Simple self-consistent prediction methods for the phase space of dark matter: from galactic dynamics to phenomenology

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Phase-space distribution of DM & theoretical uncertainties for direct and indirect searches

Speed-dependent annihilation

- $\langle \sigma v \rangle(r) \propto \langle v_r^2 \rangle$ ***p*-wave**

  $\sigma v = \sigma_1 v_r^2 \Rightarrow \langle \sigma v \rangle \equiv \langle \sigma v \rangle(r)$

  $$\langle \sigma v \rangle(r) = \sigma_1 \int d^3 v_1 d^3 v_2 f_r(\vec{v}_1) f_r(\vec{v}_2)\, v_r^2$$

- $\langle \sigma v \rangle(r) \propto \langle 1/v_r \rangle$ or $\langle 1/v_r^2 \rangle$

  Sommerfeld enhancement

Direct searches

$$\frac{dR}{dE} \propto \rho_\odot \int_{v_{\rm min} \leqslant |\vec{v}| \leqslant v_{\rm esc}} \frac{f_\odot(\vec{v})}{|\vec{v}|}\, d^3 v$$

Impact at low masses

$v_{\rm min} \sim v_{\rm esc}$

Primordial black holes

- Gravitational microlensing event rates (EROS, MACHO)

  $$\frac{d\Gamma}{dt} \propto \rho(r) \int v f(\vec{v}, \vec{r})\, d^3 v$$

- Merger rates (gravitational waves)

+ DM substructures (test masses), disruption of stellar binaries

Standard approaches 1: "Standard halo model"

Standard halo model (SHM)

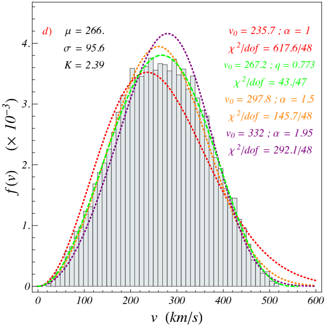
Maxwell-Boltzmann distribution

$$f(\vec{v}) = \frac{1}{v_c^3 \pi^{3/2}} \, e^{-\left(\frac{\vec{v}}{v_c}\right)^2}$$

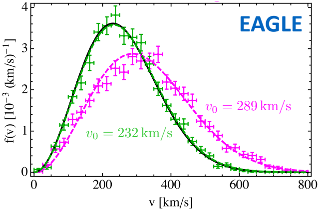
Oversimplification

- Isothermal sphere
- Infinite system
- Ad hoc truncation at v_{esc}

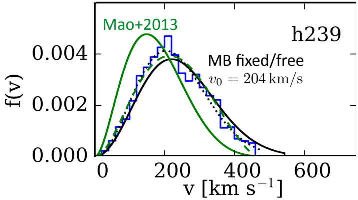
Standard approaches 2: direct fits to simulations



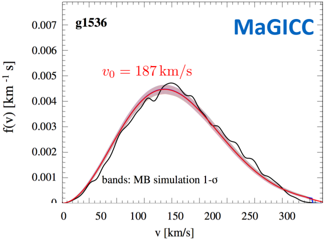
Ling+ 2010, Mollitor+ 2014



Bozorgnia+ 2016



Kelso+ 2016

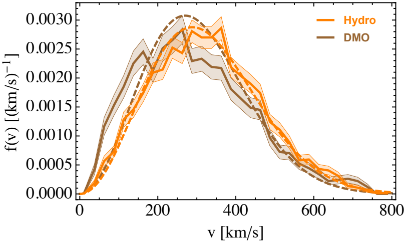


Sloane+ 2016

Standard approaches 2: direct fits to simulations

General insight

Generic features found in simulations (e.g., cusp/cores)



Bozorgnia+ 2017

But insufficient approach

- Extrapolations based on fits at 8 kpc
- **Peak speed free parameter** ⇒ not connected to circular speed
- MW one particular realization
- MW constrained system (e.g., Gaia)
- Subgrid physics

Self-consistent approach required

Eddington-like methods: next-to-minimal approach

Phase space of dark matter from first principles

Phase-space distribution $f(\vec{v},\vec{r})$: closed system

- Collisionless Boltzmann equation, steady state

$$\{f,H\} = \vec{v}\cdot\frac{\partial f}{\partial\vec{r}} - \frac{\partial\Phi}{\partial\vec{r}}\cdot\frac{\partial f}{\partial\vec{v}} = 0$$

