Impacts of Alternative Dark Matter Models on Milky Way Satellite Kinematics

Mei-Yu Wang

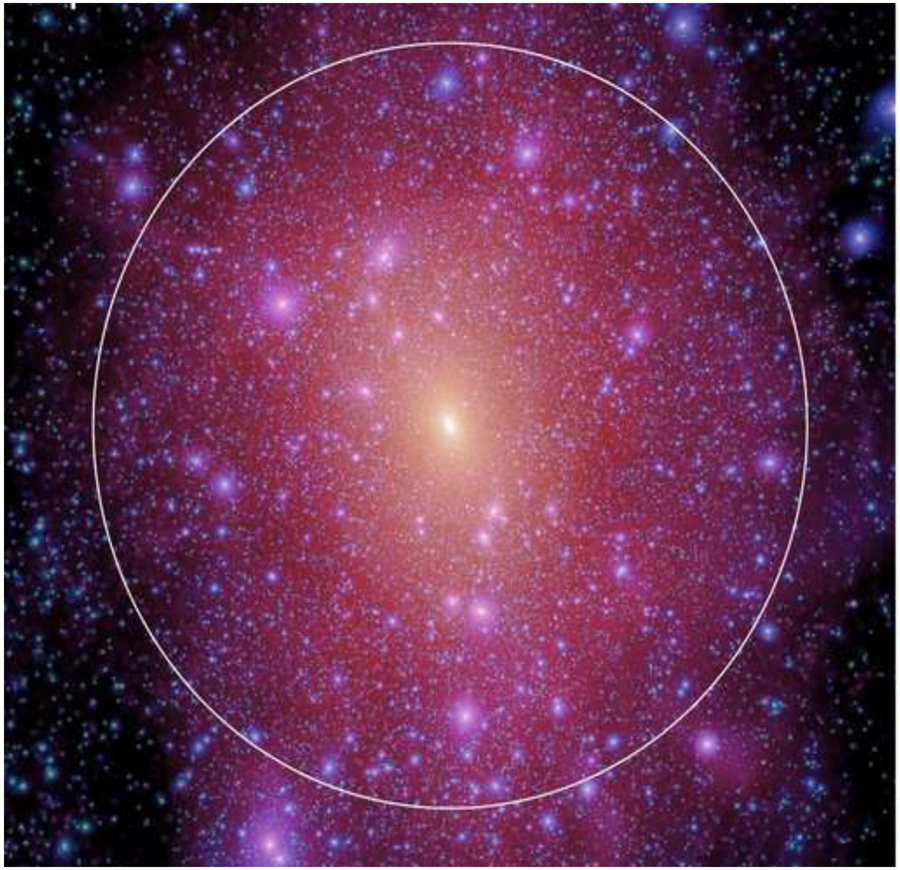
Texas A&M University

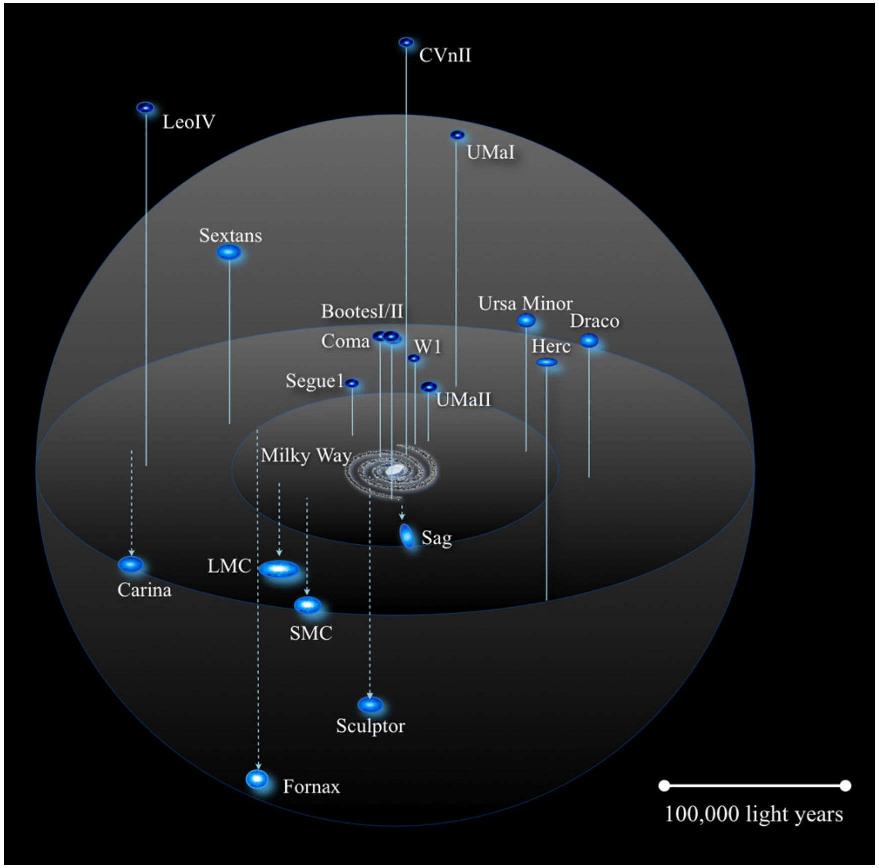
With

L. Strigari, M. Lovell, C. Frenk, and A. Zentner

(work in preparation)

Galactic Dark Matter Halo & Subhalos

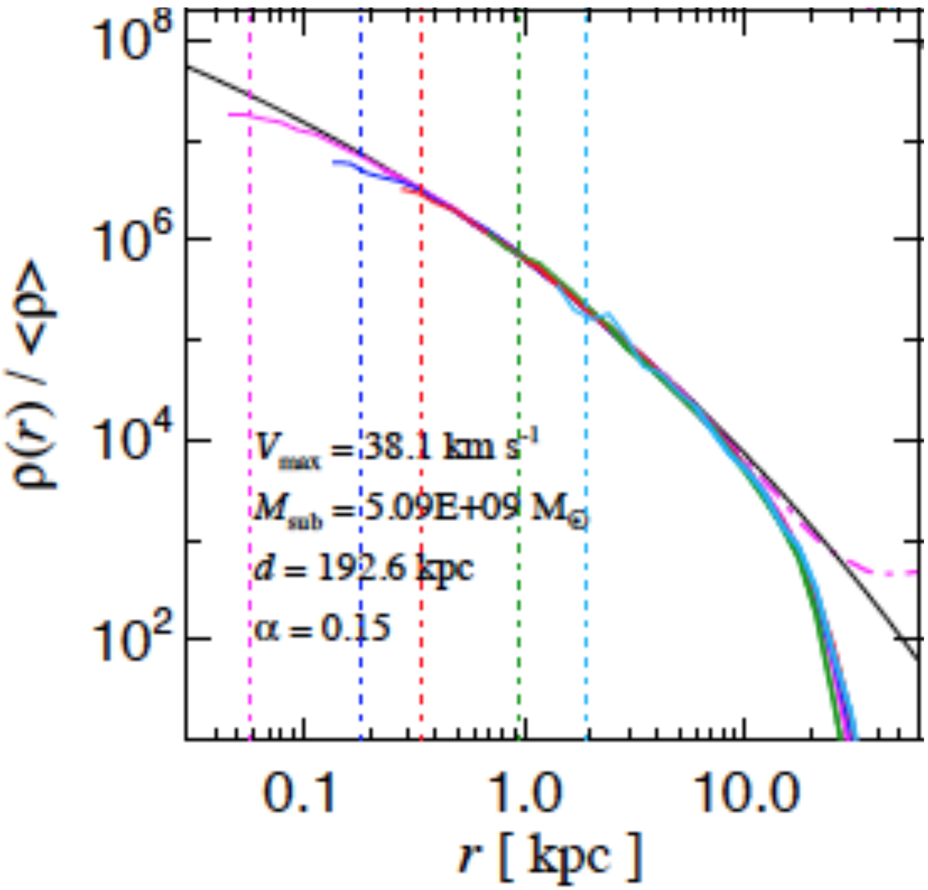




Aquarius Simulations

Springel et al. (2012)

Inner Structure of Subhalos



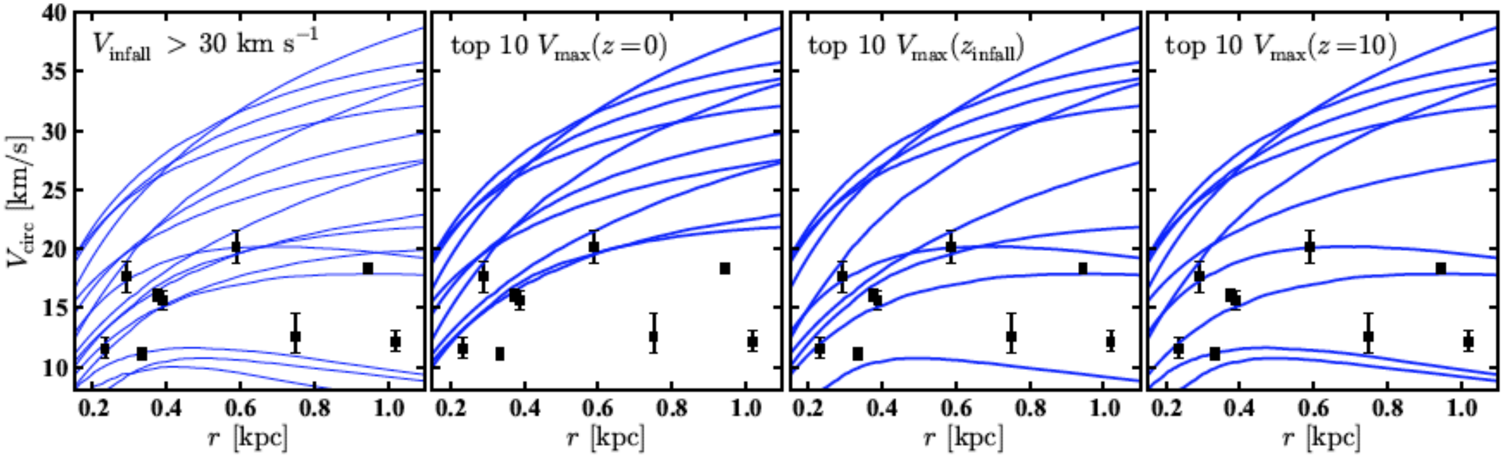
Springel et al. (2012)

NFW profile
(Navarro-Frenk-White)

