Small-scale structuring of Galactic dark matter and impact on indirect searches

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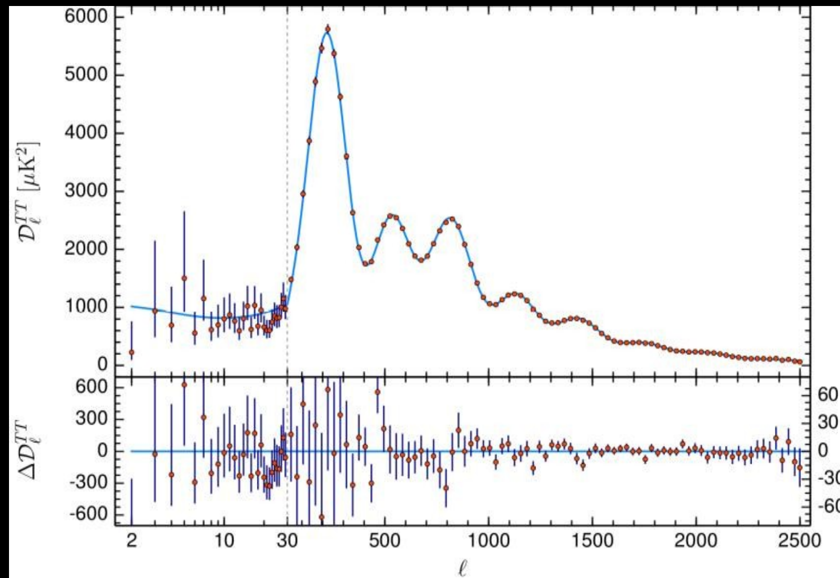
Journées théorie PNHE
2018

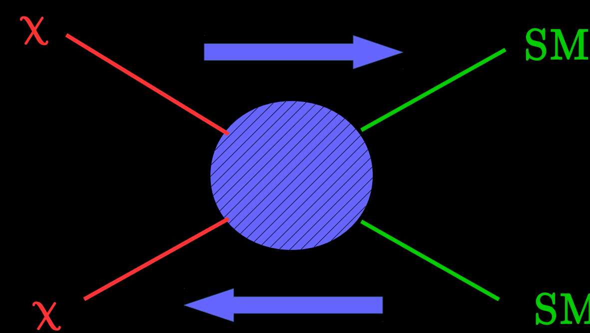
The cold dark matter paradigm

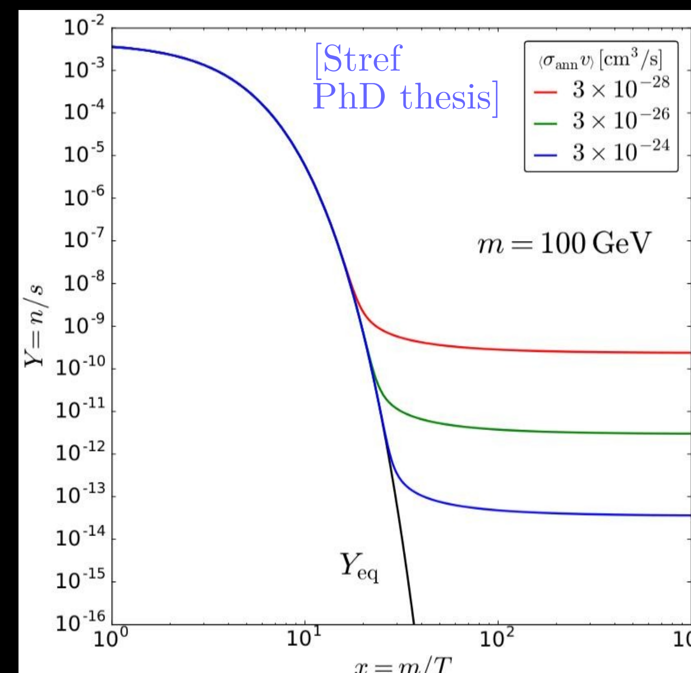
CMB temperature anisotropies [Planck 2018]



Great success above the galactic scale!

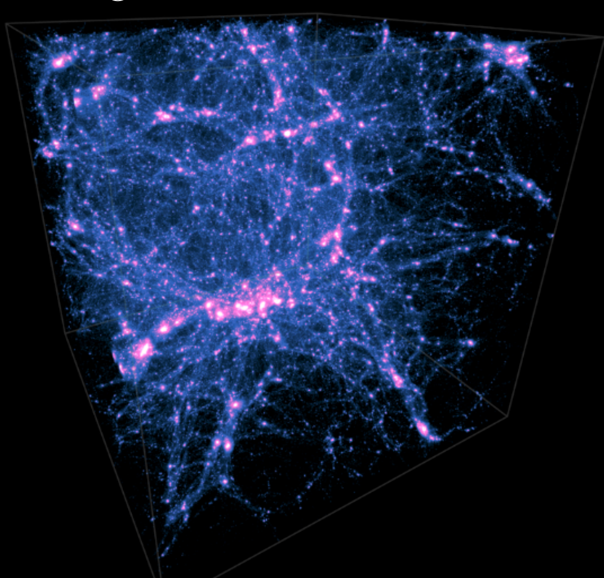
Particle realisation: the WIMP



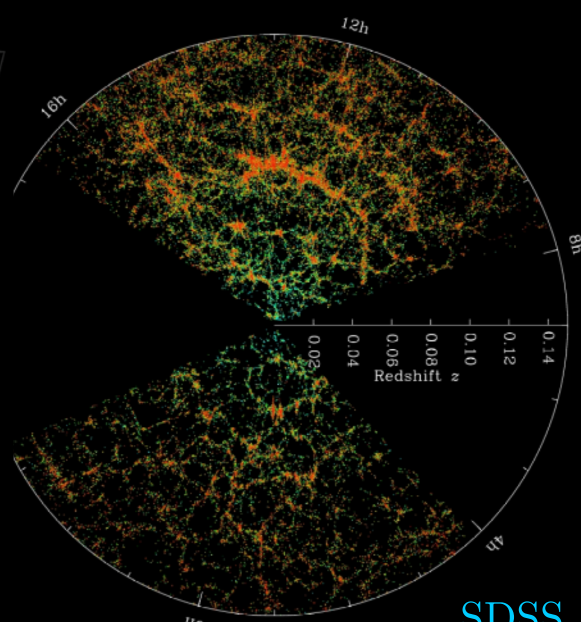


$$\Omega_{\rm cdm}h^2 \simeq 0.1\,\frac{3\times10^{-26}\,{\rm cm}^3.{\rm s}^{-1}}{\langle\sigma_{\rm ann}v\rangle}$$

