Endo- and exothermic scattering Milky Way-mass halos

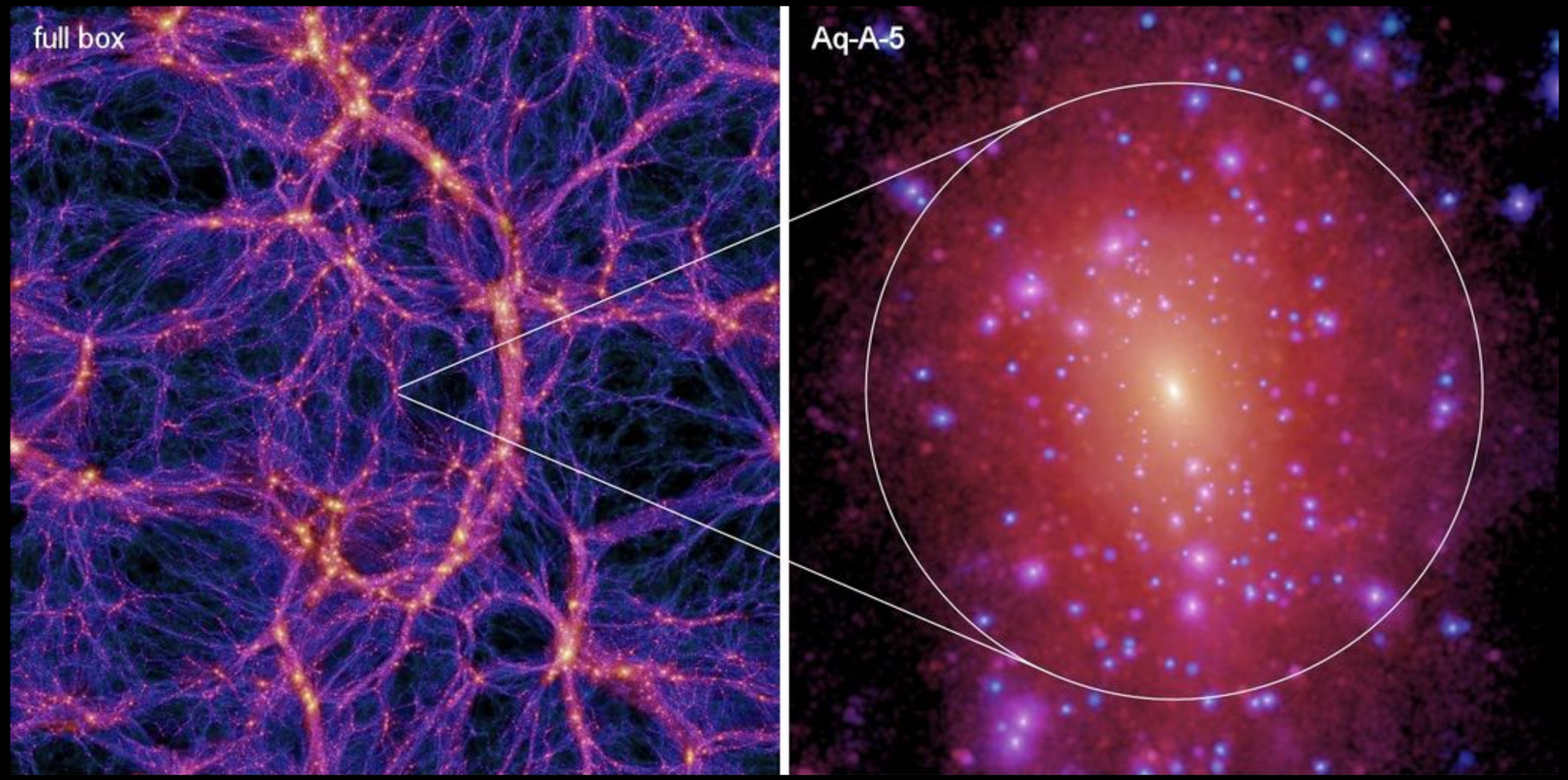
Stephanie O’Neil
June 9, 2025

A multi-state model of SIDM

- Overview of code
- Results from an example model with varying initial states
  - Main halo densities
  - Main halo shapes
  - Subhalo abundance
- Resonant DM

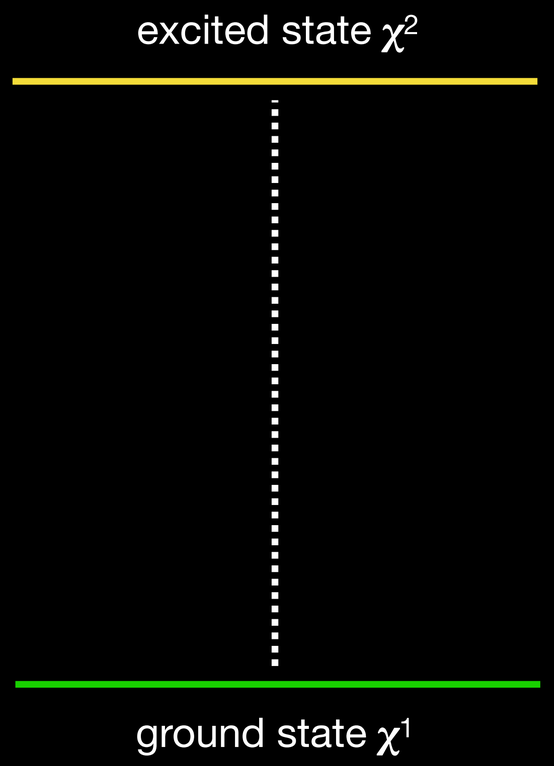
Milky Way Zoom-in simulations

- High-resolution main halo and surroundings
- Low resolution background
- Dark matter-only (for now)



Framework for SIDM model

- Hypothetical two-state particle



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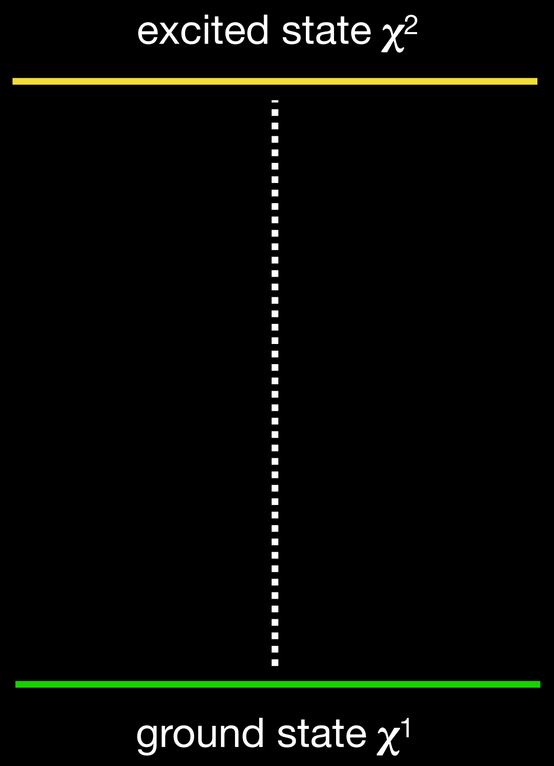

Framework for SIDM model

- Hypothetical two-state particle
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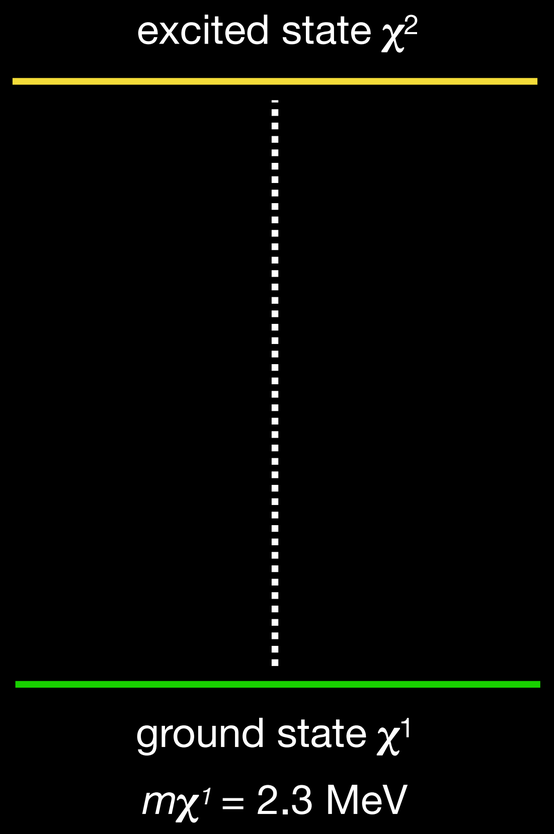
  - Ground state mass m_{χ^1}



Framework for SIDM model

- Hypothetical two-state particle
- Model parameters:
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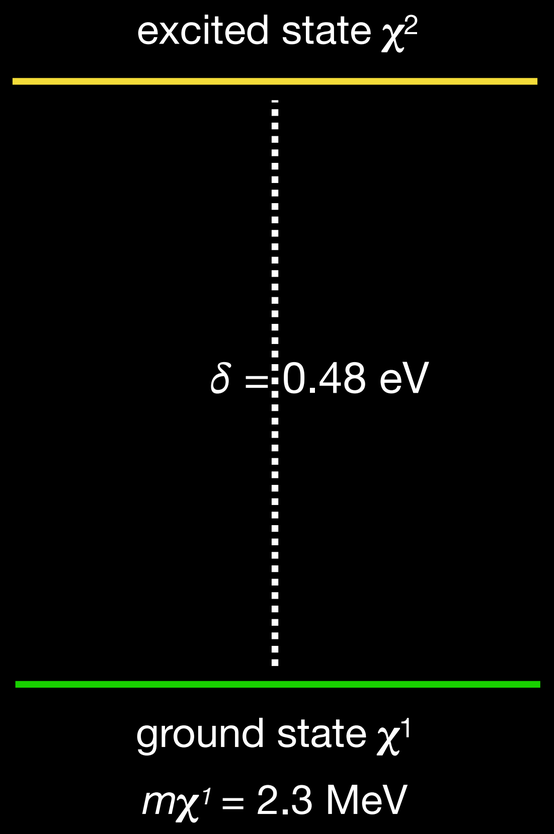
  - Mass splitting between states δ



Framework for SIDM model

m_ϕ = 7.3 MeV

- Hypothetical two-state particle
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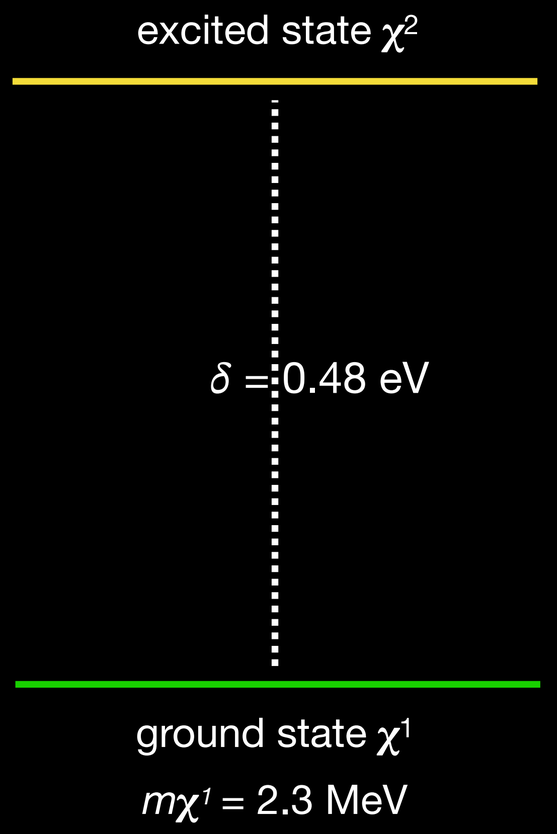
  - Dark force mediator mass m_ϕ



Framework for SIDM model

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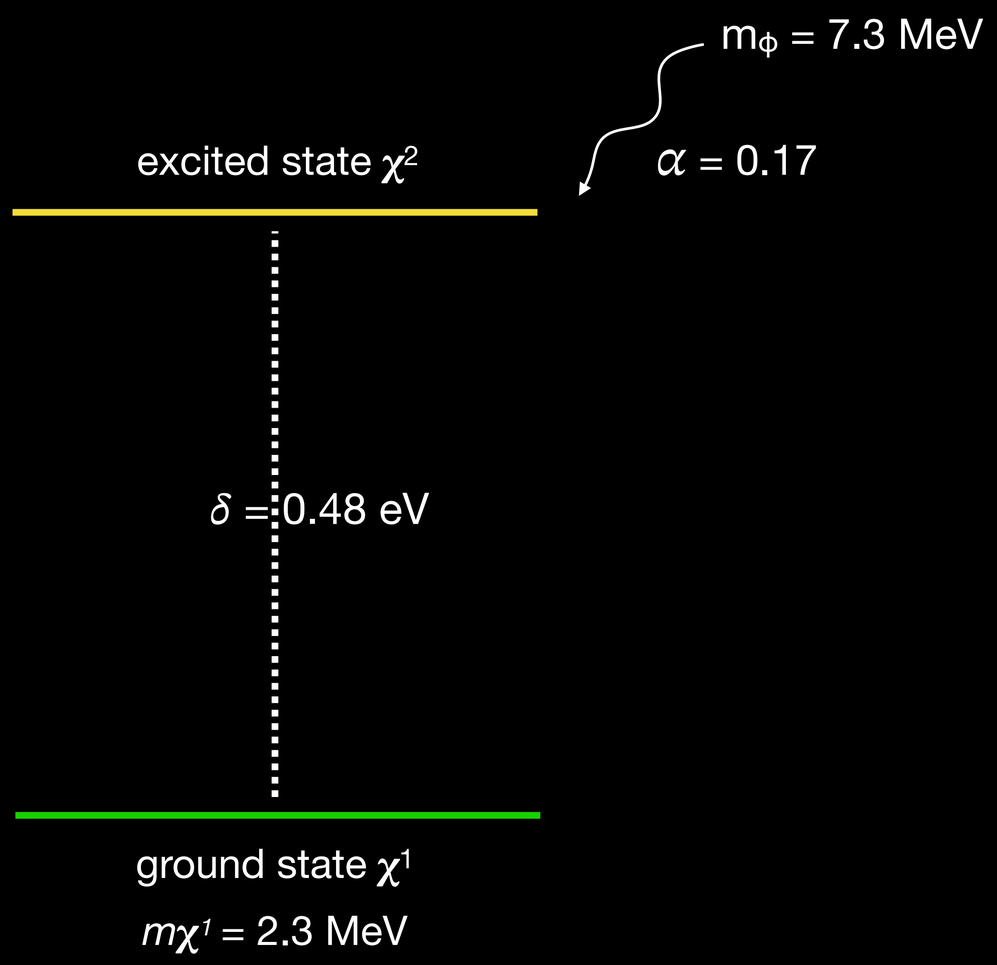
  - Coupling strength α



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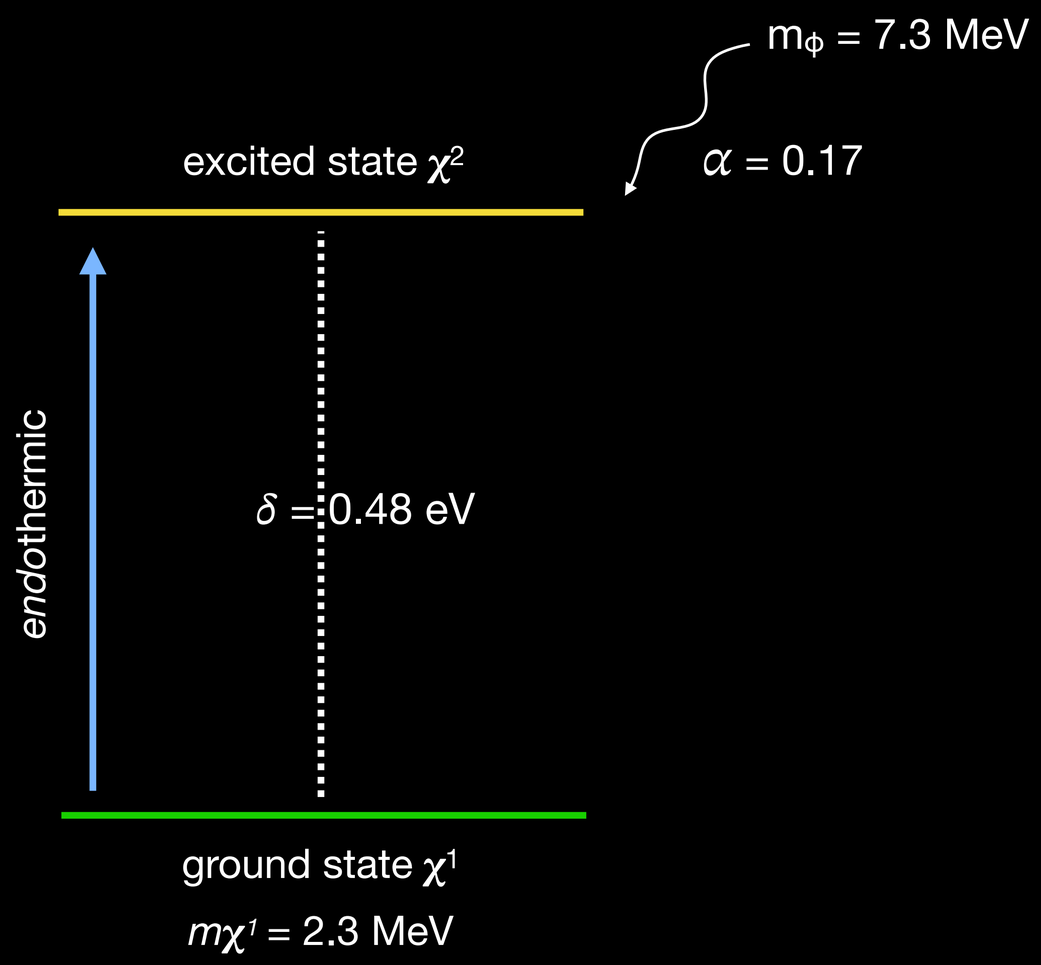

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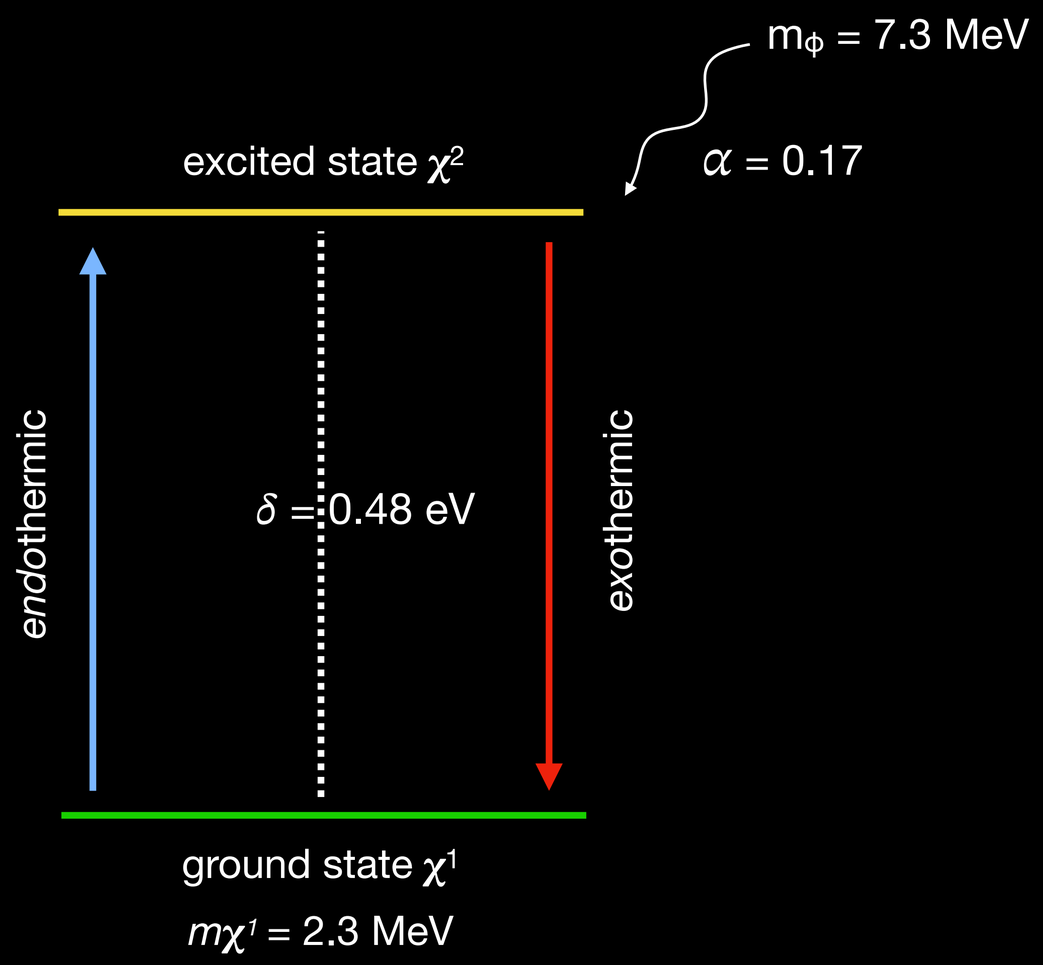

Particles scatter elastically and inelastically

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Elastic scattering:
no state changes

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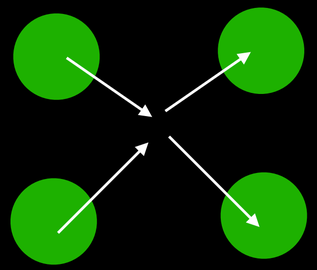
$\chi^1+\chi^1 \rightarrow \chi^1+\chi^1$



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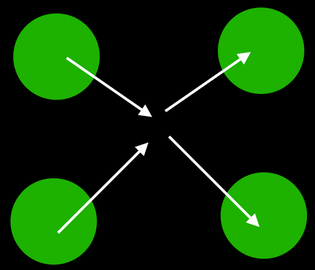

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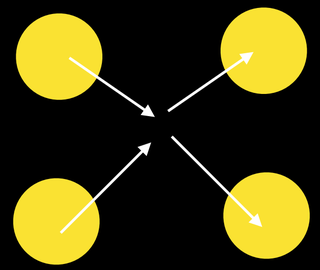

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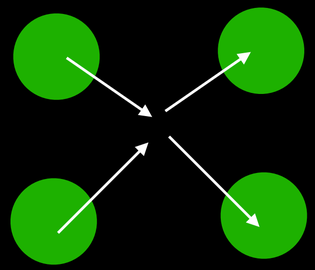

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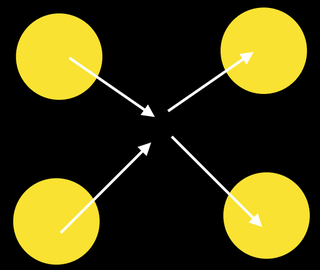

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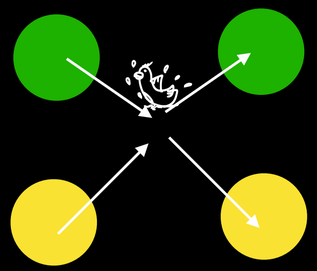

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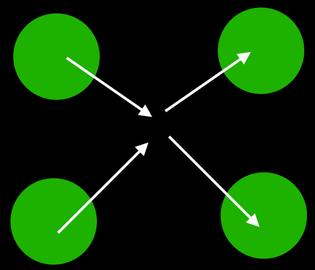

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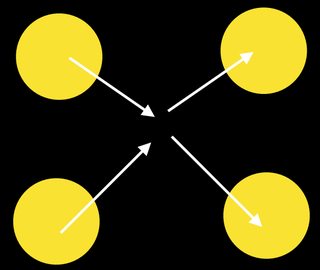

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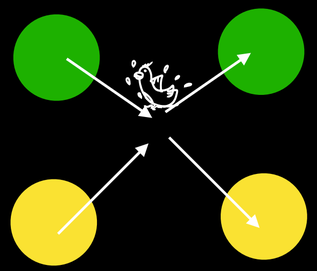

Inelastic scattering:
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Particles scatter elastically and inelastically

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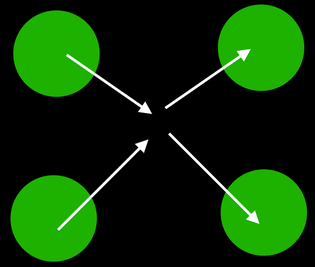

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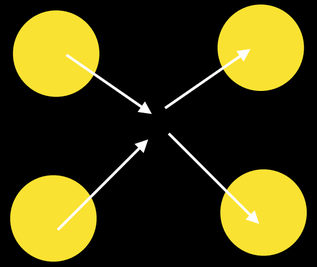

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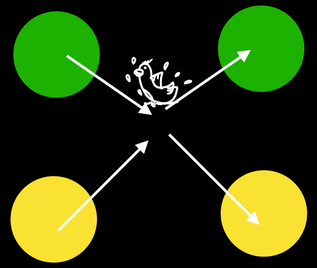

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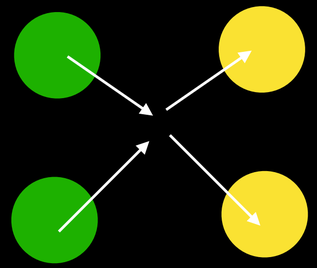

Up-scattering
Endothermic
Decreases kinetic energy

Particles scatter elastically and inelastically

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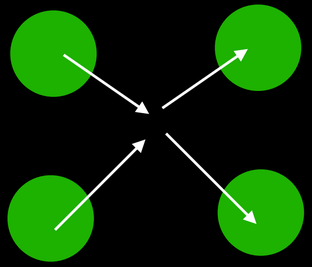

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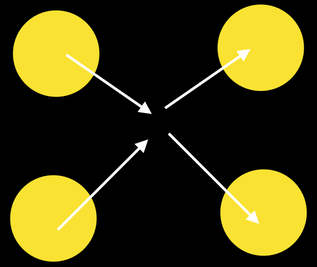

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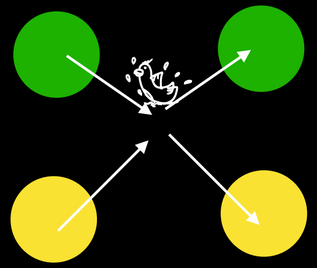

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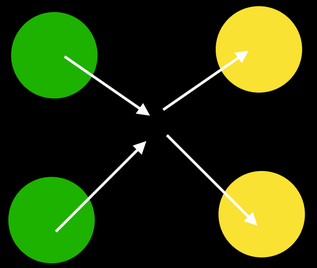

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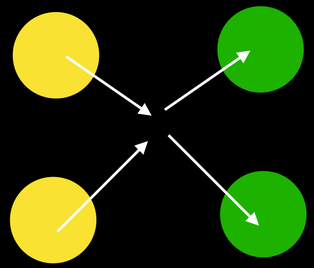
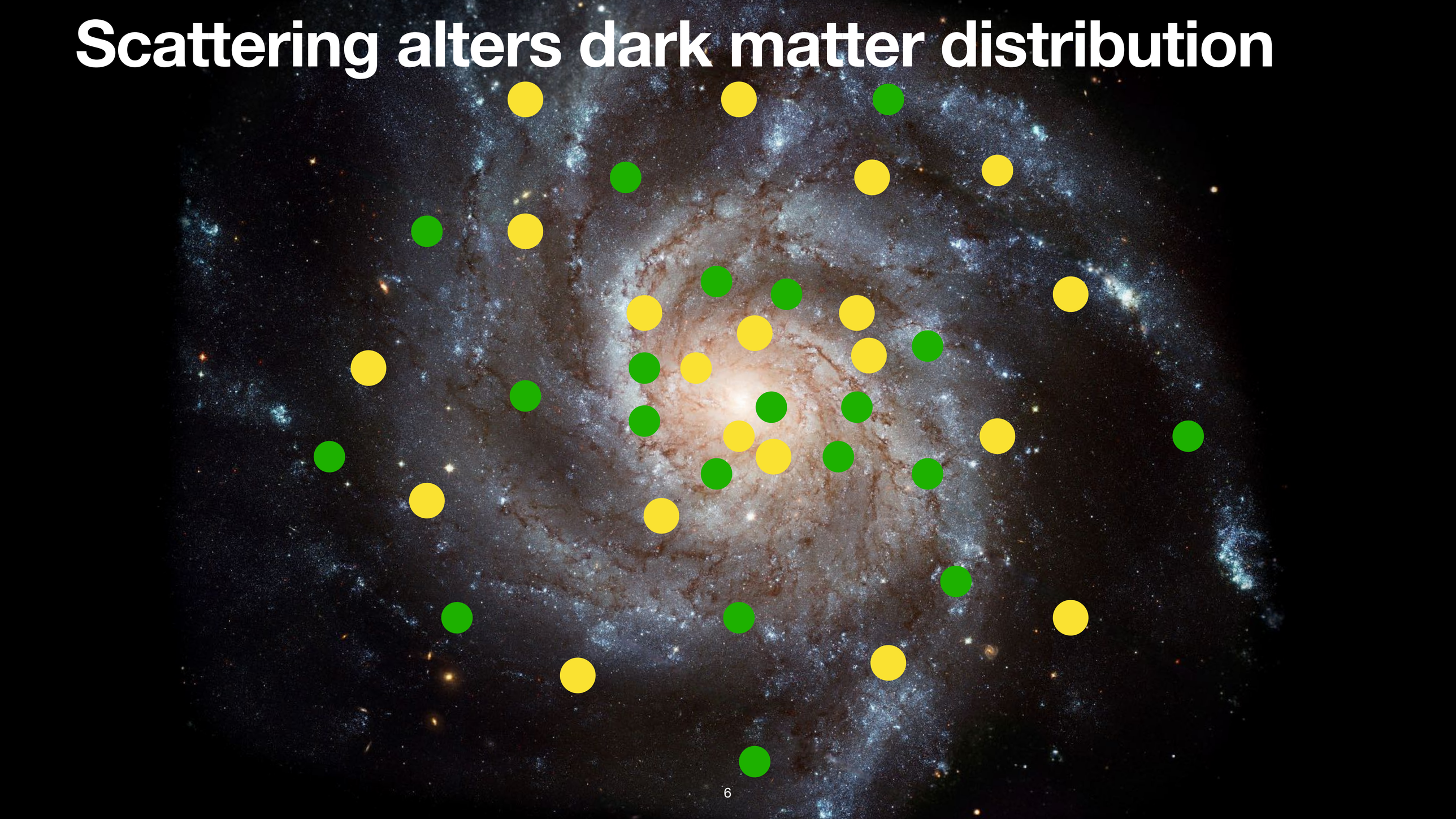