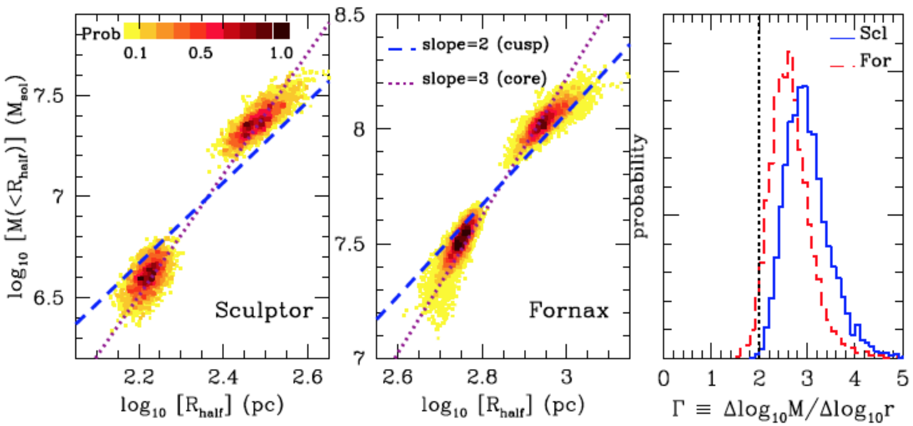
$$\rho(r) = \frac{\delta_c \, \rho_{\rm crit}}{(r/r_s)(r/r_s + 1)^2}$$

Einasto profile

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



Boylan-Kolchin et al. (2012)

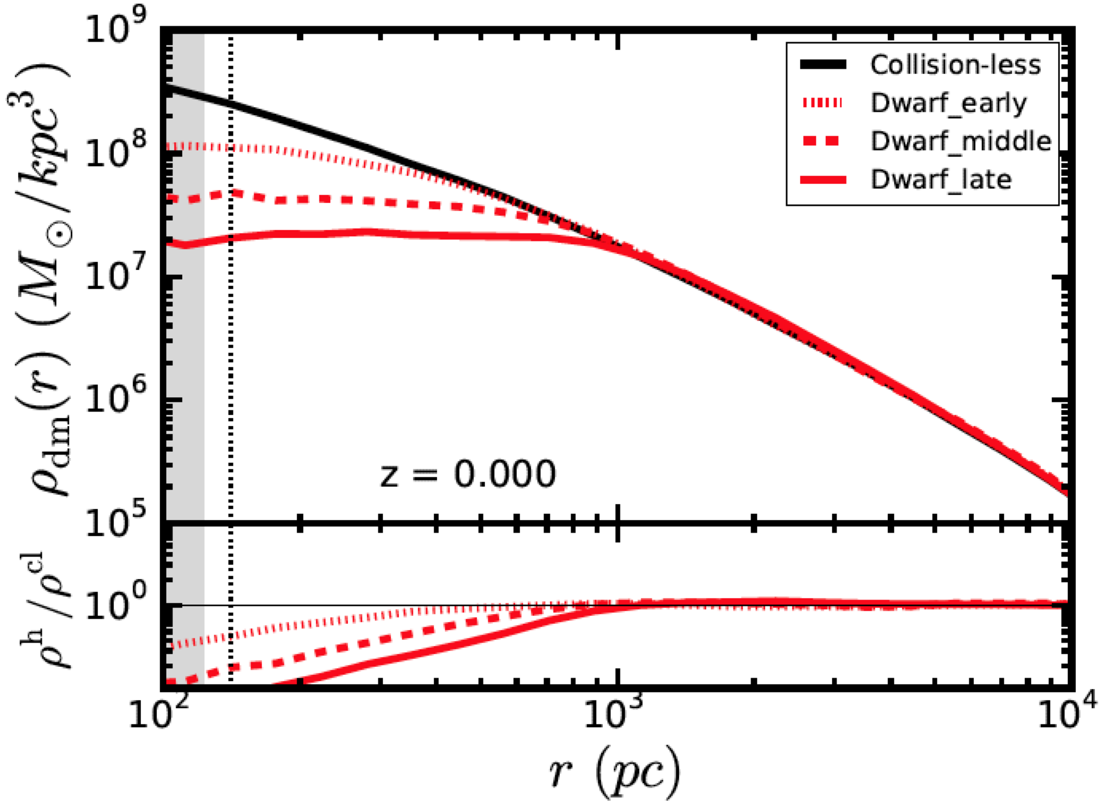


Walker & Penarrubia (2011)

- Too Big to Fail Problem
- Core/Cusp Problem

How do we make subhalo profile shallower?

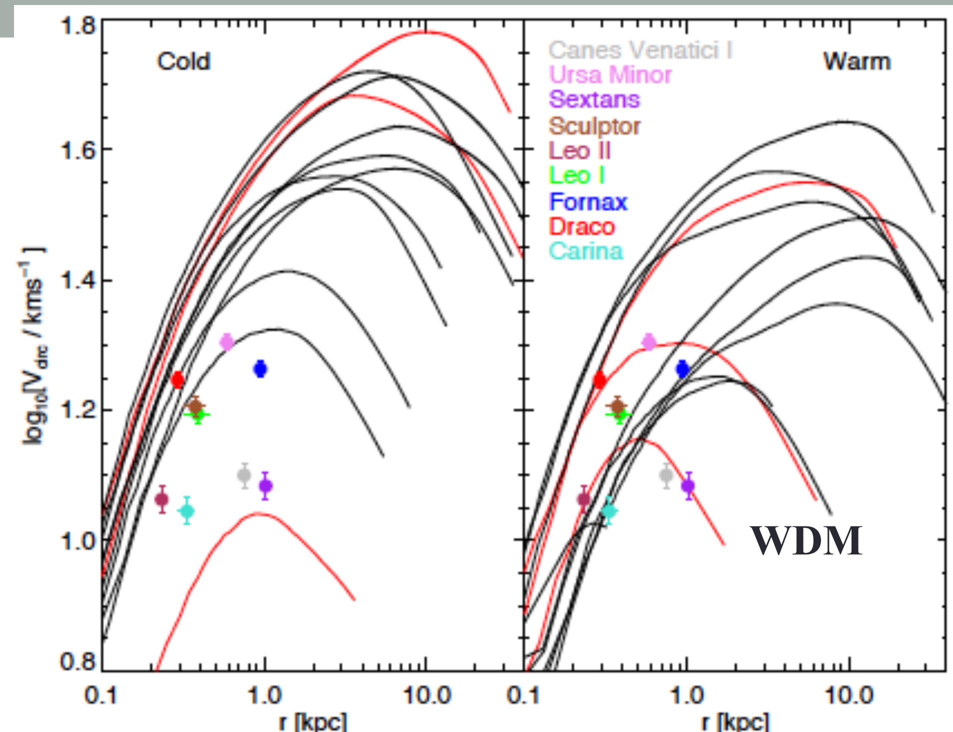
Stellar feedback from galaxy formation



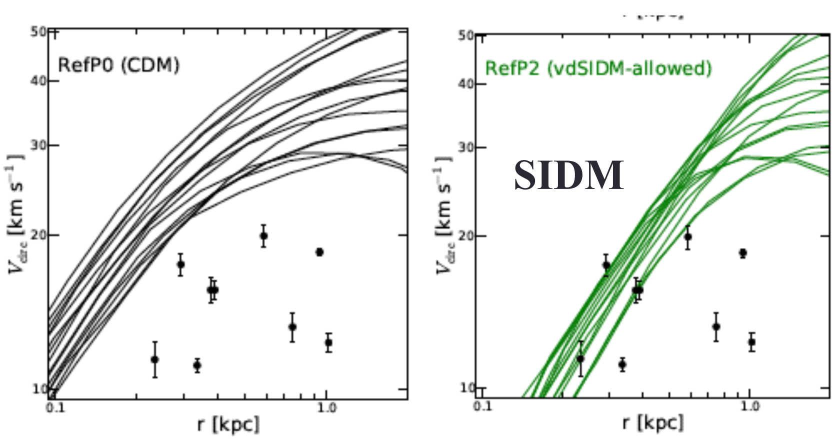
Oñorbe et al (2015)

Alternative DM models

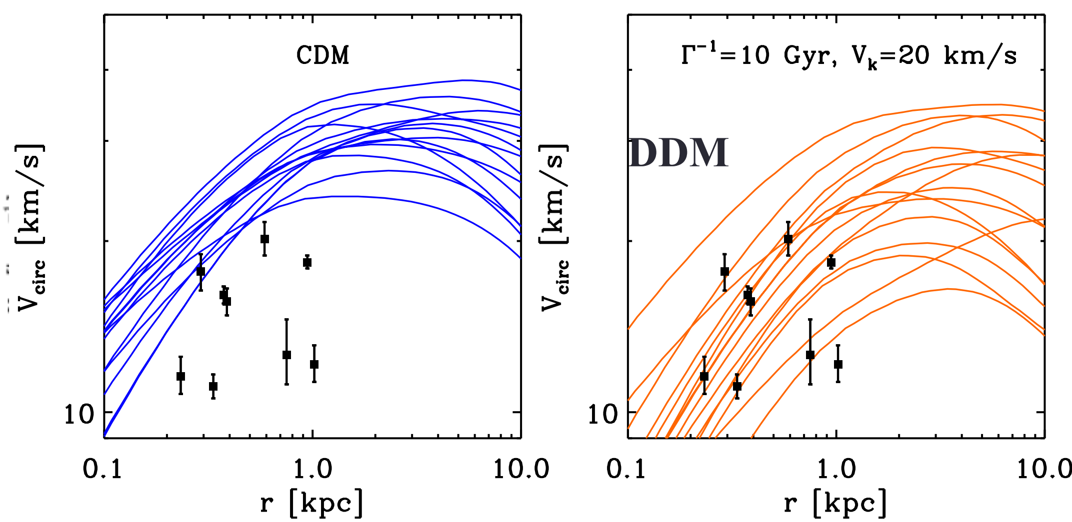
- Warm Dark Matter (WDM)
- Self-interacting Dark Matter (SIDM)
- Decaying Dark Matter (DDM)



Lovell et al. (2012)



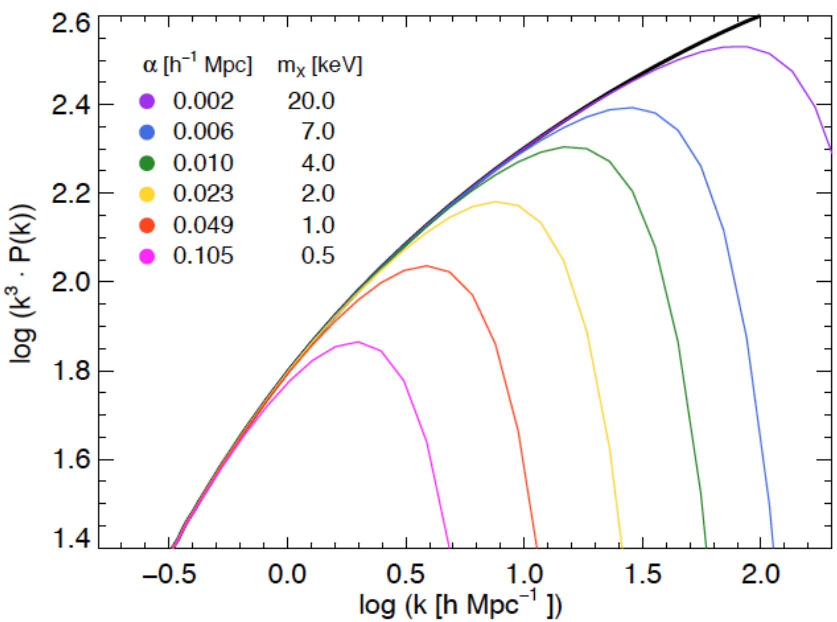
Vogelsberger et al. (2012)



