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Endothermic self-interacting dark matter in Milky Way-mass halos

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6/21/23

https://arxiv.org/abs/2210.16328

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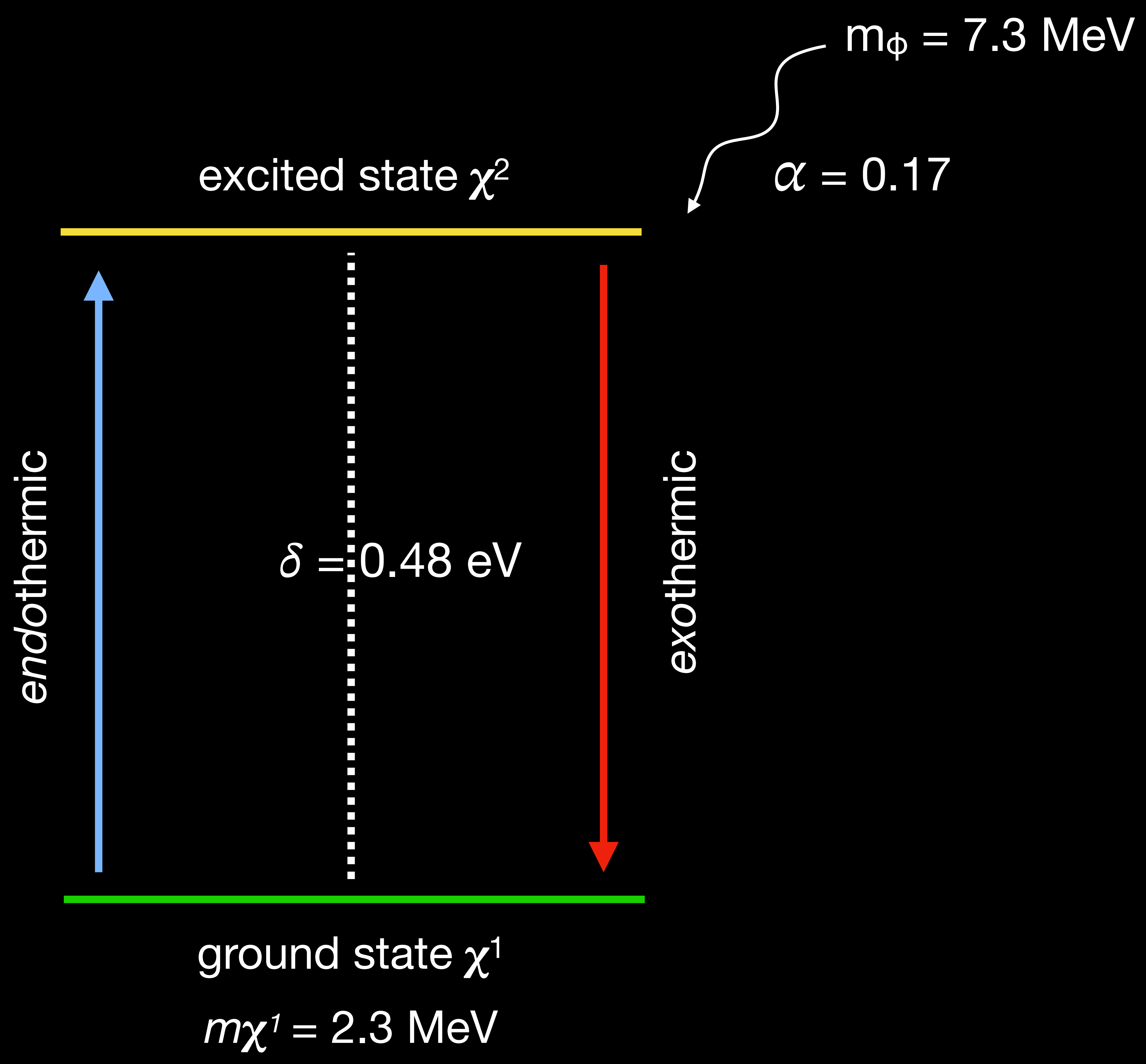
Endothermic SIDM in Milky Way-like Halos

- SIDM in simulations to test alternative dark matter models
- Focus on endothermic reactions
  - Extensive work on elastic models
  - Some work on exothermic models
  - Relatively little work incorporating endothermic reactions
- How does including endothermic reactions alter halo evolution?

Framework for SIDM model

- Hypothetical two-state particle
- Ground state m_{χ^1} separated from excited state by mass difference δ
- Particles scatter through a dark force

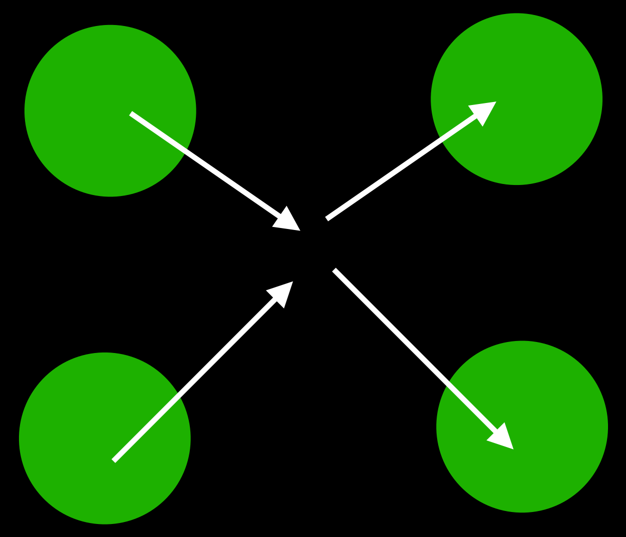


Particles scatter elastically and inelastically

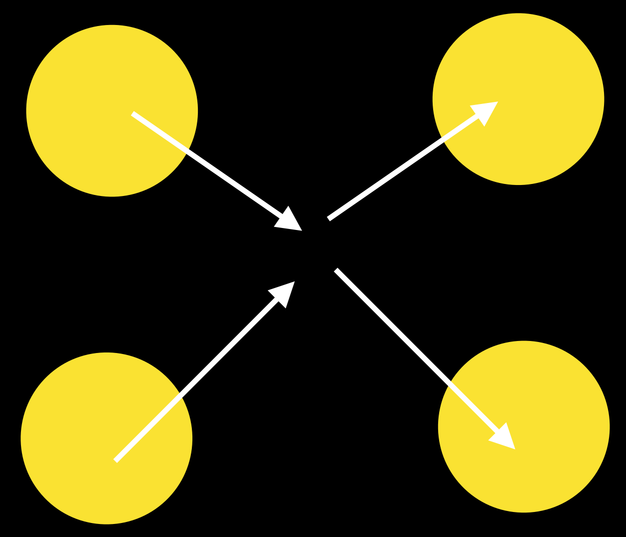
Particles scatter elastically and inelastically

Elastic scattering:
no state changes

$\chi^1+\chi^1 \rightarrow \chi^1+\chi^1$



$\chi^2+\chi^2 \rightarrow \chi^2+\chi^2$



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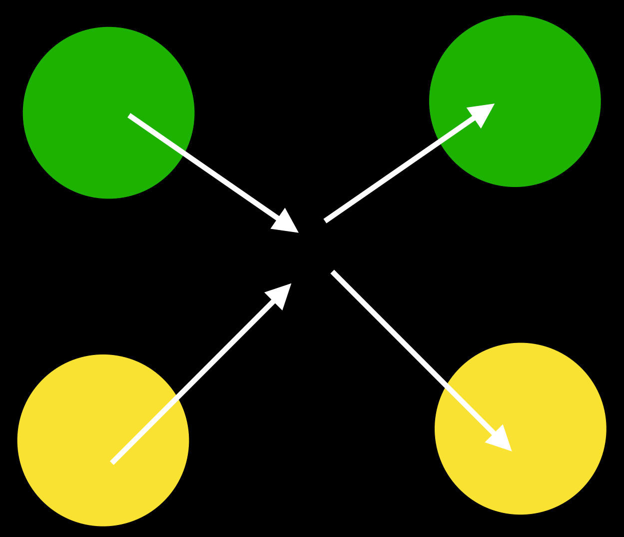
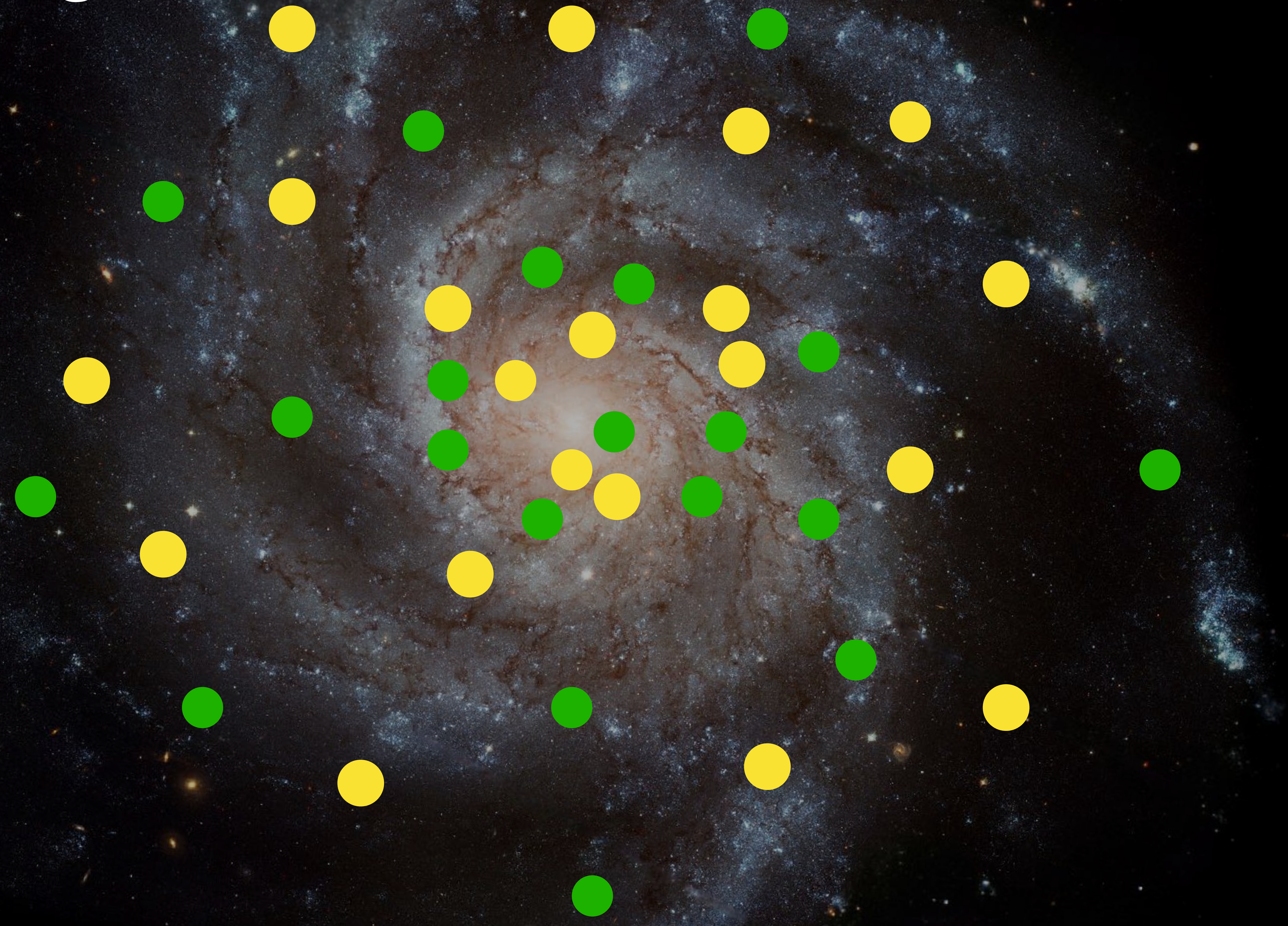


Scattering alters dark matter distribution

Elastic scattering reduces inner density



Scattering alters dark matter distribution

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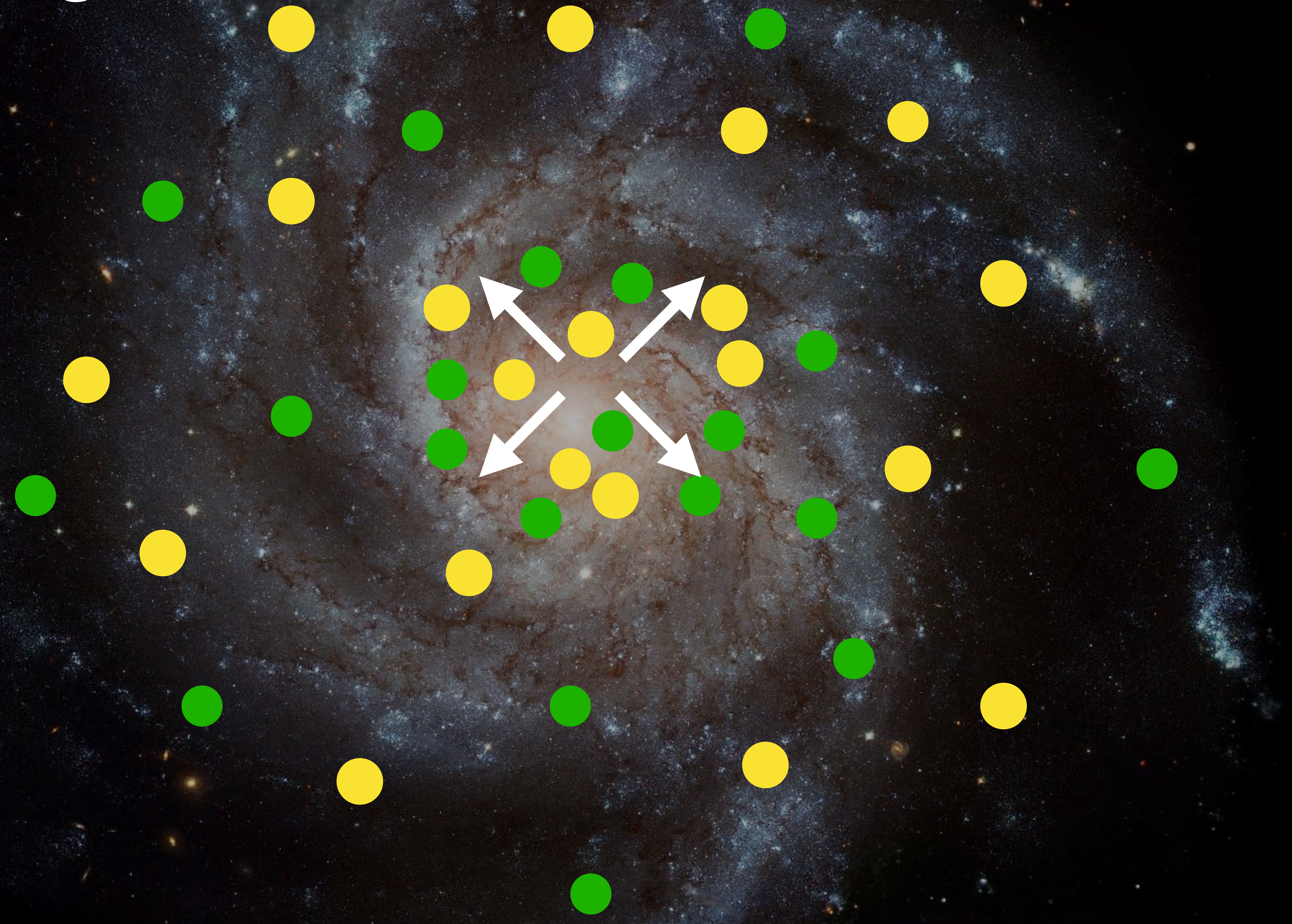

