The Montpellier model for Galactic subhalos

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Gamma-ray meeting
LAPTh
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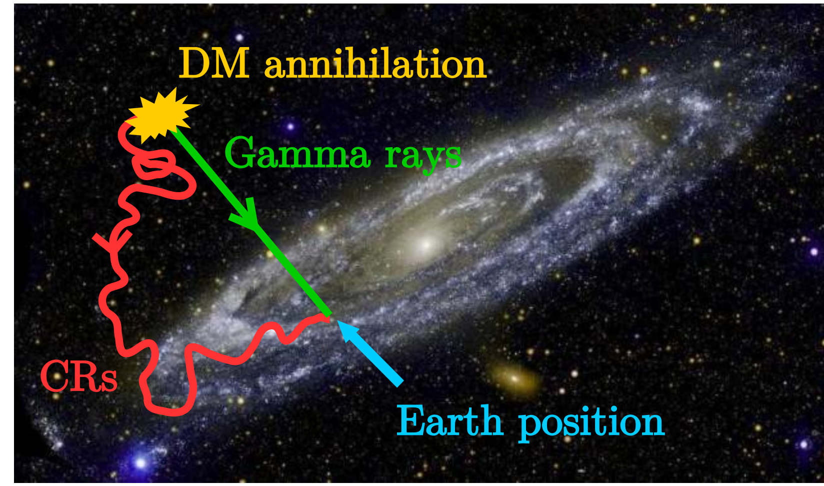
Indirect DM searches through gamma rays

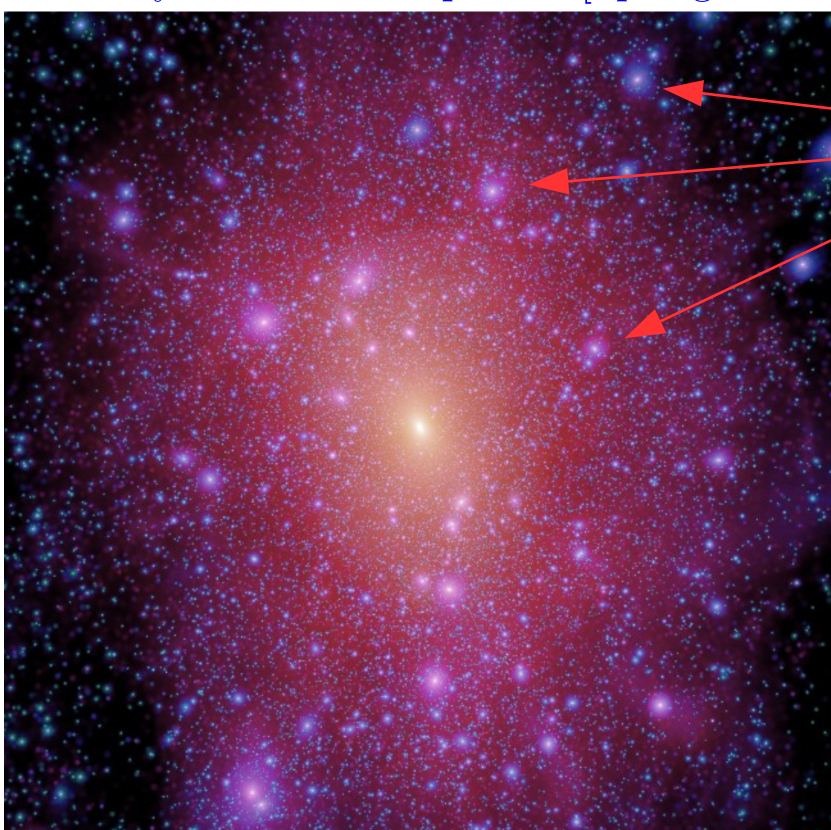
Gamma-ray flux from annihilating DM:

$$\left.\frac{d\phi_\gamma}{dE\,d\Omega}\right|_{\rm los} = \frac{\langle \sigma_{\rm ann} v\rangle}{8\pi^2\, m_\chi^2}\frac{dN_\gamma}{dE} \times \int_{\rm los} ds\, \rho^2(\vec{r})$$

Highly sensitive to inhomogeneities



DM-only simulation Aquarius [Springel+ 08]



Lots of subhalos within a galactic halo!

Subhalos **boost** the expected annihilation flux $\rightarrow$ the smooth approximation induces a systematic error

To make a reliable prediction, we need to know:
- the subhalos mass function
- their spatial distribution
- their density/concentration

Numerical vs Analytical

Numerical approach

- Self-consistent modeling of gravity
- Solve the non-linear evolution
- High computing cost
- Limited mass resolution (~$10^3\,M_\odot$ at best)
- Not the Milky Way
  (although see Calore+ 2015)

Analytic approach

- Unlimited resolution
- Easy implementation of cosmology/particle physics constraints
- Dynamically constrainable
- Approximations needed beyond the linear regime