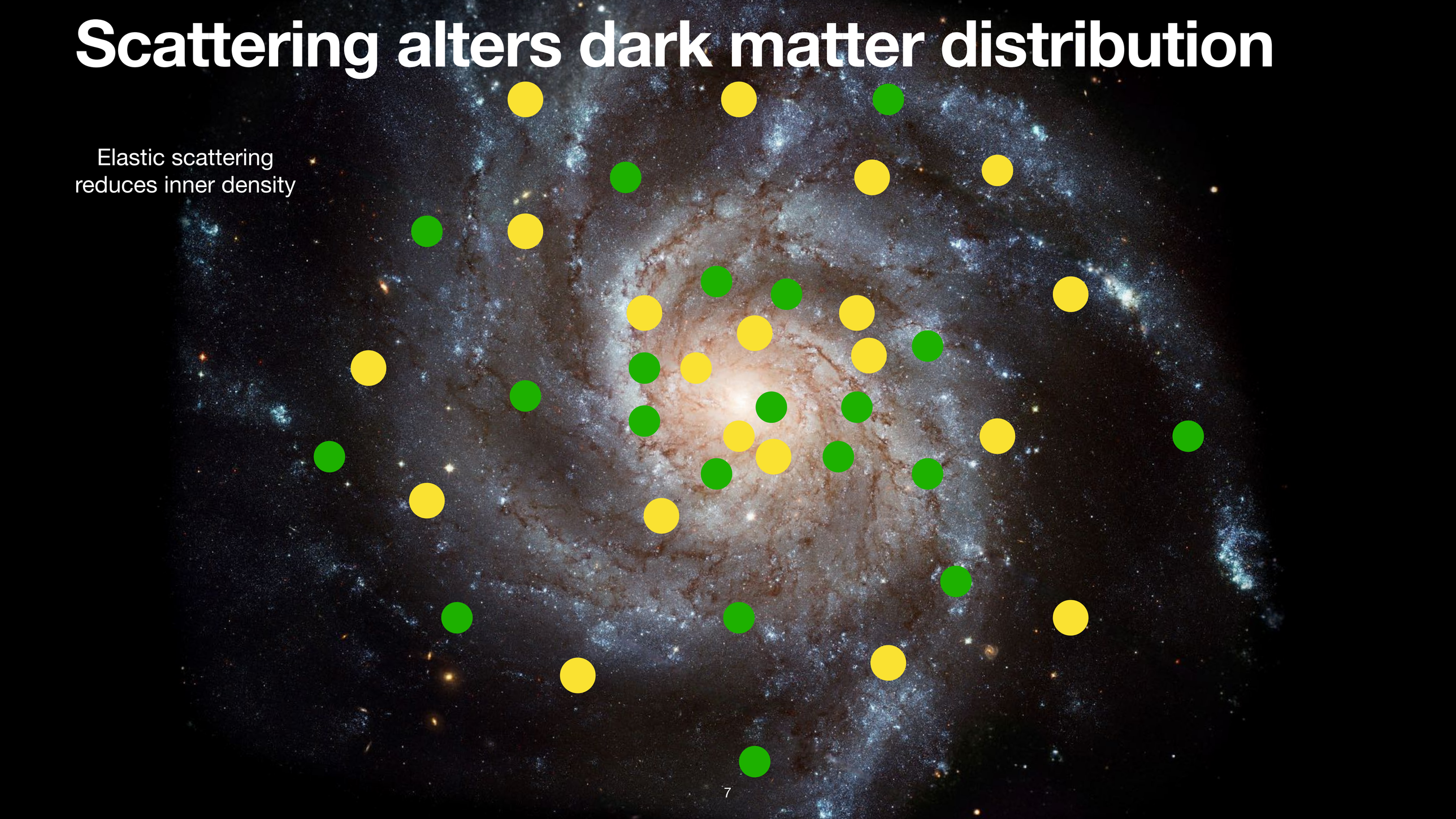
Down-scattering
Exothermic
Increases kinetic energy

Scattering alters dark matter distribution



Scattering alters dark matter distribution

Elastic scattering
reduces inner density



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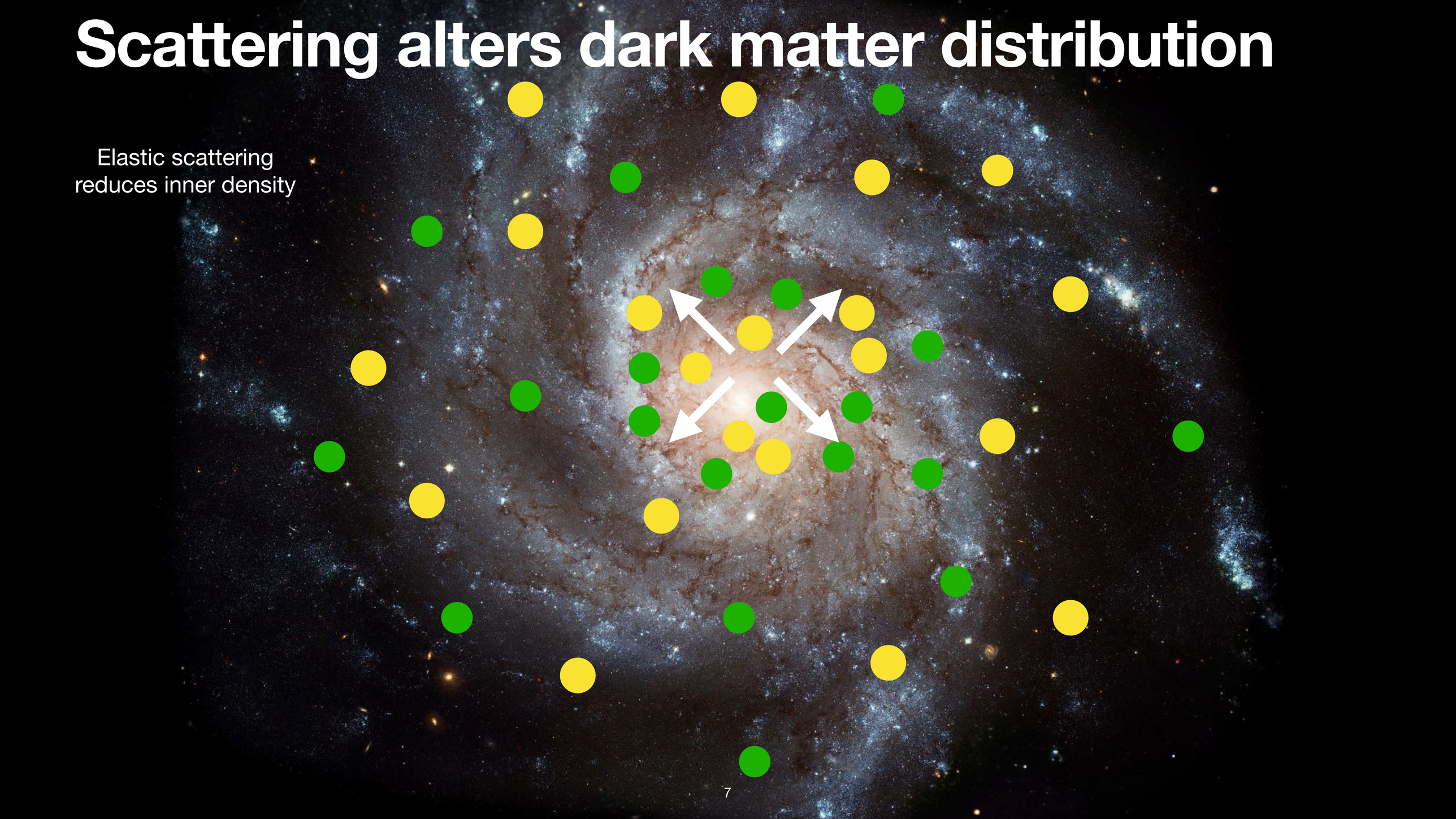
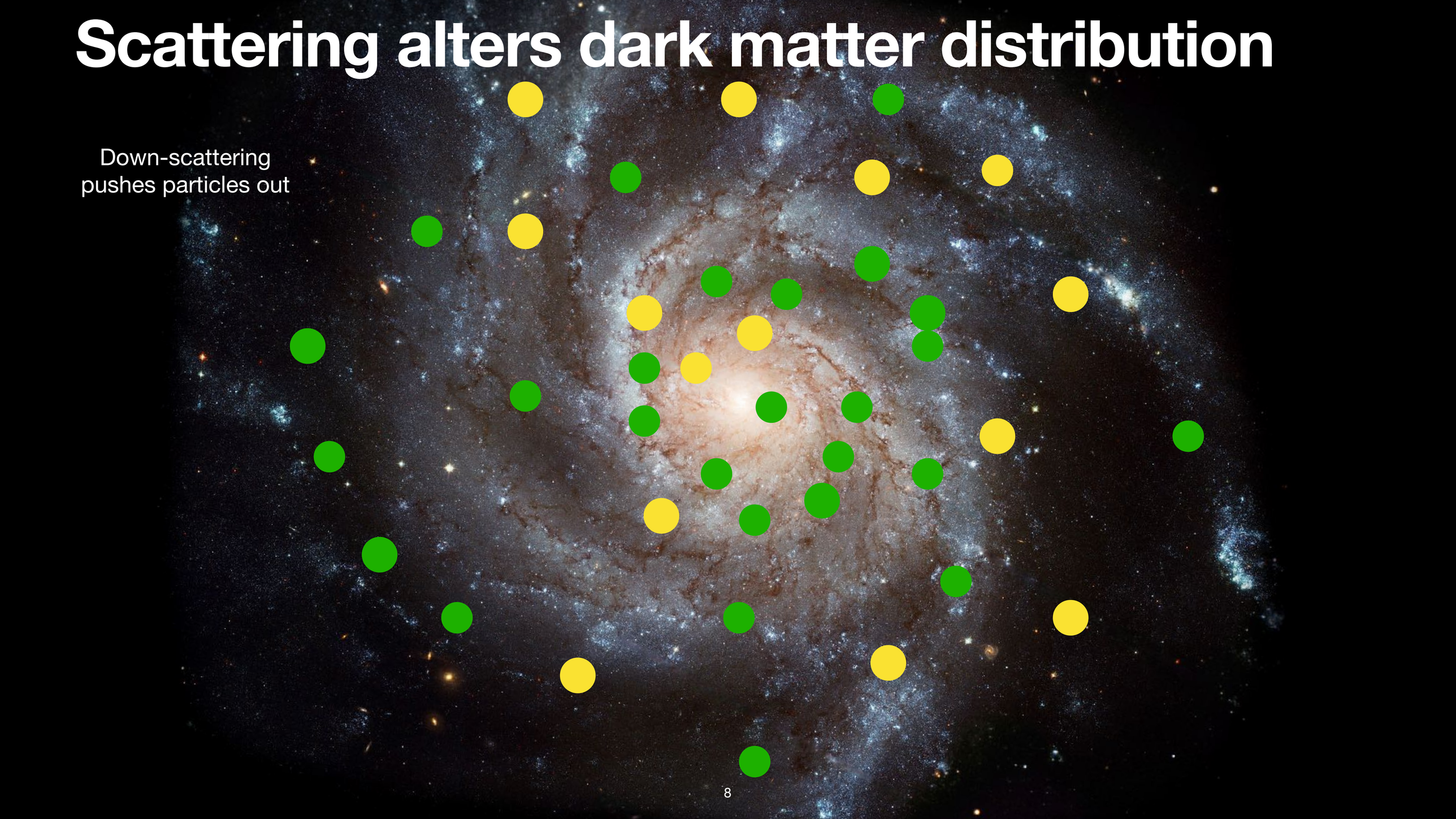


Scattering alters dark matter distribution

Down-scattering
pushes particles out



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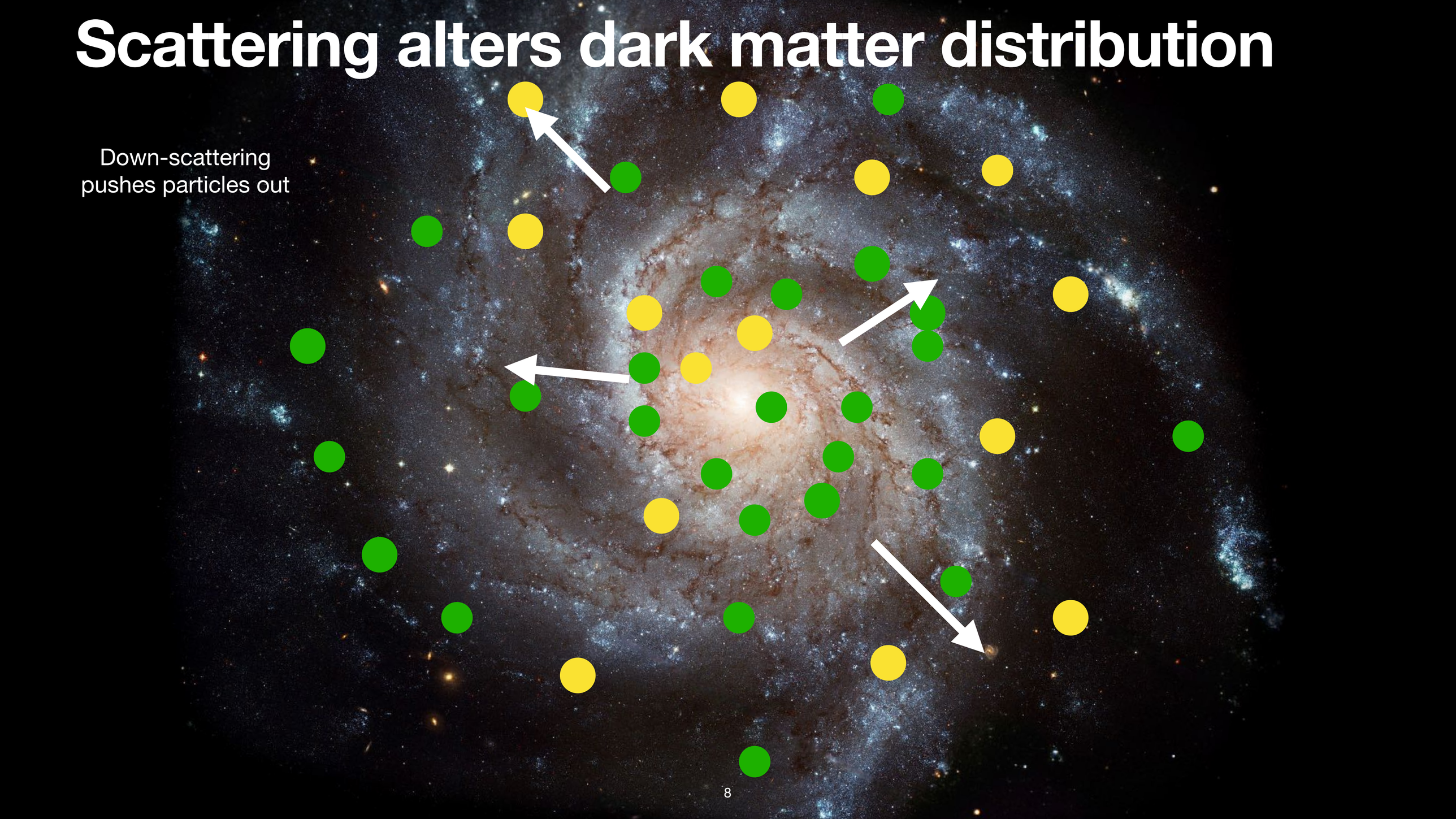
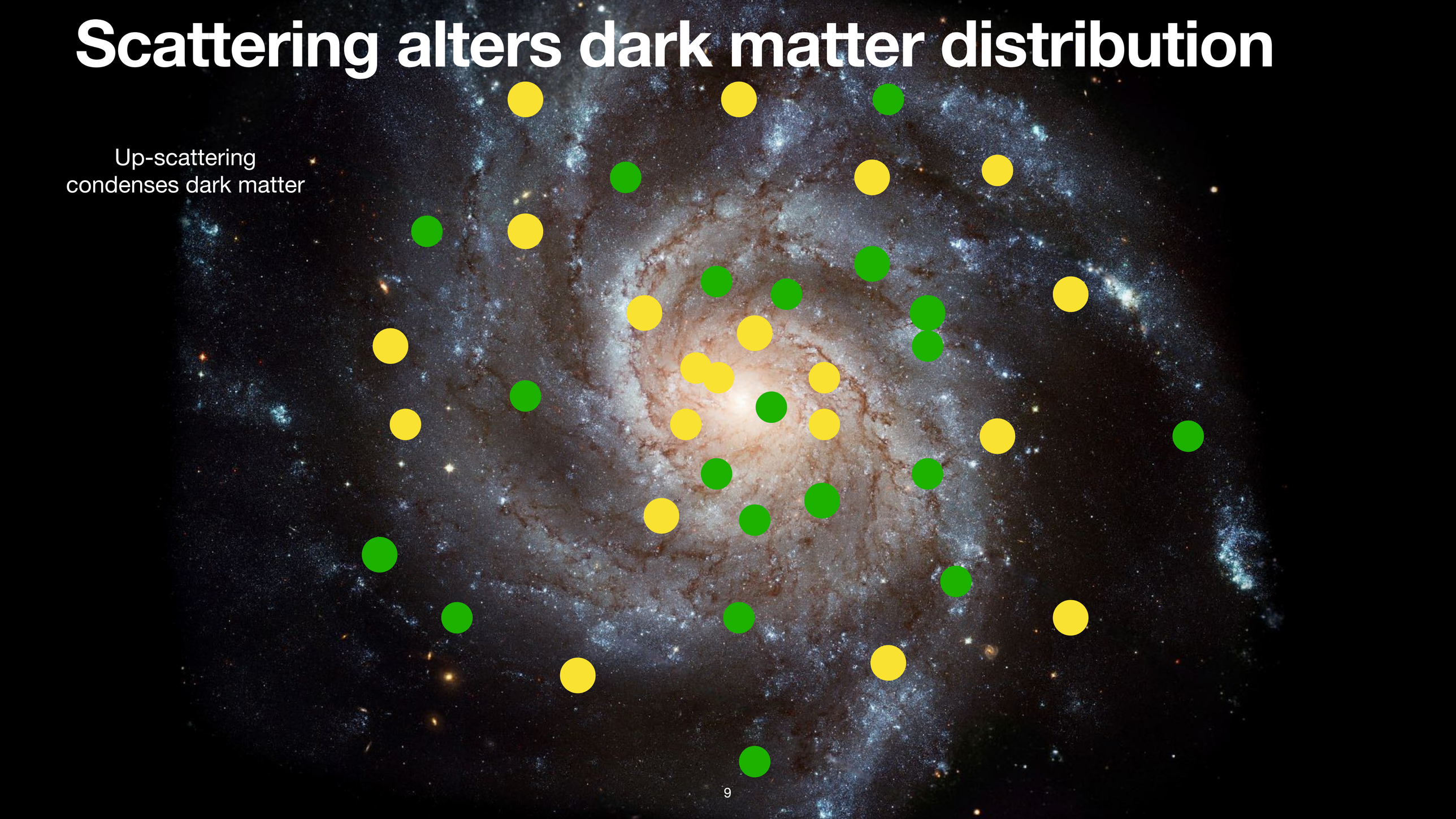


Scattering alters dark matter distribution

Up-scattering
condenses dark matter



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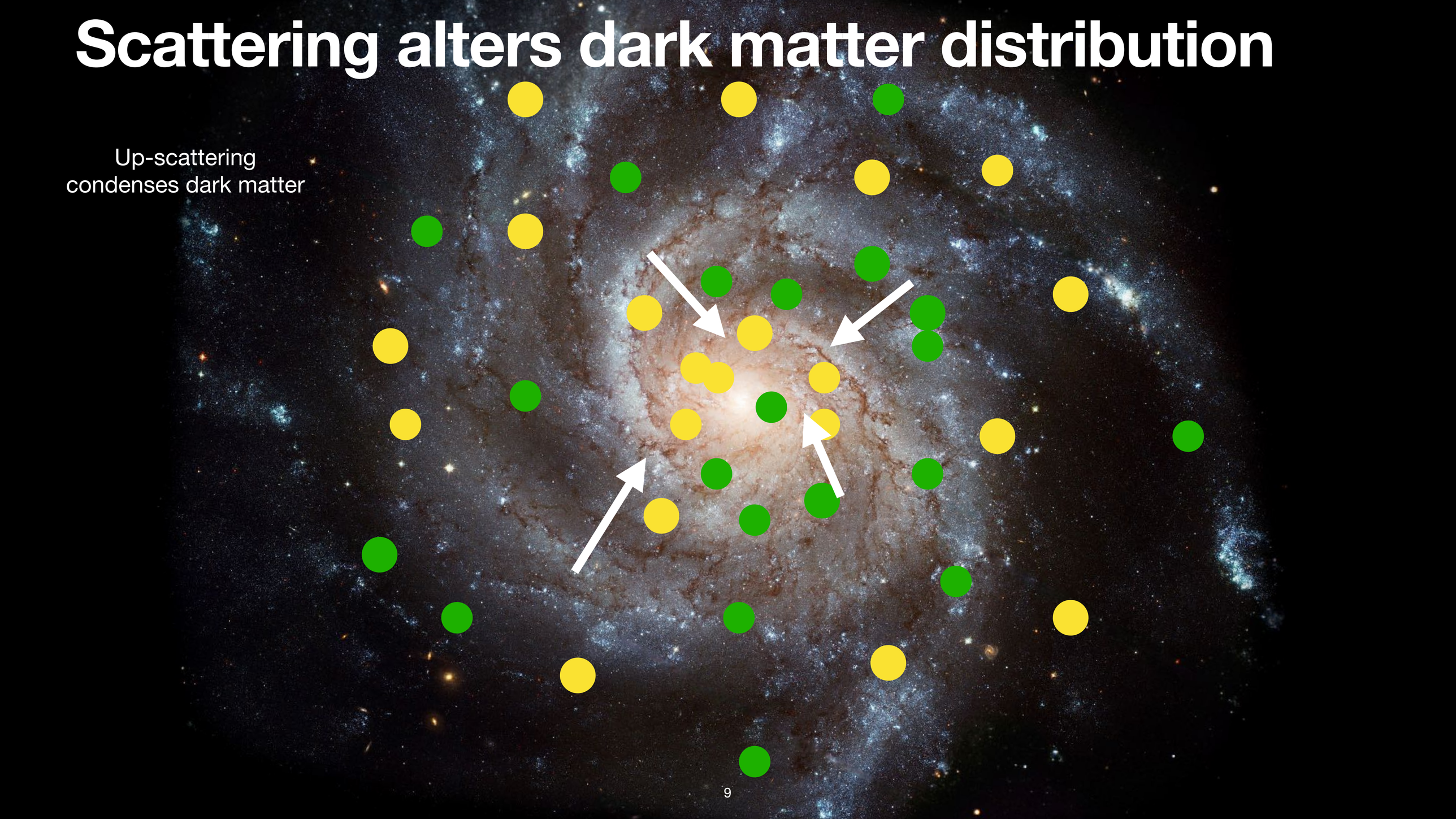
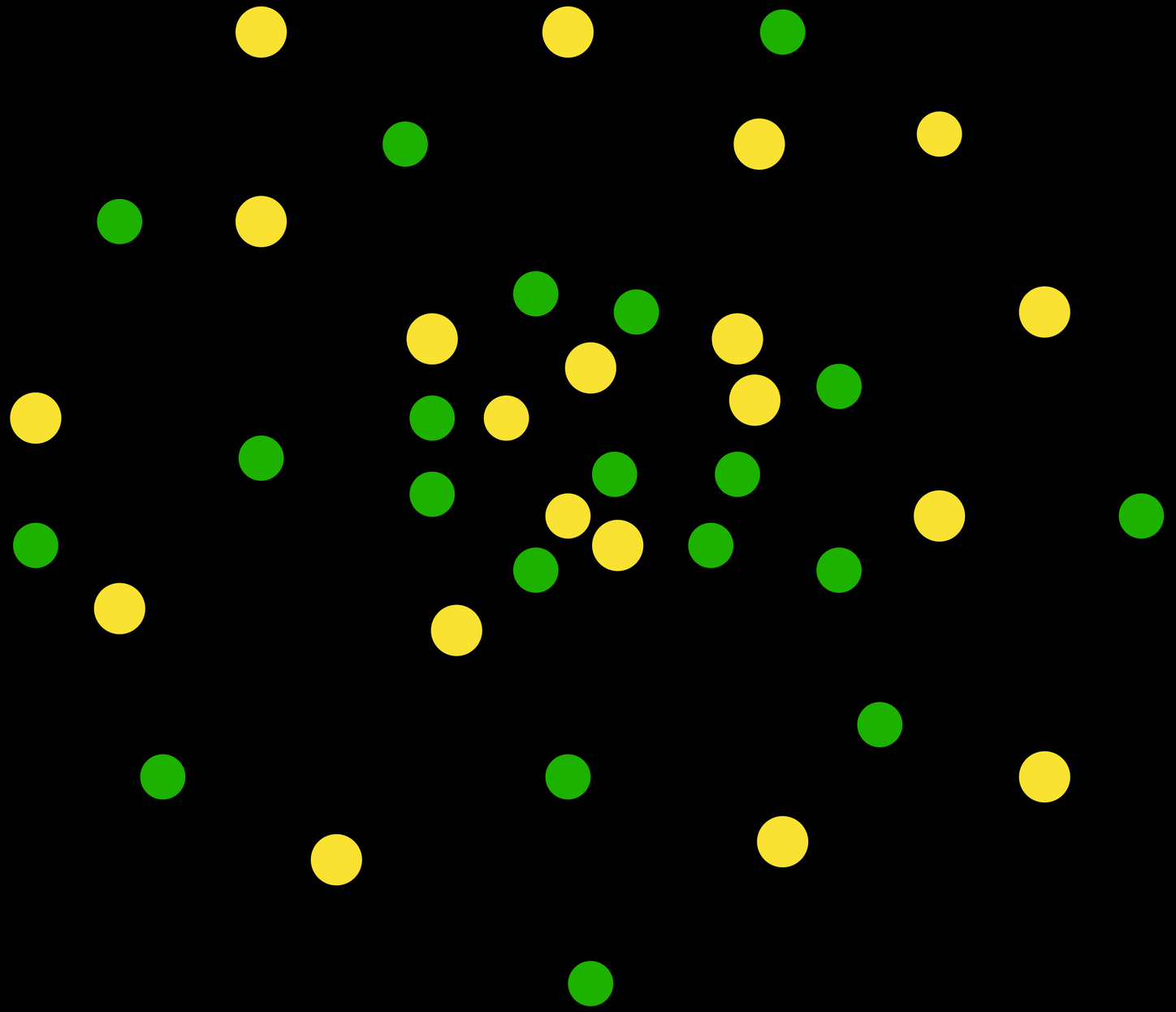


Dark matter is sub-resolution

- Macro simulation particle
  - $2 \times 10^5 M_\odot$
  - (i.e. way too many physical particles)
  - statistical sampling of dark matter distribution



