# Antiproton cosmic rays from Dark matter subhalos

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# *Dark matter indirect detection*

Hypothesis : DM particles can pair annihilate into Standard Model particles

$$\overline{\chi}\chi \;\to b\overline{b},\;\tau\overline{\tau},\ldots \;\to\; \gamma,\; e^{+},\; \overline{p},\ldots$$

→ DM might contribute to the observed cosmic-ray fluxes

To distinguish between DM and classical astrophysical sources, one needs :

- an estimation of the background
- a precise calculation of DM annihilation flux → focus on antiprotons in this talk

# *DM-induced cosmic-ray flux*

$$\frac{d\phi}{dE}(E,\vec{x}_{\rm obs}) = \delta < \sigma v > \left(\frac{\rho_0}{m_\chi}\right)^2 \int_{\rm halo} {\rm d}\vec{x}_{\rm s} \int {\rm d}E_{\rm s}\ \mathcal{G}(E,\vec{x}_{\rm obs} \leftarrow E_{\rm s},\vec{x}_{\rm s}) \frac{dN}{dE}(E_{\rm s}) \left(\frac{\rho(\vec{x}_{\rm s})}{\rho_0}\right)^2$$

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Particle physics :
Cross-section,
WIMP mass,
final state spectra

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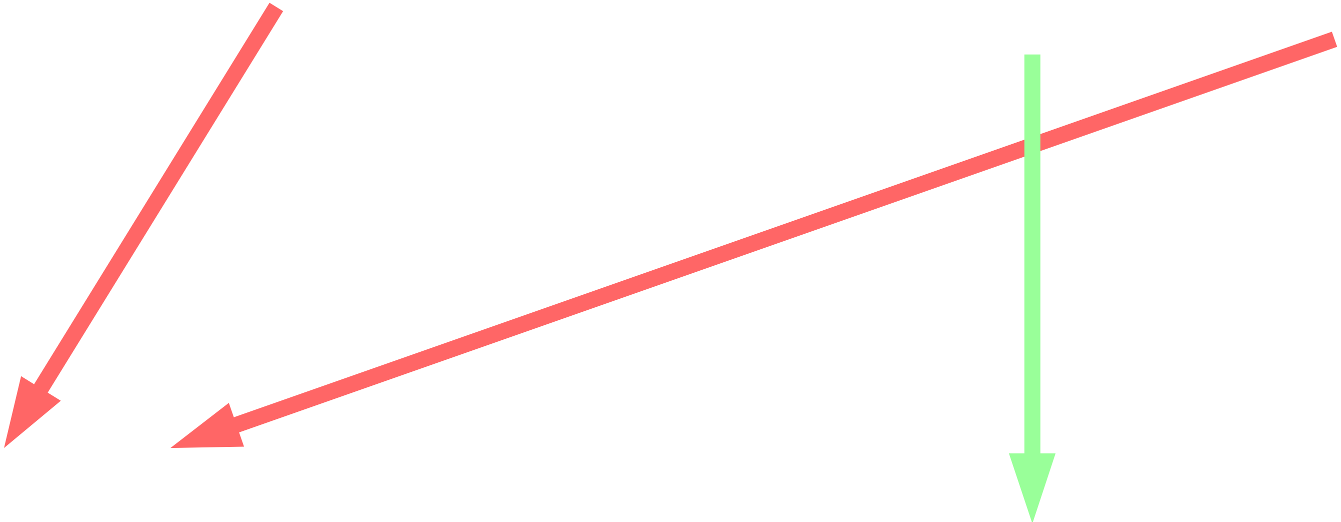

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Cosmic-ray physics:
Information on the propagation from source to observer

# *DM-induced cosmic-ray flux*

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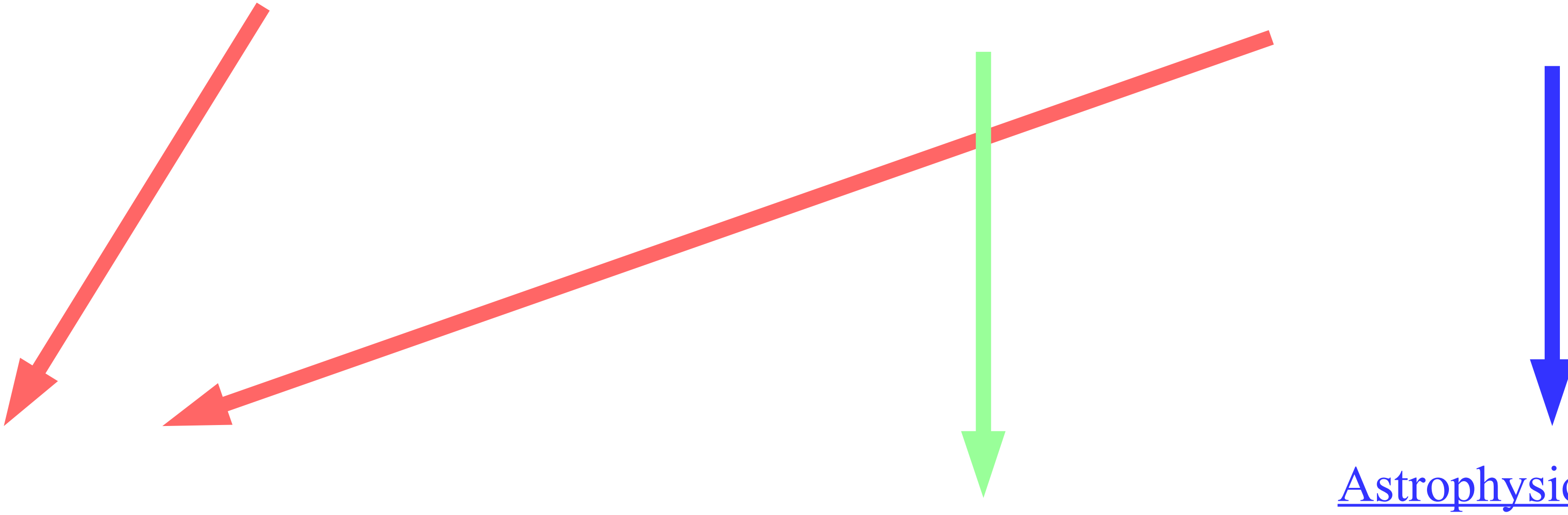

Particle physics :
Cross-section,
WIMP mass,
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Cosmic-ray physics:
Information on the
propagation from source to
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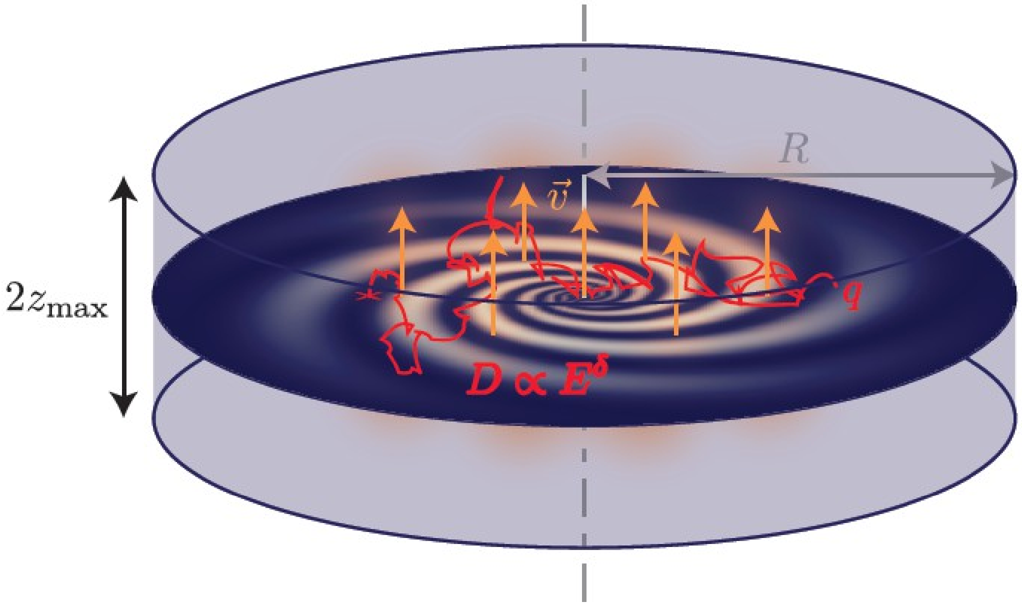
Astrophysics :
DM density profile