Large-scale structures



Illustris simulation

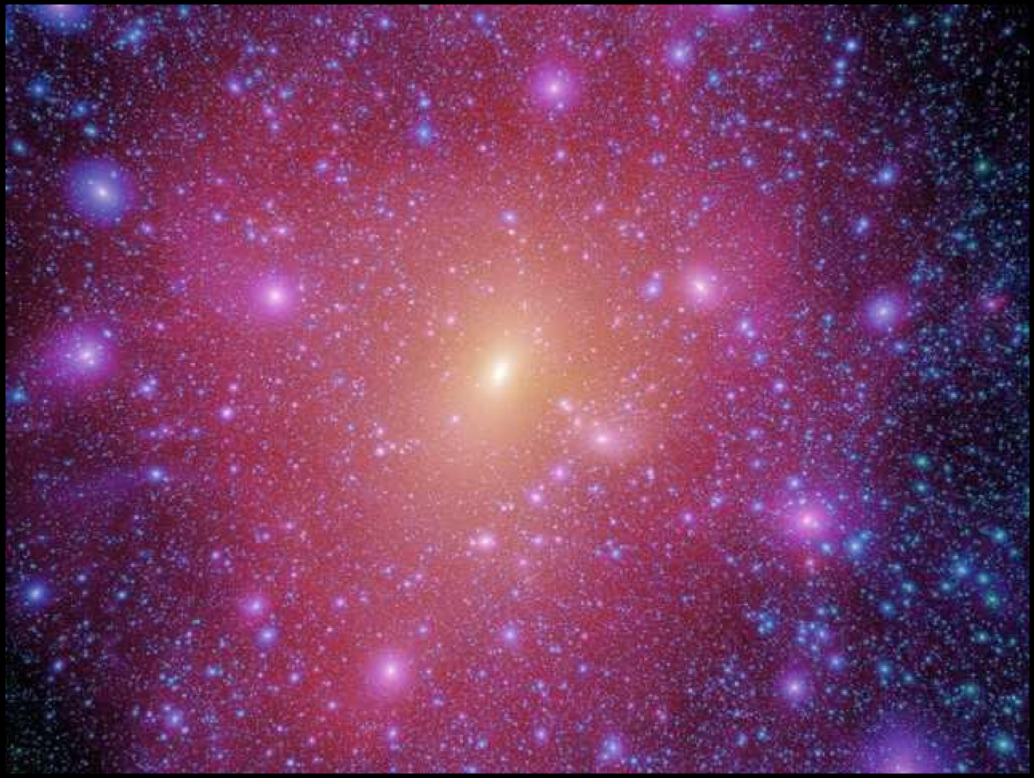


SDSS

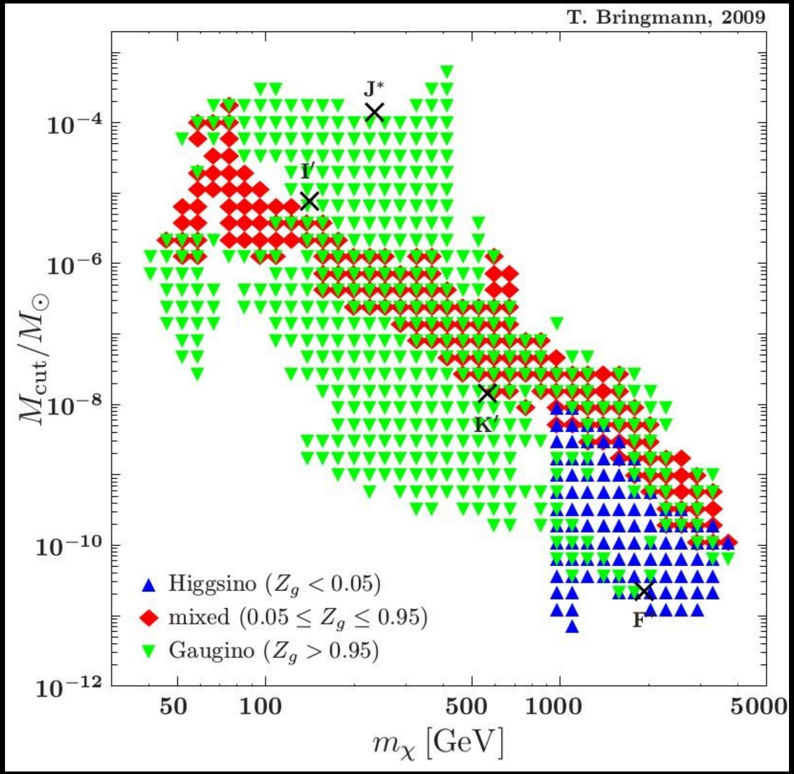
Cold dark matter below the galactic scale

Lots of structuring predicted on sub-galactic scales

Milky-Way-like halo in Aquarius [Springel+ 2008]



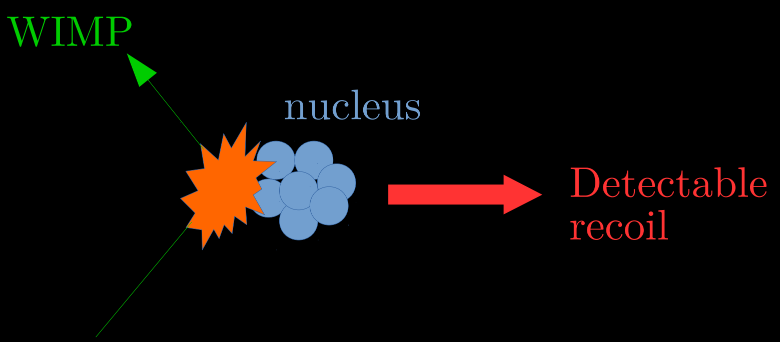
Size of the smallest structures set by the kinetic decoupling of the DM particle [Green+ 04-05, Bringmann+ 07-09, Gondolo+ 2012]



Challenges left on small scales [Bullock & Boylan-Kolchin 2017]

Small-scale structuring and dark matter searches

Direct searches



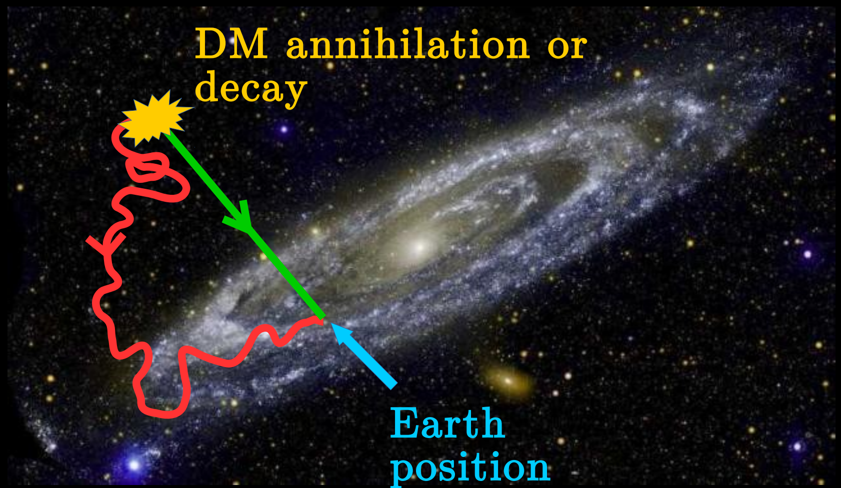
Differential recoil event rate:

$$\frac{\mathrm{d}R}{\mathrm{d}E_\mathrm{r}}(E_\mathrm{r}) = \frac{\sigma_0\, F^2(E_\mathrm{r})}{2\, m_\chi\, \mu^2} \times \rho_\odot \int_{v_\mathrm{min} \leqslant v \leqslant v_\mathrm{esc}} \frac{f_\odot(\vec{v})}{|\vec{v}|}\, \mathrm{d}^3\vec{v}$$

- **Local DM density**
- **Local DM velocity distribution**

Importance of local clustering!

Indirect searches



Photons, neutrinos
Charged species

Probe the (extra-)Galactic DM mass distribution

DM clustering **boost** the annihilation signal
[Silk & Stebbins 1993, Bergström+ 1999]

+ impact on Galactic dynamics?
(disc, binaries, stellar streams, ...)

Modelling subhalos: numerical vs analytical

Numerical simulations

- Self-consistent modelling of gravity
- Non-linear evolution
- Computing power
- (very) limited resolution
- Not the Milky Way!
- Can be difficult to interpret

Analytic models

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

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

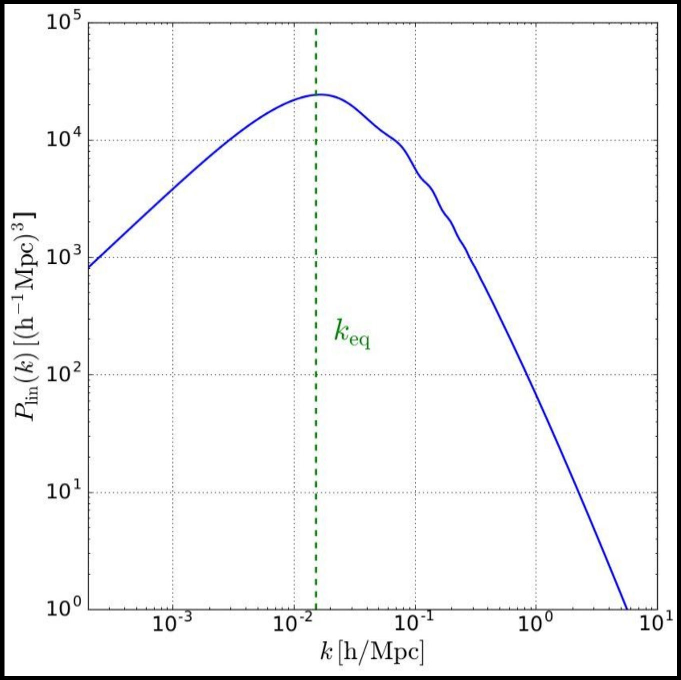
- Constraints from dynamics, cosmology and particle physics
- No resolution limit
- Reproduces numerical simulations results

Stref & Lavalle, Phys. Rev., 2017, D95, 063003

Halo mass function

Press & Schechter theory (1974): CDM halo mass function from the *linear power spectrum*

[Bond+ 1991, Sheth & Tormen 1999]



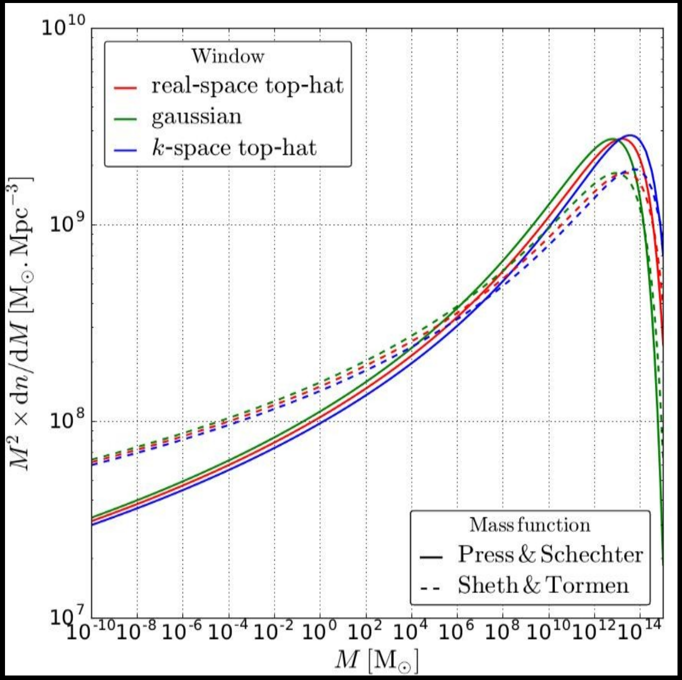
[PhD thesis]

Mass variance:

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

PS mass function:

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

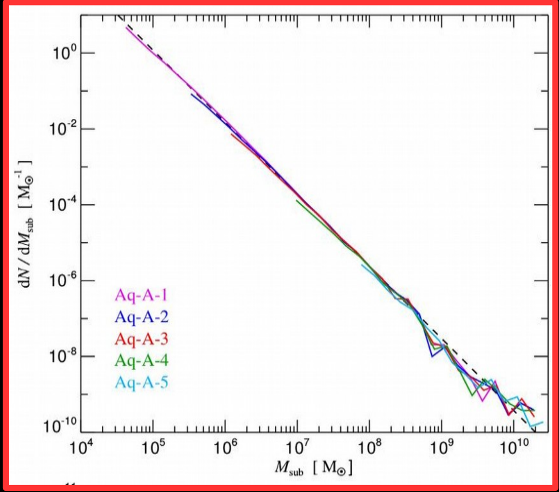


On sub-galactic scales:

$$\frac{\mathrm{d}n}{\mathrm{d}M} \propto M^{-\alpha_{\rm m}}$$

$$\alpha_{\rm m} \simeq 1.9 - 2$$

Recovered in simulations!
[Springel+ 2008]



Concentration

Hierarchical scenario of structure formation: small structures form first, in a *denser Universe*

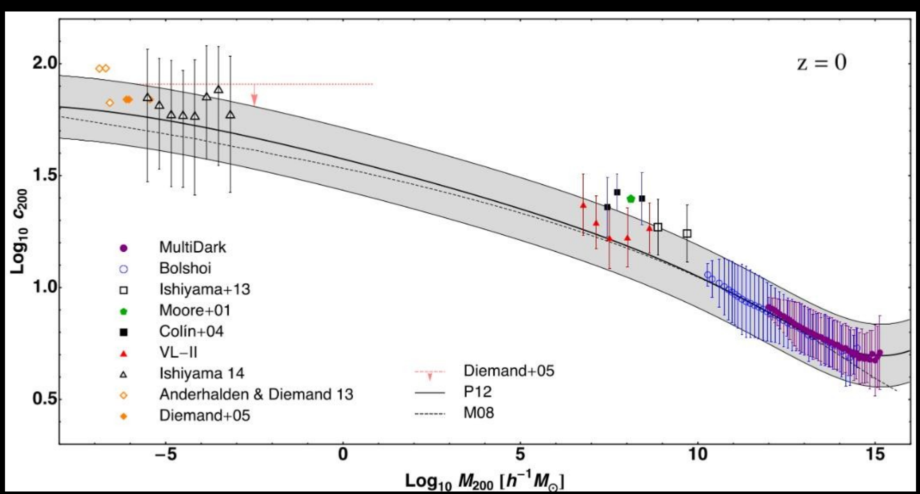
Concentration parameter:

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

One-to-one relation with the scale density

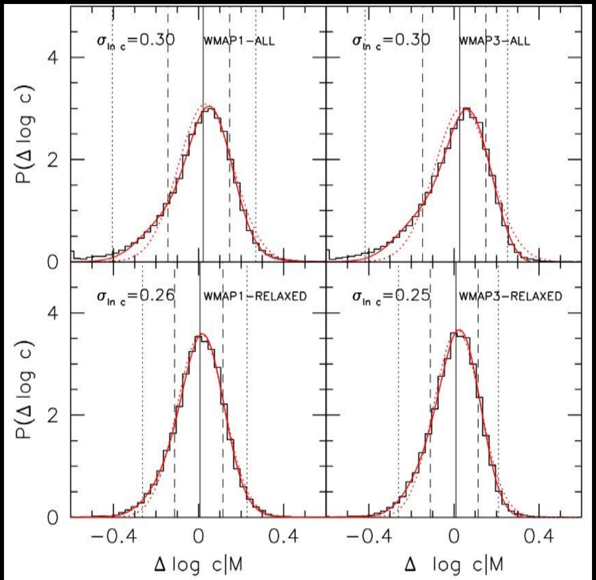
$$\rho(r) = \rho_{\mathrm{s}} \frac{r_{-2}}{r} \left[1 + \frac{r}{r_{-2}}\right]^{-2}$$

Correlation between mass and concentration



[Sanchez-Conde & Prada 2014]

- Small halos are more concentrated
- Relation recovered in simple semi-analytic models [Bullock+ 2001, Maccio+ 2008, Prada+ 2012]
- Scatter around the mass-concentration relation

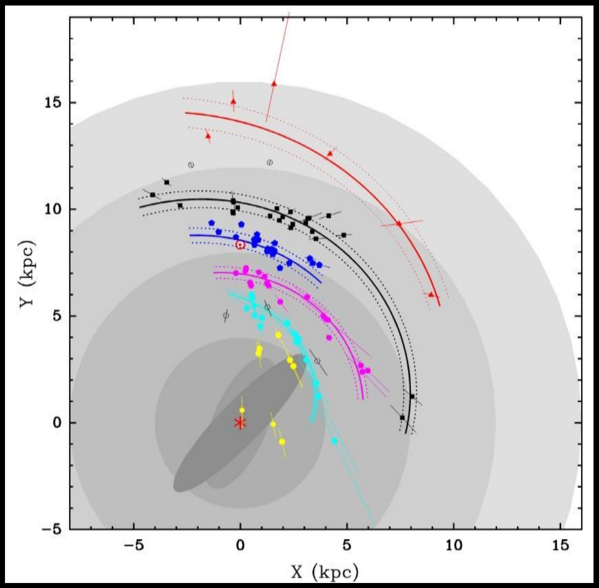


[Maccio+ 2008]

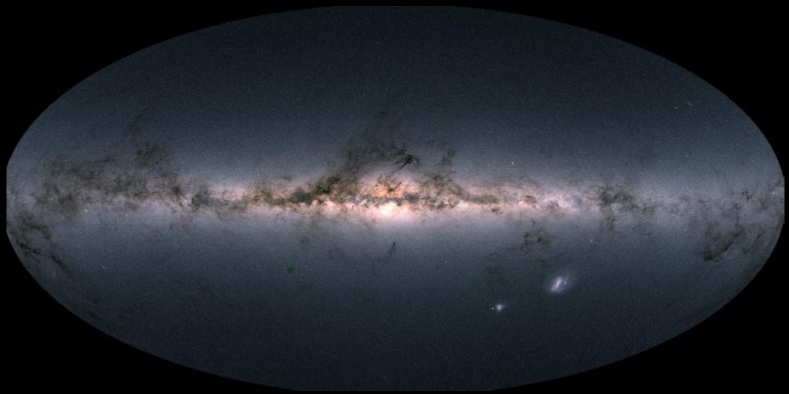
Dynamical constraints

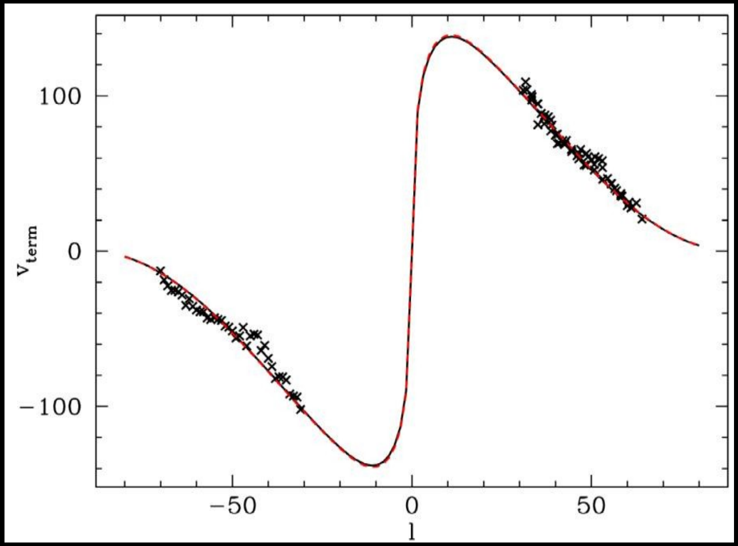
Milky Way = constrained system $\rightarrow$ cannot blindly extract subhalo distribution from simulations

Maser observations [Reid+ 2014]

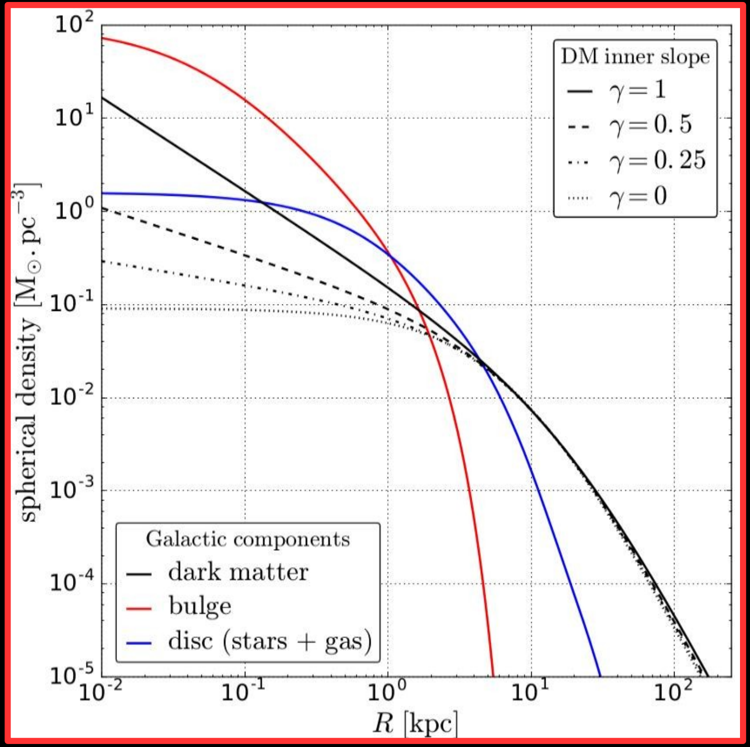


The Milky Way as seen by Gaia [Gaia coll. 2018]





Terminal velocities [McMillan 2011]



[PhD thesis]

Modelling subhalos: a statistical approach

Subhalo **initial** phase-space density:

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

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

Subhalos behave as hard spheres

Addition of tidal effects

Final phase-space density:

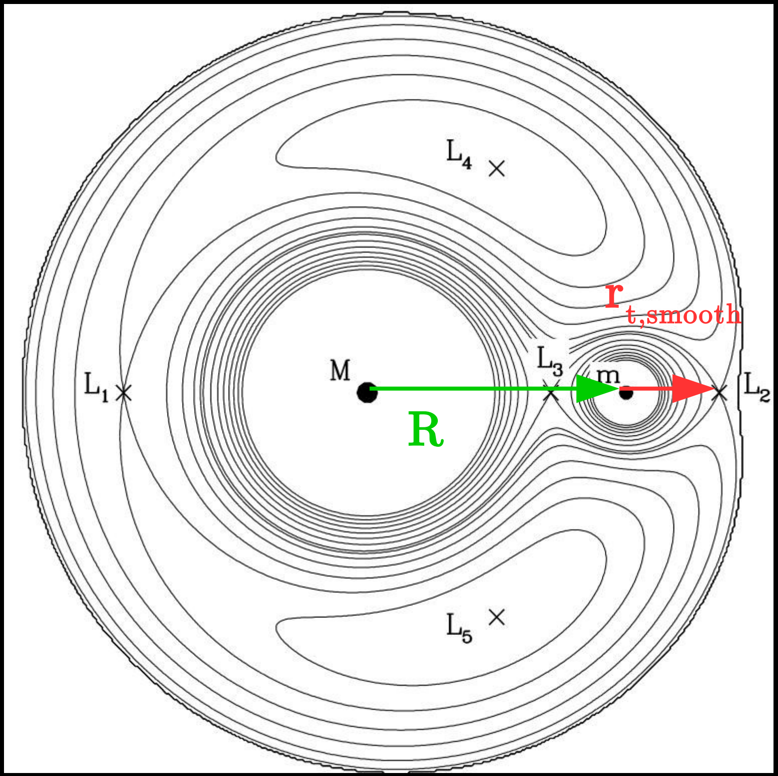
$$\frac{\mathrm{d}^n \overline{N}}{\mathrm{d}\omega^n} = \frac{N_{\mathrm{sub}}}{K} \frac{\mathrm{d}\mathcal{P}_{\mathrm{v}}(\vec{x})}{\mathrm{d}V} \times \frac{\mathrm{d}\overline{\mathcal{P}}_m(m,\vec{x})}{\mathrm{d}m} \times \frac{\mathrm{d}\overline{\mathcal{P}}_{\mathrm{c}}(c,m,\vec{x})}{\mathrm{d}c}$$

Completely intricate phase-space !

Tidal effects:
interaction between subhalos and the host galaxy

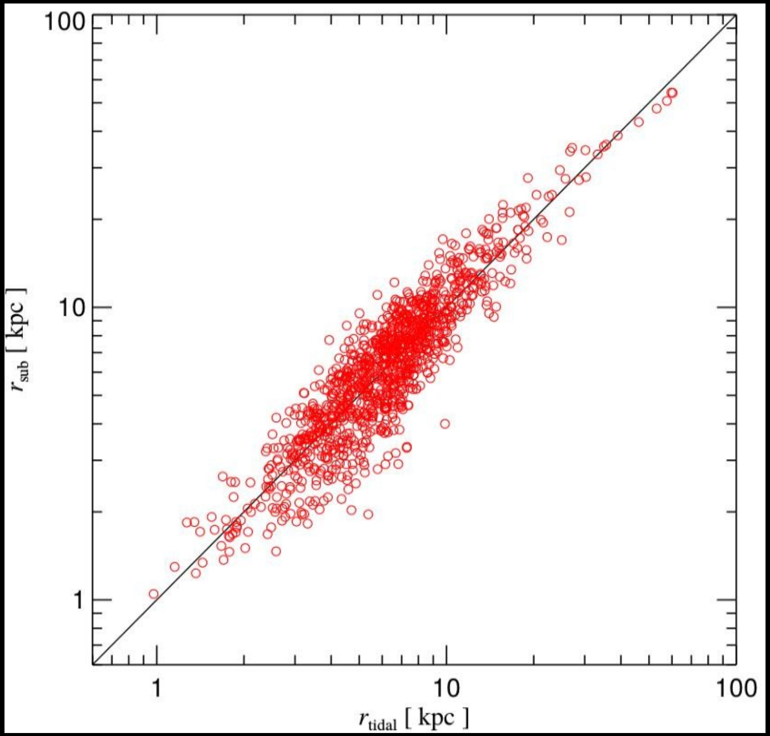
Competition between subhalo and host potential → tidal radius

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



[Binney & Tremaine 1987]

- Analytic calculation for a smooth mass distribution
- Subhalos on circular orbits
- Agrees with simulations



[Springel+ 2008]

Tidal effects: interaction between subhalos and the Galactic disc

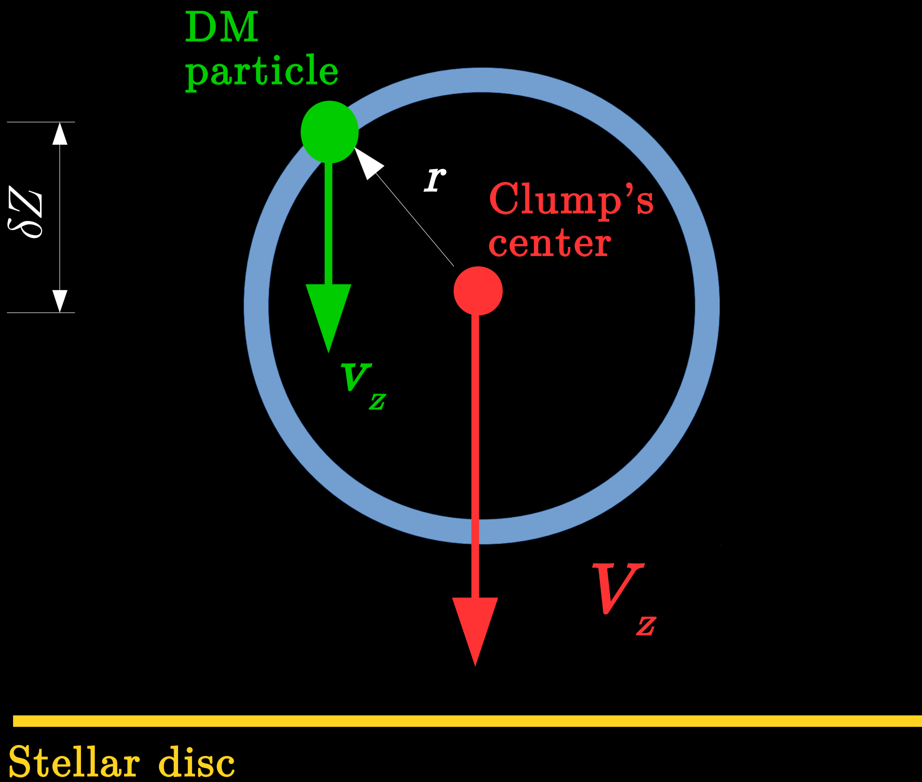
Subhalos experience **disc shocking** when they cross the stellar disc
[Ostriker+ 1972, Gnedin & Ostriker 1999]

Velocity kick along the z-direction: $\frac{\mathrm{d}v_z}{\mathrm{d}t} \simeq \delta Z \, \frac{\mathrm{d}g_z}{\mathrm{d}z}$ → $\langle \delta\epsilon \rangle = \frac{2\, g_z^2\, r^2}{3\, V_z} A(\tau\omega)$

