Impact of Galactic subhalos on indirect searches with cosmic-ray antiprotons

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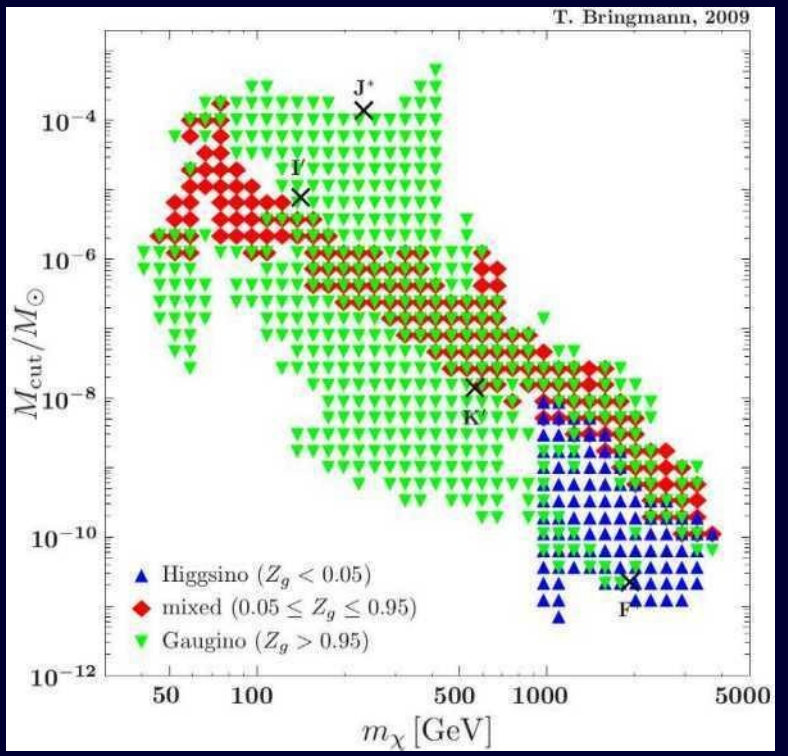
Cold Dark Matter Subhalos

CDM structures at scales much smaller than typical galaxies

Mass of the first halos given by the kinetic decoupling of the dark matter particle

According to simulations, many small halos survive up to now :

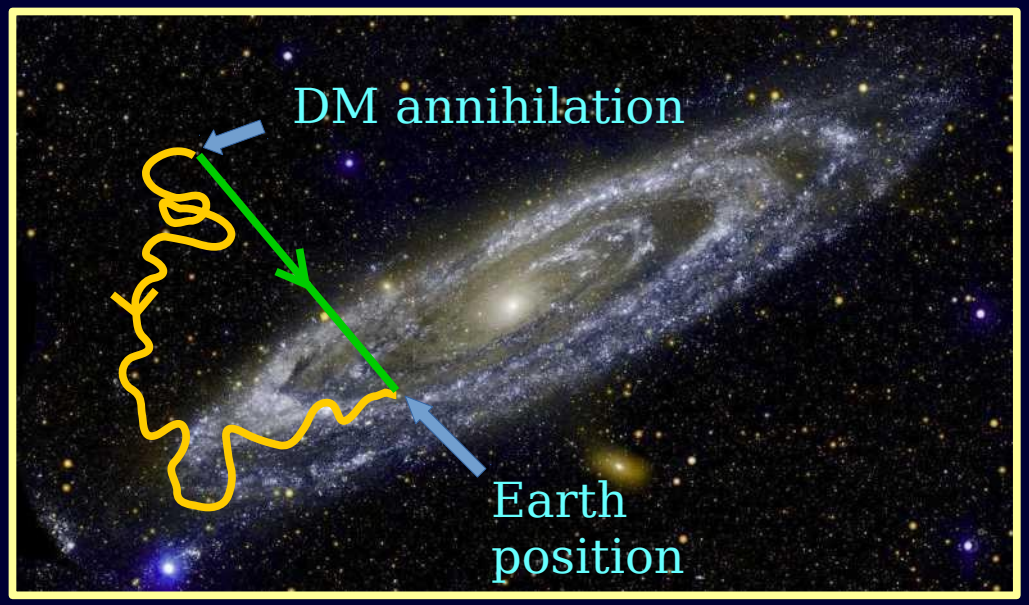


[Bringmann 09, Berezinsky+ 14]

Aquarius simulation [Springel + 08],
See also Via Lactea II [Diemand+ 08],
Illustris [Vogelsberger+ 14]

Subhalos and dark matter searches

Indirect searches:

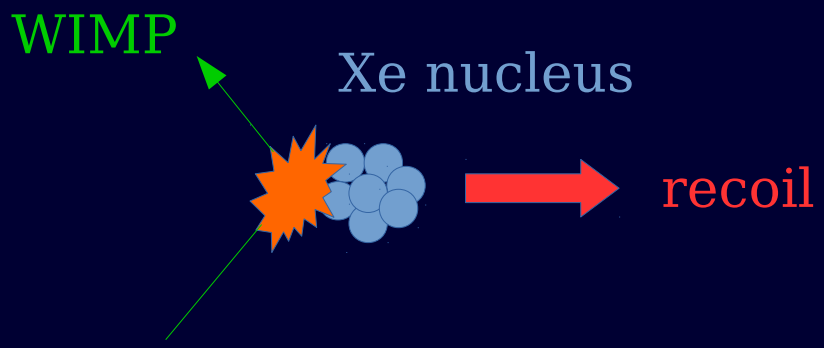


Detection via photons, neutrinos or charged cosmic rays

$$\text{flux} \propto \langle \rho^2 \rangle_V > \langle \rho \rangle_V^2$$

If subhalos present in the galaxy, signal is boosted!
[Silk & Stebbins 93]

Direct detection:



Sensitive to the local DM density.
Fraction of that density inside clumps?

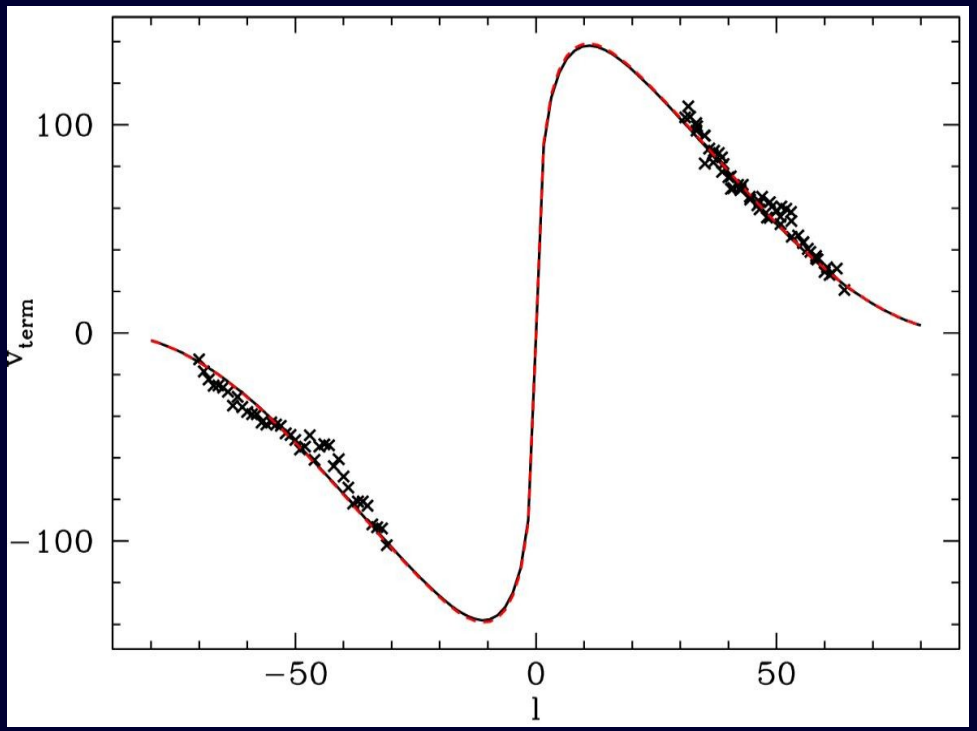
A dynamically constrained model of Galactic subhalos

