Agencia Nacional de Investigación y Desarrollo
Ministerio de Ciencia, Tecnología, Conocimiento e Innovación
Gobierno de Chile

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

UAM Universidad Autónoma de Madrid

ift Instituto de Física Teórica UAM-CSIC

A robust determination of satellite dwarf galaxy J-factors from DESI observations

Nicole Araneda-Muñoz

In collaboration with Miguel Á. Sánchez-Conde

20th MultiDark Workshop

October 25 – 27, 2023

Contents

· Introduction

· Satellite dwarf galaxies

· Goals

· DESI and dwarf galaxies

· Jeans equation

· Clumpy and Jeans Module

· Remarks

ΛCDM Cosmology

- **Ordinary matter ~ 5%**

  - Chemical elements - Atoms

  - Gas - Plasma

  - Planets - Stars, ...

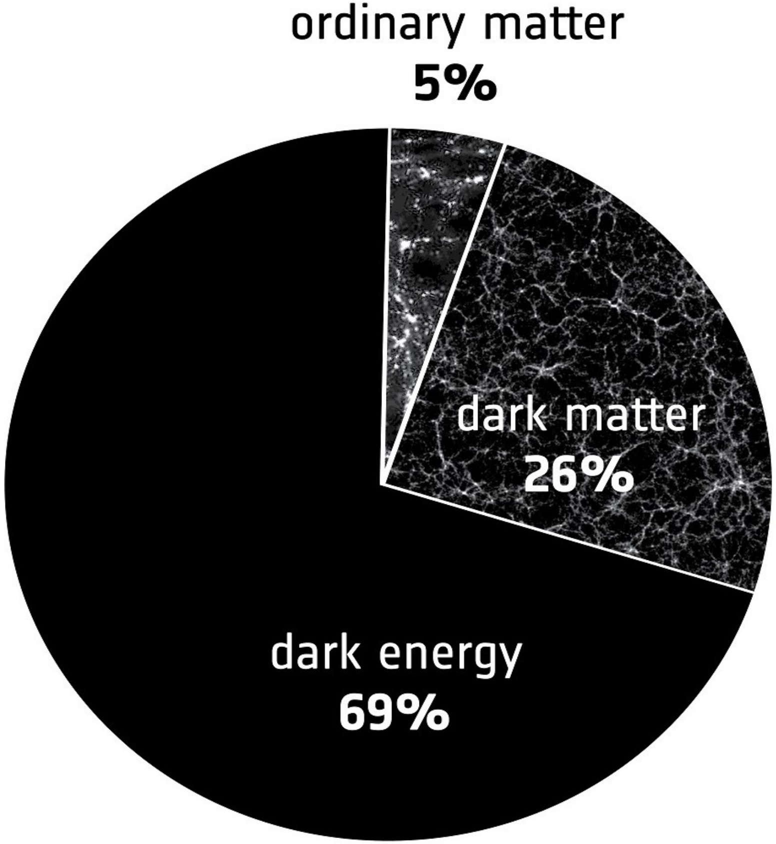
- **CDM ~ 26%**

  - Non-baryonic - Cold

  - Dissipationless - Collisionless

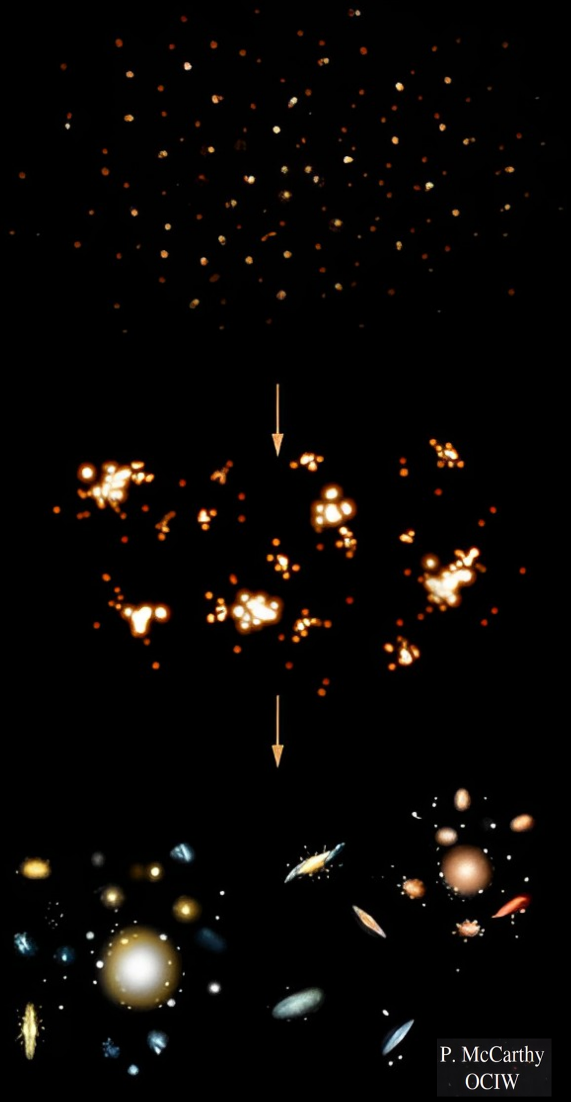
- **Cosmological Constant Ω_Λ ~ 69%**

  - Associated to "Dark Energy"



Credit: ESA

Structure Formation



Hierarchical Assembly

ΛCDM predicts:

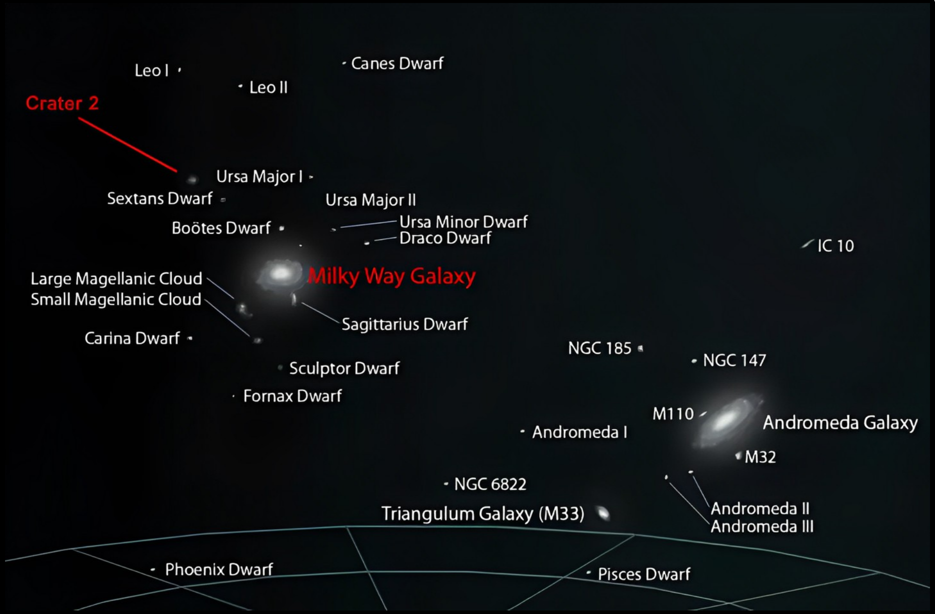
- The existence of a halo of DM hosting our galaxy.

→ The small structures are formed, and then by accretion and merging, the largest ones are formed.

- The existence of subhalos

→ A subhalo is a halo within another halo.

Satellite Dwarf Galaxies



Original image by Andrew Z. Colvin [CC BY-SA 3.0], via Wikimedia Commons.
Adapted version by Gabriel Torrealba and Will Fox.

***Formation and activity are thought to be heavily influenced by interactions with our Galaxy.**

- Most massive subhalos in our Galaxy.
- Highest Mass to light ratios known, > 100 (M. Roos 2012, arXiv:1208.3662v3).
- Mass: 10^7 – $10^9\,\mathrm{M}_\odot$.
- ~54 confirmed or probable dwarfs orbiting the MW (Drlica-Wagner et al. 2020),
  - 37 confirmed
  - 17 probable
  - 3 are excluded for being more complex systems (LMC, SMC, Segue II).
- Best targets for gamma-ray DM searches.

Goals

- Use spectroscopic data provided by DESI to accurately model and infer the density profile of dwarf galaxies.

- Knowing the density profile will allow us to subsequently get the J-Factor of those objects.

- This is essential for:

- Providing predictions on the annihilation flux.
- Setting limits on the DM with gamma-ray observations.

