TeVPA 2018

Reviving the clumpiness boost for dark matter indirect searches

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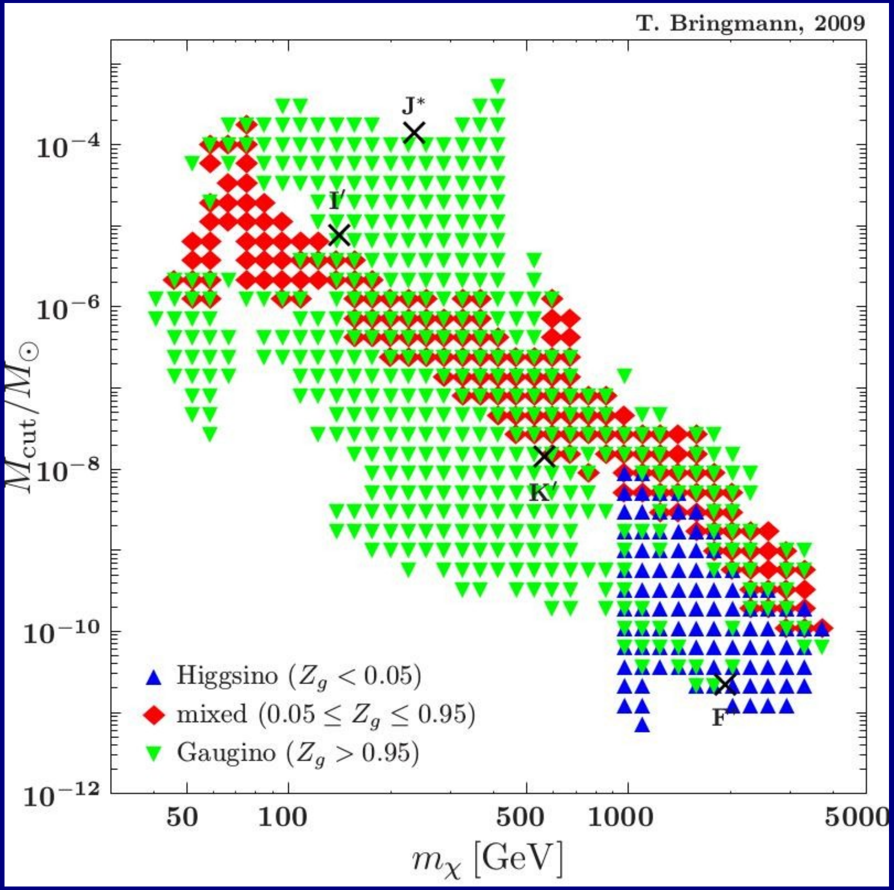
Small-scale structuring of CDM

Size of the smallest dark matter objects set by the kinetic decoupling of the DM particle [Berezinsky+ 03, Loeb & Zaldarriaga 05, Green+ 05, Bringmann & Hofmann 07]
→ typically Earth-mass objects



Neutralino DM [Bringmann 09]

According to cosmological simulations, most of these objects survive the formation of galactic halos [Diemand+ 08, Springel+ 08]

→ large population of *subhalos*

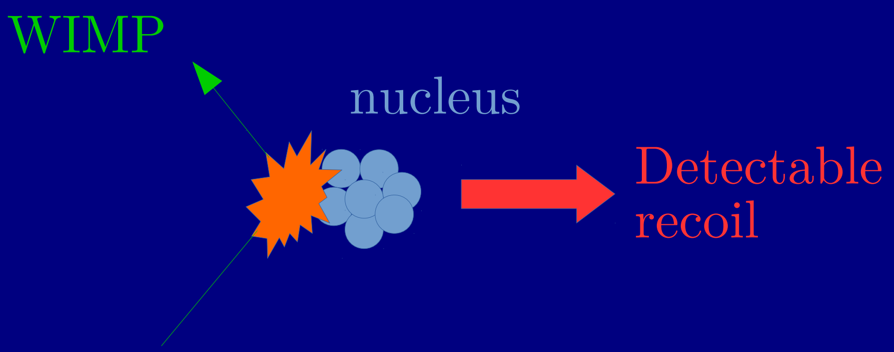
→ most subhalos not massive enough to trigger star formation : remain dark

Small-scale challenges for CDM [Bullock & Boylan-Kolchin 17]

- Missing satellites
- Too big to fail
- Core vs cusp

Subhalos and dark matter searches

Direct searches



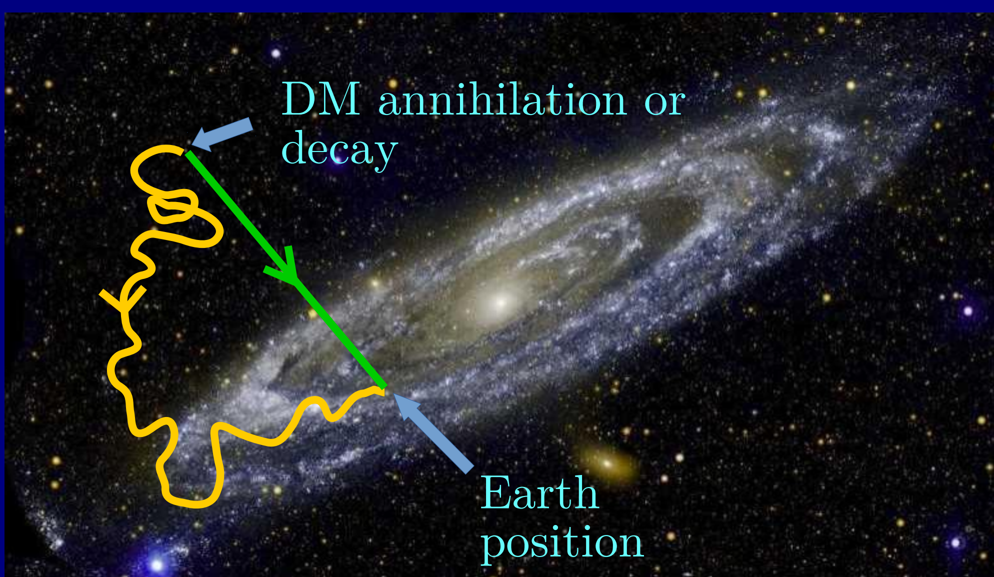
Differential event rate

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

- 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

\+ 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
- Cannot reproduce the observed dynamics

Analytic models

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

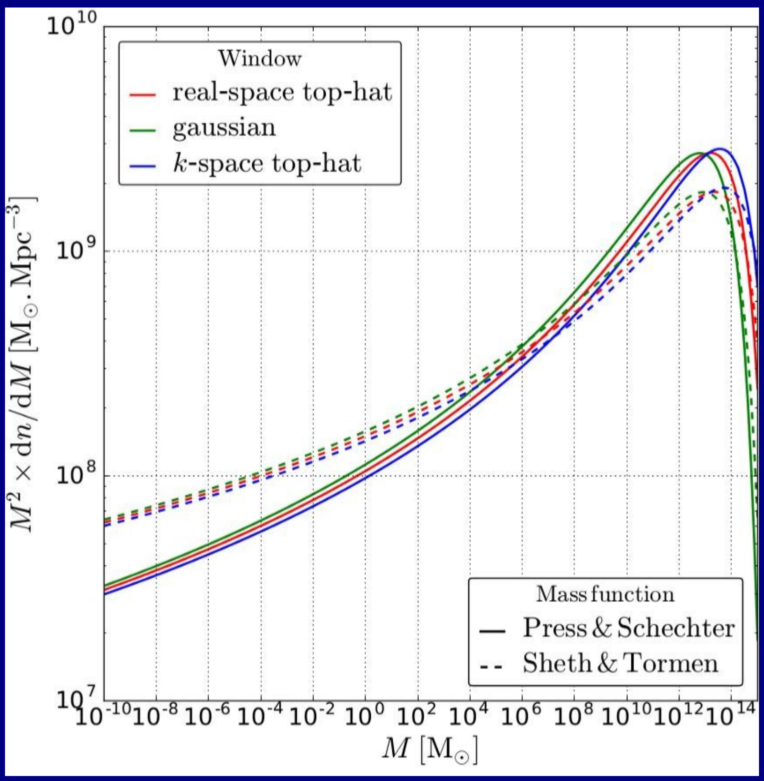
→ Semi-analytic approach = analytic calculations + calibration on simulations

