Interactions of subhalos with disks and stars : an analytical study

Martin Stref

News from the Dark 2019

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WARNING !
WORK IN PROGRESS

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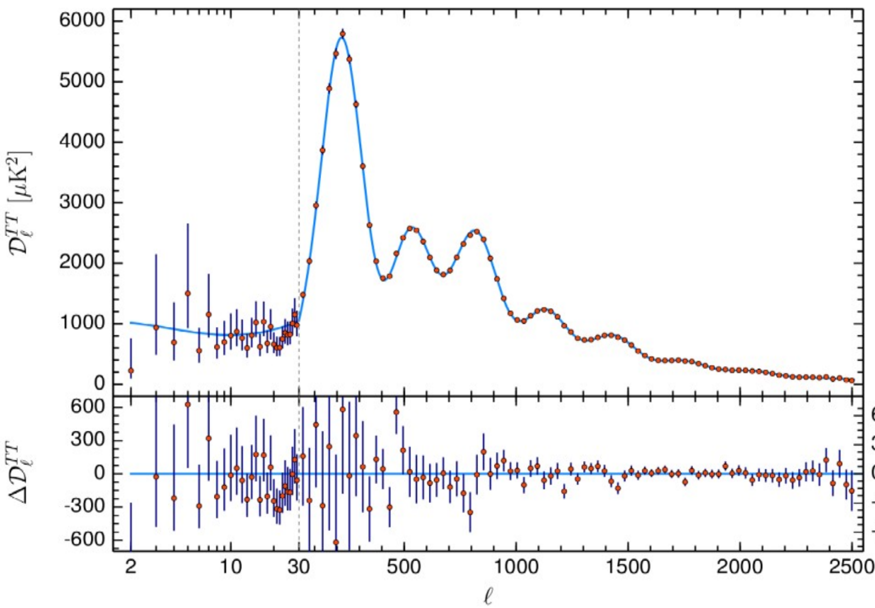
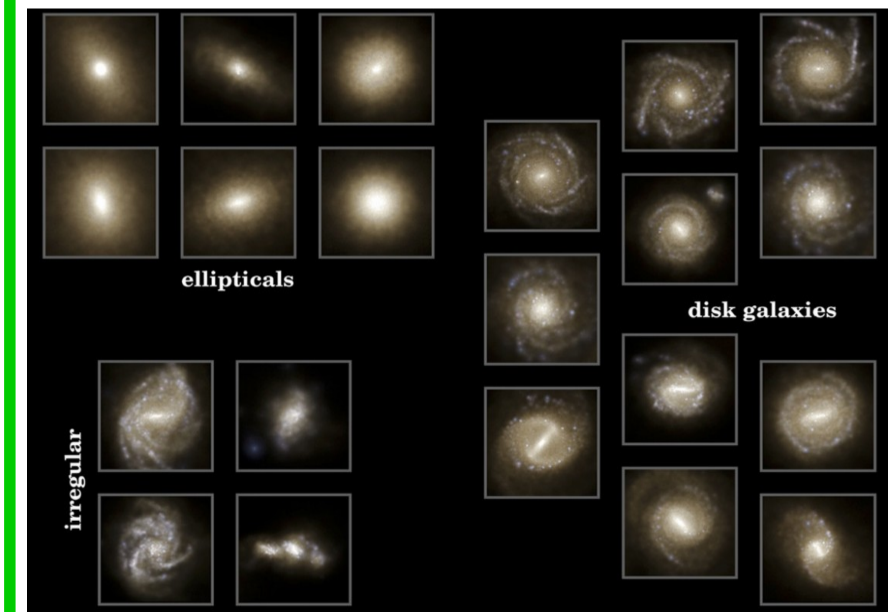
Success of ΛCDM

Planck 2018

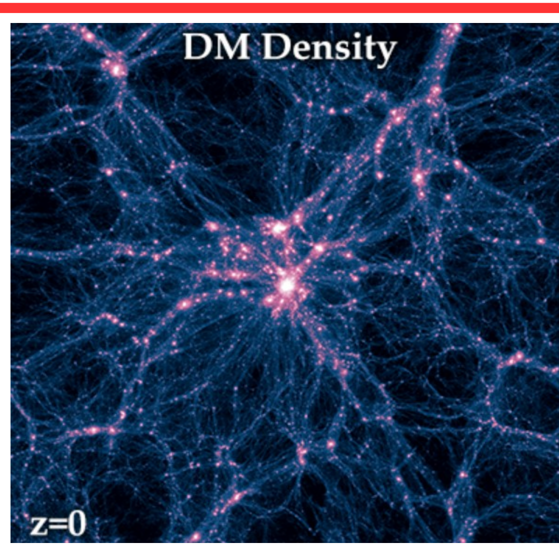


CMB

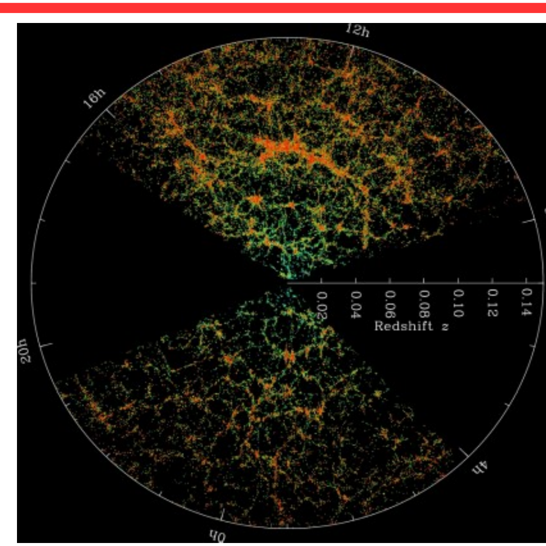
Illustris simulation



Nice-looking galaxies



Illustris simulation

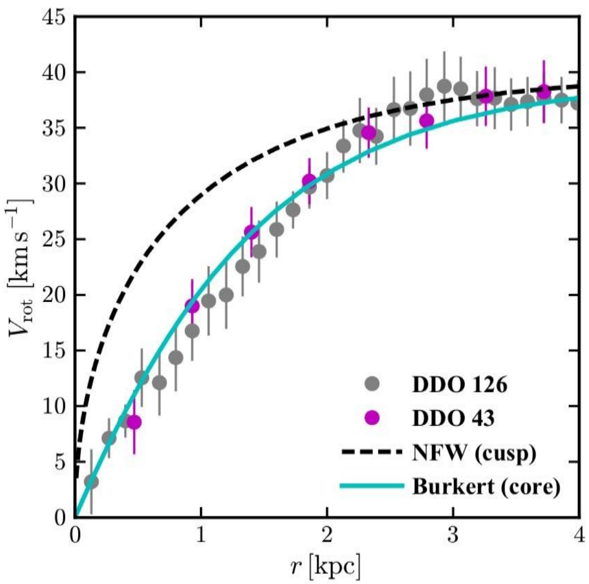


SDSS survey

Large-scale structures

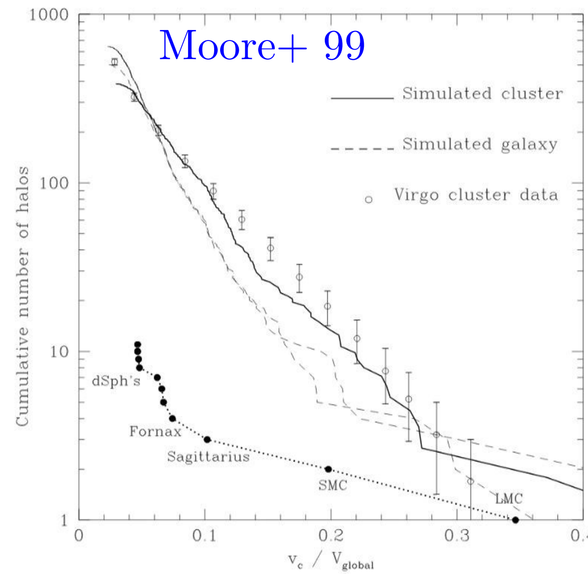
Small-scale issues for ΛCDM ?

Halos not cuspy enough?



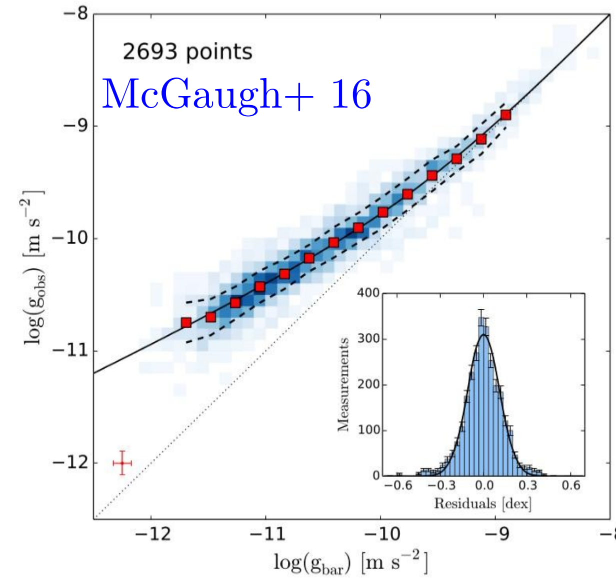
Missing satellites?

Moore+ 99

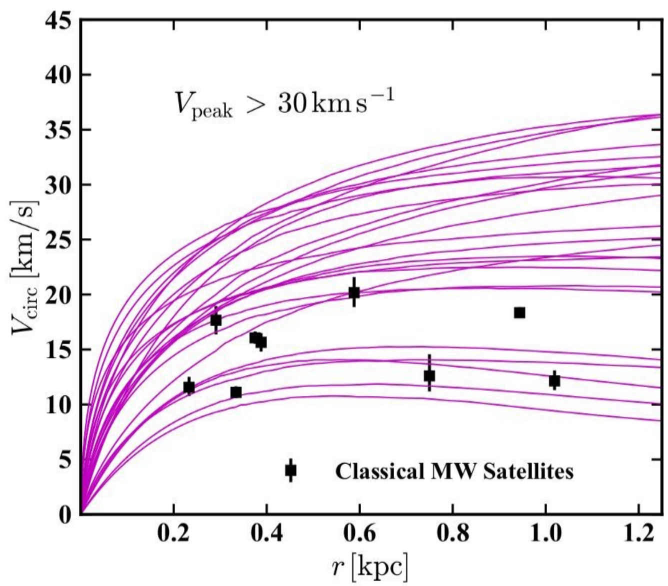


Regularity vs diversity

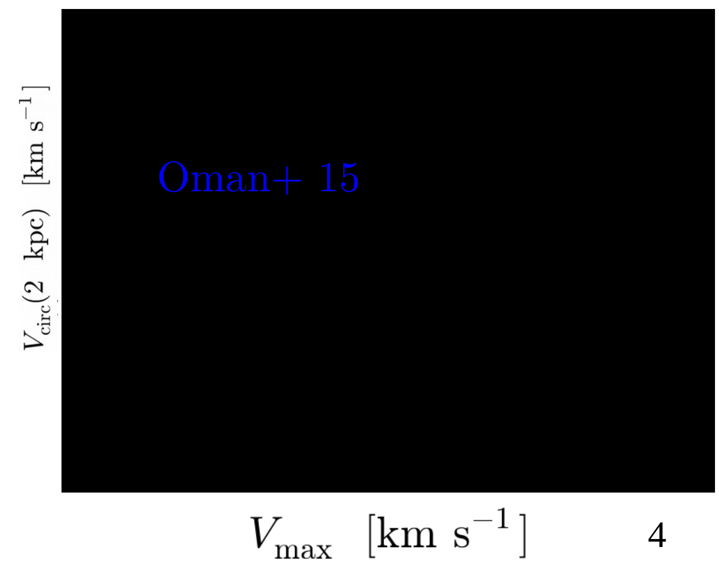
McGaugh+ 16



Satellites not massive enough?



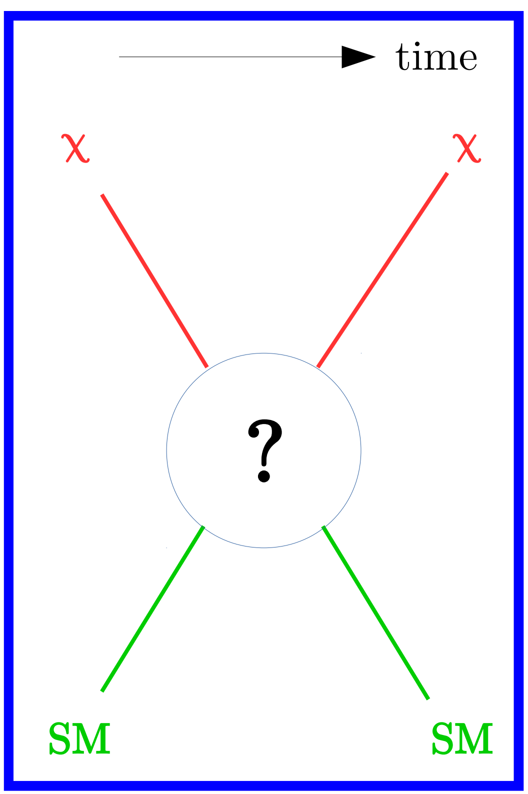
Bullock
& Boylan-Kolchin 17



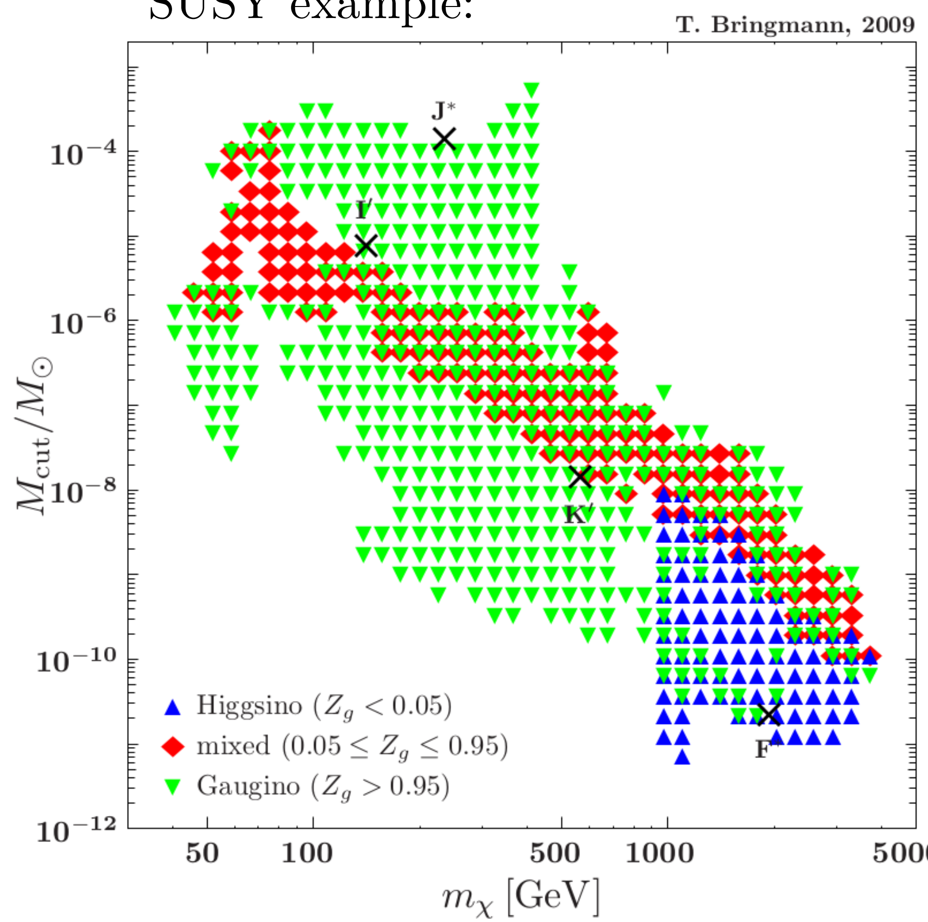
Small-scale structuring in ΛCDM

Depends on the **microscopic interactions of the DM particle**
(and/or the primordial power spectrum)

e.g. for WIMPs, mass of the first structures to form set by the time of **kinetic decoupling**
(cf Gaétan's talk)

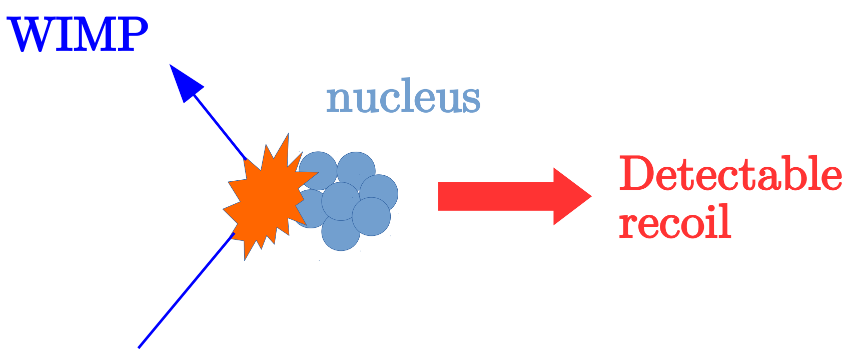


SUSY example:



Subhalos and WIMP searches

Direct searches



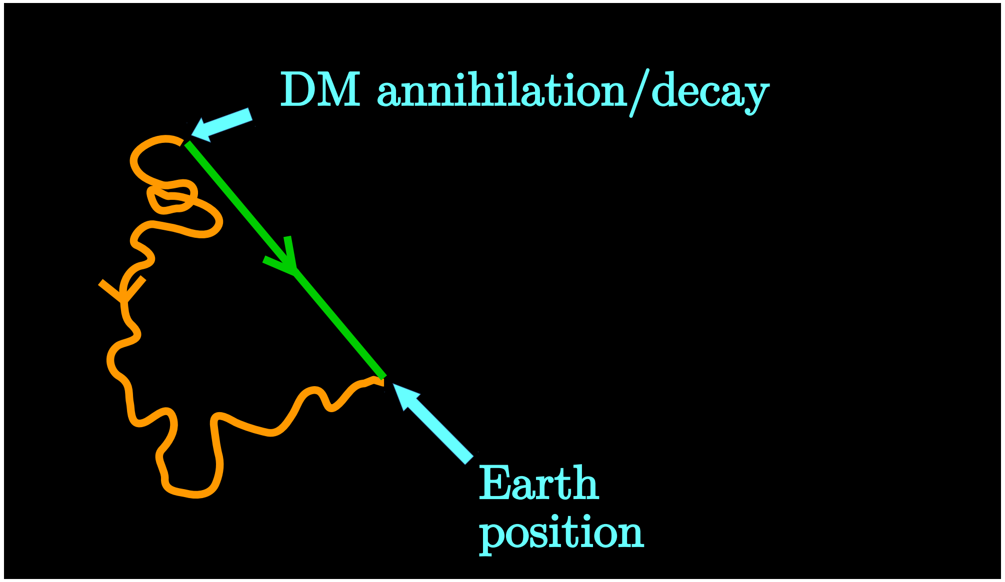
Differential event rate

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

- Local DM density
- Local DM velocity DF

➡ Importance of the local clustering

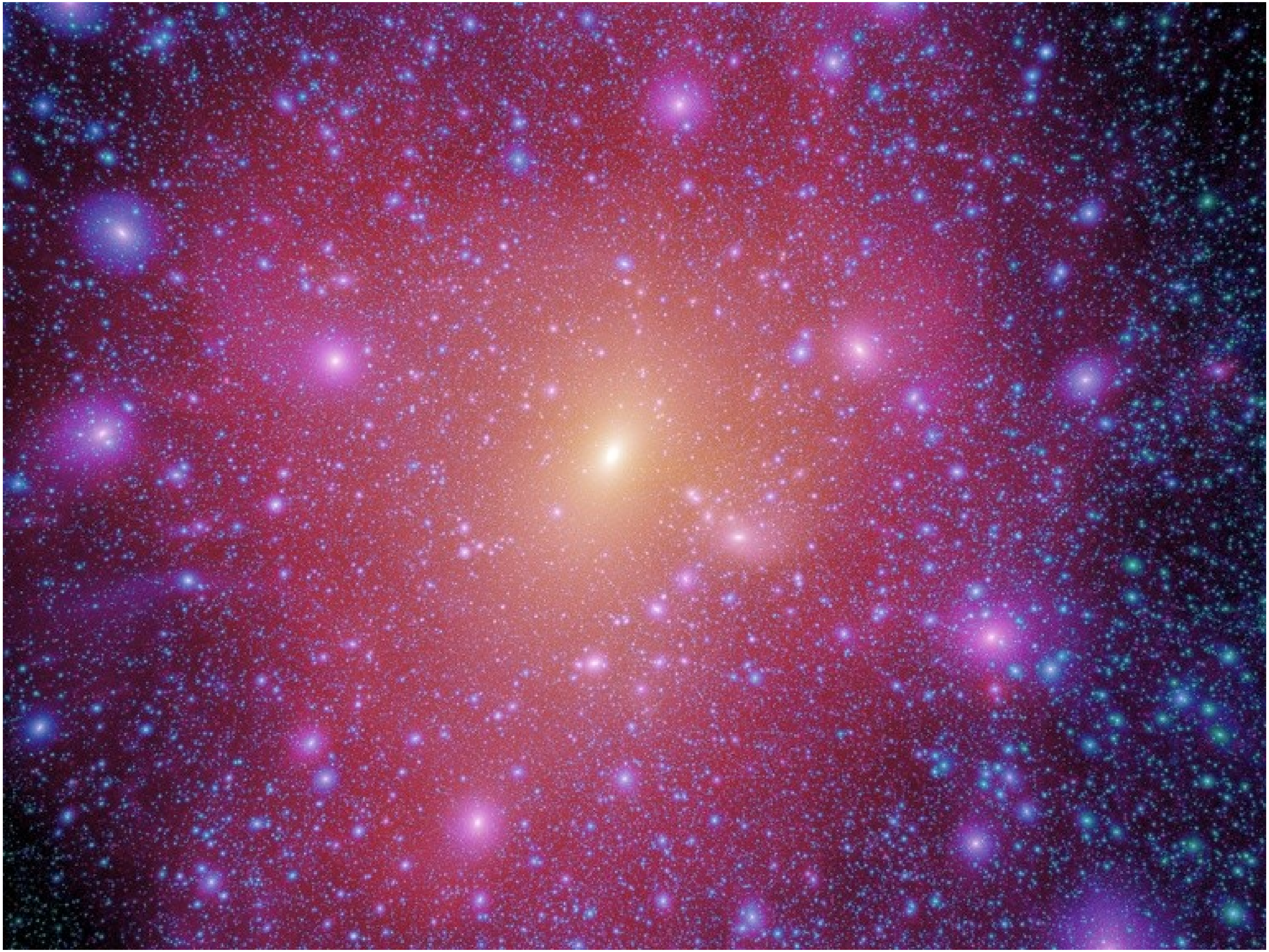
Indirect searches



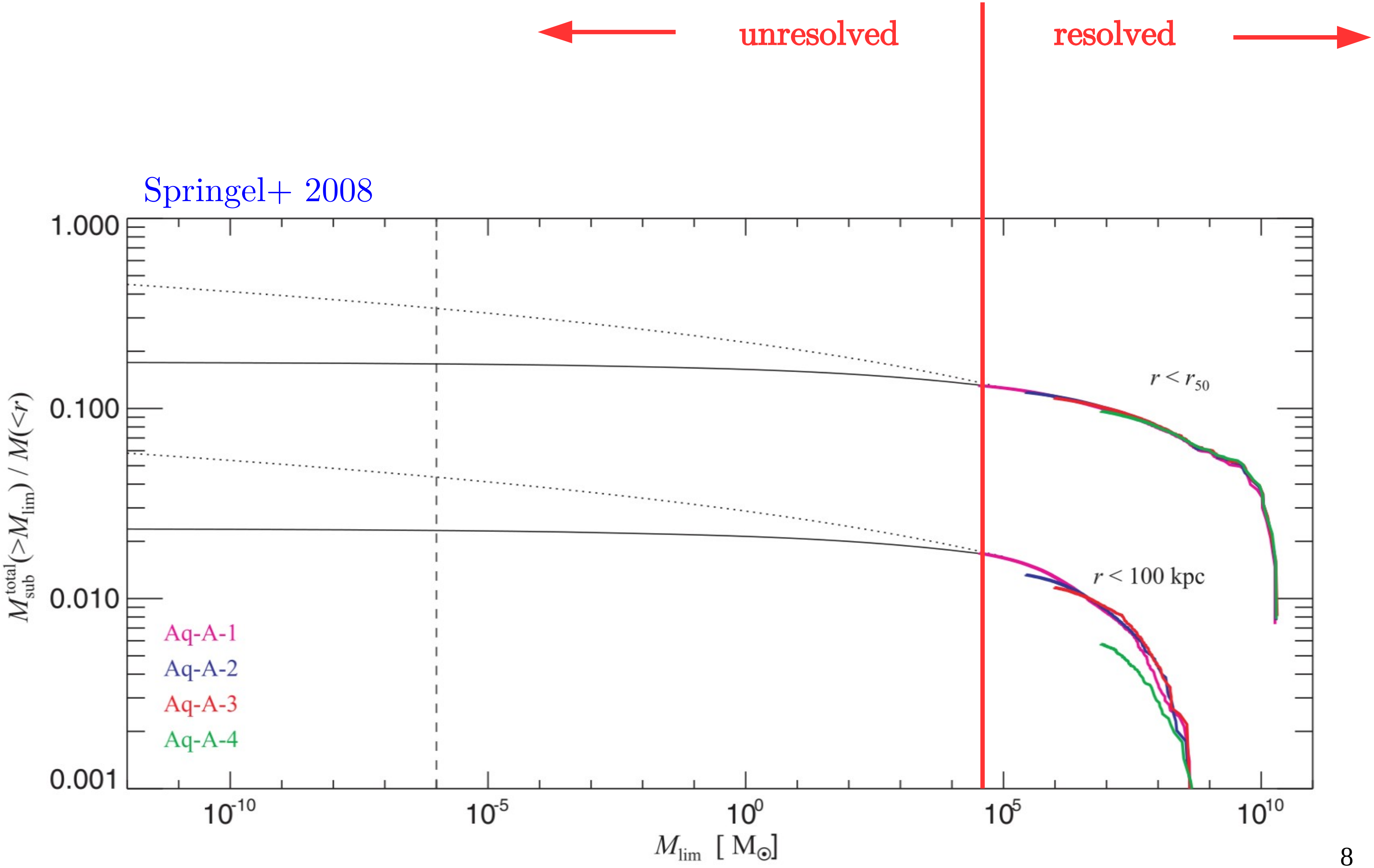
Probe of the (extra-)Galactic DM density profile via gamma rays, neutrinos or charged cosmic rays

Inhomogeneities boost the annihilation signal [Silk & Stebbins 93, Bergström+ 99]

Milky-Way-like halo (DMO simulation Springel+ 2008)



Cosmological simulations: the resolution issue



Galactic subhalos: an analytic approach

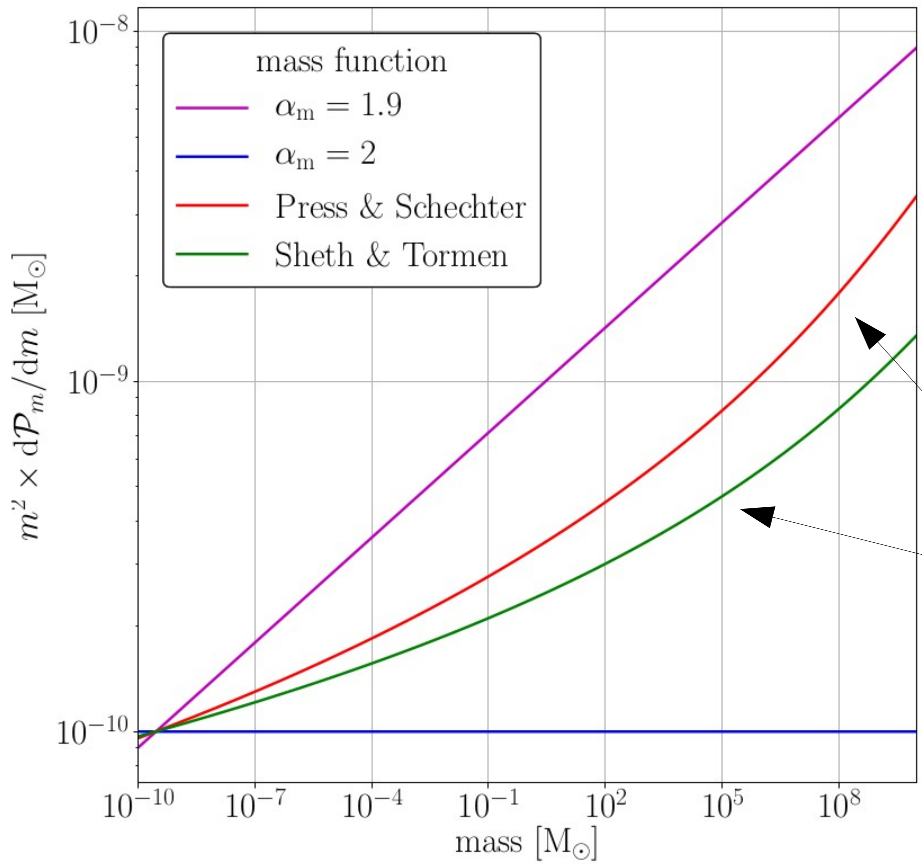
$$\frac{\mathrm{d}^n N_{\mathrm{sub}}}{\mathrm{d}\omega^n} = N_0 \, \frac{\mathrm{d}\mathcal{P}_m(m)}{\mathrm{d}m} \times \frac{\mathrm{d}\mathcal{P}_{\mathrm{c}}(c,m)}{\mathrm{d}c} \times \frac{\mathrm{d}\mathcal{P}_{\mathrm{v}}(\vec{x})}{\mathrm{d}V}$$

Subhalo “phase-space” number density

Galactic subhalos: an analytic approach

Mass function

$$\frac{\mathrm{d}^n N_{\mathrm{sub}}}{\mathrm{d}\omega^n} = \boxed{N_0 \frac{\mathrm{d}\mathcal{P}_m(m)}{\mathrm{d}m}} \times \frac{\mathrm{d}\mathcal{P}_{\mathrm{c}}(c,m)}{\mathrm{d}c} \times \frac{\mathrm{d}\mathcal{P}_{\mathrm{v}}(\vec{x})}{\mathrm{d}V}$$



Spherical collapse

Ellipsoidal collapse

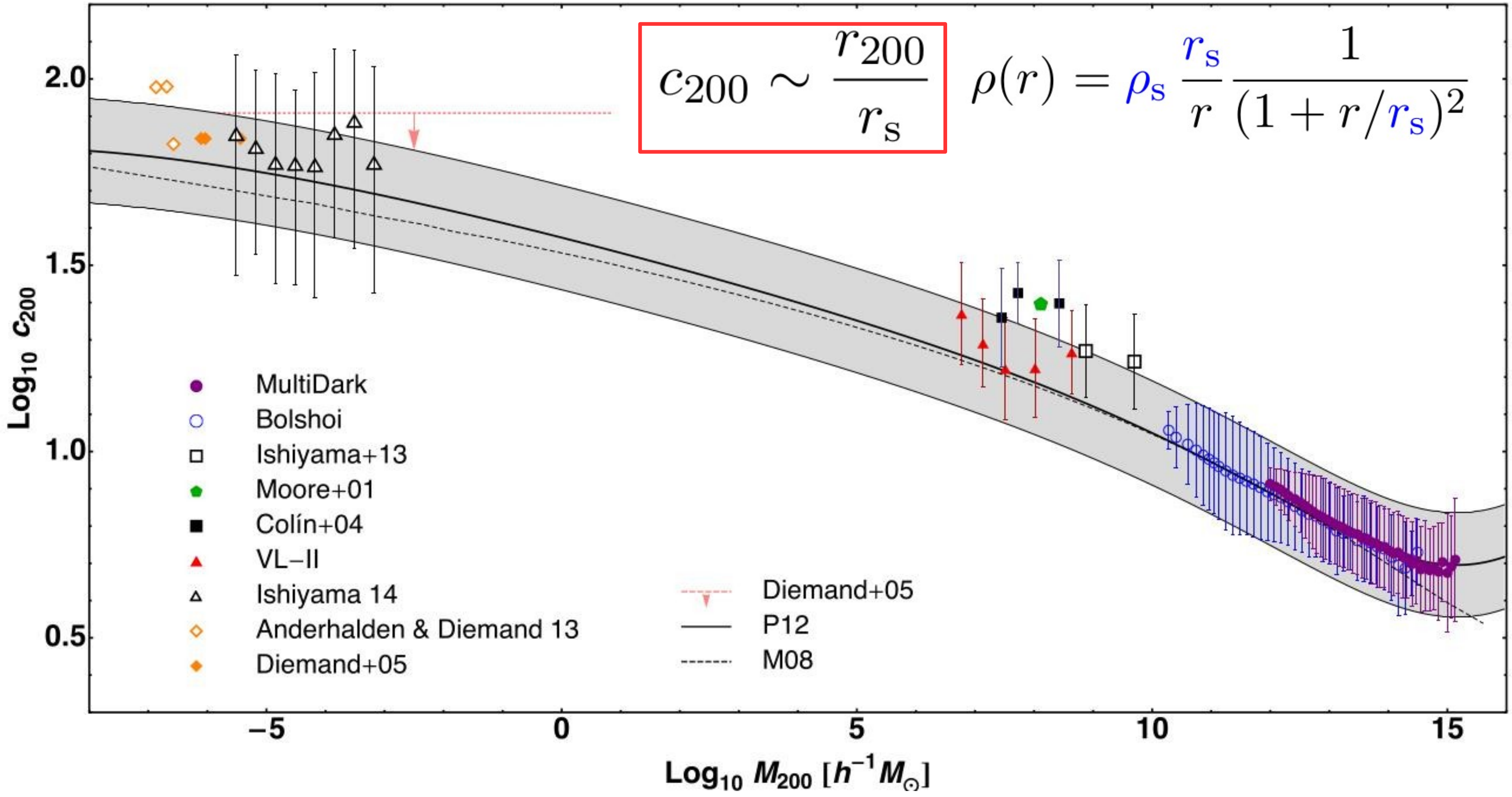
Computed from the matter power spectrum

Galactic subhalos: an analytic approach

concentrations

$$\frac{\mathrm{d}^n N_{\rm sub}}{\mathrm{d}\omega^n} = N_0 \, \frac{\mathrm{d}\mathcal{P}_m(m)}{\mathrm{d}m} \times \boxed{\frac{\mathrm{d}\mathcal{P}_{\rm c}(c,m)}{\mathrm{d}c}} \times \frac{\mathrm{d}\mathcal{P}_{\rm v}(\vec{x})}{\mathrm{d}V}$$

Sanchez-Conde & Prada 2014



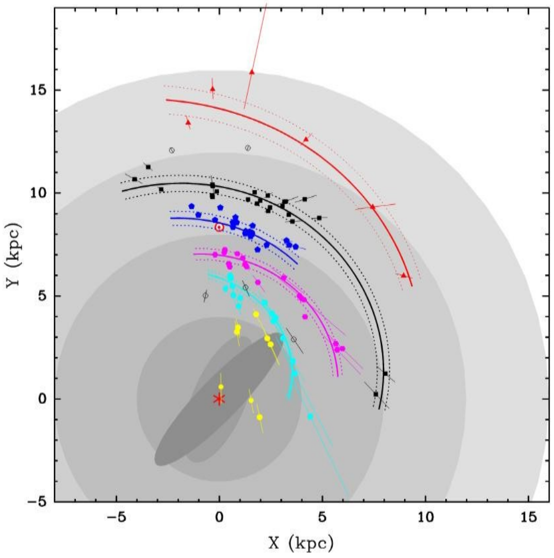
$$\boxed{c_{200} \sim \frac{r_{200}}{r_{\rm s}}} \qquad \rho(r) = \rho_{\rm s} \, \frac{r_{\rm s}}{r} \, \frac{1}{(1 + r/r_{\rm s})^2}$$

Galactic subhalos: an analytic approach

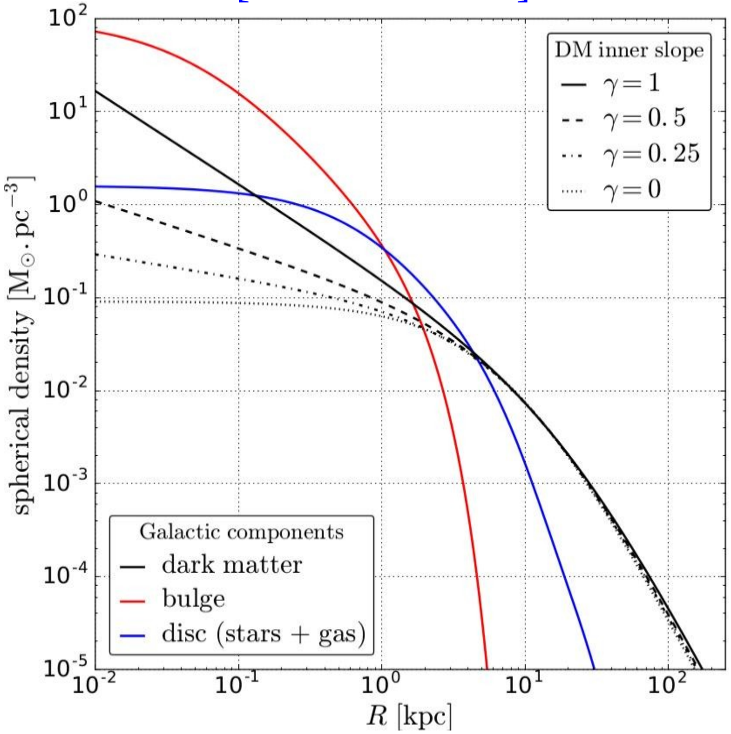
Spatial PDF

$$\frac{\mathrm{d}^n N_{\mathrm{sub}}}{\mathrm{d}\omega^n} = N_0 \, \frac{\mathrm{d}\mathcal{P}_m(m)}{\mathrm{d}m} \times \frac{\mathrm{d}\mathcal{P}_{\mathrm{c}}(c,m)}{\mathrm{d}c} \times \boxed{\frac{\mathrm{d}\mathcal{P}_{\mathrm{v}}(\vec{x})}{\mathrm{d}V}}$$

