“Even more on subhalos”

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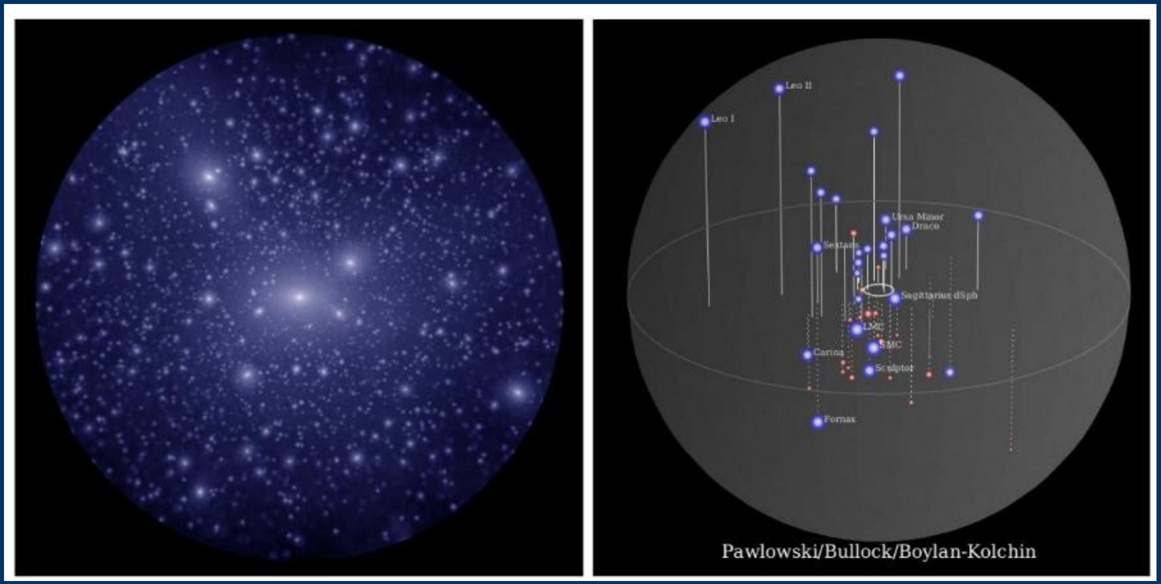
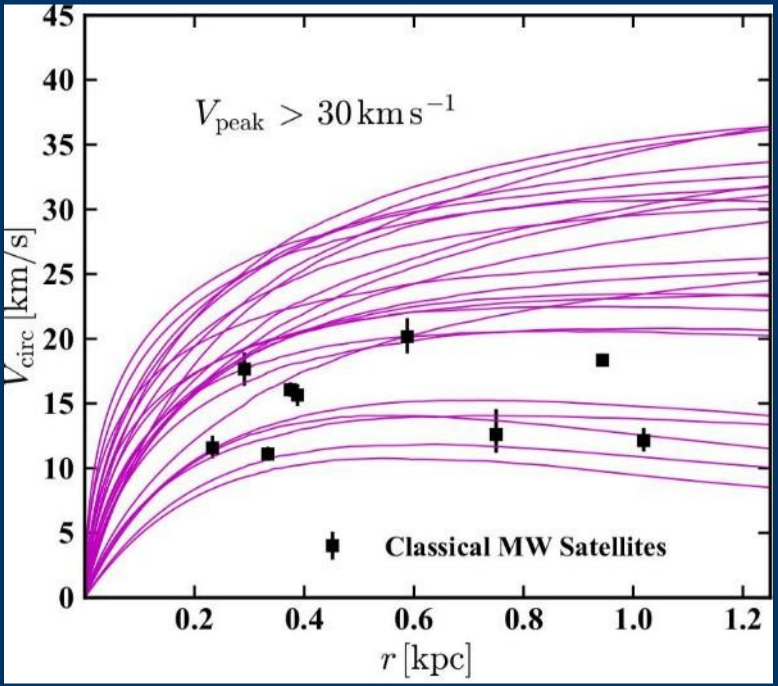
OCEVU

Small-scale challenges of ΛCDM

Missing satellites

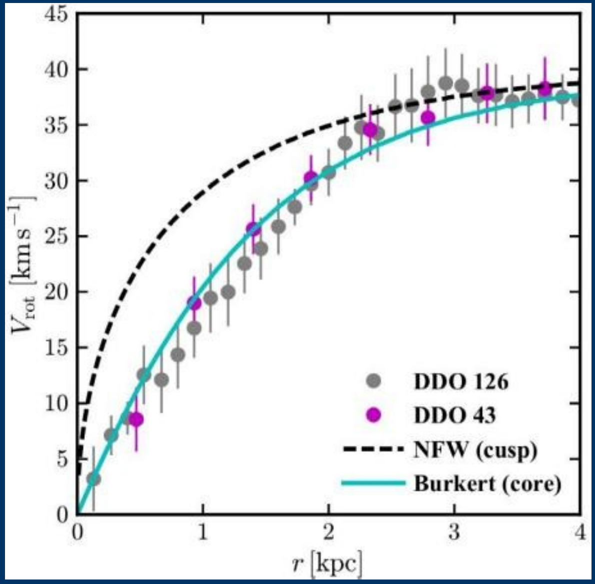


Too big to fail



Review by Bullock & Boylan-Kolchin 17

core-vs-cusp

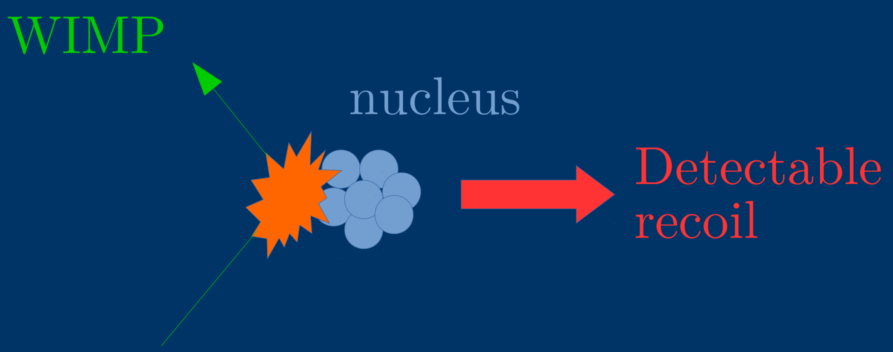


DM halos in ΛCDM are
- Too numerous
- Too concentrated

Possible solutions
- DM physics (SIDM, WDM)
- Baryonic physics

Subhalos and dark matter searches

Direct searches



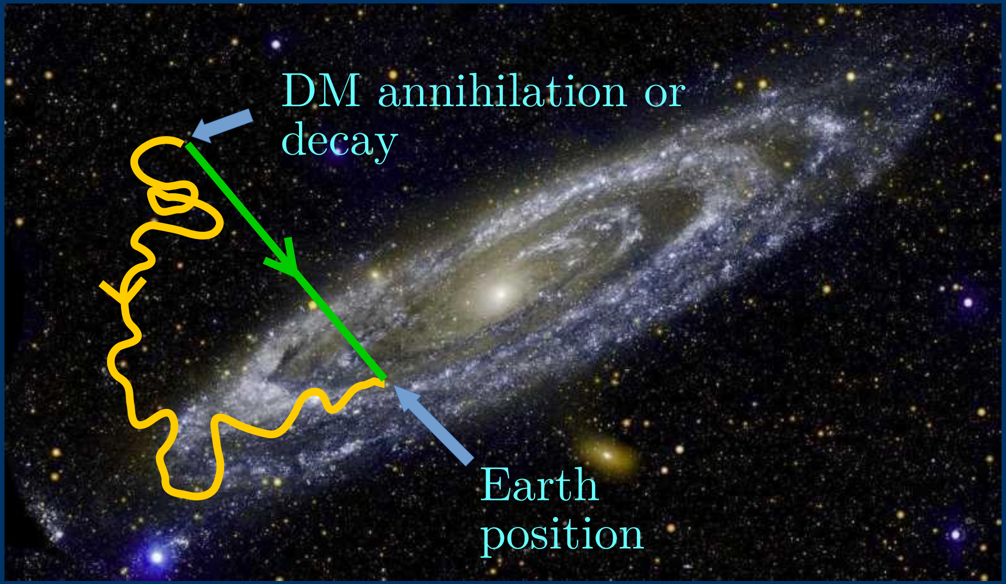
Differential event rate

$$\frac{\mathrm{d}R}{\mathrm{d}E_\mathrm{r}} = \mathrm{part.\,physics} \times \rho_\odot \int_{v_\mathrm{min}(E_\mathrm{r})}^{v_\mathrm{esc}} \frac{f_\odot(\vec{v})}{|\vec{v}|} \, \mathrm{d}^3\vec{v}$$

- Local DM density
- Local DM velocity DF

➡ Importance of the local clustering

Indirect searches



Probe of the (extra-)Galactic DM density profile via gamma rays, neutrinos or charged cosmic rays

Inhomogeneities boost the annihilation signal
Silk & Stebbins 93

+ dynamics: *e.g.* tidal force field of subhalos Penarrubia 17

Modeling subhalos: numerical vs analytical

Numerical simulations

- Self-consistent modeling of gravity
- Non-linear evolution
- Computing power
- Limited resolution
- Unconsistent with observed dynamics

Analytic models

- Unlimited resolution
- Easy implementation of cosmo/part. physics constraints
- Dynamically constrainable
- Approximations needed beyond the linear regime

→ Semi-analytic approach = analytic calculations + calibration on simulations

- Cosmo, part. phys and dynamical constraints
- No resolution limit
- Reproduces numerical simulations results

Dynamically constrained model of Galactic subhalos

Stref & Lavalle 17

<u>Cosmology and particle physics:</u>
- Halo mass function
- Concentration distribution

Subhalo spatial distribution

$$\boxed{\frac{\mathrm{d}P}{\mathrm{d}V} \propto \rho_{\mathrm{DM}}}$$

<u>Dynamical constraints:</u>
- DM density profile ρ_{DM}
- Baryonic distribution

<u>Tidal effects:</u>
- Halo stripping
- Disc shocking

Calibration on simulation

<u>Outputs:</u>
- Post-tides mass, concentration and spatial distribution
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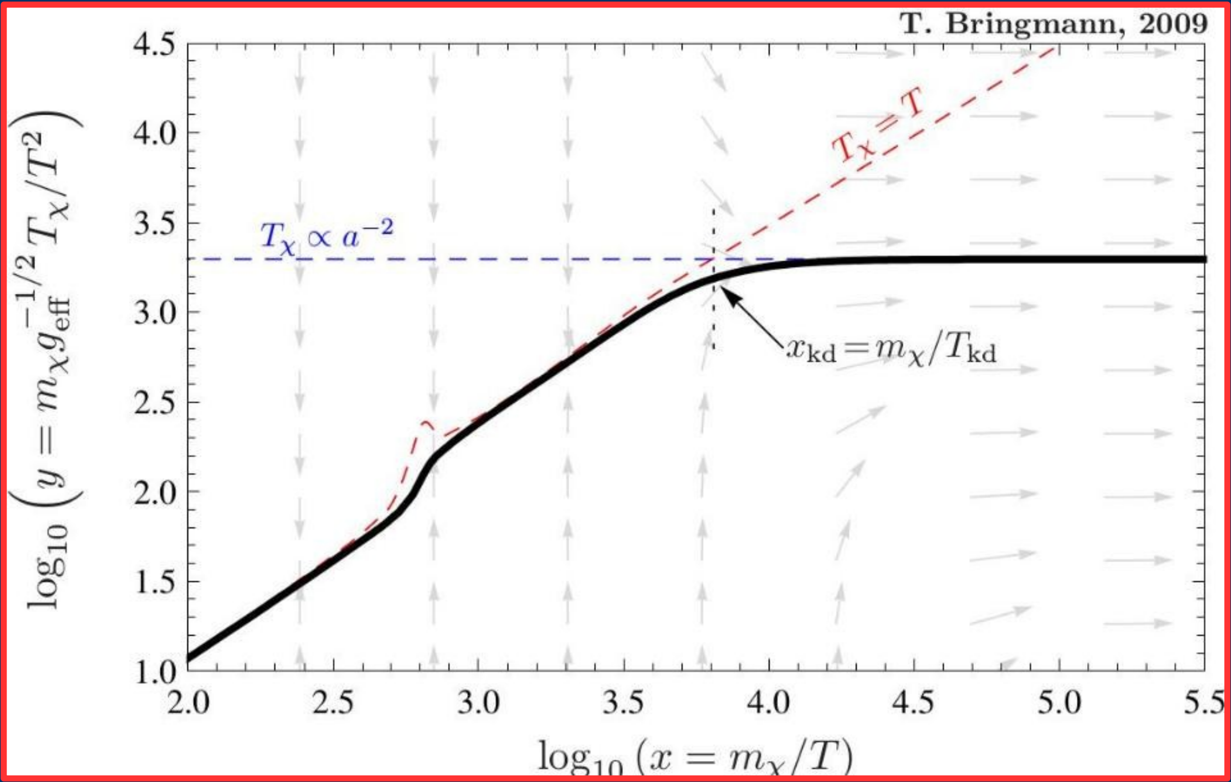
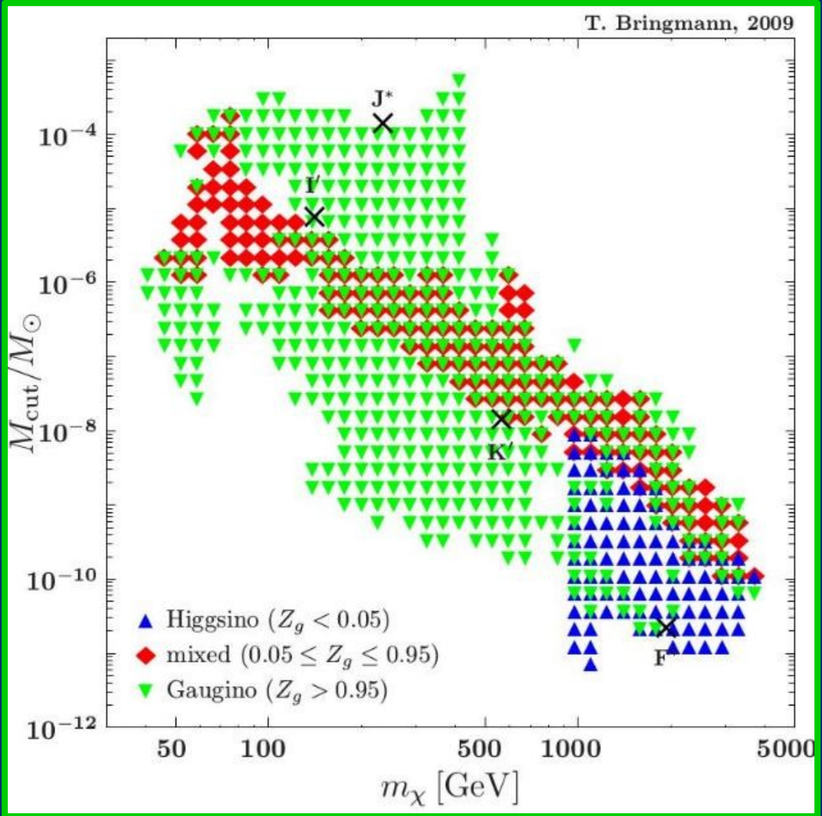
Birth of CDM halos

Size of first CDM halos set by kinetic decoupling $\boxed{H(t_{\rm kd}) = \Gamma_{\rm scat}(t_{\rm kd})}$