Based on

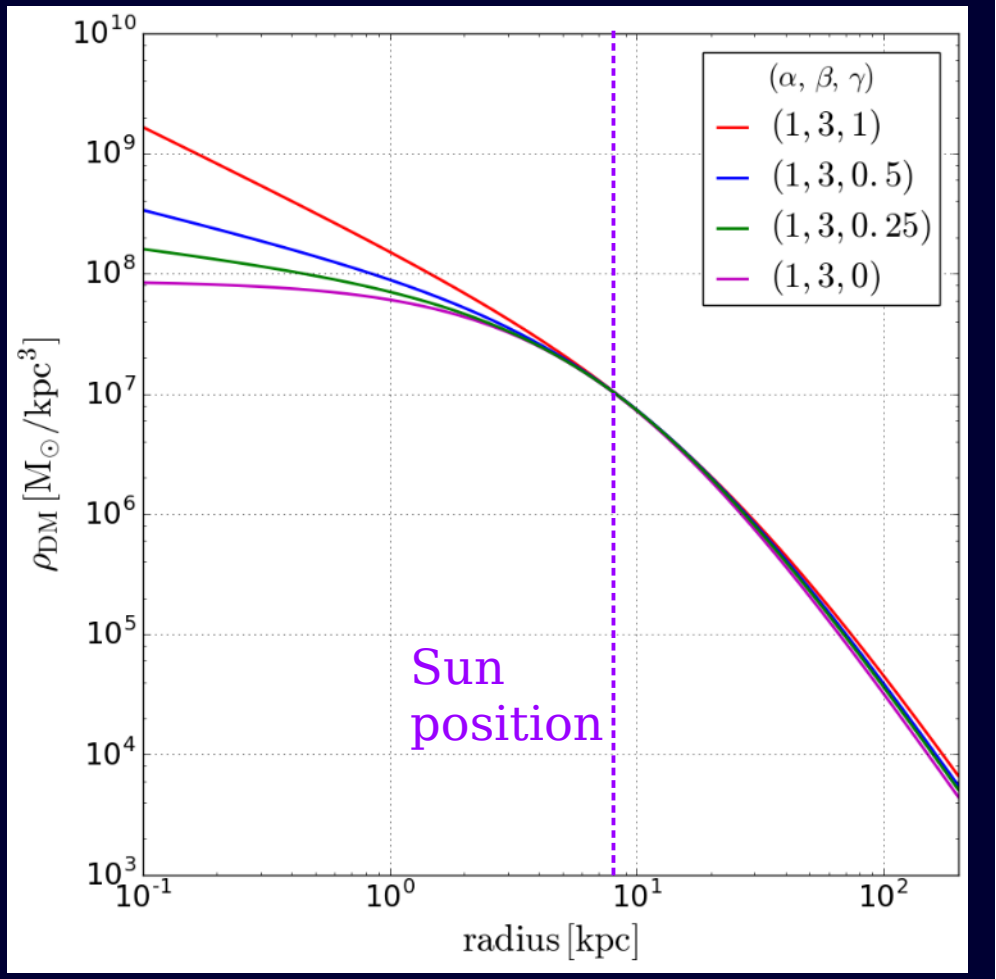
Stref & Lavalle : arXiv:1610.02233

A dynamically constrained Galaxy

The Milky Way dark halo is tightly constrained by observations



Terminal velocities from McMillan 11



Mass models from McMillan 17

A dynamically constrained Galaxy

The Milky Way dark halo is tightly constrained by observations

$$\rho_{\rm DM}(r) = \rho_{\rm sub}(r) + \rho_{\rm smooth}(r)$$

constrained

modeled/predicted

A dynamically constrained Galaxy

The Milky Way dark halo is tightly constrained by observations

$$\rho_{\rm DM}(r) = \rho_{\rm sub}(r) + \rho_{\rm smooth}(r)$$

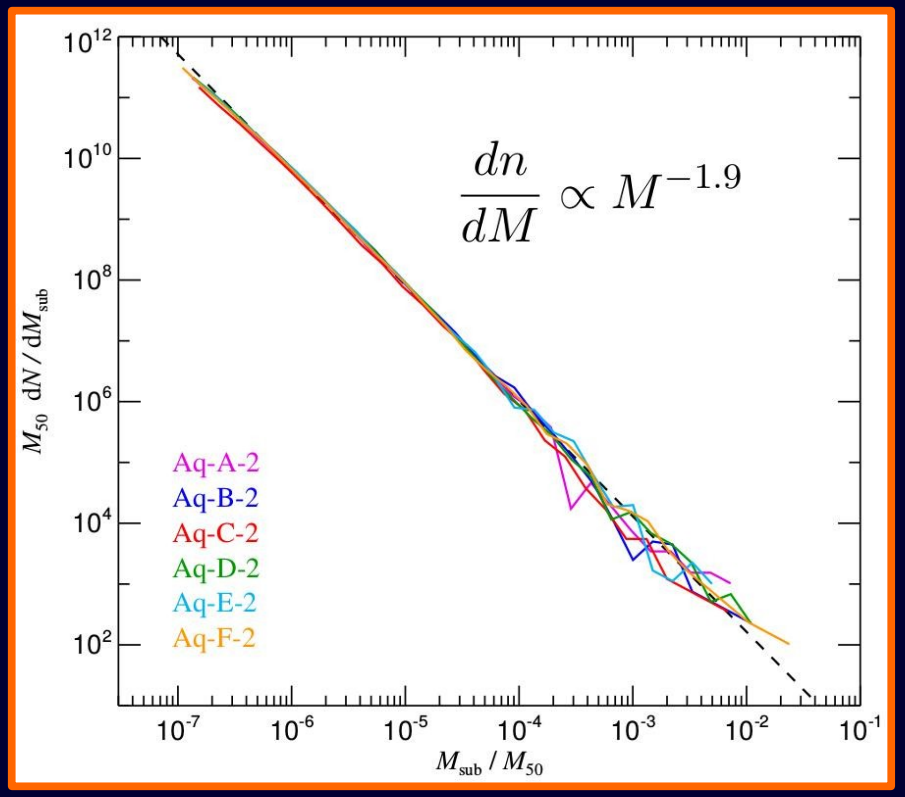
Subhalo mass function :

Press-Schechter type :

$$\frac{dn}{dM} \propto M^{-\alpha}$$

$$\alpha \sim 2 - 1.9$$

with mass cutoff $M_{\rm min}$



Aquarius simulation [Springel+ 08]

A dynamically constrained Galaxy

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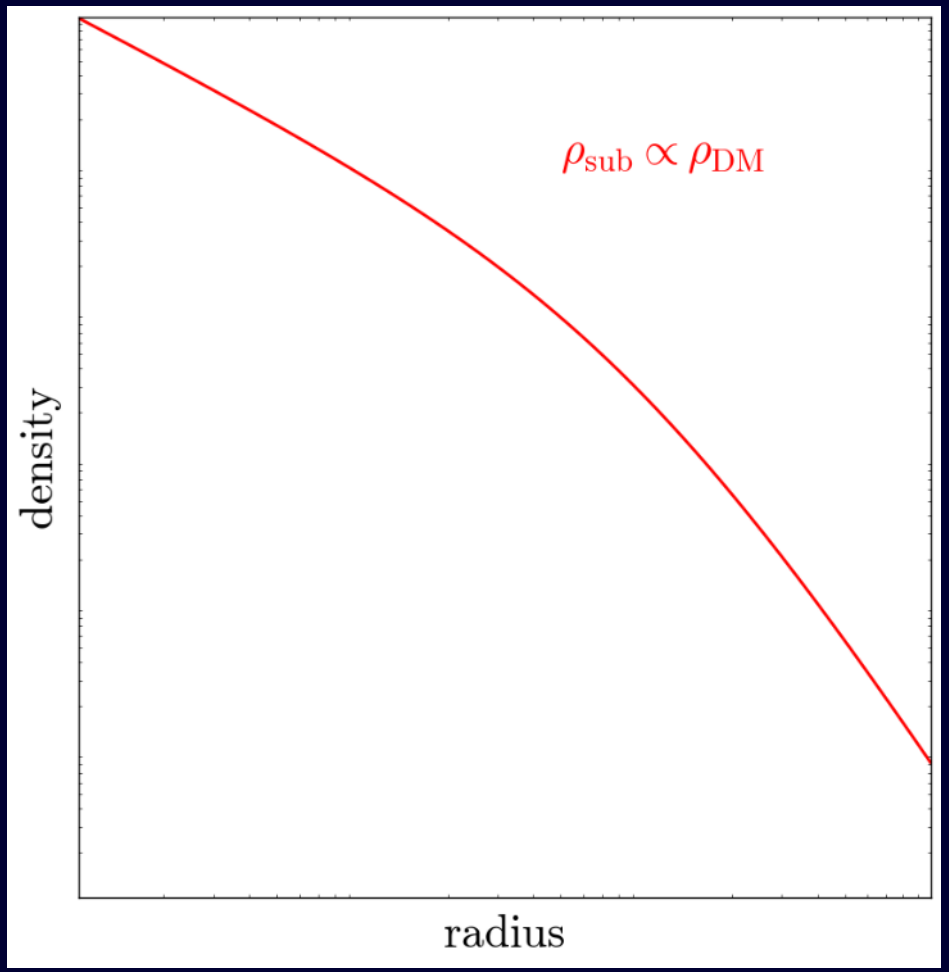

