# Disruption of Dark Matter Minihalos by Successive Stellar Encounters

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+ Ongoing work

# Axion Minihalo

- QCD axions solve the Strong CP problem and are a candidate for cold dark matter.
- During the matter-radiation equality, isocurvature axion density fluctuations decouple from Hubble flow and collapse to form a virialized gravitational structure called the axion minihalo.
- Primordial axion minihalos undergo hierarchical merging.
- Axion minihalos can affect the chances for direct dark matter detection.

# Axion minihalos – NFW Profile

- Simulations show that the minihalos have a spherically symmetric Navarro–Frenk–White (NFW) density profile: $\rho(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$
- $\rho_s$ is the scale density and $r_s$ is the scale radius.
- Concentration parameter is defined as $c \equiv r_{\mathrm{vir}} / r_s$ .

# Model of mass disruption due to stellar encounters

- Kavanagh et al. (*PRD 104, 063038*) (K2021) proposed an analytical model of mass loss using the phase-space distribution of axions in the minihalo.

Our improvements:

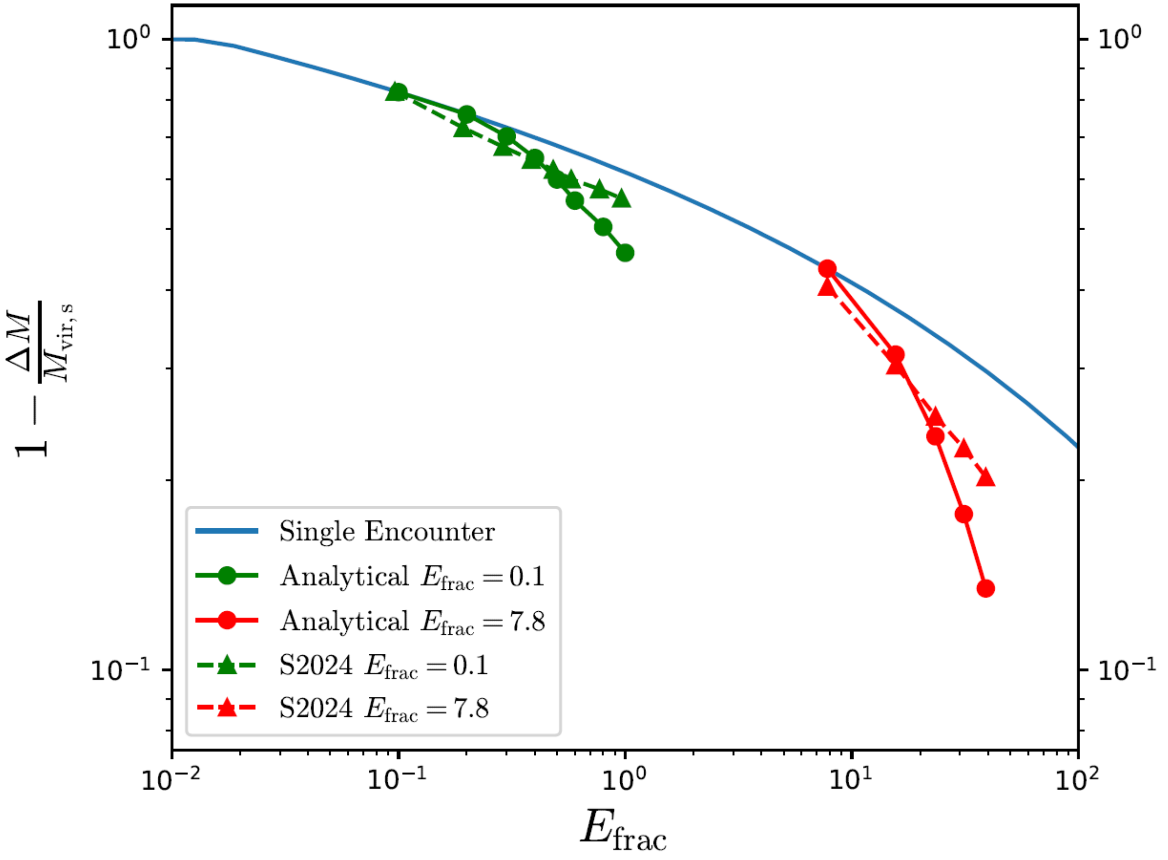
- Sequential stripping model: Outer shells are stripped off first before an inner shell is stripped off. This affects the gravitational potential of each axion.
- After stellar interaction, the remnant minihalo is assumed (based on numerical simulations) to gravitationally relax into a Hernquist density profile:

$$\rho(r) = \frac{\rho_1}{(r/r_1)(1 + r/r_1)^3}$$

# Successive Stellar Encounters

$$c_s \xrightarrow{E_{\text{frac,s}}} \underset{c_1}{\overset{\text{S.F.}_s}{\uparrow}} \xrightarrow{E_{\text{frac},1}} \underset{c_2}{\overset{\text{S.F.}_1}{\uparrow}} \xrightarrow{E_{\text{frac},2}} \underset{c_3}{\overset{\text{S.F.}_2}{\uparrow}} \xrightarrow{E_{\text{frac},3}} \cdots$$

$$E_{\text{frac}} = \frac{\Delta E}{E_b}$$




Shen et al - APJ 962:9 (25pp) – (S2024)

# Code to Evolve Minihalo Trajectory

- *lbparticles* is a Python implementation of an epicyclic orbit solver proposed by Lynden-Bell (2015) for bound orbits in a spherically symmetric potential.
- Given the initial state (position and velocity) of the minihalo, and a known potential, *lbparticles* derives a set of coefficients that can be used to evaluate the minihalo's state at an arbitrary time in the future.

# Energy injection during a disk pass

- For a single disk pass, the energy injection parameter is (S2024):

$$E_{\rm frac} = \frac{G m_\kappa \Sigma_*}{\sigma_*^2 + v_{\rm mh}^2} \frac{\alpha^2(M, z_{\rm i})}{\gamma(M, z_{\rm i})\bar{\rho}_{\rm vir}(z_{\rm i})} \frac{2}{b_{\rm s}^2(M, z_{\rm i}) + 2b_{\rm c}^2(\Sigma_*)}$$

- $\Sigma_*$ is the stellar surface density for one disk pass.

$m_\kappa$ - characteristic stellar mass
$\sigma_*$ - 1D stellar velocity dispersion
$v_{\rm mh}^2$ - variance of minihalo velocity
$\alpha^2, \gamma$ - constants that depend on density profile of minihalo
$\bar{\rho}_{\rm vir}$ - density inside the virial radius
$b_{\rm s}$ - transition radius
$b_{\rm c}$ - cut-off parameter below which shot noise becomes relevant