Pre-Gaia data
[Reid+ 2014]



MW mass models
[McMillan 2017]



$$\boxed{\frac{\mathrm{d}\mathcal{P}_{\mathrm{v}}(\vec{x})}{\mathrm{d}V} = \frac{\rho_{\mathrm{DM}}(\vec{x})}{M_{\mathrm{DM}}^{\mathrm{tot}}}}$$

Tidal interactions of subhalos in the Galaxy

- Tidal stripping by the smooth Galactic potential
- Gravitational shocking by the Galactic disk
- Gravitational shocking by stars

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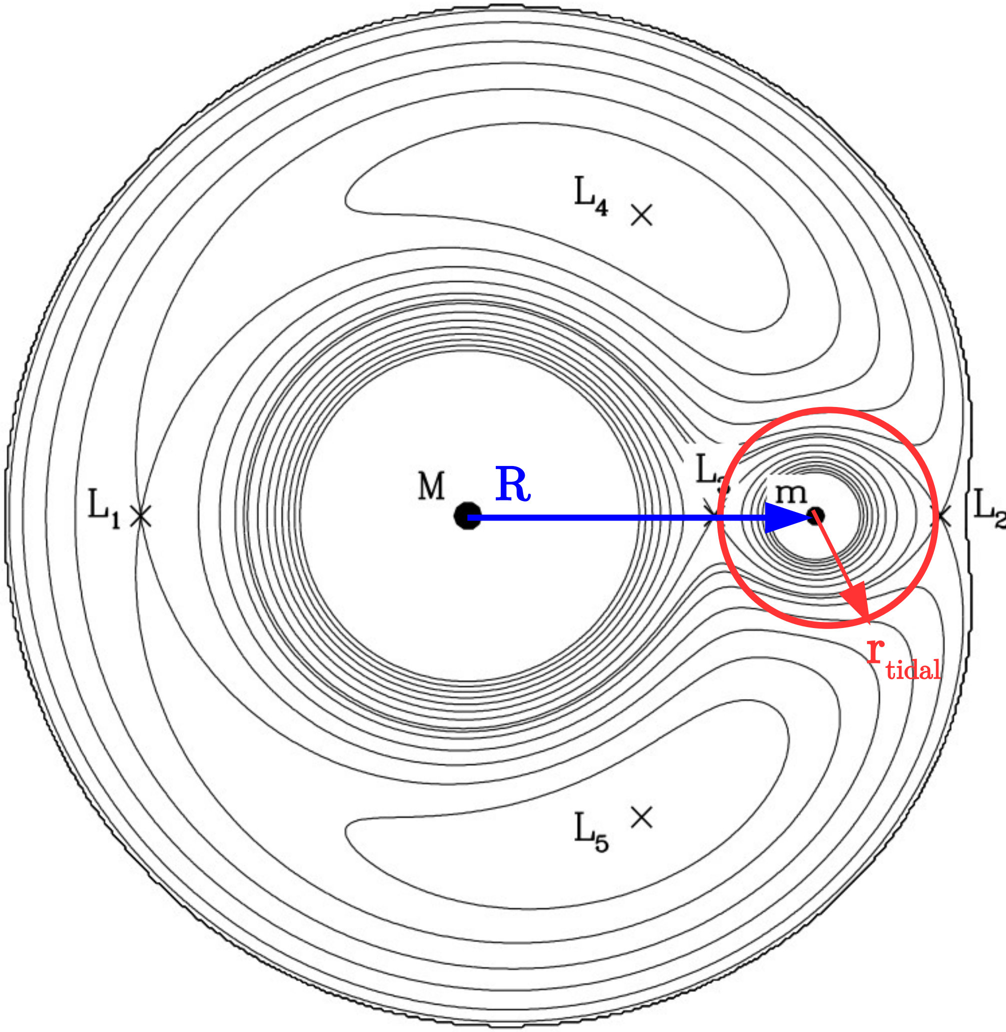
Interaction between subhalos and the host galaxy

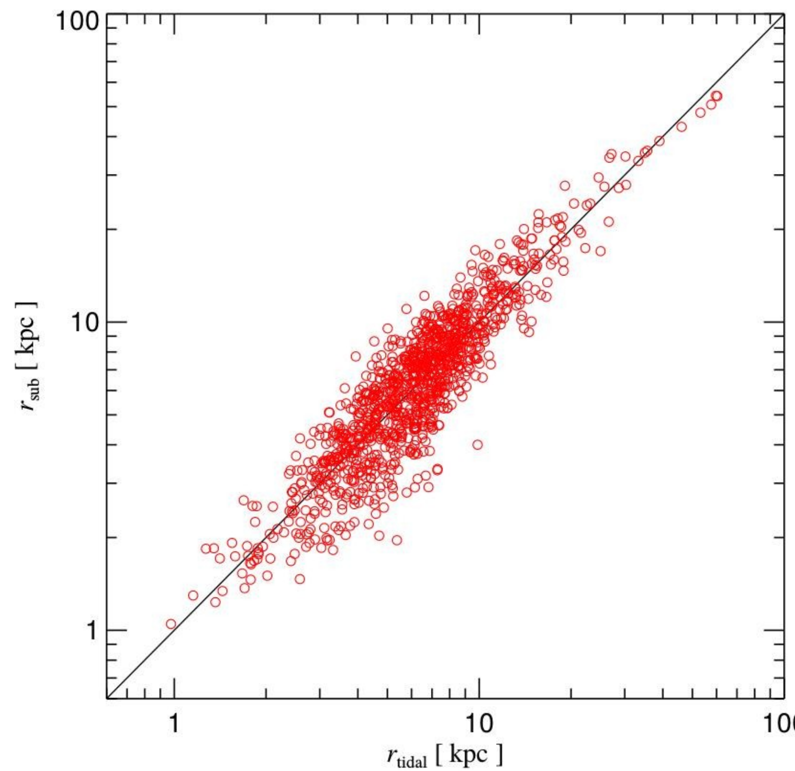
$$r_{\rm tidal} = R \left\{ \frac{m_{\rm int}(r_{\rm tidal})}{3\,M(R)\,\left(1 - \frac{1}{3}\frac{{\rm d}\ln M}{{\rm d}\ln R}\right)} \right\}^{1/3}$$



Binney & Tremaine

Extension of a subhalo depends on:

- Its position in the Galaxy
- Its density profile



Springel+ 2008

Tidal interactions of subhalos in the Galaxy

- Tidal stripping by the smooth Galactic potential
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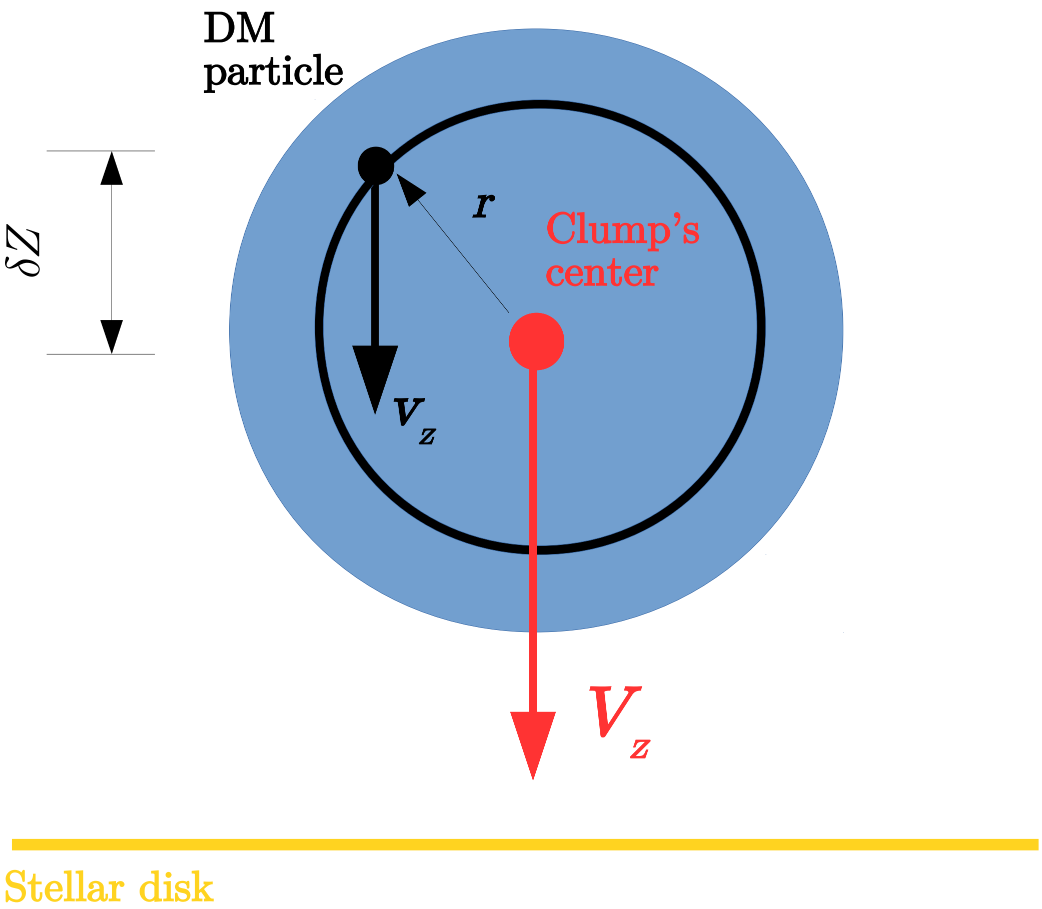
Interaction between subhalos and the Galactic disk

Subhalos experience **disk shocking** when they cross the stellar disk
[Ostriker+ 1972, Gnedin & Ostriker 1999]



$$\frac{\mathrm{d}v_z}{\mathrm{d}t} = g_z(Z_0 + \delta Z) - g_z(Z_0) \simeq \delta Z \, \frac{\mathrm{d}g_z}{\mathrm{d}z}$$

$$\Delta v_z = \int \mathrm{d}t \, \frac{\mathrm{d}v_z}{\mathrm{d}t} = \frac{\delta Z}{V_z} \, 2 \, |g_z(z=0)|$$

$$\boxed{\frac{\delta E}{m_\chi} = \frac{1}{2}(\Delta v_z)^2 = \frac{2 \, g_z^2 \, r^2}{3 \, V_z^2}}$$

Interaction between subhalos and the Galactic disk

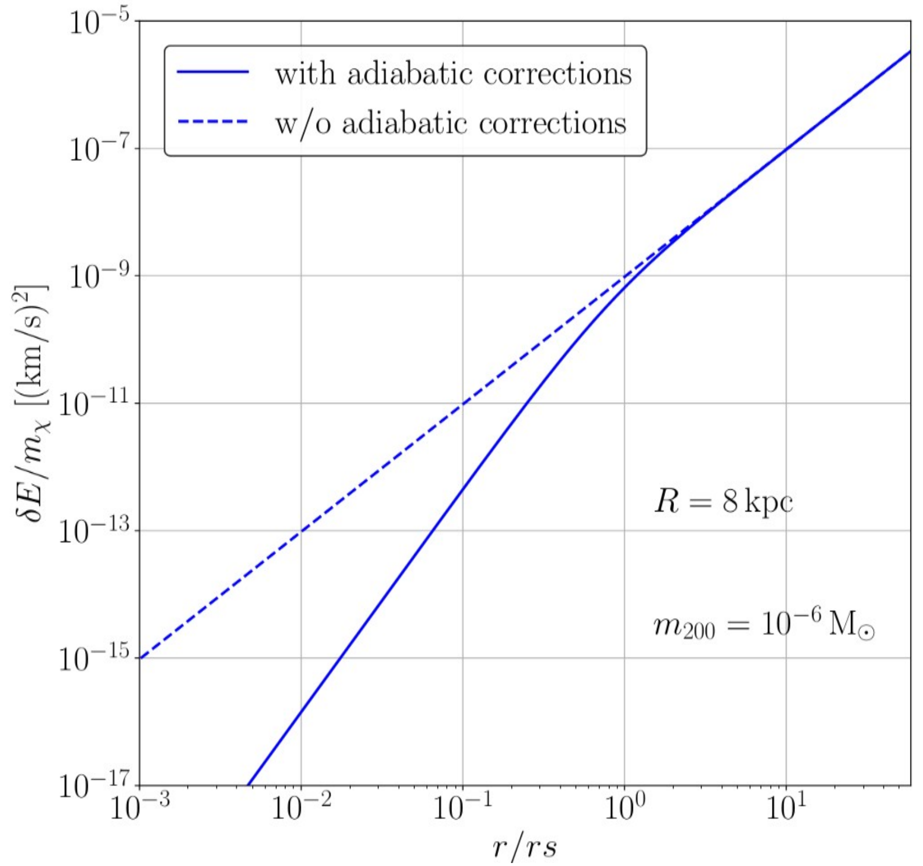
Impulsive approximation: inner clump dynamics is frozen

$\tau_{\rm disk}\,\omega_{\rm sub} \ll 1$ with $\tau_{\rm disk}$: disk crossing time

$\omega_{\rm sub}$: orbit frequency

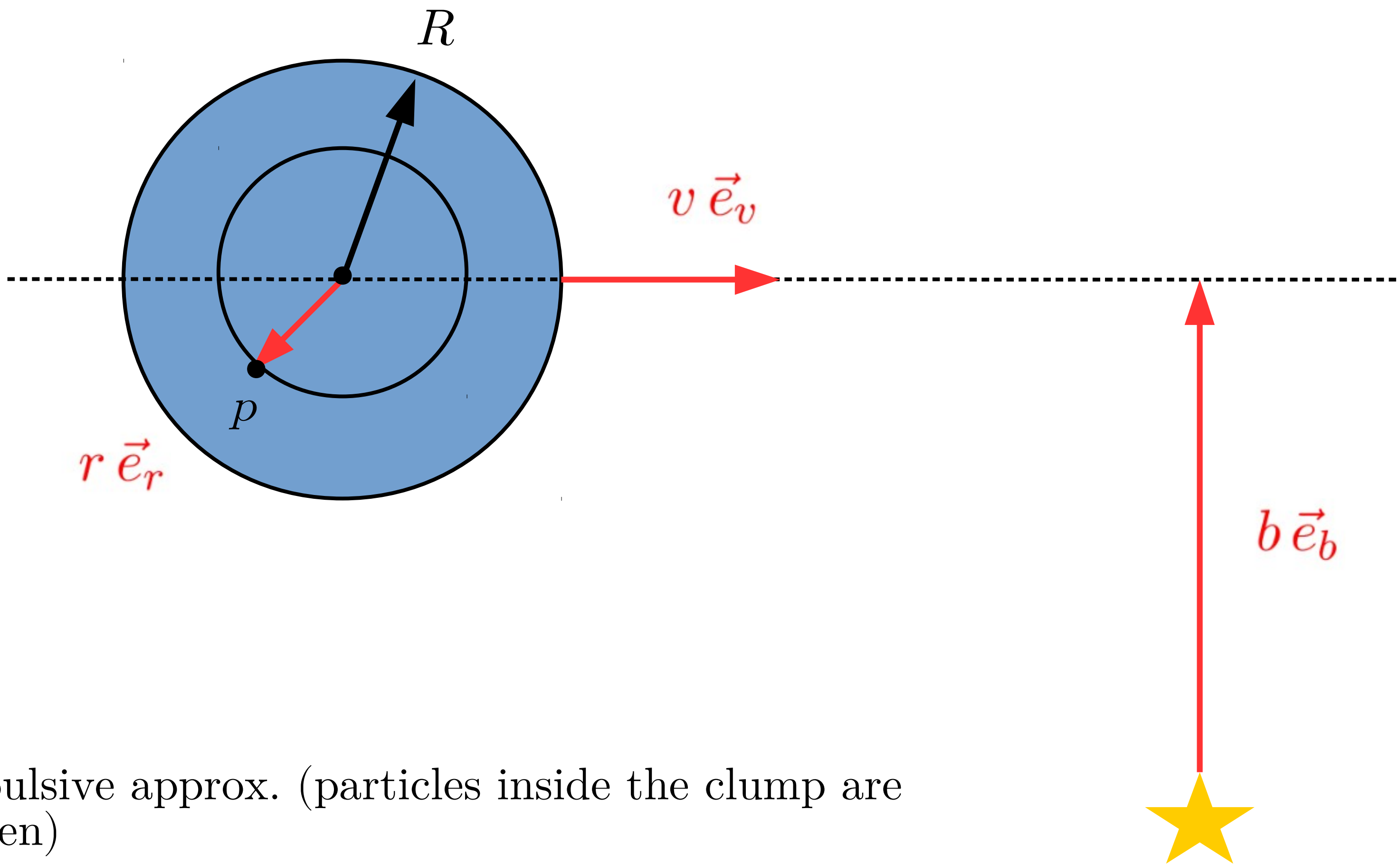
Not a good approximation at the center of a clump
→ adiabatic protection of DM particles
Gnedin & Ostriker 1999

$$\frac{\delta E}{m_\chi} = \frac{2\,g_z^2\,r^2}{3\,V_z^2}\left[1 + (\tau_{\rm disk}\,\omega_{\rm sub})^2\right]^{-3/2}$$



Tidal interactions of subhalos in the Galaxy

- Tidal stripping by the smooth Galactic potential
- Gravitational shocking by the Galactic disk
- Gravitational shocking by stars