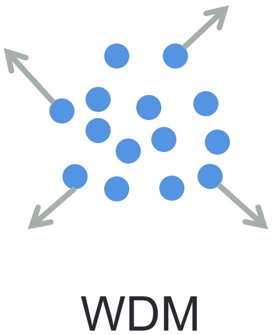
MW et al. (2014), arXiv:1406.0527

Warm Dark Matter (WDM)

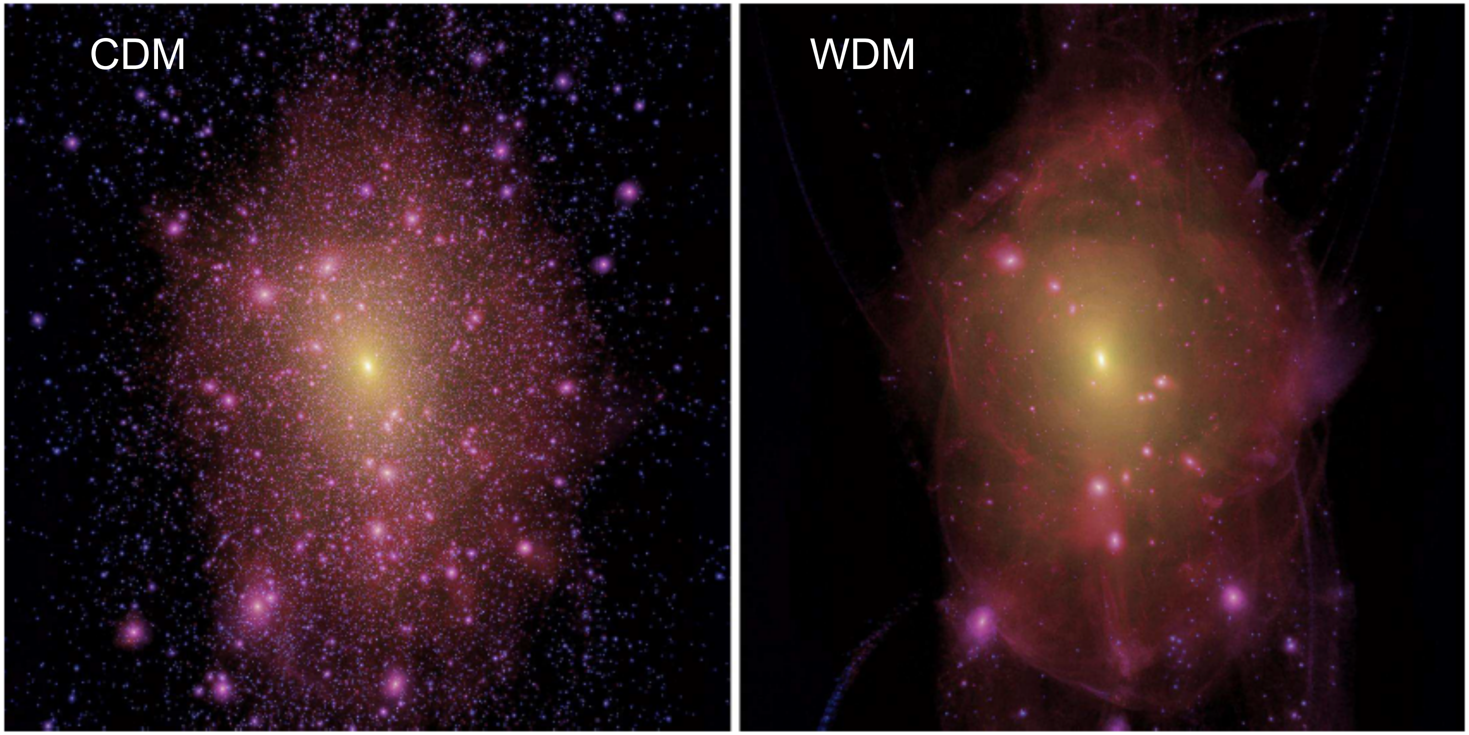
- The free-streaming effects from the DM non-negligible non-thermal velocity suppress the structure formation
- Current Lyman-alpha forest limits: m > 2-3 keV



Kennedy et al. (2013)



Warm Dark Matter Galactic Simulations



Lovell et al. (2012)

- DM halos are formed later than their CDM counterparts and have less concentrated profiles.
- We consider two WDM mass (equivalent thermal relic mass) : 1.6 keV (ruled out by currently Lyman-alpha forest), 2.3 keV (allowed)

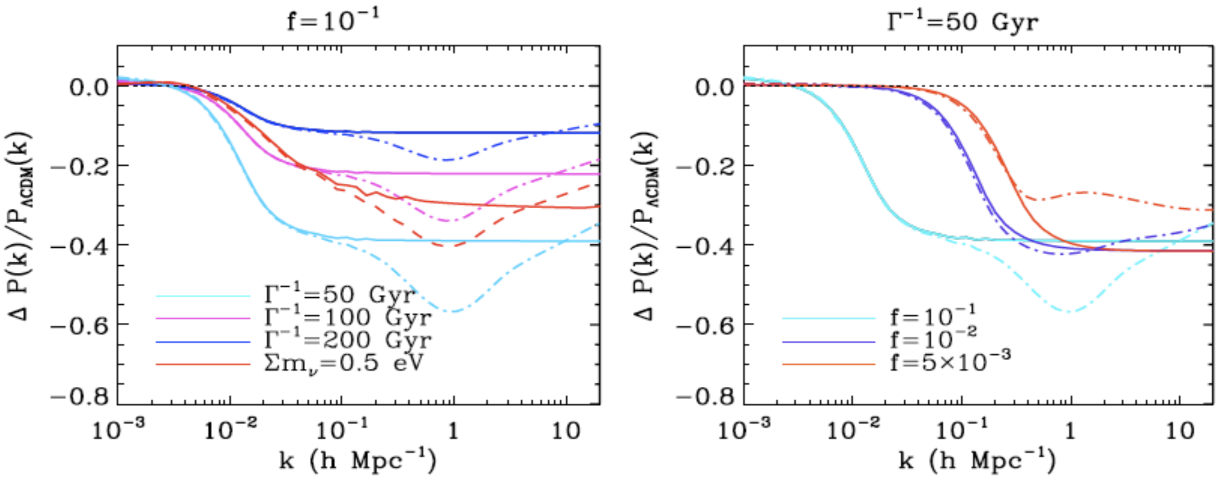
Decaying Dark Matter (DDM)

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.

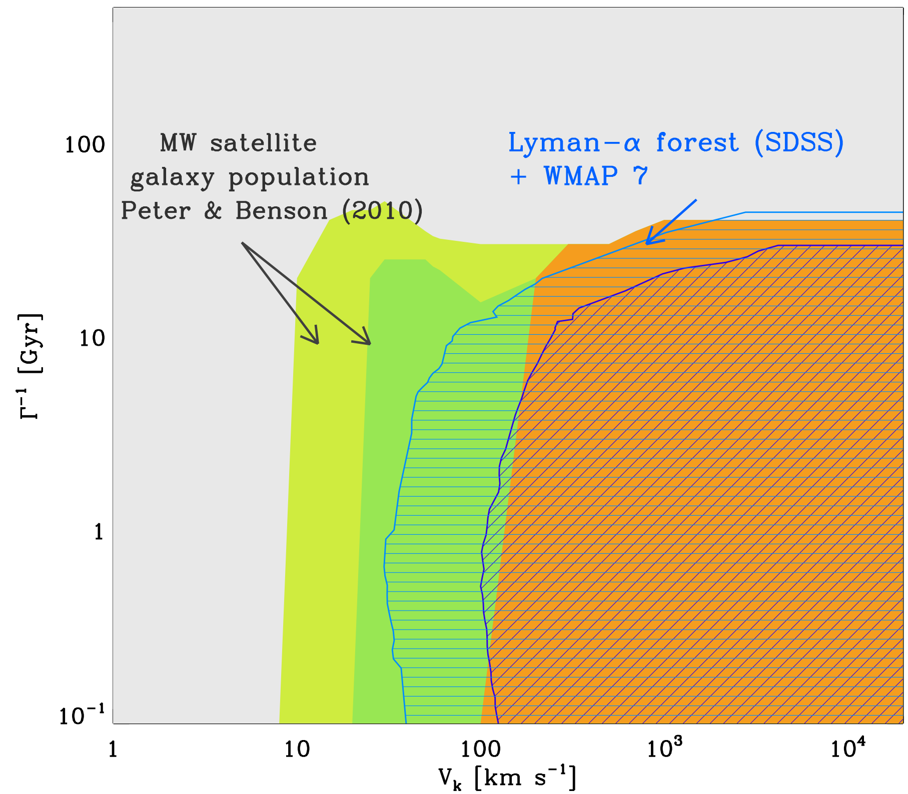
- Two parameters : decay lifetime(Γ^{-1})and mass splitting($f \approx \frac{V_k}{c}$).



