Matter model. Juan Magana, Tonatiuh Matos, Victor Robles, Abril Suarez. arXiv:1201.6107

Here

$$\mathcal{L} = \sqrt{-g}\left[R - \frac{1}{2}(\nabla\Phi)^2 - V(\Phi)\right] - e^{-2\alpha\Phi}F^2\Big]$$

$$V(\Phi) = V_0 + \frac{1}{2!}V''\Phi^2 + \frac{1}{3!}V'''\Phi^3 + \frac{1}{4!}V^{iv}\Phi^4 + \cdots$$

Bose-Einstein Condensates

Abril Suarez, Victor H. Robles, Tonatiuh Matos . A Review on the Scalar Field/ Bose-Einstein Condensate Dark Matter Model
Astrophysics and Space Science Proceedings 38, Chapter 9 (2013) arXiv:1302.0903

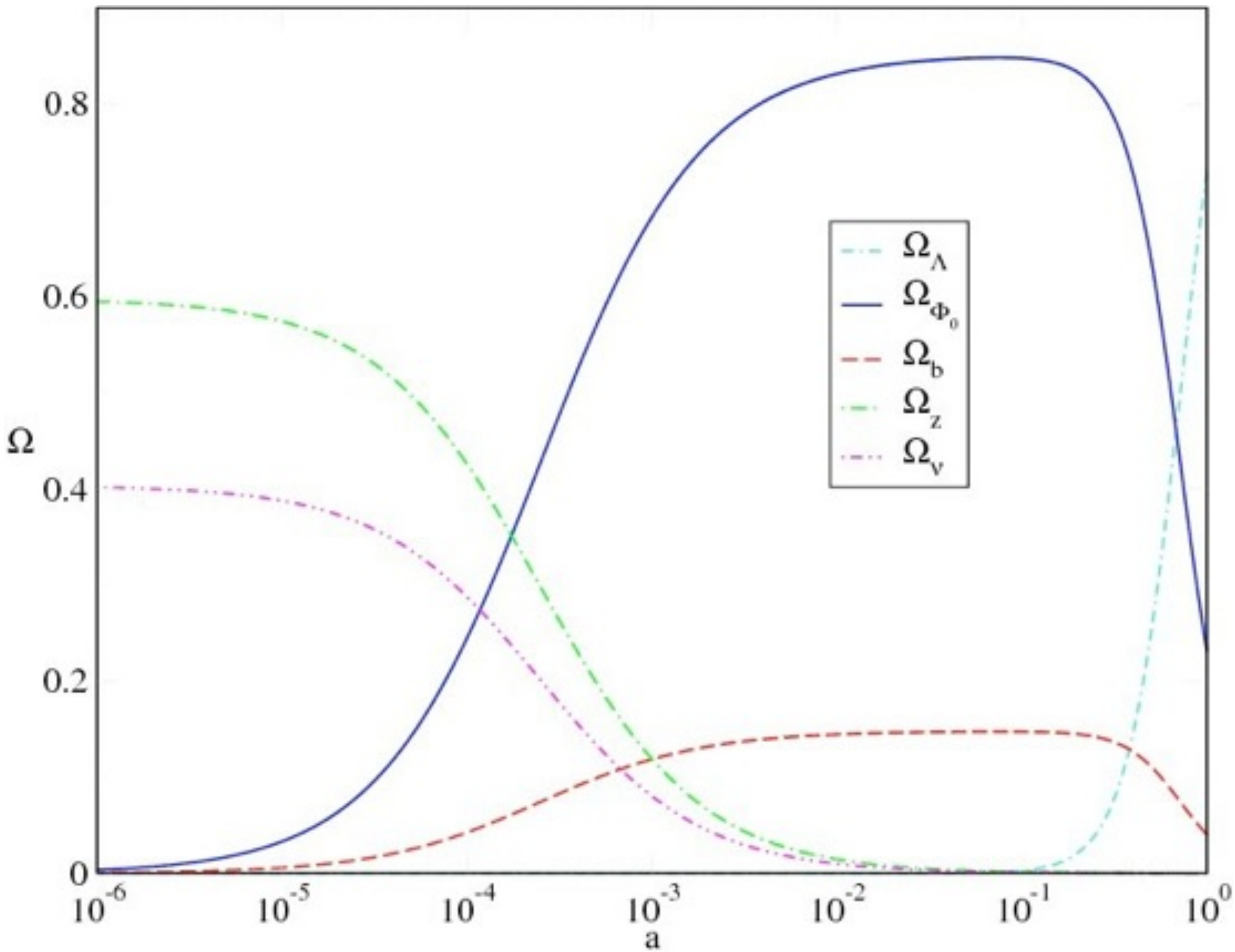
$$\Box\Phi + \frac{dV}{d\Phi} = 0$$

$$\ddot{\Phi} + 3H\dot{\Phi} + \frac{dV}{d\Phi} = 0$$

$$k_B T_c = \frac{2\pi\hbar^2}{m^{\frac{5}{3}}}\left(\frac{\rho}{g_{\frac{3}{2}}(1)}\right)^{\frac{2}{3}}$$

The Cosmology

Φ^2 as Dark Matter. T. Matos, A. Vázquez & J.A. Magaña. MNRAS, 389, (2009) 13957.



Structure Formation

Abril Suarez and TM MNRAS 311, (2011), 87

$$\delta\ddot{\Phi} + 3H\delta\dot{\Phi} - \frac{1}{a^2}\nabla^2\delta\Phi + V_{,\Phi\Phi}\,\delta\Phi + 2V_{,\Phi}\,\phi = 0$$

$$\delta\Phi = \sqrt{\hat{\rho}}\,\cos\left(\frac{mc^2\,t}{\hbar} + S\right)$$

$$\vec{v} \equiv \frac{\hbar}{m}\nabla S$$

Structure Formation

Abril Suarez and TM MNRAS 311, (2011), 87

$$\vec{v} \equiv \frac{\hbar}{m}\nabla S$$

$$\begin{aligned}
\frac{\partial\hat{\rho}}{\partial t} &+ \frac{1}{a^2}\nabla\cdot(\hat{\rho}\vec{v}) + 3H\hat{\rho} = 0 \\
&- \frac{\hbar}{m}\hat{\rho}\left(\ddot{S} + 3H\dot{S}\right) - \frac{\hbar}{m}\dot{\hat{\rho}}\dot{S} = 0 \\
\frac{\partial\vec{v}}{\partial t} &+ \frac{1}{a^2}\vec{v}\nabla\cdot\vec{v} + \nabla\phi + \frac{\hbar^2}{2m^2}\nabla\left(\frac{\Box\sqrt{\hat{\rho}}}{\sqrt{\hat{\rho}}}\right) = 0, \\
&- \frac{\hbar}{m}\dot{S}\,\frac{\partial\vec{v}}{\partial t} = 0,
\end{aligned}$$

Structure Formation

Abril Suarez and TM MNRAS 311, (2011), 87

$$\hat\rho = \hat\rho(t) \qquad S = S(t) \qquad \vec v \equiv \frac{\hbar}{m}\nabla S$$

$$\frac{\partial\hat\rho}{\partial t} + 3H\hat\rho = 0$$

$$\frac{\partial\hat\rho}{\partial t} + \frac{1}{a^2}\nabla\cdot\left(\hat\rho\vec v\right) + 3H\hat\rho = 0$$

$$\frac{\partial\vec v}{\partial t} + \frac{1}{a^2}\vec v\nabla\vec v + \frac{1}{a^3}\nabla\phi + \frac{\hbar^2}{2m^2}\nabla\left(\frac{\Box\sqrt{\hat\rho}}{\sqrt{\hat\rho}}\right) = 0,$$

Structure Formation

Abril Suarez and TM MNRAS 311, (2011), 87

$$\vec{v} \equiv \frac{\hbar}{m} \nabla S$$

$$\frac{\partial \hat{\rho}}{\partial t} + \frac{1}{a^2} \nabla \cdot (\hat{\rho} \vec{v}) + 3H \hat{\rho} = 0$$

$$\frac{\partial \vec{v}}{\partial t} + \frac{1}{a^2} \vec{v} \nabla \cdot \vec{v} + \nabla \phi + \frac{\hbar^2}{2m^2} \nabla \left(\frac{\Box \sqrt{\hat{\rho}}}{\sqrt{\hat{\rho}}} \right) = 0,$$

Structure Formation

Abril Suarez and TM MNRAS 311, (2011), 87

$$\begin{aligned}\hat\rho &= \hat\rho_0 + \rho_1(t)\exp(i\vec{k}\cdot\vec{x}/a)\\ \vec{v} &= \vec{v}_0 + \vec{v}_1(t)\exp(i\vec{k}\cdot\vec{x}/a)\\ \phi &= \phi_0 + \phi_1(t)\exp(i\vec{k}\cdot\vec{x}/a)\end{aligned}$$

$$\vec{v}_1 = \lambda\vec{k} + \vec{v}_2$$

$$\begin{aligned}\frac{\partial\rho_1}{\partial t} + 3H\rho_1 + i\frac{\hat\rho_0}{a^2}k^2\lambda &= 0\\ \frac{\partial\lambda}{\partial t} + i\left(\frac{v_q^2}{\hat\rho_0} - 4\pi G\frac{a^2}{k^2}\right)\rho_1 &= 0,\end{aligned}$$

$$\delta = \frac{\rho_1}{\hat\rho}$$

SFDM

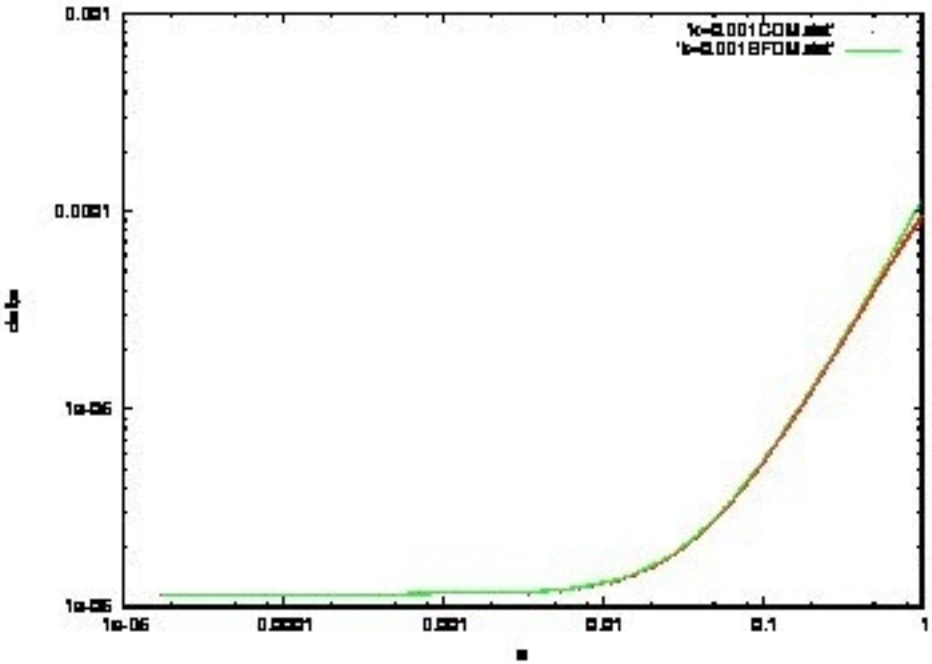
$$\frac{d^2\delta}{dt^2} + 2\,H\frac{d\delta}{dt} + \left(v_q^2\frac{k^2}{a^2} - 4\pi G\hat\rho_0\right)\delta = 0, \qquad v_q^2 = \frac{\hbar^2k^2}{4a^2m^2}$$