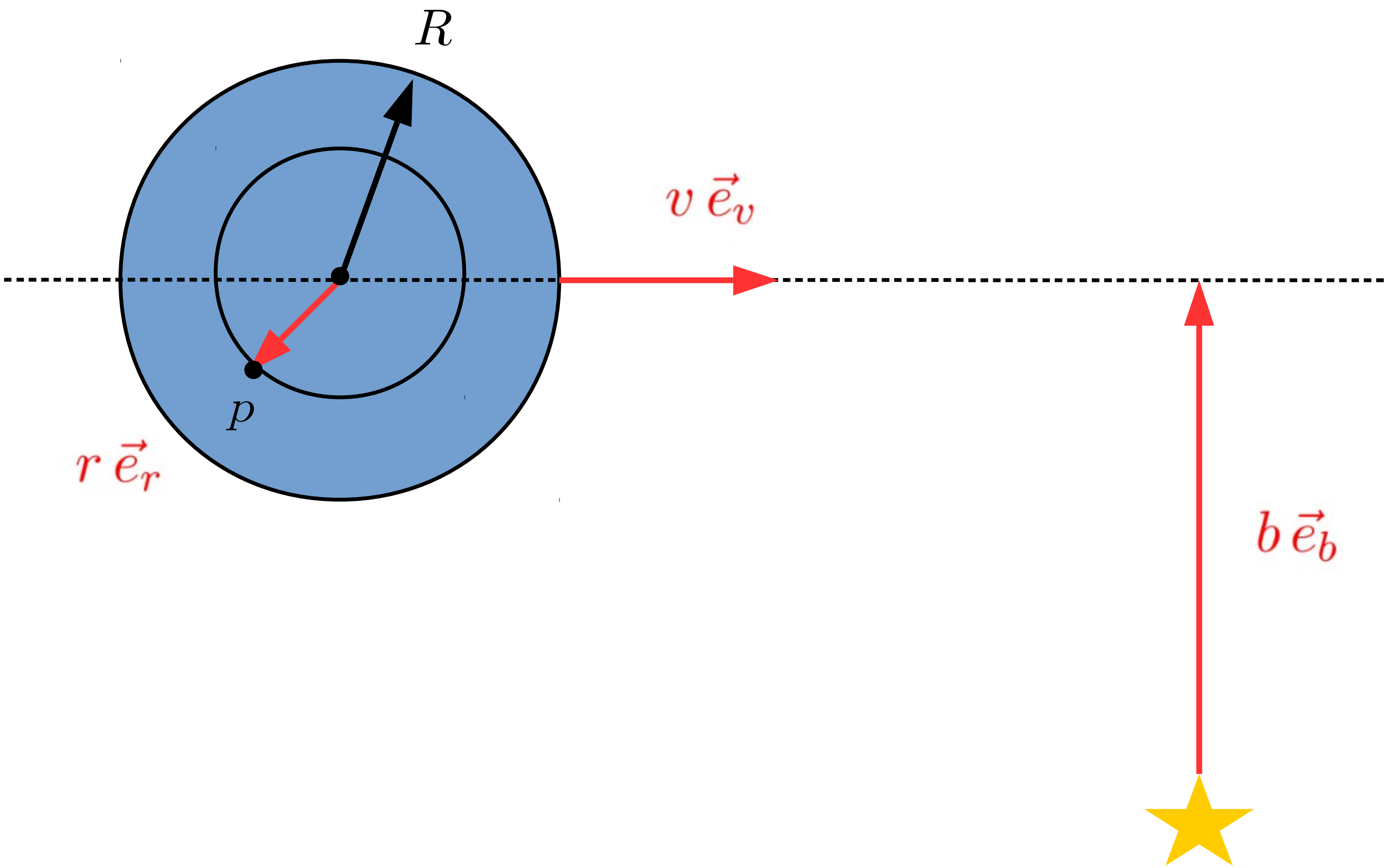


- Impulsive approx. (particles inside the clump are frozen)

- High-speed encounter :

$$|\Delta\vec{v}| \ll v \iff b \gg 1.2\times 10^{-7}\,\mathrm{pc}\left(\frac{M_\mathrm{s}}{M_\odot}\right)\left(\frac{270\,\mathrm{km/s}}{v}\right)^2$$

- Isolated encounter

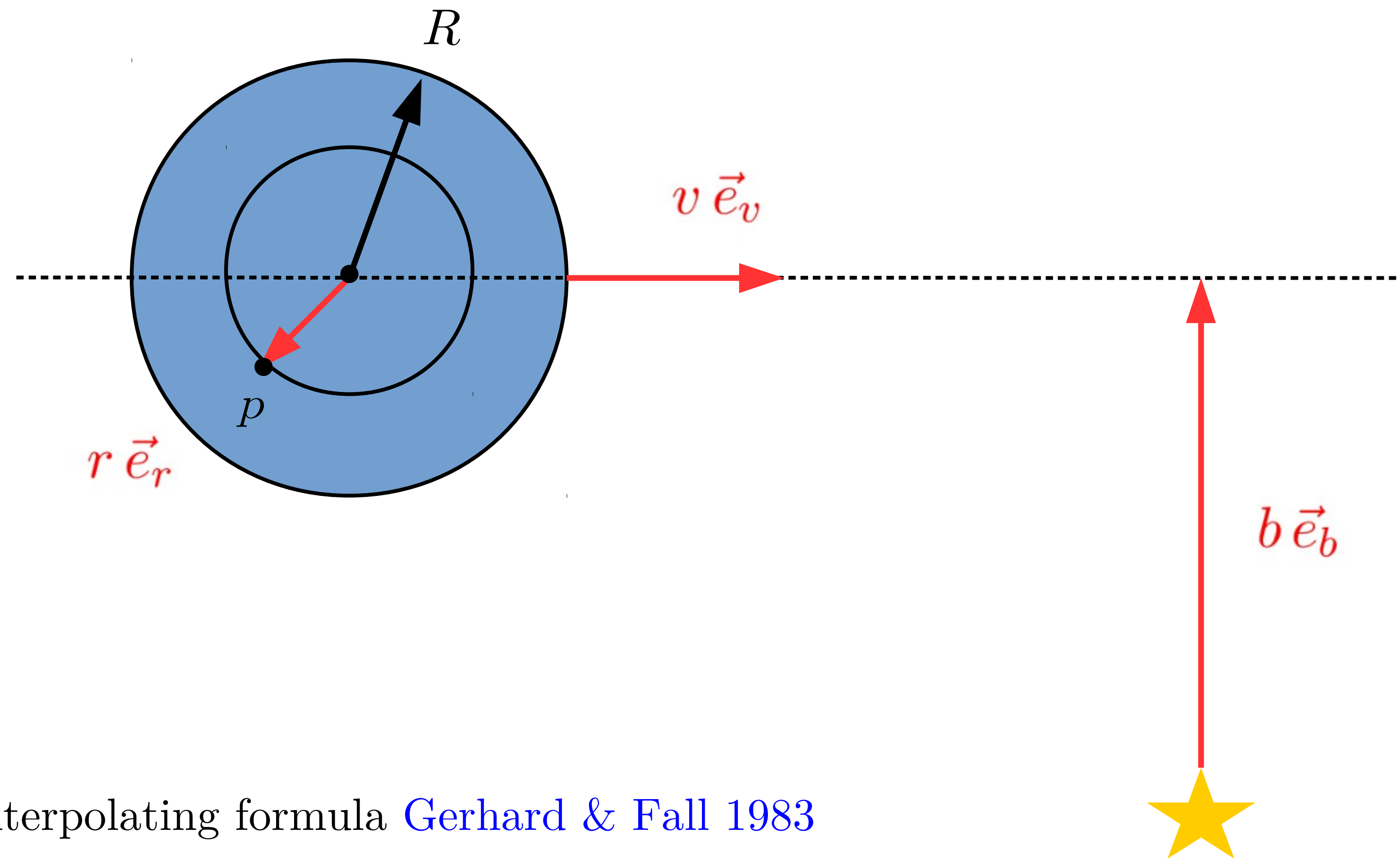


$$\Delta\vec{v}_{\rm p} = \frac{2\,G_{\rm N}\,M_{\rm s}}{b^2\,v}\,\left[2(\vec{r}.\vec{e}_b)\,\vec{e}_b + (\vec{r}.\vec{e}_v)\,\vec{e}_v - \vec{r}\right] \qquad b \gg R$$

Spitzer 1958

$$\Delta\vec{v}_{\rm p} = \frac{2\,G_{\rm N}\,M_{\rm s}}{v\,(r^2 - (\vec{r}.\vec{e}_v)^2)}\,\left[(\vec{r}.\vec{e}_v)\,\vec{e}_v - \vec{r}\right] \qquad b \ll R$$

Gerhard & Fall 1983



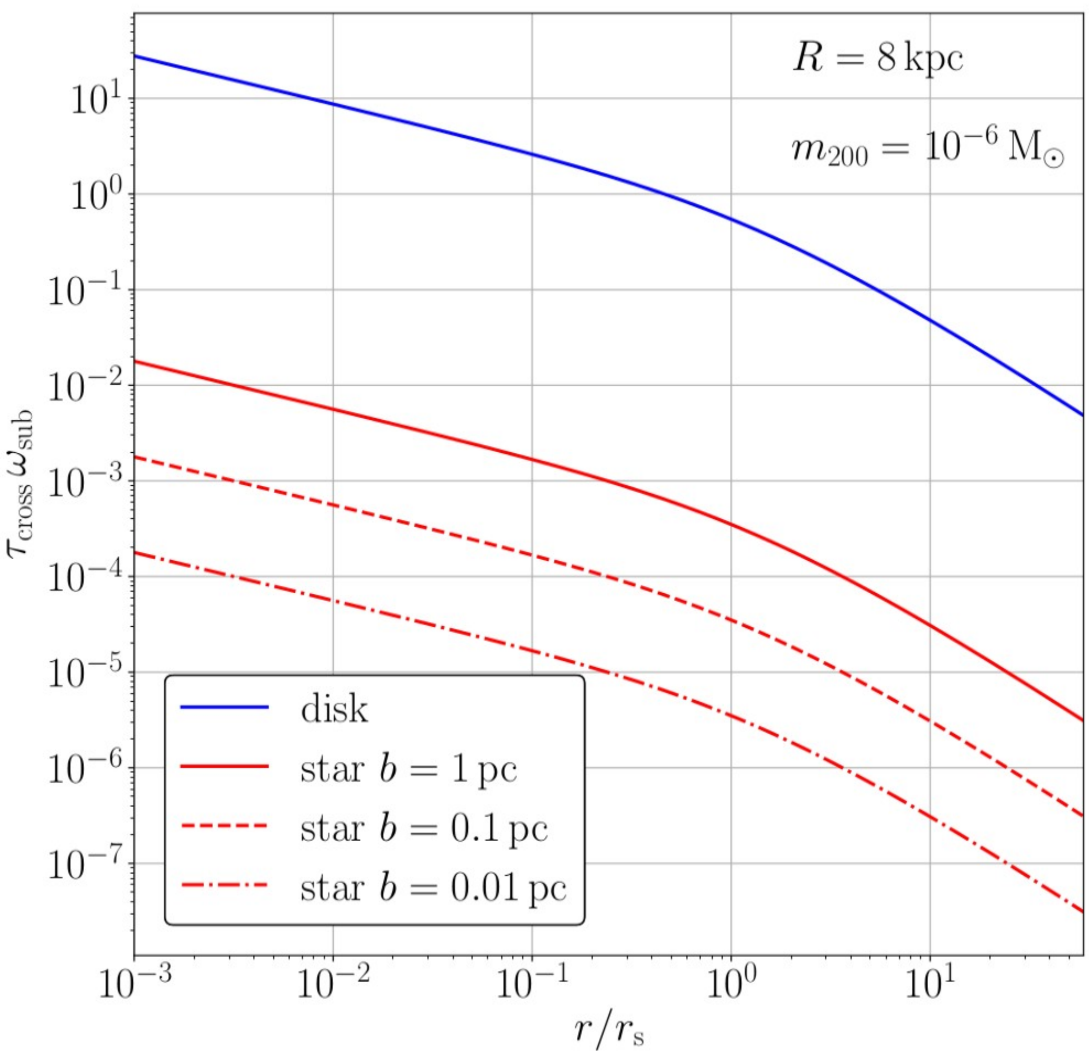
Interpolating formula Gerhard & Fall 1983

$$\Delta\vec{v}_{\rm p} = \frac{2\,G_{\rm N}\,M_{\rm s}}{v\,(b^2+2/3\,r^2)}\,\left[\frac{2\,b^2}{b^2+2/3\,r^2}\,(\vec{r}.\vec{e}_b)\,\vec{e}_b + (\vec{r}.\vec{e}_v)\,\vec{e}_v - \vec{r}\right]$$

Energy gain per particle mass :

$$\boxed{\frac{\delta E}{m_\chi} = \frac{1}{3}\left(\frac{2\,G_{\rm N}\,M_{\rm s}}{v\,b}\right)^2 \frac{r^2}{b^2}\,\frac{1+\left(\frac{2\,r^2}{3\,b^2}\right)^2}{\left[1+\frac{2\,r^2}{3\,b^2}\right]^4} \propto \begin{cases} r^2 & \text{for } r \ll b \\ r^{-2} & \text{for } r \gg b \end{cases}}$$

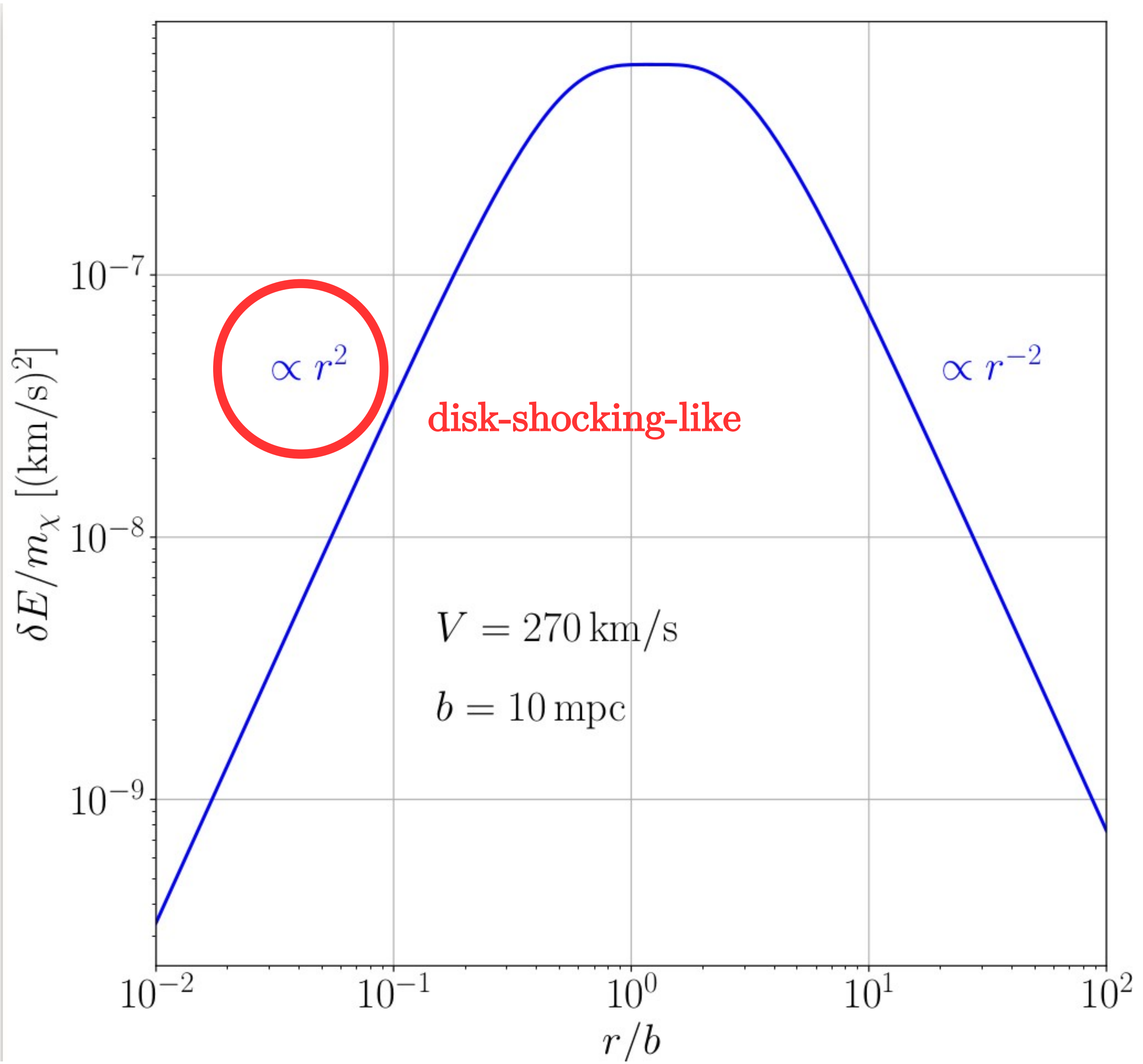
Adiabatic corrections?

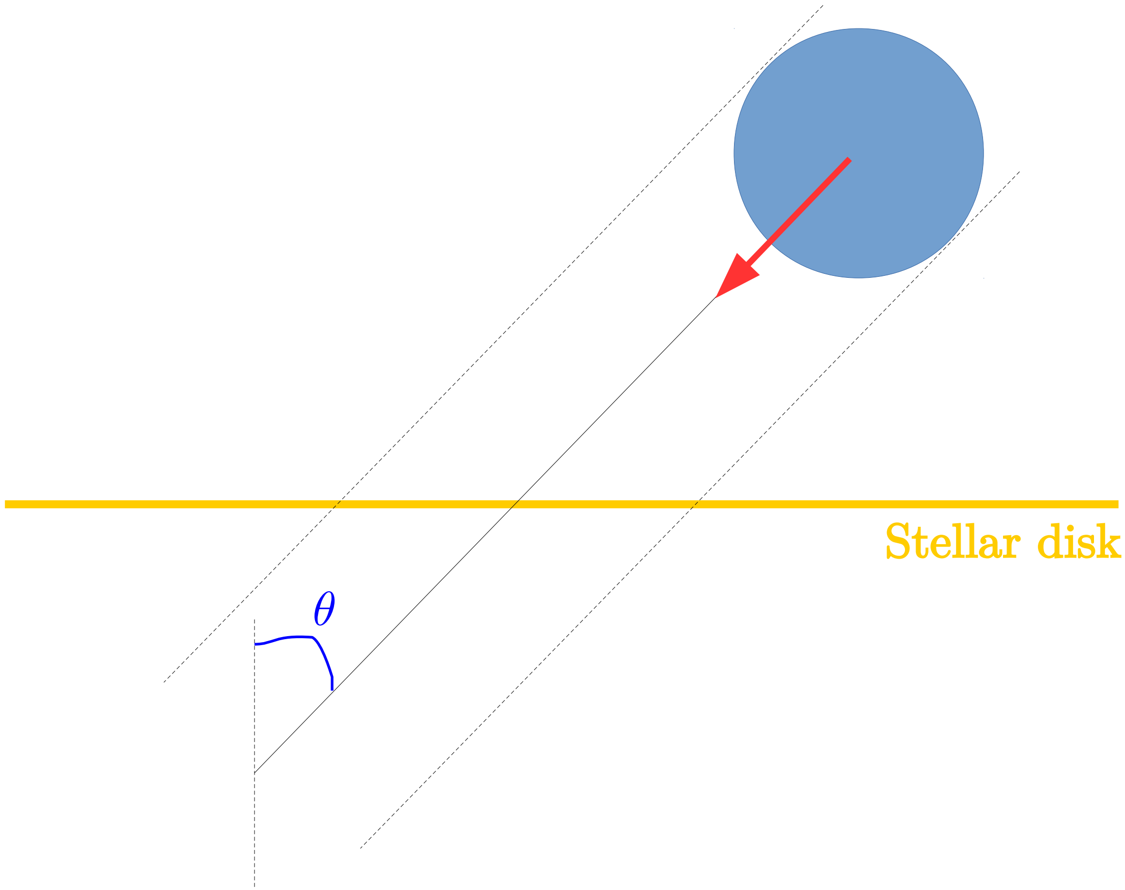


$$\tau_* = \frac{b}{v} \ll \tau_{\mathrm{disc}} = \frac{h_{\mathrm{disc}}}{v_{\mathrm{z}}}$$

$$\tau_*\,\omega_{\mathrm{sub}} \ll 1$$

Impulsive approximation justified in most cases!