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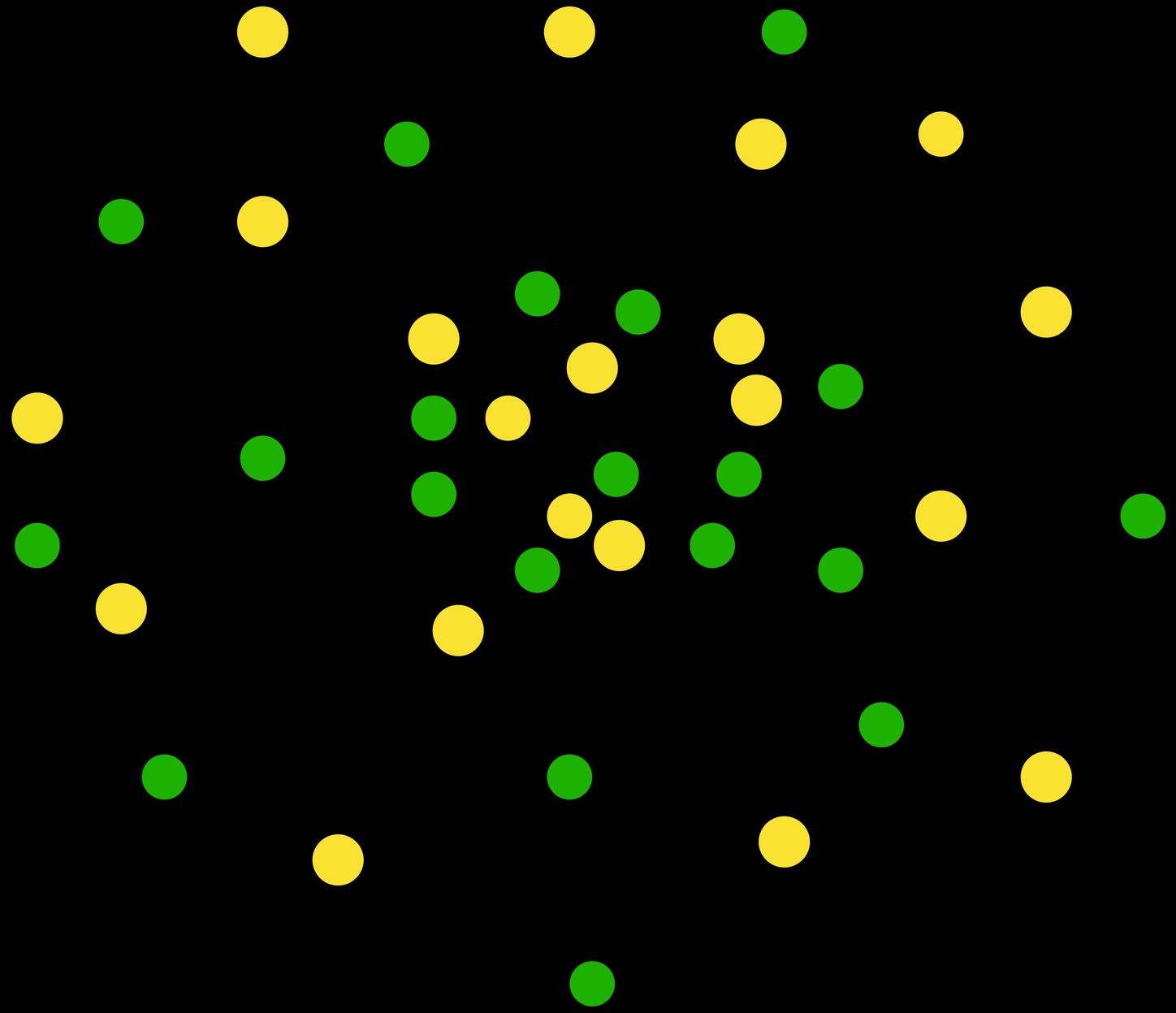
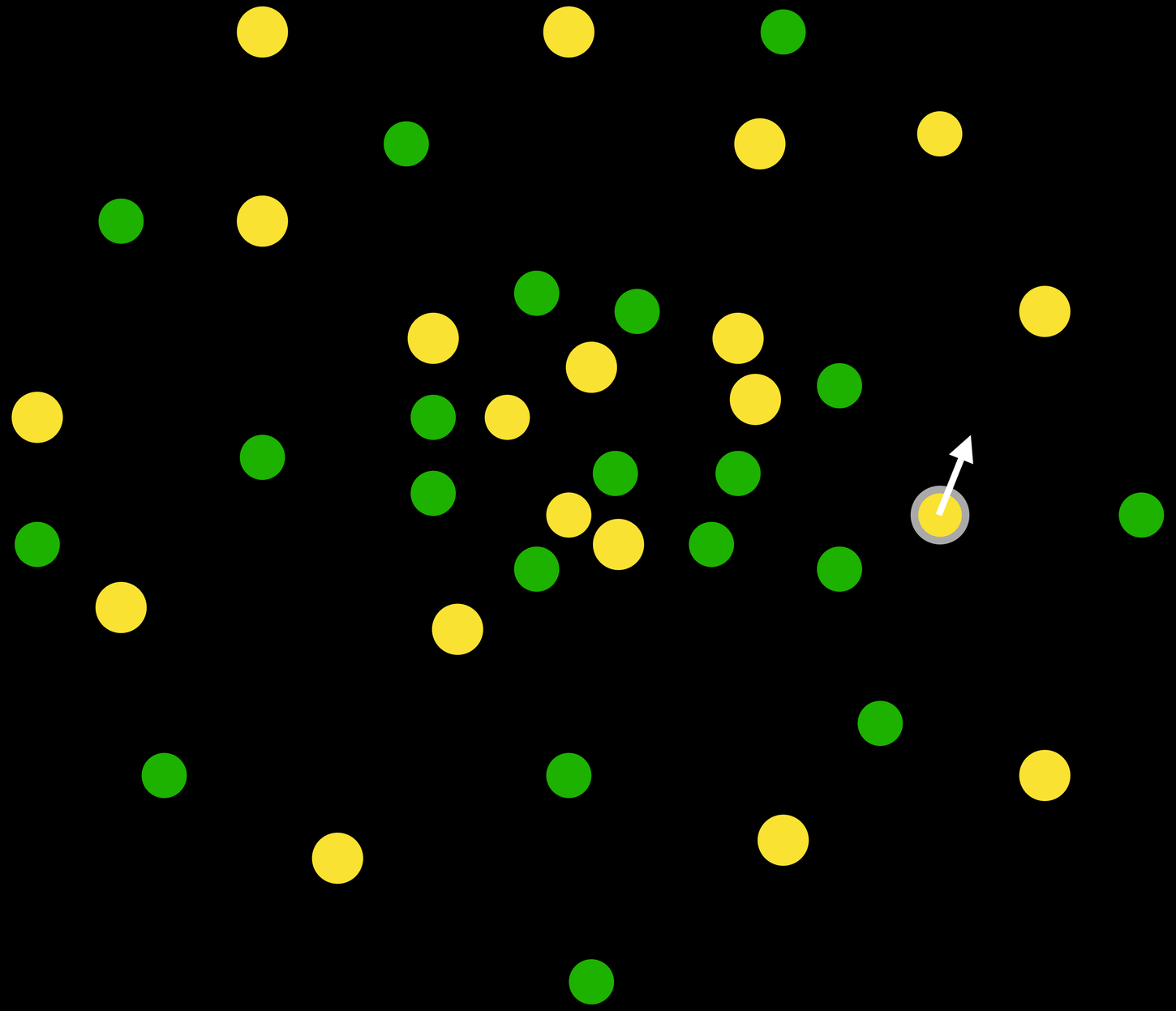


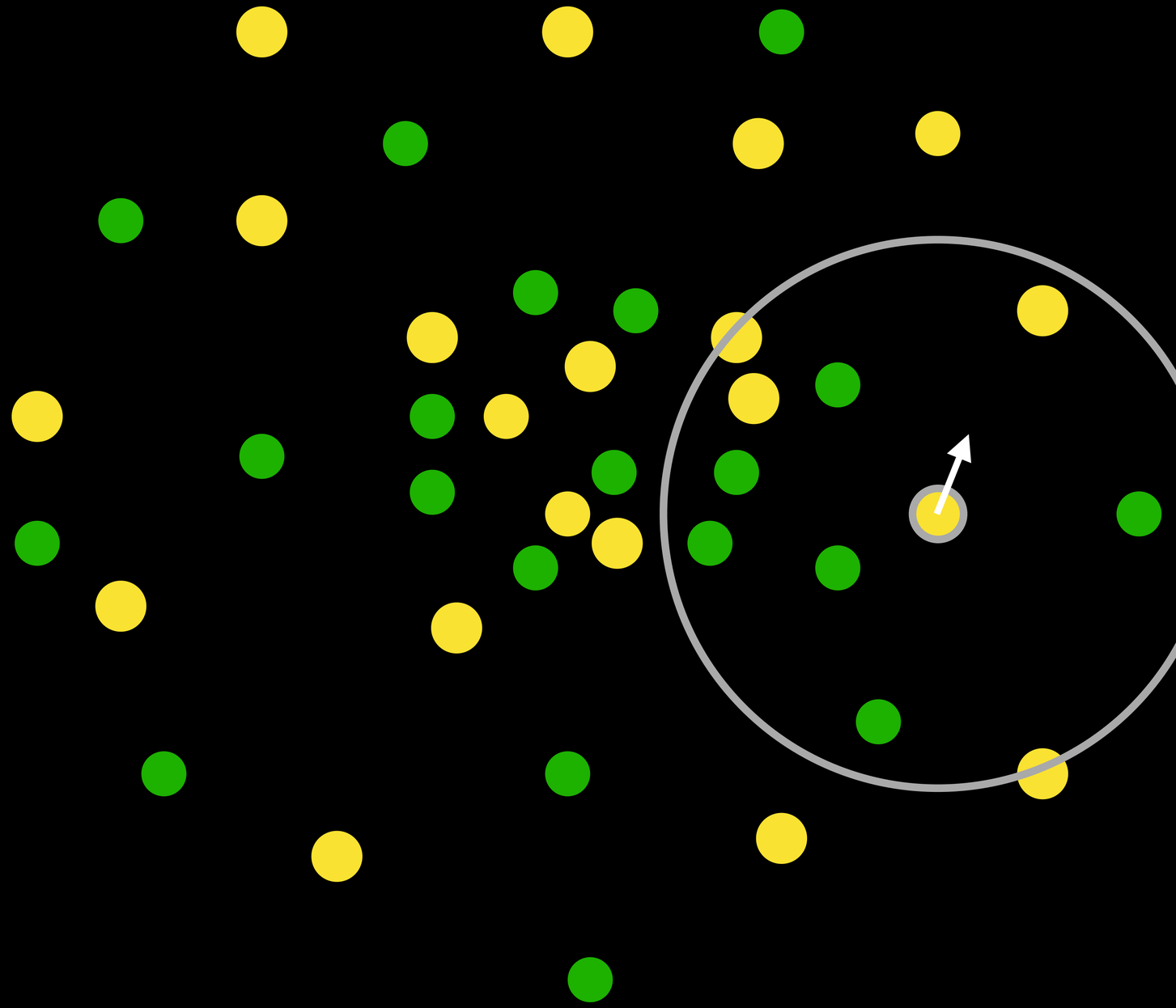
Dark matter is sub-resolution

- Select particle



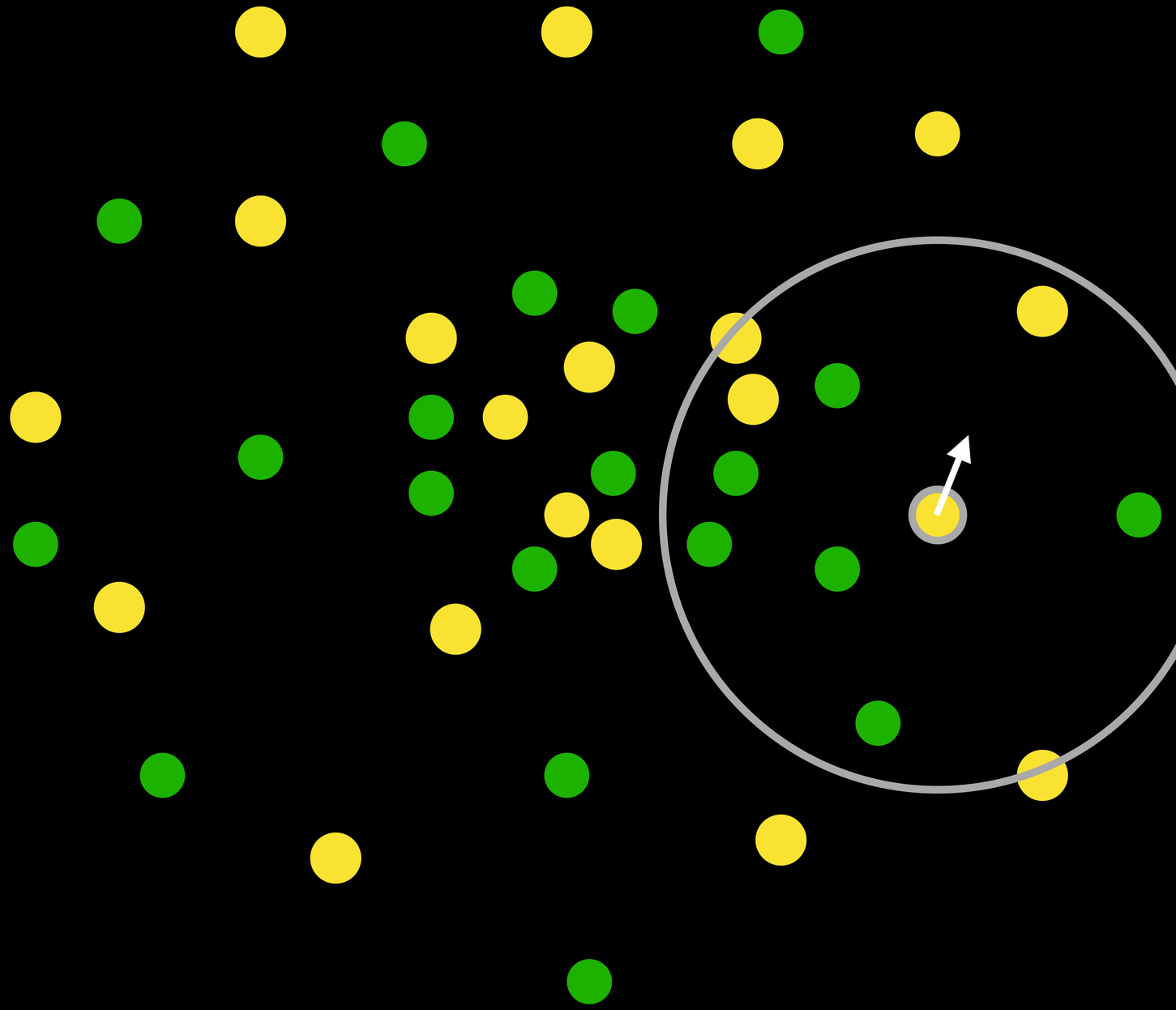
Dark matter is sub-resolution

- Select particle
- Identify nearby particles



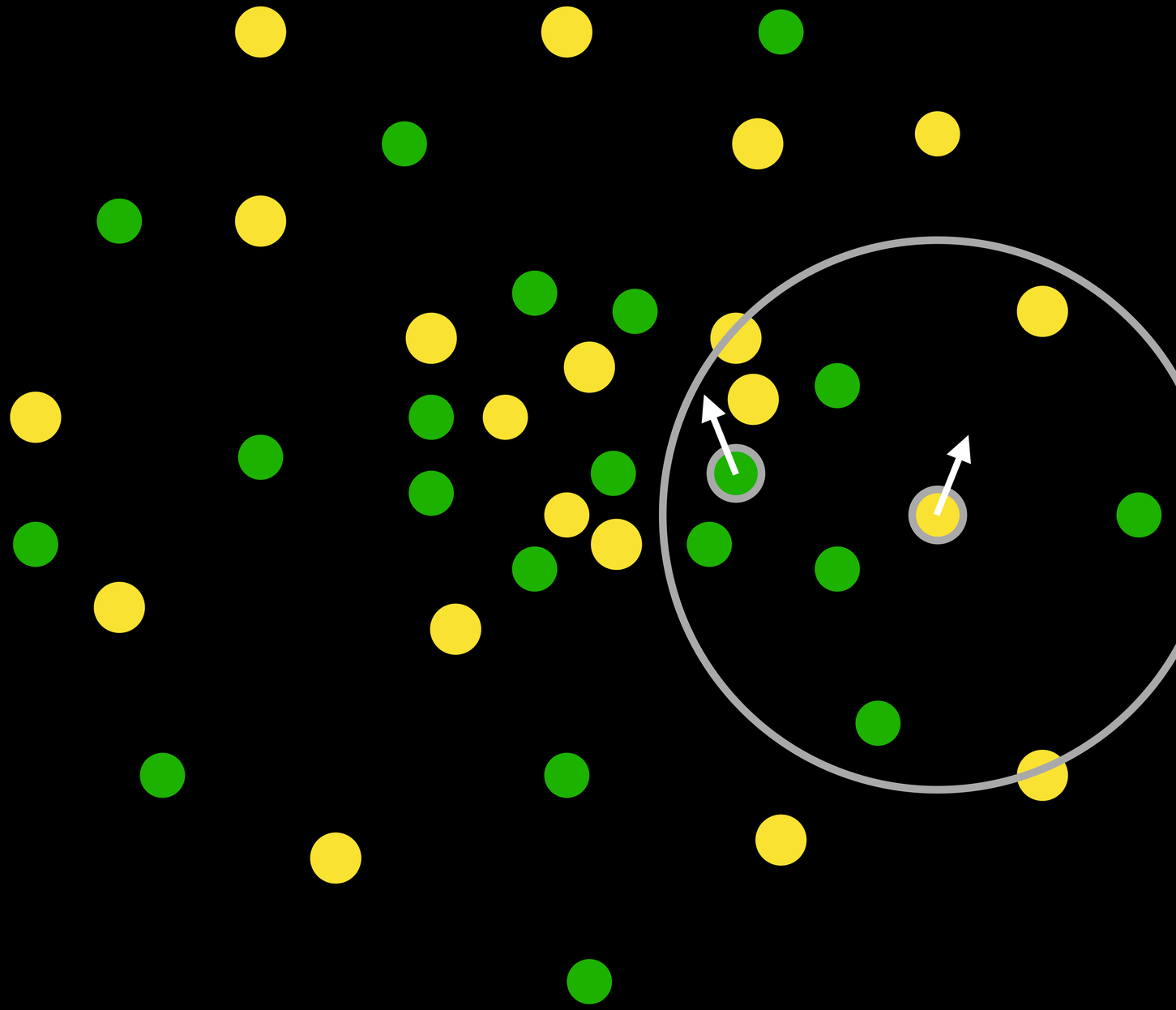
Dark matter is sub-resolution

- Select particle
- Identify nearby particles
- Scattering probability
  - Does not scatter



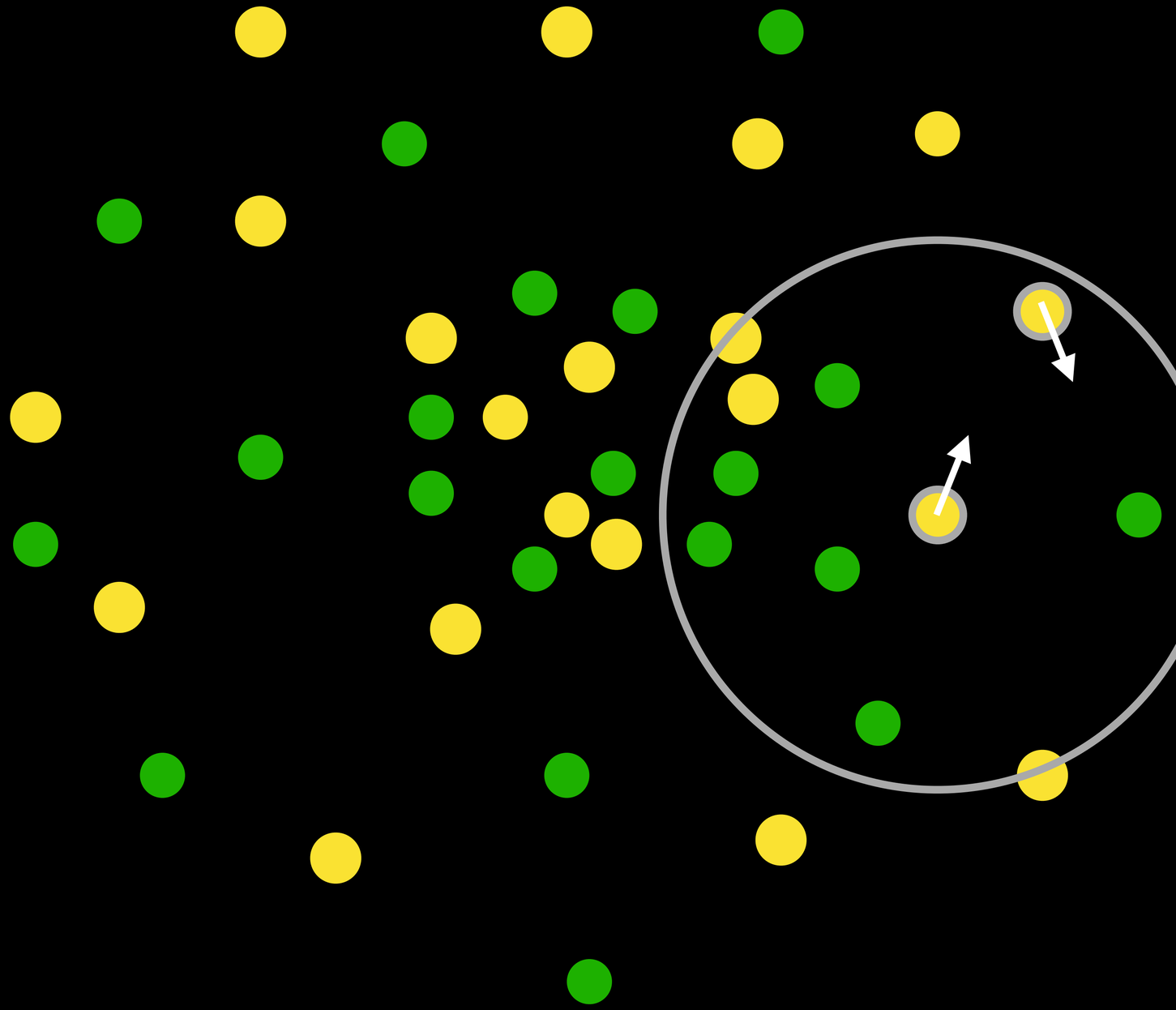
Dark matter is sub-resolution

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



Dark matter is sub-resolution

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



Dark matter is sub-resolution

- Select particle
- Identify nearby particles
- Scattering probability
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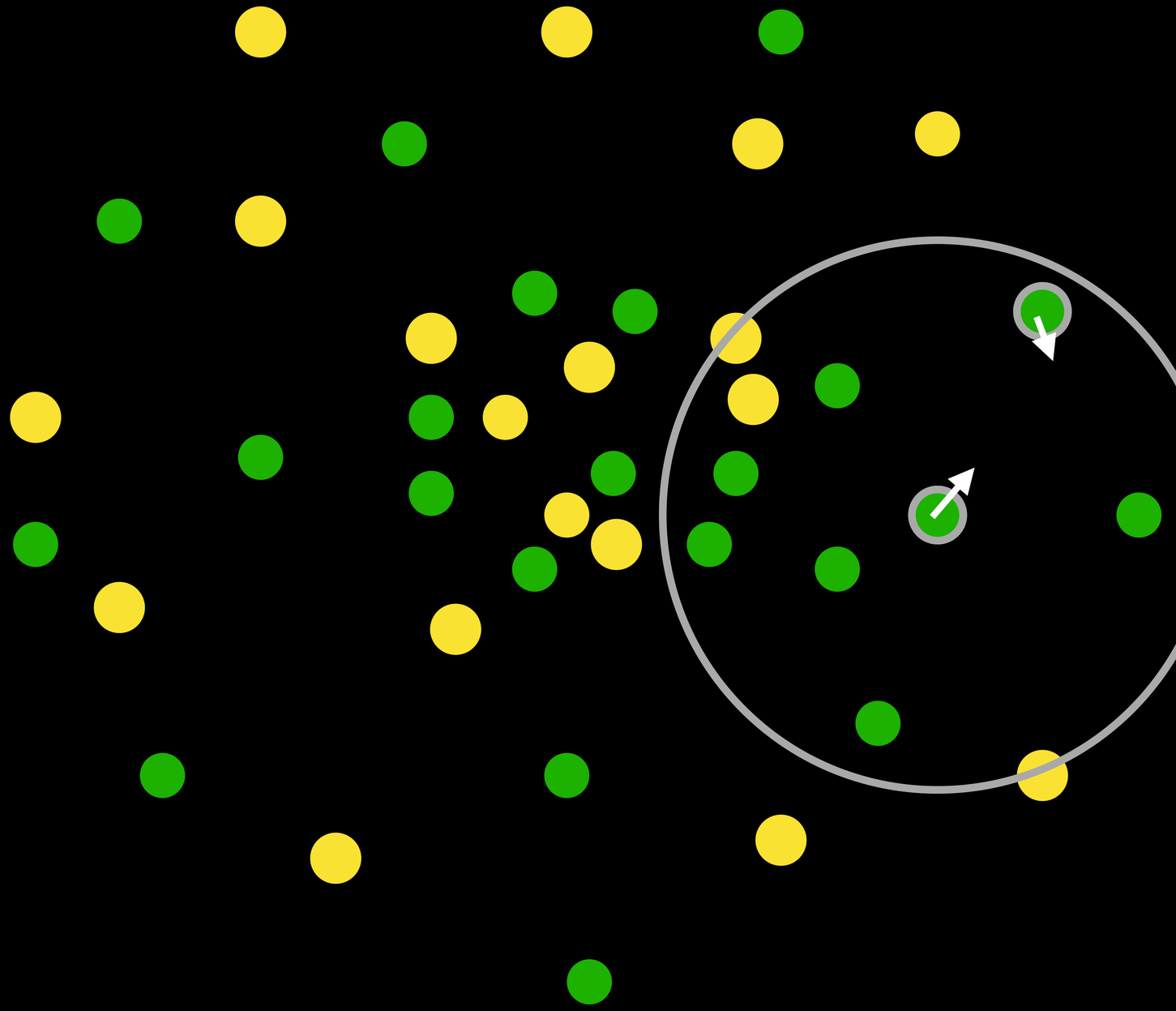
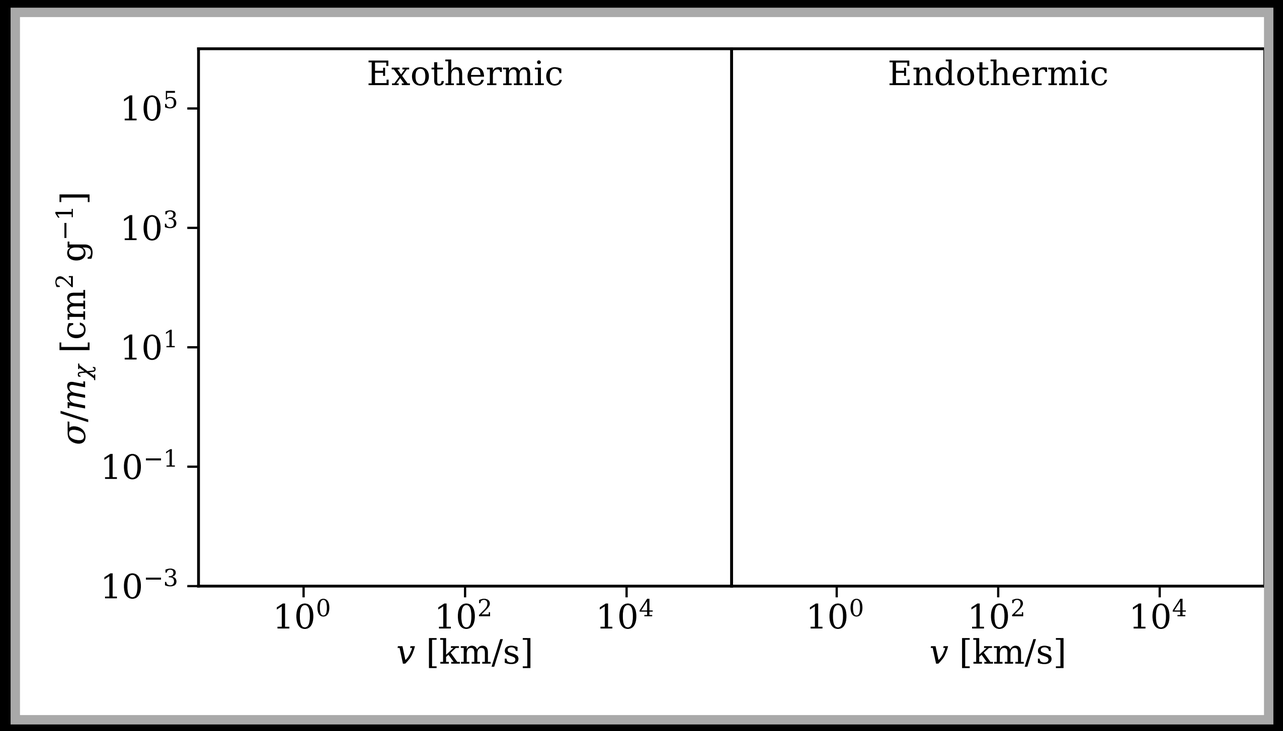
  - Elastic scattering with opposite state
  - Elastic scattering with same state
  - Inelastic scattering with same state



Scattering cross sections determine likelihood of reaction



Vogelsberger+ 2019

O'Neil+ 2023

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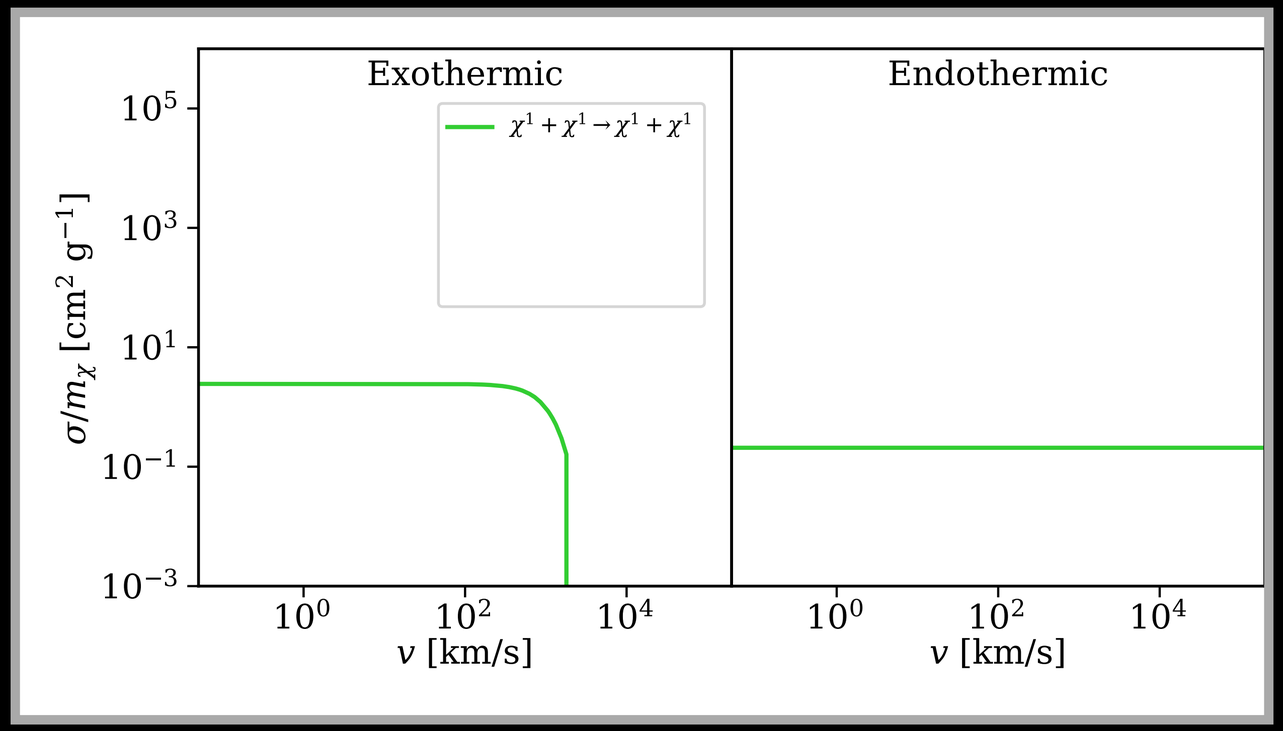

