Dark matter cores in galaxies and galaxy clusters

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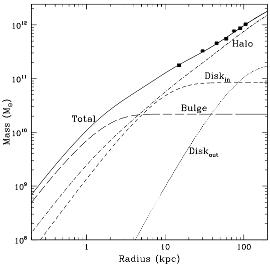
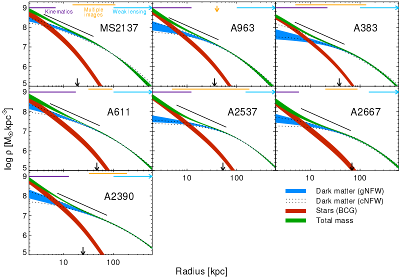
"Missing mass" problem and DM distribution

Conceptually, dark matter is a solution to the 'missing' (**dynamical** vs **visible**) mass problem.
In **outskirts**, visible ('baryonic') mass density falls rapidly with radius, it is (rather) simple to distinguish it from DM.
But in **central parts** of many objects, baryons dominate:





Courtesy of Seigar, PASP 2008; Newman et al., ApJ 2013b.

⇒ **LARGE uncertainty on DM inner slope**.

Cores and cusps

Define inner density slope $\alpha = d\log(\rho_{\text{DM}})/d\log(r)$ at $r \to 0$

$\alpha \sim 1$ – **cusp**, e.g. **Navarro-Frenk-White profile**

$$\rho_{\text{NFW}}(r) = \frac{\rho_s r_s}{r\left(1 + r/r_s\right)^2}$$

(Navarro et al., ApJ 1996, 1997) consistent with **DM-only simulations** and **observations of galaxy clusters**.

$\alpha \sim 0$ means $\rho_{\text{DM}}(0) = \text{const}$ – **core**, e.g. **pseudo-isothermal profile**

$$\rho_{\text{ISO}}(r) = \frac{\rho_c}{1 + r^2/r_c^2}$$

and **Burkert profile** (Burkert, ApJ 1995)

$$\rho_{\text{BURK}}(r) = \frac{\rho_B}{\left(1 + r/r_B\right)\left(1 + r^2/r_B^2\right)}$$

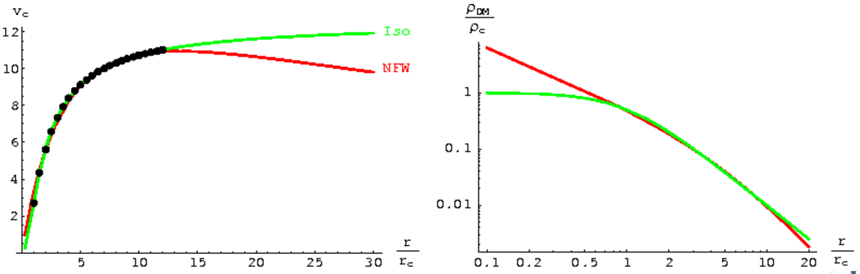
motivated by **observations of galaxies**.

What can we say regardless of core-cusp problem?

Approximation of cored (ISO, BURK) profiles with cusp (NFW) at **intermediate** radii (down to r_{max}) yields (Boyarsky, Ruchayskiy, DI et al. 2009)

$$r_s \simeq 6.1 r_c; \quad \rho_s \simeq 0.10 \rho_c \qquad \text{(ISO vs NFW)}$$

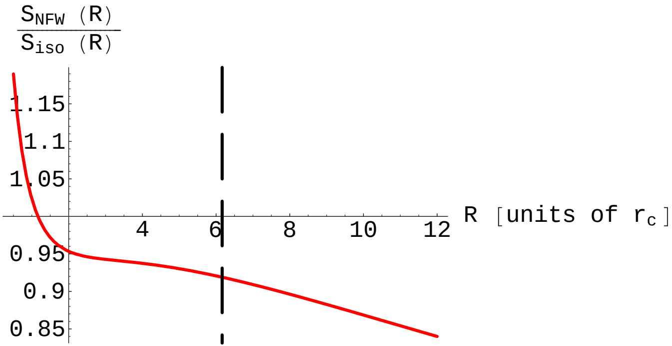
$$r_s \simeq 1.6 r_B; \quad \rho_s \simeq 0.37 \rho_B \qquad \text{(BURK vs NFW)}$$