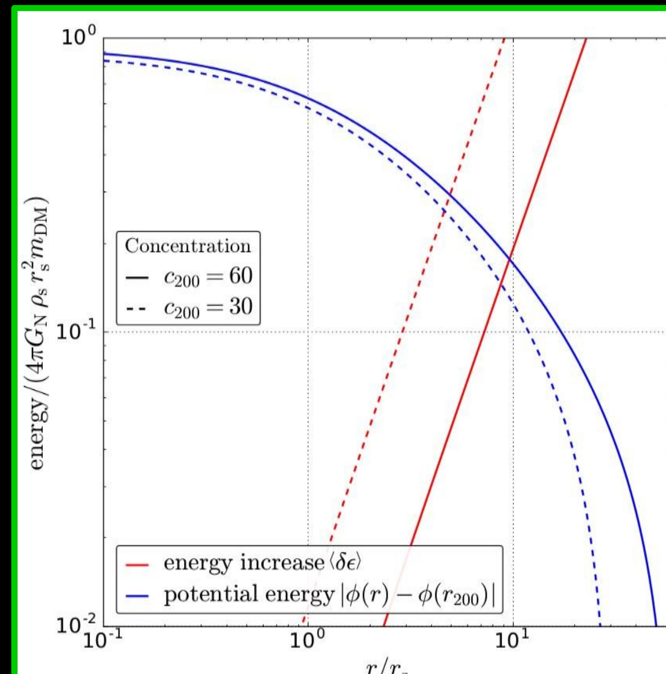
Kinetic energy gain

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

Adiabatic correction



Simple criterion: $\langle \delta\epsilon \rangle (r) > |\phi(r)|$

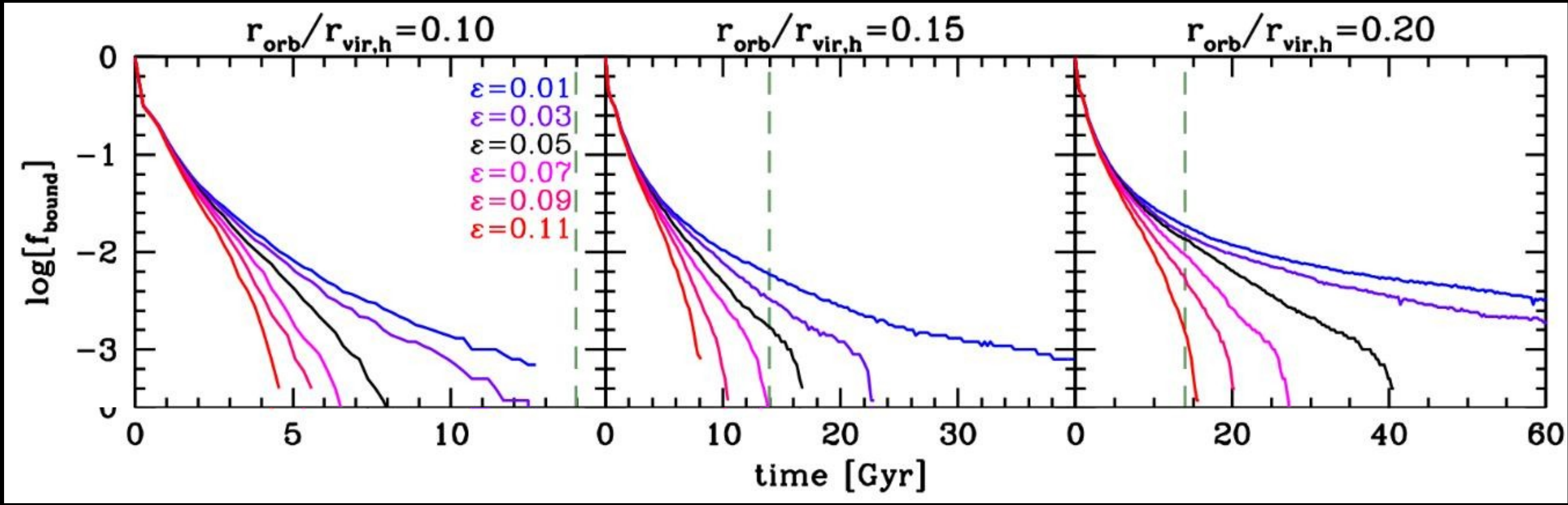


[PhD thesis]

Can a subhalo be completely disrupted?

Theory says **NO** $\rightarrow$ small halos very concentrated + protected by adiabatic invariance
Simulations say **YES** $\rightarrow$ all subhalos disrupted at the center of galaxies

Recent analysis by van den Bosch et al. 2017-2018 $\rightarrow$ importance of the softening length



Disruption criterion:

$$r_t < \epsilon_t \, r_s$$

$$\epsilon_t \simeq 1$$

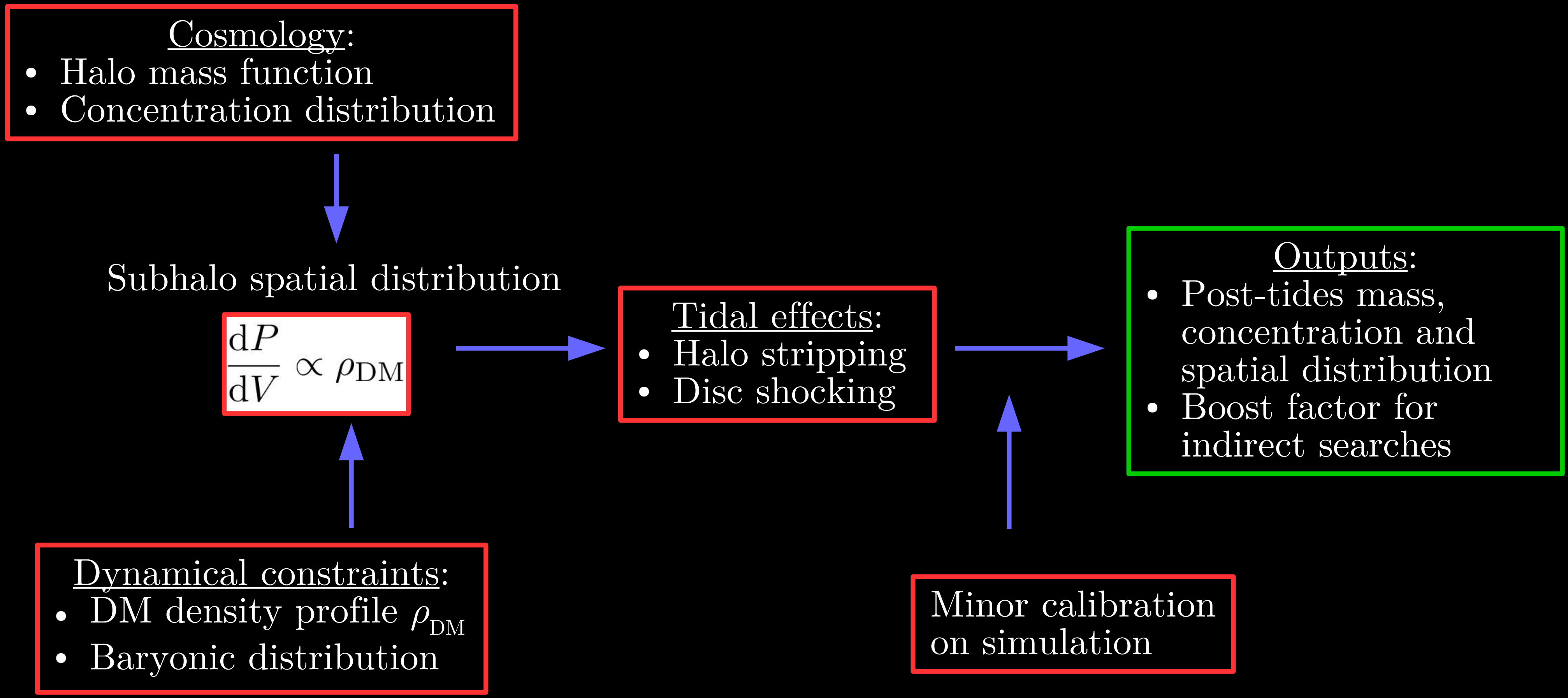
Simulation-like value
[Hayashi+ 2003]

