Indirect detection in Milky Way satellites

Self-annihilating DM in presence of light force mediator

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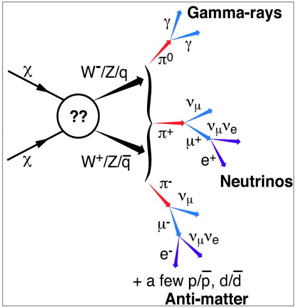
Indirect detection

Search for **DM** annihilation/decay **signatures in the sky**

- Use galaxies as particle physics laboratories
- Strong constraints on thermal relics
- Rapid improvements in observational data

arXiv:0912.3828



⇒ Need for accurate modeling of DM related signals

Current constraints

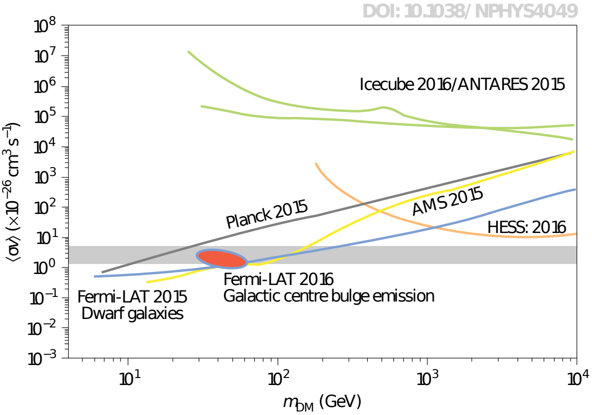


Figure: Indirect detection constraints on DM annihilation cross-section.

Project outline - arXiv:1804.05052

Motivation:

- Generic enhancement of signal in presence of light mediators [1]
- Probe effect of DM velocity anisotropy on annihilation signal
- Era of high precision cosmology and astronomy (Fermi-LAT, accurate measurements of stellar kinematics, ...)

Outline:

- Model the **DM halo phase-space distribution**
- Study the annihilation rates in presence of **Sommerfeld enhancement**
- Apply the analysis to **Milky Way satellites**

[1] Boddy et al. arXiv:1702.00408, Bergström et al. arXiv:1712.03188

Indirect detection

Focus on gamma rays from DM annihilations.

Differential photon flux produced by annihilations:

$$\frac{\mathrm{d}\Phi}{\mathrm{d}E_\gamma} = \frac{1}{8\pi}\frac{\mathrm{d}N}{\mathrm{d}E_\gamma}\int \mathrm{d}\Omega \int \mathrm{d}\ell \int \mathrm{d}^3 v_1 \frac{f(\vec{r},\vec{v}_1)}{m_\chi} \int \mathrm{d}^3 v_2 \frac{f(\vec{r},\vec{v}_2)}{m_\chi} \cdot (\sigma v_{\mathrm{rel}})$$

Non-standard ingredients:

- Annihilation cross-section boosted by relative velocity dependent factor - **Sommerfeld enhancement**: $\langle \sigma v_{\mathrm{rel}} \rangle_0 \rightarrow \langle \sigma v_{\mathrm{rel}} \rangle_0 \cdot S(v_{\mathrm{rel}})$
- **Compute phase-space distribution** for various DM density profiles (NFW, Burkert and non-parametric profile)

Sommerfeld enhancement

Generic **boost of cross-section** for non-relativistic particles for interactions mediated light scalar or vector force mediator ϕ (i.e. requires $E_\chi \approx m_\chi$ and $m_\phi \ll \alpha_\chi m_\chi$).

Yukawa coupling gives rise to the following potential:

$$V(r) = \mp \frac{\alpha_\chi}{r} exp\left(-m_\phi r\right)$$

Solve Schrödinger equation to obtain the **wave function distortion** due to the mediator exchange:

$$\chi''(x) + \left(\frac{v_{\rm rel}^2}{\alpha_\chi^2} + V(x)\right)\chi(x) = 0 \quad \Rightarrow \quad S(v_{\rm rel};\xi) = \left|\frac{\chi(0)}{\chi(\infty)}\right|^2 \propto \frac{1}{v_{\rm rel}^{\alpha}}$$

DM phase-space distribution function

Different **isotropic** modelings present in literature

- Maxwell-Boltzmann approximation:

$$f(r,v) = \frac{\rho_{\rm DM}(r)}{(2\pi\sigma^2(r))^{3/2}} \cdot \exp\left(\frac{v^2}{2\sigma^2(r)}\right)$$

- Eddington's inversion (based on spherical Jeans equation):

$$f(\mathcal{E}) = \frac{1}{\sqrt{8}\pi^2}\frac{\mathrm{d}}{\mathrm{d}\mathcal{E}}\int_0^{\mathcal{E}} \frac{\mathrm{d}\Psi}{\sqrt{\mathcal{E}-\Psi}}\frac{\mathrm{d}\rho}{\mathrm{d}\Psi} \quad , \quad \mathcal{E} = \Psi(r) - \frac{v^2}{2}$$

Eddington's inversion gives unique solution for **spherically symmetric** and **ergodic** (hence isotropic) system.