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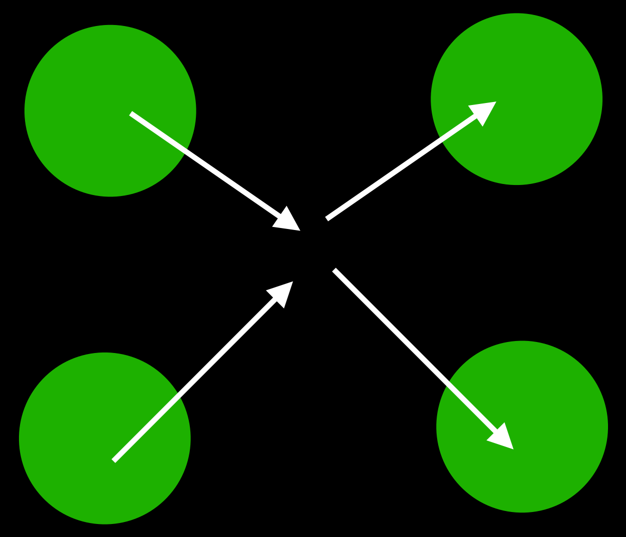
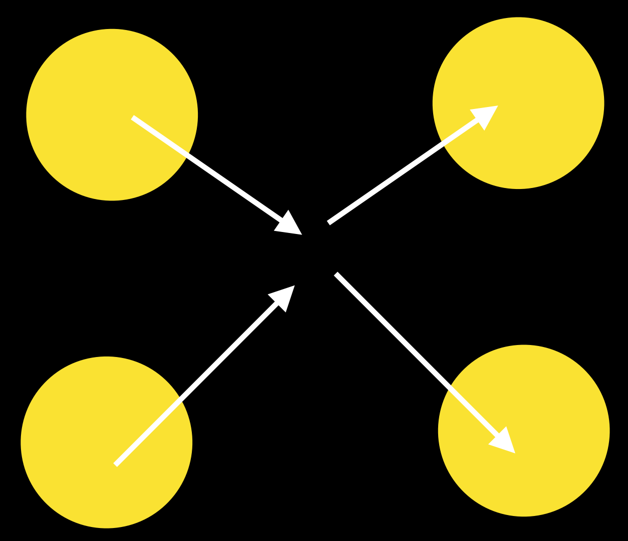


$\chi^2 + \chi^2 \rightarrow \chi^2 + \chi^2$



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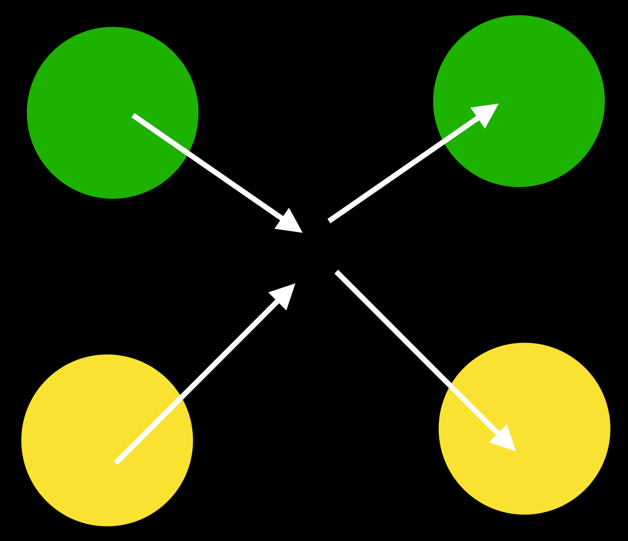
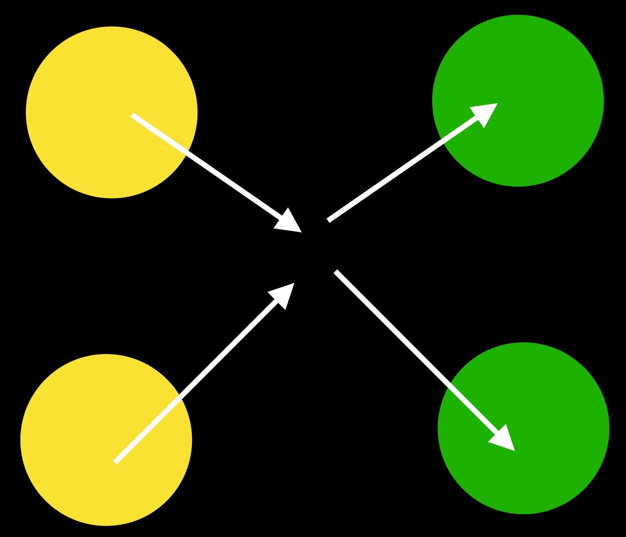


Inelastic scattering:
state changes

$\chi^2 + \chi^2 \rightarrow \chi^1 + \chi^1$



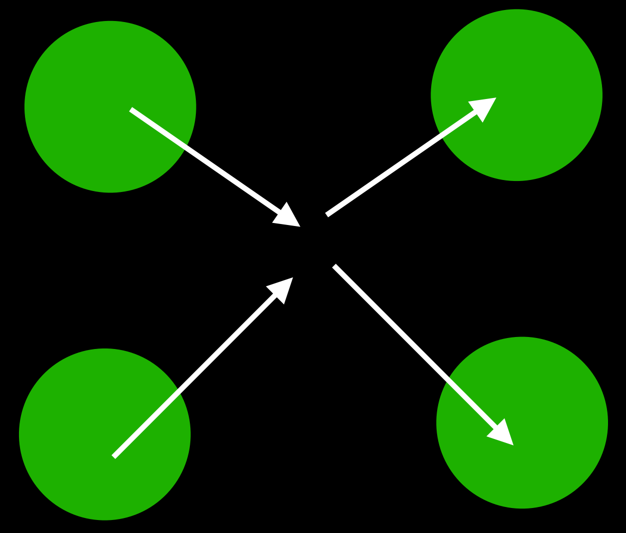
Down-scattering
Exothermic
Increases kinetic energy

Scattering alters dark matter distribution

Particles scatter elastically and inelastically

Elastic scattering:
no state changes

$\chi^1 + \chi^1 \rightarrow \chi^1 + \chi^1$



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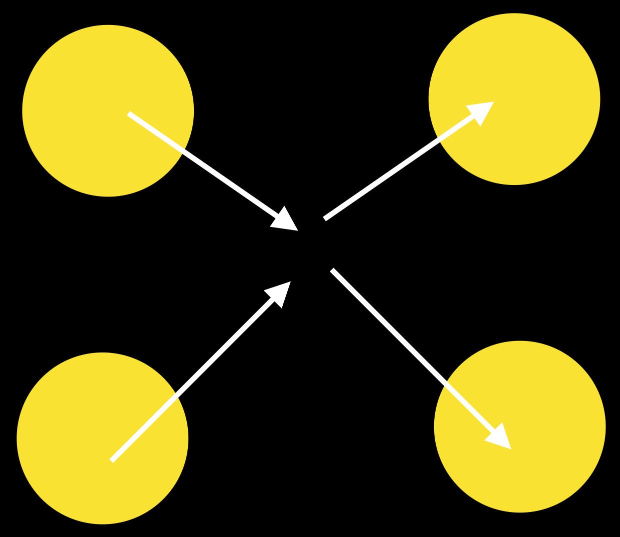

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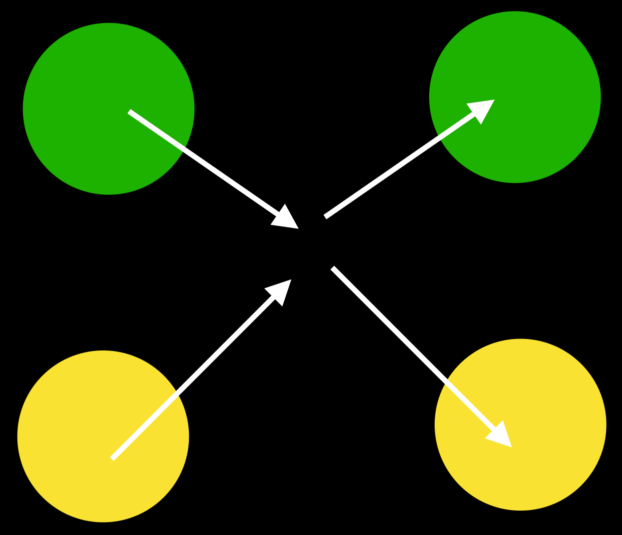

Inelastic scattering:
state changes

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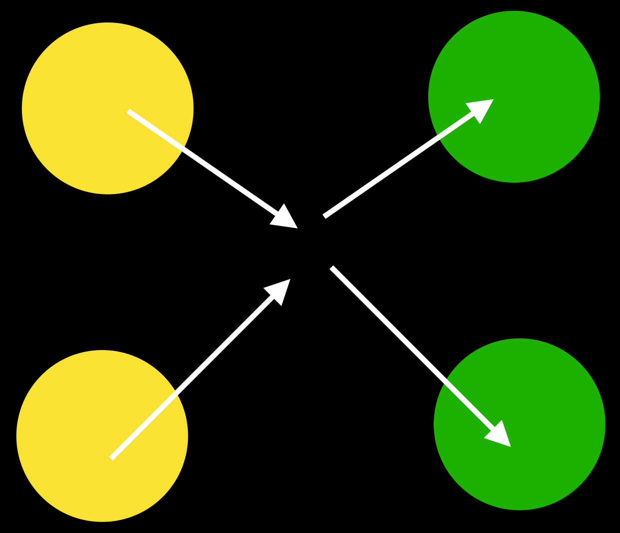

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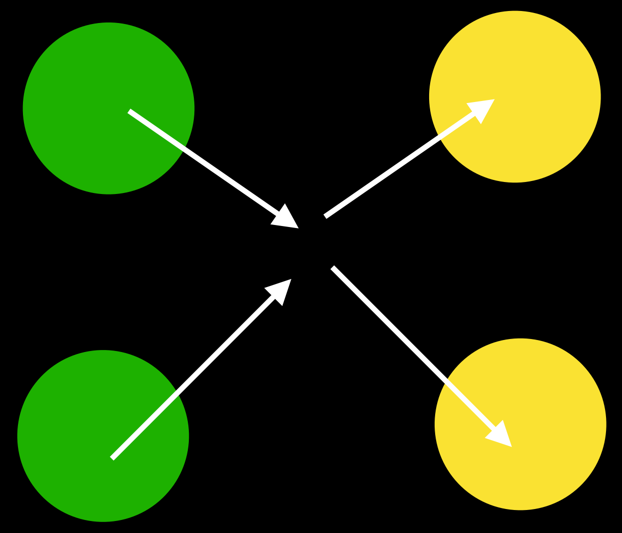
Increases kinetic energy

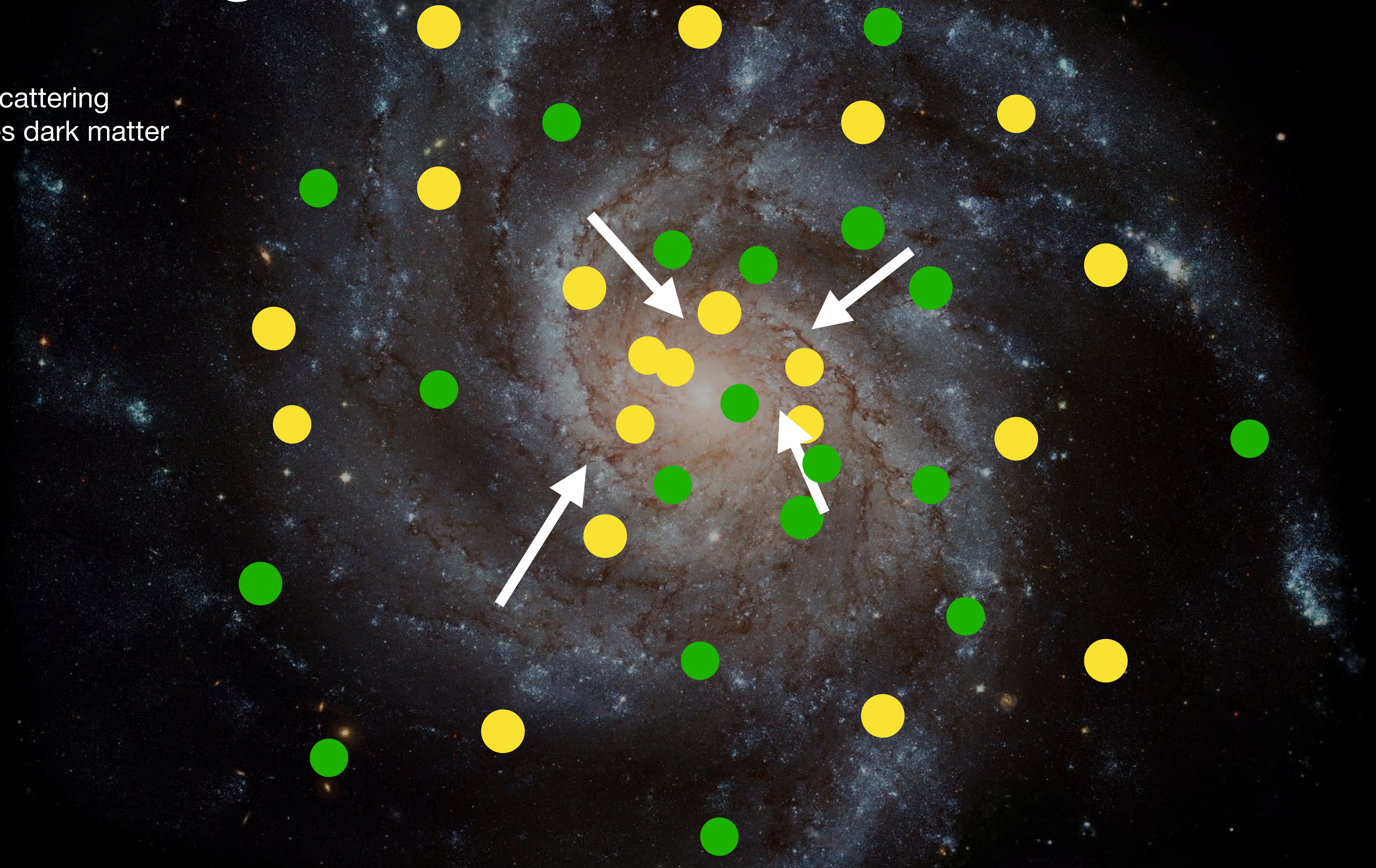
$\chi^1 + \chi^1 \rightarrow \chi^2 + \chi^2$