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

Dynamically constrained model of Galactic subhalos

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

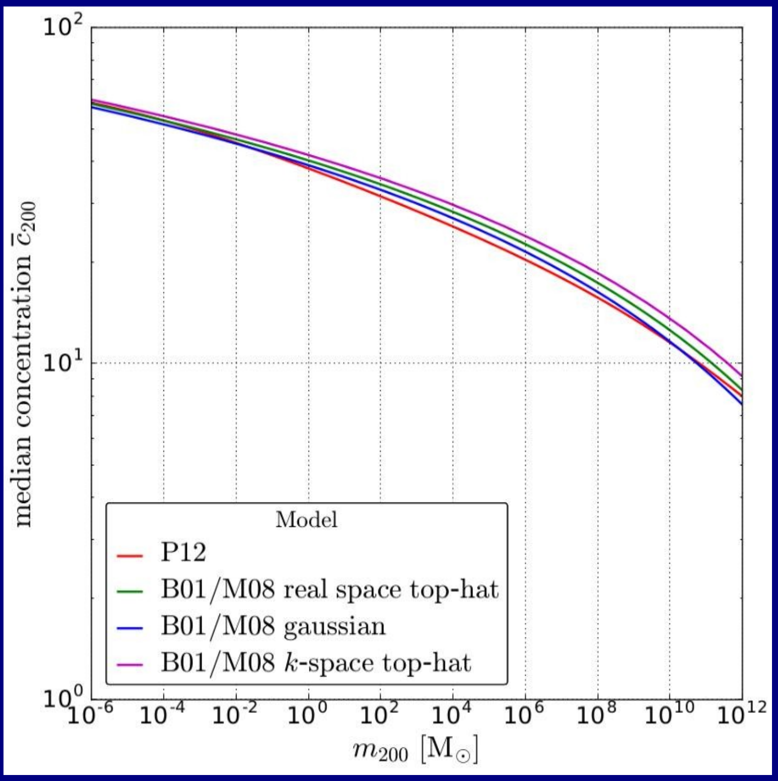
<u>Cosmological mass function</u>
Press & Schechter 74
Sheth & Tormen 99



$$\frac{\mathrm{d}n}{\mathrm{d}M} \propto M^{-\alpha_\mathrm{m}}$$
$$\alpha_\mathrm{m} \simeq 2$$

Recovered for simulated subhalos (Springel+ 08)

<u>Mass-concentration correlation</u>
Bullock+ 01, Maccio+ 08
Prada+ 12



Smaller halos are more concentrated on average

Dynamically constrained model of Galactic subhalos

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

Cosmology and particle physics:
- Halo mass function
  + kinetic decoupling cutoff
- Mass-concentration relation

Dynamical constraints:
- DM density profile ρ_{DM}
- Baryonic distribution

e.g. McMillan 17

Tidal effects:
- Halo stripping
- Disk shocking

Outputs:
- Post-tides mass, concentration and spatial distribution
- Boost factor for indirect searches

Tidal effects: tides from the host

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

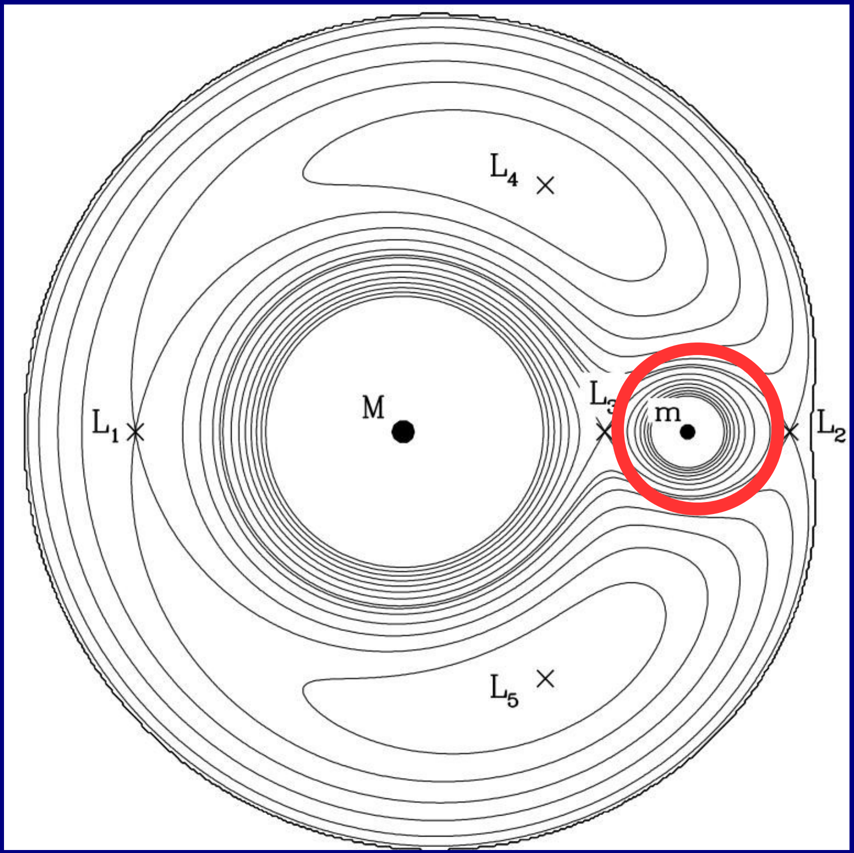
→ Tidal radius

For a host with a smooth mass distribution:

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

Subhalo's tidal radius

Position in the Galaxy



Binney & Tremaine 08

Circular orbits assumed for the subhalos

Tidal effects: disk shocking

Original computation by Ostriker+ 72 for globular clusters crossing the disk

Impulsive approximation : clump's inner dynamics is frozen

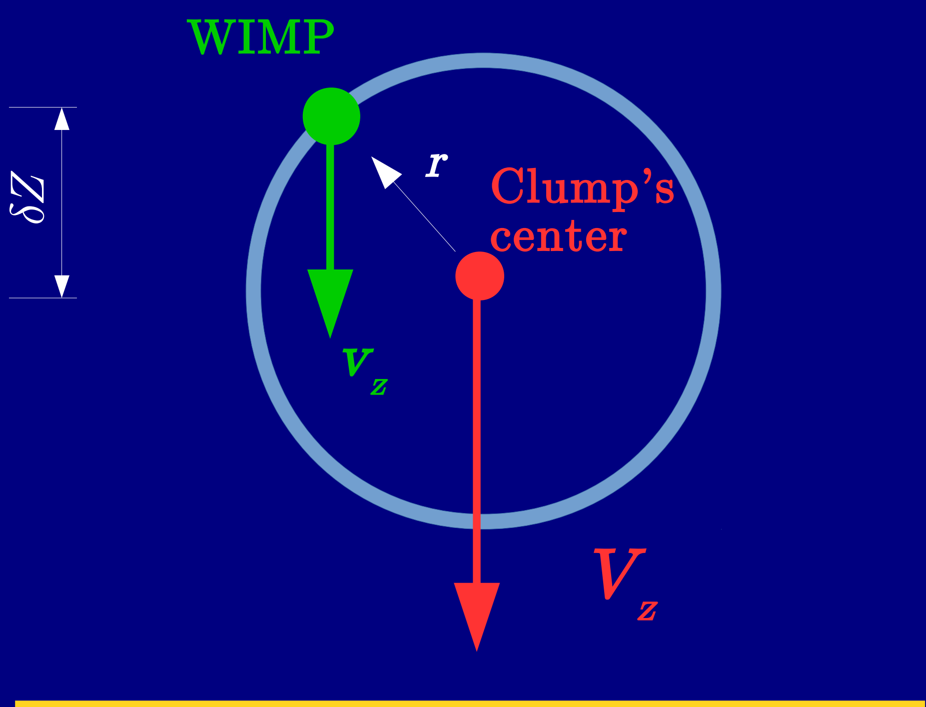
$$\frac{\mathrm{d}v_z}{\mathrm{d}t} \simeq \delta Z \, \frac{\mathrm{d}g_z}{\mathrm{d}z}$$

Kinetic energy gain per DM particle:

$$\langle \delta\epsilon \rangle = \frac{2\, g_z^2\, r^2}{3\, V_z}$$

DM particle stripped away if

$$\langle \delta\epsilon \rangle\,(r) > |\phi(r)|$$

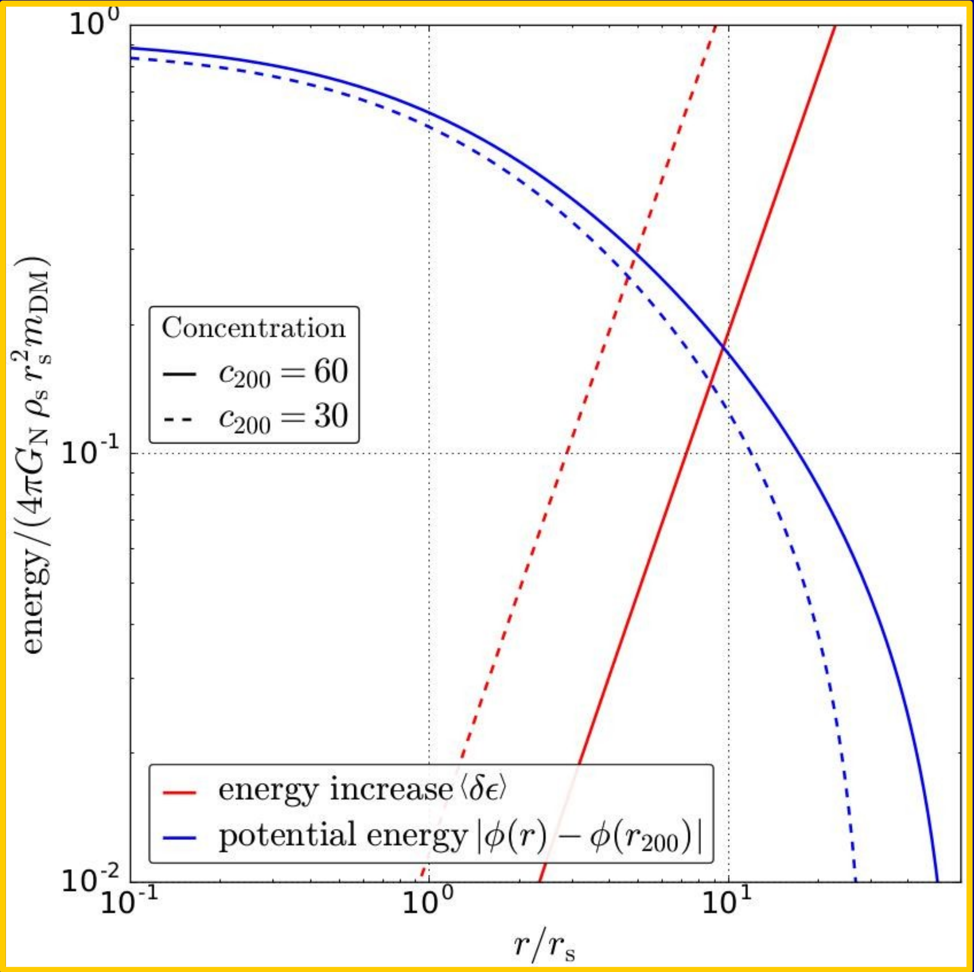


Stellar disk

Tidal effects: disk shocking

Computation by Ostriker+ 72 for globular clusters crossing the disk

Impulsive approximation : clump's inner dynamics is frozen



$$\frac{dv_z}{dt} \simeq \delta Z \, \frac{dg_z}{dz}$$

Kinetic energy gain per DM particle:

$$\langle \delta\epsilon \rangle = \frac{2\, g_z^2\, r^2}{3\, V_z}$$

DM particle stripped away if

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

→ Definition of a tidal radius associated to disk shocking

Can a subhalo be completely disrupted?

Theory says NO
- Cuspy subhalos are much denser than the Galactic halo
- Adiabatic invariance protects particles in the inner parts of subhalos

[Weinberg 94, Gnedin & Ostriker 99]

Simulations say YES
- Subhalos are disrupted when $r_t \lesssim r_s$ [Hayashi+ 03]

BUT!

Subhalo disruption in simulations might be artificial
→ most disruptions are numerical artifacts coming from the limited resolution
[van den Bosch 17, van den Bosch+ 17, van den Bosch & Ogiya 18]

⇒ Subhalos may never be completely disrupted!

