Dark Matter Properties from the Faintest Galaxies

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Particle Dark Matter and the angular power spectrum reduces to C₀, E_γ W²((1 + z)Eγ, z) k²Pρ2,ρ² (k, z) i_ol for Dain Mattel

^d^M (M,z)ρ²

^h(r|M,z),

(

60 − 100 GeV, and FGST sees more cosmic electrons than expected at around 500 GeV [5]. It is possible that these

anomalies will be understood in terms of improved models of emission from supernova remnants [6], or pulsar wind

it becomes more likely that emissions from dark matter annihilation might be extracted. If such a signal is to be

Weakly Interacting Massive Particles (WIMPs) in equilibrium in early Universe, may freeze-out with significant relic abundance

2

Point Sources in Fermi

Fermi-LAT Collaboration 1108.1435

Notable non-Fermi sources (yet)

Galaxy clusters [Pinzke, Pfrommer, Bergstrom 2011; Gao et al. 2012; Ando & Nagai 2012; Han et al. 2012]

Dwarf spheroidals (dSphs) [Tyler 2002; Evans, Ferrer, Sarkar 2004; Strigari et al. 2007, 2008]

(Optically) dark subhalos [Tasitsiomi & Olinto 2002; Koushiappas et al. 2004; Pieri et al. 2008; Baltz et al. 2008; Springel et al. 2008; Anderson et al. 2010; Baxter et al. 2011; Buckley & Hooper 2011; Belikov et al. 2011] $\left(\bigcap_{\alpha=1}^{\infty} \mathbb{I}^{\alpha} \right)$ \downarrow $\frac{1}{2004}$ Pieri et al. 2008; Baltz et al. 2008;

If they are dark matter sources, then: i and subhalos were studied in 25 structure defined as $\frac{1}{2}$ a are dark matter sources, 1 and the term that the term in the term in the term that the term that the term that contains in the term in t the microscopic dark matter physics is given explicitly as If they are dark matter sources, then:

the spectrum of photons emitted from dark matter anni-

 \mathbb{R}^2

more massive galaxies in the local group were considered in \mathbb{Z} \mathbb{R}

 \blacksquare the first to combine theoretical predictions for \mathbb{R}^n profile shapes and normalizations with specific dynamical constraints for each observed system. Though the observed velocity dispersion profiles are equally well fit $\mathbf b$ $\frac{1}{\sqrt{2}}$ $\overline{}$ set of dark matter candidates that actually annihilate \blacksquare tainty in the smooth dark matter flux contribution for CDM halos comes not from the relatively narrow range

 $\sigma_{\rm{eff}}$ are equality dispersion profiles are equality well fitting as

$$
\left\{\int_{E_{\text{th}}}^{M_{\chi}}\sum_{i}\frac{dN_{\gamma,i}}{dE}\frac{\langle\sigma v\rangle_{i}}{M_{\chi}^{2}}dE\right\}\left\{\int_{0}^{\Delta\Omega}\left\{\int_{\text{LOS}}\rho^{2}[r(\theta,\mathcal{D},s)]ds\right\}d\Omega\right\}
$$
J value

the microscopic dark matter physics is given explicitly as

Search for dark matter from dSphs

- Well understood dark matter distributions
- Nearby, may be modeled as point sources
- No sources of gamma-rays from cosmic rays or star formation

Outstanding questions

- How precise can the masses be determined? (Strigari et al. ApJ 2007; Lokas et al. MNRAS 2009; Walker et al ApJ 2009; Wolf et al. MNRAS 2009)
- Do CDM-based NFW profiles provide best model? Core / cusp issue? (e.g. Gilmore et al. ApJ 2007; Walker & Penarrubia ApJ 2011)
- Degeneracy with kinematics variables (e.g. light profile, anisotropy of stars) (Strigari, Kaplinghat, Bullock, 2007 ApJL; Evans and An MRNAS 2008)?
- Are the kinematic solutions self-consistent?