$$\epsilon_t \ll 1$$

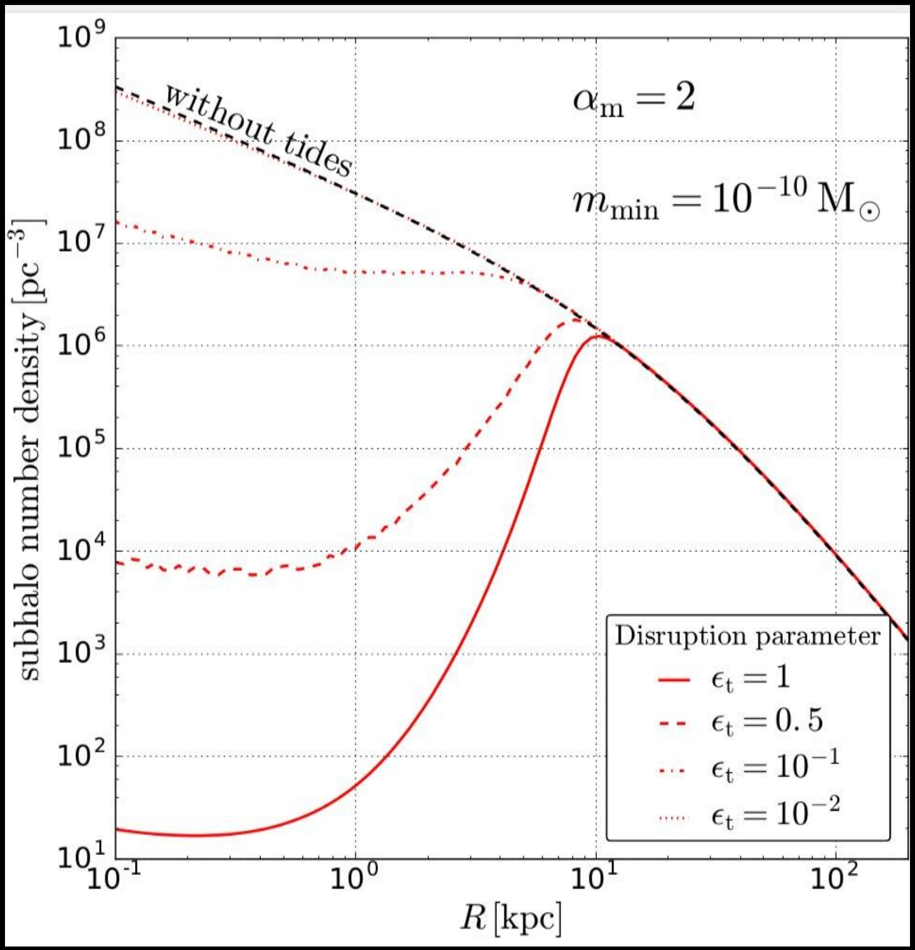
Realistic value

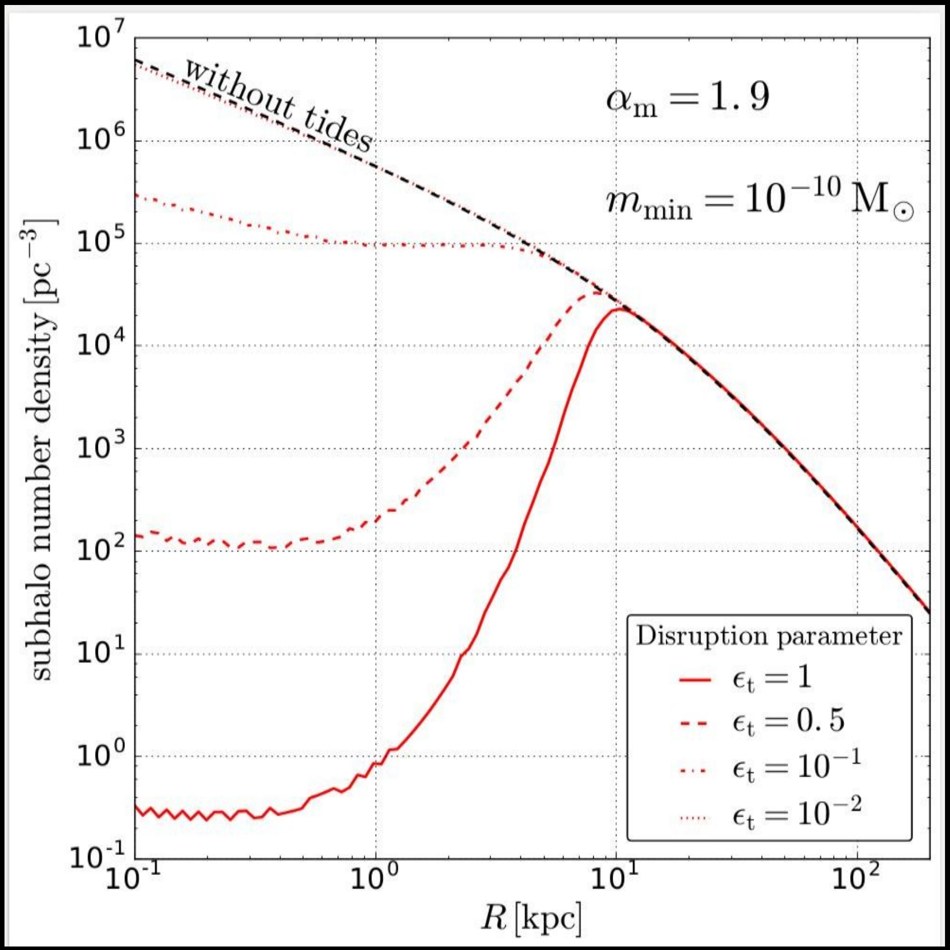
Dynamically constrained model of Galactic subhalos

Stref & Lavalle, Phys. Rev., 2017, D95, 063003



Subhalo number density in the Galaxy



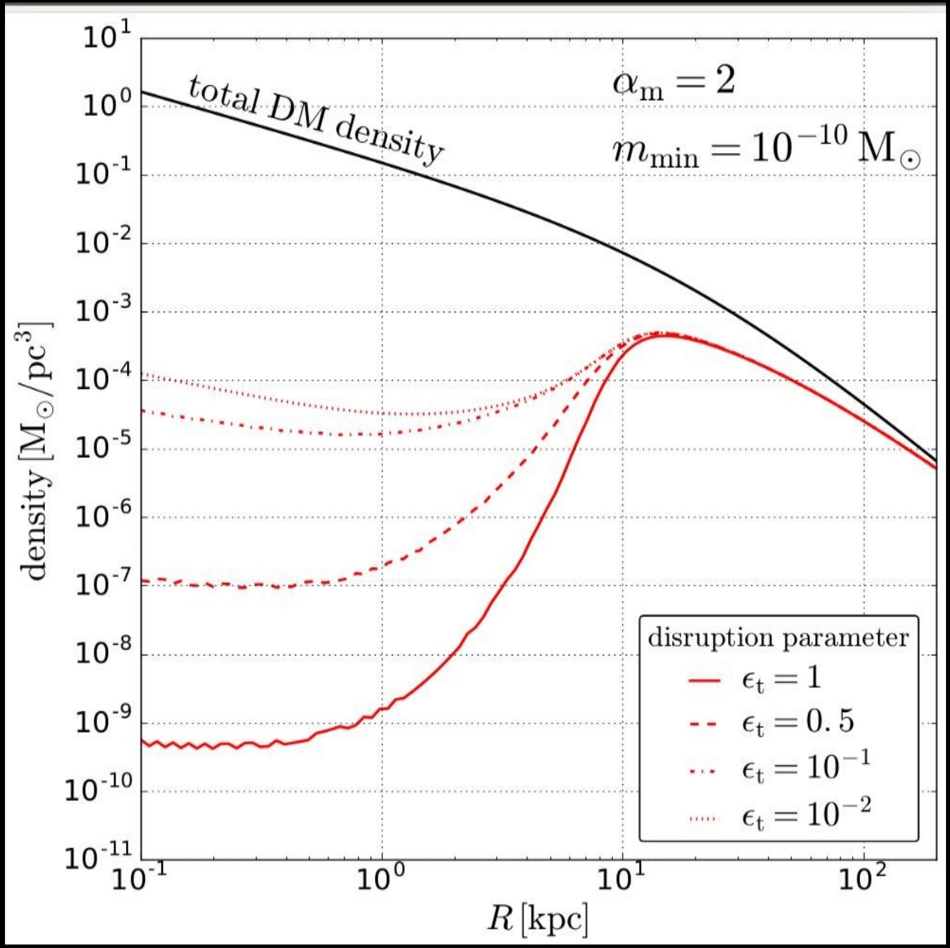


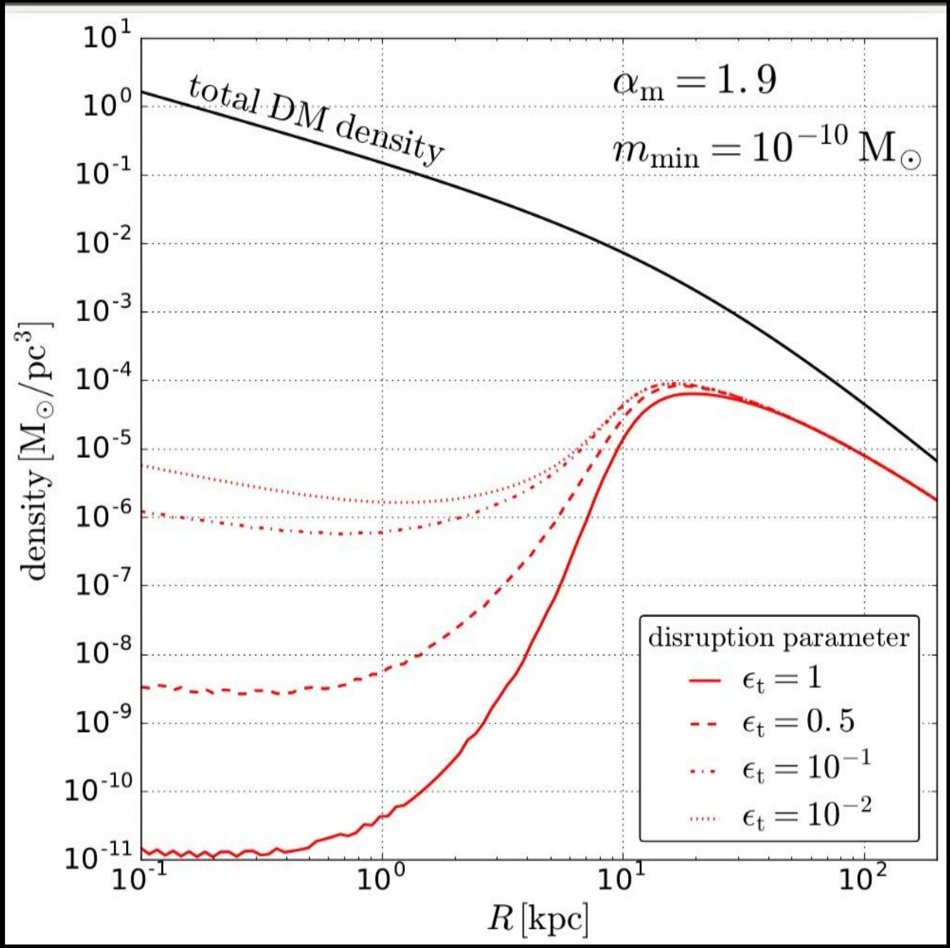
[Stref PhD thesis]

Large local population!!!