MW & Zentner (2012)

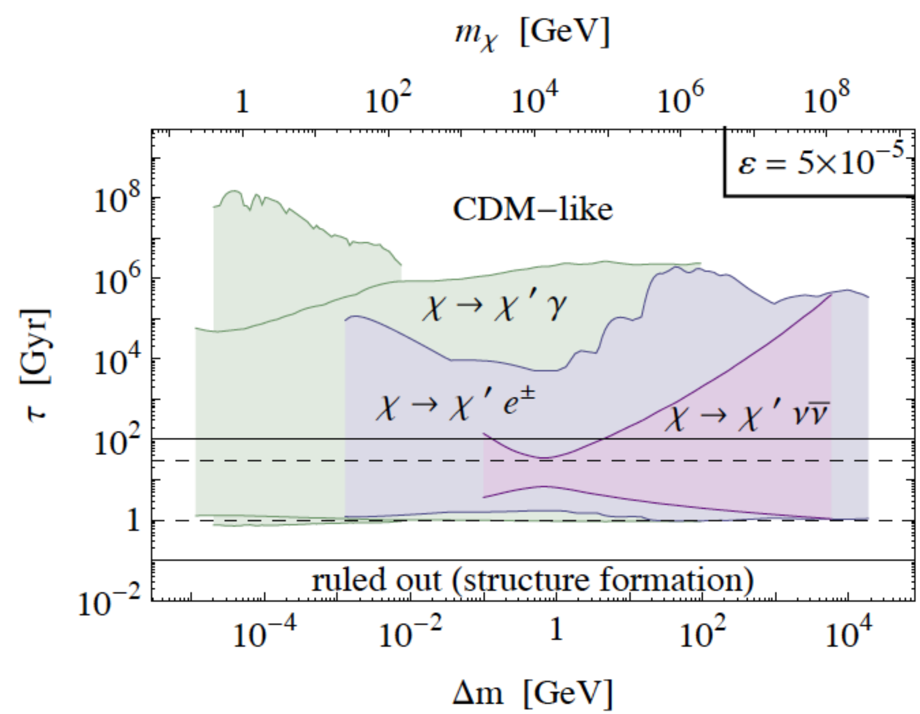
Limits on Decaying DM models

Limits from DM free-streaming



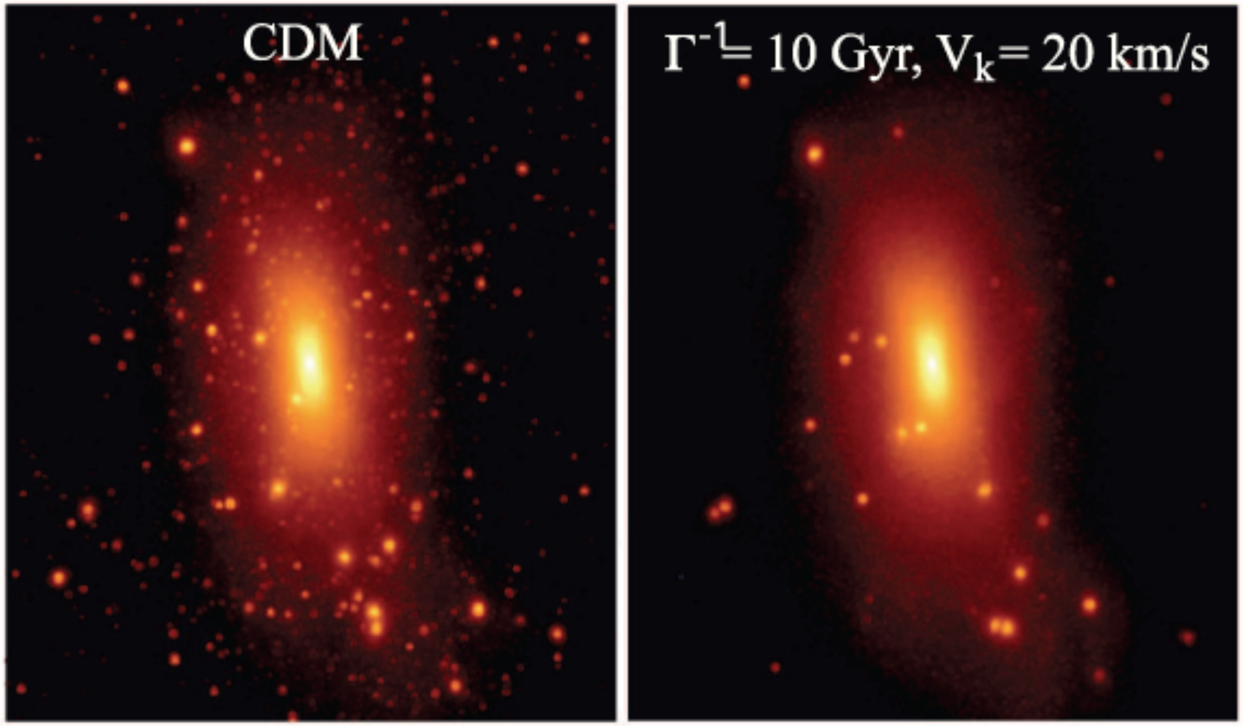
MW, Croft, Peter, Zentner, and Purcell (2013)

Limits derived using SM decay products

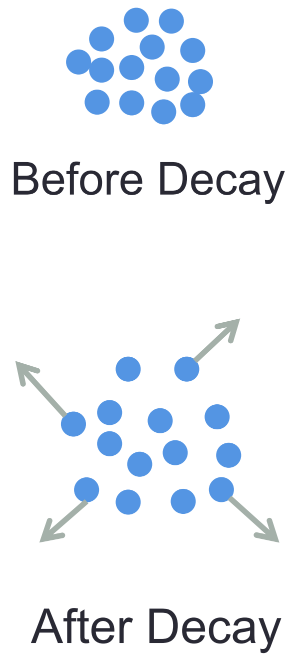


Bell et al. (2010)

Decaying DM Galactic Simulations

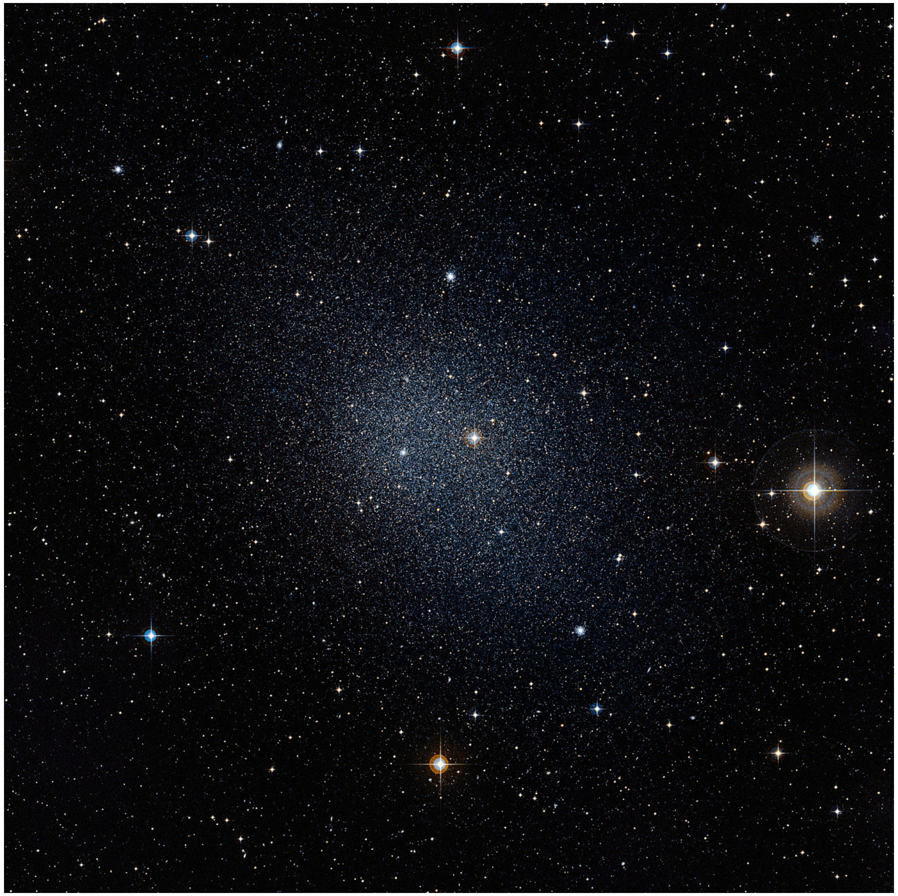


MW et al (2014), arXiv:1406.0527



- DDM halos are less concentrated than their CDM counterpart because the excess recoil kick velocity received by daughter particles can perturb the halo structure.
- Decay models simulated are well-within the parameter space allowed by current astrophysical limit (Lyman-alpha forest)

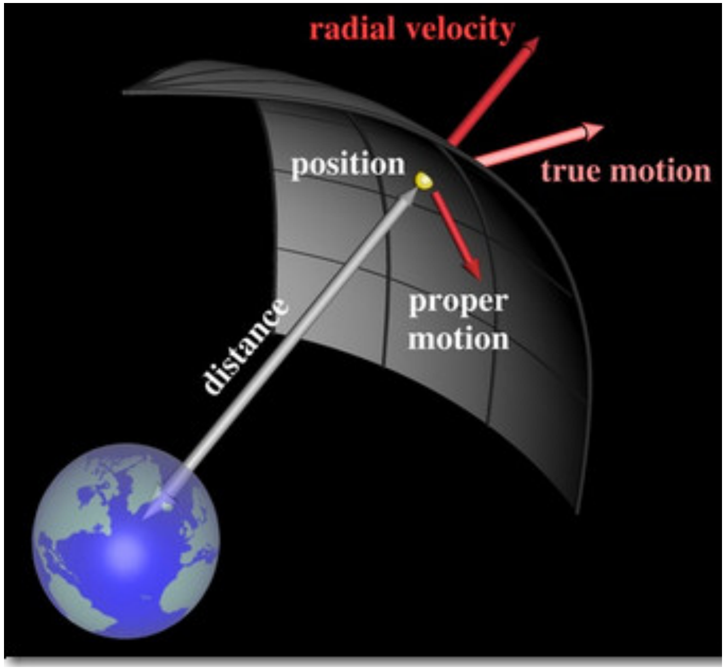
Using Stellar Kinematics to Measure the Milky Way Satellite Dynamical Mass



Fornax dwarf galaxy

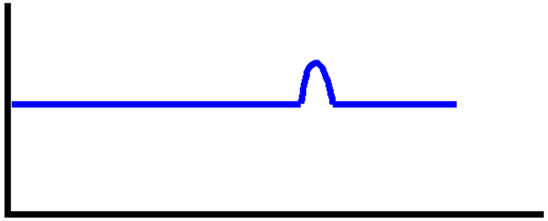
- Other than LMC and SMC, these Milky Way dwarf satellite galaxies have very little gas.
- The way to measure the dynamical mass is to use the motion of stars

Stellar Velocity Measurement



- Radial velocity (line-of-sight velocity):

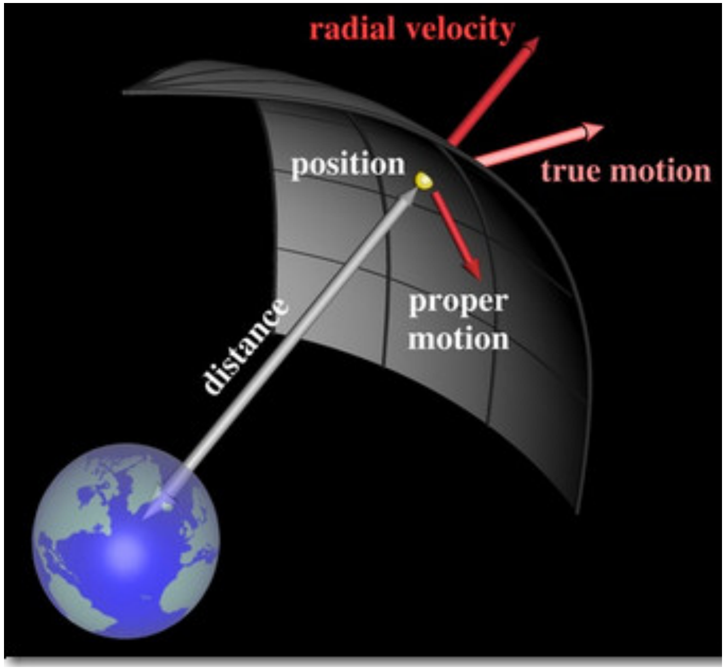
  Stellar spectrum line features are shifted due to Doppler shift (redshift or blueshift)



- Proper motion:

  It is difficult to measure the proper motion because these systems are very far.

