Impacts of Galaxy Formation and Alternative DM Models on Milky Way Satellite Kinematics

Mei-Yu Wang
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Outline

- **Motivation**
  - Inner structure of Milky Way subhalos
- **Numerical Simulation of Galactic Halos**
  - Hydrodynamic simulations of Local Group
  - Alternative Dark Matter model simulations (WDM, DDM)
- **Methodology and Data**
- **Impacts of Galaxy Formation and Dark Matter Properties on Milky Way Dwarf Galaxies Kinematics**
- **Implication on Milky Way Satellite Galaxy Luminosity**
- **Conclusion**

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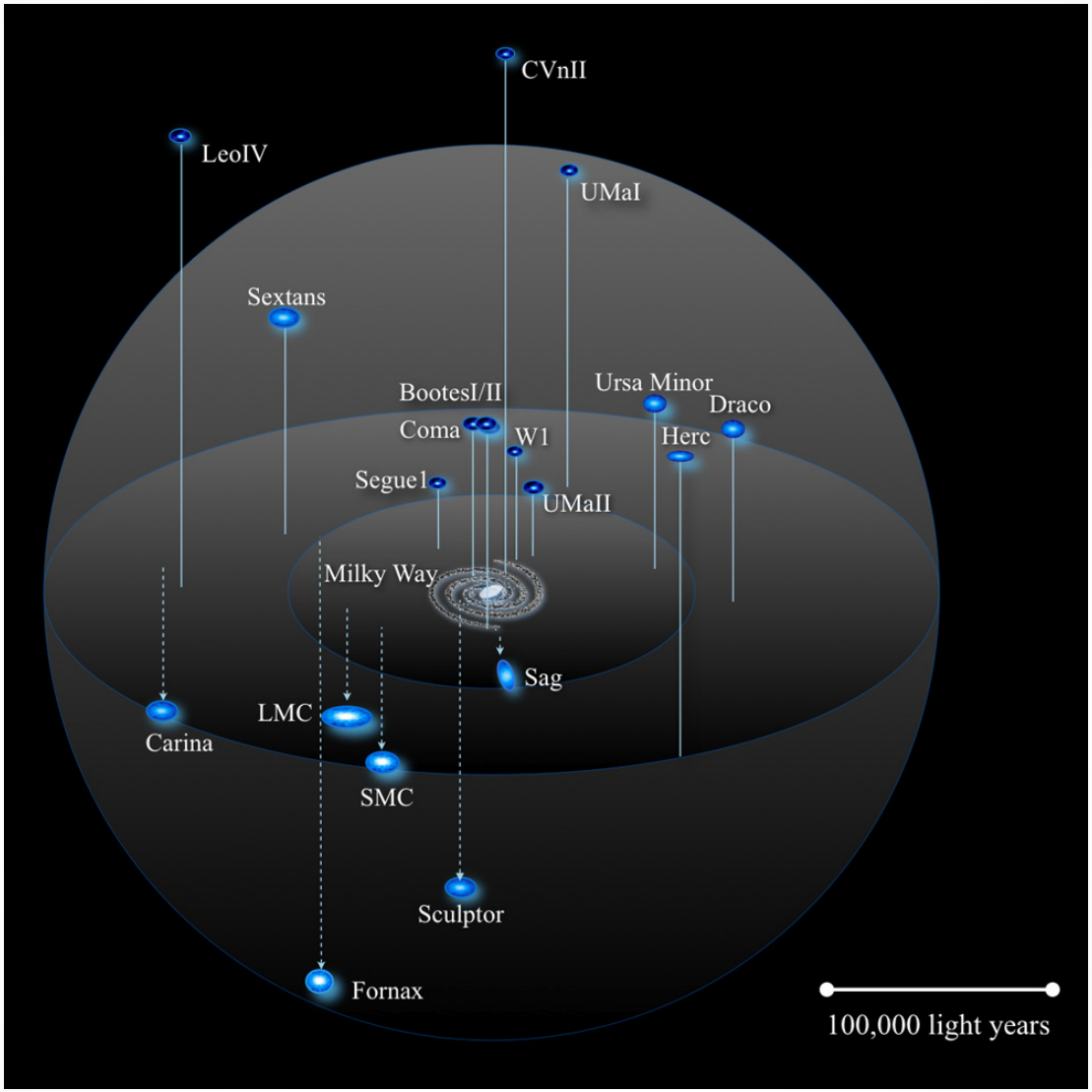
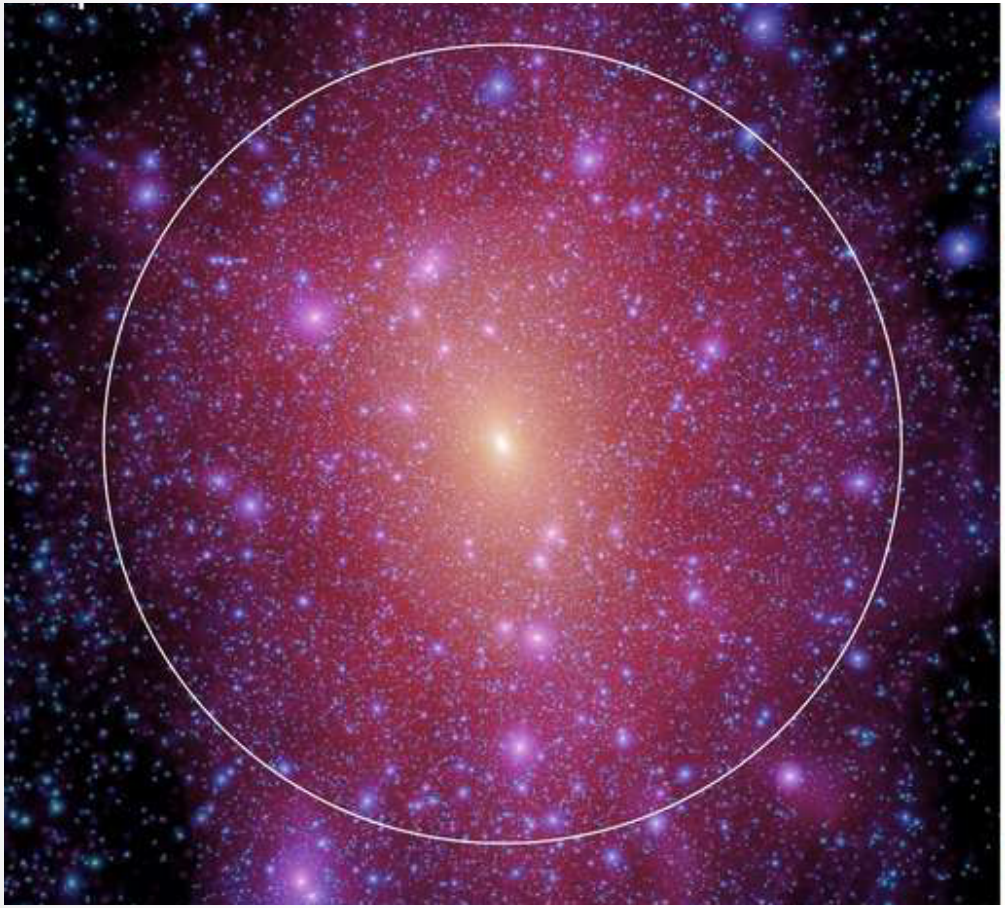
Milky Way Satellite Galaxies

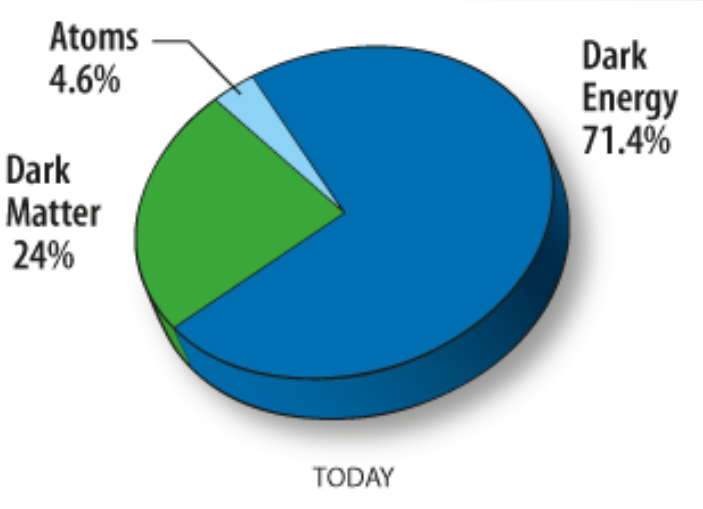


Galactic Dark Matter Halo & Subhalos

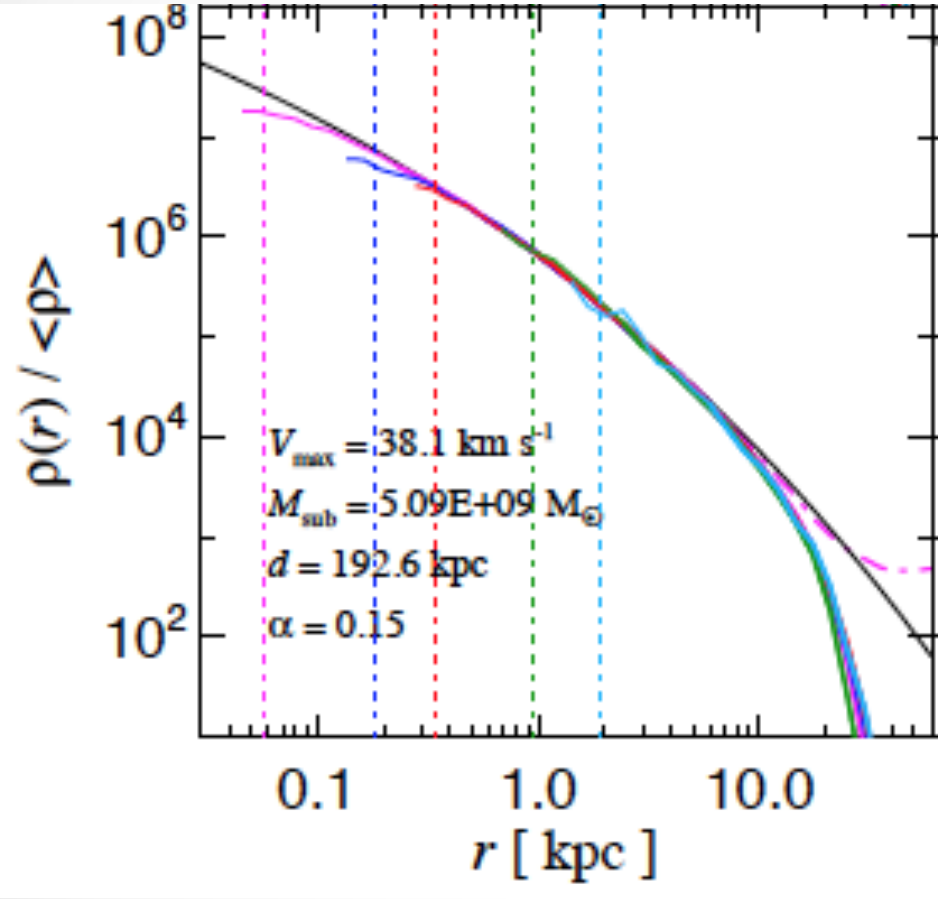


Aquarius Simulations

Springel et al. (2012)



Inner Structure of Subhalos



Springel et al. (2012)

