Substructure of Warm Dark Matter Halos: Simulations and a Semi-Analytic Model

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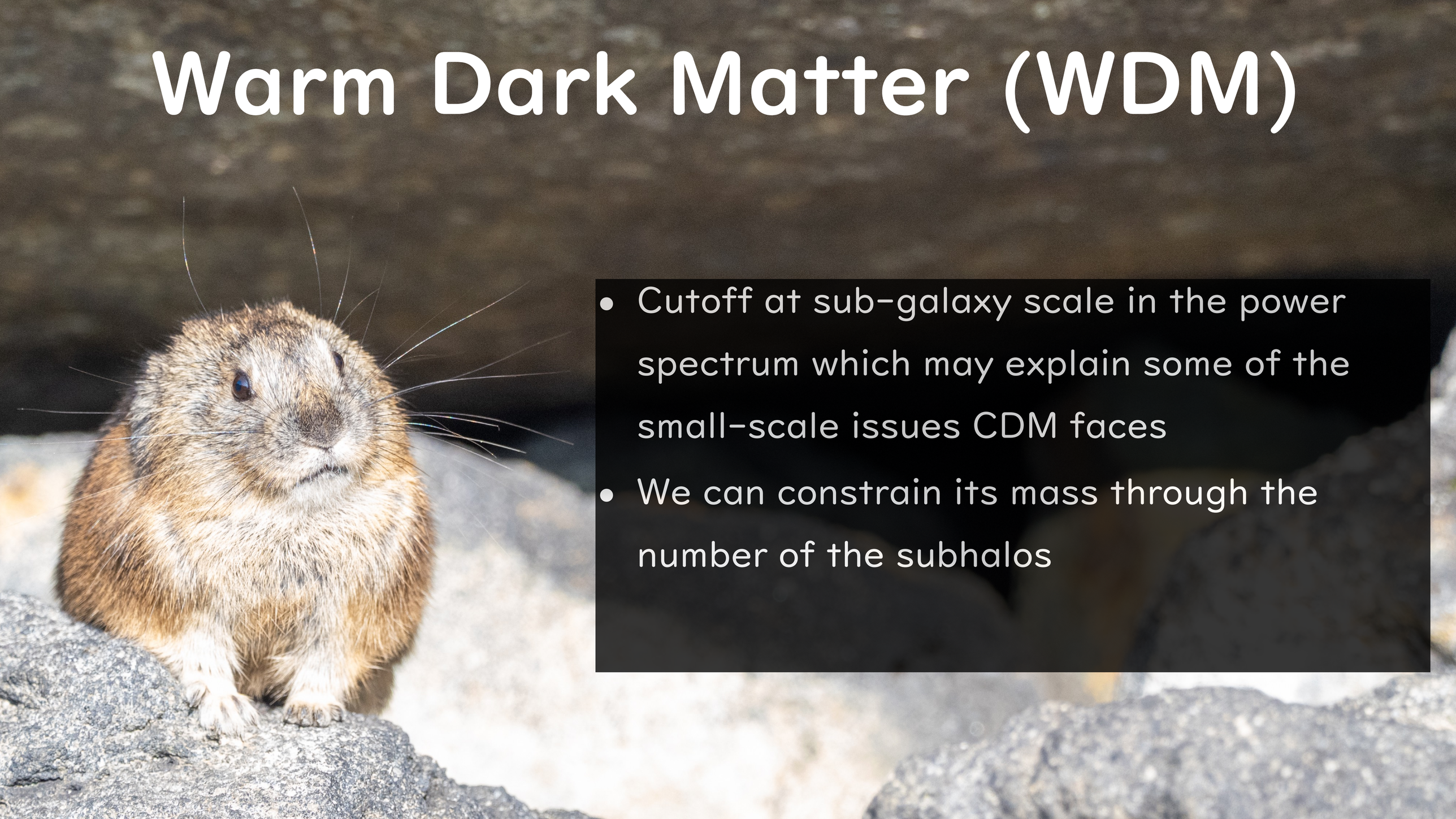
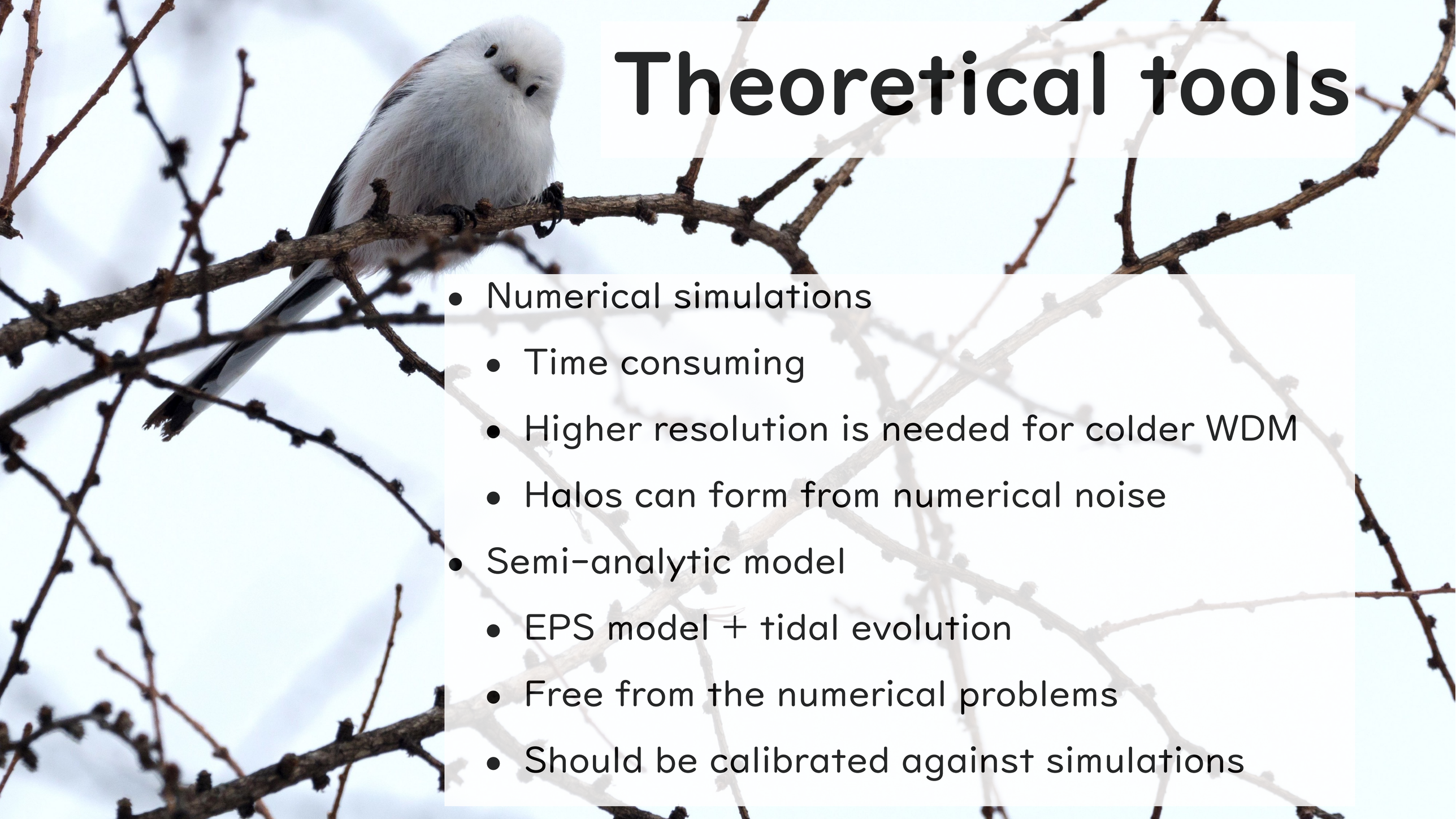
Warm Dark Matter (WDM)