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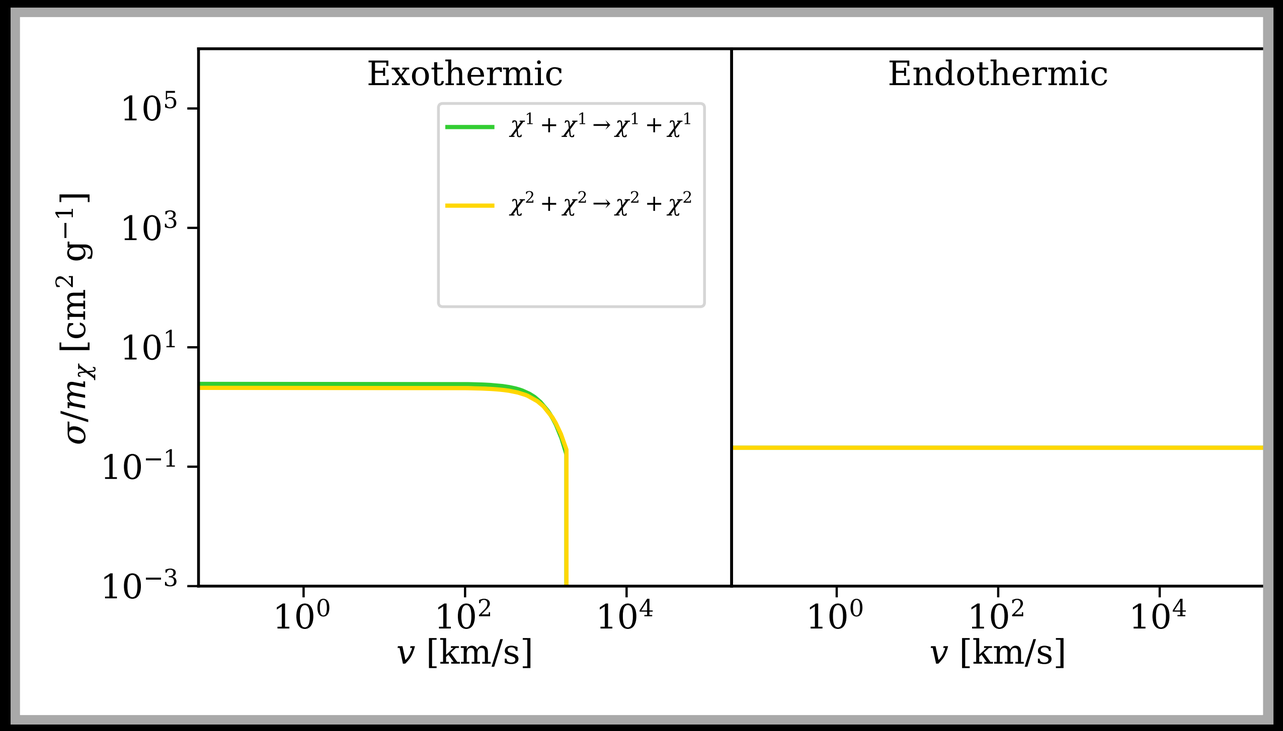

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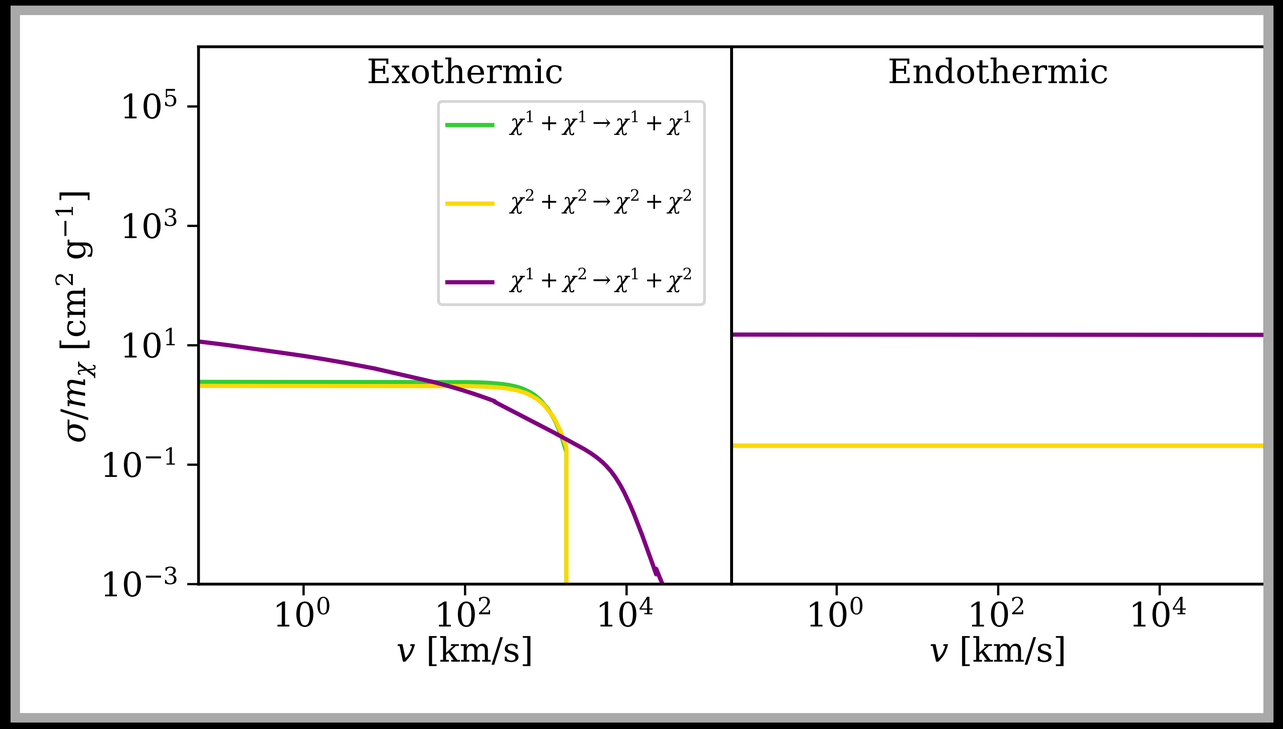

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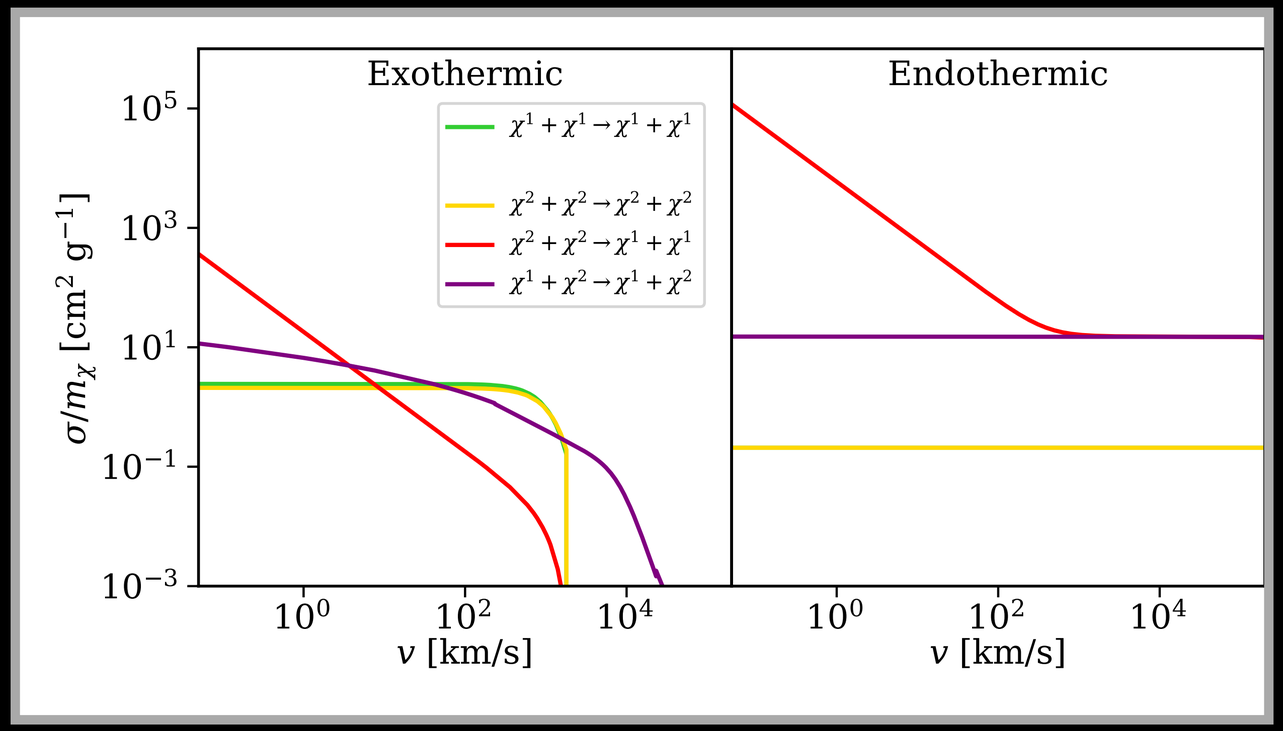

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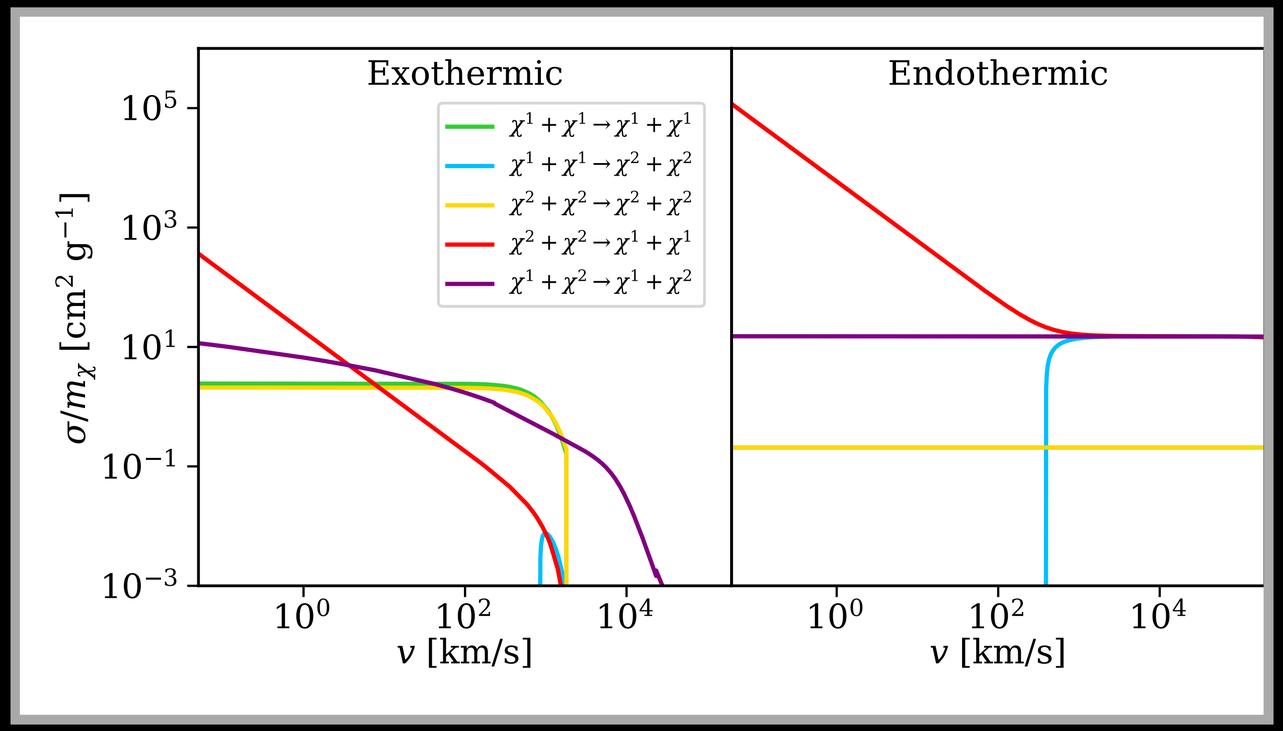

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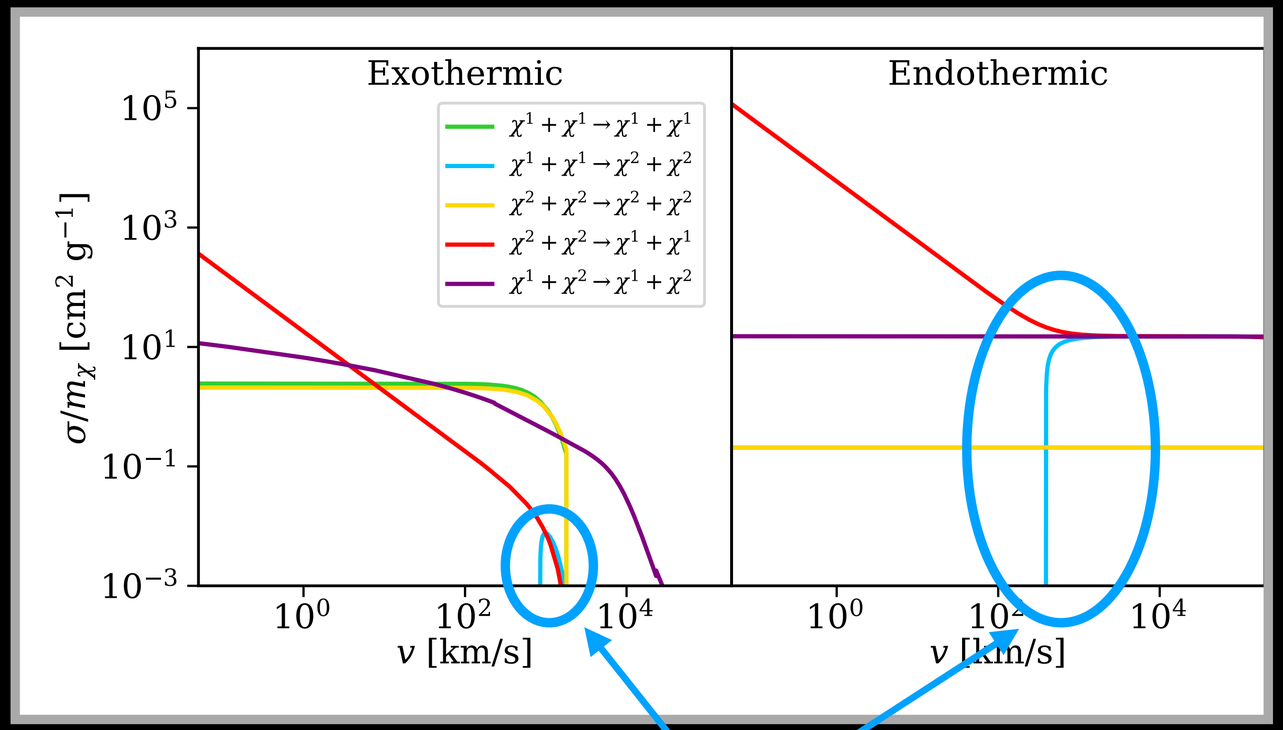
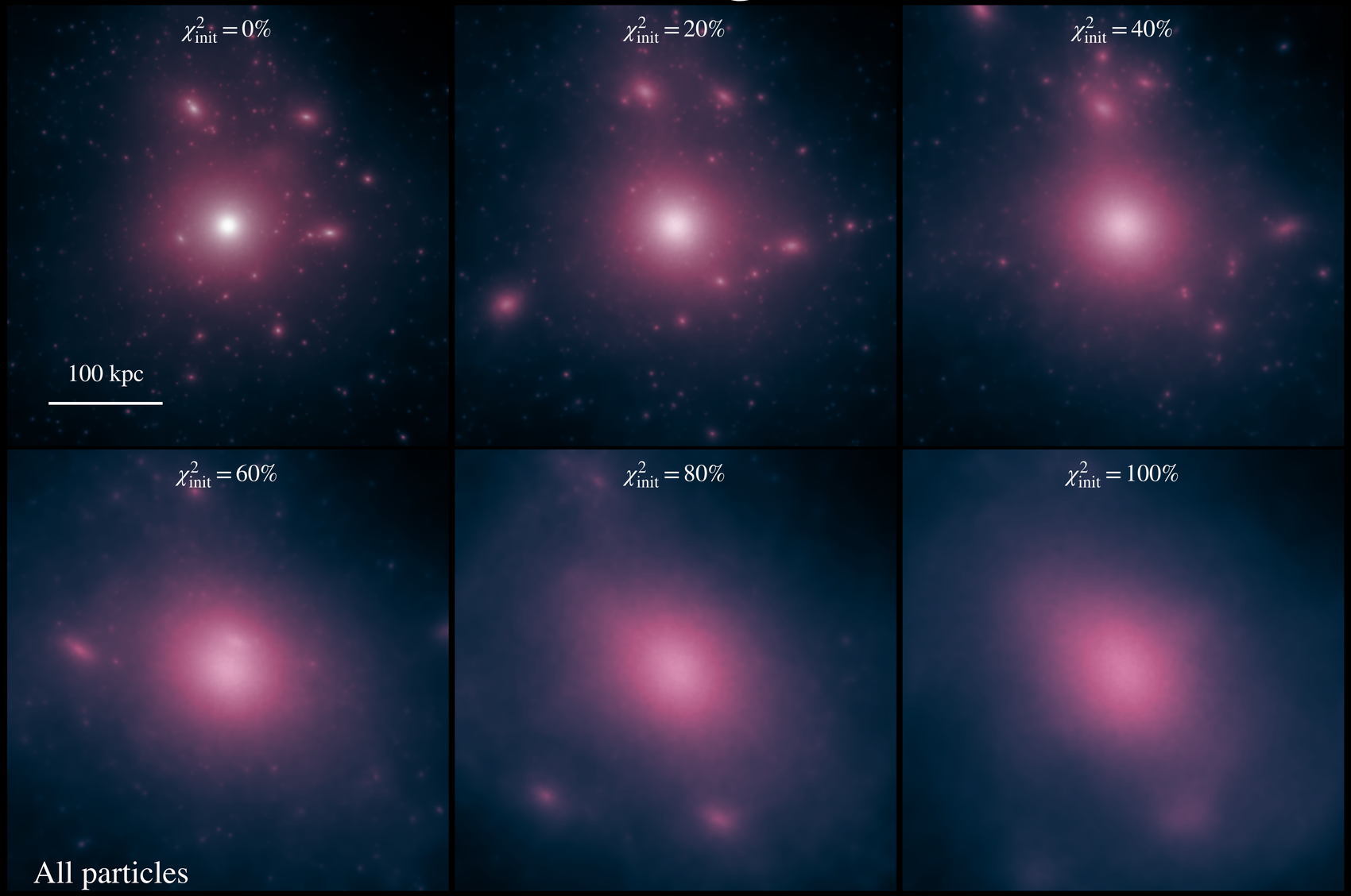
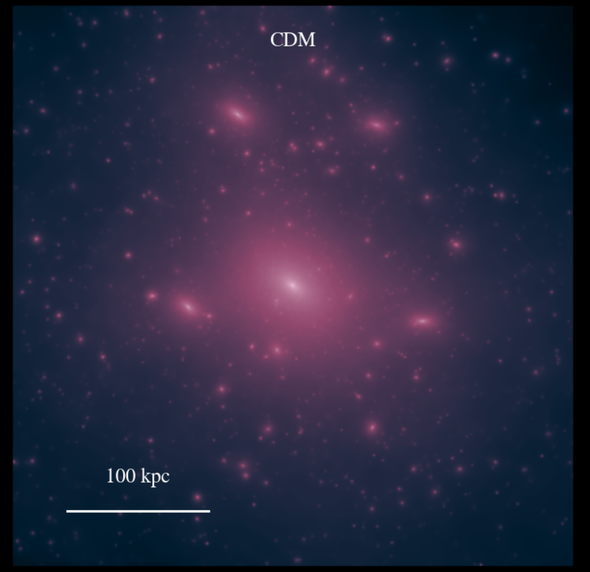


Aidan Leonard, MIT

Simulate varying initial states

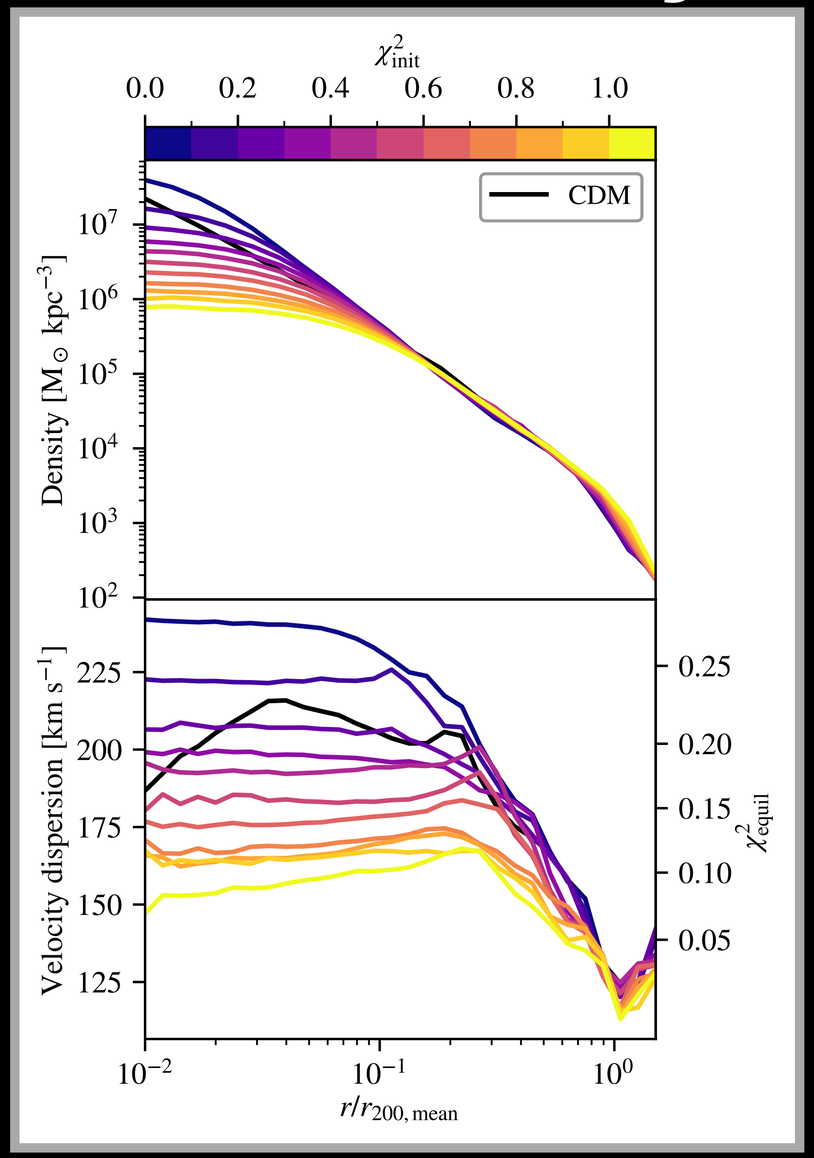




- Same initial cosmological conditions
- Set particle state at simulation start
- Ran 11 simulations with initial excited state fraction at intervals of 10%

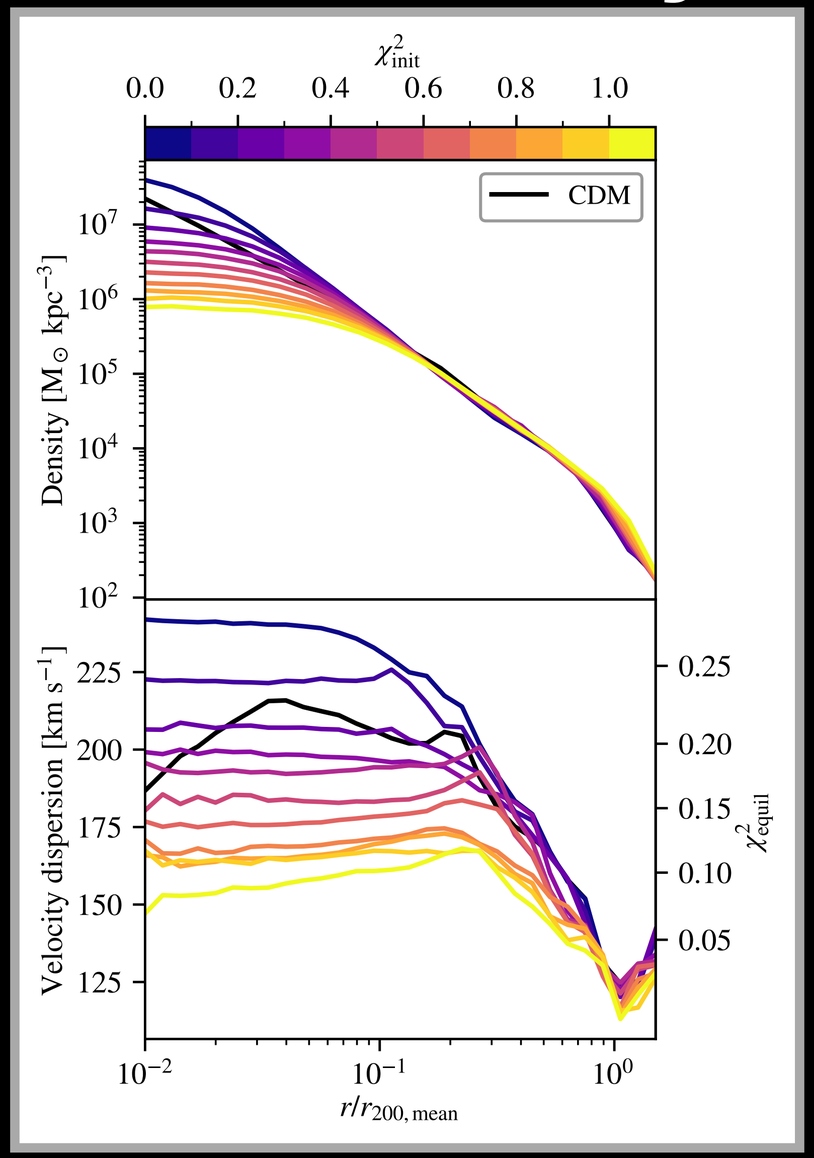
Leonard+ 2024

Main halo density depends on initial state fraction



Leonard+ 2024

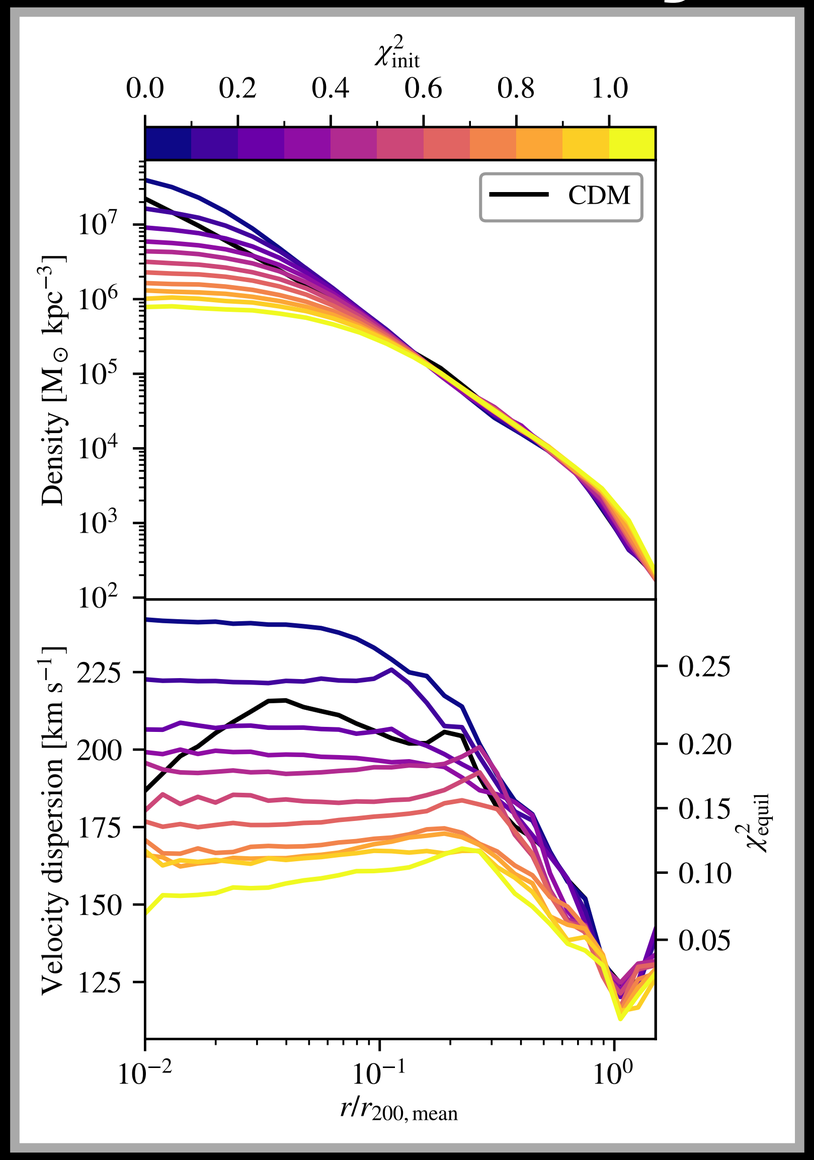
Main halo density depends on initial state fraction