Up-scattering
Endothermic
Decreases kinetic energy

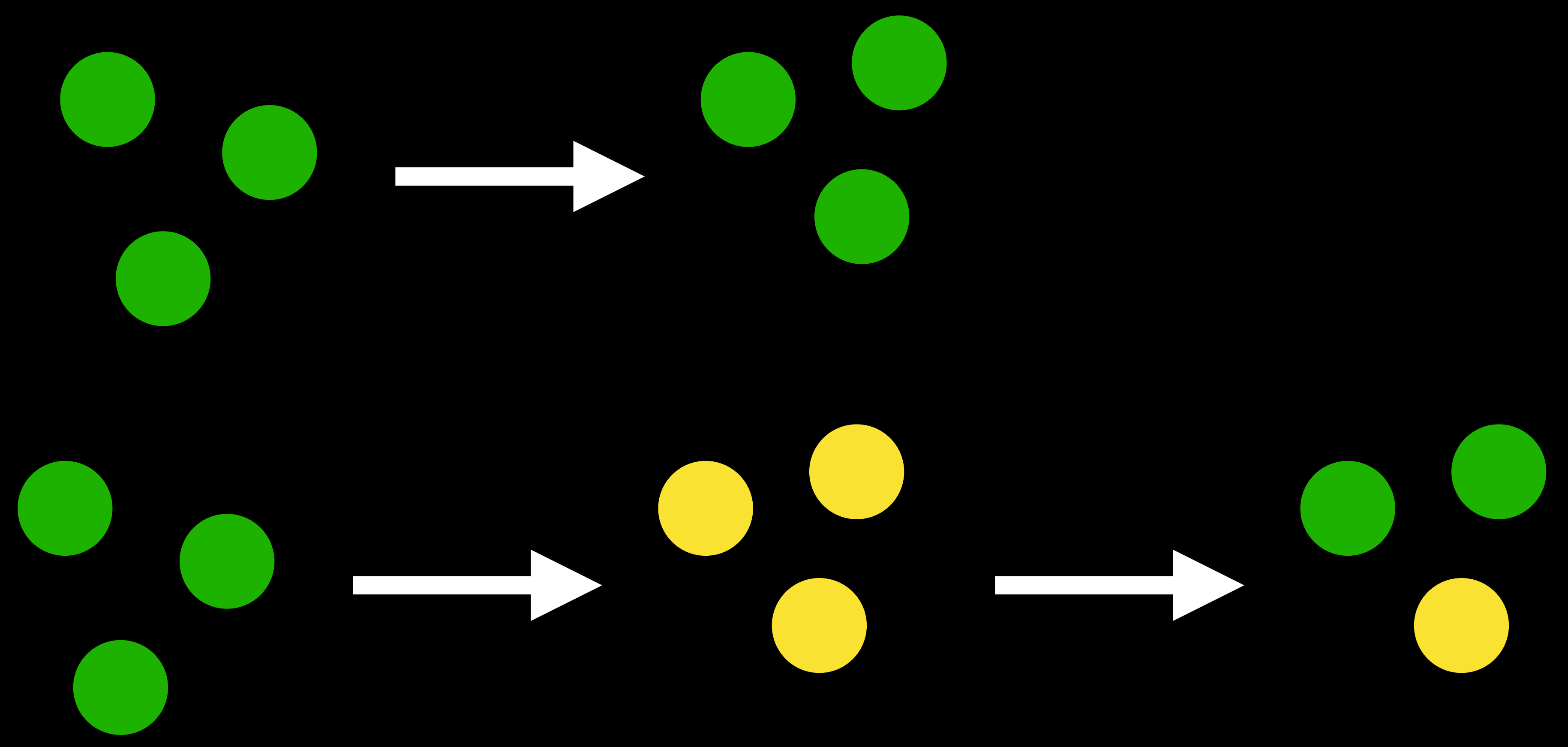
Scattering alters dark matter distribution

Up-scattering
condenses dark matter



Early universe conditions

- Dense early universe favors lighter states
- Models relying on down-scattering will act like CDM if particles are in the ground state
- Late-time up-scattering provides an avenue for particles to (re-)enter the excited state
- Does including this reaction in SIDM models ruin its potential to alleviate small-scale problems?