Anisotropic DM phase-space distribution function

Velocity anisotropy characterized by: $\beta(r) \equiv 1 - \frac{\sigma_t^2}{2\sigma_r^2}$

Slope-anisotropy inequality[2]: $-\frac{d \ln \rho}{d \ln r} \geq 2\beta$

We consider the following possible choices:

- **Osipkov-Merritt model**: $\beta(r) = \frac{r^2}{r^2 + r_a^2}$

$$\mathcal{E} \rightarrow \mathcal{Q} = \mathcal{E} - \frac{L^2}{2r_a^2} \quad , \quad \rho(r) \rightarrow \rho(r) \cdot \left(1 + \frac{r^2}{r_a^2}\right)$$

- **Constant orbital anisotropy:** $\beta(r) = \beta_c$

$$f(\mathcal{E}, L) = L^{-2\beta_c} \cdot f_{\beta_c}(\mathcal{E})$$

[2] An&Evans arXiv:astro-ph/0511686v4, Ciotti&Morganti arXiv:1006.2344

DM velocity distribution

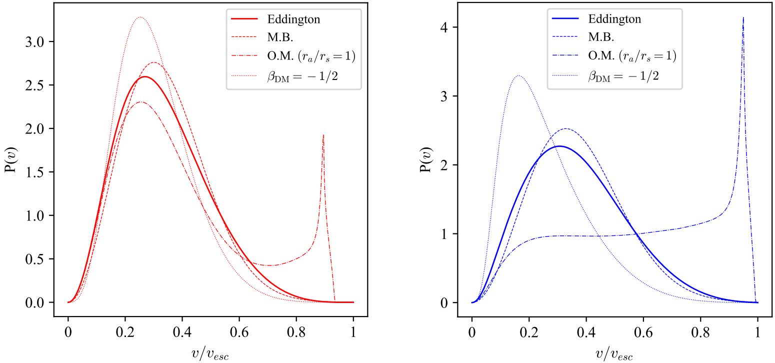


Figure: Velocity distributions computed under different assumptions for NFW (left) and Burkert (right) density profiles.

Velocity averaged enhancement and J-factors

The effect of Sommerfeld enhancement can be enraptured in **velocity-averaged boost factor**:

$$\langle S(v_{\rm rel})\rangle(r) = \frac{1}{\rho^2(r)} \int \mathrm{d}^3 v_1 f(r,\vec{v}_1) \int \mathrm{d}^3 v_2 \; f(r,\vec{v}_2) S(v_{\rm rel})$$

Corresponding astrophysical J-**factor** can be obtained as follows:

$$J = \int \mathrm{d}\Omega \int \mathrm{d}\ell \; \rho^2(r) \cdot \langle S(v_{\rm rel})\rangle(r)$$

Differential annihilation flux proportional to J-factor:

$$\frac{d\Phi}{dE_\gamma} = \frac{1}{8\pi} \frac{\langle \sigma v_{\rm rel}\rangle_0}{m_\chi^2} \frac{dN}{dE_\gamma} \cdot J$$

Velocity averaged enhancement

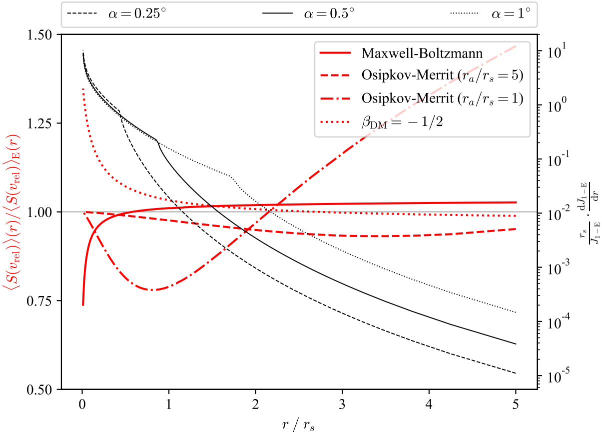


Figure: Velocity averaged enhancement factor ratio as function of r/r_s.

