Improved constraints on annihilating dark matter from cosmic-ray antiprotons

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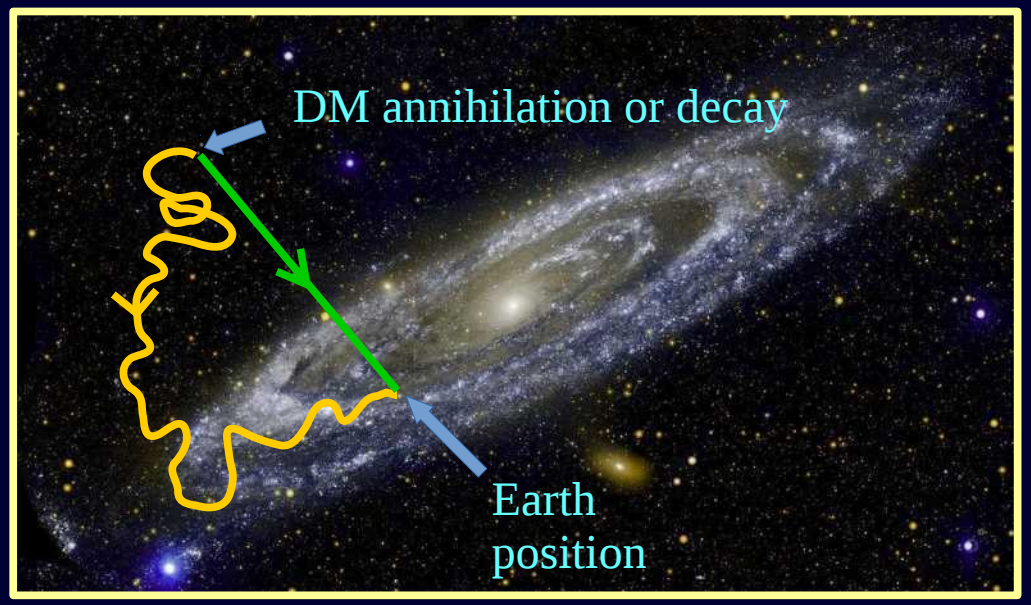
Importance of the dark halo modeling

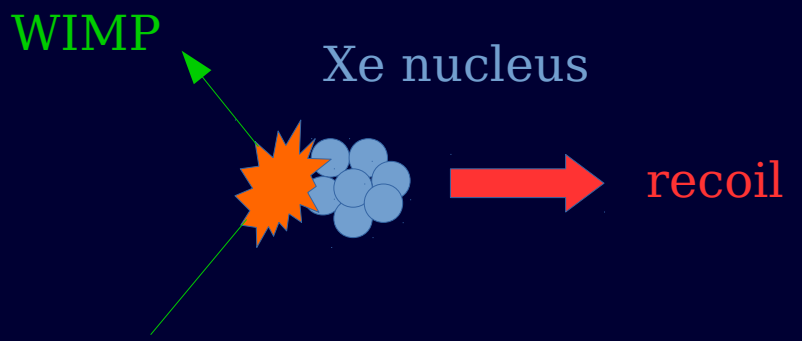
Indirect detection:



DM detection via
photons, neutrinos or
charged cosmic rays

→ Dependent on the
DM density profile

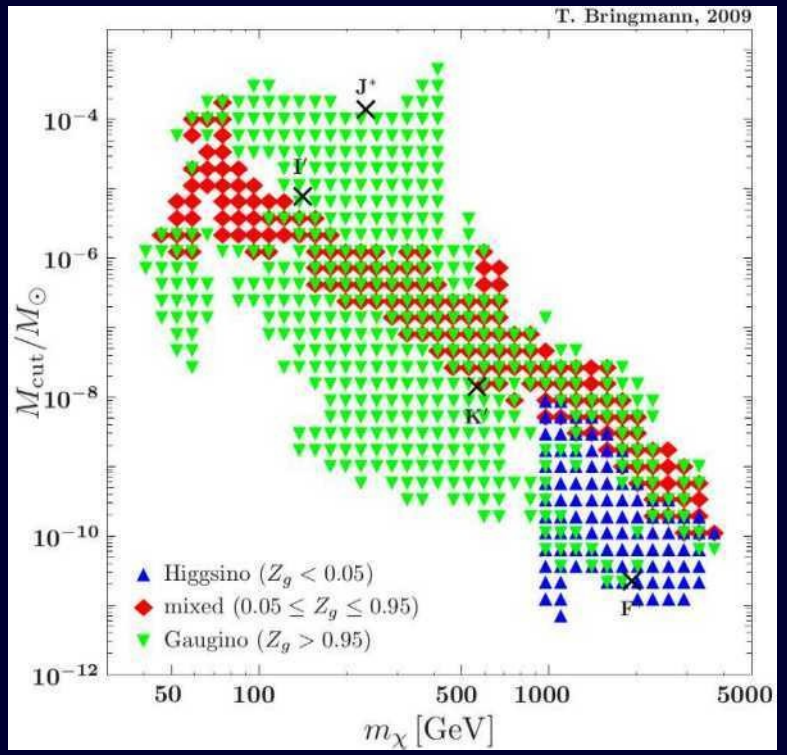
Direct detection:



→ Dependent on the
local DM density

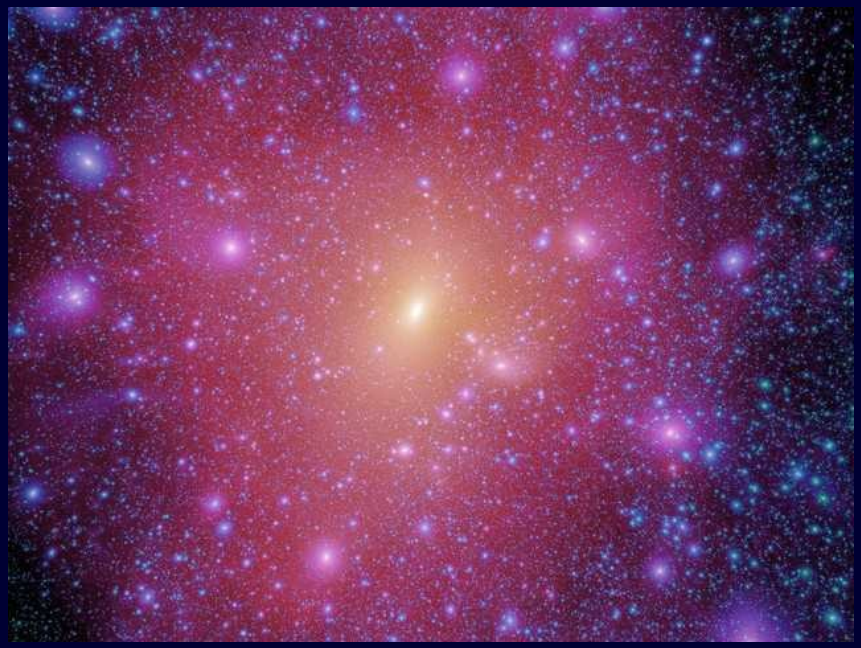
Importance of subhalos

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 model of the galactic halo and its subhalos