See *e.g.* Berezinsky+ 03, Green+ 05, Profumo+ 06
Bringmann & Hofmann 07,
Bringmann 09

SUSY example:



Free-streaming length

$$l_{\rm fs} = \int_{t_{\rm kd}}^{t_{\rm eq}} \frac{v_\chi(t')}{a(t')}\, {\rm d}t'$$

Minimal mass

$$\boxed{M_{\rm fs} = \frac{4}{3}\pi\, \rho_\chi(t_{\rm eq})\, l_{\rm fs}^3}$$

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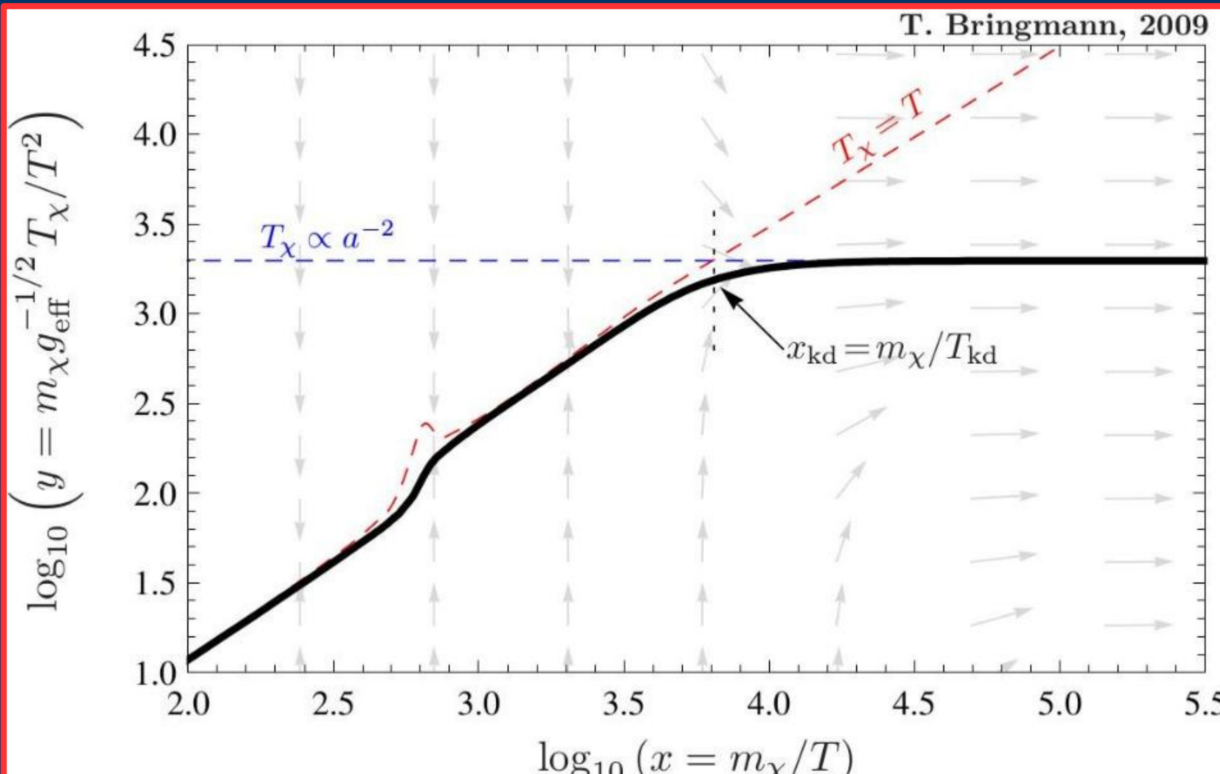

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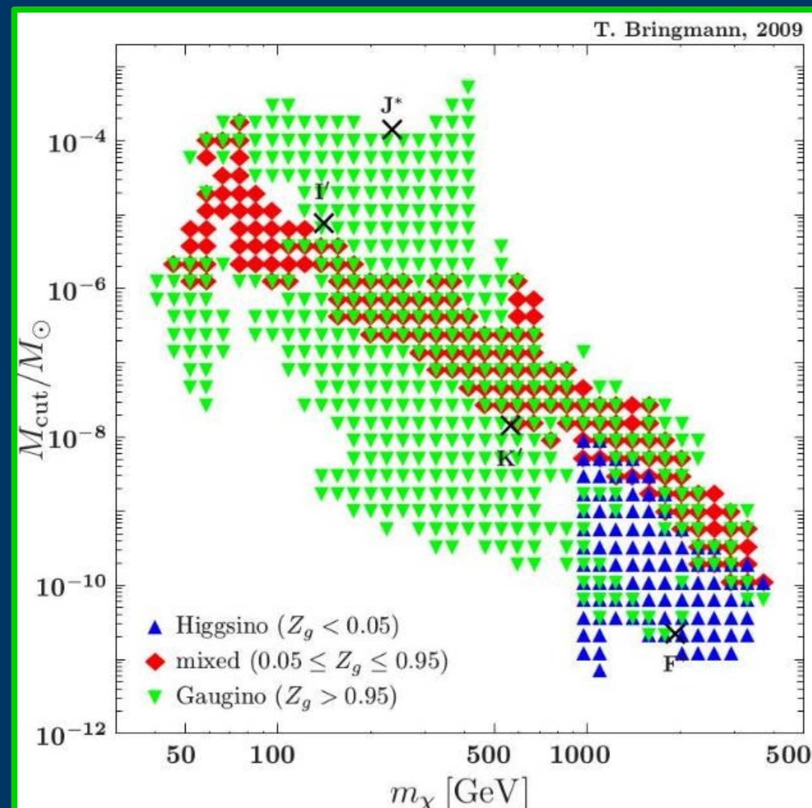


Similar cutoff for QCD axion CDM (non-thermal):
Minicluster mass

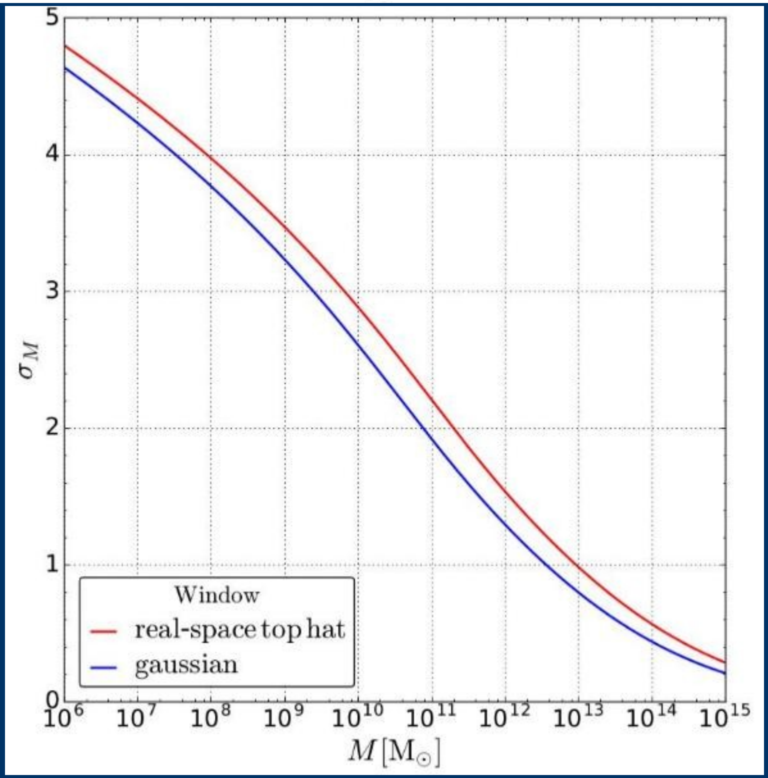
$$M_{\rm mc} \sim 10^{-10} - 10^{-12}\,{\rm M}_\odot$$

Kolb & Tkachev 96

Halo mass function

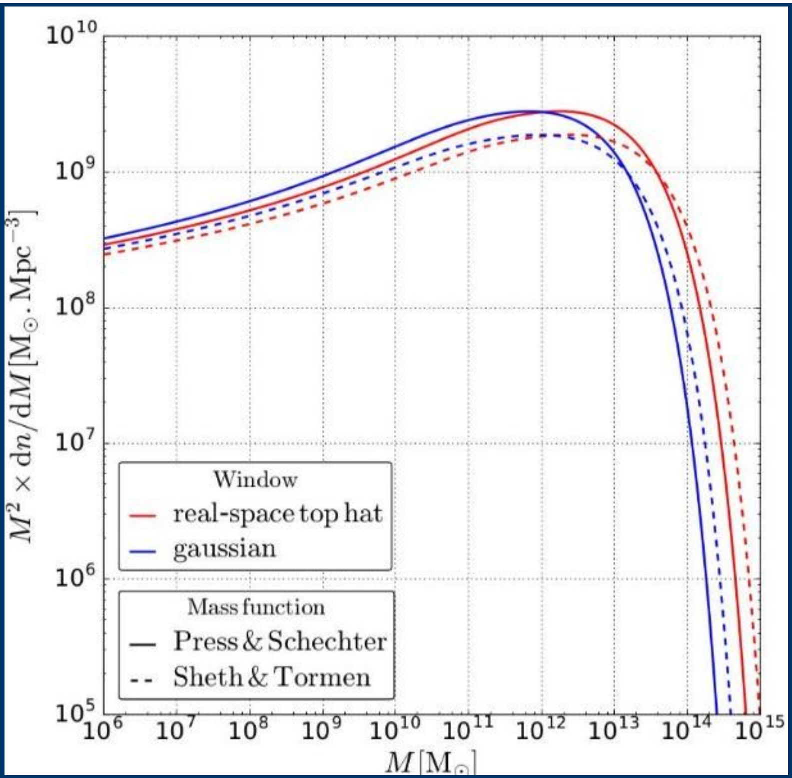
Mass variance

$$\sigma^2(M) = \frac{1}{2\pi^2} \int \mathrm{d}k\, k^2\, P(k)\, |W(k,M)|^2$$



Press & Schechter mass function (1974)

$$\frac{\mathrm{d}n}{\mathrm{d}M} = \sqrt{\frac{2}{\pi}}\, \frac{\rho_\mathrm{M}}{M^2}\, \frac{\delta_\mathrm{c}}{\sigma} \left| \frac{\mathrm{d}\ln\sigma}{\mathrm{d}\ln M} \right| \exp\left(-\frac{\delta_\mathrm{c}^2}{2\sigma^2}\right)$$



See *e.g.* Bond+ 91, Sheth & Tormen 99, Zentner 07

Halo mass function

Cosmological parameters n_s σ_8 Ωcdm

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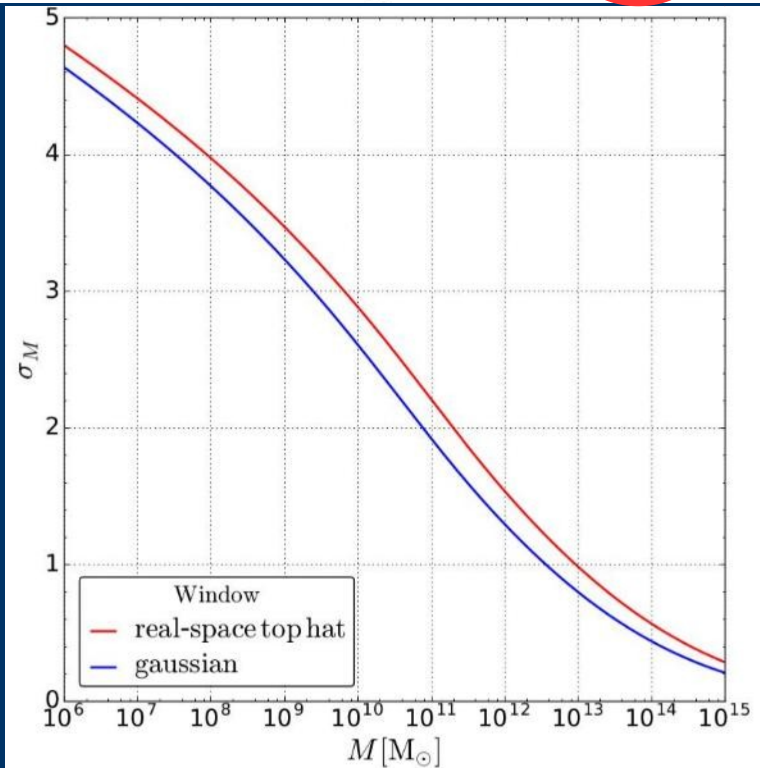
$$\sigma^2(M) = \frac{1}{2\pi^2}\int \mathrm{d}k\, k^2 P(k)\, |W(k,M)|^2$$



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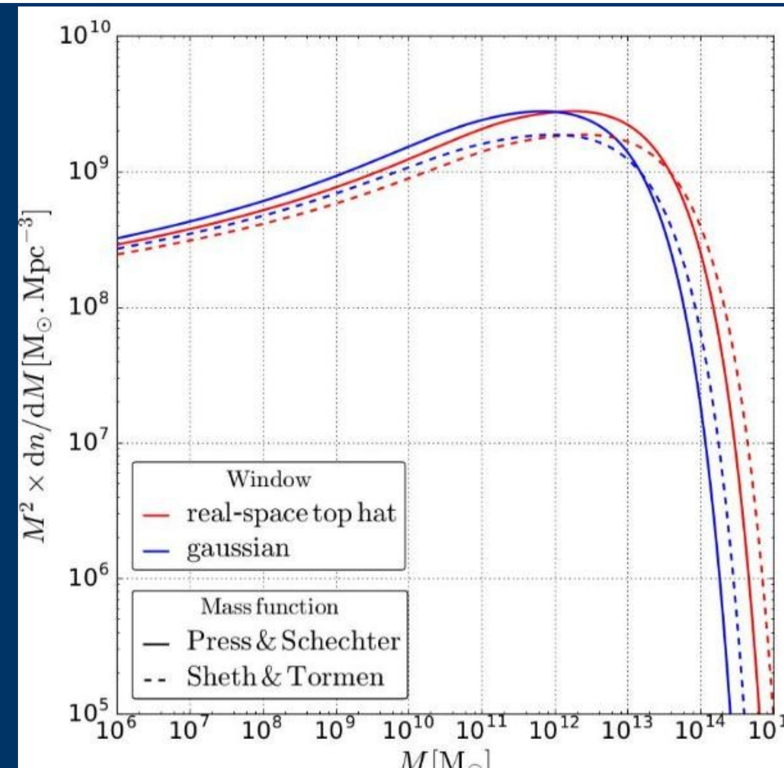


