Indirect detection of DM

Self-annihilating DM in presence of light force mediator

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Evidence for Dark Matter

The existence of particle dark matter (DM) is well motivated by many independent observations

- Rotation curves in spiral galaxies and cluster dynamics
- Galaxy counts and halo mass function
- Cosmic microwave background
- Big Bang nucleosynthesis
- Gravitational lensing

Alternative theories, such as modifications of General Relativity, have problems in explaining all of the observed phenomena

What could it be?

Beyond it's existence, very little is known about the DM

- Constitutes roughly 27% of the total energy density in the visible Universe today
- It is pressureless, i.e. behaves as non-relativistic particles
- Stable on the cosmological timescales
- DM cannot consist of Standard Model (SM) particles
- Strong upper bounds on the DM coupling to the SM
- Bounds on DM self-interaction strength

Most popular models

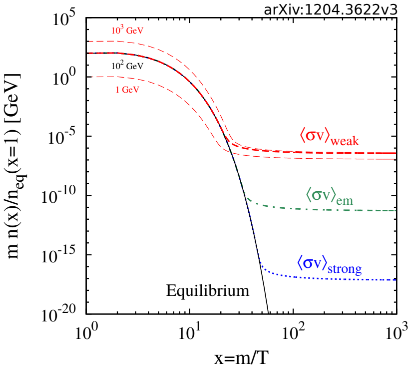
Numerous attempts to construct a model that yields the **correct abundance** of DM and avoids all the **detection constraints**

- WIMPs (LSP, LKP, LTP)
- Sterile neutrinos
- (Ultra-)light bosons

Many of these require fine tunning to be in accordance with the latest experiments

WIMP miracle

Heavy particles ($m_{DM} \approx 100$ GeV) with a **typical weak coupling** ($\langle \sigma v \rangle \approx 3 \cdot 10^{-26}$ cm^2) that were initially in **thermal equilibrium** with the SM would produce the correct DM abundance



Number density eqution

$$\frac{\mathrm{d}n}{\mathrm{d}t} = \langle \sigma v \rangle \left(n_{eq}^2 - n^2 \right) - 3Hn$$

Current constraints

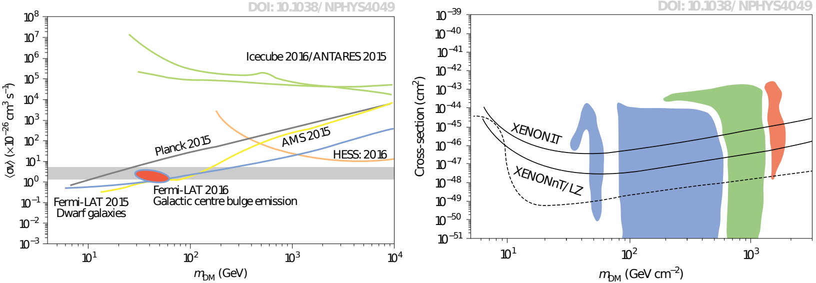


Figure: Indirect (left) and direct (right) detection exclusion plots. The colored area is the parameter space excluded by LHC and Antares.

Project outline

Motivation

- Collisionless cold DM suffers from **small scale problems**
- It is natural to expect **substructure in the dark sector**
- Era of high **precision cosmology**

$\Rightarrow$ Study annihilation flux in models with velocity dependent $\langle \sigma v \rangle$

- Generic prediction in models where DM couples to light force mediator, which helps to elevate the small scale problems
- Going beyond the Maxwell-Boltzmann velocity distribution approximation

Indirect detection

Consider a model where DM can annihilate into photons

$$\frac{d\Phi}{dE_\gamma} = \frac{1}{8\pi}\frac{dN}{dE_\gamma}\int d\Omega \int d\ell \int d^3 v_1 \frac{f(\vec{r},\vec{v}_1)}{m_\chi}\int d^3 v_2 \frac{f(\vec{r},\vec{v}_2)}{m_\chi}(\sigma_{\chi\chi\to\gamma s} v_{rel})$$

Phase-space distribution function computed through Eddingtion inversion formula, not assuming $f(\vec{r},\vec{v}) = \rho(\vec{r}) \cdot \exp\left(-\frac{v^2}{2\sigma_v^2}\right)$

Coupling to a light mediator induces non-perturbative corrections to the annihilation cross-section - Sommerfeld enhancement

$$(\sigma_A v_{rel}) = (\sigma v_{rel})_0 \to (\sigma v_{rel})_0 \cdot S(v_{rel};\xi)$$