Standard dSph Kinematics Cookbook K limentowski et al. (2006) have shown that discrete al. (2006) have shown that discrete \sim idard dSph Kinematics Cookbo as long as long as unbound, interloper stars are removed with a superior of the stars are removed with a superior

note that even in the case of tidally disturbed dwarfs,

 $\mathcal{L}(\mathcal{G})=\mathcal{L}(\mathcal{G})$

generate set of shape parameters. Below, we show that

while the shape parameters are not well constrained by

 δ denote the physical quantities of δ

the scale of the stellar core radius, r# ' 2 rking, may be

3. FORECASTING ERRORS ON PARAMETERS

velocity components of stars in dSphs can be used to

probe the underlying dark matter distribution. We will

consider a model with six independent parameters: a,

 \mathbf{b}_i , and \mathbf{c}_i

 ϵ is the profile below. In order to keep the profile below. In order to ke

shape relatively smooth (as is expected for dark matter

halo profiles) we restrict the range of b and c by adding

of the Fisher matrix, F−1, provides an estimate of the

imates the error in the estimate on the parameter pı.

the minimum possible variance on the ıth parameter for

 $T_{\rm eff}$ in $T_{\rm eff}$

covariance between the parameters, and \$F [−]¹

The errors attainable on these parameters will de-

Our goal is to estimate the accuracy with which the

constrained to high precision.

Gaussian priors of ±2.

standard procedures. We derive the three resulting ob-

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

•Model both the stellar and the dark matter distribution the stellar lar and .
.
. " e dark mat # ν#σ² ^r rdr r distributic

• Statistics of stellar orbits (velocity anisotropy) 0 10 \mathbb{R} R elocity anisot vanisotropy)

servable velocity dispersions:

- Assume hydrostatic equilibrium, determine mass I#(R) is the surface density of stars, and ν∗(r) is the
- Warning!: acceptable solutions don't guarantee consistent distribution function of the stars and the measurement errors are distribution function as distribution t_{sc} and t_{c} and t_{c} is clear from t_{c} three-dimensional from α star acceptable solutions don't guarantee consti p $\frac{1}{2}$ imate by the $\frac{1}{2}$ "∂² lnL/∂pı∂p# (Kendall & Stuart 1969). The inverse

$$
\mathcal{L}(\mathcal{A}) \equiv P(\{v_i\}|\mathcal{A}) = \prod_{i=1}^{n} \frac{1}{\sqrt{2\pi(\sigma_{los,i}^2 + \sigma_{m,i}^2)}} \exp\left[-\frac{1}{2} \frac{(v_i - u)^2}{\sigma_{los,i}^2 + \sigma_{m,i}^2}\right]
$$

where {*vi*} are the individual l.o.s. stellar velocity measurements and σ*m*,*ⁱ* are the measurement errors on

concentrations, retraining concentrations, retraining the sextans having the sextand

Testing for self-consis \sim 10 \sim 10 \sim 10 parts, the inconsistent with the simulations. Which is inconsistent with the simulations. While the simulations is in the simulation of the simulations. While the simulations is in the simulations. While the simulations is exist some suggestions on the form of anisotropic DFs with a *Festing for sel n* for self-cons For NFW-like profiles, *n*⇢ and *n* are given in Eq. (9), (0) . (32)

² ² *< <* ³*.* (10)

Assuming Isotropic Orbits: \overline{O} for \overline{O} for most density profiles is often analytically intractable \mathcal{I}_1 but Sum *^d* ln *^E* (11) and the outer southern signals of the NFW*f*1(*E*) ⇠ ⇢ *^E*² *>* ³*, E* **7** Isotropic Orbits: King (1966) models have η = 9. In models with cuspy cores,

$$
f(\mathcal{E}) = \frac{1}{\sqrt{8}\pi^2} \left[\int_0^{\mathcal{E}} \frac{d^2 \rho}{d\Psi^2} \frac{d\Psi}{\sqrt{\mathcal{E} - \Psi}} + \frac{1}{\mathcal{E}^{1/2}} \left(\frac{d\rho}{d\Psi} \right)_{\Psi = 0} \right]
$$

FIG. 1:

[*r*1*, r*2] is the radial region that we are interested in. For isotropic systems, the DF depends on *r* and v only