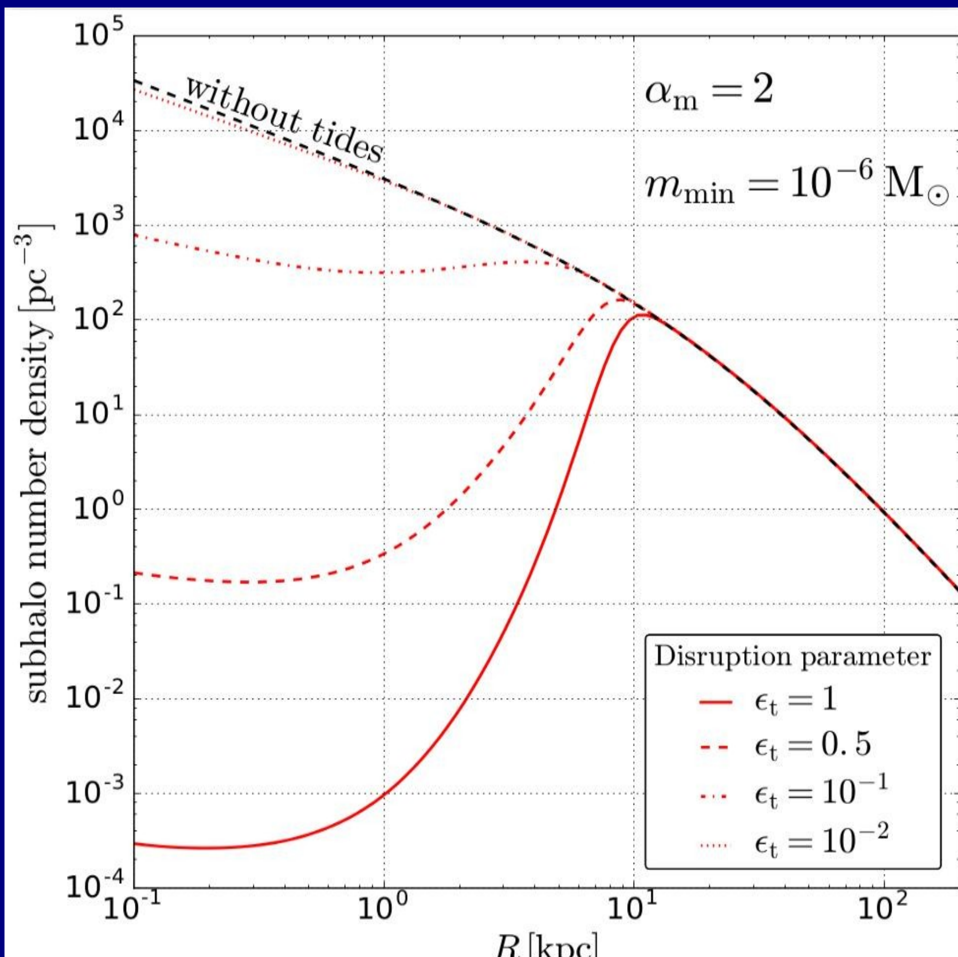
Simple parametrization

A subhalo is disrupted if $r_t < \epsilon_t \, r_s$ with ε_t a free parameter

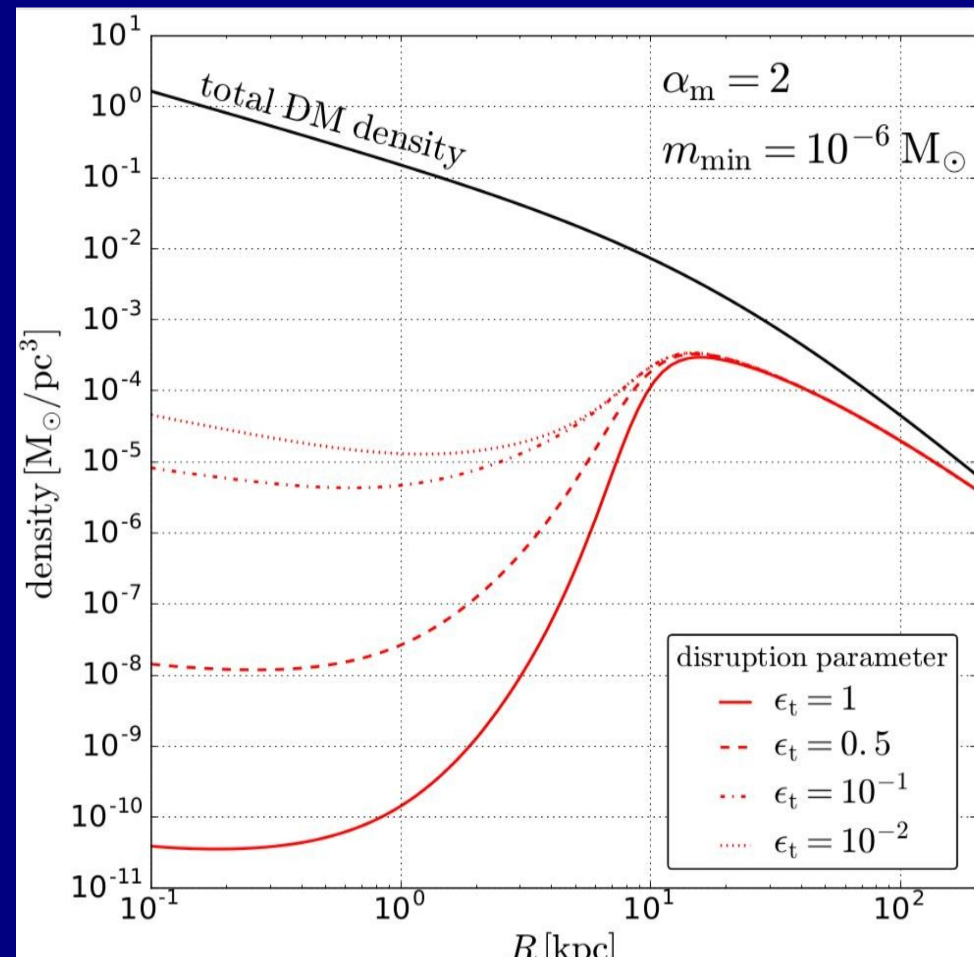
Realistically $\epsilon_t \ll 1$

Galactic subhalo population

Subhalo number density



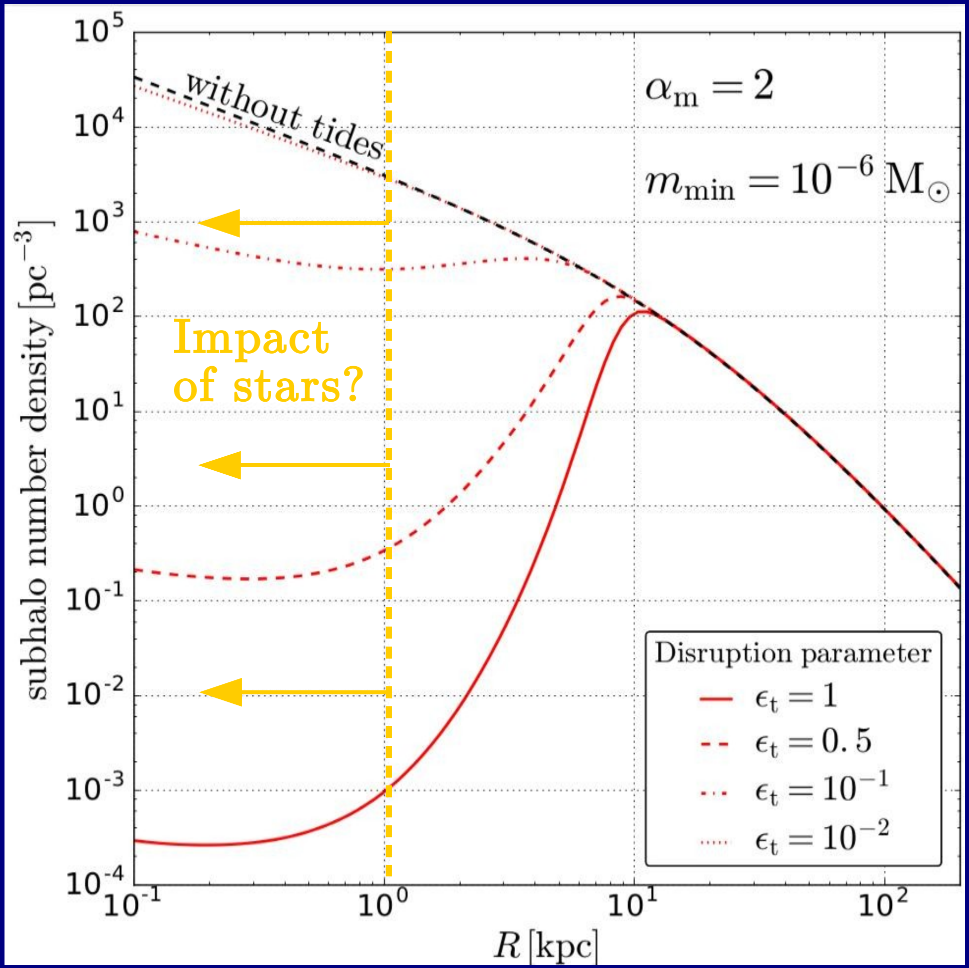
mass density



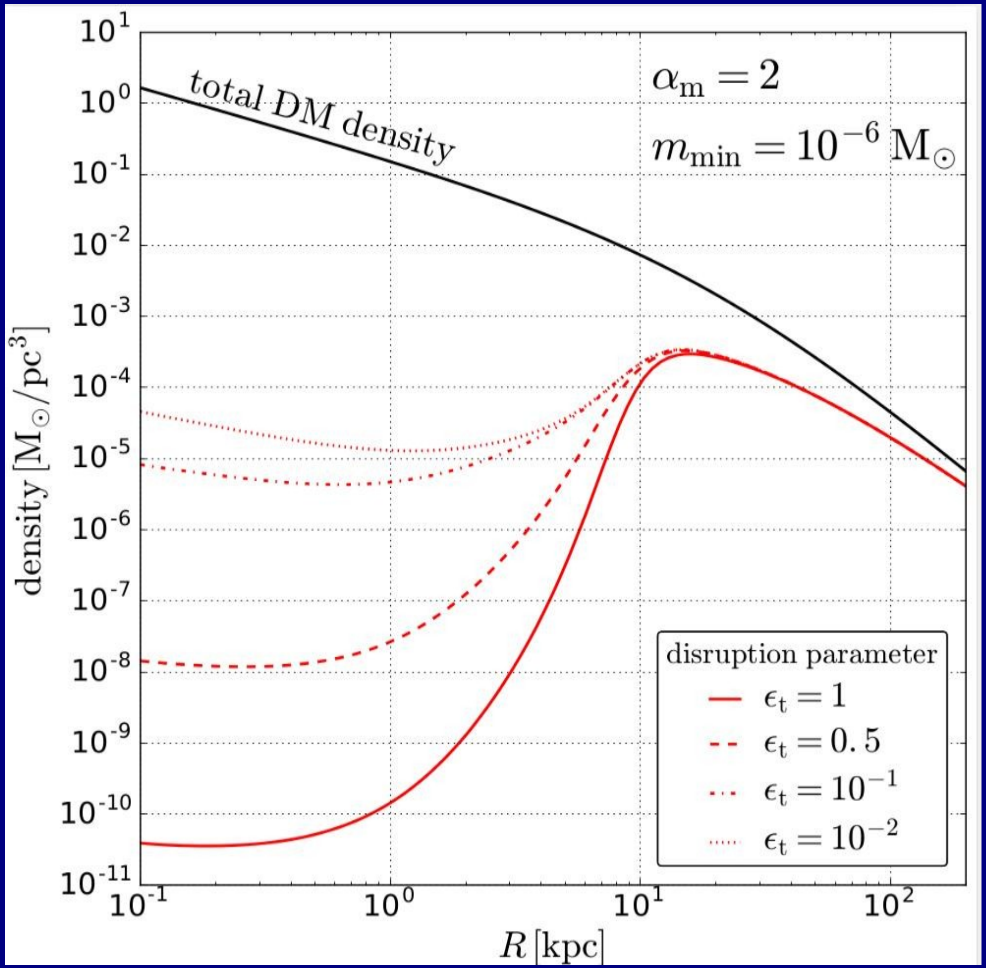
Potentially many, very stripped subhalos at the center of the Galaxy