10^{-7}
10^{-8}
10^{-9}
$\delta E/m_\chi$ [(km/s)^2]
$\propto r^2$
$\propto r^{-2}$
disk-shocking-like
$V = 270$ km/s
$b = 10$ mpc
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
r/b

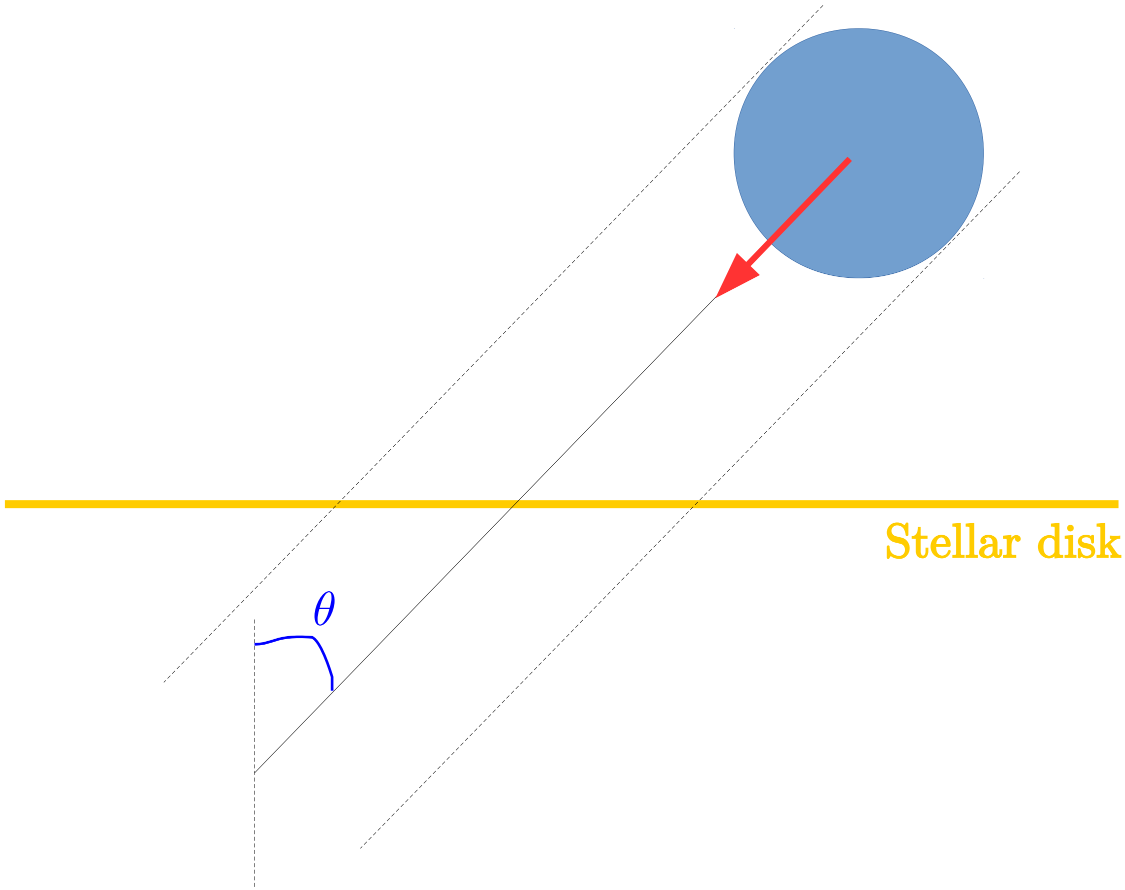


Number of stars with impact parameter < b

$$N_*(< b) = \frac{\Sigma_*}{\langle m_* \rangle} \frac{\pi\, b^2}{\cos\theta} = \frac{\Sigma_*}{\langle m_* \rangle} \pi b^2 \frac{v}{v_z}$$

Energy gain after one disk crossing:

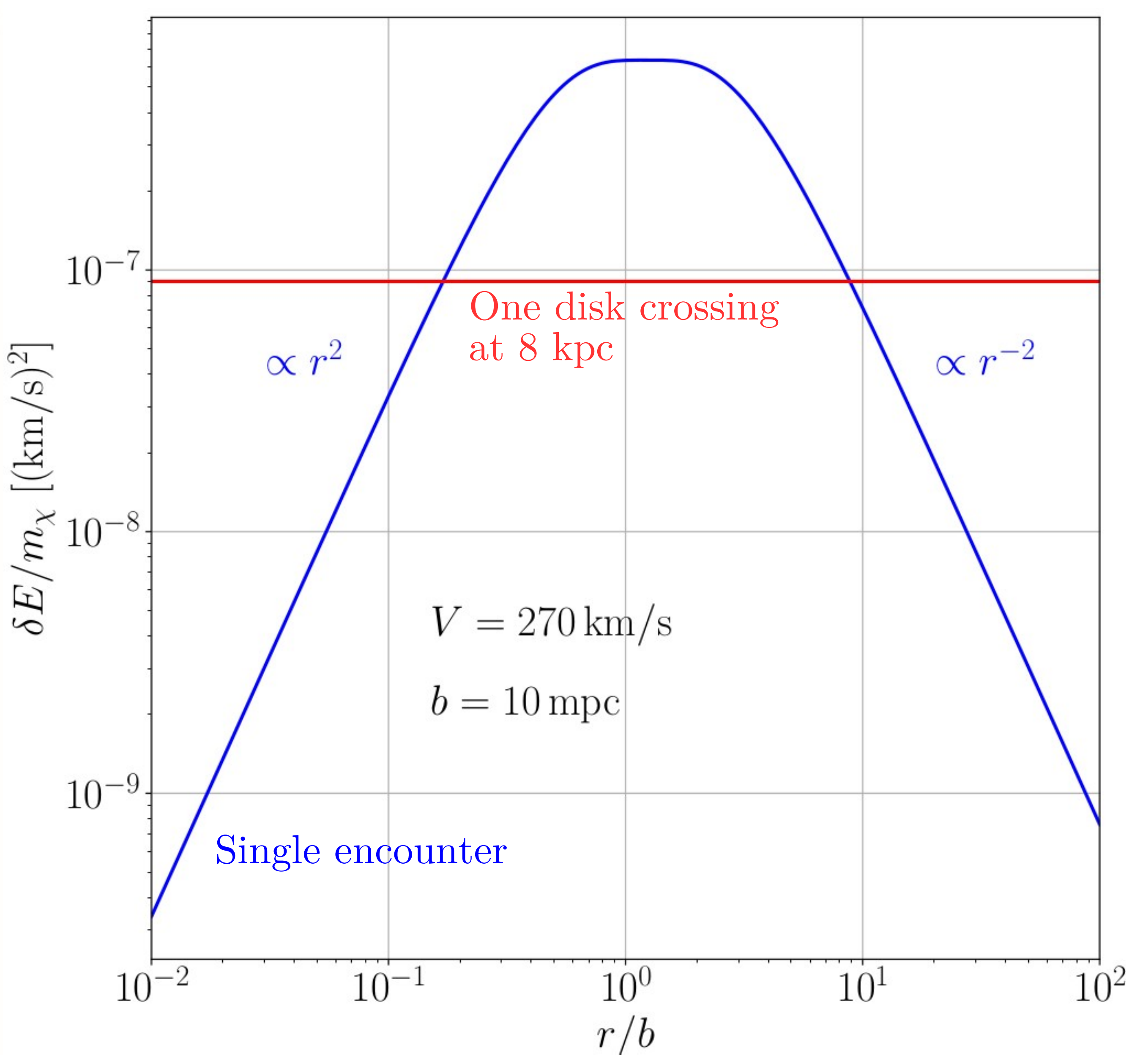
$$\left.\frac{\delta E}{m_\chi}\right|_{\rm cross}(r) = \int \mathrm{d}N_* \frac{\delta E}{m_\chi} \propto \int_{b_{\rm min}}^{b_{\rm max}} \mathrm{d}b\, b\, \frac{\delta E}{m_\chi}(b, r)$$

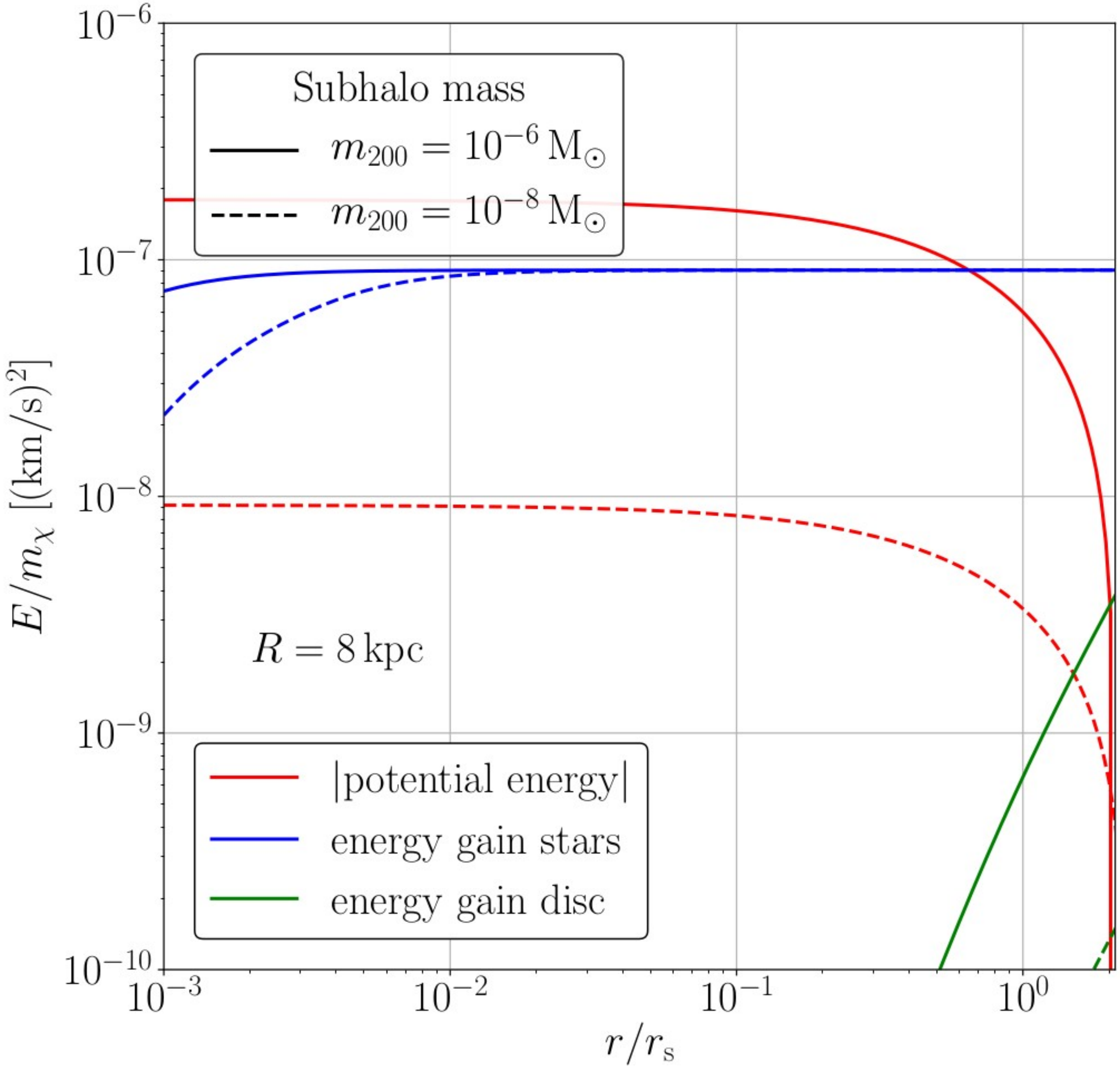


$$\left.\frac{\delta E}{m_\chi}\right|_{\rm cross}(r) \simeq \frac{\Sigma_*}{\langle m_* \rangle}\frac{\pi}{\sqrt{3}}\left(\frac{2\,G_{\rm N}\,M_{\rm s}}{v}\right)^2$$

Nearly independent of r !

$\rightarrow$ homogeneous heating of the clump at disk crossing


$\delta E/m_\chi$ [(km/s)^2]
10^{-7}
10^{-8}
10^{-9}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
r/b
One disk crossing
at 8 kpc
$\propto r^2$
$\propto r^{-2}$
$V = 270\,\mathrm{km/s}$
$b = 10\,\mathrm{mpc}$
Single encounter



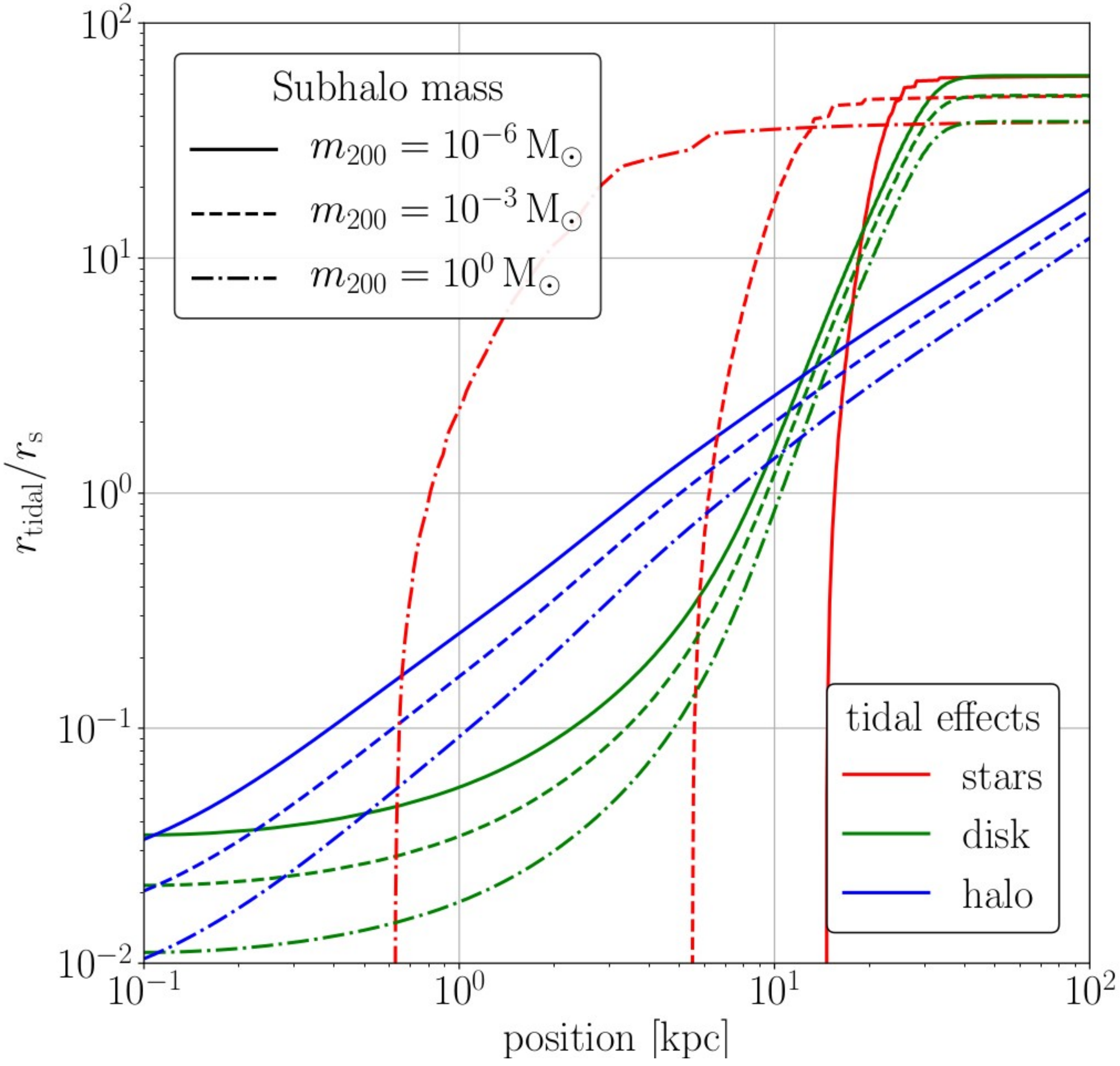
Stars can heat small subhalos much more efficiently than the disk

Too small subhalos are completely disrupted!