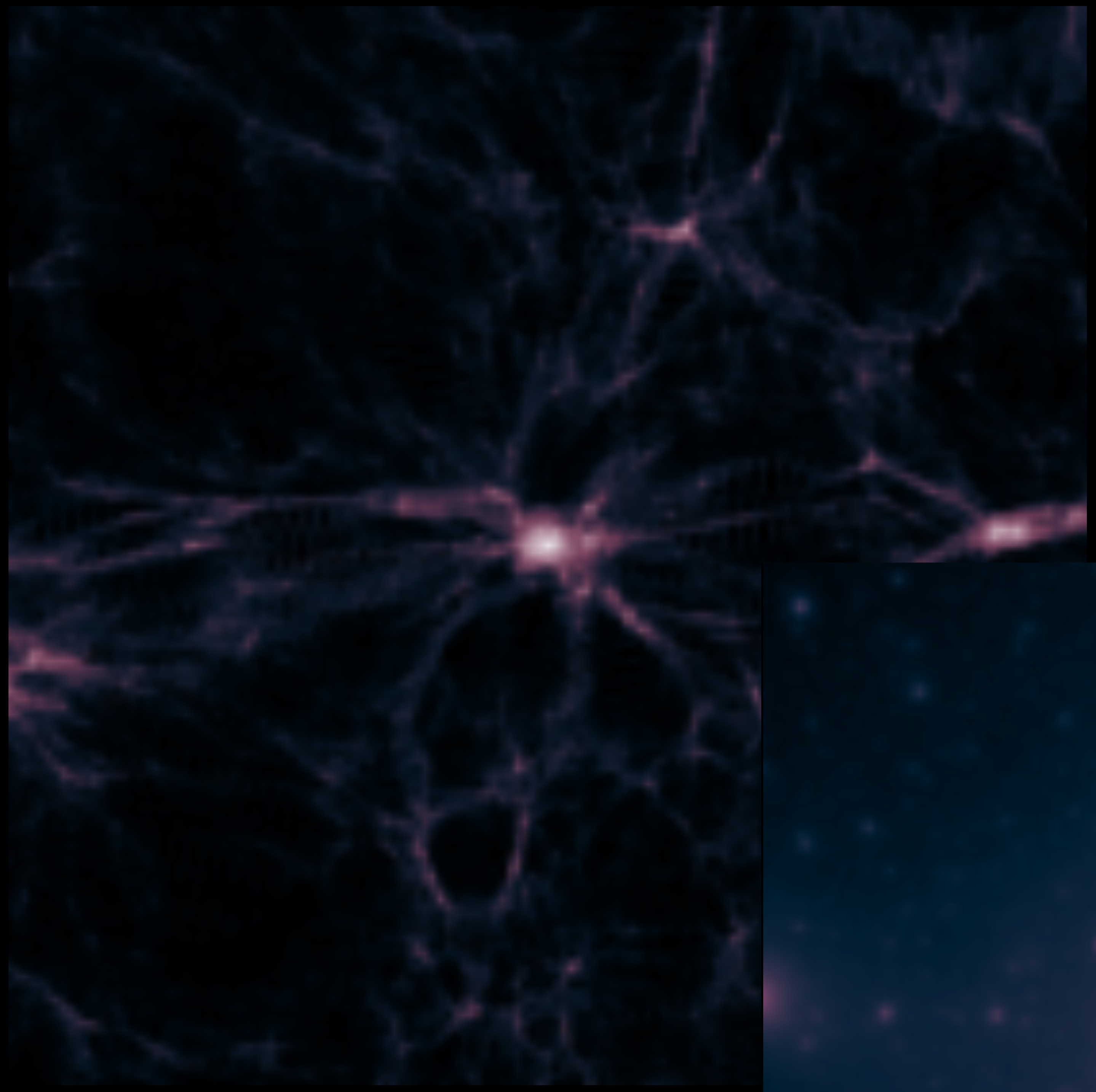


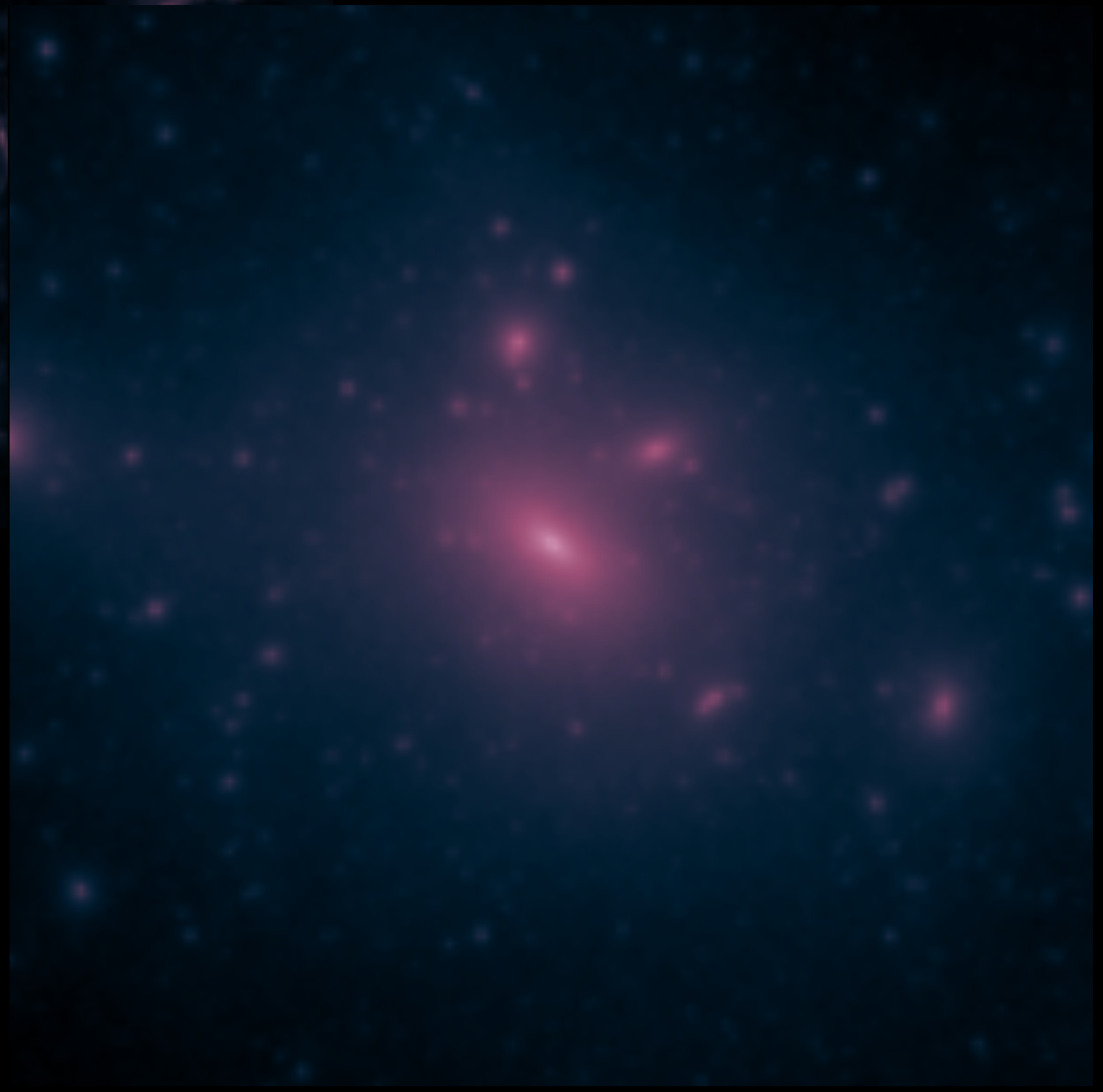
Milky Way Zoom-in simulations

- High resolution region around Milky Way halo in a low resolution background

- Simulations run from early universe to present day

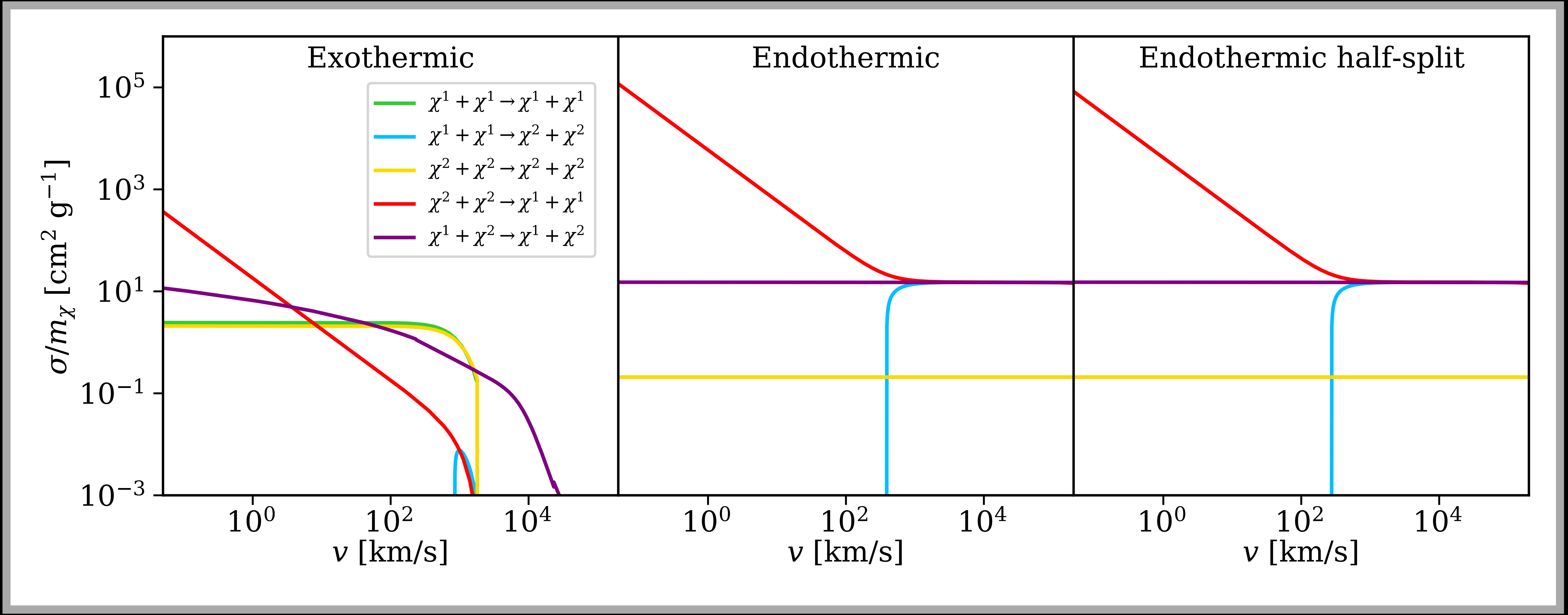
- Dark matter only





Scattering cross sections determine likelihood of reaction

Vogelsberger+ 2019



O'Neil+ 2022

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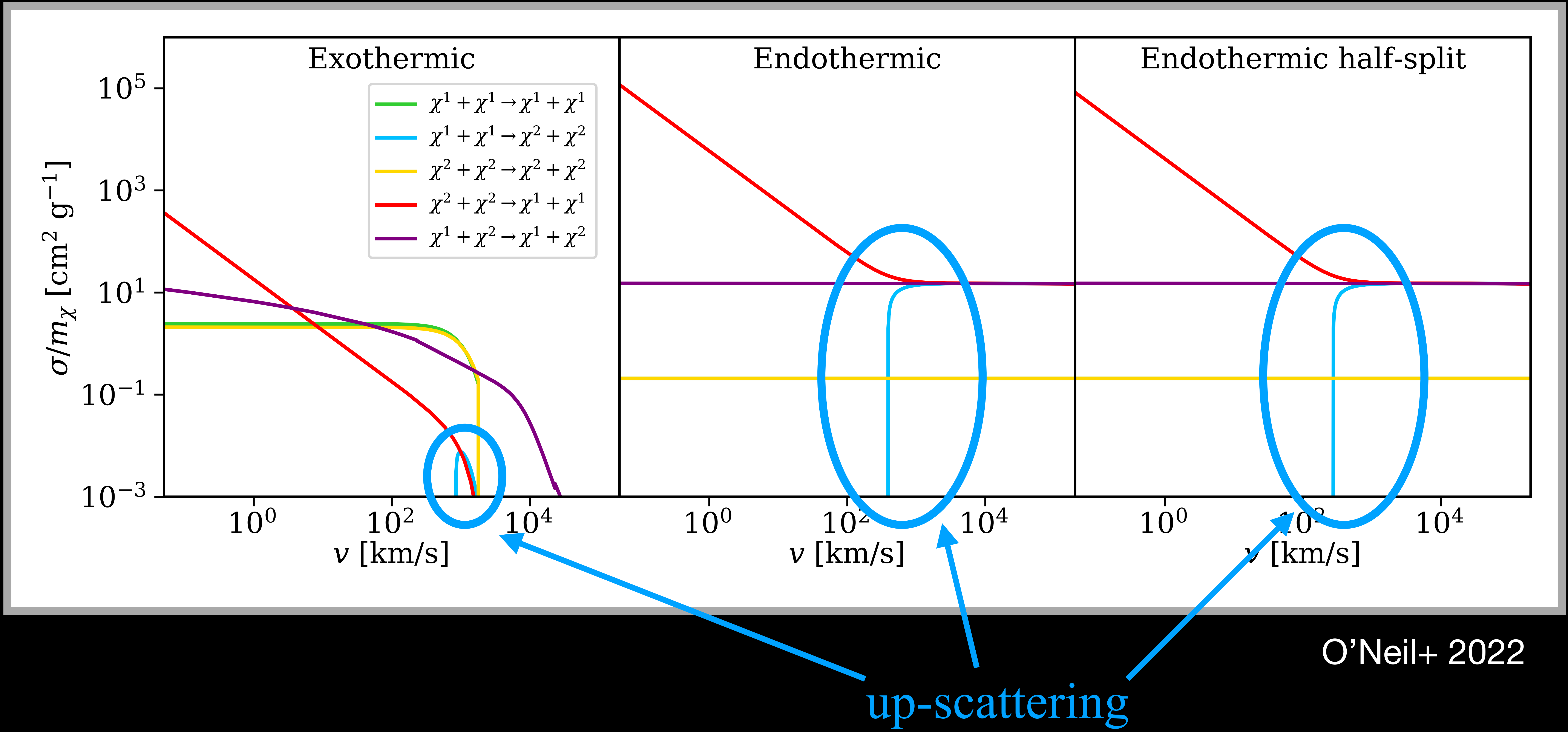

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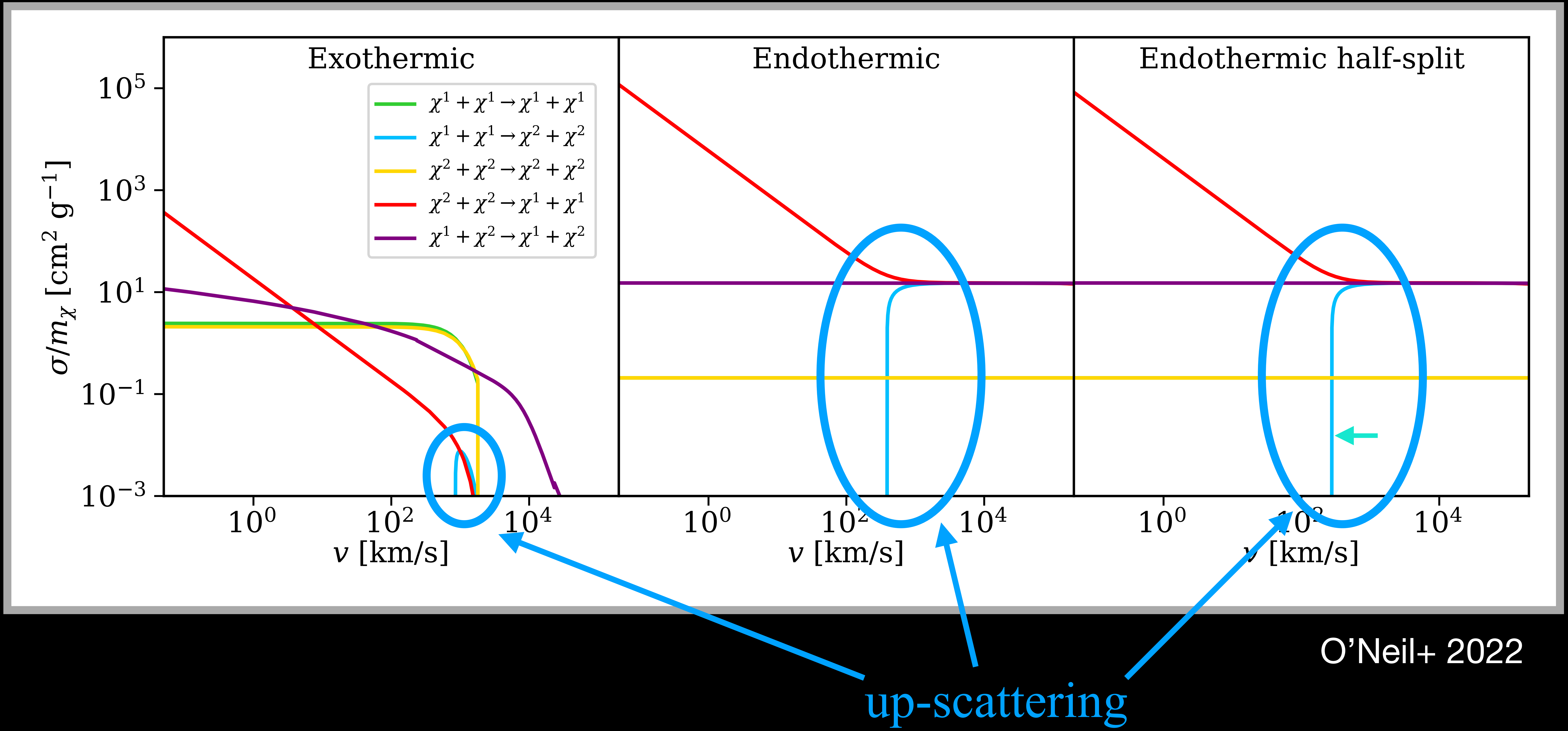

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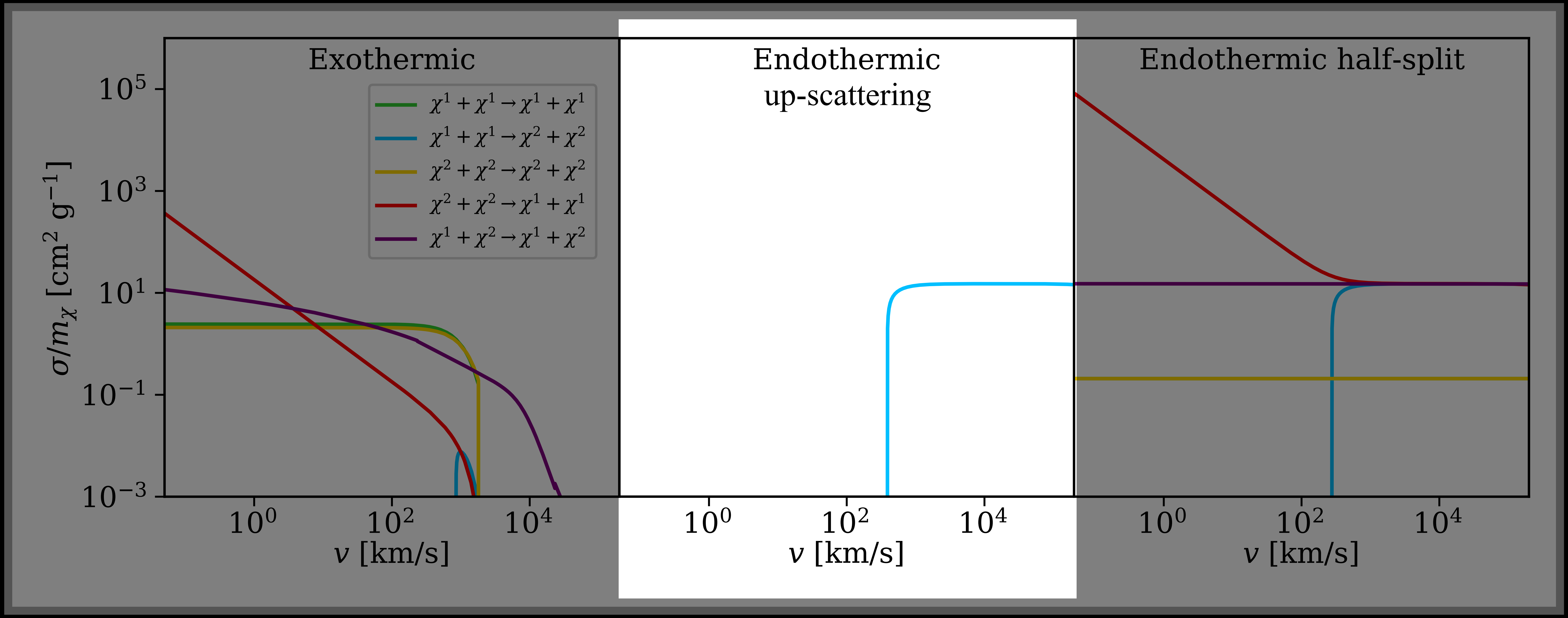

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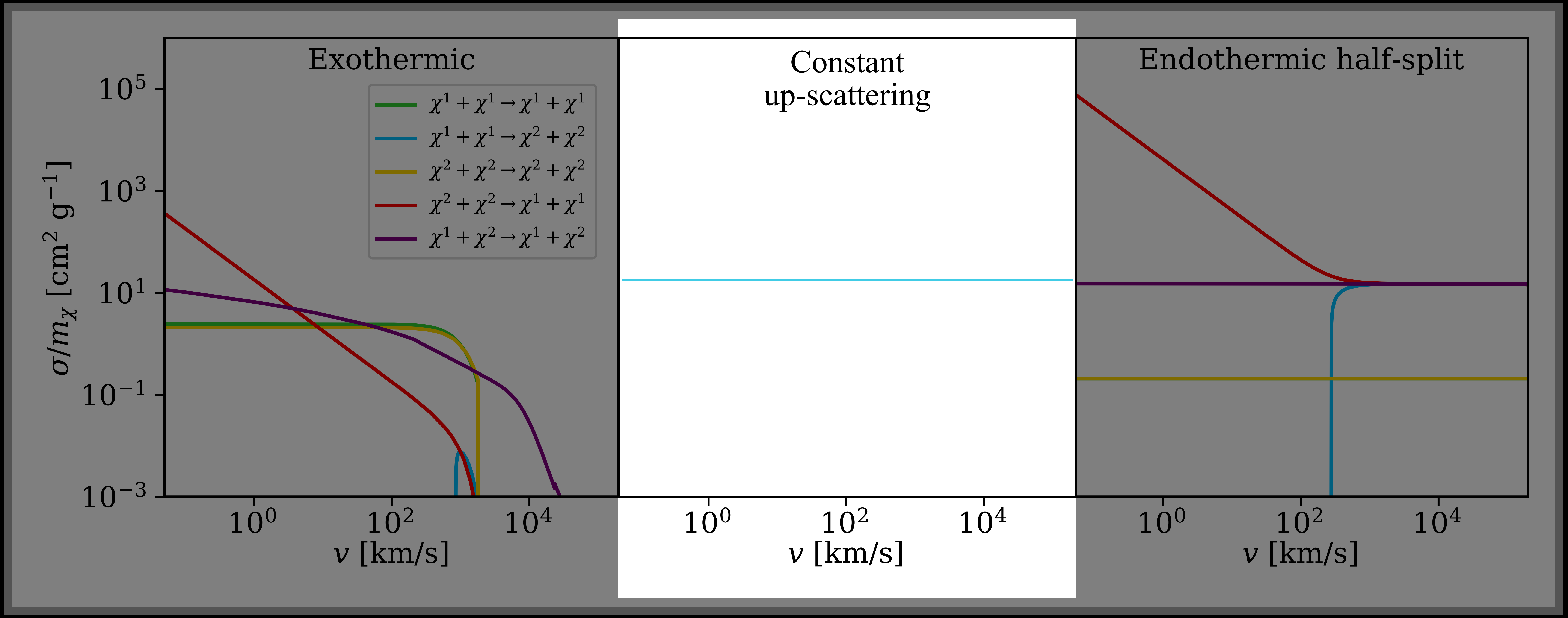
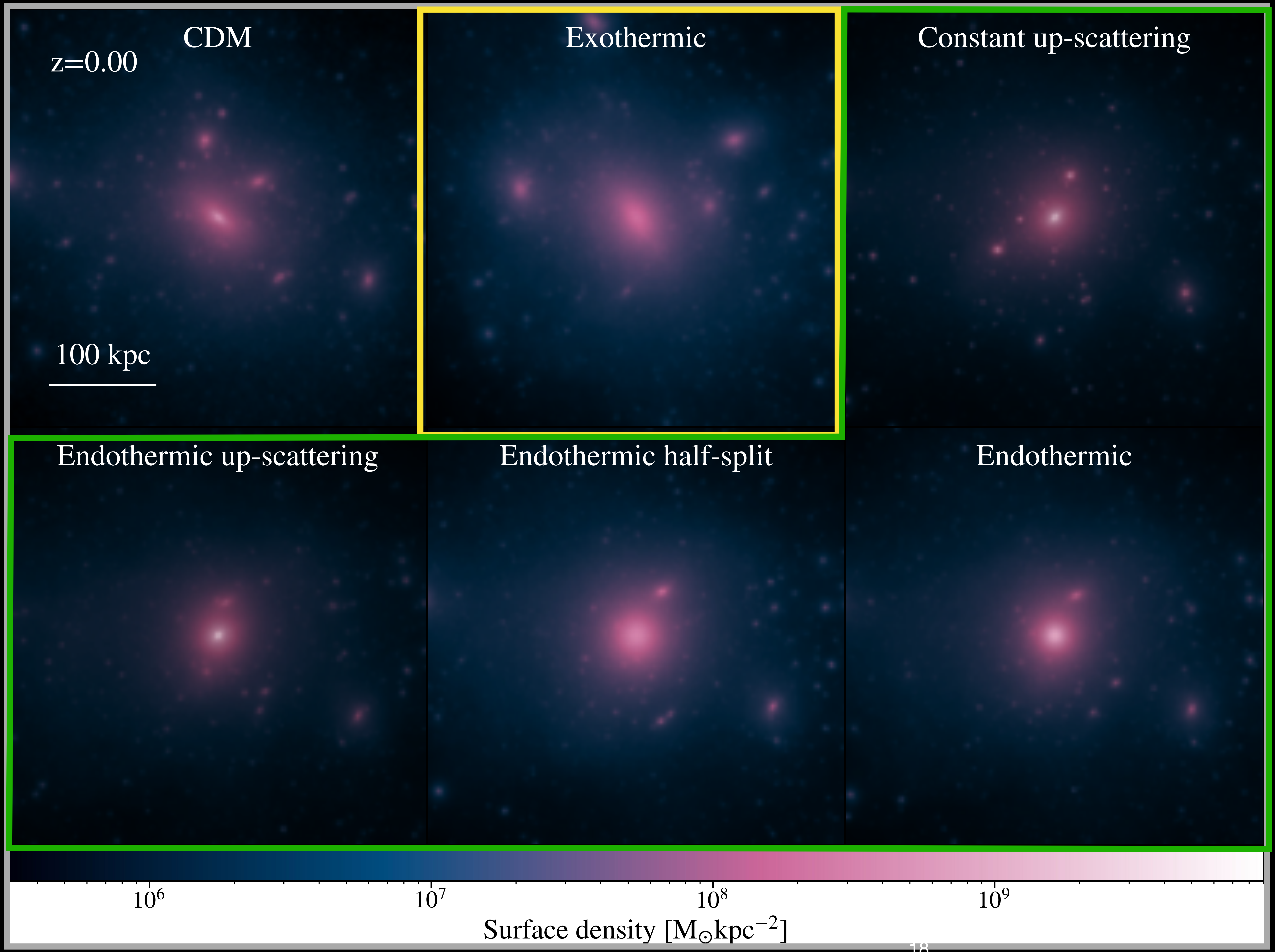