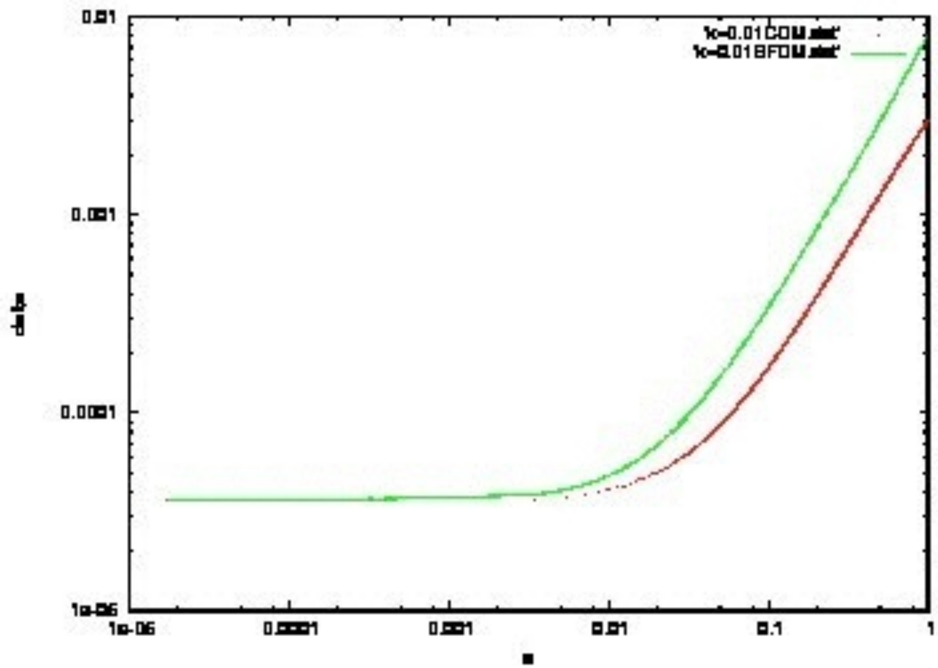
CDM

$$\frac{d^2\delta}{dt^2} + 2\,H\frac{d\delta}{dt} + \left(v_s^2\frac{k^2}{a^2} - 4\pi G\hat\rho_0\right)\delta = 0,$$

Structure Formation

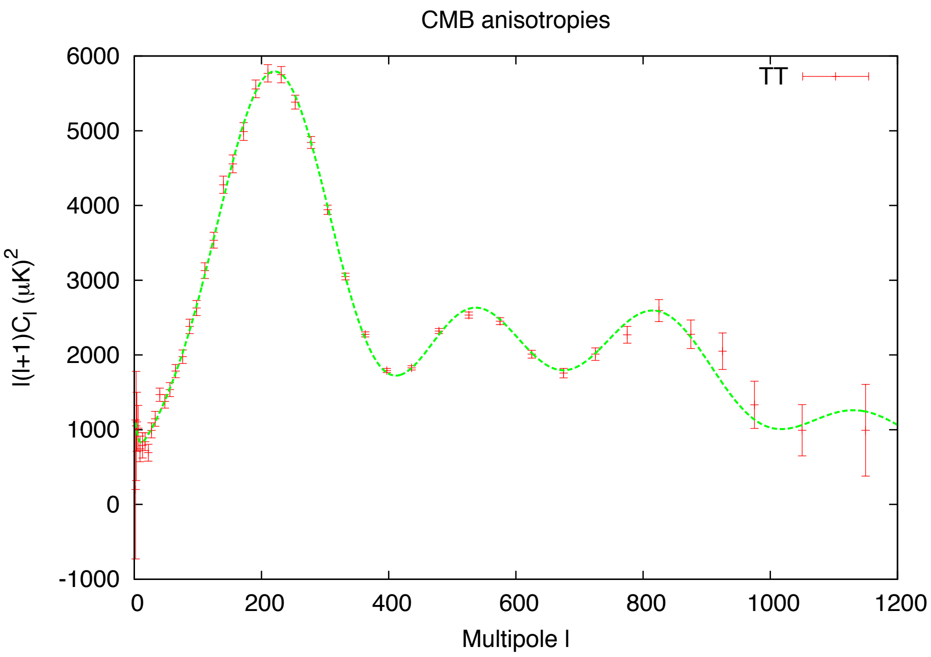
Abril Suarez and TM MNRAS 311, (2011), 87

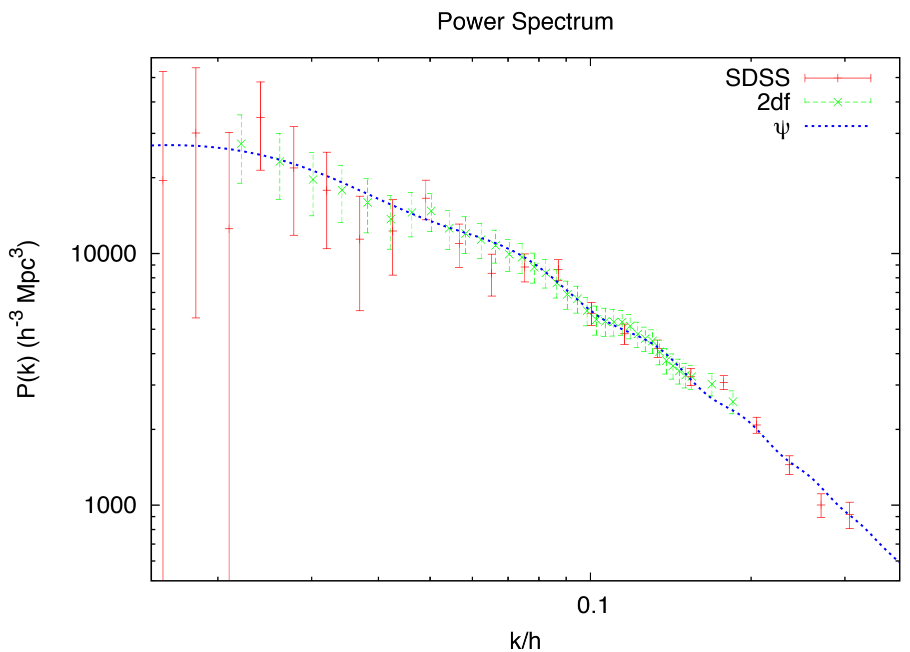




The Cosmology

I. Rodriguez, A. Pérez-Lorenzana, E. de la Cruz, Y. Giraud-Héraud and TM. Bosonic Cosmic Dark Matter. arXiv:1110.2751





Scalar Field Fluctuation = Halo

M.Alcubierre, F. S. Guzmán, T. Matos, D. Núñez, L. A. Ureña and P. Wiederhold.
Galactic Collapse of Scalar Field Dark Matter. CQG 19(2002)5017. arXiv:gr-qc /0110102.

Pau Amaro-Seoane, Juan Barranco, Argelia Bernal and Luciano Rezzolla.
Constraining scalar fields with stellar kinematics and collisional dark matter. JCAP11 (2010)002

J. Balakrishna, E. Seidel and W. Suen. PRD 58(1998)104004

$m \sim 1\text{eV} \Rightarrow \lambda = 1 \times 10^{-6}$

$$M \sim 0.06\sqrt{\lambda}\,\frac{m_{pl}^3}{m^2} \qquad T_c = \frac{2m}{\sqrt{\lambda}}$$

$$M \sim 10^{14}\,M_\odot \qquad T_c \sim 2000\,eV$$

Axions vs SFDM

Barranco and Bernal, PRD 83,(2011)043525

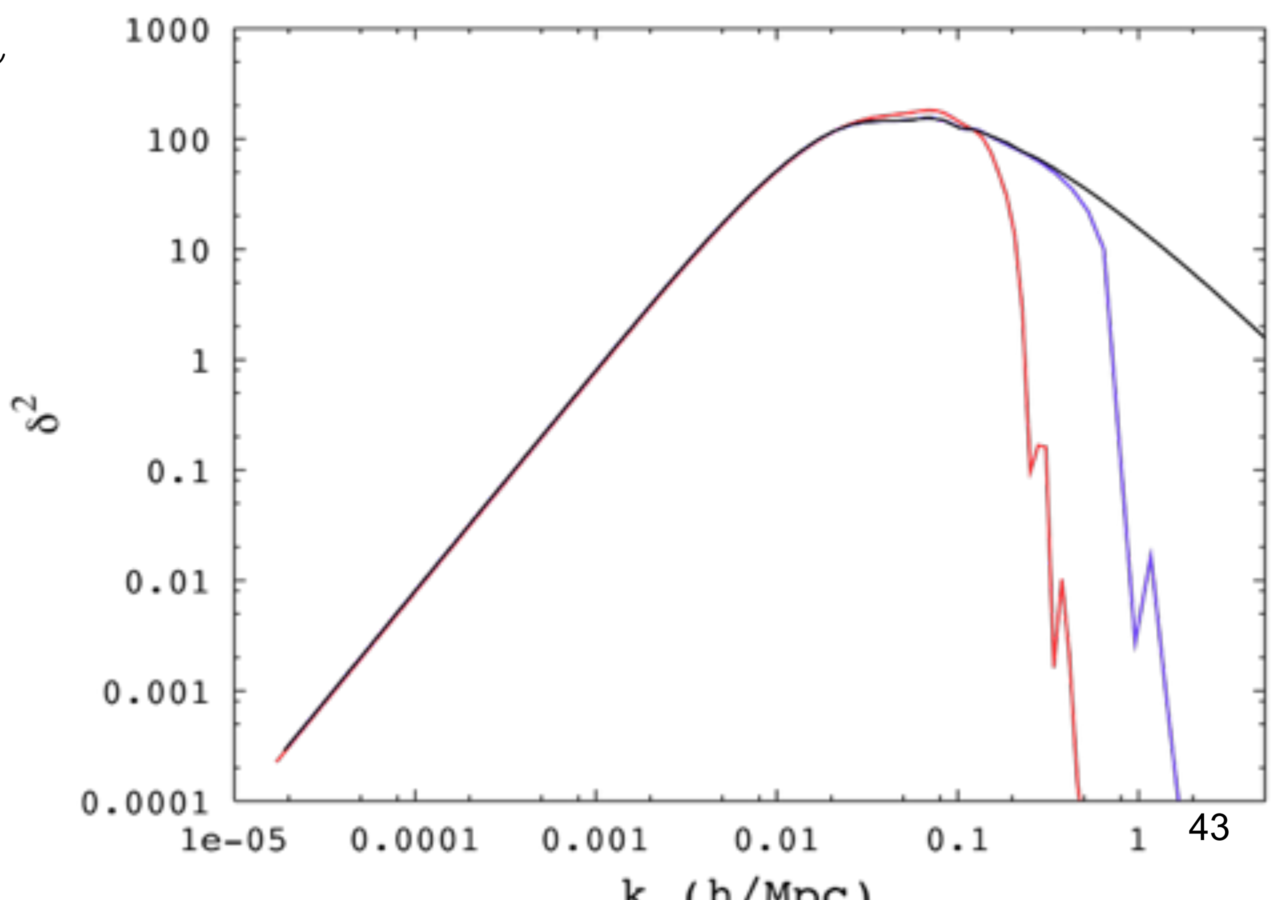
Natural Cut off

Tonatiuh Matos and Luis A. Ureña. Phys Rev. D63, (2001), 063506. Available at: astro-ph/ 0006024

$$\delta\ddot{\Phi}_k + 3H\delta\dot{\Phi}_k + \left(\frac{k^2}{a^2} + V_{,\Phi\Phi}\right)\delta\Phi_k - 4\dot{\Phi}_0\dot{\phi}_k + 2V_{,\Phi}\phi_k = 0 \quad m^2\left(\frac{k^2}{m^2a^2} - 1 + \frac{\lambda}{4}\Phi^2 + \frac{T^2}{T_c^2}\right)$$

