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

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in collaboration with

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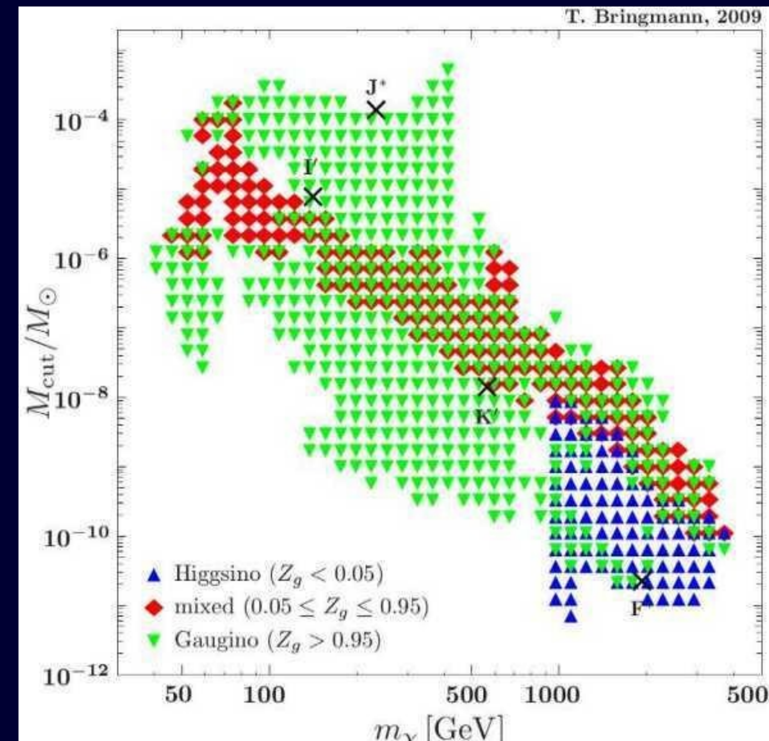
Cold Dark Matter Subhalos

CDM structures at scales much smaller than typical galaxies

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



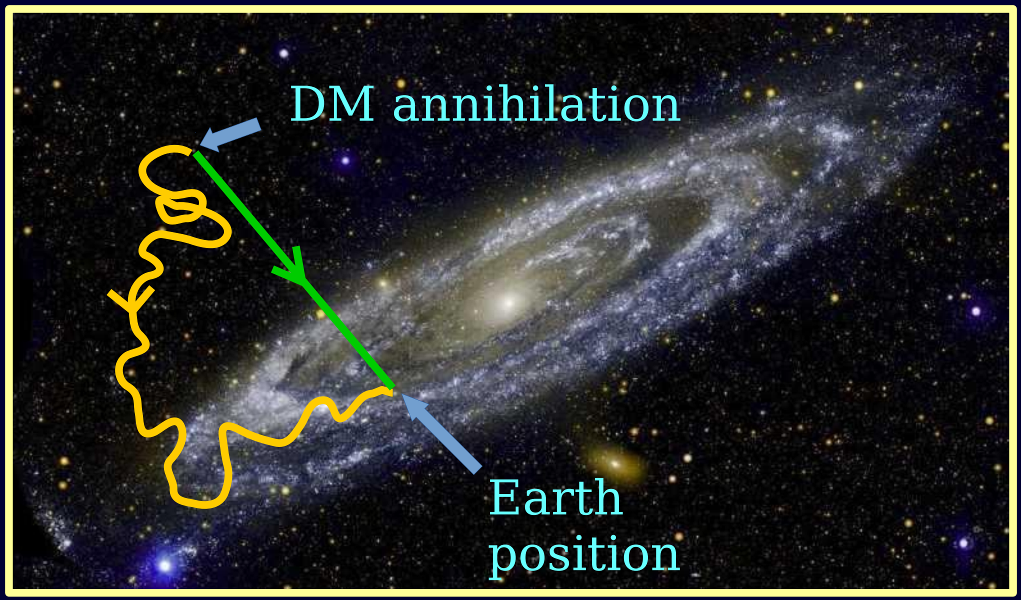
[Bringmann 09, Berezinsky+ 14]

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

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

Subhalos and dark matter searches

Indirect searches:

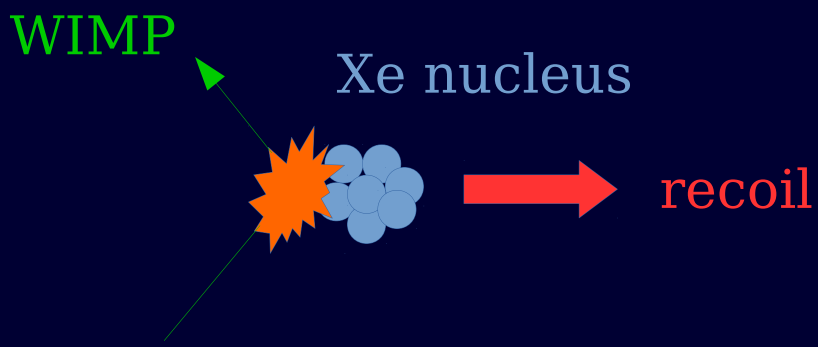


Detection via photons, neutrinos or charged cosmic rays

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

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?

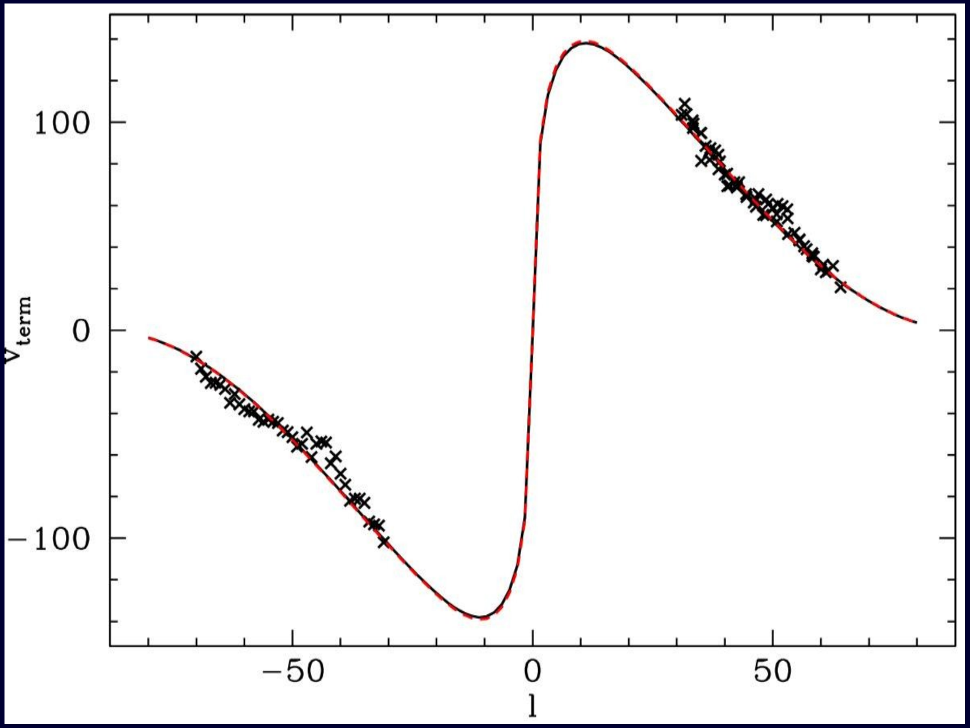
A dynamically constrained model of Galactic subhalos