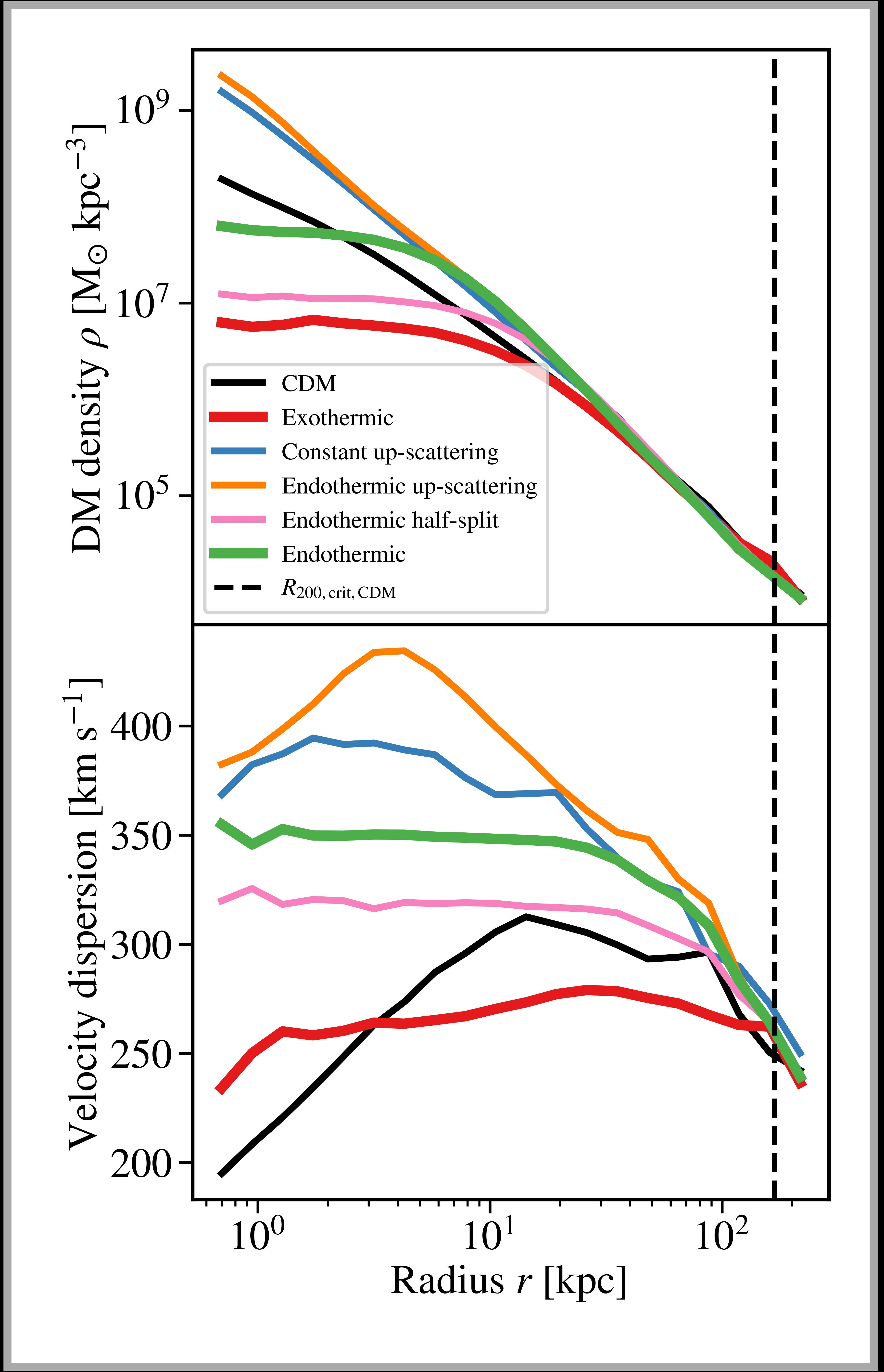
Main halo appearance differs for each model



- Same initial conditions
- Set particle state at simulation start
- Main and satellite halos differ

Radial density profile of the main halo

- Down-scattering and elastic reactions create a core
- Up-scattering increases central density
- Up- and down-scattering cores at a higher density
  - Central density is set by velocity threshold
  - Lower threshold means onset of down-scattering is earlier



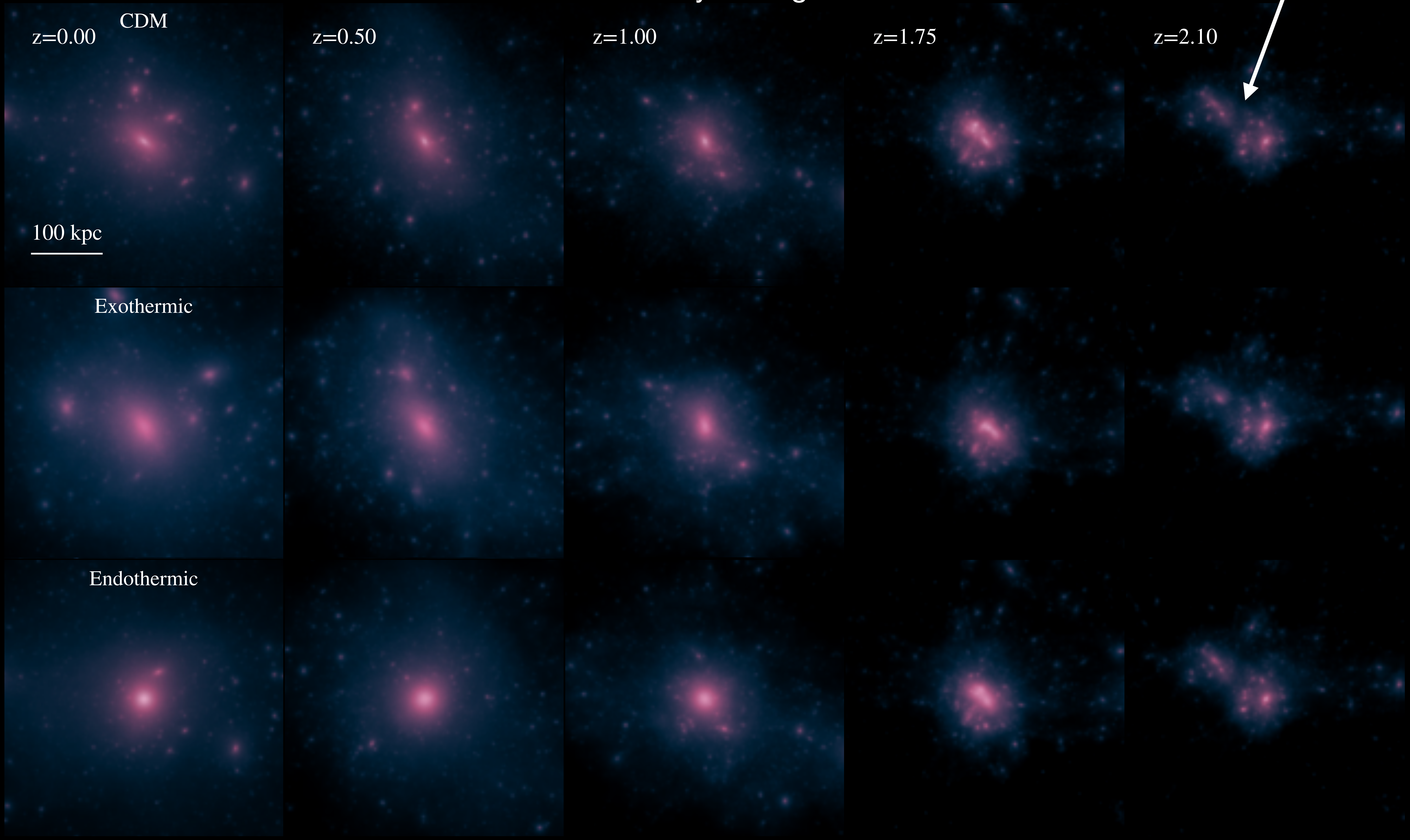
Redshift evolution

Present day

6 billion years ago

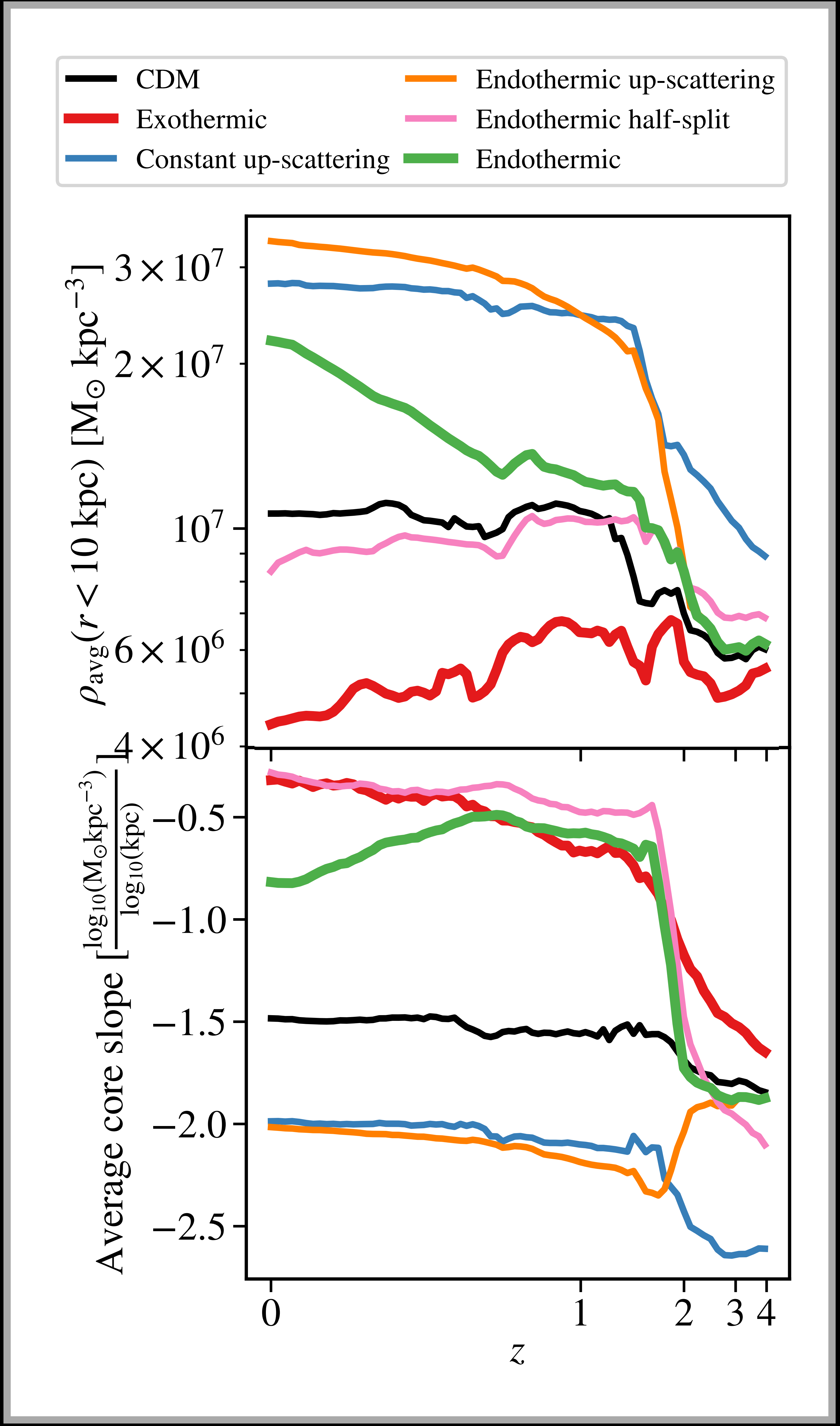
merger
(triggers scattering)

10 billion
years ago



Evolution of inner halo

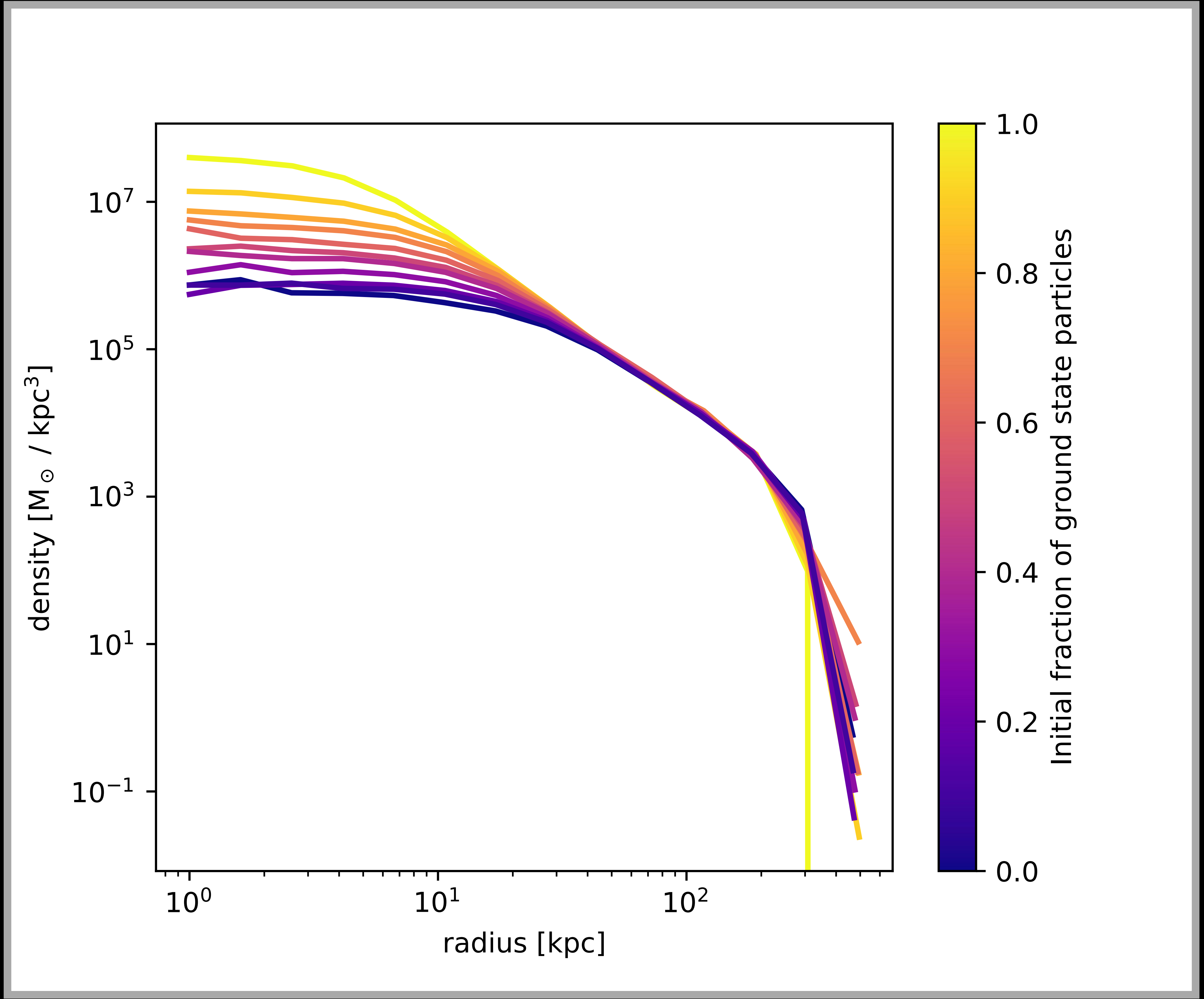
- CDM steady after z=2
- Exothermic model continuously decreases in central density with flat slope
- Up-scattering only models maintain high density and steep slope
- Endothermic models initially increase with up-scattering then decrease with down-scattering
- Are the present-day halo properties sensitive to the assembly history?