Stellar Velocity Measurement



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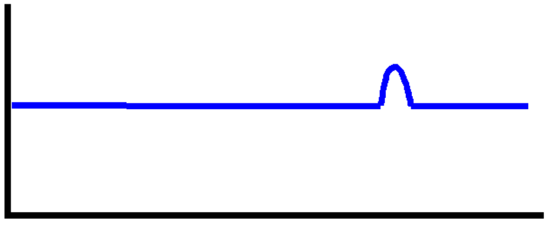

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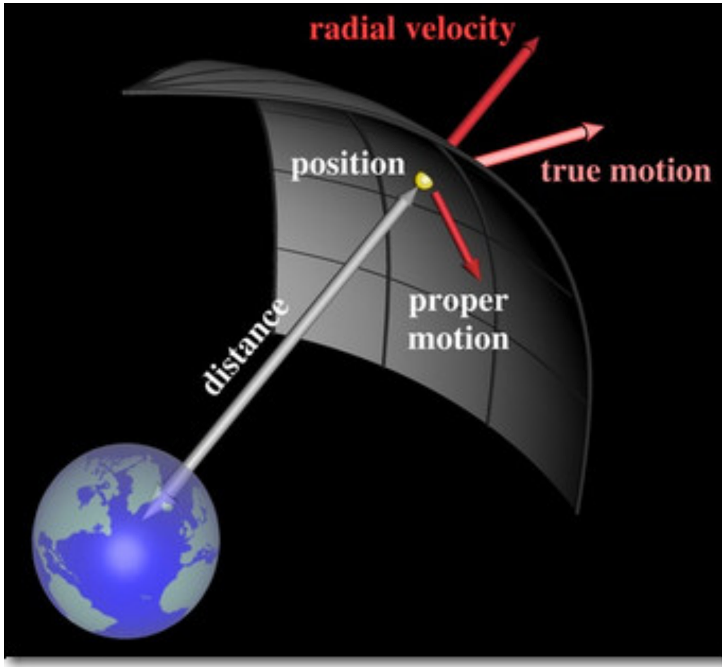

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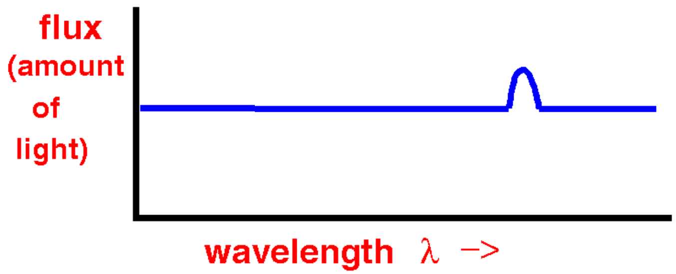

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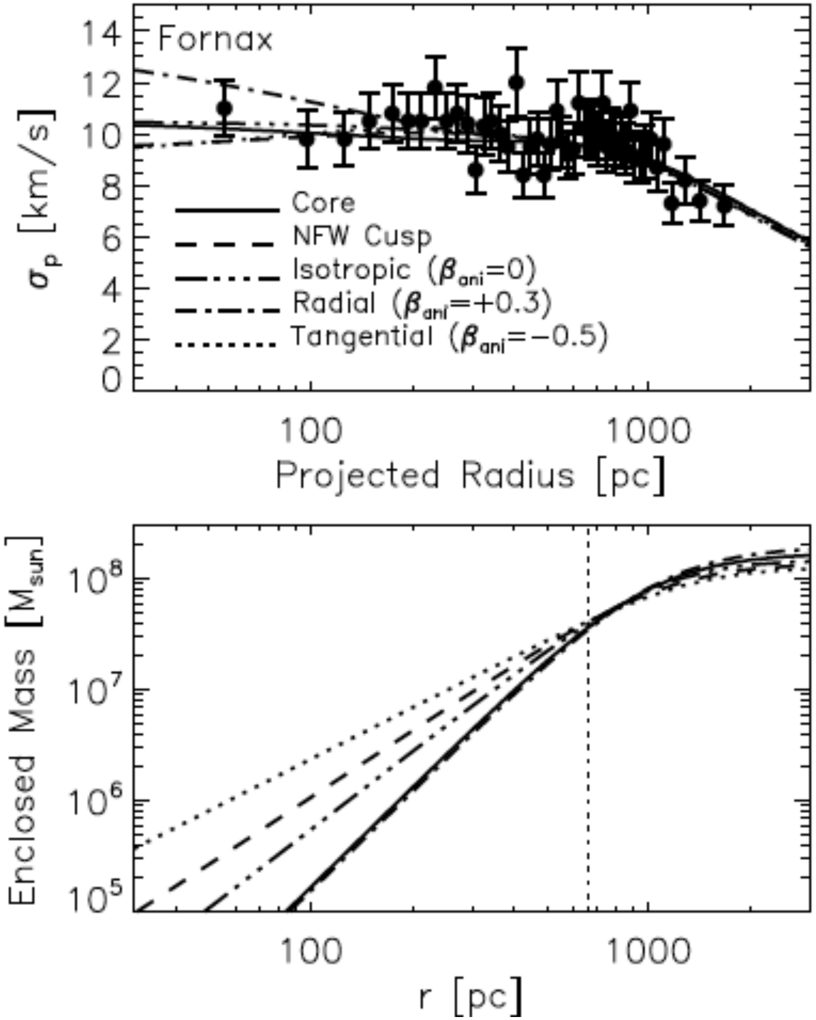
Degeneracy between mass and anisotropy

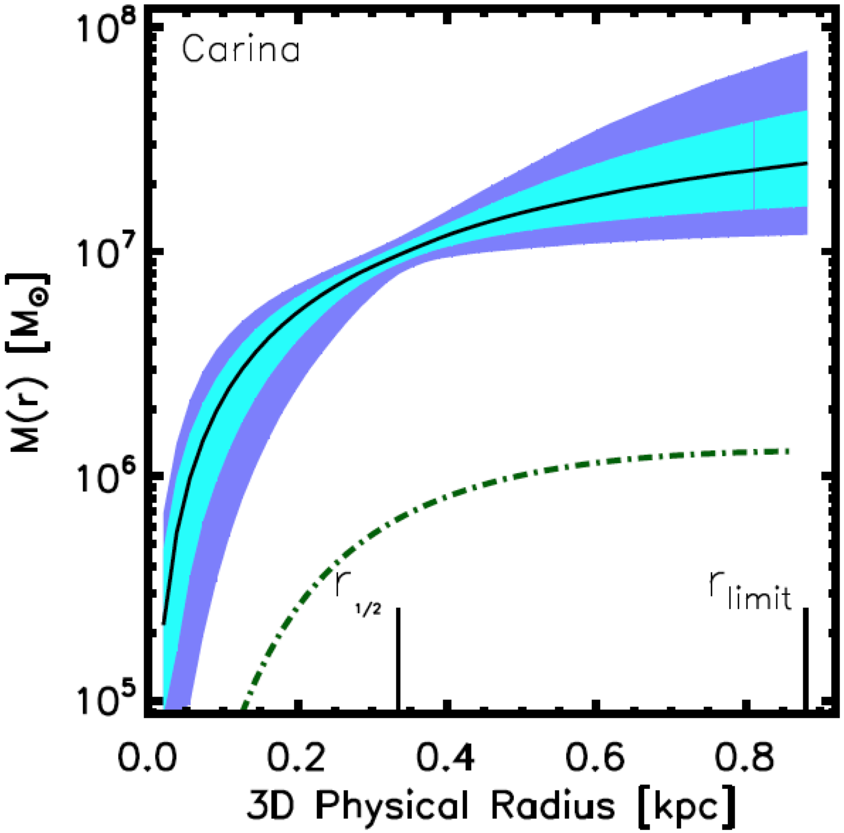


Walker & Penarrubia (2011)

Anisotropy parameter:

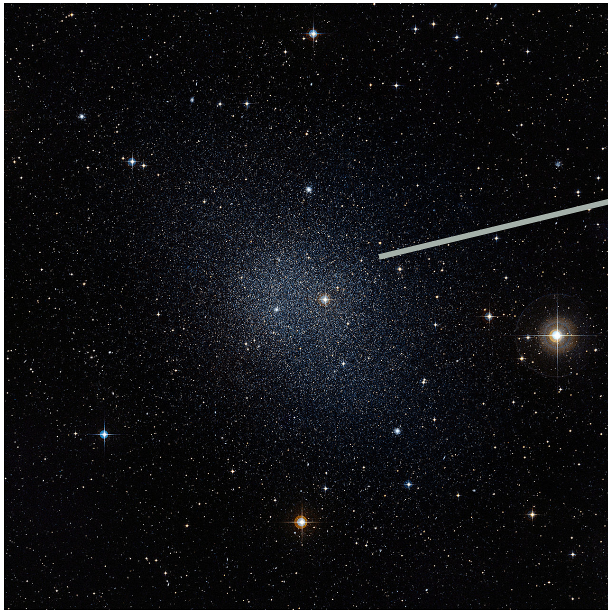
$$\beta(r) \equiv 1 - \sigma_t^2/\sigma_r^2$$

Mass Constraints on Stellar Half-light Radius



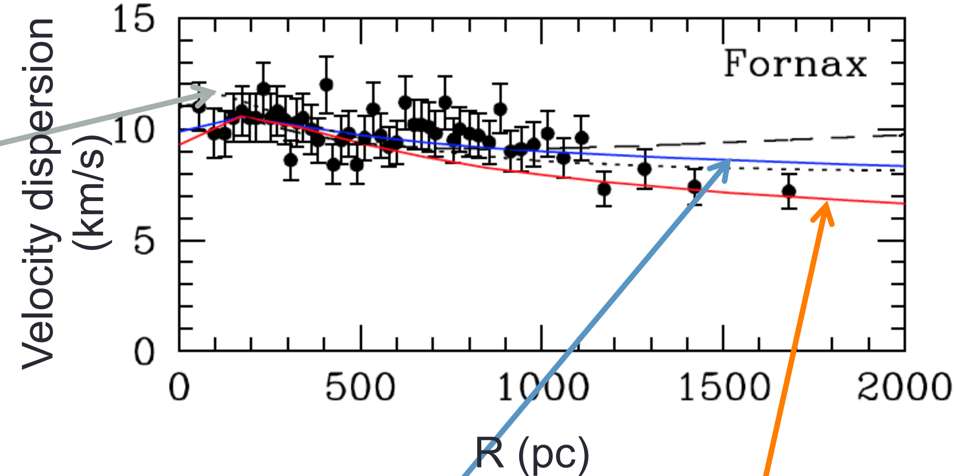
Wolf et al. (2010)

