Comparisons of Dark Matter Halos in Rotation Curve Observations and ΛCDM Hydrodynamic Simulations

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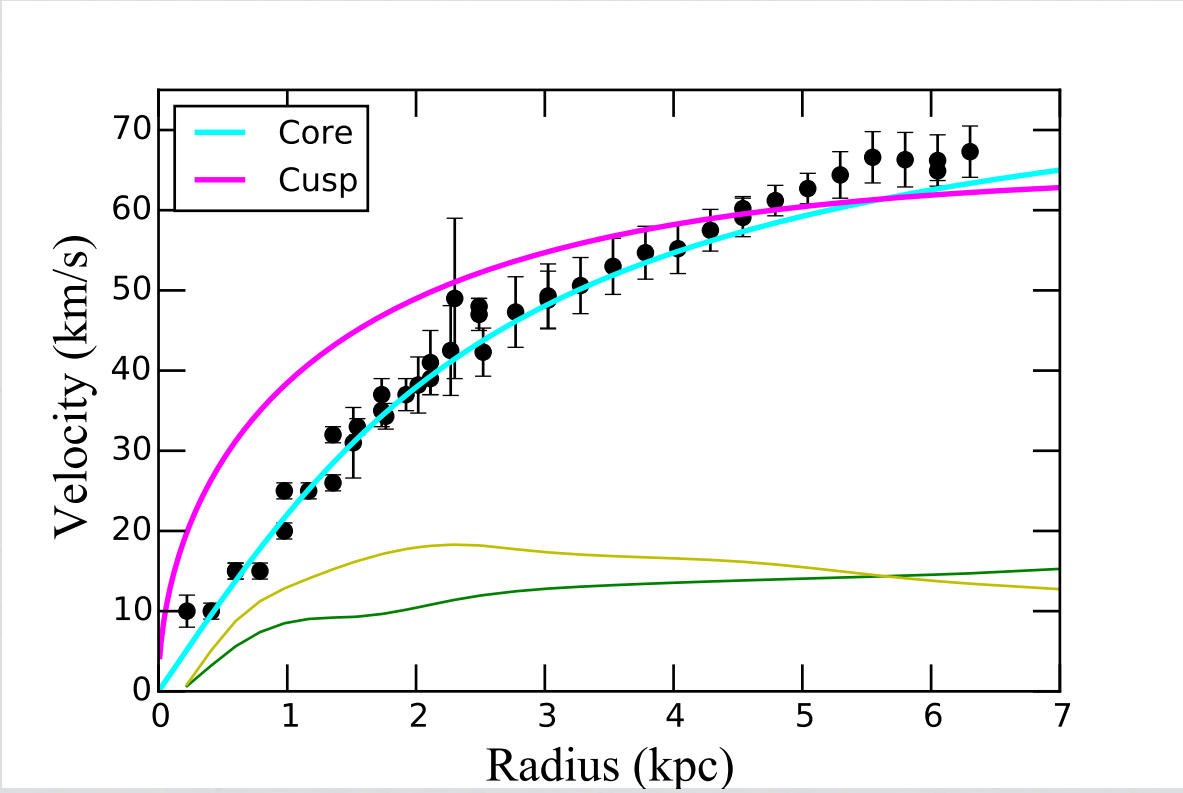
Outline

- Rotation Curves
- Small Scale Problems in ΛCDM
    - Core/Cusp
    - Too big to fail
- Baryonic Solutions
    - Rotation Curves Fits
    - Mstar-Mhalo, cvir-Mhalo Relations
- Conclusions