DM column density

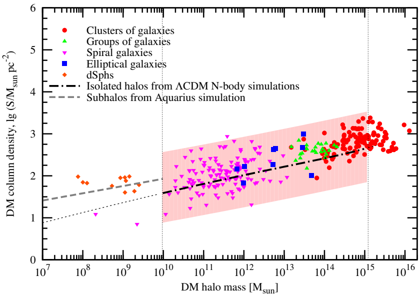
$\mathcal{S}(r_s) \simeq 1.2\rho_s r_s$ is **almost independent** from type of DM profile:

$$\frac{\mathcal{S}_{\text{NFW}}}{\mathcal{S}_{\text{ISO}}} \approx 0.91; \quad \frac{\mathcal{S}_{\text{NFW}}}{\mathcal{S}_{\text{BURK}}} \approx 0.98$$



Dependence on halo mass

$\mathcal{S}$ grows **slowly** with DM halo mass, $\mathcal{S} \sim \left(M_{\text{halo}}\right)^{\approx 0.2}$ **consistent** with ΛCDM expectations (**Boyarsky, Ruchayskiy, DI et al. 2009**)



Also in agreement with the semi-analytical **secondary infall** model (**Boyarsky, Neronov, Ruchayskiy, Tkachev, PRL 2009**)

Dwarf spheroidal galaxies (dSphs)

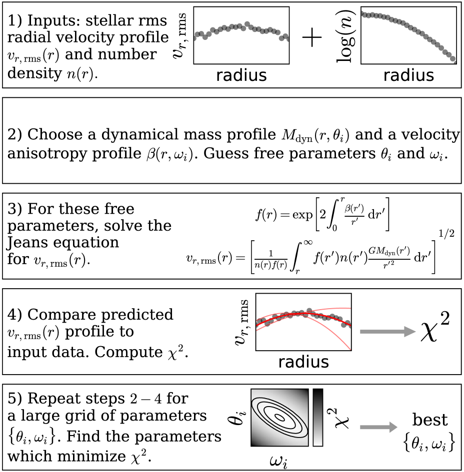
dSphs are **dispersion-dominated** systems (with no or little rotation). The standard modeling procedure is to solve the **spherically-symmetric** Jeans equations with **unknown** velocity anisotropy (**Binney, MNRAS 1980**):

$$\frac{d[n(r)\overline{v_r^2}(r)]}{dr} + 2\frac{\beta(r)}{r}n(r)\overline{v_r^2}(r) = -n(r)\frac{GM_{\mathsf{dyn}}(r)}{r^2},$$

$n(r)$ is the stellar number density, $\overline{v_r^2}(r)$ is the stellar velocity dispersion, $\beta(r)$ is the stellar velocity anisotropy parameter:

$$\beta(r) = 1 - \frac{\overline{v_\theta^2} + \overline{v_\phi^2}}{2\overline{v_r^2}}$$

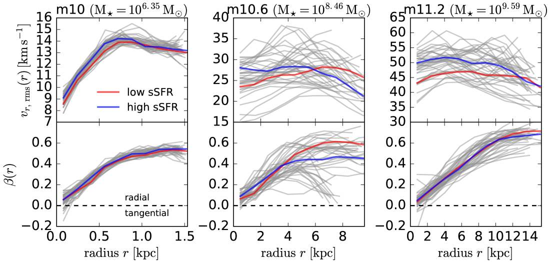
Jeans modeling procedure



(courtesy of El-Badry et al., ApJ 2017)

Velocity anisotropy in dSphs

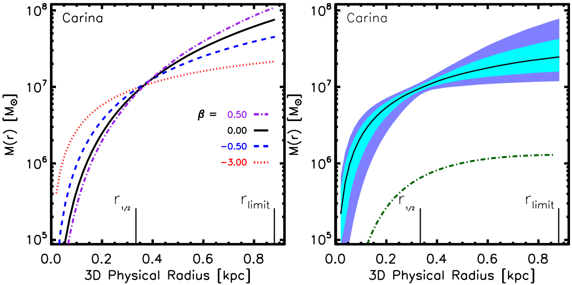
$\beta(r)$ usually goes to 0 when $r \to 0$, see e.g. pure-DM dSph (**Sparre & Hansen, JCAP 2012**), FIRE (**El-Badry et al., ApJ 2017**) or APOSTLE simulations (**Campbell et al., MNRAS 2017**):



$\beta(r)$ can be **measured** with future proper motion measurements (**Gaia** – **Jin, Helmi & Breddels, 2015**, **Hubble Astrometry Initiative** – **Kallivayalil et al., 2015** and **Theia** – **Boehm et al., 2017**).

