Proper Motions of Stars in Dwarf Spheroidal Galaxies

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WIMPs and Their Successes

CDM WIMPs are the most successful dark matter model to date.

The dark matter consists of nonrelativistic particles which interact weakly at short distances and gravitationally at large distances.

Some of its most noted successes are:

I) The bullet cluster mass is separated from the ionized gas (many other examples are now known)

II) Galaxy cluster density profiles

III) The CMB power spectrum scaling and peaks at $l < 1500$

IV) Large scale structure and in particular the BAO peak

These successes are all at very large scales (10+ Mpc today)

Testing WIMPs at short distances

The smallest scales at which dark matter has been confirmed are those of dwarf spheroidal (dSphs) and ultrafaint (UFDs) galaxies

What predictions do WIMPs make on these scales?

Simulations of *pure* dark matter structure formation:

1) A cusped density profile in galactic cores
(Dubinski and Carlberg, 1991; Navarro et al., 1996 and 1997).

2) Dark matter halos are triaxial:
Minor-major (intermediate-major) axis ratios of $0.6 - 0.7$ $(0.8 - 0.9)$ (Schneider, Frenk and Cole, 2012)

... But the universe isn't made of pure dark matter

Including baryons?

Both of these predictions can potentially be modified by the presence of baryons

For example, in a galaxy with sufficient luminous matter, supernova (SN) feedback may transform the cusp into a core (Mashchenko et al., 2006; Governato et al., 2010)

How much luminous matter is sufficient?

The main proponents of this mechanism say $10^{6.5-7}\ M_\odot$ (Governato et al., 2012; Pontzen and Governato, 2014)

The lowest estimates are less than $10^6\ M_\odot$ but well over $10^4\ M_\odot$ (Onorbe et al., 2015)

Consensus of opinion: In ΛCDM, dSphs ($10^5\ M_\odot \lesssim M_* \lesssim 10^7\ M_\odot$) are likely cusped. UFDs ($M_* \lesssim 10^{4-5} M_\odot$) are certainly cusped.

Testing ΛCDM

Conclusions:

1) Measuring the dark matter distribution in dSphs one can test ΛCDM
Disagreement with pure DM predictions will not falsify ΛCDM, but it will impose strong constraints on baryonic physics
(In other words, you'd learn something about SN histories/efficiencies, star formation density thresholds, etc.)

2) A definitive test of ΛCDM can be made by measuring cusps or triaxiality in ultrafaint dwarfs (UFDs)

How can these be tested with TMT?

Testing ΛCDM with TMT

Traditional approach:

1) 2025: Observe a dSph or UFD with TMT to obtain precise relative positions of all possible stars with respect to background galaxies

2) 2030: Wait 5 years and observe the same galaxy again

3) 2030: Comparing the observations, stellar proper motions can be determined $\rightarrow$ determine the dark matter density profile

How to save 5 years:

1) 2015-2020: Observe a dSph (UFD) with Gaia (Hubble) to obtain precise relative positions of all possible stars with respect to background galaxies

2) 2025: Observe the same galaxy again with TMT

3) 2025: Comparing the observations, stellar proper motions can be determined $\rightarrow$ determine the dark matter density profile

Observing Sculptor

The Sculptor dSph is only 79 kpc away

$M_* \sim 2.3 \times 10^6\ M_\odot \Rightarrow$ According to Governato et al. it is *cusped*
(Little star formation in last 7 Gyr $\Rightarrow$ Perhaps Onorbe et al. agree)

It is quite far south, and so is not an ideal target for TMT

However the Magellan/MMFS survey (Walker, Mateo and Olszewski, 2009) has provided a catalog of 1541 potential members, allowing for a reasonably precise forecast for such a study

It sits at a particularly favorable location for Gaia, allowing for unusually precise astrometry by Gaia

The DM Slope

What is the precision with which Gaia+TMT can measure the dark matter slope?

Define : $\gamma(r) = -3 + 4\pi r^3 \frac{\rho(r)}{M(r)}$

For a power-law density $\rho(r)$ the slope is just the exponent.

However unlike the usual definition of $\gamma(r)$ it only depends on $\rho(r)$, not its derivative, so is less model dependent

ΛCDM simulations suggest that, for sufficiently little baryonic matter, $\gamma(r) \lesssim -1$ for reasonably small values of r

We consider r equal to the 3d half light radius $r_{1/2} = 375$ pc

Methodology

We assume that the dark matter distribution is spherically symmetric and assumes the Zhao-Hernquist form

$$\rho(r) = \rho_0 \left(\frac{r_0}{r}\right)^a \left(1 + \left(\frac{r}{r_0}\right)^b\right)^{(a-c)/b}$$

with a constant velocity anisotropy β .

We consider only the 1355 Sculptor members in the MMFS catalog with a membership probability over 90%.