# *Antiprotons propagation*



Mertsch PhD thesis 2010

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

# *Antiprotons propagation*

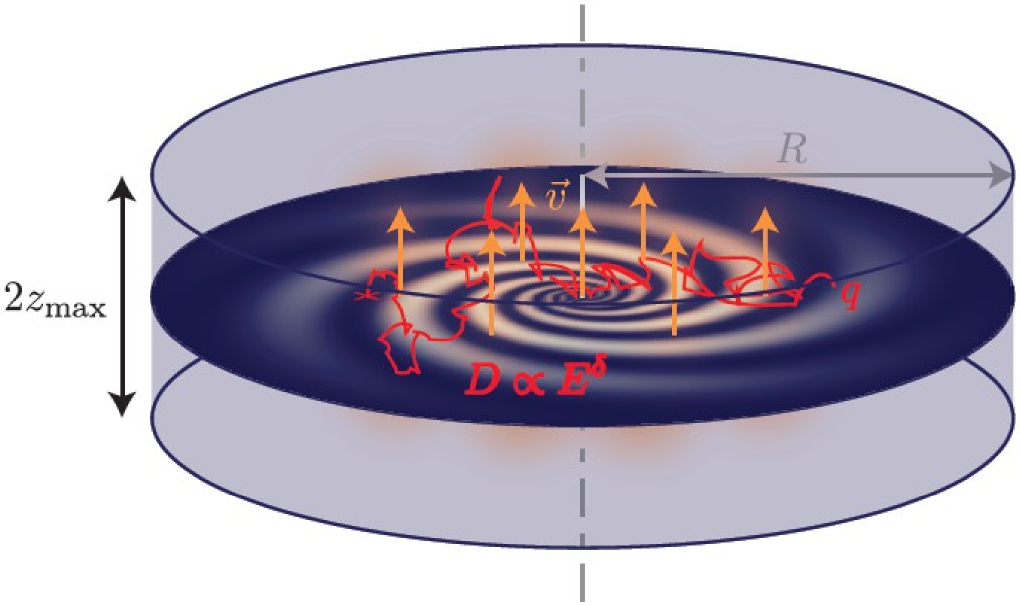
$$p + H \longrightarrow \bar{p}/\bar{n} + X$$

$$\mathcal{Q}_{\rm sec}(T,\vec{x}) = 4\pi \sum_{\substack{i={\rm CRs}\\ j={\rm ISM}}} \int dT_i \, \frac{d\phi_i(T_i,\vec{x})}{dT_i} \, \frac{d\sigma_{ij\to{\rm sec}}(T_i \to T)}{dT} \, n_j(\vec{x})$$

**Secondary Production**

**Primaries:**
**WIMP annihilation**
**+ astrophysical sources**

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



Mertsch PhD thesis 2010

$$\bar{p} + H \longrightarrow X$$

$$1/\tau_s(T,\vec{x}) = v_{\bar{p}}\, \sigma_{\not{\bar{p}}}(T)\, n_{\rm ISM}(\vec{x})$$

**Destruction**

# *The Milky Way dark matter halo*

Cosmological simulations give tyical shape :

NFW : $\rho(r) = \dfrac{\rho_{\rm s}}{\frac{r}{r_{\rm s}}(1+\frac{r}{r_{\rm s}})^2}$

Einasto : $\rho(r) = \rho_{\rm s} \exp\left\{-\dfrac{2}{\alpha}\left[\left(\dfrac{r}{r_{\rm s}}\right)^{\alpha} - 1\right]\right\}$

$\rho_{\rm s}$ and $r_{\rm s}$ can be determine

in a mass model for the Milky Way

(e.g. McMillan 2011 for NFW profile),

consistent with dynamical constraints

(rotation curves)

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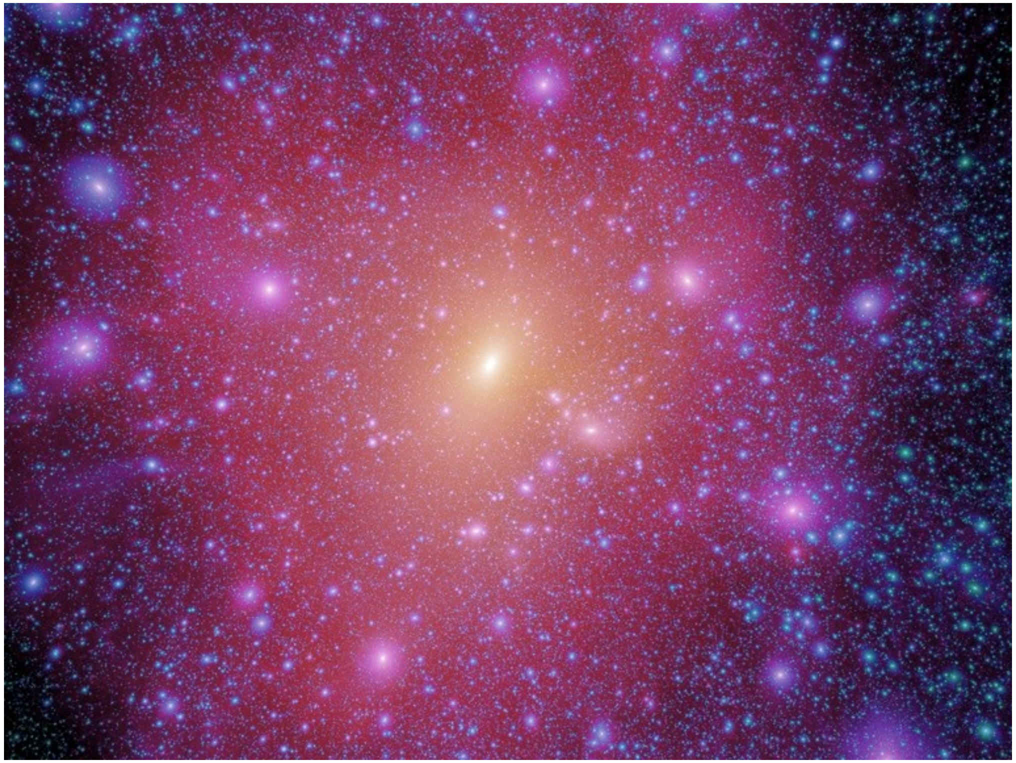
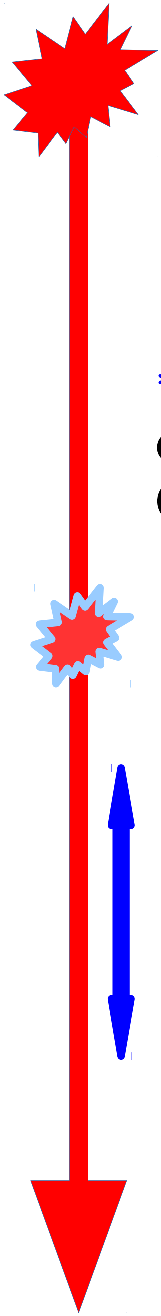
**BUT** cold dark matter scenario predicts this :



http://wwwmpa.mpa-garching.mpg.de/aquarius/

# *From WIMPs to subhalos*



* **T > m and $\Gamma_{ann}$ > H** (and $\Gamma_{scat}$ > H):
Chemical equilibrium, n/s = cst

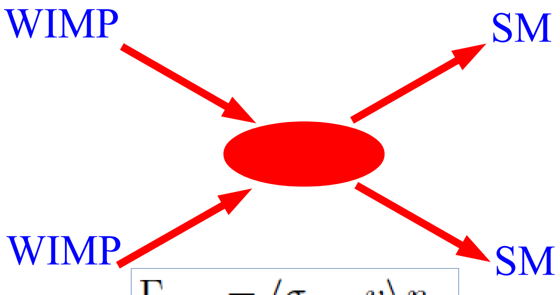
* **T < m and $\Gamma_{ann}$ > H** (and $\Gamma_{scat}$ > H):
Chemical equilibrium, n/s ∝ exp(-m/T)
(Boltzmann suppression)

* **T < m and $\Gamma_{ann}$ < H** (and $\Gamma_{scat}$ > H):
Chemical decoupling (freeze out)

* **T < m and $\Gamma_{scat}$ < H**:
Kinetic decoupling
=> free-streaming scale
=> minimal mass scale for structure formation
(modulo extra-damping from acoustic oscillations)