$\longrightarrow$ Jeans' theorem: $f \equiv f(I_1,\ldots,I_N)$ where $\{I_i,H\} = 0$

- Poisson equation

$$\Delta\Phi = 4\pi G\rho \;\; \text{with} \;\; \rho = \int f(\vec{v},\vec{r})\mathrm{d}^3v$$

Eddington's inversion formula (Eddington 1916)

Isotropic system + spherical symmetry: $f(\vec{v},r) \equiv f(\mathcal{E})$

with $\mathcal{E} = \Psi(r) - \frac{v^2}{2}$ and $\Psi(r) = \Phi(R_{\mathrm{max}}) - \Phi(r)$

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

+ anisotropic extensions

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+ anisotropic extensions

Velocity distribution

Central ingredient for observables

$$f_{\vec{v}}(\vec{v}, r) \equiv \frac{f(\mathcal{E}, L)}{\rho_{\text{DM}}(r)}$$

Speed distribution ($v = |\vec{v}|$)

$$f_v(v, r) \equiv v^2 \int \mathrm{d}\Omega_v \, f_{\vec{v}}(\vec{v}, r)$$

Encapsulates most of the dynamical information

For isotropic distribution

$$f_v(v, r) = \frac{4\pi v^2}{\rho_{\text{DM}}(r)} f\left(\Psi(r) - \frac{v^2}{2}\right)$$

Going beyond spherical symmetry

Angle-action coordinates

- More suitable coordinate system if no spherical symmetry
  Binney & Tremaine 1987
- Best way to account for complexity revealed by Gaia
- But very cumbersome calculations
- Ansatz for $f(\vec{r}, \vec{v}) \Rightarrow$ theoretical uncertainties
- Level of refinement not necessarily required for DM searches
  $\rightarrow$ Evaluate astrophysical uncertainties

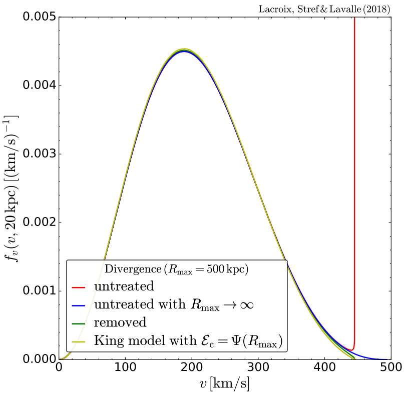
Eddington's formalism

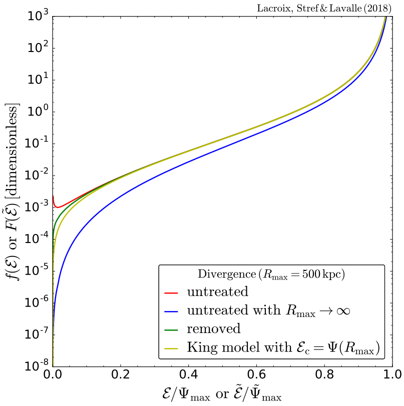
- Lower level of technicalities to account for dynamical constraints
- Method applied blindly to direct searches so far
  $\rightarrow$ Timely to study validity range in detail

Theoretical consistency and radial boundary

Imposing a radial boundary

- Finite system ($R_{\rm max}$) $\Rightarrow$ divergence of $f(\vec{r},\vec{v})$ at $v_{\rm esc}$ (from $1/\sqrt{\mathcal{E}}$)
- Phase-space compression
- $v_{\rm esc}$ crucial (direct DM searches at low masses, stellar surveys)





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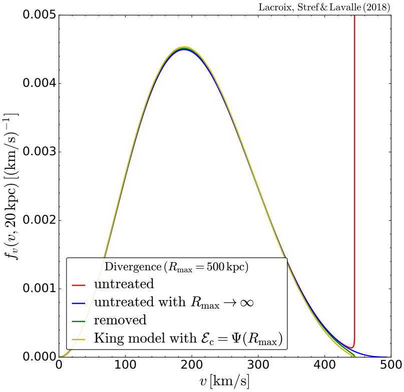
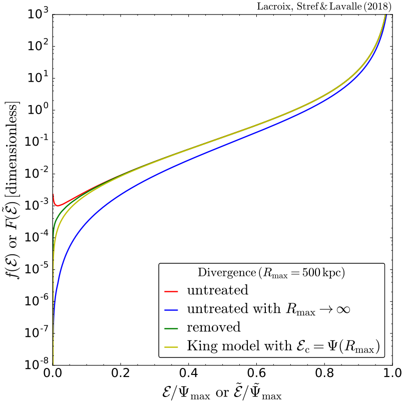
Theoretical consistency and radial boundary