DESI: Dark **E**nergy **S**pectroscopic **I**nstrument

Mounted on the Mayall 4-meter reflector Telescope at KPNO.

Located in the Sonoran Desert, Arizona, USA.

Started scientific observations ~ early 2020.

Deep and wide spectroscopic surveys.

Observation lifetime ~ 5 years.

Credit: Desi Project web site

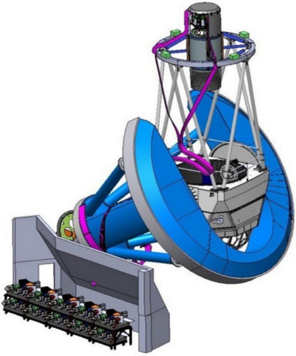
Main Goals

Measures:

· The spectra of more than 30 million galaxies and quasars covering 14,000 square degrees.

· The dynamical state of the Milky Way halo and thick disk in great detail.

· The effect of dark energy on the expansion of the universe.



DESI and Dwarfs

Astrophysics > Astrophysics of Galaxies

[Submitted on 17 Aug 2022 (v1), last revised 4 Sep 2022 (this version, v3)]

Overview of the DESI Milky Way Survey

Andrew P. Cooper, Sergey E. Koposov, Carlos Allende Prieto, Christopher J. Manser, Namitha Kizhuprakkat, Adam D. Myers, Arjun Dey, Boris T. Gaensicke, Ting S. Li, Cons ance Rockosi, Monica Valluri, Joan Najita, Alis Deason, Anand Raichoor, Mei-Yu Wang, Yuan-Sen Ting, Bokyoung Kim, Andreia Carrillo, Wenting Wang, Leandro Beraldo e Silva, Jiwon Jesse Han, Jiani Ding, Miguel Sanchez-Conde, Jessica N. Aguilar, Steven Ahlen, Stephen Bailey, Vasily Belokurov, David Brooks, Katia Cunha, Kyle Dawson, Axel de la Macorra, Peter Doel, Daniel J. Eisenstein, Parker Fagrelius, Kevin Fanning, Andreu Font-Ribera, Jaime E. Forero-Romero, Enrique Gaztanaga, Satya Gontcho A Gontcho, Julien Guy, Klaus Honscheid, Robert Kehoe, Theodore Kisner, Anthony Kremin, Martin Landriau, Michael E. Levi, Paul Martini, Aaron M. Meisner, Ramon Miquel, John Moustakas, Jundan Nie, Nathalie Palanque-Delabrouille, Will J. Percival, Claire Poppett, Francisco Prada, Nabeel Rehemtulla, Edward Schlafly, David Schlegel, Michael Schubnell, Ray M. Sharples, Gregory Tarle, Risa H. Wechsler, David H. Weinberg, Zhimin Zhou, Hu Zou

We describe the Milky Way Survey (MWS) that will be undertaken with the Dark Energy Spectroscopic Instrument (DESI) on the Mayall 4m Telescope at the Kitt Peak National Observatory. Over the next 5 years DESI MWS will observe approximately 7 million stars at Galactic latitudes |b|>20 deg, with an inclusive target selection scheme focused on the thick disk and stellar halo. MWS will also include several high-completeness samples of rare stellar types, including white dwarfs, low-mass stars within 100pc of the Sun, and horizontal branch stars. We summarize the potential of DESI to advance understanding of Galactic structure and stellar evolution. We introduce the final definitions of the main MWS target classes and estimate the number of stars in each class that will be observed. We describe our pipelines to derive radial velocities, atmospheric parameters and chemical abundances. We use ~500,000 spectra of unique stellar targets from the DESI Survey Validation program (SV) to demonstrate that our pipelines can measure radial velocities to approximately 1 km/s and [Fe/H] accurate to approximately 0.2 dex for typical stars in our main sample. We find stellar parameter distributions from 100 sq. deg. of SV observations with >90% completeness on our main sample are in good agreement with expectations from mock catalogues and previous surveys.

· DESI extends 5000 fibers over a 3.2 degrees diameter field of view (area of 8 square degrees).

· The fiber positioners can be reconfigured in 3 to 5 minutes.

- · This design allows the inspection of large sky areas at a density of ~600 targets per square degree.