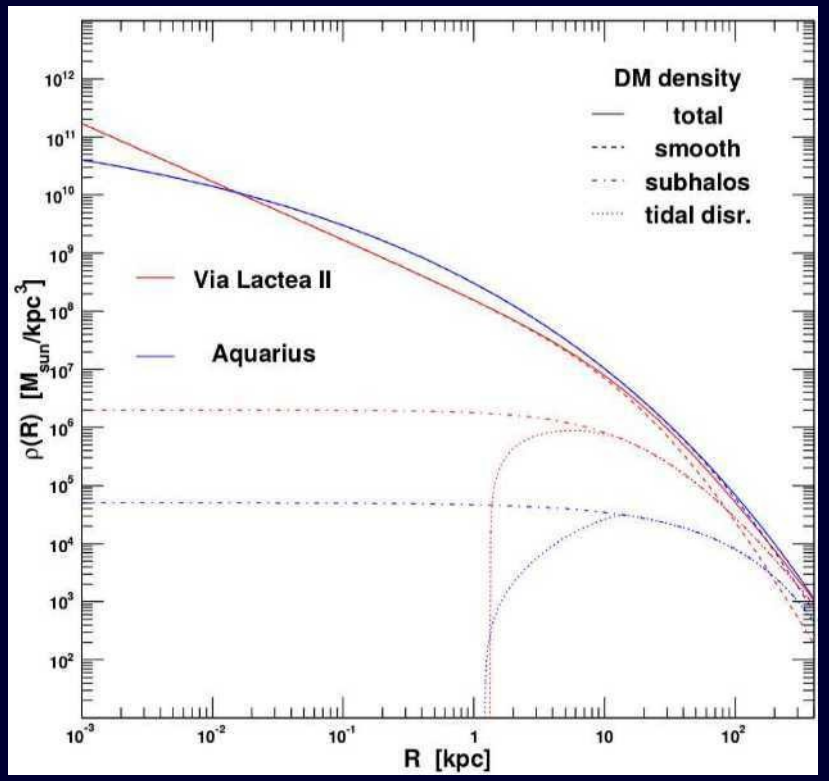
based on
MS and J.Lavalle, arXiv:1610.02233

Requirements

- Respect dynamical constraints (+adaptable to updated constraints from Gaia)
- Calibrate on cosmological simulations [Pieri et al, 2011]

  (subhalos mass fraction)
- Tidal effects from the DM halo
- Tidal effects from baryons

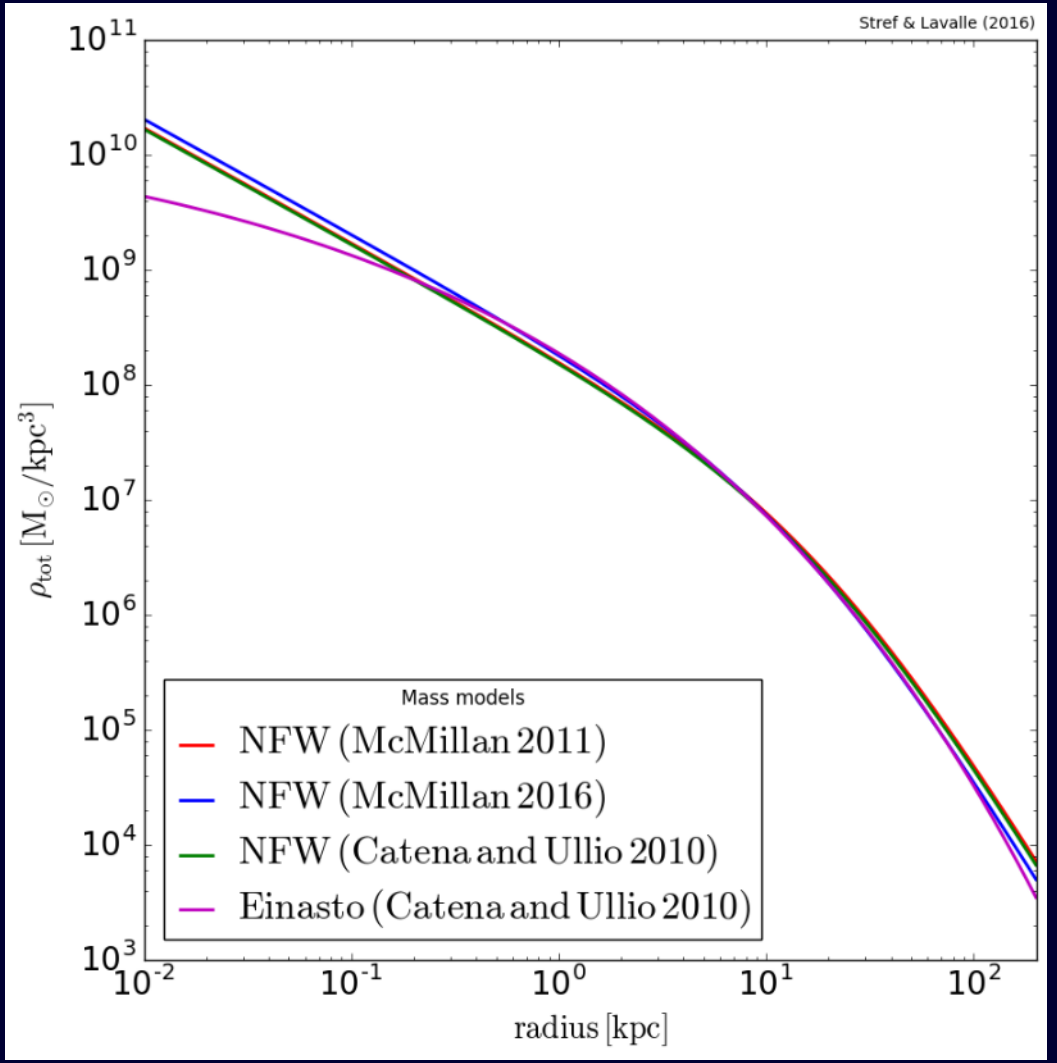
  (halo+disc)



Accommodating with dynamical constraints

Constrained dark halo

from MW mass models



Dark halo is part smooth, part clumpy:

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

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

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

Method

at “infall”

Position PDF:

$$f_{\rm v}(R) = \frac{\rho_{\rm tot}(R)}{M_{\rm tot}^{\rm DM}}$$

Mass PDF:

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

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

Concentration PDF:

$$f_{\rm c}(c, m)$$

= log-normal

$$\overline{c} = \overline{c}(m)$$

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at “infall”

Position PDF:

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+tidal effects

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+tidal effects

today

Full PDF:

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

Position PDF today:

$$f_{\rm v}^{\rm eff}(R) = \int dm \int dc\, f(R, m, c)$$

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:

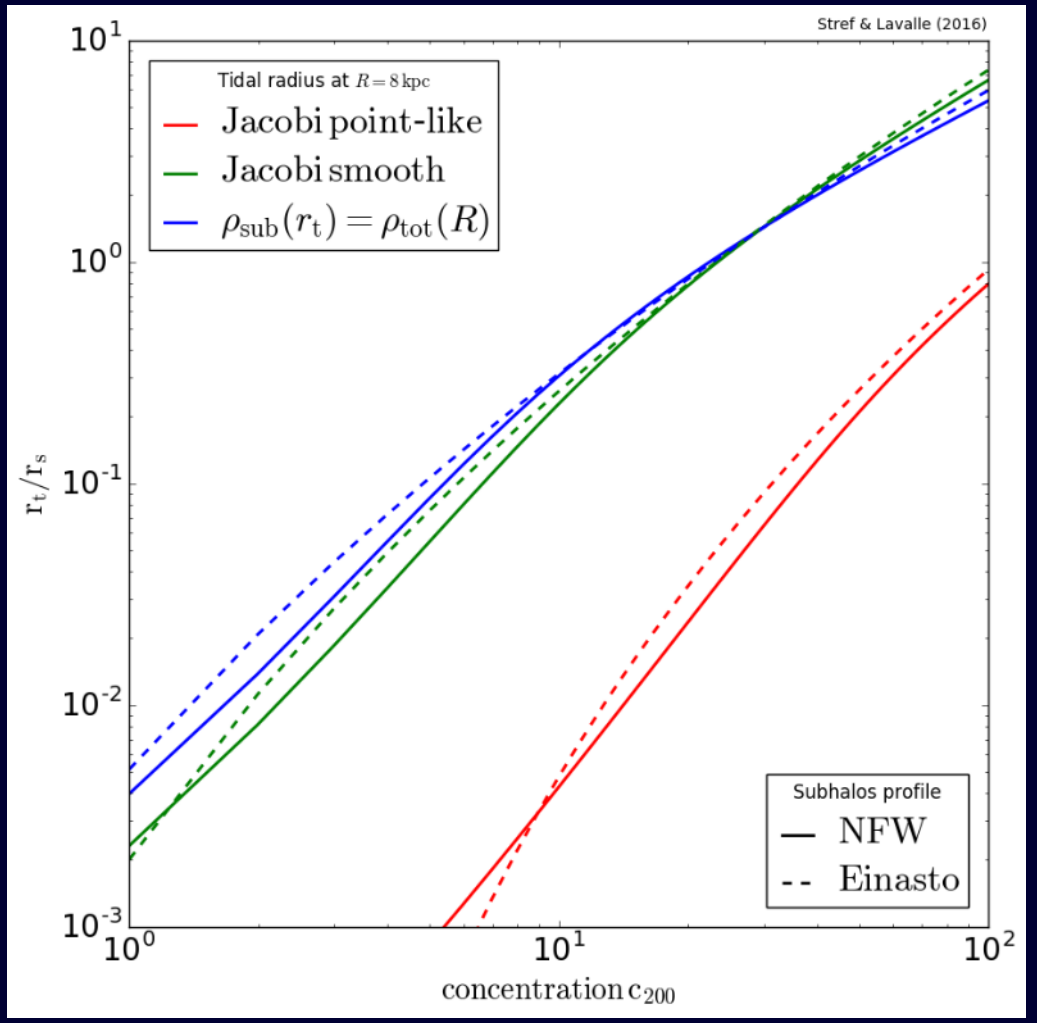
$$r_\mathrm{t} = \left(\frac{m(r_\mathrm{t})}{3M}\right)^{1/3} R$$

- Extended host:

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

- Density criterion:

$$\rho_\mathrm{sub}(r_\mathrm{t}) = \rho_\mathrm{tot}(R)$$



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:

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

Tidal effects: tides from the disc (2)