Future Directions

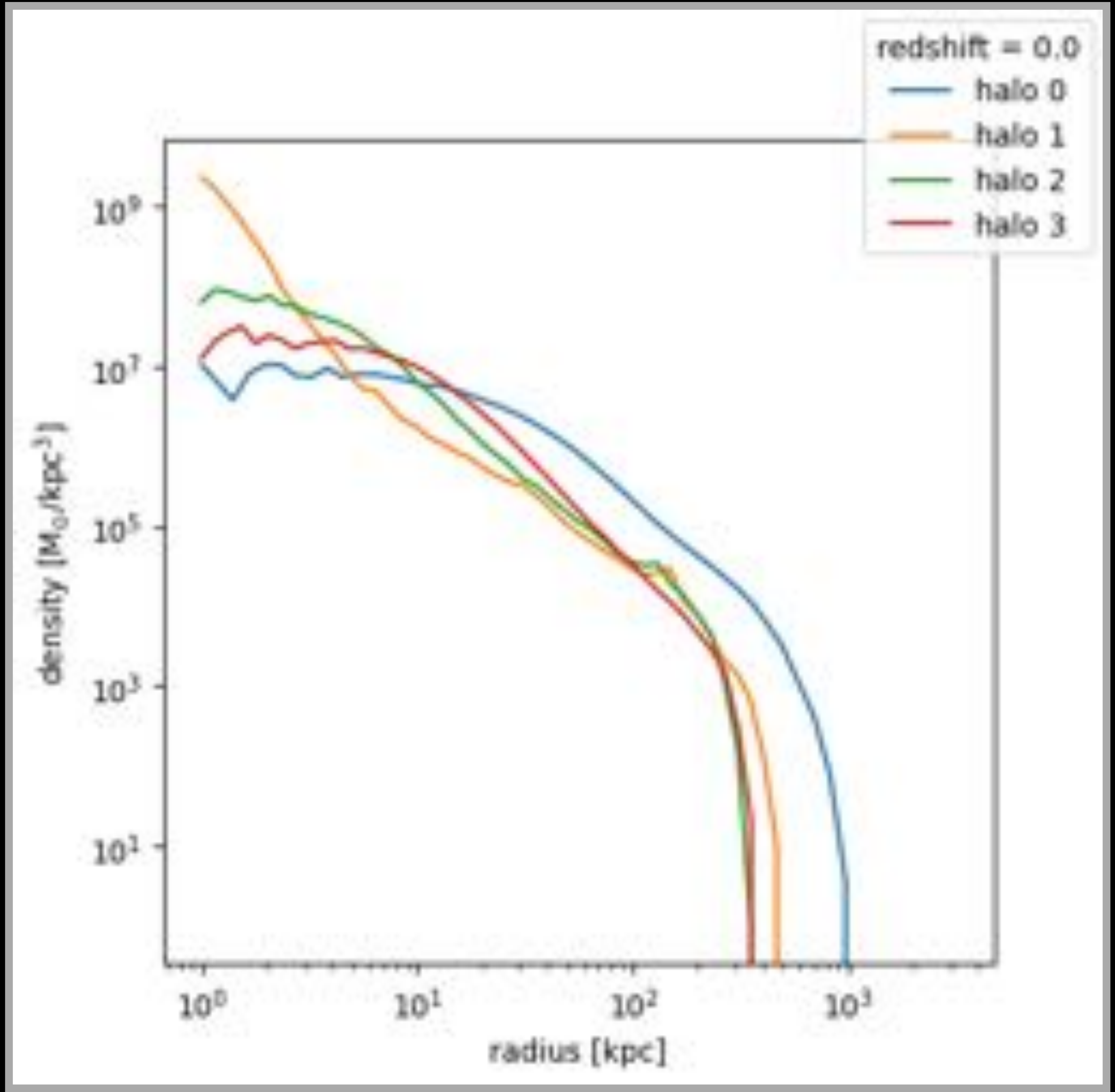
Varying initial particle states

(Aidan Leonard, MIT)



Varying zoom halo

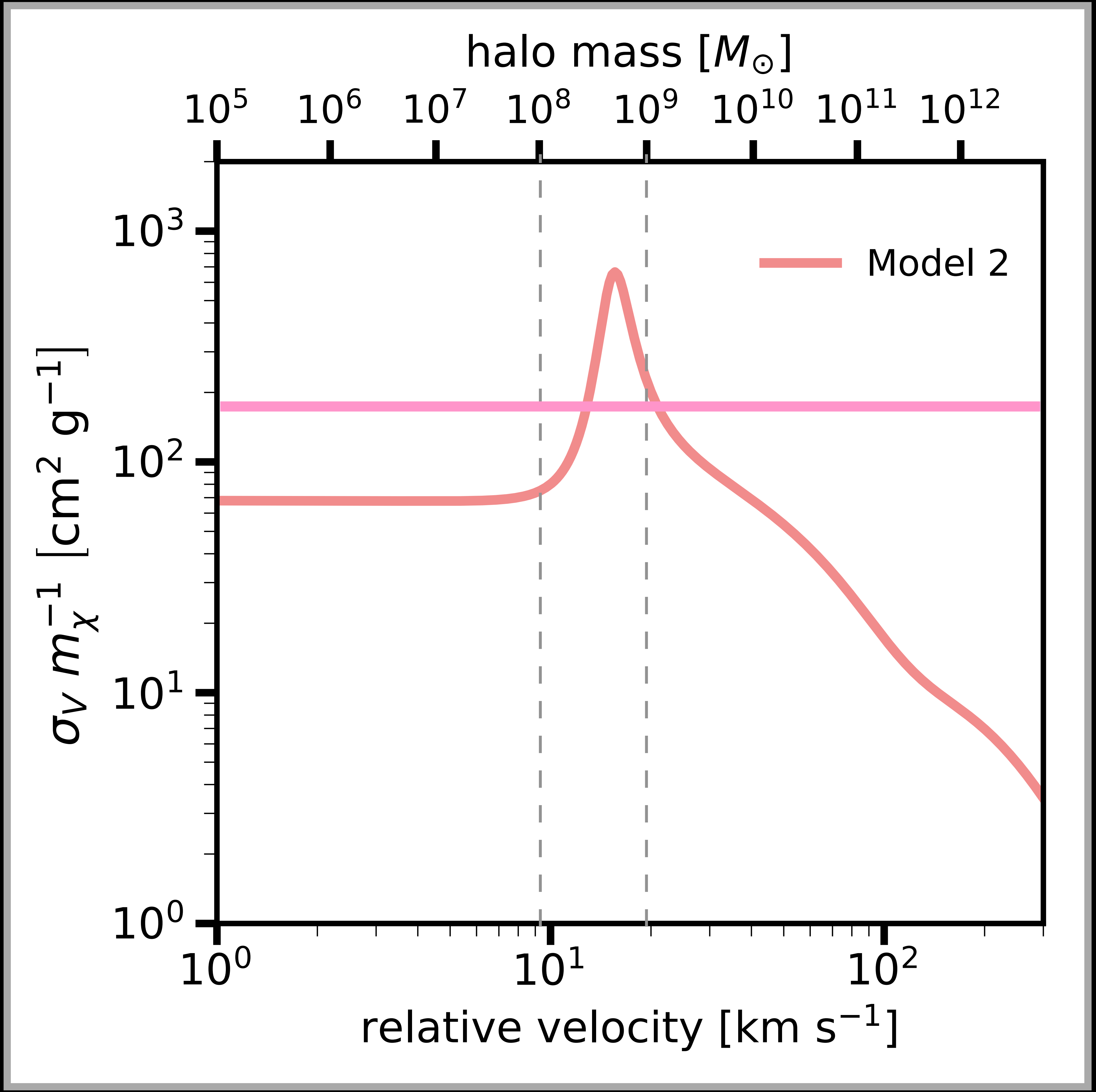
(Olivia Rosenstein, MIT)

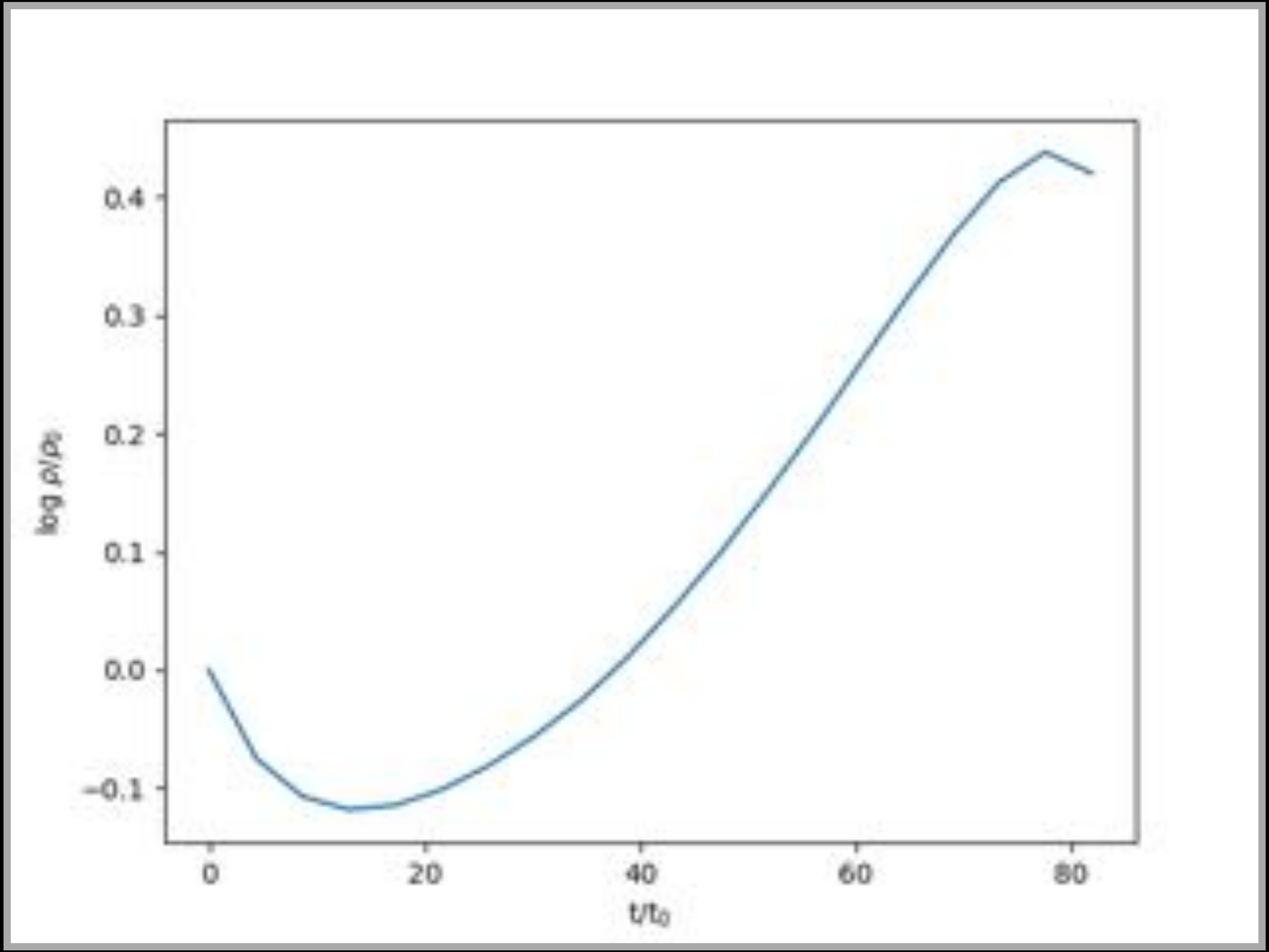


Future Directions

Isolated halos with resonant cross section models

(Vinh Tran, MIT; Daniel Gilman, UToronto)