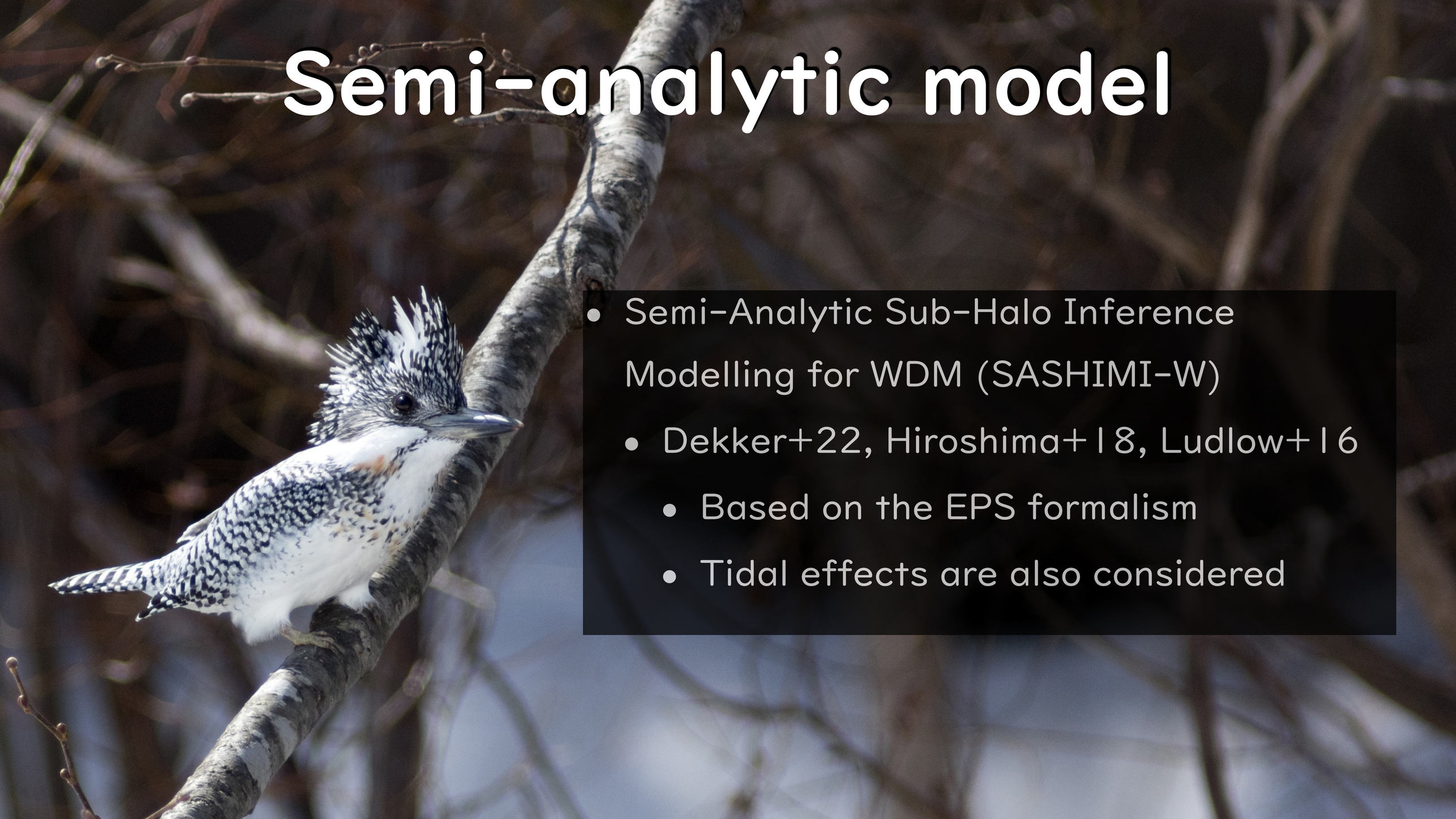
- Cutoff at sub-galaxy scale in the power spectrum which may explain some of the small-scale issues CDM faces
- We can constrain its mass through the number of the subhalos