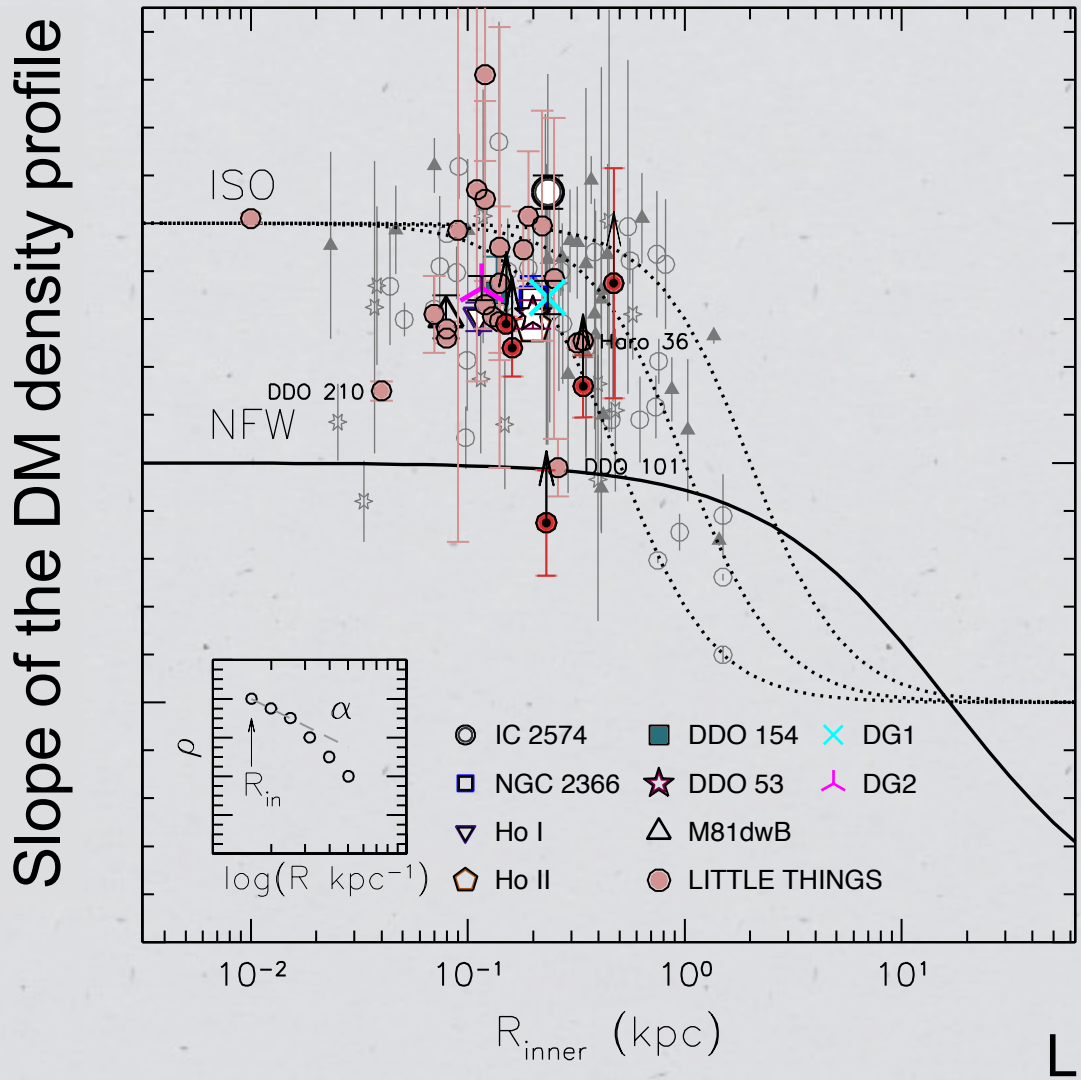
Rotation Curves



NGC 3109

Jobin & Carignan 1990; Blais-Ouellette et al. 2001; Carignan et al. 2013

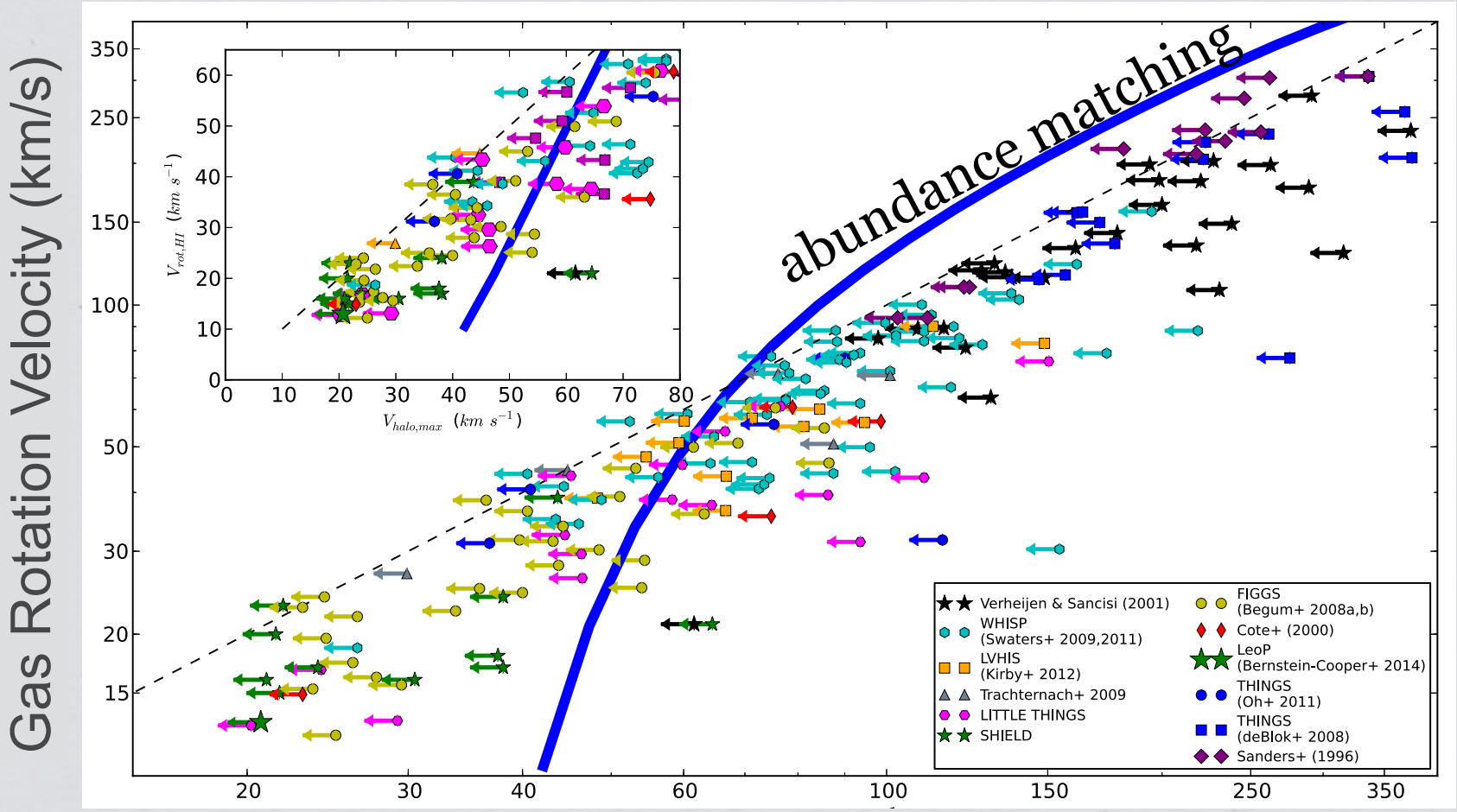
Cores in dwarf galaxies



Inner slopes lower than dark matter-only N-Body simulations

LITTLE THINGS, Oh et al 2015

Too Big To Fail



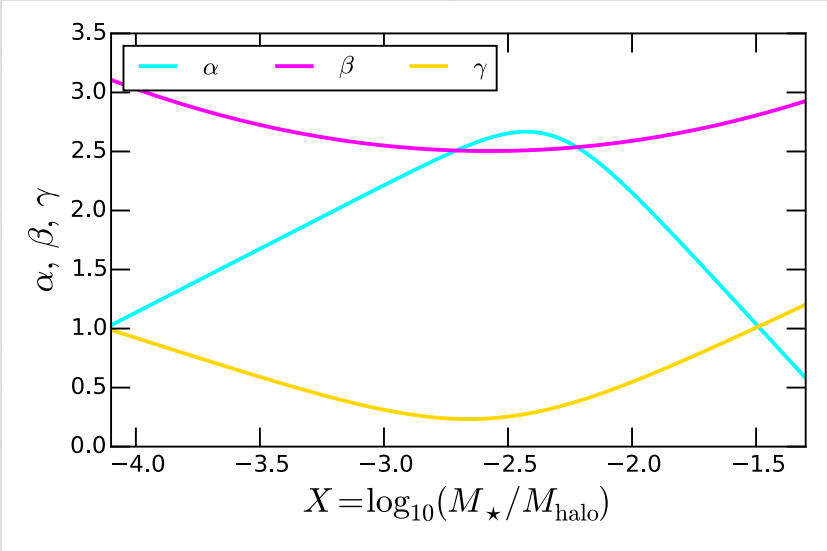
Papastergis et al 2014.
Previously pointed out by
Ferrero et al 2012

[Boylan-Kolchin+2011, 2012, Tollerud + 2014, Kirby + 2014, Garrison-Kimmel + 2014]

How does Galaxy Formation Affect the Dark Matter Halo ?

- Two Main Processes:
  - Formation of Disk (Adiabatic Contraction)
    - increases cusp / central density
    - e.g. Blumenthal+ 1986; Gnedin+ 2004
  - Stellar Feedback from Supernova Winds
    - creates cores
    - e.g. Governato+ 2010, Oñorbe+ 2015, Di Cintio+ 2014
- ΛCDM hydrodynamic simulations will contain both (if feedback is implemented correctly)

How does Galaxy Formation Affect the Dark Matter Halo ?



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

Assume α, β, γ are functions of integrated star formation efficiency

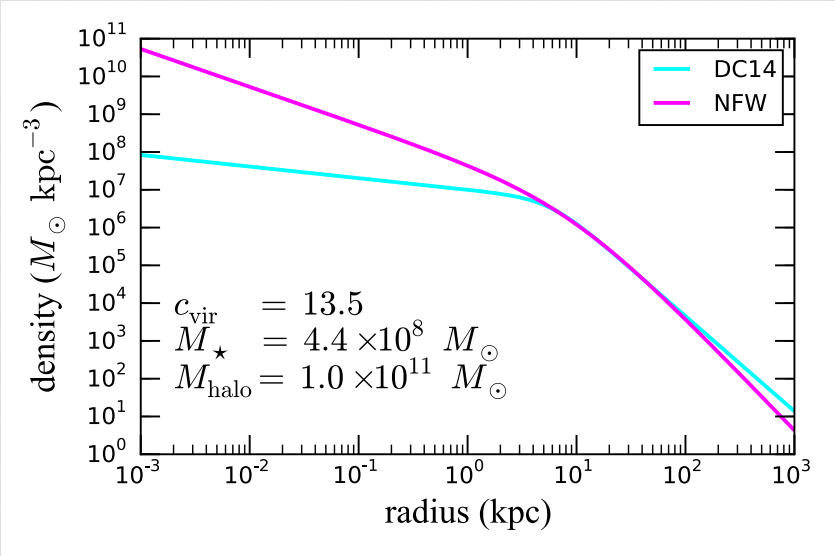
$$X \equiv \log_{10}\left(\frac{M_\star}{M_{\rm halo}}\right)$$