Conclusions

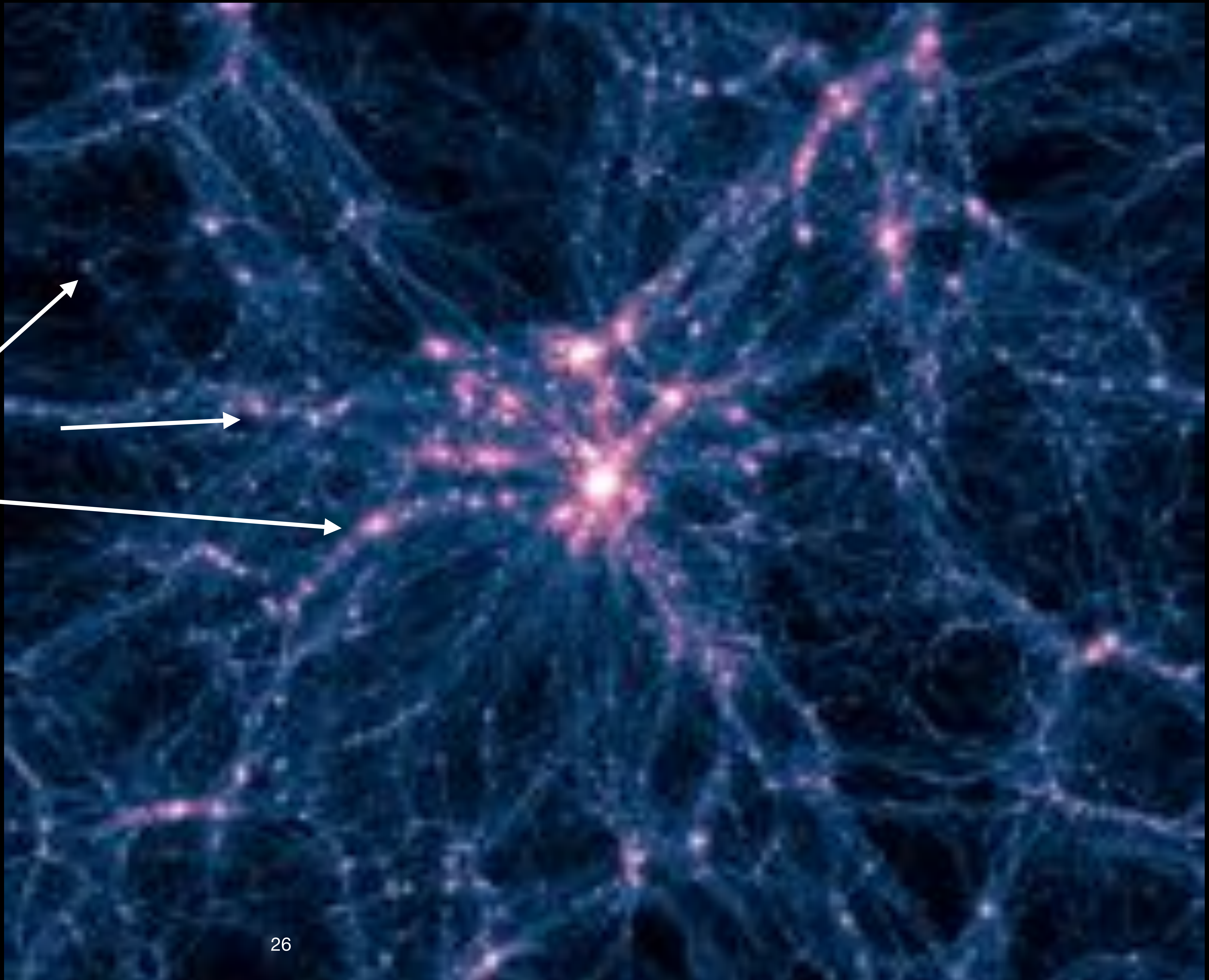
- SIDM can alleviate certain small-scale dark matter problems
- Up-scattering provides a mechanism for particles to enter a high energy state
  - Alone, up-scattering exacerbates small-scale problems
  - In combination with elastic and down-scattering, these problems can be mitigated

Future:

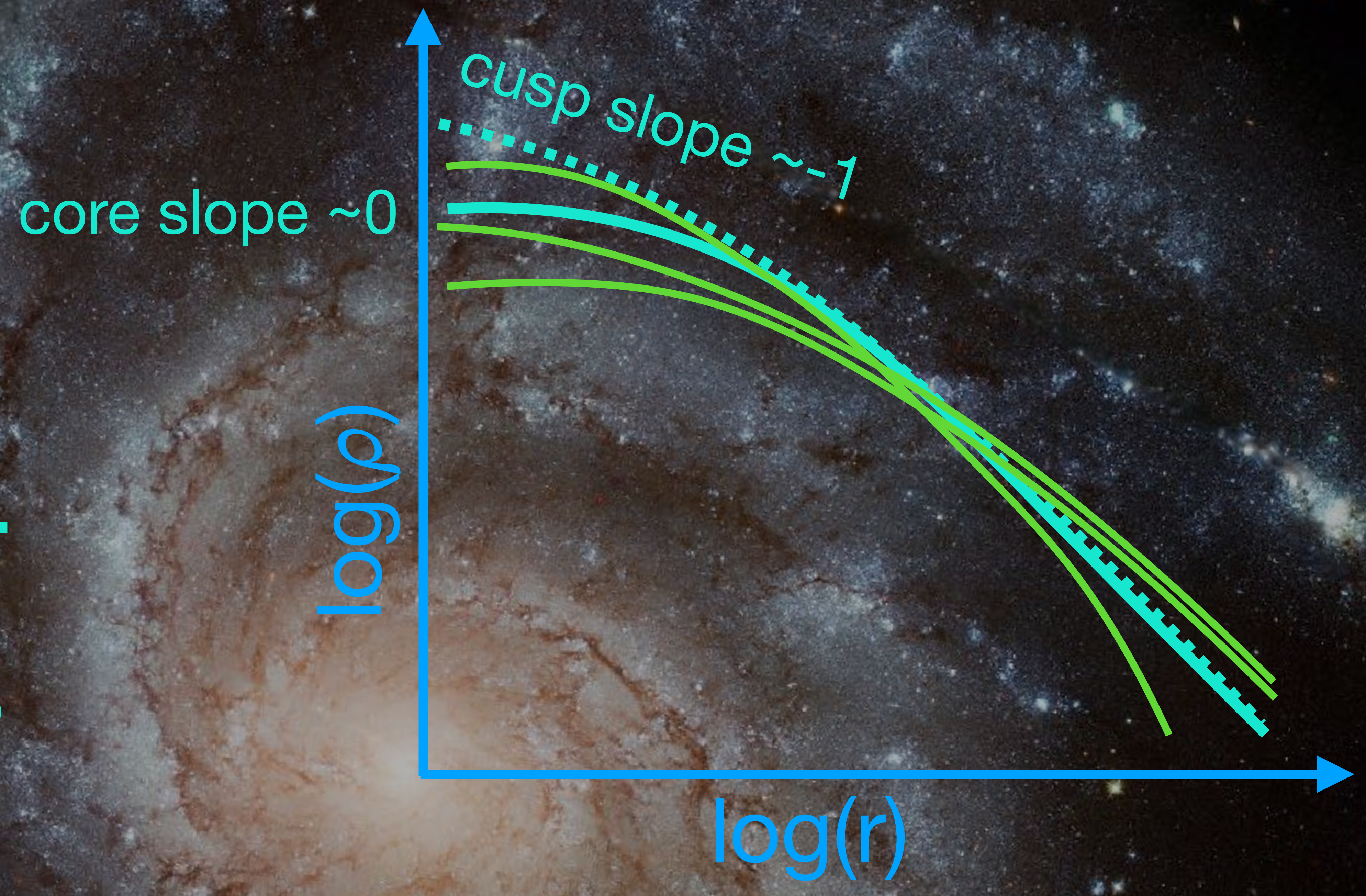
- What is the interaction between SIDM and baryons?
- What observational signatures are there?
- How sensitive are the results to initial conditions?
- How much variation is there in different halos?

Large-scale structure is consistent with CDM

- N-body (dark matter-only) simulations create a cosmic web
- Galaxies and clusters form in overdense halos



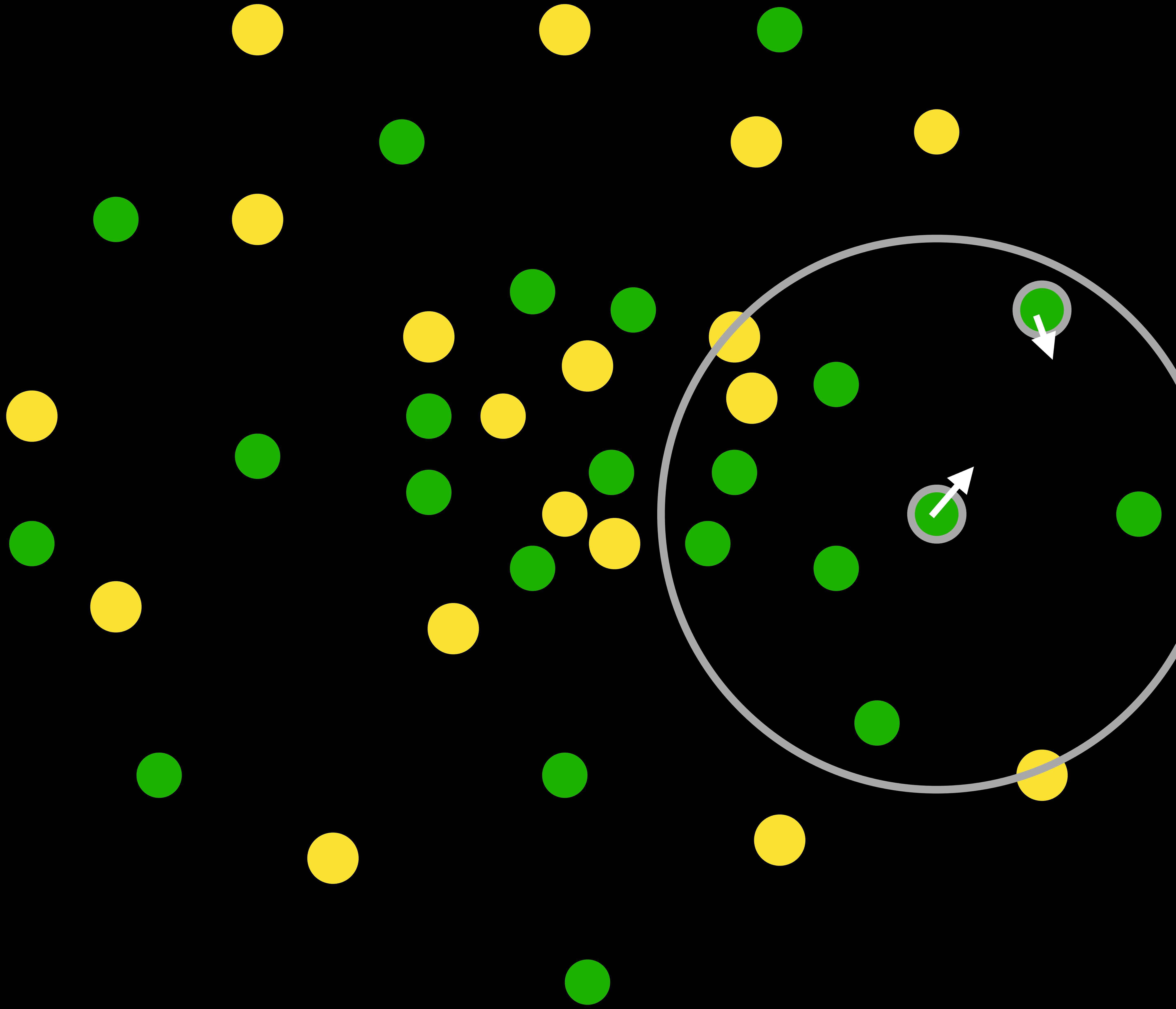
Small scale discrepancies between simulations and observations



- Core-cusp
  - Cuspy simulation halos ············
  - Cored observed halos ——
- Diversity of shapes in observed satellites

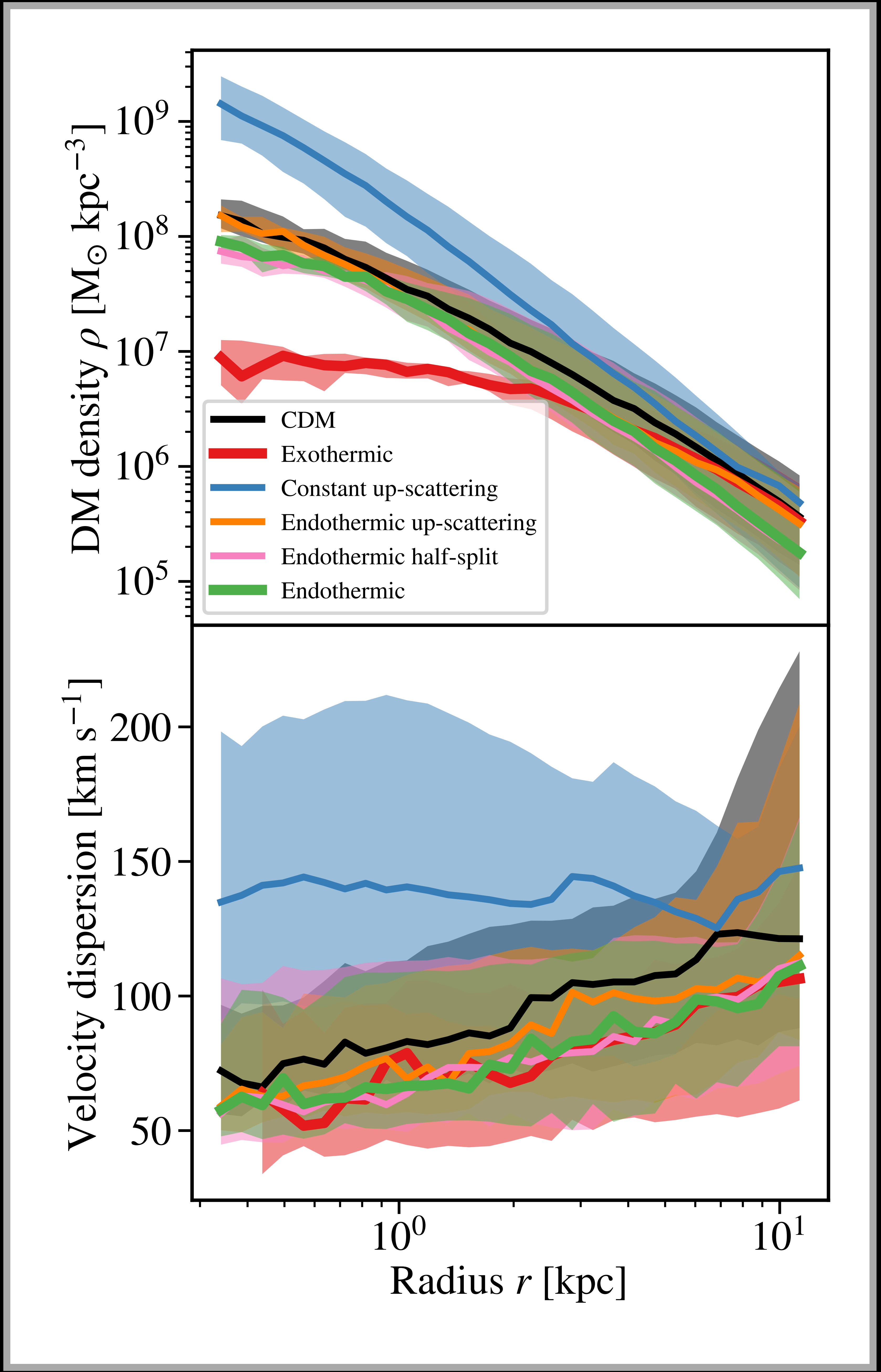
Scattering in the simulation

- Select particle
- Identify nearby particles
- Scattering probability
  - Does not scatter
  - Elastic scattering with opposite state
  - Elastic scattering with same state
  - Inelastic scattering with same state