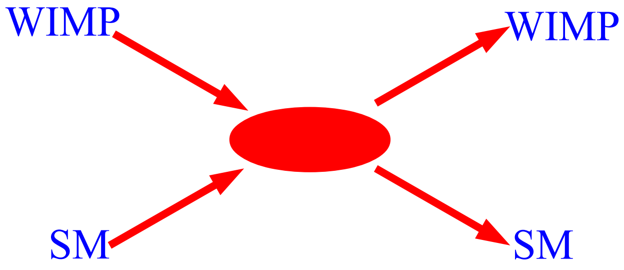
$$10^{-10} M_\odot \leq M_{\rm min} \leq 10^{-4} M_\odot$$

Annihilation
(→ chemical decoupling)



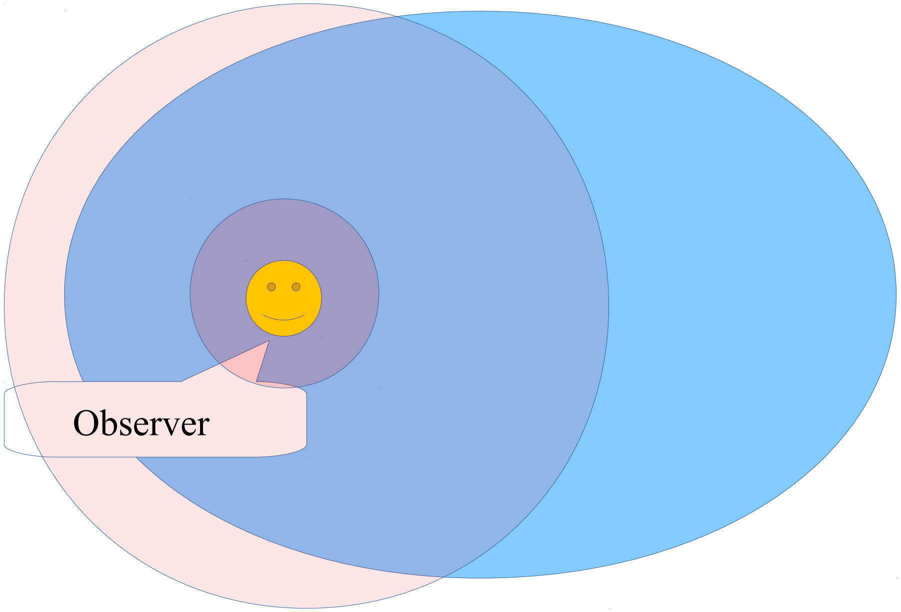
$$\Gamma_{\rm ann} = \langle \sigma_{\rm ann}\, v \rangle \, n_\chi$$

Scattering
(→ kinetic decoupling)

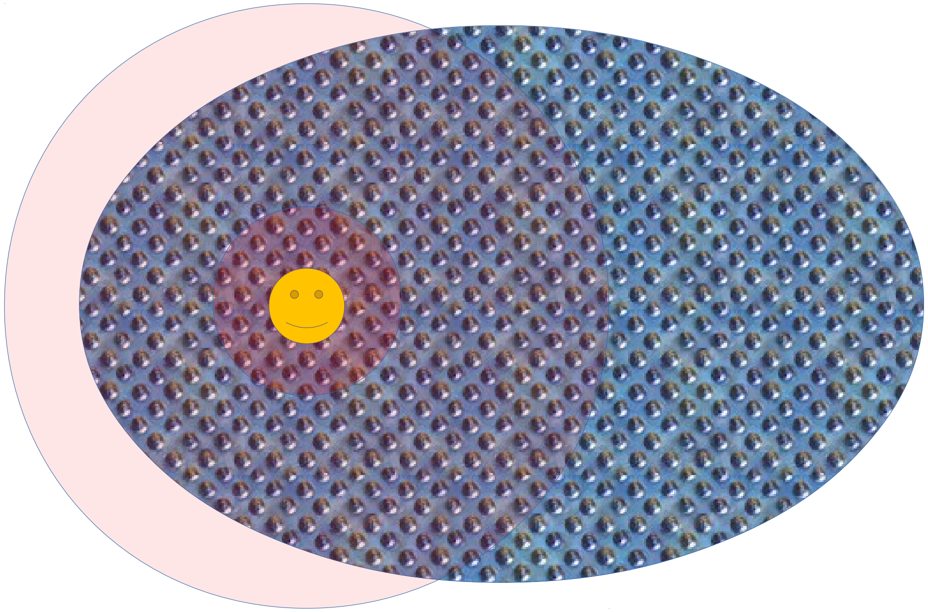


$$\Gamma_{\rm scat} = \langle \sigma_{\rm scat}\, v \rangle \, n_{\rm plasma}$$

# *Impact of subhalos*



Smooth halo



Clumpy halo

Boost factor : $\mathcal{B} = \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2} \geq 1$ for clumpy halo

Antiprotons cosmic rays:

Large propagation scale (high energy) => « see » the Galactic Center => moderate boost

Small propagation scale (low energy) => large boost + large statistical variance

# *Toward a consistent clumpy MW model*

Set subhalos properties :

- Mass function
- Internal properties
- Spatial distribution

Inclusion in a MW mass model :

- McMillan 2011 for NFW profile

Propagation :

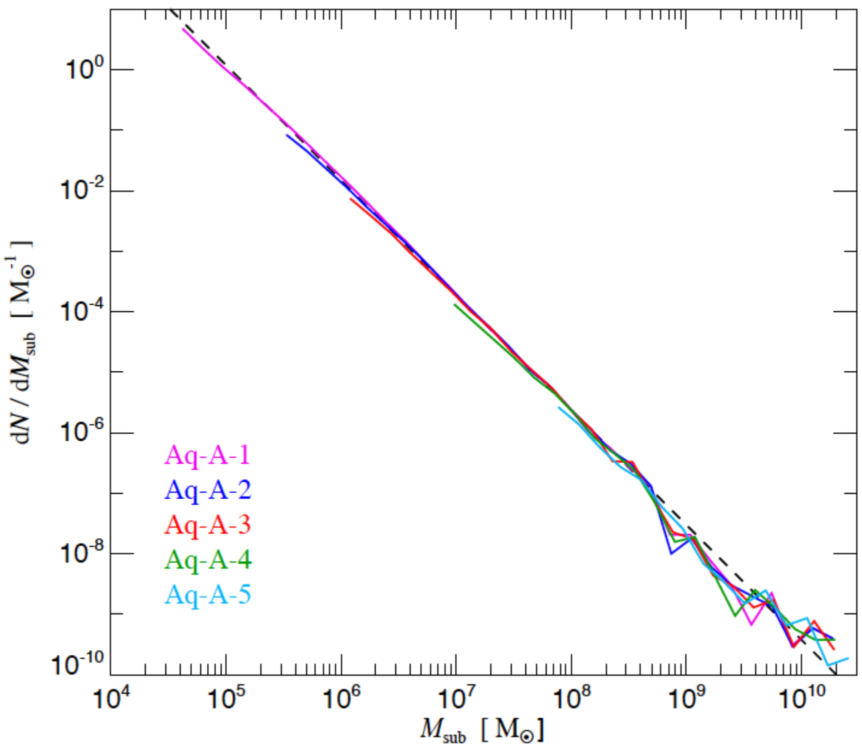
- MED as a template

Spectra :

- Spectra from PPPC4DM table (Cirelli 11-15)

# *Subhalos Properties I : mass function*

Aquarius simulation (Springel et al. 2008)



Mass function : $\dfrac{dP}{dM} = K_{\rm M} \left(\dfrac{M}{M_\odot}\right)^{-\alpha}$

Press-Schechter : $\alpha \sim 2$

Simulations : $\alpha \sim 1.9 - 2$

# *Subhalos properties II: internal shape and concentration*

Subhalos profile : inferred from simulations → NFW or Einasto

Concentration : $c = \dfrac{R_{200}}{r_{-2}}$ where : $M = \dfrac{4}{3}\pi R_{200}^3\ 200\rho_c$