Because we are mostly interested in the VDF tail, for

esc *^v*²

*^r*²*drf*DF(*E*)*.* (22)

 $t = \frac{1}{2}$ $\mathcal{L} = \mathcal{L} \mathcal{L}$ and potential; here en indet mplest constant anisotropy mode Gimplest constant anisotropy models: \bullet Simplest constant anisotropy m

 $f(E, I) = I^{-2\beta} f(E)$ $\widehat{f(E, L)} = L^{-2\beta} f_E(E)$ DF *f*(*E, L*) only depends on the variable E, L) = $L^{-2\beta} f_E(E)$ For different velocity \overline{G} for three different values of the concentration parameter.

The unknown function *fE*(*E*) then can be recovered from the

is constant at all radii, the DF will have the form

anisotropic DFs [e.g., 10, 11, 12, 13] are unsuitable, as they

² ¹

E

Eq. (4), we have

k = lim

so we have

f(*E*) ⇠

more flexible behavior of β [e.g., 14, 15], recovering such DFs

when ϵ is 3, the asymptotic behavior of DF cannot behavior of DF cannot behavior of DF cannot be a symptotic behavior of DF cannot be a symptotic behavior of DF cannot be a symptotic behavior of DF cannot be a symptotic

B. DF of NFW-like Models with Constant

d ln *f*(*E*)

⁸T(1/c, ^β) . (34)

" ².797, (35)

the core radius r^c and the central 3-D velocity dispersion

defined as

" ².138, (36)

" ¹.212, (37)

accuracy.

^ρ ⁼ *^r*−2^β (2π)

For different velocity anisotropy models we then have

 $w = \frac{1}{2}$

no longer a constant but we find 1.902 < η < 2.797 in the

 $r_{\rm eff}$, $r_{\rm eff}$

 $f(\theta) = \frac{1}{2} \int_{-\infty}^{\infty} \frac{d\theta}{\theta} \, d\theta$

brought forward by Seidov & Skvirsky (2000) with the moti-

vation of WUM being constant for different self-gravitating

^M(s)Φ(0) (38)

where we have used to the fact the fact of the fact of

 $\frac{1}{\sqrt{2}}$ all cases with β =const. For the Osipkov-Merritt model η is

by contribution from large s where β is close to unity.

behaviour is due to the fact that for large c the integration $\overline{}$ \mathbb{R}^n is close to \mathbb{R}^n Simplest radially-varying anisotropy $\frac{1}{\text{in} \times \text{out} \cdot \text{Morr}}$ posiprov-weiling to E found numerical *r representatively* and α is the specific angular momentum, and α Simplest radially-varying anisotropy models [Osipkov-Merritt] For anisotropic system, the DF is no longer ergodic. \blacksquare Simplest radially-vary in $\frac{1}{\sqrt{1-\frac{1$ [OSIPKOV-METTITI] 2*r*² *a a r*_{ull}est radially-valying anisotropy [Osipkov-Merritt] and reaches 1 asymptotically at infinite *r* through the energy *^E* ⁼ (*r*) *^v*²*/*2, so up to an overall py model 1.797, (35) \sim 1987), and can be derived through the Eddington through the Ed $\text{Tr} \mathbf{U}$

The calculations of the distribution function are usually

where E and Ψ are the conventional ly defined relative energy defined relative energy and the conventional

 α = α is the total energy per α is the total energy per α is the total energy per α

 $\mathcal{L}_{\mathcal{A}}$ = $\mathcal{L}_{\mathcal{A}}$ = $\mathcal{L}_{\mathcal{A}}$ is given by equation (9). The $\mathcal{L}_{\mathcal{A}}$

Tremaine 1987), where M is the total mass of the system and the system and the system and the system and the system

The solution for *f*(*Q*) is very similar to Eddington's for-

$$
\beta = 1 - \frac{\sigma_{\theta}^2 + \sigma_{\phi}^2}{2\sigma_r^2} = \frac{1}{1 + (r_a/r)^2}
$$

^f(*E, L*) = *^L*2*f*1(*E*)*,* (12)