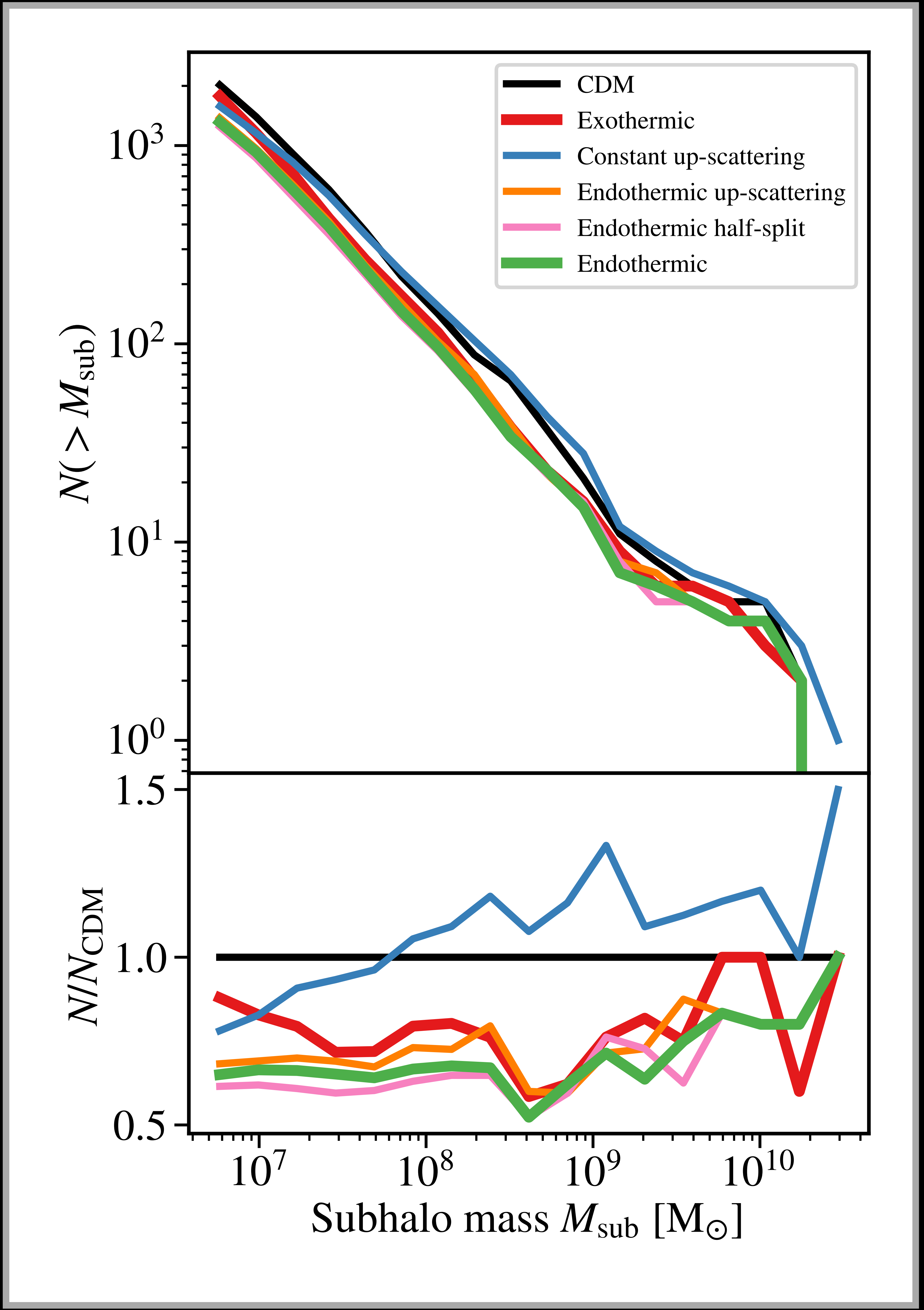
Up-scattering threshold sets satellite properties

- No velocity threshold:
  - Satellite halos look similar to main halos
- Velocity threshold:
  - Particles in satellites don't move fast enough to scatter
  - Satellite halos look similar to CDM halos



Satellite population differs from CDM

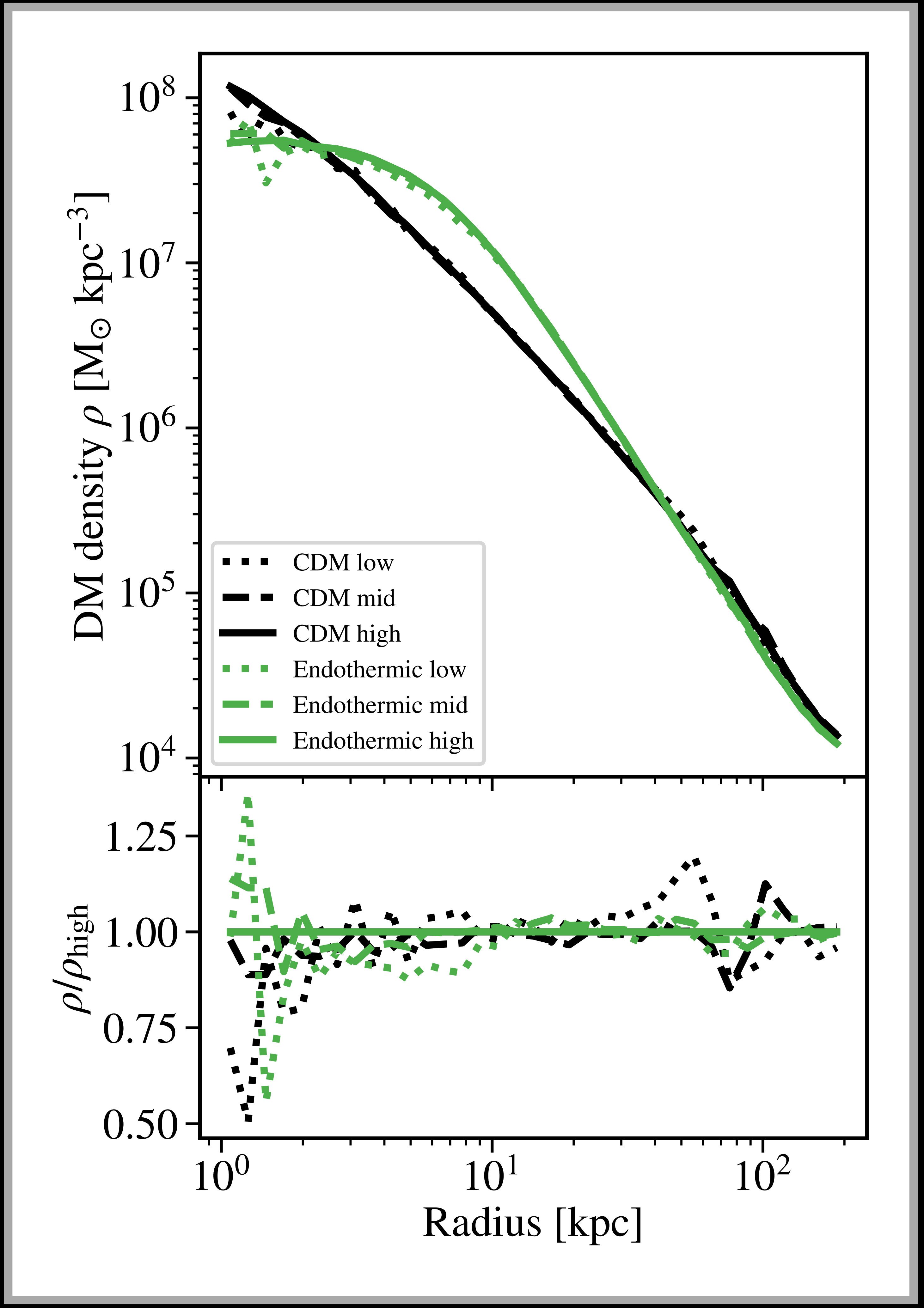
- All models except Constant up-scattering have fewer satellite halos
- Down-scattering “evaporates” satellites
  - Expected effect on Exothermic model
  - More dominant in subhalos for Endothermic and Endothermic half-split models

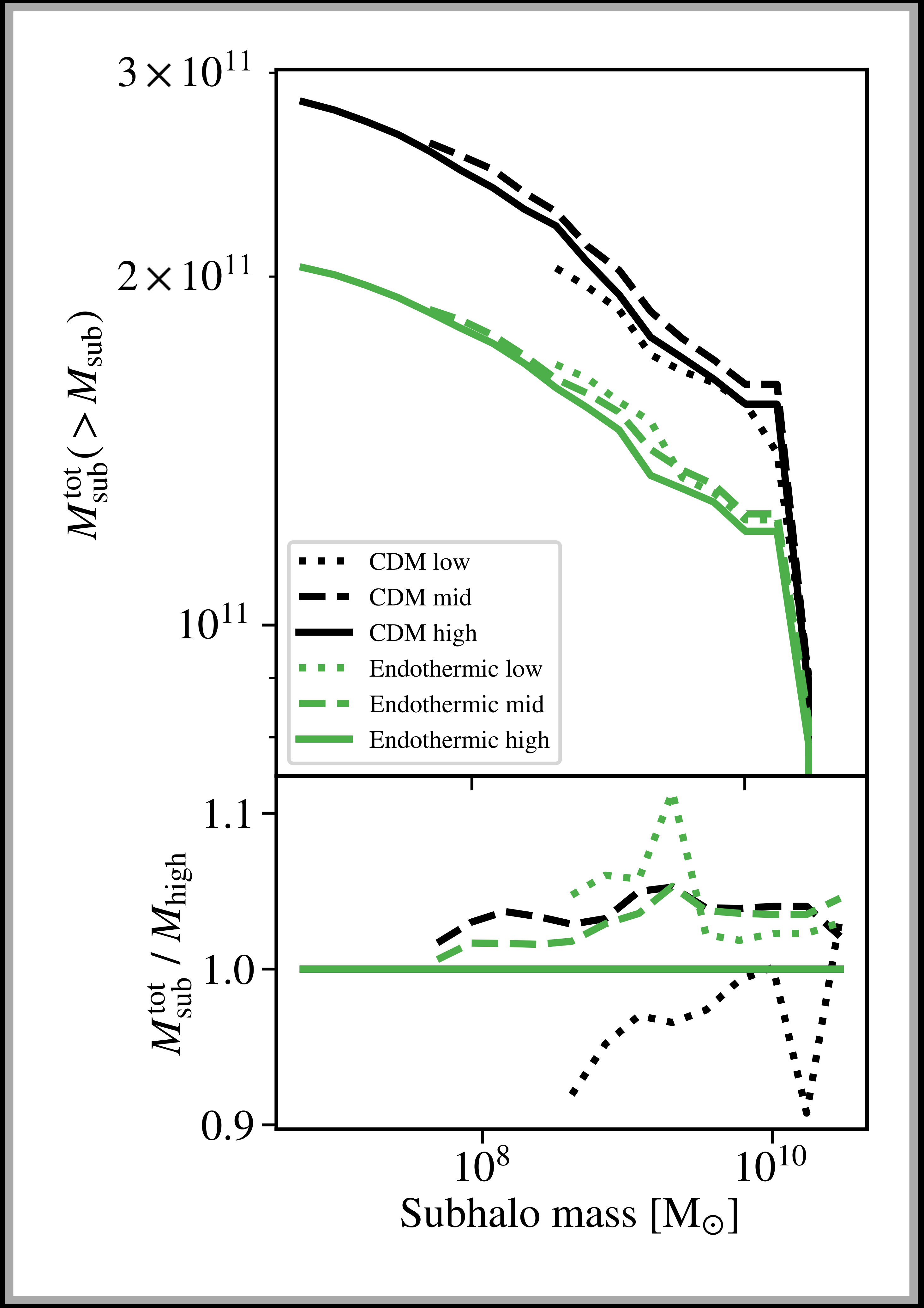


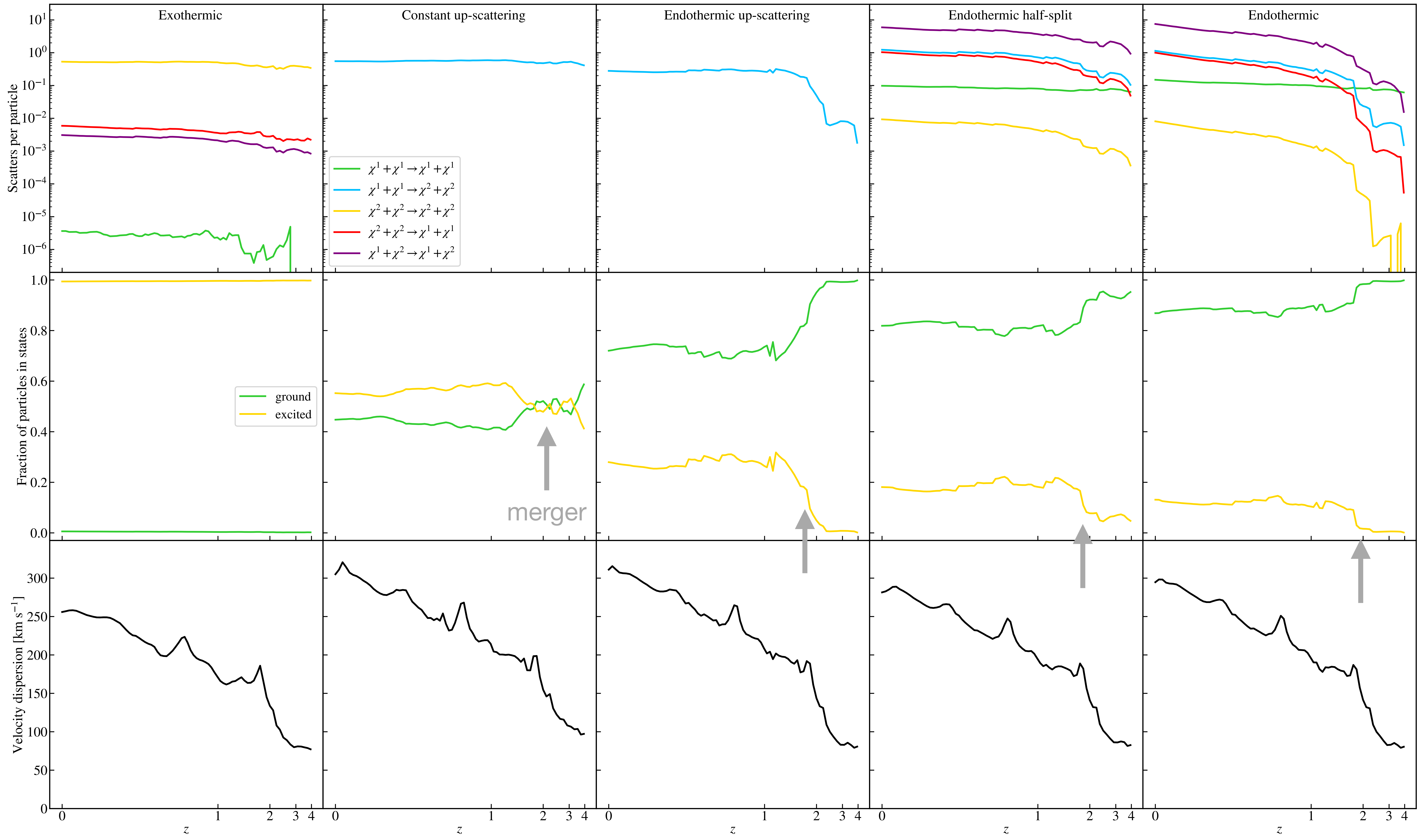
Change in density causes tidal disruptions

- Tidal radius is proportional to satellite density / host density
- For up-scattering only with velocity threshold, satellites are similar to CDM but main halo is more dense
  - density / (10 x host density)
- Without velocity threshold, satellites are also dense
  - (10 x density) / (10 x host density)

Results are not driven by resolution







Exothermic
Constant up-scattering
Endothermic up-scattering
Endothermic half-split
Endothermic
Scatters per particle
$\chi^1+\chi^1\rightarrow\chi^1+\chi^1$
$\chi^1+\chi^1\rightarrow\chi^2+\chi^2$
$\chi^2+\chi^2\rightarrow\chi^2+\chi^2$
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$\chi^1+\chi^2\rightarrow\chi^1+\chi^2$
Fraction of particles in states
ground
excited
merger
Velocity dispersion [km s^{-1}]
z

Density changes correspond to scattering

- For only up-scattering (—, —):
  - Velocity threshold makes it more difficult for particles farther out to up-scatter
- For full models (—, —):
  - Lowering velocity threshold for up-scattering ultimately results in more down-scattering