Application: Milky Way satellites

Dwarf spheroidal galaxies (dSph) present one of the prime targets for detection of DM annihilation events:

- **DM dominated** objects; $10 - 100\times$ higher mass to luminosity ratio then in regular galaxies
- Relative **proximity** of MW dwarfs
- **Small DM velocities** expected

Strong **Fermi-LAT** constraint on gamma ray flux

Stellar distribution and velocity dispersion measurements allow for **reconstruction of gravitational potential** $\rightarrow$ DM density profile

Special thanks to M. Walker for providing us with the pruned data

Application: Bayesian analysis of dSph

Observations provide us with **projected surface brightness** $\Sigma_\star$ and **line-of-sight velocity dispersion** $\sigma_{\rm los}$.

Using Jeans analysis one can compute the $\sigma_{\rm los}$ for a given model:

$$\sigma^2_{\rm los}(R) = \frac{1}{\Sigma_\star(R)} \int_{R^2}^{\infty} \frac{dr^2}{\sqrt{r^2 - R^2}} \left(1 - \beta_\star(r)\frac{R^2}{r^2}\right) p_{r\,\star}(r)$$

$$p_{r\,\star}(r) = G_N \int_r^{\infty} dx\, \frac{\rho_\star(x) M_{\rm tot}(x)}{x^2} \exp\left[2\int_r^x dy\, \frac{\beta_\star(y)}{y}\right]$$

Use the following likelihood for radially binned data:

$$\mathcal{L}_{\rm kin} \equiv \prod_{k=1}^{\rm N} \frac{1}{\sqrt{2\pi}\,\Delta\sigma_{los\,(k)}\left(\alpha_{(k)}\right)} \exp\left[-\frac{1}{2}\left(\frac{\overline{\sigma}_{los\,(k)} - \sigma_{los}\left(\alpha_{(k)}\right)}{\Delta\sigma_{los\,(k)}\left(\alpha_{(k)}\right)}\right)^2\right]$$

Application: Bayesian analysis of dSph

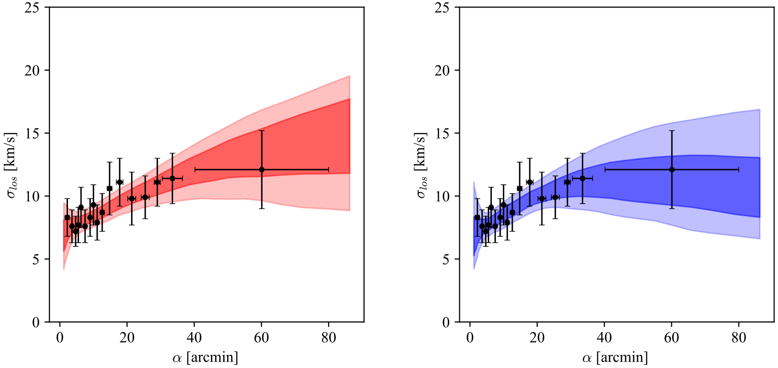
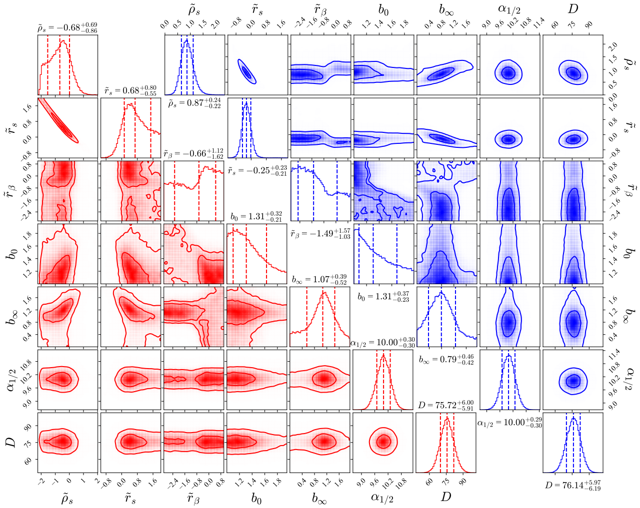


Figure: Draco line-of-sight velocity dispersion data and 68% and 95% credibility intervals for fits using NFW (left) and Burkert (right) profile.