Testing LCDM with subhalo kinematics

- Consider a subhalo in simulation
- Imagine a galaxy with the stellar density profile lives there
- Predict velocity dispersion (assuming isotropy)
	- Compare with observed velocity dispersion
- Test goodness-of-fit

dSph Photometric profiles R_S $\log n$ density $\log n$ Γ

[1 + (R/rpl)²] Core in 3D

3

$$
\rho_{\rm pl}(r) = \frac{\rho_0}{\left[1 + (r/r_{\rm pl})^2\right]^{5/2}}
$$

To model the three-dimensional stellar density profile, Core in 3D Cusp in 3D

$$
\frac{1}{5/2}
$$
 $\left[\rho_{\star}(r) \propto \frac{1}{x^a (1+x^b)^{(c-a)/b}}\right]$

 $E_{\rm eff}$ that sets the stellar mass-to-light ratio, $M_{\rm eff}$ is the stellar mass-to-light ratio, $M_{\rm eff}$

ever, if the stars contribute significantly to the stars contribute significant later α

Matching 2nd moment of distribution

Kinematics of Milky Way Satellites in a Lambda Cold Dark Matter Universe 5

Higher order moments

-30 -20 -10 0 10 20 30

Kinematics: Implications

- Isotropic, NFW models are consistent with data
- No core/cusp issue for bright dwarf spheroidals
- Further testing for anisotropic, non-spherical models [Breddels et al. 2011; Jardel & Gebhardt ApJ 2012; Baghramian, Afshordi, LS]
- Circular velocities range 10-25 km/s

Stellar systems of a really new kind Preprint typeset using L^ATEX style emulateapj v. 6/22/04

A COMPLETE SPECTROSCOPIC SURVEY OF THE MILKY WAY SATELLITE SEGUE 1: THE DARKEST GALAXY*

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ABSTRACT

6 Simon et al.

crosses are spectroscopically confirmed background galaxies and quasars. The red curve shows the location of the red giant branch, subgiant branch, and main sequence turnoff populations in the globular cluster M92 and the cyan curve shows the location of the horizontal branch of M13, both corrected for Galactic extinction and shifted to a distance of 23 kpc (data from Clem et al. 2008). (b) Spatial distribution of observed stars in Segue 1. Symbols are the same as in (a), and the ellipse represents the half-light radius of Segue 1 from Martin et al.

Keck Observatory, which is operated as a scientific partnership

Fig. 2.— (a) Color-magnitude diagram of observed stars in Segue 1. The large black circles represent stars identified as radial velocity members of the galaxy using our subjective approach, the small black dots represent stars identified as non-members, and the magenta same objects represent critical targets for indirect dark

of dark matter particles (e.g., Hogan & Dalcanton

WILLMAN 1 - A PROBABLE DWARF GALAXY WITH AN IRREGULAR KINEMATIC DISTRIBUTION Beth Willman¹, Marla Geha², Jay Strader^{3,4}, Louis E. Strigari⁵, Joshua D. Simon⁶, Evan Kirby^{7,8}, Nhung Ho², ALEX WARRES¹

Draft 7/14/11

Fig. 1.— Dereddened color-magnitude diagram of all stars within two elliptical half-light radii of the center of Willman 1 from KPNO g- and r-band photometry. We used (position angle, ellipticity, rhalf) = (77,0.47,2.3!) from Martin et al. (2008a) to calculate halflight distances. The region inside the dotted boxes is the location \sim of our highest priority spectroscopic selection criteria, \sim

2007; Sakamoto & Hasegawa 2007; Irwin et al. 2007; Irwin et al. 2007; Irwin et al. 2007; Irwin et al. 2007; Ir
Discovered al. 2007; Irwin et al.

