Phase-space distribution of relaxed galactic DM component

Mihael Petač
Supervised by Piero Ullio

Astroparticle physics group
SISSA, Trieste

June 23, 2019

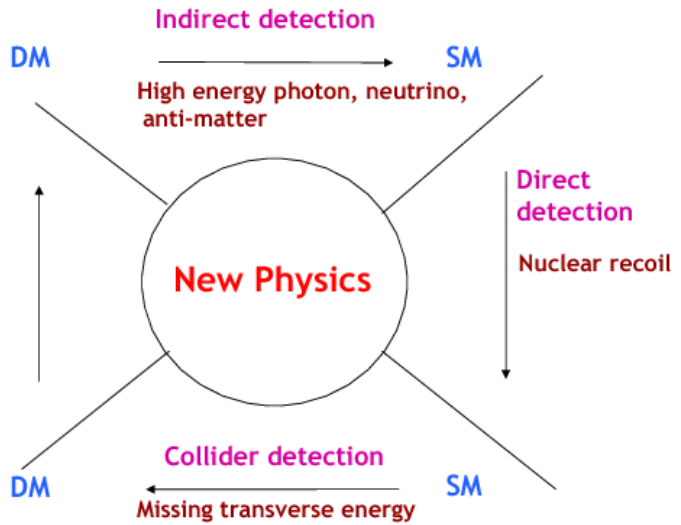
Introduction

Strong evidence for existence of particle-like DM:

- Supported by **independent observations** (e.g. galactic rotation curves, gravitational lensing, CMB)
- Alternative explanations can not account for all the phenomena

Numerous experimental searches for DM particle:

- Collider searches
- Direct detection
- Indirect detection



Current constraints

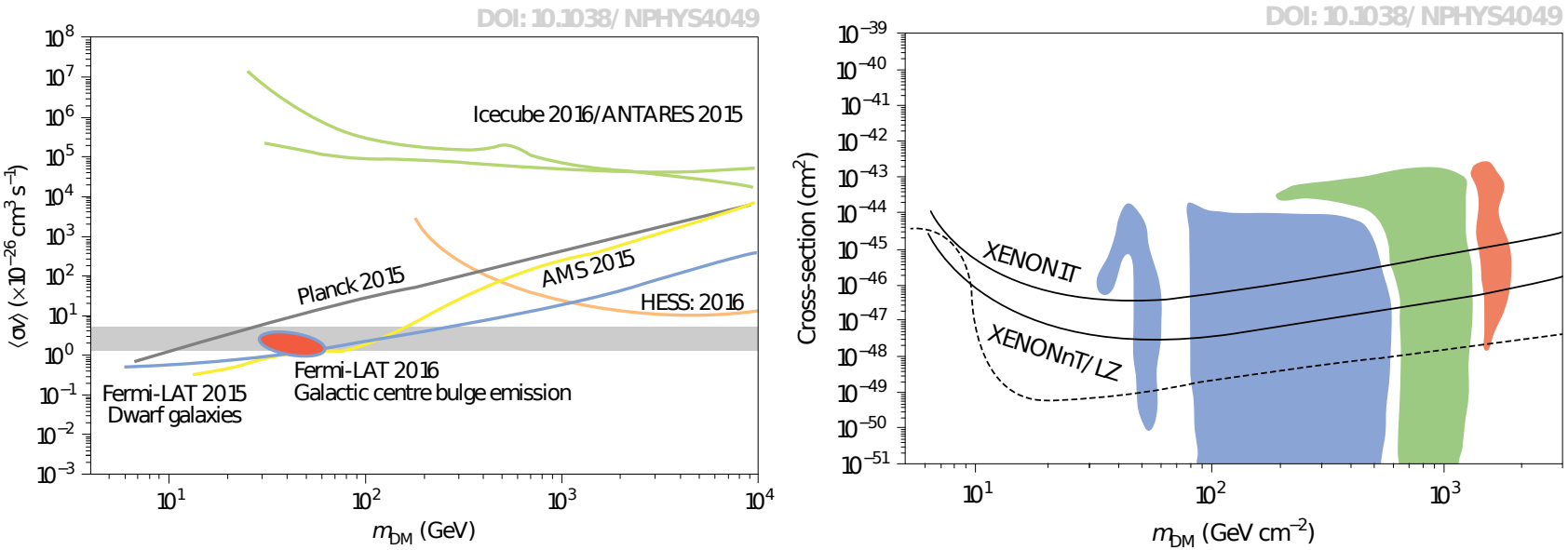


Figure: Indirect detection constraints on annihilation cross-section (left) and direct detection constraints on spin independent DM-nucleon cross-section (right).

Research outline

Motivation:

- Era of **high precision experiments** (Planck, Fermi-LAT, Xenon1T, Gaia ...)
- Direct and indirect detection signals generically depend on **DM velocity distribution**

Outline:

- Obtain self-consistent **DM halo phase-space distribution**
- Address general **velocity dependent cross-sections** (DM-nucleus or DM annihilation)
- Analyze some of the prime targets: **Milky Way** and its **dwarf satellite galaxies**

Indirect detection

Search for high energy particles produced in DM annihilations (or decays) $\rightarrow$ focus on annihilations into γ-rays

Differential photon flux produced by annihilations:

$$\frac{\mathrm{d}\Phi}{\mathrm{d}E_\gamma} = \frac{1}{8\pi m_\chi^2}\frac{\mathrm{d}N}{\mathrm{d}E_\gamma}\int \mathrm{d}\Omega \int \mathrm{d}\ell \int \mathrm{d}^3 v_1 f(\vec{r},\vec{v}_1) \int \mathrm{d}^3 v_2 f(\vec{r},\vec{v}_2)\cdot(\sigma v_{\mathrm{rel}})$$

- **Phase-space distribution** of DM needed for accurate prediction of annihilation flux
- Annihilation cross-section velocity dependence - phenomenologically motivated **Sommerfeld enhancement**: $\langle\sigma v_{\mathrm{rel}}\rangle_0 \rightarrow \langle\sigma v_{\mathrm{rel}}\rangle_0 \cdot S(v_{\mathrm{rel}})$

Phase-space distribution functions

For a **spherically symmetric** system there exists an unique **ergodic** (hence isotropic) phase-space distribution function:

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

Similar expressions can be obtained also for **anisotropic** velocity distributions, where $\beta(r) \equiv 1 - \frac{\sigma_t^2}{2\sigma_r^2} \neq 0$:

- Osipkov-Merritt model: $\beta(r) = \frac{r^2}{r^2+r_a^2}$
  $f(\mathcal{E}) \to f(\mathcal{Q} = \mathcal{E} - \frac{L^2}{2r_a^2}) \quad , \quad \rho \to \left(1 + \frac{r^2}{r_a^2}\right) \rho$
- Constant orbital anisotropy: $\beta(r) = \beta_c$
  $f(\mathcal{E}) \to f_{\beta_c}(\mathcal{E}) \cdot L^{-2\beta_c}$