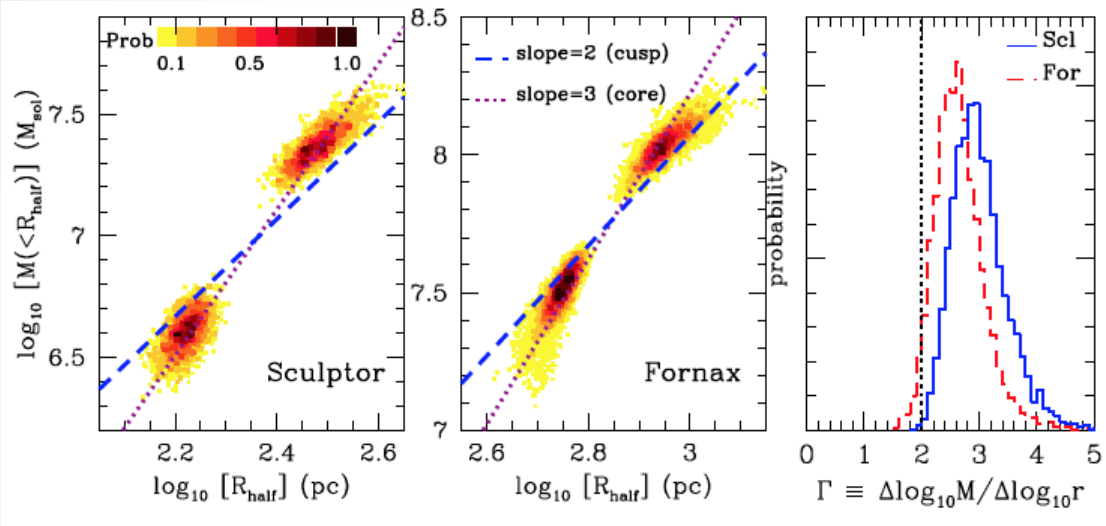
NFW profile
(Navarro-Frenk-White)

$$\rho(r) = \frac{\delta_c \, \rho_{\rm crit}}{(r/r_s)(r/r_s + 1)^2}$$

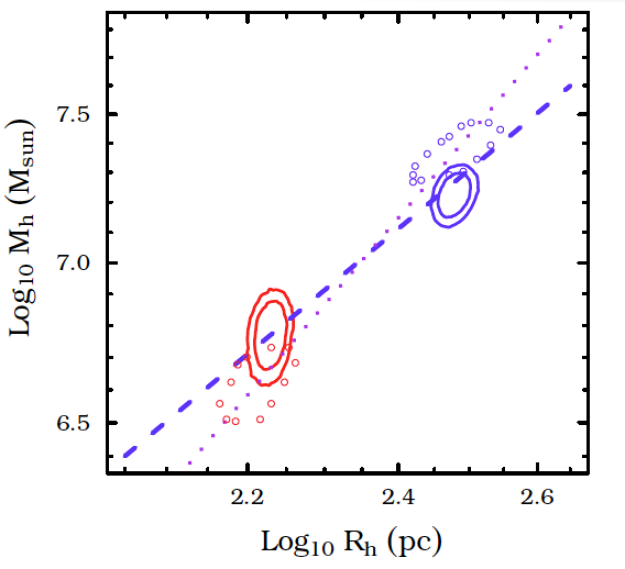
Einasto profile

$$\rho(r) = \rho_{-2} \exp\left(-\frac{2}{\alpha}\left[\left(\frac{r}{r_{-2}}\right)^{\alpha} - 1\right]\right)$$

Stellar Velocity Dispersion Measurement
Cusp v.s. Core ?

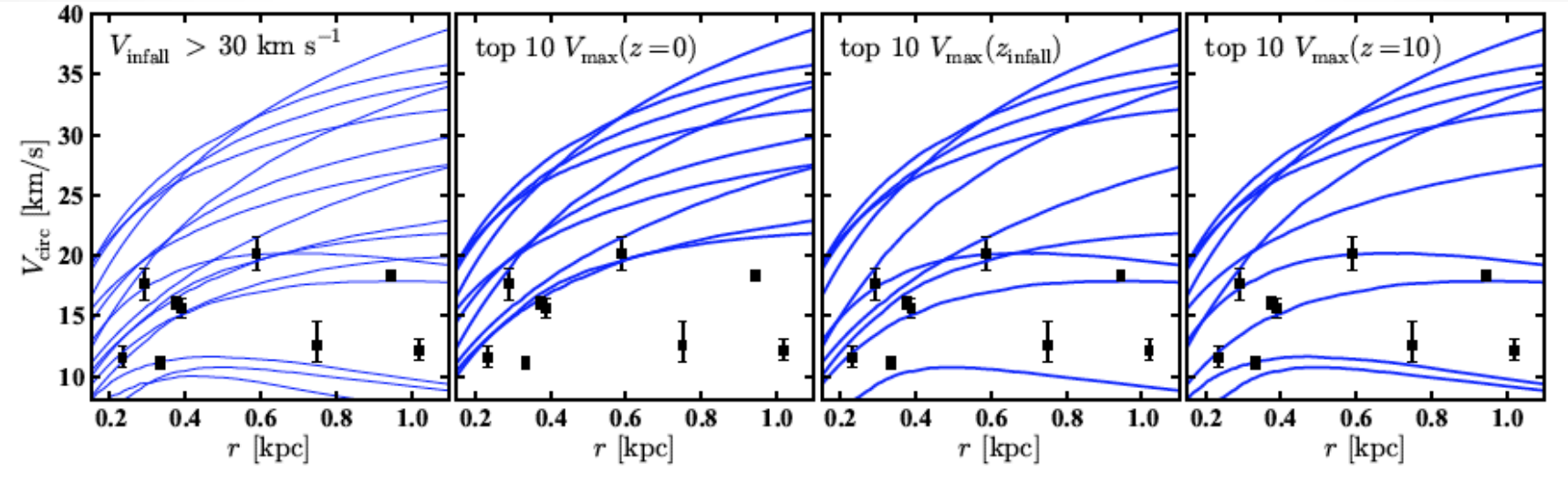


Walker & Penarrubia (2011)



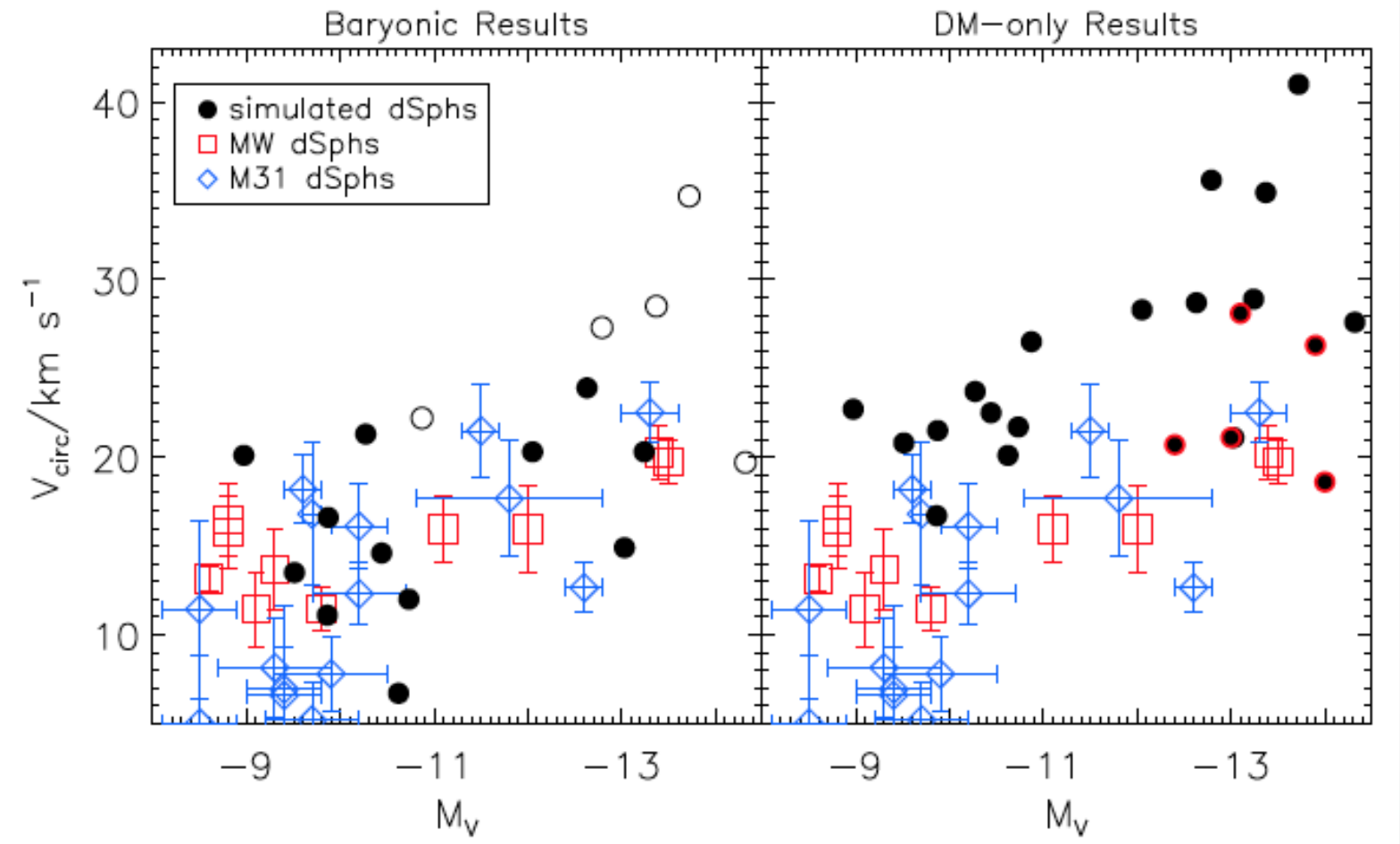
See Strigari et al. (2014) for different argument

“Too Big to Fail” Problem



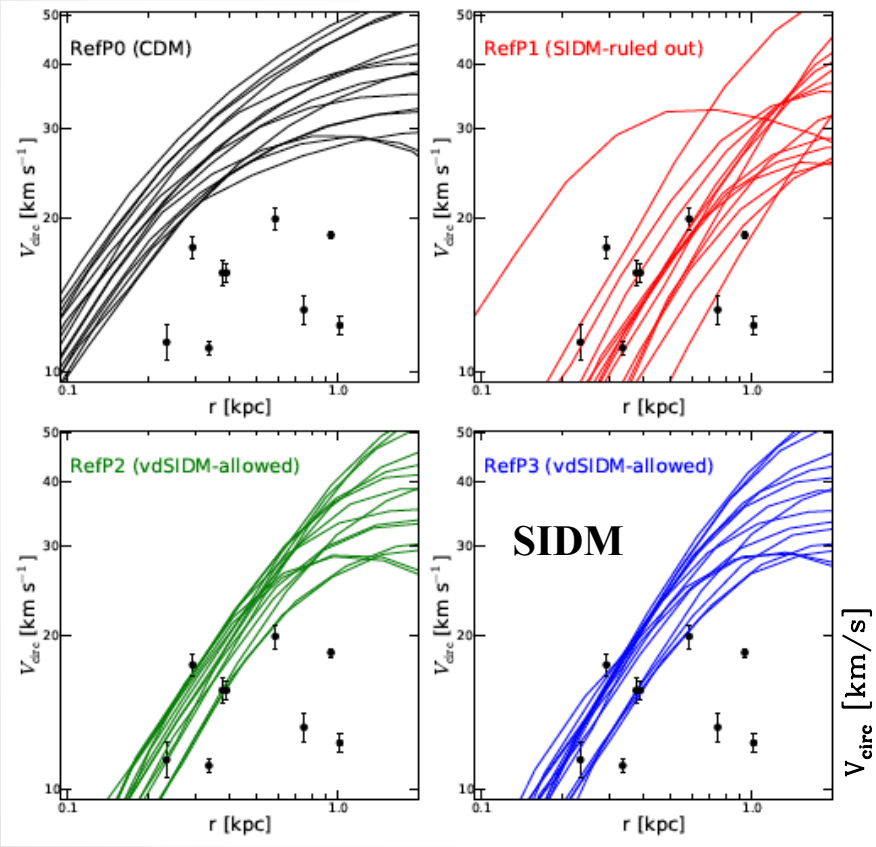
Boylan-Kolchin et al. (2012)