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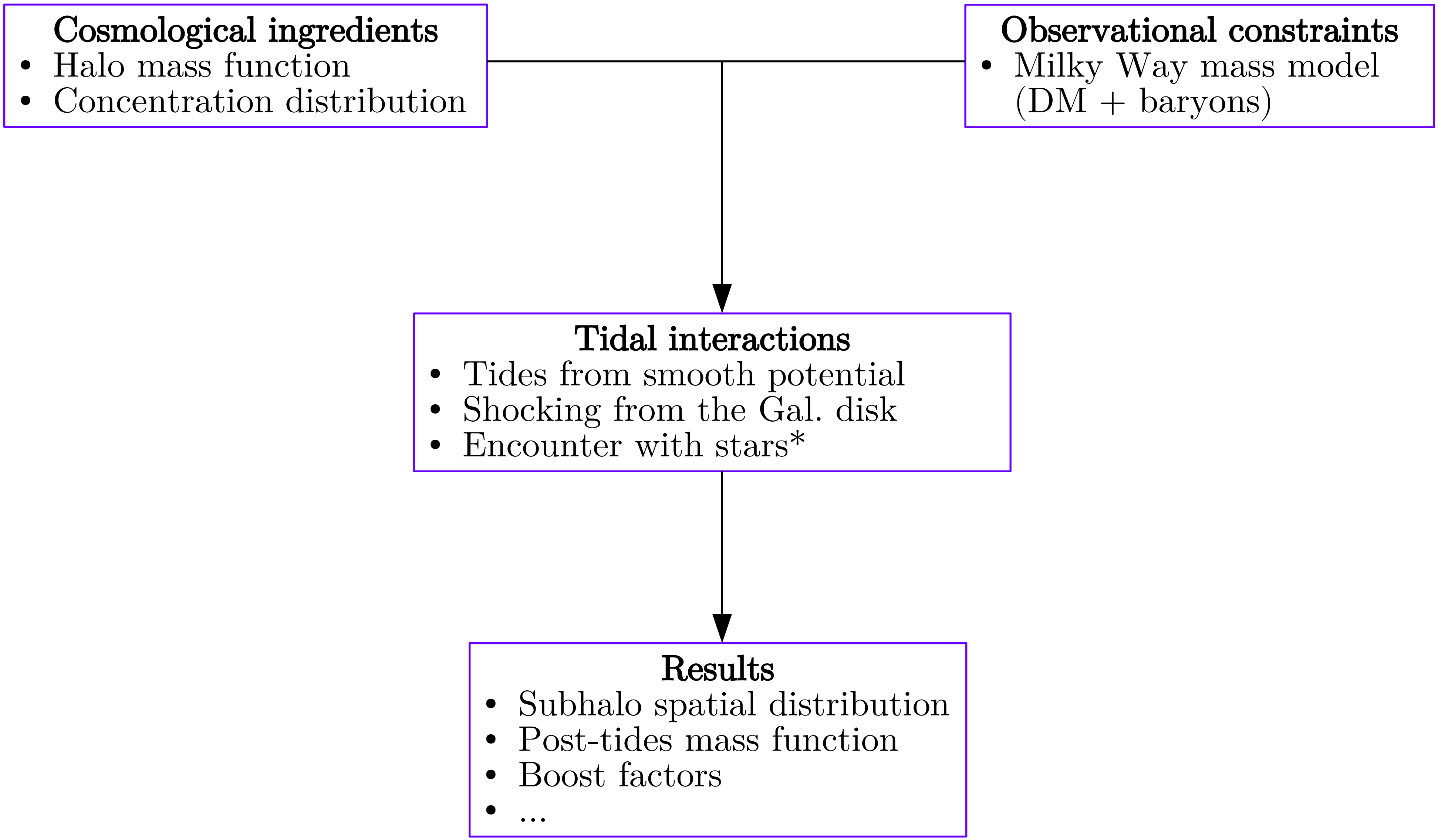
Our choice