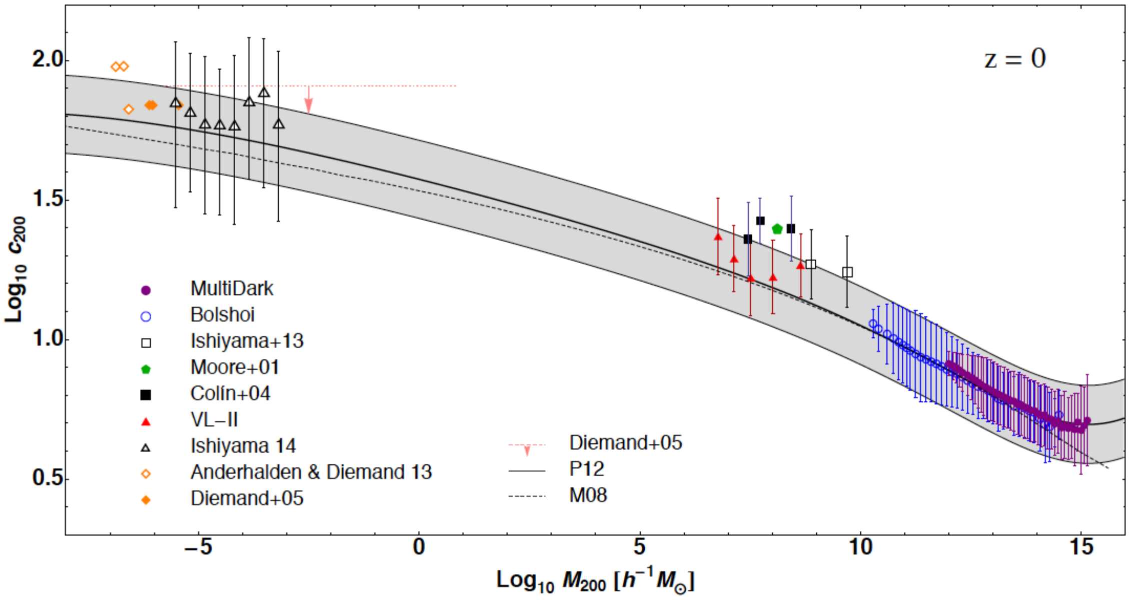
Log-normal distribution for c :

$$\frac{\mathrm{d}P}{\mathrm{d}c}(c,\overline{c}) = \frac{1}{\sqrt{2\pi}\sigma_c c}\exp\left[-\left(\frac{\ln(c)-\ln(\overline{c})}{\sqrt{2}\sigma_c}\right)^2\right]$$

Average concentration function of mass :

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

Sanchez-Conde 2013

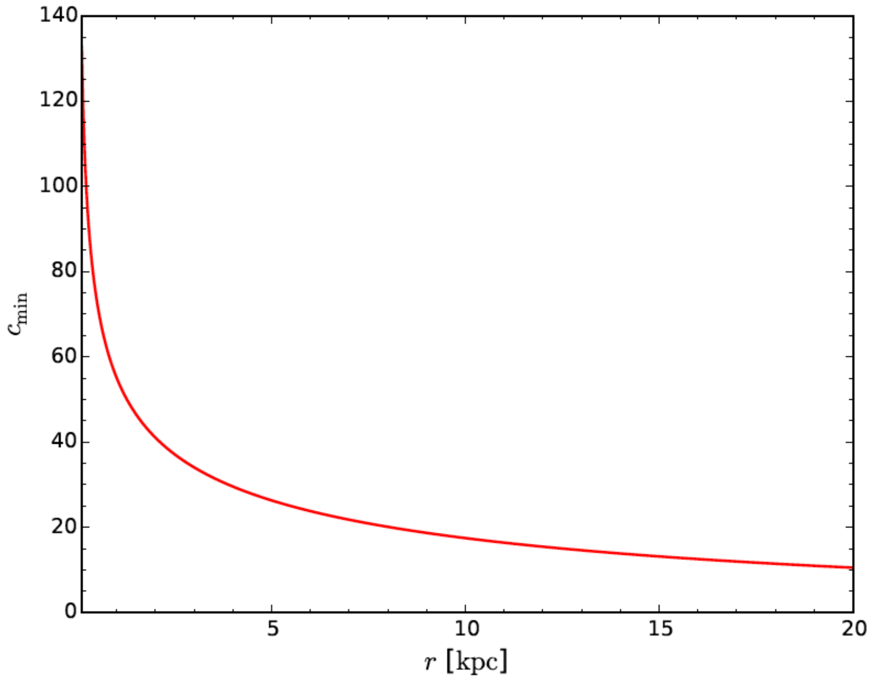


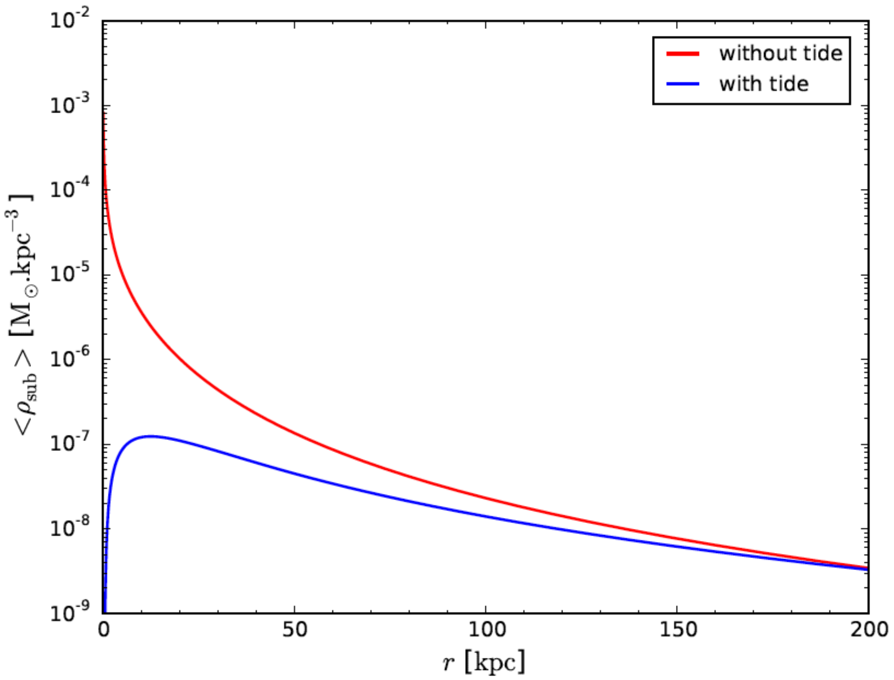
# *Subhalos properties III: spatial distribution*

Initially follows the main halo density profile: $\frac{\mathrm{d}P}{\mathrm{d}V}(r) = \frac{\rho(r)}{M_{\mathrm{MW}}}$ ⟶ central cusp

**BUT...**

Subhalos at the center destroyed by tidal effects ⟶ cored distribution





# *Consistent inclusion of subhalos*

Density profile :

