Astronomy in Focus
XXXIInd IAU General Assembly, August 2024
Diana M. Worrall, ed.
doi:10.1017/S1743921324002989

Dark matter cusps & cores

Kyle A. Oman

Institute for Computational Cosmology & Centre for Extragalactic Astronomy, Physics Department, Durham University, South Road, Durham DH1 3LE, United Kingdom
email: kyle.a.oman@durham.ac.uk

Abstract. The cusp-core problem is a long-standing tension between the prediction of the simplest cold dark matter simulations that galaxies have a dense central dark matter cusp and the observational inference that many, especially low-mass galaxies, have low-density cores. I review the problem and offer perspectives on how we might solve it. I argue that of the four possible resolutions of the problem, one stands out: systematic uncertainties in models of the gas kinematics of low-mass galaxies give us an inaccurate inference on the central dark matter densities in these objects. This does not rule out the possible need to invoke a modification to gravity, dark matter physics, galaxy formation theory, or a combination thereof. Current observational evidence is unlikely to support a scenario where all galaxies host dense dark matter cusps, but the scatter in central dark matter densities is plausibly much less than it suggests.

Keywords. dark matter, galaxies

These proceedings are closely based on a transcript of the corresponding presentation.

1. The origins of the cusp-core problem

Simulations predict that dark matter halos have central cusps – the density rises steeply towards the centre, as first shown by Dubinski and Carlberg (1991). Their fig. 2 shows the dark matter density as a function of radius fit with a Hernquist profile that rises as far towards the centre as could be resolved at the time. Rotation curves are an observational tracer of the dynamical mass in galaxies. There is an important distinction between a rotation curve – the actual orbital speed of a tracer – and a circular velocity curve – the speed that a particle would have on a circular orbit in a spherically symmetric potential with a given mass profile. Two papers started the cusp-core debate: Flores and Primack (1994, see their fig. 1) and (Moore 1994, see their fig. 1). The four galaxies in the Moore (1994) figure are shown with the same Hernquist profile that was fit by Dubinski and Carlberg (1991). It doesn't follow the rotation curves measured (but interpreted as circular velocity curves) for these galaxies.

There are four possible escapes from the cusp-core problem. First, dark matter can be redistributed via dark matter physics. For example the dark matter could have a scattering interaction that imposes a density maximum near the centre. This was already discussed in Moore (1994). Second, dark matter could be redistributed via baryonic physics. For example, gas that condenses and cools in a galaxy makes it contract. If supernovae then expel that gas, the change in the potential can expel dark matter from the centre. This process can be repeated to carve out a core. This was also proposed early (Flores and Primack 1994; Navarro et al. 1996). Third, it could be that Newtonian (or GR) is the wrong gravity theory. More than 10 years before the cusp-core debate began, the MOND theory (Milgrom 1983) was used to predict the rotation curves of galaxies. Finally, it could be that the rotation curves that we measure are not tracing

© The Author(s), 2026. Published by Cambridge University Press on behalf of The International Astronomical Union. This is an Open Access article, distributed under the terms of the Creative Commons Attribution licence (https://creativecommons.org/licenses/by/4.0/), which permits unrestricted re-use, distribution and reproduction, provided the original article is properly cited.

https://doi.org/10.1017/S1743921324002989 Published online by Cambridge University Press

the circular velocity curves and therefore the gravitational potentials of galaxies. This was also discussed early on (e.g. Moore 1994). These are all of the possible solutions to the problem and all have been known since the beginning, so why are we still stuck?