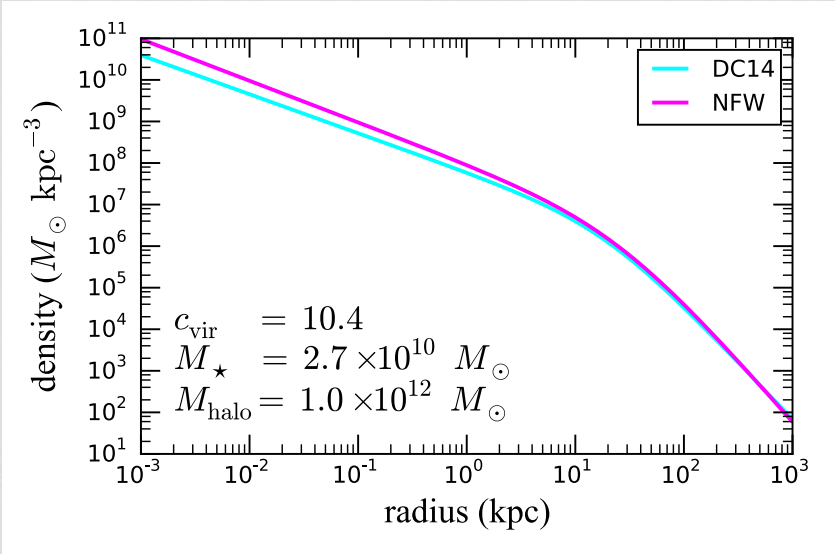
NFW profile: α=1, β=3, γ=1

Di Cintio+ 2014a, b

See also: Tollet+ 2016, Chan+ 2015, Dutton+ 2016

How does Galaxy Formation Affect the Dark Matter Halo ?