Based on

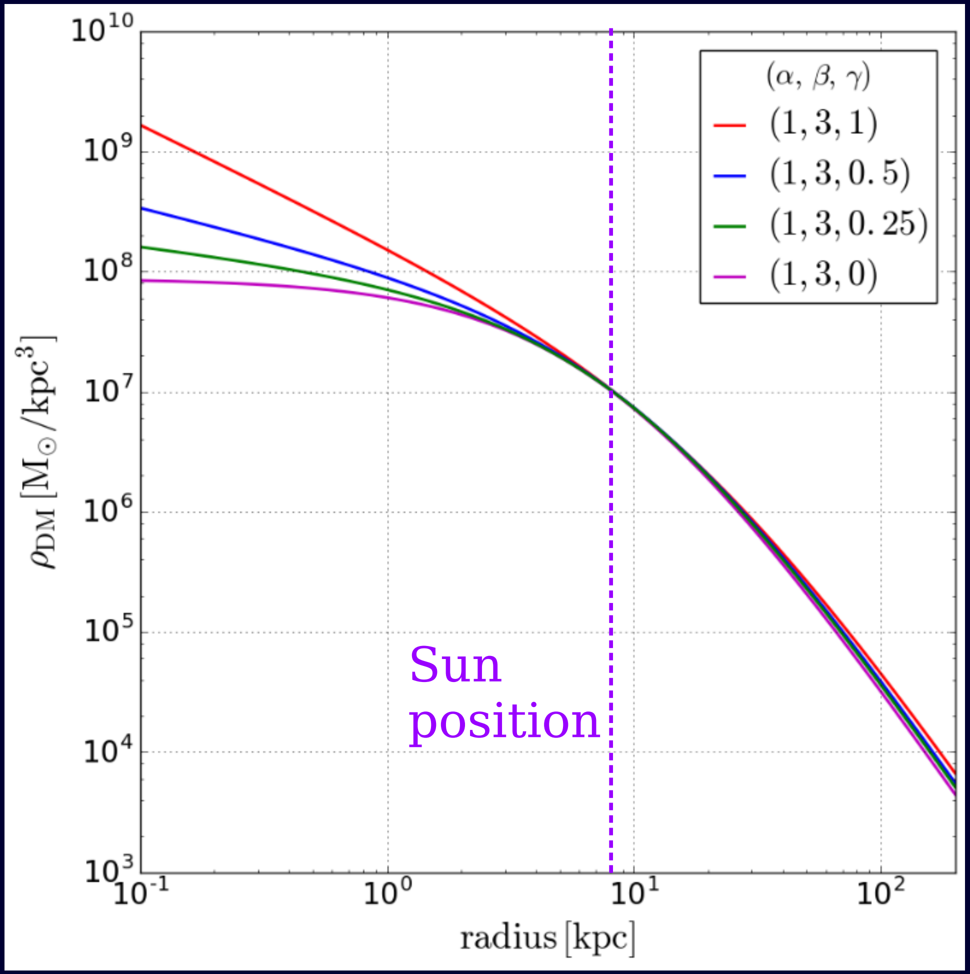
Stref & Lavalle : arXiv:1610.02233

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

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

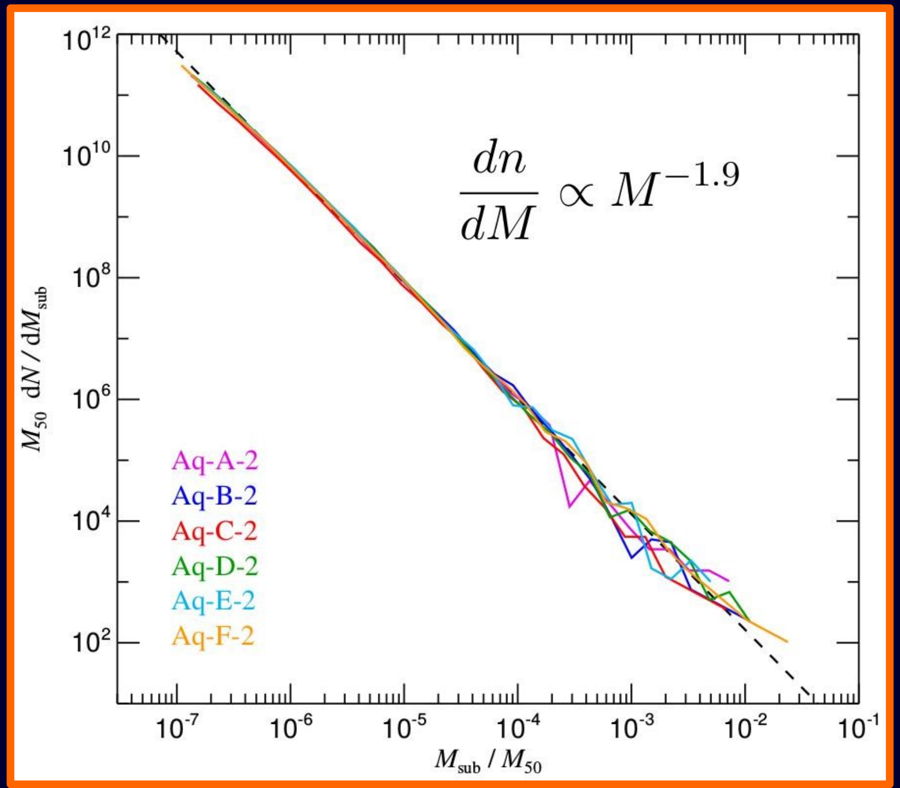
<u>Subhalo mass function</u> :

Press-Schechter type :

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

$\alpha \sim 2 - 1.9$

with mass cutoff $M_{\rm min}$



Aquarius simulation [Springel+ 08]

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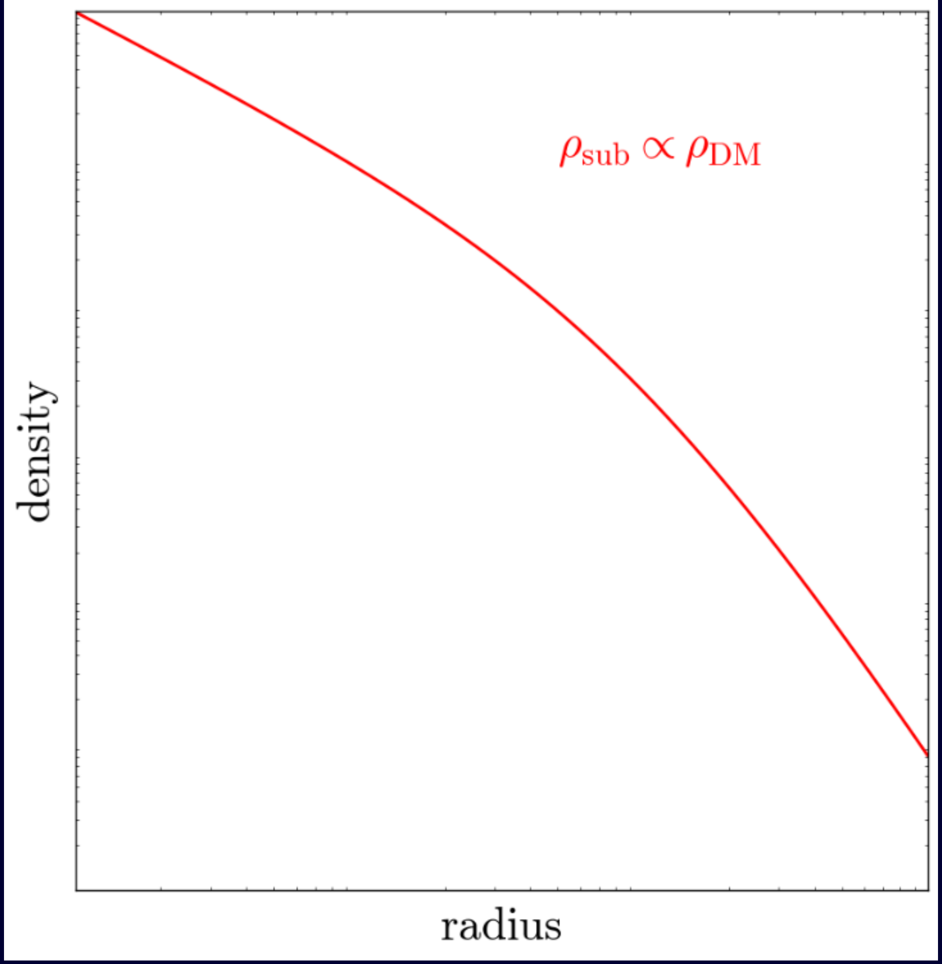