2. Current status and the diversity of dwarf galaxy rotation curves

There is a recent review by Sales et al. (2022). They present an interesting perspective: in their view the classical cusp-core problem is basically solved because we know a way to make dark matter cores through supernova-driven gas flows (see also Navarro et al. 1996; Gelato and Sommer-Larsen 1999; Read and Gilmore 2005; Mashchenko et al. 2008; Governato et al. 2012; Pontzen and Governato 2012; Teyssier et al. 2013; Di Cintio et al. 2014; Oñorbe et al. 2015; Chan et al. 2015; Tollet et al. 2016; Bose et al. 2019; Benítez-Llambay et al. 2019; Dutton et al. 2019, 2020; Jackson et al. 2024). The existence of a plausible physical mechanism for galaxies to form cores alleviates a lot of the tension between simulations and observations. This emphasizes that attention in the past few years has shifted from "can we explain how a core might exist in a galaxy" to "can we explain the apparent distribution of dark matter densities in the centres of galaxies". I led a study (Oman et al. 2015) where we showed that at fixed total mass there are galaxies with a wide range of central dark matter densities but otherwise broadly similar properties (see also Di Cintio et al. 2014; Brook 2015; Read et al. 2016; Pineda et al. 2017; Kamada et al. 2017; Santos-Santos et al. 2018; Ren et al. 2019; Fitts et al. 2019; Santos-Santos et al. 2020; Frosst et al. 2022; Jahn et al. 2023; Roper et al. 2023; Downing and Oman 2023; Sands et al. 2024; Muni et al. 2024). This could result from some connection to the galaxy formation histories, but I don't think that anyone has yet presented an entirely satisfactory explanation of this kind.

This idea of diversity in the population can be captured in a few different ways – one example is figs. 2 & 4 from Santos-Santos et al. (2020). In fig. 2 we show the maximum of the the rotation curve (loosely speaking a proxy for the total dynamical mass) on the x-axis. On the y-axis we show the rotation velocity at an inner radius (how big that radius is scales with the mass of the galaxy), which is a proxy for the central dynamical mass, or in other words how fast the rotation curve rises and the central density. The area between the two vertical lines is where we focused a lot of attention. Here there is a lot of scatter: galaxies that are otherwise broadly similar can seem to have anything from a very steep cusp to a large, completely flat core. The other figure (their fig. 4, reproduced in Fig. 1) takes the two axes of the first and compresses them onto the one axis ($\eta_{\rm rot}$), roughly capturing a continuum from cores to cusps. On the other axis is the square of the ratio of the rotation speed near the centre and the rotation speed that would be predicted from the central baryon density, $\eta_{\rm bar}$. This is roughly the central baryon fraction with respect to the the central total mass density. These are coloured by (the proxy for) total dynamical mass. An interesting correlation emerges: more centrally dense galaxies seems to have lower central baryon fractions (when focusing on the lower mass galaxies – the darker orange points). This turns out to be challenging to explain; reproducing this correlation is a strong test of theories.

So where do we stand? Of the four possible solutions to the cusp-core problem, I think that the first three are uncertain. The fourth I'm convinced plays a role: kinematic models and their interpretation are significantly affected by systematic errors and uncertainties. I give the three most egregious examples that I could think of below.

The first example is IC 2574. In fig. 6 of Oman et al. (2015, similar to fig. 2 in Santos-Santos et al. 2020) it is in the lower-right part of the galaxy distribution. The broken lines are labeled with masses; if that mass is removed from the centre of a galaxy with an initial cusp (solid black line), it moves to the corresponding broken line. Where the lines

https://doi.org/10.1017/S1743921324002989 Published online by Cambridge University Press