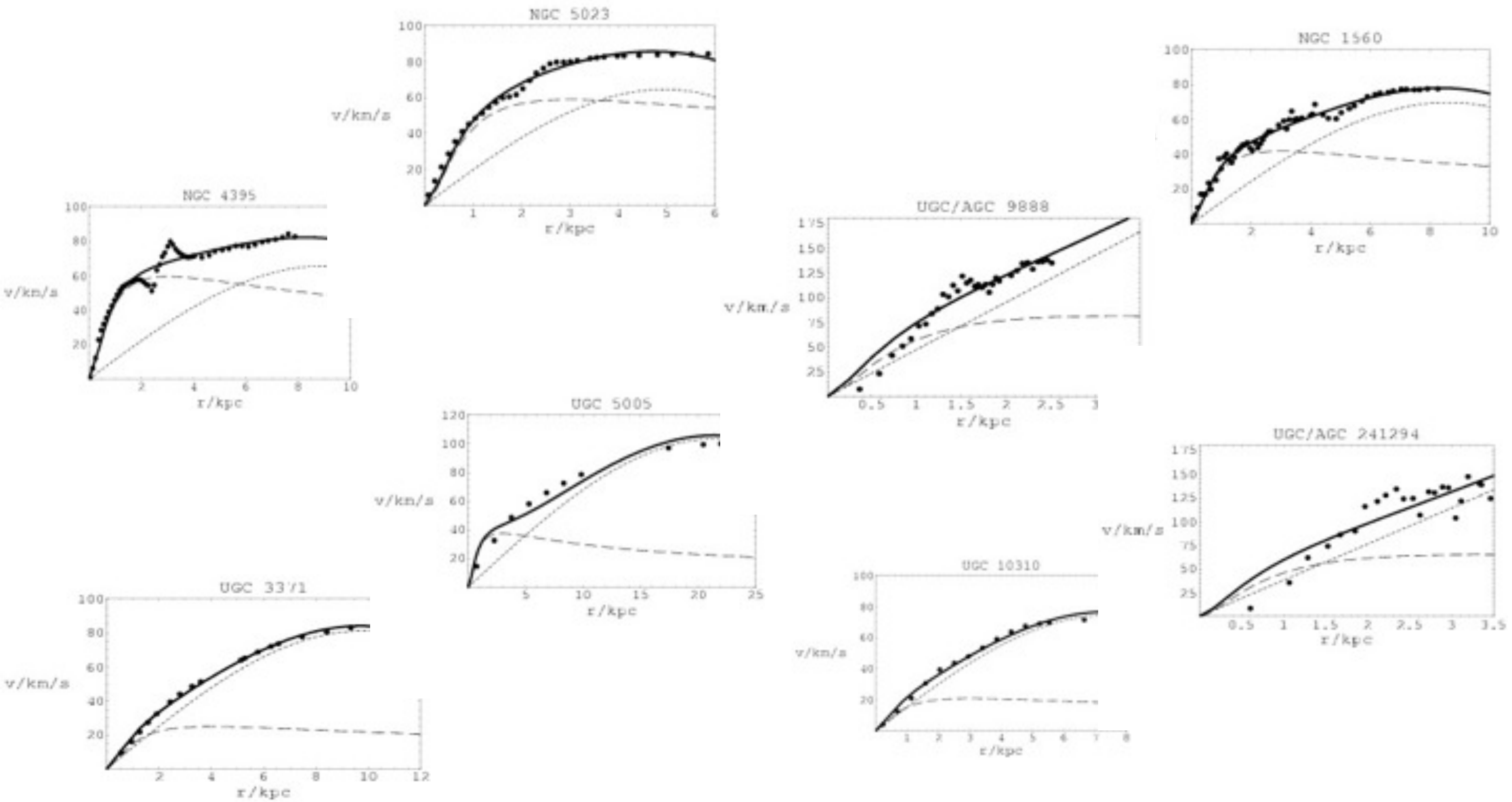
In Φ_{min}

$T << T_c$



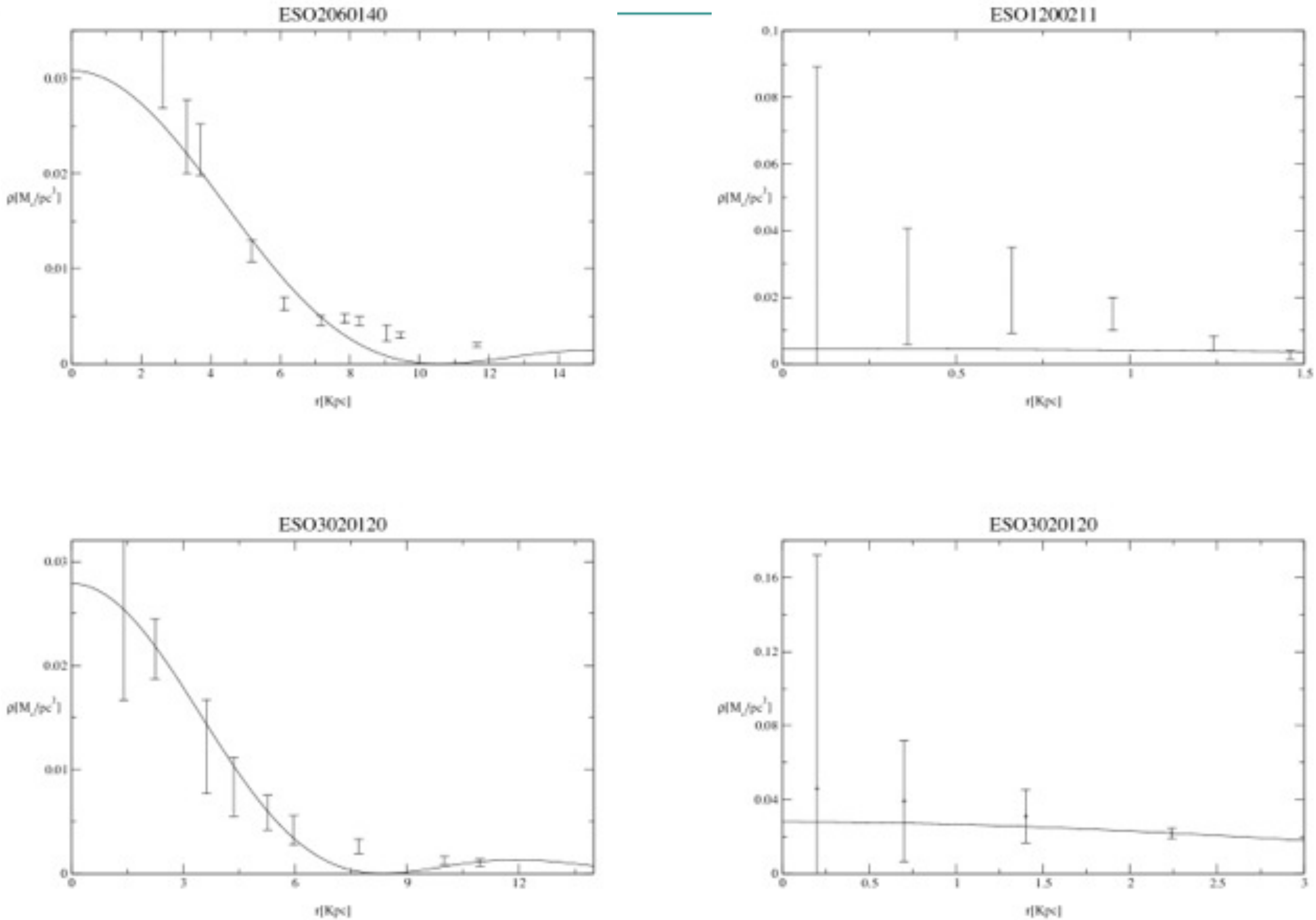
Galaxy Formation

T. Harko & C. G. Bhömer JCAP 0706:025,(2007) arXiv:0705.4158



Galaxy Formation

A. Bernal, TM, D. Nuñez. Rev. Mex. A.A. 44, (2008), 149-160



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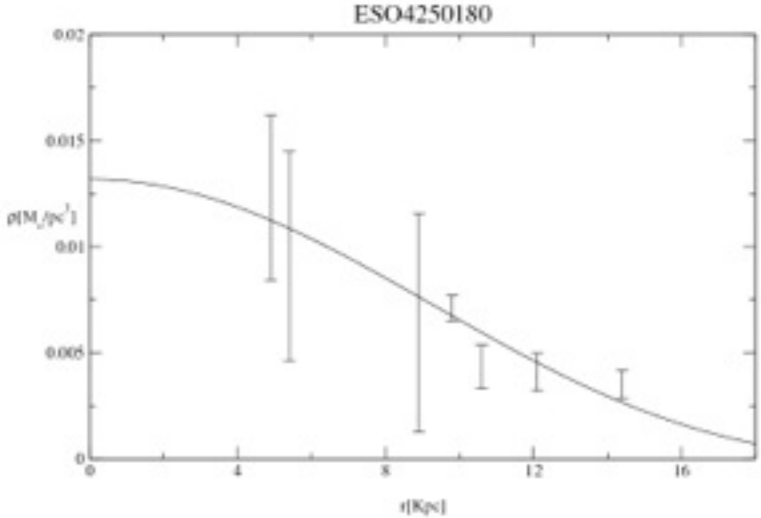
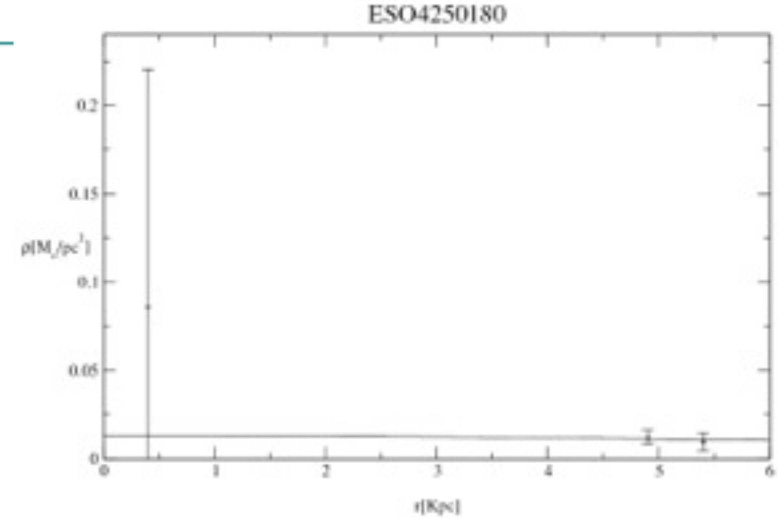
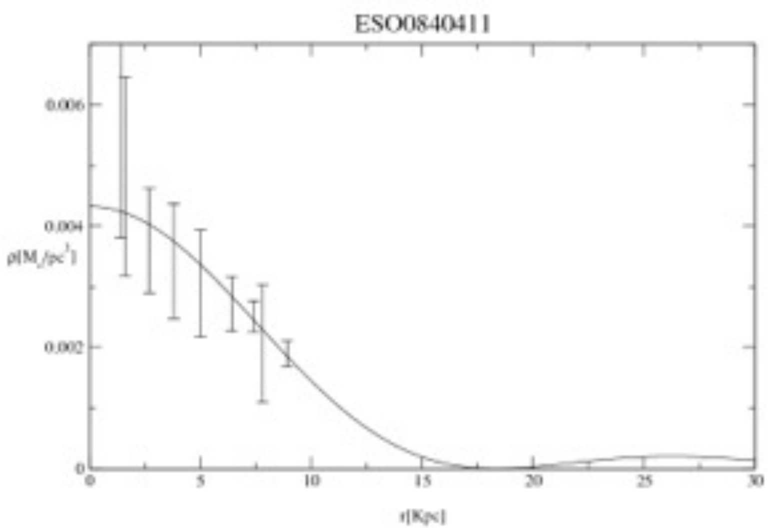
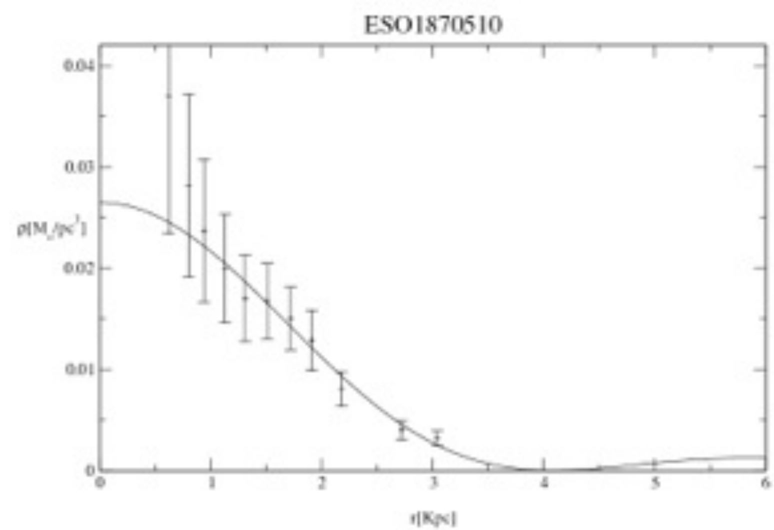