Regularization

- Modified profile, flat at $R_{\rm max}$
- Energy cutoff (King)





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Not possible for radial anisotropy (e.g., Osipkov-Merritt)

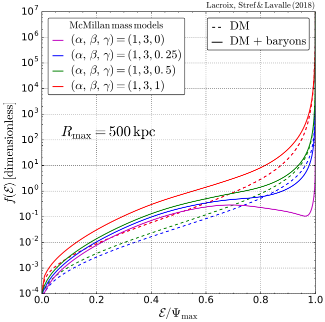
Theoretical consistency: instabilities

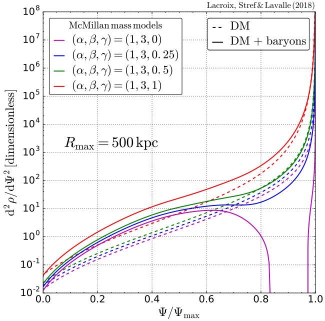
Validity range of the method

- Standard criterion:
  $f \geqslant 0$
- Antonov instabilities for some DM-baryon configurations
- Stable solution if
  $$\frac{\mathrm{d}f}{\mathrm{d}\mathcal{E}} > 0 \Leftrightarrow \frac{\mathrm{d}^2\rho}{\mathrm{d}\Psi^2} > 0$$
  Doremus+ 1971, Kandrup & Sygnet 1985
- Select mass models

Lacroix+ 2018a

For anisotropic systems criteria against radial perturbations only
Doremus+ 1973



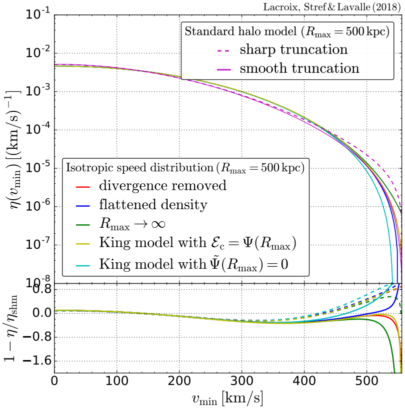


Impact on predictions for direct DM searches

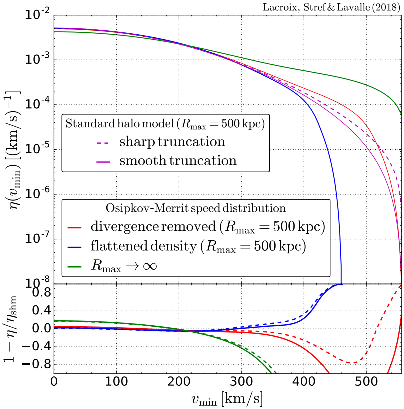
Event rate proportional to

$$\eta(v_{\rm min}) = \int_{v_{\rm min} \leqslant v \leqslant v_\oplus + v_{\rm esc}} \frac{f_{\vec{v},\oplus}(\vec{v})}{v}\, d^3v$$

Isotropic



Osipkov-Merritt



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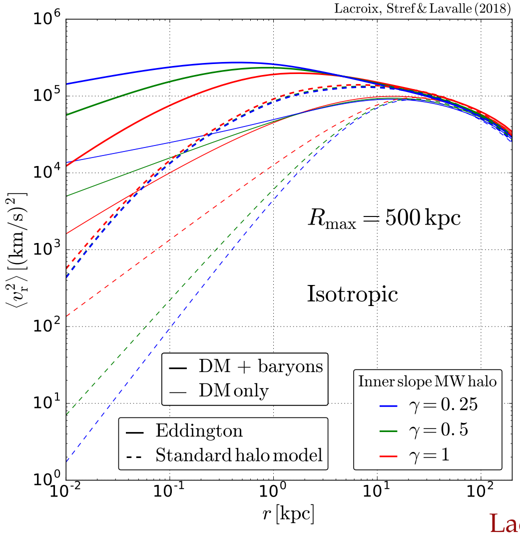
Impact on predictions for indirect DM searches