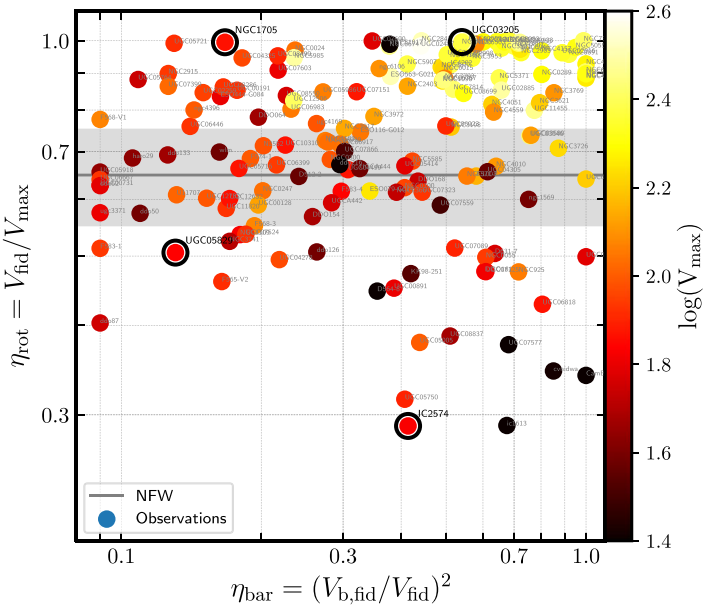


Figure 1. How steeply the rotation curve of a galaxy rises, parametrized as $\eta_{\rm rot}$, as a function of its central dark-to-total mass ratio, parametrized with $\eta_{\rm bar}$, coloured by total dynamical mass parametrized as $V_{\rm max}$, for a sample of galaxies compiled by Santos-Santos et al. (2020). Reproduced from Santos-Santos et al. (2020).

become vertical all of the mass has been removed from the centre. The most extreme outliers appear to have no mass left in their centres. The dark matter cores inferred in these galaxies are so large and low density that they are difficult to reproduce in any physical model. Is there instead a problem in the dynamical modeling?

The second example are gas-rich ultra-diffuse galaxies. Placed on the baryonic Tully-Fisher relation (McGaugh et al. 2000) that relates the total baryonic (stellar plus cold gas) mass on the y-axis to the circular velocity (a proxy for the total dynamical mass) on the x-axis, these are strong outliers (Mancera Piña et al. 2019, fig. 3) to the left of the main, tight relation. This work was led by P. Mancera-Piña while we were both in Groningen. I remember him coming to my office and saying "look at these". I immediately replied "you got the inclinations wrong". He convinced me otherwise and over the next years went through many other possible systematic issues. None offer a fully satisfying explanation. We have to assume (i) that these galaxies have a baryon fraction equal to or higher than the cosmic mean; (ii) a new cosmology; or (iii) that there are issues in the modeling of the data. Occam's razor points to the latter as the preferred interpretation.

The third example is IC 1613, another galaxy that appears to have less dark matter than expected given its baryonic mass based on its gas rotation curve, shown with the black points in fig. 3 in Oman et al. (2016). The circular velocity curve expected from something like an abundance matching prediction is shown with the red band. The blue point is a stellar dynamical mass measurement within a single aperture that doesn't agree with the gas, telling us that (at least) one of them is wrong. Forcing the gas and stellar kinematics to agree by adjusting the inclination of the gas disc makes the galaxy much more "normal", although it does still appear to have a large dark matter core.

These three examples of serious systematic issues affecting models of galaxies suggest very strongly that there could be more subtle issues in the modeling of other galaxies.

https://doi.org/10.1017/S1743921324002989 Published online by Cambridge University Press

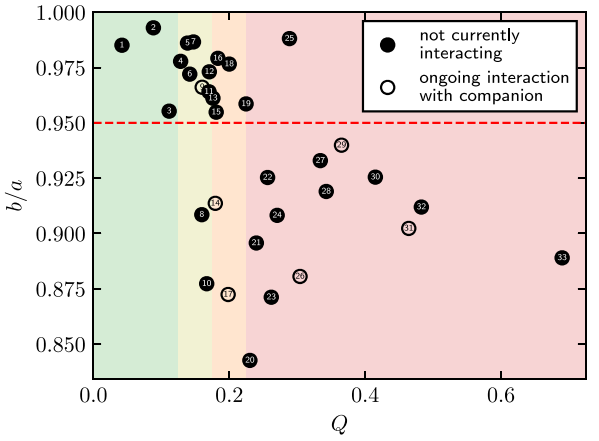


Figure 2. The intermediate-to-major axis ratio of the dark matter halo b/a is 1 when the dark matter halo is spherical/oblate (within an aperture similar to the size of the gas disc), and < 1 when it is prolate/triaxial. Q is a measure of how well the rotation curve traces the circular velocity curve, with lower Q corresponding to a better tracer. Reproduced from fig. 6 in Downing and Oman (2023).

3. Towards progress on the cusp-core problem

I find it helpful to break this question into two aspects. First, are we accurately recovering the dynamics of the gas (or stars) from the measurements? Second, there's a more pernicious question: do the dynamics actually trace the underlying potential, or are we looking at a galaxy that's out of equilibrium?