A dynamically constrained Galaxy

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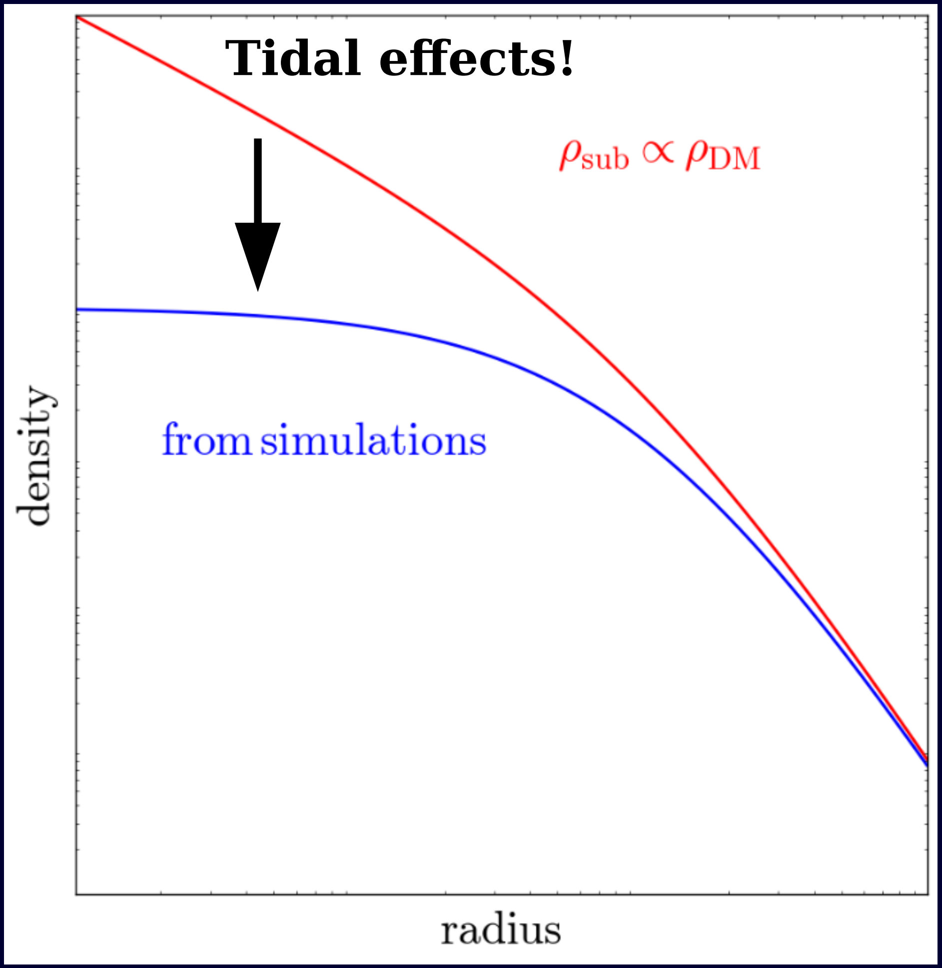
$$\rho_{\mathrm{DM}}(r) = \rho_{\mathrm{sub}}(r) + \rho_{\mathrm{smooth}}(r)$$



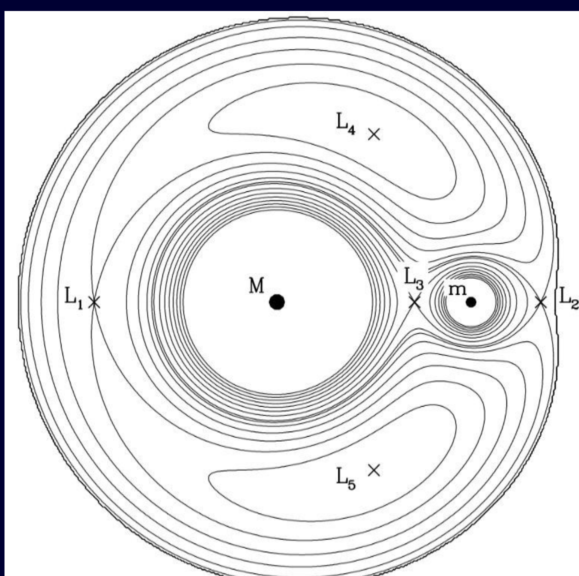
Tidal effects

Interaction of subhalos with external gravitational fields.

Two different effects :

Halo stripping

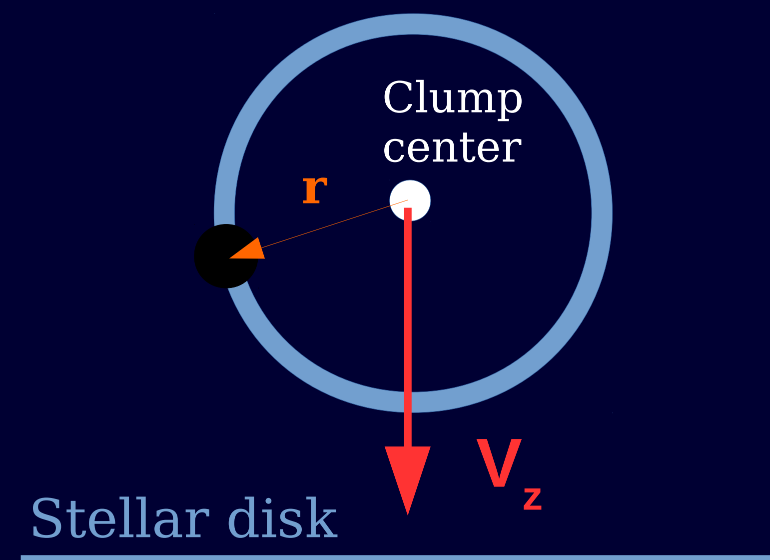
Subhalos are stripped by
the potential of the Galaxy



[Binney & Tremaine 87]