Too Big to Fail Solution in Galaxy Formation Physics

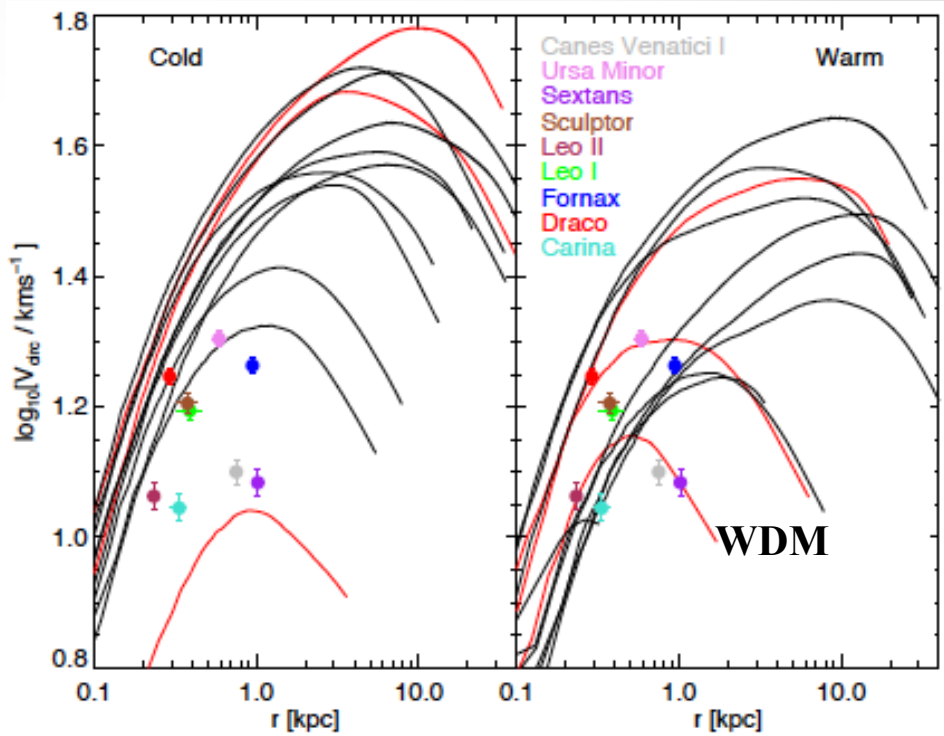


Brooks & Zolotov (2012)

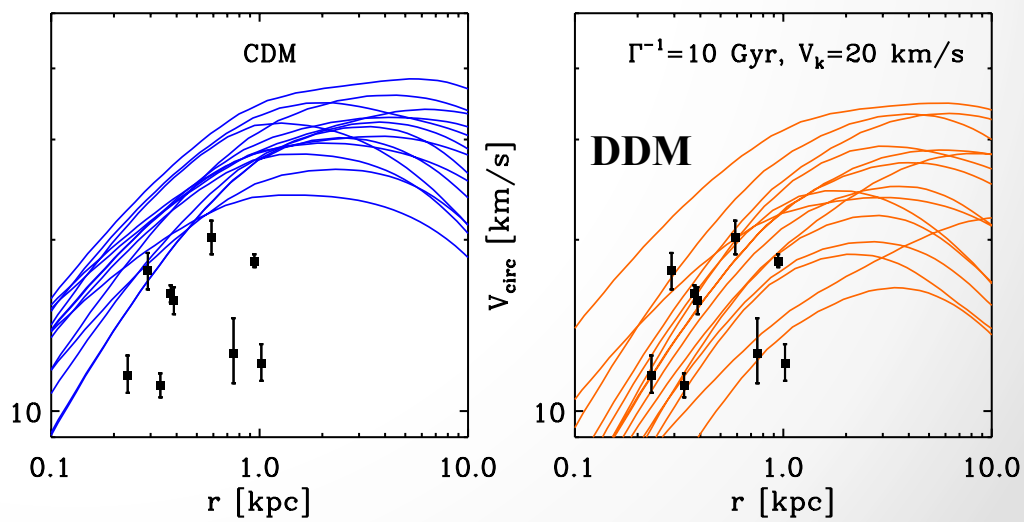
Too Big to Fail Solution in Alternative DM models?



Vogelsberger et al. (2012)



Lovell et al. (2012)



M.W. et al. (2014), arXiv:1406.0527

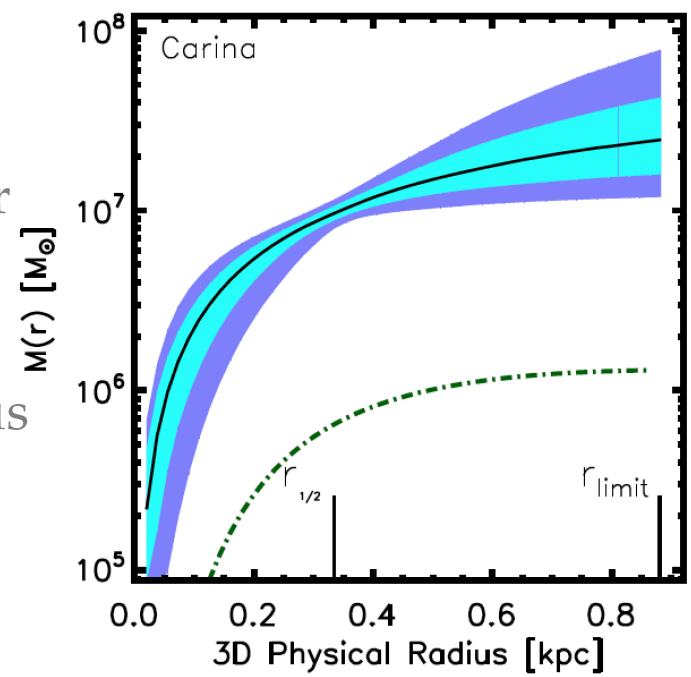
- Different mechanisms (galaxy formation, different DM properties) can result in different subhalo potential.
- Stellar kinematic data can only tell us the matter distribution (roughly) in MW dwarf satellites.

=> The mass enclosed within the half-light radius can be determined with only mild assumptions.

- How do we distinguish between these different models?

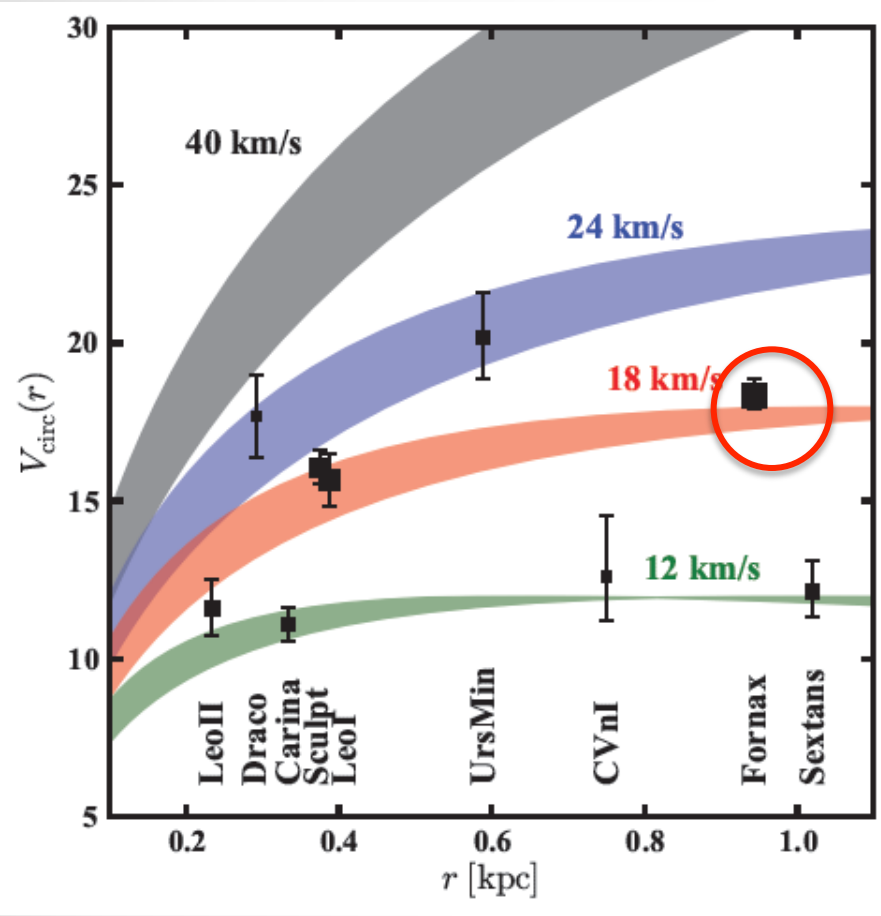
⇒ Subhalo formation history (numerical simulation)

⇒ Stellar component. Like luminosity, effects from reionization, and stellar distribution.



Wolf et al. (2010)

Puzzling Fornax



Boylan-Kolchin et al. (2012)

Galaxy	Distance [kpc]	Luminosity [$L_{\odot,V}$]
Carina (723)	105 ± 2 [a]	$4.3^{+1.1}_{-0.9} \times 10^5$ [b]
Draco (206)	76 ± 5 [d]	$2.2^{+0.7}_{-0.6} \times 10^5$ [b]
Fornax (2409)	147 ± 3 [a]	$1.7^{+0.5}_{-0.4} \times 10^7$ [b]
Leo I (305)	254 ± 18 [f]	$5.0^{+1.8}_{-1.3} \times 10^6$ [b]
Leo II (168)	233 ± 15 [h]	$7.8^{+2.5}_{-1.9} \times 10^5$ [i]
Sculptor (1355)	86 ± 5 [j]	$2.5^{+0.9}_{-0.7} \times 10^6$ [b]
Sextans (423)	96 ± 3 [k]	$5.9^{+2.0}_{-1.4} \times 10^5$ [b]
Ursa Minor (212)	77 ± 4 [l]	$3.9^{+1.7}_{-1.3} \times 10^5$ [b]

Wolf et al. (2010)

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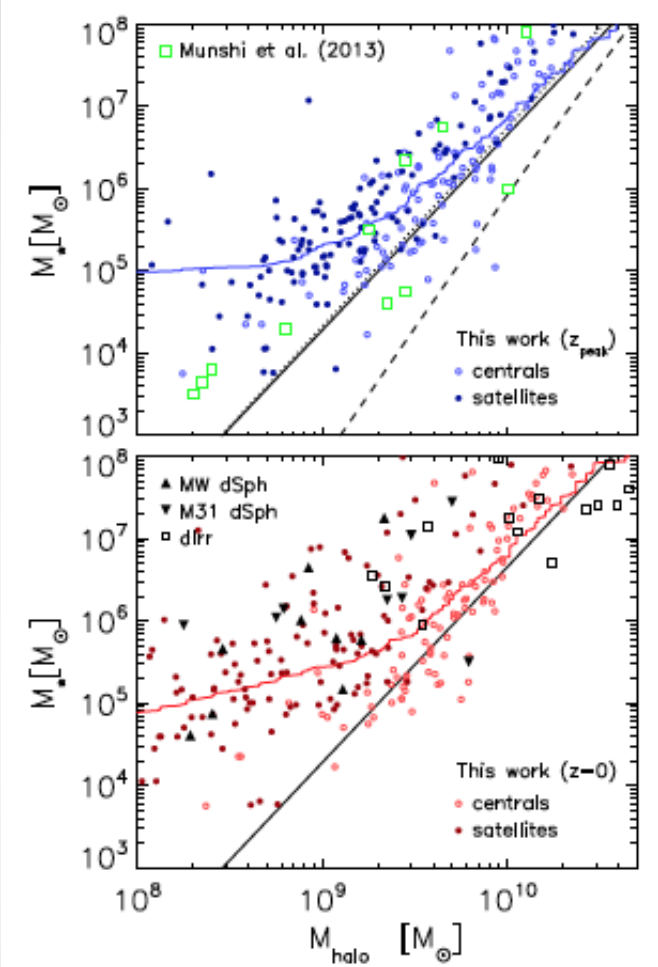
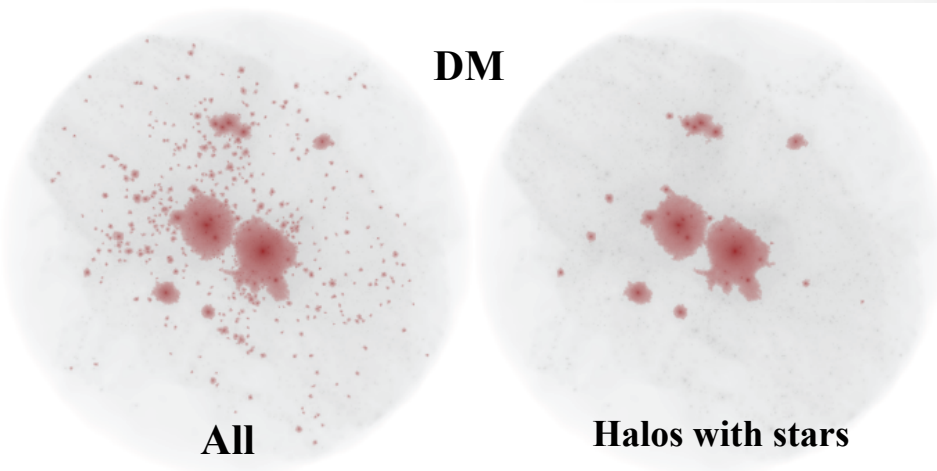
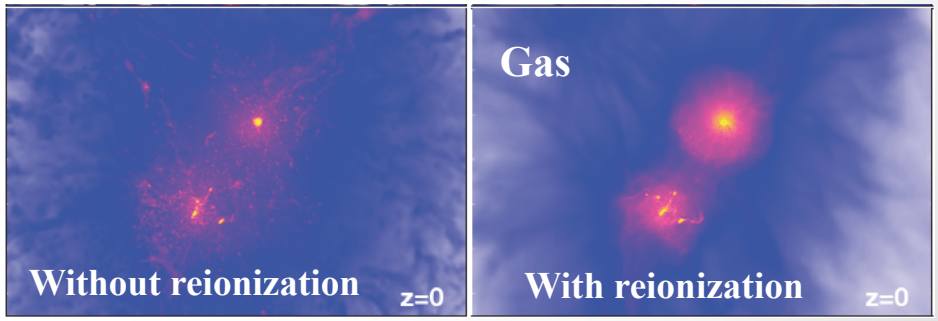
Hydrodynamic simulations of Local Group with reionization