Impact on the subhalo population

Subhalo number density

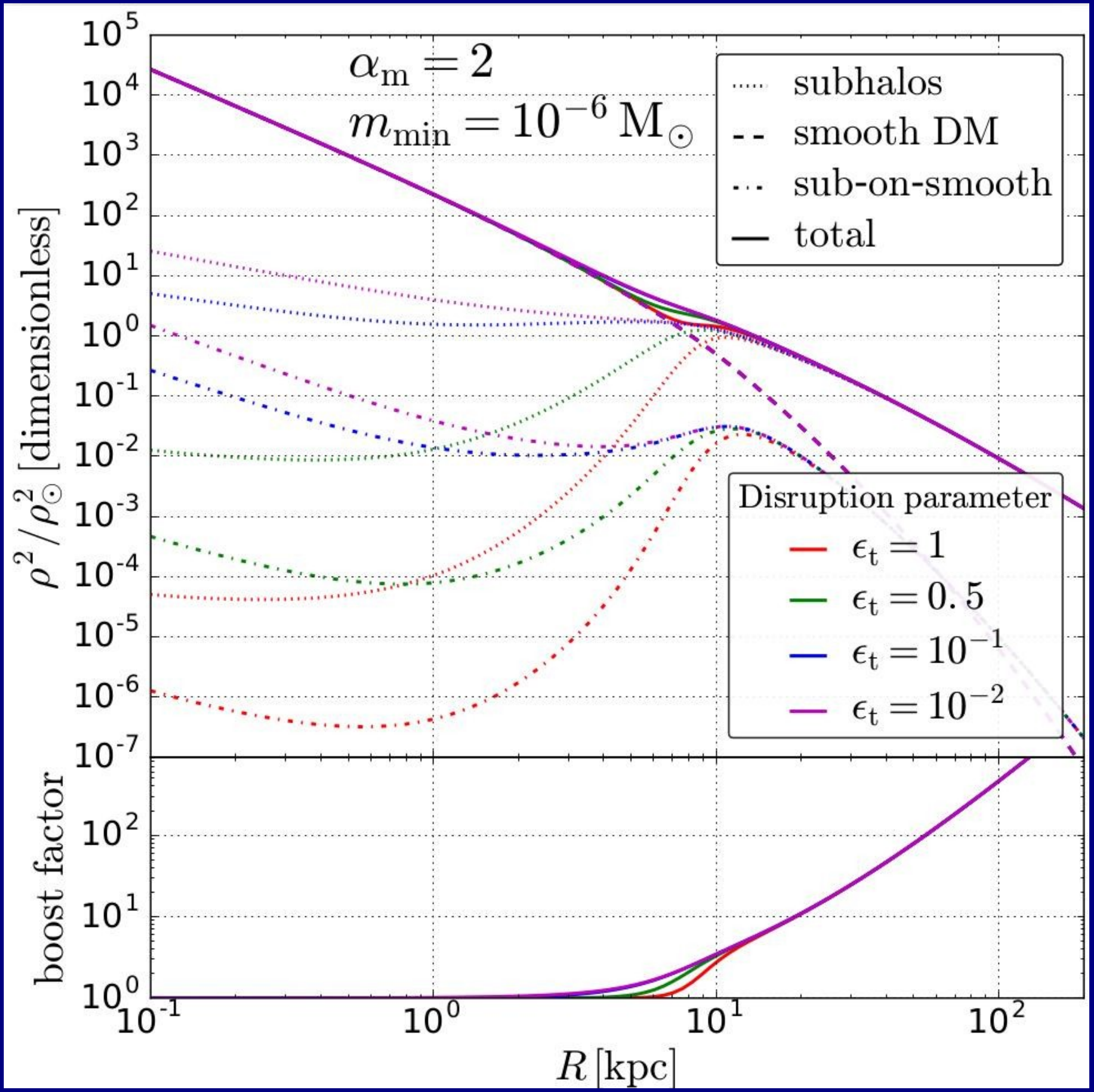


mass density



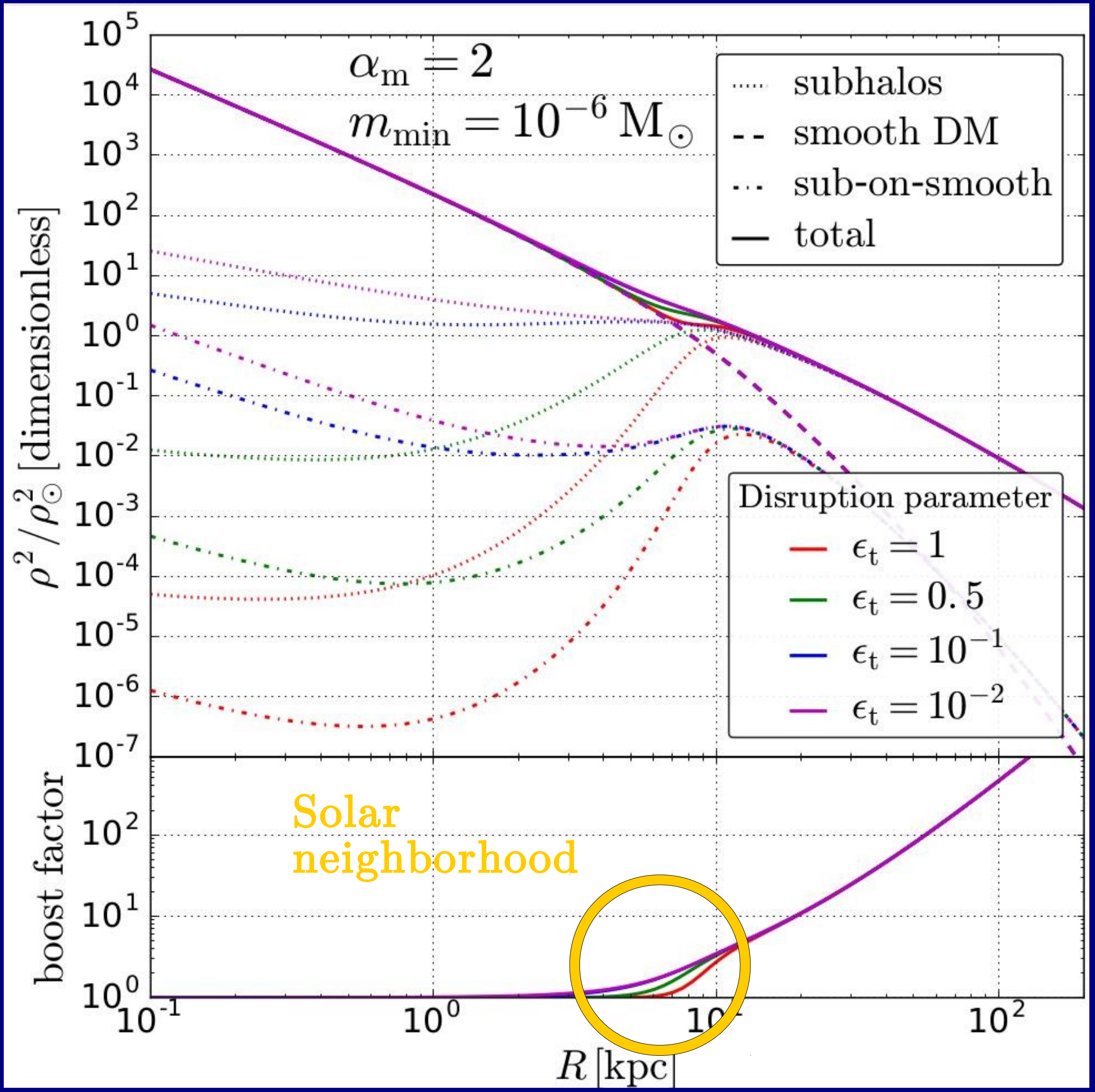
Potentially many, very stripped, subhalos at the center of the Galaxy

Clumpiness enhancement for indirect searches



- No boost in the Galactic bulge
- The boost is unchanged outside the Galactic disk

Clumpiness enhancement for indirect searches



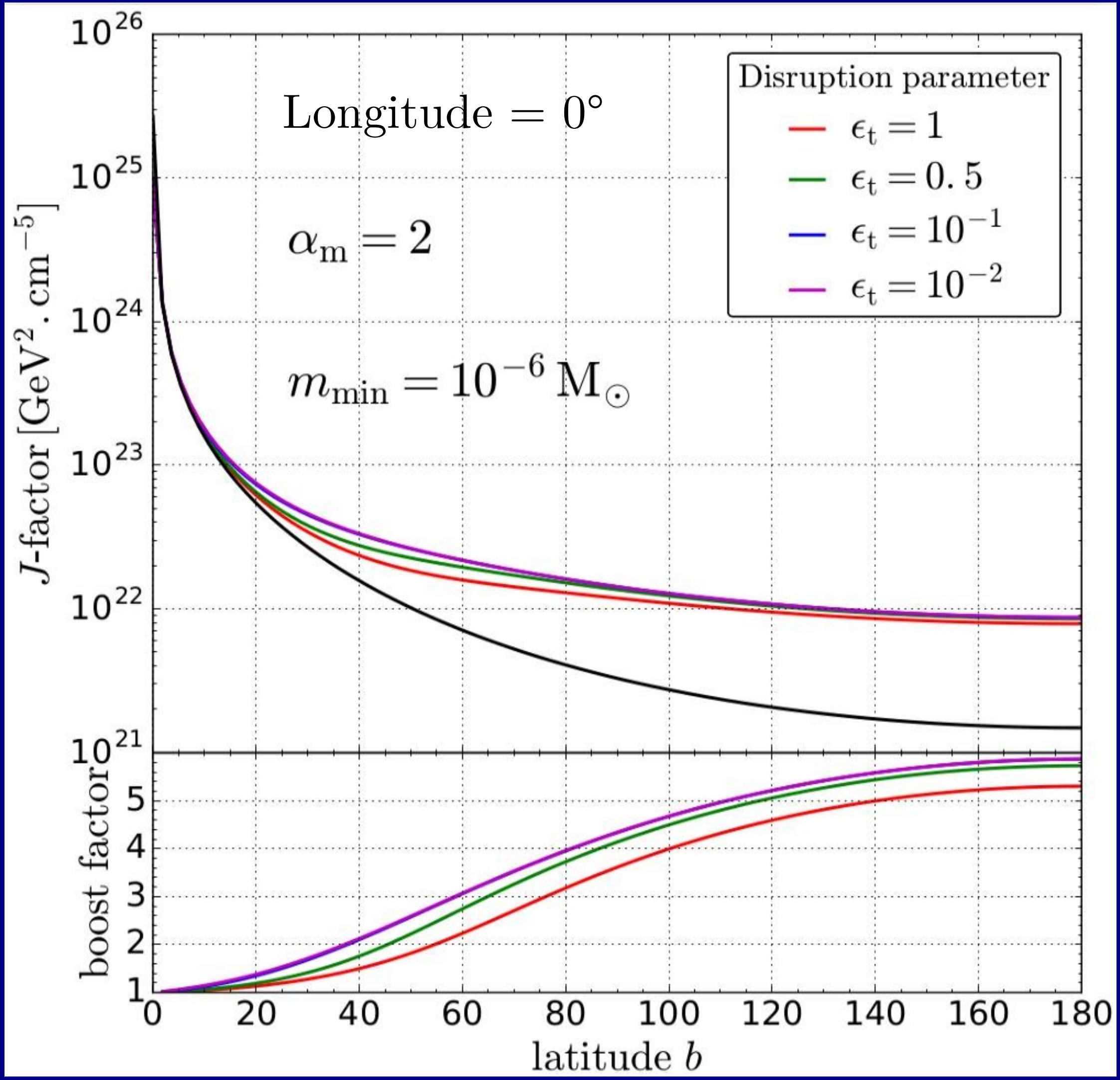
- No boost in the Galactic bulge
- The boost is unchanged outside the Galactic disk