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

Disk shocking



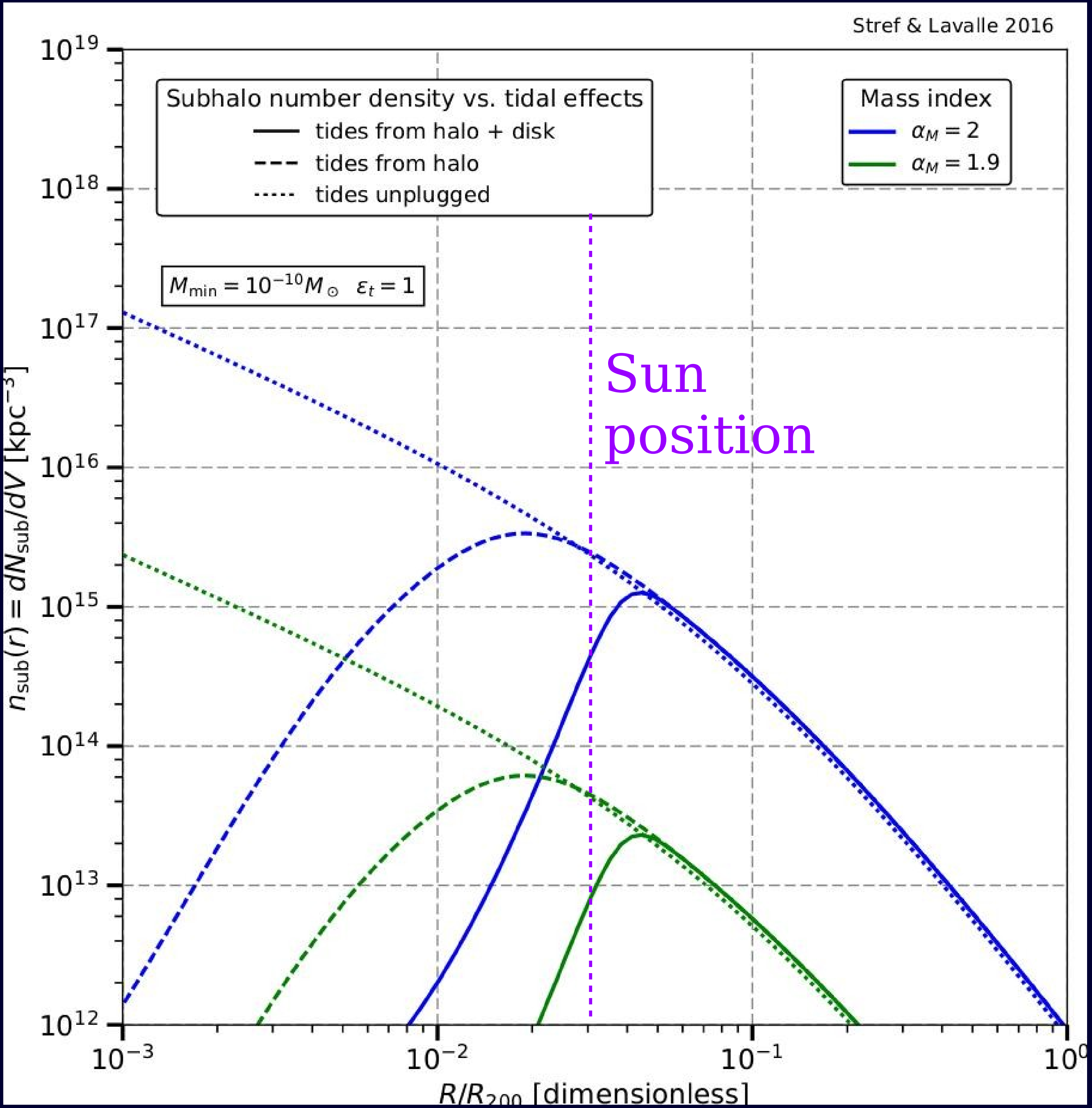
DM particles get a net velocity kick
[Ostriker+ 72]

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

[Stref & Lavalle 17]

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

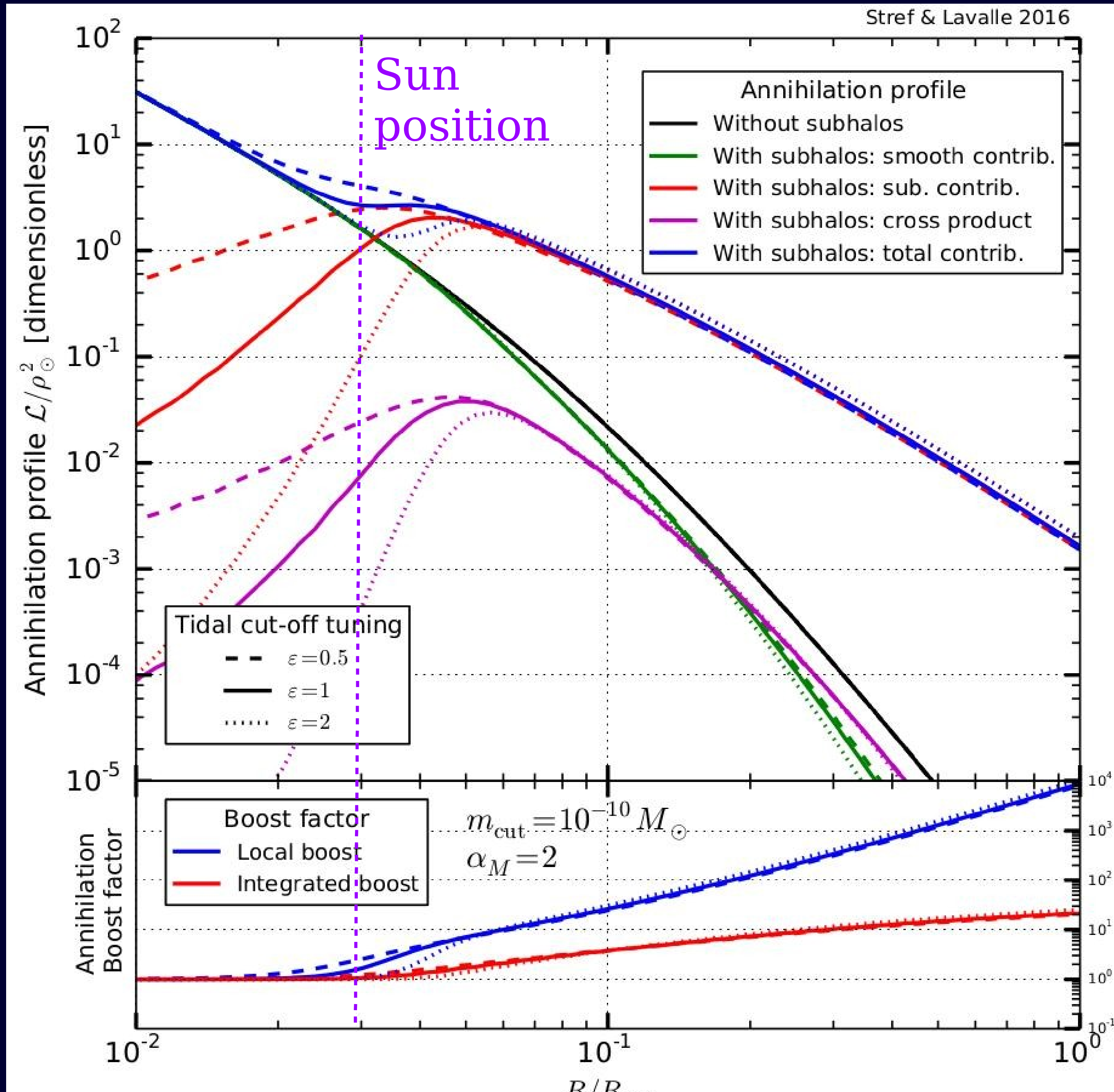
Number density



Luminosity and boost factors

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

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



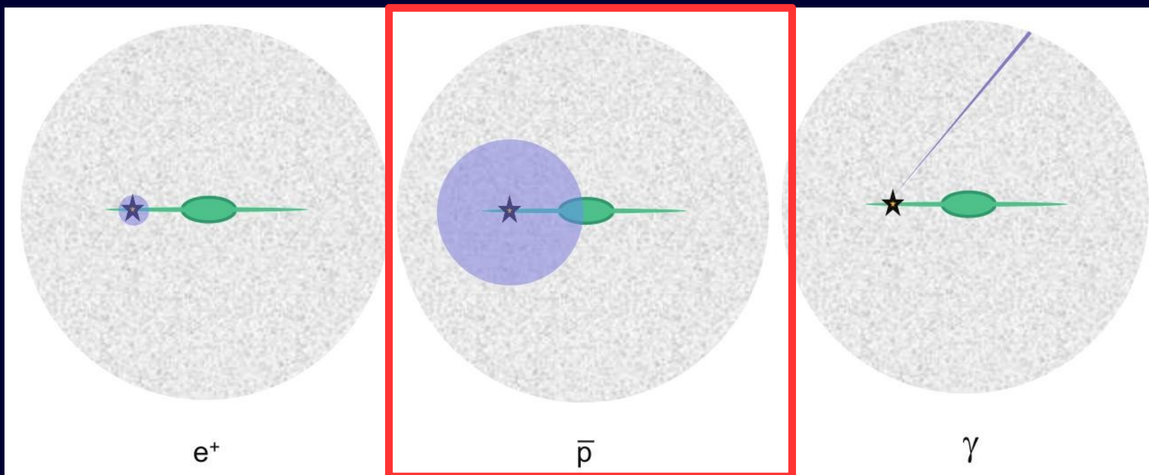
Indirect searches with cosmic-ray antiprotons