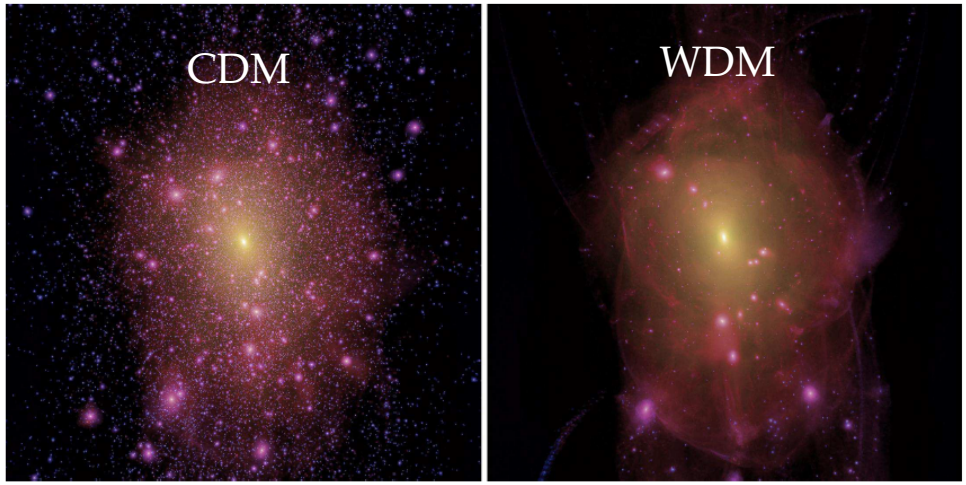
Label	Type	Particle Masses DM [$M_\odot$]	Particle Masses Gas [$M_\odot$]	Max Softening [pc]
L1	hydro	5.0×10^4	1.0×10^4	94
L1	DMO	6.0×10^4	–	94

Sawala et al. (2014)

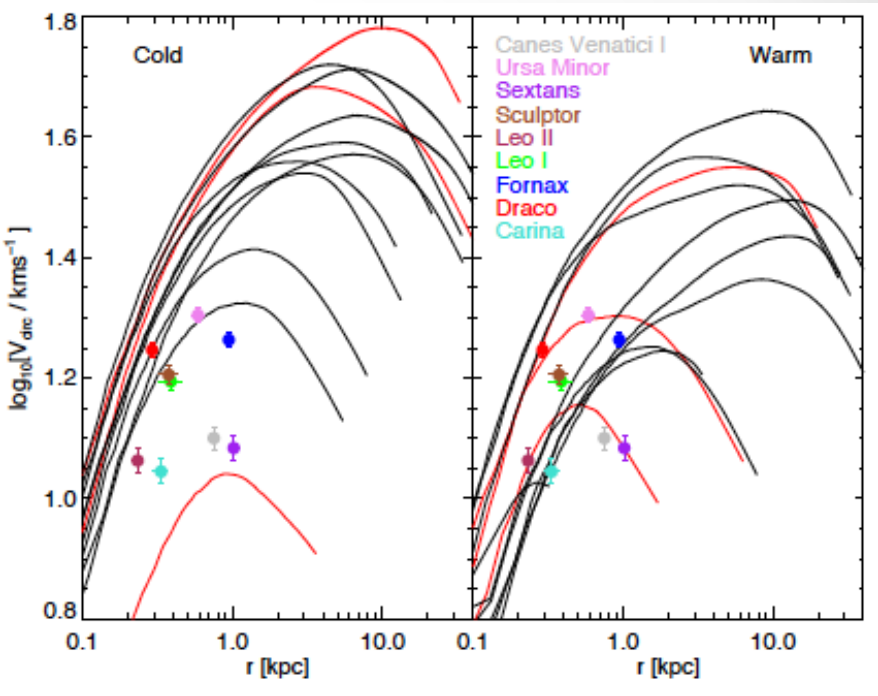




Warm Dark Matter Galactic Simulations

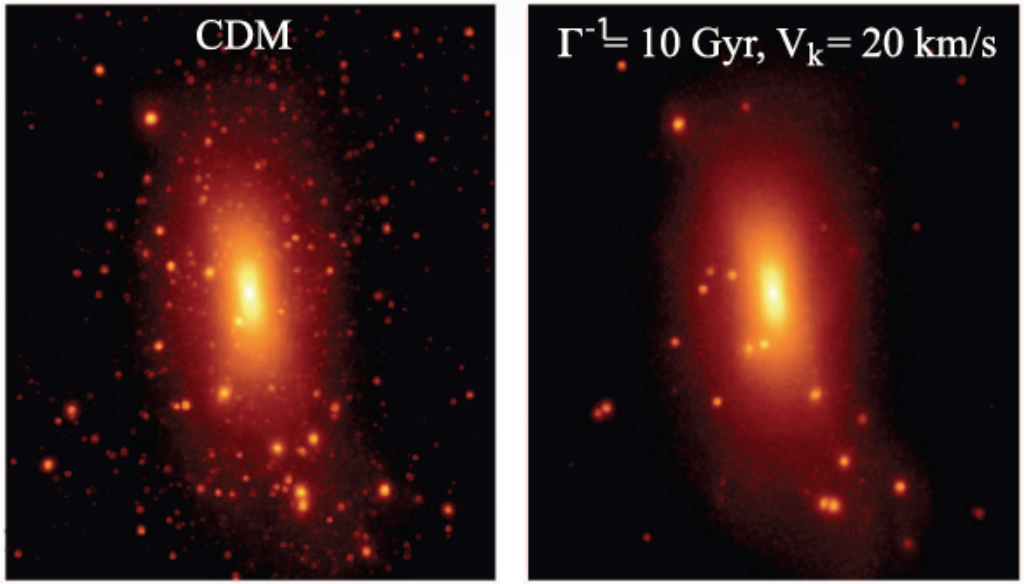


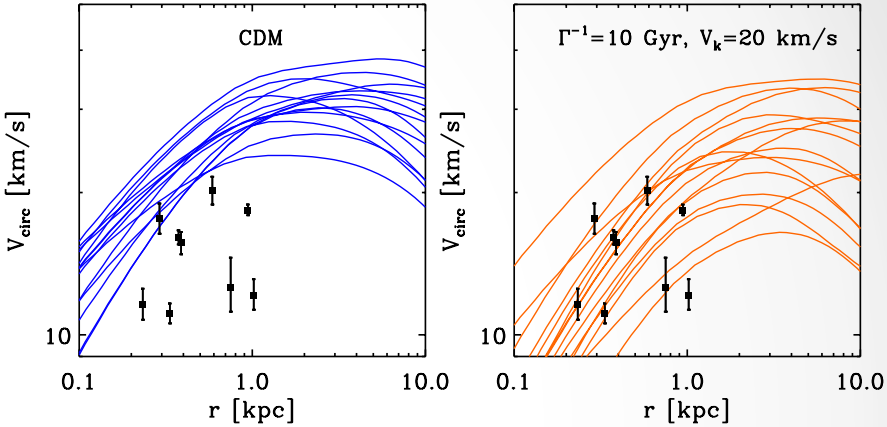
Lovell et al. (2012)



- Re-simulated Aquarius A level-2 simulation with WDM initial condition
- With resolution of highest-resolution particle mass and softening scale : $m_p = 1.4\times10^4 M_\odot$, $\epsilon = 65.8$ pc
- With two WDM mass (equivalent thermal relic mass) : 1.6 keV (ruled out by currently Lyman-alpha forest), 2.3 keV (allowed)

Decaying DM Galactic Zoom-in Simulations





M.W. (2014), arXiv:1406.0527

- Modified version of Gadget3 to include the decaying dark matter physics in N-body simulation (Peter et al. 2010)
- With resolution of highest-resolution particle mass and softening scale :

m_p=2.4 × $10^4 M_\odot$, ϵ=72pc

- A Monte-Carlo simulation at each time step t to determine whether a particle should decay with decay probability P = **Δ**t Γ.
- Decay models simulated are well-within the parameter space allowed by current astrophysical limit (Lyman-alpha forest)

Late-Decay Dark Matter

Cen (2001), Sanchez-Salcedo (2003), Kaplinghat (2005), Strigari et al. (2007), Peter (2010), Peter et al. (2010), M.W. & Zentner (2012), Aoyama (2010, 2014)

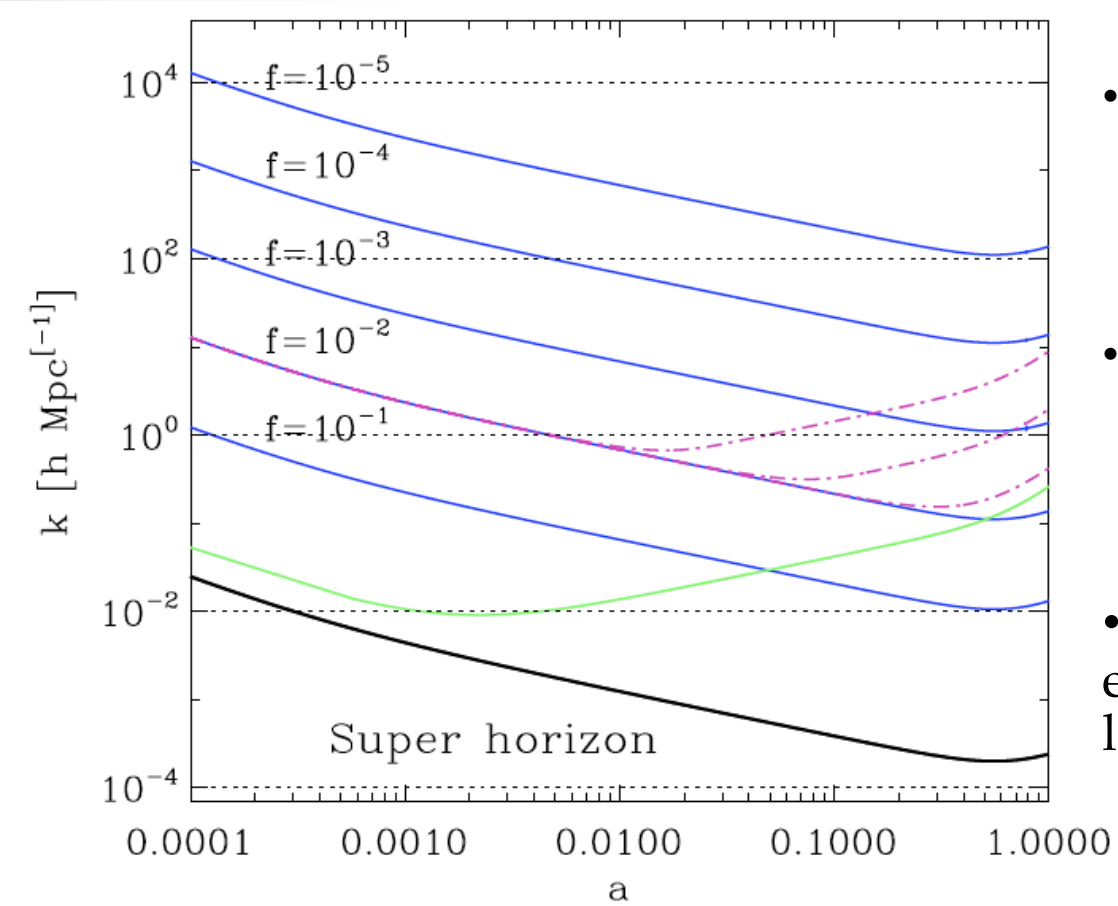
- A dark matter particle decays into a slightly less massive stable dark matter particle and an non-interacting comparably light particle via two-body decay.