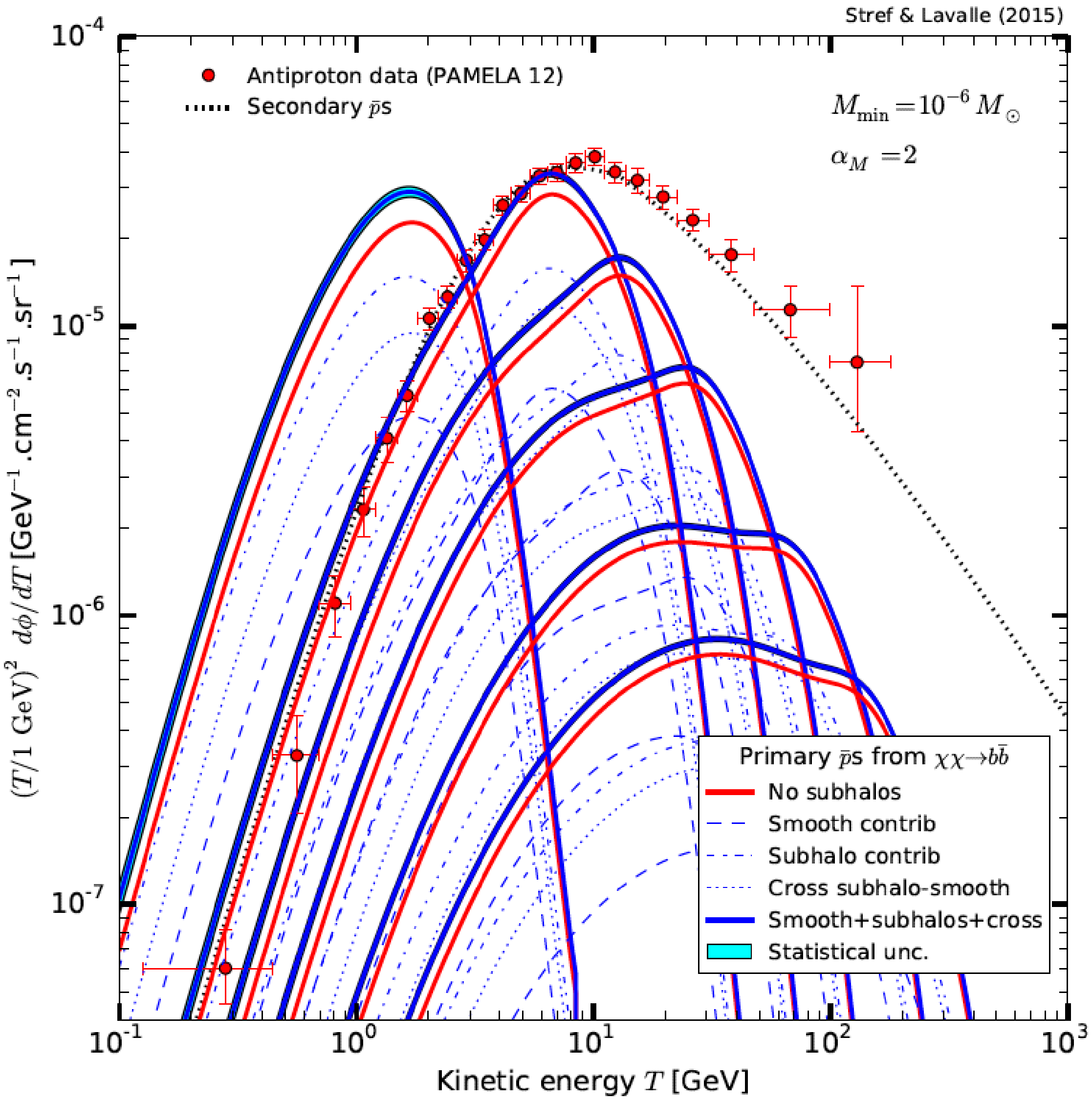
Smooth component + subhalos = main halo → Consistent with dynamical constraints

Number of subhalos :

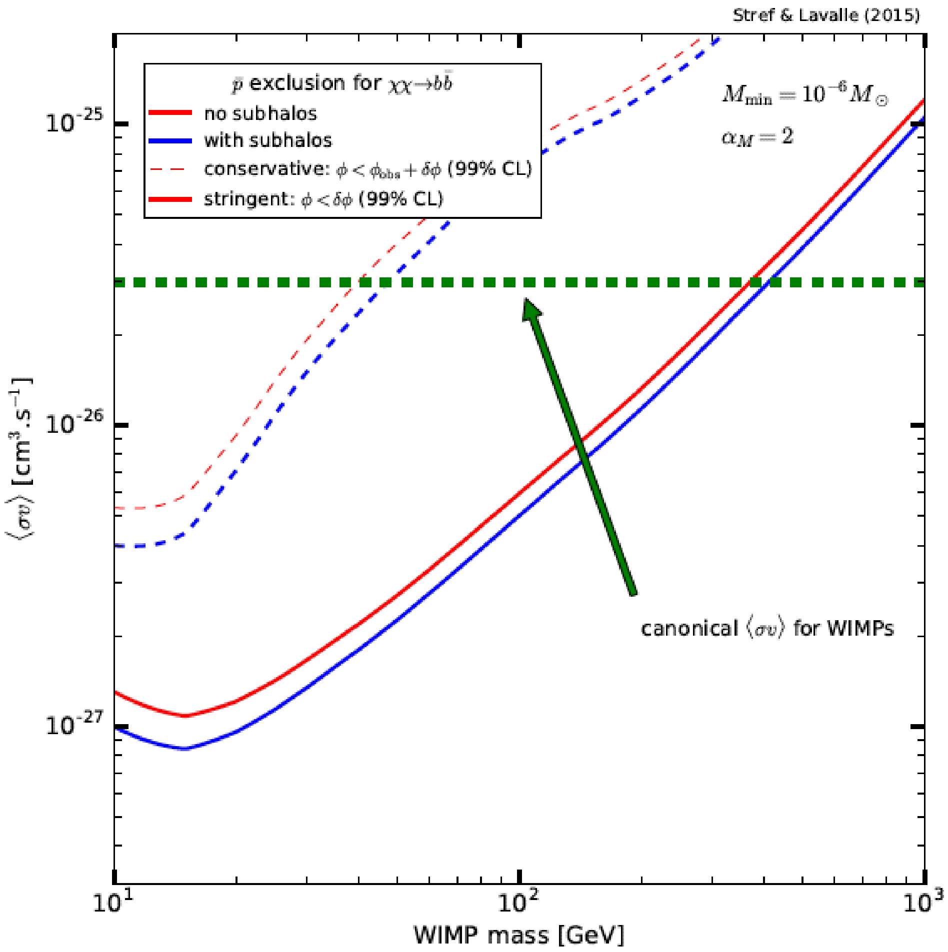
Calibrated on cosmological simulations using the mass fraction : $f = N_{\rm sub} \frac{< M >}{M_{\rm MW}}$

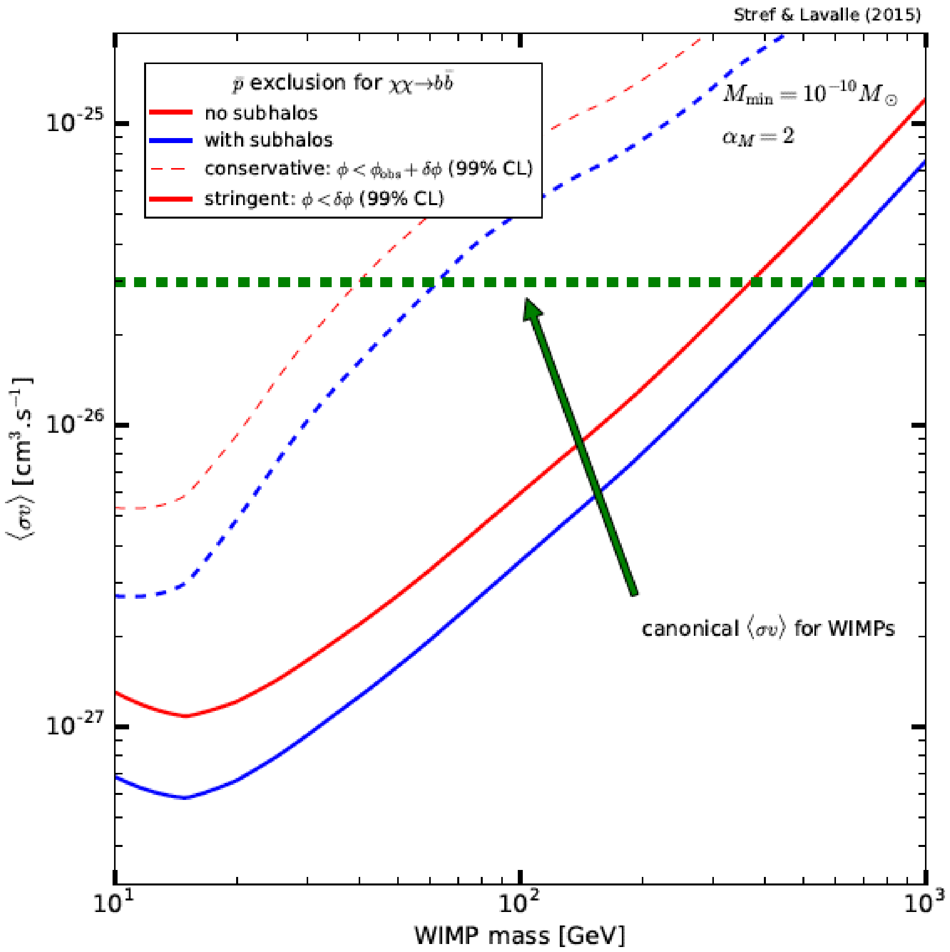
e.g. for *Via Lactea II* : $f = 10\%$ in the range $[10^{-5} M_{\rm halo},\ 10^{-2} M_{\rm halo}]$