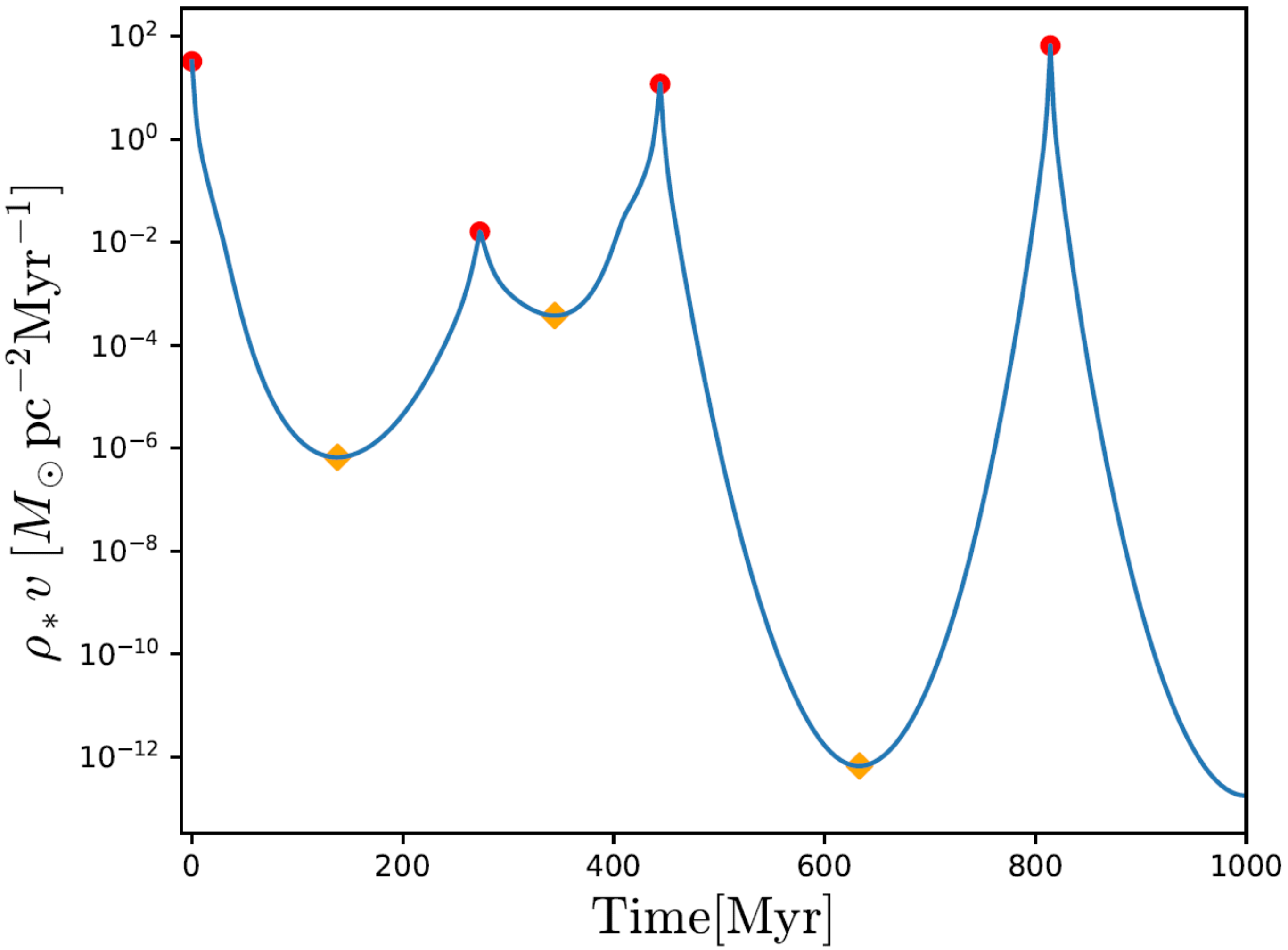
# Energy injection during a disk pass

$$\Sigma_* = \int_{\rm traj} \rho_* {\rm d}l = \int_{\rm traj} \rho_* v {\rm d}t$$

$$\rho_*(R, z) = \sum_{d=t,T} \frac{\Sigma_{\rm d,0}}{2 z_{\rm d}} \exp\left(-\frac{|z|}{z_{\rm d}} - \frac{R}{R_{\rm d}}\right)$$

McMillan (2011) – MNRAS 414, 2446–2457

- $\rho_*$ - stellar volume density
- $\Sigma_{\rm d,0}$ - central surface density
- $z_{\rm d}$ - scale height
- $R_{\rm d}$ - scale length



# Effective energy injection

- Stücker et al. proposed a formula for effective energy injection in the multiple disk passes: $$E_{\mathrm{frac,eff}}^{p/2} = \sum_i E_{\mathrm{frac},i}^{p/2}$$

- S2024 assumed p=2. They did not take into account the density profile changes in the minihalo, in between disk passes.