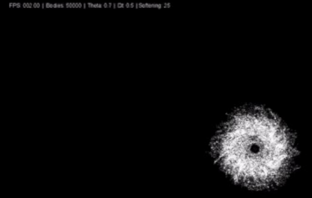
"The distribution of dark matter on small scales, including the subhalo mass function and the central density profiles of dwarf galaxies, are extremely important probes of the nature of dark matter" (Zavala & Frenk 2019) .

The DESI MWS can constrain some properties in the MW and Local Group through observations of tidal streams and dwarf galaxies.

From Star Velocities to DM distributions

Jeans Equations: Set of equations that describe the motion of a group of stars in a gravitational field.

We can then link the enclosed mass in radius and moments of the stellar distribution:



University of Texas N-body Simulation. Governed by Jeans equations in a gravitational potential

$$\underbrace{\frac{1}{\nu}\frac{\mathrm{d}}{\mathrm{d}r}(\nu\bar{v_r^2}) + 2\frac{\beta_{\mathrm{ani}}(r)\bar{v_r^2}}{r}}_{\text{DESI data}} = \underbrace{-\frac{GM(r)}{r^2}}_{\text{DM density profile (CLUMPY)}}$$

$\bar{v}_r^2(r)$: Radial velocity dispersion of baryons (e.g. stars in dwarf galaxies).

$\beta_{ani}(r)$: Orbital anisotropy of the stellar component (depending on the radial and tangential velocity dispersion).

$\nu(r)$ or $\rho(r)$: Spatial density (spherical symmetry) of the light profile.

$M(r)$: Enclosed mass in a radius r.

Our Tool: Clumpy

Credit: Clumpy web site

References:

Charbonnier et al. 2012
Bonnivard et al. 2015
Hütten et al. 2018

Website:

http://clumpy.gitlab.io/CLUMPY/

Open source code developed by C. Combet, M. Hütten and D. Maurin, widely used in the DM community.

Calculation of gamma-ray or neutrino signals from annihilating and decaying astrophysical DM.

Clumpy also allows computing the DM density profile from the star velocities **(Jeans analysis)**.

We are in close contact with the developers.