=> The mass splitting ($f = \frac{\Delta M}{M}$) introduces a recoil kick velocity (V_k) to the stable dark matter relative to the original dark matter due to momentum conservation.

- Two parameters : decay lifetime(Γ^{-1})and mass splitting($f \approx \frac{V_k}{c}$).

We consider lifetime around the order of Hubble time.

Free-streaming Scale of Decaying Dark Matter



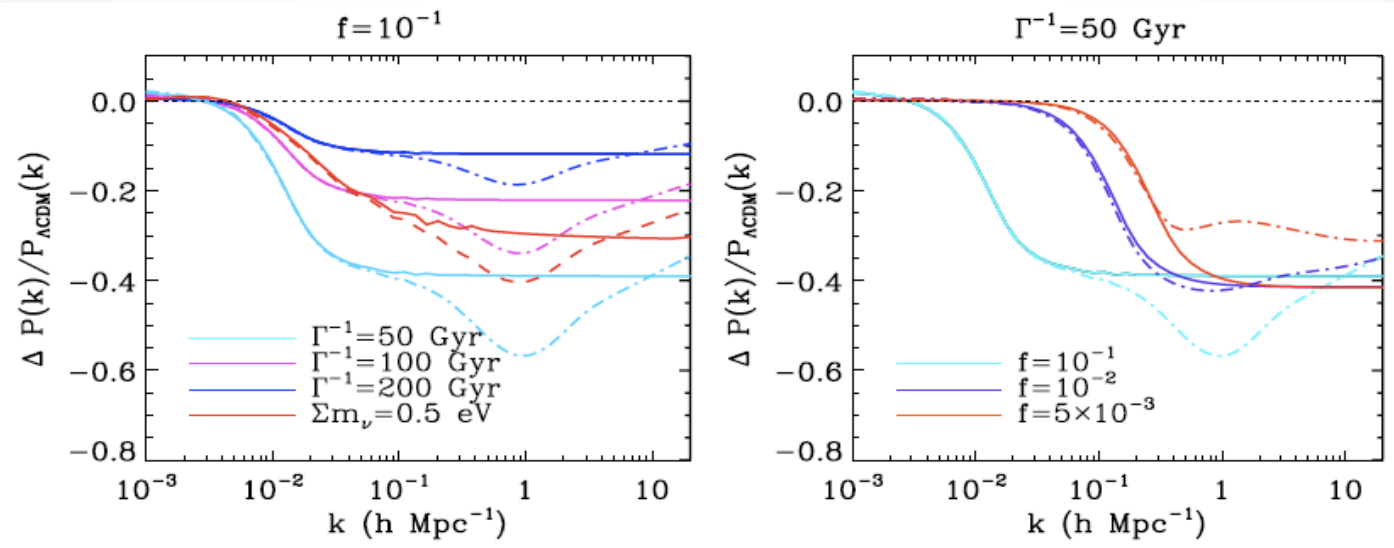
M.W. & Zentner (2012)

- Lifetime >> the age of universe :
  constant sound speed
  => ks traces horizon
  (blue lines)

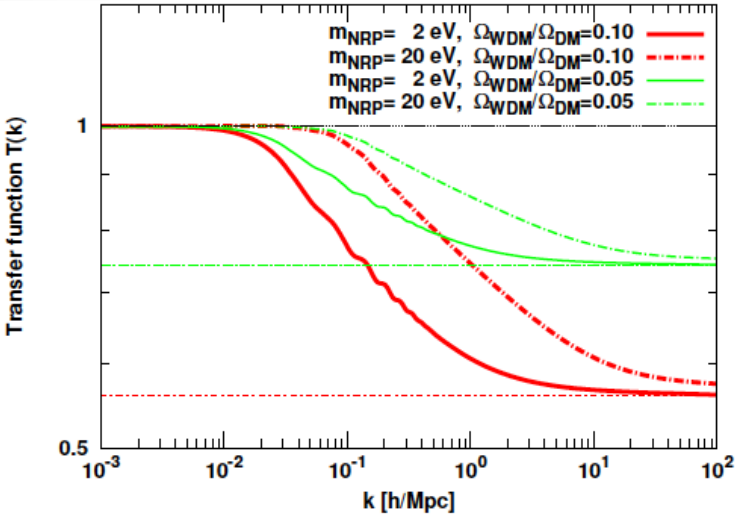
- Lifetime << the age of universe :
  sound speed redshift away
  after decay process is done.
  => ks decreases (purple lines)

- SM Neutrinos : relativistic at early time and non-relativistic at late time. (green)

A Mixture of Cold+Warm Dark Matter



M.W. & Zentner (2012), DDM model

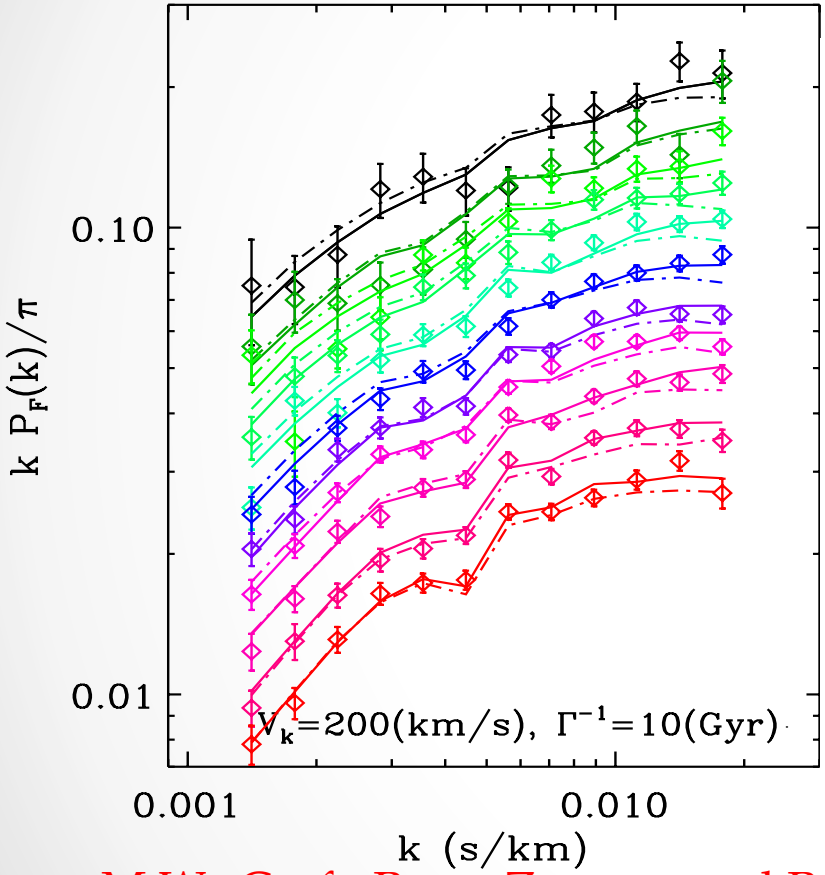


The effects on matter power spectrum are similar to a mxiture of WDM + CDM. However the redshift evolution is quite different.

Boyarsky et al. (2009), cold + warm DM

Limits on Decaying DM models

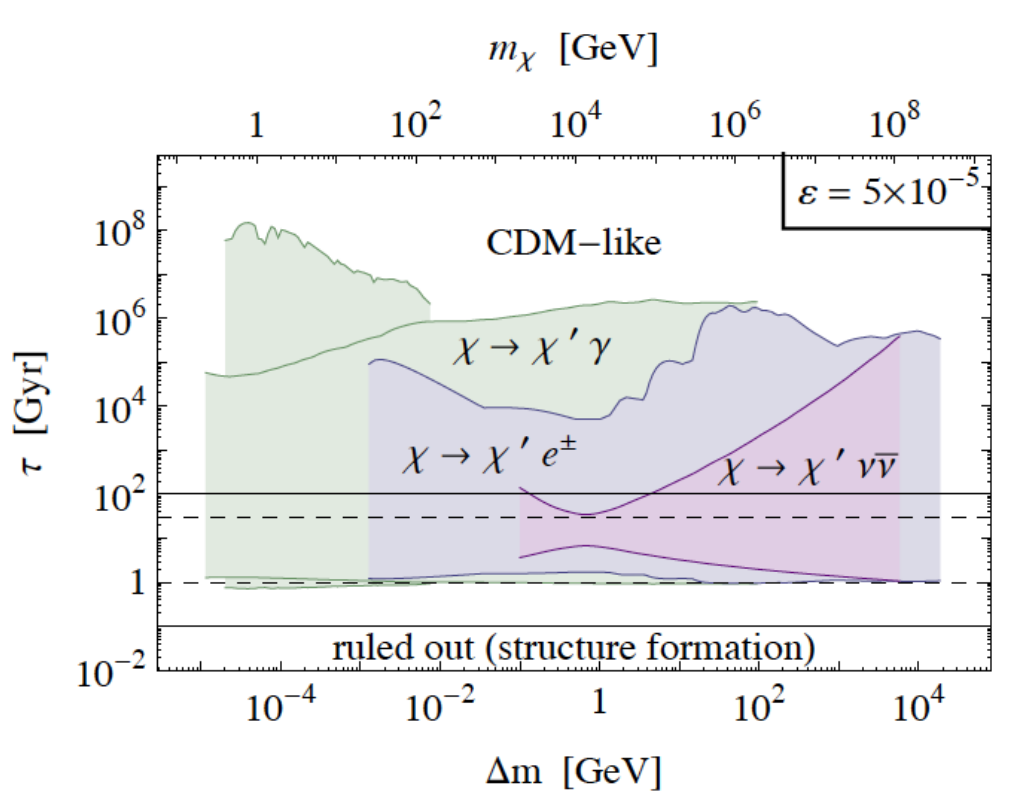
Limits from DM free-streaming



M.W., Croft, Peter, Zentner, and Purcell (2013)