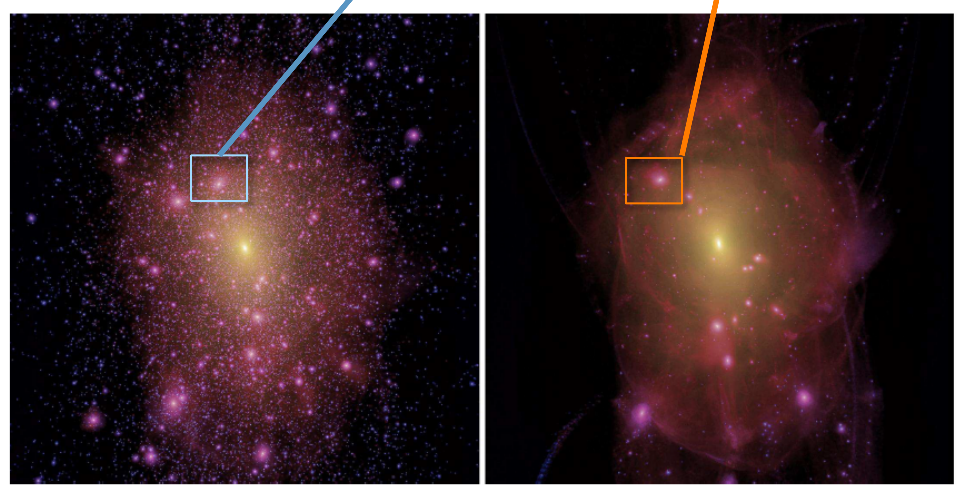
Stellar Kinematics for Fornax



Line-of-sight stellar velocity measurement

Walker et al (2009)