 W is 1 color-magnitude selection criteria (open) and the 39 stars μ that do not satisfy the dotted using the dotted using μ the velocity range of −30 < vhelio < 0 km s−1used to select Wil 1 $\frac{1}{2010}$ Willman et al., 2010 bonda iyo uu wadanaa ee ah, Zulu

DEEP2 team at the University of California-Berkeley for that survey. A detailed description of the two-

Irregular kinematics of Wil 1 3

the 58 stars passing the color-magnitude criteria for membership.

of known old stellar populations (Milky Way GCs and

Irregular kinematics of Wil 1 5

$$
\mathcal{L}(\mathscr{A}) = P(\{v_i\}|\mathscr{A}) = \prod_{i=1}^{n} \frac{1}{\sqrt{2\pi(\sigma_{los,i}^2 + \sigma_{m,i}^2)}} \exp\left[-\frac{1}{2}\frac{(v_i - u)^2}{\sigma_{los,i}^2 + \sigma_{m,i}^2}\right]
$$

0.8
0.6
0.6
0.6
0.4
0.9
0.8
0.9
0.9
0.18.6 18.8 19.0 19.2 19.4 19.6 19.8 20.0
18.6 18.8 19.0 19.2 19.4 19.6 19.8 20.0
Log [j(dark matter density)² dI (GeV²/cm⁵)]

density has a negligible impact on the overall J computation, and at higher energies, the statistics with the statistics w

as Strigari et al. (2007)

Dark matter distributions

Search for emission from satellites **!0.4**

(counts

Energy (MeV)

Energy (MeV)

³ 10 ⁴ 10

³ 10 ⁴ 10

Search for emission from satellites

6 Simon et al.

crosses are spectroscopically confirmed background galaxies and quasars. The red curve shows the location of the red giant branch, subgiant branch, and main sequence turnoff populations in the globular cluster M92 and the cyan curve shows the location of the horizontal branch of M13, both corrected for Galactic extinction and shifted to a distance of 23 kpc (data from Clem et al. 2008). (b) Spatial distribution

3 Limits robust to background treatments Geringer-Sameth & Koushiappas PRL 2012

tion used to generate upper limits on PP. Each axis rep-

Improvements in analysis

- Better data on stellar kinematics
	- Improved models
	- Proper motions
- More MW satellites will be discovered
	- Only used 2 years of possible 10 years of Fermi data
- Complementarily with ground-based detectors

Distribution function modeling

- Discretize the distribution function in (E,L) space [Richstone & Tremaine (1984); Wu & Tremaine (2006); Wu (2007); Magorrian MNRAS (2006)]
- Solve for the weights
- Schwarschild modeling: DF is smooth in phase space and weights are maximized (not marginalized over) [Breddels et al. 2011; Jardel & Gebhardt ApJ 2012]
- Marginalizing over weights via MCMC captures nonsmooth features in phase-space
- Implications for J values [Braghmain, Afshordi, LS, to appear]

FIG. 3. 95% CL ULs from the VERITAS observations of Segue 1 on the WIMP velocity-weighted

annihilation \mathcal{C} as a function of the WIMP mass, considering different final states \mathcal{C}

and background subtraction. The black cross indicates the position of Segue 1. The black circles

correspond to the two exclusions used for the two exclusions used for the background determination. See the fu

How well will we do? *Fermi* Senior Review Proposal Science Case

discoveries of dwarf spheroidal satellite galaxies by optical sur-

 \mathcal{A}_eff through a strong guest investigator p

Search for Dark Subhalos

and the extrapolation the extrapolation to low-mass satellites (in red). Low-mass in the upper visit to low-mass satisfies

How rare is our Milky Way Galaxy?

Dark matter in all satellites

Luminosity-mass mapping

vast majority of the ∼ 2500 potential satellite galaxies; for

these low-mass halos, all star formation must happen before

*z*reion. With this in mind, we can define a subhalo as being a

satellite galaxy using a two parameter model: A subhalo must

grow to a threshold mass, *M*t, above which HI cooling will

allow star formation, before the host halo reionizes at *z*reion in

eters in the next section, the work of Abel et al. (2002) uses

high resolution AMR simulations to model the formation of

the first stars and indicates that we anticipate *^M*^t [≈] ¹⁰⁶ [−]