Impact of/on stars? [Berezinsky+ 2006, Green & Goodwin 2007]

Mass density inside subhalos

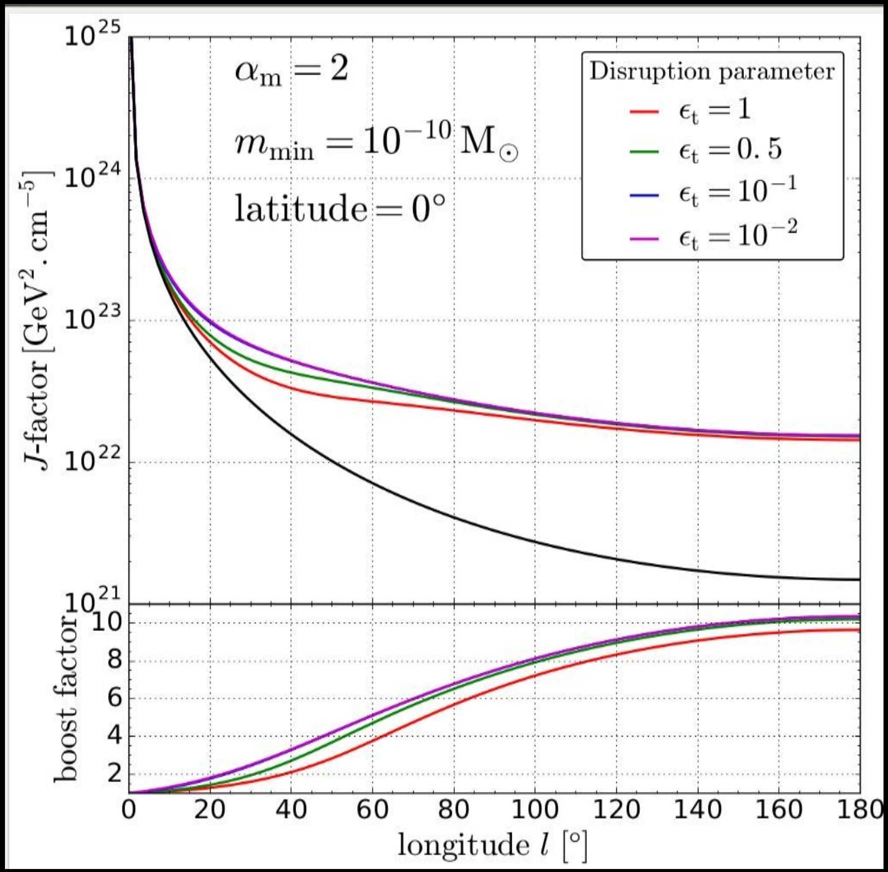


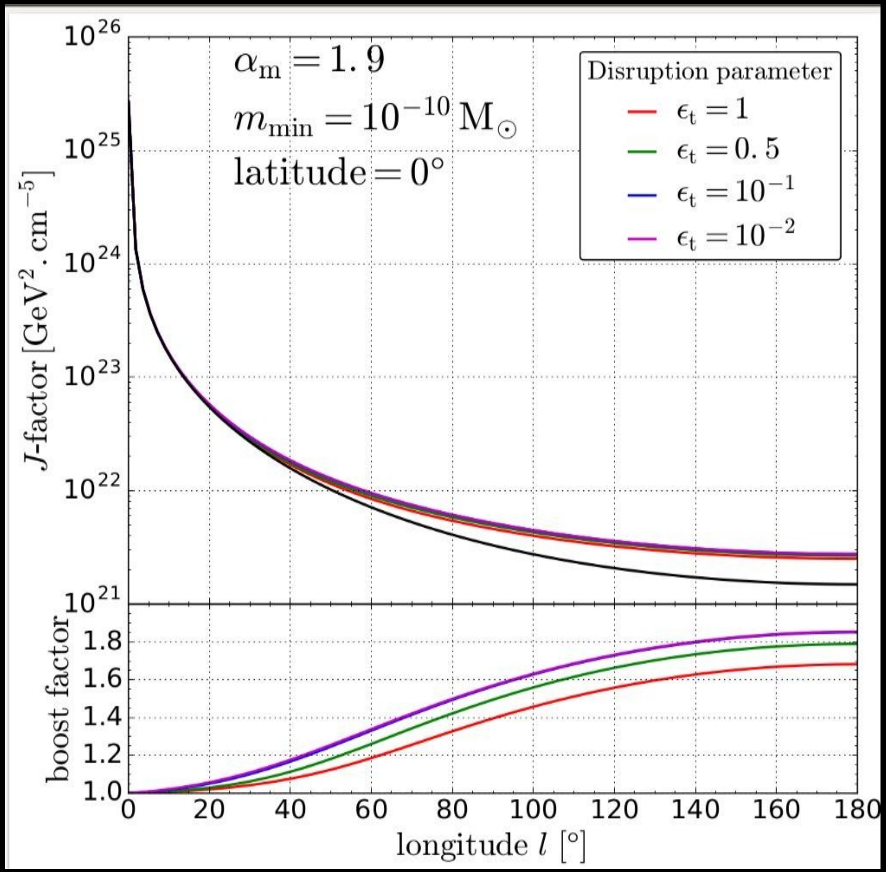


[Stref PhD thesis]

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

Gamma rays





[Stref PhD thesis]

$$J \equiv \int d\Omega \int_{los} ds\, \rho^2$$

- Potentially very large boost
- Consistent with other studies [e.g. Bartels & Ando 2015]
- Highly sensitive to α_m

Cosmic-ray antiprotons

Phenomenological transport equation:

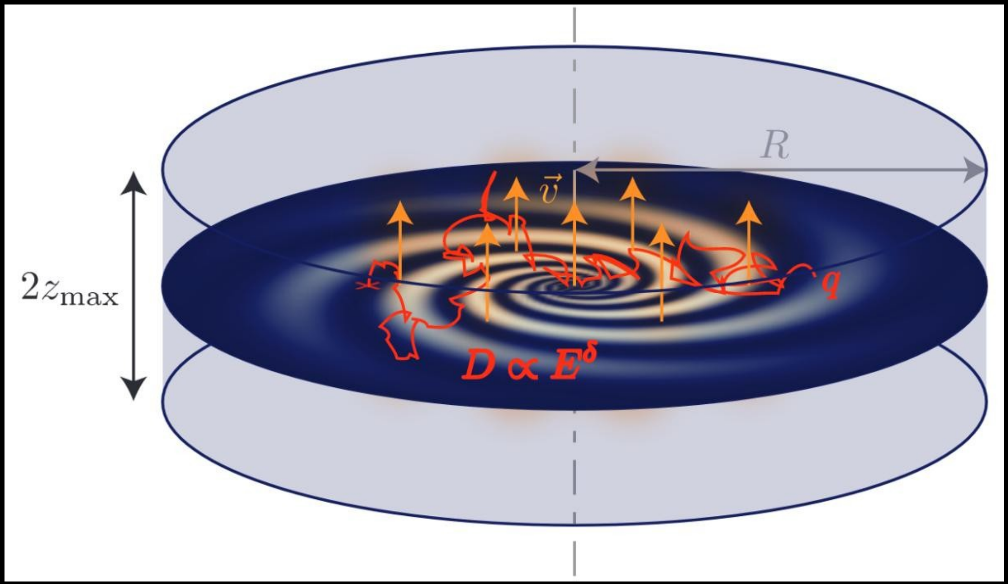
$$\partial_t \Psi + \vec{\nabla}.\left[\vec{V}_c \Psi - K(E)\,\vec{\nabla}\Psi\right] - \partial_E\left[b(E)\Psi - D(E)\partial_E \Psi\right] + \Gamma_{tot}\Psi = Q$$

DM ann. source term

$$Q(\vec{x}, E) = \frac{\langle \sigma_{ann} v \rangle}{2} \left(\frac{\rho(\vec{x})}{m}\right)^2 \frac{dN_{\bar{p}}}{dE}$$

Solved with the Green's function formalism

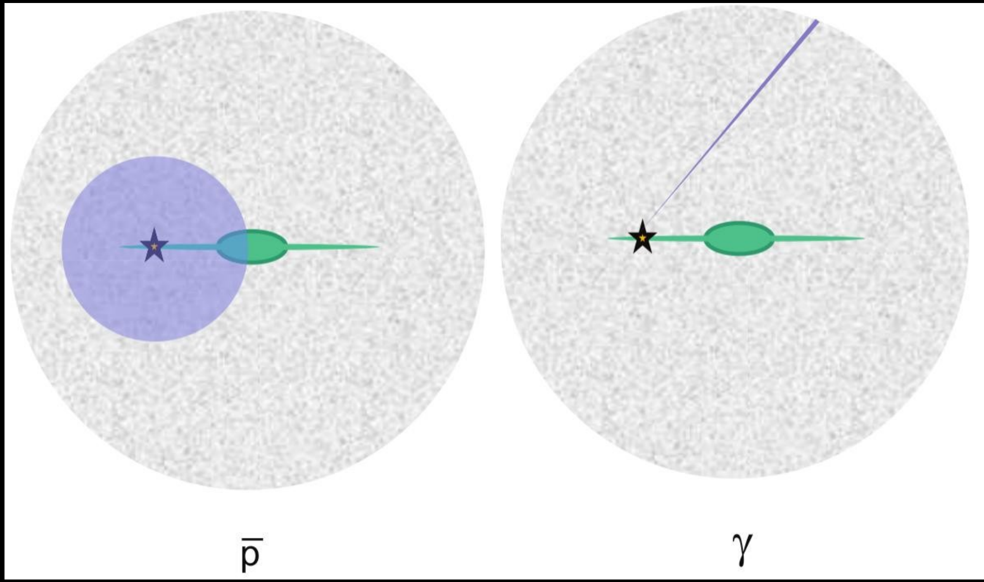
Propagation parameters constrained by (secondaries/primaries) ratio like B/C [Strong & Moskalenko 1998, Maurin+ 2001-2002]



[Mertsch 2010]

Interesting probe of DM annihilation [Silk & Srednicky 84, Bergström+ 99, Donato+ 2004, Bringmann & Salati 2007, Boudaud+ 2015]

