Improved constraints on annihilating dark matter from cosmic-ray antiprotons

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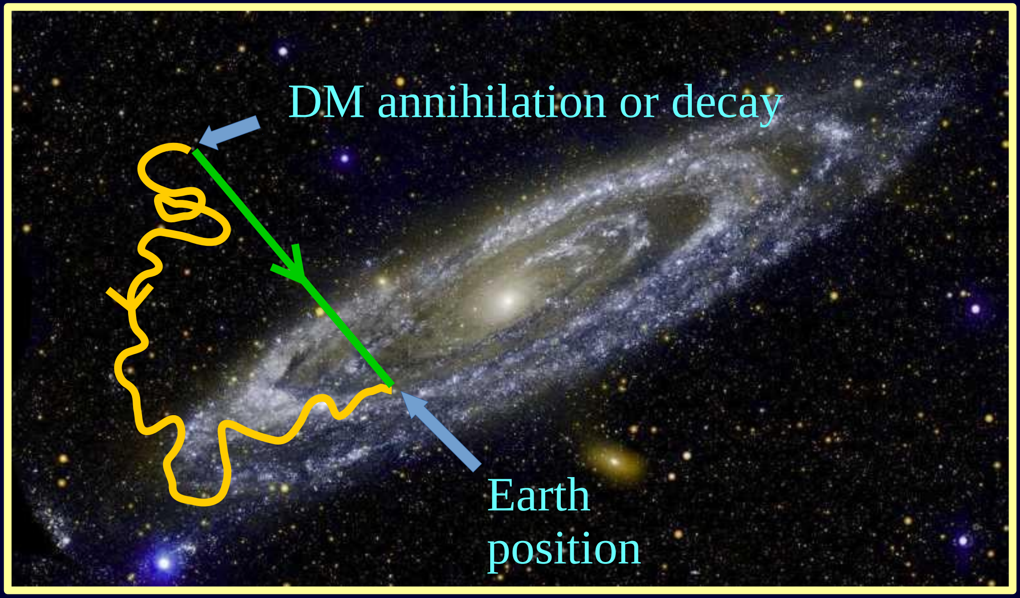
Importance of the dark halo modeling

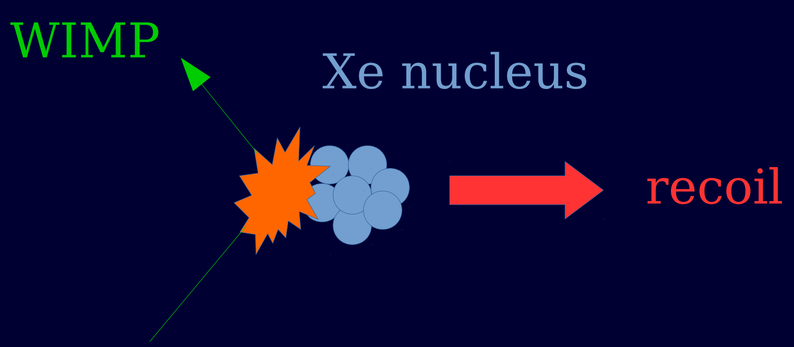
Indirect detection:



DM detection via
photons, neutrinos or
charged cosmic rays

→ Dependent on the DM density profile

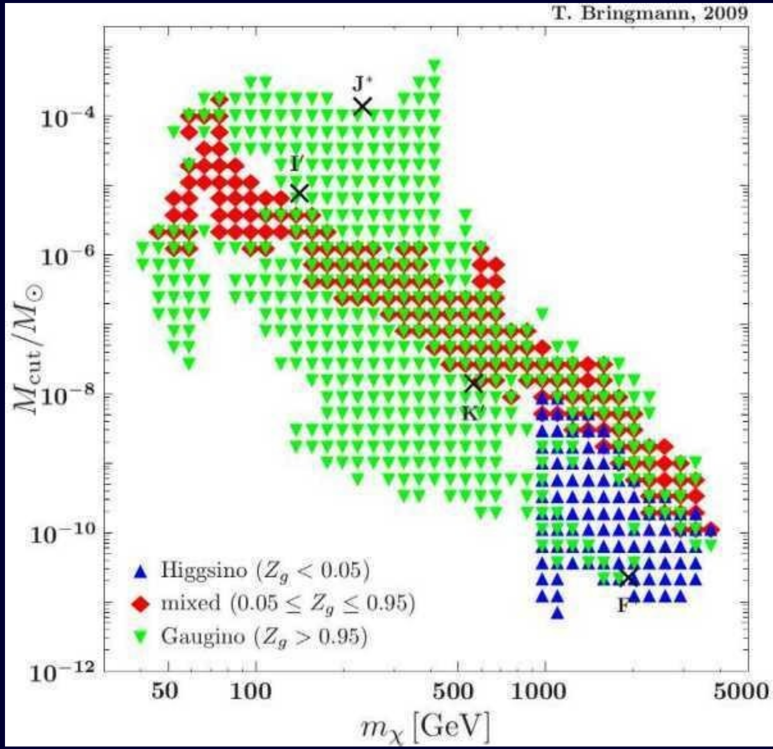
Direct detection:



→ Dependent on the local DM density

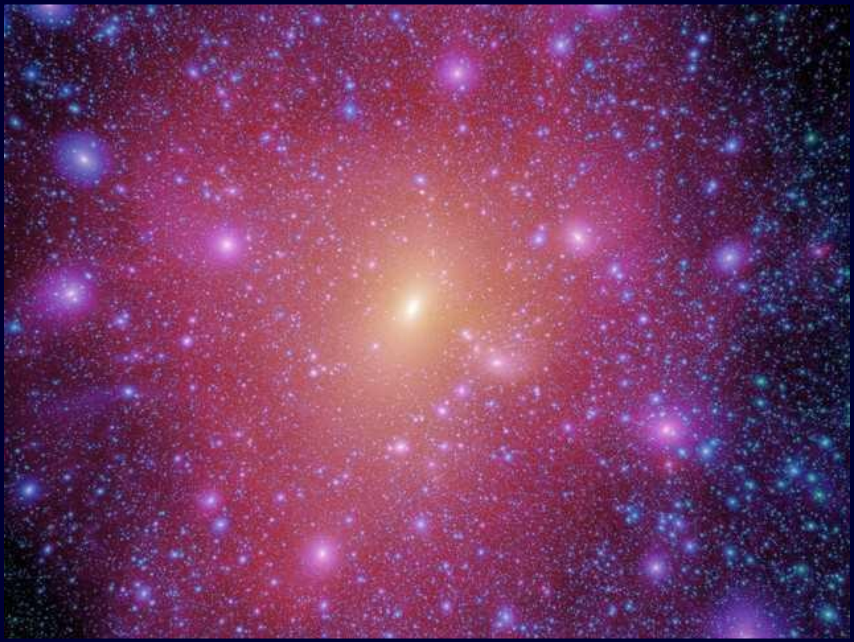
Importance of subhalos

Small-scale structuring of CDM



[Bringmann, 2009]