→ Biggest impact in the Solar neighborhood $R \sim 8$ kpc

Galactic gamma-ray searches

$$\left.\frac{\mathrm{d}\phi}{\mathrm{d}E}\right|_{\mathrm{los}} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2\,m^2}\frac{\mathrm{d}N}{\mathrm{d}E} \times \int_{\Delta\Omega}\mathrm{d}\Omega \int_{\mathrm{los}}\mathrm{d}l\,\rho^2$$

J-factor



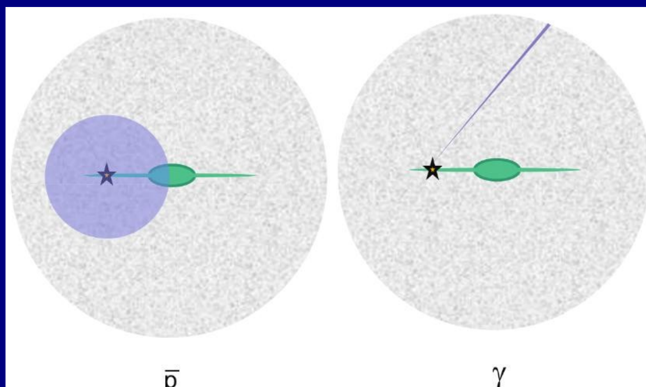
$$\mathrm{boost} \sim \frac{J_{\mathrm{sub}} + J_{\mathrm{smooth}}}{J_{\mathrm{smooth}}}$$

Large enhancement at high latitudes

→ should impact latest diffuse gamma-ray constraints (see Laura Chang's talk on Thursday)

Cosmic-ray antiprotons searches

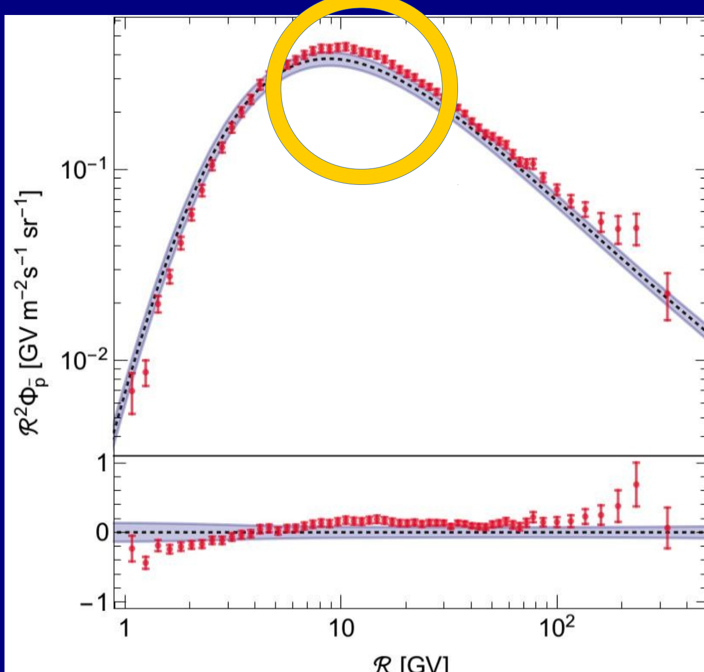
Cosmic-ray antiprotons diffuse on the inhomogeneities of the Galactic magnetic field
→ probe a volume centered on the Solar system



Bergström 09

→ standard probe of dark matter annihilation Silk & Srednicki 84, Jungman & Kamionkowski 94, Bergström+ 99, Donato+ 04, Bringmann & Salati 07, Boudaud+ 15

Secondary background estimations in tension with latest data from AMS-02
→ room for DM annihilation Cui+ 17, Cuoco+ 17, Cui+ 18, Reinert & Winkler 18, Cui+ 18