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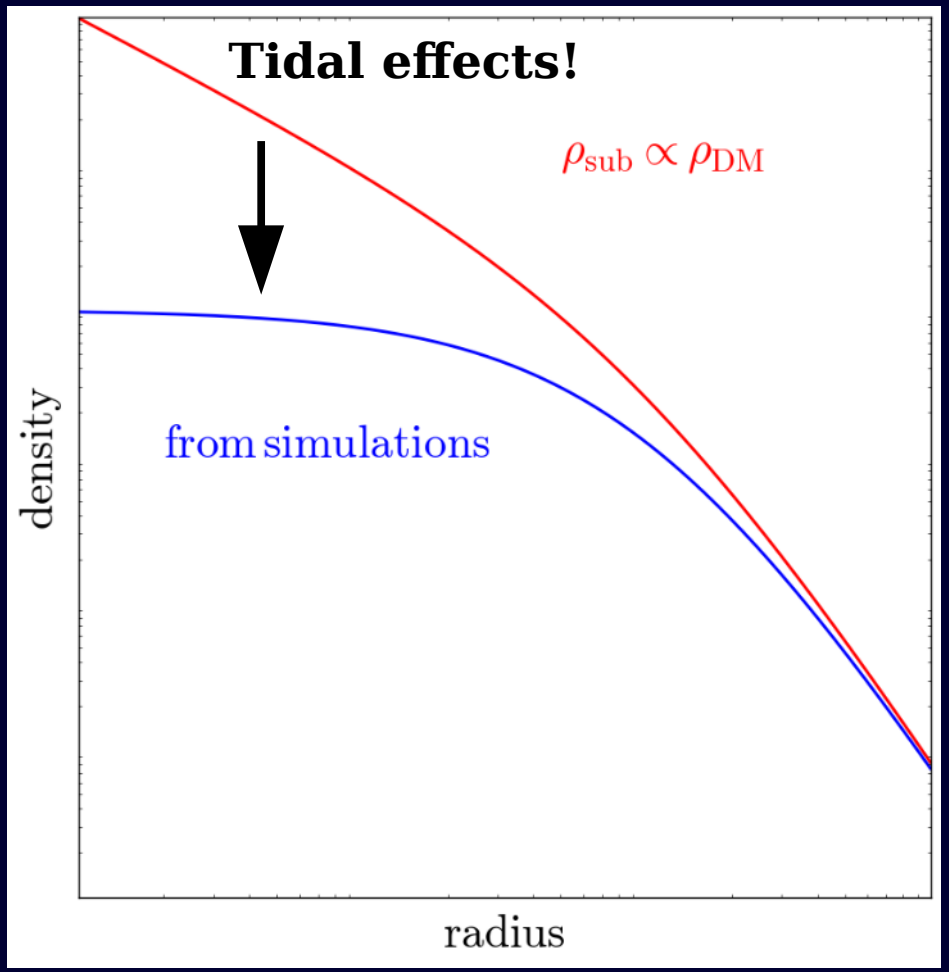


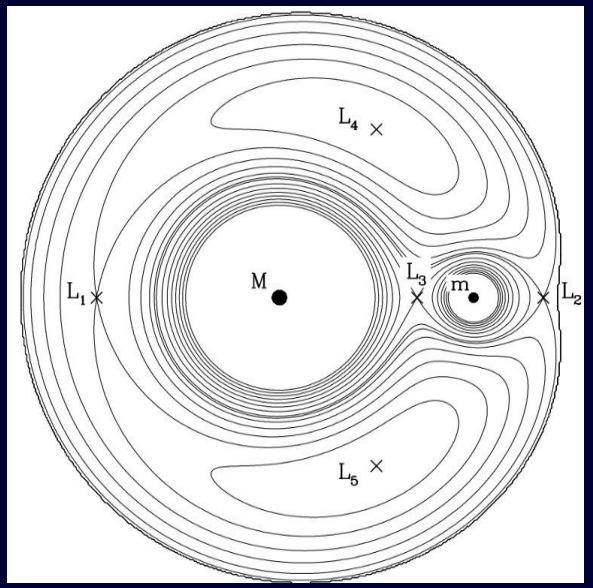
Tidal effects

Interaction of subhalos with external gravitational fields.

Two different effects :

Halo stripping

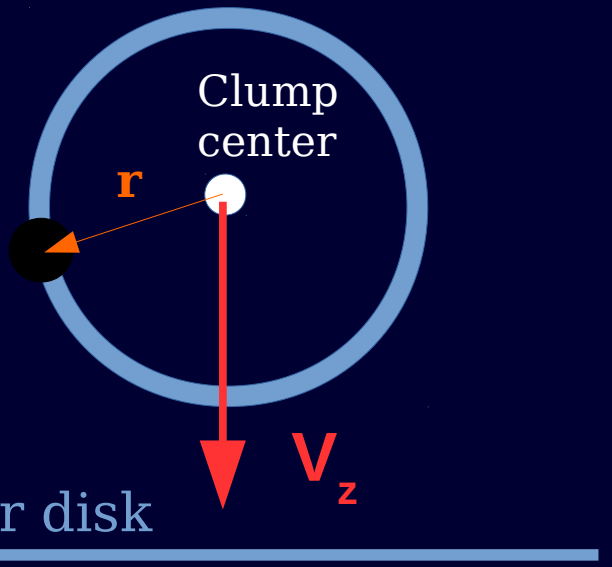
Subhalos are stripped by the potential of the Galaxy



[Binney & Tremaine 87]

$$r_{\rm f} = \left[\frac{m_{\rm sub}(r_{\rm f})}{3M(R)\left(1 - \frac{1}{3}\frac{d\ln M}{d\ln R}\right)} \right]^{1/3} R$$

Disk shocking



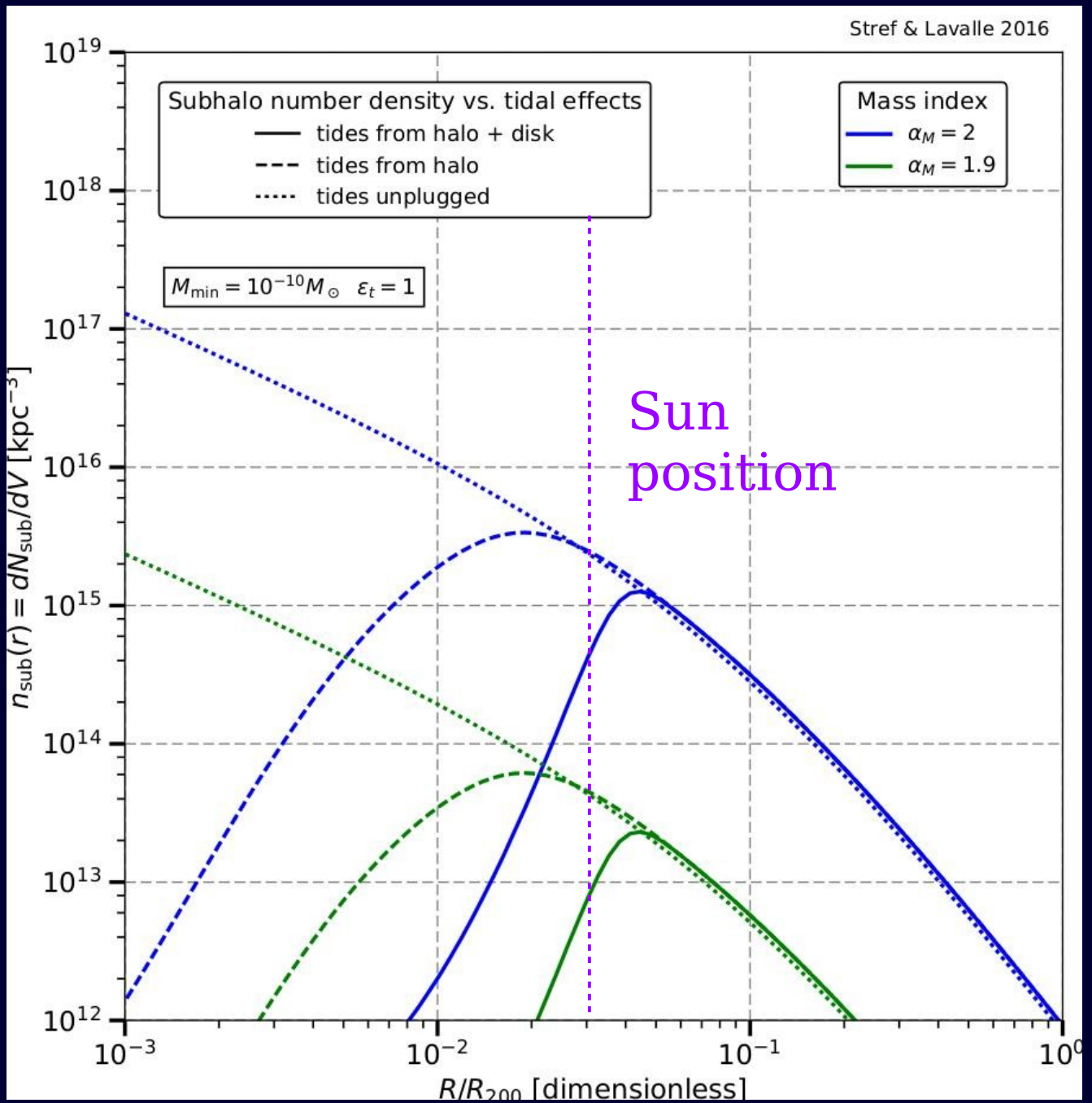
DM particles get a net velocity kick [Ostriker+ 72]