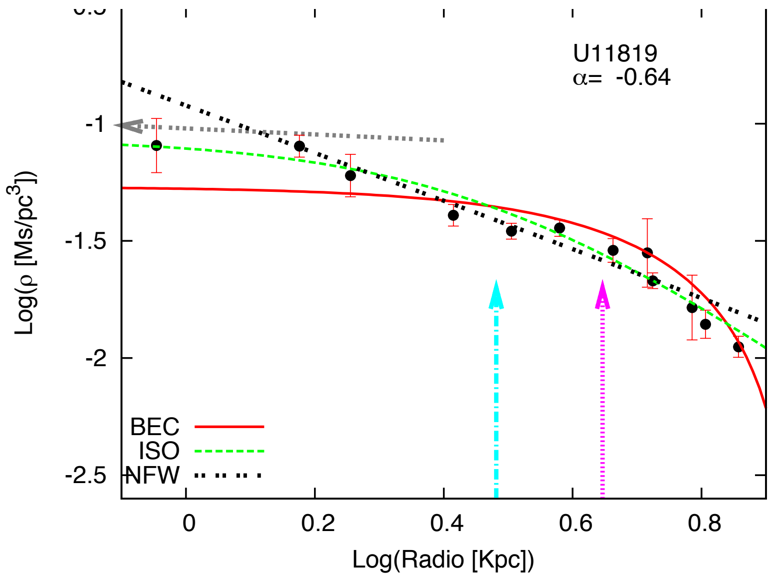


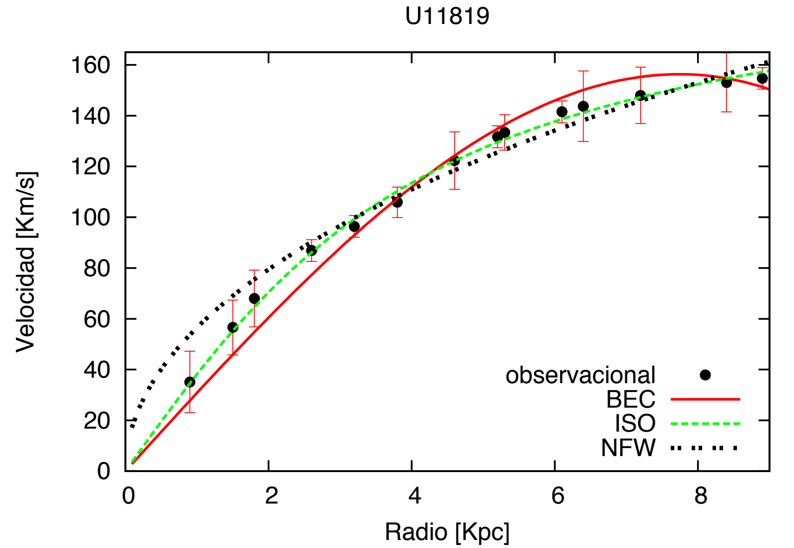


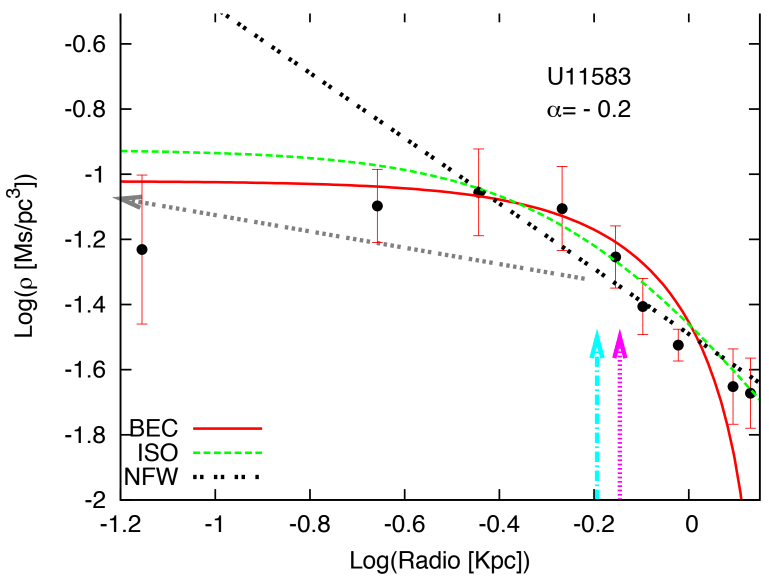


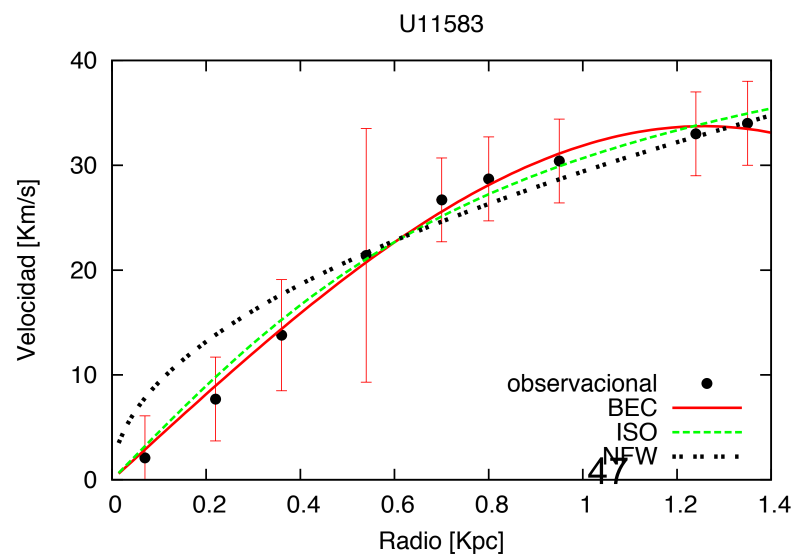
Galaxy Formation

V. H. Robles and TM. MNRAS 392, (2012) in press. arXiv:1201.3032









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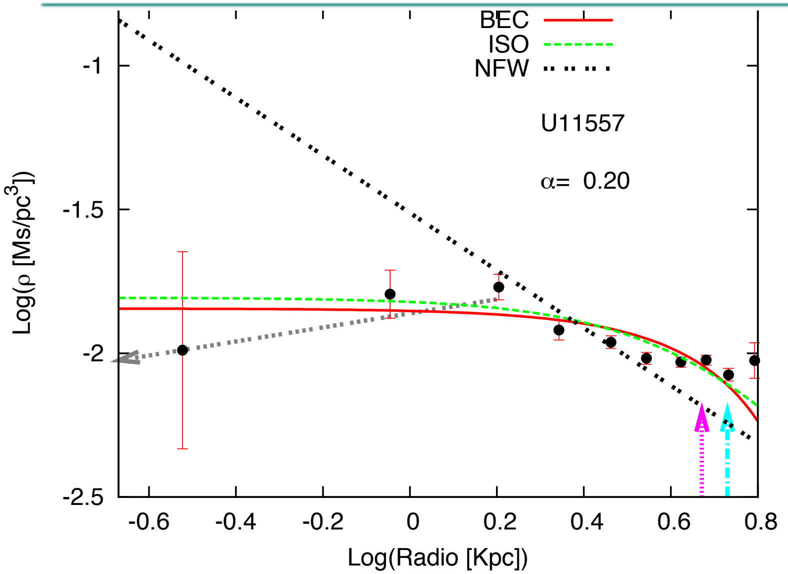