DM phase-space distribution function

For a spherically symmetric system there exists an unique ergodic phase-space distribution function

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

Used different relative potentials $\Psi(r)$ - either assumed NFW or Burket profile, or computed it from Jean's equation

DM velocity distribution can significantly differ from Maxwell-Boltzmann distribution

DM velocity distribution

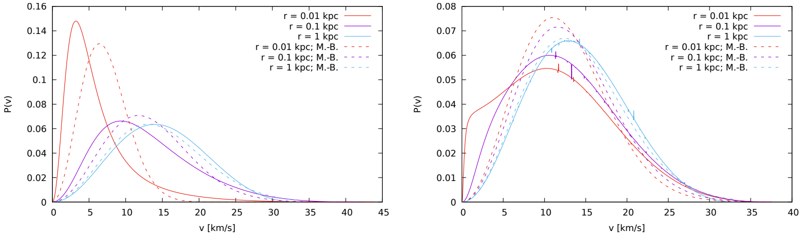


Figure: Velocity distribution computed according to Eddington's formula for NFW (left) and Burkert (right) density profiles. The dashed lines represent corresponding Maxwell-Boltzmann distributions.

Sommerfeld enhancement

The potential felt by a non-relativistic DM particles that interacts through a scalar or vector mediator of mass m_ϕ is

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

Solve Schrödinger equation to obtain the non-perturbative enhancement of annihilation cross-section due to the mediator exchange

$$\chi''(x) + \left(\epsilon_v^2 + V(x)\right)\chi(x) = 0\ ;\ \ \epsilon_v = \frac{v}{\alpha_x}\ ,\ \ \epsilon_\phi = \frac{m_\phi}{\alpha_x m_\chi}$$

$$\Rightarrow S(\epsilon_v, \epsilon_\phi) = \left|\frac{\chi(0)}{\chi(\infty)}\right|^2 \propto \frac{1}{v^\gamma}$$

Computation of J-factors

The effect of DM distribution on the annihilation flux (including Sommerfeld enhancement) can be absorbed in the J-factor

$$\frac{d\Phi}{dE_\gamma} = \frac{1}{8\pi}\frac{dN}{dE_\gamma}\left\langle \sigma_{\chi\chi\to\gamma s} v_{rel}\right\rangle_0 J(\Delta\Omega)$$

I have developed numerical code that computes $J(\Delta\Omega)$ for an arbitrary input DM density profile and velocity dependent annihilation cross-section.

We applied it to the classical MW dwarf galaxies (dSph)

dSph

Dwarf spherioidal 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

Fermi-LAT constraint on annihilation flux

Stellar distribution and velocity dispersion measurements can be used to reconstruct DM density profile

- fit NFW and Burkert profiles
- derivation of a density profile through Jean's equation

J-factors

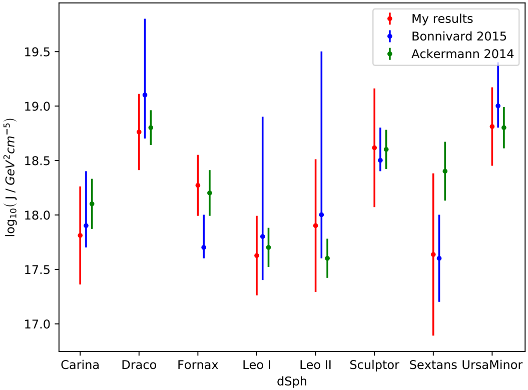


Figure: J-factors for classical dSph, assuming NFW and constant $\langle \sigma v \rangle$.

J-factors

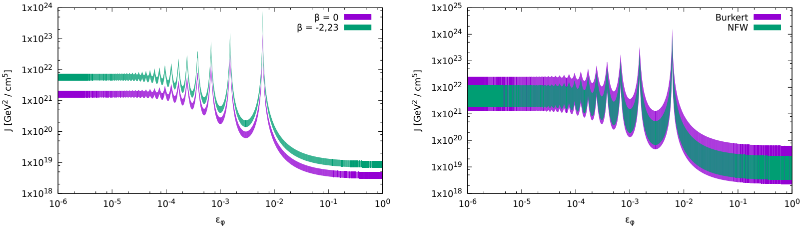


Figure: J-factors as a function of $\epsilon_\phi = \frac{m_\phi}{\alpha_x m_\chi}$ for Draco dSph with DM density profile obtained through Jean's equation (left) and NFW & Burkert profiles (right).