- Given enough time for relaxation in between disk passes, we found that p~1. Thus, multiple disk passes incur more mass loss (higher $E_{frac,eff}$) than simply adding the energy injection parameters. A qualitatively similar result was reported by Delos (2019).

# Summing energy injection for multiple disk passes

- Time scale of relaxation (post-encounter) for a minihalo is called the dynamical time:

$$t_{\rm dyn} = \sqrt{\frac{3\pi}{16G\bar{\rho}_{\rm vir}(z_{\rm i})}}$$

- If time between consecutive disk passes < dynamical time, energy injection parameters are added up linearly (p=2):

$$E_{\rm frac,eff} = E_{\rm frac,1} + E_{\rm frac,2}$$

- If time between consecutive disk passes > dynamical time, energy injection parameters are added non-linearly (p=1):

$$E_{\rm frac,eff} = \left(E_{\rm frac,1}^{1/2} + E_{\rm frac,2}^{1/2}\right)^2$$

# Mass today after stellar disruption

- To find the mass contained in minihalos in the Milky Way galaxy:

$$\text{Mass in minihalos} \propto \int M \frac{\mathrm{d}n}{\mathrm{d}M} \mathrm{d}M$$

- We compute the mass in minihalos both in the presence of stellar disruption ($M_{\text{surv}}$) and separately without considering stellar disruption ($M_{\text{ori}}$). We compute the percentage of minihalo mass that survives today as: $M_{\text{surv}}/M_{\text{ori}}(> 10^{-12} h M_{\odot})$
- S2024 finds this value ~ 58%
- Our result ~ **30%**

# Conclusion

- We improved upon the K2021 analytical model by introducing the sequential stripping method, and minihalo relaxation.
- We explored successive encounters and found the mass loss is more severe than simply adding up the energy injection parameters, given enough time for minihalo relaxation.
- We developed a new code to evolve the minihalo orbit.
- We compared the time between consecutive stellar disk passes to the dynamical time, to more accurately add energy injection parameters.
- We found that the percentage of minihalo mass that survives today is significantly smaller than that reported in the literature.

# Mass Function of Minihalos

- Primordial adiabatic perturbations of axion collapse to form large adiabatic halos which become hosts to galaxies.
- For a population of minihalos, the mass function tells us the number density of minihalos in a unit mass interval (S2024, Xiao et al - *PRD 104, 023515*).