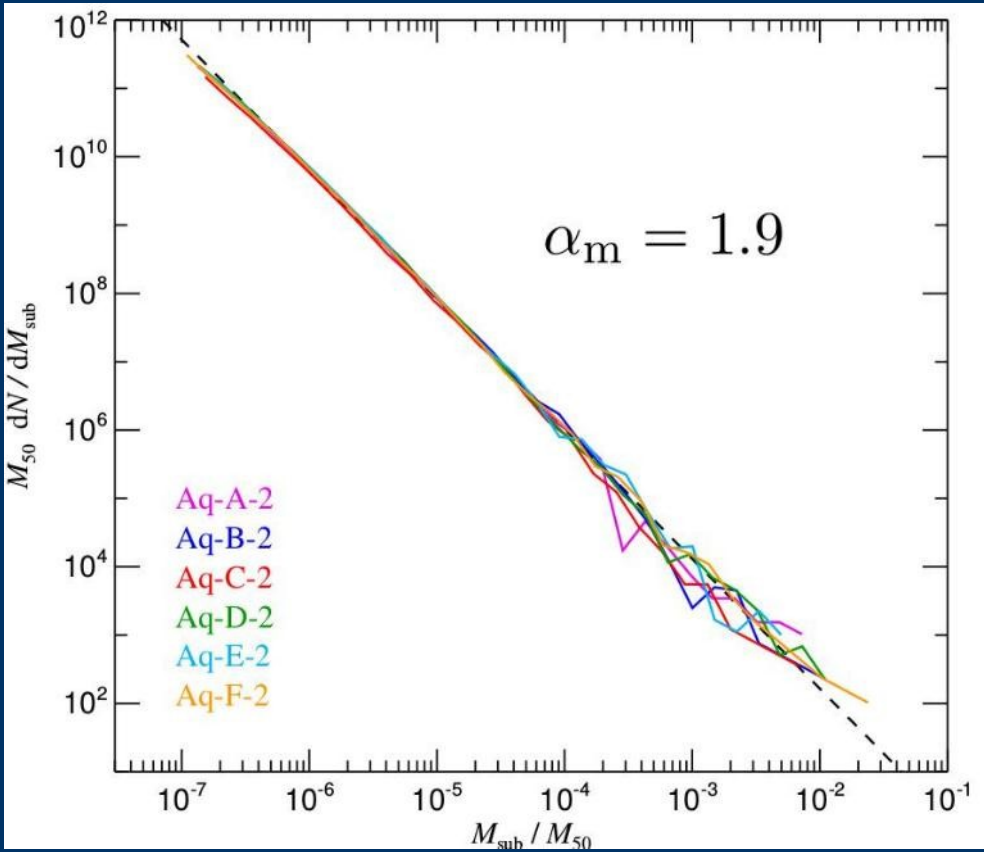
See *e.g.* Bond+ 91, Sheth & Tormen 99, Zentner 07

Halo mass function: Effective description

Aquarius simulation (Springel+ 08)

Below the galactic scale: power-law

$$\boxed{\begin{aligned} \frac{\mathrm{d}n}{\mathrm{d}m} &\propto m^{-\alpha_\mathrm{m}} \\ \alpha_\mathrm{m} &\simeq 2 \end{aligned}}$$



Sharp cutoff at $\mathrm{m} = \mathrm{m}_\mathrm{min}$

- Cosmology in α_m
- Particle physics in m_min

Concentration

Pseudo-virial radius:

$$\frac{m(r_{200})}{\frac{4}{3}\pi r_{200}^3} = 200\,\rho_{\rm crit}$$

$\sim$ scale radius:

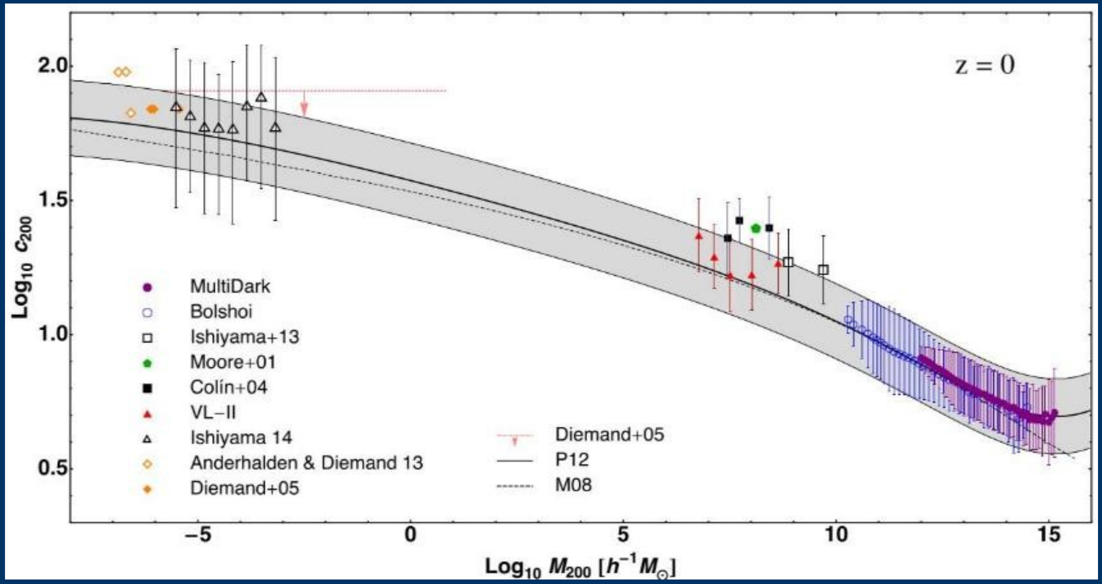
$$\left.\frac{\mathrm{d}\ln\rho}{\mathrm{d}\ln r}\right|_{r=r_{-2}} = -2$$

$$\boxed{c_{200} \equiv \frac{r_{200}}{r_{-2}}}$$

Direct measure of the internal density

Smaller halos collapse earlier in a denser Universe → correlation between mass and concentration

Mass-concentration correlation



Relation recovered in simple semi-analytic models (Bullock+ 01, Maccio+ 08, Prada+ 12)

→ Link to cosmological parameters

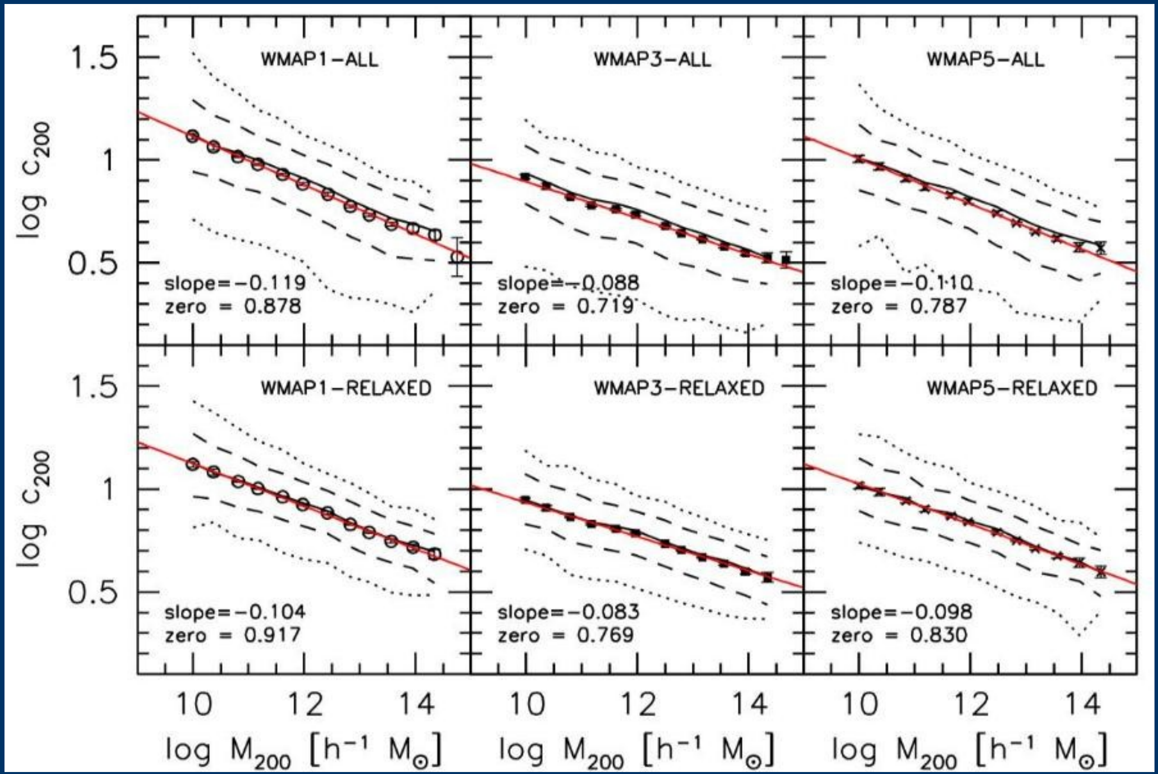
Sanchez-Conde & Prada 14

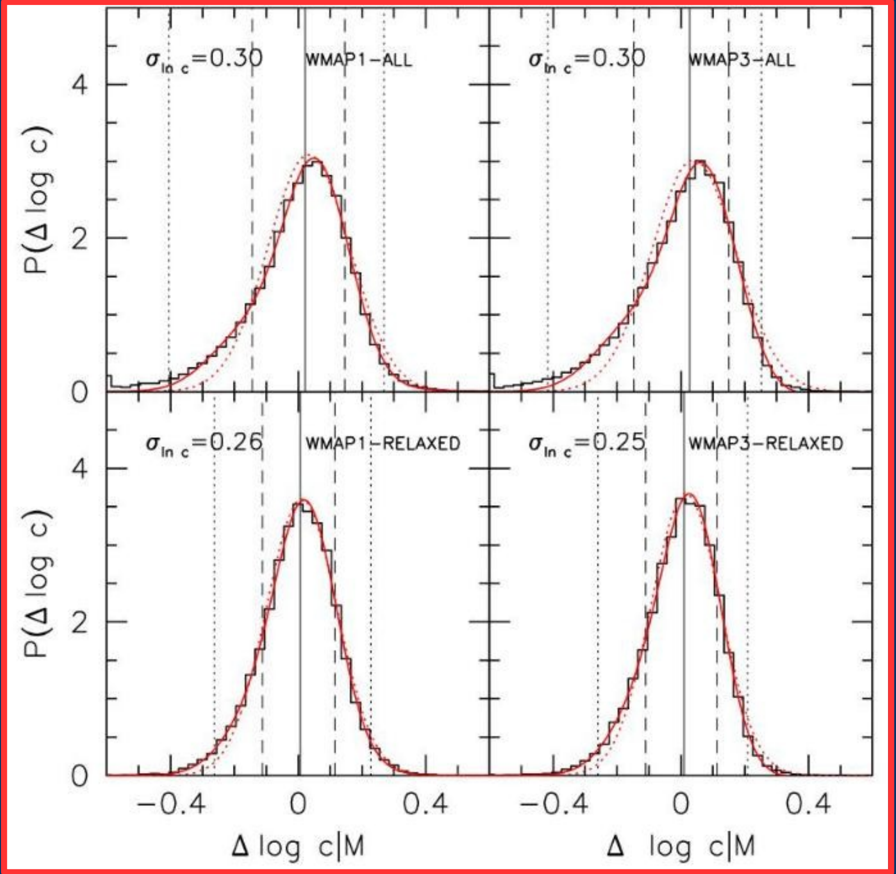
Concentration II

Log-normal distribution

$$\frac{\mathrm{d}P}{\mathrm{d}c_{200}}(c_{200}, \bar{c}) = \frac{1}{\sqrt{2\pi\sigma_{\mathrm{c}}^2}\, c_{200}} \exp\left[-\frac{(\ln c_{200} - \ln \bar{c})^2}{2\sigma_{\mathrm{c}}^2}\right]$$

- $\bar{c} = \bar{c}(m_{200})$ median concentration
- σ_c = constant, independent of the mass





Maccio+ 08

Dynamically constrained model of Galactic subhalos

Stref & Lavalle 17

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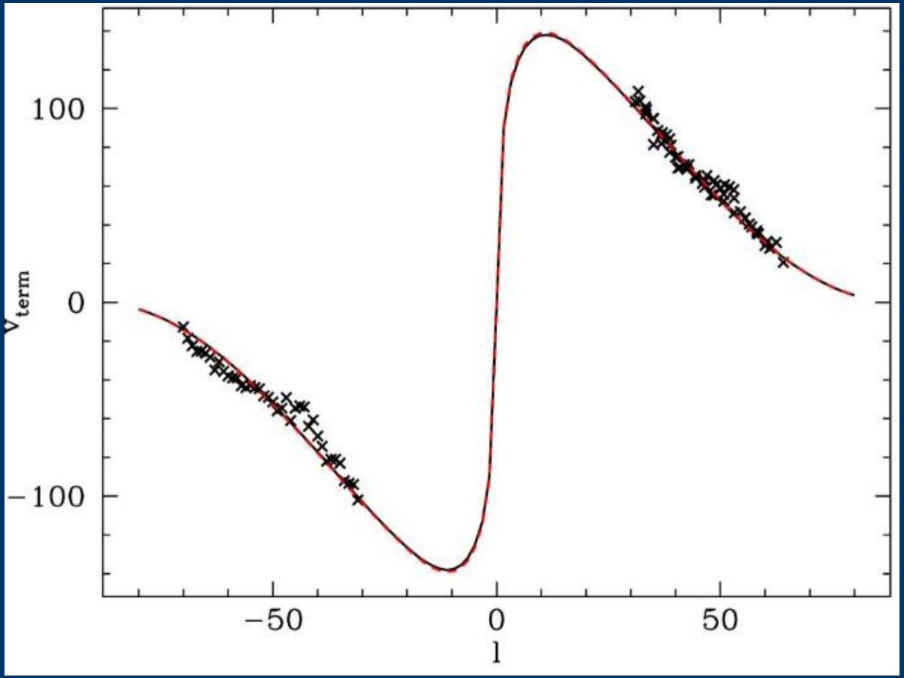
Dynamical constraints

Mass distribution of DM and baryons: ρ_{DM} ρ_{bulge} ρ_{disc} …

e.g. McMillan 11, 17

Kinematical data:

- Maser observations
- Solar velocity
- Terminal velocity curves
- Vertical force
- Mass within large radii



McMillan 11

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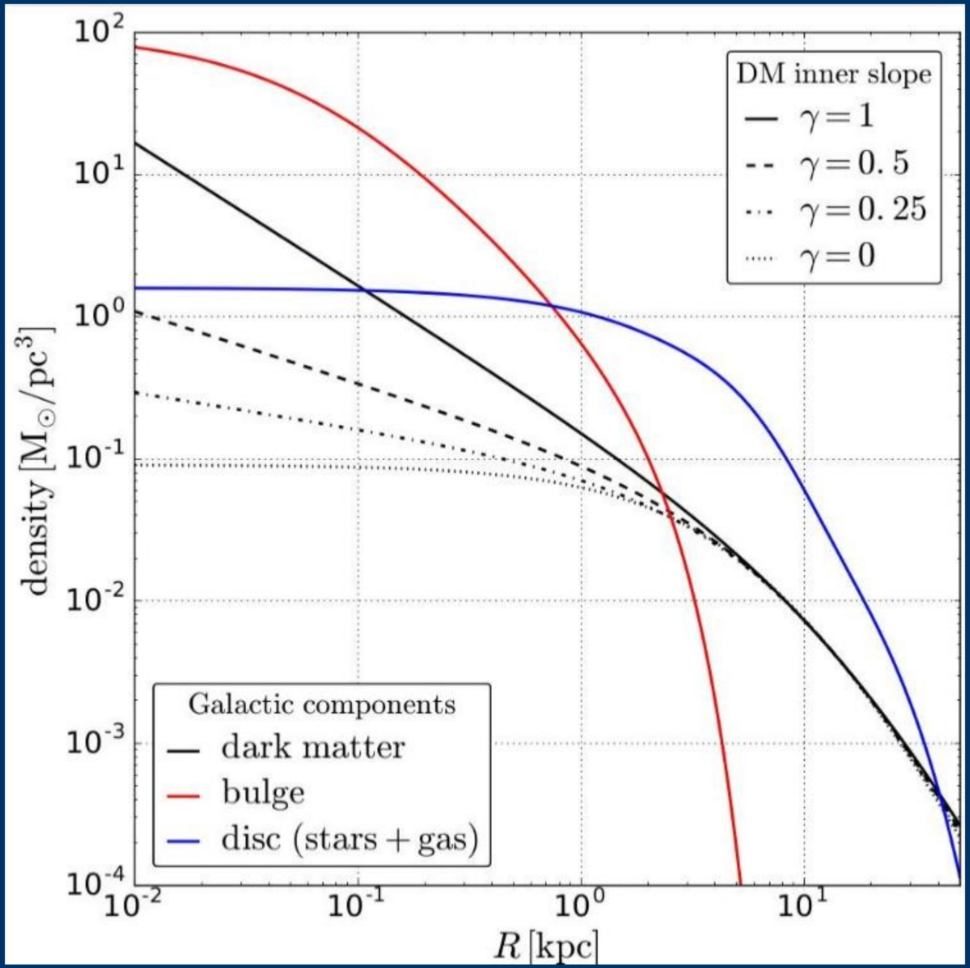