Effect of the velocity distribution

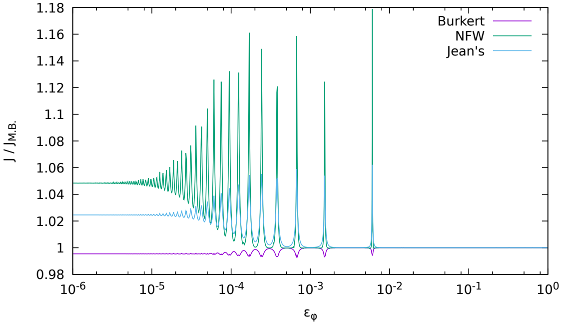


Figure: The ratio of J-factors computed using Eddington's inversion PSDF (J) and Maxwell-Boltzmann approximation ($J_{M.B.}$).

Summary

Developed numerical code for computing

- PSDF for any input density distribution
- J-factors based on the PSDF for arbitrary cross-section velocity dependence

Recomputed J-factors of classical dSph using a new type of mass and density estimators $\Rightarrow$ good match

Computed the parametric dependence (ϵ_ϕ) of the annihilation flux in presence of Sommerfeld enhancement for classical dSph

Outlook

Reanalysis of Galactic center excess

- Use conservative DM density profile estimates derived from dynamical tracers
- Check for consistency with dSph

Fermi-LAT data

- Attempt a more detailed analysis of spectral features
- Update the cross-section limits for different models

Study the evolution of PSDF of weakly self-interacting DM (small perturbation on top of background solution)

dSph DM profile from Jean's equation

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

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

Degeneracy between stellar velocity dispersion anisotropy $\beta(r)$ and gravitational potential $\Phi(r)$

Assuming isotropy ($\beta = 0$) and Plummer stellar profile one finds

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

Mass and density estimators by Mauro Valli

One can show that there exists a radius r_* where the mass is independent of $\beta(r)$

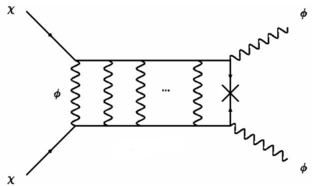
$$M(r) - M_{\beta=0}(r) = -\frac{\beta(r)\sigma_r^2(r)r}{G}\left(3 + \frac{\mathrm{d}\log\nu}{\mathrm{d}\log r} + \frac{\mathrm{d}\log\sigma_r^2}{\mathrm{d}\log r} + \frac{\mathrm{d}\log\beta}{\mathrm{d}\log r}\right)$$

$$\Rightarrow M(r_*) = M_{\beta=0}(r_*) = \frac{3\sigma_{los}^2 r_*}{G}$$

A similar density and density derivative estimator can be found by taking derivative with respect to r

Sommerfeld enhancement (arXiv:0903.5307)

Non-perturbative effect due to infinite light mediator exchange



Use Bethe-Salpeter equation

$$i\Gamma(p_1, p_2; p_3, p_4) = i\tilde{\Gamma}(p_1, p_2; p_3, p_4) + \int \frac{d^4q}{(2\pi)^4}\tilde{\Gamma}(;q, P-q)G(q)G(P-q)\Gamma(q, P-q;)$$

Sommerfeld enhancement

In the non-relativistic limit the Bethe-Salpeter wavefunction satisfies the Schrödinger equation

$$\left(\frac{\vec{p}^2}{m_\phi} - E\right)\ \tilde{\psi}_{\text{BS}}(\vec{p}) + \int \frac{\mathrm{d}^3 q}{(2\pi)^3}\ V(\vec{p}-\vec{q})\ \tilde{\psi}_{\text{BS}}(\vec{q}) = 0$$

with Yukawa potential $V(r) = \mp \frac{\alpha_x}{r} exp\left(-m_\phi r\right)$

Analytically solvable for Hulten potential $V(r) = \alpha_x m_\phi \frac{exp\left(-m_\phi r\right)}{1-exp\left(-m_\phi r\right)}$

$$\Rightarrow S(v,\xi) = \frac{\sigma v}{\langle \sigma v \rangle_0} = \frac{\alpha\pi}{v} \frac{\sinh\left(\frac{12v}{\pi\xi}\right)}{\cosh\left(\frac{12v}{\pi\xi}\right) - \cos\left(2\pi\sqrt{\frac{6\alpha}{\pi^2\xi} - \left(\frac{6v}{\pi^2\xi}\right)^2}\right)}$$