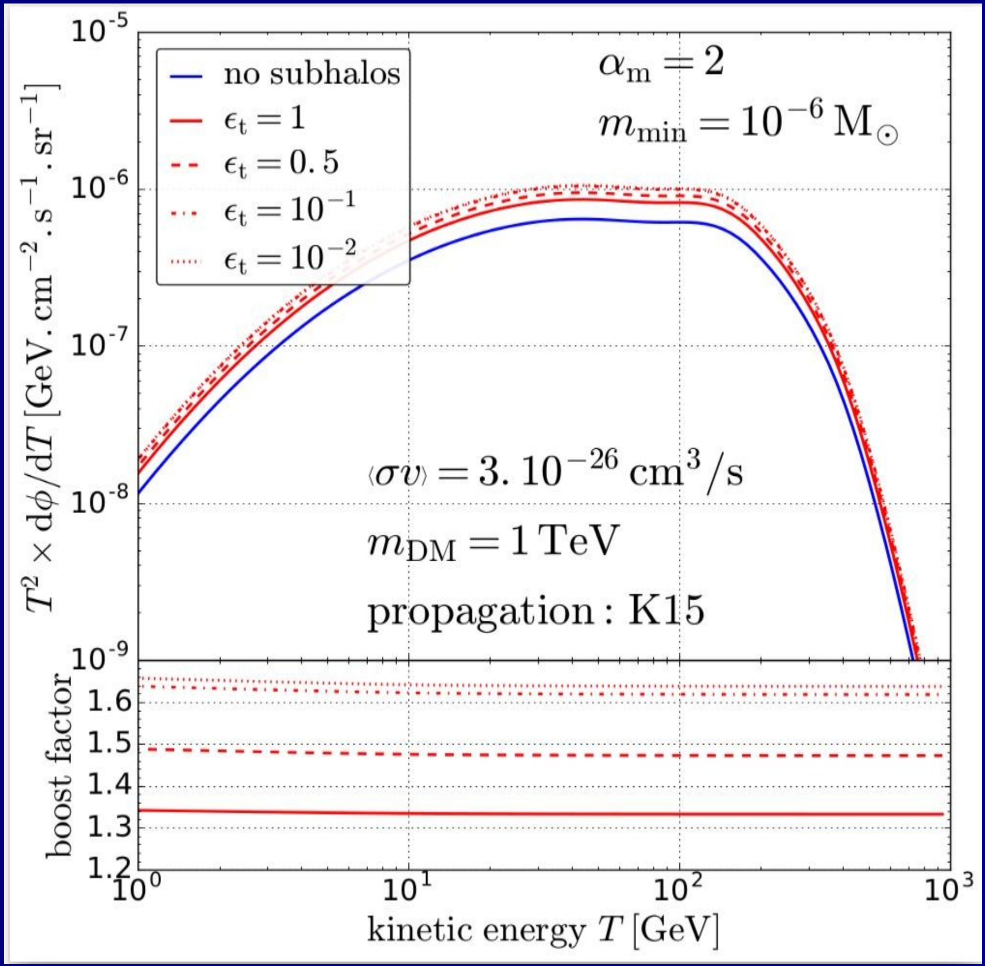
Reinert & Winkler 18

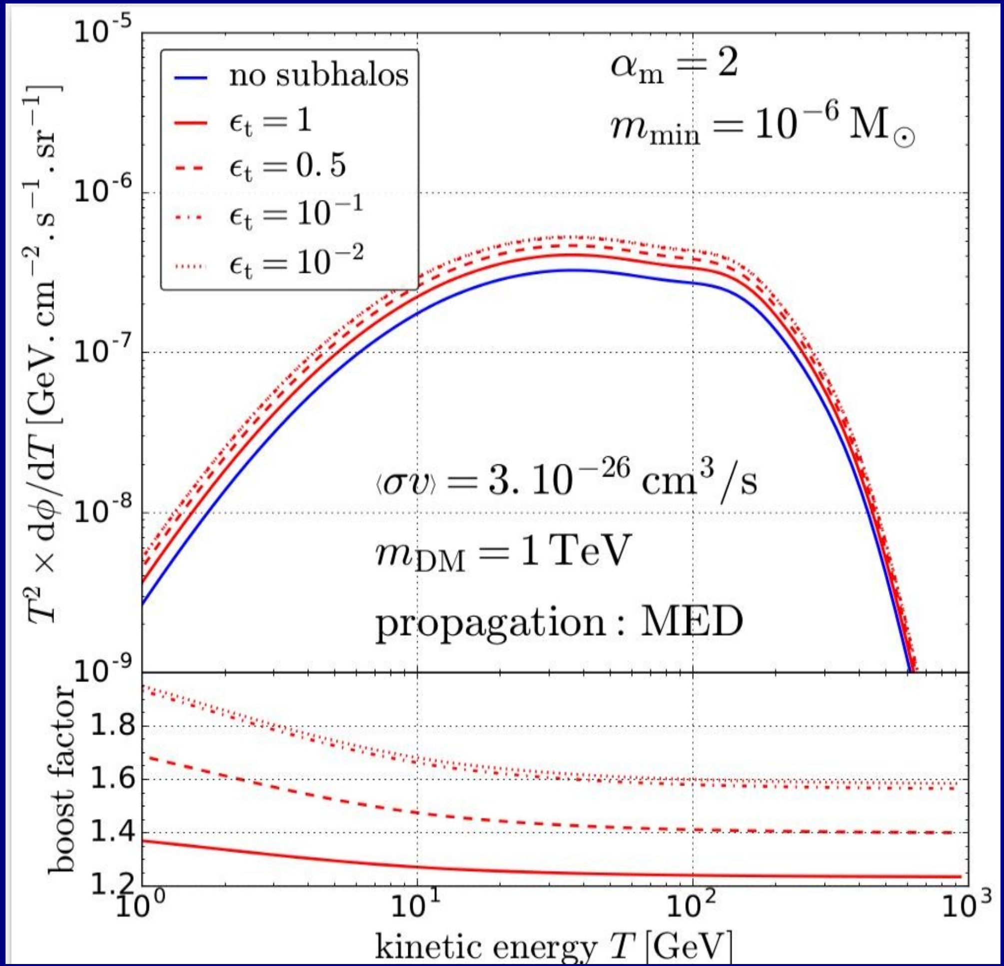
BUT!

DM clustering is known to be important for antiproton searches Lavalle+ 08, Pieri+ 11

→ should impact the inferred annihilation cross-section and mass

Cosmic-ray antiprotons searches





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

Propagation model MED (Donato+ 04)
Magnetic halo half-height = 4 kpc

- Enhancement much smaller than for gamma-rays
- Can still be around 60% if subhalos survive tides
  → larger than theoretical uncertainties on transport

Conclusion

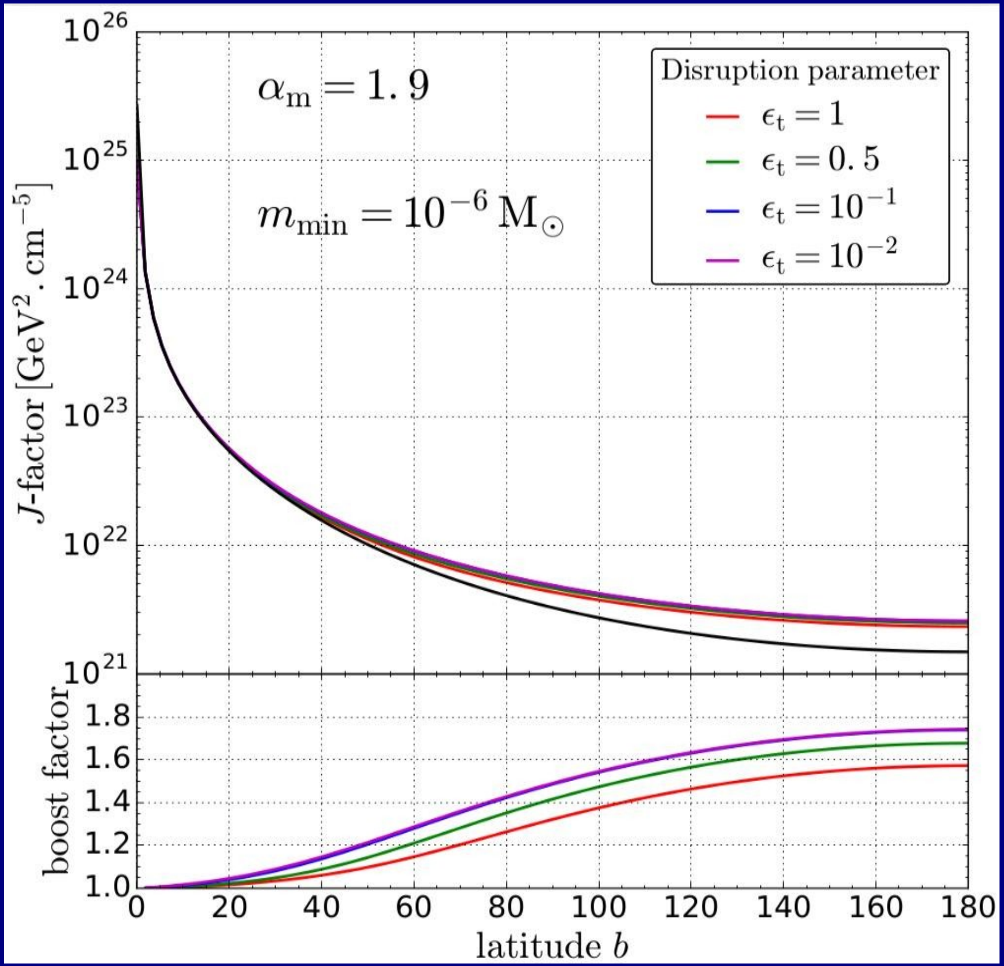
- Complete model of the Galactic subhalo population including mass, concentration and spatial information, consistent with dynamical constraints

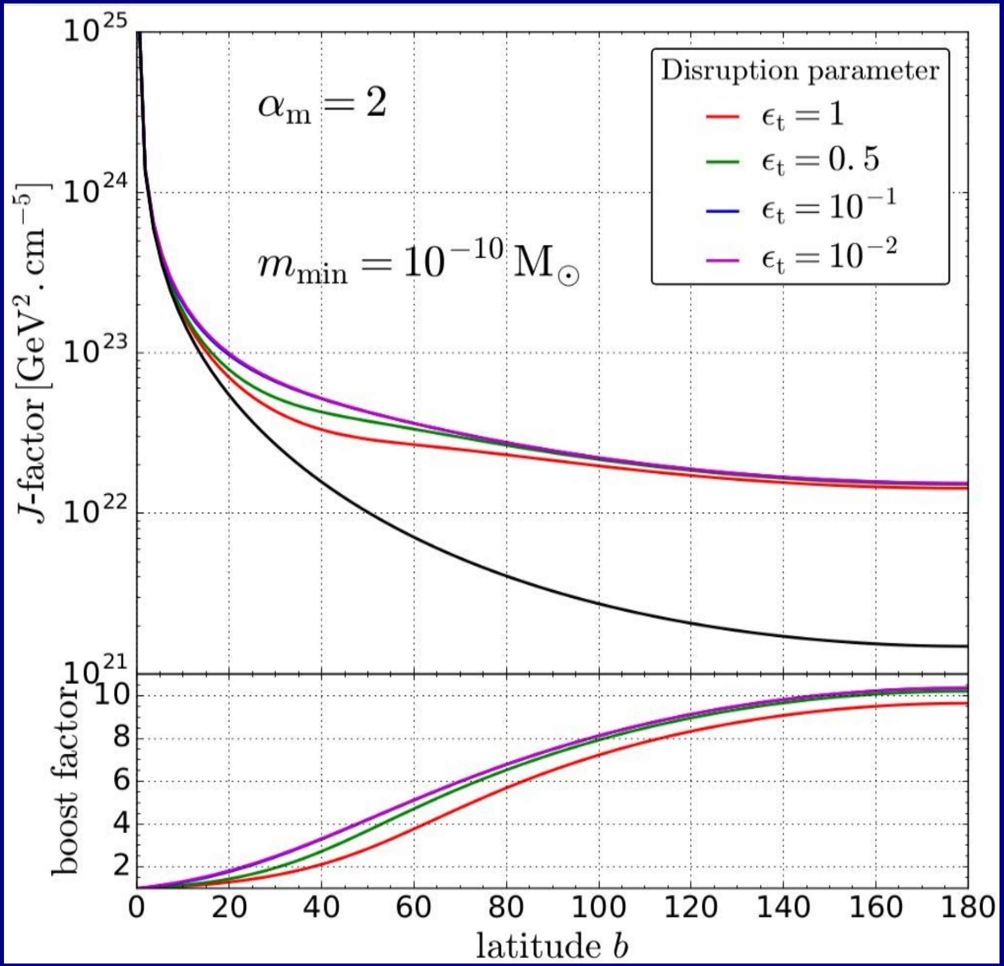
- Consistent description of tidal effects, including disk shocking