Di Cintio+ 2014a, b

See also: Tollet+ 2016, Chan+ 2015, Dutton+ 2016

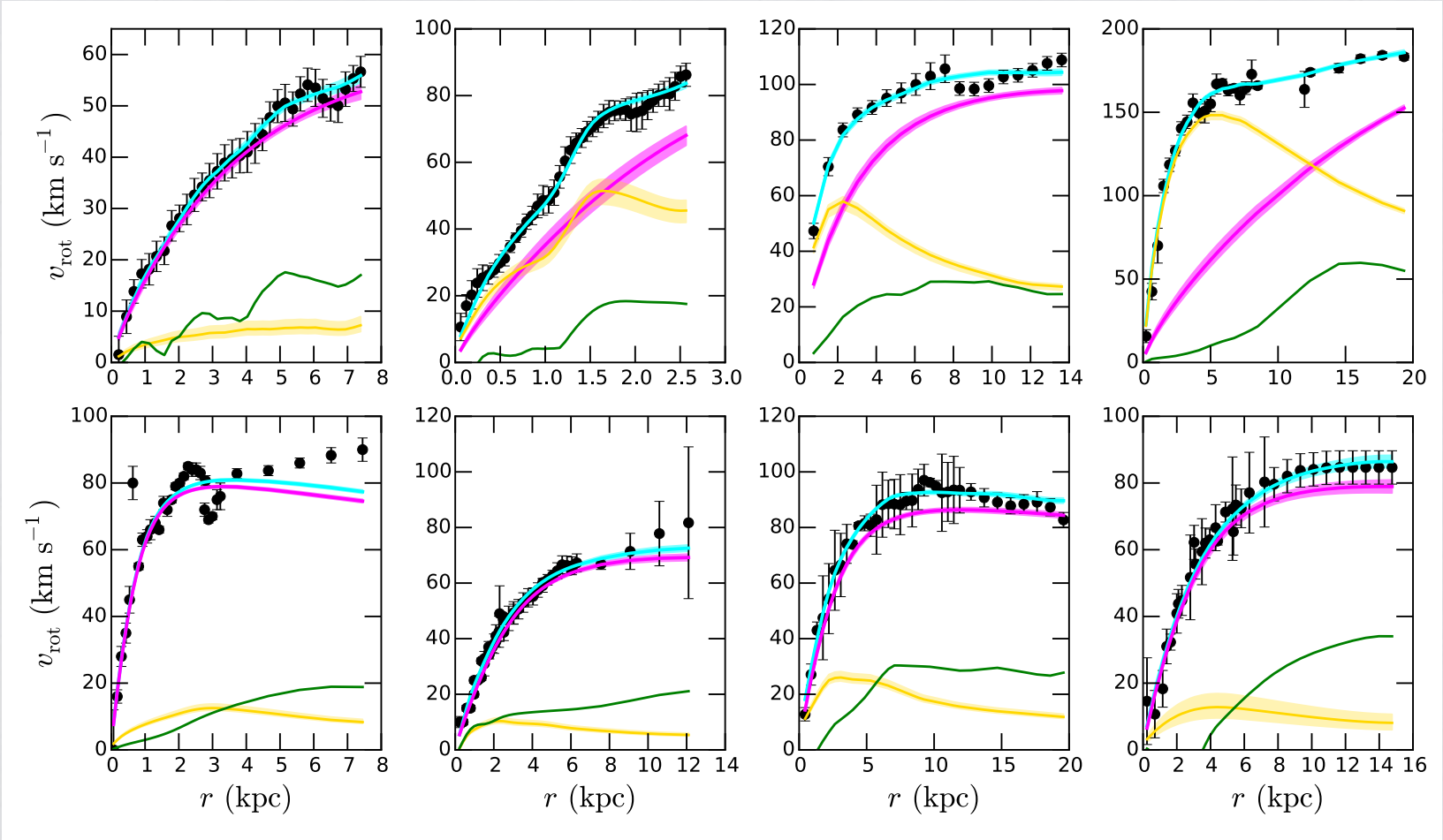
Rotation Curve Data

Total 186 Galaxies

- Little THINGS
- THINGS
- WHISP
- Ursa Major Cluster
- Low Surface Brightness Galaxies
- Many many others

Our sample includes rotation curves from the following sources: LITTLE THINGS (Hunter et al. 2012; Oh et al. 2015), THINGS (Walter et al. 2008; de Blok et al. 2008; Oh et al. 2008; Trachternach et al. 2008; Oh et al. 2011a), WHISP (Swaters et al. 2002; Swaters & Balcells 2002; Noordermeer et al. 2005; Swaters et al. 2009), the Ursa Major cluster (Tully et al. 1996; Tully & Verheijen 1997; Sanders & Verheijen 1998; Trentham et al. 2001; Verheijen & Sancisi 2001; Verheijen 2001; Bottema & Verheijen 2002; Bottema 2002), low surface brightness galaxies (van der Hulst et al. 1993; de Blok et al. 1996; McGaugh et al. 2001; de Blok & Bosma 2002; Swaters et al. 2003; Kuzio de Naray et al. 2006, 2008), and a miscellaneous sample (Begeman 1987; Carignan et al. 1988; Jobin & Carignan 1990; Lake et al. 1990; Côté et al. 1991; Gonzalez-Serrano & Valentijn 1991; Blais-Ouellette et al. 1999; van Zee & Bryant 1999; Weiner et al. 2001; Blais-Ouellette et al. 2001; Weldrake et al. 2003; Gentile et al. 2004, 2007, 2010; Elson et al. 2010; Kreckel et al. 2011; Frusciante et al. 2012; Lelli et al. 2012; Fraternali et al. 2011; Carignan et al. 2013; Elson et al. 2013; Corbelli et al. 2014; Lelli et al. 2014b; Kam et al. 2015; Richards et al. 2015; Randriamampandry et al. 2015; Karachentsev et al. 2015; Bottema & Pestaña 2015; Carignan & Puche 1990; Puche et al. 1990, 1991a,b; Chemin et al. 2006; Hlavacek-Larrondo et al. 2011b,a; Westmeier et al. 2011, 2013; Lucero et al. 2015; Verdes-Montenegro et al. 1995). Galaxies with multiple rotation curve

Rotation Curve Fits with DC14 Halo Profile



top: UGC 5918 (LITTLE THINGS; Oh et al. 2015), NGC 2976 (THINGS; de Blok et al. 2008), NGC 4288 (WHISP; Swaters et al. 2009), ESO 287-G15 (Gentile et al. 2004), bottom: UGC 2259 (Carignan et al. 1988; Blais-Ouellette et al. 2004), NGC 3109 (Jobin & Carignan 1990; Blais-Ouellette et al. 2001; Carignan et al. 2013), NGC 300 (Puche et al. 1990; Westmeier et al. 2011; Hlavacek-Larrondo et al. 2011b), and F583-01 (de Blok et al. 1996; McGaugh et al. 2001; Kuzio de Naray et al. 2006)