Prototypical case: p-wave annihilation

$\langle \sigma v \rangle (r) \propto \langle v_r^2 \rangle$



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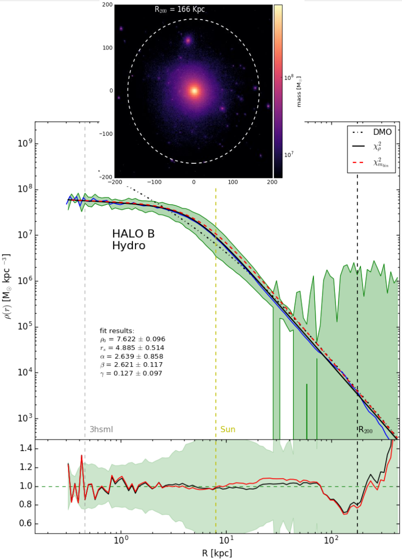
Actual predictivity of Eddington's formalism? Tests with cosmological simulations

Description

- 2 sets of simulations
  Mollitor+ 2015
  $M_{\rm DM} = 2.3 \times 10^5\,{\rm M}_\odot$, Hsml = 150 pc
  Núñez+ 2018, in prep.
  $M_{\rm DM} = 1.9 \times 10^5\,{\rm M}_\odot$, Hsml = 280 pc
- 20 Mpc boxes + zoom-in
- DM-only + hydro

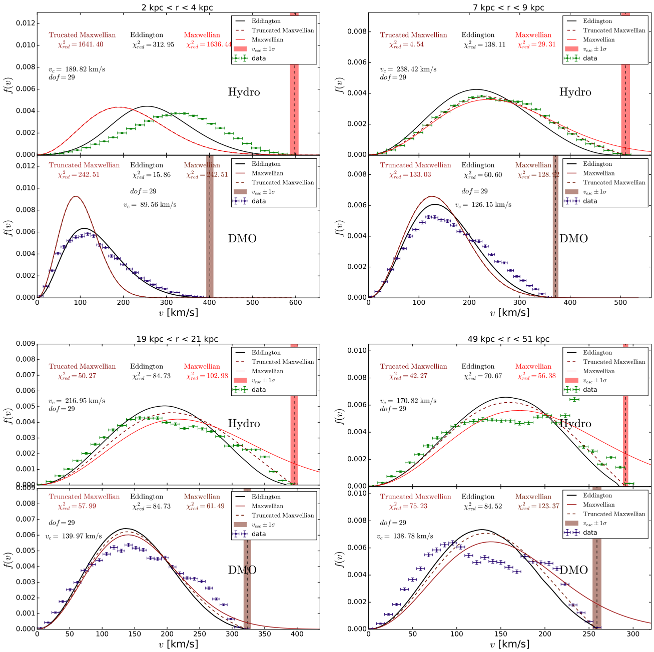
Procedure

- Fit mass model from simulation
  $\Rightarrow \rho_{\rm DM}, \rho_{\rm B}, \Psi = \Psi_{\rm DM} + \Psi_{\rm B}$
- Input for Eddington's method
- Comparison with simulation outputs



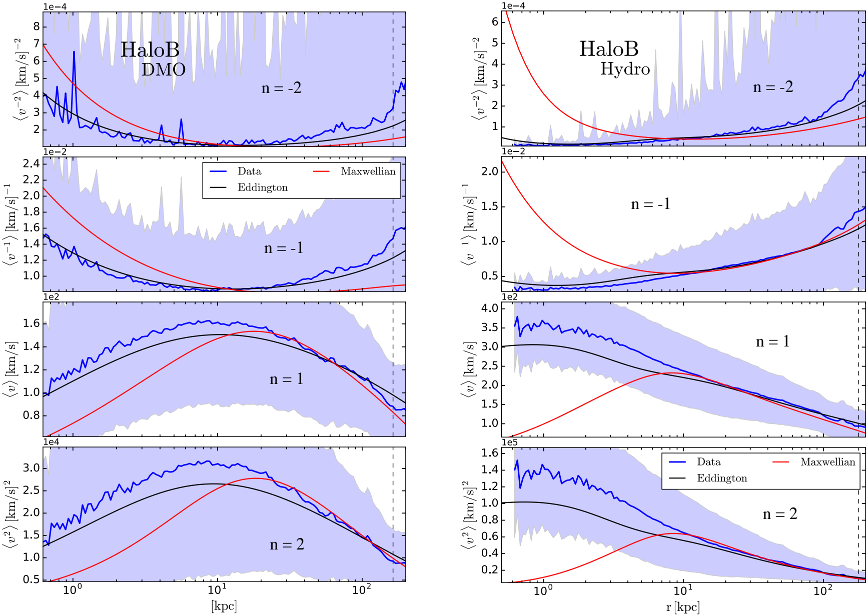
Lacroix+ 2018b, in prep.