I think that the way to attack the question of whether the dynamics trace the potential is mostly from the the theory and simulations side. Two recent studies illustrate this approach. In Downing and Oman (2023) we looked at simulated dwarf galaxies and asked "how are these perturbed, and and how often?". The answer seems to be "in many ways and very frequently". Fig. 2 illustrates my favourite example of such perturbations. An even slightly ($\sim 5\%$) prolate dark matter halo (as most are) leads to large scatter in how well the gas rotation curve traces the underlying gravitational potential. This is because an oblate gas disc cannot be stable in a prolate halo.

The other work that I want to highlight is (Sands et al. 2024). Their table 1 summarizes how they looked at simulated galaxies in detail and decomposed the different contributions of terms in the stress energy tensor to the rotational support of the discs. This includes rotation, pressure support, magnetic pressure, etc. Considering many combinations of these terms allowed them to pick apart ways that a galaxy can be perturbed causing its rotation speed to depart from pure gravitationally-driven rotation.

Regarding the other question, "are the dynamics correctly recovered?", the main point that I want to make is that modeling observations is difficult. We have limited information – that's fine, but what I think that we're really missing in this area are better estimates of the uncertainties. We can tell very clearly from the point-to-point scatter in the rotation curves that in many cases the the uncertainties are underestimated, making them very difficult to interpret. There have been some efforts in this direction (Read et al. 2016; Genina et al. 2018; Oman et al. 2019; Roper et al. 2023). I particularly like the approach to uncertainty estimates taken by Sellwood et al. (2021).

In conclusion, I think that we need effort from both the theory and modeling communities (and more data won't hurt). I've glossed over connections with other scaling relations, especially the radial acceleration relation (McGaugh et al. 2016), but see F. Lelli's talk.

https://doi.org/10.1017/S1743921324002989 Published online by Cambridge University Press

Do all galaxies have cusps? Probably not. Once we sort out the models we'll likely see a distribution spanning cusps and cores with less scatter than we think that we see now.

References

Benítez-Llambay, A., Frenk, C. S., Ludlow, A. D., & Navarro, J. F. 2019, Baryon-induced dark matter cores in the EAGLE simulations. MNRAS, 488(2), 2387–2404.

Bose, S., Frenk, C. S., Jenkins, A., Fattahi, A., Gómez, F. A., Grand, R. J. J., Marinacci, F., Navarro, J. F., Oman, K. A., Pakmor, R., Schaye, J., Simpson, C. M., & Springel, V. 2019, No cores in dark matter-dominated dwarf galaxies with bursty star formation histories. MNRAS, 486(4), 4790–4804.

Brook, C. B. 2015, The variation of rotation curve shapes as a signature of the effects of baryons on dark matter density profiles. MNRAS, 454(2), 1719–1724.

Chan, T. K., Kereš, D., Oñorbe, J., Hopkins, P. F., Muratov, A. L., Faucher-Giguère, C. A., & Quataert, E. 2015, The impact of baryonic physics on the structure of dark matter haloes: the view from the FIRE cosmological simulations. MNRAS, 454(3), 2981–3001.

Di Cintio, A., Brook, C. B., Macciò, A. V., Stinson, G. S., Knebe, A., Dutton, A. A., & Wadsley, J. 2014, The dependence of dark matter profiles on the stellar-to-halo mass ratio: a prediction for cusps versus cores. MNRAS, 437(1), 415–423.

Downing, E. R. & Oman, K. A. 2023, The many reasons that the rotation curves of low-mass galaxies can fail as tracers of their matter distributions. MNRAS, 522(3), 3318–3336.

Dubinski, J. & Carlberg, R. G. 1991, The Structure of Cold Dark Matter Halos. ApJ, 378, 496.

Dutton, A. A., Buck, T., Macciò, A. V., Dixon, K. L., Blank, M., & Obreja, A. 2020, NIHAO - XXV. Convergence in the cusp-core transformation of cold dark matter haloes at high star formation thresholds. MNRAS, 499(2), 2648–2661.