Simulations

Spherical Jeans Equation

Assuming the system is spherically symmetric and in equilibrium

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

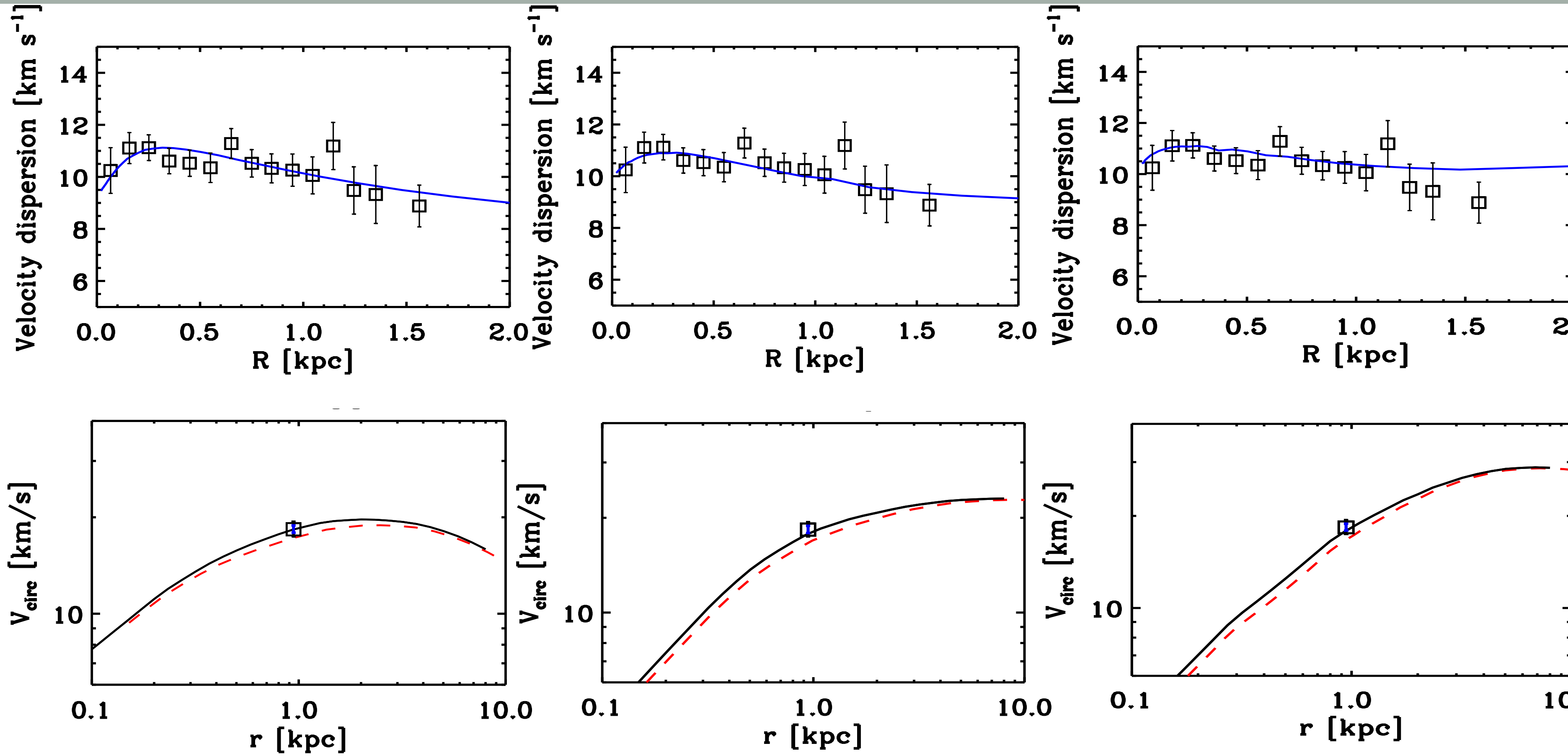
DM subhalo profile from simulation

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

Stellar profile from photometry data

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

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



CDM

$M_{sub} = 5.08 \times 10^8 M_\odot$

$V_{max} = 18.9$ km/s

$\chi^2_\sigma / d.o.f. = 0.782$

β = -0.5

WDM 2.3 keV

$M_{sub} = 1.96 \times 10^9 M_\odot$

$V_{max} = 22.4$ km/s

$\chi^2_\sigma / d.o.f. = 0.773$

β = -0.08

DDM

$M_{sub} = 2.43 \times 10^9 M_\odot$

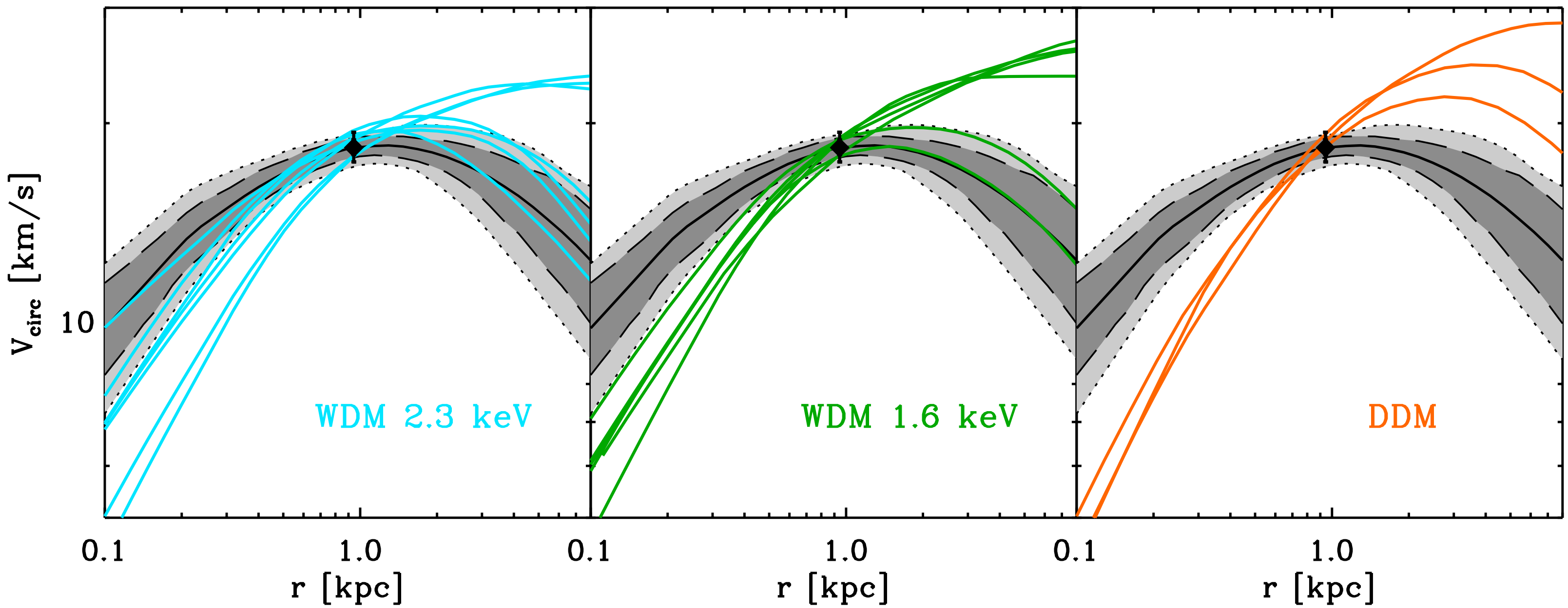
$V_{max} = 28.9$ km/s

$\chi^2_\sigma / d.o.f. = 0.95$

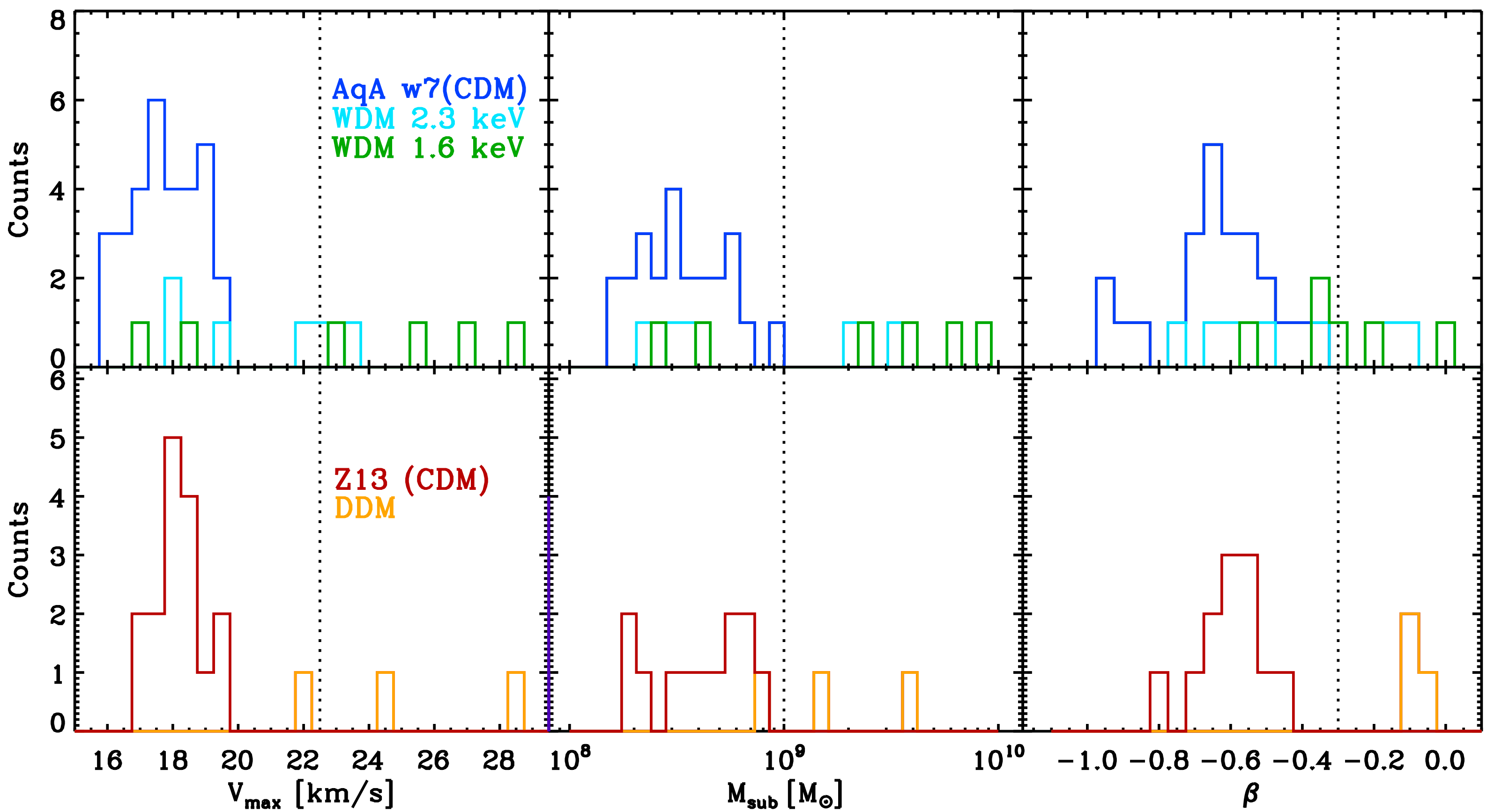
$\beta = 0.17$

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

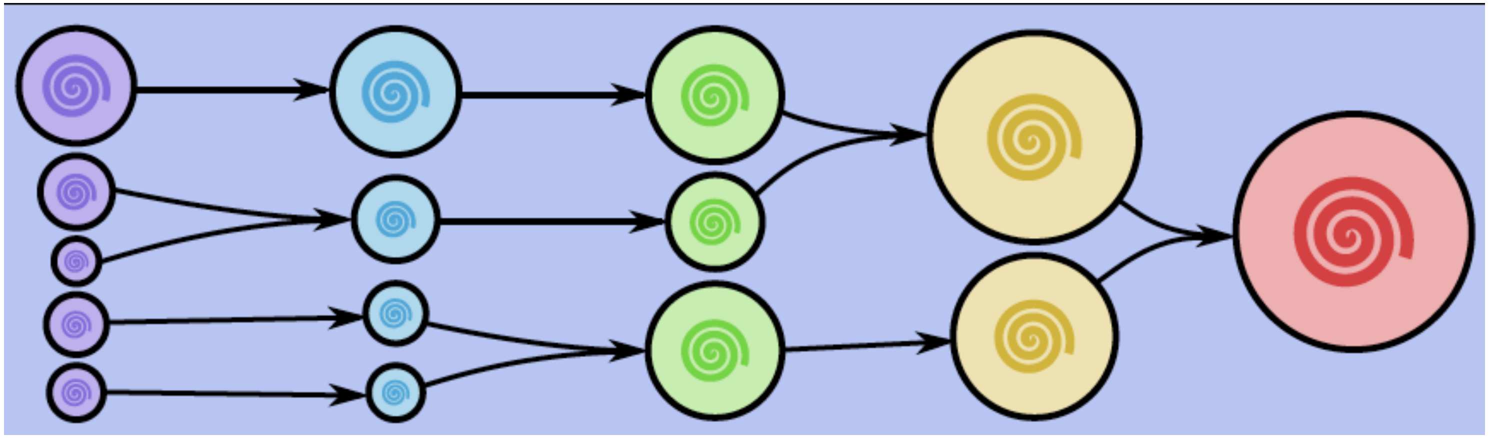
Mass estimation is the tightest at the Fornax 3D half-light radius, which agrees well within the Wolf et al. 2010 results. However, various different DM profiles can fit Fornax kinematic data.



Subhalo Properties of Fornax Good-fits



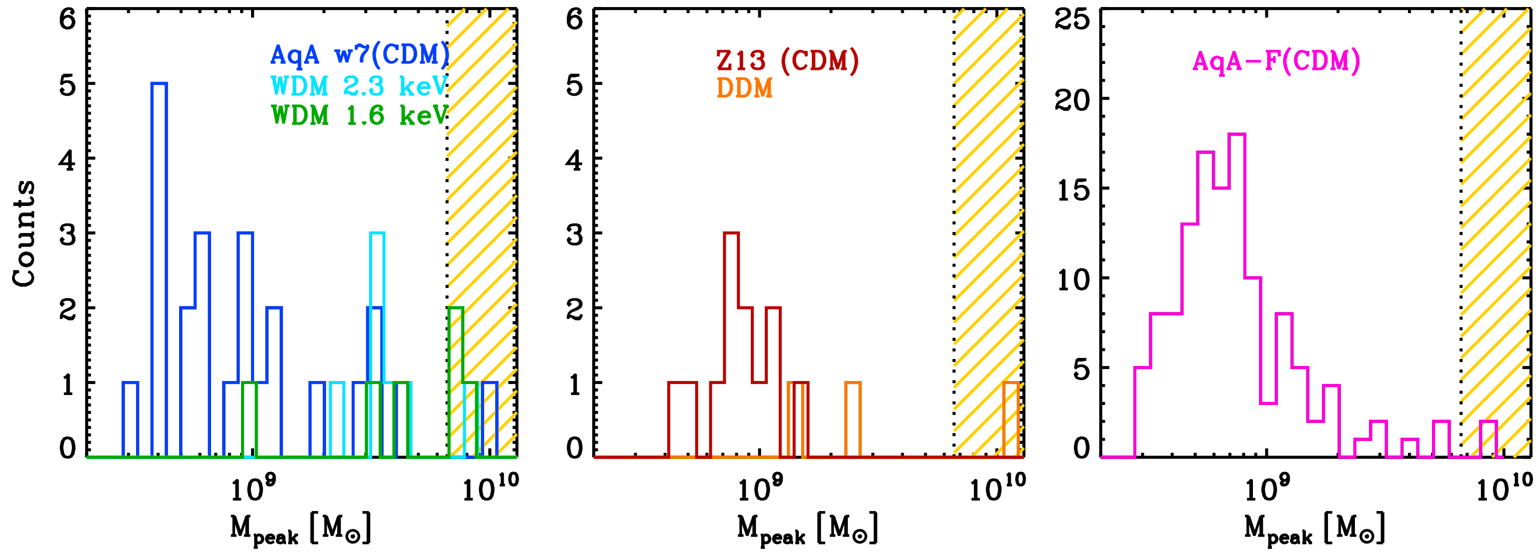
Assigning Galaxy to Halos – Abundance Matching



Behroozi et al. (2013)

The average star formation history in the Universe can be modeled by assuming galaxy mass is associate its DM halo mass. The more massive DM halo progenitors have been, the brighter the galaxy could be.

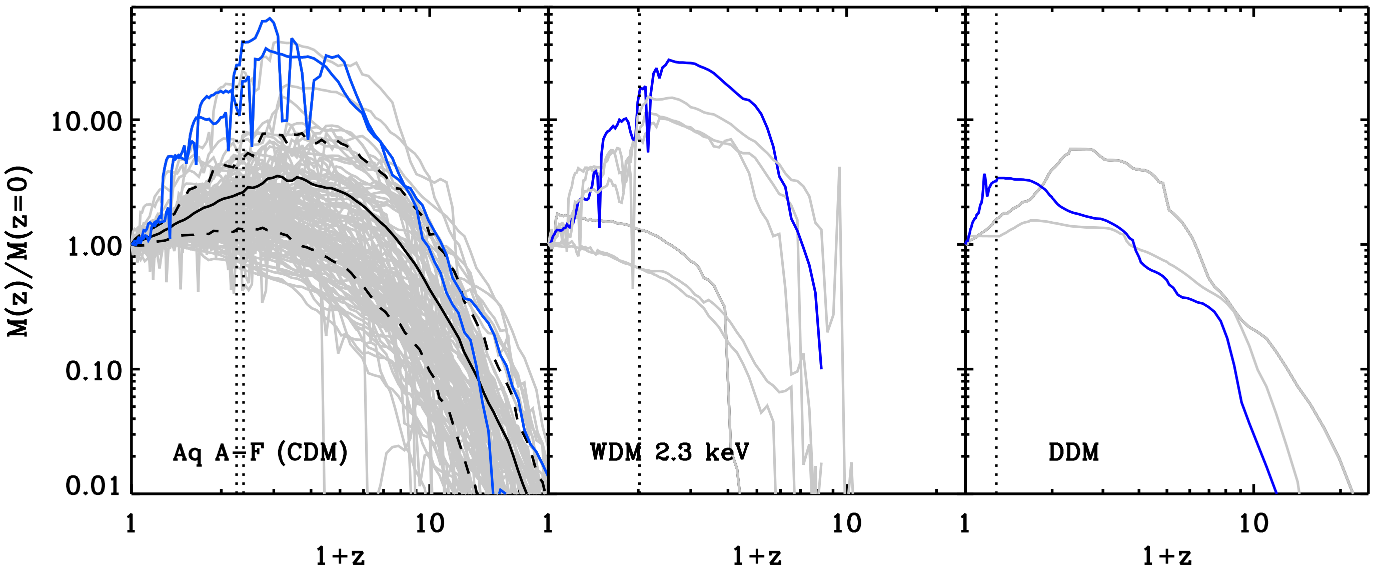
Implied Stellar mass for Fornax

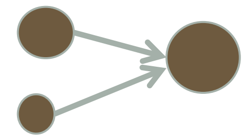


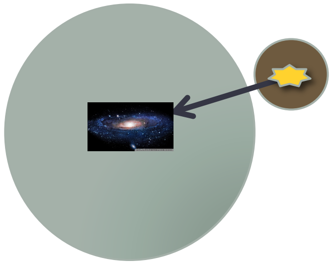
Using abundance matching technique that assuming massive halo progenitors can host bright galaxies (Behroozi et al. (2013)), CDM simulation (six Aquarius halos) have 2 out of 124 kinematic good-fits that also fit Fornax stellar mass.