Speed distribution $f_v(v, r)$



Lacroix+ 2018b, in prep.

Moments of the speed distribution

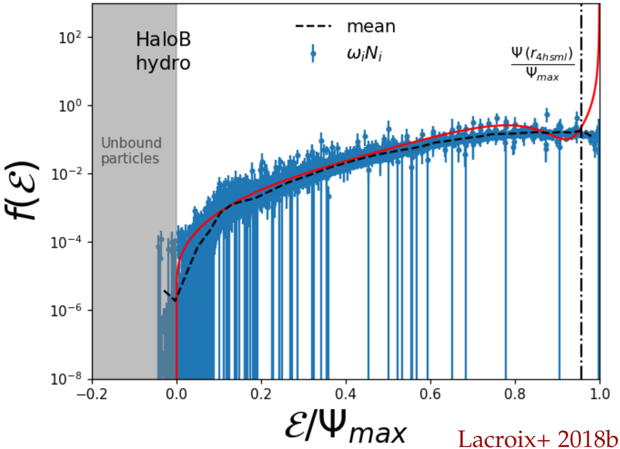


Lacroix+ 2018b, in prep.

Full phase-space distribution

Reconstruction from 2D bins ij in phase space (r_i, v_j)

$$f(\mathcal{E}) = m\frac{\mathrm{d}^6N}{\mathrm{d}^3x\mathrm{d}^3v} \rightarrow f(\mathcal{E})_{ij} = \frac{m}{(4\pi r_i v_j)^2}\frac{N_{ij}}{\Delta r_i \Delta v_j}$$



Lacroix+ 2018b, in prep.

⇒ Very good agreement for isotropic distribution

Application: constraints on sub-GeV DM from cosmic positrons - *p*-wave annihilation

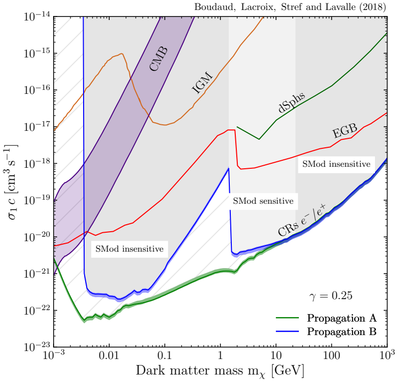
p-wave annihilation

$$\sigma v = \sigma_1 v_{\rm r}^2 \Rightarrow \langle \sigma v \rangle \equiv \langle \sigma v \rangle (r)$$

$$\langle \sigma v \rangle (r) = \sigma_1 \int {\rm d}^3 v_1 {\rm d}^3 v_2 f_r(\vec{v}_1) f_r(\vec{v}_2)\, v_{\rm r}^2$$

$$\Rightarrow \psi_{\rm e} \neq \langle \sigma v \rangle \int \rho^2(r)\, {\rm d}^3 r$$

- Very strong e^+ constraints (**Voyager 1**, AMS-02)
- Justifies focusing on Eddington's methods
- Robust w.r.t. uncertainties on anisotropy and propagation



Boudaud+ 2018

Summary

Eddington's inversion method

- A few physical assumptions
- Moderate level of technicalities
- Mass model direct input
- Better control astrophysical uncertainties for DM searches
- Dramatic changes wrt Maxwell-Boltzmann