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Tidal effects: tides from the host (1)

Competition between host's potential and subhalo's potential :

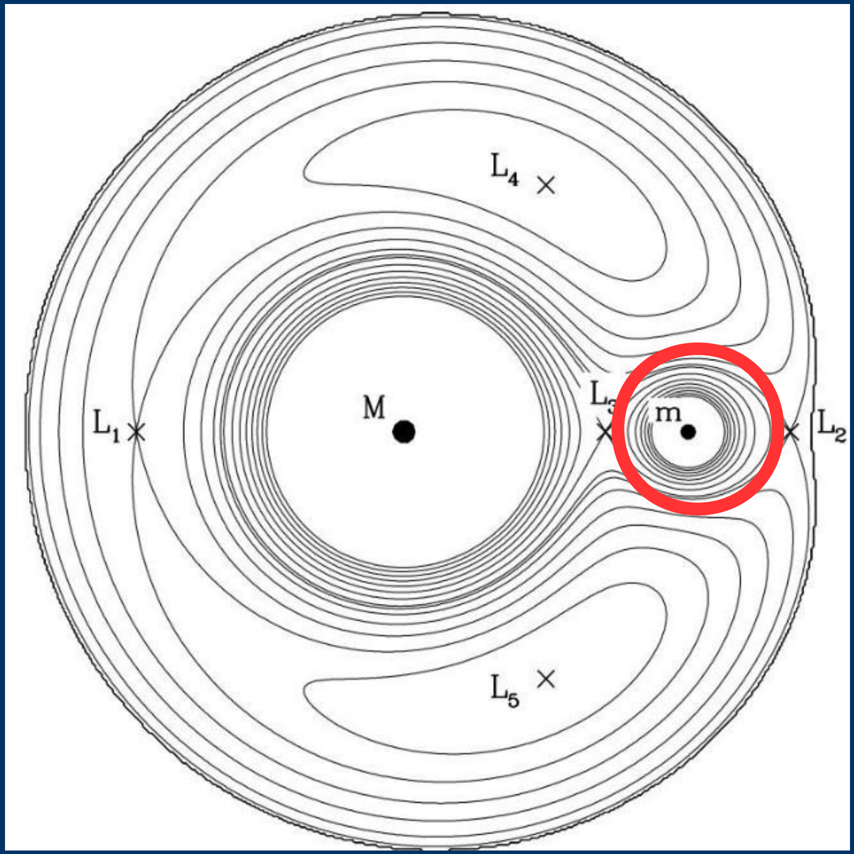
→ Tidal radius

For a host with a smooth mass distribution:

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

subhalo's tidal radius

Position in the Galaxy



Binney & Tremaine 08

Assumes circular orbits for the subhalos

Tidal effects: tides from the host (2)

Competition between host's potential and subhalo's potential :
→ Tidal radius

For a host with a smooth mass distribution:

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

subhalo's tidal radius

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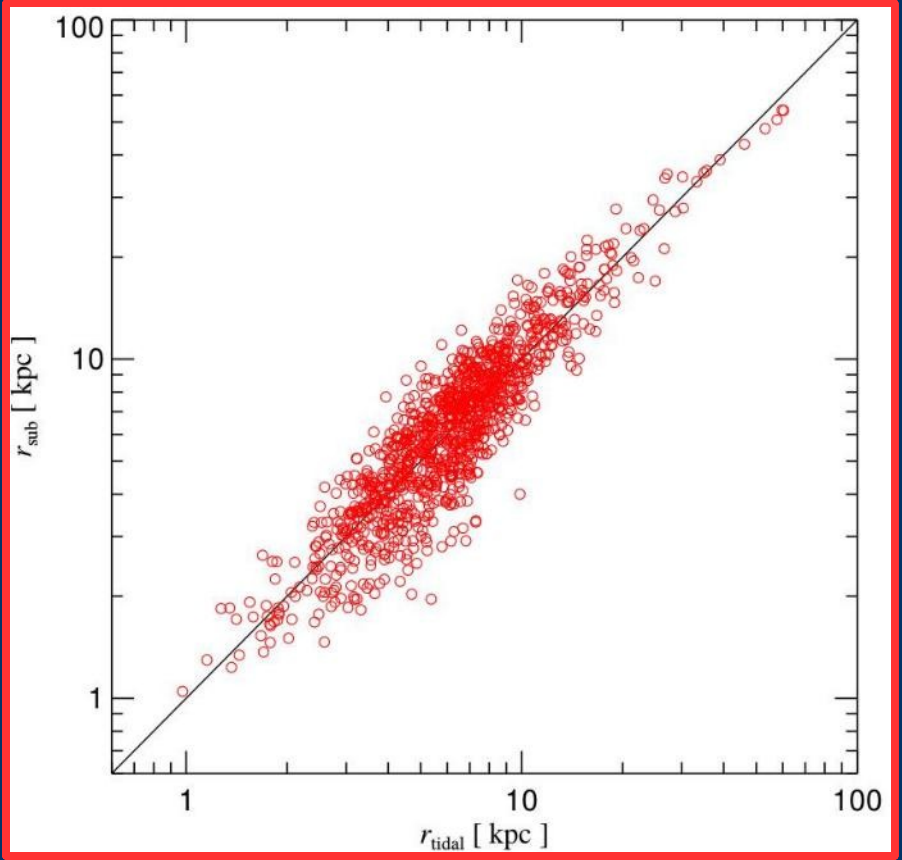


Aquarius simulation Springel+ 08

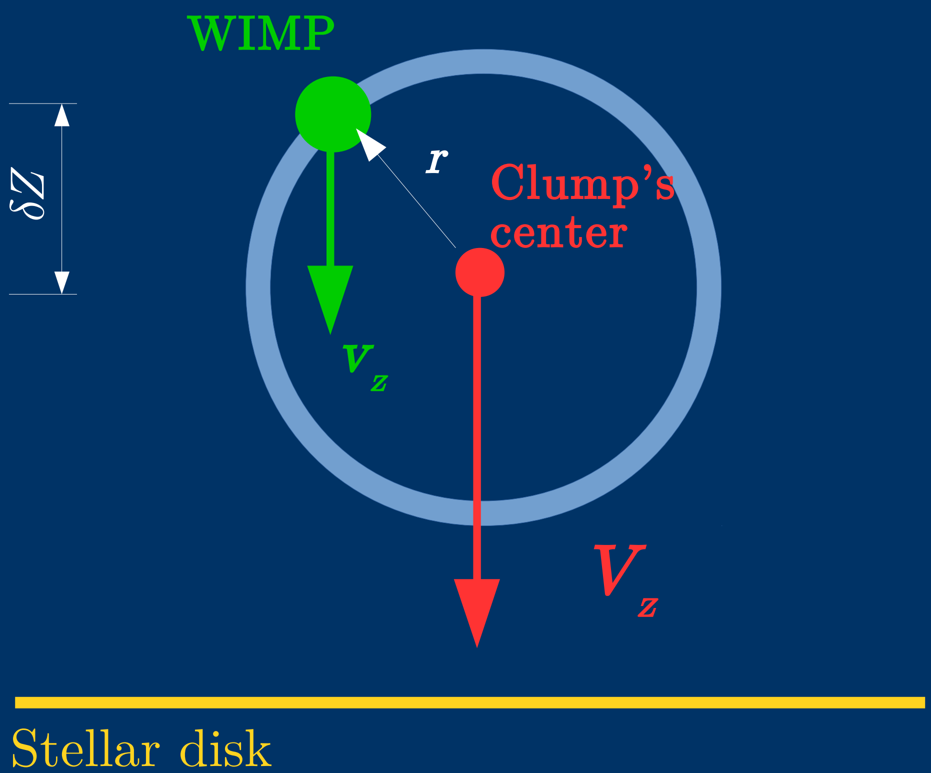
Assumes circular orbits for the subhalos

Tidal effects: disc shocking (1)

Computation by Ostriker+ 72 for globular clusters crossing the disc

Impulsive approximation : clump's inner dynamics is frozen

$$\frac{\mathrm{d}v_z}{\mathrm{d}t} \simeq \delta Z \, \frac{\mathrm{d}g_z}{\mathrm{d}z}$$



Average kinetic energy increase per particle mass:

$$\langle \delta\epsilon \rangle = \frac{2\, g_z^2\, r^2}{3\, V_z}\, A(\tau\omega)$$

A adiabatic correction Gnedin & Ostriker 99
τ crossing time
ω clump orbital frequency

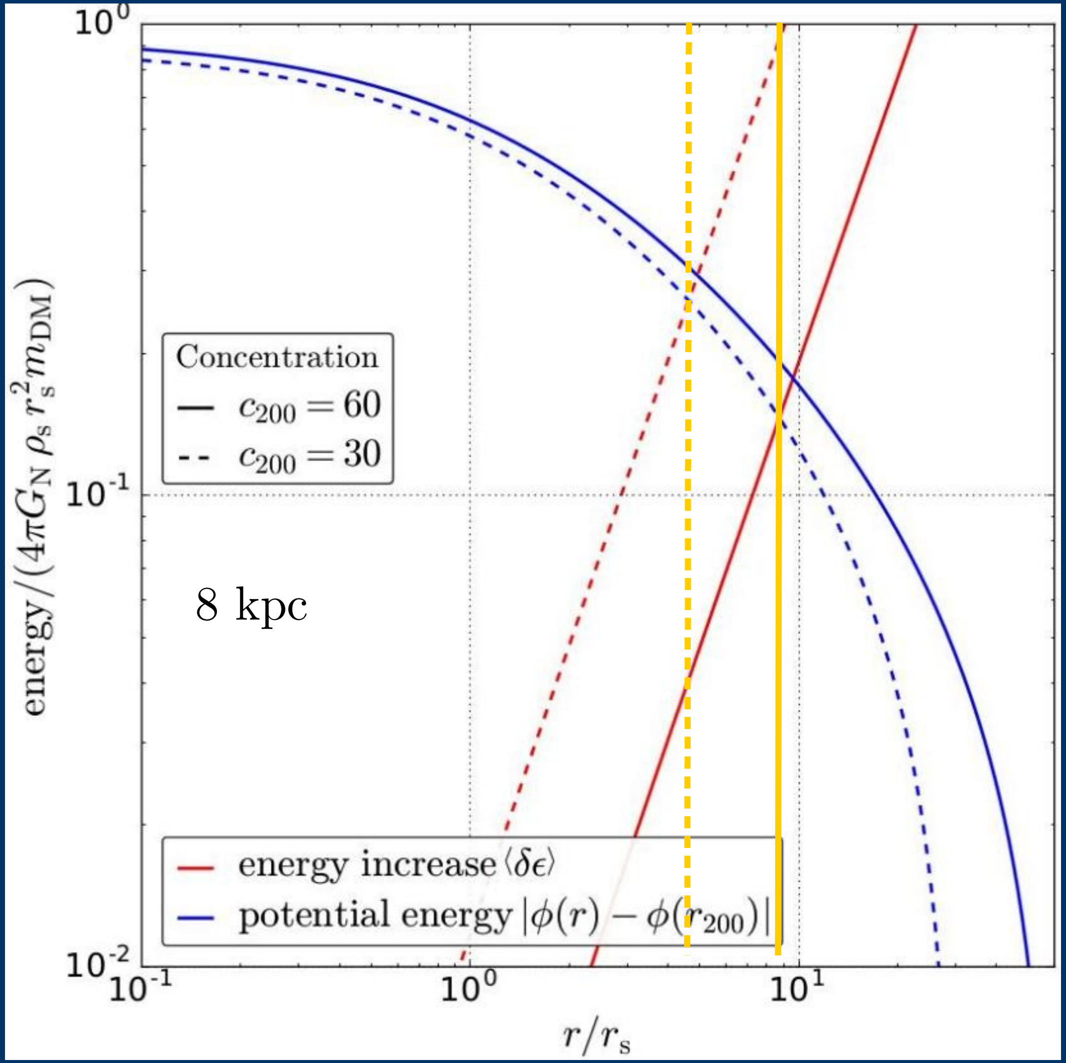
$$A(\tau\omega) \to \begin{cases} 1 & \text{for } \tau\omega \ll 1 \\ 0 & \text{for } \tau\omega \gg 1 \end{cases}$$

Tidal effects: disc shocking (2)

Tidal shocking radius definition

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

- Iterative computation: r_t changes at each crossing
- Assumes circular orbits



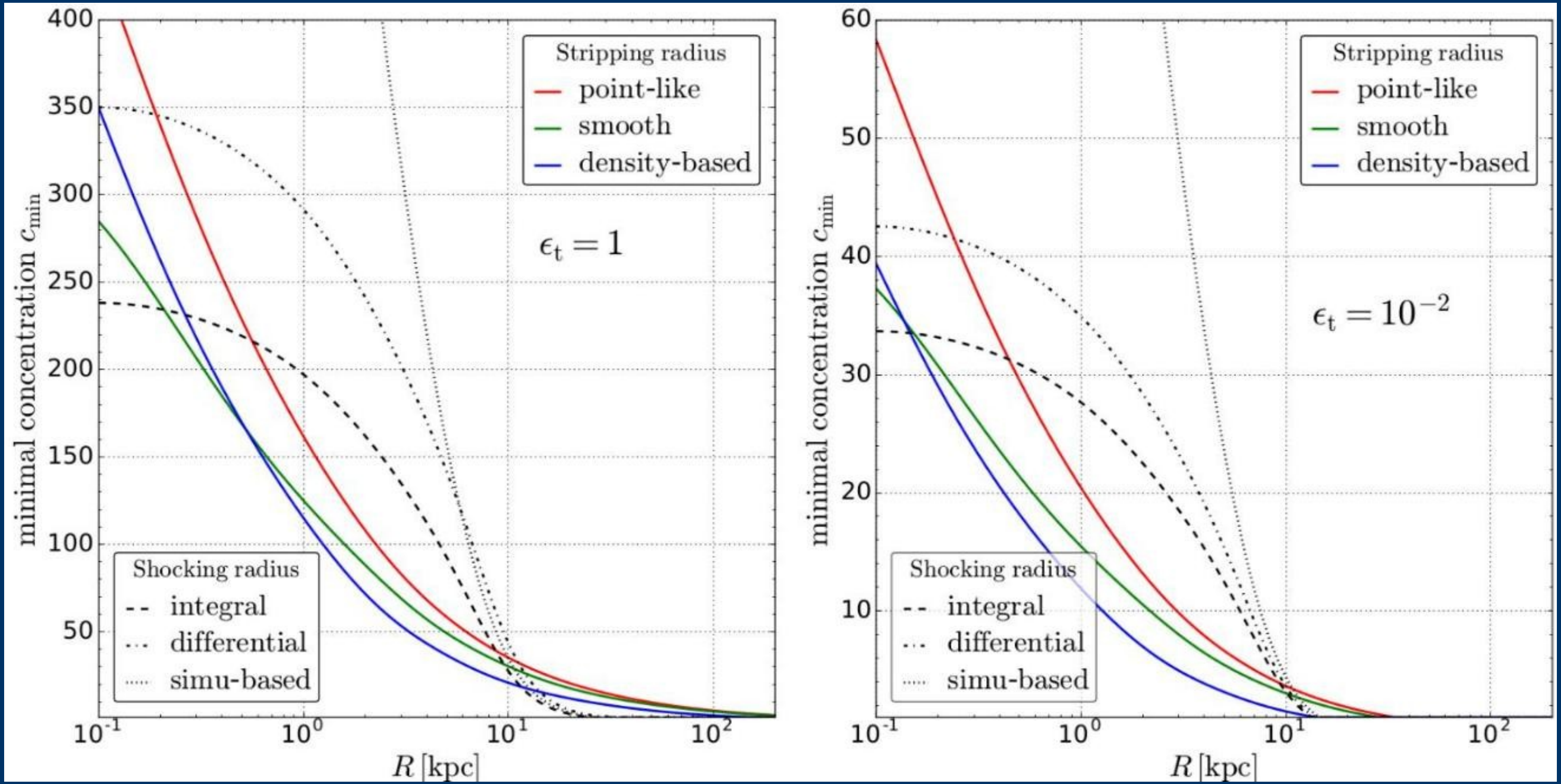
Numerical studies of disc shocking
D'Onghia+ 10, Errani+ 17

Subhalo disruption?

$$\frac{r_t}{r_s} \leqslant \epsilon_t \iff c_{200} \leqslant c_{\min}$$ Disruption criterion

Realistic value for ε_t ?