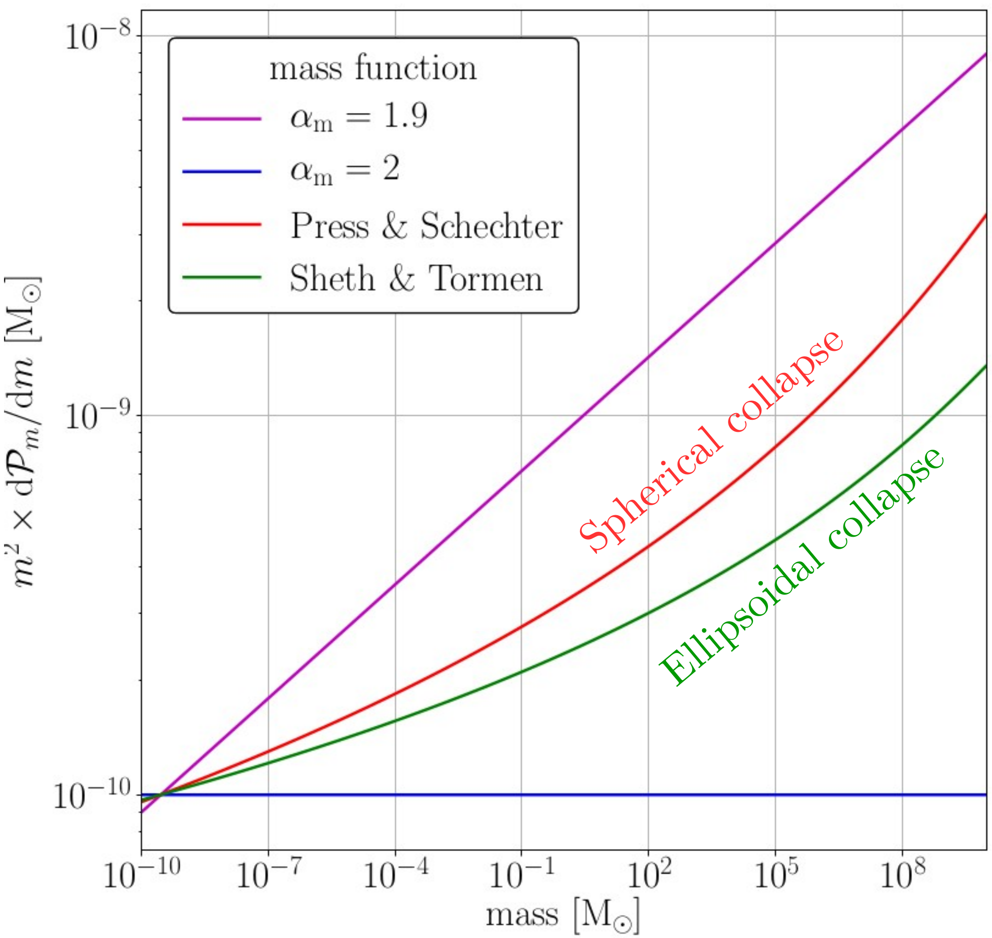
Anatomy of the model



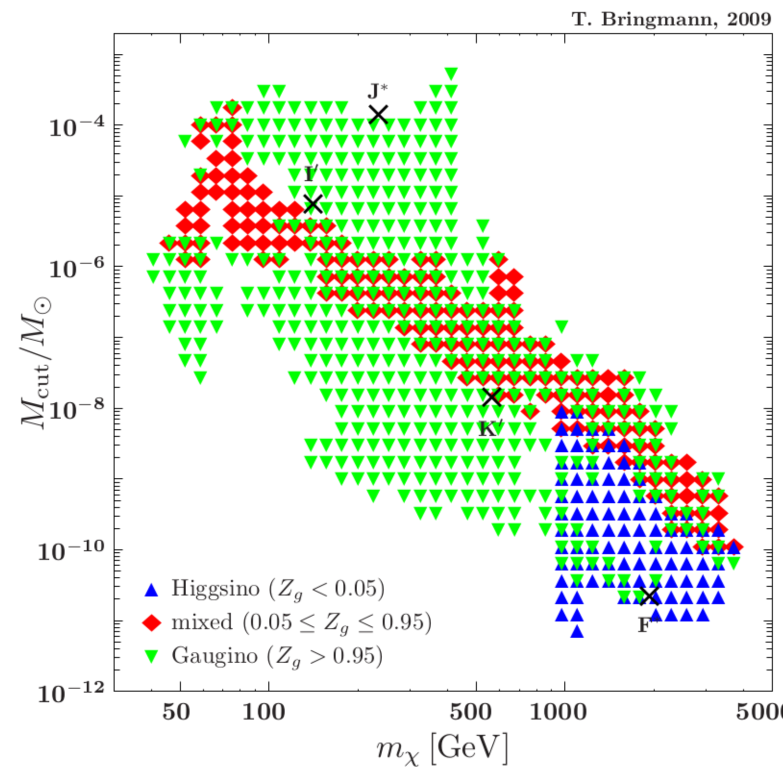
*work in progress

Cosmological ingredients:
The halo mass function

Matter power spectrum $P(k)$ $\xrightarrow[\text{theory}]{\text{Press-Schechter}}$ $\dfrac{dn}{dm}$ Halo mass function: Number density of DM halos per unit of mass



+ mass cutoff from particle physics (set by kinetic decoupling):



Cosmological ingredients: concentrations

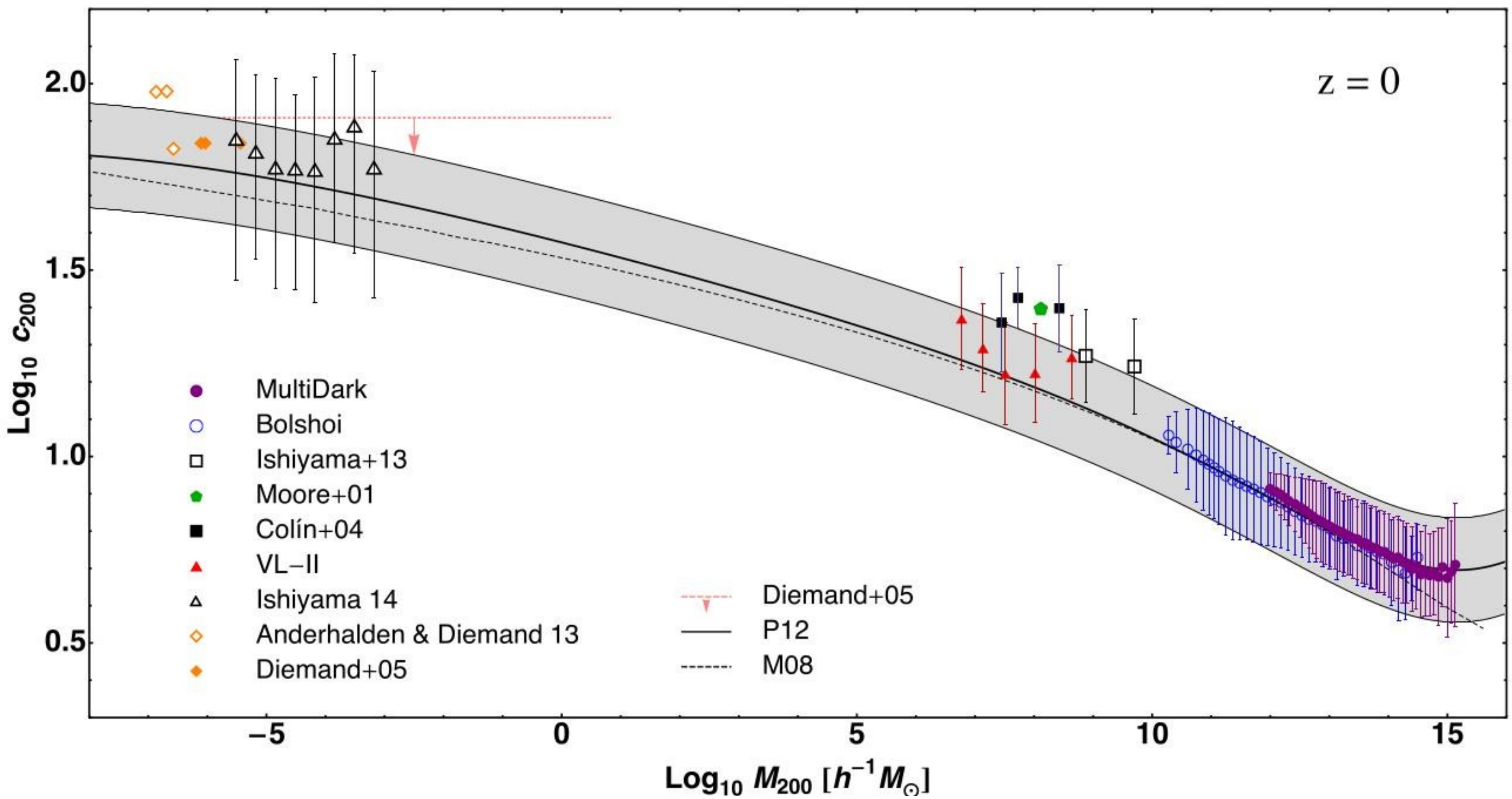
DM density profile:

$$\rho(r) = \rho_s \frac{r_s}{r} \frac{1}{(1 + r/r_s)^2}$$

Concentration parameter:

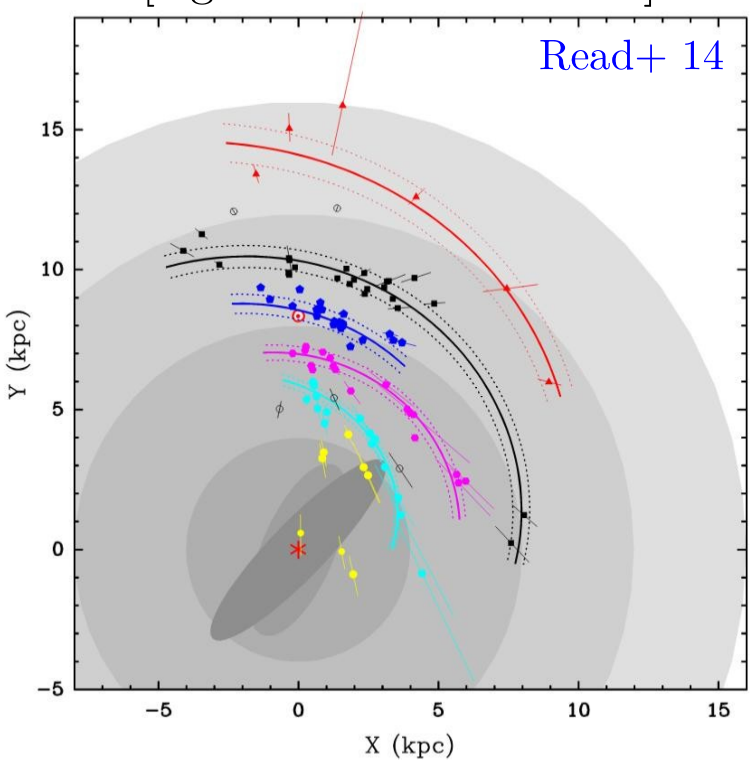
$$c_{200} \sim \frac{r_{200}}{r_s}$$

Sanchez-Conde & Prada 2014

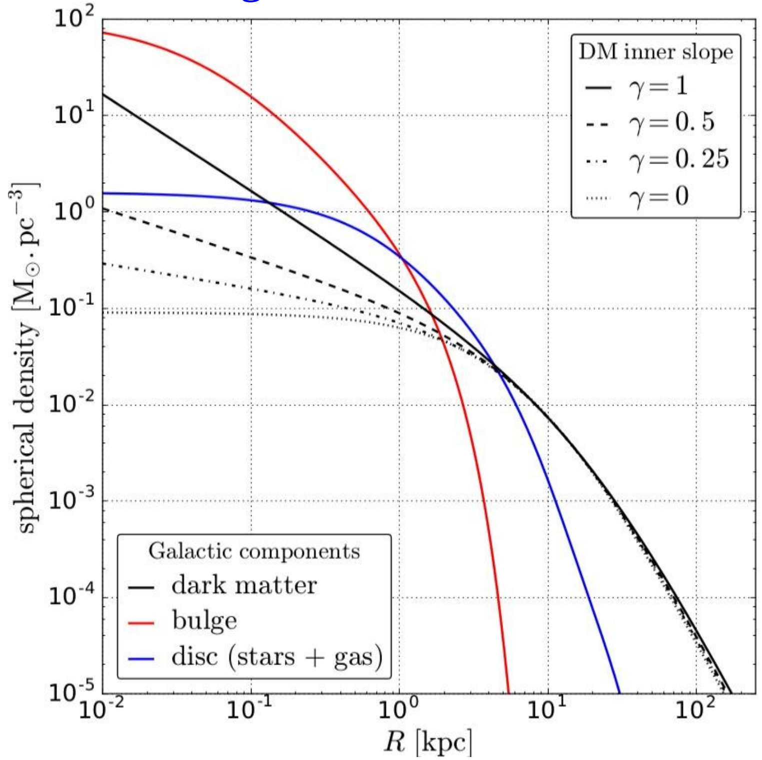


Observational constraints

Pre-Gaia data
[e.g. maser observations]



MW mass models
[e.g. McMillan 2017]