Increasing initial excited state fraction gives lower density

Leonard+ 2024

Main halo density depends on initial state fraction

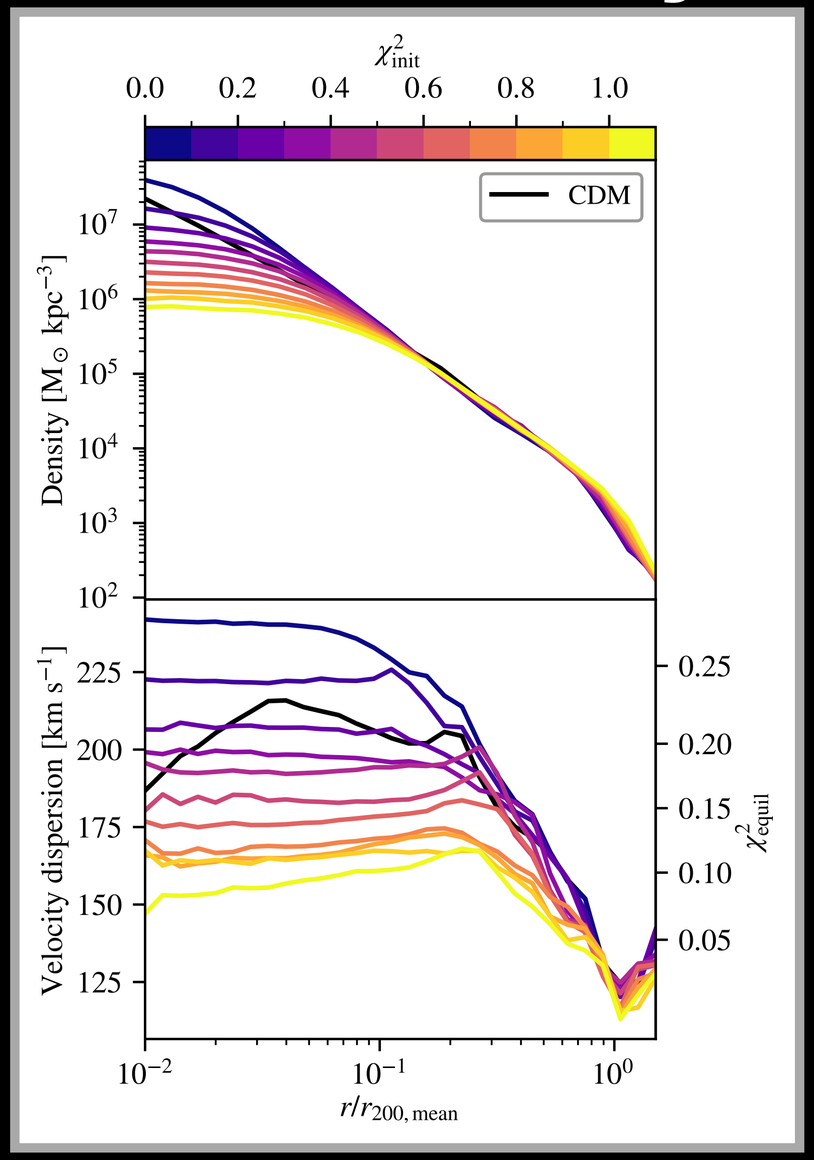


Increasing initial excited state fraction gives lower density

More excited particles

Leonard+ 2024

Main halo density depends on initial state fraction



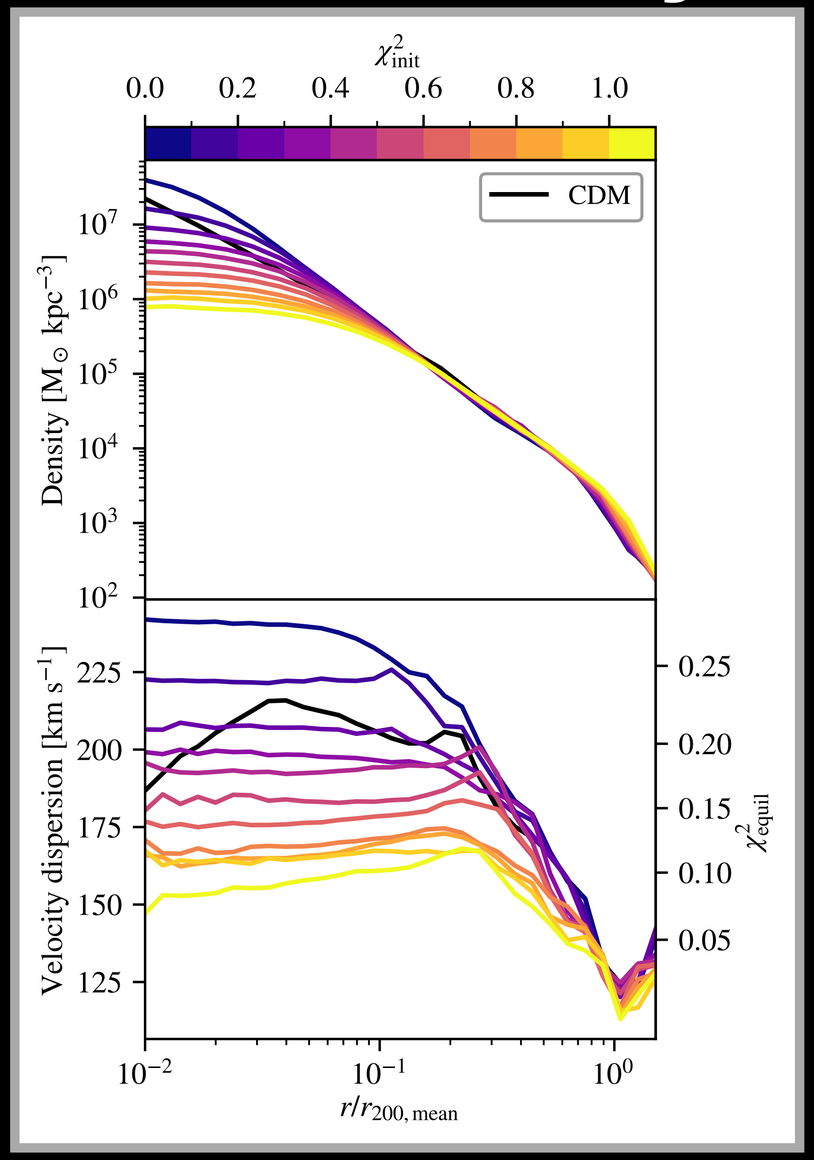
Increasing initial excited state fraction gives lower density

More excited particles

→ More down-scattering

Leonard+ 2024

Main halo density depends on initial state fraction



Increasing initial excited state fraction gives lower density

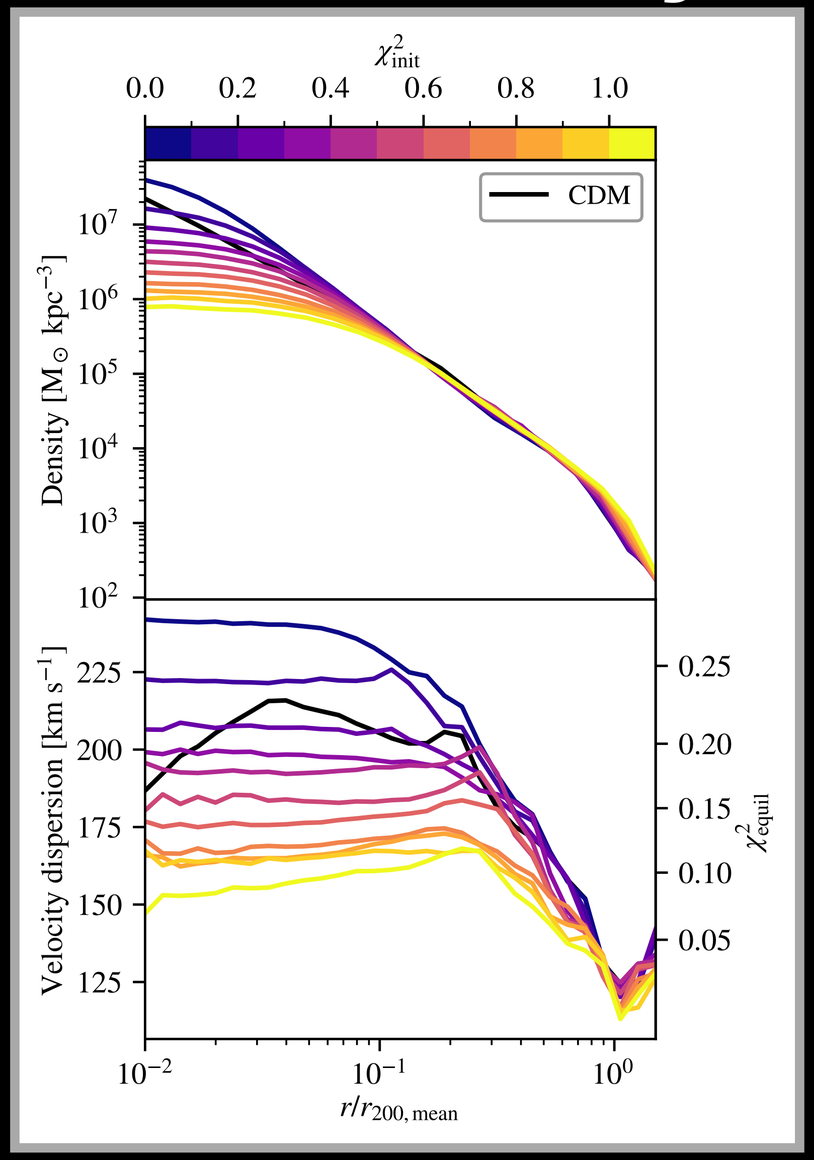
More excited particles

→ More down-scattering

→ Velocity kicks

Leonard+ 2024

Main halo density depends on initial state fraction



Increasing initial excited state fraction gives lower density

More excited particles

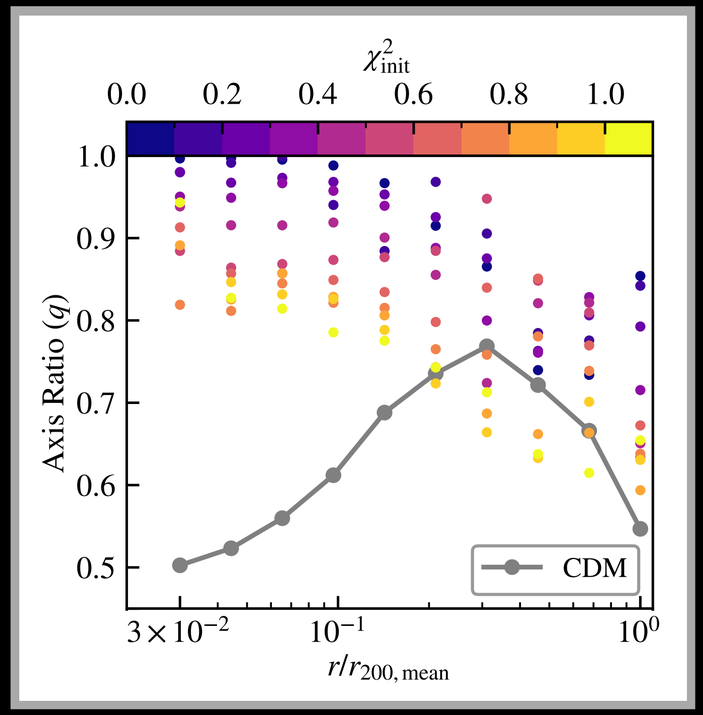
→ More down-scattering

→ Velocity kicks

→ Particles move outwards

Leonard+ 2024

Up-scattering makes halos spherical



Leonard+ 2024

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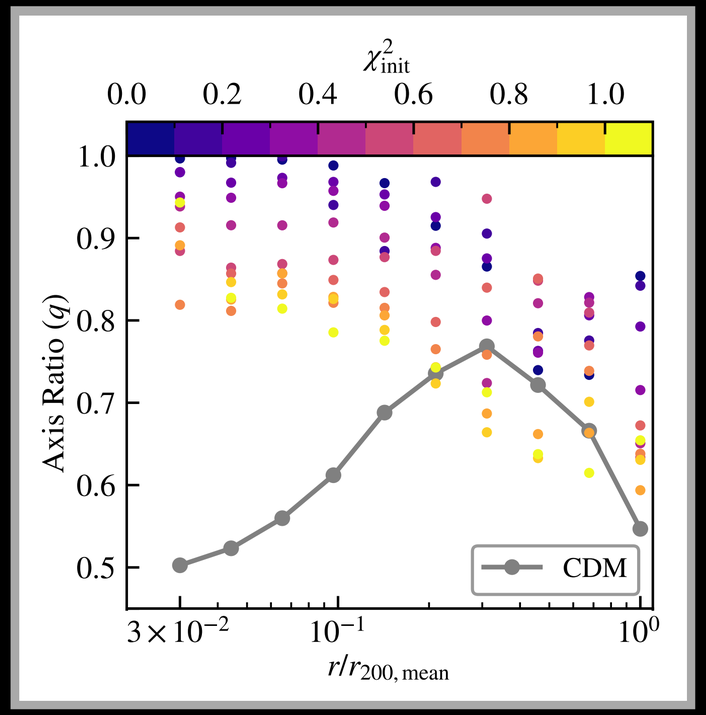
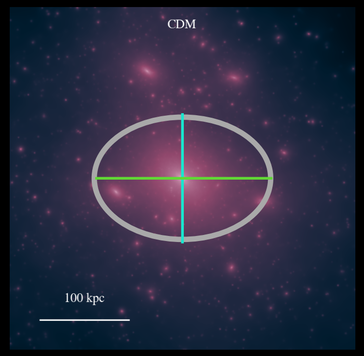
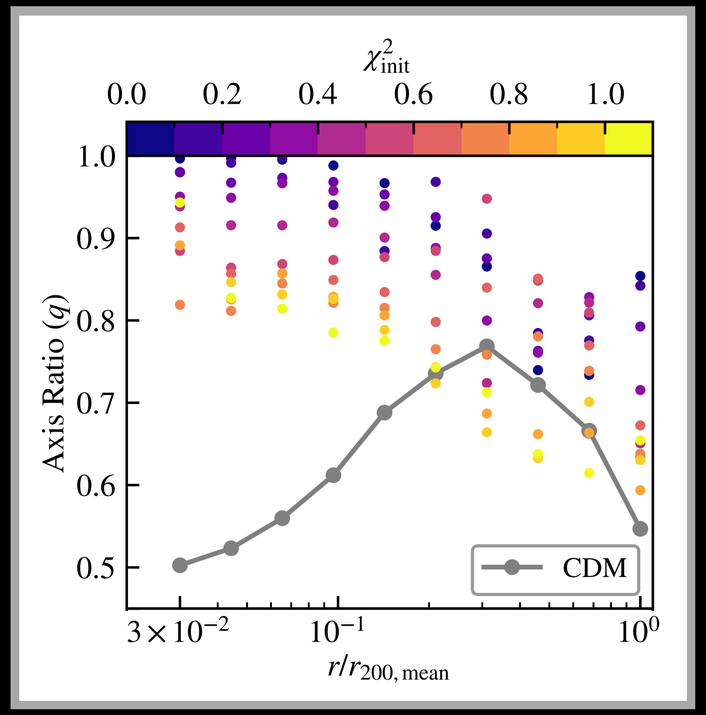
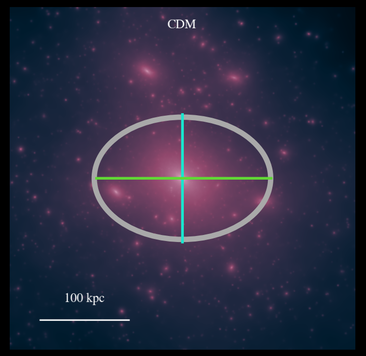


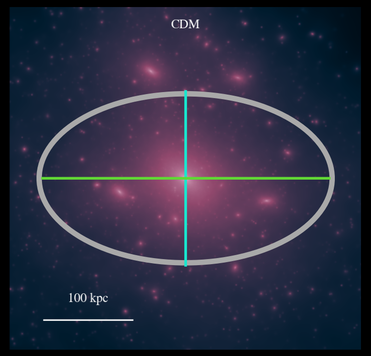


Leonard+ 2024

Up-scattering makes halos spherical

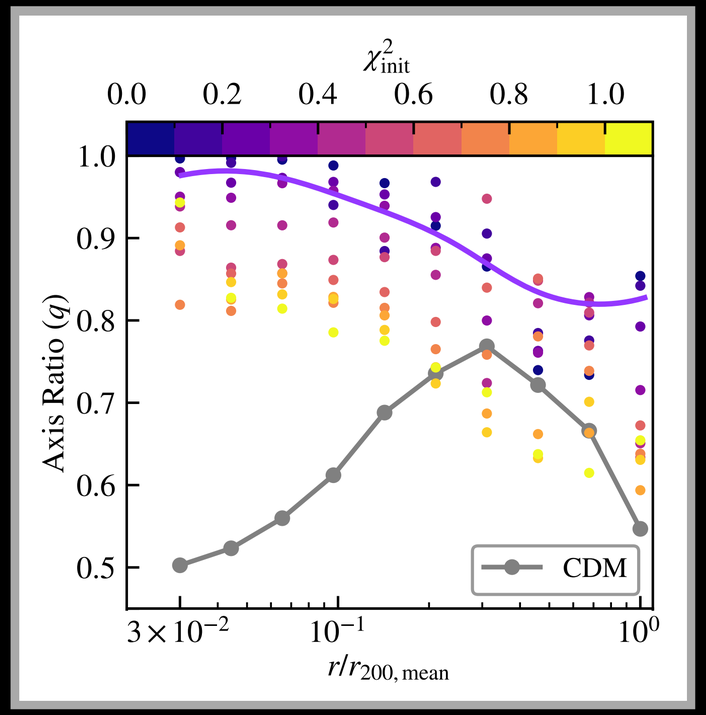




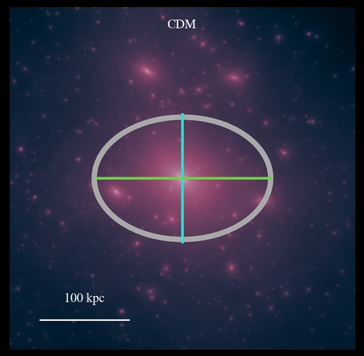


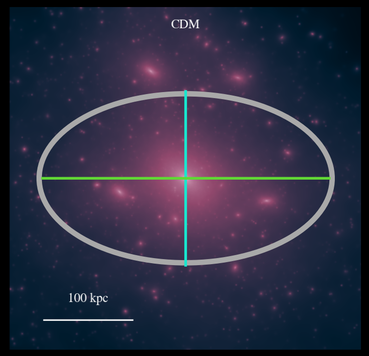
Leonard+ 2024

Up-scattering makes halos spherical



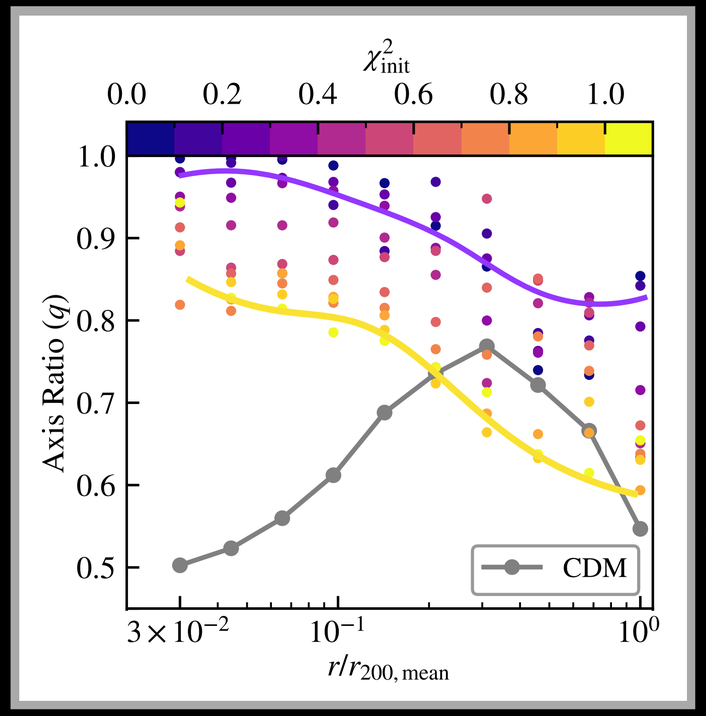
Fits at various radii for low initial excited fraction





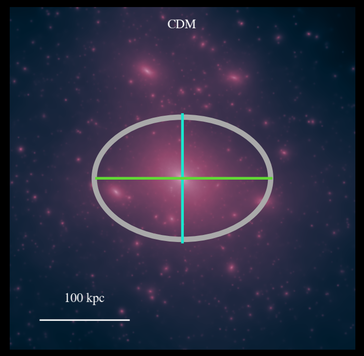
Leonard+ 2024

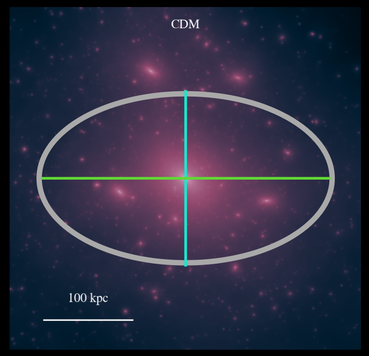
Up-scattering makes halos spherical



Fits at various radii for low initial excited fraction

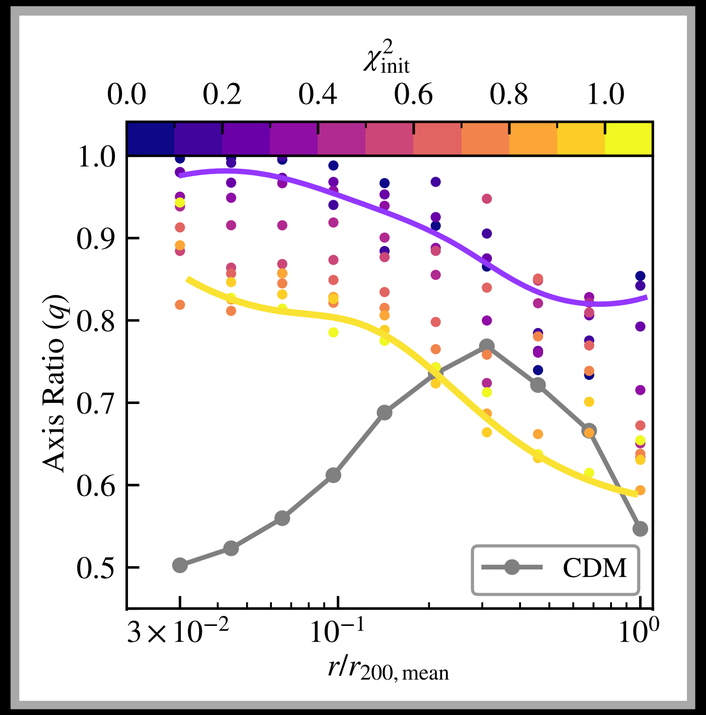
Fits at various radii for high initial excited fraction





Leonard+ 2024

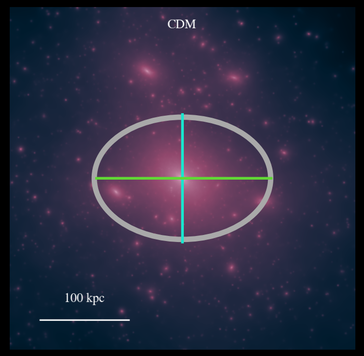
Up-scattering makes halos spherical

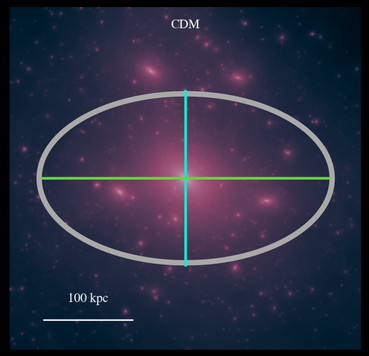


Fits at various radii for low initial excited fraction

Fits at various radii for high initial excited fraction

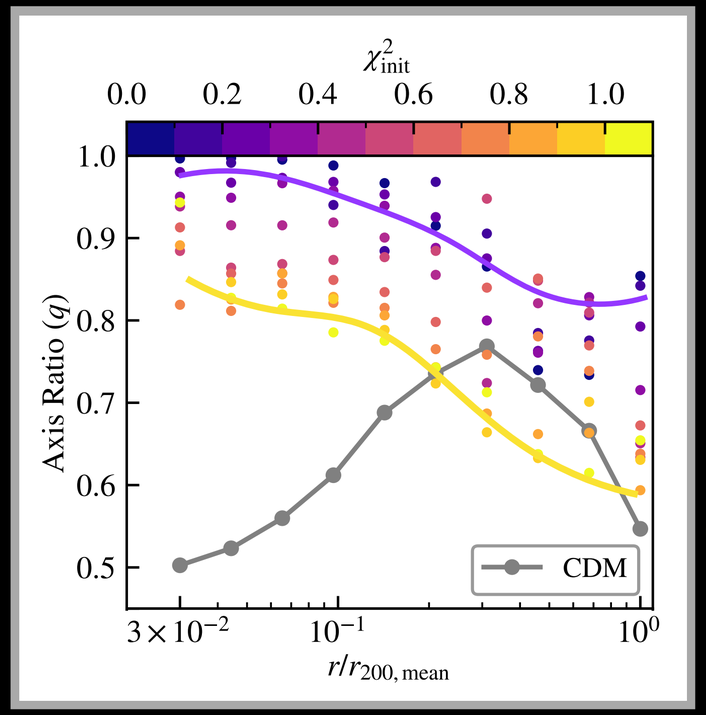
More ground state particles





Leonard+ 2024

Up-scattering makes halos spherical

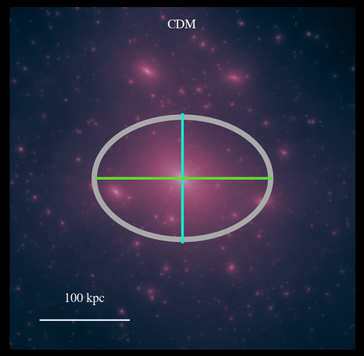


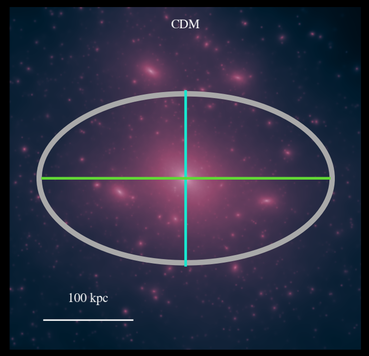
Fits at various radii for low initial excited fraction

Fits at various radii for high initial excited fraction

More ground state particles

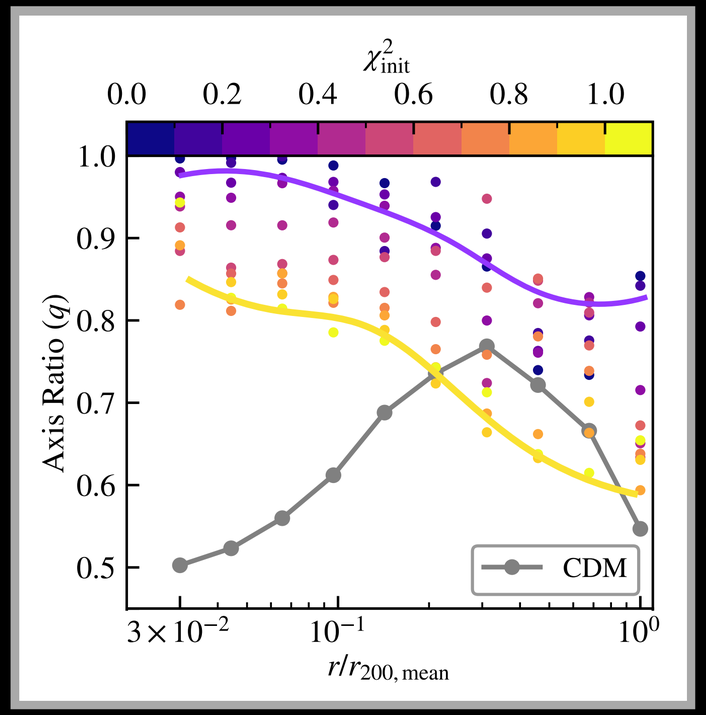
→ More up-scattering





Leonard+ 2024

Up-scattering makes halos spherical



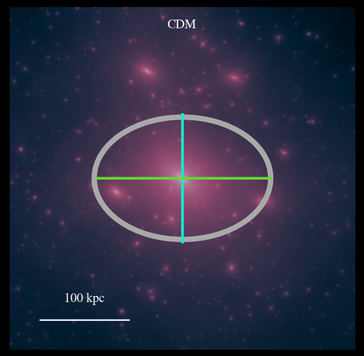
Fits at various radii for low initial excited fraction

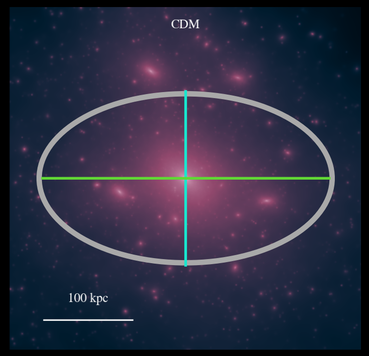
Fits at various radii for high initial excited fraction

More ground state particles

→ More up-scattering

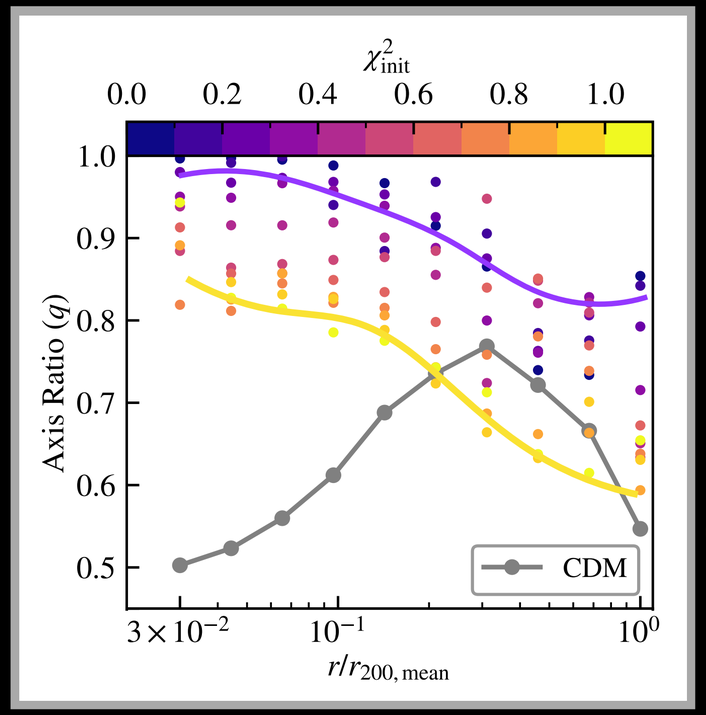
→ Particles fall in





Leonard+ 2024

Up-scattering makes halos spherical



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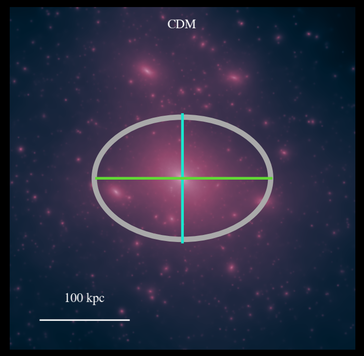
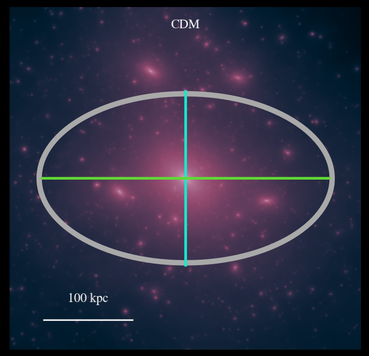