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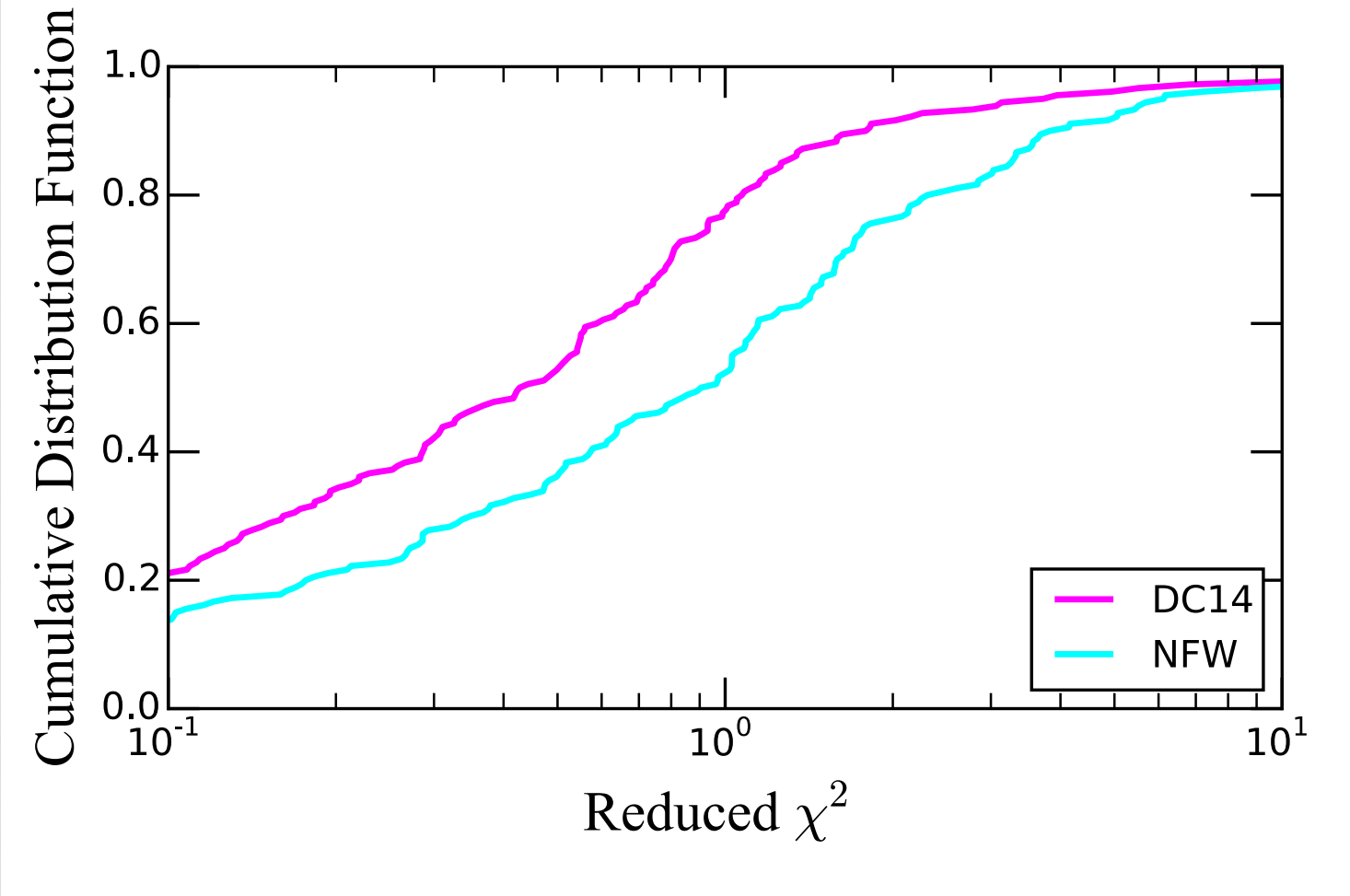
Rotation Curve Fits with DC14 Halo Profile