New tidal radius:

$$\boxed{\frac{\delta E}{m_\chi}(r_\mathrm{tidal}) = |\phi(r_\mathrm{tidal})|}$$

Tidal radius

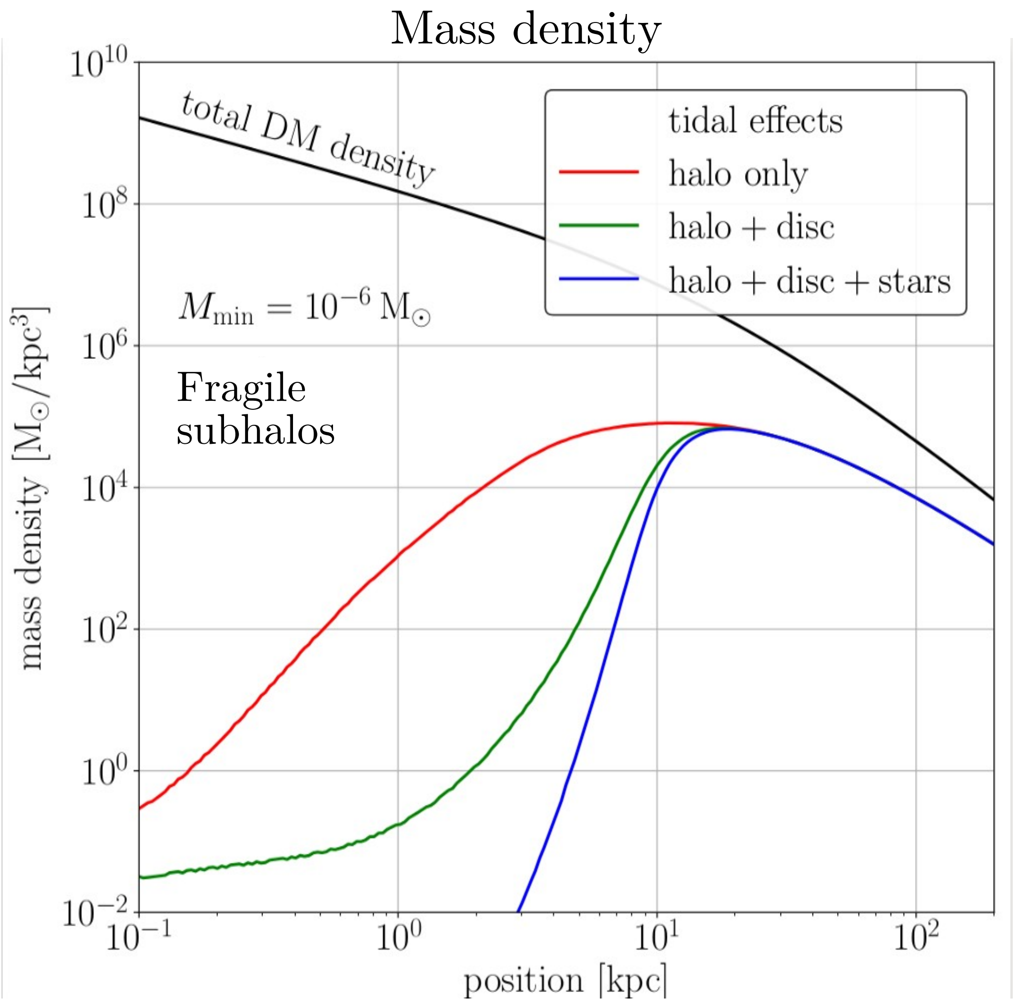


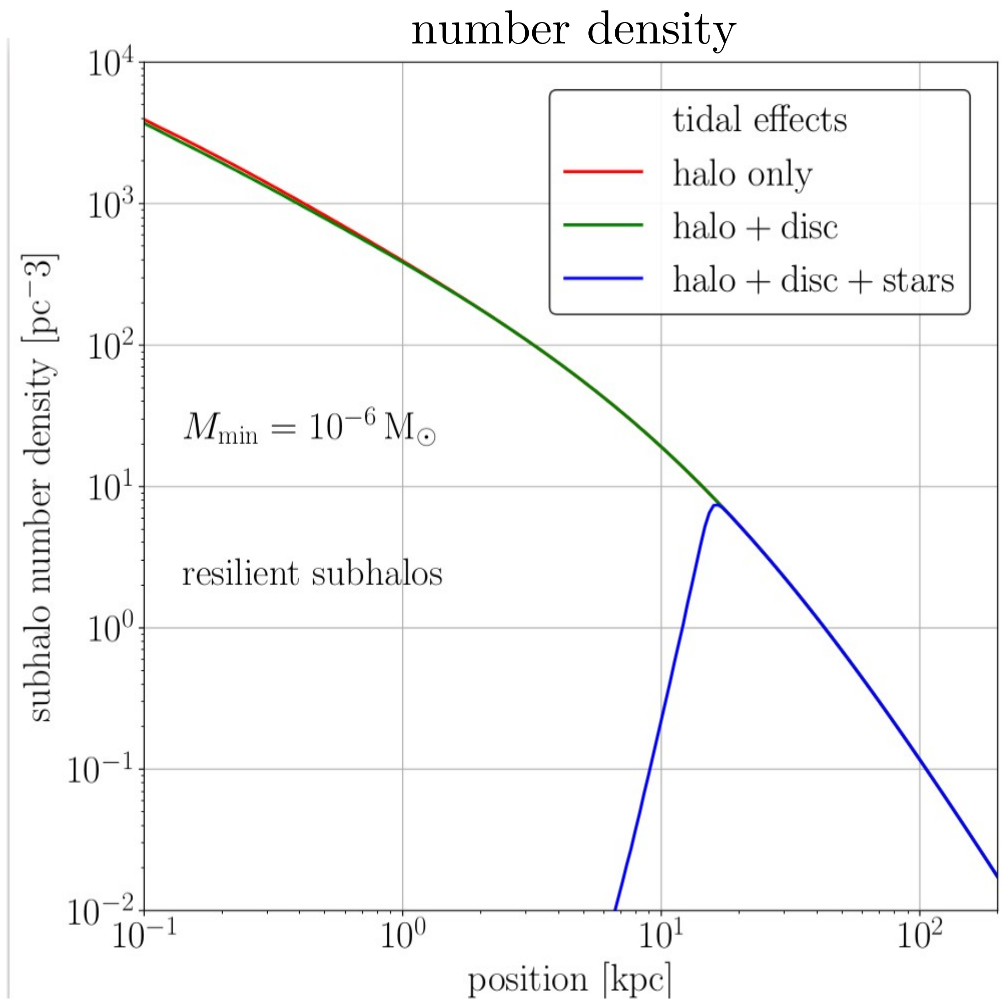
According to several studies [Penarrubia+ 10, van den Bosch+ 2018], subhalos can survive even if

$$r_{\rm tidal} \ll r_{\rm s}$$

Star shocking might be the only effect able to completely disrupt subhalos

My only two plots with the effect of stars...





Conclusions

- Fully-analytical model of Galactic subhalos, which incorporates **cosmological ingredients** and **kinematic constraints**

- **Disk shocking effects** are very effective at stripping DM clumps

- **Shocking by stars** seems very efficient at destroying small clumps

- **Uncertainties** on the **small-scale power spectrum** and **complete disruption** dominate the predicted Galactic population

- Results important for direct and indirect searches, Galactic dynamics, ...

Conclusions

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WORK IN PROGRESS

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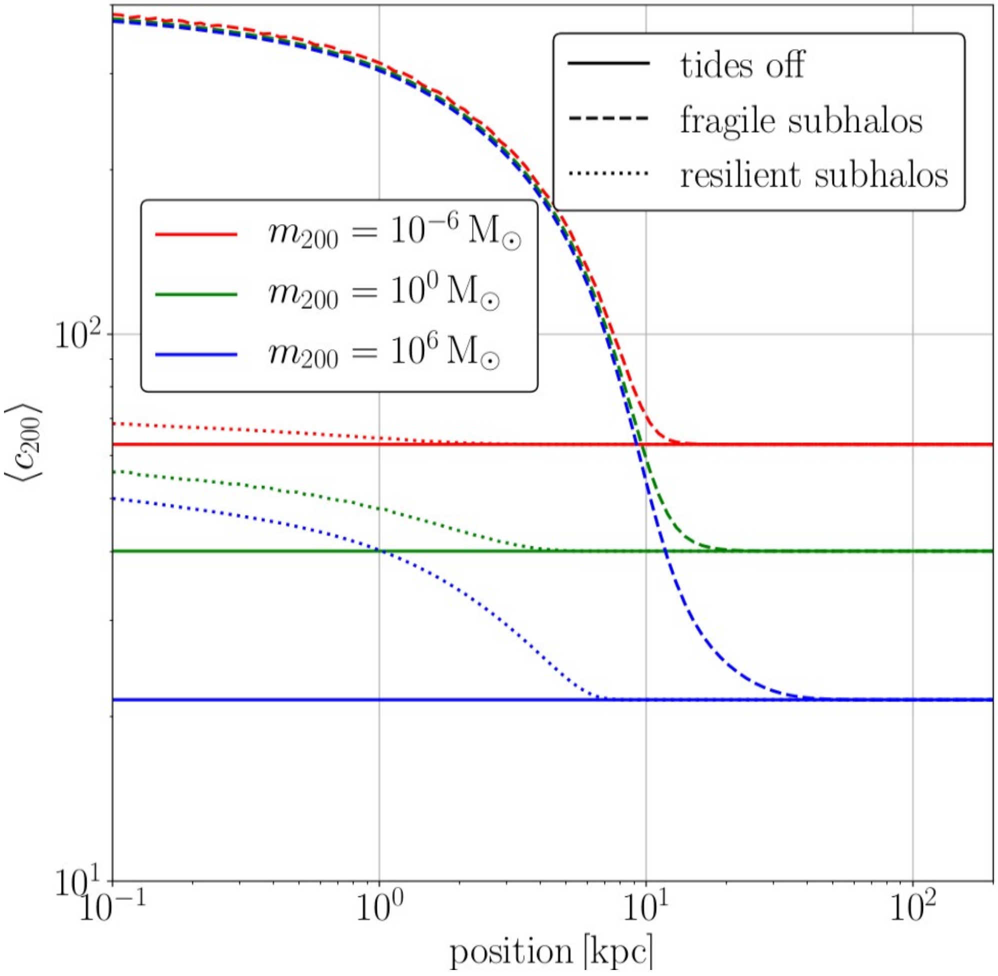
Backup

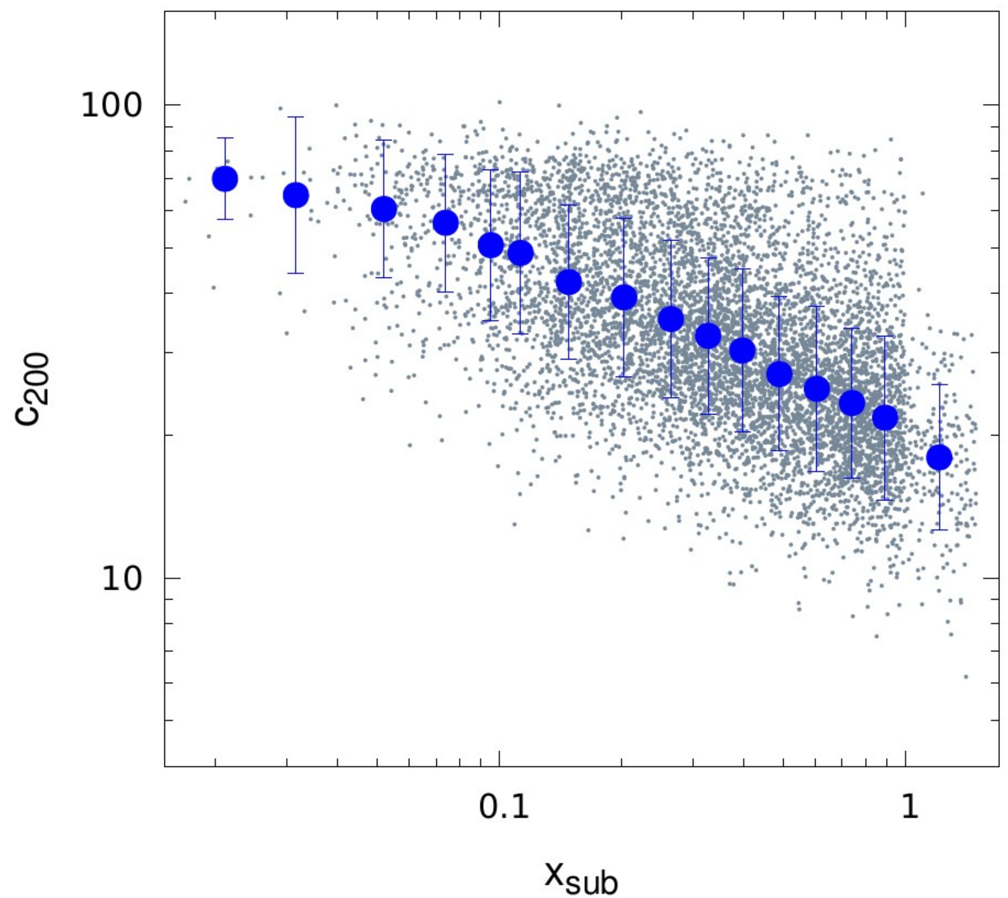
Post-tides concentrations

Tidal effects destroy subhalos based on their concentration

$\rightarrow$ the most concentrated objects are more likely to survive

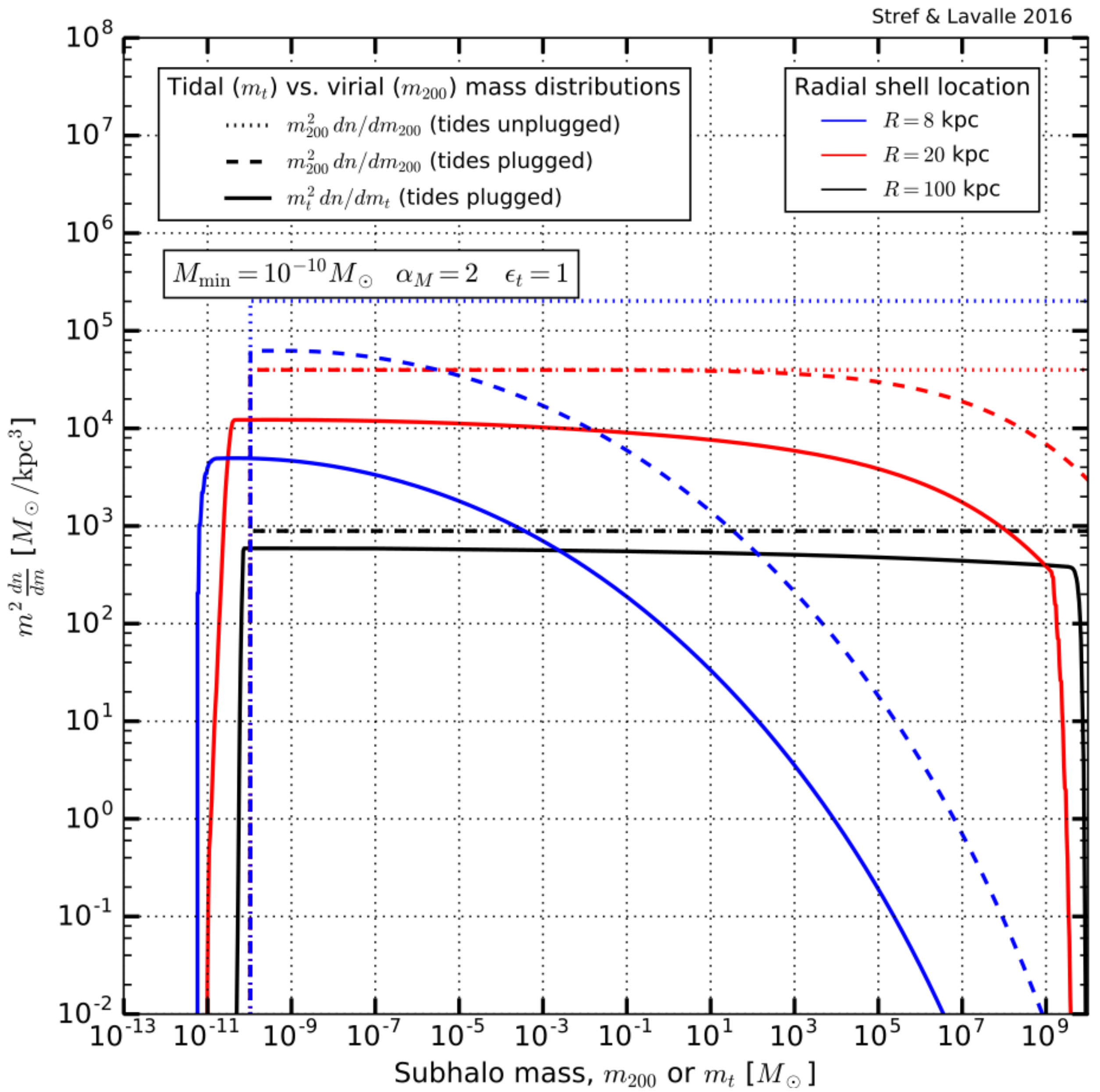


Moliné+ 2016



Post-tides mass function

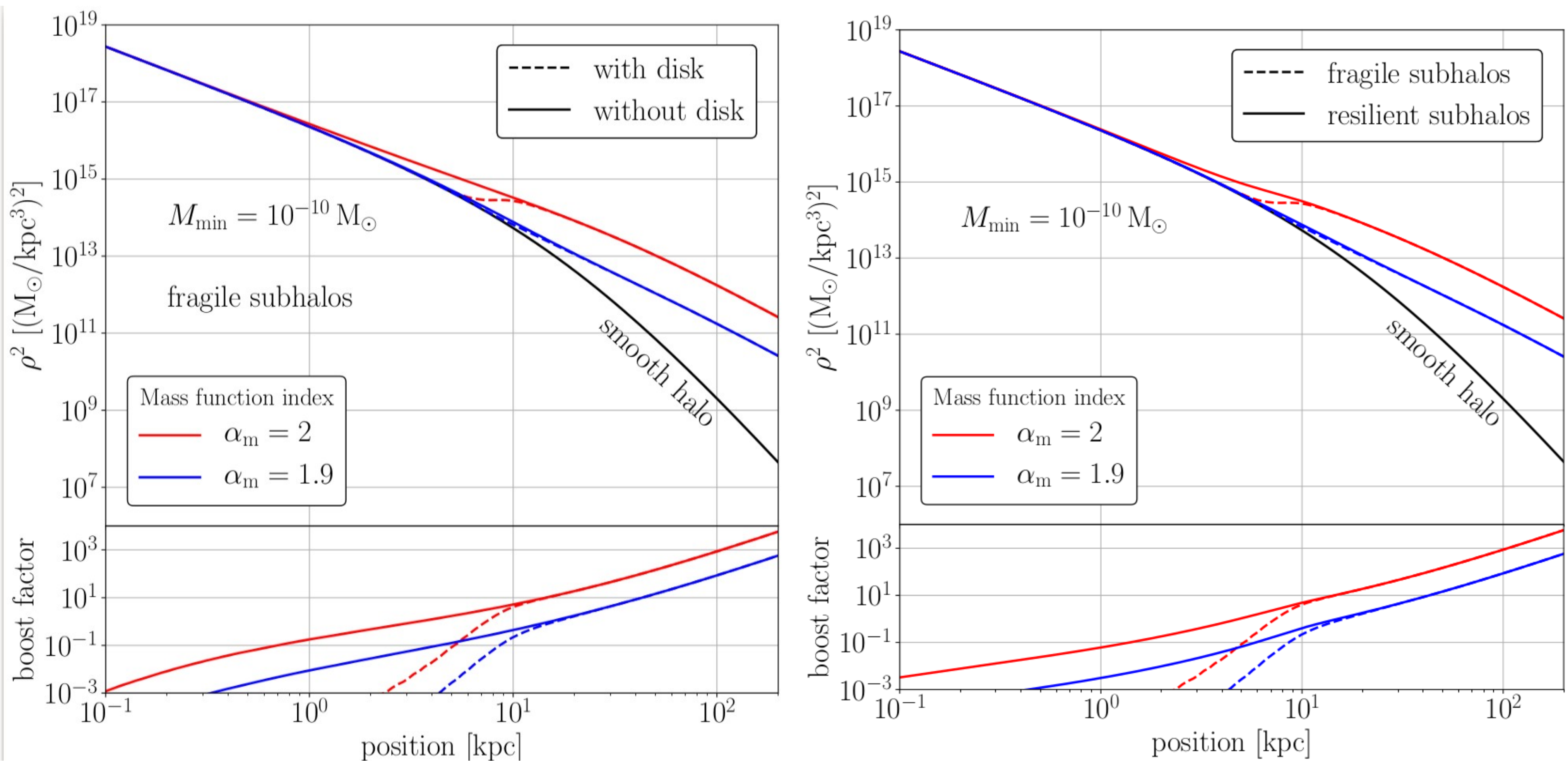
Tidal selection of the most concentrated objects = the smallest ones