DM mass estimates in dSphs: Jeans equations

Mass inside half-light radius is largely independent on anisotropy, see e.g. **Wolf et al., MNRAS 2010**: (for 3D half-light radius)

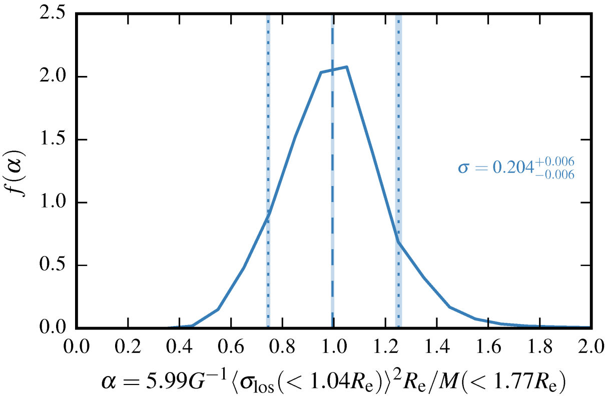


or **Walker et al., ApJ 2009** (for 2D half-light radius R_e):

$$M(R_e) = \frac{5\langle\sigma_{los}(R_e)\rangle^2 R_e}{2G_N}$$

DM mass estimates in dSphs: simulations

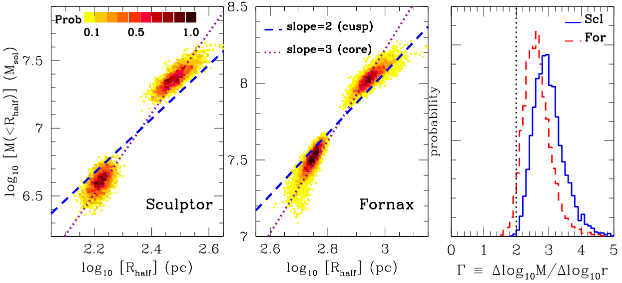
Recent mass estimates based on APOSTLE simulations (**Campbell et al., MNRAS 2017**):



and FIRE simulations (**Gonzalez-Samaniego et al., 2017**).

Multiple stellar populations

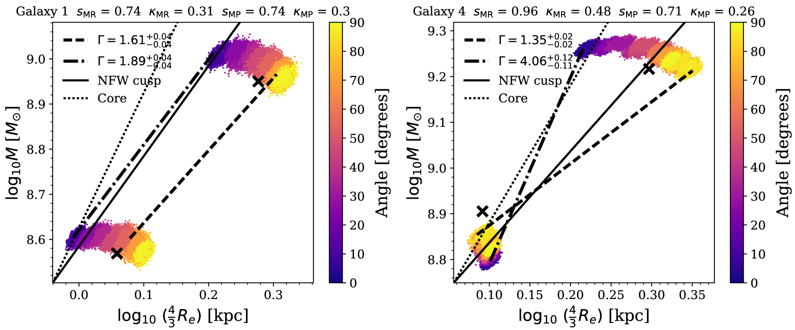
If one has **two** kinematically distinct stellar populations with different R_e, we can use them to measure the **slope** of $M(r)$, see e.g. **Walker & Peñarrubia, ApJ 2011**:



For **three** stellar populations one can derive not only mass (density) slope, but also core radius – e.g. **Amorisco et al., MNRAS 2013** found $r_c = 1.0^{+0.8}_{-0.4}$ kpc in Fornax.