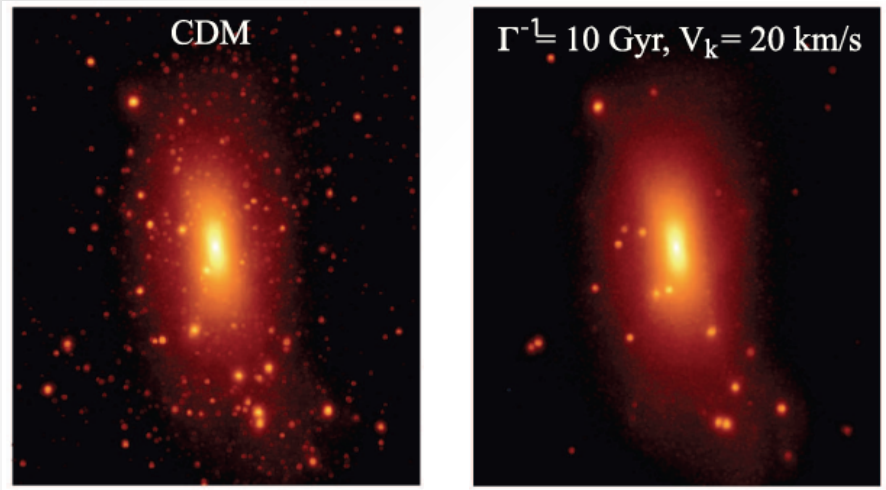
SDSS Lyman-alpha forest data (McDonald et al (2006))

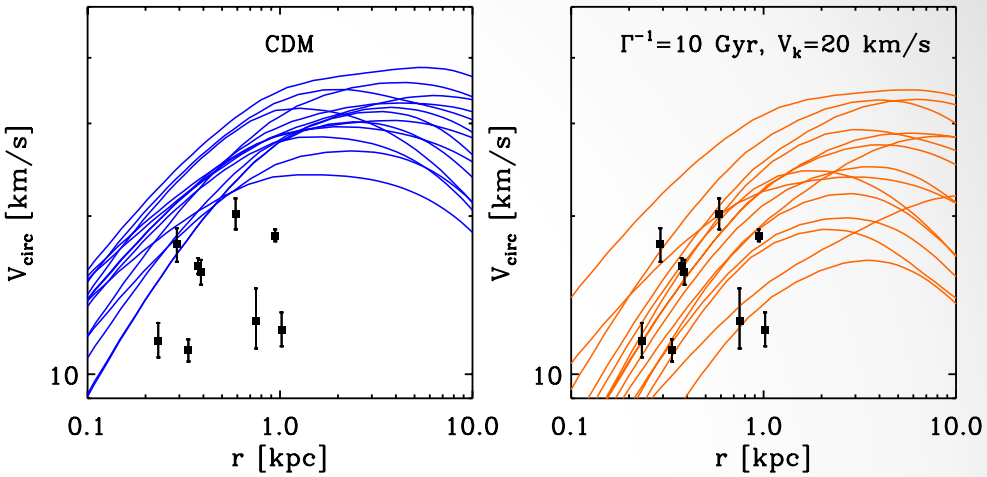
Limits derived using decay products



Bell et al. (2010)

Decaying DM Galactic Zoom-in Simulations





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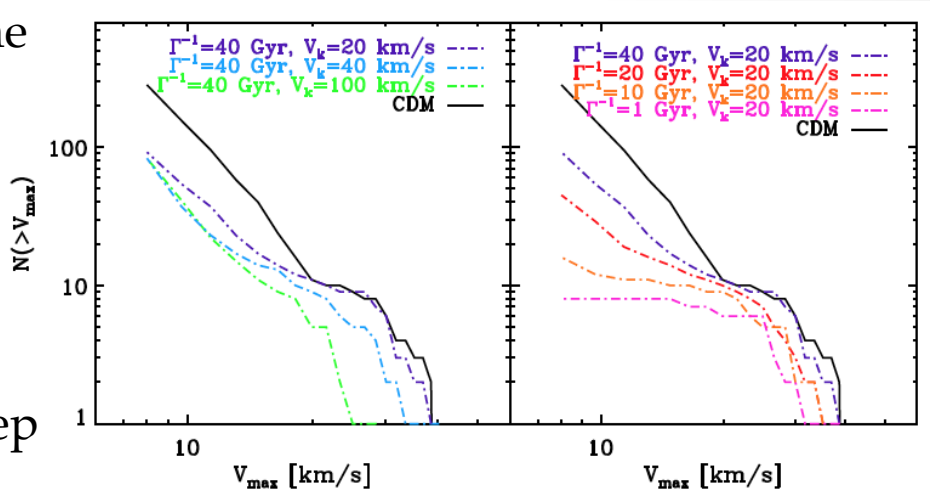

M.W., Peter, Strigari, Zentner, Garrison-Kimmel, Rocha, and Arant (2014) arXiv:1406.0527

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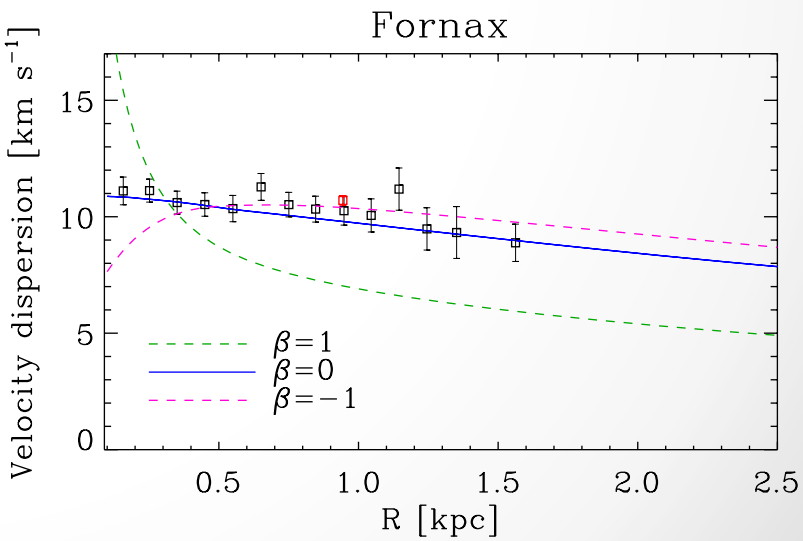
Spherical Jeans Equation

$$r\frac{d(\rho_\star\sigma_r^2)}{dr} = -\rho_\star(r)GM(r)/r - 2\beta(r)\rho_\star\sigma_r^2$$

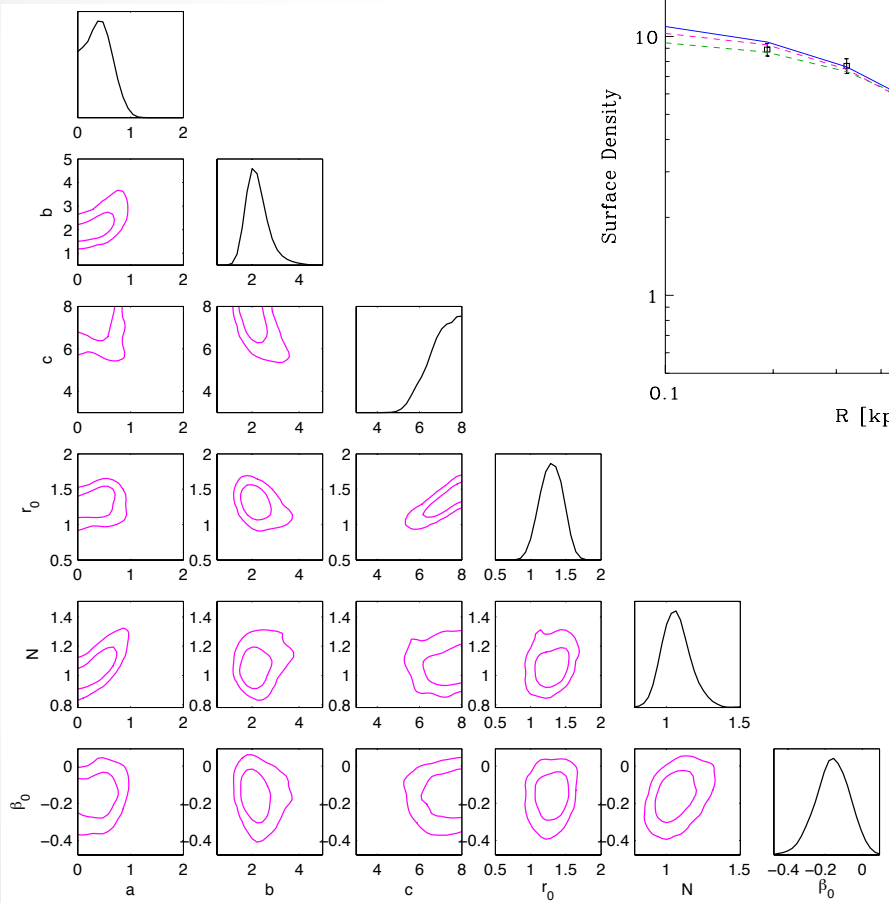
$$\sigma_{los}^2(R) = \frac{2}{I_\star(R)}\int_R^\infty \left[1-\beta(r)\frac{R^2}{r^2}\right]\frac{\rho_\star(r)\sigma_r^2\, r}{\sqrt{r^2-R^2}}dr,$$

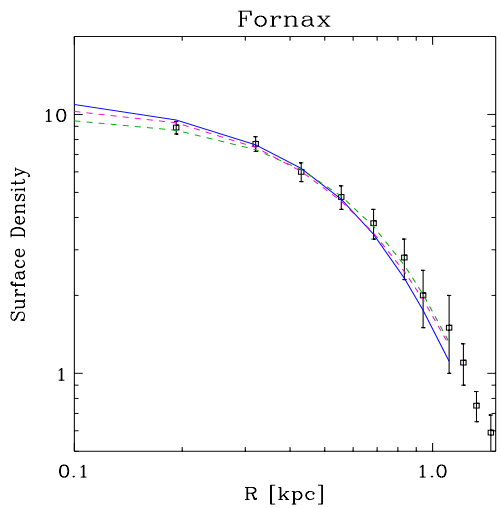
$$\beta(r) \equiv 1 - \sigma_t^2/\sigma_r^2$$

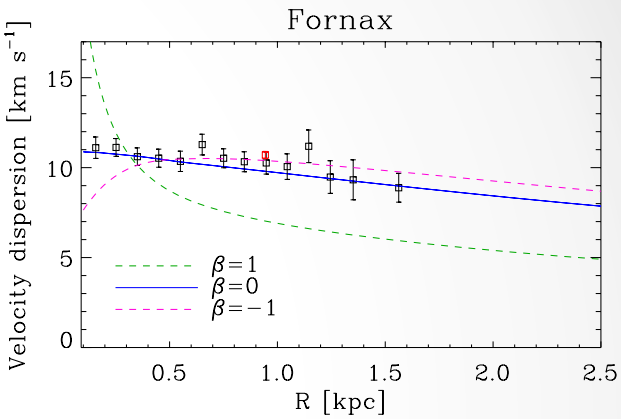
- We assume $\beta(r) = \text{const.}$ models