Lacroix T., Stref M. & Lavalle J.: JCAP09(2018)040 / arXiv:1805.02403

DM velocity distribution

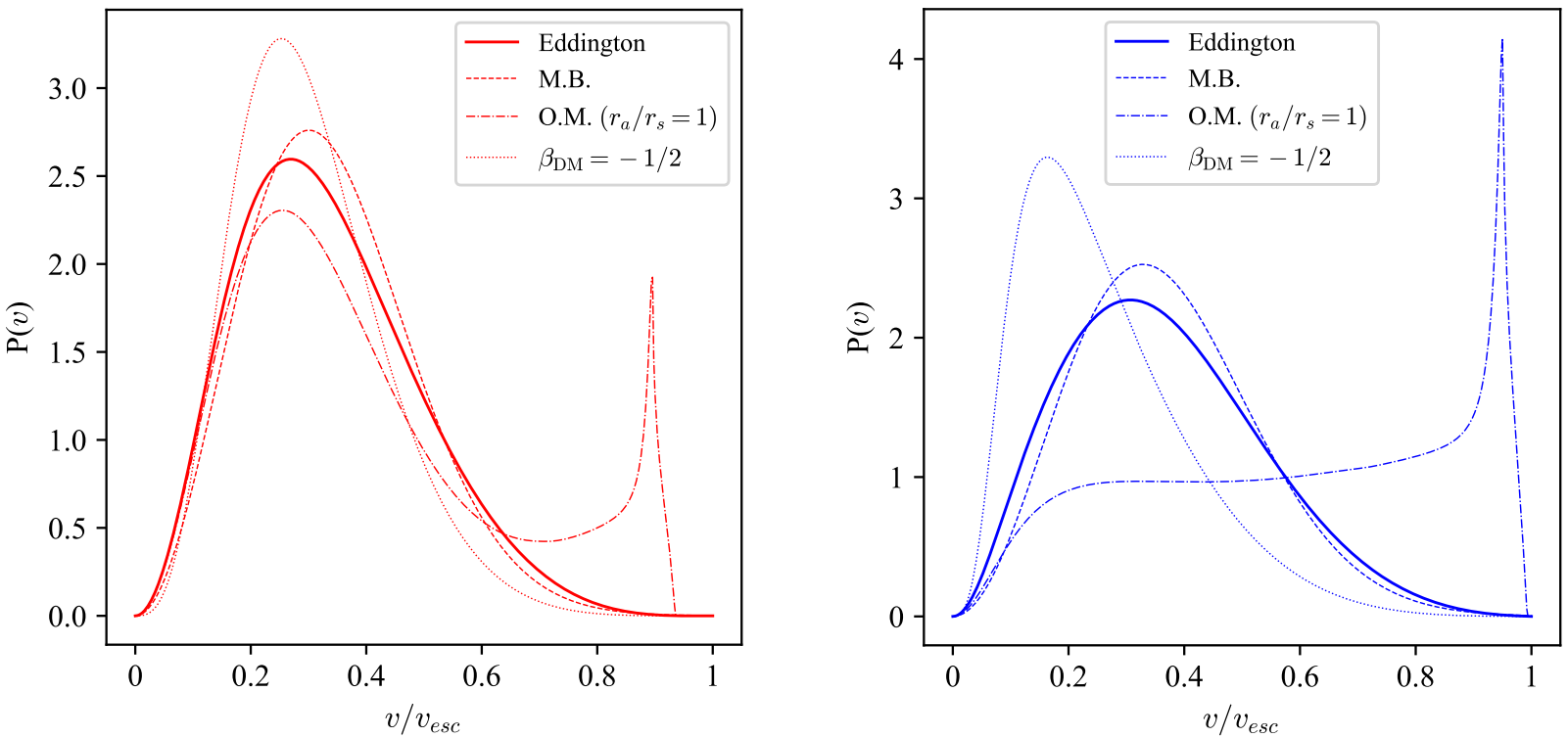


Figure: Velocity distributions computed under different assumptions for NFW (left) and Burkert (right) density profiles.

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
- Expecting **small DM velocities**

Strong **Fermi-LAT** constraint on annihilation 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