Based on

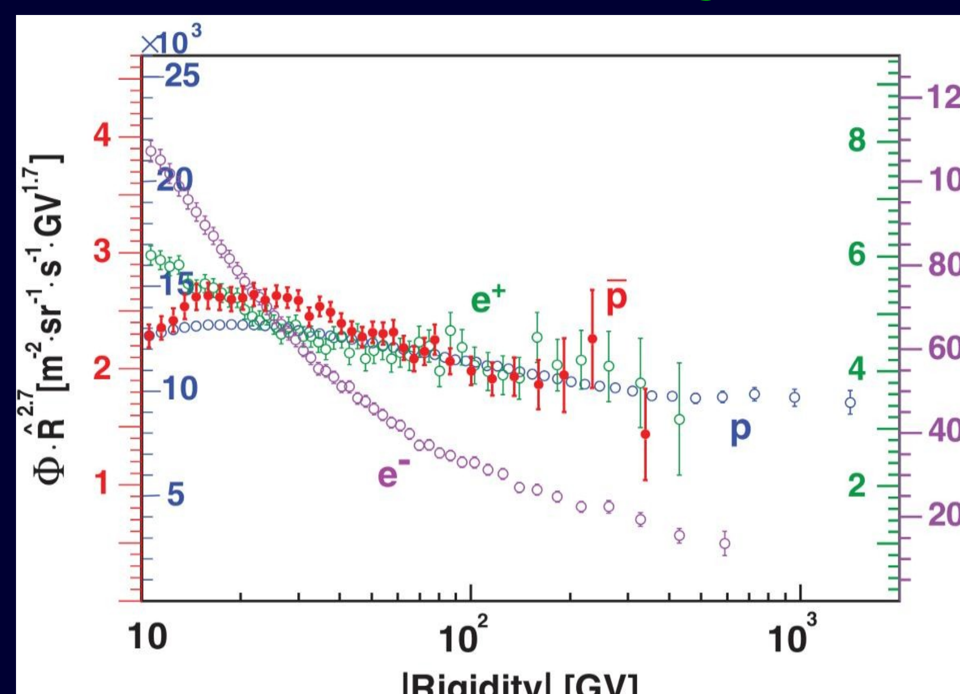
Stref, Lacroix & Lavalle : arXiv:17xx.xxxxx

Why antiprotons?

[Bergstrom 09]



AMS-02 data [Aguilar+ 16]



Indirect searches :

with gamma rays
[Bergstrom+ 99],

with antimatter cosmic rays
[Lavalle+ 07,08]

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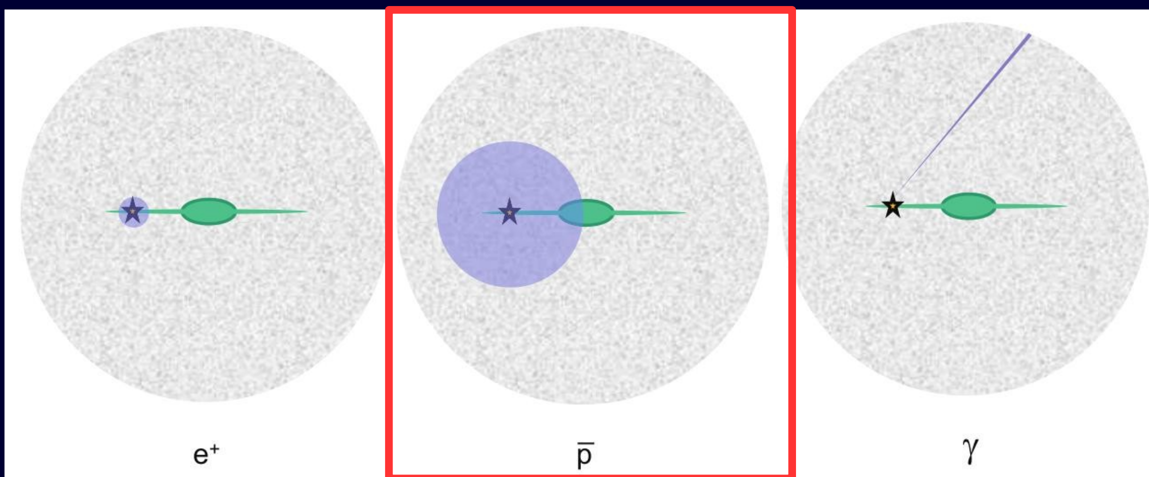
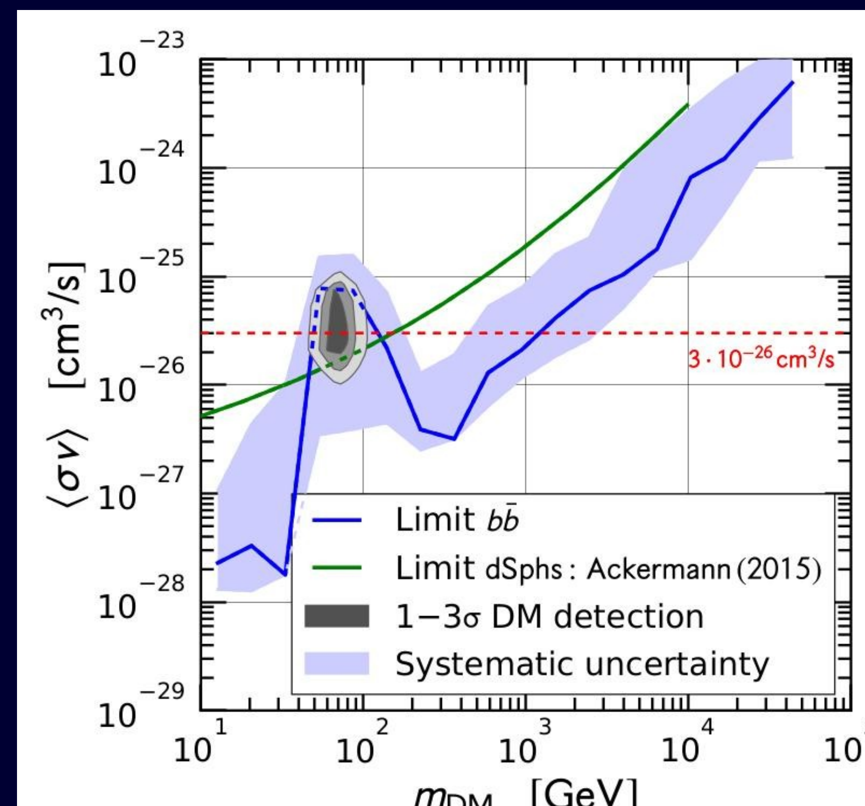


AMS-02 “hot spot”

[Cuoco+ 16, see also Cui+ 16]



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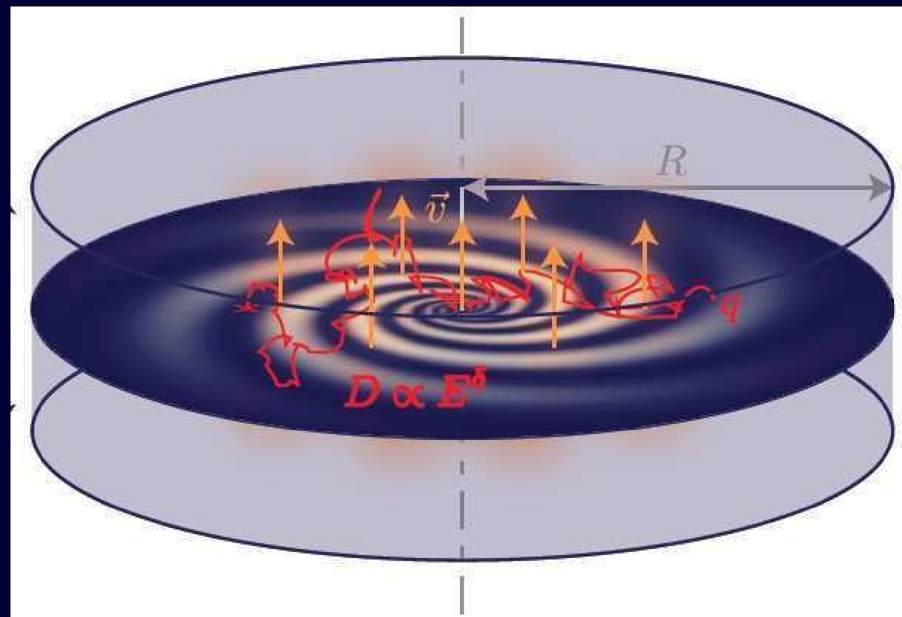
Cosmic-ray propagation