Many subhalos survive up to now:



Aquarius simulation
[Springel et al, 2008]

Important for indirect detection of annihilating DM

$$\langle \rho^2 \rangle \geq \langle \rho \rangle^2$$

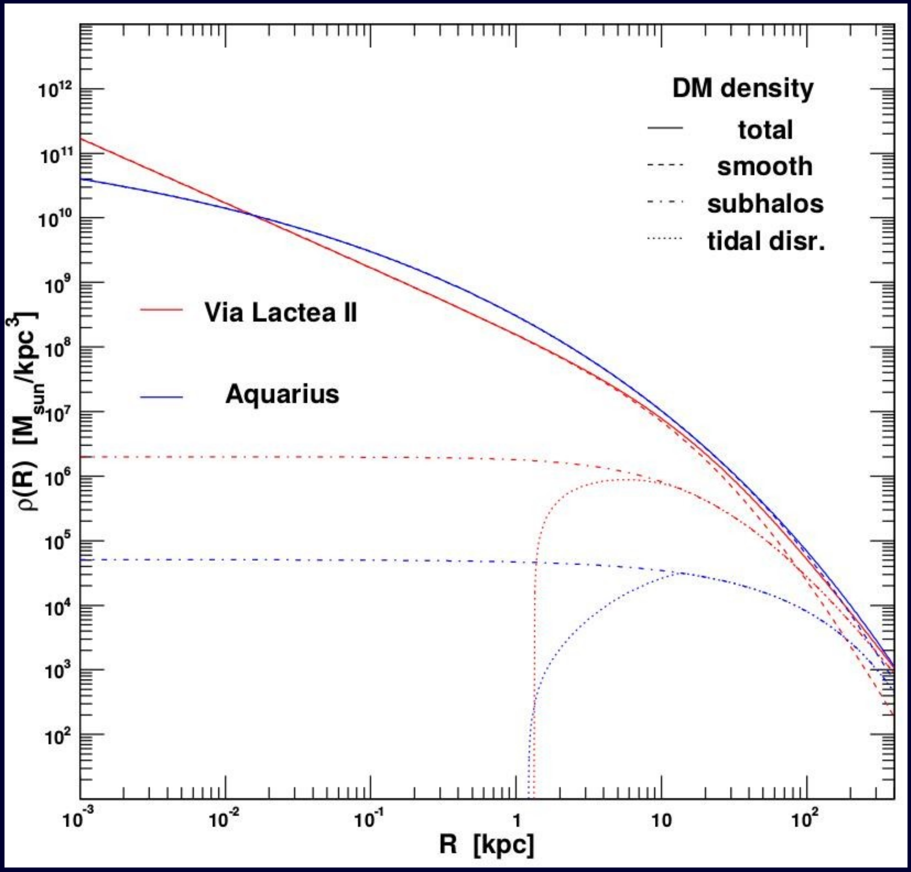
A semi-analytic model of galactic subhalos

based on
MS and J.Lavalle, arXiv:1610.02233

Requirements

- Respect available dynamical constraints
- Calibrate on cosmological simulations (subhalos mass fraction)
- Tidal effects from the DM halo
- Tidal effects from baryons (halo+disc)

[Pieri et al, 2011]



Accommodating with dynamical constraints

Start from a Milky Way mass model:

$$\rho(\vec{x}) = \rho_{\rm DM}(\vec{x}) + \rho_{\rm bulge}(\vec{x}) + \rho_{\rm disc}(\vec{x}) + \ldots$$

e.g. NFW [McMillan ‘11, ‘16],
Einasto [Catena and Ullio ‘10], ...

→ Take the DM density as an input

Dark halo is part smooth, part clumpy:

$$\rho_{\rm DM}(\vec{x}) = \rho_{\rm sm}(\vec{x}) + \langle \rho_{\rm sub}(\vec{x}) \rangle$$

Description of subhalos

- Universal form for the subhalos profile is assumed (NFW, Einasto, …)
- Subhalo fully characterized by 3 quantities: position, mass and concentration
- Statistical description: we want the PDF

$$f(R, m, c)$$

PDF computation

Ansatz:

$$f(R, m, c) = \frac{1}{K} f_{\mathrm{v}}(R)\, f_{\mathrm{m}}(m)\, f_{\mathrm{c}}(c, m)$$

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PDF computation

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$$f_{\rm m}(m) \propto m^{-\alpha_{\rm M}}$$

Power: $\alpha_{\rm M} \sim 2$

Cutoff: $M_{\rm min}$

PDF computation

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Median concentration: $\overline{c} = \overline{c}(m)$

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BUT… what about tidal effects?

Tidal effects: tides from host halo (1)

DM particles inside a clump experience two potentials:
• subhalo's potential
• host's potential (DM+baryons)

Competition between the two results in a tidal stripping of subhalos

→ the mass/radius today is smaller than the mass/radius at infall

→ stripping stronger near the galactic center

Tidal effects: tides from host halo (2)

Grav. potentials competition results in a tidal radius

- Point-like host:

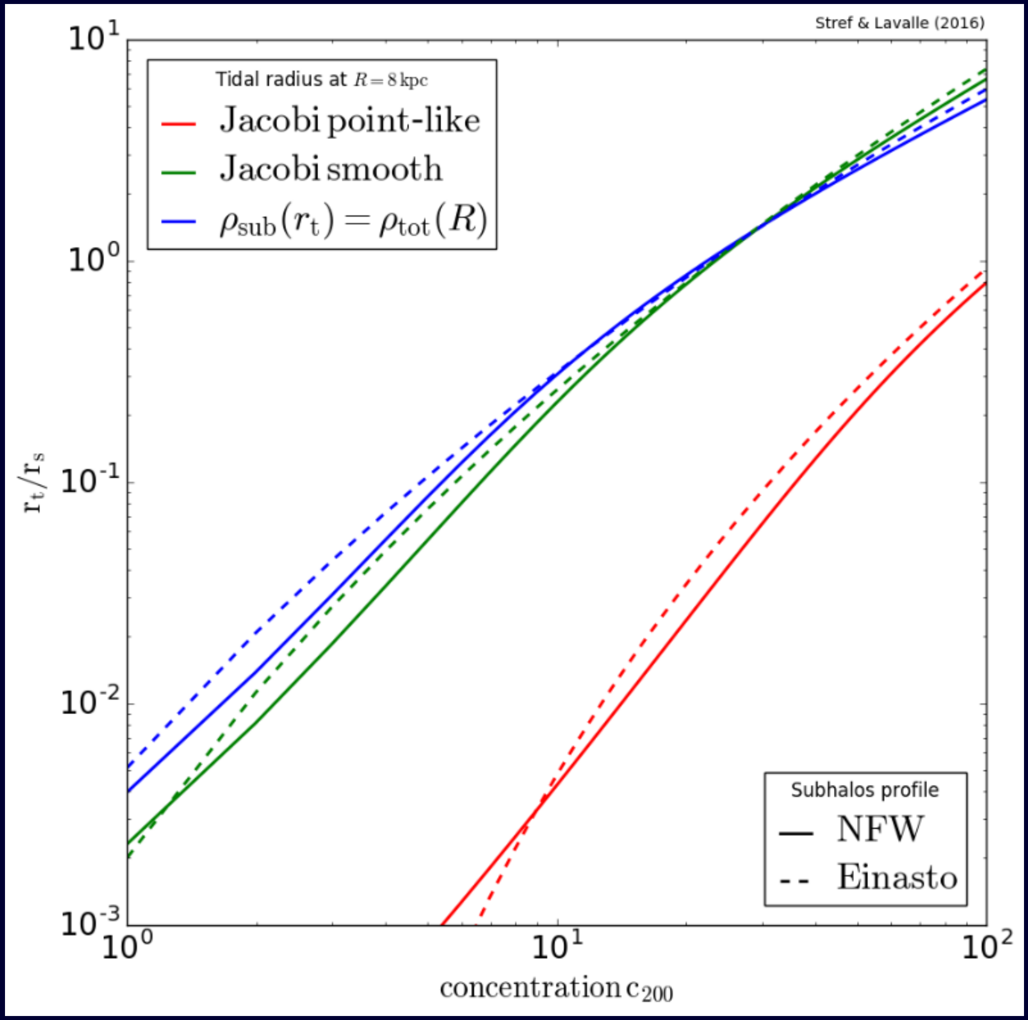
$$r_t = \left(\frac{m(r_t)}{3M}\right)^{1/3} R$$