Dutton, A. A., Macciò, A. V., Buck, T., Dixon, K. L., Blank, M., & Obreja, A. 2019, NIHAO XX: the impact of the star formation threshold on the cusp-core transformation of cold dark matter haloes. MNRAS, 486(1), 655–671.

Fitts, A., Boylan-Kolchin, M., Bozek, B., Bullock, J. S., Graus, A., Robles, V., Hopkins, P. F., El-Badry, K., Garrison-Kimmel, S., Faucher-Giguère, C.-A., Wetzel, A., & Kereš, D. 2019, Dwarf galaxies in CDM, WDM, and SIDM: disentangling baryons and dark matter physics. MNRAS, 490(1), 962–977.

Flores, R. A. & Primack, J. R. 1994, Observational and Theoretical Constraints on Singular Dark Matter Halos. ApJ, 427, L1.

Frosst, M., Courteau, S., Arora, N., Stone, C., Macciò, A. V., & Blank, M. 2022, The diversity of spiral galaxies explained. MNRAS, 514(3), 3510–3531.

Gelato, S. & Sommer-Larsen, J. 1999, On DDO 154 and cold dark matter halo profiles. MNRAS, 303(2), 321–328.

Genina, A., Benítez-Llambay, A., Frenk, C. S., Cole, S., Fattahi, A., Navarro, J. F., Oman, K. A., Sawala, T., & Theuns, T. 2018, The core-cusp problem: a matter of perspective. MNRAS, 474(1), 1398–1411.

Governato, F., Zolotov, A., Pontzen, A., Christensen, C., Oh, S. H., Brooks, A. M., Quinn, T., Shen, S., & Wadsley, J. 2012, Cuspy no more: how outflows affect the central dark matter and baryon distribution in Λ cold dark matter galaxies. MNRAS, 422(2), 1231–1240.

Jackson, R. A., Kaviraj, S., Yi, S. K., Peirani, S., Dubois, Y., Martin, G., Devriendt, J. E. G., Slyz, A., Pichon, C., Volonteri, M., Kimm, T., & Kraljic, K. 2024, The formation of cores in galaxies across cosmic time - the existence of cores is not in tension with the ΛCDM paradigm. MNRAS, 528(2), 1655–1667.

Jahn, E. D., Sales, L. V., Marinacci, F., Vogelsberger, M., Torrey, P., Qi, J., Smith, A., Li, H., Kannan, R., Burger, J. D., & Zavala, J. 2023, Real and counterfeit cores: how feedback expands haloes and disrupts tracers of inner gravitational potential in dwarf galaxies. MNRAS, 520(1), 461–479.

Kamada, A., Kaplinghat, M., Pace, A. B., & Yu, H.-B. 2017, Self-Interacting Dark Matter Can Explain Diverse Galactic Rotation Curves. Phys. Rev. Lett., 119(11), 111102.

https://doi.org/10.1017/S1743921324002989 Published online by Cambridge University Press

Mancera Piña, P. E., Fraternali, F., Adams, E. A. K., Marasco, A., Oosterloo, T., Oman, K. A., Leisman, L., di Teodoro, E. M., Posti, L., Battipaglia, M., Cannon, J. M., Gault, L., Haynes, M. P., Janowiecki, S., McAllan, E., Pagel, H. J., Reiter, K., Rhode, K. L., Salzer, J. J., & Smith, N. J. 2019, Off the Baryonic Tully-Fisher Relation: A Population of Baryon-dominated Ultra-diffuse Galaxies. ApJ, 883(2), L33.

Mashchenko, S., Wadsley, J., & Couchman, H. M. P. 2008, Stellar Feedback in Dwarf Galaxy Formation. *Science*, 319(5860), 174.

McGaugh, S. S., Lelli, F., & Schombert, J. M. 2016, Radial Acceleration Relation in Rotationally Supported Galaxies. Phys. Rev. Lett., 117(20), 201101.

McGaugh, S. S., Schombert, J. M., Bothun, G. D., & de Blok, W. J. G. 2000, The Baryonic Tully-Fisher Relation. ApJ, 533(2), L99–L102.