- Tidal radius definition

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

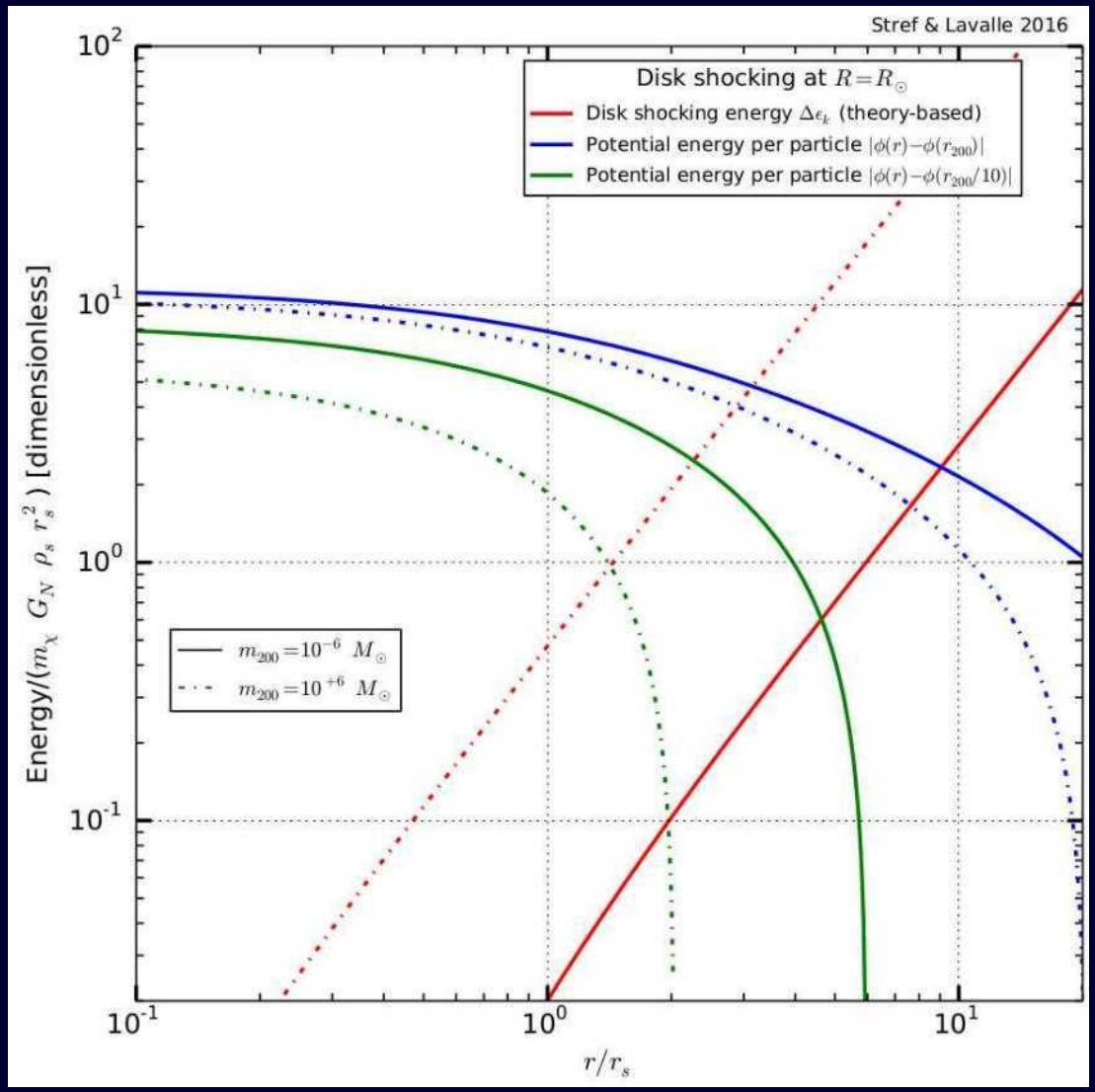
- Total energy increase

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

- “Integral” version

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

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

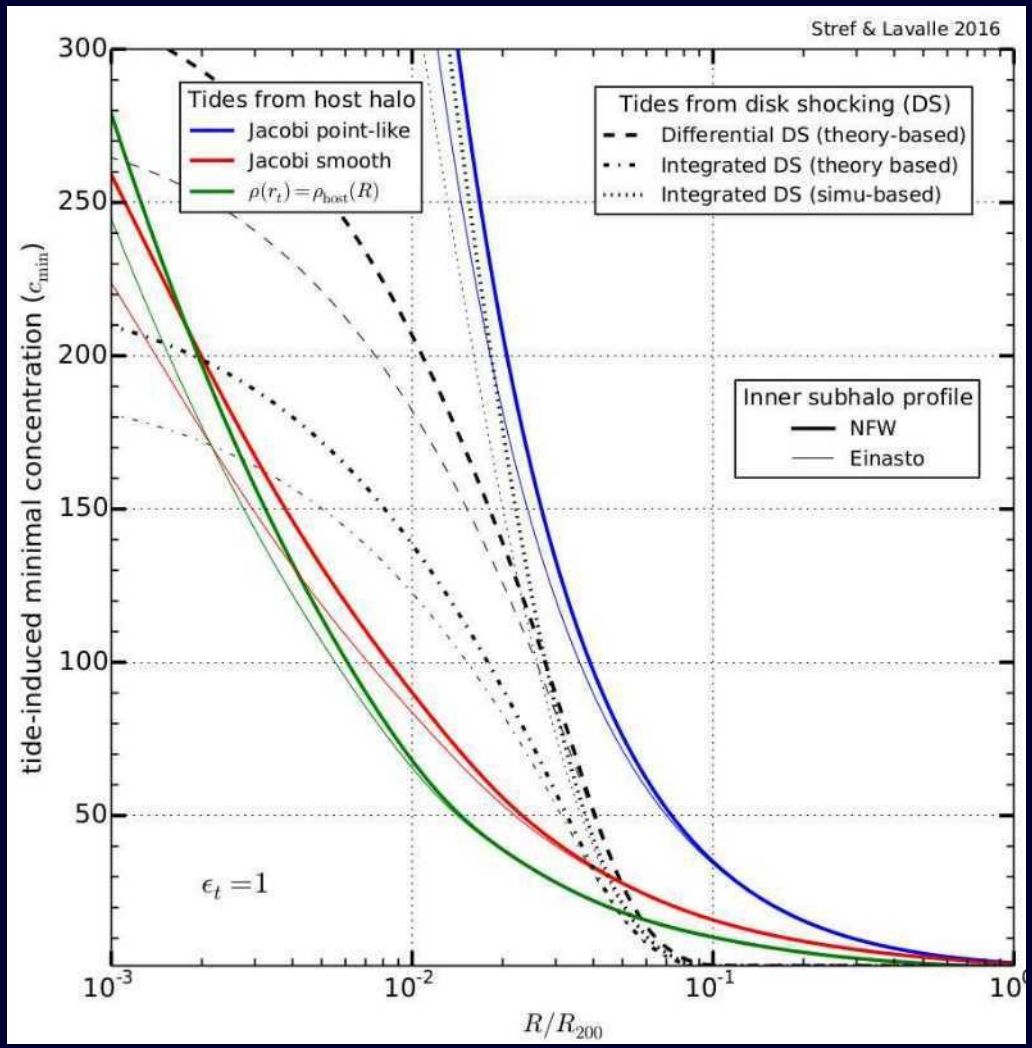


Minimal concentration

- Suhalo destroyed if $\frac{r_{\rm t}}{r_{\rm s}} \leq \epsilon_{\rm t}$
- Subhalo survives tidal effects if:

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

- Entanglement of spatial, mass and concentration distributions



Calibration and computation

Number of subhalos calibrated on cosmological simulation without baryons *(Via Lactea II,* [Diemand et al., 08])

- avoid modeling uncertainties
- make the model predictive

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

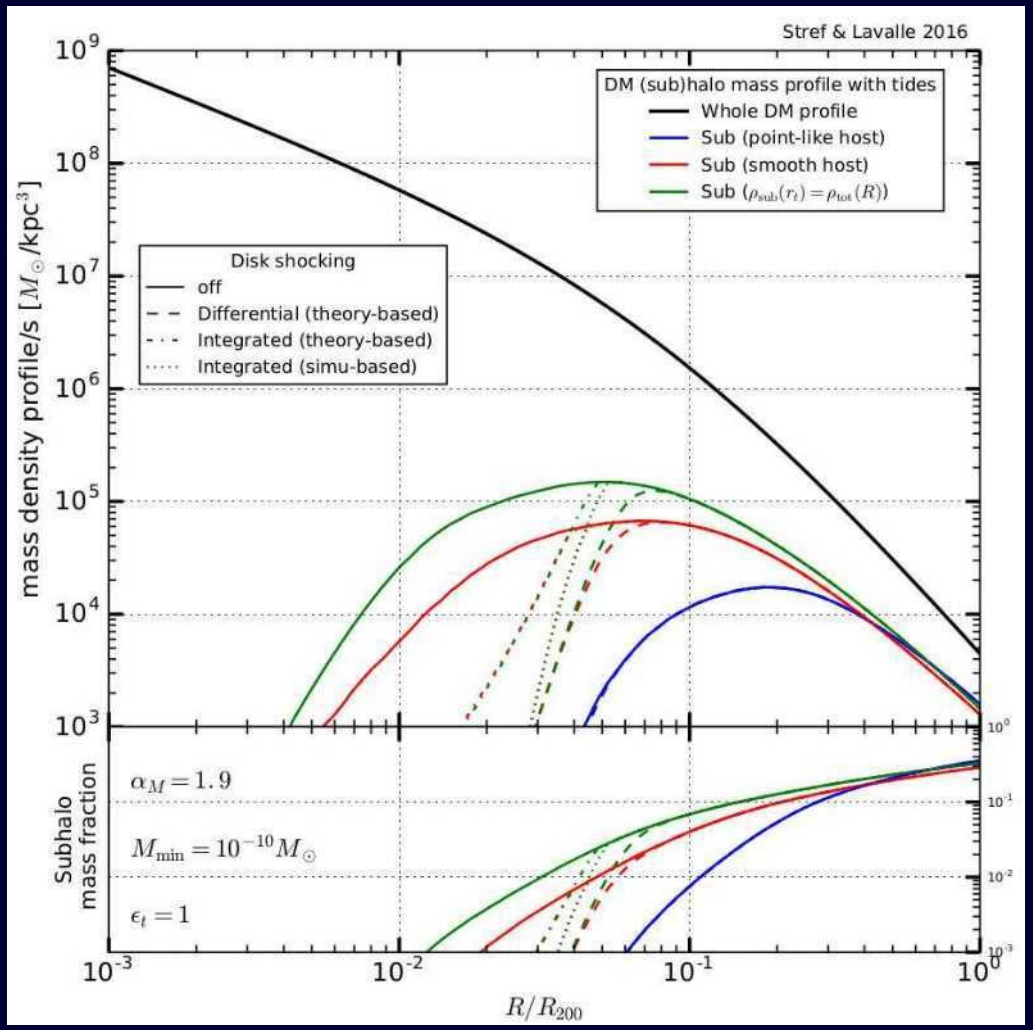
Subhalos contribution to the density:

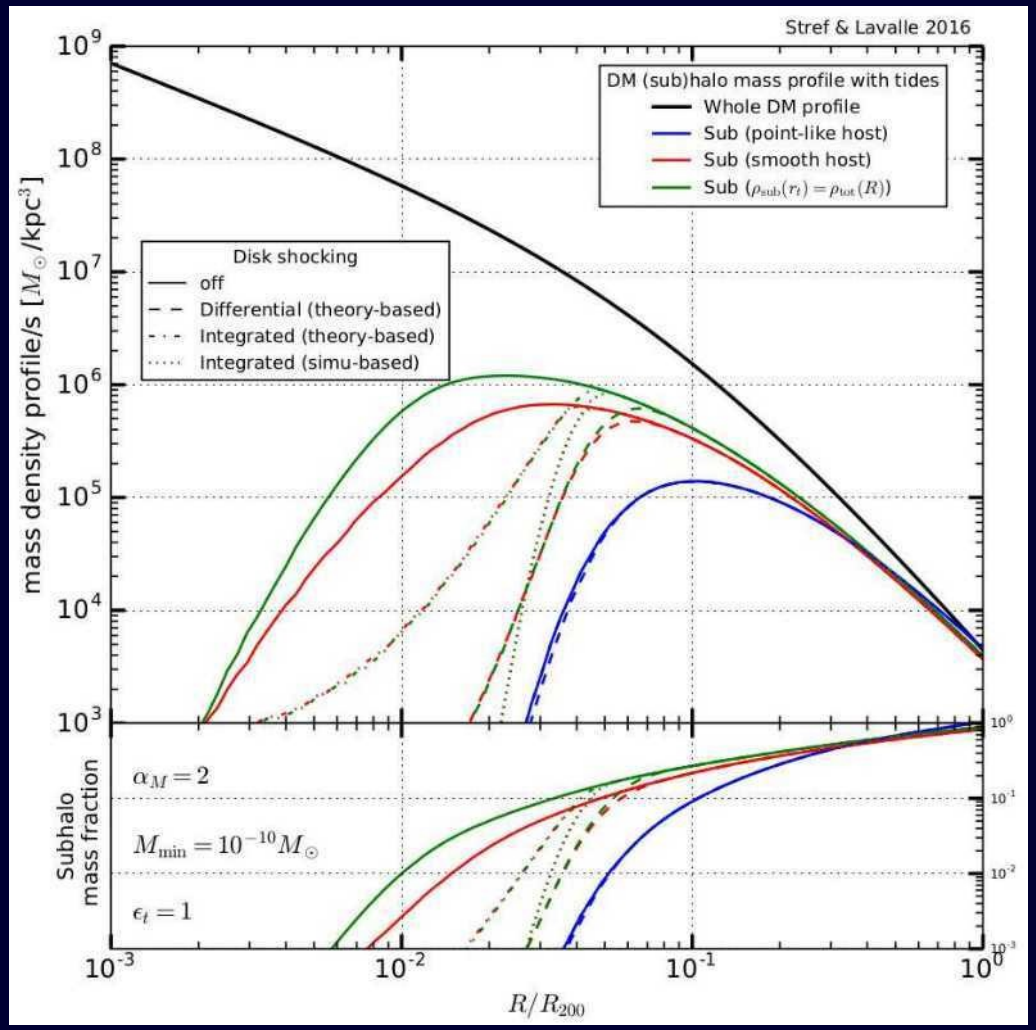
$$\langle \rho_{\rm sub}(R) \rangle = \frac{N_{\rm sub}}{K} f_{\rm v}(R) \int_{\rm M_{min}}^{\rm M_{max}} {\rm d}m\, f_{\rm m}(m) \int_{\rm c_{min}(R)}^{\infty} {\rm d}c\, f_{\rm c}(c, m)\, m_{\rm t}(R, m, c)$$

Smooth contribution:

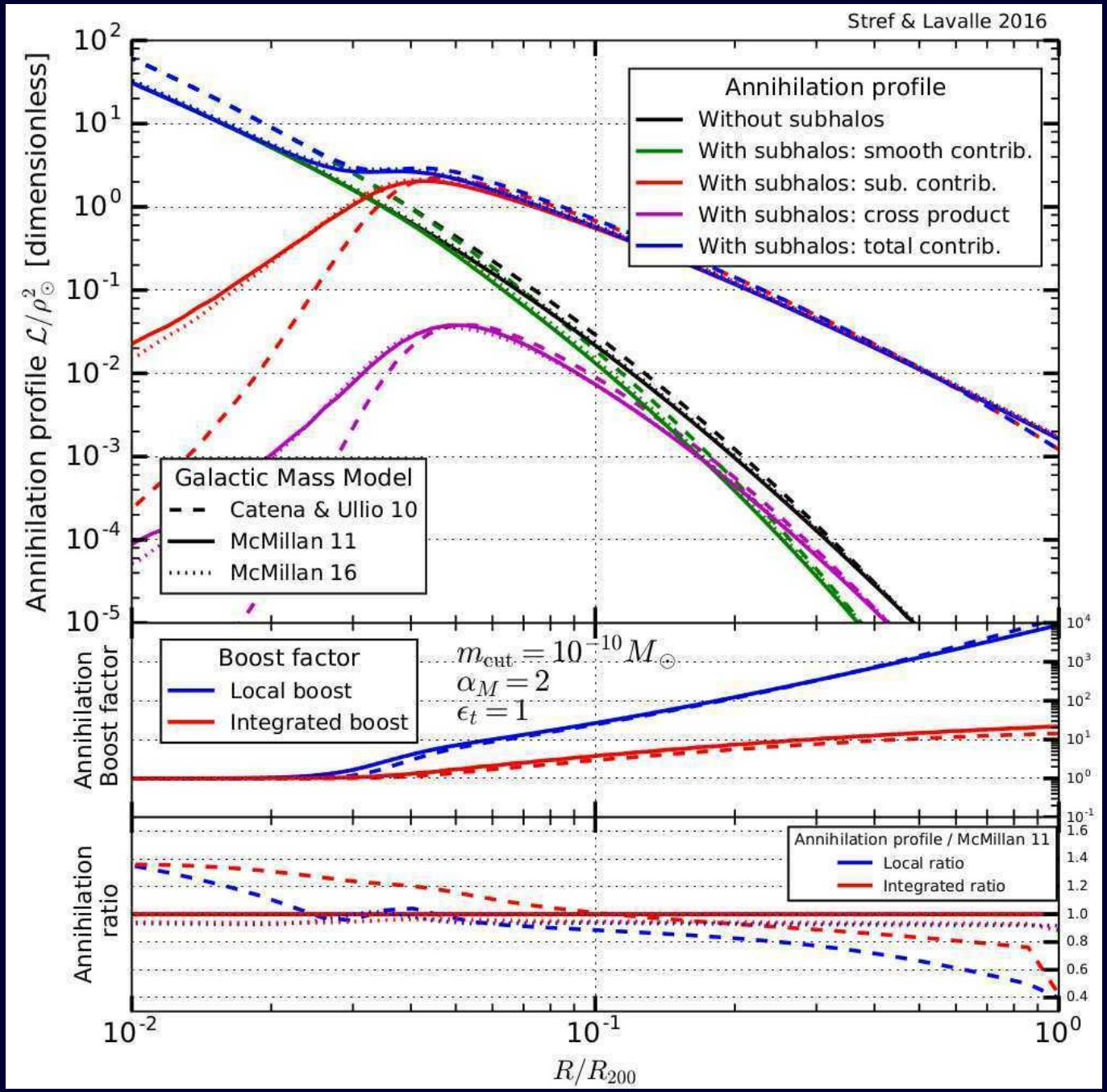
$$\rho_{\rm sm}(R) = \langle \rho_{\rm tot}(R) \rangle - \langle \rho_{\rm sub}(R) \rangle$$