- Extended host:

$$r_t = \left[\frac{m(r_t)}{3M(R)\left(1-\frac{1}{3}\frac{d\ln M}{d\ln R}\right)}\right]^{1/3} R$$

- Density criterion:

$$\rho_{\rm sub}(r_t) = \rho_{\rm DM}(R)$$



Tidal effects: tides from the disc (1)

Disc shocking: as subhalos cross the Galactic disc, they experience a rapidly changing potential

Increase kinetic energy per DM particle

→ some particles escape the subhalo

Effect computed for globular clusters [Ostriker et al. 72, Gnedin et al. 96]

Kinetic energy increase per particle mass:

$$\langle \delta\epsilon \rangle \, (r) = \frac{2\, g^2_{\mathrm{z,disk}}(z=0)\, r^2}{3\, V_{\mathrm{z}}^2(R)}\, A(\eta)$$

Tidal effects: tides from the disc (2)

- Tidal radius definition

$$\delta\epsilon(r_{\rm t}) = |\phi(r_{\rm t}) - \phi(r_{200})|$$

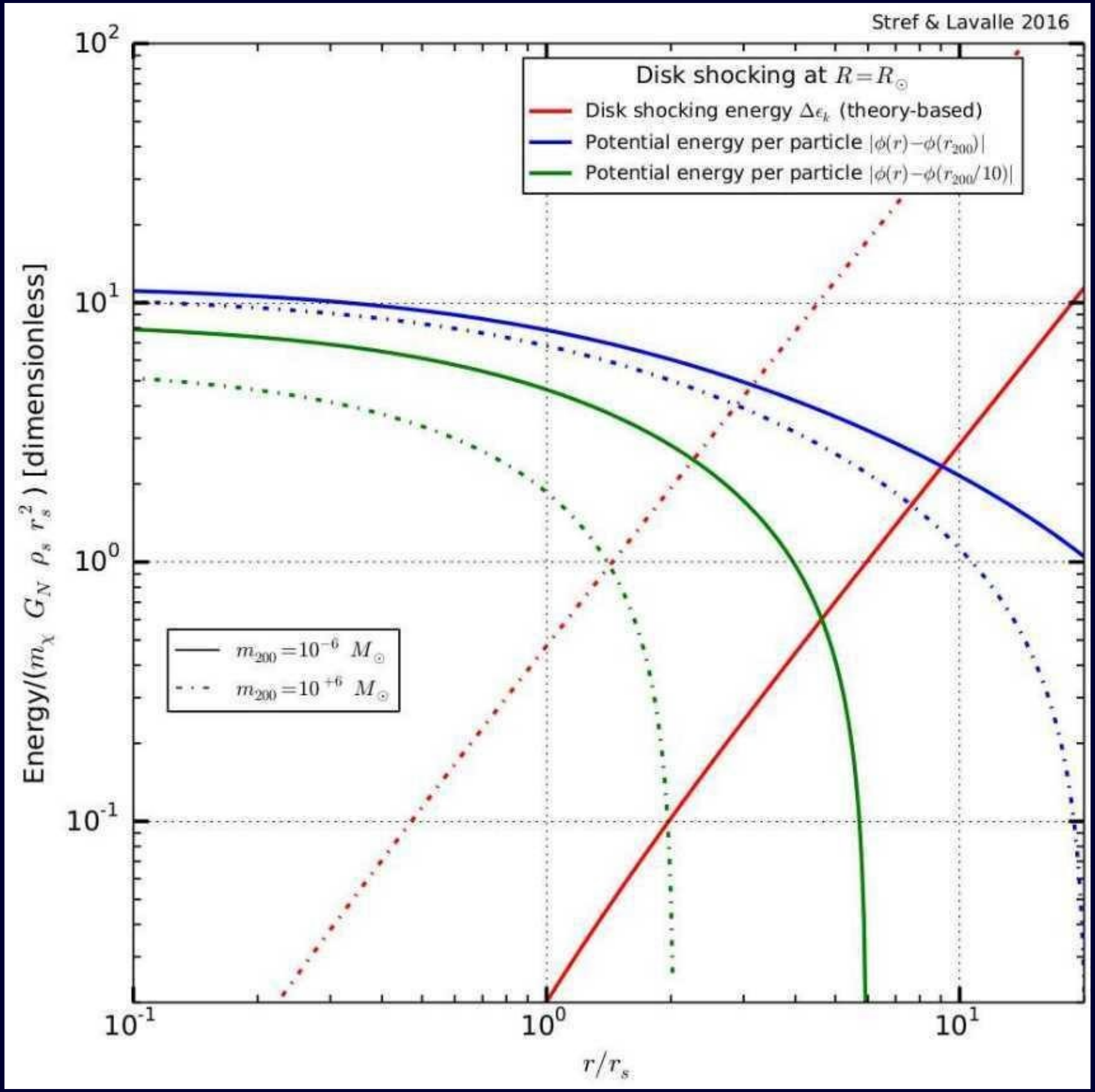
- Total energy increase

$$\Delta E = \int_{\rm V_{sub}} d^3\vec{x}\,\rho_{\rm sub}(\vec{x})\,\delta\epsilon(\vec{x})$$

- “Integral” version

$$\Delta E(r_{\rm t}) = E_{\rm bind}(r_{\rm t})$$

- + criterion from simu
[D’Onghia et al., 2010]