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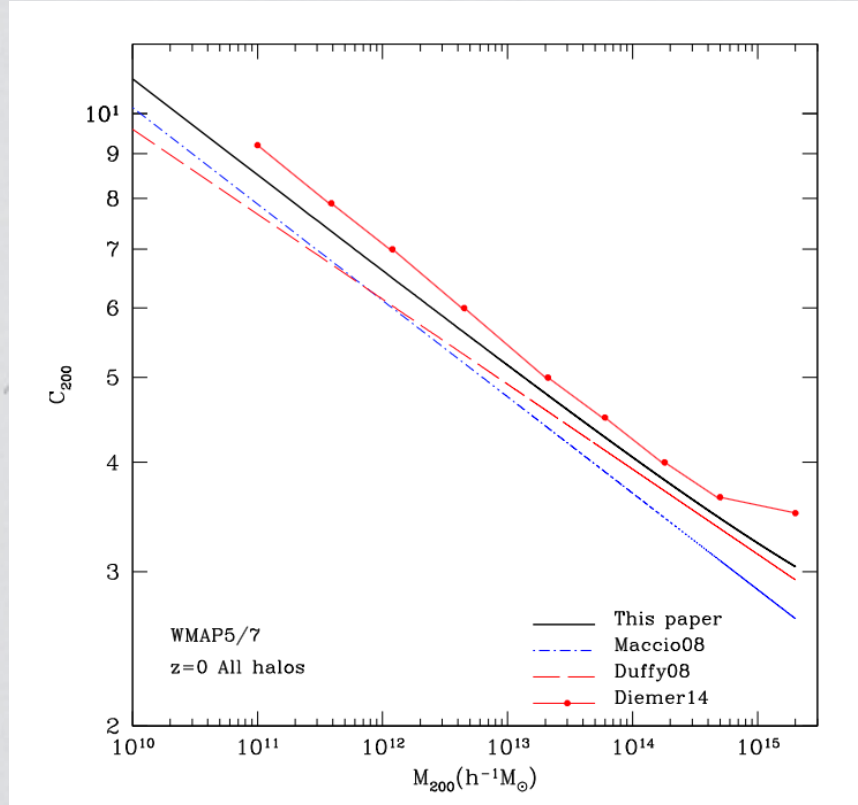
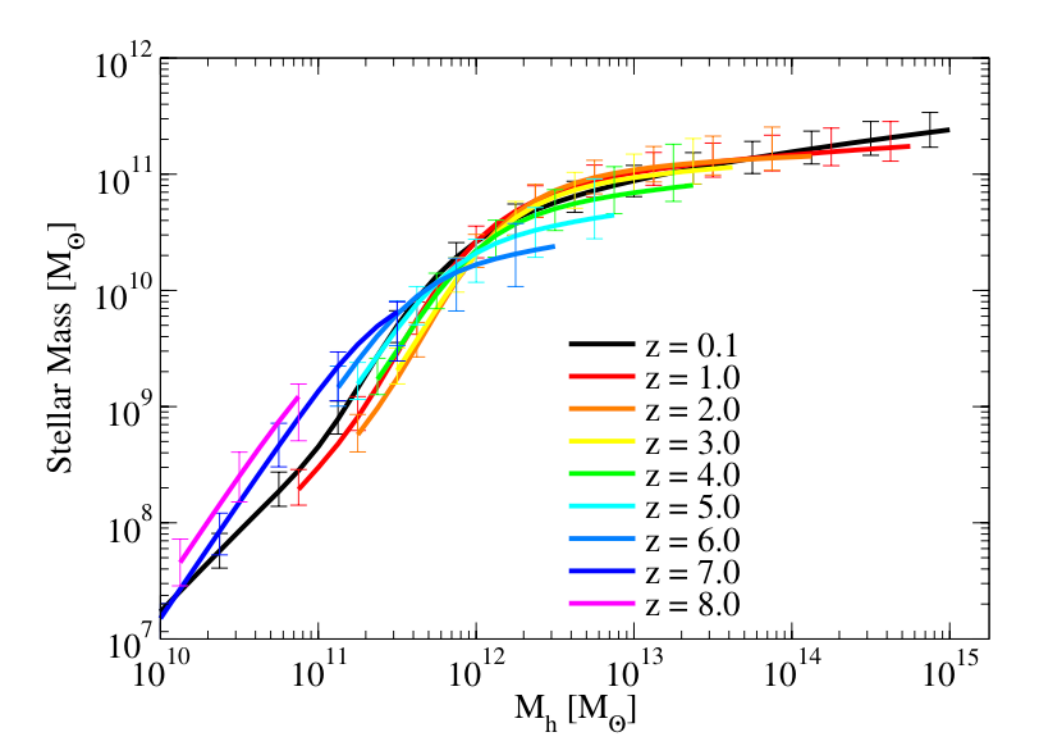
Cosmological Relations