The annihilation "boost" factor

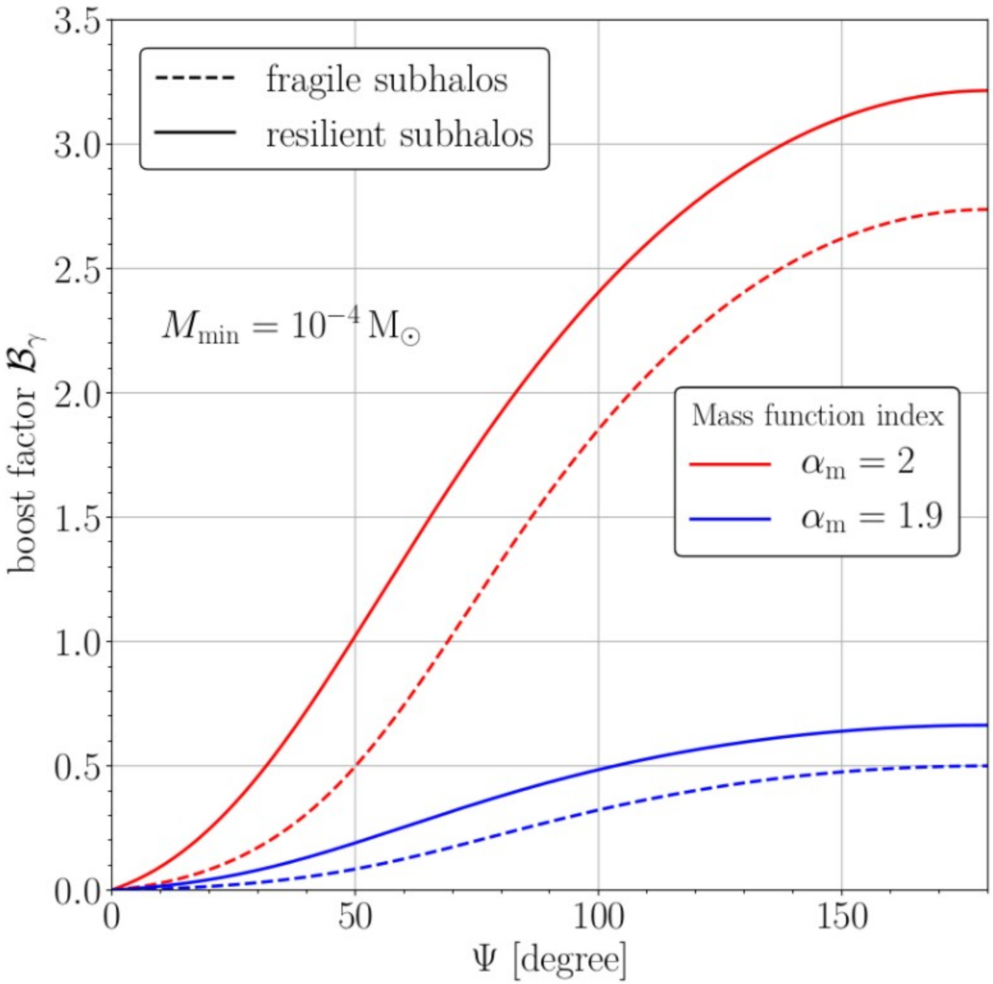
Originally pointed out by Silk & Stebbins 1993 : clustering "boosts" the annihilation rate!

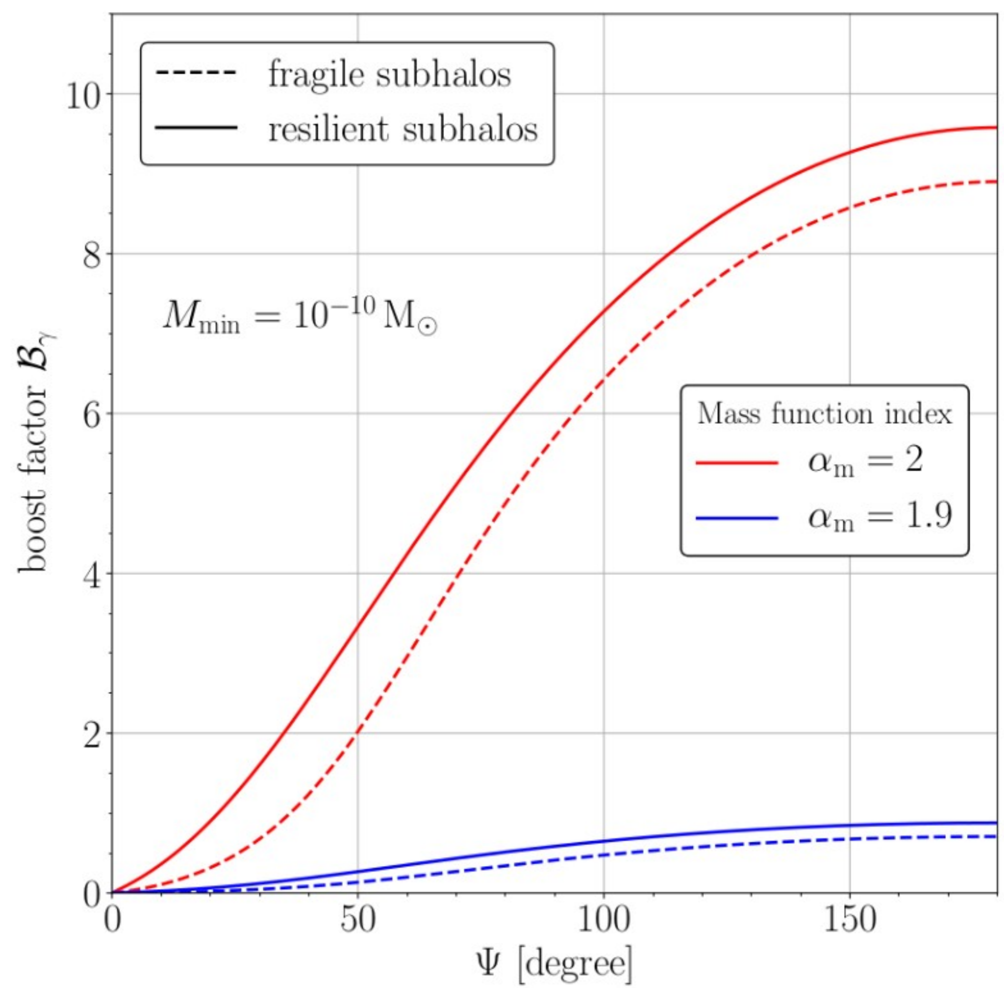
$$1 + \mathcal{B}(\vec{r}) = \frac{\left\langle \rho^2(\vec{r}) \right\rangle_{\text{clumpy}}}{\left\langle \rho^2(\vec{r}) \right\rangle_{\text{smooth}}}$$



Gamma rays

$$J(\psi) = \int \mathrm{d}s\, \rho^2(s,\psi) \longrightarrow 1 + \mathcal{B}_\gamma(\psi) = \frac{J_{\text{clumpy}}(\psi)}{J_{\text{smooth}}(\psi)}$$

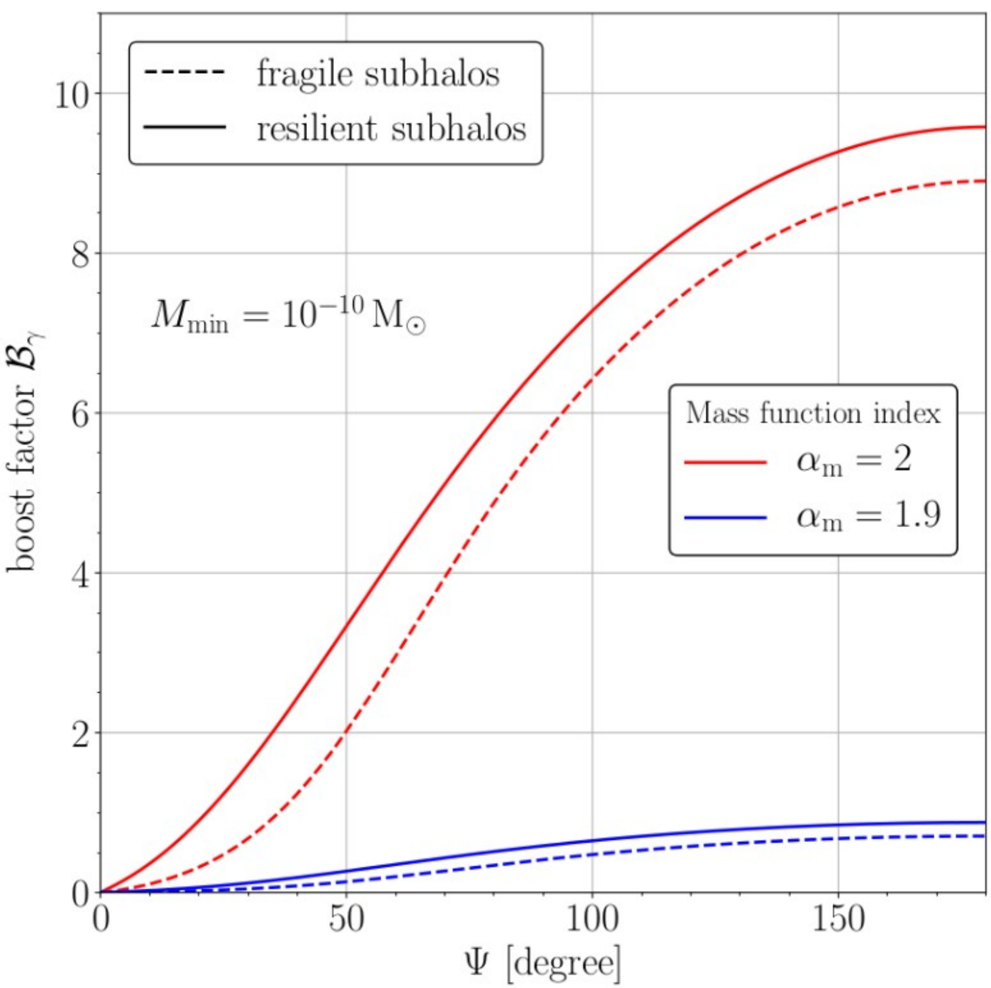




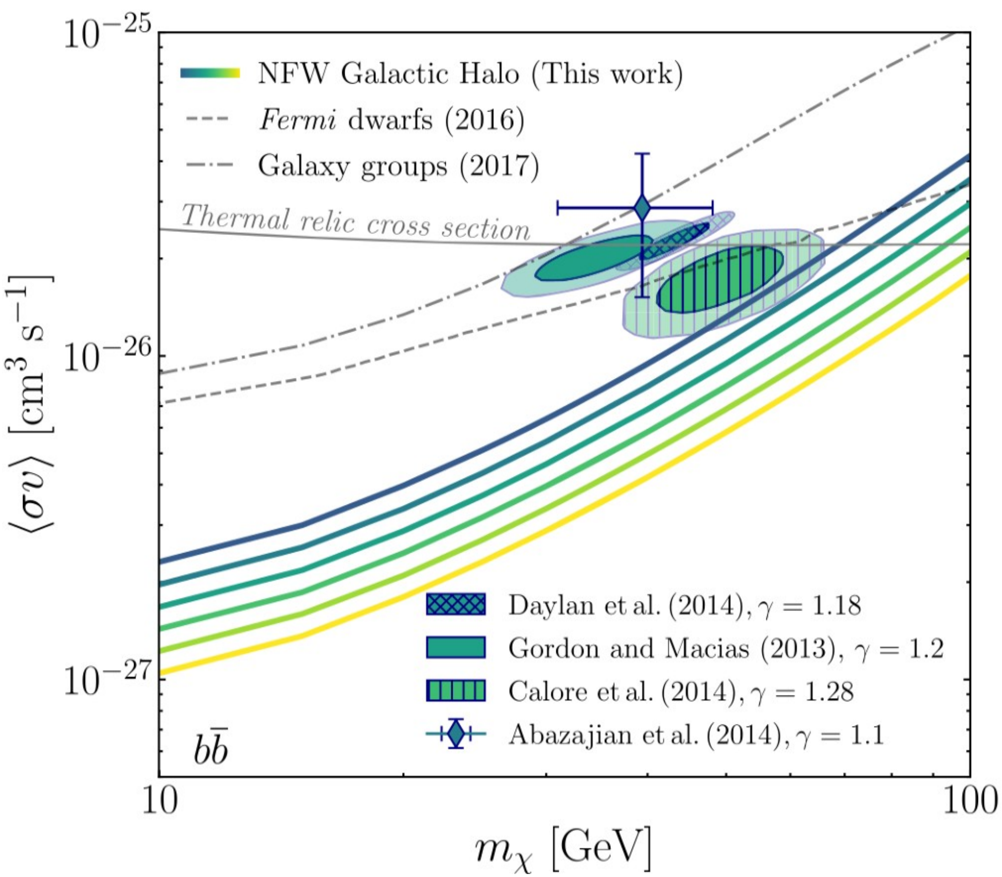
- Highly sensitive to $\alpha_{\rm m}$
- Factor of a few at high latitudes

Gamma rays

Crucial since high latitudes can be very constraining!

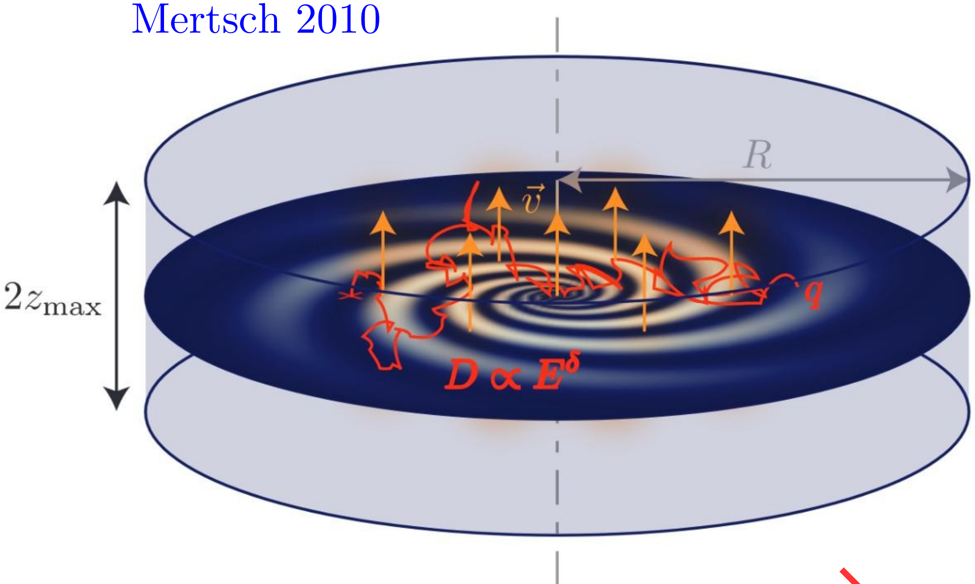


Limits derived using high latitudes
and a *smooth halo* [Chang+ 2018]



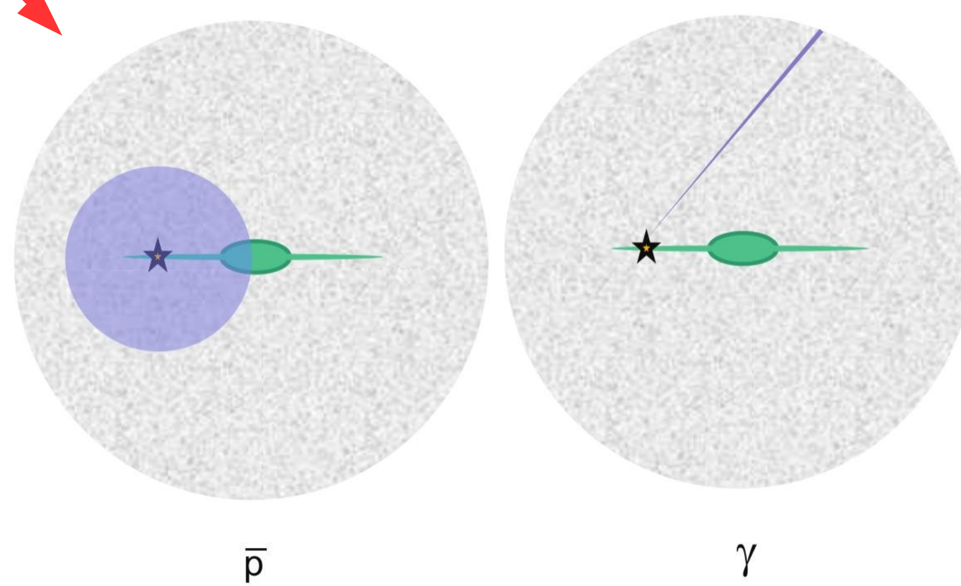
Cosmic-ray antiprotons

Mertsch 2010



Antiprotons diffuse in the turbulent Galactic magnetic field

Bergström 2009



Antiprotons are a probe complementary to gamma rays [Silk & Srednicki 1984]

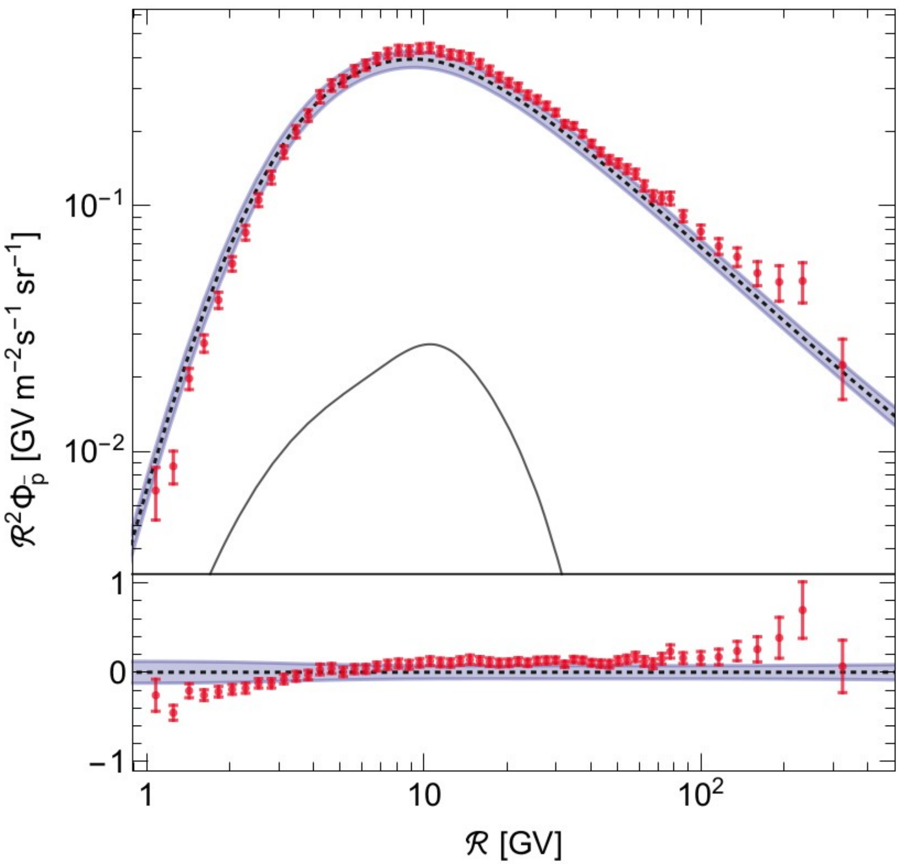
Cosmic-ray antiprotons

Excess of antiprotons in the AMS-2 data compared to the secondary prediction [Cuoco+ 2017-2019, Cui+ 2017-2018, Cholis+ 2019]

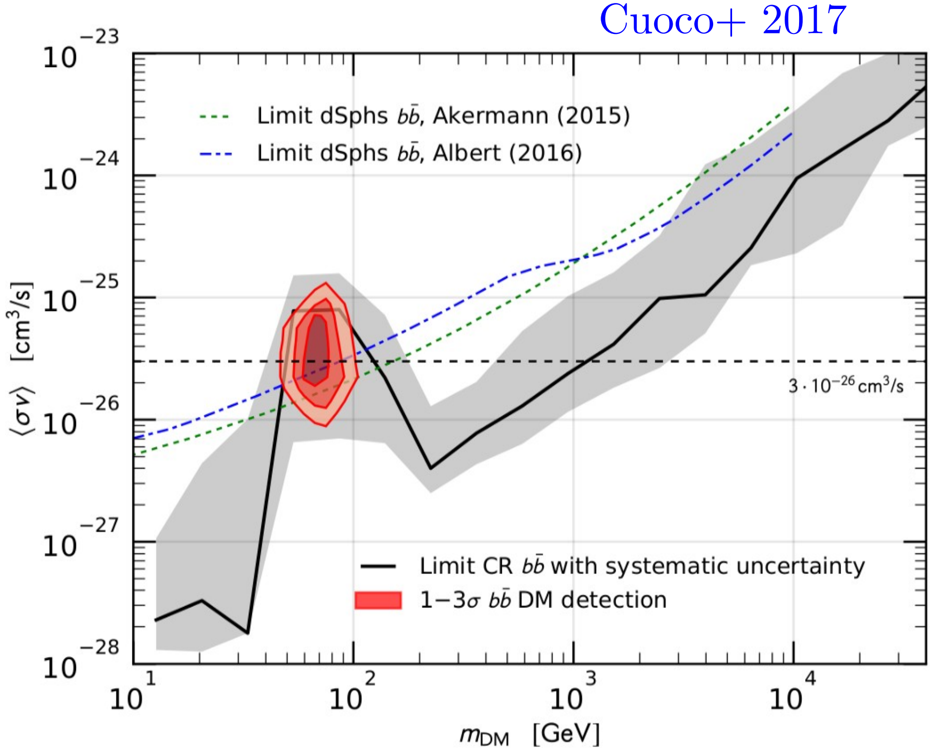
Significant or not [~2σ in Reinert & Winkler 2018] depending on the treatment of systematic uncertainties

DM annihilation ???