Calibration and computation

Number of subhalos calibrated on cosmological simulation
<u>without baryons</u> *(Via Lactea II,* [Diemand et al., 08])
• avoid modeling uncertainties
• make the model predictive

$$f(R,m,c) = \frac{1}{K}\, f_{\rm v}(R)\, f_{\rm m}(m)\, f_{\rm c}(c,m)$$

Subhalos contribution to the density:

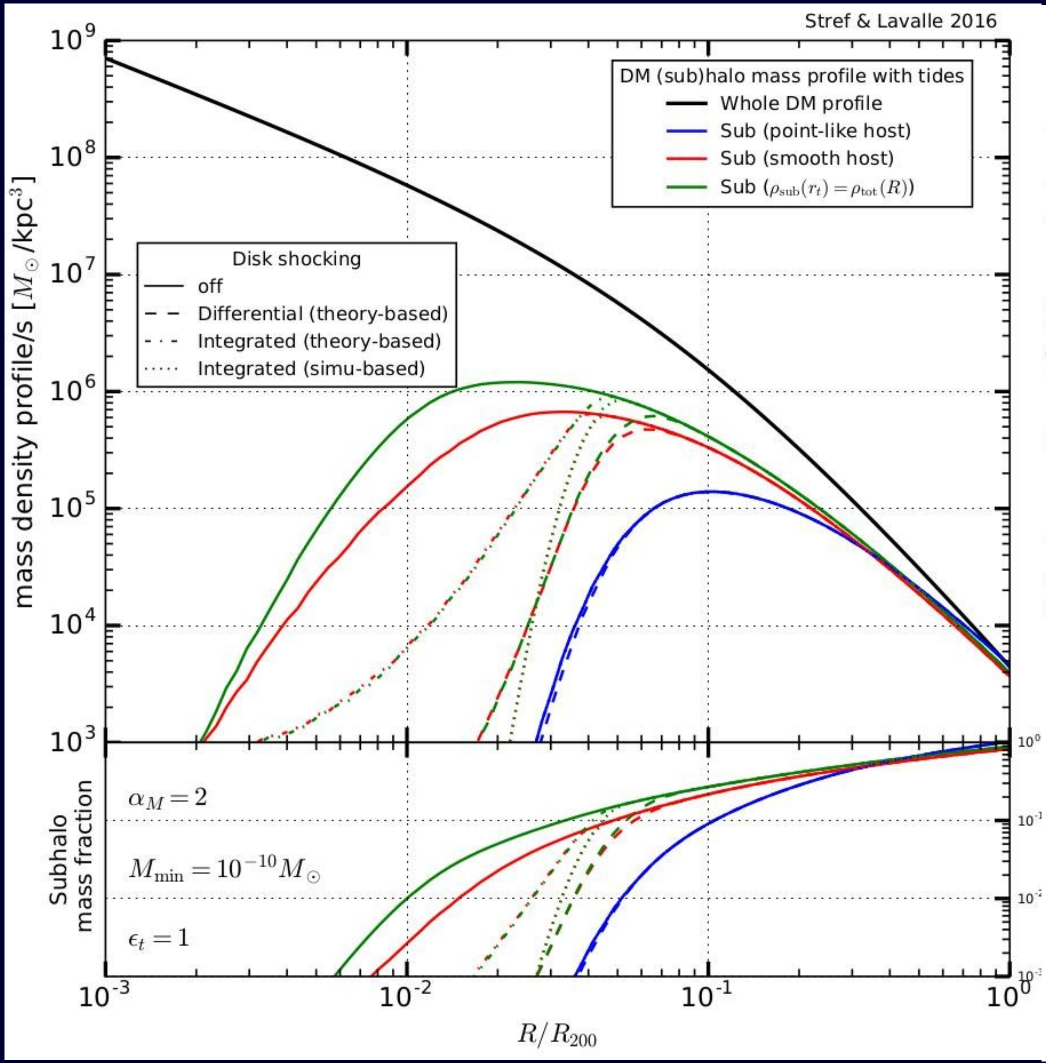
$$\langle \rho_{\rm sub}(R)\rangle = \frac{N_{\rm sub}}{K}\, f_{\rm v}(R) \int_{\rm M_{min}}^{\rm M_{max}} {\rm d}m\, f_{\rm m}(m) \int_{\rm c_{min}(R)}^{\infty} {\rm d}c\, f_{\rm c}(c,m)\, m_{\rm t}(R,m,c)$$

Smooth DM density:

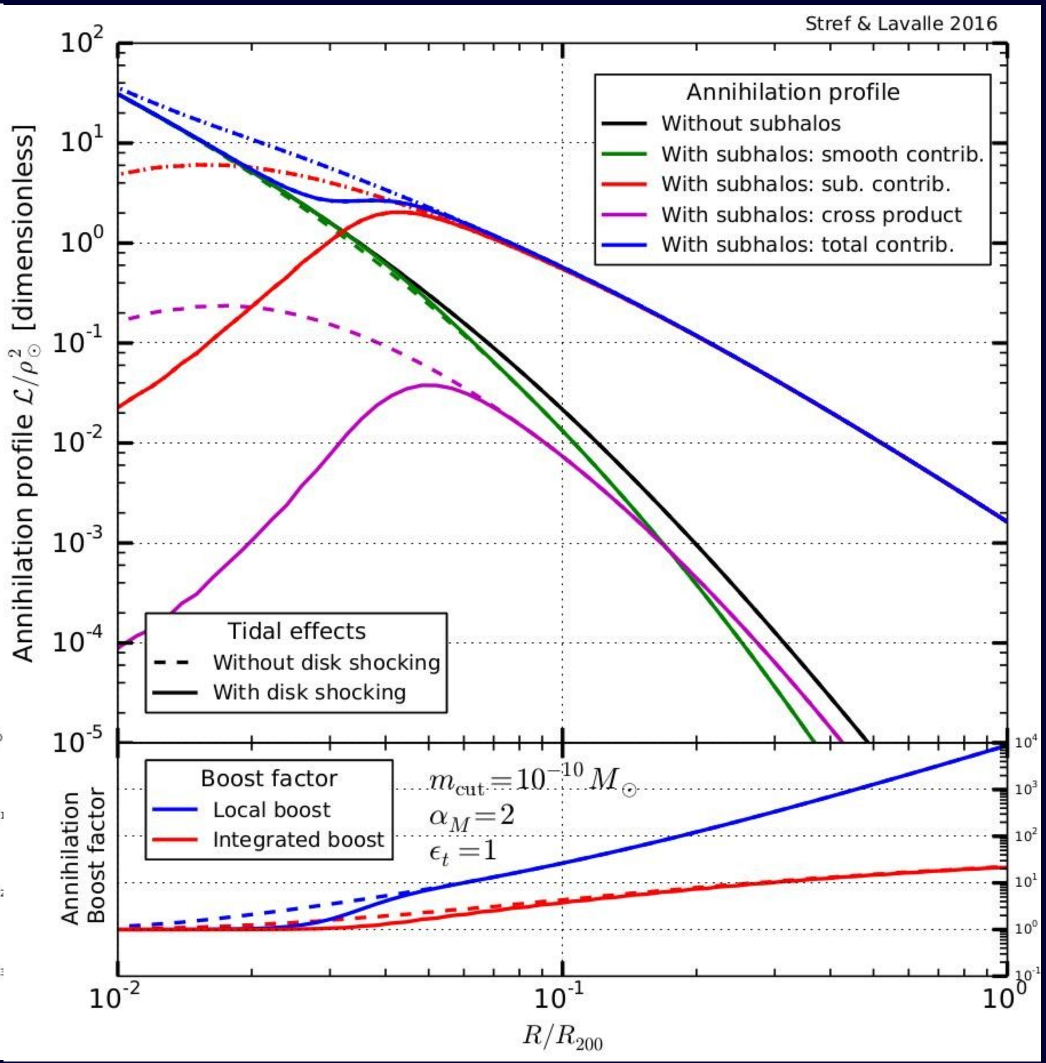
$$\rho_{\rm sm}(R) = \rho_{\rm DM}(R) - \langle \rho_{\rm sub}(R)\rangle$$