More ground state particles

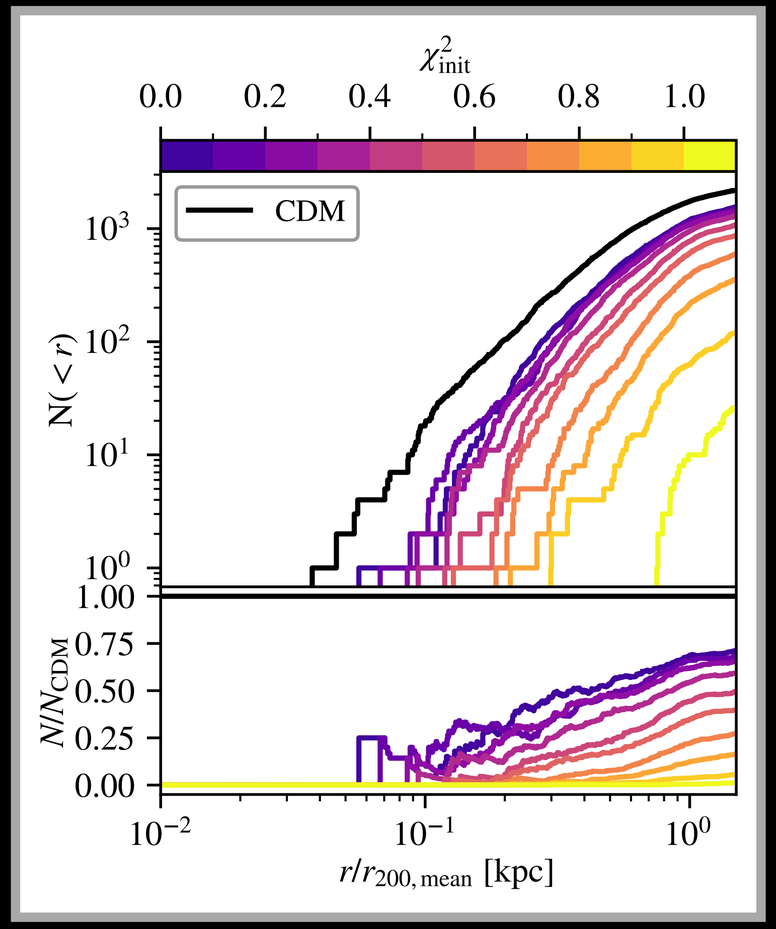
→ More up-scattering

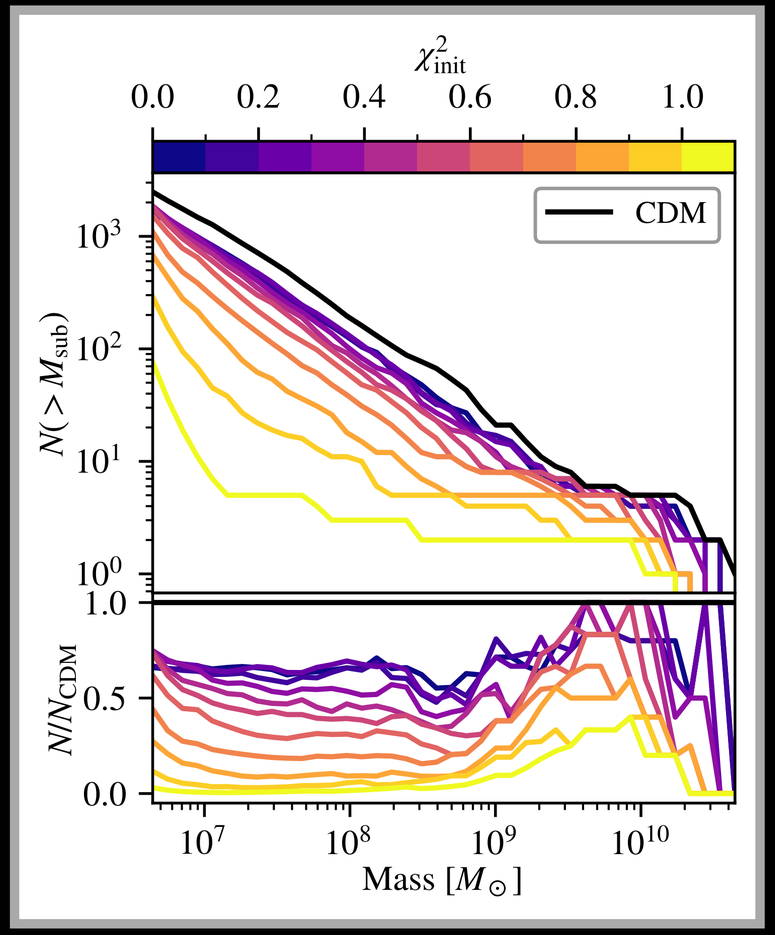
→ Particles fall in

→ Condensing particles lose shape

Leonard+ 2024

Satellites are decreased with all scattering





Leonard+ 2024

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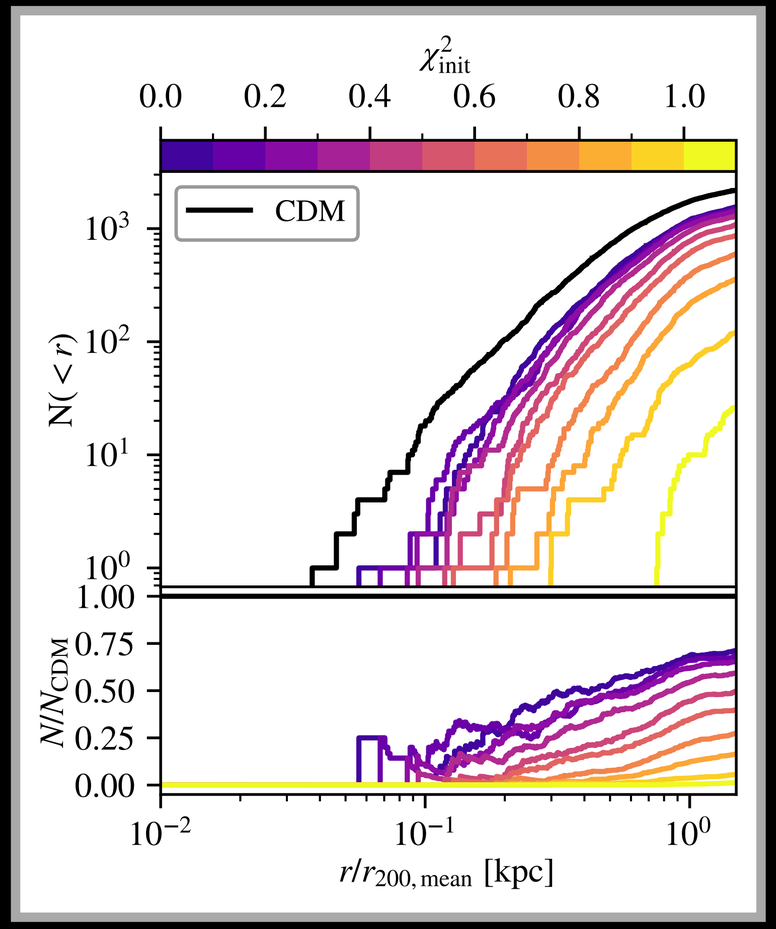
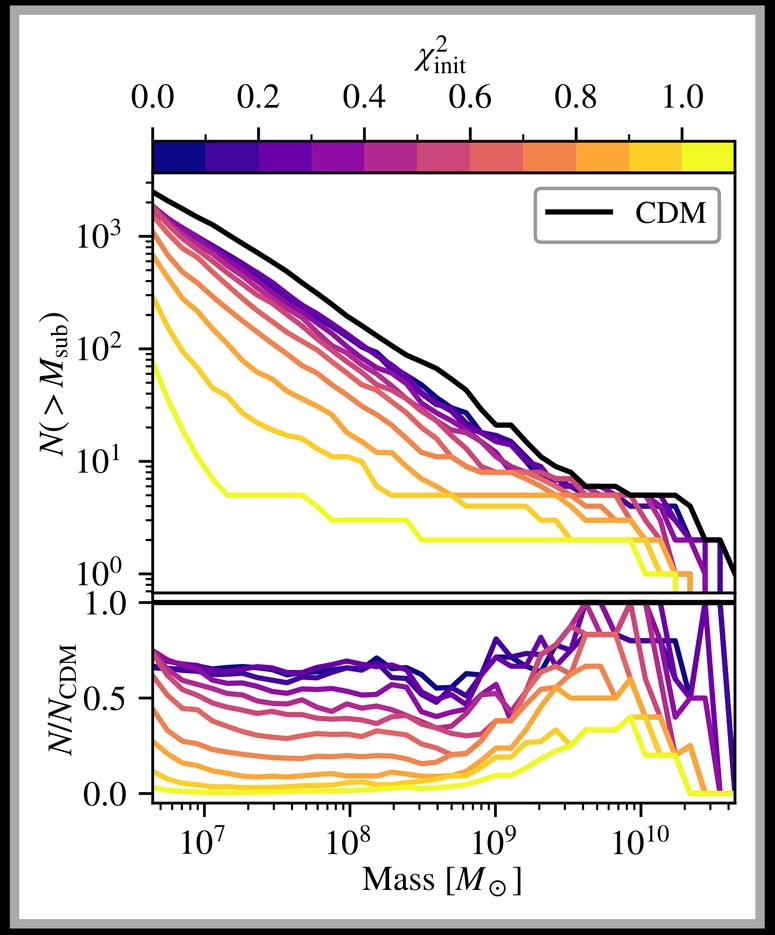
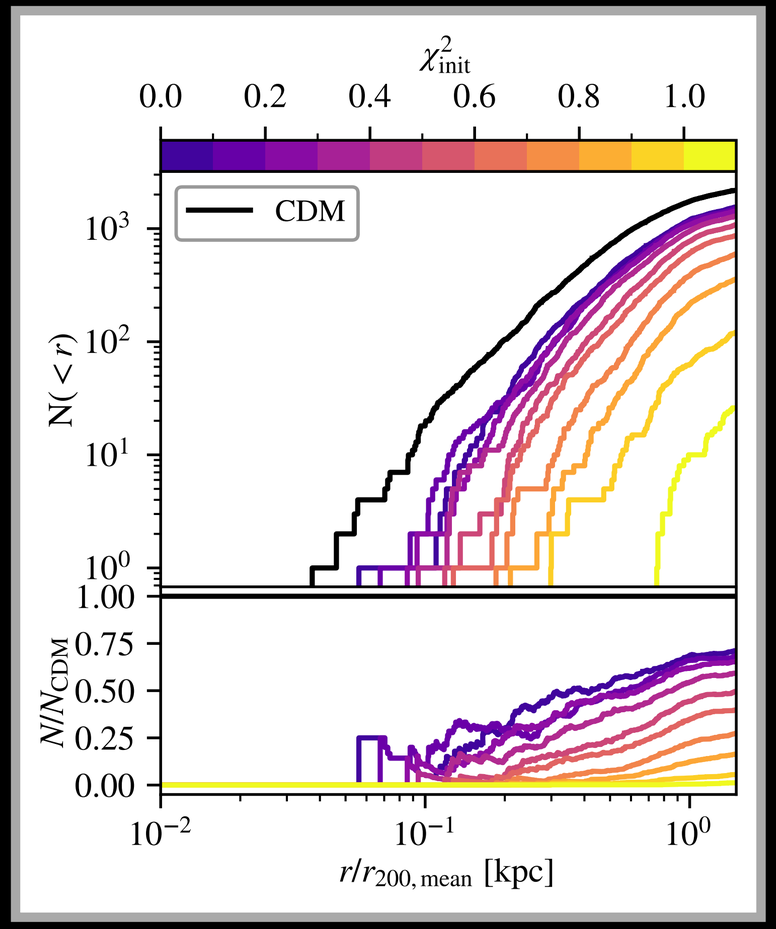


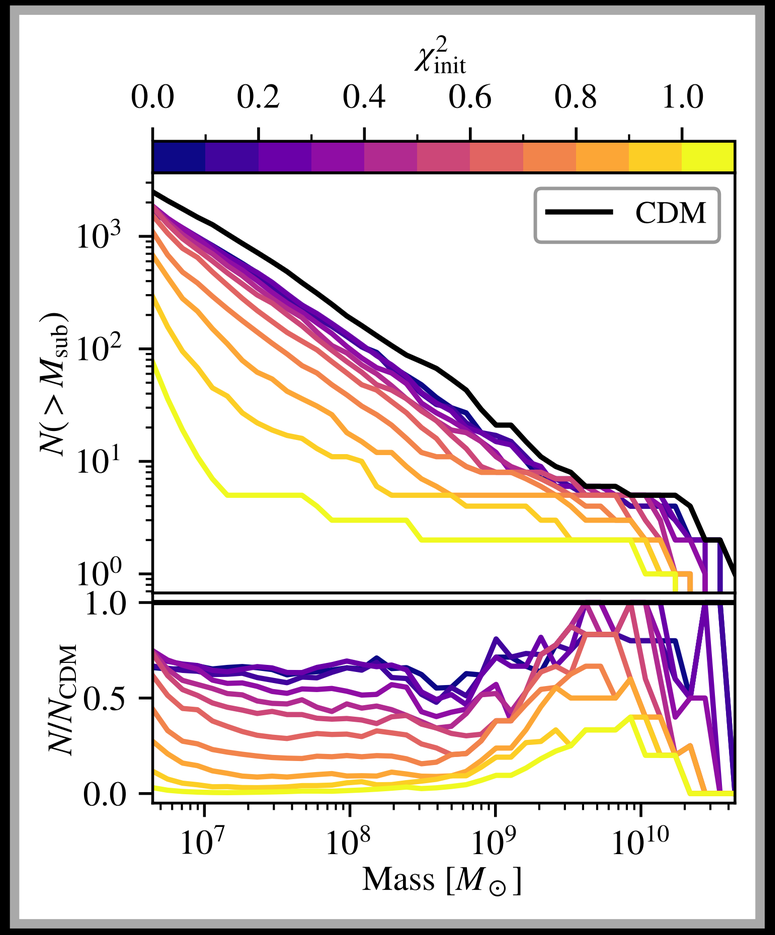


More excited particles

Leonard+ 2024

Satellites are decreased with all scattering



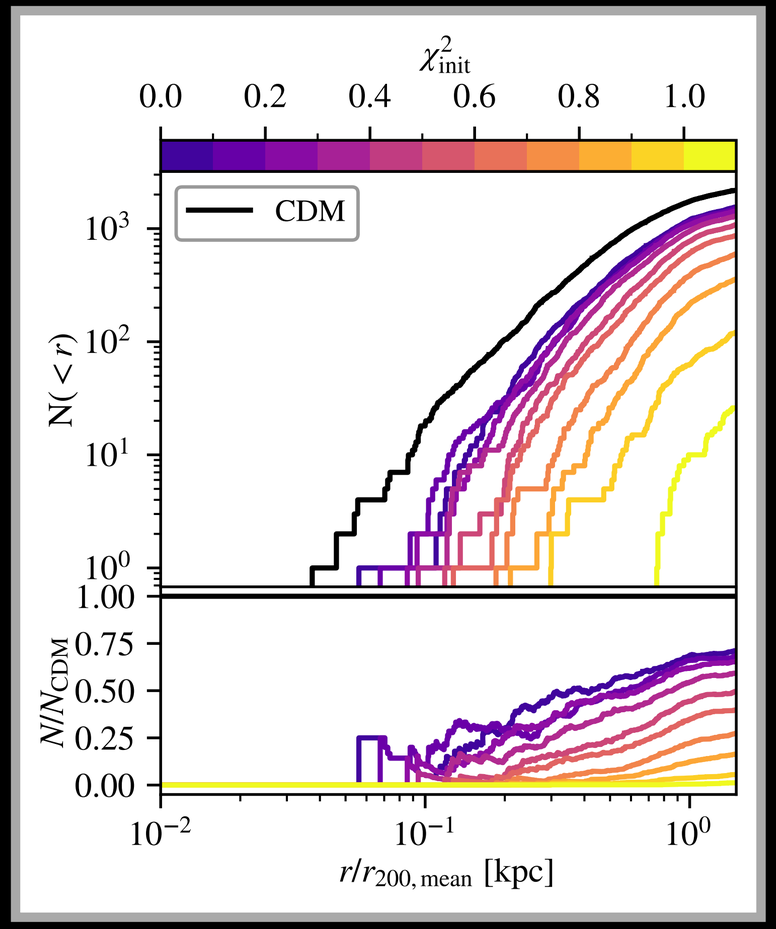


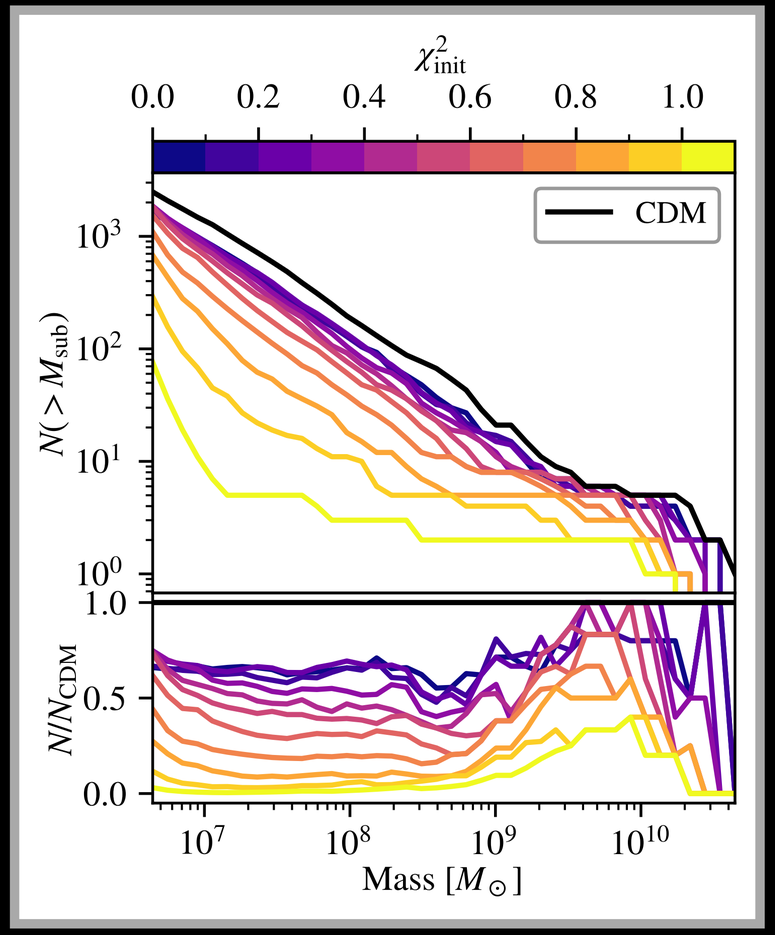
More excited particles

→ More down-scattering

Leonard+ 2024

Satellites are decreased with all scattering





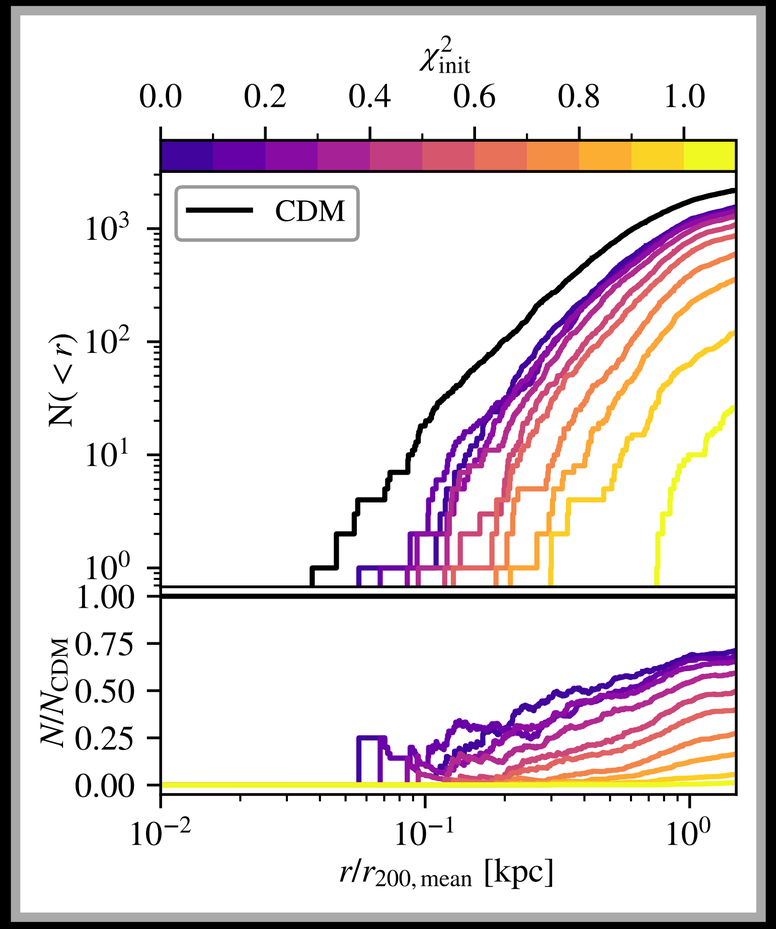
More excited particles

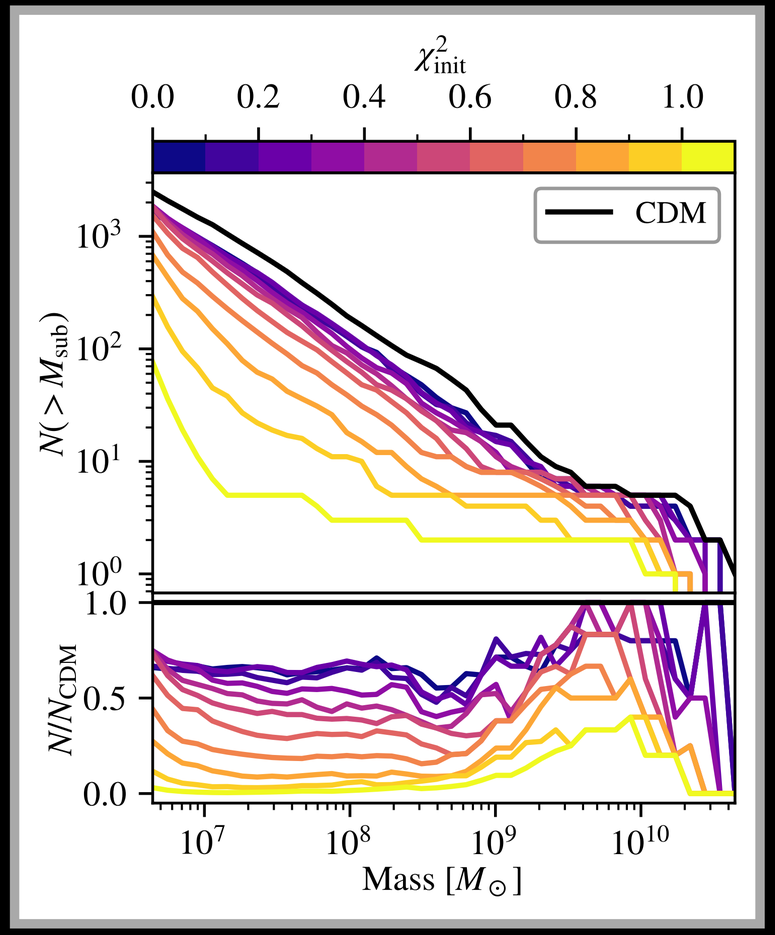
→ More down-scattering

→ Particles escape potential

Leonard+ 2024

Satellites are decreased with all scattering





More excited particles

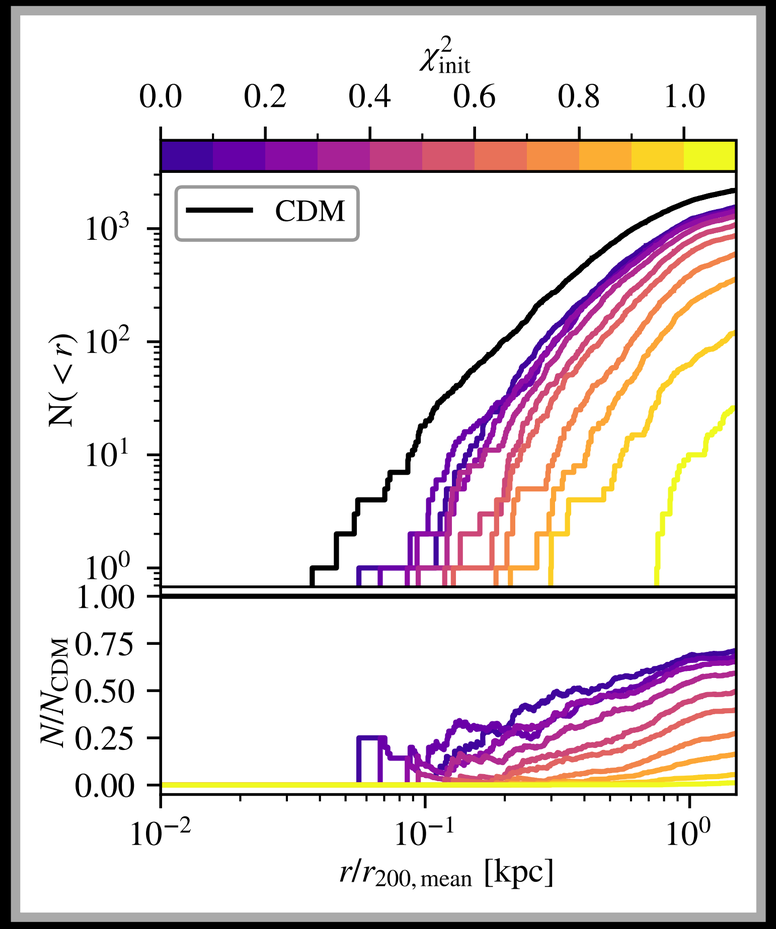
→ More down-scattering

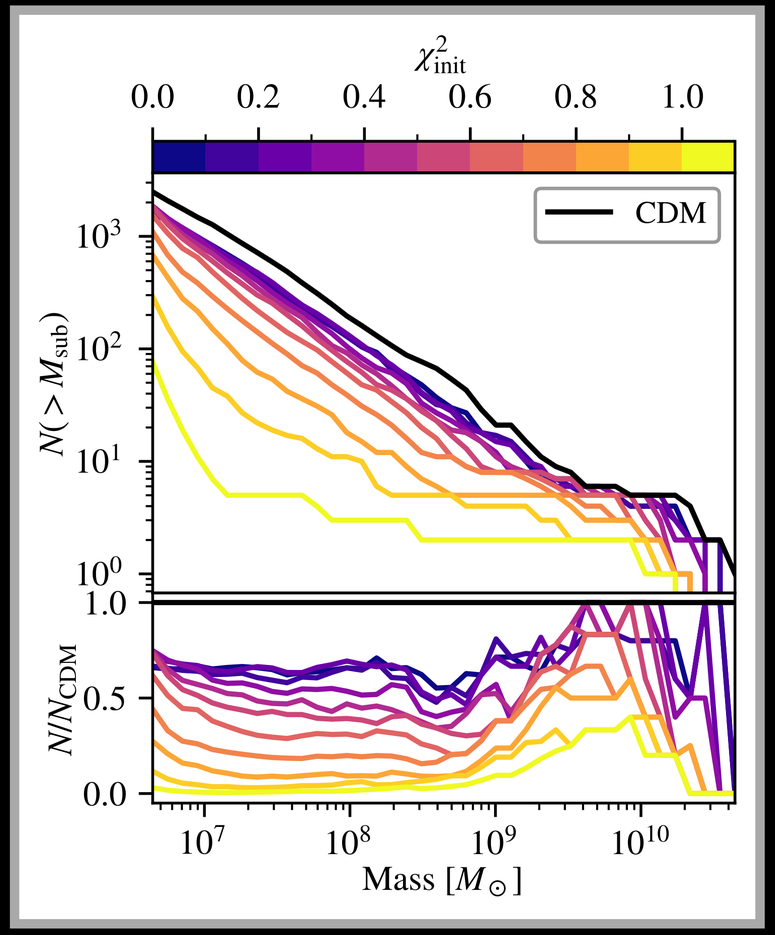
→ Particles escape potential

→ Fewer satellites

Leonard+ 2024

Satellites are decreased with all scattering





Leonard+ 2024

More excited particles

→ More down-scattering

→ Particles escape potential

→ Fewer satellites

Simulations with primarily up-scattering also decrease the satellite population due to tidal disruption

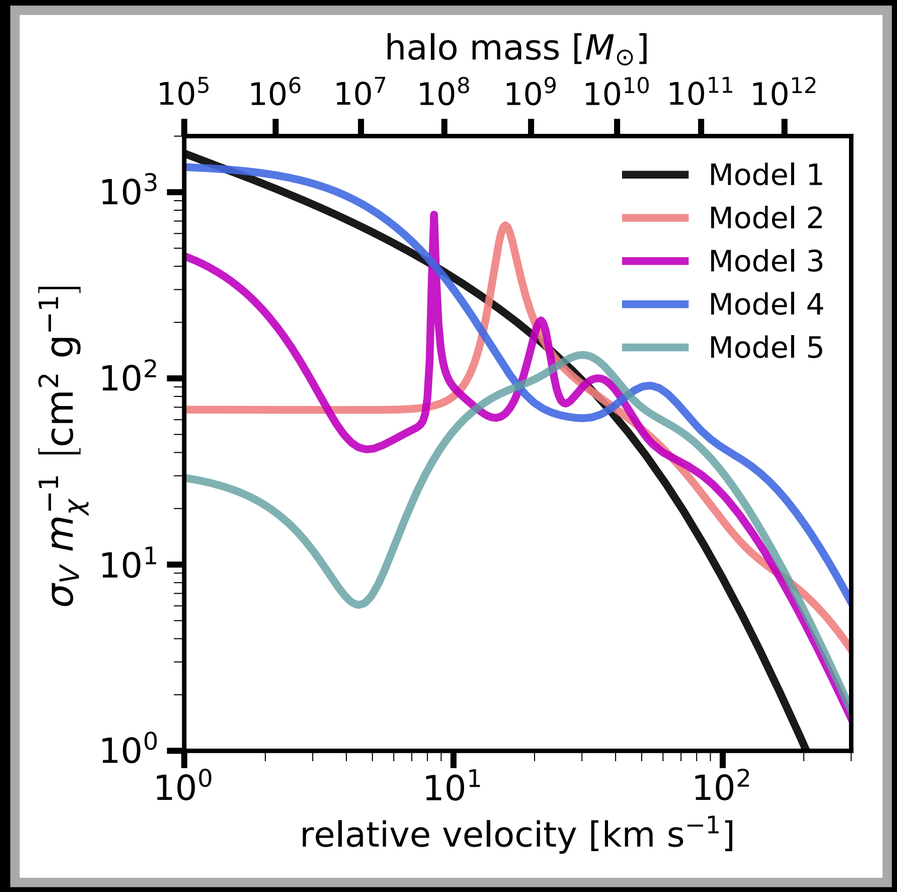
Upcoming

Lily Noyes, Penn

- Satellite evolution
- Satellite infall properties
- Merger histories?