[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

$$-K\,\Delta\psi + \partial_{\mathrm{z}}(V_{\mathrm{C}}\,\psi) + \partial_{\mathrm{E}}\{b_{\mathrm{loss}}(E)\psi - K_{\mathrm{EE}}(E)\partial_{\mathrm{E}}\psi\} + Q_{\mathrm{collision}} = Q_{\mathrm{DM}}$$

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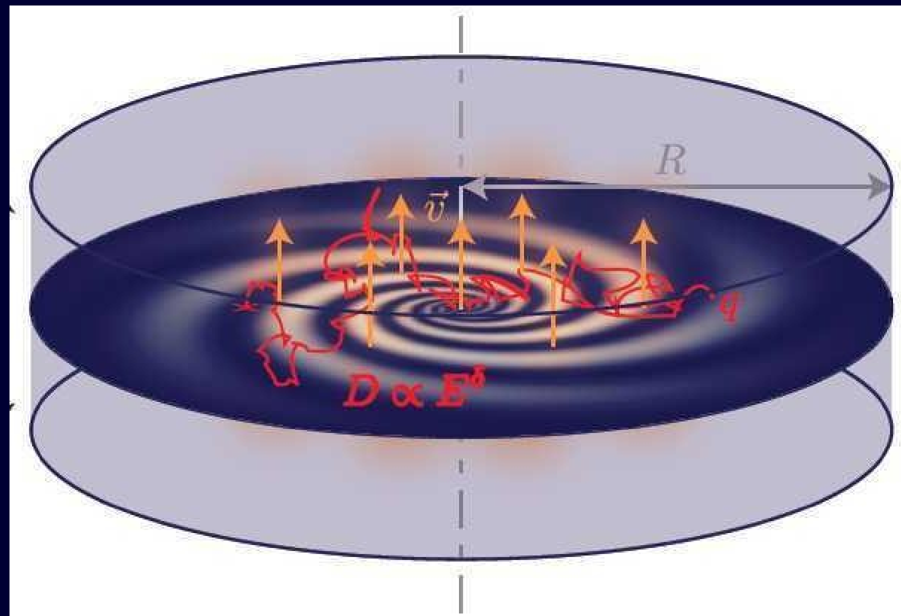

[Mertsch, 2010]

Critical for DM searches

L

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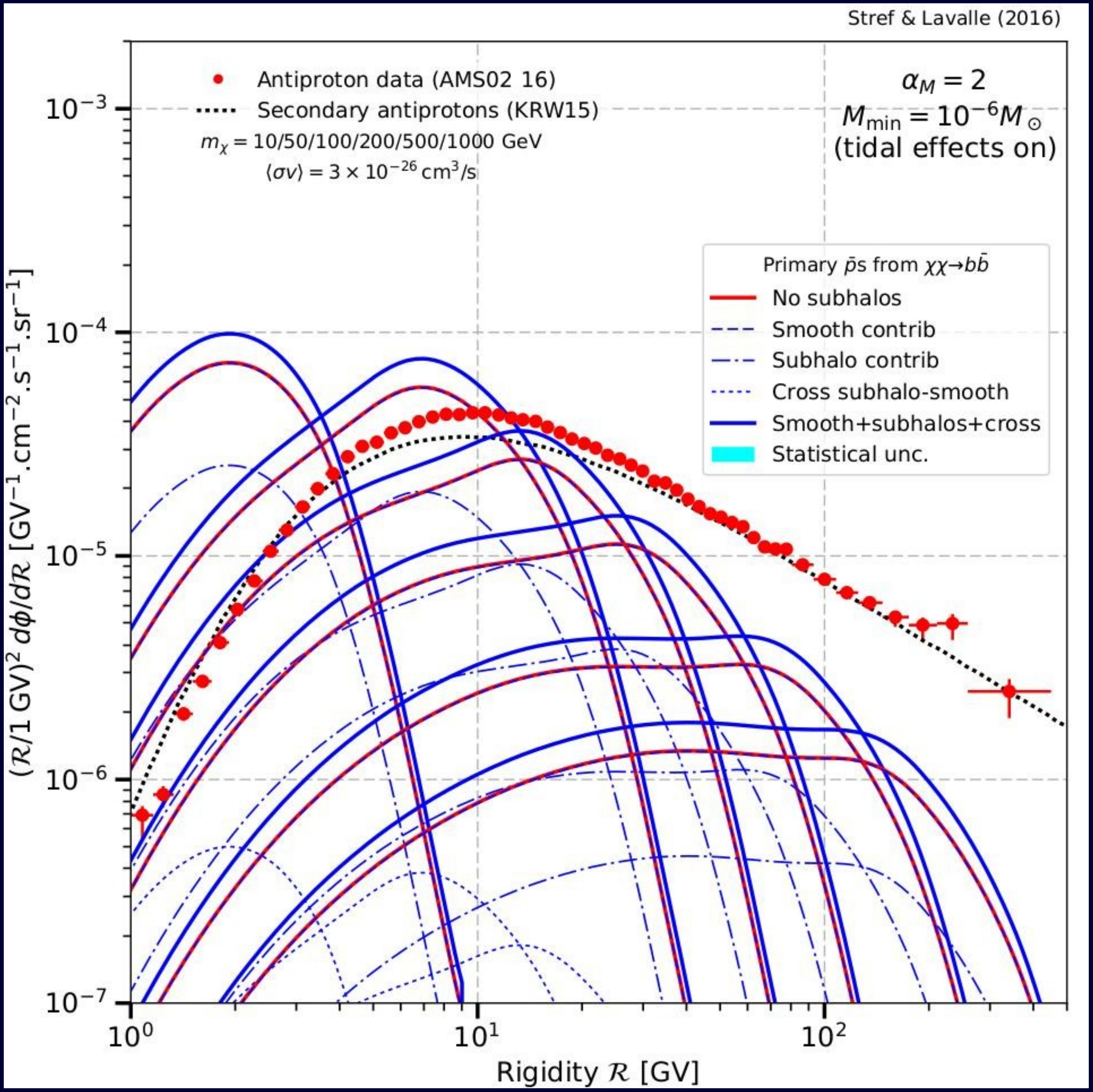
Antiproton flux