# *DM annihilation flux*



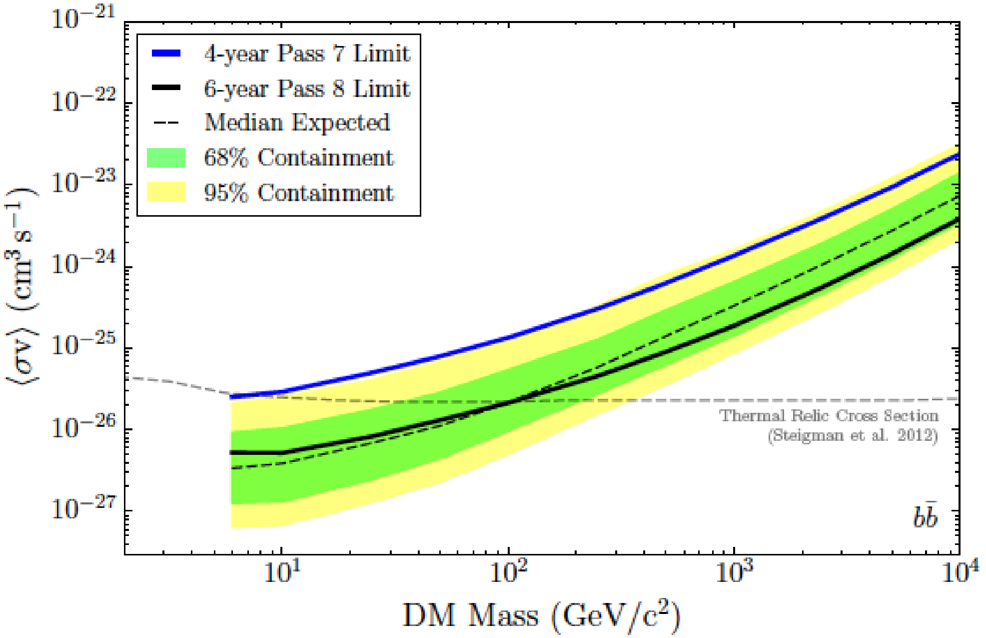
# *Constraints on annihilating WIMPs*

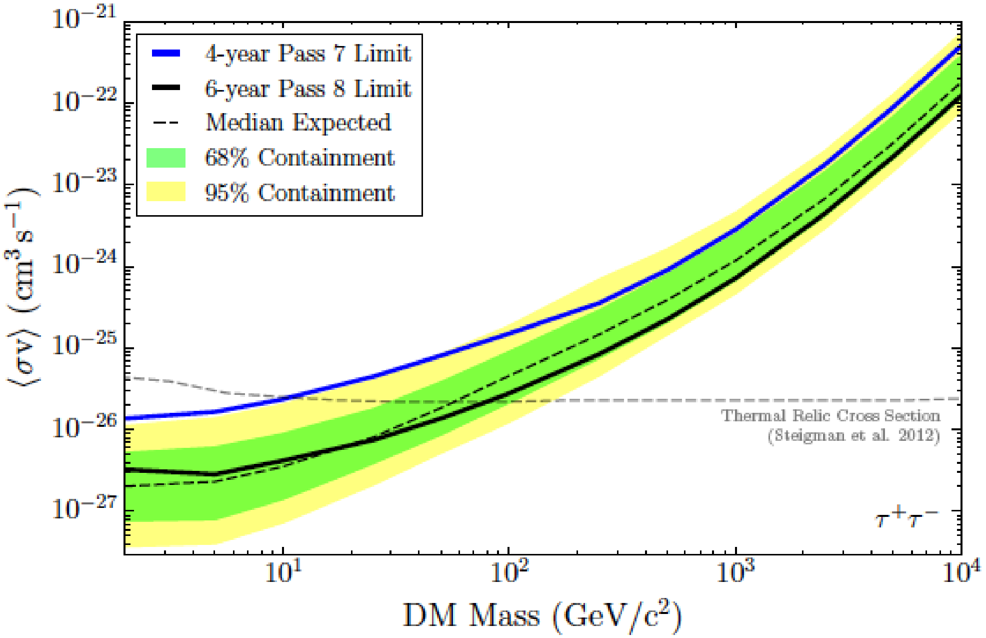




# *Backup*

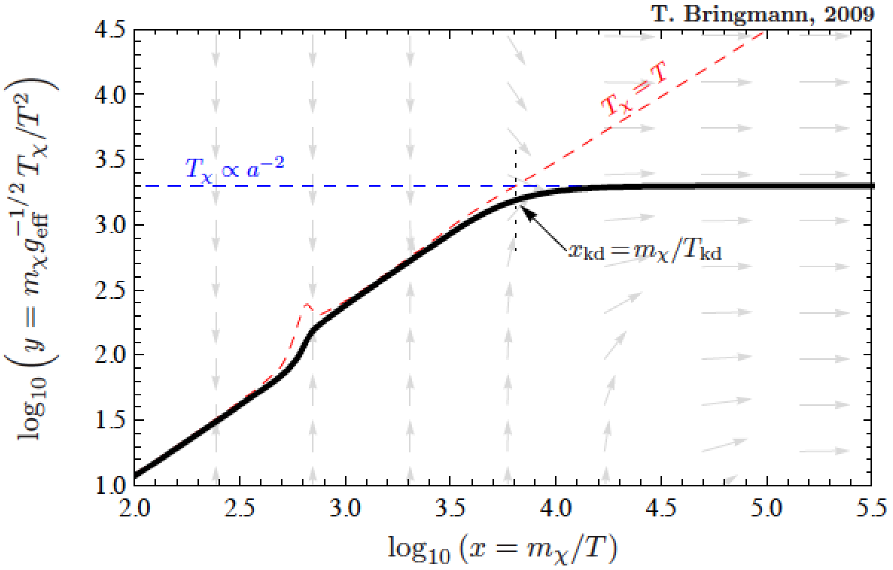
# *Gamma-rays constraints*





# *SUSY templates*

T. Bringmann 09

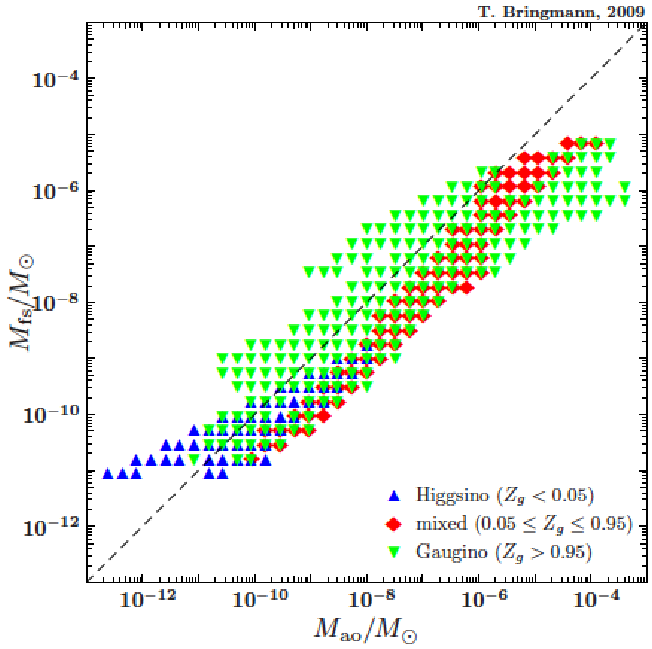


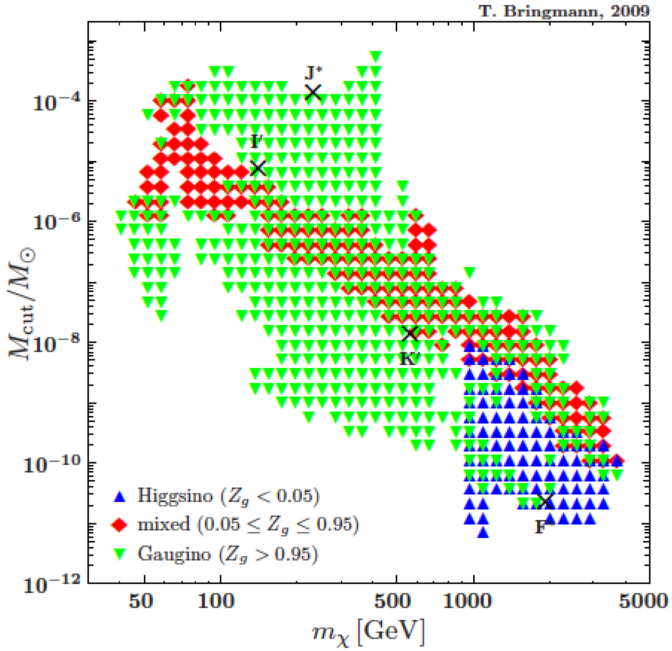
$$\hat{L}\,f = E\,\partial_t f - H\,|\vec{p}|^2\,\partial_E f = \hat{C}[f]$$