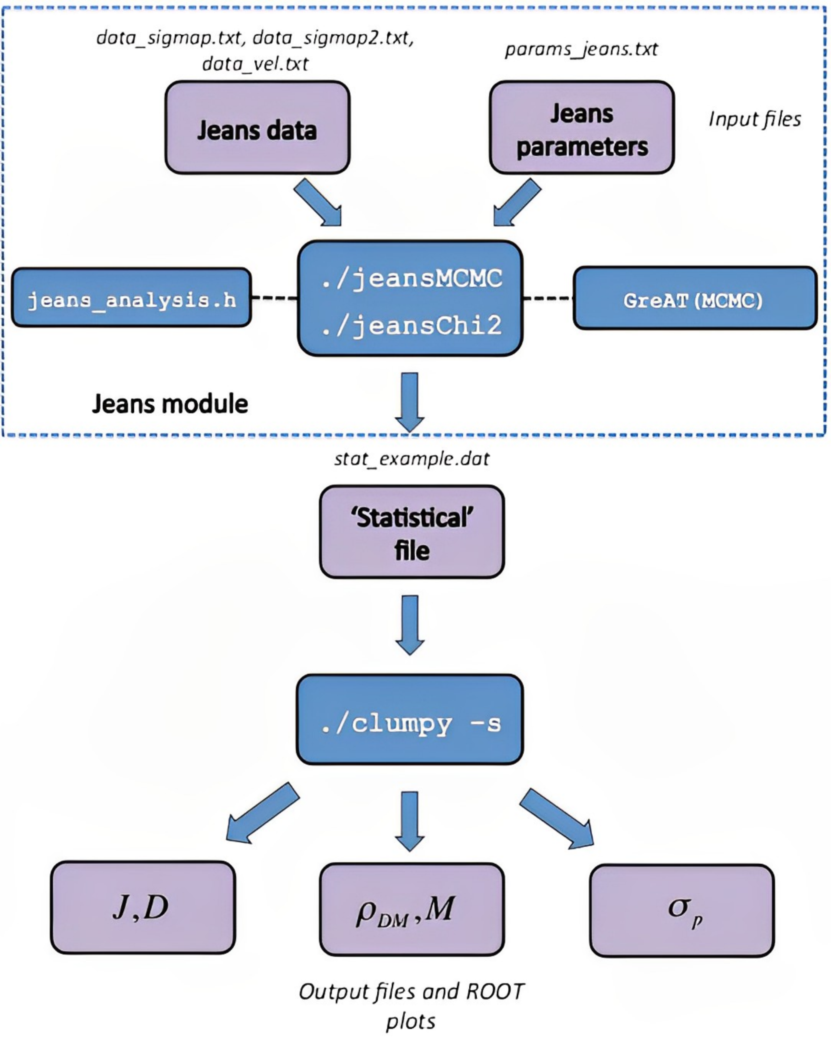
Clumpy: Jeans Module

The Jeans equation relates the DM content of an object (potential well) to its light content (dynamics in the potential).

We need to provide functional form of:

- **DM Density Profile** (Zhao, Einasto).
- **Surface Brightness Profiles** (Plummer, King, Sersic).
- **Anisotropy Profile** (constant, Osipkov-Merritt).

- ** 2 to 5 free parameters (normalization, scale radius, plus some structural parameters).



Credit: Clumpy web site

More robust determination of DESI dwarfs J-Factors

We will derive the density profile from star dispersion velocities. It will allow us to compute,

J-Factor → **Astrophysical factor in the annihilation flux.**

$$\sigma(r) \xrightarrow{\text{Jeans Module}} \rho(r) \longrightarrow \mathrm{J}_{Factor}\,.$$

We calculate J-Factor from the integration of the squared DM density profile of an object of volume V,

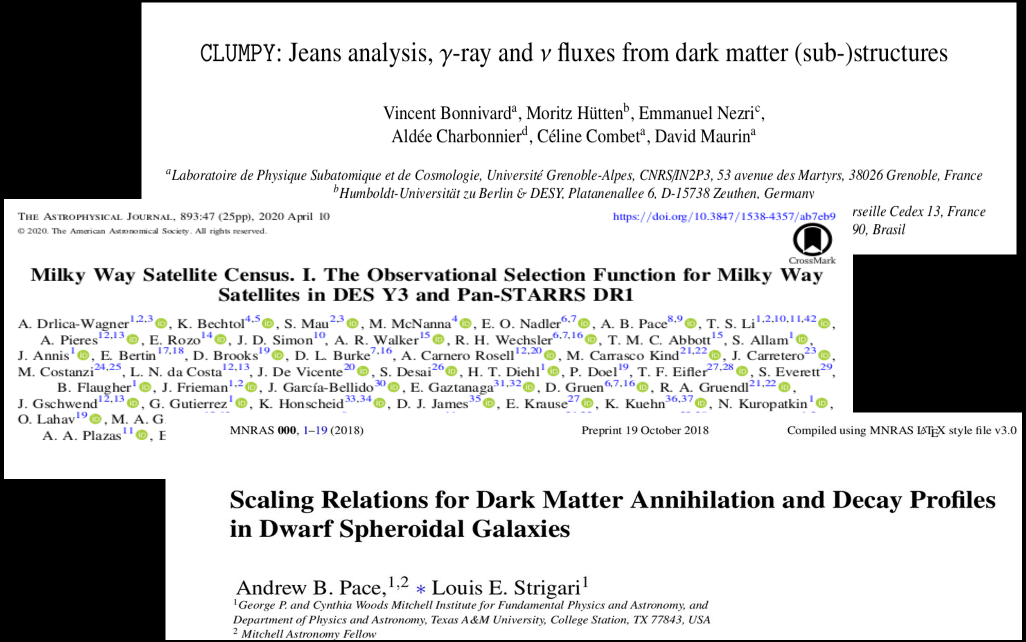
$$J_{Factor} \propto \int_V \rho^2(r)dV\,.$$

Uncertainties in the density profile translate into
larger uncertainties in the J-Factor.

Ongoing work

- Familiarization with DESI and CLUMPY, Dwarfs Galaxies literature, etc.

- Next immediate steps:
  - Use CLUMPY Jeans module on brand new DESI data from Draco and compare with previous Draco J-Factors.