Their luminosities determine the precision with which Gaia, followed 7 years later by TMT, can measure their proper motions

Finally the Fisher matrix determines the precision with which various parameters can be determined

Gaia Proper Motion Precisions

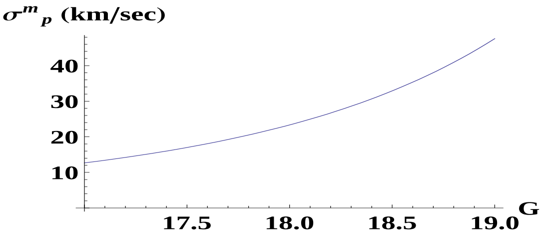


Figure: The precision with which Gaia can measure the proper motion of a Sculptor member with Gaia magnitude G and color $V - I_C = 1.35$

We will make the conservative assumption that TMT measures each of these stars with a precision of 20 μas.

Our results do not depend strongly on this approximation, as Gaia dominates the uncertainty

Sculptor Proper Motion Precisions

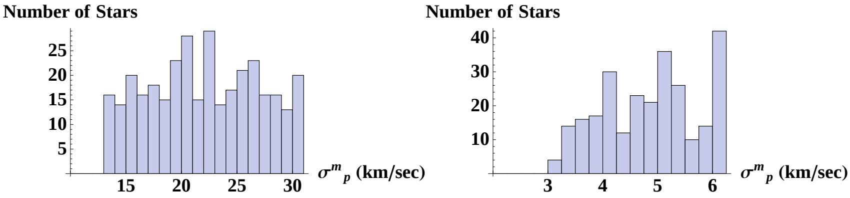


Figure: Number of Sculptor's stars whose proper motion can be measured with precision σ^m_p by Gaia alone (left) and Gaia with TMT (right).

The inclusion of TMT improves the astrometric precison by about a factor of 4.

Typical stellar dispersions in Sculptor are 8-10 km/s:
With TMT the uncertainty will be smaller than the dispersion

Sculptor DM Slope Precision Forecasts

Use a 2-component Plummer model for the stellar density profile.

Precision expected for mass M and slope γ with/without the assumption that $c = 3$ (valid for CDM, WDM and many interacting DM models) is:

	$\delta M(r_{1/2})/M(r_{1/2})$	$\delta\gamma(r_{1/2})$
LOS only	30%	1.3
LOS only, $c = 3$	25%	0.86
Gaia	13%	0.47
Gaia, $c = 3$	13%	0.44
Gaia+TMT	9%	0.22
Gaia+TMT, $c = 3$	6%	0.21

So in the spherical symmetry approximation Gaia may provide a 2σ hint for a core/cusp, but perhaps 5σ is possible with TMT (Yesterday Alan McConnachie said this should be possible.)

IRIS Astrometric Precision

TMT astrometry will be done by the first light instrument: The InfraRed Imaging Spectrometer (IRIS) operating behind the Narrow-Field Infrared Adaptive Optics System (NFIRAOS)

Shöck et al. (Work in progress) estimate the statistical uncertainty of a K-band (differential) astrometric measurement to be

$$\sigma = \frac{7500}{\mathrm{SNR}}\ \mu\mathrm{as}$$

Systematic errors are expected to be about 10 μas

For observations of Milky Way satellite dSphs (and near UFDs) separated by 5 years, the systematic error is less than the stellar velocity dispersion and so has limited effect

Signal to Noise Ratio

According to the on-line calculator at

http://tmt.mtk.nao.ac.jp/ETC_image.shtml

With one time t exposure, a source with apparent magnitude K_{AB} can be measured with signal/noise ratio

$$SNR = 4 \times 10^2 \sqrt{\frac{t}{10 \text{ sec}}} 10^{(20-K_{AB})/5}$$

when $K_{AB} \lesssim 22$

Putting everything together, the (2d) astrometric precision is about

$$\sigma = 18 \sqrt{\frac{10 \text{ sec}}{t}} 10^{(K_{AB}-20)/5} \ \mu\text{as}$$

For Sculptor, all stars used above have $K_{AB} < 20$ so 10 sec exposures are sufficient for the assumed 20 μsec precision

IRIS Proper Motion Precision

For a star at a distance L, two observations separated by 5 years then give a (2d) proper motion with an uncertainty of

$$\sigma = 2.4\frac{L}{100\ \mathrm{kpc}}\sqrt{\frac{10\ \mathrm{sec}}{t}}10^{(K_{AB}-20)/5}\ \mathrm{km/sec},\ \ \text{if } \mathrm{K_{AB}} \lesssim 22$$

If $K_{AB} = 23$ we find

$$\sigma = 13\frac{L}{100\ \mathrm{kpc}}\sqrt{\frac{10\ \mathrm{sec}}{t}}\ \mathrm{km/sec}$$

To measure stellar velocity dispersions and so dark matter density profiles, σ should be less than these dispersions, which are about 10 km/s (5 km/s) for dSphs (UFDs)

At 100 kpc, with 10 sec (1 min) exposures, 5 km/s 2d proper motion precisions can be obtained down to $K_{AB} \sim 21.6$ (23.0)

Observing Time

Milky Way satellites are rather large in the sky, and so require considerable observing time

Fortunately the field of view of IRIS has recently been more than quadrupled to 34 arcsec $\times$ 34 arcsec

The tidal radius r_t of the large dSph Sculptor is about 75'