Resonant SIDM

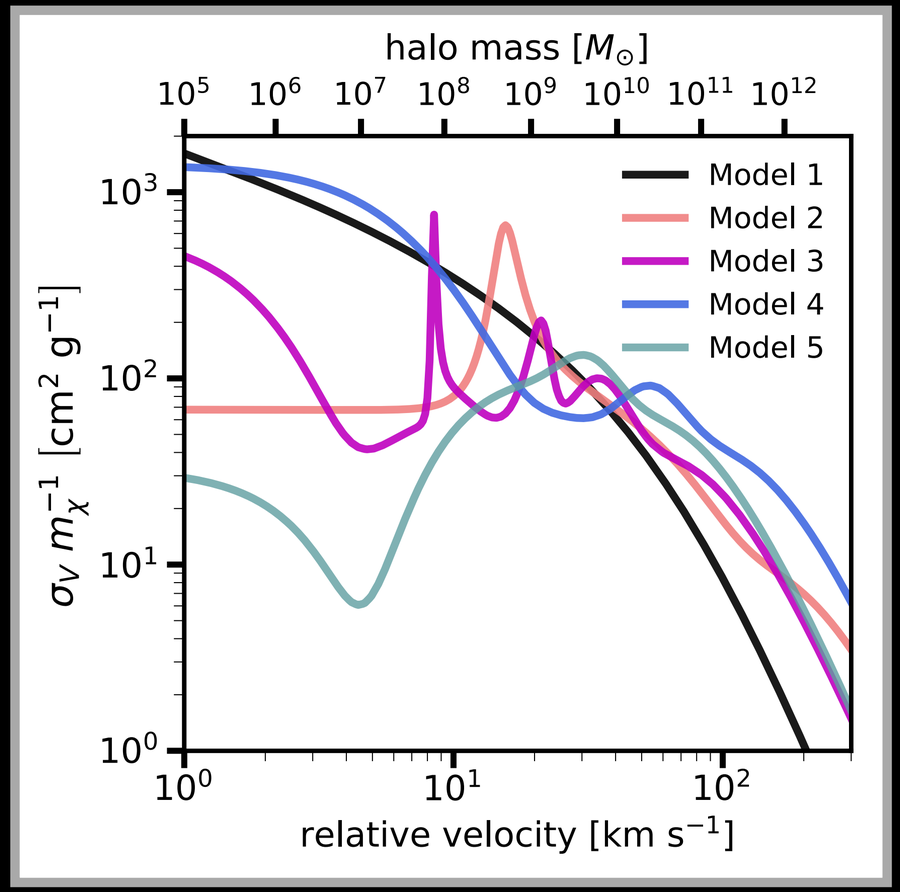
- Enhanced cross section around particular velocities
  - Model 2: M_{res}~10^8 $M_\odot$



Gilman+ 2023

Resonant SIDM

- Enhanced cross section around particular velocities
  - Model 2: $M_{res} \sim 10^8\ M_\odot$



Resonant SIDM

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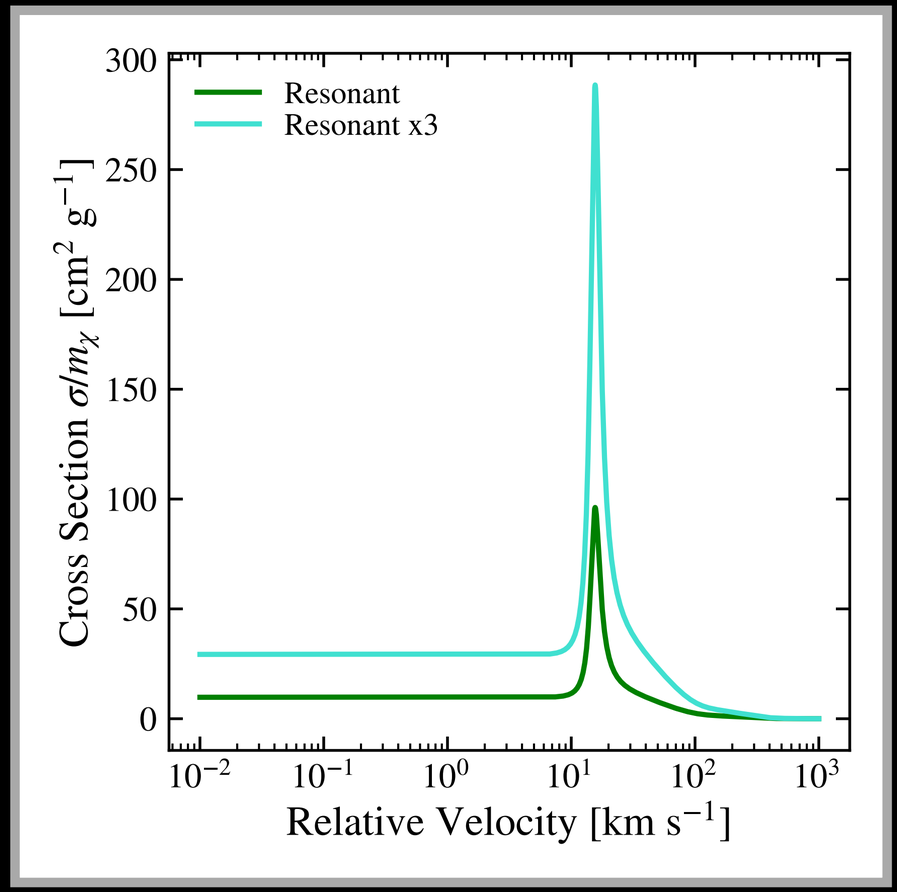
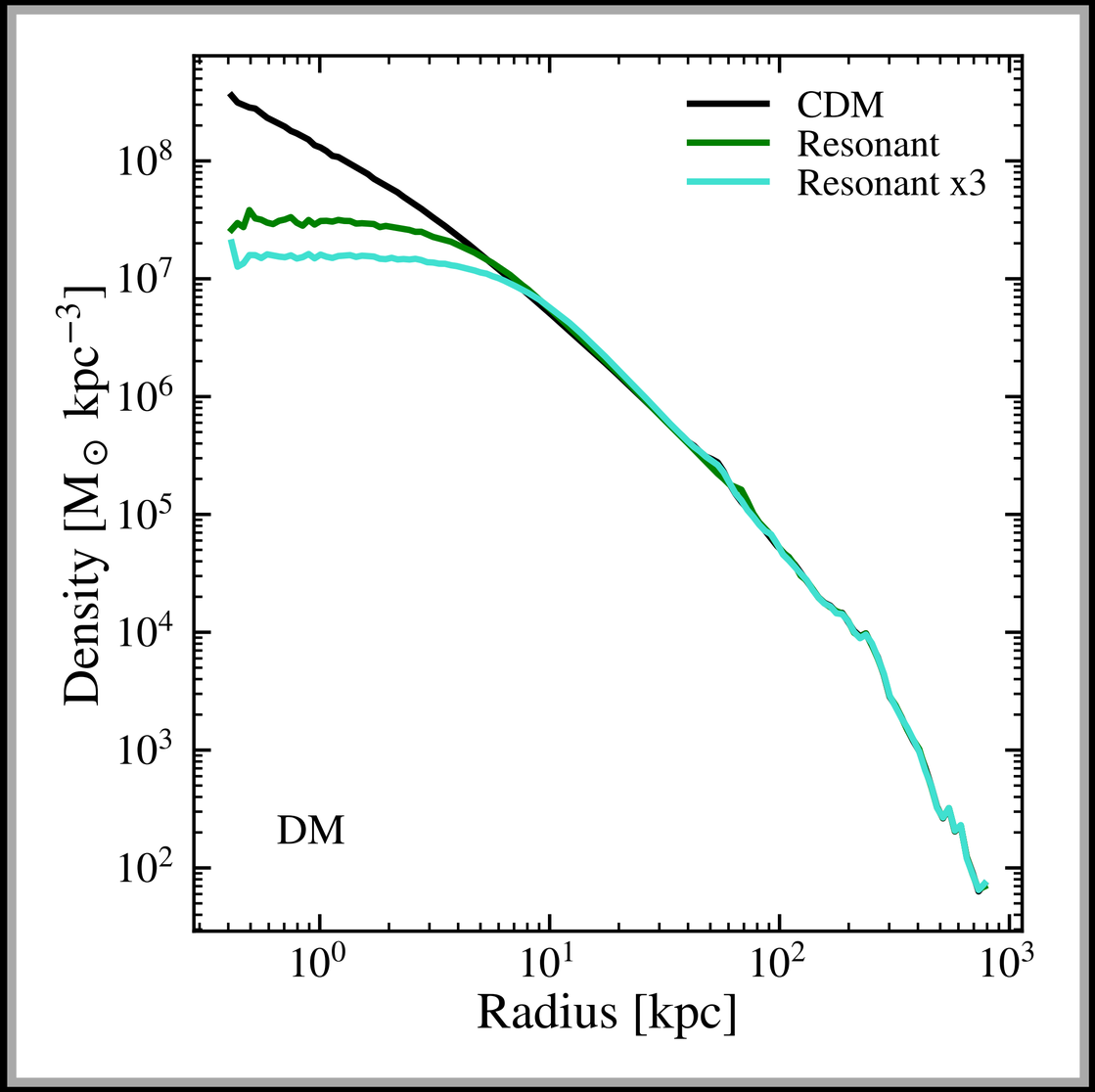
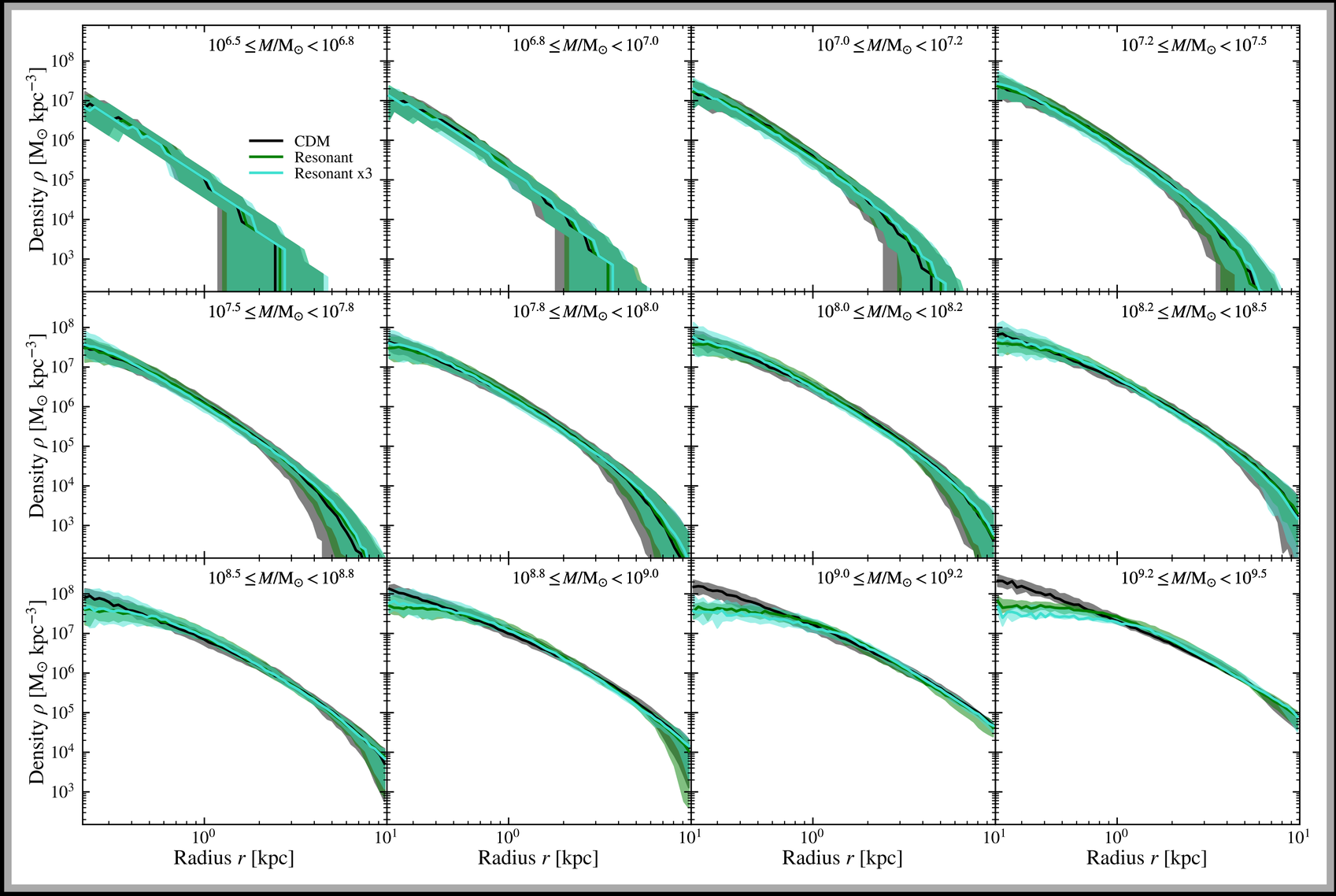
  - Model 2: M_{res}~10^8 $M_\odot$



Main halo is cored with more scattering



Subhalos cored at high mass end



Conclusions

- Increased up-scattering
  - increases central density
  - Increases halo sphericity
- Increased down-scattering
  - Decreases satellite population
  - Somewhat decreased satellite population with up-scattering velocity threshold

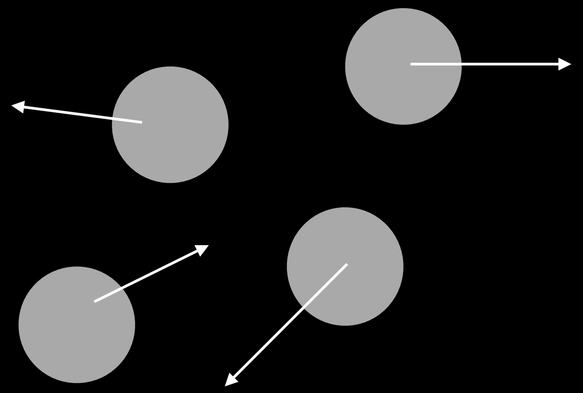
Conclusions

- Large parameter space
- Scattering can get computationally expensive
- Form of scattering cross sections is flexible but currently isotropic
- Currently DMO

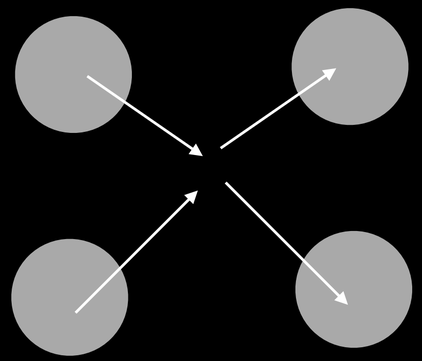
Self-interacting dark matter (SIDM)

- Dark matter interacts with baryons through gravity
- Additional dark force between dark matter particles

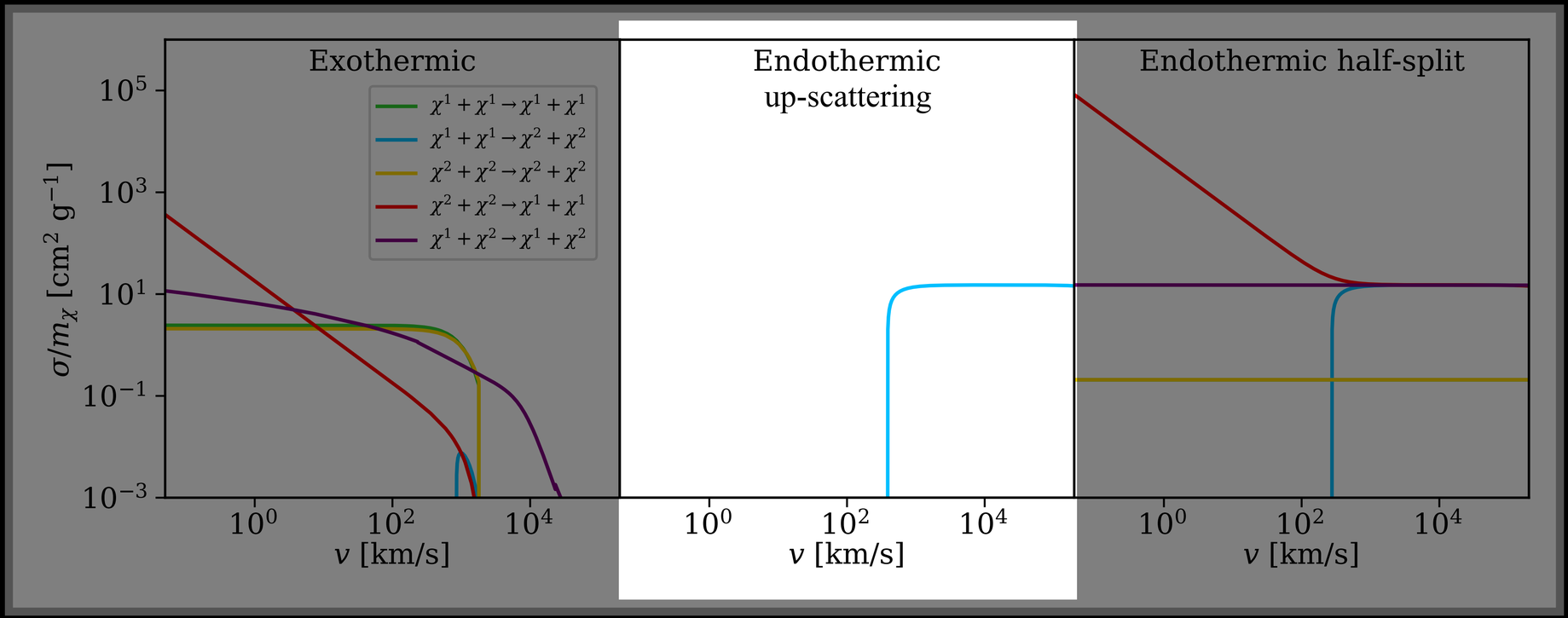
CDM



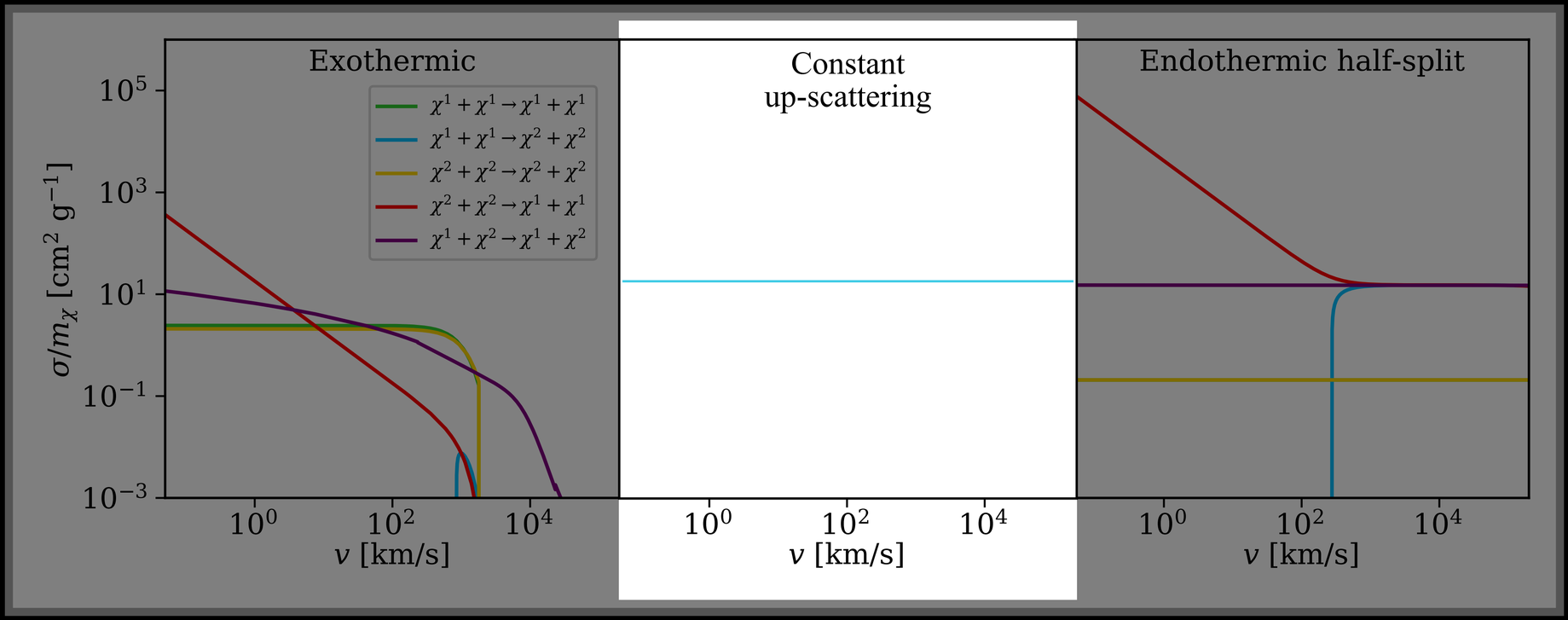
SIDM



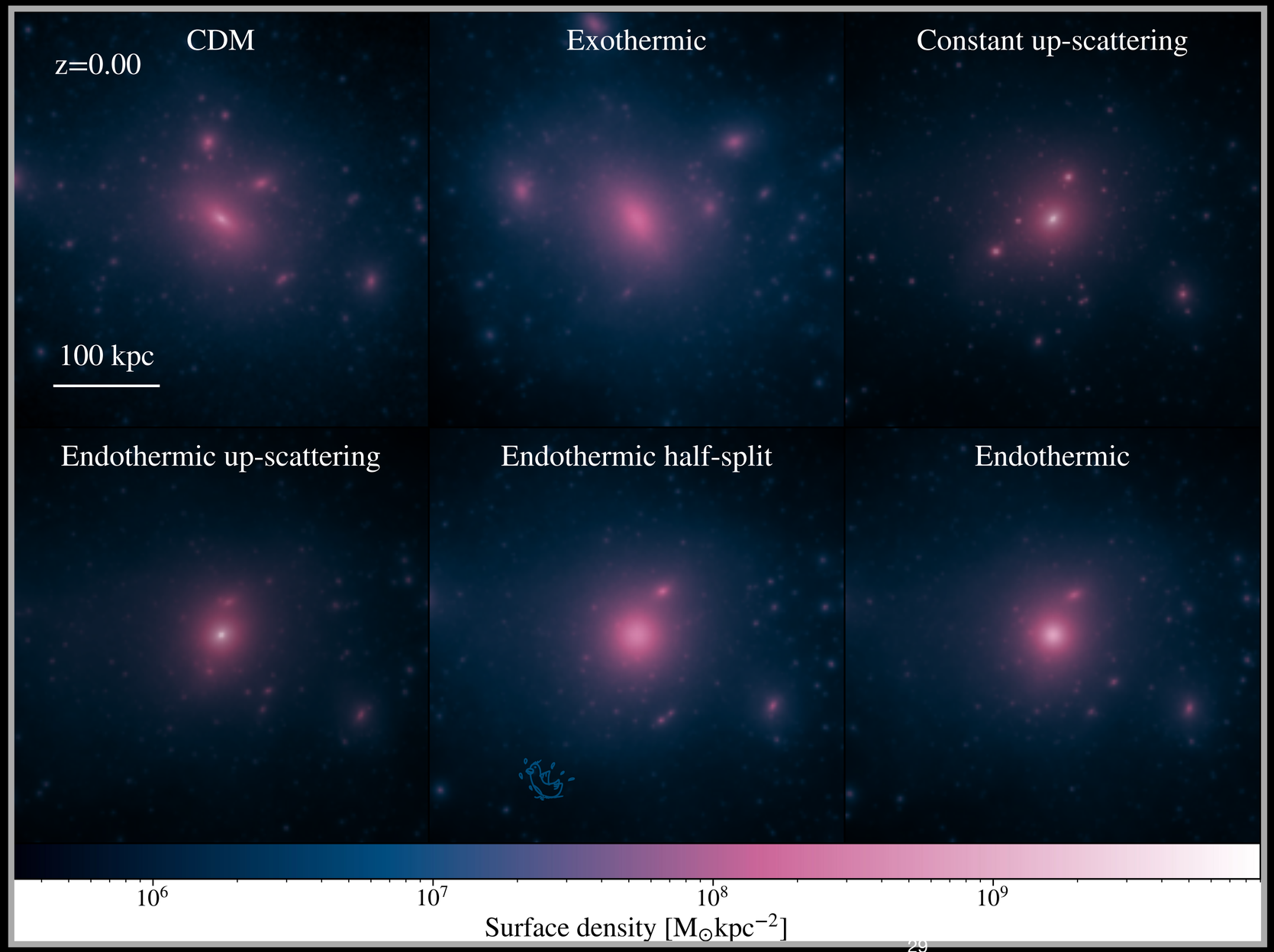
Scattering cross sections determine likelihood of reaction



Scattering cross sections determine likelihood of reaction

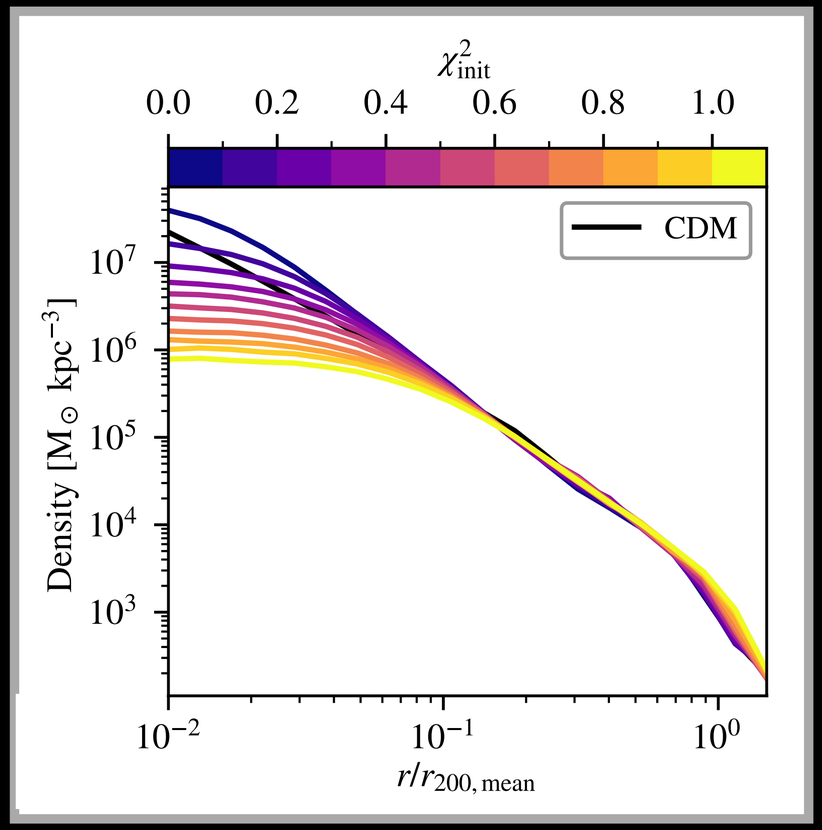


Main halo appearance differs for each model



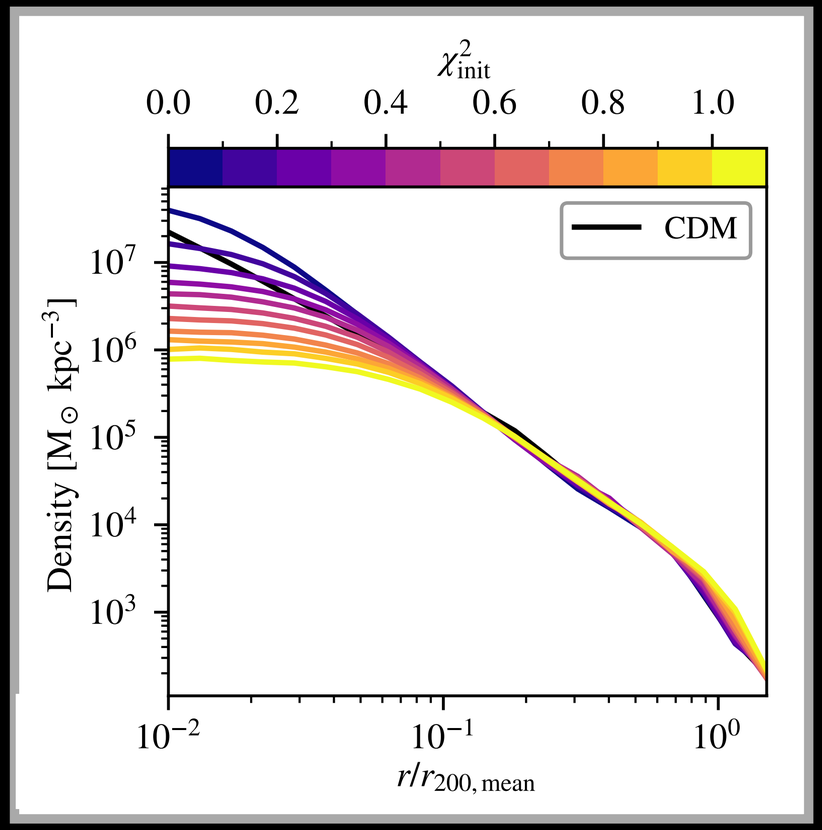
- Same initial conditions
- Set particle state at simulation start