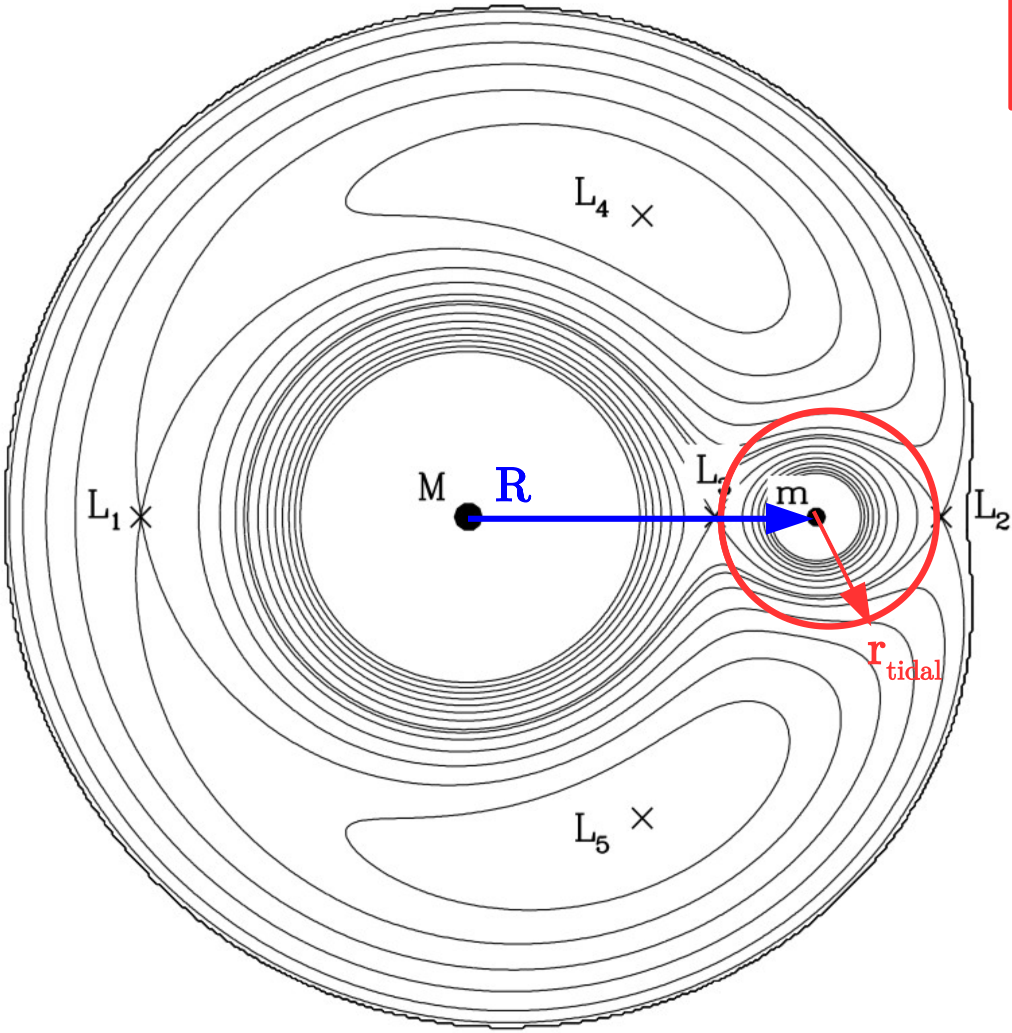


What we need:

- DM mass budget → Total = smooth + clumps
- Total gravitational potential
- Potential of the disk

→ Important for tidal interactions

Tidal interactions:
Effect of the smooth potential

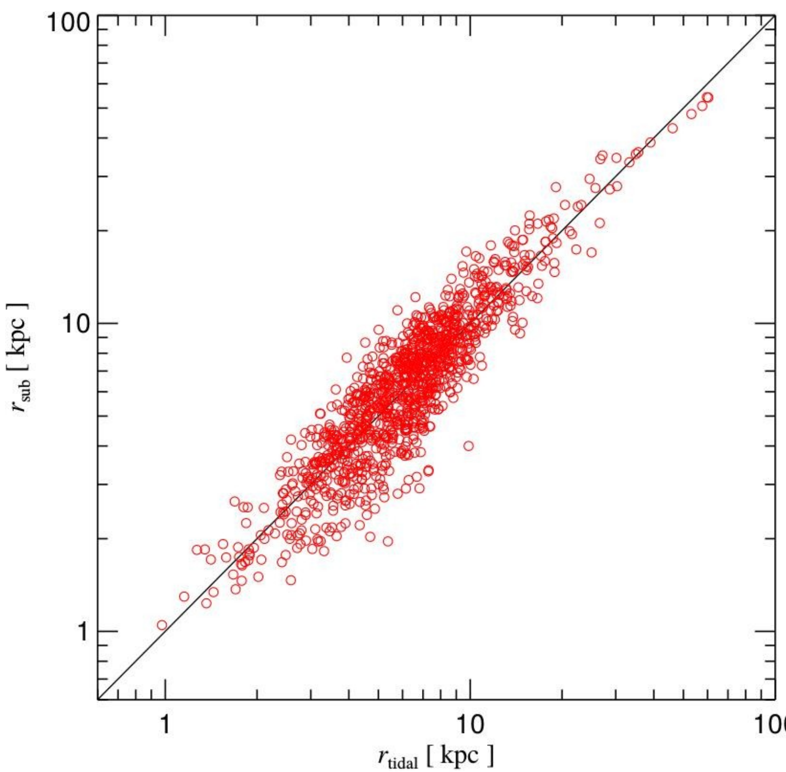


Binney & Tremaine

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

Extension of a subhalo depends on:

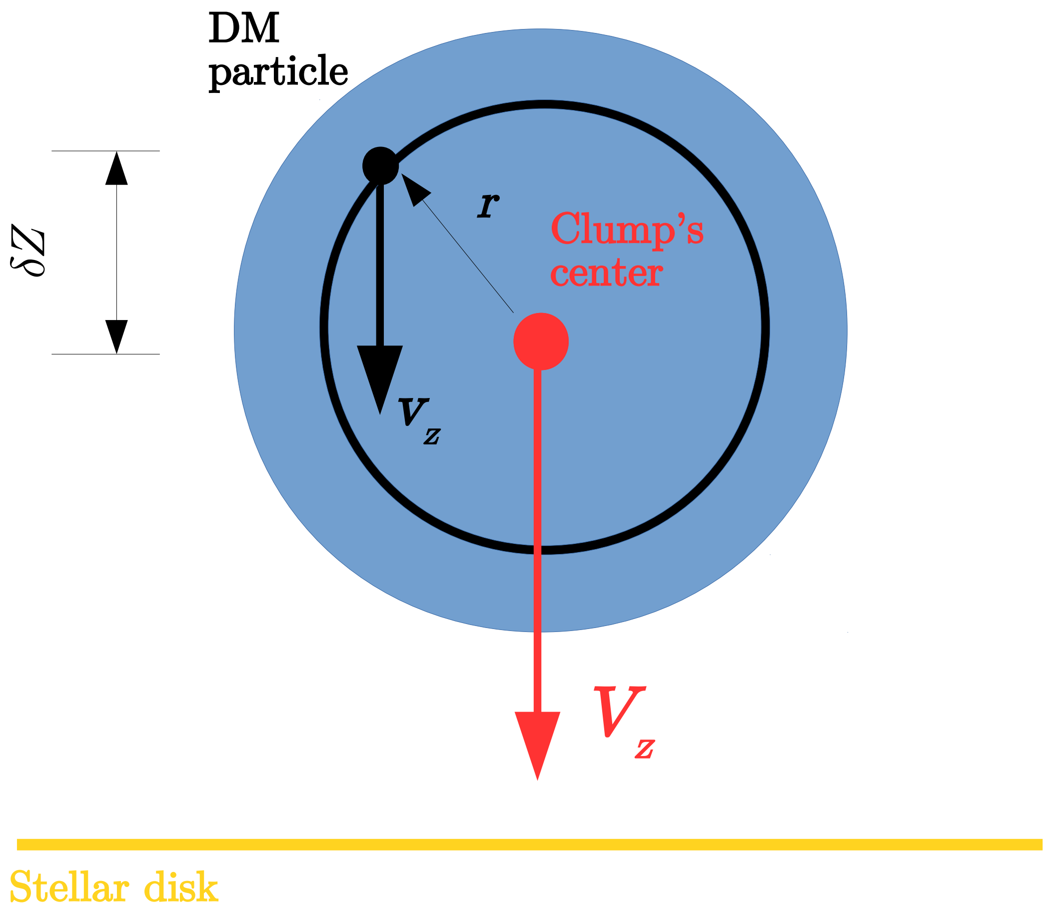
- Its position in the Galaxy
- Its density profile



Springel+ 2008

Tidal interactions:
Effect of the Galactic disk

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



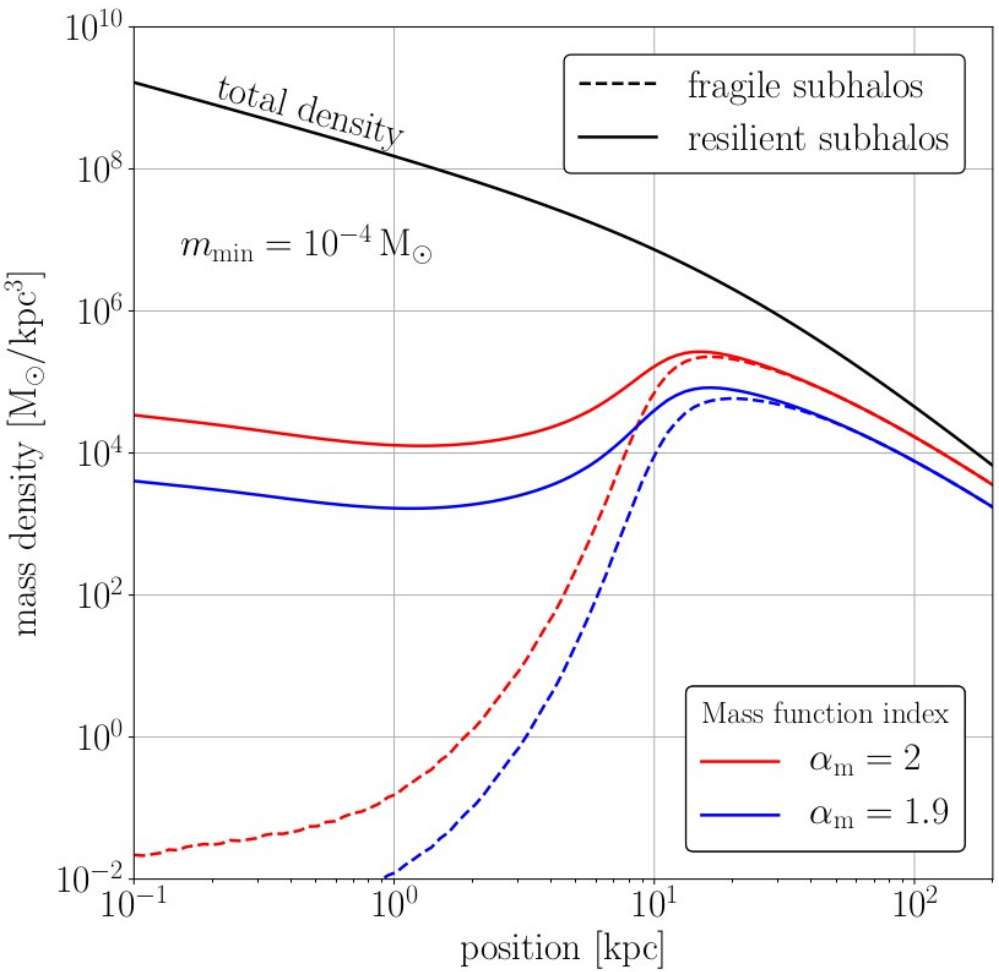
$$\frac{\mathrm{d}v_z}{\mathrm{d}t} = g_z(Z_0 + \delta Z) - g_z(Z_0) \simeq \delta Z \, \frac{\mathrm{d}g_z}{\mathrm{d}z}$$