$$\langle \delta\epsilon \rangle \propto \frac{g_{\rm z,disk}^2 r^2}{V_{\rm z}^2}$$

[Stref & Lavalle 17]

$$\langle \delta\epsilon \rangle = |\phi(r_{\rm f}) - \phi(r_{\rm i})|$$

Number density



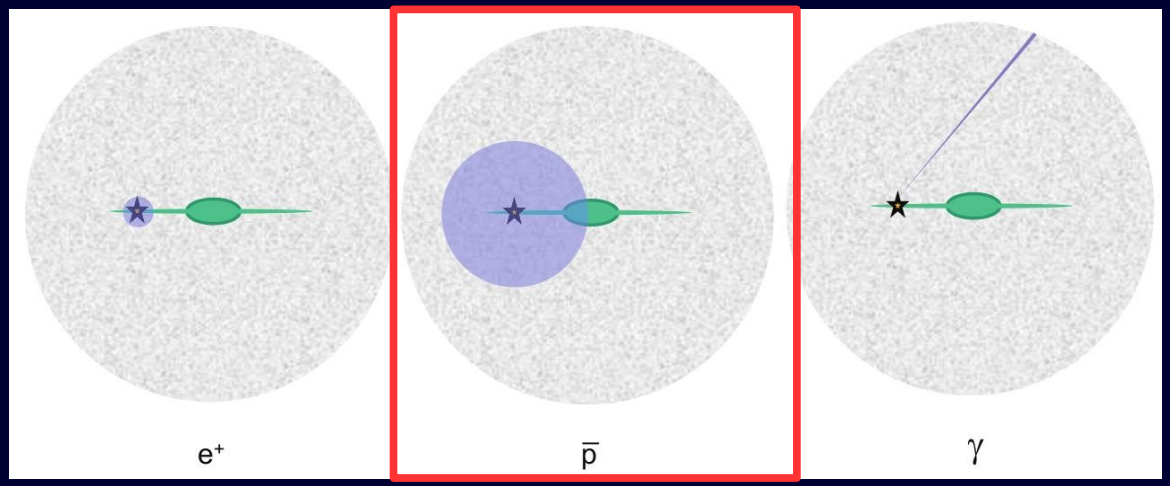
Indirect searches with cosmic-ray antiprotons

Based on

Stref, Lacroix & Lavalle : arXiv:17xx.xxxxx

Why antiprotons?

[Bergstrom 09]

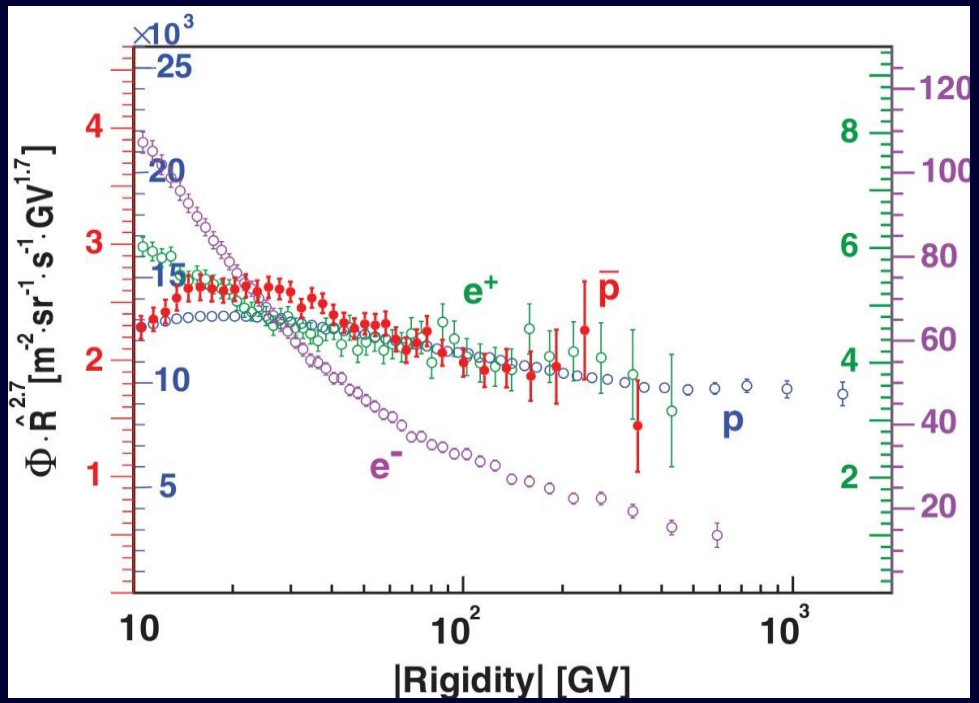


Indirect searches :

with gamma rays
[Bergstrom+ 99],

with antimatter cosmic rays
[Lavalle+ 07,08]

AMS-02 data [Aguilar+ 16]



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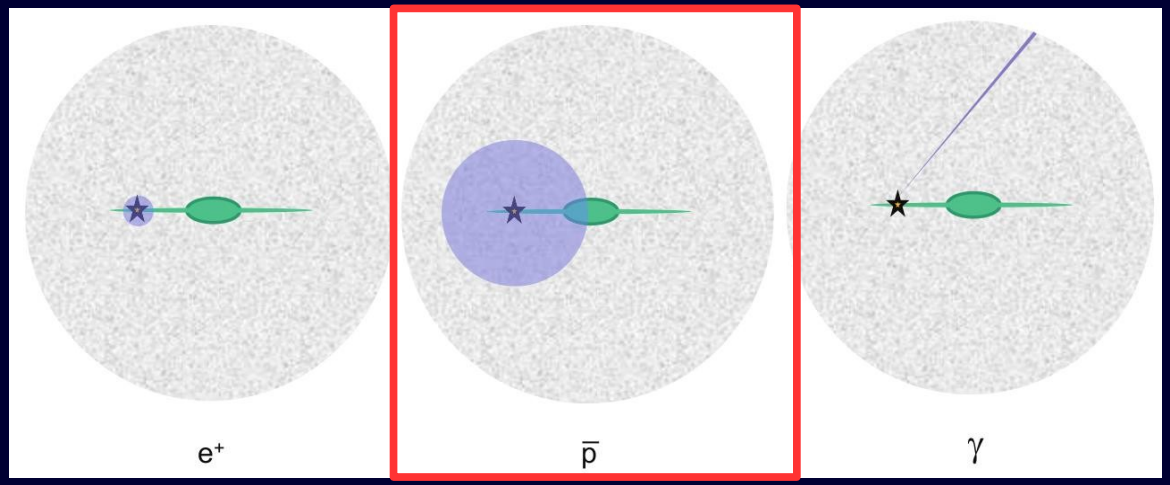