Main halo density depends on initial state fraction



Leonard+ 2024

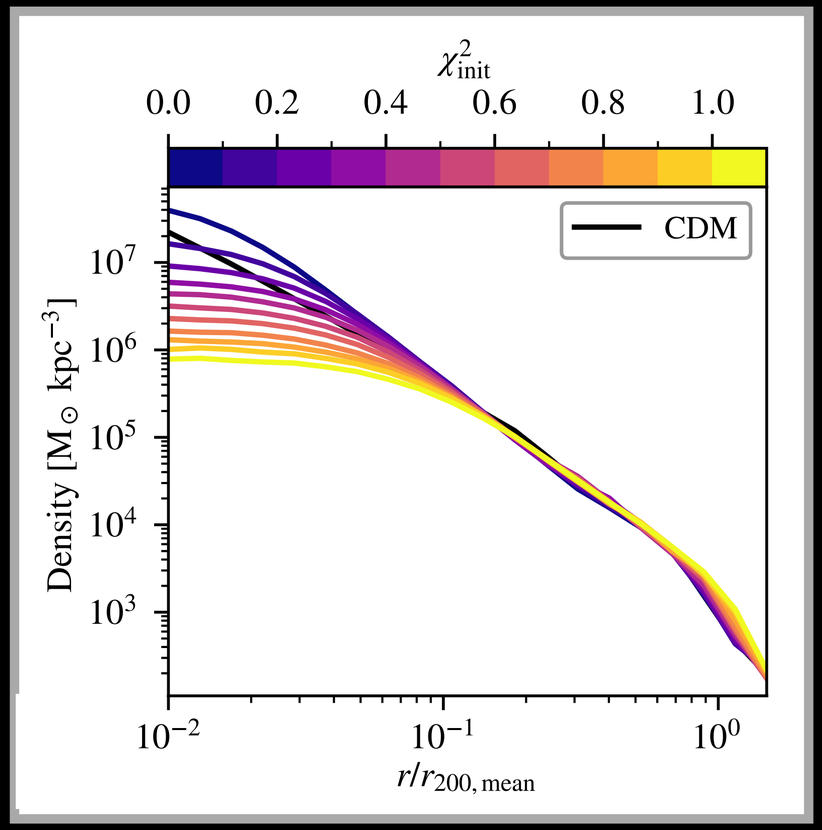
Main halo density depends on initial state fraction



Increasing initial excited state fraction gives lower density

Leonard+ 2024

Main halo density depends on initial state fraction

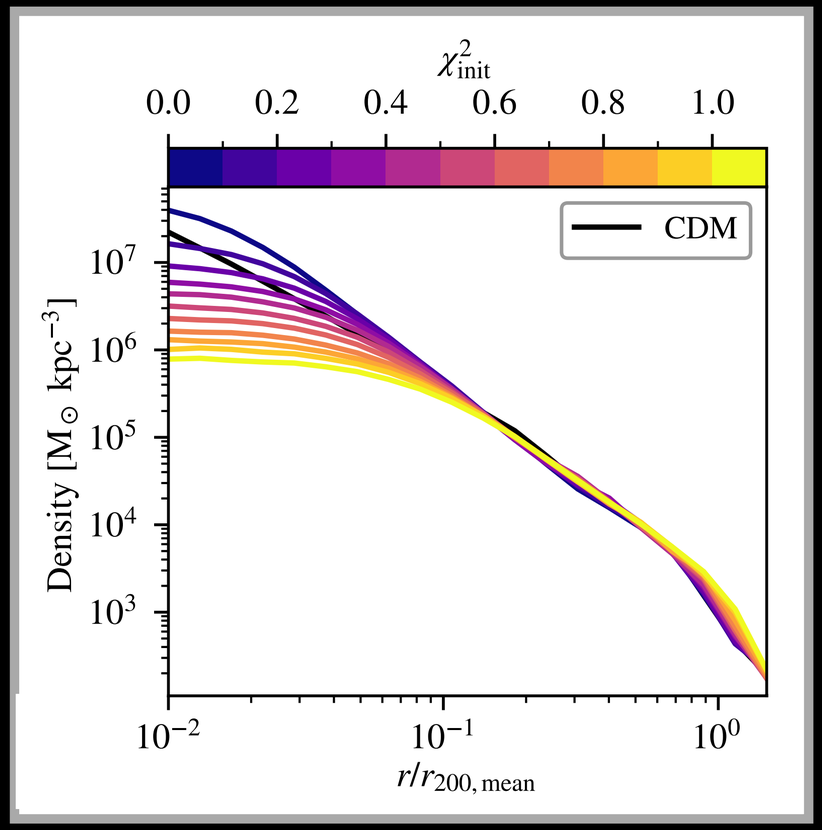


Increasing initial excited state fraction gives lower density

More excited particles

Leonard+ 2024

Main halo density depends on initial state fraction



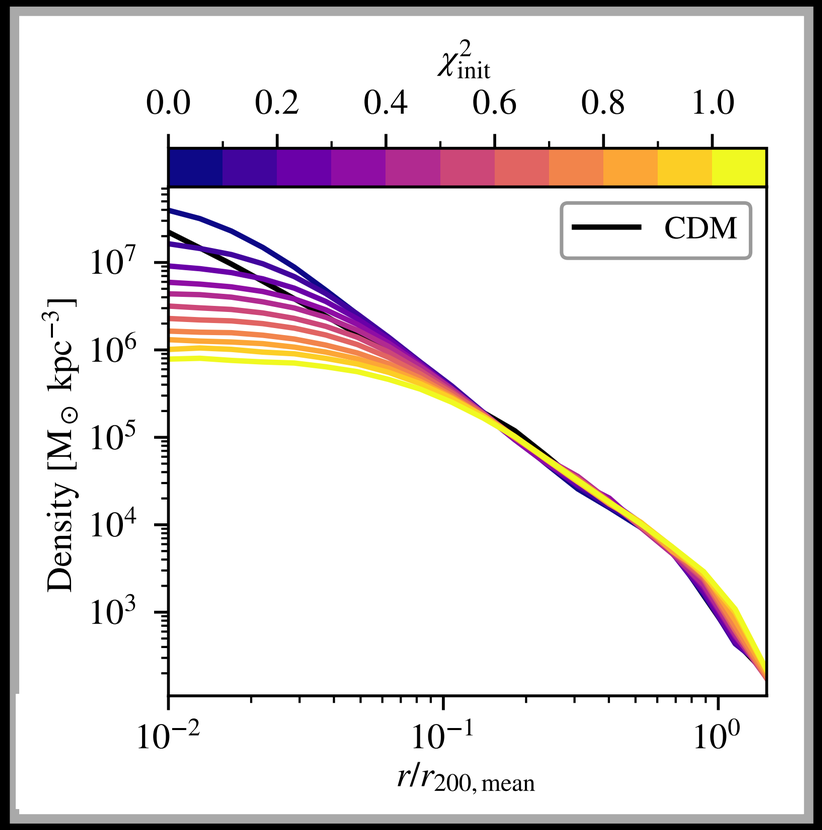
Increasing initial excited state fraction gives lower density

More excited particles

→ More down-scattering

Leonard+ 2024

Main halo density depends on initial state fraction



Increasing initial excited state fraction gives lower density

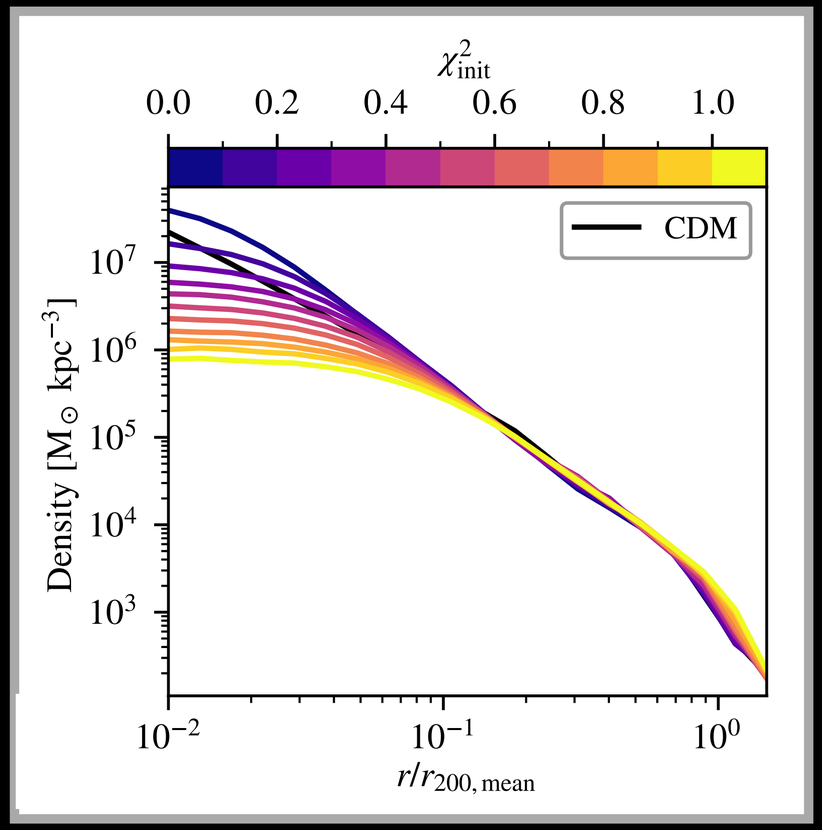
Leonard+ 2024

More excited particles

→ More down-scattering

→ Velocity kicks

Main halo density depends on initial state fraction



Increasing initial excited state fraction gives lower density

Leonard+ 2024

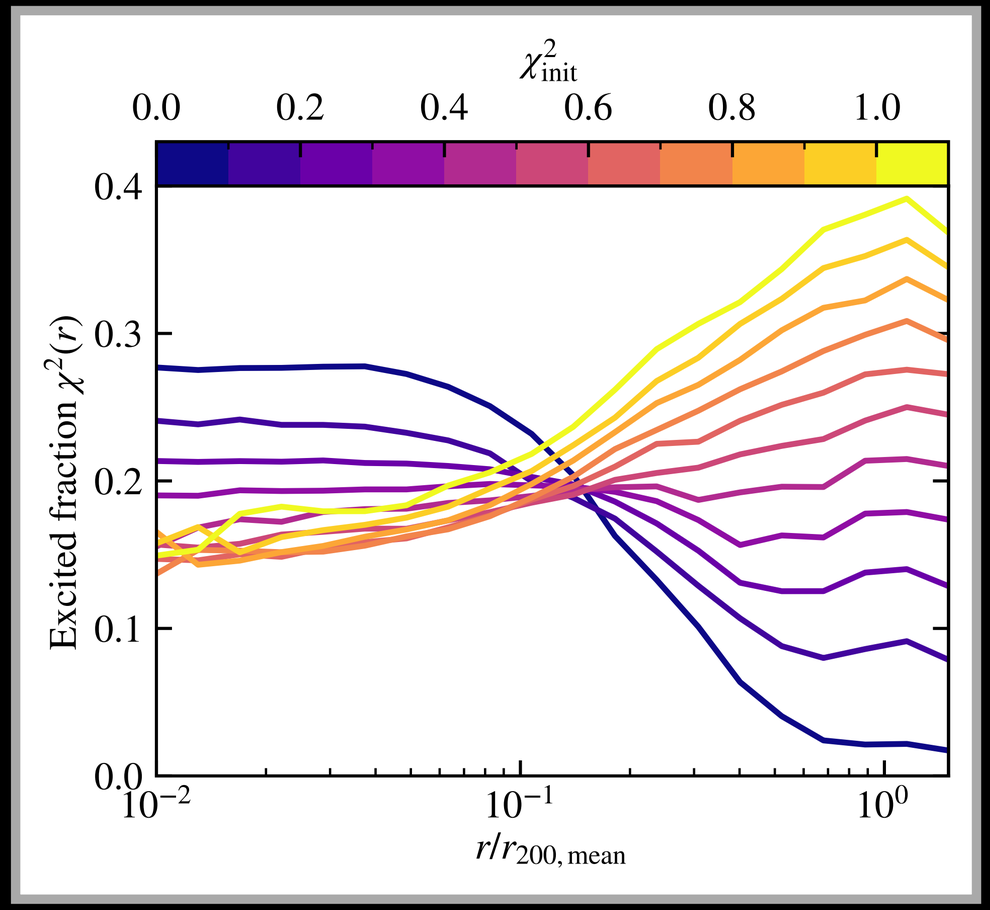
More excited particles

→ More down-scattering

→ Velocity kicks

→ Particles move outwards

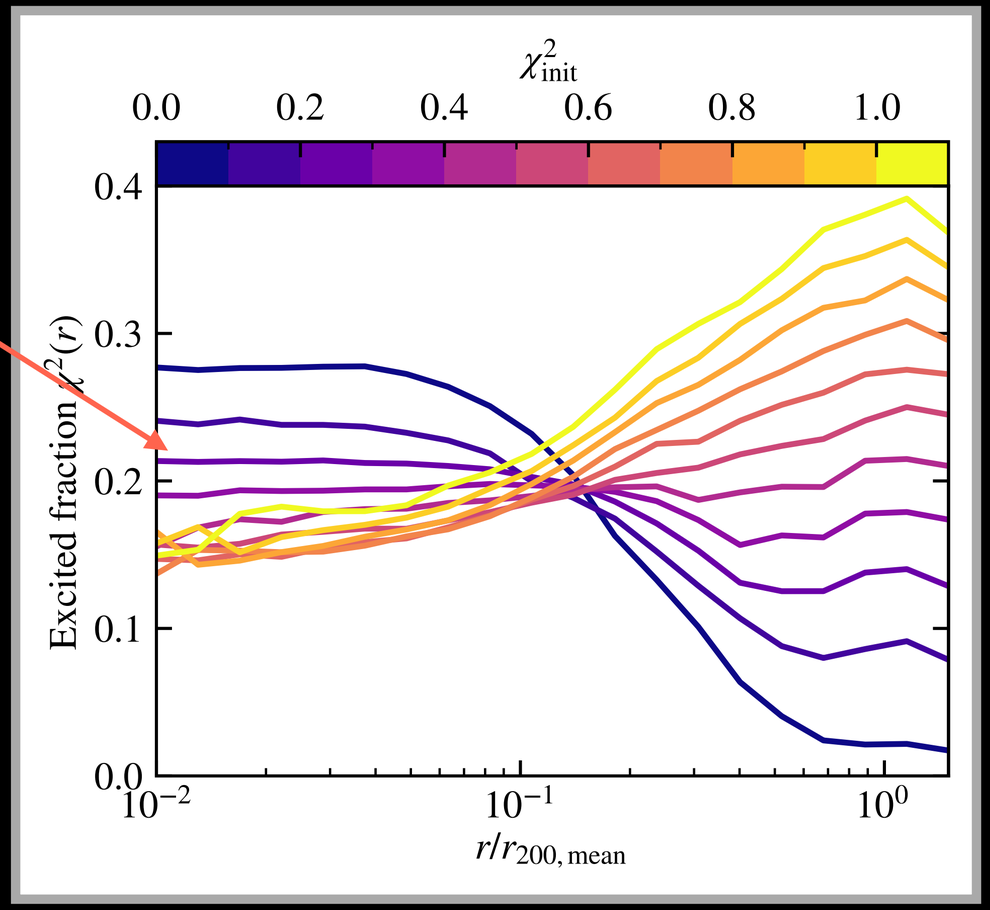
More scattering in the center alters particle states



Leonard+ 2024

More scattering in the center alters particle states

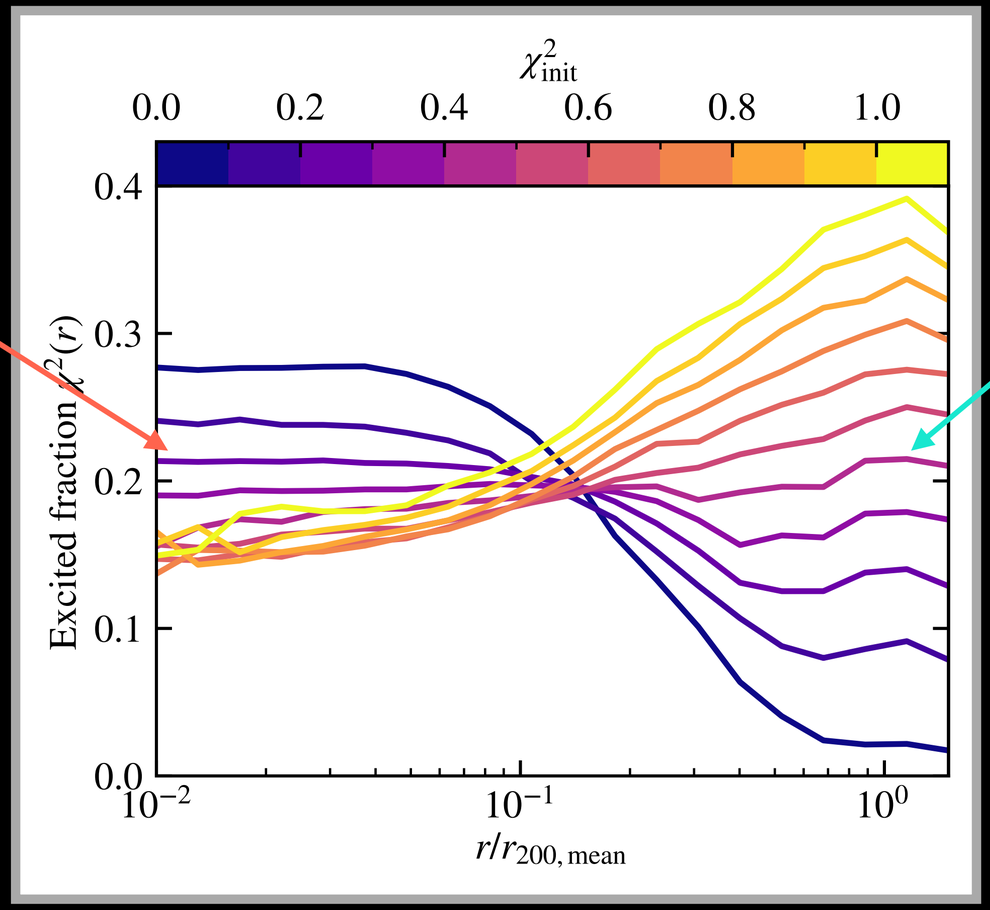
Dependent on velocity dispersion



Leonard+ 2024

More scattering in the center alters particle states

Dependent on velocity dispersion

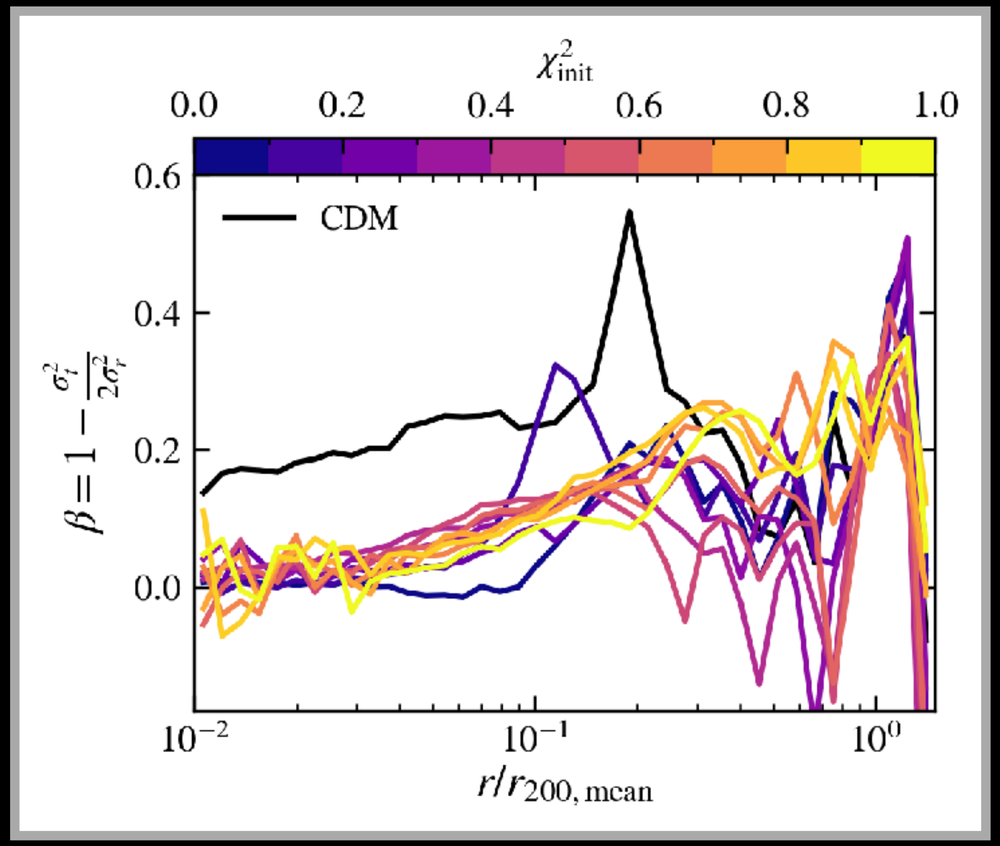


Dependent on number density

Lower *v* suppresses up-scattering

Leonard+ 2024

Up-scattering makes halos spherical



Leonard+ 2024

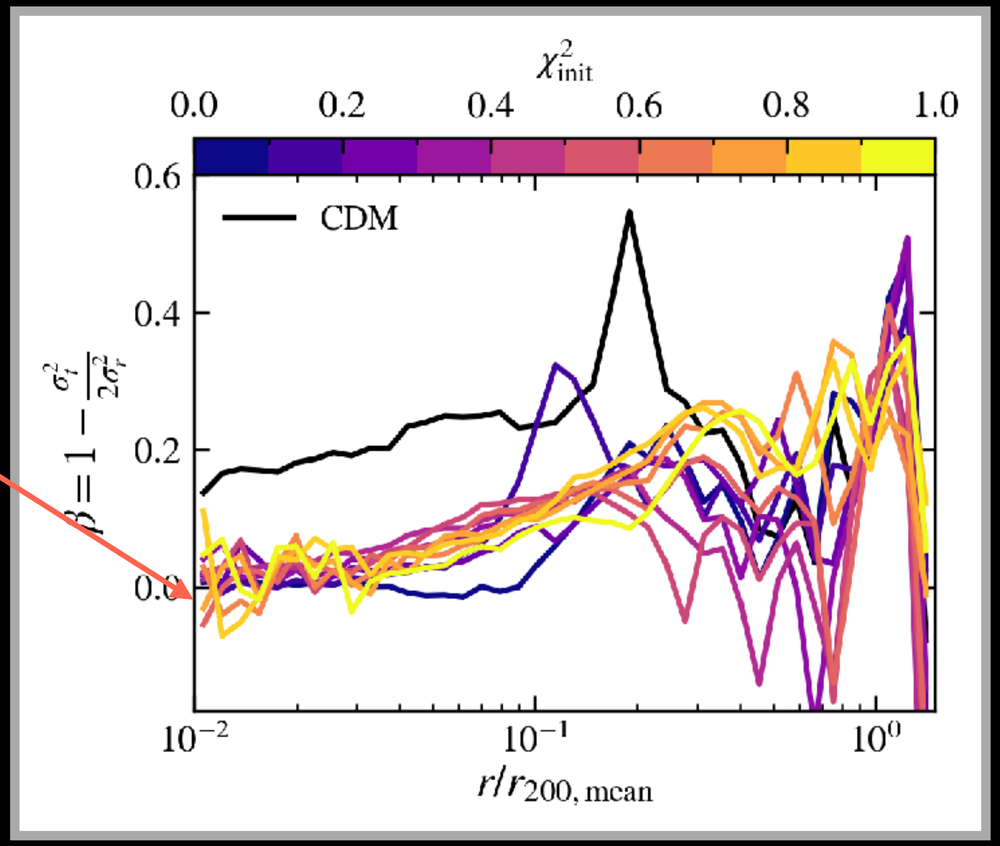
- Inelastic scattering causes particles to change orbit

Up-scattering makes halos spherical

Inner region anisotropy dependent on density slope

More cored →lower β

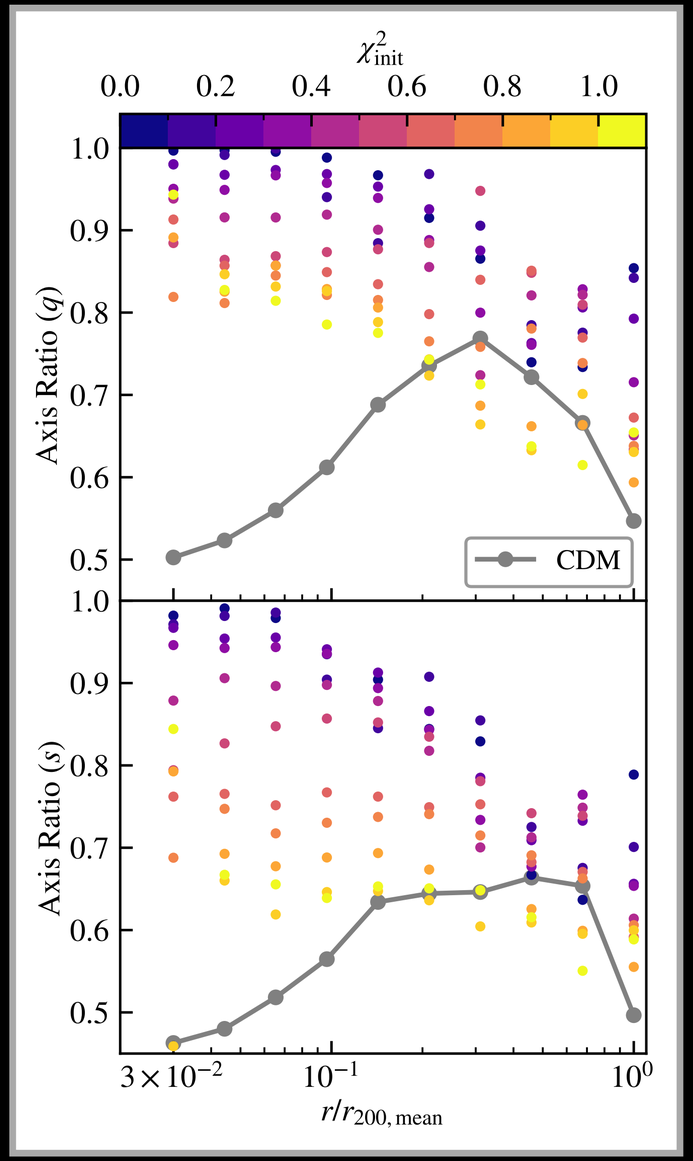
(Hansen & Moore 2006, Navarro+ 2010)



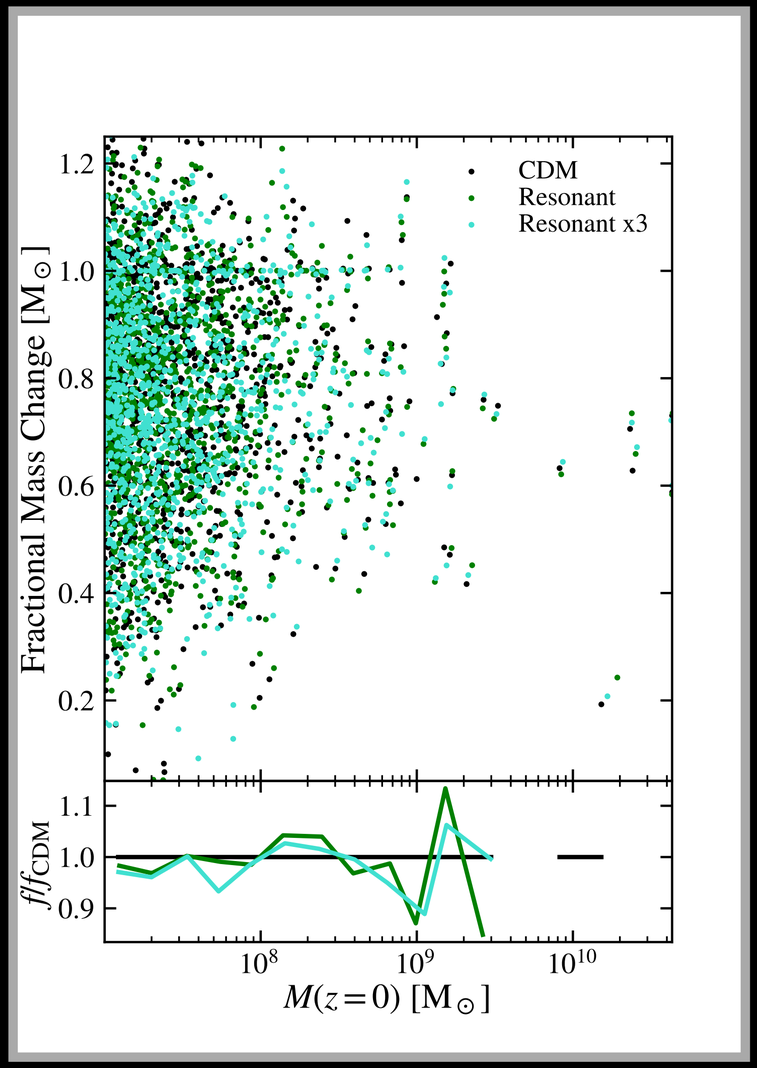
Leonard+ 2024

- Inelastic scattering causes particles to change orbit

Up-scattering makes halos spherical



DM stripping similar to CDM



DM stripping similar to CDM