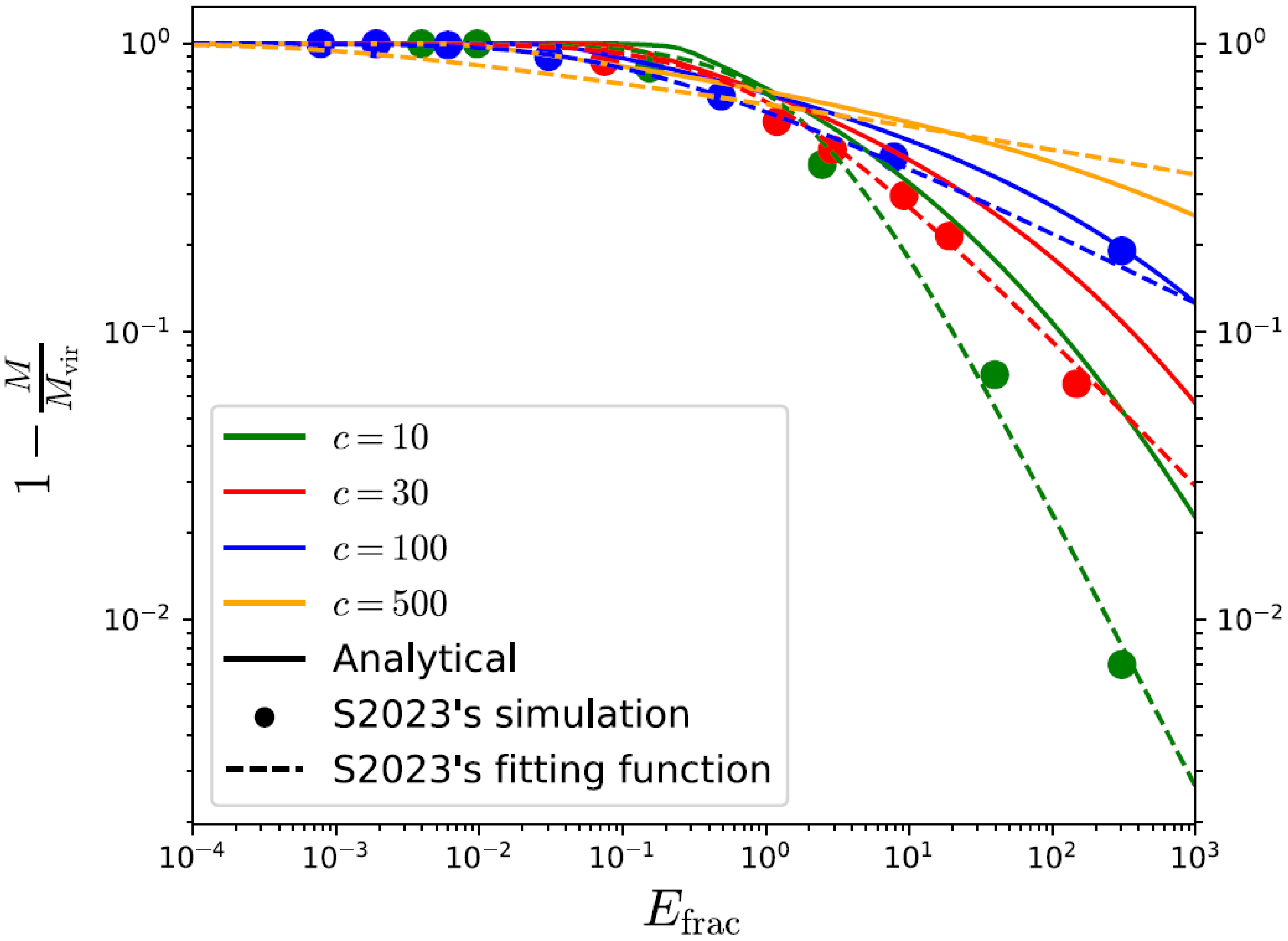
$$\frac{\mathrm{d}n_{\mathrm{f}}}{\mathrm{d}M}(M,z) = \int_{z_{\mathrm{eq}}}^{z} \mathrm{d}z_{\mathrm{i}} \frac{\mathrm{d}f_{\mathrm{col}}^{\mathrm{CDM}}}{\mathrm{d}z}(z_{\mathrm{i}}) \frac{\mathrm{d}n_0}{\mathrm{d}M}(M, z_{\mathrm{i}})$$