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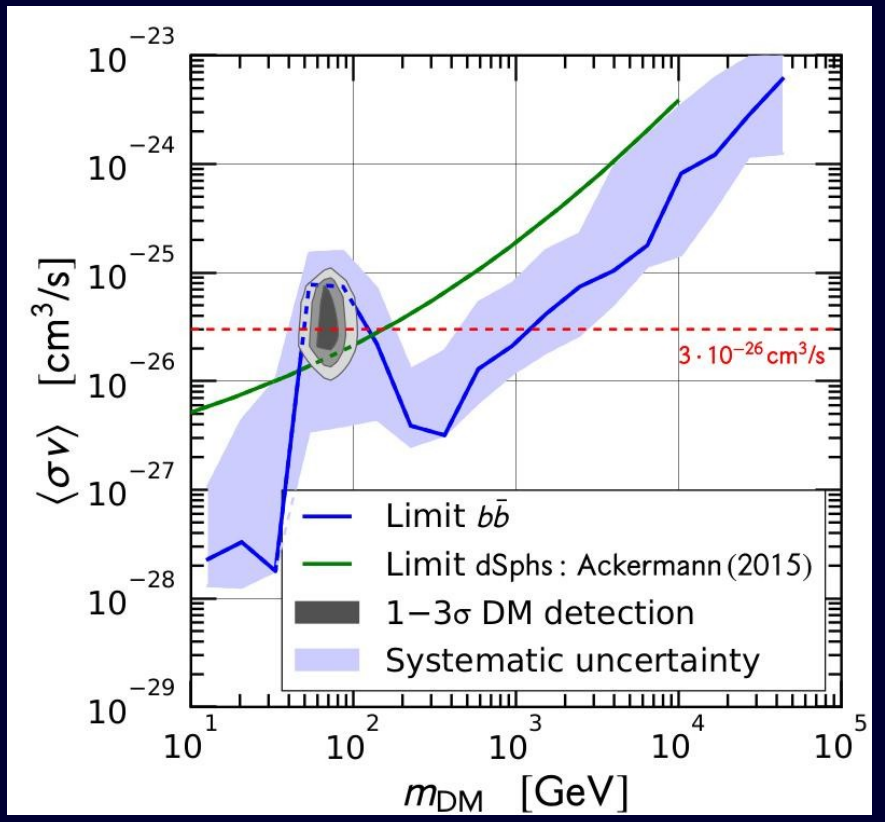
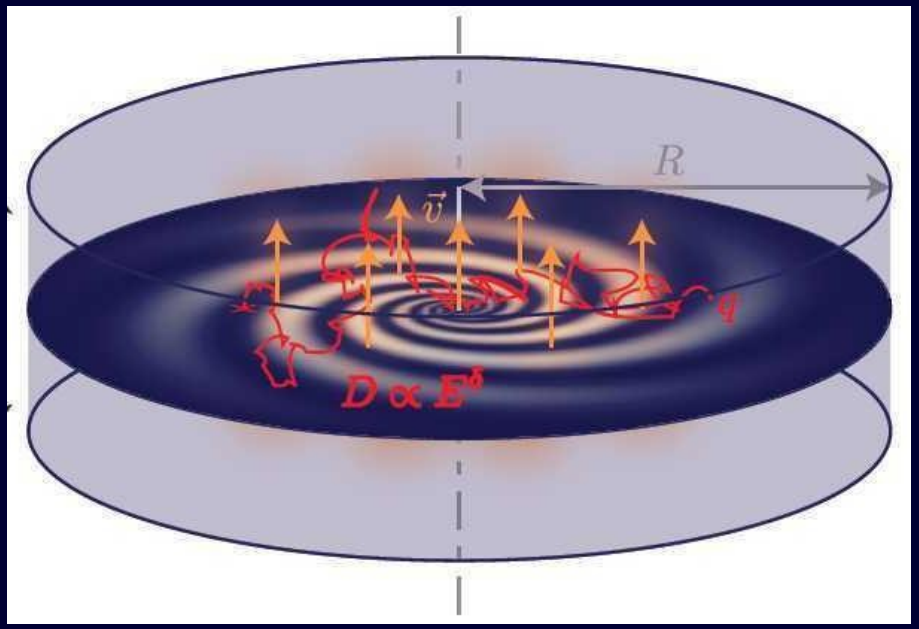
AMS-02 “hot spot” [Cuoco+ 16]



Cosmic-ray propagation



[Mertsch, 2010]

Propagation parameters fixed by B/C (secondaries/primaries) :

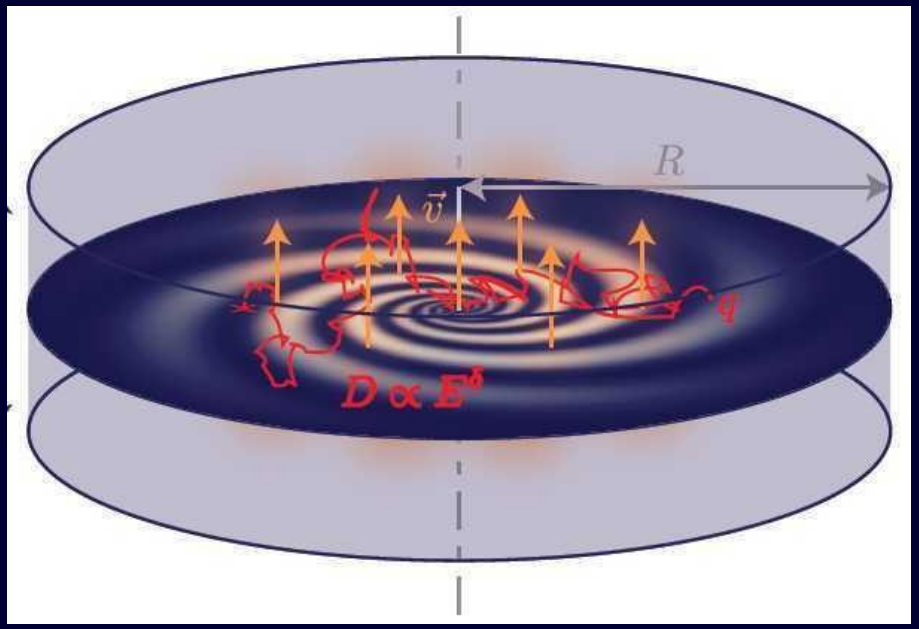
model	δ	K_0 [kpc^2/Myr]	L [kpc]	V_C [km/s]	V_a [km/s]
MED [Maurin + 01]	0.7	0.0112	4	12	52.9
Kappl + 15	0.408	0.0967	13.7	0.2	31.9

Propagation eq. for cosmic rays sourced by DM

$$-K\Delta\psi + \partial_z(V_C\,\psi) + \partial_E\{b_{loss}(E)\psi - K_{EE}(E)\partial_E\psi\} + Q_{collision} = Q_{DM}$$

Cosmic-ray propagation

Critical for DM searches



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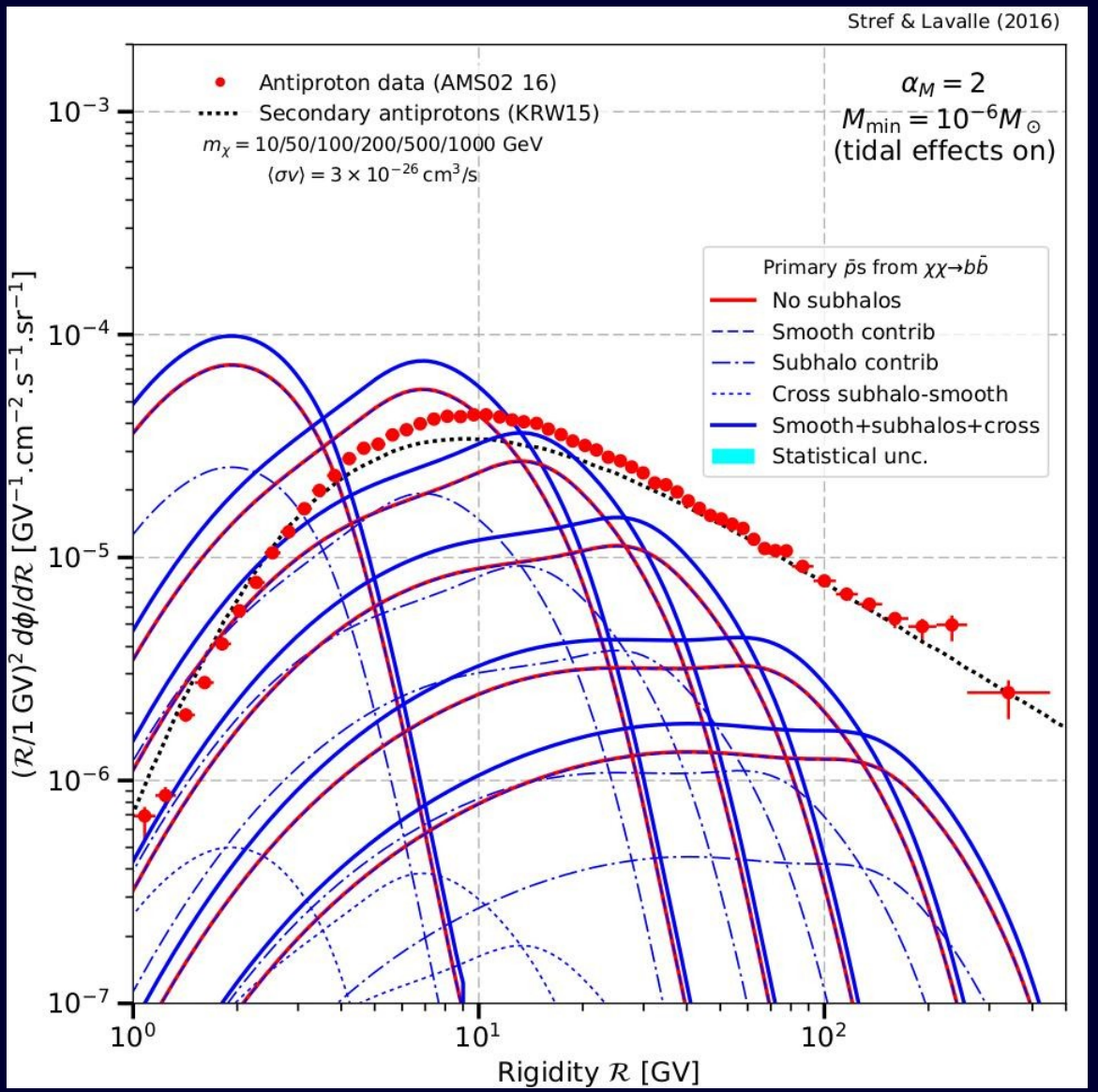
Antiproton flux