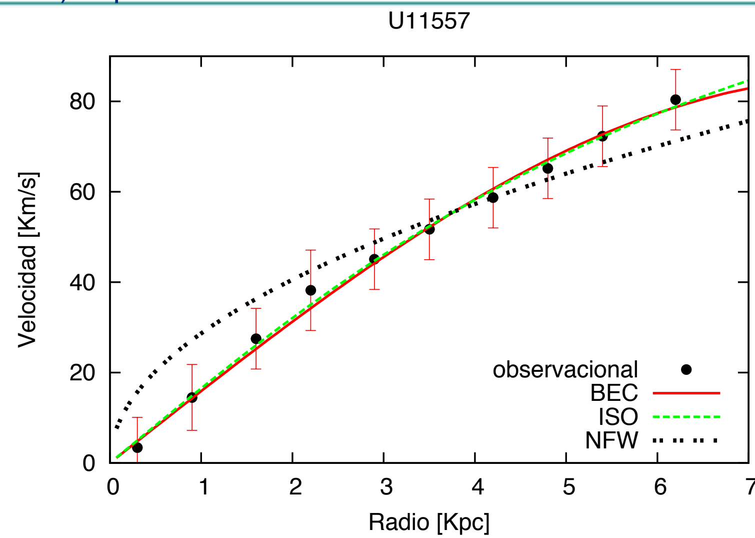

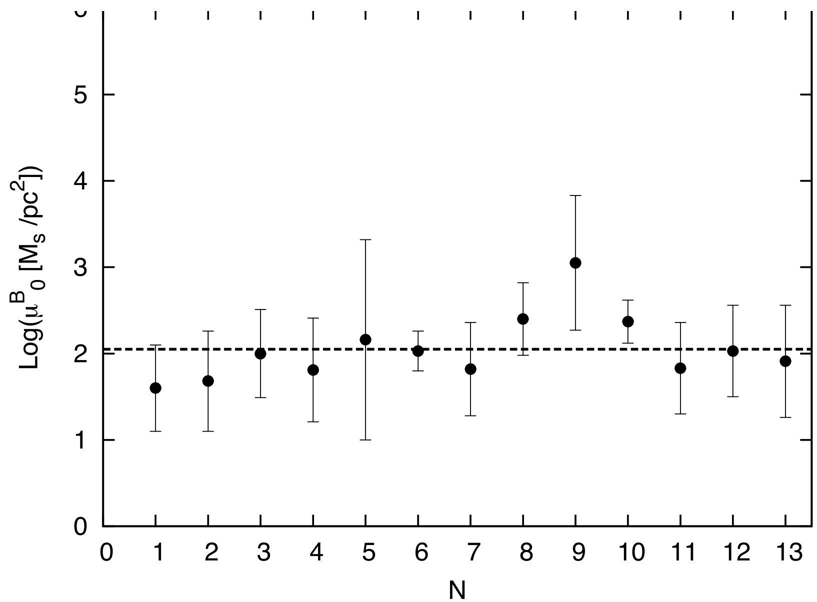

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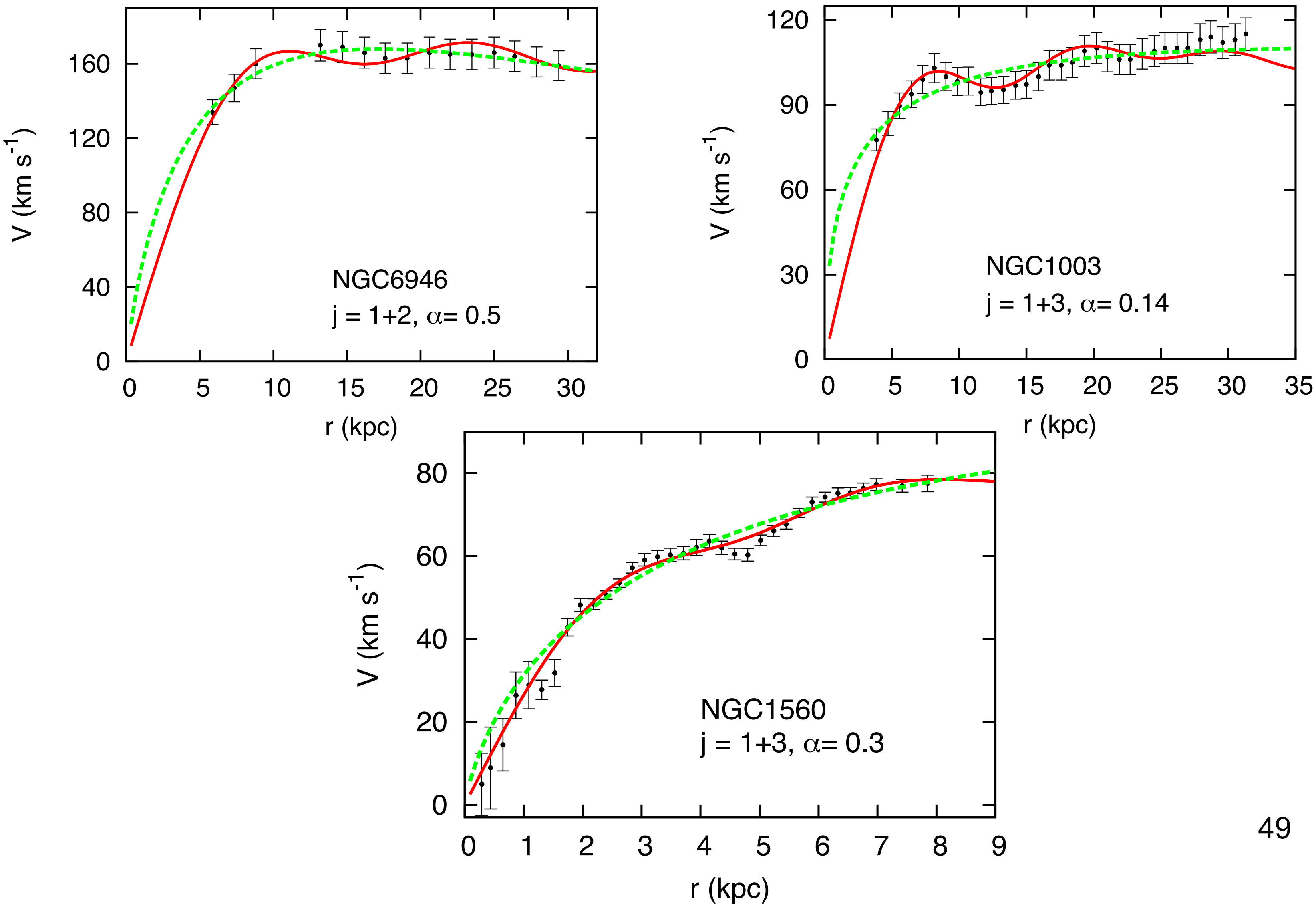
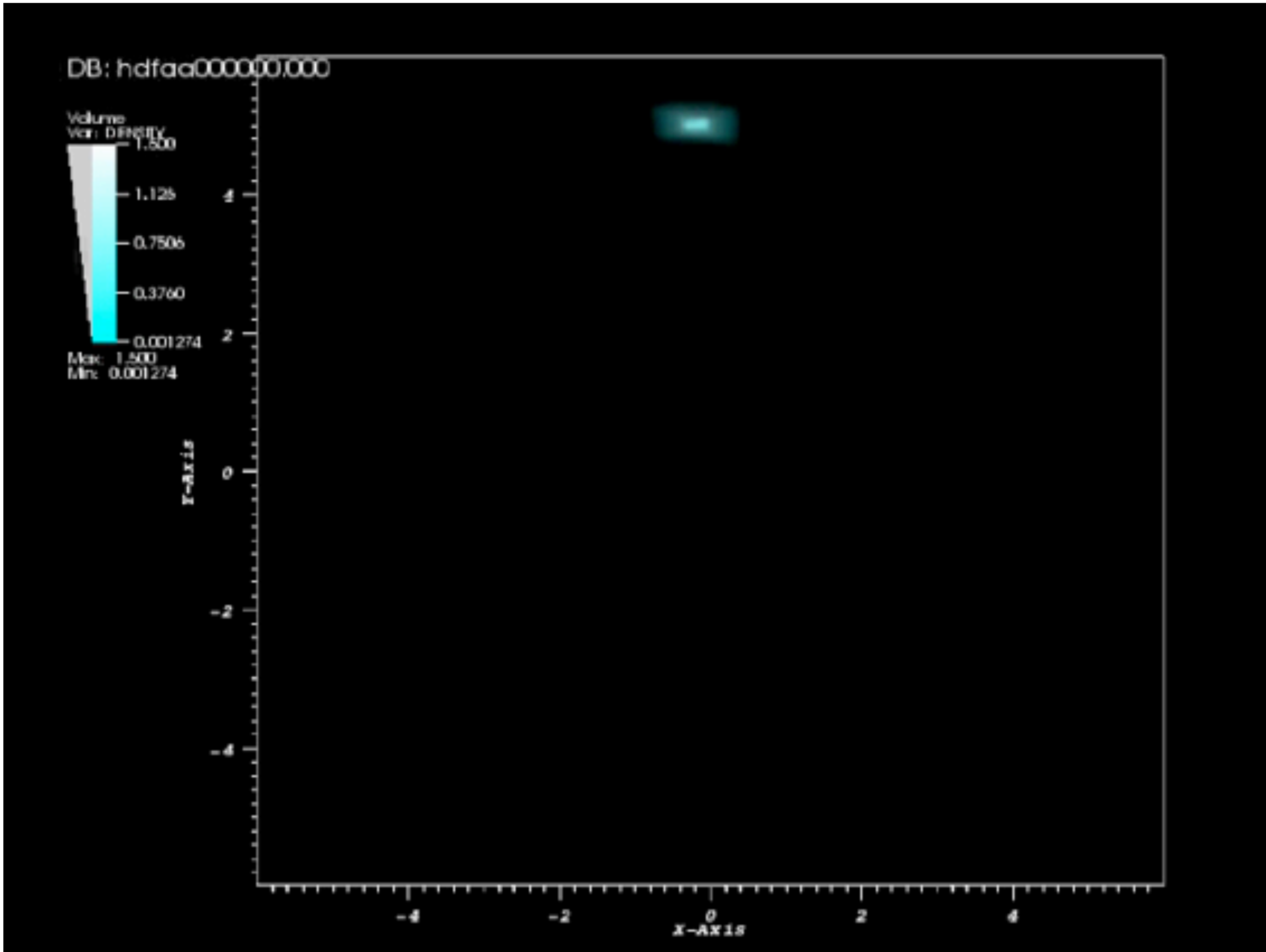


Scalar Field Fluctuation = Halo

Luis A. Medina and Tonatiuh Matos. MNRAS (2014) in press



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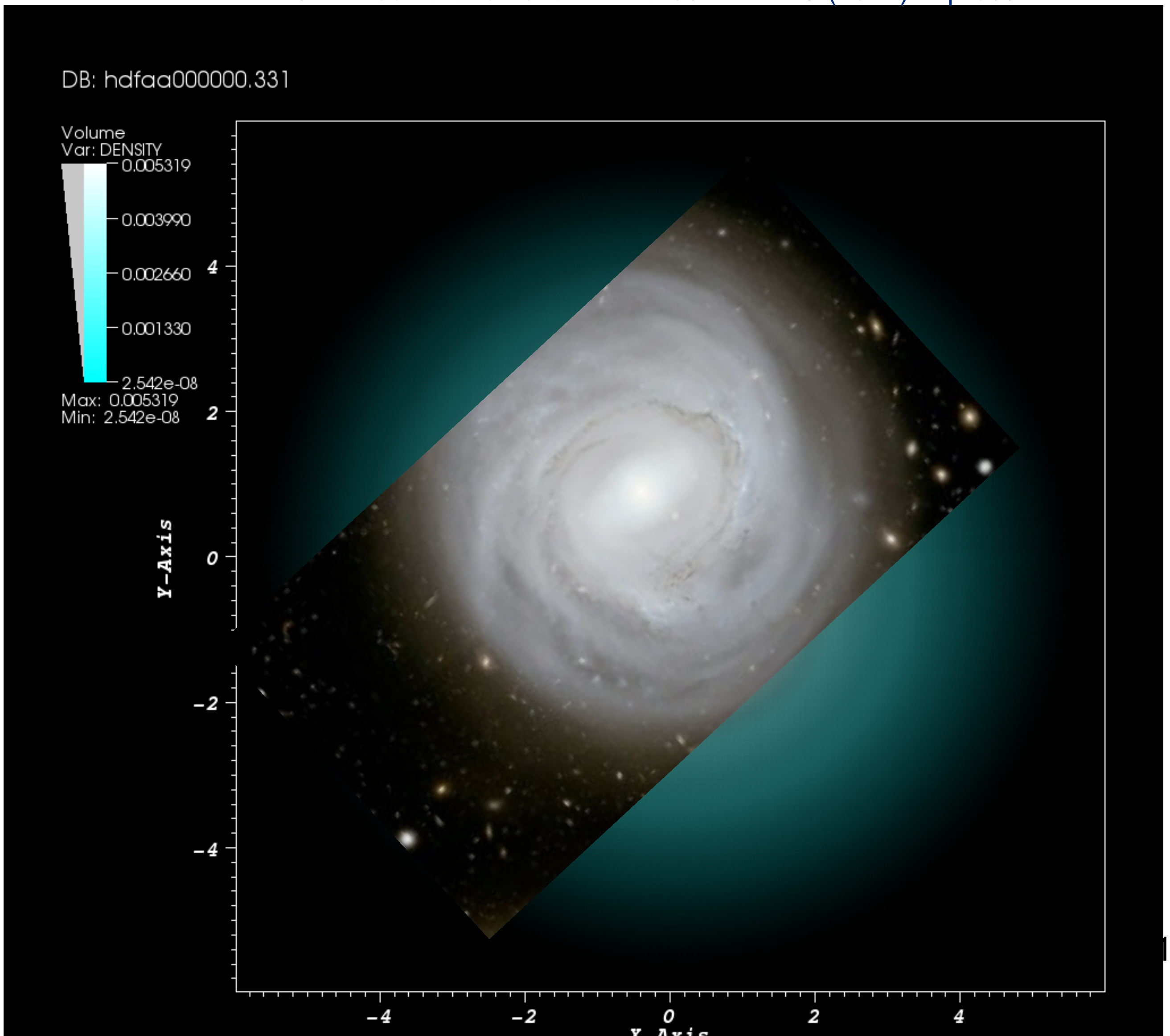