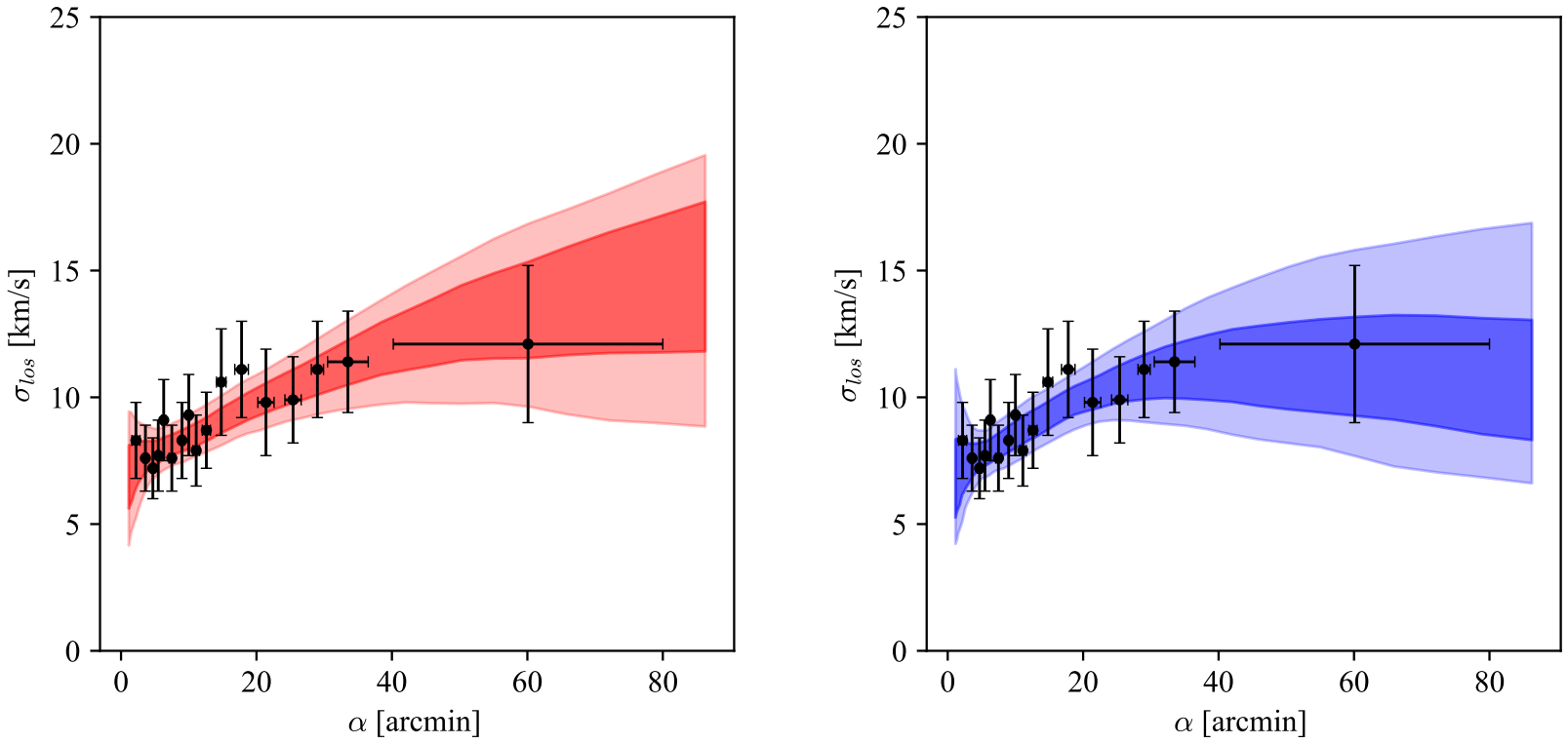
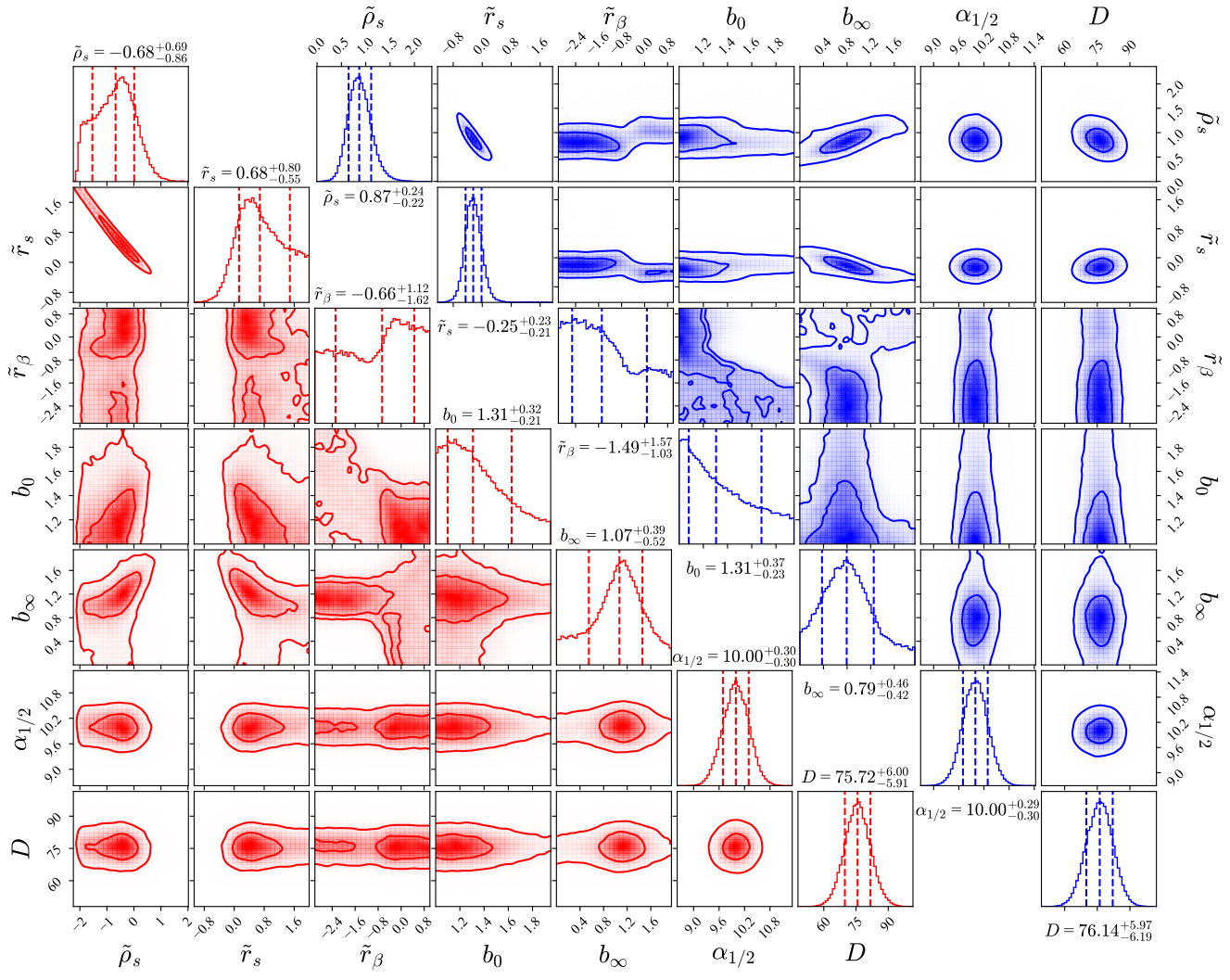


Figure: Draco line-of-sight velocity dispersion data and 68% and 95% credibility intervals for fits using NFW (left) and Burkert (right) profile.