Density and luminosity profiles

Mass density:

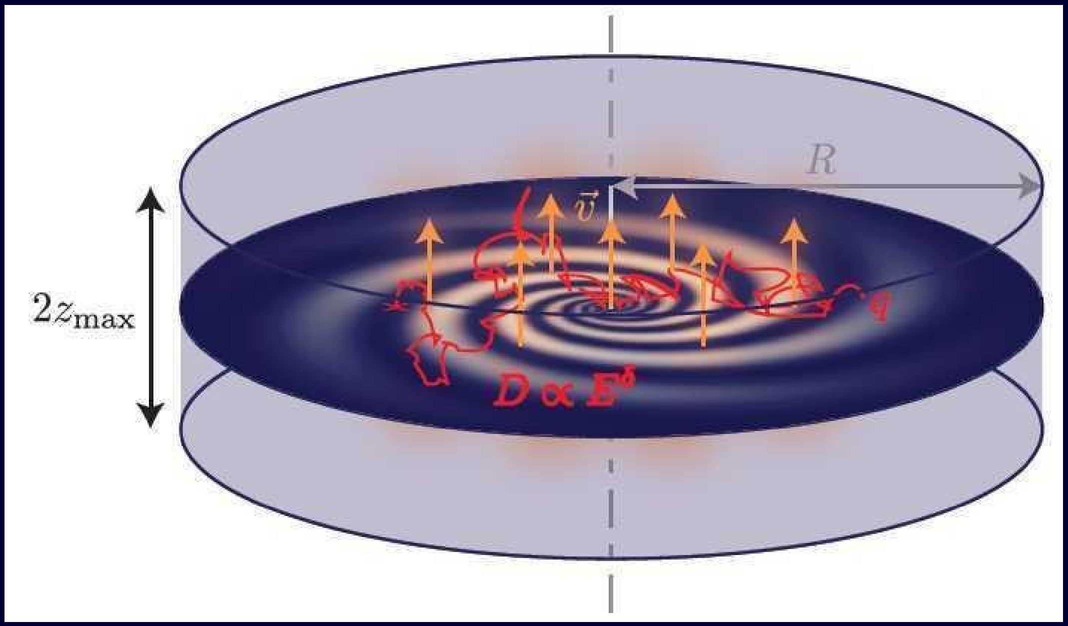


Luminosity profile:



Application to indirect searches with cosmic-ray antiprotons

Cosmic-ray propagation



[Mertsch, 2010]

- MED [Maurin et al., 2001]