Density profiles



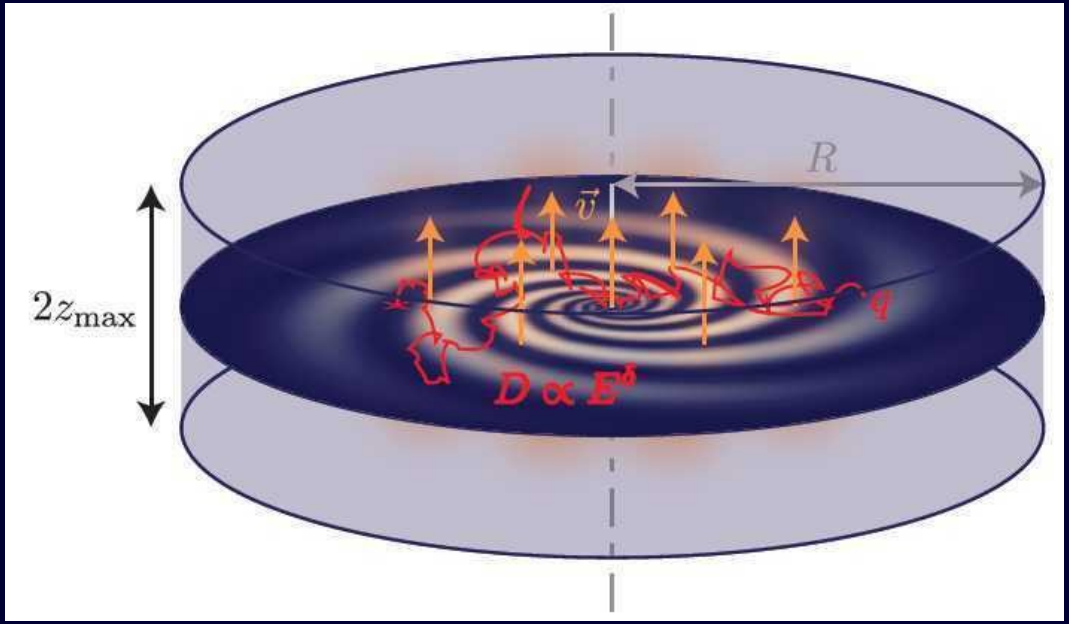


Boost factors



Application to indirect searches with cosmic-ray antiprotons

Cosmic-ray propagation



[Mertsch, 2010]

- MED [Maurin et al., 2001]