`CLUMPY`: Jeans analysis, γ-ray and ν fluxes from dark matter (sub-)structures

Vincent Bonnivard[a], Moritz Hütten[b], Emmanuel Nezri[c],
Aldée Charbonnier[d], Céline Combet[a], David Maurin[a]

[a]*Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, 53 avenue des Martyrs, 38026 Grenoble, France*
[b]*Humboldt-Universität zu Berlin & DESY, Platanenallee 6, D-15738 Zeuthen, Germany*
rseille Cedex 13, France
90, Brasil

The Astrophysical Journal, 893:47 (25pp), 2020 April 10 https://doi.org/10.3847/1538-4357/ab7eb9
© 2020. The American Astronomical Society. All rights reserved.

CrossMark

Milky Way Satellite Census. I. The Observational Selection Function for Milky Way Satellites in DES Y3 and Pan-STARRS DR1

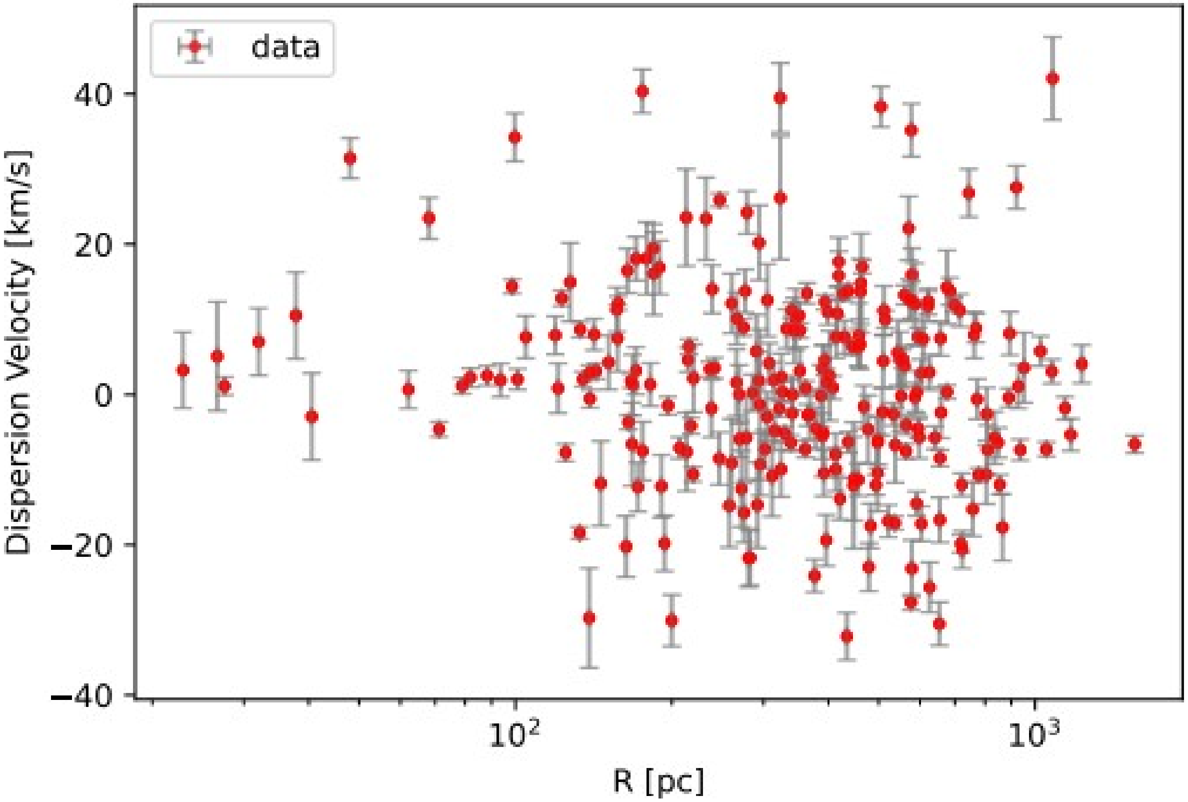
A. Drlica-Wagner[1,2,3], K. Bechtol[4,5], S. Mau[2,3], M. McNanna[4], E. O. Nadler[6,7], A. B. Pace[8,9], T. S. Li[1,2,10,11,42], A. Pieres[12,13], E. Rozo[14], J. D. Simon[10], A. R. Walker[15], R. H. Wechsler[6,7,16], T. M. C. Abbott[15], S. Allam[1], J. Annis[1], E. Bertin[17,18], D. Brooks[19], D. L. Burke[7,16], A. Carnero Rosell[12,20], M. Carrasco Kind[21,22], J. Carretero[23], M. Costanzi[24,25], L. N. da Costa[12,13], J. De Vicente[20], S. Desai[26], H. T. Diehl[1], P. Doel[19], T. F. Eifler[27,28], S. Everett[29], B. Flaugher[1], J. Frieman[1,2], J. García-Bellido[30], E. Gaztanaga[31,32], D. Gruen[6,7,16], R. A. Gruendl[21,22], J. Gschwend[12,13], G. Gutierrez[1], K. Honscheid[33,34], D. J. James[35], E. Krause[27], K. Kuehn[36,37], N. Kuropatkin[1], O. Lahav[19], M. A. G
A. A. Plazas[11], E