Application: Bayesian analysis of dSph



Application: J-factors

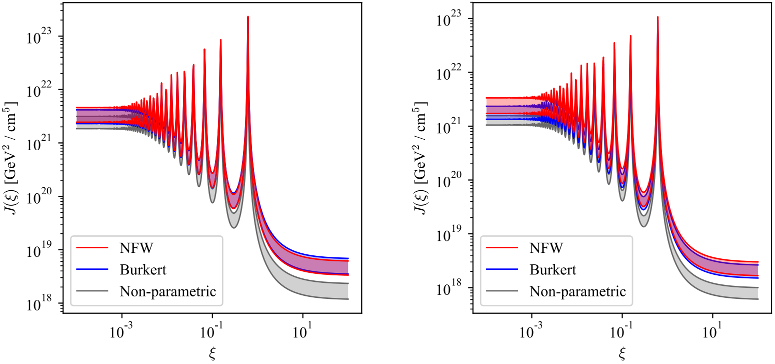


Figure: 68% confidence band for J-factors as a function of $\xi = \frac{m_\phi}{\alpha_\chi m_\chi}$ for Draco (left) and Sculptor (right).

Application: J-factors

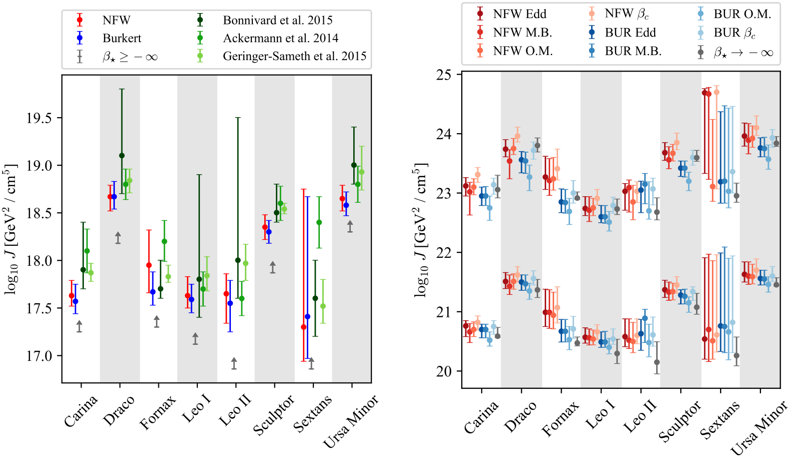


Figure: *J*-factors for 8 dSph with the 68% confidence intervals.

Summary

Developed numerical code for computing:

- **phase-space distribution of DM** for an arbitrary density profile and different orbital anisotropy assumptions
- **J-factors for arbitrary cross-section velocity dependence** based on the phase-space distribution

Bayesian inference of the **dSph DM halo parameters**.

Careful analysis of **J-factors** in presence of Sommerfeld enhancement.

Novel results for various **DM orbital anisotropies**.

Conclusions and outlook

Conclusions:

- In presence of Sommerfeld enhancement the dSph **constraints on $\langle \sigma v \rangle_0$ strengthen by $\mathcal{O}(10^3)$ - $\mathcal{O}(10^5)$**
- Circularly (radially) biased DM orbits lead enhancement (suppression) of annihilation rate
- Systematic uncertainties due to **DM orbital anisotropy at the level of observational uncertainties**

Outlook:

- Use detailed phase-space modeling in the context of direct detection experiments
- Obtain conservative (non-parametric) bounds on Milky Way DM density distribution

Non-parametric DM profile from Jean's equation

Jean's equation allows to reconstruct the gravitational potential from the stellar distribution and kinematics:

$$\frac{\mathrm{d}p}{\mathrm{d}r} + \frac{2\beta_\star(r)}{r}p(r) = -\rho_\star(r)\frac{\mathrm{d}\Phi}{\mathrm{d}r} \quad , \quad p(r) = \rho_\star(r)\sigma_r^2(r)$$

Degeneracy between stellar velocity dispersion anisotropy $\beta_\star(r)$ and gravitational potential $\Phi(r)$.

Assuming Plummer stellar profile, isotropy ($\beta_\star = 0$) and constant $\sigma_{\rm los}(R) \equiv \sigma_{\rm los}$ one finds:

$$\rho_{\rm DM}(r) = \frac{5\sigma_{\rm los}^2}{4\pi G}\frac{r^2 + 3R_{1/2}^2}{(r^2 + R_{1/2}^2)^2}$$