Application: Bayesian analysis of dSph



Application: J-factors

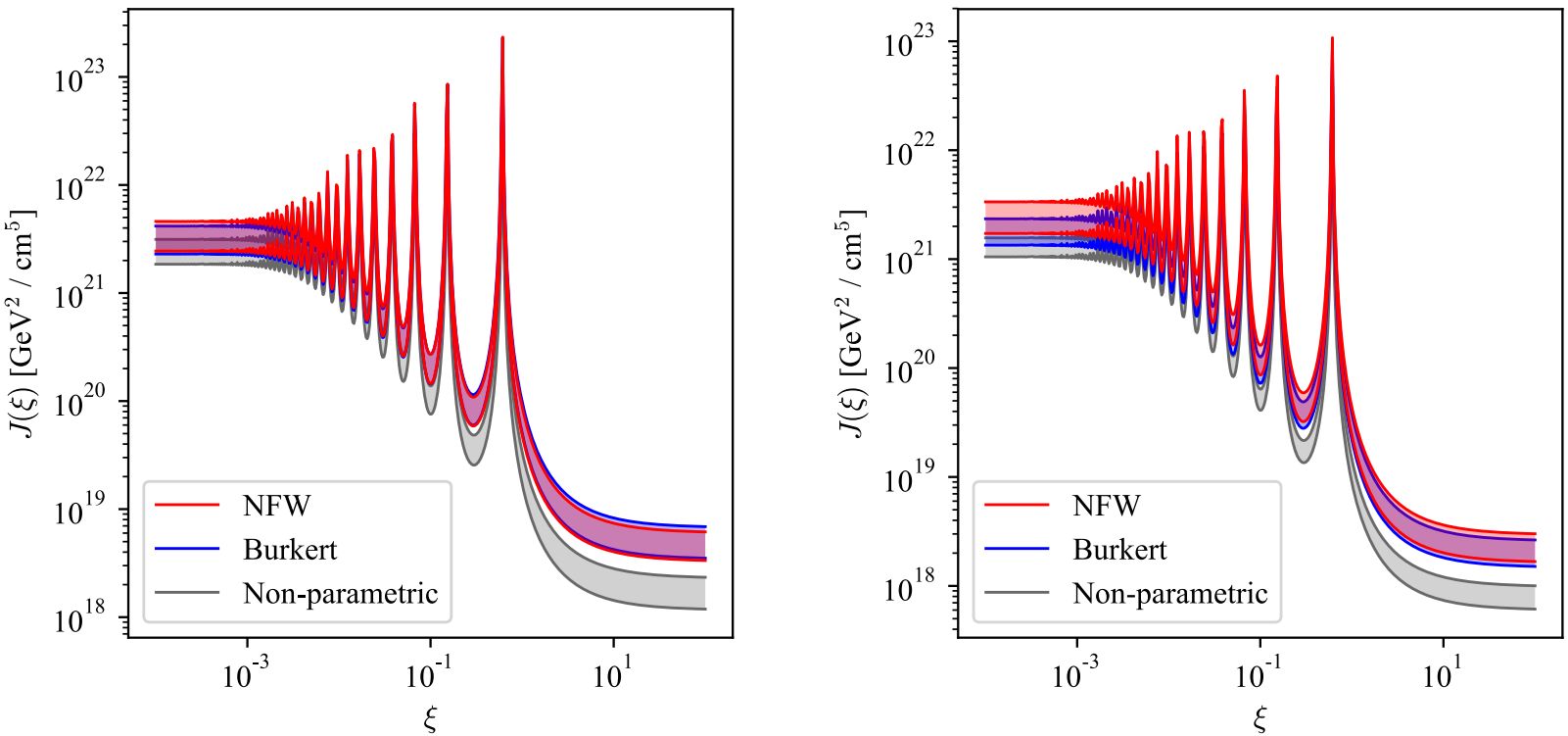


Figure: 68% credibility band for J-factors as a function of $\xi = \frac{m_\phi}{\alpha_\chi m_\chi}$ for Draco (left) and Sculptor (right).

Application: J-factors

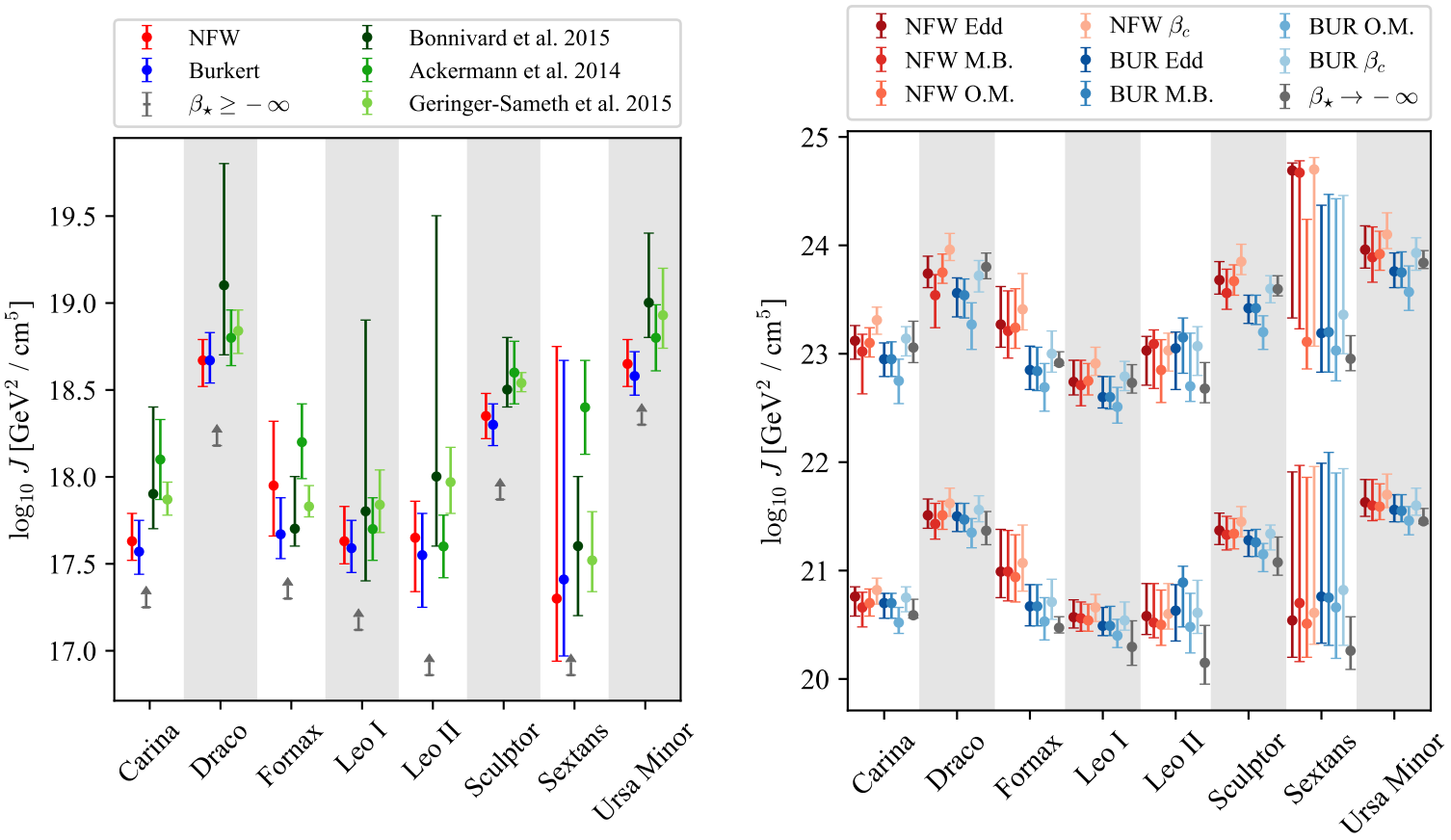


Figure: *J*-factors for 8 dSph with the 68% confidence intervals.

Summary

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

Careful analysis of J-**factors** in presence of Sommerfeld enhancement with **consistent error propagation**.

Novel results for various DM orbital anisotropies.

Conclusions:

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

Axisymmetric modelling

To address **DM searches in spiral galaxies** one needs to go beyond the spherical approximation

- Direct detection rates in Milky Way
- Indirect detection in the galactic center or nearby spirals

Even if DM halo spherically symmetric, the **gravitational potential is significantly flattened due to baryonic disc**!

Numerous tracers of gravitational potential:

- Gas: rotation curves
- Stars: various disc and halo populations
- Globular clusters & satellite galaxies

Axisymmetic modelling

Stationary solution of Boltzmann equation $\Leftrightarrow$ **relaxed system**

Allows for self-consistent modelling of **additional features**:

- Presence of baryonic disc
- Halo flattening
- Halo rotation

Possible non-relaxed components:

- Debris flow

  Necib L. et al.: arXiv:1810.12301
- Substructure

Phase-space distribution function

Assume that the phase-space distribution is fully described by **two integrals of motion**