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

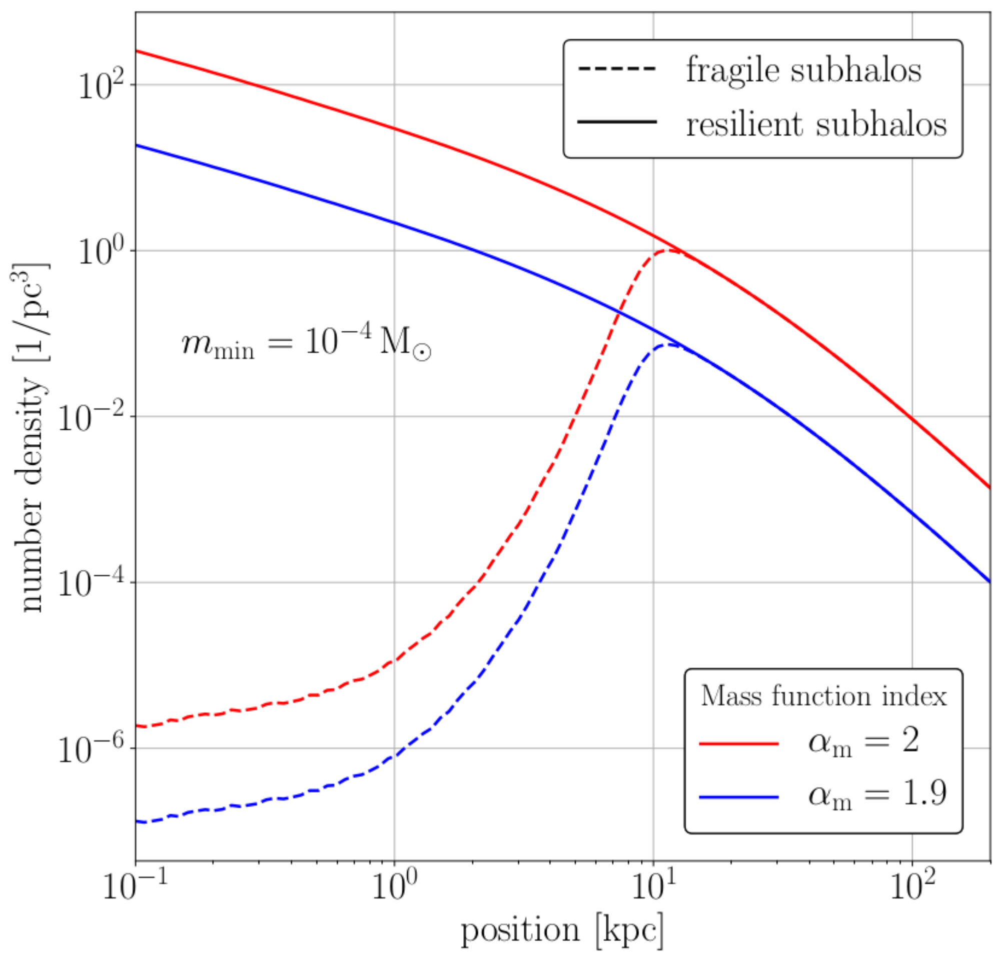
$$\frac{\delta E}{m_\chi} = \frac{1}{2} (\Delta v_z)^2 = \frac{2 \, g_z^2 \, r^2}{3 \, V_z^2}$$