- $\varepsilon_t \sim 1$ from simulations Hayashi+ 03
- $\varepsilon_t \sim 0$? from recent studies van den Bosch+ 17, van den Bosch & Ogiya 18



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Calibration on an N-body simulation

Calibration of the *resolved* subhalo mass fraction on a DMO simulation

➡ Avoid uncertainties related to baryons

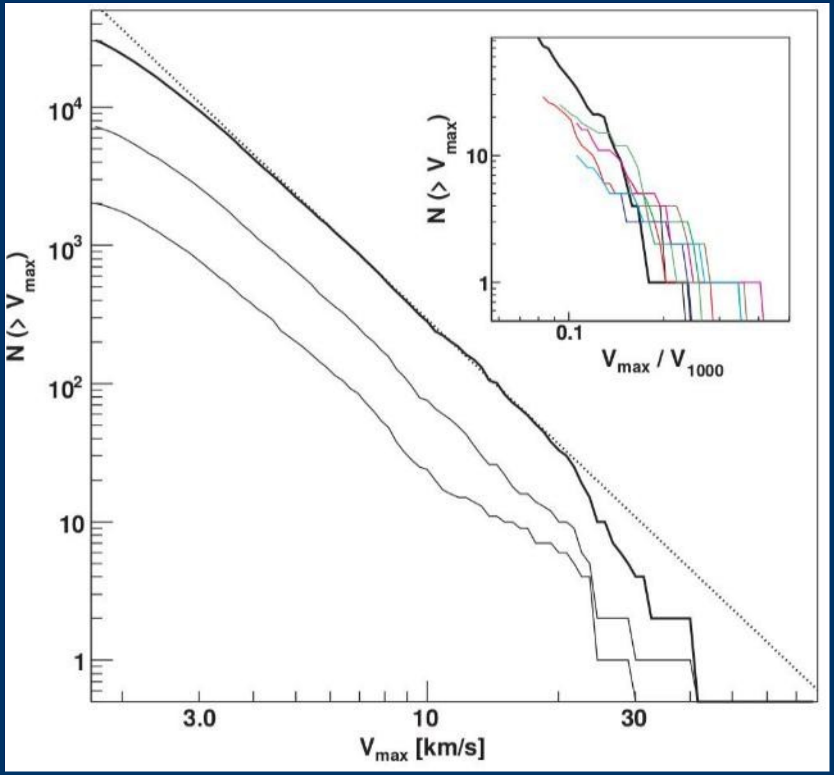
Limit : only valid for DMO tides and $\varepsilon_t \sim 1$

In other configurations (*e.g.* with the disc or low ε_t), the number of subhalos is found by assuming tides don't affect subhalos in the outskirts of the Galactic halo

$N_{\rm sub}\,(\epsilon_{\rm t}=1)$	$M_{\rm min}=10^{-10}$	$M_{\rm min}=10^{-6}$
$\alpha_{\rm m}=1.9$	4.79×10^{18}	1.20×10^{15}
$\alpha_{\rm m}=2$	2.60×10^{20}	2.59×10^{16}

$N_{\rm sub}\,(\epsilon_{\rm t}=0)$	$M_{\rm min}=10^{-10}$	$M_{\rm min}=10^{-6}$
$\alpha_{\rm m}=1.9$	4.97×10^{18}	1.25×10^{15}
$\alpha_{\rm m}=2$	2.70×10^{20}	2.70×10^{16}

Diemand+ 08



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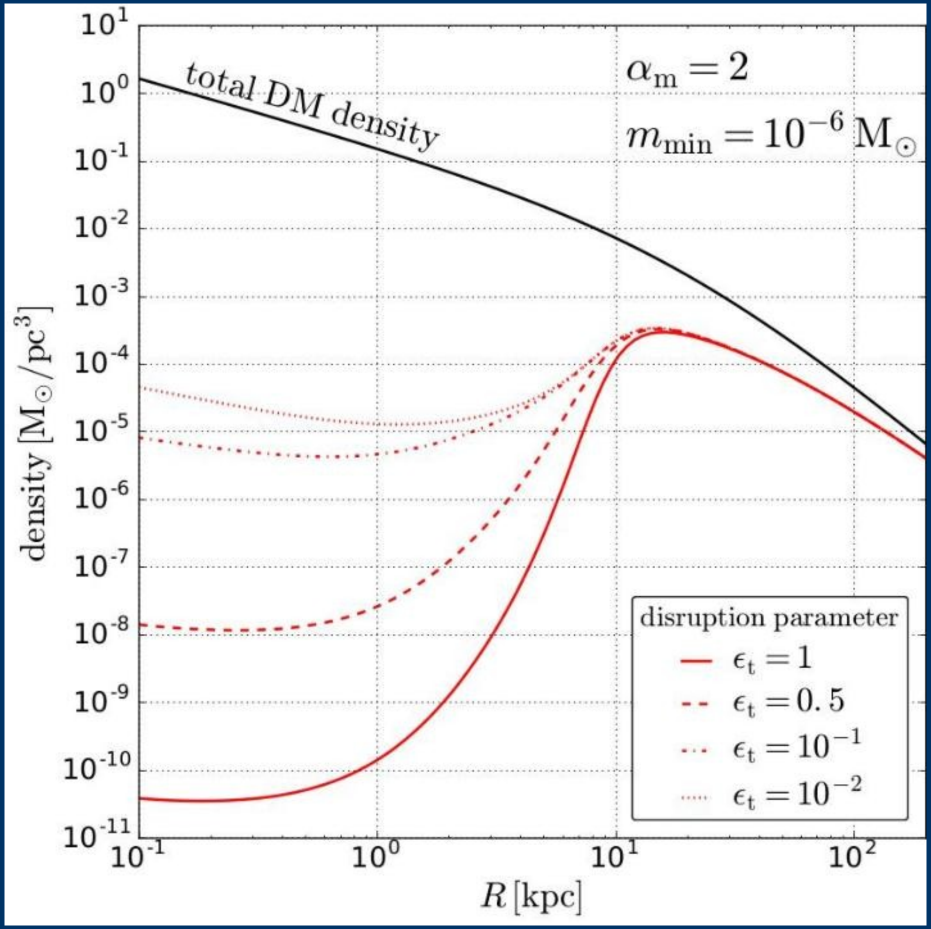
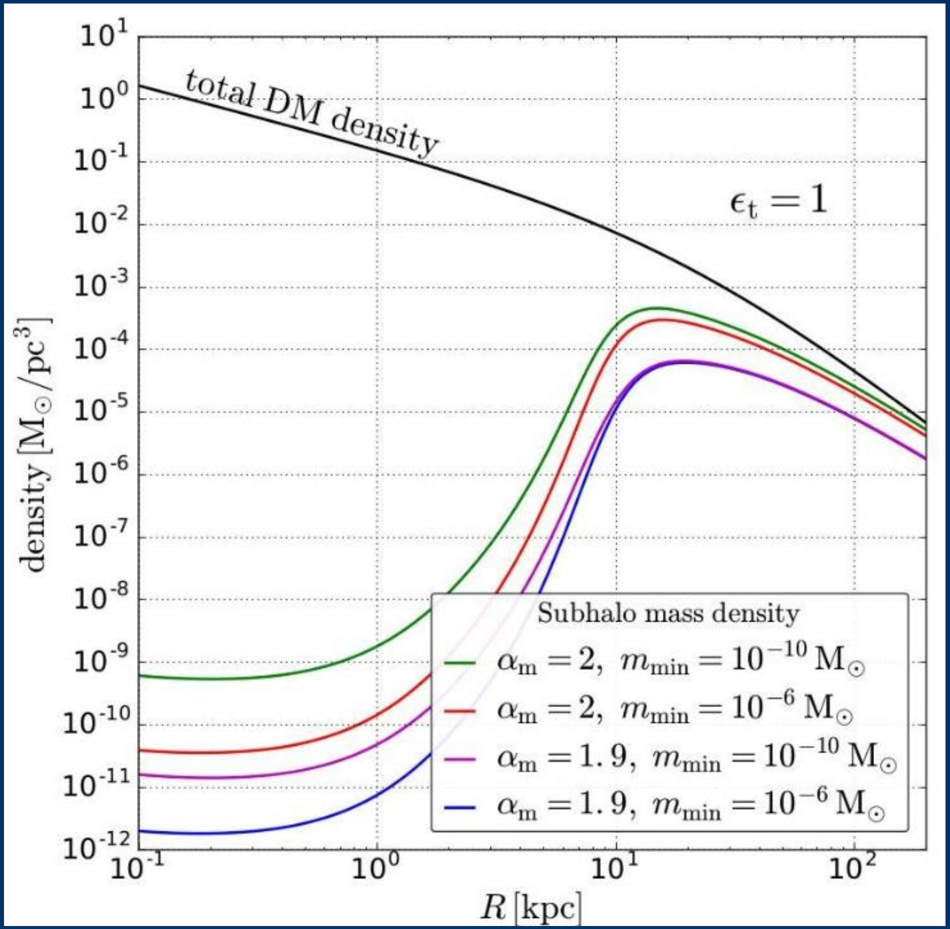
Mass density

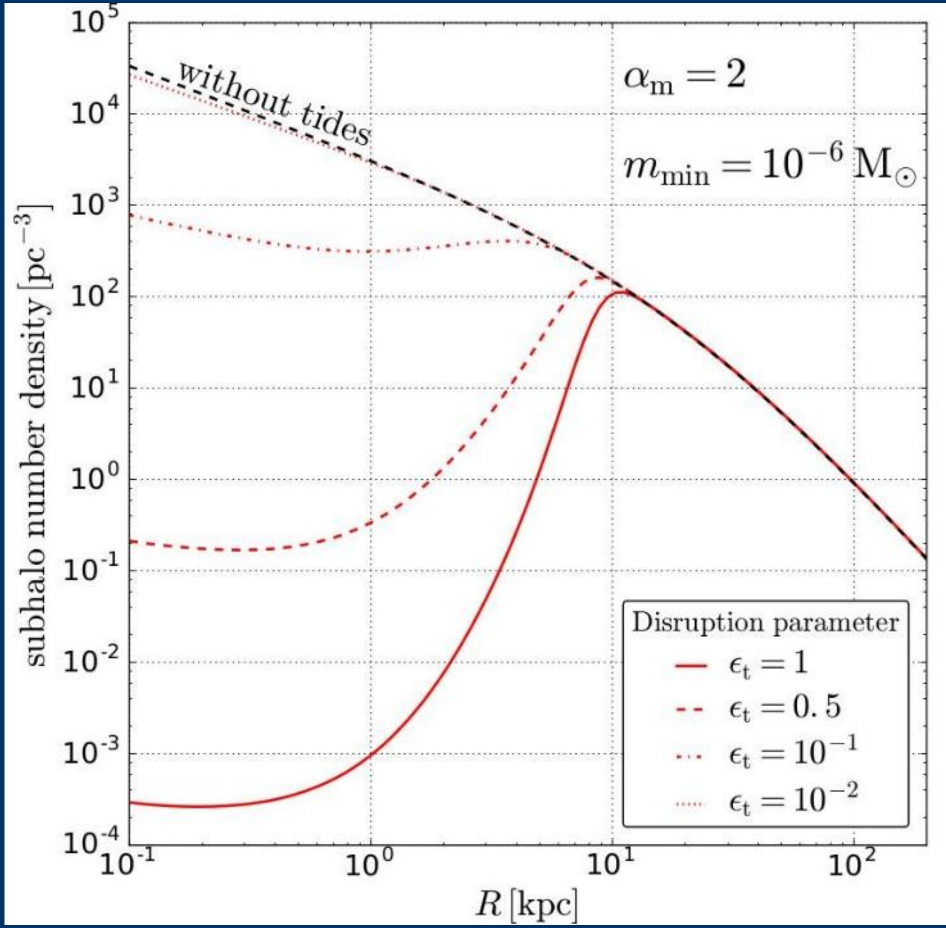
Impact of the disruption parameter



Impact of the mass function



Number density



Potentially very high number at the center!