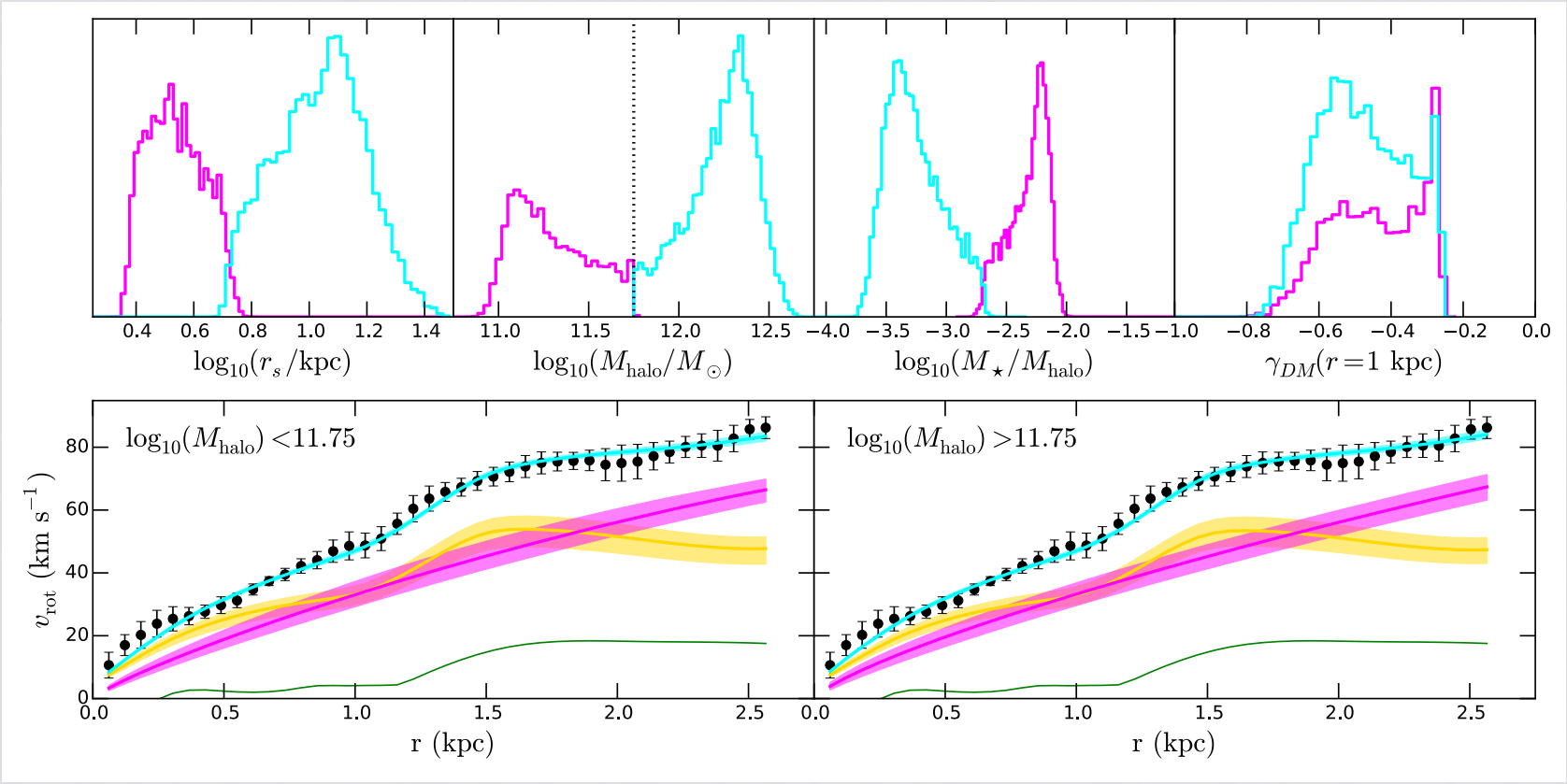




Klypin+ 2016

Behroozi+ 2013

MultiModal Posteriors



Galaxies without extended rotation curve measurements have multimodal Mhalo posteriors

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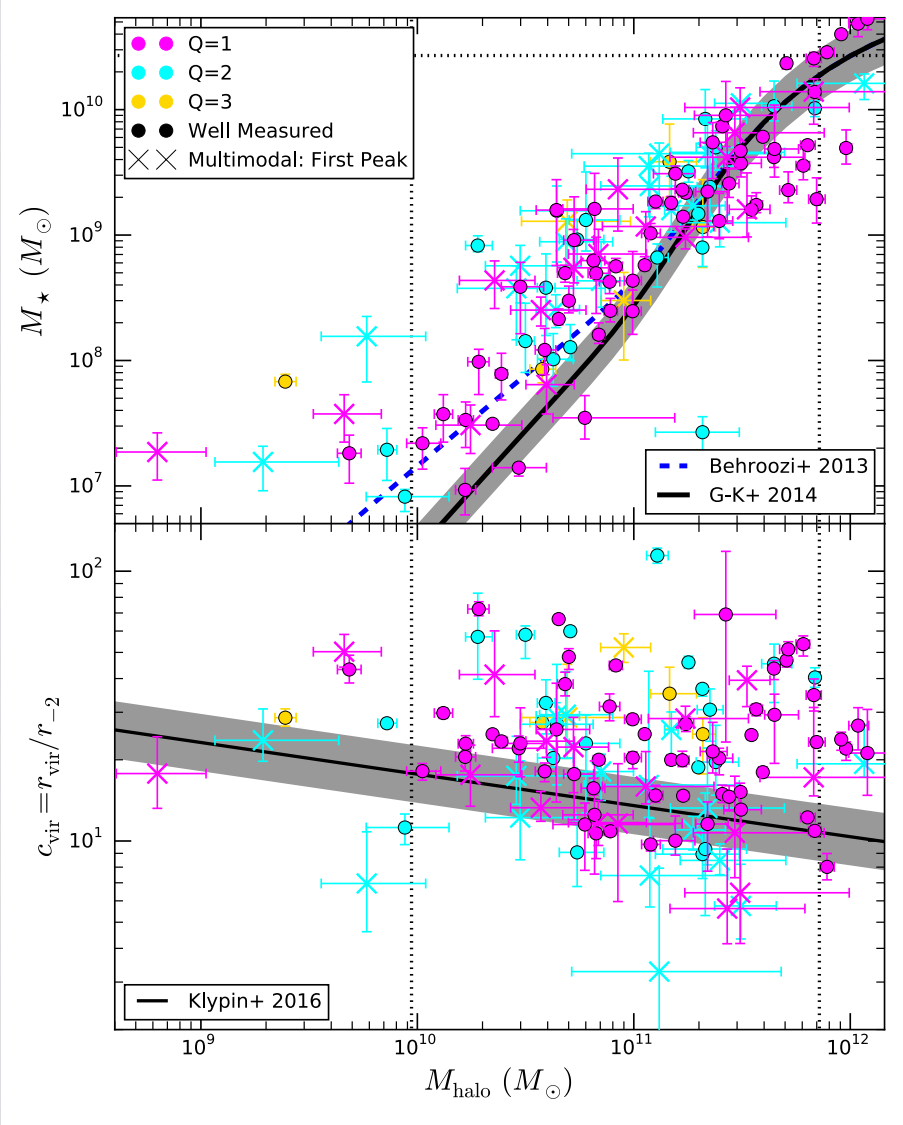
Cosmological Relations from Rotation Curve Fits and the DC14 halo profile



- Scatter around abundance matching above Mstar ~ 10^9 Msun
- Preferentially, favors places galaxies in smaller halos below Mstar ~10^9 Msun
- Large scatter in concentration Mhalo relation.

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See also: Katz+ 2016

Conclusions

- DC14 profile can explain rotation curves
  - i.e. solve the core-cusp problem
- The rotation curves kinematics do not favor halos that match the cosmological Mstar-Mhalo and Mhalo-cvir relations
- Why
  - Systematics in Rotation Curve Observations
  - Incorrect (stellar) mass dependent halo profile
  - Non-Standard Dark Matter