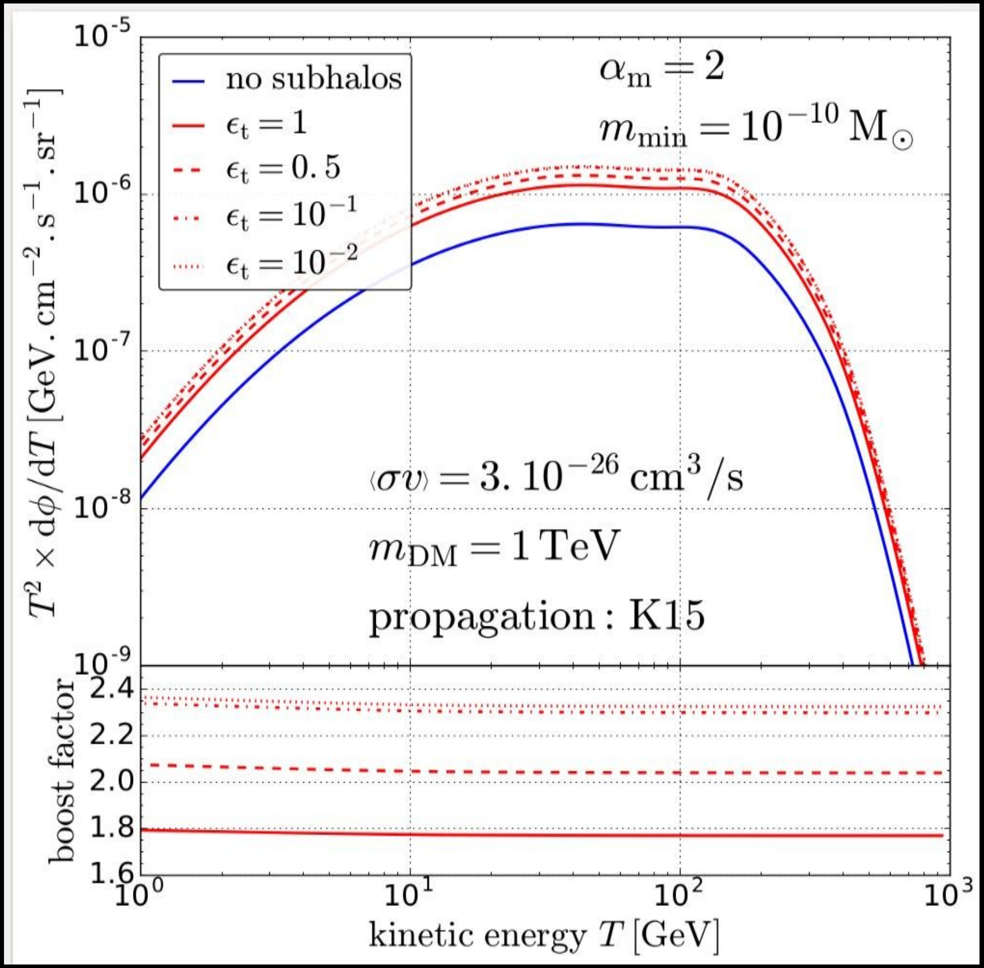
Complementarity with gamma rays:



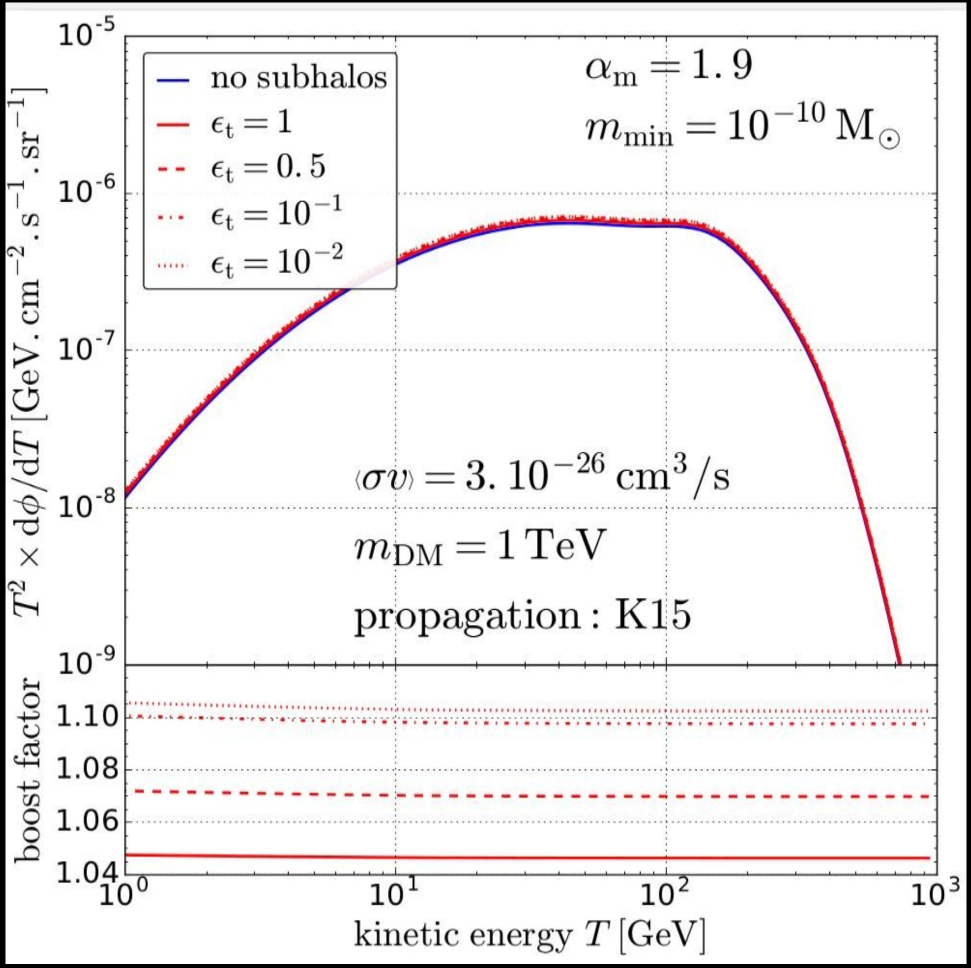
[Bergström 2009]

Impact of clumpiness

[PhD thesis]



[PhD thesis]



Propagation model of Kappl+ 15 → **Magnetic halo half-height = 13.7 kpc**

- Small boost, consistent with previous studies [Lavalle+ 2008, Pieri+ 2011]
- Can still be larger than systematic uncertainties on propagation

Conclusion

- Complete model of the Galactic subhalo population including mass, concentration and spatial information, consistent with dynamical constraints

- Consistent description of tidal effects, including disc shocking

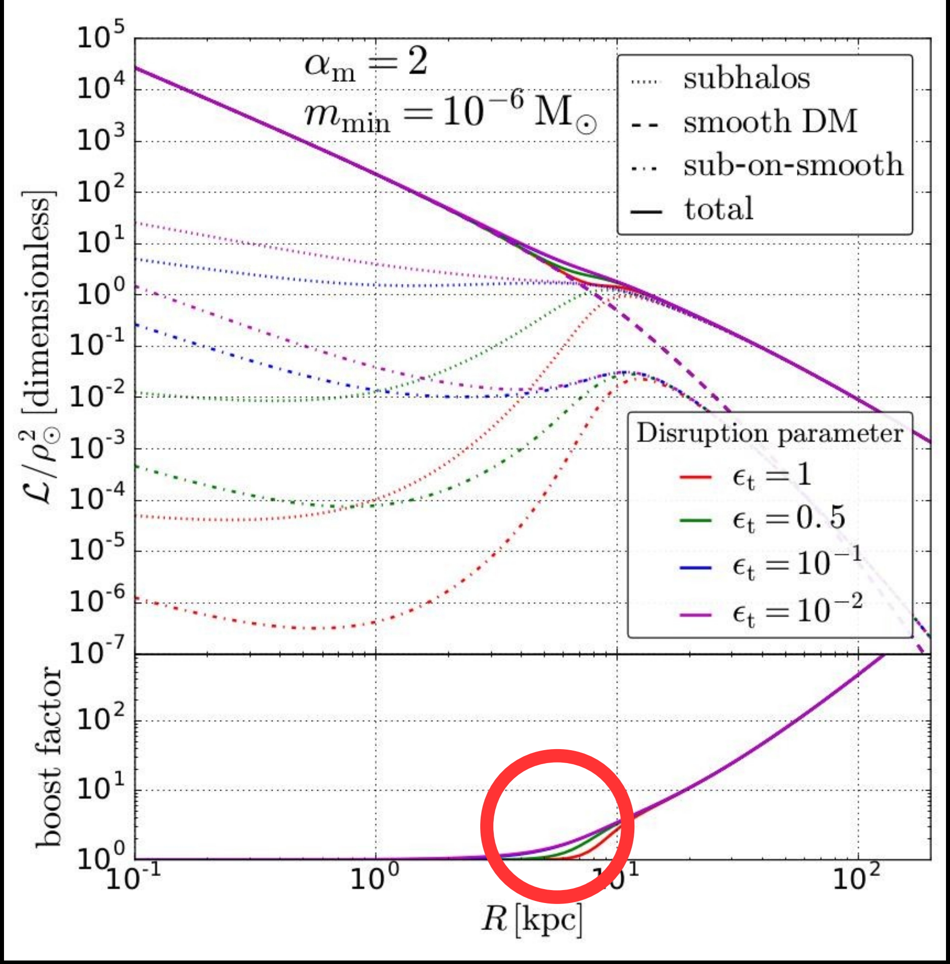
- Survival of clumps core to tidal effects significantly increases the boost factor with respect to previous estimations

- Sizeable boost expected for gamma-ray and antiproton searches

Backup

Impact on indirect searches

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



[PhD thesis]

$$\text{boost factor} \simeq \frac{\mathcal{L}_{\rm tot}}{\mathcal{L}_{\rm no\ sub}} > 1$$

- No boost within 3 kpc
- Large boost in the outskirts ~ 10^2 - 10^3
- **Impact of disruption around 8 kpc!**

→ Local boost = 2 – 3

→ Impact on local probes?