- Very light objects ~m_{min}
- Very stripped

To be checked:

- Shocking by stars
- Impact on dynamics ?
- Two-body relaxation?
- Impact on DM searches

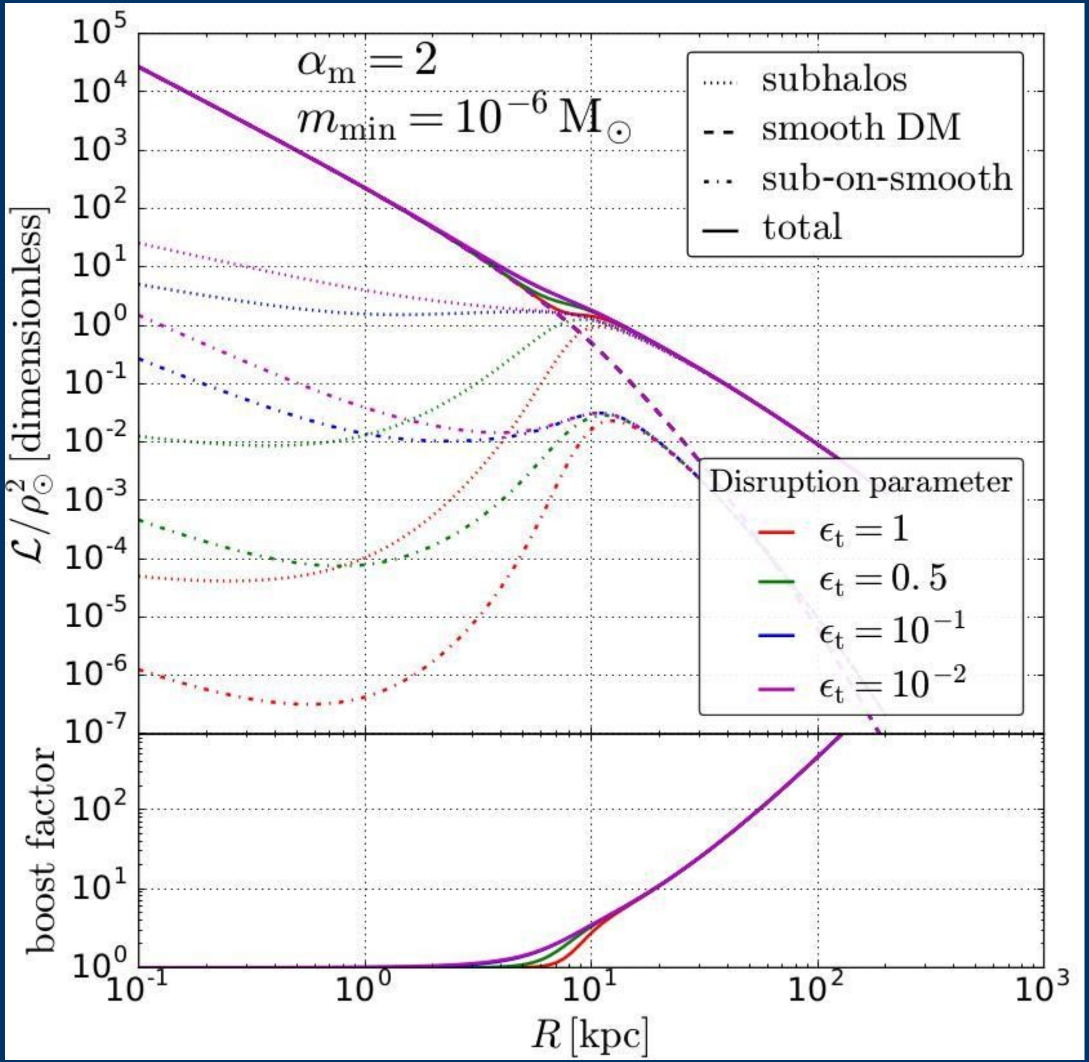
Boost factors

Indirect searches for annihilating DM sensitive to

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

Subhalos boost the annihilation signal
Silk & Stebbins 93

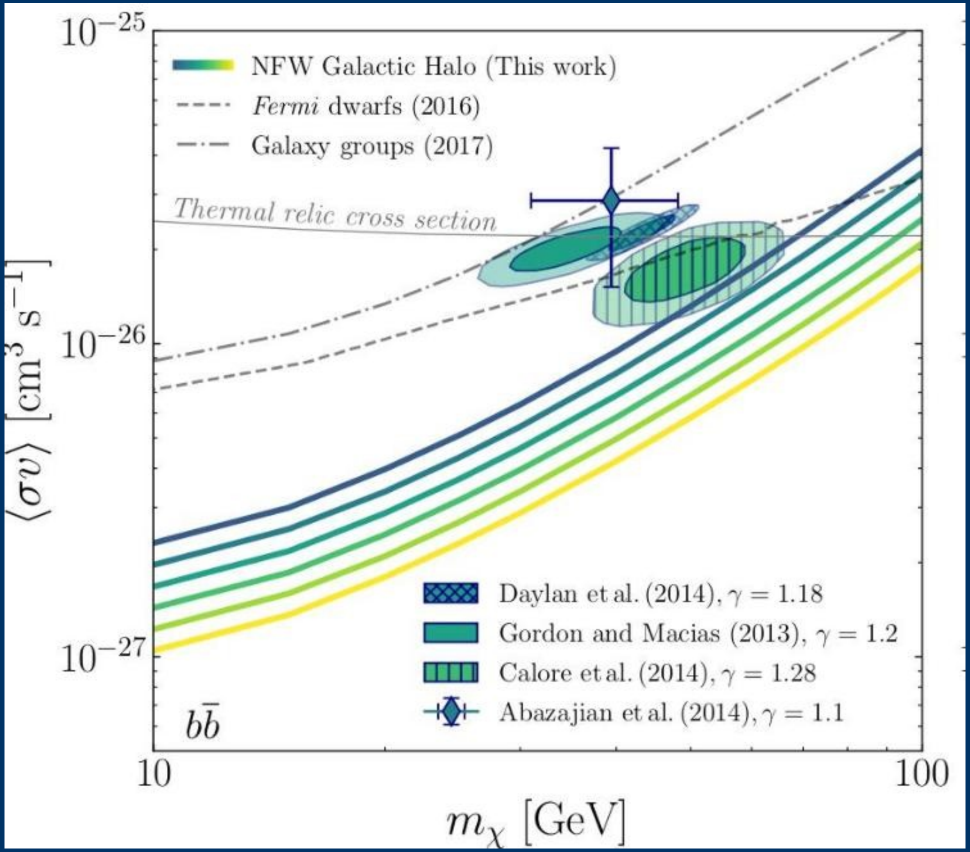
$$\text{boost factor} \simeq \frac{\mathcal{L}_{\text{tot}}}{\mathcal{L}_{\text{smooth}}} > 1$$

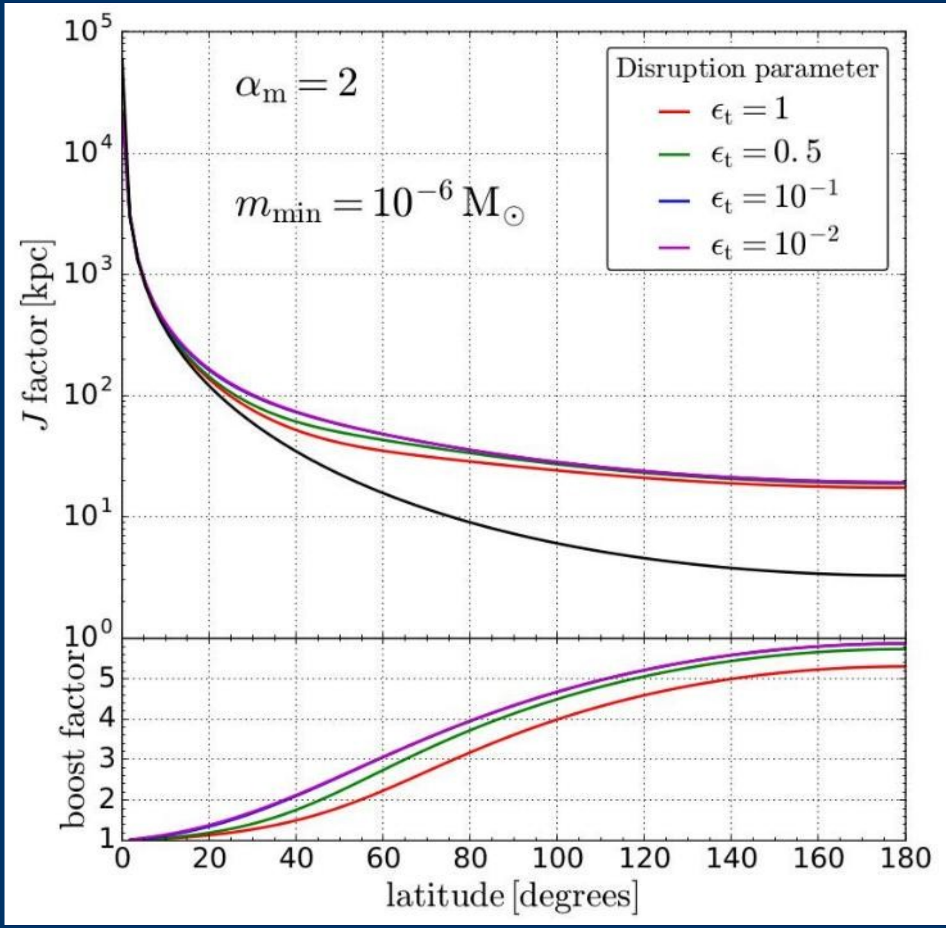


Gamma rays

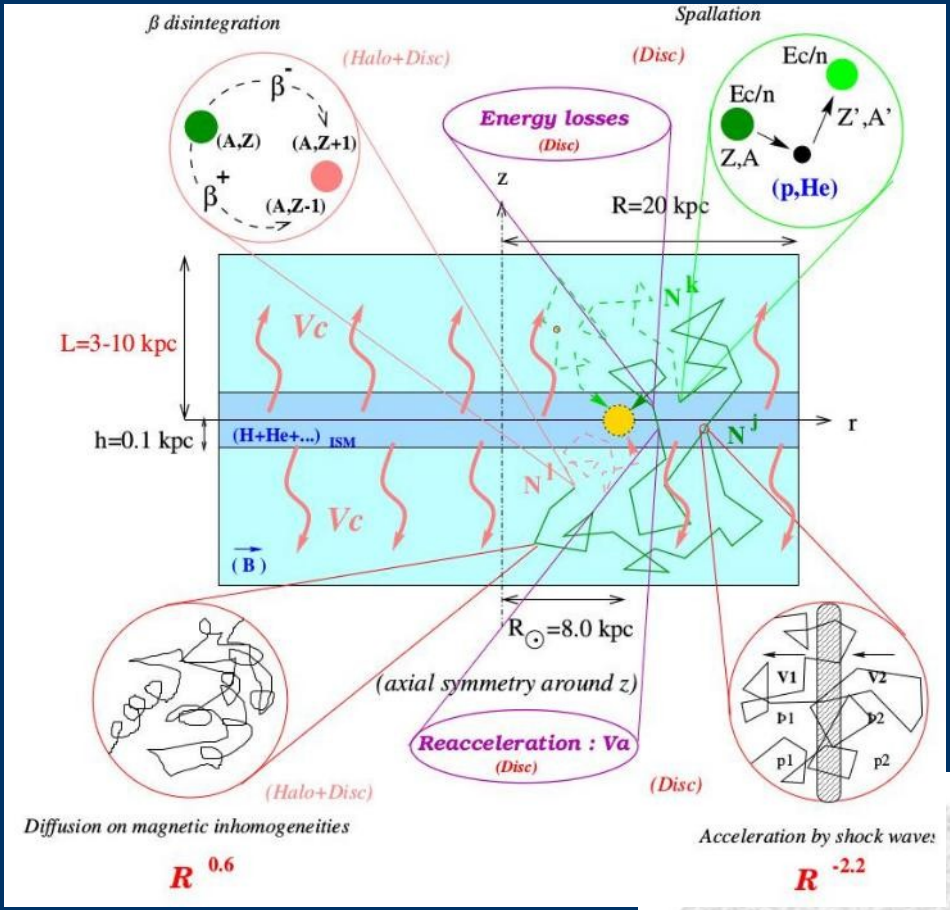
Chang+ 18: |b|>20° & r>50°
Smooth halo

But line-of-sight boost important!





Cosmic-ray antiprotons

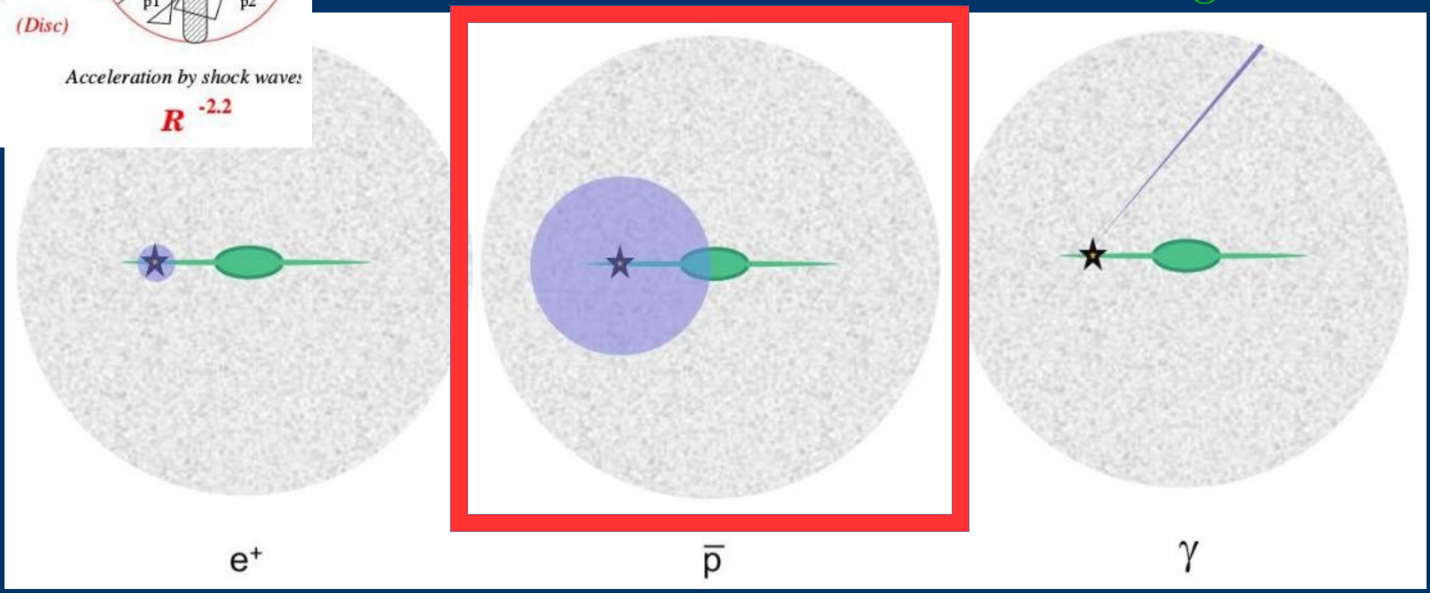


Maurin+ 04

Diffusive propagation in the MW magnetic halo

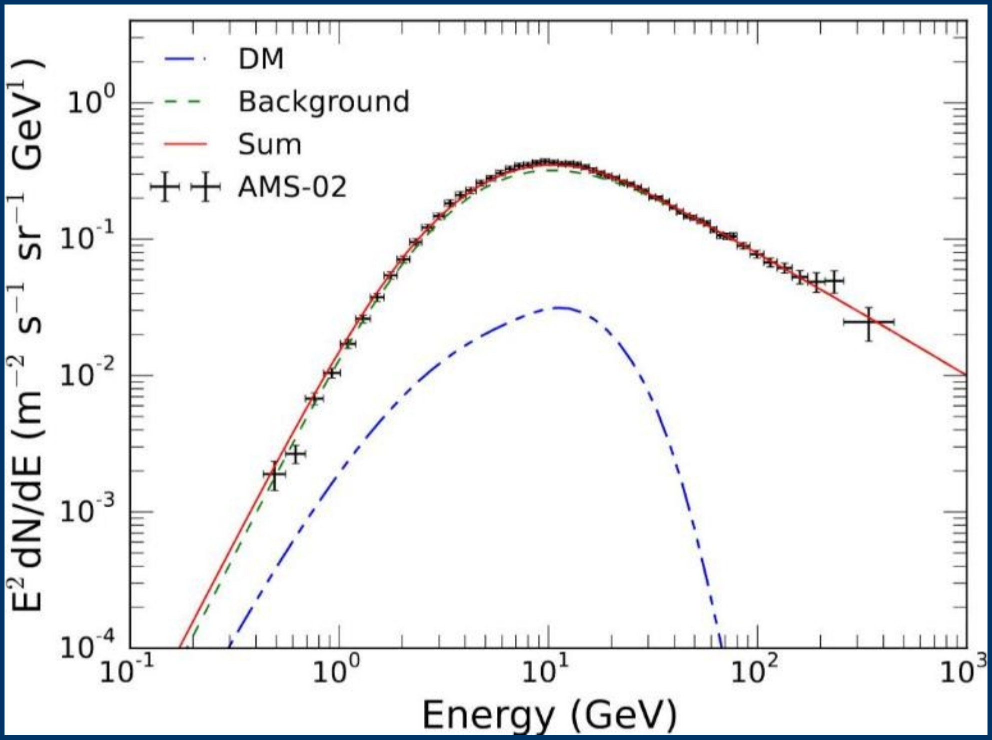
- Acceleration by SN shock waves
- Reacceleration
- Spallation
- Energy losses