Theoretical tools

- Numerical simulations
  - Time consuming
  - Higher resolution is needed for colder WDM
  - Halos can form from numerical noise
- Semi-analytic model
  - EPS model + tidal evolution
  - Free from the numerical problems
  - Should be calibrated against simulations

Semi-analytic model



- Semi-Analytic Sub-Halo Inference Modelling for WDM (SASHIMI-W)
  - Dekker+22, Hiroshima+18, Ludlow+16
    - Based on the EPS formalism
    - Tidal effects are also considered

Simulations

- Previous simulations are limited to WDM models with the half-mode mass of $M_{\rm hm} \gtrsim 10^8\ {\rm M}_\odot$
- We simulate wider range of WDM masses with $M_{\rm hm} = [1.4 \times 10^{10},\ 3.5 \times 10^6]\,{\rm M}_\odot$ to study if the known results can be extrapolated to colder WDM models.
- Compare them with SASHIMI

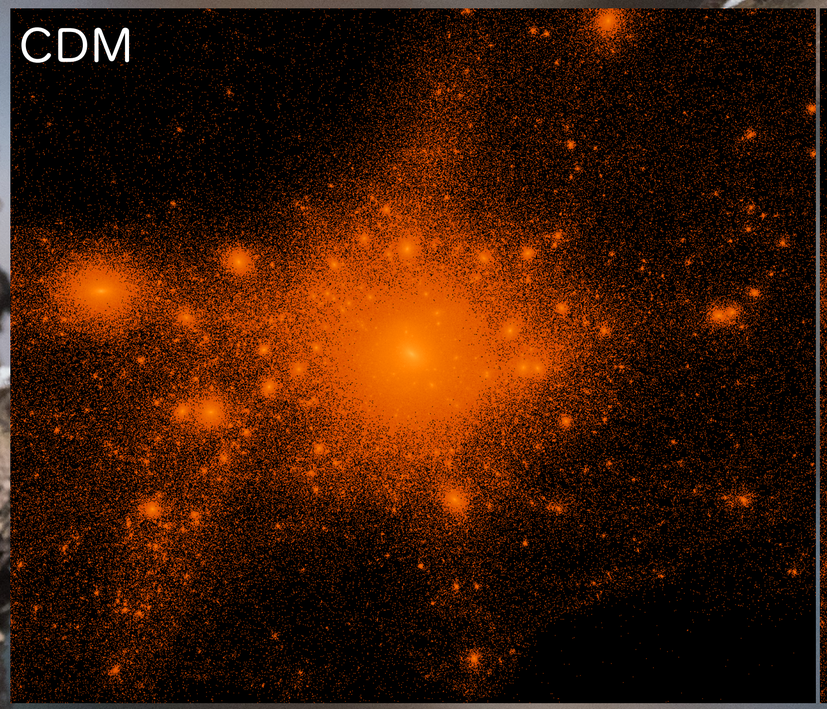
Simulations

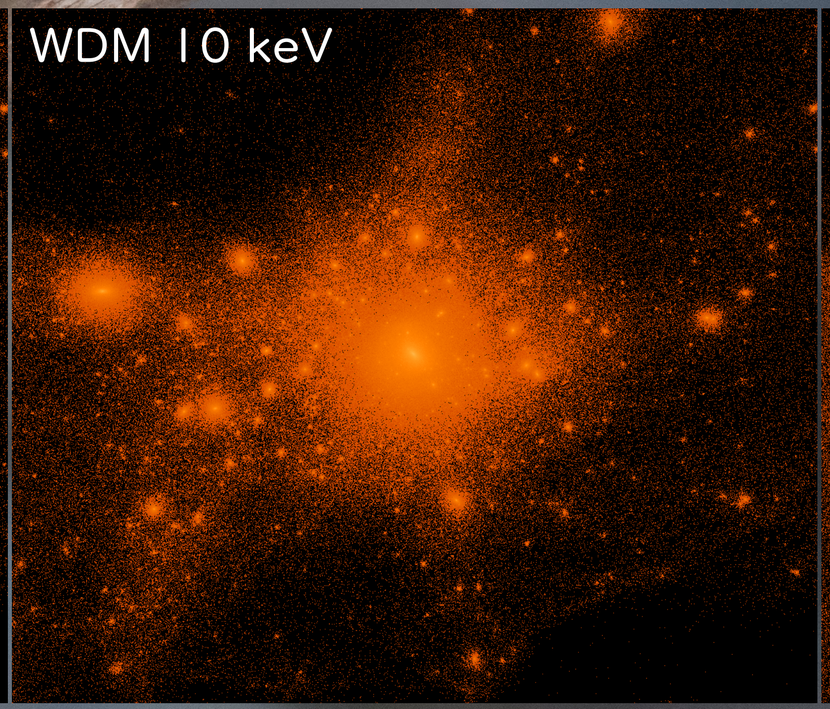
- Mean particle separation: $3.05 \times 10^{-3}\, h^{-1}\,\mathrm{cMpc}$
- $m_{\mathrm{DM}} = 2.491 \times 10^{3}\, h^{-1}\,\mathrm{M}_{\odot}$
- The selected halo properties at $z = 0$
  - $M_{200} = 1.18 \times 10^{12}\,\mathrm{M}_{\odot}$
  - $V_{\mathrm{max}} = 171\,\mathrm{km\,s^{-1}}$
- CDM, WDM 1 keV, and WDM 10 KeV