  $z_{\mathrm{max}} = 4\,\mathrm{kpc}$

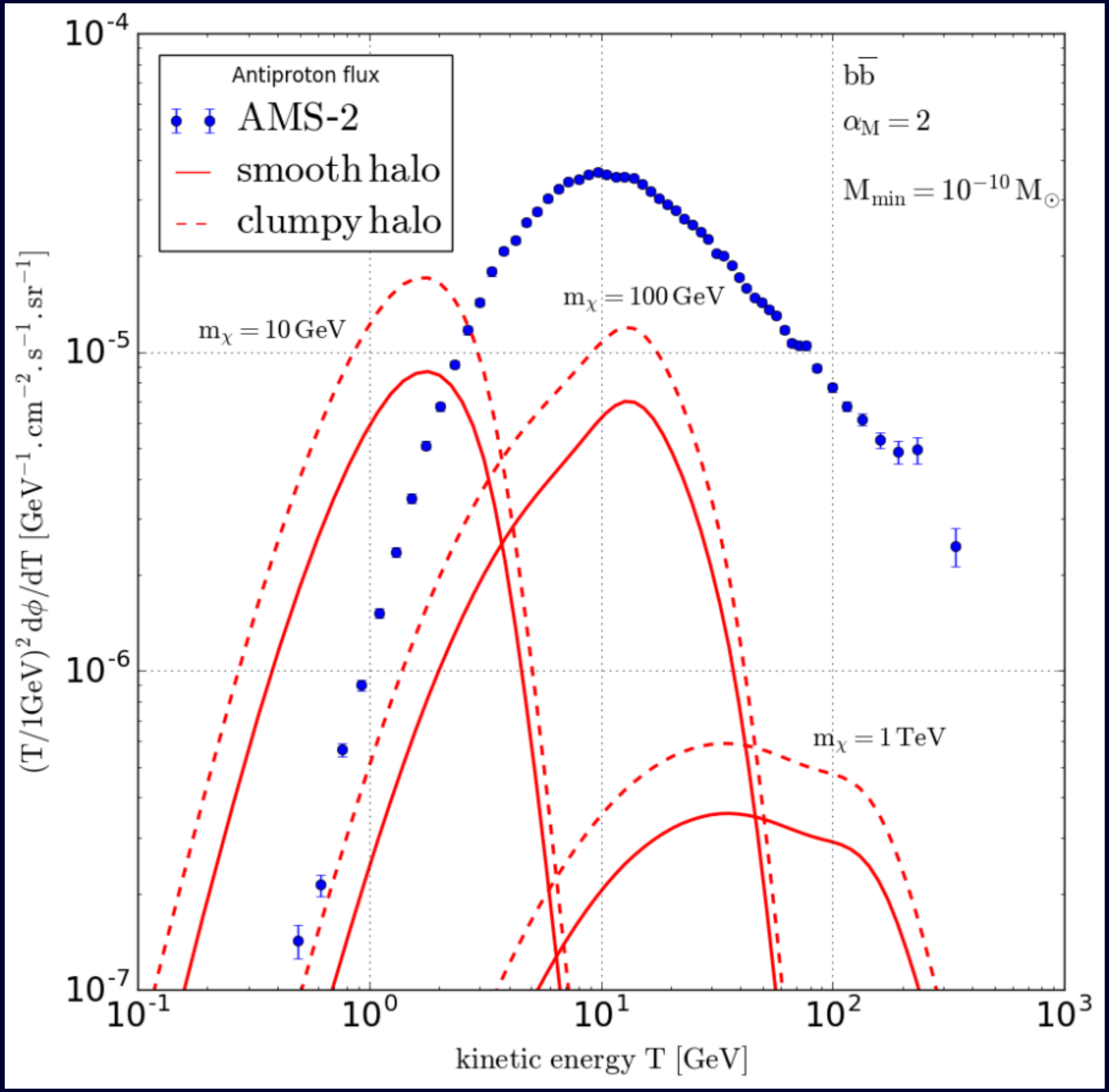
- Kappl et al., 2015

  $z_{\mathrm{max}} = 13.7\,\mathrm{kpc}$

$$
\begin{aligned}
\underbrace{\partial_t \mathcal{N}}_{\text{time evolution}} = & \underbrace{\mathcal{Q}(\vec{x}, E, t)}_{\text{source}} \\
& + \vec{\nabla} \underbrace{\left\{ \left(K_{xx}(E) \vec{\nabla} - \vec{V}_c \right) \mathcal{N} \right\}}_{\text{spatial current } \vec{\mathcal{J}}_{xx}} \\
& - \partial_p \underbrace{\left\{ \left(\dot{p} - \frac{p}{3} \vec{\nabla} \cdot \vec{V}_c - p^2 K_{pp}(E) \partial_p \frac{1}{p^2} \right) \mathcal{N} \right\}}_{\text{momentum current } \mathcal{J}_{pp}} \\
& - \underbrace{\frac{\tau_s + \tau_r}{\tau_s \, \tau_r} \mathcal{N}}_{\text{spallation, decay}}
\end{aligned}
$$

Antiprotons flux

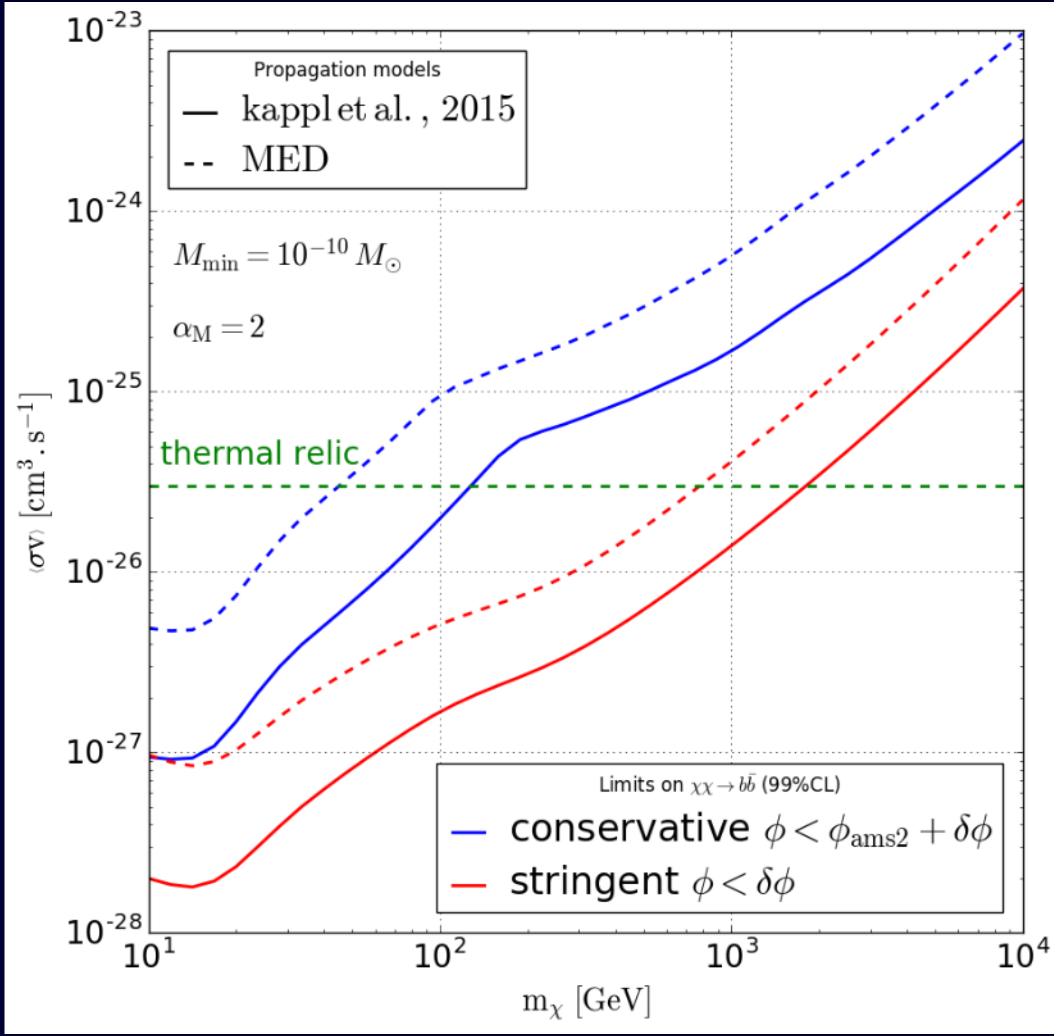
$$\phi(E) = \frac{\langle \sigma v \rangle}{2\, m_\chi^2} \frac{dN}{dE} \int d^3\vec{x}\, G_{\rm prop}(\vec{x}, E)\, \langle (\rho_{\rm sm}(\vec{x}) + \rho_{\rm sub}(\vec{x}))^2 \rangle$$