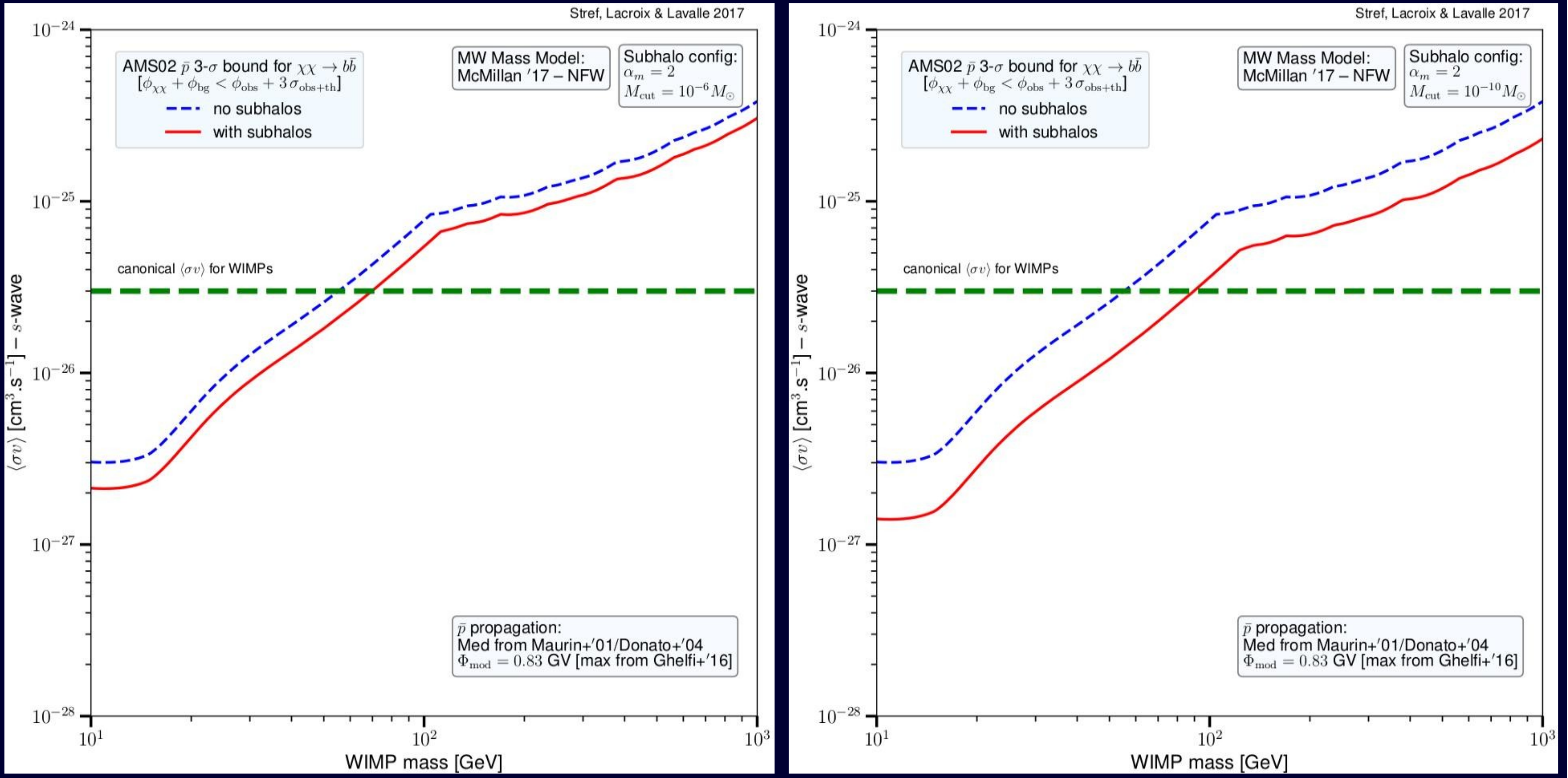
$$\frac{\mathrm{d}\phi}{\mathrm{d}\mathcal{R}} = \frac{\langle\sigma v\rangle}{2\,m_\chi^2}\frac{\mathrm{d}N}{\mathrm{d}\mathcal{R}}\int \mathrm{d}^3\vec{x}\,G_{\rm prop}(\vec{x},E)\;\left\langle\left(\rho_{\rm sm}(\vec{x})+\rho_{\rm sub}(\vec{x})\right)^2\right\rangle$$



Spectra from PPPC4DM ID [Cirelli+ 11]

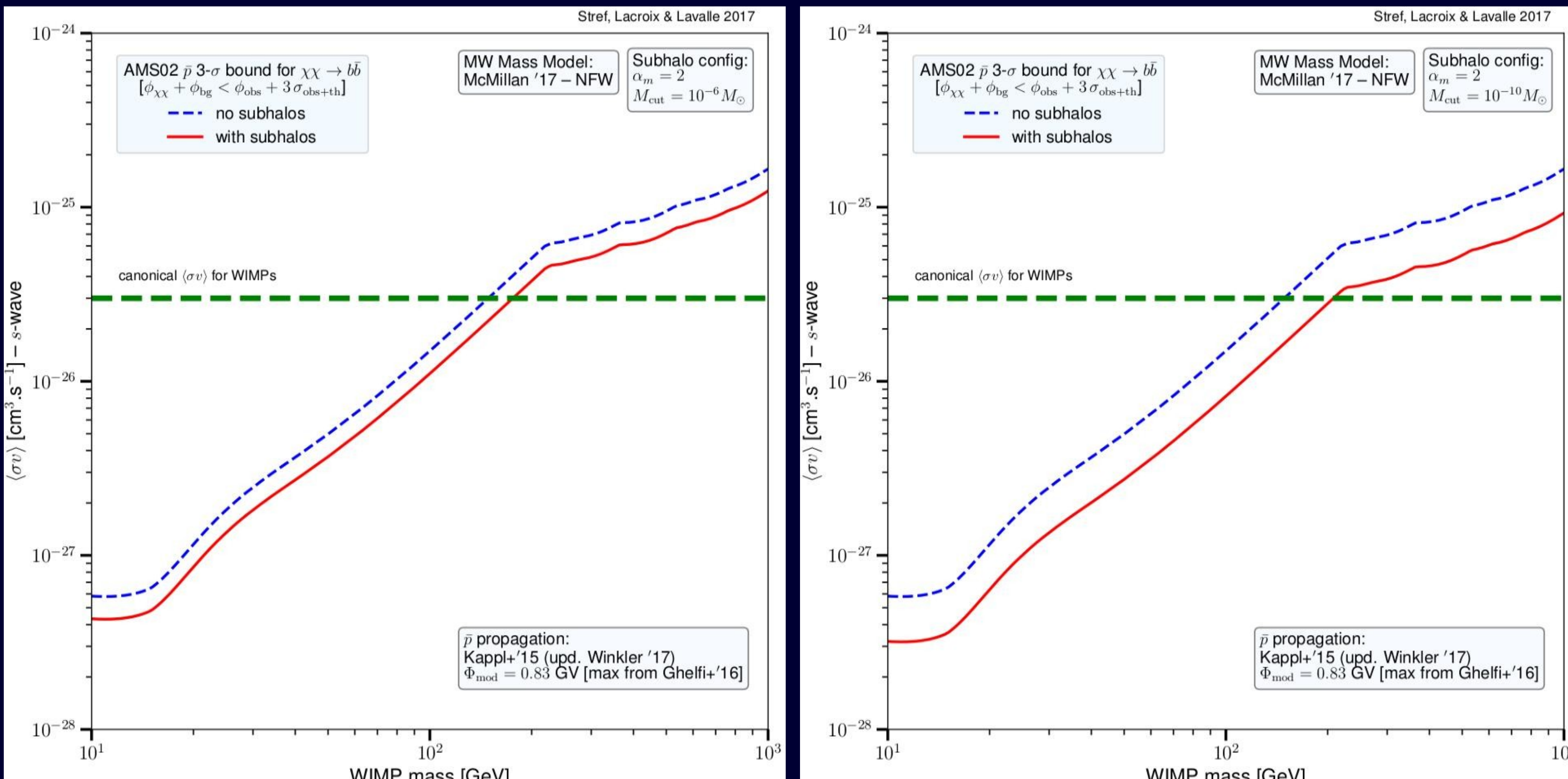
Exclusion curves : MED model

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



Exclusion curves : model of Kappl et al.