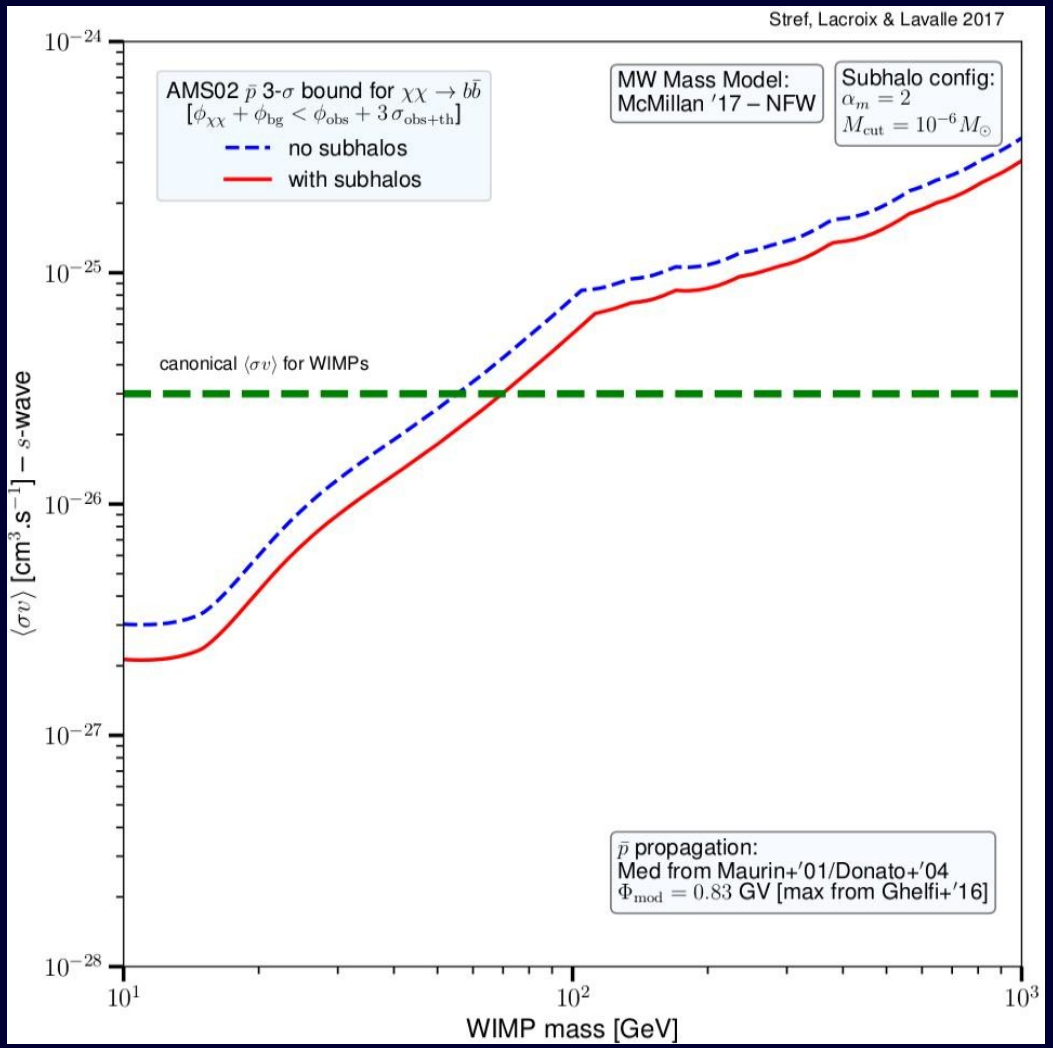
$$\frac{\mathrm{d}\phi}{\mathrm{d}\mathcal{R}} = \frac{\langle\sigma v\rangle}{2\,m_\chi^2}\frac{\mathrm{d}N}{\mathrm{d}\mathcal{R}}\int \mathrm{d}^3\vec{x}\,G_{\mathrm{prop}}(\vec{x},E)\,\left\langle(\rho_{\mathrm{sm}}(\vec{x})+\rho_{\mathrm{sub}}(\vec{x}))^2\right\rangle$$

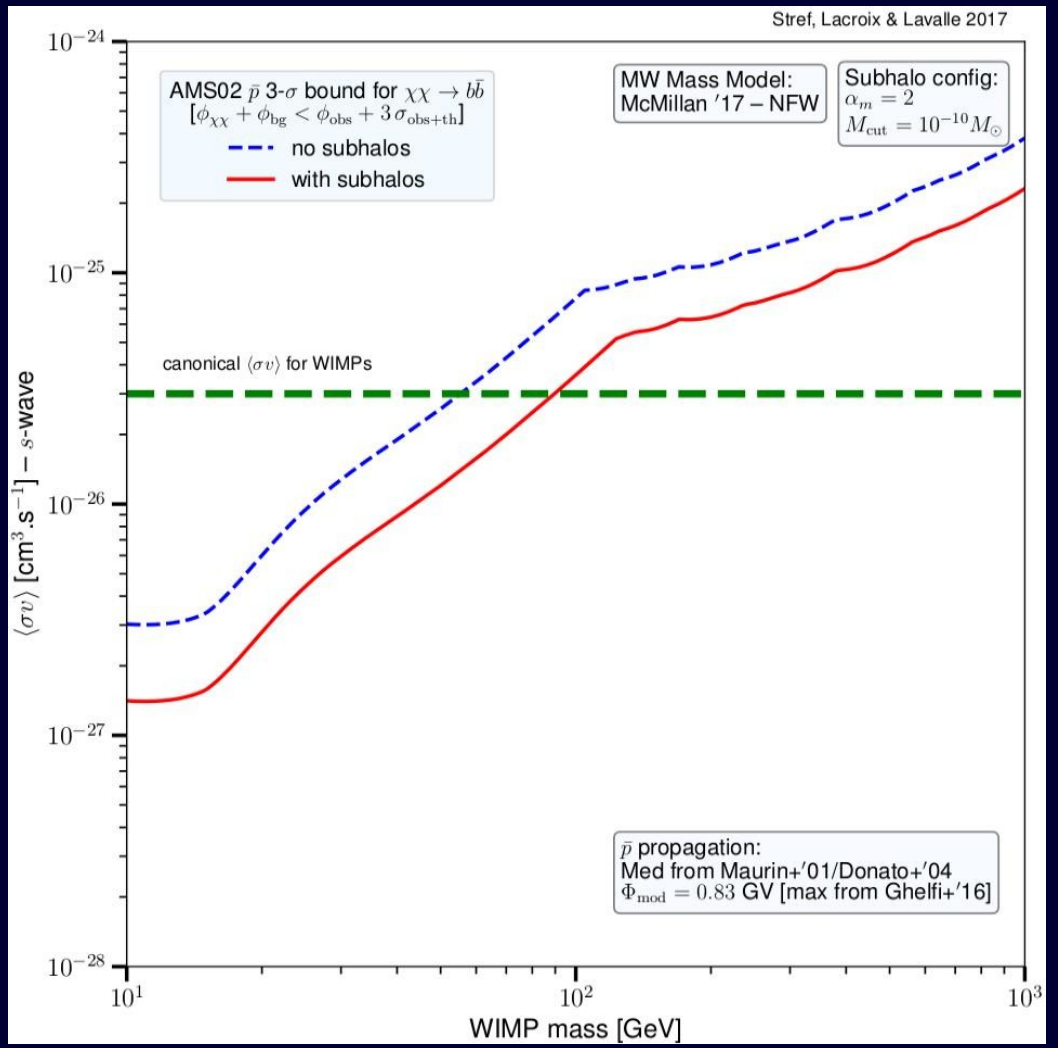


Spectra from PPPC4DM ID [Cirelli+ 11]