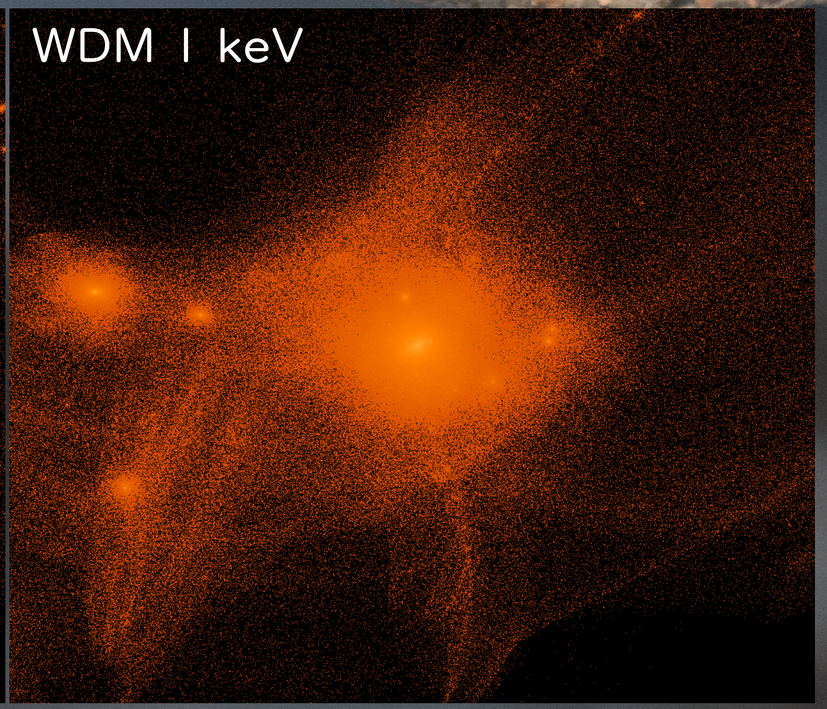
	1 keV	10 keV
$M_{\mathrm{hm}}\,(h^{-1}\,\mathrm{M}_{\odot})$	1.37x10^{10}	6.40x10^{6}
$\lambda_{\mathrm{fs}}\,(h^{-1}\,\mathrm{cMpc})$	0.048	0.0037