Thus 5.5×10^4 images are needed to cover Sculptor out to r_t

5 km/s precision down to $K_{AB} \sim 22.1$ ($\gtrsim 10^4$ stars) will require 10 sec exposures and so about 152 hours of observations

As extratidal populations are frequently reported, on may wish to survey beyond r_t, but perhaps with shorter exposures

Other dSphs are smaller, in all two 1000 hour observation periods, separated 5 years, suffices for a thorough astrometric survey

Ultrafaint Dwarfs

While one expects that TMT can easily determine the dark matter density profiles of dSphs, uncertainties in the baryonic physics nonetheless imply that this will not yield a robust test of CDM

For this one needs to determine the profile of at least one ultrafaint dwarf (UFD)

We propose a detailed survey of Bootes I

It is only 65 kpc away and has a tidal radius of just 10'.

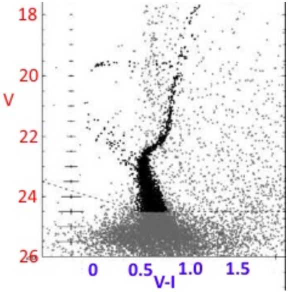
5 minute exposures to r_t will require 82 hours of observations

At $K_{AB} = 24$ it will yield $SNR = 2 \times 10^2$ and so 2d prop motion precision better than 4 km/s, and better than 3 km/sec for each proper motion component

May need 3 observation periods to identify binaries

Bootes I Stars

Suburu (Okamoto et al., 2012) did a deep survey of Bootes I



Comparison with a globular cluster (NGC3201) indicates $V - K > 1$ so precise proper motions should be available for all stars here with $V > 25$.

It has hard to count them from the figure, but this appears to be at least $10^2 - 10^3$ stars: Sufficient for a clean core/cusp distinction

Observing Programs

In March, J. Navarro and I wrote a 1 page Key Project proposal for the Fundamental Physics and Cosmology ISDT:
Above observations + 2 observations separated by *10 years* for dSphs that are in the Local Group but are not MW satellites

For some UFDs, Kallivayalil N., Wetzel A. R., Simon J. D. *et. al.* have proposed the *Hubble Astrometry Initiative*:

Hubble observes these dwarfs soon, at first light TMT may observe them again and obtains their velocity dispersions immediately

We have discussed with them the idea of doing this with Bootes I

In the past month, members of other ISDTs such as Nearby Galaxies have expressed interest in this Key Project

They bring relevant observational experience + new scientific goals

Together $\Rightarrow$ richer scientific program

Spherical Symmetry

Unfortunately: Forecasts for the precision of the measurement of γ such as that above are always overoptimistic because they assume spherical symmetry, yet few dark matter models predict spherical symmetry

Fortunately: This means that a measurement of the ellipticity/axis ratios of a halo can provide a powerful test of CDM

Thus it is essential to determine the deviation from spherical symmetry of dSph and if possible UFD dark matter halos

In the last two minutes of this talk I'll sketch work in progress on how this may be done

Cylindrical Jeans Equation: Sketch of Derivation

The following is work in progress.

The time-independent, collisionless Boltzmann equation is

$$v_i \frac{\partial f}{\partial x_i} - \frac{\partial \Phi}{\partial x_i} \frac{\partial f}{\partial v_i} = 0$$

Multiplication by v_j and integration over v yields the Jeans equation

$$\frac{\partial(\eta_s \langle v_i v_j \rangle)}{\partial x_i} + \eta_s \frac{\partial \Phi}{\partial x_j} = 0$$

To get the ellipticity in the 2d plane orthogonal to the observer:
Use cylindrical coordinates, with long axis along the line of sight

The θ component then becomes

$$\eta S \frac{\partial \Phi}{\partial \theta} = -\frac{1}{\rho} \frac{\partial(\rho \eta_s \langle v_\rho v_\theta \rangle)}{\partial \rho} - \frac{1}{\rho^2} \frac{\partial(\eta S \langle v_\theta^2 \rangle)}{\partial \theta}$$

Cylindrical Jeans Equation: Comments

$$\eta_S \frac{\partial \Phi}{\partial \theta} = -\frac{1}{\rho} \frac{\partial(\rho \eta_s \langle v_\rho v_\theta \rangle)}{\partial \rho} - \frac{1}{\rho^2} \frac{\partial(\eta_S \langle v_\theta^2 \rangle)}{\partial \theta}$$

1) θ and ρ coordinates are invariant along line of sight (not Φ, η_S)
   $\Rightarrow$ When integrated over line of sight get η_S-weighted $\partial\Phi/\partial\theta$

2) First term on the right hand side is related to the stellar ellipticity

3) The θ-dependence of the potential Φ is related to that of the dark matter density by an integral

4) Integrating $(\partial\Phi/\partial\theta)\, cos(2\theta + \delta)$ over θ one obtains the ellipticity of the gravitational potential

5) Next step: Calculate the line-of-sight integrated quantities expected for ΛCDM (ellipticity of $0.7 - 0.9$) and test to see if TMT can distinguish them from spherical symmetry