Markov chain Monte Carlo method for fitting Velocity dispersion +photometry data







$$\rho_\star(r) \propto \frac{1}{x^a(1+x^b)^{(c-a)/b}}$$

$$x = r/r_0$$

$$\chi^2 = \chi^2_\sigma + \chi^2_{photometry}$$

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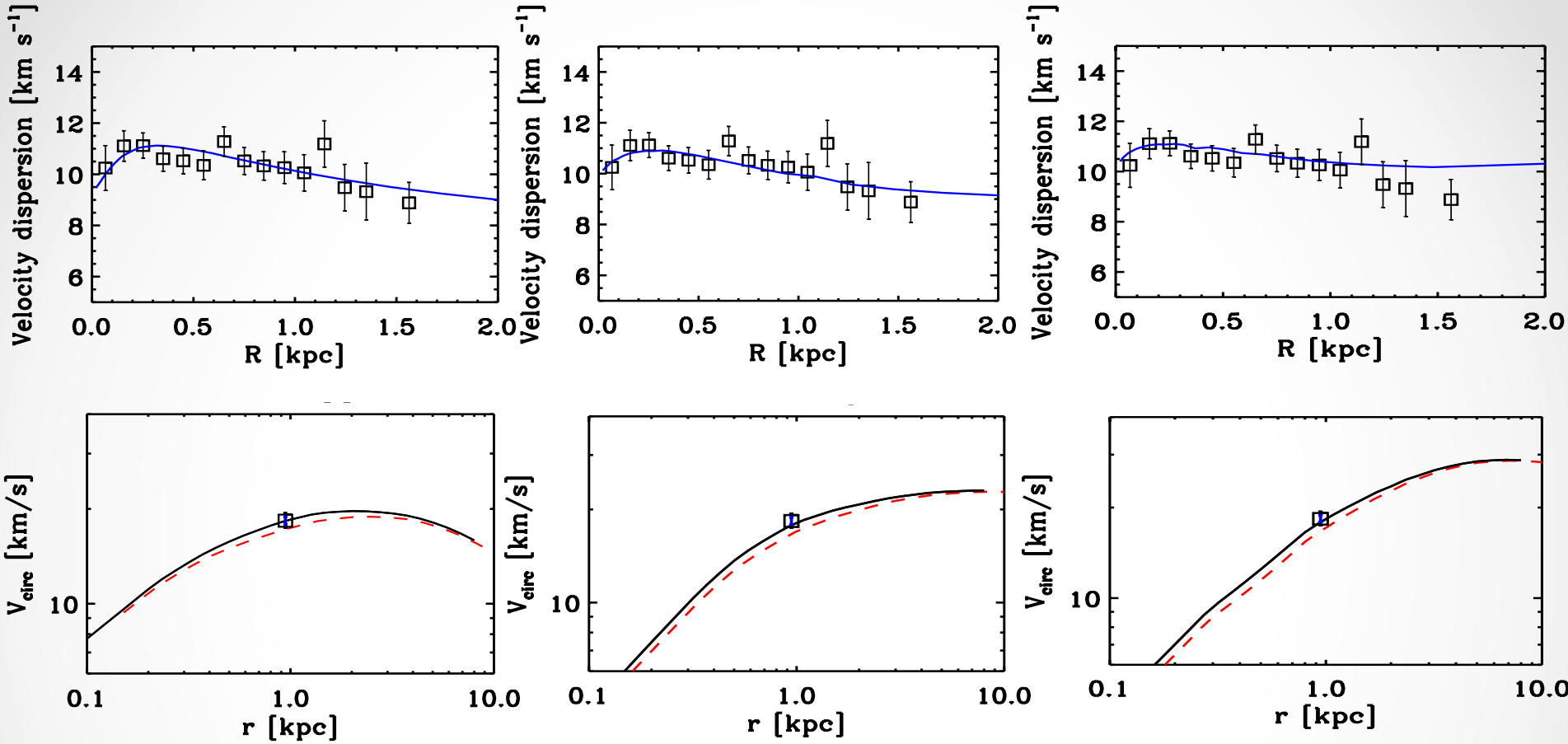
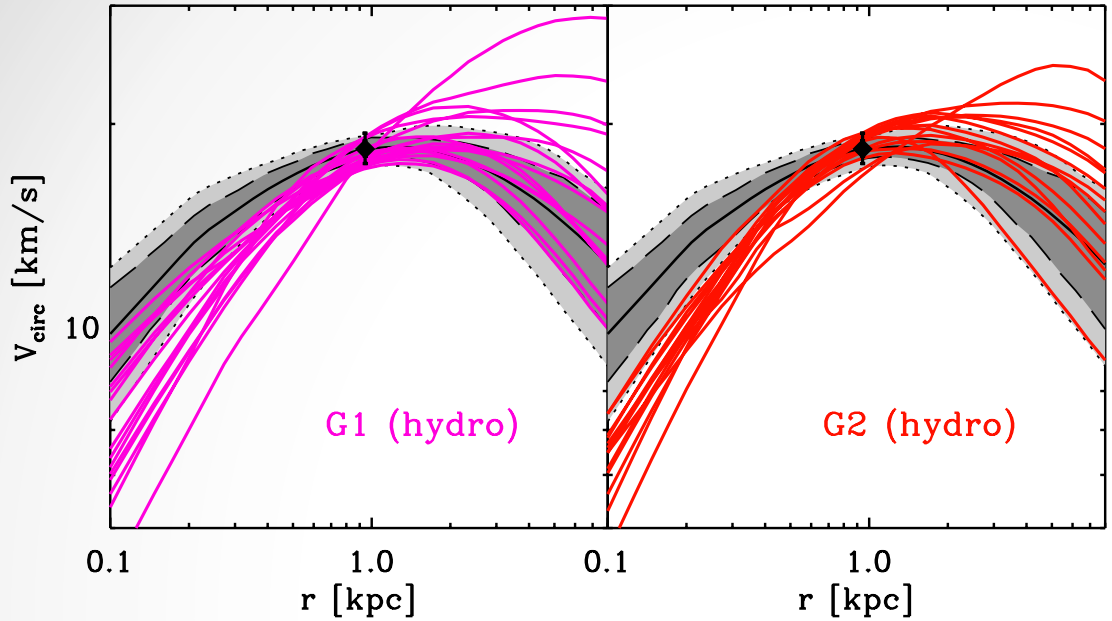
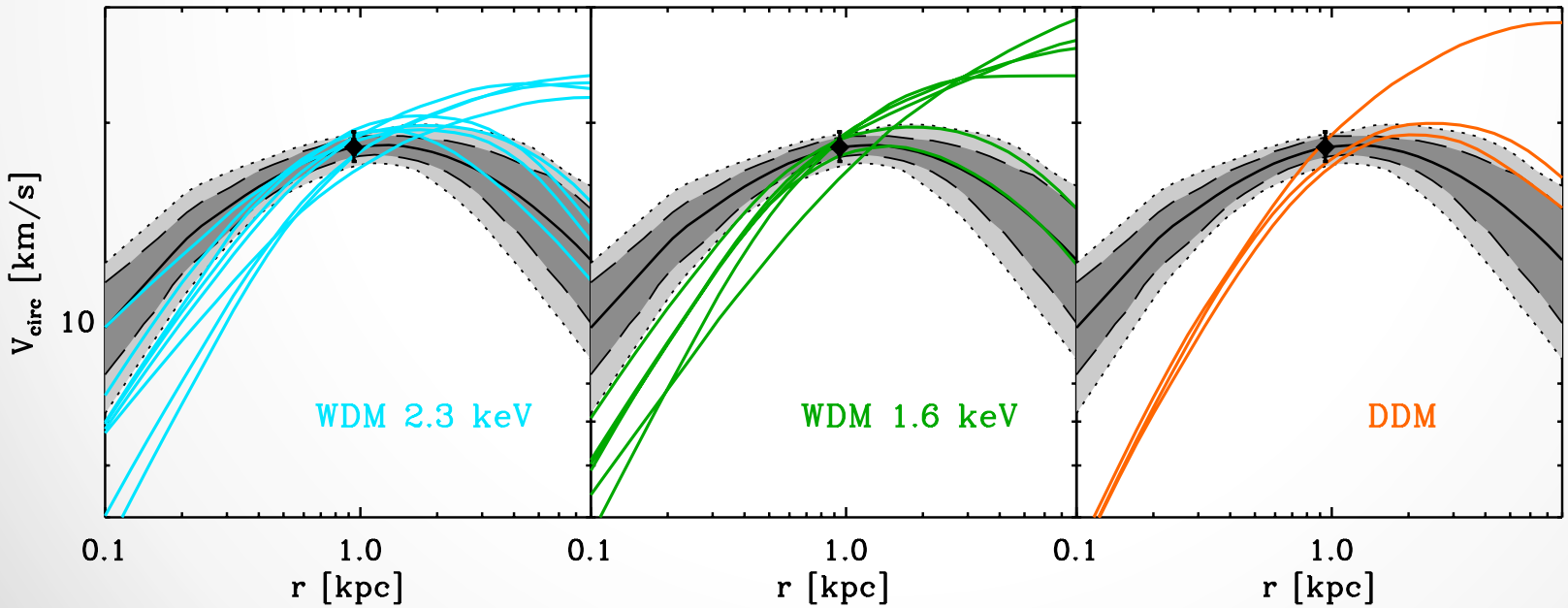


CDM	WDM 2.3 keV	Hydro-simulation
$M_{sub} = 5.08 \times 10^8 M_\odot$	$M_{sub} = 1.96 \times 10^9 M_\odot$	$M_{sub} = 2.43 \times 10^9 M_\odot$
$V_{max} = 18.9$ km/s	$V_{max} = 22.4$ km/s	$V_{max} = 28.9$ km/s
$\chi^2_\sigma/d.o.f. = 0.782$	$\chi^2_\sigma/d.o.f. = 0.773$	$\chi^2_\sigma/d.o.f. = 0.95$
$\beta = -0.5$	$\beta = -0.08$	$\beta = 0.17$

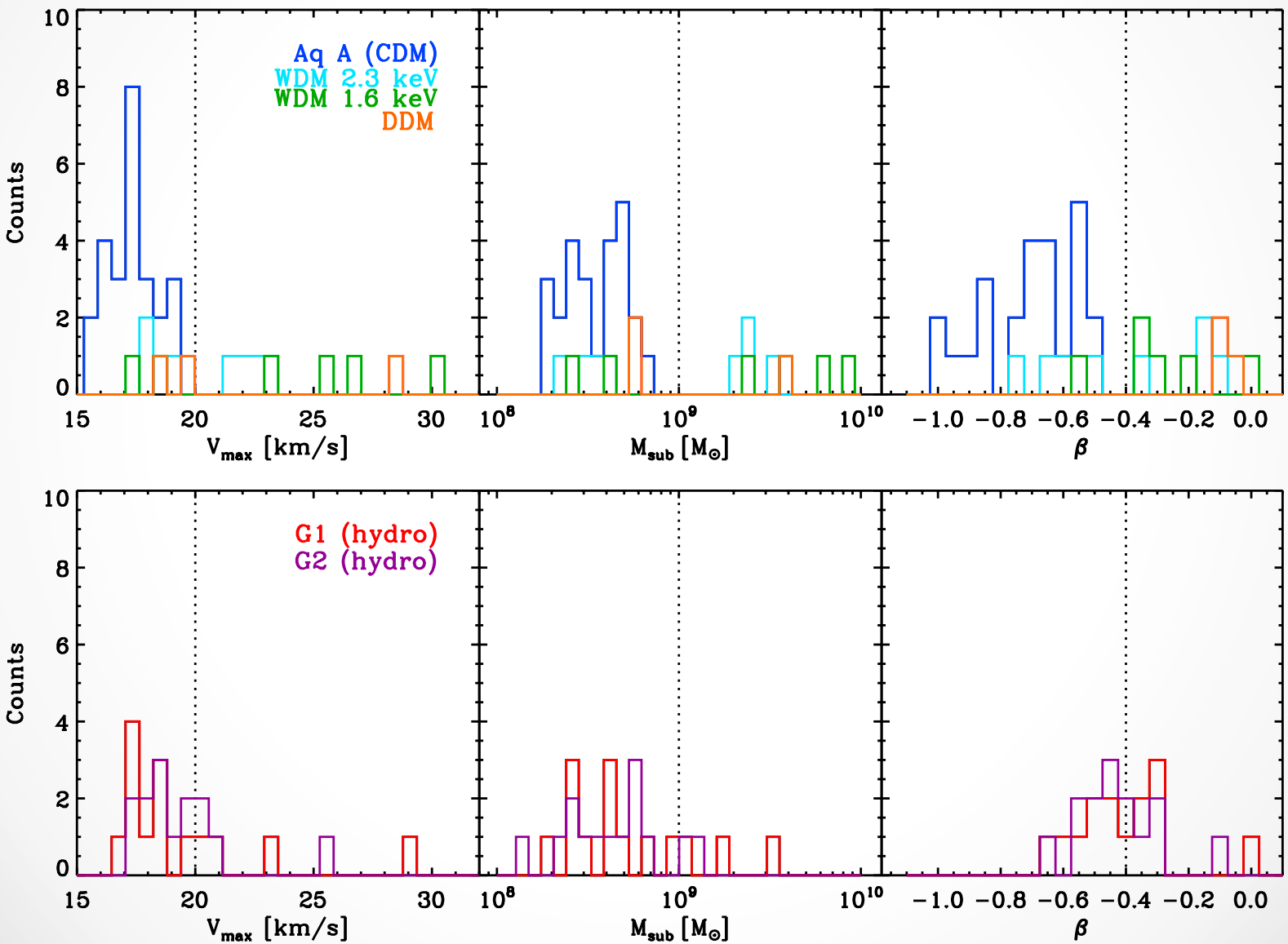


- Diamond point (2σ) : Wolf et al. (2010)
- Grey bands (68 % & 95 %): Aquarius simulation fits

Mass estimation is the tightest at the Fornax 3D half-light radius, which agrees well with the Wolf et al. 2010 results.