Milgrom, M. 1983, A modification of the Newtonian dynamics - Implications for galaxies. ApJ, 270, 371–383.

Moore, B. 1994, Evidence against dissipation-less dark matter from observations of galaxy haloes. Nature, 370(6491), 629–631.

Muni, C., Pontzen, A., Read, J. I., Agertz, O., Rey, M. P., & Taylor, E. 2024, Dark matter core creation depends on the timing of star formation. *arXiv e-prints*,, arXiv:2407.14579.

Navarro, J. F., Eke, V. R., & Frenk, C. S. 1996, The cores of dwarf galaxy haloes. MNRAS, 283(3), L72–L78.

Oñorbe, J., Boylan-Kolchin, M., Bullock, J. S., Hopkins, P. F., Kereš, D., Faucher-Giguère, C.-A., Quataert, E., & Murray, N. 2015, Forged in FIRE: cusps, cores and baryons in low-mass dwarf galaxies. MNRAS, 454(2), 2092–2106.

Oman, K. A., Marasco, A., Navarro, J. F., Frenk, C. S., Schaye, J., & Benítez-Llambay, A. 2019, Non-circular motions and the diversity of dwarf galaxy rotation curves. MNRAS, 482(1), 821–847.

Oman, K. A., Navarro, J. F., Fattahi, A., Frenk, C. S., Sawala, T., White, S. D. M., Bower, R., Crain, R. A., Furlong, M., Schaller, M., Schaye, J., & Theuns, T. 2015, The unexpected diversity of dwarf galaxy rotation curves. MNRAS, 452(4), 3650–3665.

Oman, K. A., Navarro, J. F., Sales, L. V., Fattahi, A., Frenk, C. S., Sawala, T., Schaller, M., & White, S. D. M. 2016, Missing dark matter in dwarf galaxies? MNRAS, 460(4), 3610–3623.

Pineda, J. C. B., Hayward, C. C., Springel, V., & Mendes de Oliveira, C. 2017, Rotation curve fitting and its fatal attraction to cores in realistically simulated galaxy observations. MNRAS, 466(1), 63–87.

Pontzen, A. & Governato, F. 2012, How supernova feedback turns dark matter cusps into cores. MNRAS, 421(4), 3464–3471.

Read, J. I. & Gilmore, G. 2005, Mass loss from dwarf spheroidal galaxies: the origins of shallow dark matter cores and exponential surface brightness profiles. MNRAS, 356(1), 107–124.

Read, J. I., Iorio, G., Agertz, O., & Fraternali, F. 2016, Understanding the shape and diversity of dwarf galaxy rotation curves in ΛCDM. MNRAS, 462(4), 3628–3645.

Ren, T., Kwa, A., Kaplinghat, M., & Yu, H.-B. 2019, Reconciling the Diversity and Uniformity of Galactic Rotation Curves with Self-Interacting Dark Matter. *Physical Review X*, 9(3), 031020.

Roper, F. A., Oman, K. A., Frenk, C. S., Benítez-Llambay, A., Navarro, J. F., & Santos-Santos, I. M. E. 2023, The diversity of rotation curves of simulated galaxies with cusps and cores. MNRAS, 521(1), 1316–1336.

Sales, L. V., Wetzel, A., & Fattahi, A. 2022, Baryonic solutions and challenges for cosmological models of dwarf galaxies. *Nature Astronomy*, 6, 897–910.

Sands, I. S., Hopkins, P. F., Shen, X., Boylan-Kolchin, M., Bullock, J., Faucher-Giguere, C.-A., Mercado, F. J., Moreno, J., Necib, L., Ou, X., Wellons, S., & Wetzel, A. 2024, Confronting the Diversity Problem: The Limits of Galaxy Rotation Curves as a tool to Understand Dark Matter Profiles. *arXiv e-prints*,, arXiv:2404.16247.