Bergstrom 09

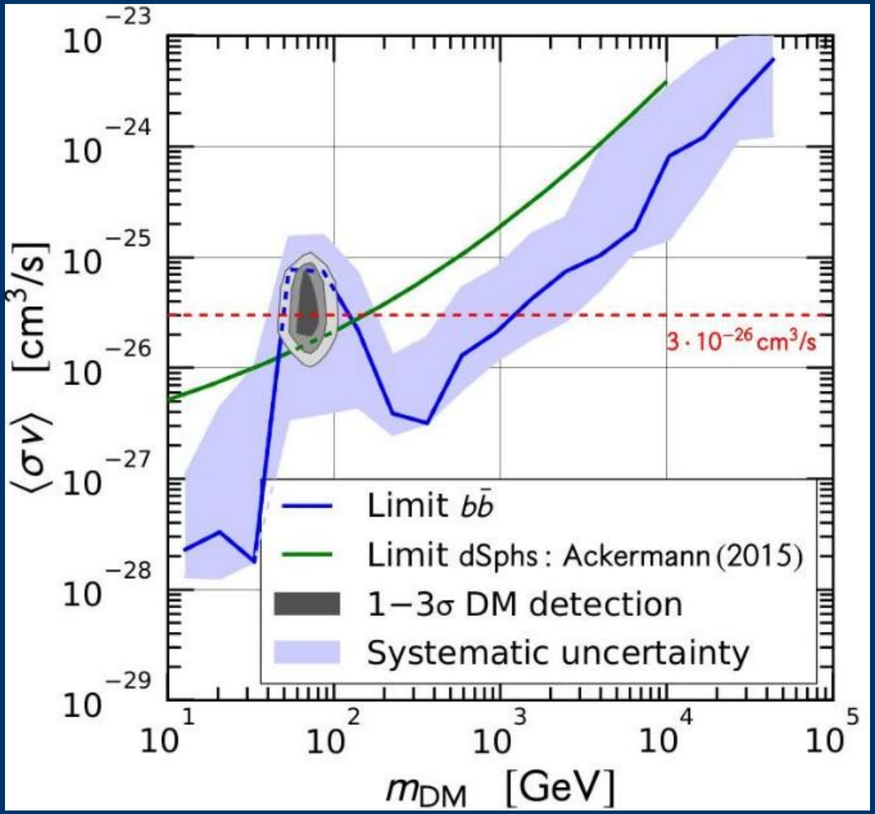


Cosmic-ray antiprotons

Evidence for DM in antiprotons?



Cui+ 18



Cuoco+ 16

Cosmic-ray antiprotons

Evidence for DM in antiprotons?
Subhalos important for consistency!

$$\bar{p}\ \text{flux} \propto \int_{\text{mag. halo}} \mathrm{d}V\, G(E,\vec{r})\, \langle \rho^2 \rangle$$

Lavalle+ 07
Lavalle+ 08

Green's function of the propagation equation

$$\boxed{\left\{\partial_t + \partial_z(V_c\,.) - K\Delta + \partial_E\left(b_{\rm loss}\,. - K_E\partial_E\,.\right)\right\} G = \delta(E-E_0)\delta^{(3)}\left(\vec{r}-\vec{r}_0\right)}$$

Cosmic-ray antiprotons

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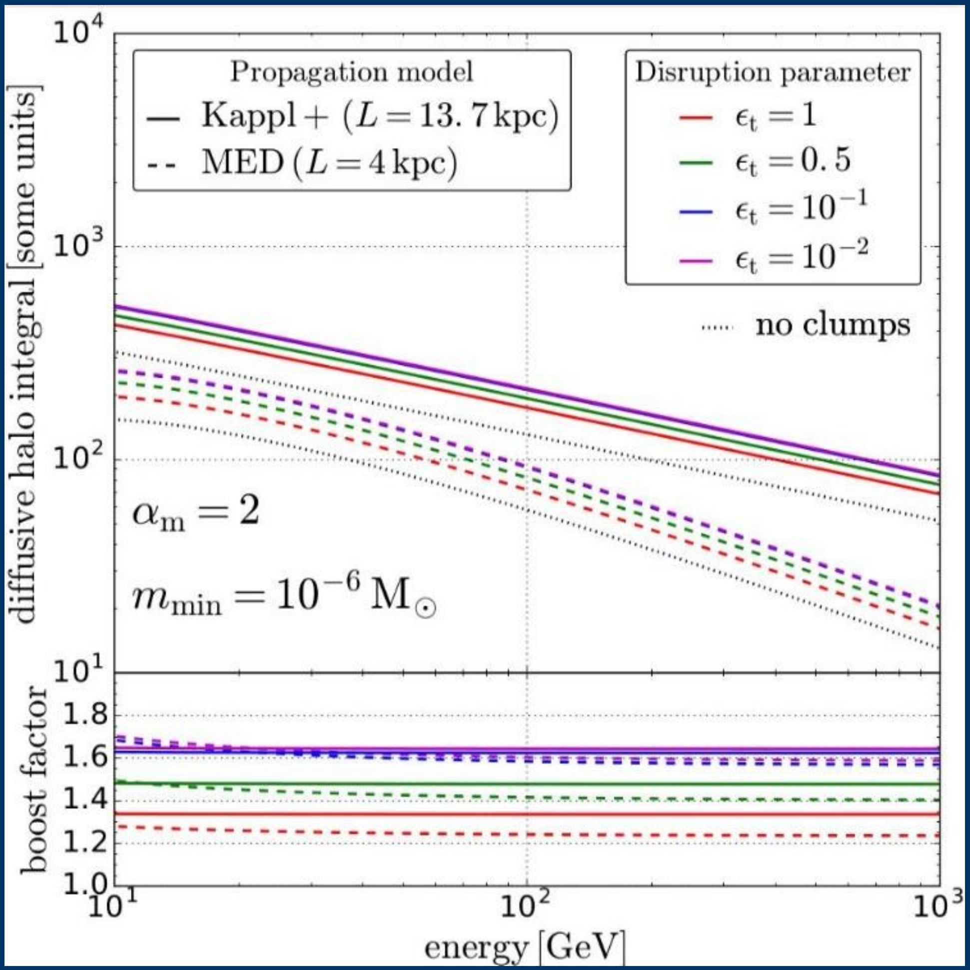
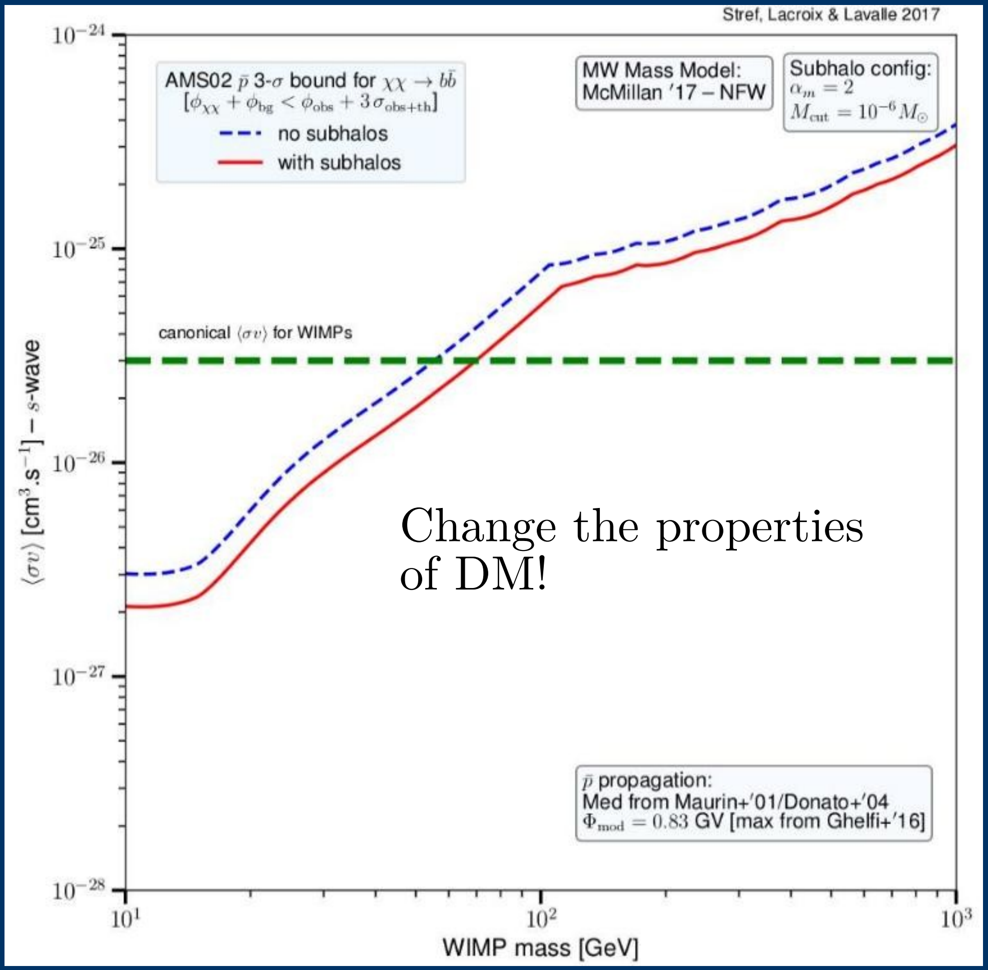




Change the properties of DM!

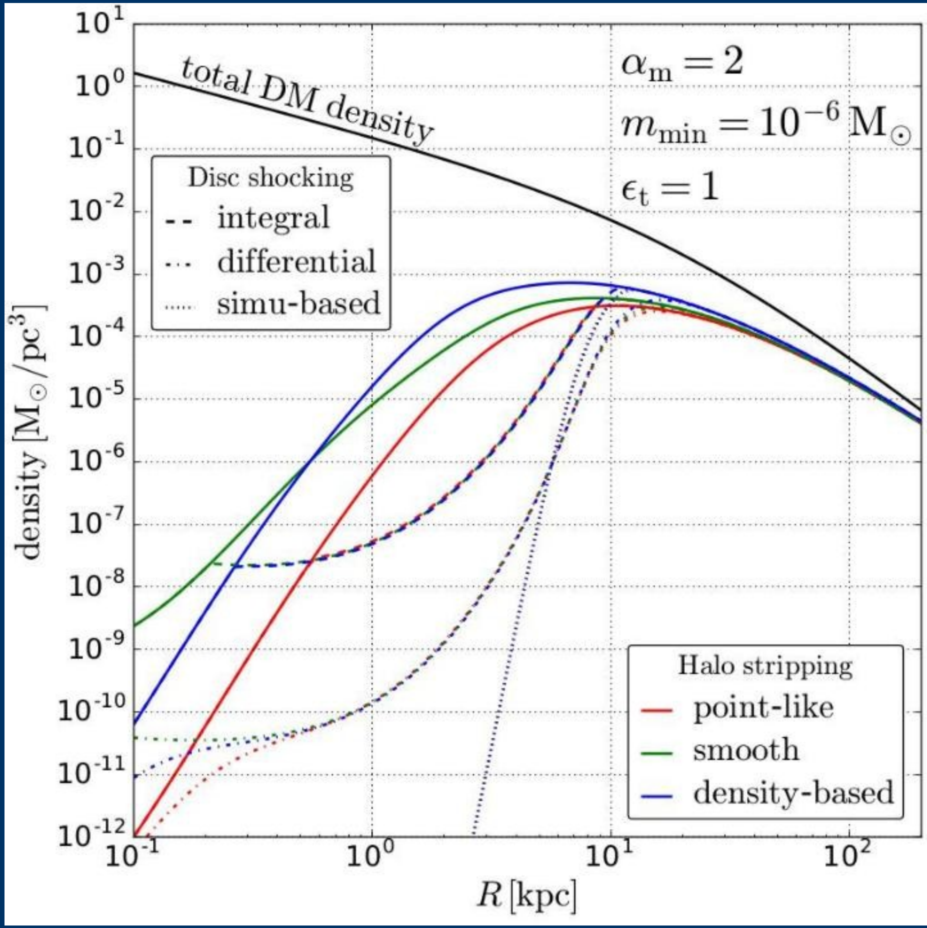
Conclusion

- Dynamical constraints are important when discussing subhalos, especially now that we have Gaïa DR2!
- Survival of cores?
- Subhalos crucial for indirect searches and microlensing (PBHs, axions miniclusters)
- Impact on dynamics? Stellar streams, binaries, ...