$$\frac{3}{2}T_\chi = \frac{\langle p_\chi^2\rangle}{2\,m_\chi} = \frac{\int d^3p\,p^2\,f(p)}{2\,m_\chi\int d^3p\,f(p)} = \frac{\int d^3p\,p^2\,f(p)}{2\,m_\chi\,(2\,\pi)^3\,n_\chi}$$

$$\{\partial_t + 5\,H\}\,T_\chi = 2\,m_\chi\,c(T)\,\{T - T_\chi\}$$

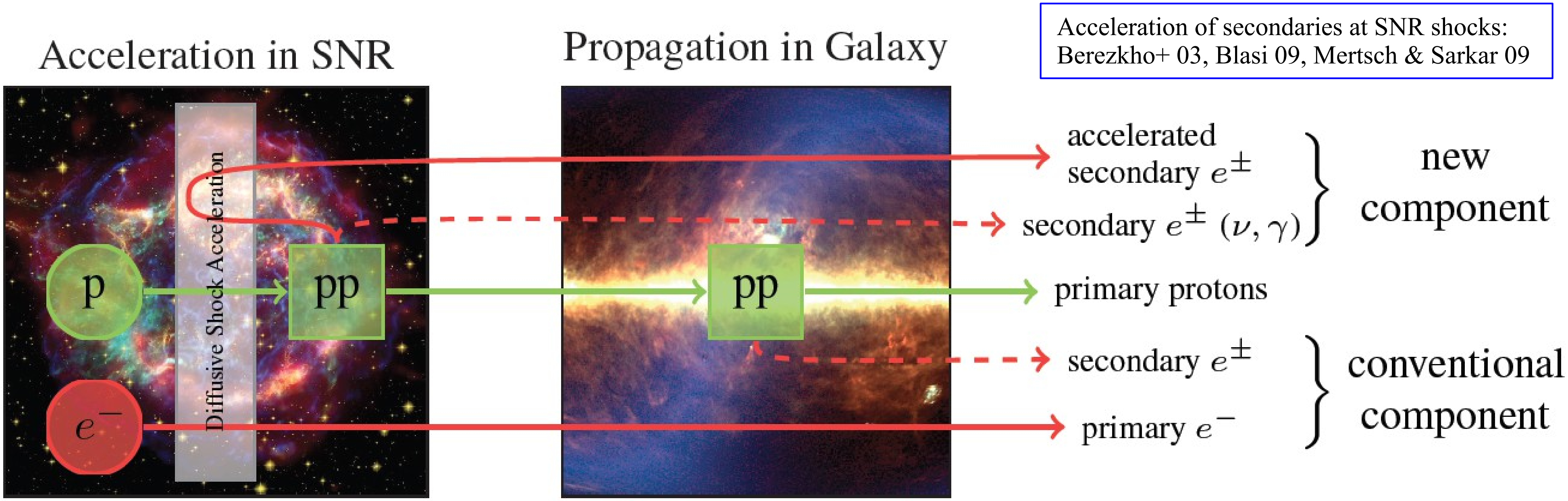
$$l_{\rm fs} = \frac{\pi}{k_{\rm fs}} = \int_{t_{\rm kd}}^{t_{\rm eq}} dt'\,\frac{v_\chi(t')}{a(t')} \propto (T_\chi^{\rm kd}/m_\chi)^{1/2}(a_{\rm kd}/a_{\rm eq}) \propto (m_\chi T_\chi^{\rm kd})^{-1/2}$$





# *Astrophysical primaries?*

Acceleration of secondaries at SNR shocks:
Berezkho+ 03, Blasi 09, Mertsch & Sarkar 09