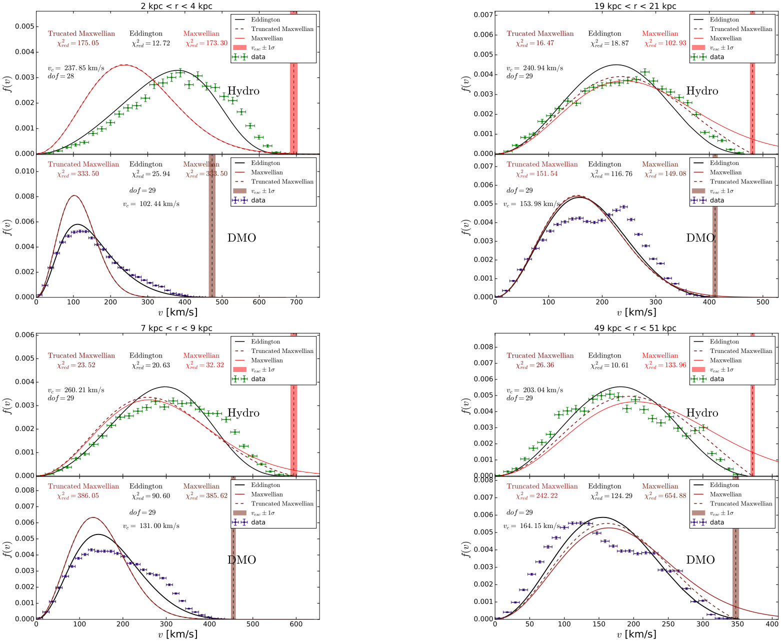
Self-consistency: theoretical validity range

- Radial boundary (direct searches)
- Positive DF + stability

Actual predictivity?

- Testing the method against cosmological simulations
- Not direct fits!!!
- Preliminary results: Eddington method globally performs much better than SHM Lacroix+ 2018b, in prep.

Thank you for your attention!



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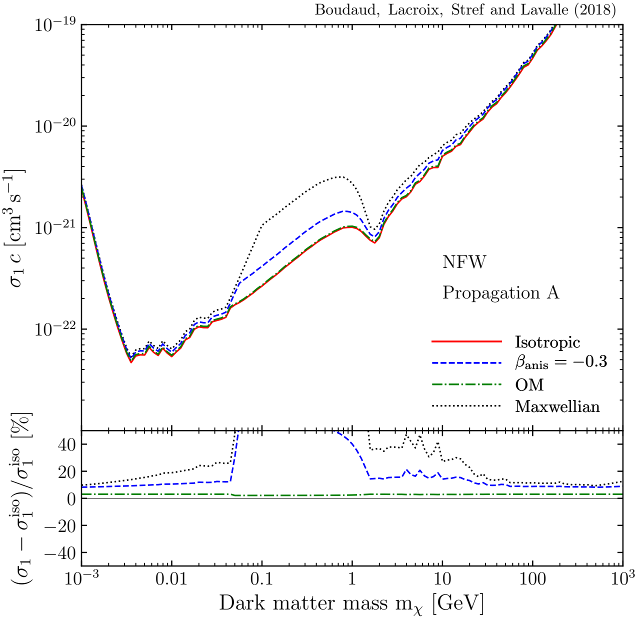

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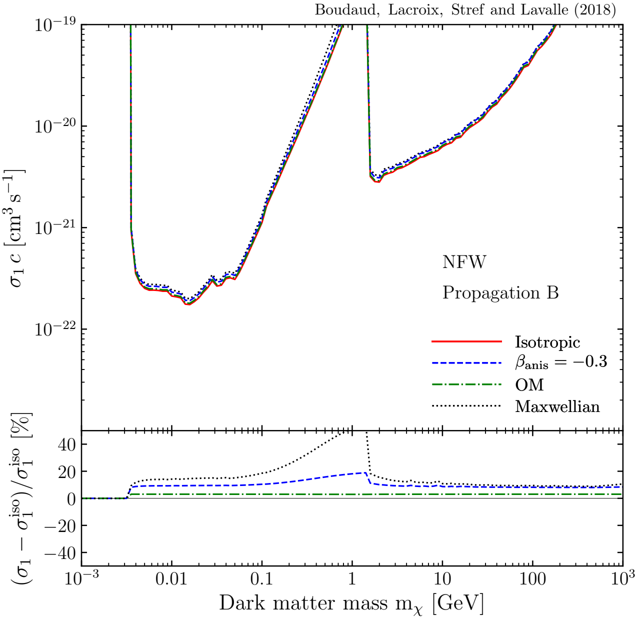

Boudaud+ 2018