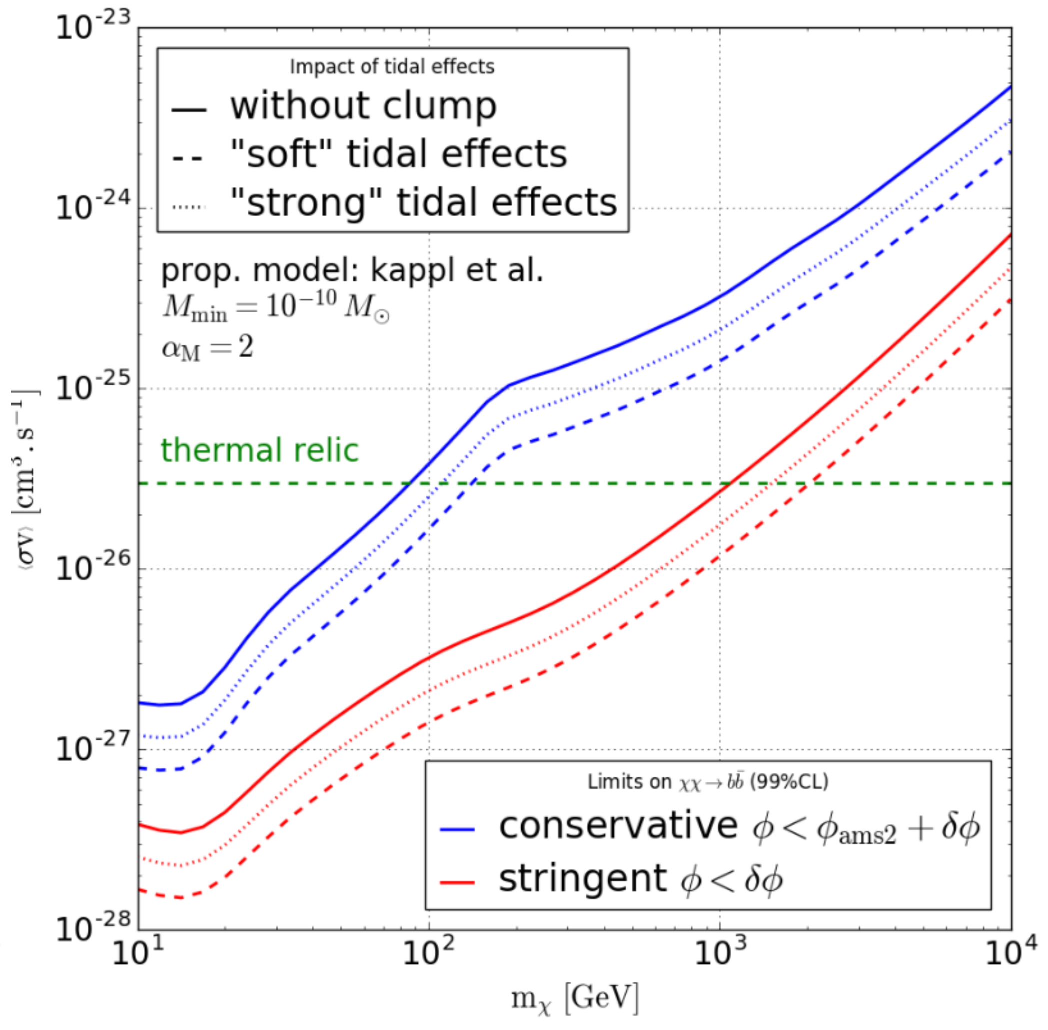
Constraints from AMS-2 data

(preliminary)

Propagation model:



Tidal effects:



Summary

- Consistent modeling of galactic subhalos, including tidal effects from halo and disc
- Reproduces results from cosmological simulations
- Easily adaptable to new dynamical constraints from Gaïa → DM density profile is an input
- Can be used for indirect searches (antiprotons, but also positrons, gamma rays, ...)