1. Relative energy: $\mathcal{E} = \Psi(r) - \frac{v^2}{2}$
2. Angular momentum around z-axis: $L_z = R \cdot v_\phi$

$$\Rightarrow f(\mathcal{E}, L_z) = f_+(\mathcal{E}, |L_z|) + f_-(\mathcal{E}, L_z)$$

$$f_+(\mathcal{E}, L_z) = \frac{1}{4\pi^2 i\sqrt{2}} \oint_{C(\mathcal{E})} \frac{\mathrm{d}\xi}{\sqrt{\xi - \mathcal{E}}} \left.\frac{\mathrm{d}^2\rho(R^2, \Psi)}{\mathrm{d}\Psi^2}\right|_{\substack{\Psi=\xi \\ R^2=\frac{L_z^2}{2(\xi-\mathcal{E})}}}$$

$$f_-(\mathcal{E}, L_z) = \frac{\mathrm{sign}(L_z)}{8\pi^2 i} \oint_{C(\mathcal{E})} \frac{\mathrm{d}\xi}{\xi - \mathcal{E}} \left.\frac{\mathrm{d}^2\left(\rho\bar{v}_\phi\right)}{\mathrm{d}\Psi^2}\right|_{\substack{\Psi=\xi \\ R^2=\frac{L_z^2}{2(\xi-\mathcal{E})}}}$$

Hunter C. & Qian E.: MNRAS262, 401 (1993)

Sample spiral galaxy model

1. **Spherical bulge** (Hernquist potential):

$$\Psi_{\mathrm{bulge}}(R^2, z^2) = \frac{GM_b}{\sqrt{R^2 + z^2} + a_b}$$

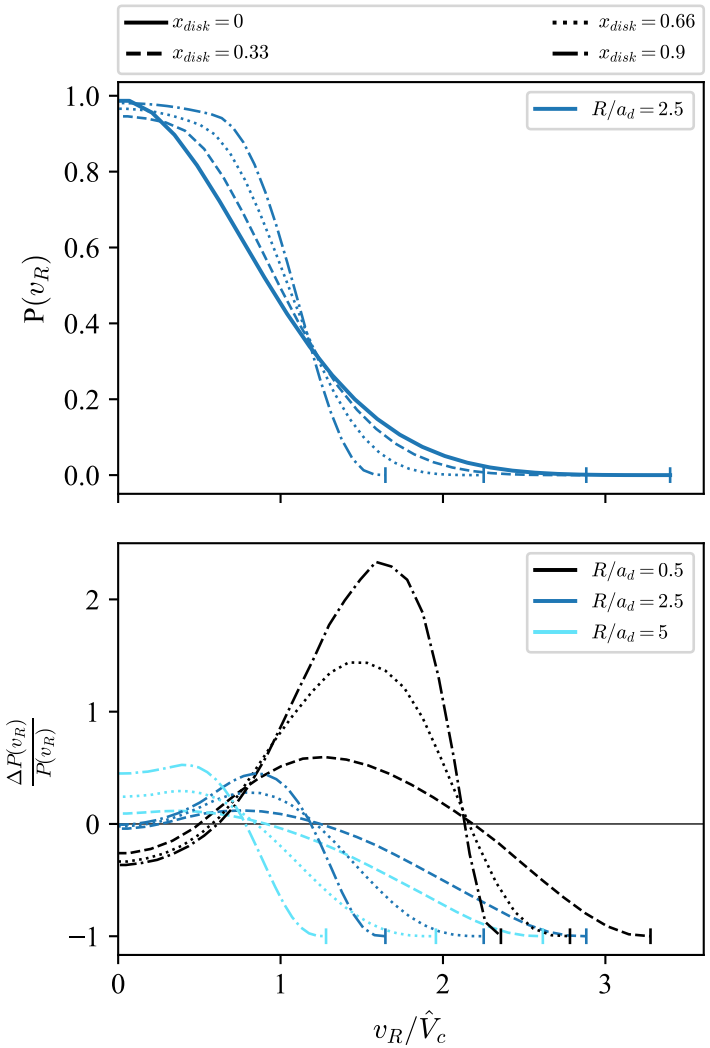
2. **Axisymmetric disc** (Myamoto-Nagai potential):

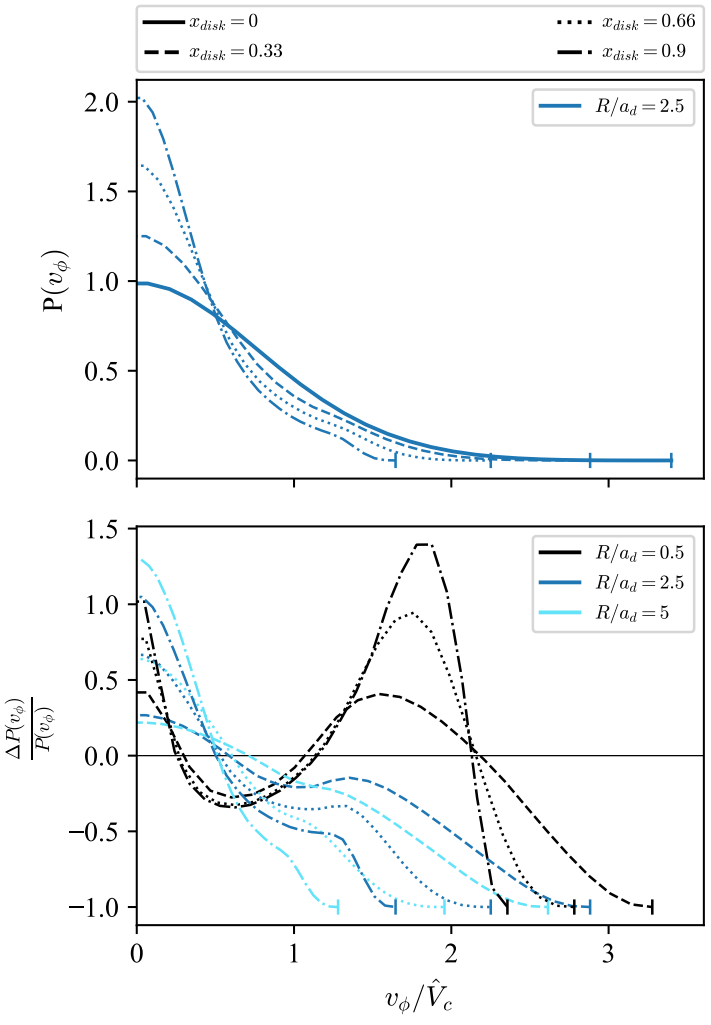
$$\Psi_{\mathrm{disc}}(R^2, z^2) = \frac{GM_d}{\sqrt{R^2 + (a_d + \sqrt{z^2 + b_d^2})^2}}$$

3. **Axisymmetric halo** (spherioidal NFW profile):

$$\rho_{\mathrm{DM}}(m) = \frac{\rho_s}{m/r_s \cdot (1 + m/r_s)^2} \quad \text{where} \quad m^2 = R^2 + z^2/q^2$$

Disc normalization





Halo rotation

Highly unconstrained

S. E. Bryan et al.: MNRAS 429, 3316 (2013)

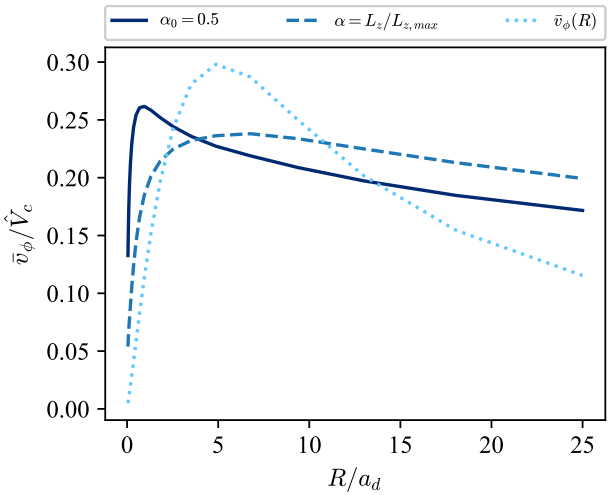
Chua et al.: MNRAS 484, 476 (2019)