Results

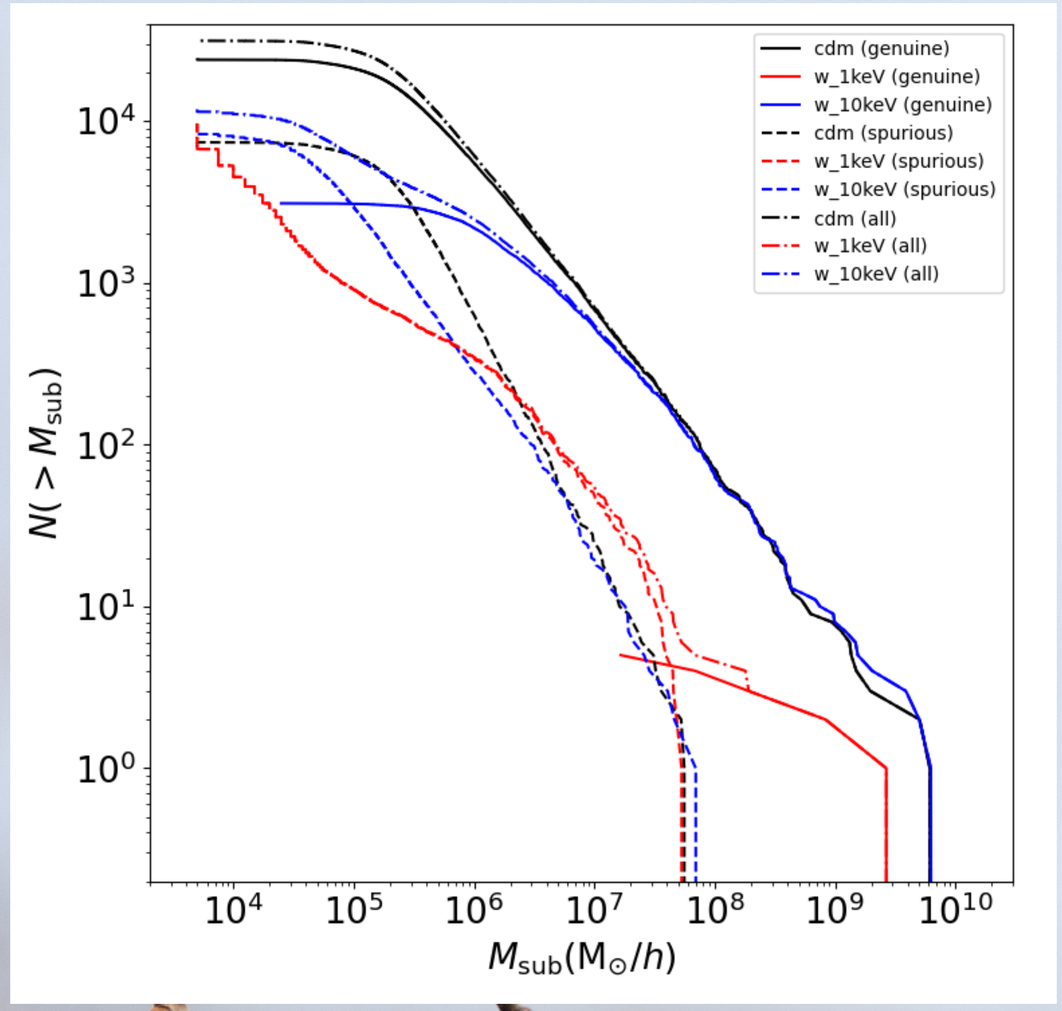
DM distribution at $z = 0$





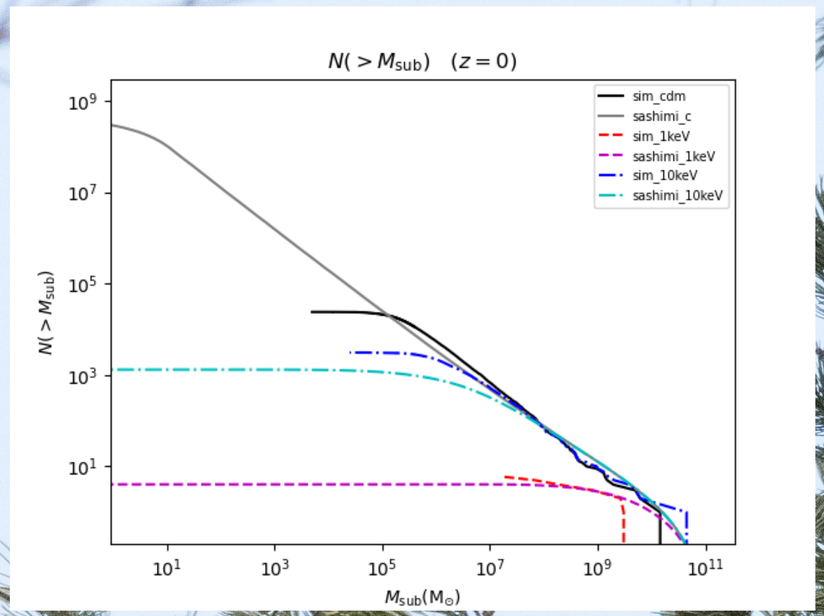


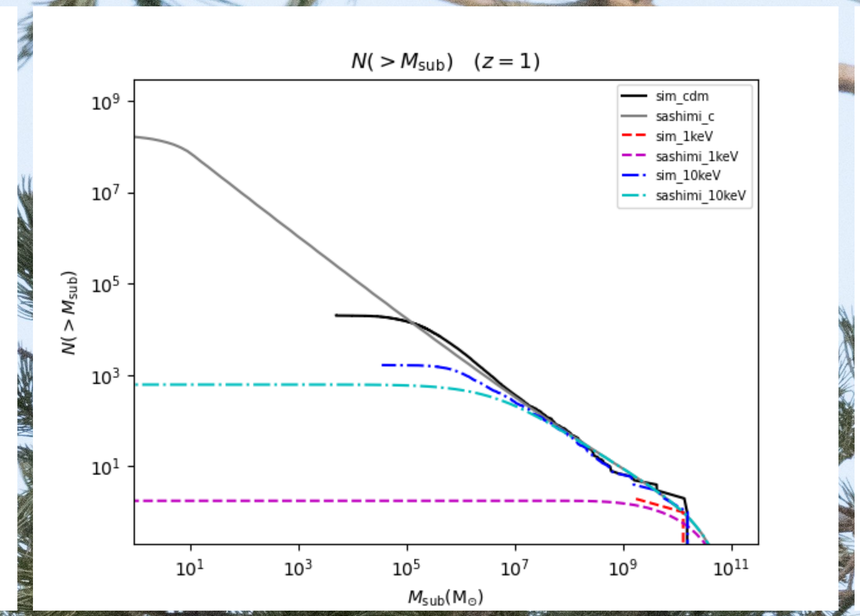
Removal of spurious subhalos

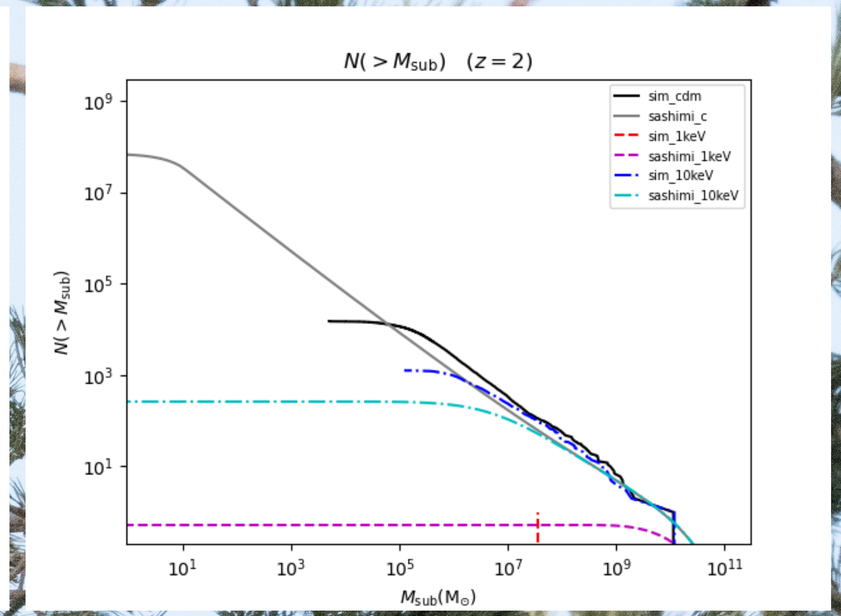


- We have removed spurious subhalos as in Lovell+14; if a Lagrangian region in