Exclusion curves : MED model

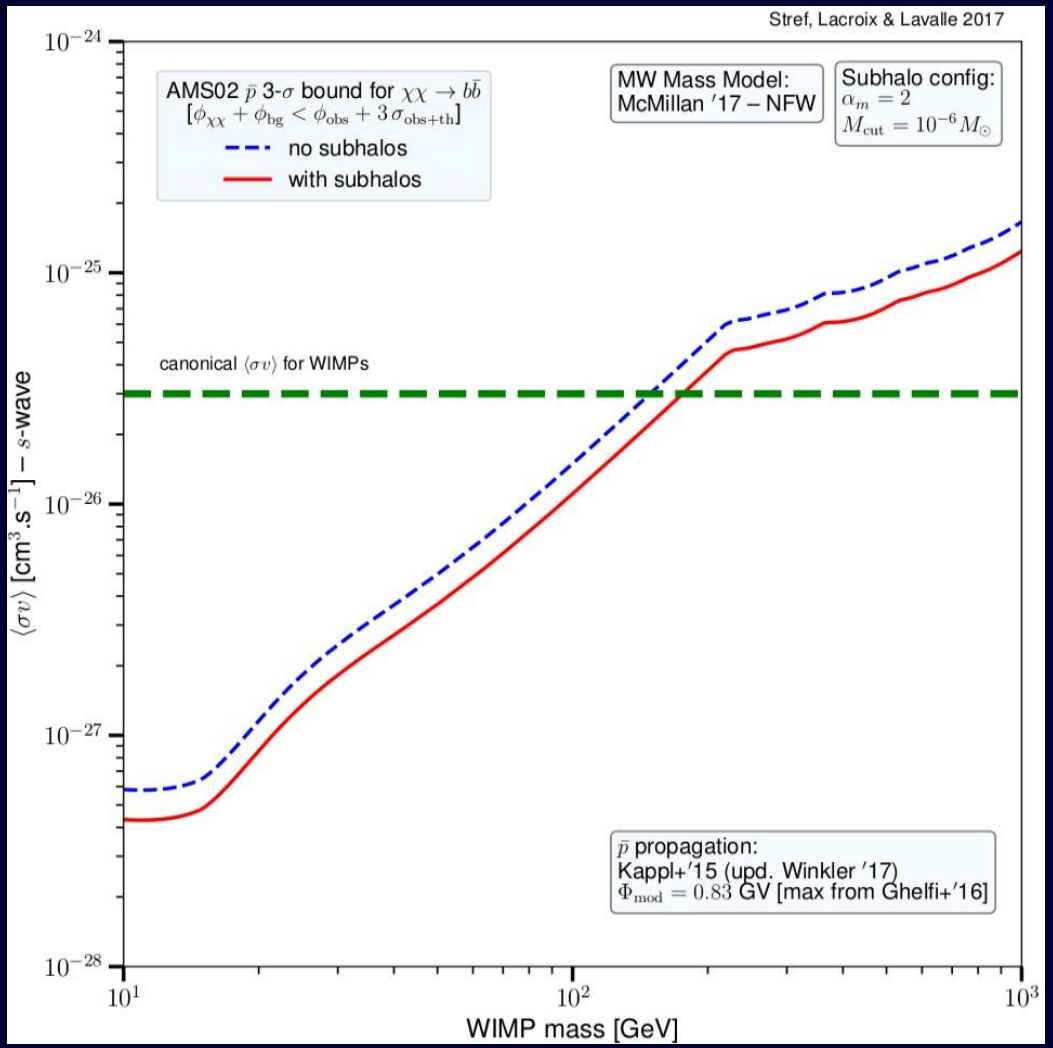
$$L = 4\,\mathrm{kpc}$$

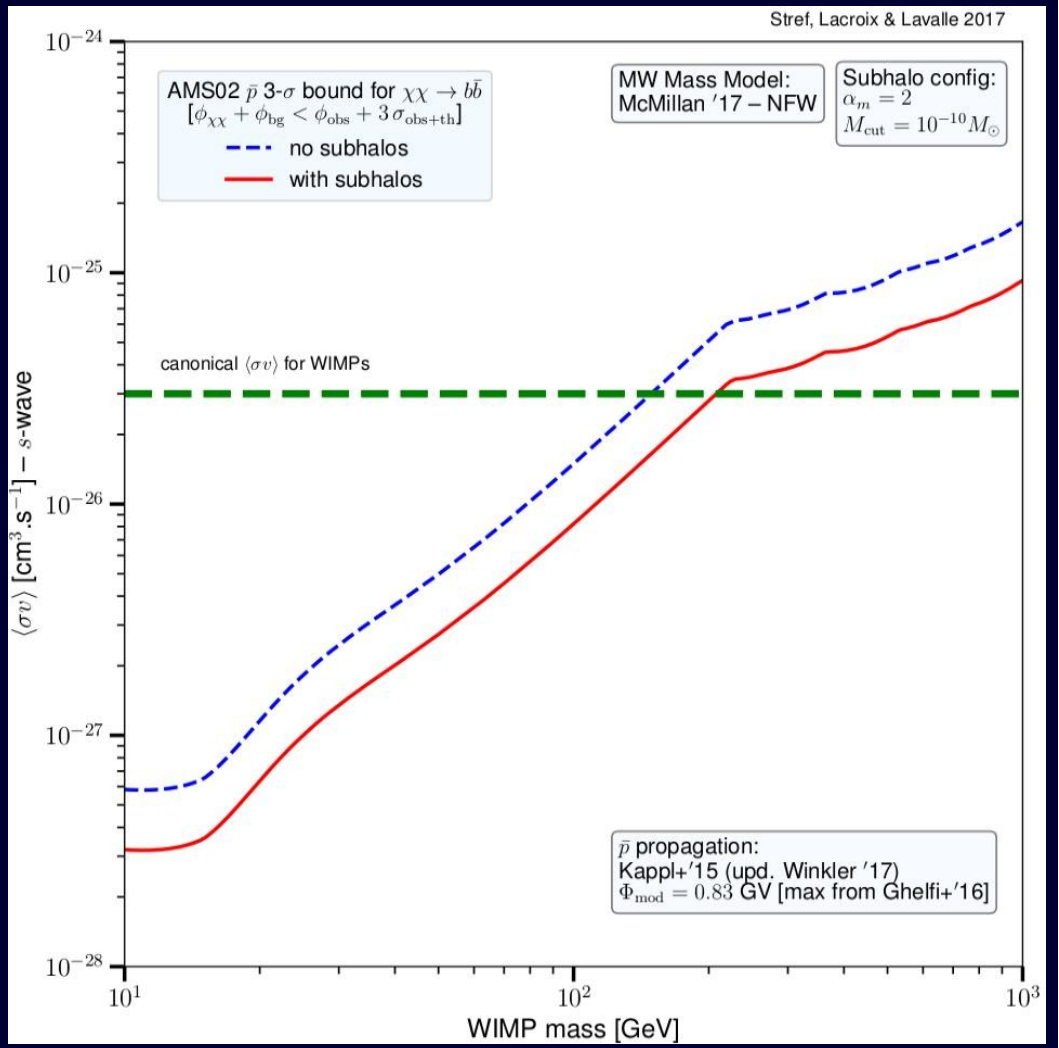




Exclusion curves : model of Kappl et al.

$$L = 13.7\,\mathrm{kpc}$$





Summary

- DM distribution is fondamental to make predictions on direct/indirect searches : dynamical constraints must be accounted for.

- Cold dark matter, and WIMPs in particular, forms very small-scale subhalos.

- The subhalo population can be modeled in a dynamically consistent way, including tidal disruption effects.