MNRAS **000**, 1–19 (2018) Preprint 19 October 2018 Compiled using MNRAS LaTeX style file v3.0

Scaling Relations for Dark Matter Annihilation and Decay Profiles in Dwarf Spheroidal Galaxies

Andrew B. Pace,[1,2] ⋆ Louis E. Strigari[1]
[1]*George P. and Cynthia Woods Mitchell Institute for Fundamental Physics and Astronomy, and Department of Physics and Astronomy, Texas A&M University, College Station, TX 77843, USA*
[2] *Mitchell Astronomy Fellow*

Draco dwarf galaxy



Right ascension	17h 20m 12.4s
Declination	+57° 54′ 55″
Distance	80 ± 10 kpc

Remarks

- Dwarf galaxies are the best targets for DM annihilation searches at present.

- However, current dwarf J-factor determinations are subject to large uncertainties.

- This work will use DESI precision spectroscopy of dwarfs galaxies to derive state-of-the-art density profiles and more accurate J-factor values.

- Having more robust J-factor determinations will allow us to set more robust constraints on the DM properties.

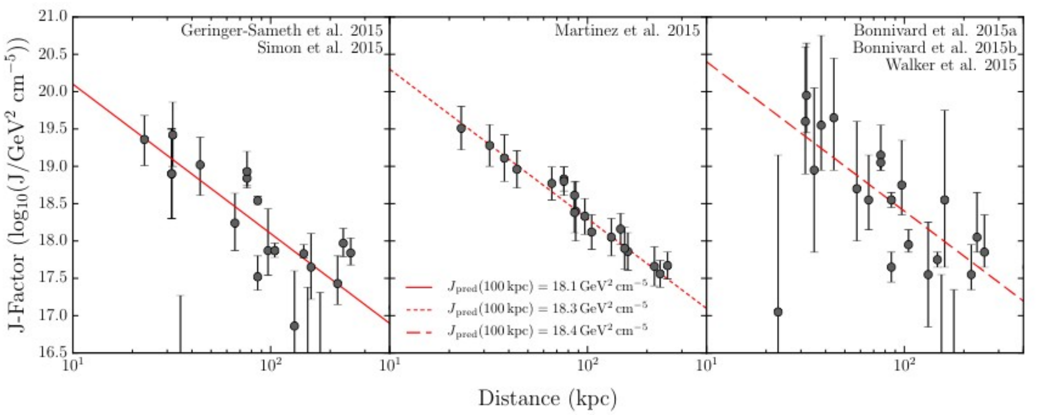


Figure 5. Relationship between the distances and spectroscopically determined J-factors of known dSphs is derived with three different techniques: (left) non-informative priors (Geringer-Sameth et al. 2015a), (center) Bayesian hierarchical modeling (Martinez 2015), and (right) allowing for more flexible parametrizations of the stellar distribution and orbital anisotropy profile (Bonnivard et al. 2015a).