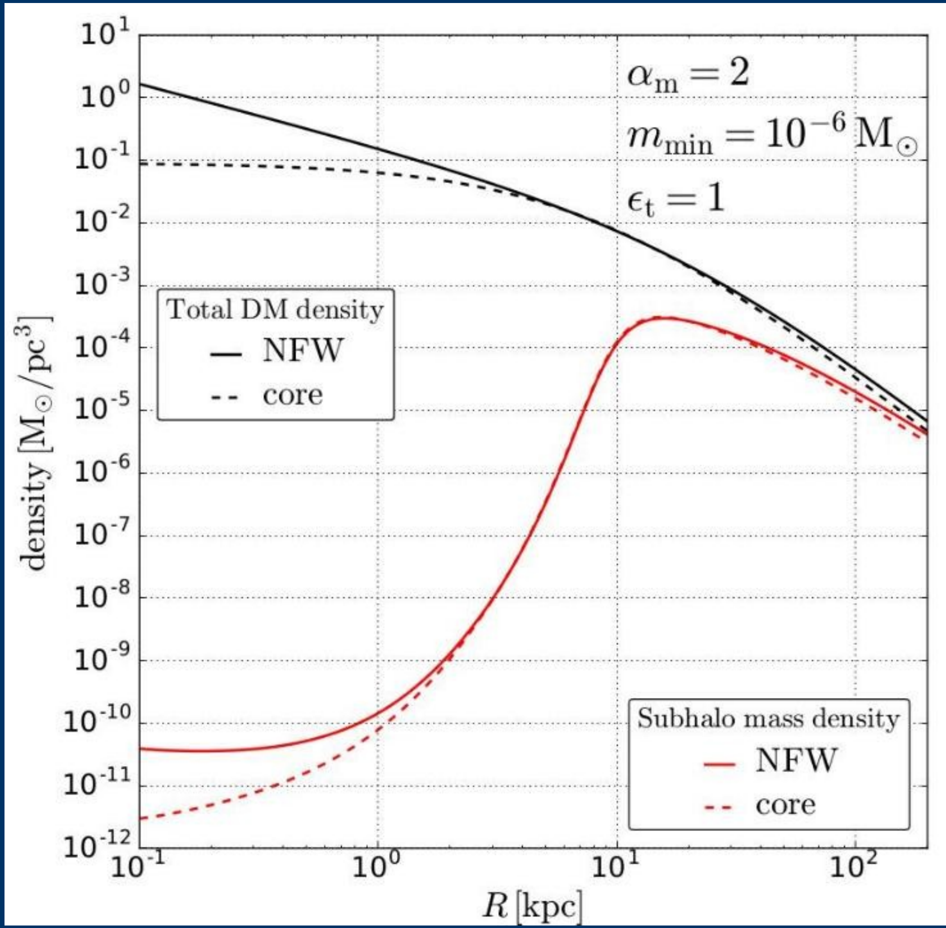
backup

More on the mass density

Various definitions of the tidal radius

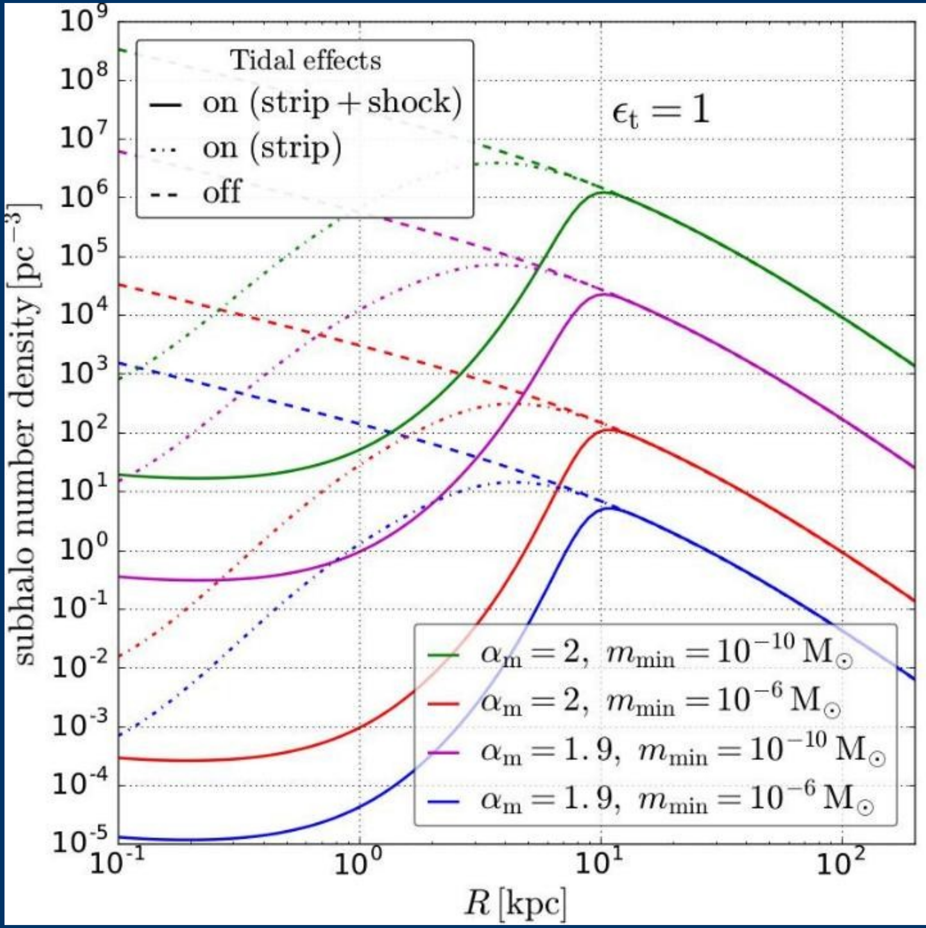


Impact of the inner DM slope

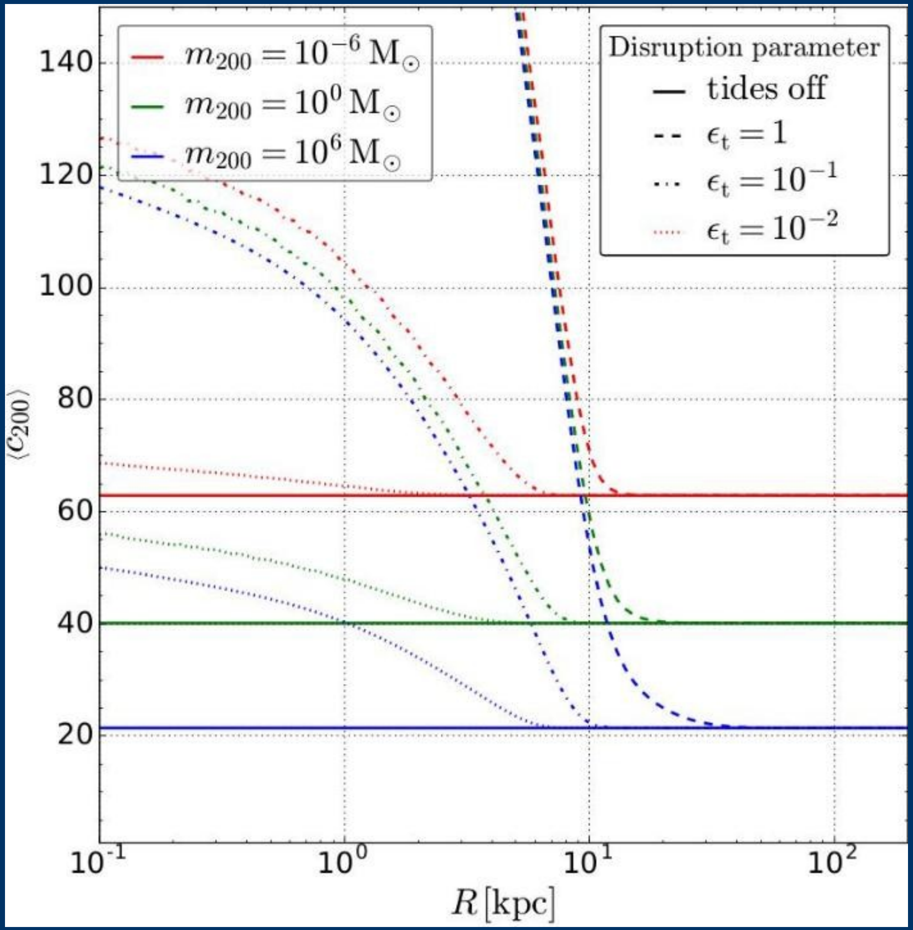


More on the number density

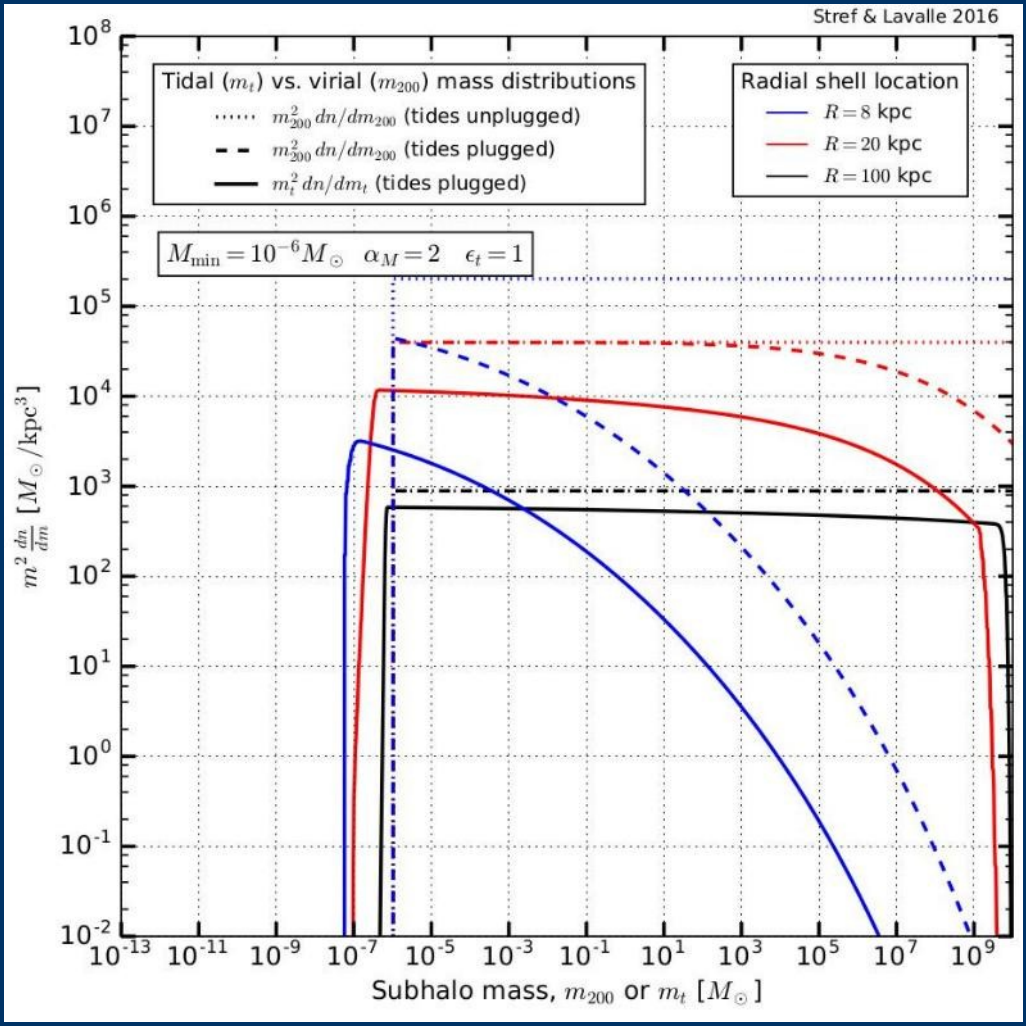
Disc + mass function



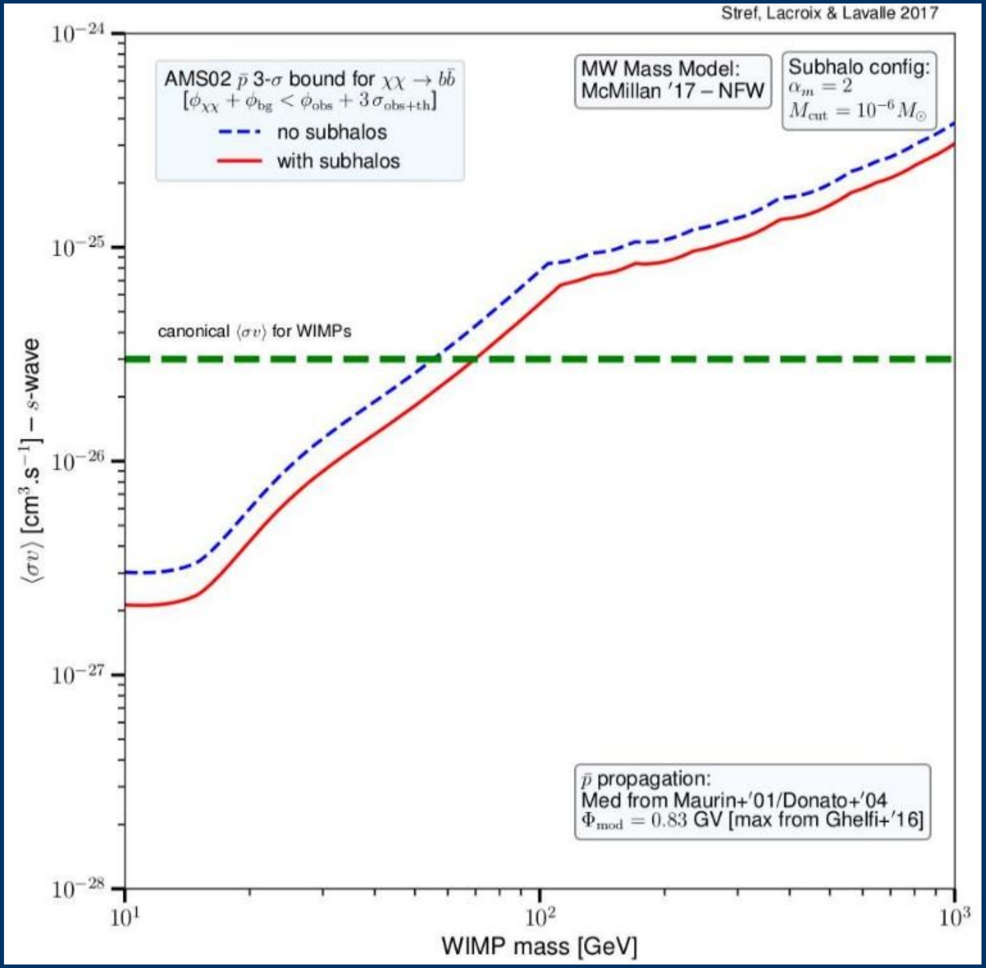
Selection of concentrations



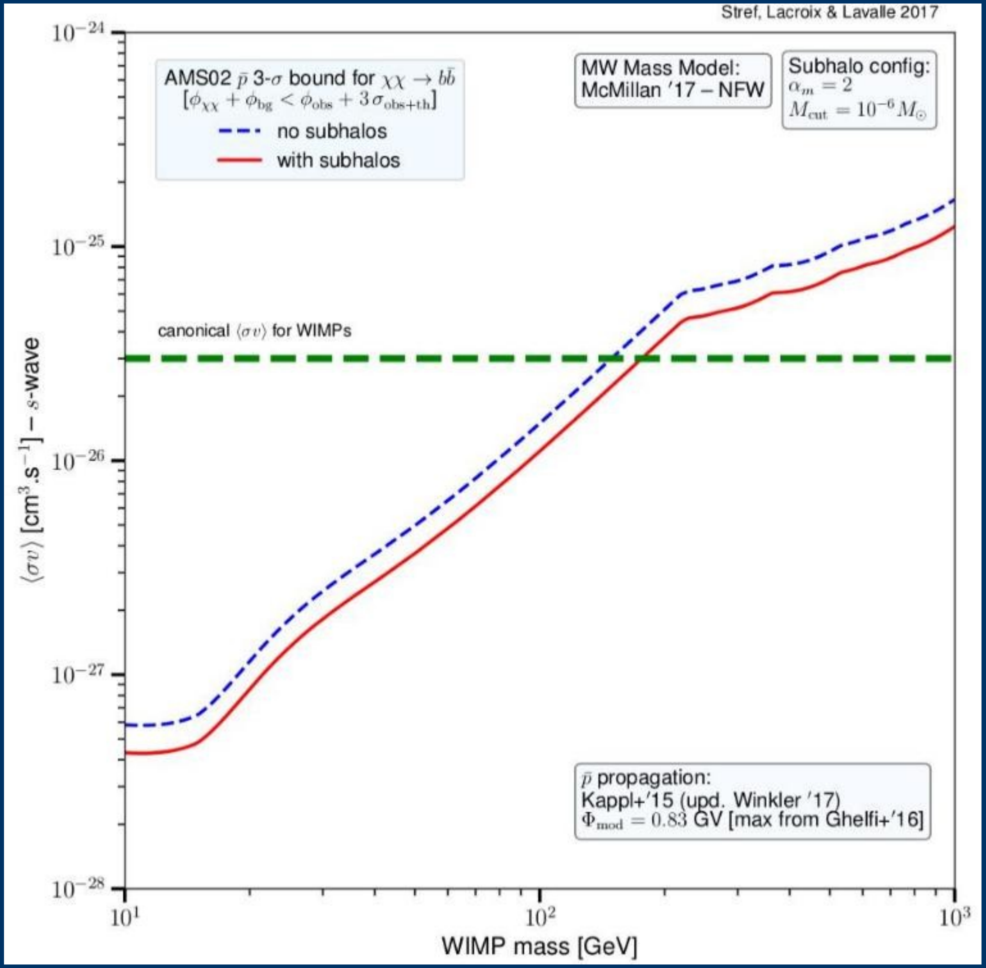
Modification of the mass function



DM in antiprotons



L = 4 kpc



L = 13.7 kpc