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



Summary

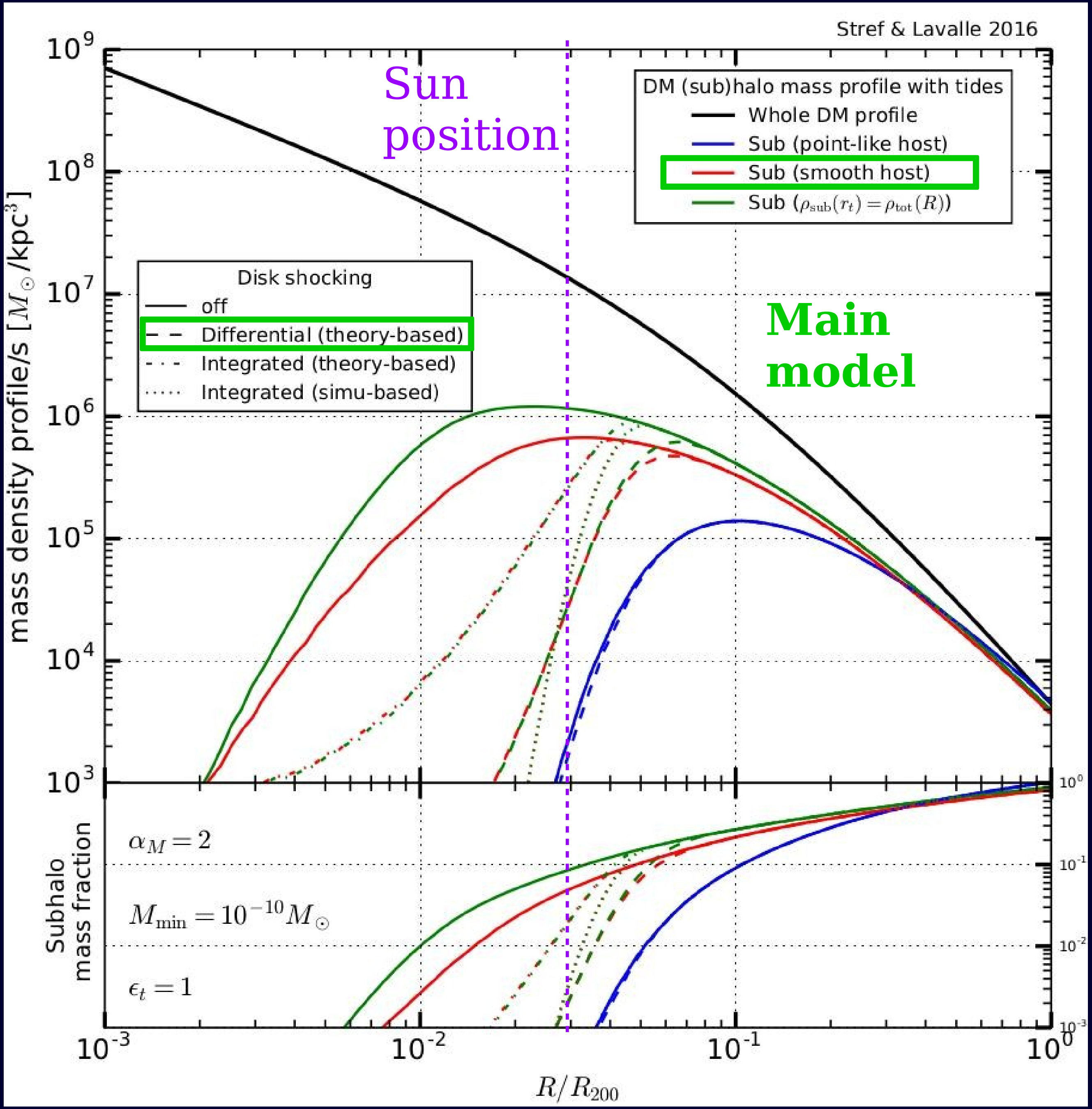
- DM distribution is fondamental to make predictions on direct/indirect searches : dynamical constraints must be accounted for.
- Cold dark matter, and WIMPs in particular, forms very small-scale subhalos.
- The subhalo population can be modeled in a dynamically consistent way, including tidal disruption effects.
- Subhalos strongly impact indirect searches, e.g. with cosmic-rays antiprotons, and should be accounted for (at least as a theoretical uncertainty).

Backup

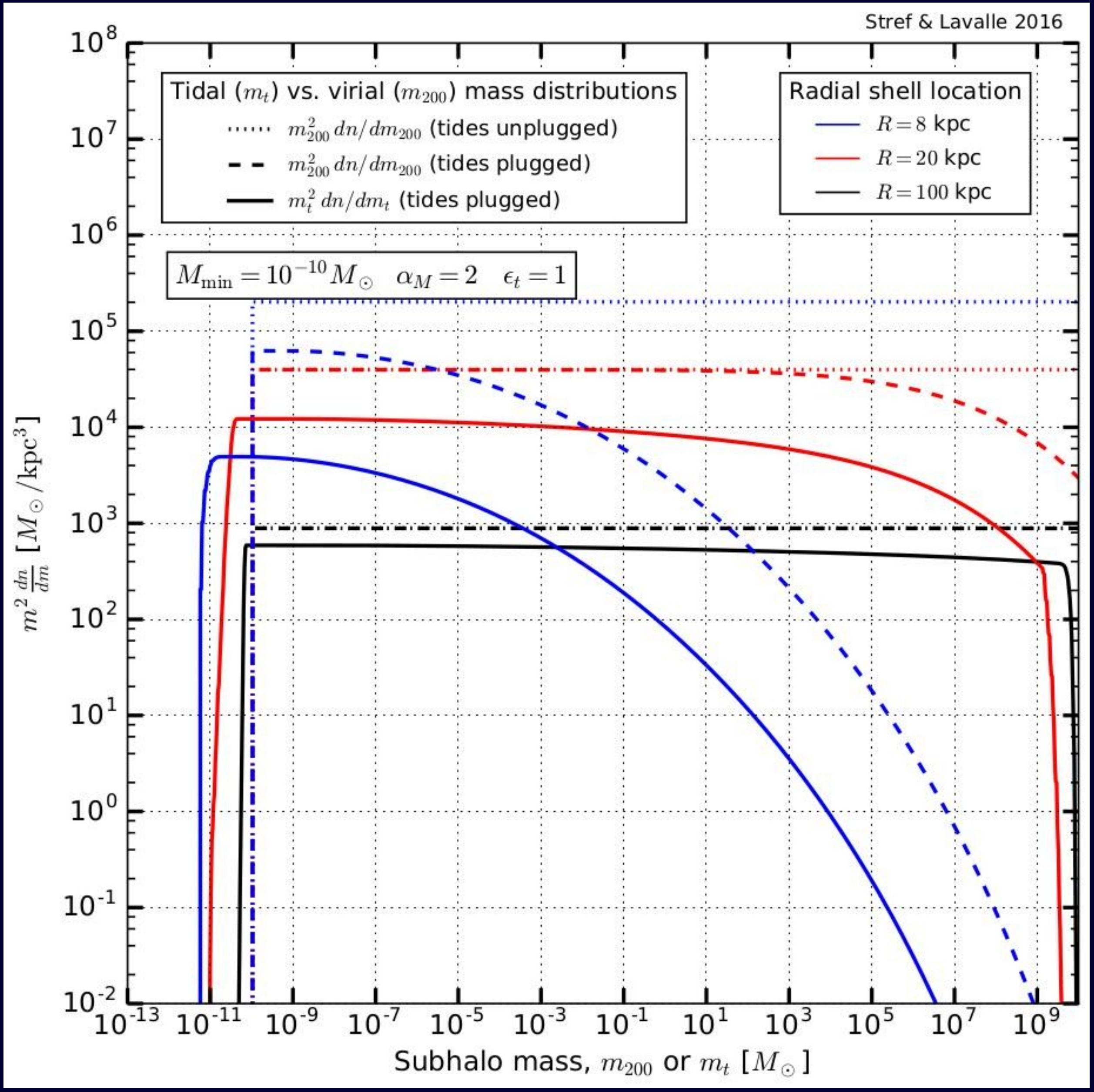
Predicted mass density profiles

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

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



Posterior mass function



Cored DM profile