Credit: A. Albert et al. 2016

DAMASCO research group

https://projects.ift.uam-csic.es/damasco/

Agencia Nacional de Investigación y Desarrollo
Ministerio de Ciencia, Tecnología, Conocimiento e Innovación
Gobierno de Chile

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

UAM Universidad Autónoma de Madrid

ift Instituto de Física Teórica UAM-CSIC

Thank you

DESI MWS footprint

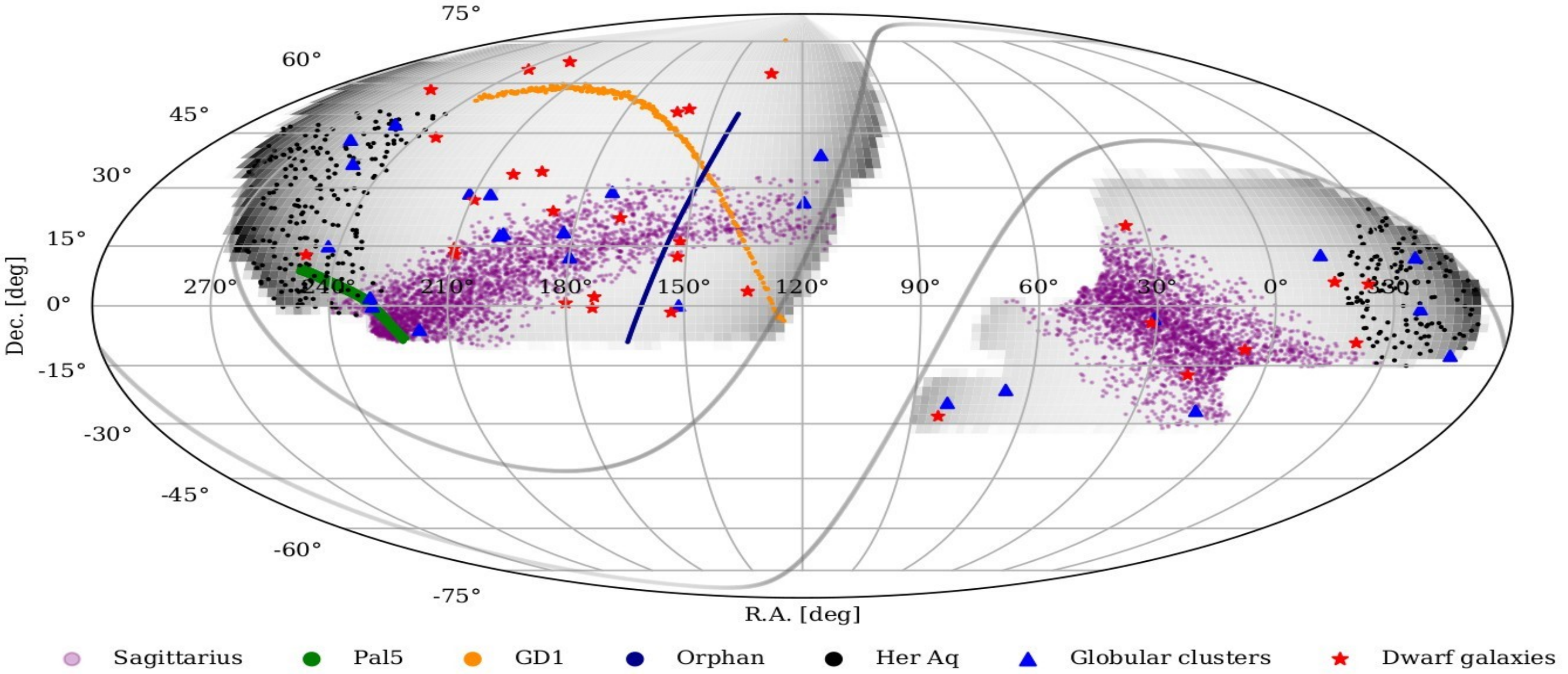


Figure 1. The DESI MWS footprint. Grey lines indicate the approximate Galactic latitude limit of the survey, $|b| \pm 20^\circ$. The density of MWS targets is shown in greyscale. Colored symbols indicate known Milky Way satellites (stars) and globular clusters (triangles). Points and tracks (colors given in the legend) show the four most prominent streams, as reported in the `galstreams` compilation (Mateu 2017): Sgr, represented by the Law & Majewski (2010) model; Palomar 5 (Price-Whelan et al. 2019); GD1 (Price-Whelan & Bonaca 2018a) and Orphan (Koposov et al. 2019). We also show the approximate extent of the Hercules-Aquila cloud as reported in `galstreams` (based on Grillmair & Carlin 2016). Many other less prominent streams and stellar overdensities are known in the MWS footprint (see e.g. Mateu 2022).

Cooper et al. 2022