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

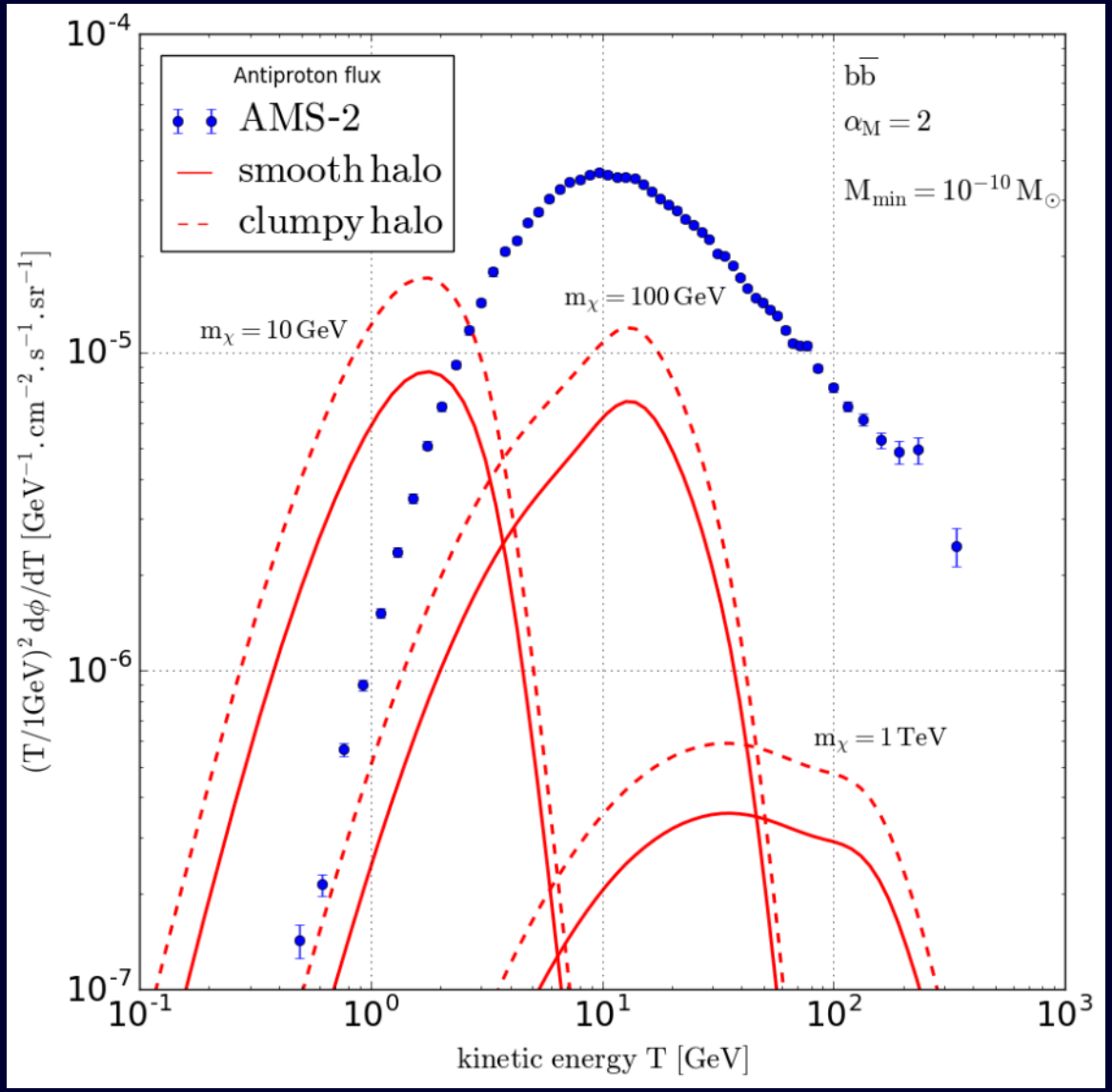
- Kappl et al., 2015

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

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

Antiprotons flux

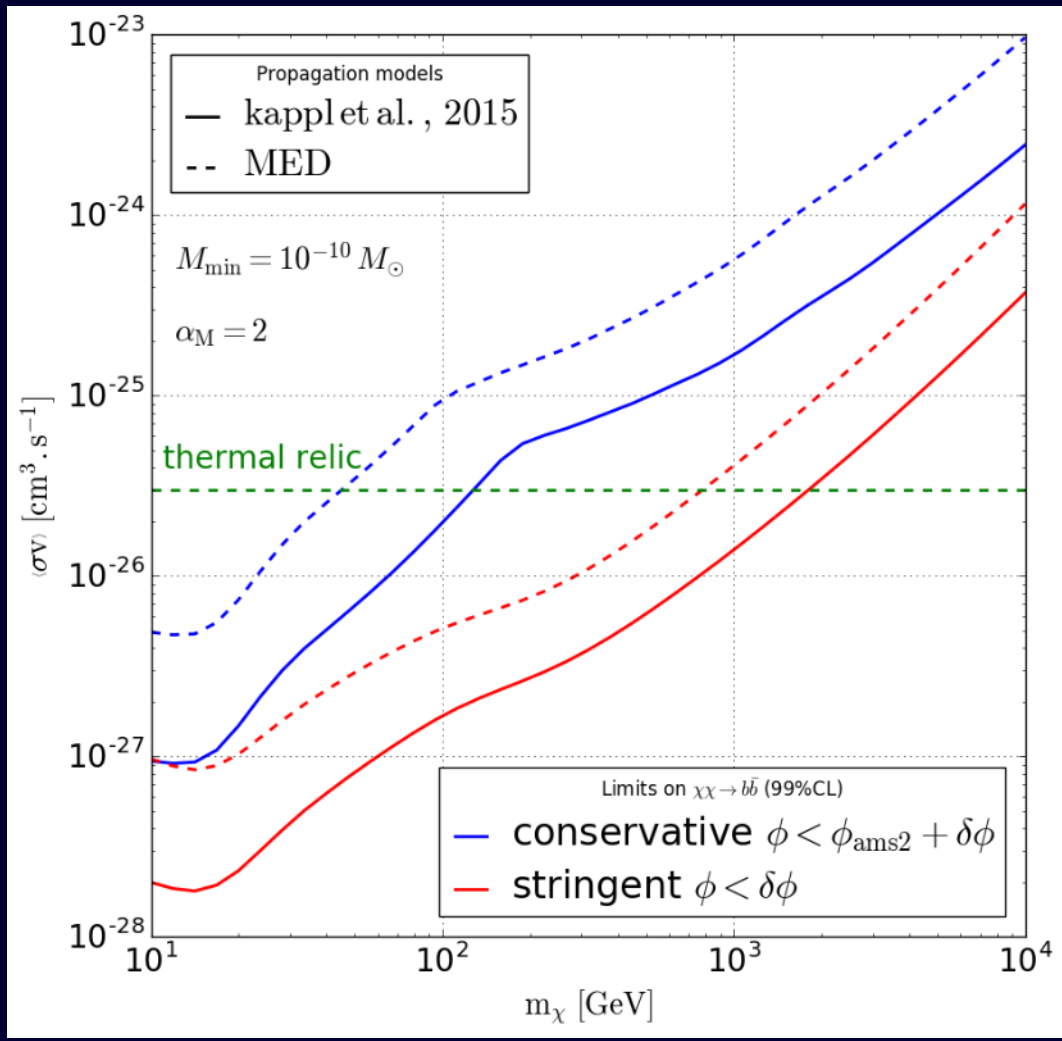
$$\phi(E) = \frac{\langle \sigma v \rangle}{2\, m_\chi^2} \frac{dN}{dE} \int d^3\vec{x}\, G_{\rm prop}(\vec{x}, E)\, \left\langle (\rho_{\rm sm}(\vec{x}) + \rho_{\rm sub}(\vec{x}))^2 \right\rangle$$



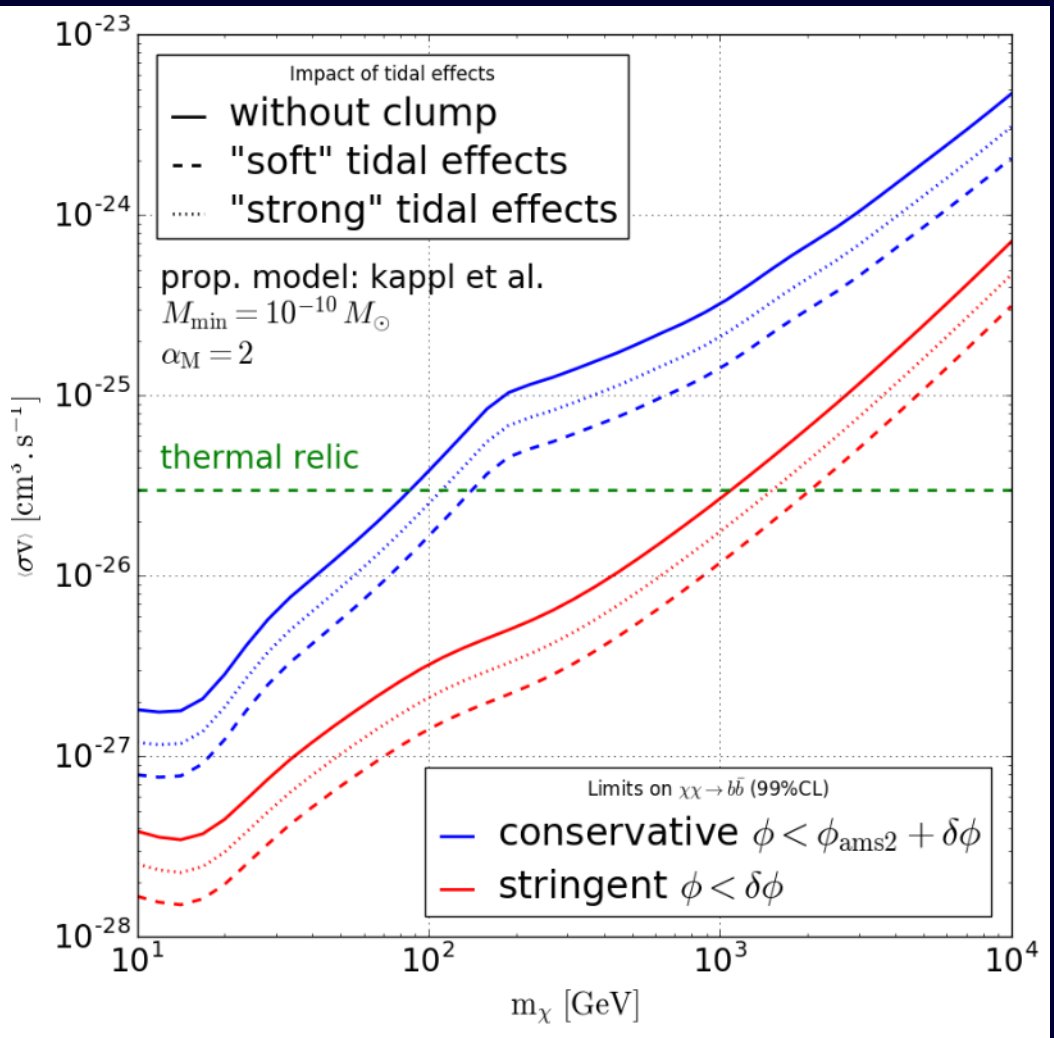
Constraints from AMS-2 data

(preliminary)

Propagation model:



Tidal effects:

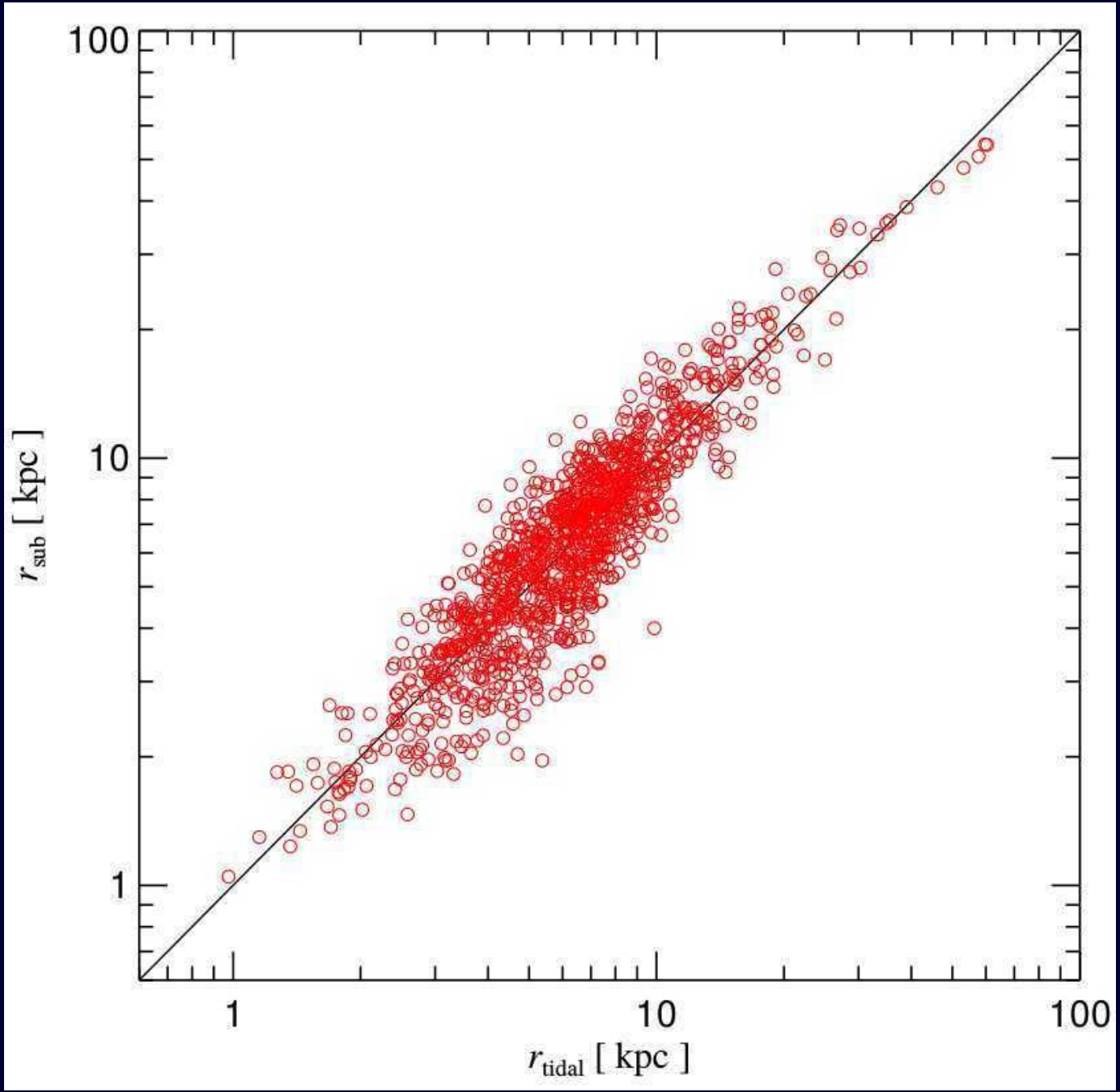


Summary

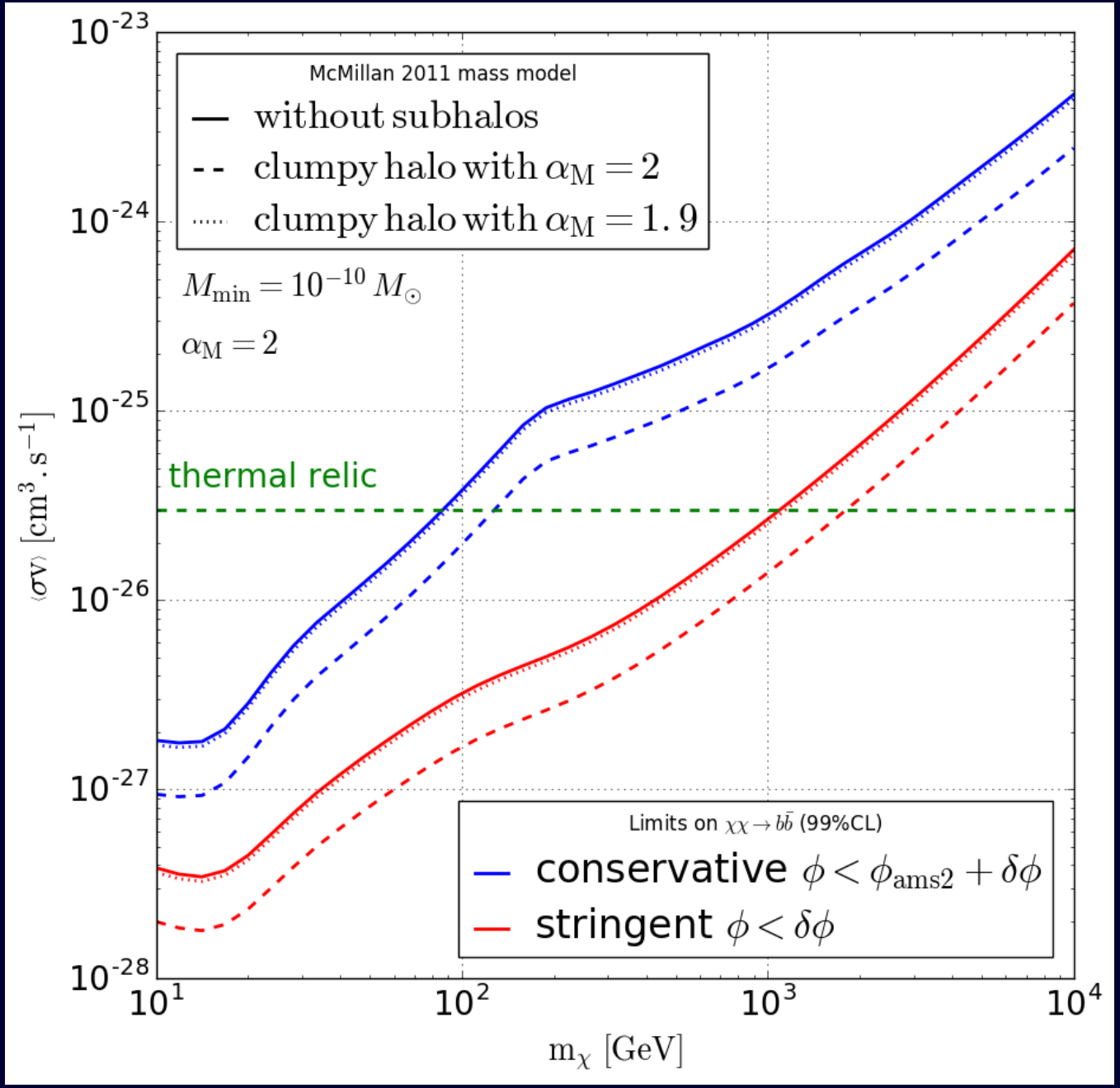
- Consistent modeling of galactic subhalos, including tidal effects from halo and disc
- Reproduces results from cosmological simulations
- Easily adaptable to new dynamical constraints from Gaïa → DM density profile is an input
- Can be used for indirect searches (antiprotons, but also positrons, gamma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

Backup

Tidal radius in Aquarius



Impact of the mass power



Limit from FERMI