the initial condition has too small an axis ratio ($c/a < 0.16$), the subhalo is considered spurious.

Cumulative subhalo mass functions







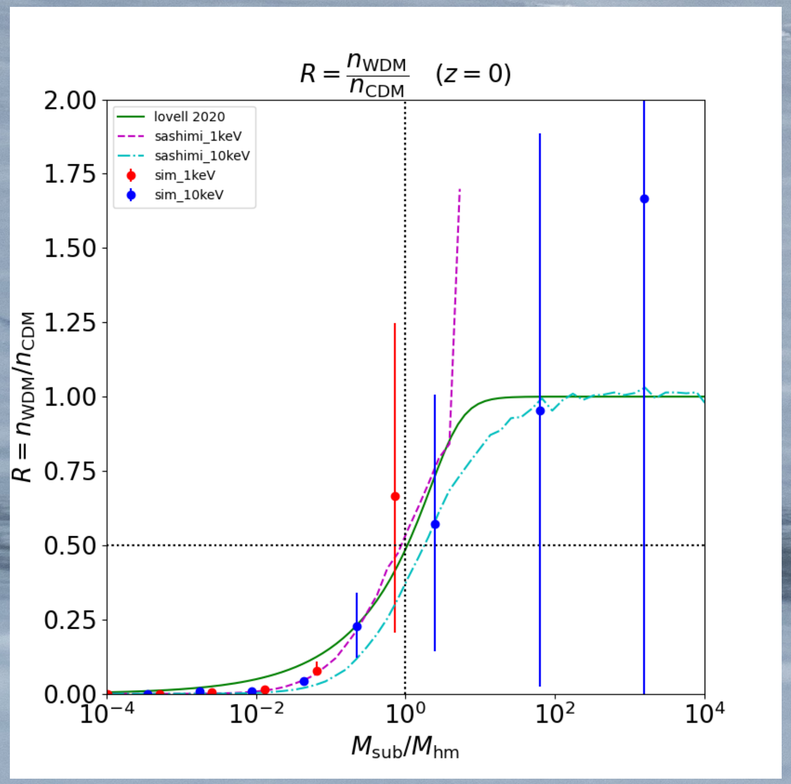
- The model slightly underpredicts the number of subhalos.
- But there must be halo-to-halo variation (we simulate only one halo)