adiabatic

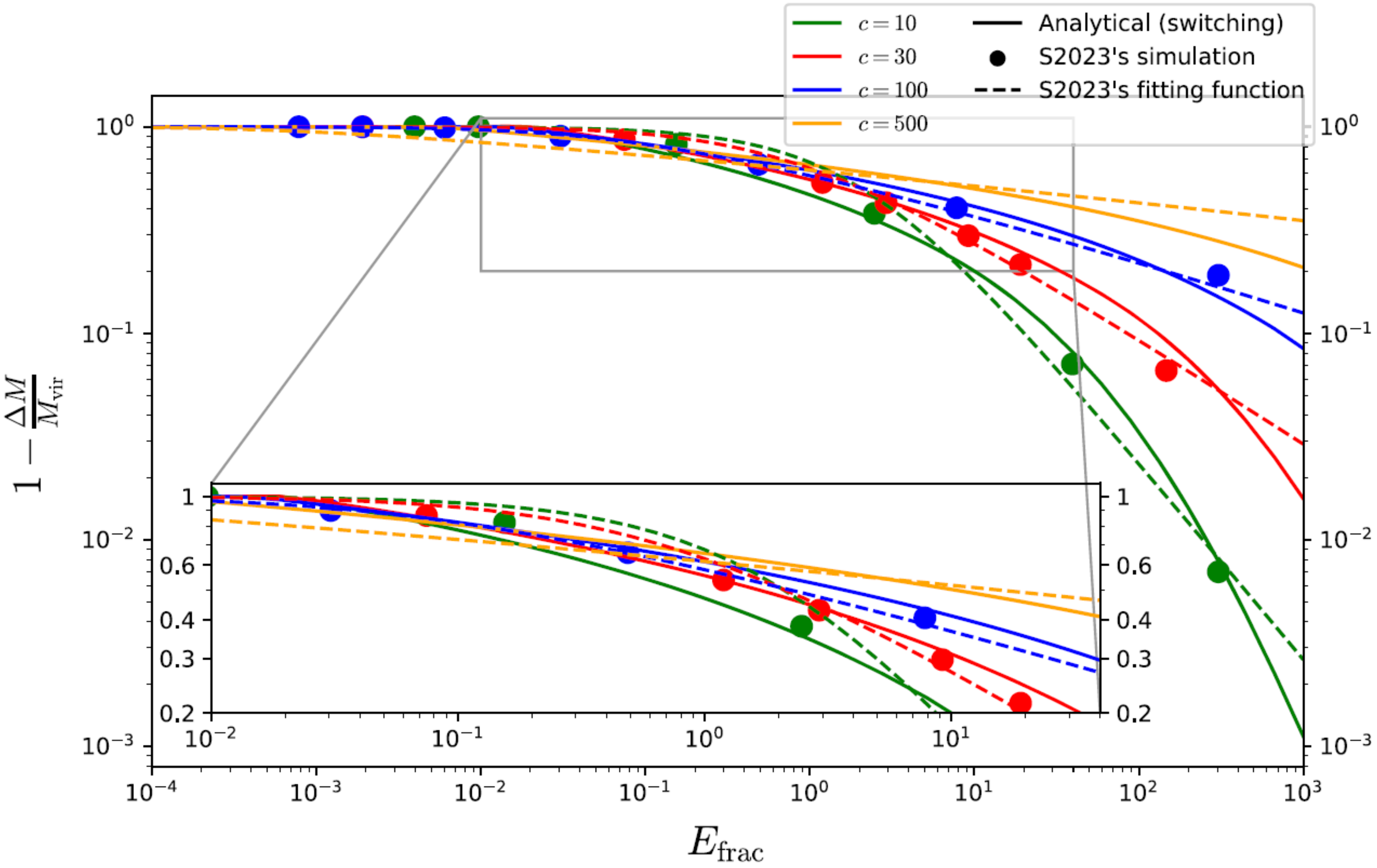
isocurvature

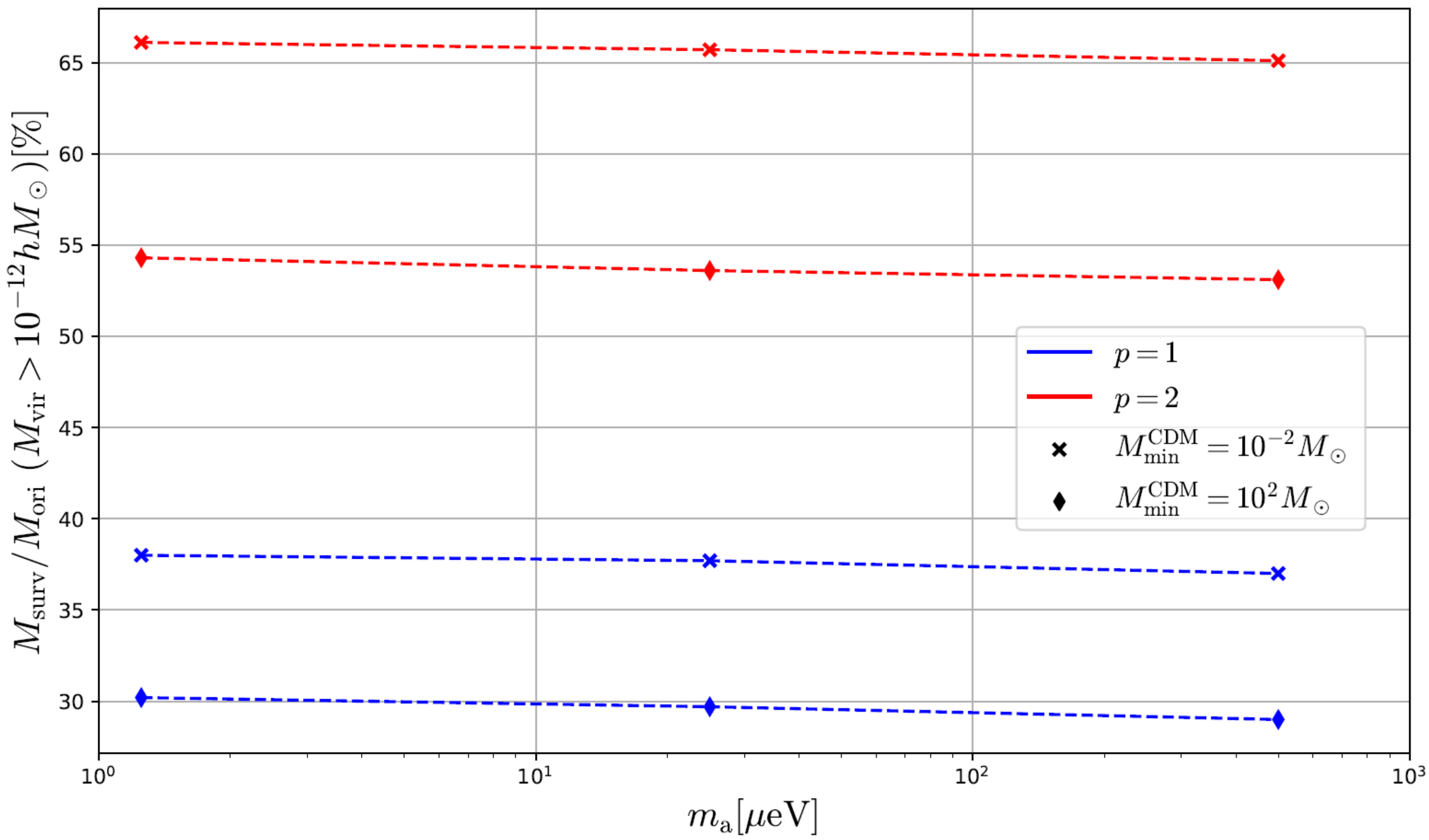
- m_\kappa is the characteristic mass of the most effective disruptor. It is derived from the present-day stellar mass function.
- It is unlikely that we would be inside a minihalo. So, lower the value of M_{surv}/M_{ori}(> 1e-12 MSolar), the more likely that dark matter will be detected in direct detection experiments because the mass that has been disrupted ends up becoming part of the background dark matter density.

# Compare to K2021



# Compare to S2024





65
60
55
50
45
40
35
30
$M_{\rm surv}/M_{\rm ori}\ (M_{\rm vir} > 10^{-12} h M_\odot)[\%]$
$10^0$
$10^1$
$10^2$
$10^3$
$m_{\rm a}[\mu{\rm eV}]$
$p = 1$
$p = 2$
$M^{\rm CDM}_{\rm min} = 10^{-2} M_\odot$
$M^{\rm CDM}_{\rm min} = 10^{2} M_\odot$