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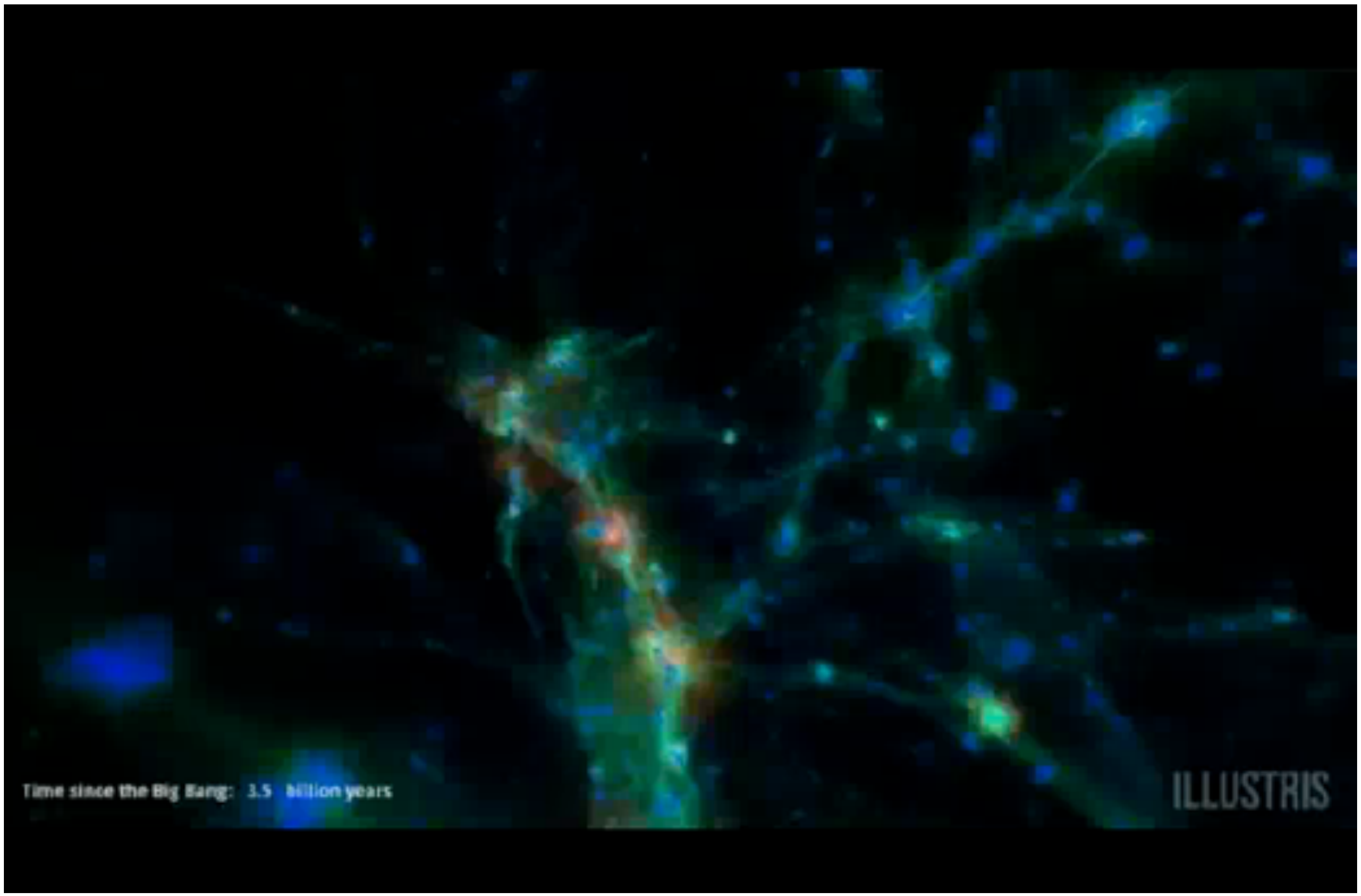
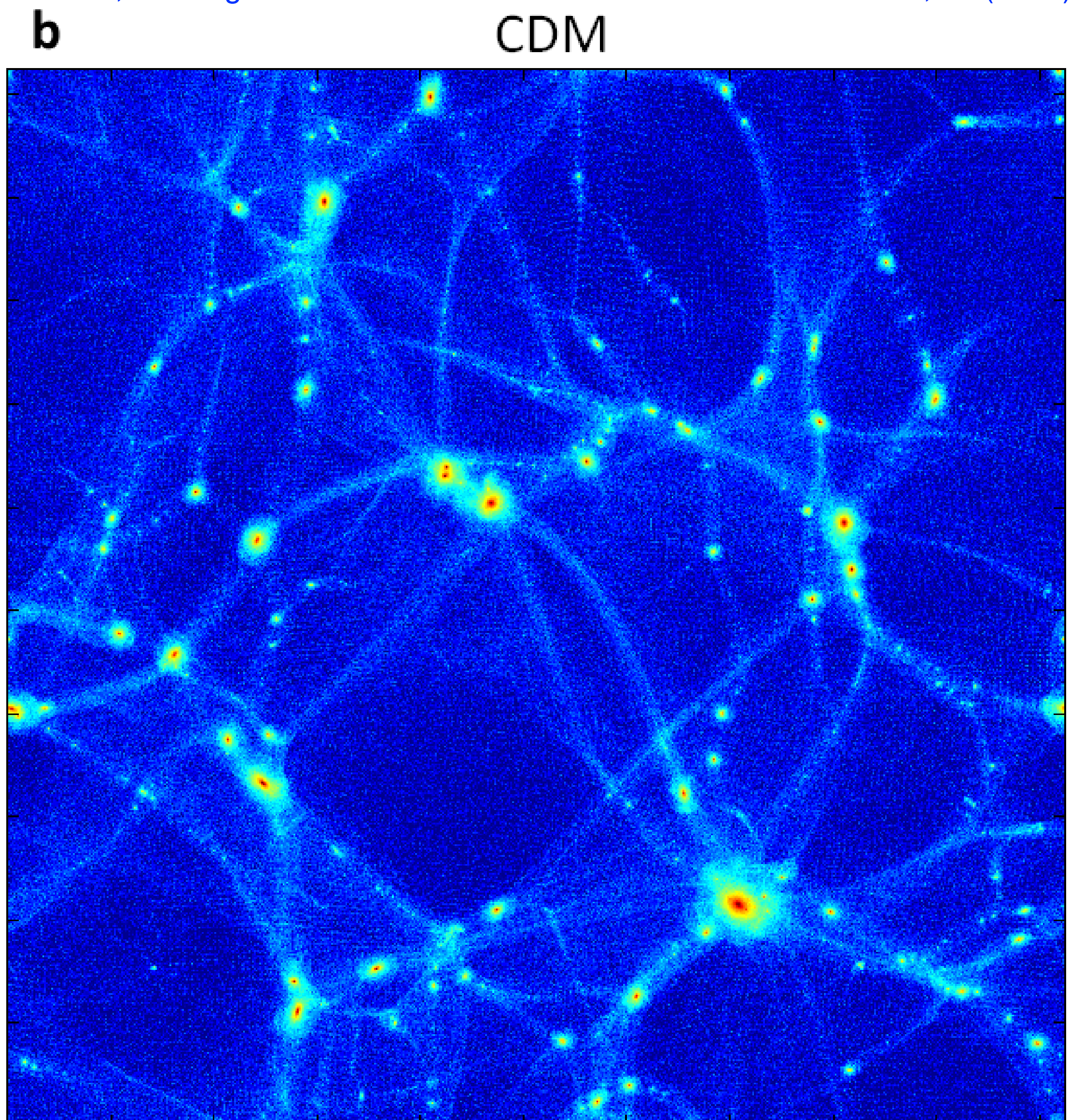


Numerical Simulations

Hsi-Yu Schive, Tzihong Chiueh and Tom Broadhurst. NATURE PHYSICS, 10 (2014), 246



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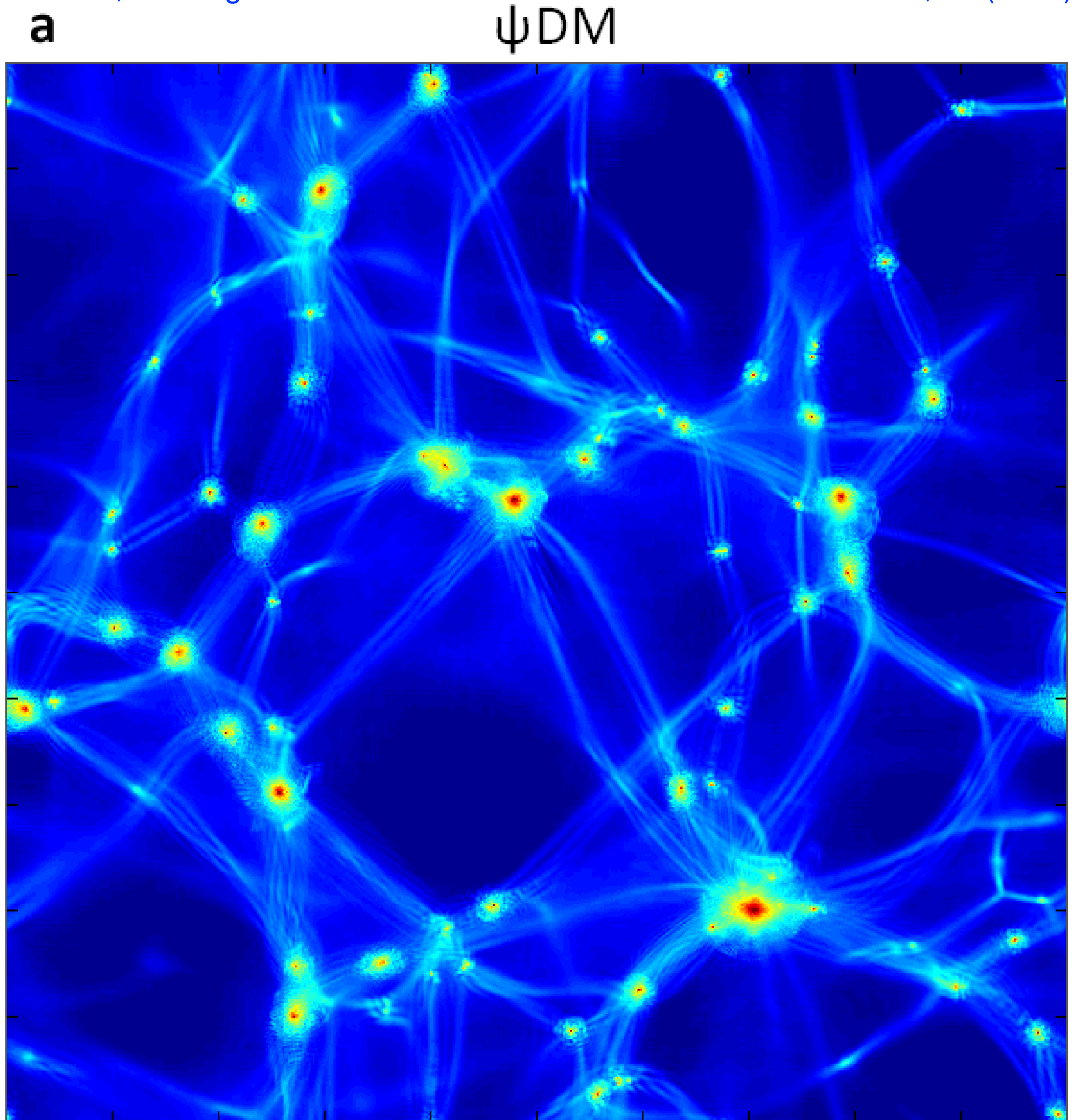
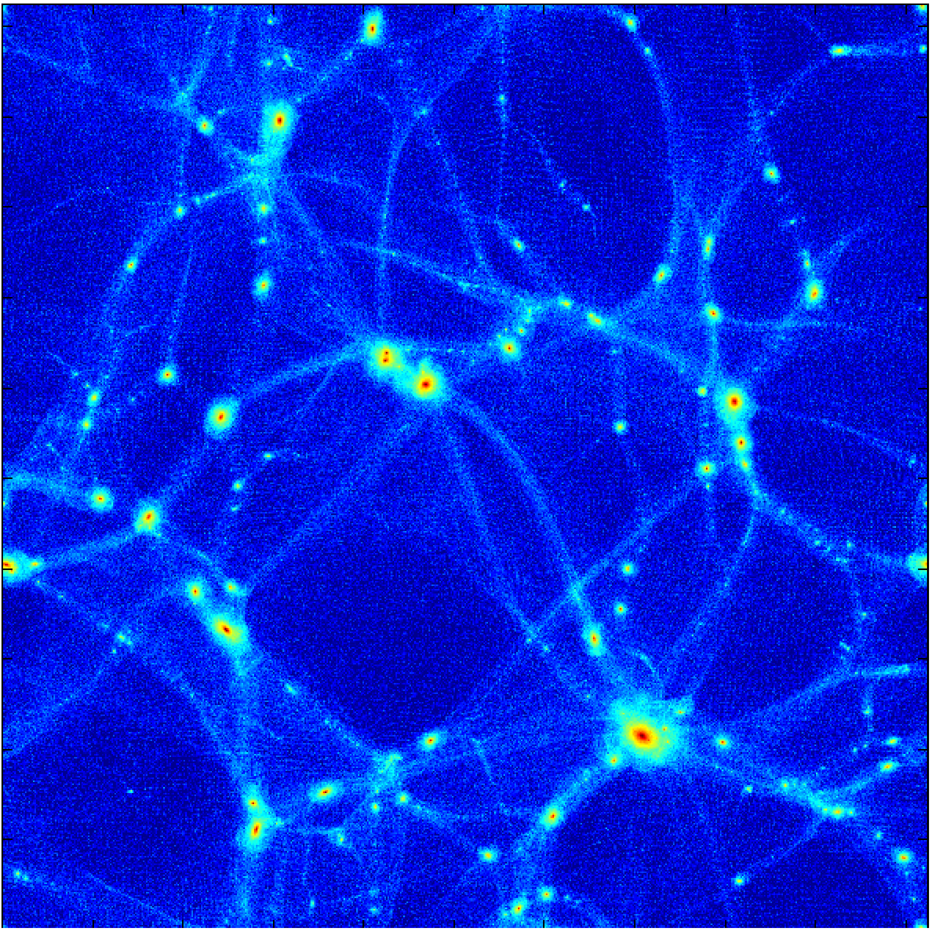