Reinert & Winkler 2018



Cuoco+ 2017



Cosmic-ray antiprotons

Phenomenological transport equation:

$$\boxed{\partial_t \Psi + \vec{\nabla}.\left[\vec{V}_c \Psi - K(E)\,\vec{\nabla}\Psi\right] - \partial_E\left[b(E)\Psi - D(E)\partial_E \Psi\right] + \Gamma_{\rm tot}\Psi = Q}$$

DM annihilation source term: $$Q(\vec{x},E) = \frac{\langle\sigma_{\rm ann} v\rangle}{2}\left(\frac{\rho(\vec{x})}{m}\right)^2 \frac{\mathrm{d}N_{\overline{p}}}{\mathrm{d}E}$$

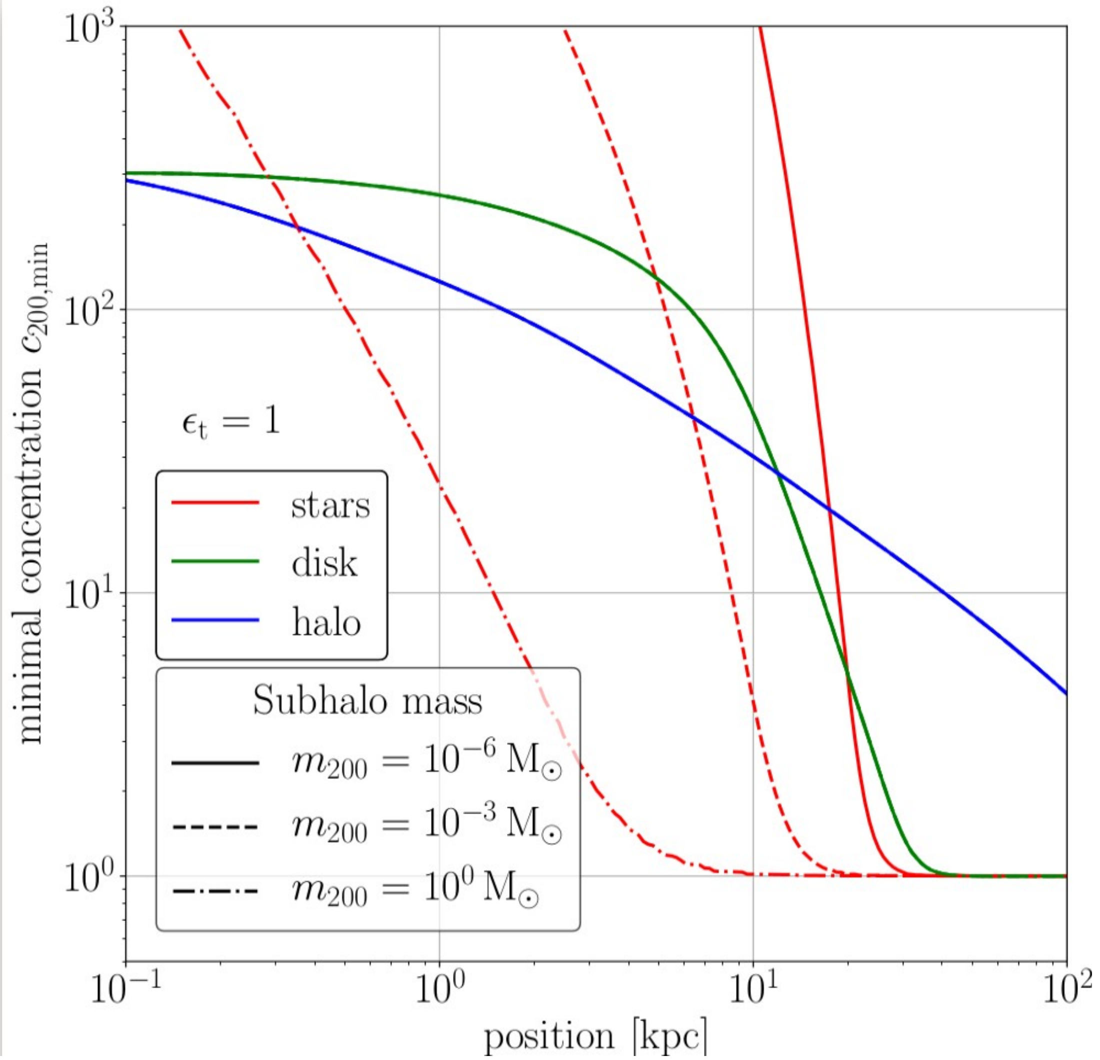
<u>Two approaches</u>:

- Fully numerical solutions (e.g. GALPROP [Strong & Moskalenko 1998], DRAGON [Maccione+ 2011])
- Semi-analytical solutions (e.g. USINE [Maurin+ 2001,2016])

We choose a semi-analytical treatment and express the CR flux with a Green's function:

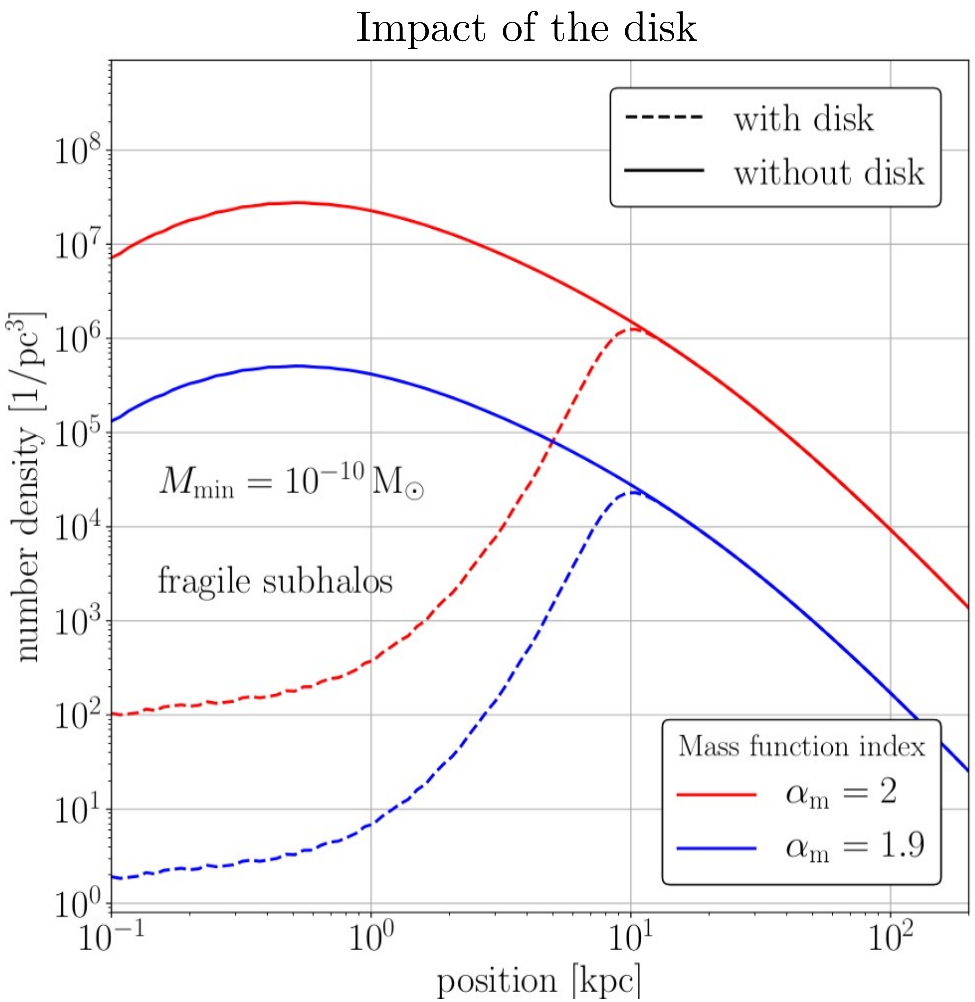
$$\frac{\mathrm{d}\Phi_{\overline{p}}}{\mathrm{d}T} = \frac{v_{\overline{p}}}{4\pi}\frac{\langle\sigma v\rangle}{2\,m_\chi^2}\int \mathrm{d}E_{\rm s}\int \mathrm{d}^3\vec{r}_{\rm s}\, G(E \leftarrow E_{\rm s}; \vec{r}_\odot \leftarrow \vec{r}_{\rm s})\,\frac{\mathrm{d}N_{\overline{p}}}{\mathrm{d}E}(E_{\rm s})\,\rho^2(\vec{r}_{\rm s})$$

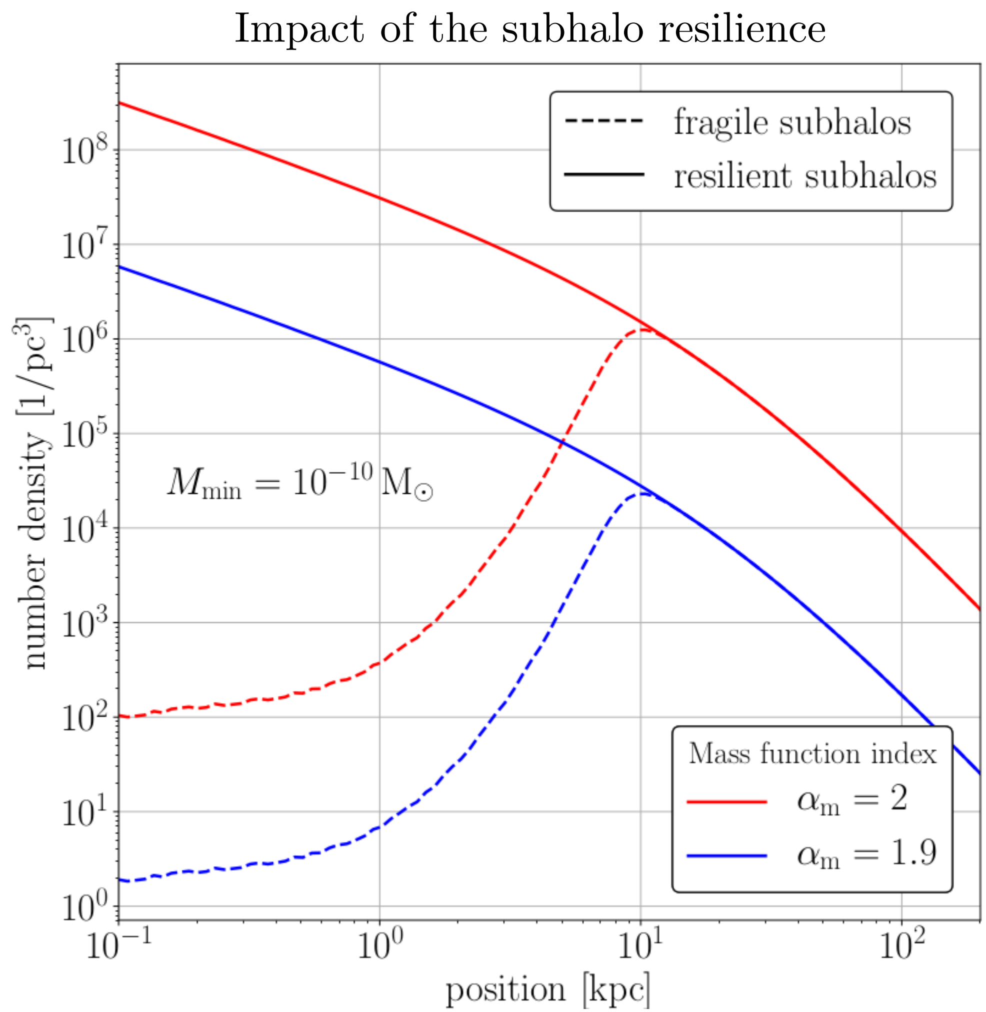
antiprotons boost factor: $$1 + \mathcal{B}_{\overline{p}}(T) = \frac{\mathrm{d}\Phi_{\overline{p}}/\mathrm{d}T|_{\rm clumpy}}{\mathrm{d}\Phi_{\overline{p}}/\mathrm{d}T|_{\rm smooth}}$$



10^3
10^2
10^1
10^0
minimal concentration $c_{200,\mathrm{min}}$
10^{-1}
10^0
10^1
10^2
position [kpc]
$\epsilon_t = 1$
stars
disk
halo
Subhalo mass
$m_{200} = 10^{-6}\,\mathrm{M}_\odot$
$m_{200} = 10^{-3}\,\mathrm{M}_\odot$
$m_{200} = 10^{0}\,\mathrm{M}_\odot$

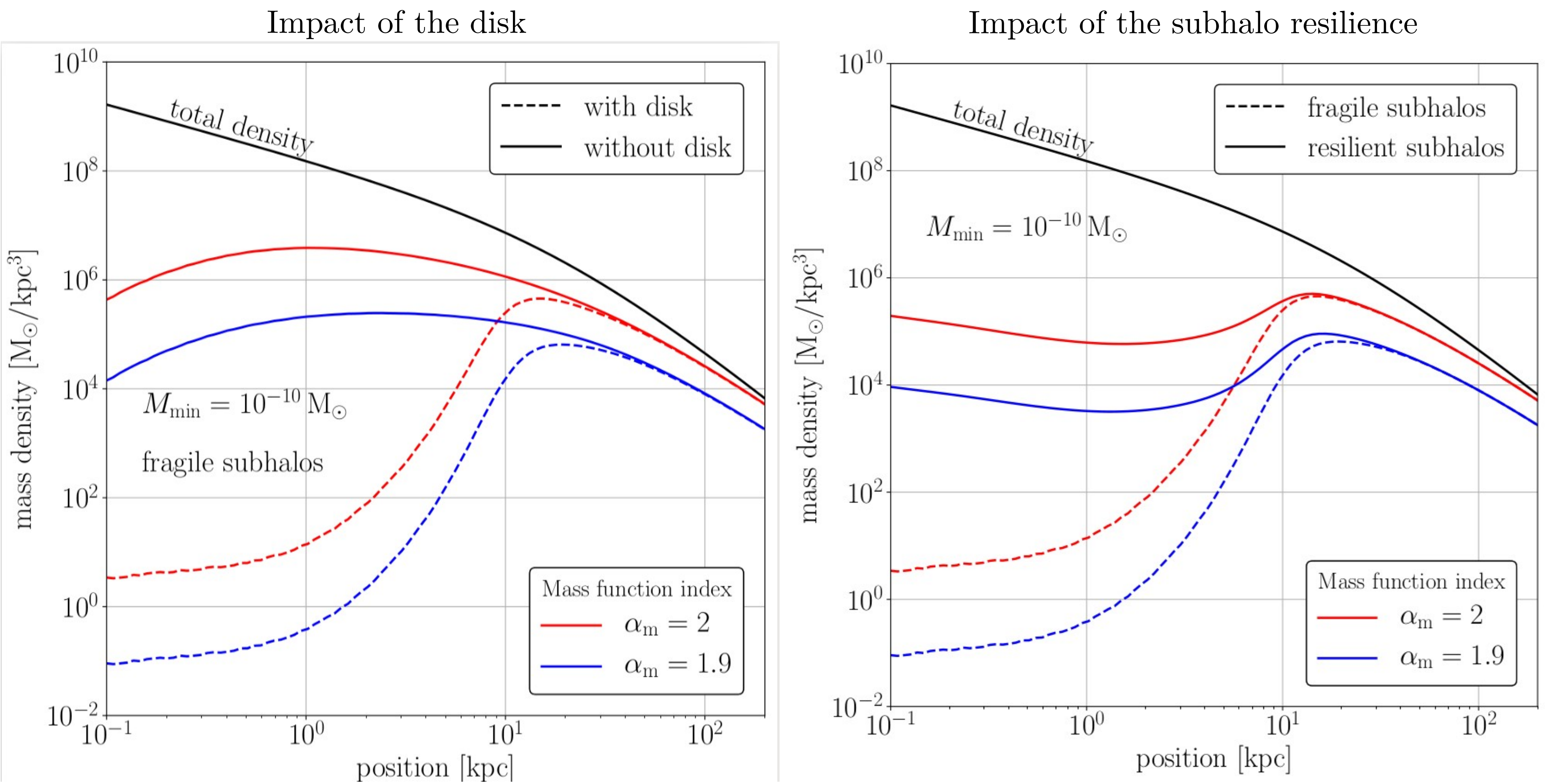
Subhalo number density in the Galaxy





Potentially very large local population!

DM mass density inside subhalos



Subhalo very stripped at the centre → low contribution to the total mass density

Results with Mmin = 10^{-4} Msun