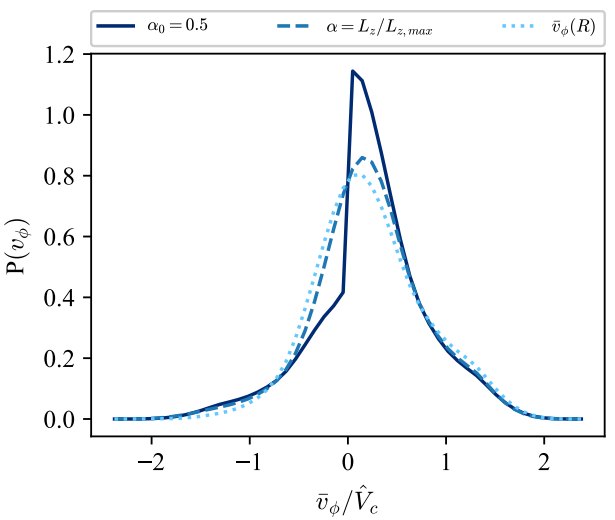
Simulations predict spin parameter:

$$\lambda(r) \equiv \frac{J(r)}{\sqrt{2} r\, M_{\rm DM}(r)\, V_c(r)} \sim 0.03 - 0.07$$

Consider several choices:

1. $f_-(\mathcal{E}, L_z) = \alpha_c \cdot \mathrm{sign}(L_z) \cdot f_+(\mathcal{E}, L_z)$
2. $f_-(\mathcal{E}, L_z) = \frac{L_z}{|L_{z,max}|} \cdot f_+(\mathcal{E}, L_z)$
3. $\bar{v}_\phi(R) = \frac{\omega R}{1+R^2/r_a^2}$





Direct detection

Attempts to measure **nuclear recoils** in laboratory targets due to interactions with **galactic DM**

$$\frac{\mathrm{d}R}{\mathrm{d}E_r} = \frac{1}{m_A m_\chi} \cdot \int_{|\vec{v}|>v_{\min}} \mathrm{d}^3 v \; f(\mathcal{E}, L_z) \cdot v \cdot \frac{\mathrm{d}\sigma}{\mathrm{d}E_r} \quad , \quad v_{\min} = \sqrt{\frac{m_A E_r}{2\mu_{A\chi}^2}}$$

Spin-independent interaction: $\frac{\mathrm{d}\sigma}{\mathrm{d}E_r} = \frac{m_A \sigma_n^{\mathrm{SI}}}{2\mu_{A\chi}^2 v^2} A^2 F^2(E_r)$

For general $\frac{\mathrm{d}\sigma}{\mathrm{d}E_r}$ useful to define:

$$g(v_{\min}) \equiv \frac{1}{\rho_\odot} \int_{|\vec{v}|>v_{\min}} \mathrm{d}^3 v \; \frac{f(\mathcal{E}, L_z)}{v}$$

$$h(v_{\min}) \equiv \frac{1}{\rho_\odot} \int_{|\vec{v}|>v_{\min}} \mathrm{d}^3 v \; v \cdot f(\mathcal{E}, L_z)$$

Application: Milky Way model (Bovy2015)

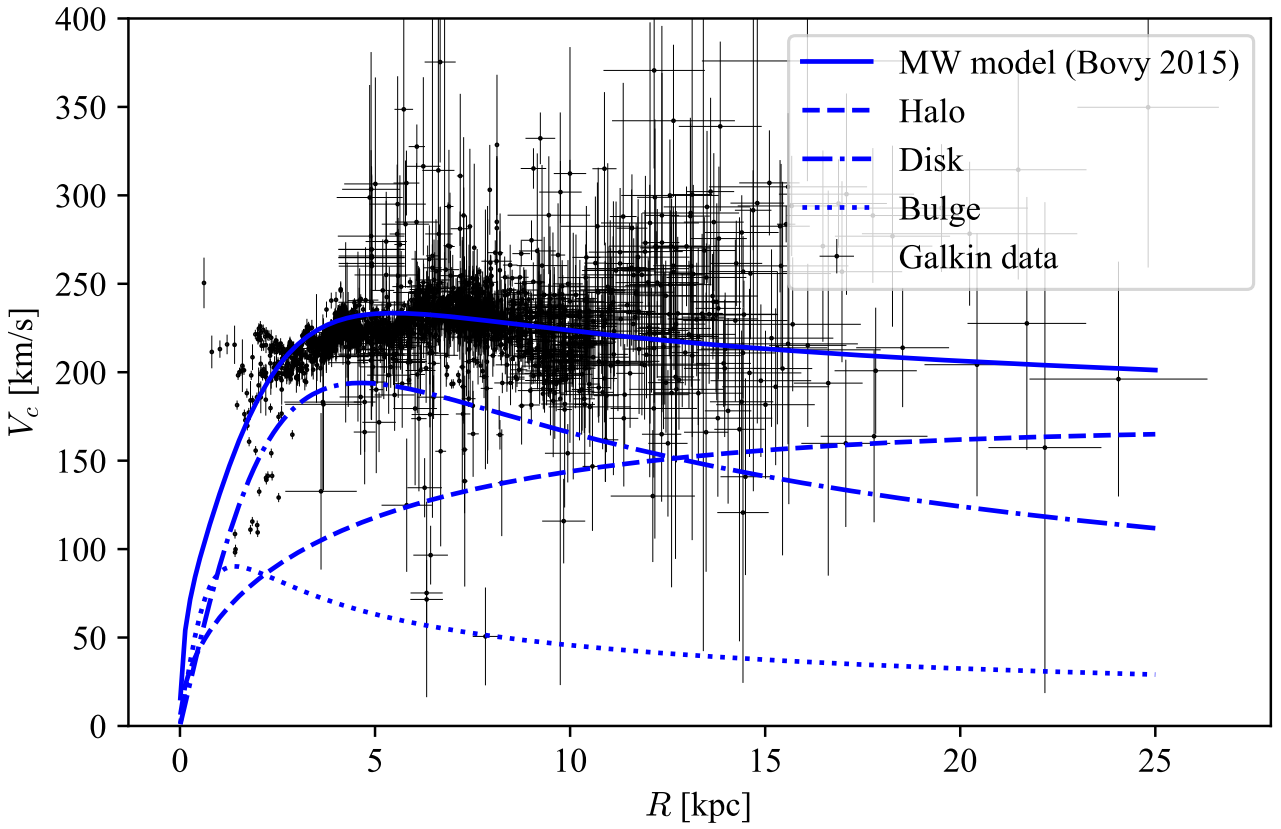


Figure: Comparison of the Milky Way model to the circular velocity data.