Numerical Simulations

Hsi-Yu Schive, Tzihong Chiueh and Tom Broadhurst. NATURE PHYSICS, 10 (2014), 246

b CDM



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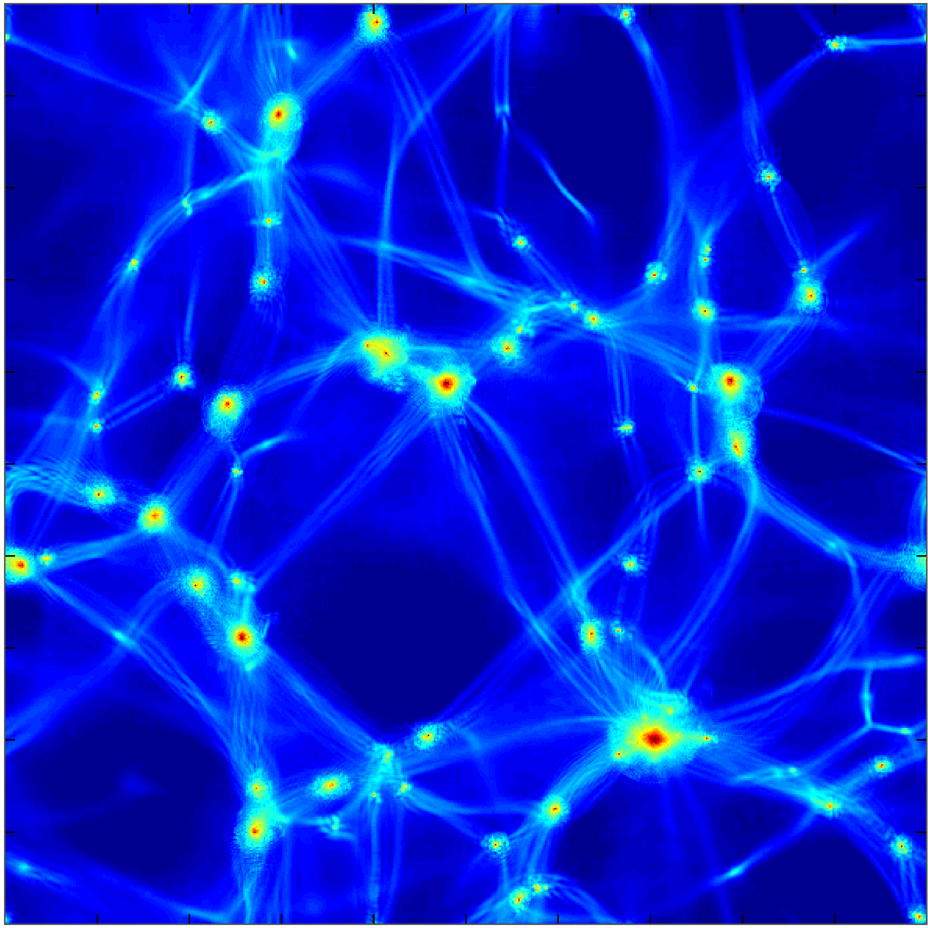

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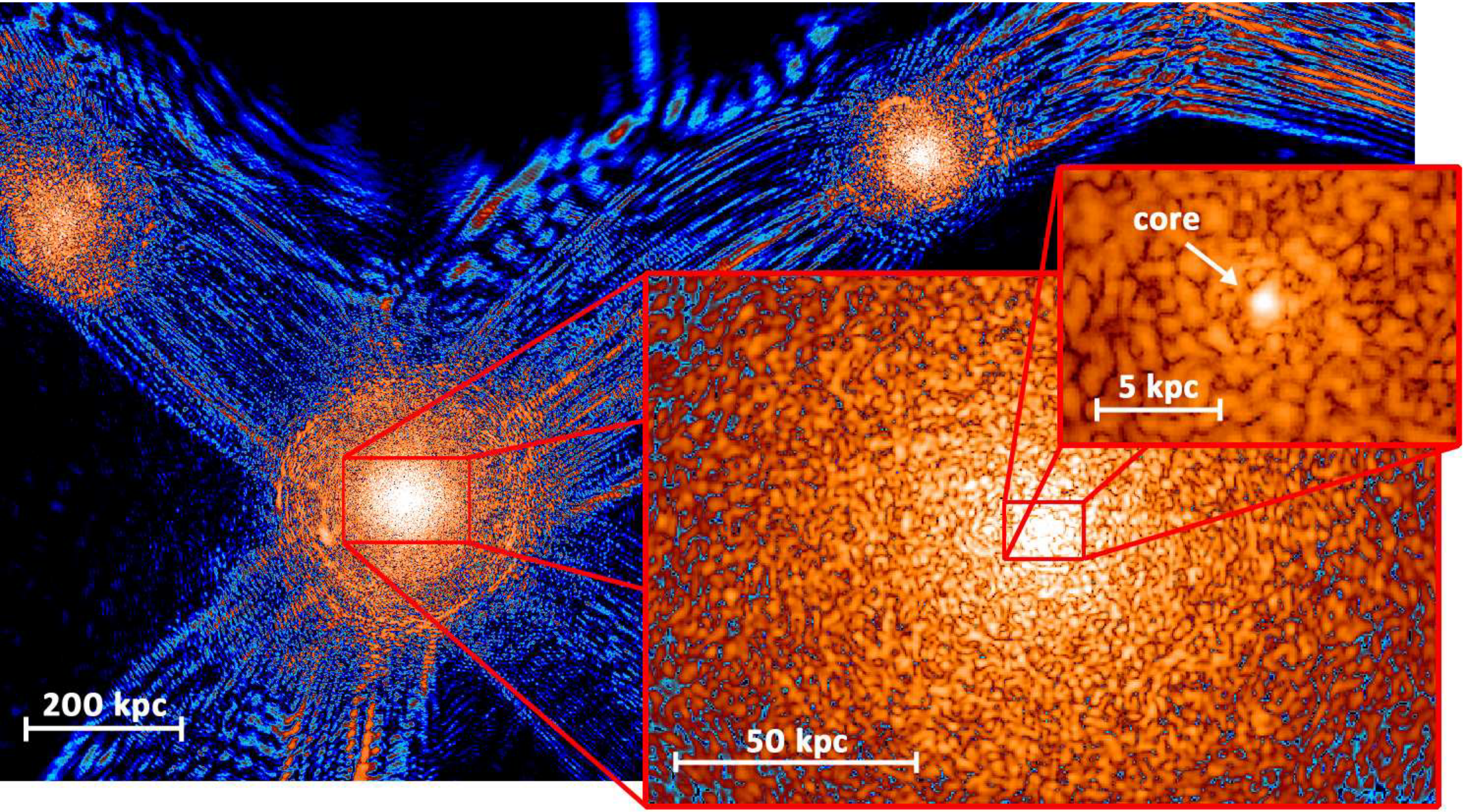

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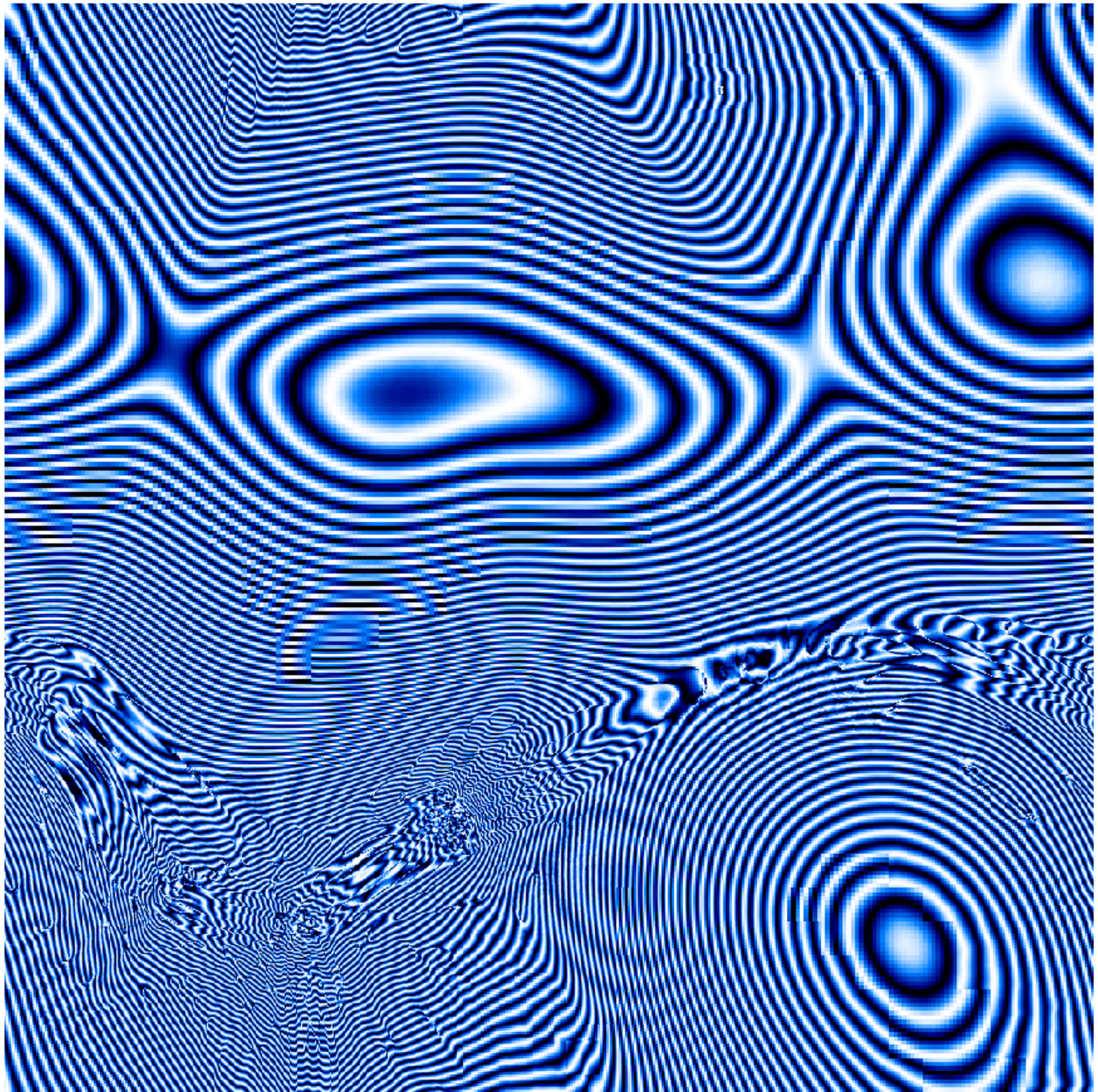

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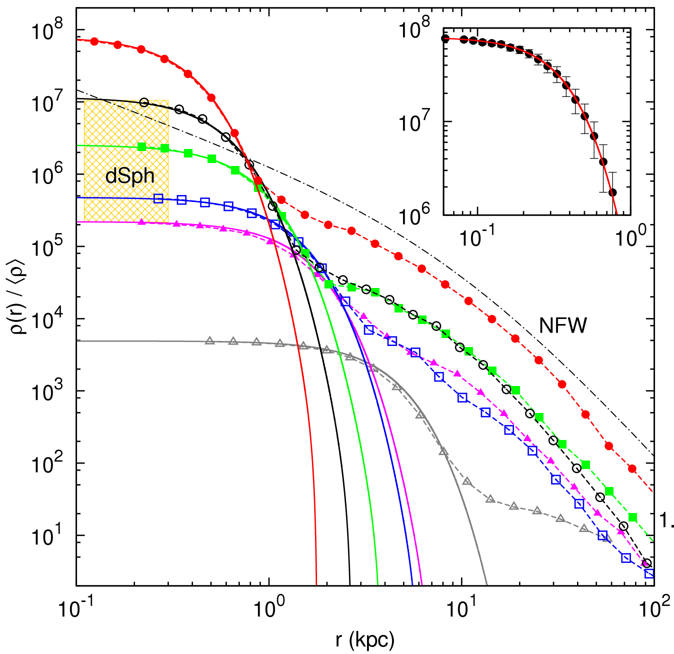