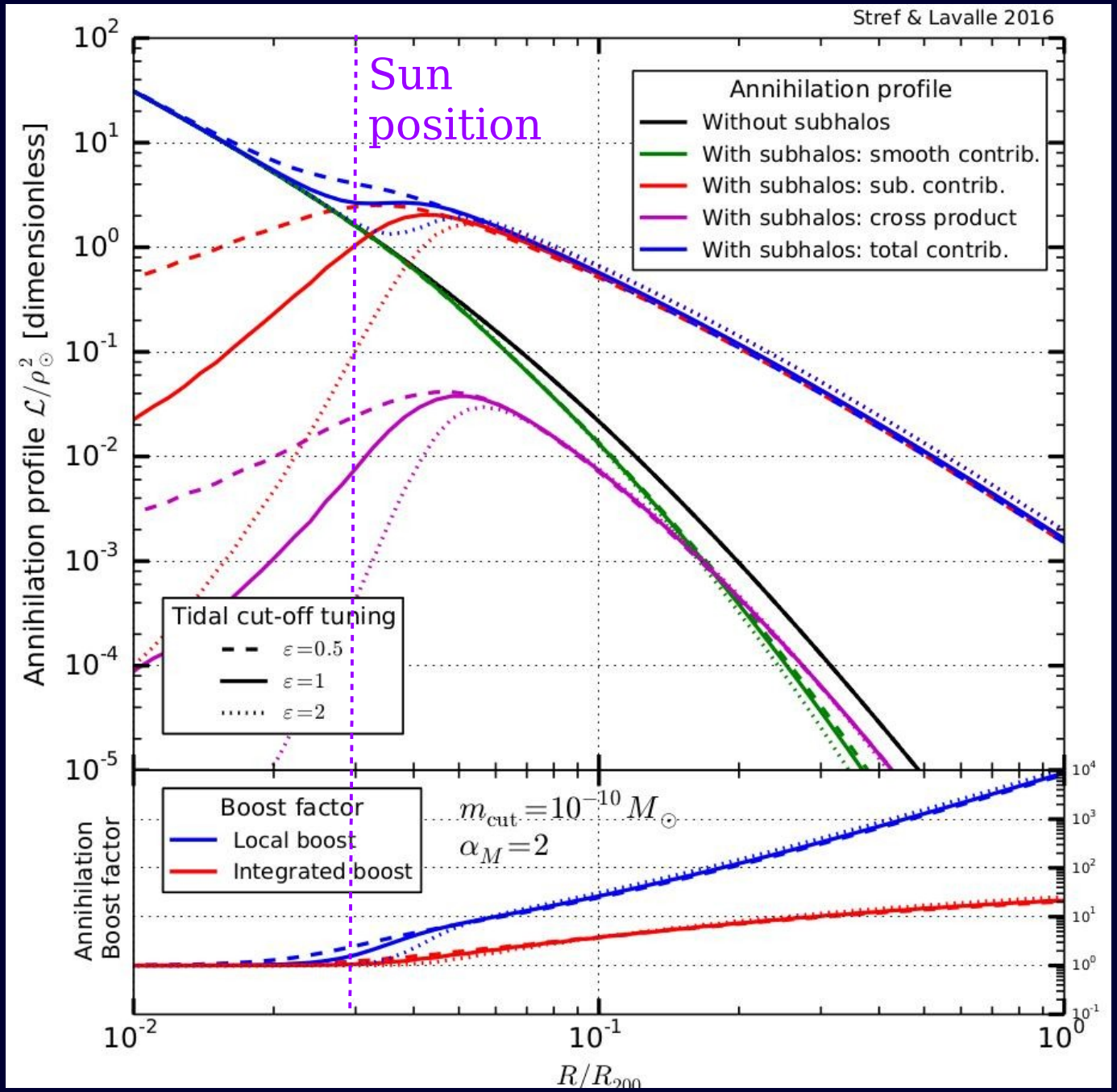
- Subhalos strongly impact indirect searches, e.g. with cosmic-rays antiprotons, and should be accounted for (at least as a theoretical uncertainty).

Backup

Luminosity and boost factors

$$\mathcal{L} = \langle \rho^2 \rangle$$

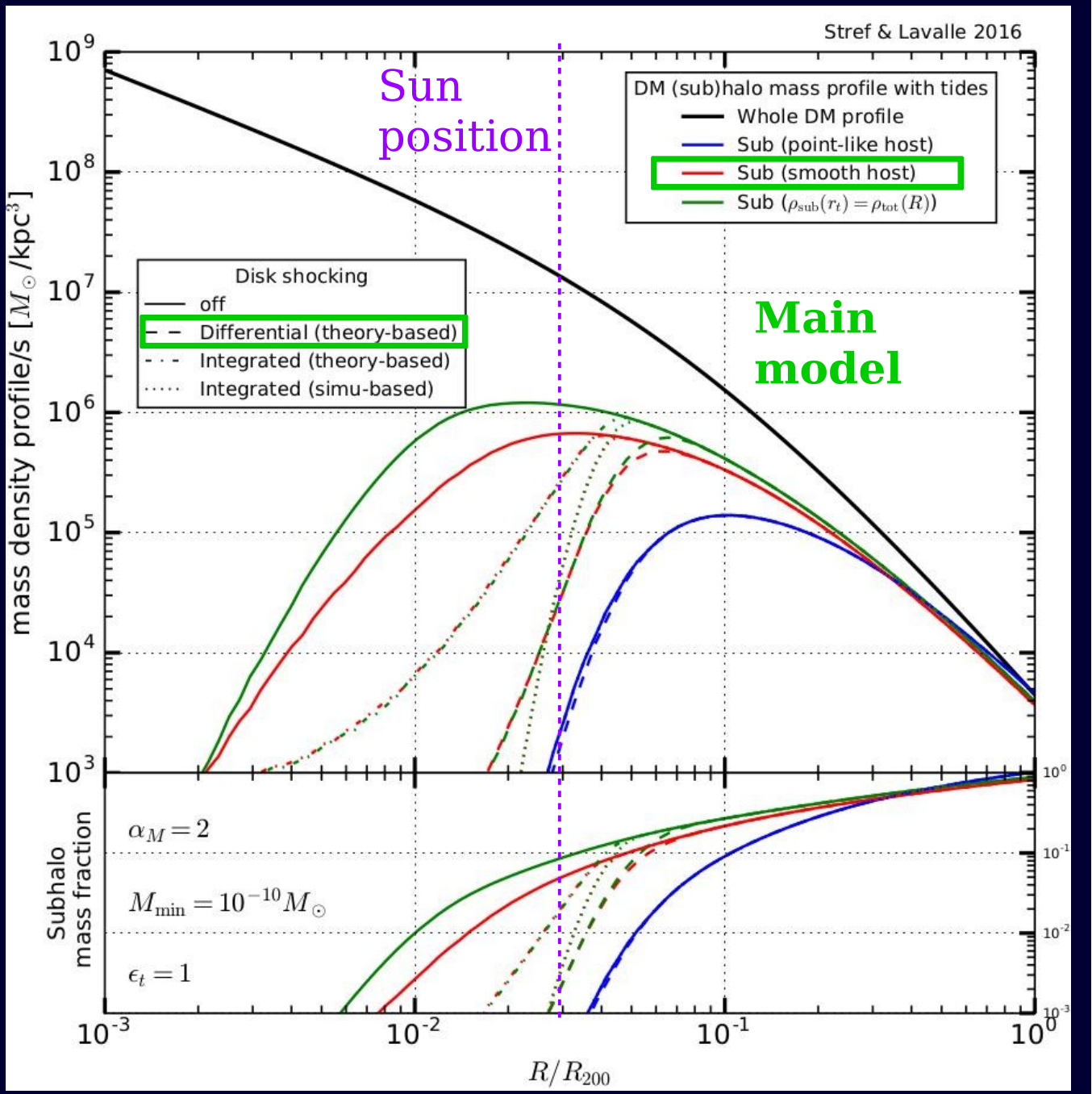
$$\text{boost} = \frac{\mathcal{L}_{\text{clumpy}}}{\mathcal{L}_{\text{smooth}}}$$



Predicted mass density profiles

$$\rho_{\rm sub}(R) = N_{\rm sub} \times \int_{\rm m_{min}}^{\rm m_{max}} dm \int_1^\infty dc\, \mathcal{F}(R,m,c)\, m_{\rm t}(R,m,c)$$

$$\rho_{\rm DM}(r) = \rho_{\rm sub}(r) + \rho_{\rm smooth}(r)$$



Posterior mass function