Application: Direct detection

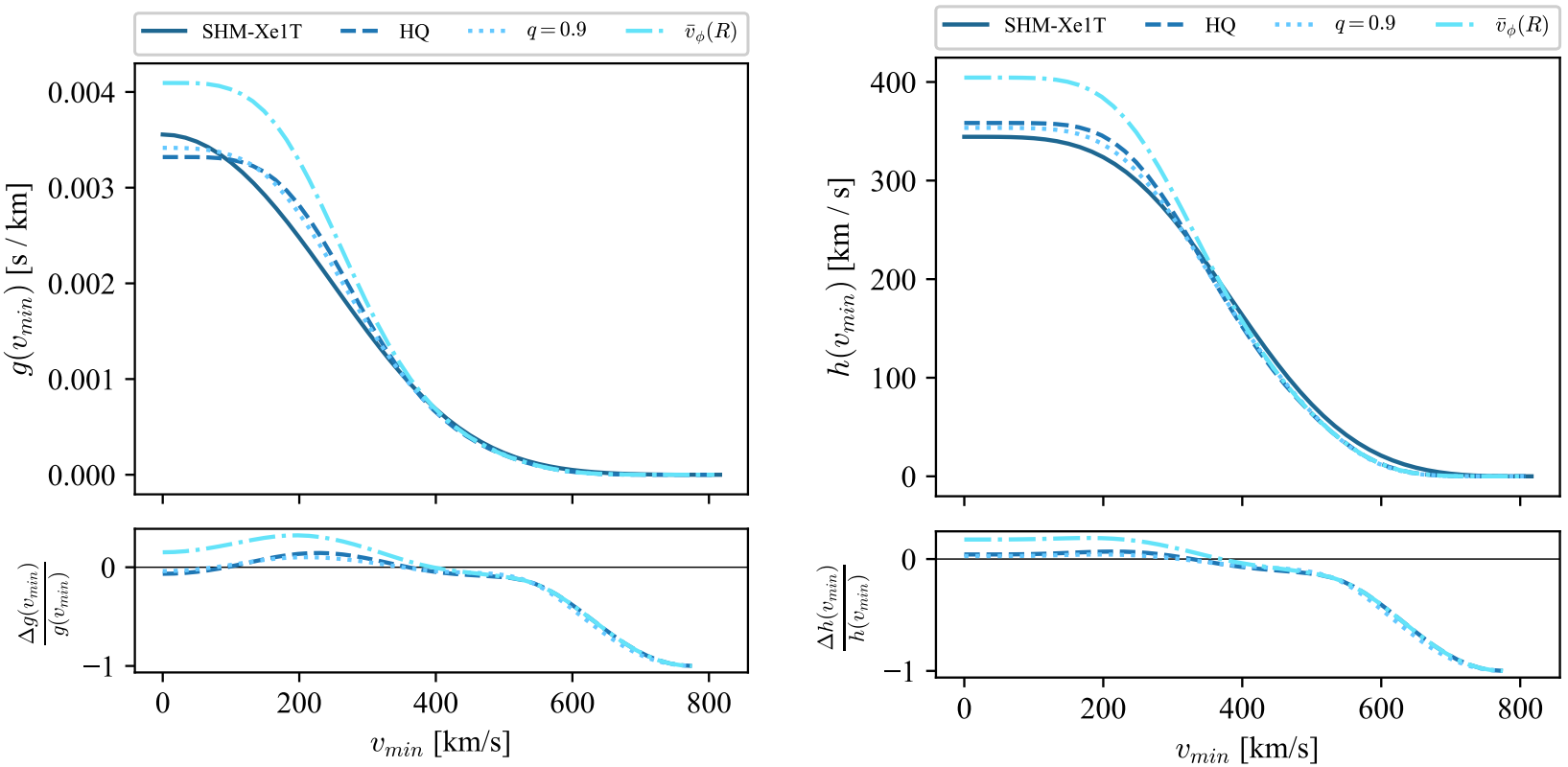


Figure: Dependence of the differential recoil rate on the DM velocity distribution for $\frac{\mathrm{d}\sigma}{\mathrm{d}E_r} \propto v^{-2}$ (left) and $\frac{\mathrm{d}\sigma}{\mathrm{d}E_r} \propto v^0$ (right).

Application: Cross-section limits

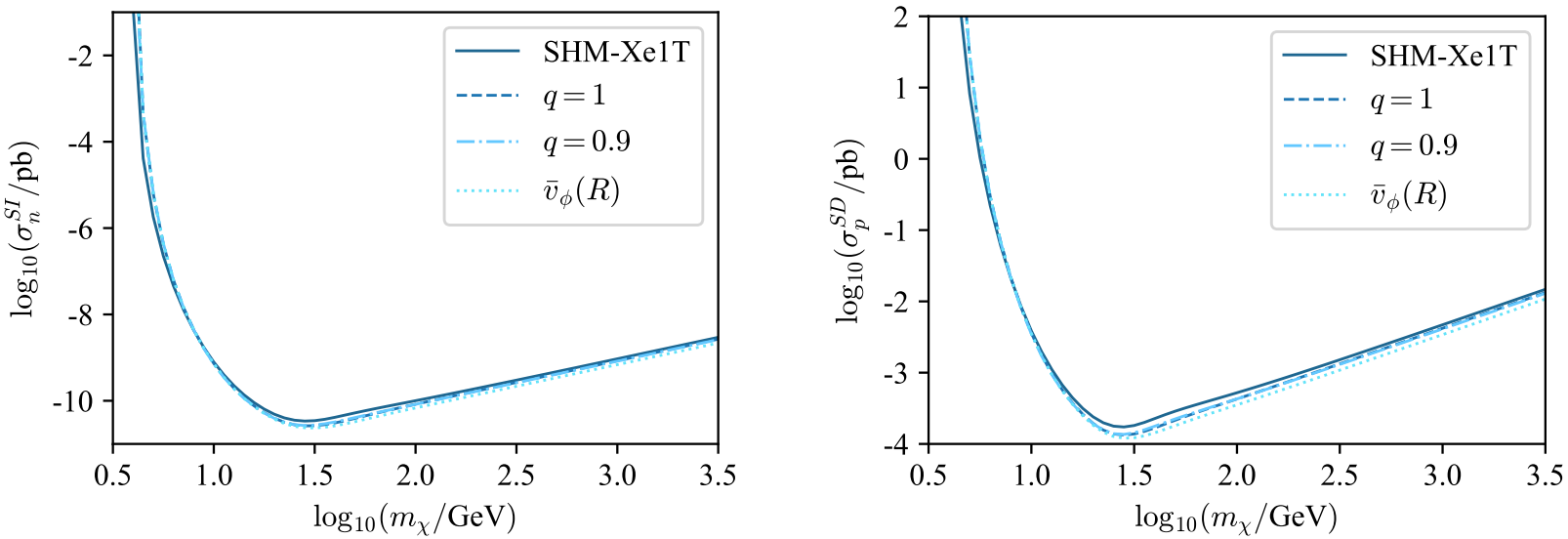


Figure: Cross-section limits for spin-independent (left) and spin-dependent (right) scattering operator.