Correlation between 2 subpopulations

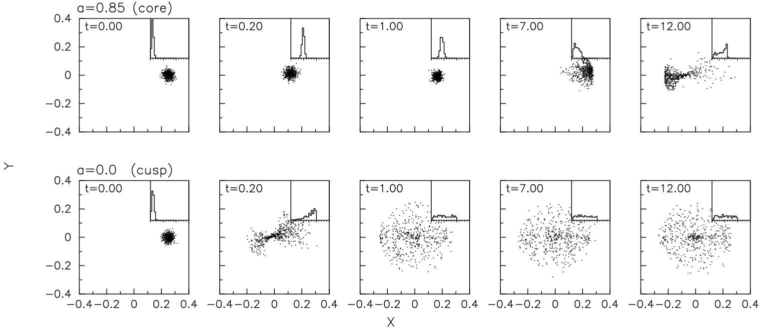
APOSTLE simulations yield 2-26% of cusps mimicking as cores (**Genina et al., 2017**):



Taking this into account decreases inconsistency between **Walker & Peñarrubia (2011)** measurements and NFW in Sculptor and Fornax to 95.4% (from $> 99\%$) and to 91.8% (from $> 96\%$), respectively.

Globular clusters in dSphs

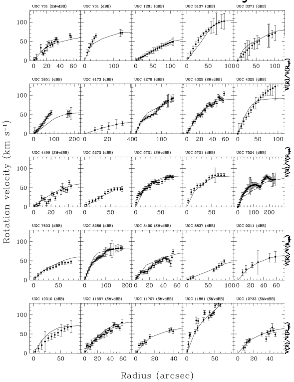
GCs need **cored** DM distribution to survive inside a dSph:

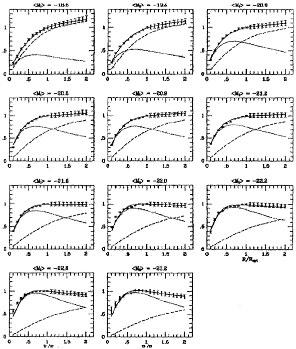


Kleyna et al., ApJ 2003 (Ursa Minor)
See also **Goerdt et al., MNRAS 2006** (Fornax), **Contenta et al., 2017** (Eri II), **Amorisco, ApJ 2017** (Eri II & And XXV).

Spiral galaxies

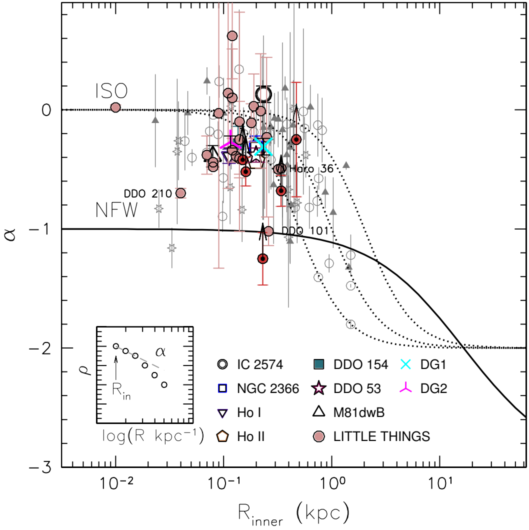
Rotation-dominated systems, dynamics is traced by **rotation curve**.





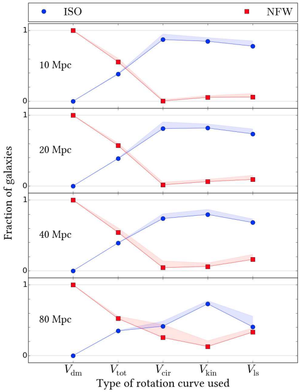
$$V^2(r) = \frac{G_N M(<r)}{r} \Rightarrow \rho(r) = \frac{V_{\rm rot}(r)\left[V_{\rm rot}(r) + 2rV'_{\rm rot}(r)\right]}{G_N r^2}$$

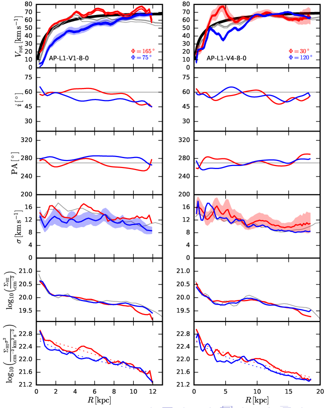
THINGS + LITTLE THINGS (Oh et al. AJ 2015)



What can turn cusp into (apparent) core?