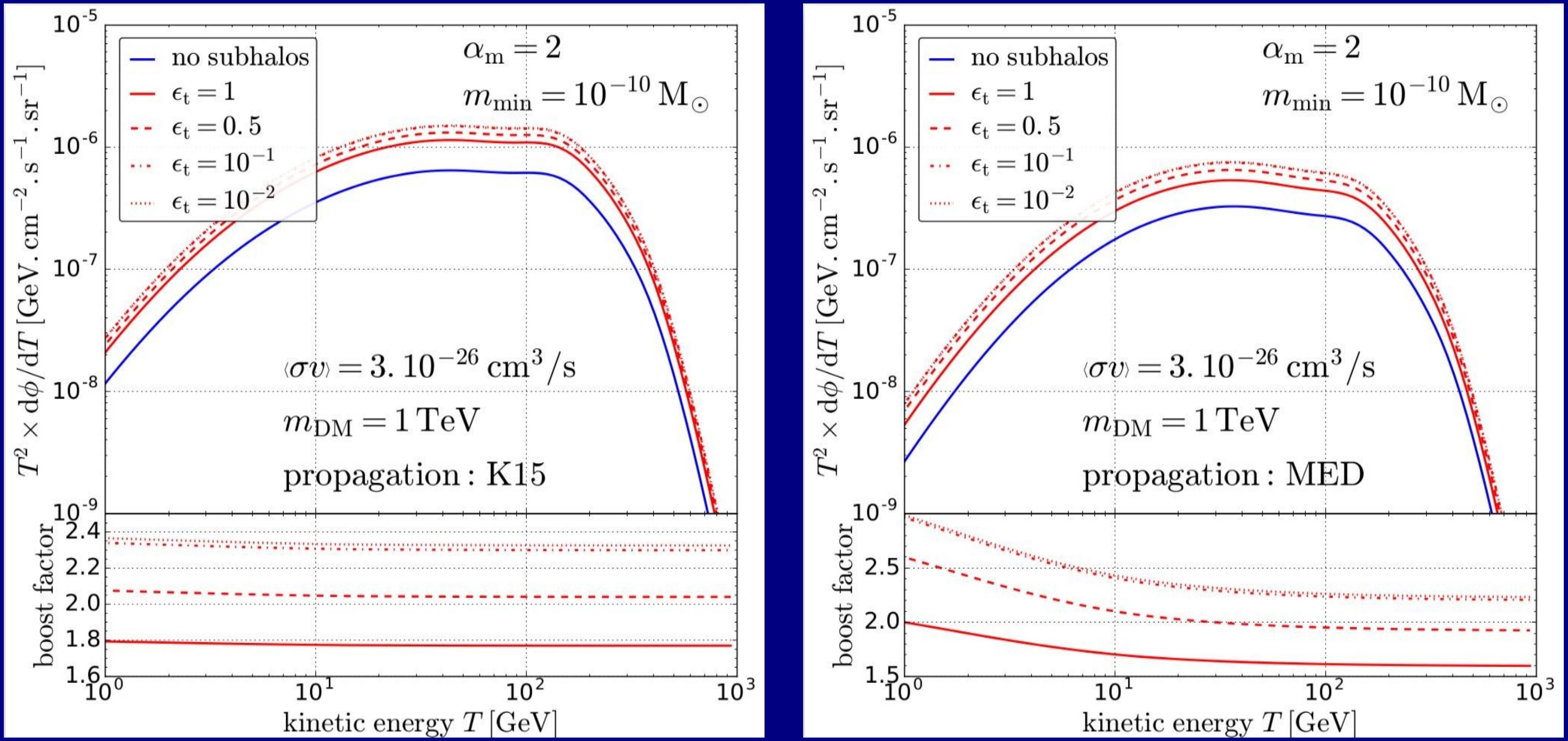
- Survival of clumps core to tidal effects significantly increases the boost factor with respect to previous estimations

- Sizeable boost expected for gamma-ray and antiproton searches

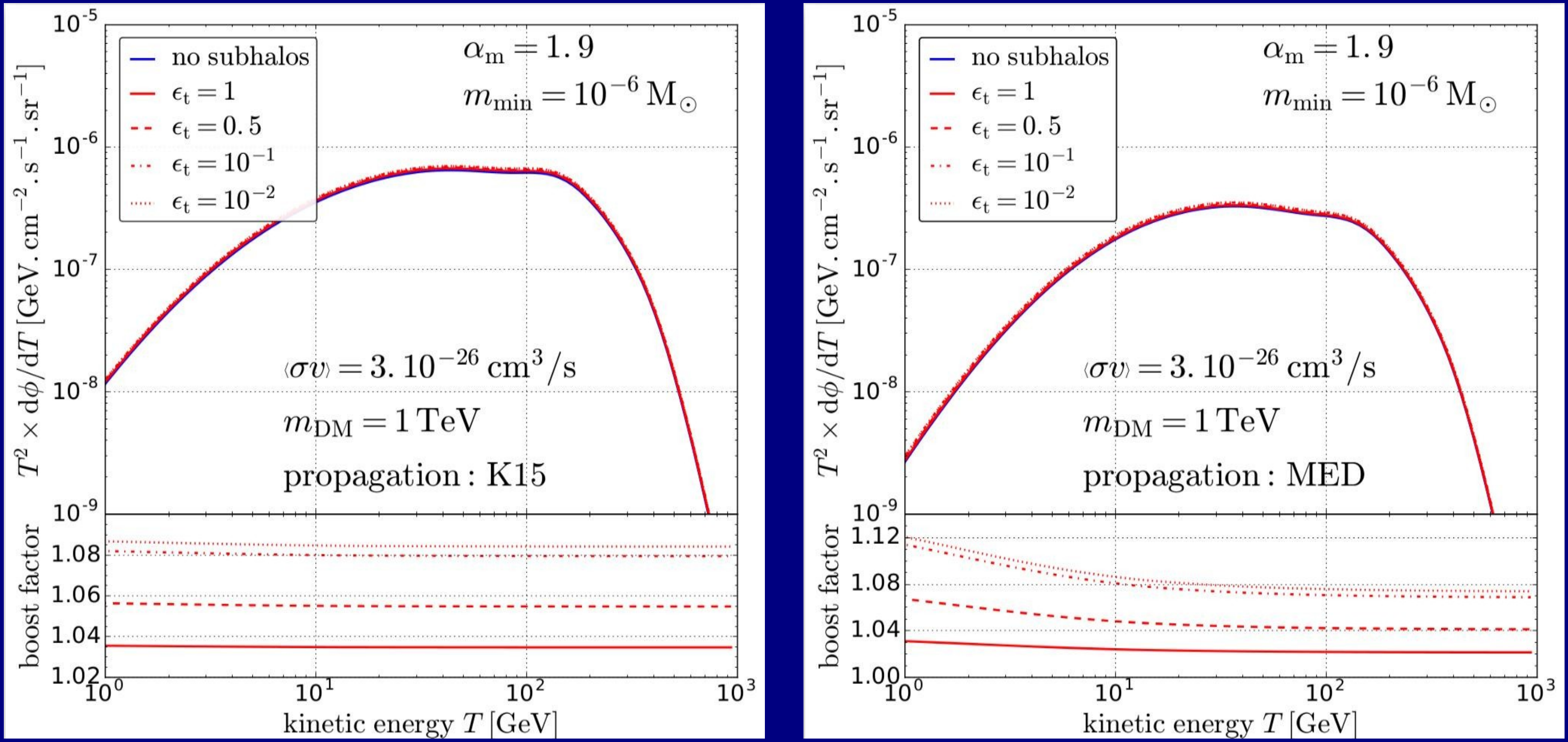
Backup


$\alpha_m = 1.9$
$m_{min} = 10^{-6}\,M_\odot$
Disruption parameter
$\epsilon_t = 1$
$\epsilon_t = 0.5$
$\epsilon_t = 10^{-1}$
$\epsilon_t = 10^{-2}$
J-factor [$GeV^2 . cm^{-5}$]
boost factor
latitude b


$\alpha_m = 2$
$m_{min} = 10^{-10}\,M_\odot$
Disruption parameter
$\epsilon_t = 1$
$\epsilon_t = 0.5$
$\epsilon_t = 10^{-1}$
$\epsilon_t = 10^{-2}$
J-factor [$GeV^2 . cm^{-5}$]
boost factor
latitude b



no subhalos
$\epsilon_t = 1$
$\epsilon_t = 0.5$
$\epsilon_t = 10^{-1}$
$\epsilon_t = 10^{-2}$
$\alpha_m = 2$
$m_{min} = 10^{-10}\,M_\odot$
$\langle\sigma v\rangle = 3.\,10^{-26}\,cm^3/s$
$m_{DM} = 1\,TeV$
propagation : K15
propagation : MED
$T^2 \times d\phi/dT\,[GeV.\,cm^{-2}.\,s^{-1}.\,sr^{-1}]$
boost factor
kinetic energy T [GeV]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$T^2 \times d\phi/dT\,[GeV.\,cm^{-2}.\,s^{-1}.\,sr^{-1}]$
boost factor
kinetic energy T [GeV]