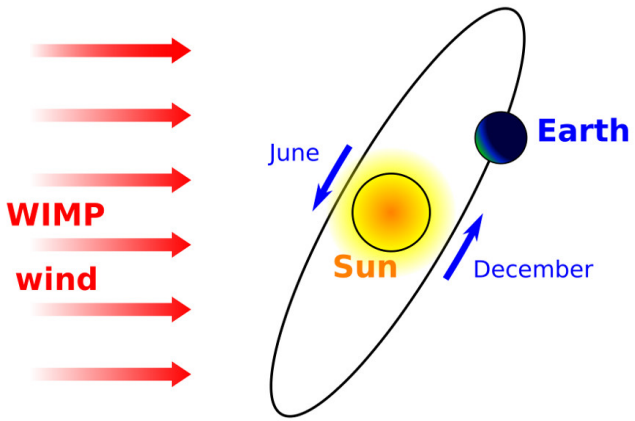
Application: Annual modulation

Annual modulation of $\frac{\mathrm{d}R}{\mathrm{d}E_r}$ expected due to the **Earth's relative movement** with respect to the galactic rest frame.

Additional boost ($v_\oplus \approx 30$ km/s):

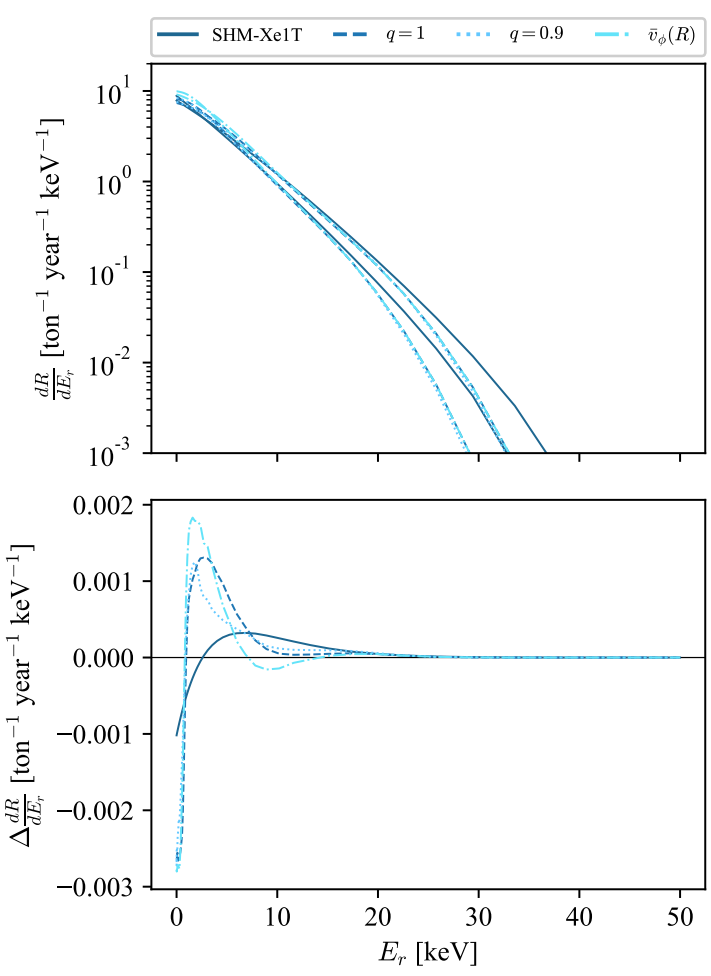
$$\mathcal{E} \to \mathcal{E} - \frac{v_\oplus^2}{2}$$

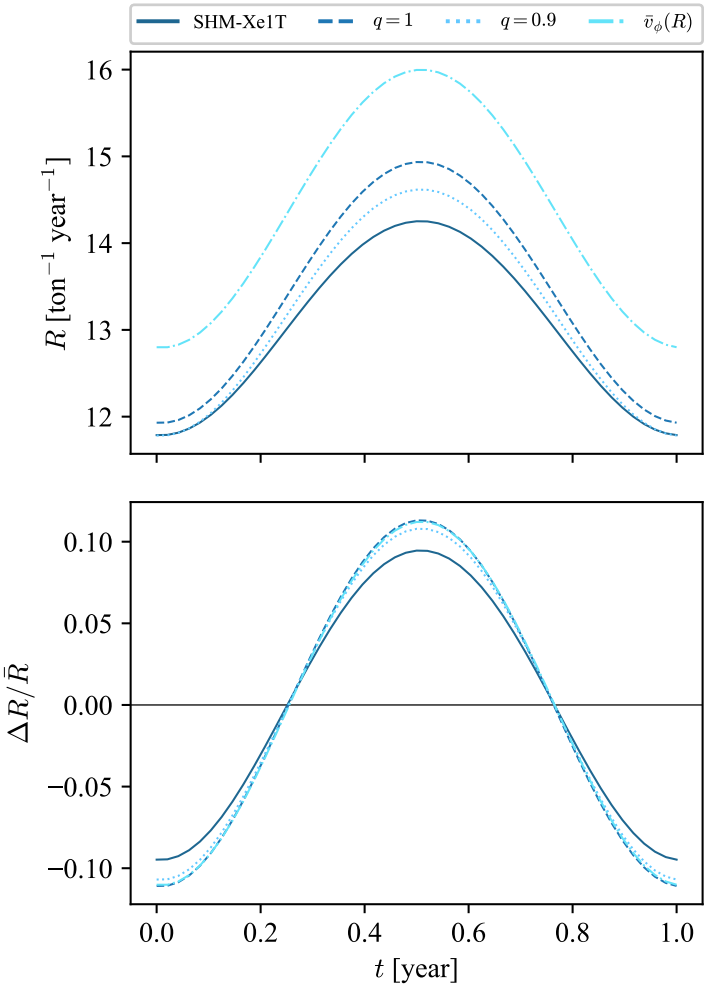
$$L_z \to L_z + R_\odot(\vec{v}_\oplus \cdot \hat{e}_\phi)$$



Upon detection could provide new information regarding the Milky Way's halo and/or type of DM-nucleon coupling.

Application: Annual modulation





Summary

Implementation of **novel method for phase-space reconstruction in axisymmetric systems**.

Study of **additional halo features**:

- Influence of flattened disc potential
- Halo flattening
- Halo rotation

Reinterpretation of **DM-nucleus cross-section limits**.

Effects of DM phase-space modelling on **annual modulation**.

Conclusion

Rapid **improvements in sensitivity of experiments** call for refined modelling of DM distribution within galaxies.

Detailed analysis needed for:

- **Interpretation of tensions** among different experiments (Galactic center excess, DAMA annual modulation signal)
- **Legitimate exclusion of DM models**

Precise understanding of modelling crucial upon eventual detection of DM signals.

Sommerfeld enhancement

Generic **non-perturbative boost of cross-section** for non-relativistic particles in presence of light force mediator:

$$m_\phi \ll \alpha_\chi m_\chi \quad \text{and} \quad E_\chi \approx m_\chi$$

Coupling of the mediator to DM gives rise to **Yukawa 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:

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

Application: Bayesian analysis of dSph

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

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:

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