107*h*[−]1M!. It is important to note that this process of hy-

drogen cooling simply defines a minimum mass of the pop-

ulation of the dark matter subhalos that could host satellite

galaxies. However, this work predicts the stars forming in

these halos to be very massive and short–lived. As such

these very first star forming halos cannot be the direct pro-

 $\frac{1}{2}$ which are observed to be

While we demonstrate the effects of varying both param-

Further Implications

- Semi-analytic models predict more bright satellites than observed [e.g. Cooper et al. MNRAS 2010; Bovill & Ricotti ApJ 2011]
- Does the mapping between circular velocity and luminosity imply a ``massive failure" of LCDM? [e.g. Boylan-Kolchin et al., 2011]

A few ways out

1) Inclusion of Baryons in simulations [Wadepuhl & Springel MNRAS 2011, Parry et al. MNRAS 2012]

2) More fundamental modification simulations

- warm dark matter
- •primordial power spectrum

3) Low mass of the Milky Way [Vera-Ciro et al. 2012; Wang et al. 2012] 4) The Milky Way is an oddball

Testing the oddball hypothesis Leo IV -5.0 8.55 × 10³ 158 116 0.79 PSTING THE OCCIDALI N OCHILA CHUCCHILI Bo in 1980, a construction of the construction of the construction of the construction of the construction of IE O PROPERTIES OF KNOWN MILKY WAY SATELLITE GALAXIES. DATA ARE FROM

Hundreds of Milky Way Satellites? 5

Bo i -6.3 2.83 × 104 × 104 × 104 × 104 × 104 × 104 × 104 × 104 × 104 × 104 × 104 × 104 × 104 × 104 × 104 × 104

will make the contract of the c
Second contract of the contrac Segue 1 -1.5 3.40 × 10² 23 29 1.0

& GEHA (2007); MARTIN ET AL. (2008); DE JONG ET AL. (2008).

Classical (Pre-SDSS) Satellites

Sculptor -9.8 7.11 and 2007 -0.8 7 Sextander of the sextander

DR5 detection limits are not applicable. We do include Segue 1 in an alternative correction scenario below (see Table 3).

subhalo populations: the 65 largest vpeak(upper) subhalos (65 LBA) as discussed in Madau et al. (2008), vpeak > 10 km

Magellanic Cloud-like Galaxies

• About 600 systems with spectra on MC-like satellites

•About 10,000 systems with photometric redshifts on MC-like satellites

Probability for Magellanic Clouds

•5% probability a MW-like system hosts 2 satellites brighter than MCs

• Mean of 0.25 satellites brighter than MCs per MW-like galaxy

Faintest satellites in SDSS

•Very few systems with spectra for Fornax-like satellites

• About 1,000 systems with photometric redshifts for Fornaxlike satellites

from the photometric sample (method 3). The solid errors are the uncertainty on the mean, the thin, dashed errors are the intrinsic scatter

Improvements with Future Surveys

- Dark energy survey will provide at least 4x more MW-like galaxies
- For satellites will reach down to at least two magnitudes fainter than SDSS analysis
- For nearby systems satellites are identified and velocity dispersions can be determined

Going forward

16 G. Angloher et al.: Results from 730 kg days of the CRESST-II Dark Matter Search $5 \mid 0.3$ gnal bck pck 10 100 1000 WIMP mass [GeV] $10⁻$ 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} $10⁷$ WIMP-nucleon cross section [pb] CRESST 1σ CRESST 2σ CRESST 200 EDELWEISS CDMS-II XENON100 DAMA chan. DAMA CoGeNT **M2 M1**

Fig. 13. The WIMP parameter space compatible with the

 $G_{\rm eff}$ and $G_{\rm eff}$ and $G_{\rm eff}$ and $G_{\rm eff}$ (with intervalse α) and with intervalse α

Fig. 12. (Color online) Light yield distribution of the accepted $e^+e^$ grounds and the possible signal. The solid and dashed lines correspond to the parameter values in M1 and M2, respec-

- Fermi-LAT results now rule out thermal relic particle DM in the mass range 10-25 GeV
- More Galactic satellites are out there, and more data is on the way
- Complementarity with direction detection results
- Stay tuned...