Caveat : need to extrapolate abundance matching models to subgalactic scale and alternative DM models

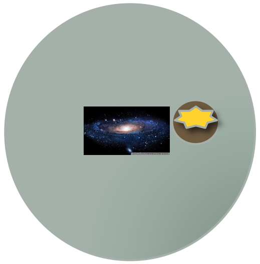
Implied Subhalo Formation History -- Severe Tidal Stripping?

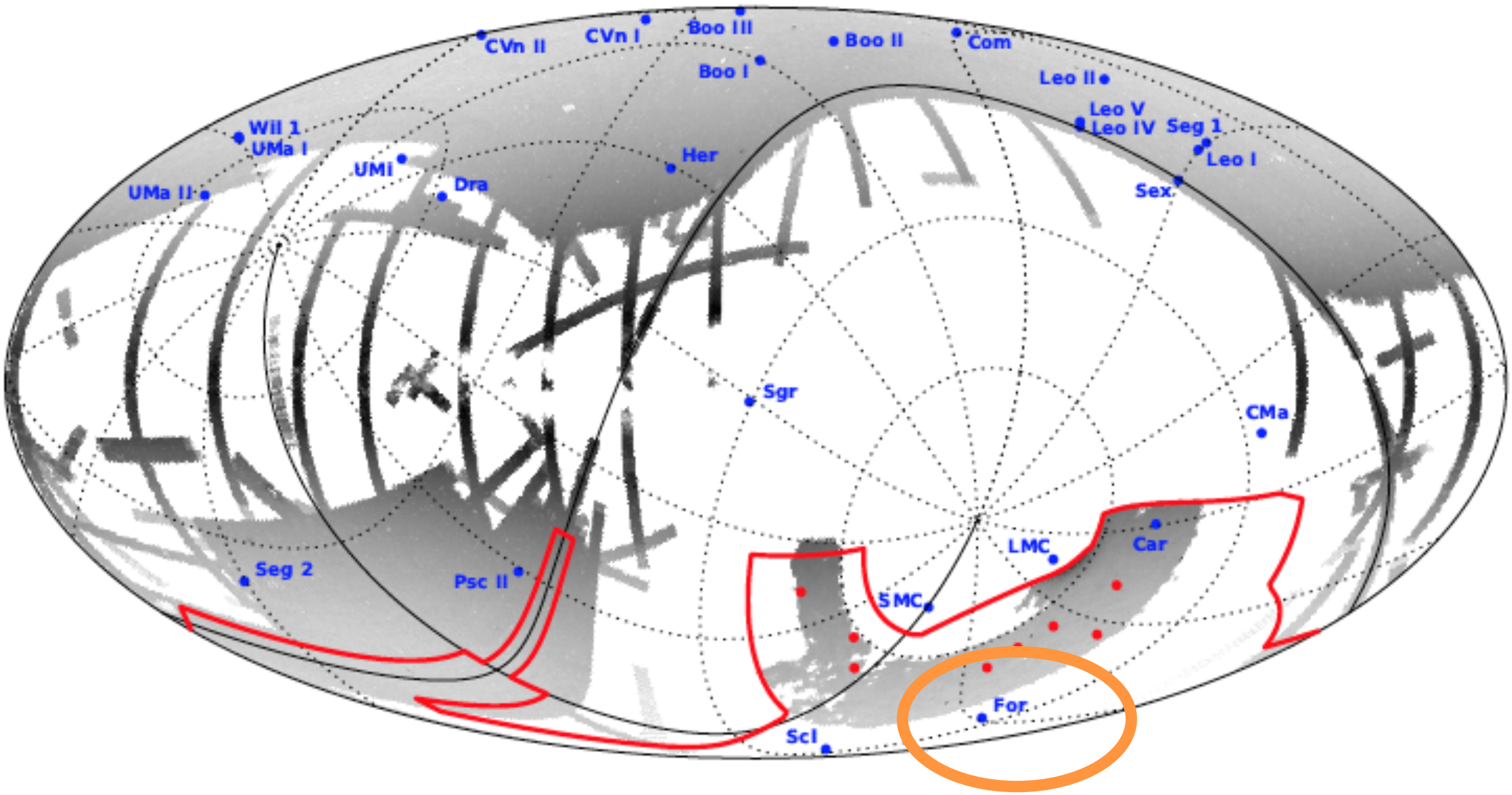






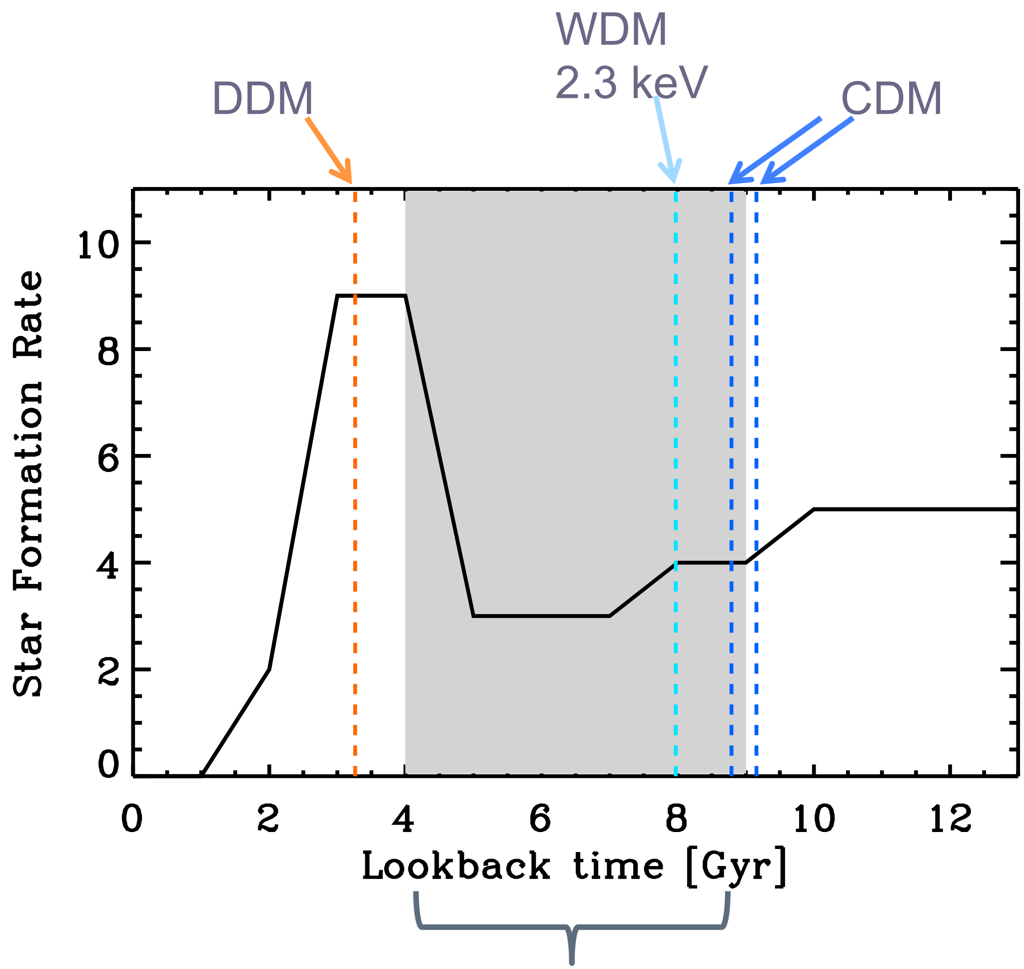
Tidal stripping that causes significant DM halo mass loss is implied in CDM scenarios because massive halo progenitor is require for Fornax's bright luminosity while current mass range is limited to m< 10^9 M_sun from Fornax kinematic data





Deep wide-field survey like Dark Energy Survey (DES) can help to find possible tidal stripping signatures from Fornax.

Fornax stellar formation history V.S. infall time

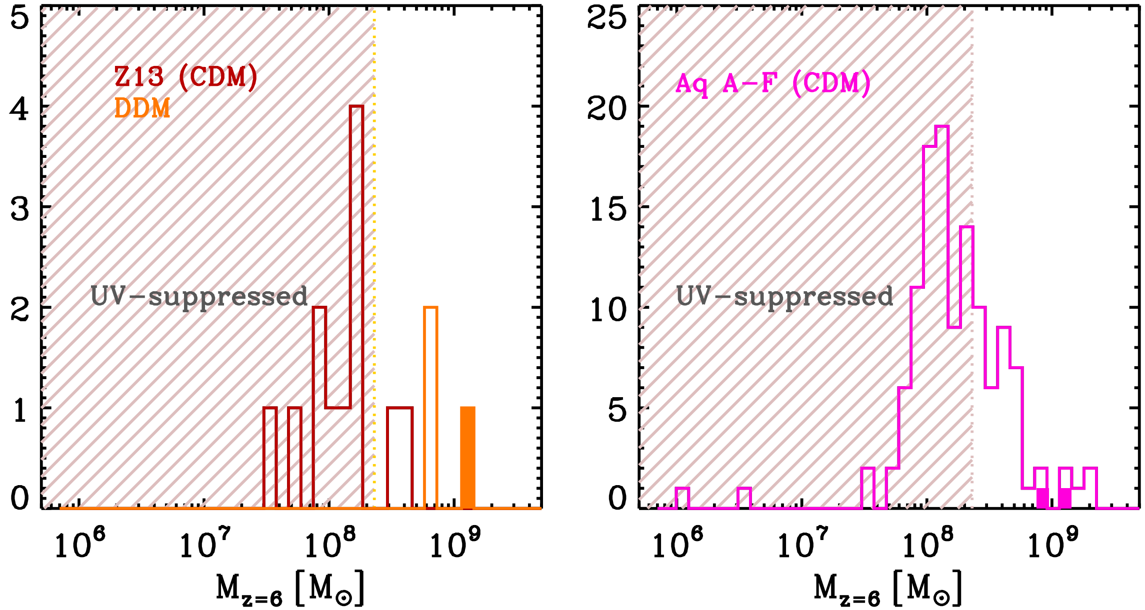


Rocha et al. (2011)
Orbital Motion from simulation

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 stellar and halo formation history, and whether or not its subhalo have been severely tidally stripped may reveal certain properties of DM.
- Similar arguments can also be applied to test other alternative DM models or stellar feedback strengthen. It depends on how much the predicted DM profiles deviate from NFW profile and halo formation history.

Most of The Candidates may not be visible – Killed by reionization



Reionization suppresses star formation efficiently for low-mass halos