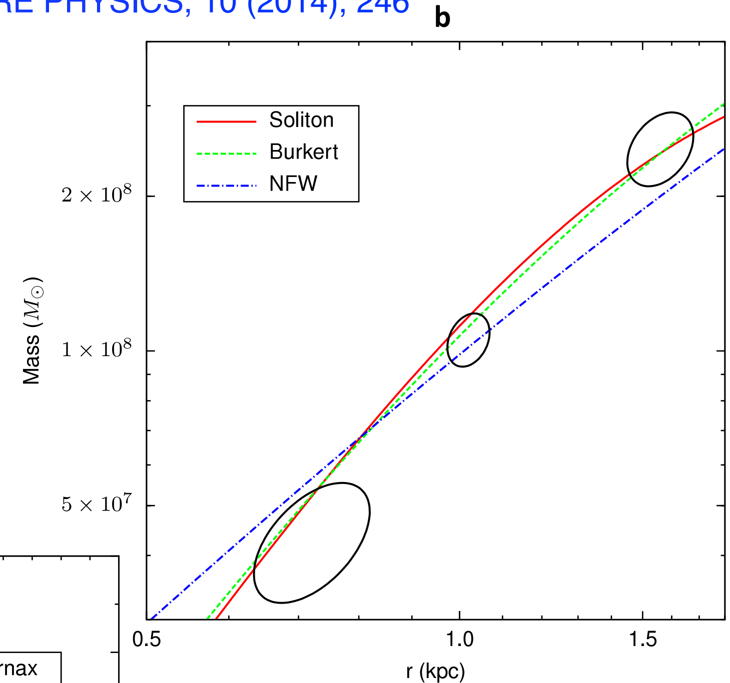

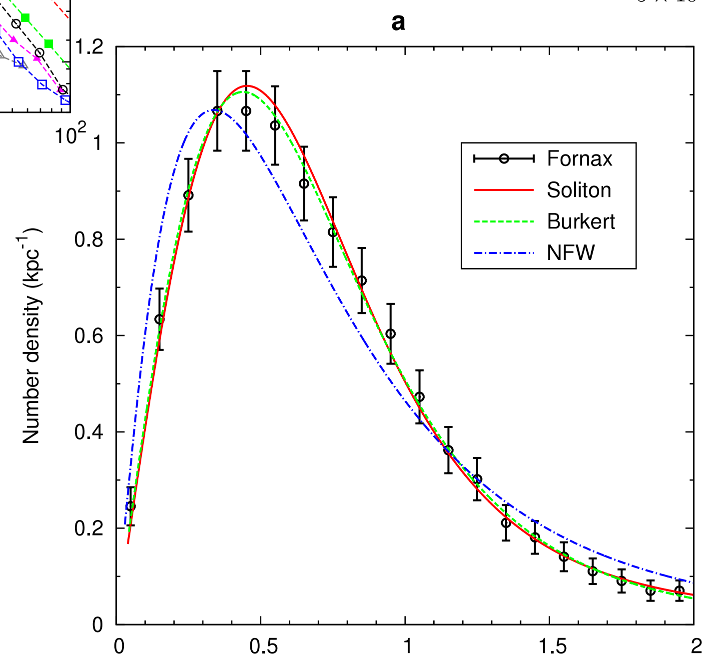

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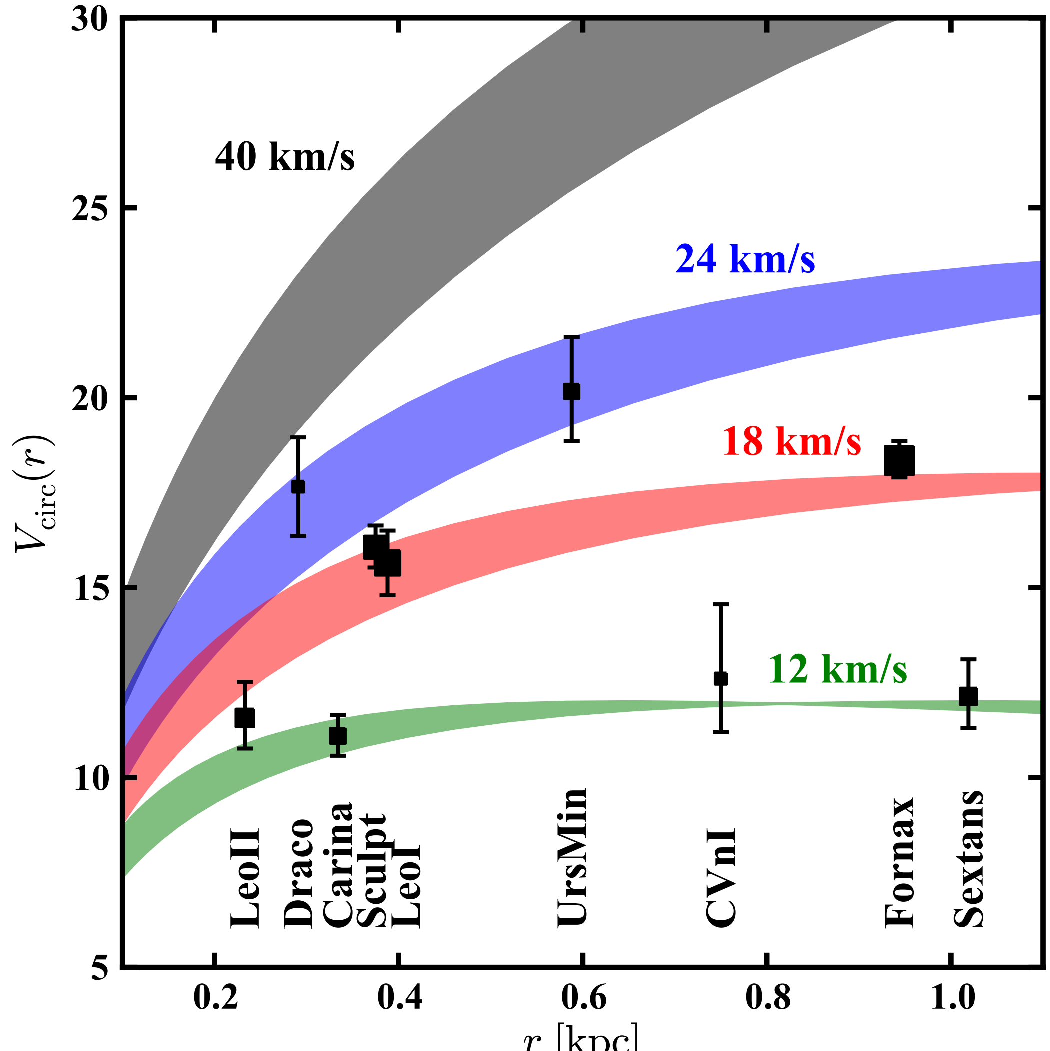
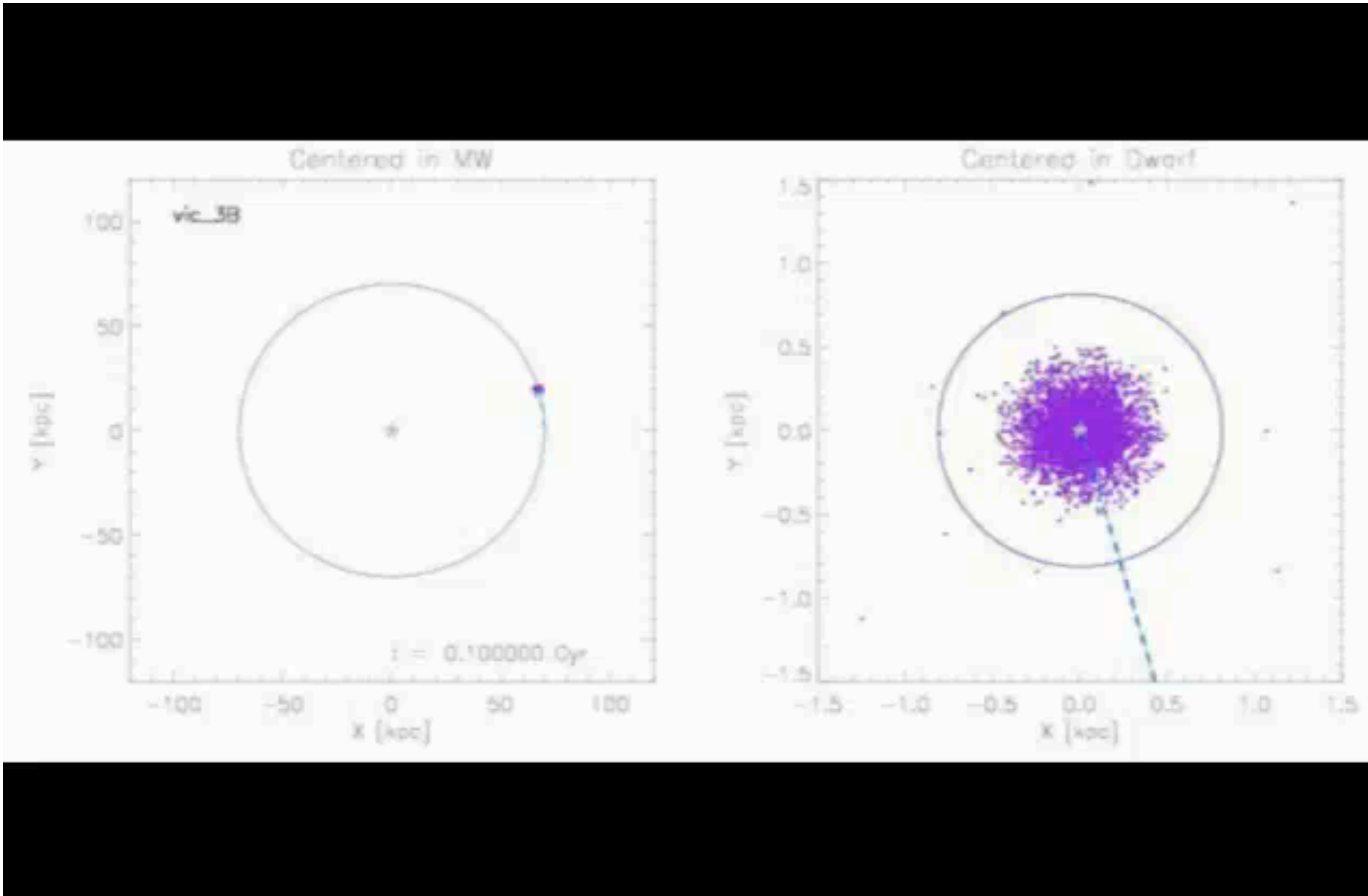

40 km/s
24 km/s
18 km/s
12 km/s
LeoII
Draco
Carina
Sculpt
LeoI
UrsMin
CVnI
Fornax
Sextans
$V_{\rm circ}(r)$
r [kpc]
30
25
20
15
10
5
0.2
0.4
0.6
0.8
1.0

Galactic Dynamics

Victor H. Robles, V. Lora, T. Matos & F. J. Sánchez-Salcedo arXiv:1404.3424



SFDM

Abril Suarez, Victor H. Robles, Tonatiuh Matos . A Review on the Scalar Field/ Bose-Einstein Condensate Dark Matter Model
Astrophysics and Space Science Proceedings 38, Chapter 9 (2013) arXiv:1302.0903

Behaves like dust at cosmological lebel → Same predictions for CMB and MPS

Clusters form by hierarchy → Same predictions for structure formation

Galaxies form by condensation of the SF → Galaxies haloes form erlier and are similar

Haloes are BEC drops → Galaxies are core

MPS has a natural cut off → Substructure is restricted

Conclusion

- Scalar Field Dark Matter or Ultra light Boson particles are alternative candidates to be the Dark Matter of the Universe

Conclusion

- We are in the threshold for a new era in Cosmology, Science and Thought