Thank you for your attention

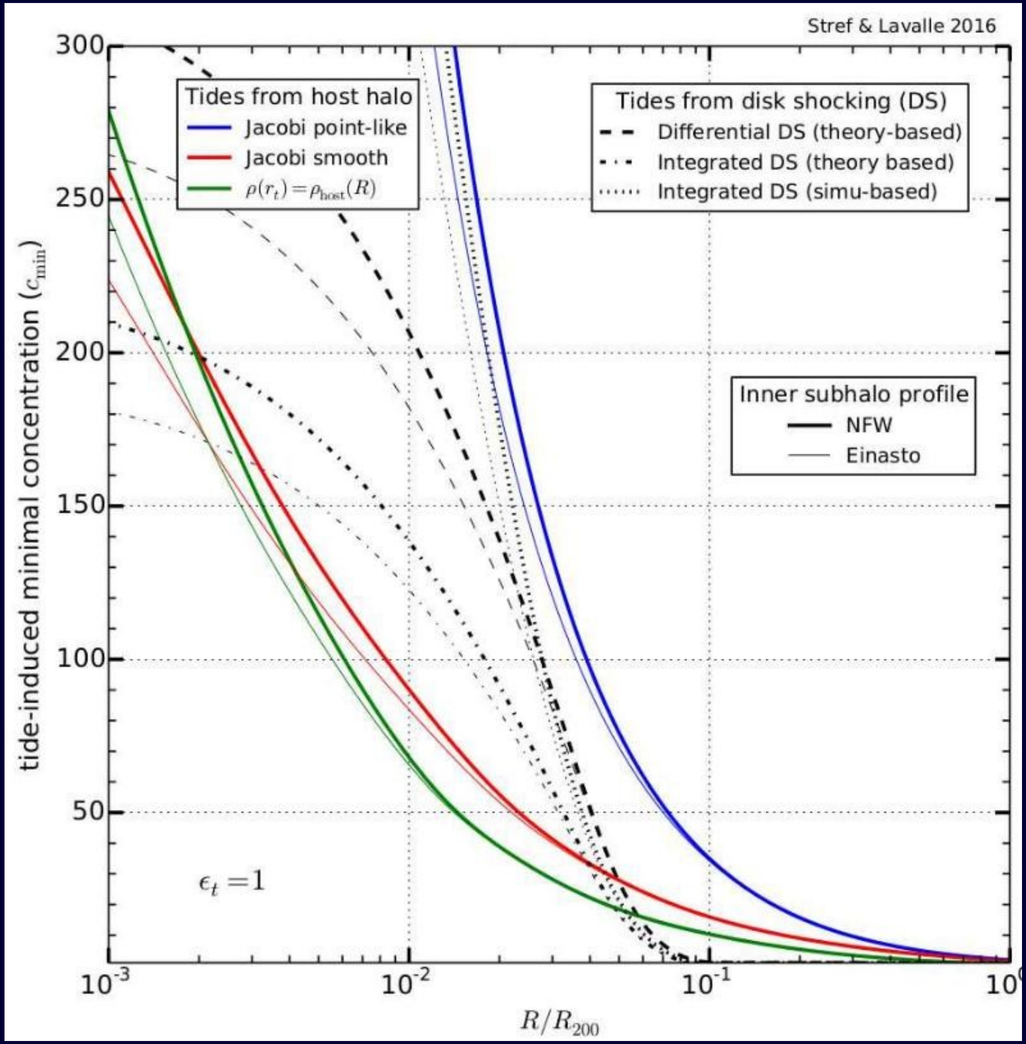
Minimal concentration

- Suhalo destroyed if $\frac{r_t}{r_s} \leq \epsilon_t$

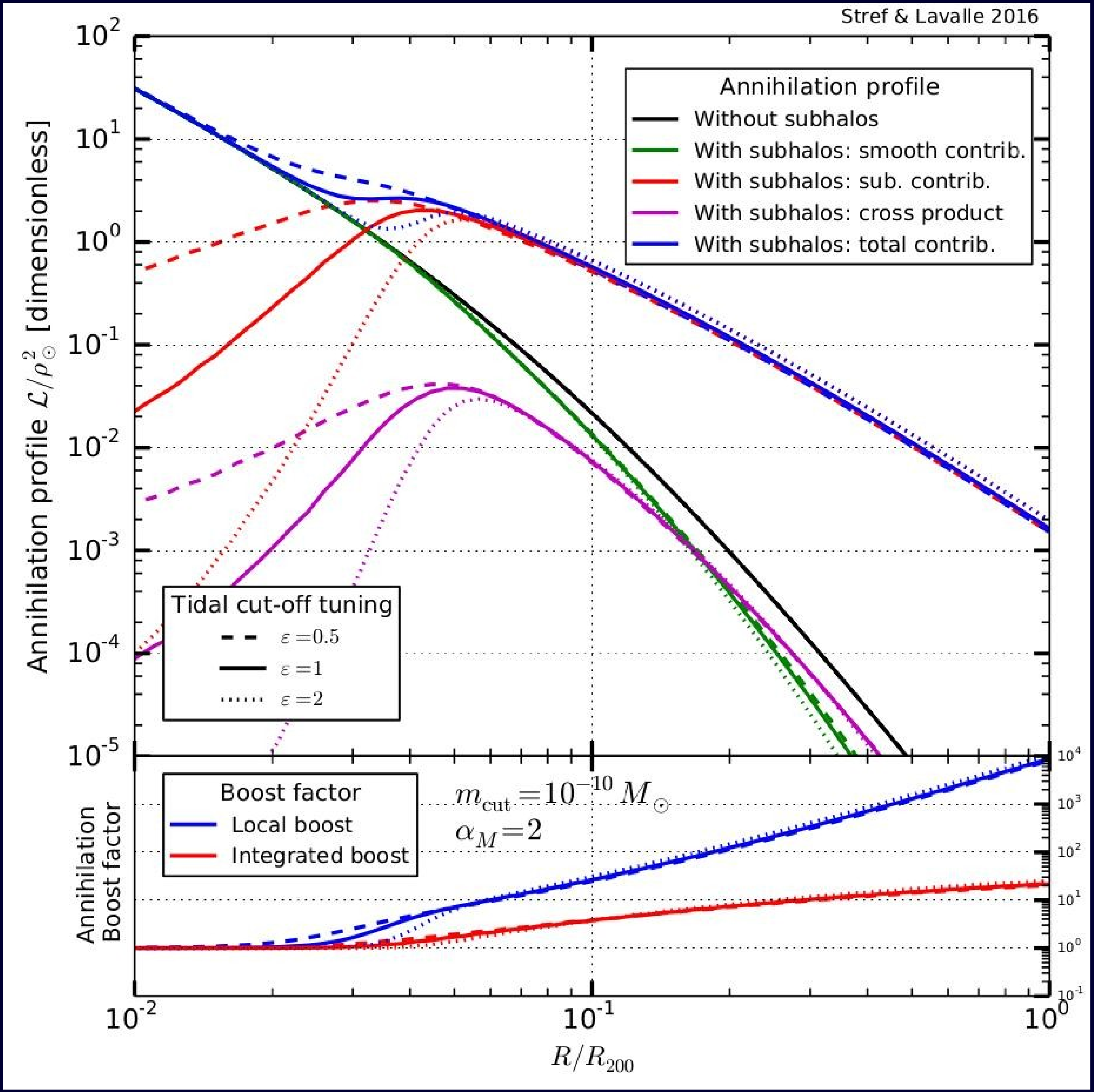
- Subhalo survives tidal effects if:

$$c_{200} \geq c_{min}(R)$$

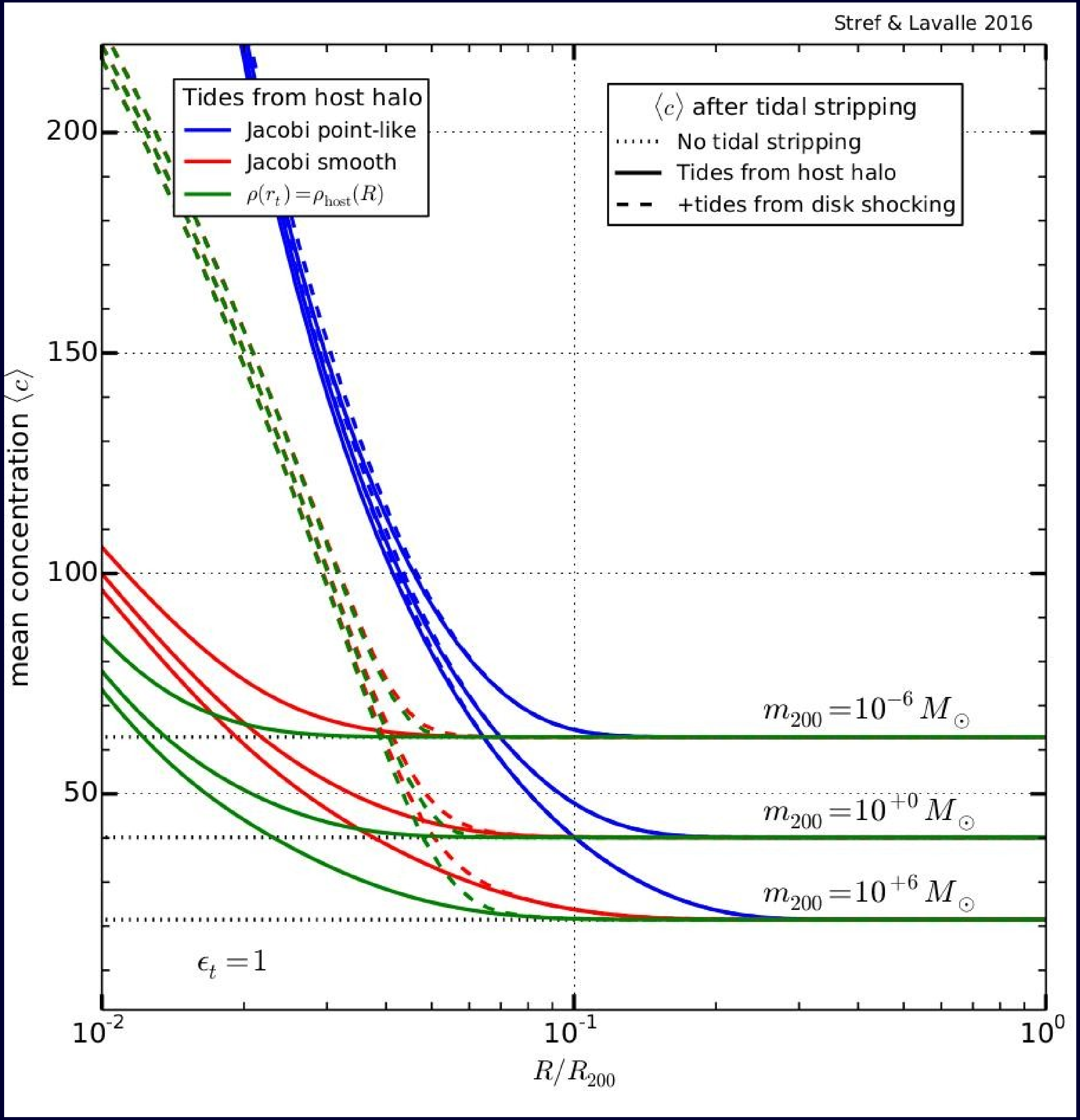
- Entanglement of spatial, mass and concentration distributions



Tidal disruption



Mean concentration



Impact of the mass power