Results:
Milky Way subhalo population

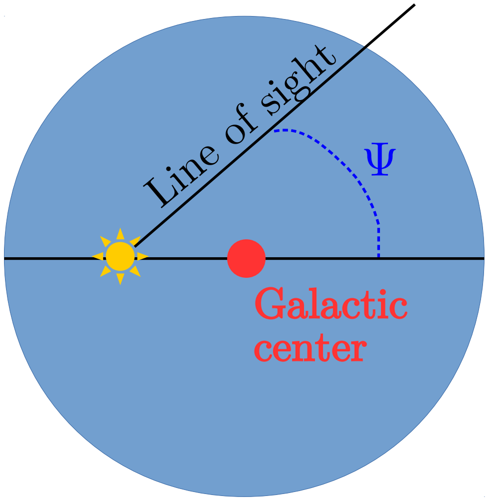
Mass density



Number density

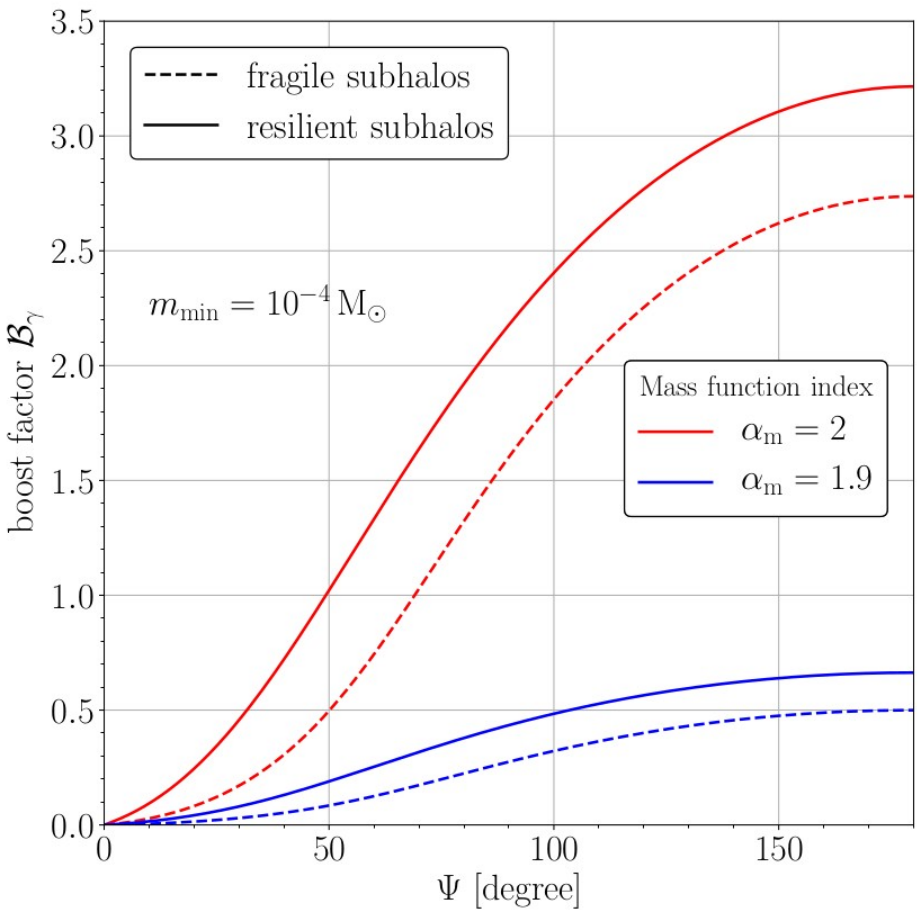


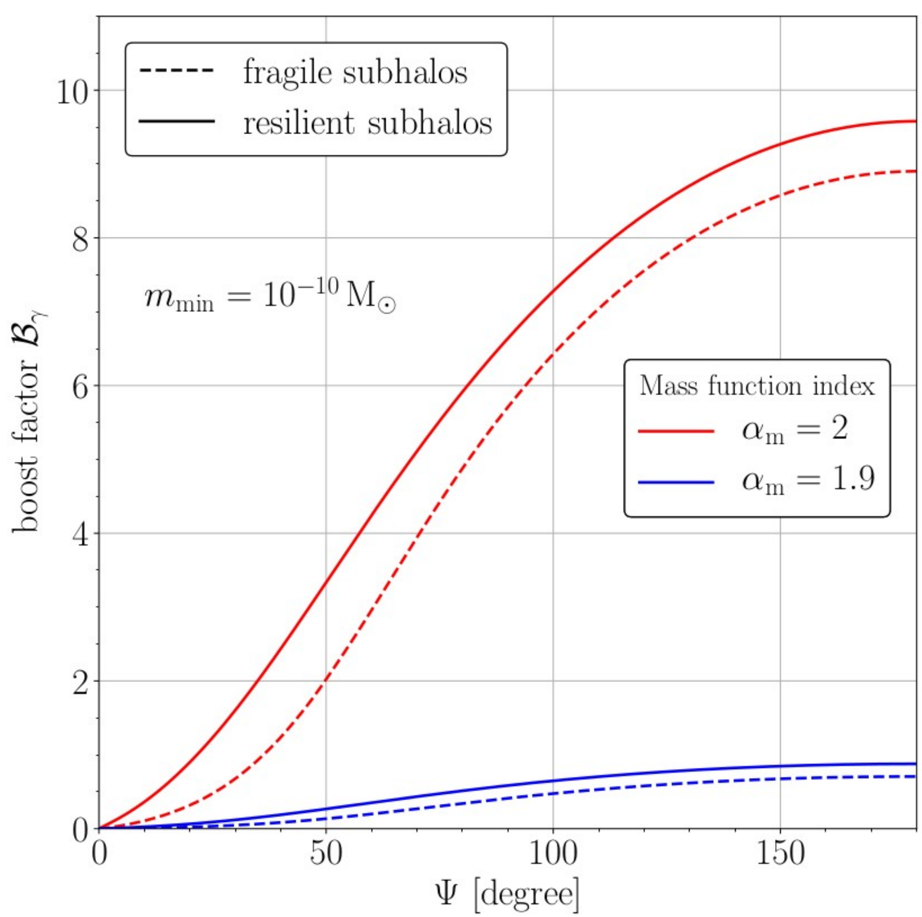
Results:
gamma-ray boost factors



Boost factor definition

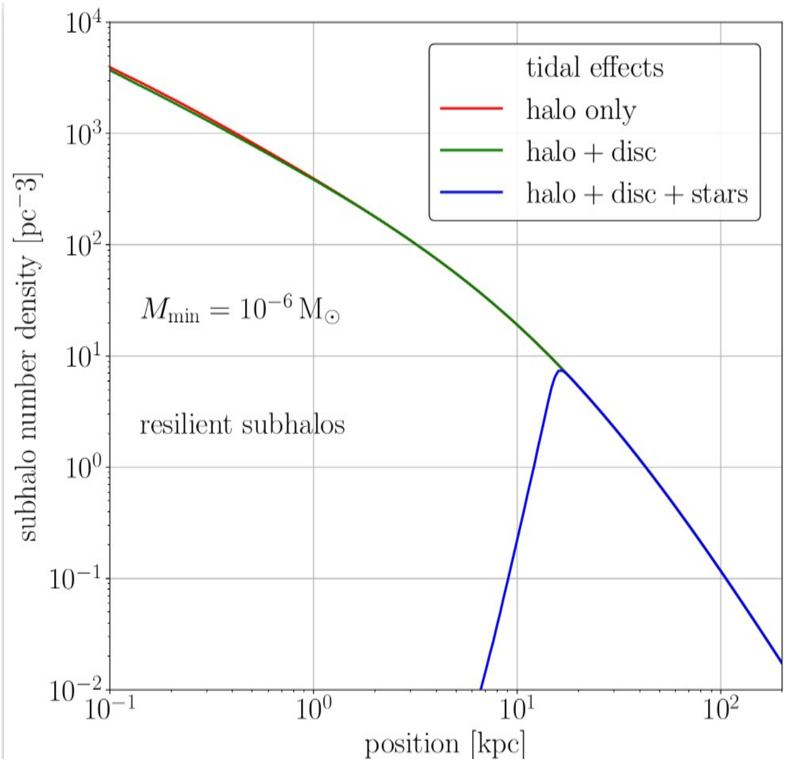
$$1 + \mathcal{B}_\gamma(\psi) = \frac{\phi_{\gamma,\mathrm{clumpy}}(\psi)}{\phi_{\gamma,\mathrm{smooth}}(\psi)}$$





Improvements in the near future

Tidal interactions with stars:



Preliminary results show stars are very efficient at destroying the smallest clumps!

Application beyond the Milky Way:

- Other galaxies
- Dwarf galaxies
- Galaxy clusters

Conclusions

Ongoing work:

- Constraints on annihilating DM from gamma-ray observations at high latitudes
- Detectability of individual subhalos (cf next talk)

Preliminary results from G. Facchinetti