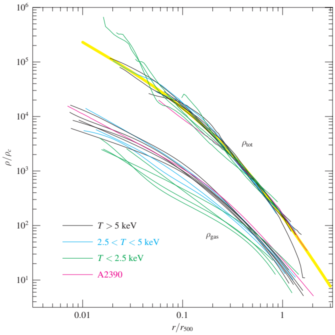
- ‘Pressure support’ provided by the finite gas velocity dispersion (**Pineda et al., MNRAS 2017**)
- Non-circular motions in HI disks (**Oman et al., 2017**)

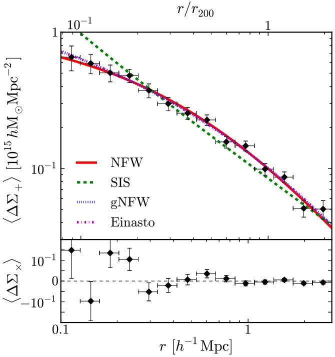




Groups and clusters of galaxies

Dispersion-supported systems, DM is probed by galaxy velocities, strong and weak lensing and X-rays.
Kinematics of galaxy clusters **alone** is consistent with NFW profile.

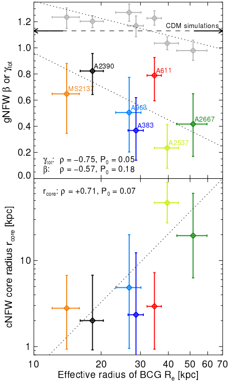


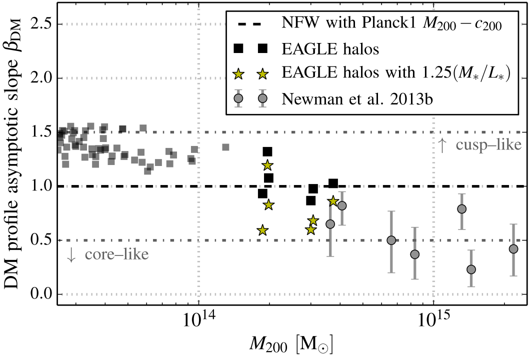


(courtesy of Vikhlinin et al., ApJ 2006 and Okabe et al., ApJL 2013)

Galaxy clusters + BGCs

Adding brightest cluster galaxy (BCG) kinematics tends to a cusp flattening to $\alpha \sim 0.5$, in tension with simulations:

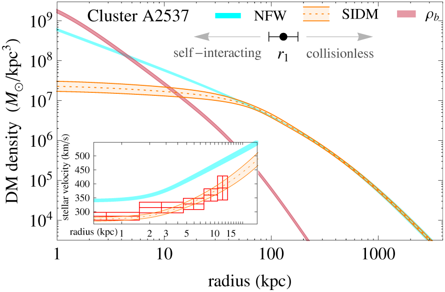


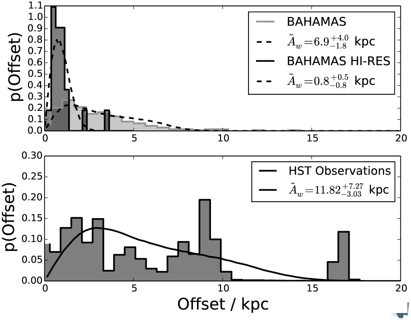


(courtesy of **Newman et al., ApJ 2013b** and **Schaller et al, MNRAS 2015**)

Wobbles in galaxy clusters

Possible solution – BCG can be **offset** of DM halo center.
However, for CDM the expected wobbles are much smaller (< 2 kpc) to explain the apparent inconsistency (see **David Harvey talk**).





(courtesy of **Kaplinghat, Tulin & Yu, PRL 2016** and **Harvey et al, 2017b**)

Summary:

- To look for deviations from LCDM, inner DM slope measuremets are essential;
- For many dark matter-dominated objects, the existence of cores have been reported;
- It results in an open window for alternative (e.g. SIDM) interpretations.

Thank you for your attention!