Acceleration in SNR

Propagation in Galaxy

accelerated secondary $e^\pm$

secondary $e^\pm$ $(\nu, \gamma)$

} new component

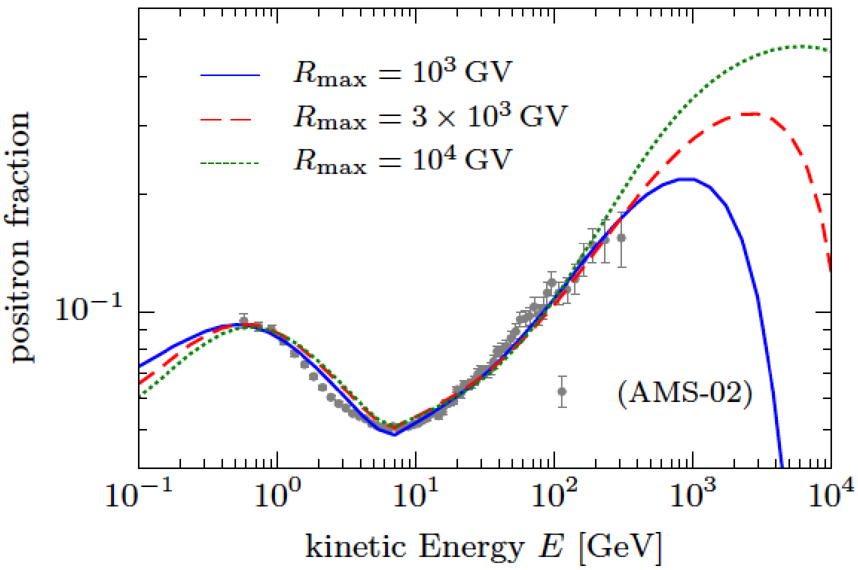
primary protons

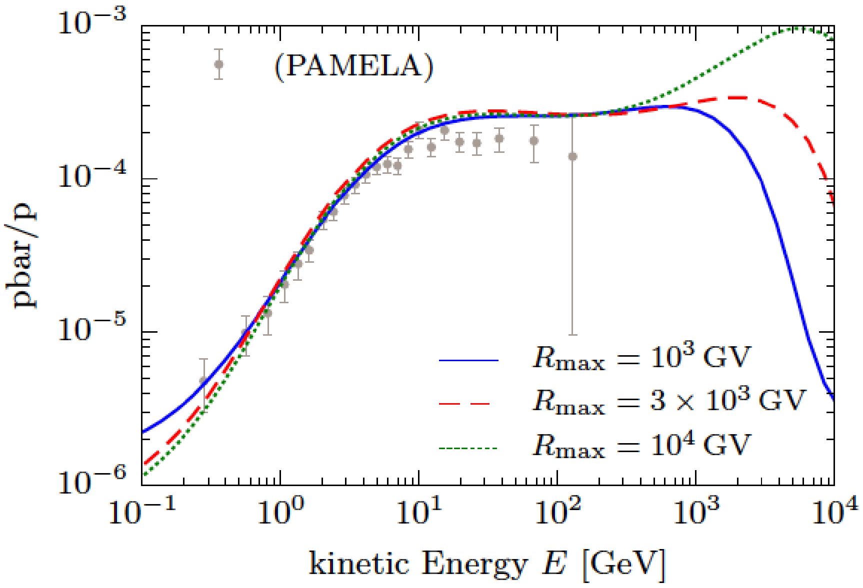
secondary $e^\pm$

primary $e^-$

} conventional component

Alhers+ 09

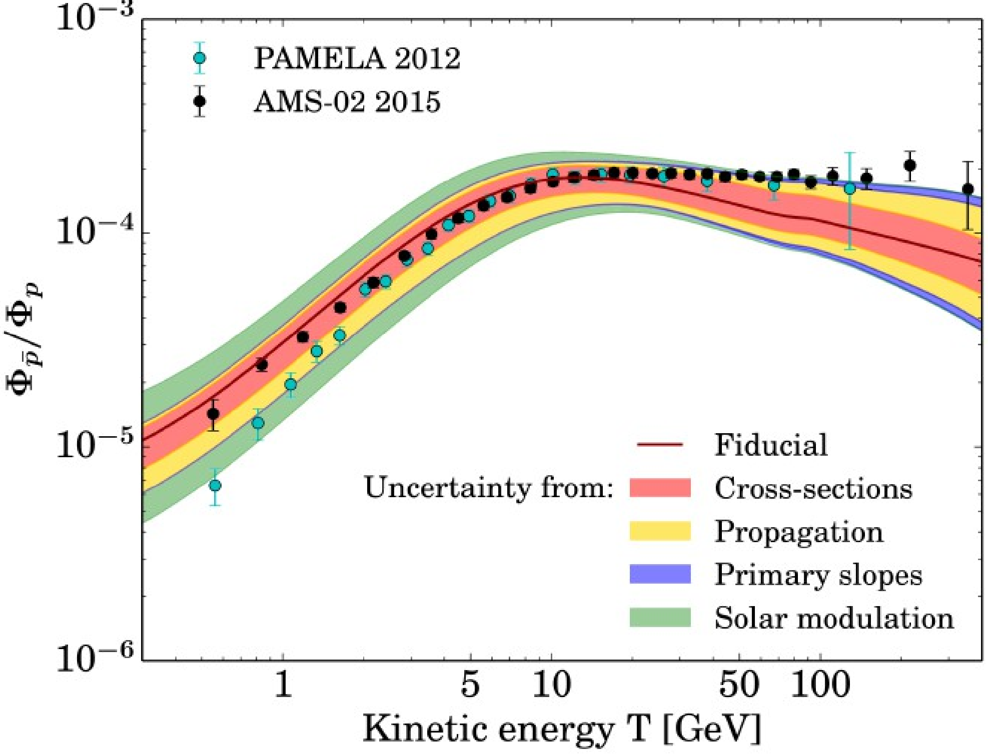




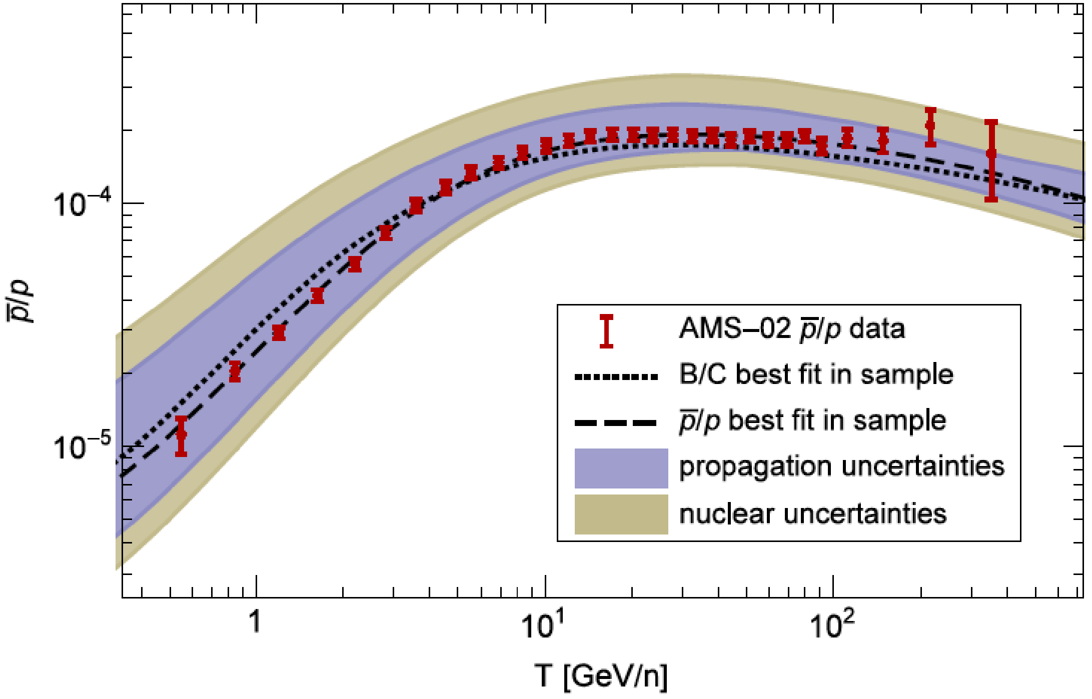
Mertsch & Sarkar 14

# *Predictions for secondaries?*

Giesen, Boudaud++15 (USINE)
Transport parameters from pre-AMS02 B/C data

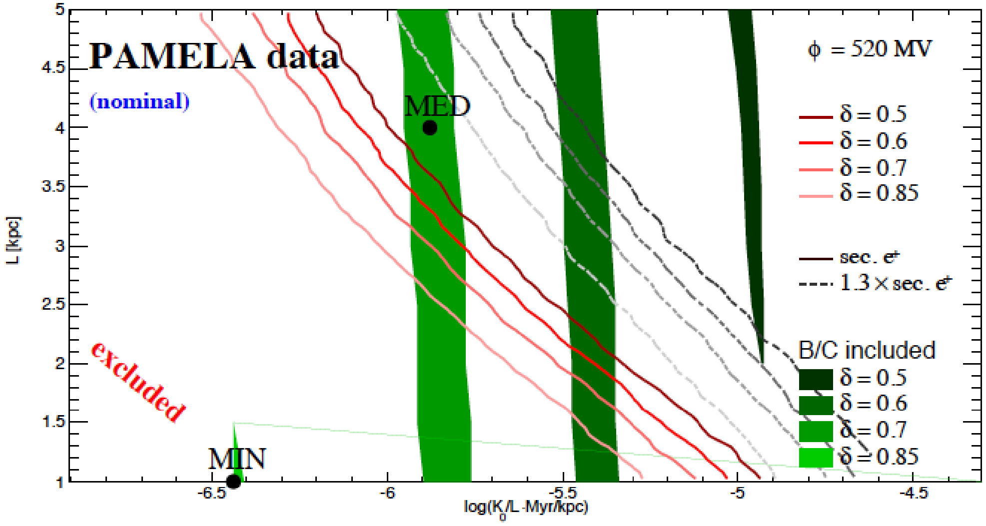


Kappl, Reinert & Winkler 15
Transport parameters from prelim. B/C AMS-02

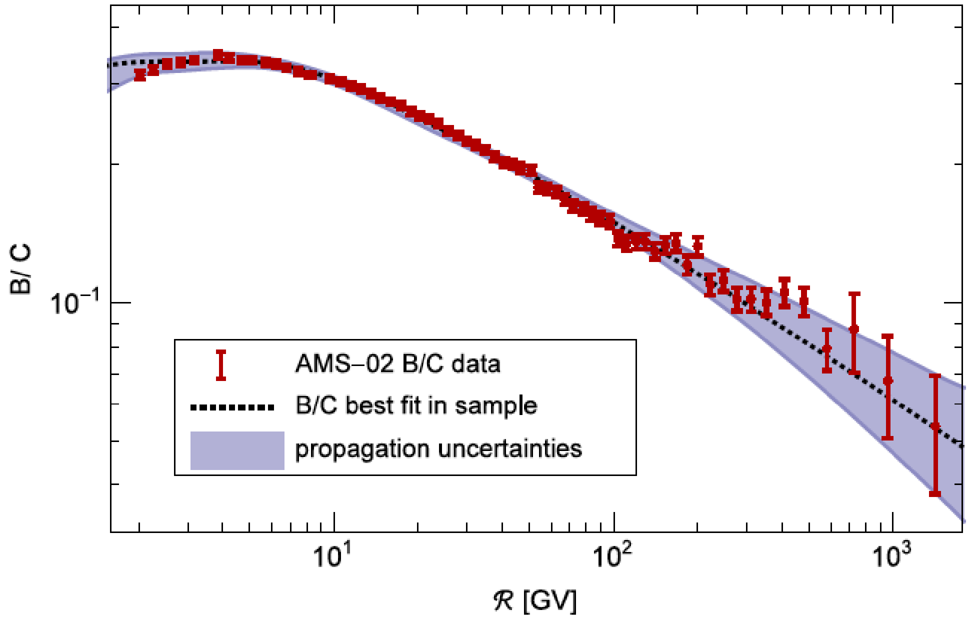


# *From WIMPs to subhalos*

JL, Maurin, Putze 14
Positron constraints on diffusion models



Kappl+15
B/C from AMS-02 prelim. data



| $\delta$ | $K_0$ (kpc$^2$ Myr$^{-1}$) | $L$ (kpc) | $V_c$ (km s$^{-1}$) | $V_a$ (km s$^{-1}$) |
|---|---|---|---|---|
| 0.408 | 0.0967 | 13.7 | 0.2 | 31.9 |