Subhalo properties of Fornax Good-fits



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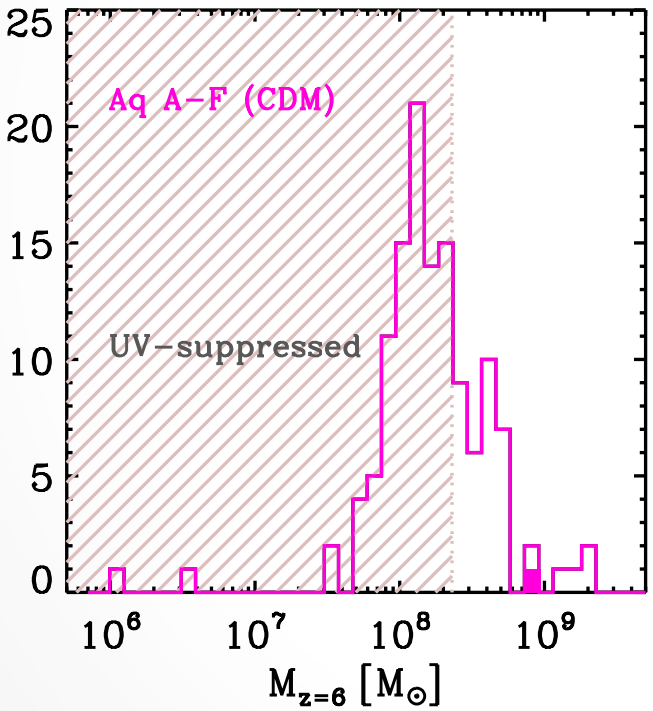
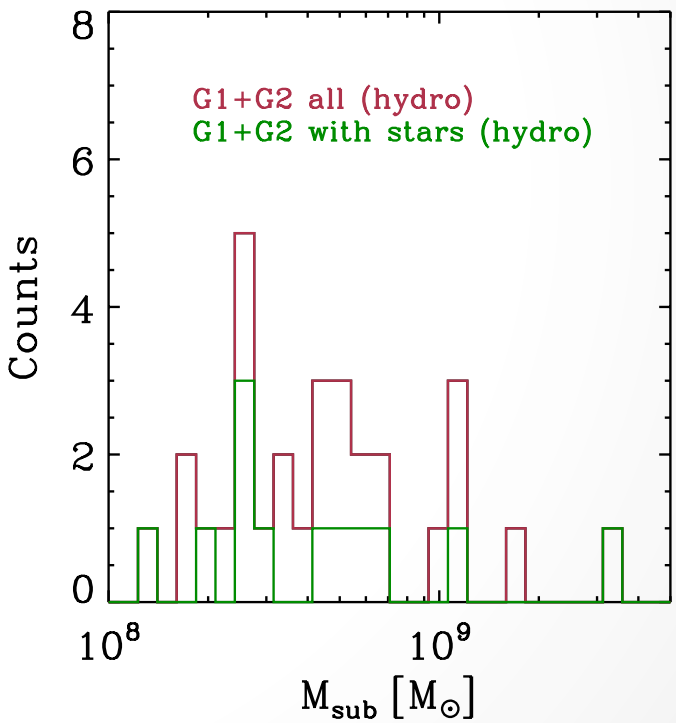
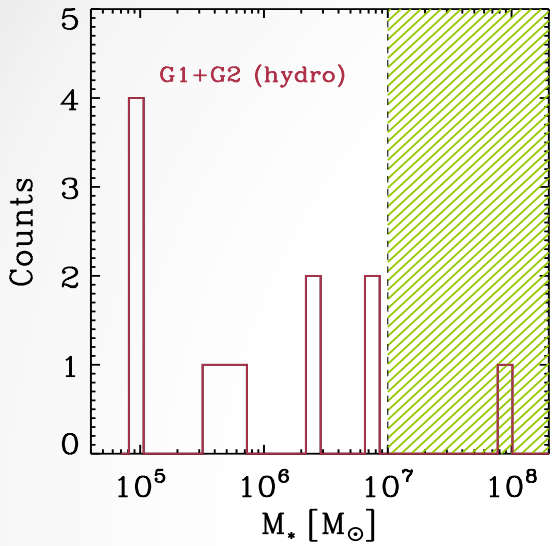
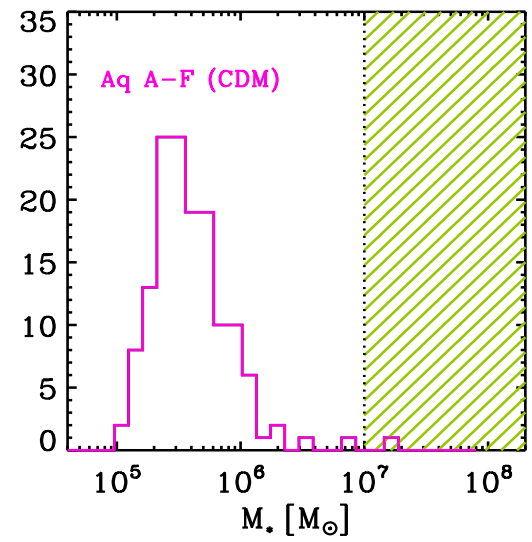
Most of the candidates may not be visible – Killed by reionization ?





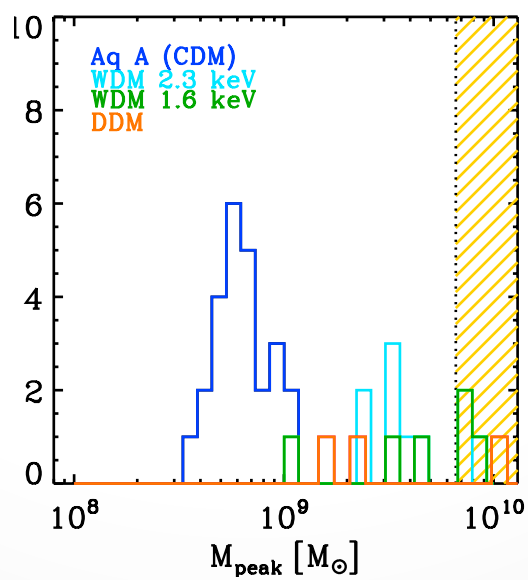
(Implied) Stellar mass for Fornax

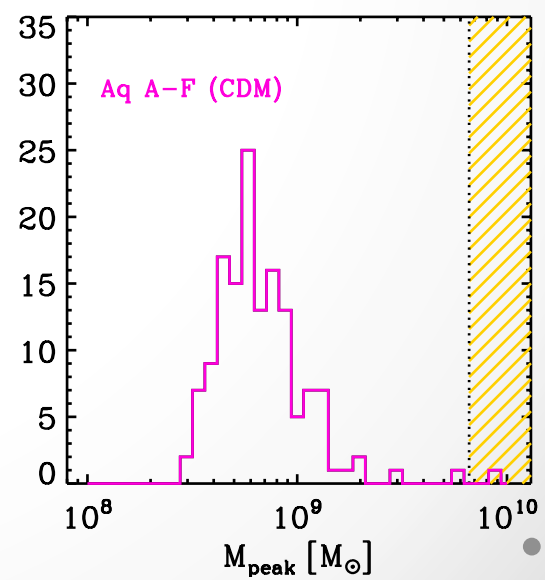




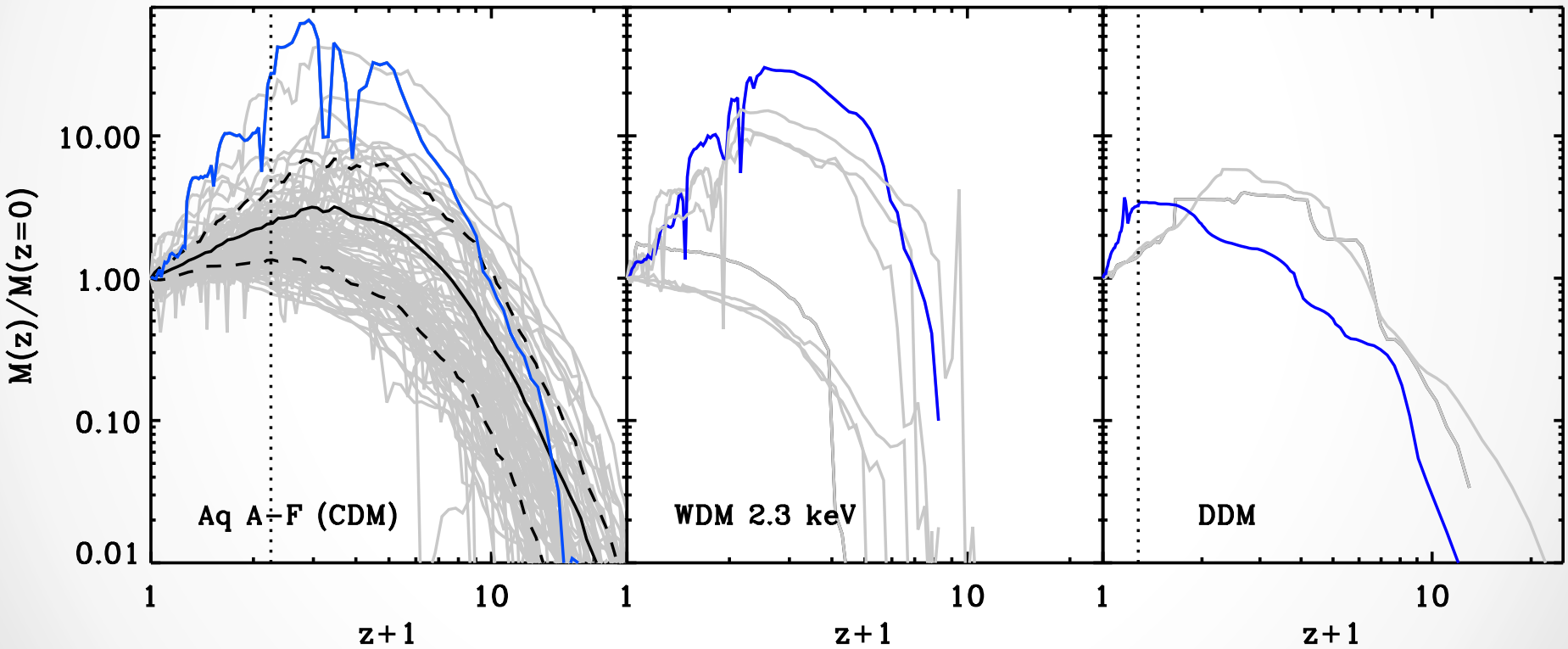
Hydrodynamic simulations

Abundance matching





Implied subhalo formation history -- Severe tidal stripping or not?



Work in progress

- Star-formation histories (SFHs), metallicity…in hydrodynamic simulations.
- Stellar orbits (calculating anisotropy parameter β)

=> See Hubble white paper from Kallivayalil et al.(2015) regarding ideas for measuring stellar proper motions in MW dwarf satellites.

Conclusion

- Both galaxy formation physics and alternative DM models can change the inner structure of galactic subhalos.
- For a given subhalo potential, different cosmologies predict different subhalo properties (subhalo mass, Vmax, stellar orbit properties)
- Even though there are many good candidates for matching Fornax kinematic data, only a few also provide the correct luminosity prediction. This indicate that Fornax data may have predicted certain particular star and halo formation history, and whether or not its subhalo have been severely tidally stripped may reveal certain properties of dark matter.