Santos-Santos, I. M., Di Cintio, A., Brook, C. B., Macciò, A., Dutton, A., & Domínguez-Tenreiro, R. 2018, NIHAO - XIV. Reproducing the observed diversity of dwarf galaxy rotation curve shapes in ΛCDM. MNRAS, 473(4), 4392–4403.

https://doi.org/10.1017/S1743921324002989 Published online by Cambridge University Press

Santos-Santos, I. M. E., Navarro, J. F., Robertson, A., Benítez-Llambay, A., Oman, K. A., Lovell, M. R., Frenk, C. S., Ludlow, A. D., Fattahi, A., & Ritz, A. 2020, Baryonic clues to the puzzling diversity of dwarf galaxy rotation curves. MNRAS, 495(1), 58–77.

Sellwood, J. A., Spekkens, K., & Eckel, C. S. 2021, Uncertainties in galaxy rotation curves. MNRAS, 502(3), 3843–3854.

Teyssier, R., Pontzen, A., Dubois, Y., & Read, J. I. 2013, Cusp-core transformations in dwarf galaxies: observational predictions. MNRAS, 429(4), 3068–3078.

Tollet, E., Macciò, A. V., Dutton, A. A., Stinson, G. S., Wang, L., Penzo, C., Gutcke, T. A., Buck, T., Kang, X., Brook, C., Di Cintio, A., Keller, B. W., & Wadsley, J. 2016, NIHAO - IV: core creation and destruction in dark matter density profiles across cosmic time. MNRAS, 456(4), 3542–3552.

Discussion

Di Teodoro: About your last point, that our models for modeling the rotation curves probably are not appropriate for dwarf galaxies. What, do you think, is the problem? Is it that we often assume a disc model? Do we need to take into account non-circular motions? The thickness of the disc? Why does it fail so badly? I think that it's not just the uncertainties, it's also the the rotation curve that we get: they're not great.

Oman: Most models for these galaxies are based on the tilted-ring idea that started from "let's model warped giant spirals" and maybe going back to the drawing board and asking "what's the best way to actually model a dwarf irregular" is not a bad idea. One of the limitations in these codes is that they tend to fit ring by ring. Dwarfs are geometrically thick: the rings overlap, so the whole problem should probably be optimized in one go.

Mancera-Piña: I know that you share this view: simulations don't tell us reality but what may happen. For the plot you showed with different rotation curves that you get from simulations – in your opinion how much do you think this is really a problem when it comes to real data? Many of them show spikes or are very irregular. With real data if observers got something like this they probably wouldn't fit a mass model.

Oman: I feel very lucky to have worked with simulations that are so messy and unrealistic because they exaggerate effects and make the kinds of things that you might worry about in real data easier to see. So yes, I agree, the simulations are messier than real galaxies. They have these wiggles, spikes and so on and probably you would shy away from these observationally, but studying these simulations I think I've learned a lot about the kinds of issues that you run into. It seems very reasonable to me that the same issues affect real galaxies to a lesser extent. The amplitude of the scatter is probably less observationally.

Basti: I have a question about the plot that you showed with the observed and the true rotation curves. In that figure it seems that past 6 kpc the deviation between the observed and true rotation curves becomes more prominent, but I expected the opposite.

Oman: As you get out to those large radii you start running into the transition between an atomic gas dominated disc and an ionized gas dominated halo. In these particular simulations there are challenging issues around that so I wouldn't worry about this.

Lelli: My interpretation of your simulation results is very different. I think that simulations are totally unrealistic in that regime because they have too much non-circular motion that drives things out of equilibrium. Otherwise we wouldn't be able to observe the tight empirical relationships that we do observe like the baryonic Tully-Fisher relation, the RAR. If everything was out of equilibrium we should see scatter plots but we

https://doi.org/10.1017/S1743921324002989 Published online by Cambridge University Press

see tight relationships. So my question is what if one does a step back and simulates an isolated low-mass galaxy with weak stellar feedback? Would that be in equilibrium?

Oman: In our study of the different ways that a galaxy can be out of equilibrium we identified a number of things. Where there are supernova-driven gas flows, if you turn down the feedback then that will get better. But, for example, there's no stable configuration for a gas disc in a prolate halo. So if you give your low-mass, isolated, gentle feedback dwarf a prolate halo it will still have strong non-circular motions and be disequilibrated.

https://doi.org/10.1017/S1743921324002989 Published online by Cambridge University Press