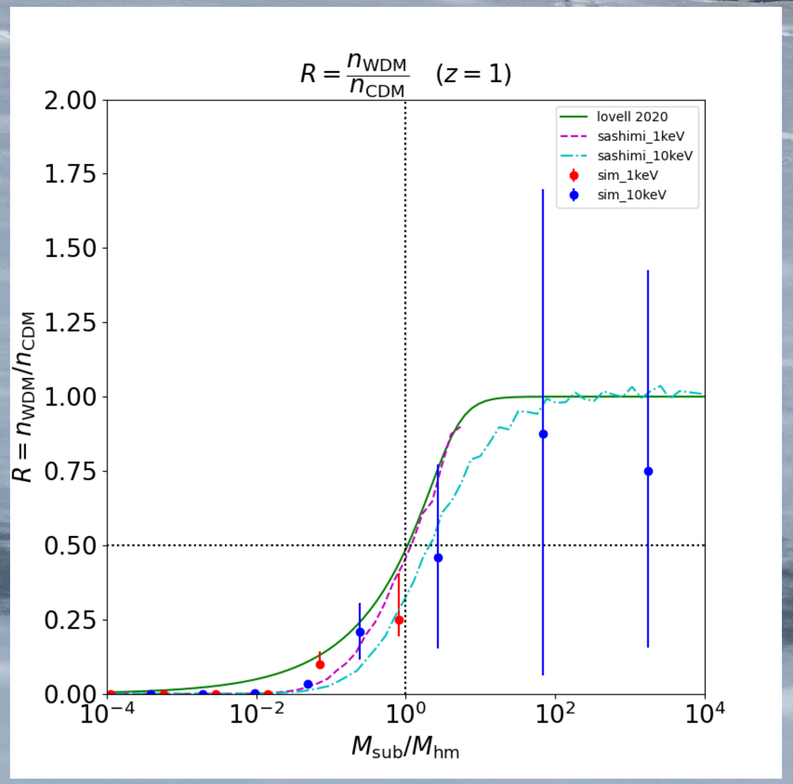
Suppression relative to CDM

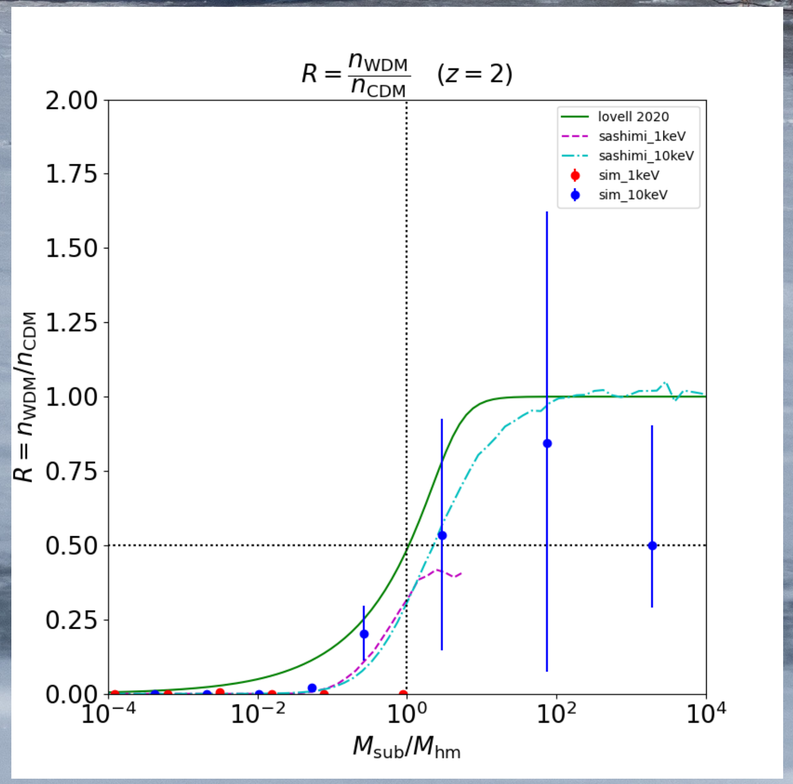
- We calculate $R = \dfrac{n_{\rm WDM}}{n_{\rm CDM}}$ where $n = \dfrac{{\rm d}N_{\rm sub}}{{\rm d}\log M_{\rm sub}}$
- Lovell 20 found $R_{\rm fit} = \left[1 + \left(\dfrac{\alpha M_{\rm hm}}{M_{\rm SUB}}\right)^{\beta}\right]^{\gamma}$ provides a reasonable fit to R

  with $(\alpha, \beta, \gamma) = (4.2, 2.5, -0.2)$, where $\alpha M_{\rm hm}$ is the cut-off mass scale

$R = n_{\mathrm{WDM}}/n_{\mathrm{CDM}}$







- Our simulations reasonably agree with R_{fit} by Lovell
- SASHIMI can reproduce simulation results
- R seems to have a weak dependence on redshift

Discussion

- The results obtained by previous WDM simulations can be extrapolated to colder WDM
- SASHIMI can reproduce simulation results quite well
- We don’t need fitting functions. SASHIMI can do.
- R seems to be slightly dependent on WDM mass and redshift