Fake it 'til you make it:

Embedding galaxies in cosmological simulations

Shea Garrison-Kimmel (Caltech)
with Andrew Wetzel, James Bullock, Phil Hopkins,
Mike Boylan-Kolchin, Robyn Sanderson, and Tyler Kelley

Hydro sims are great!

Movies mostly from P. Hopkins, J. Oñorbe

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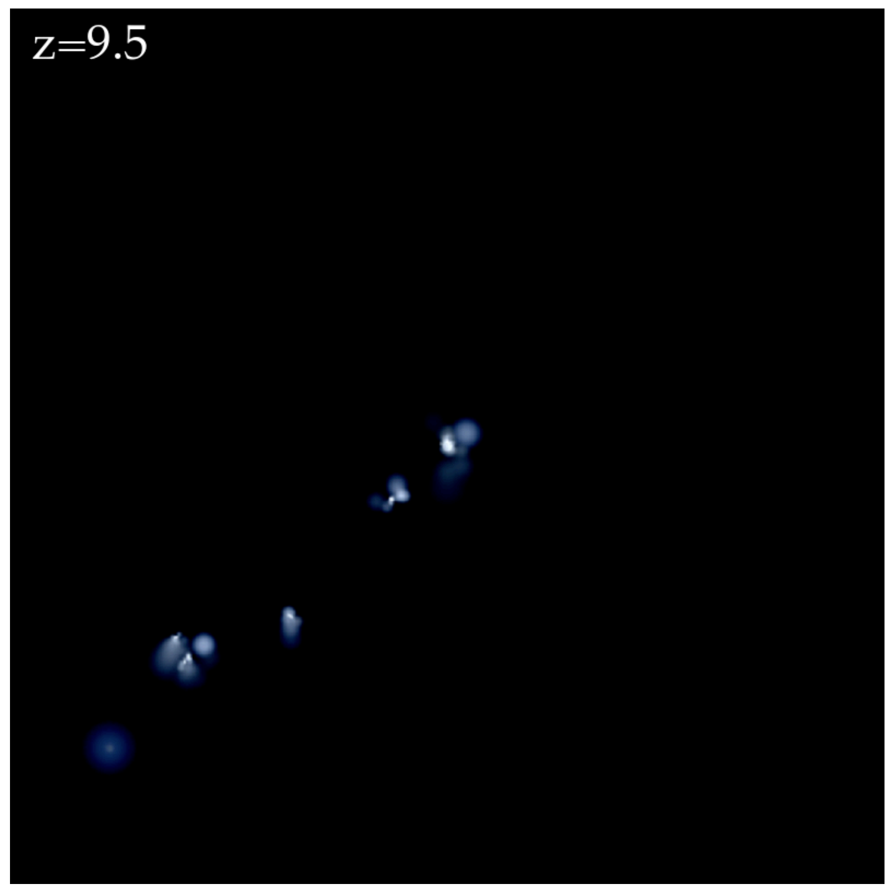

star/galaxy
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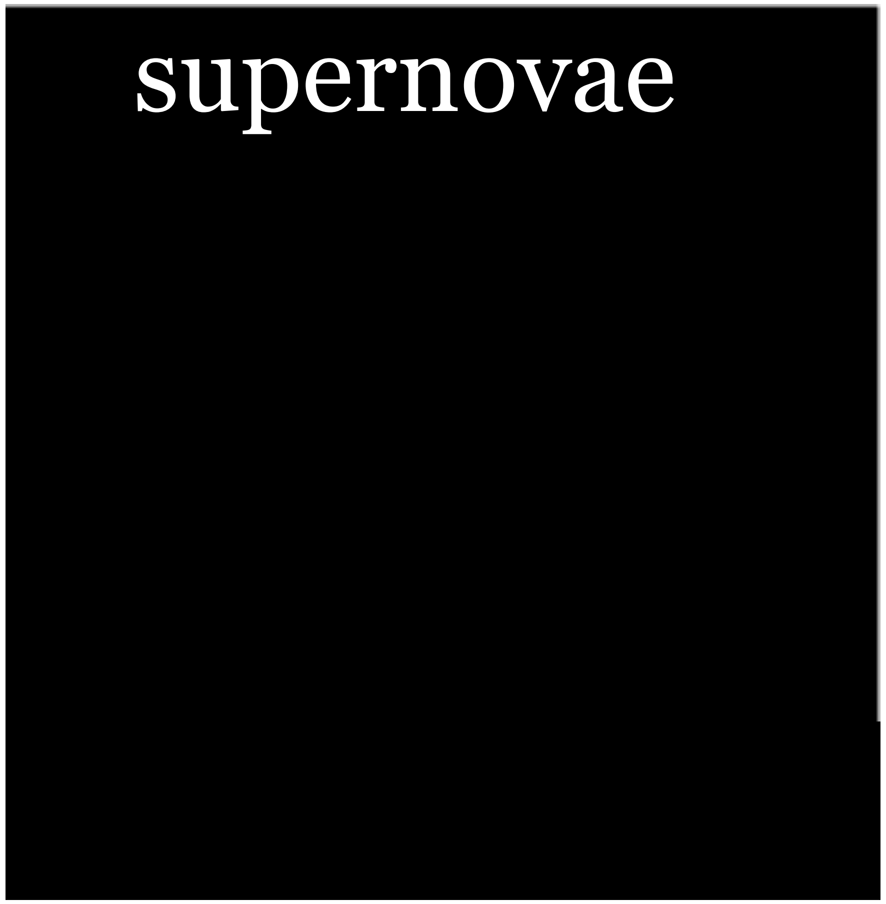

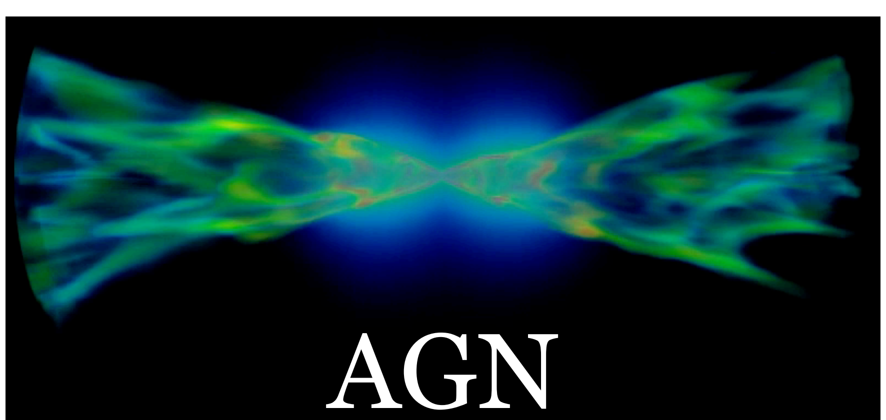

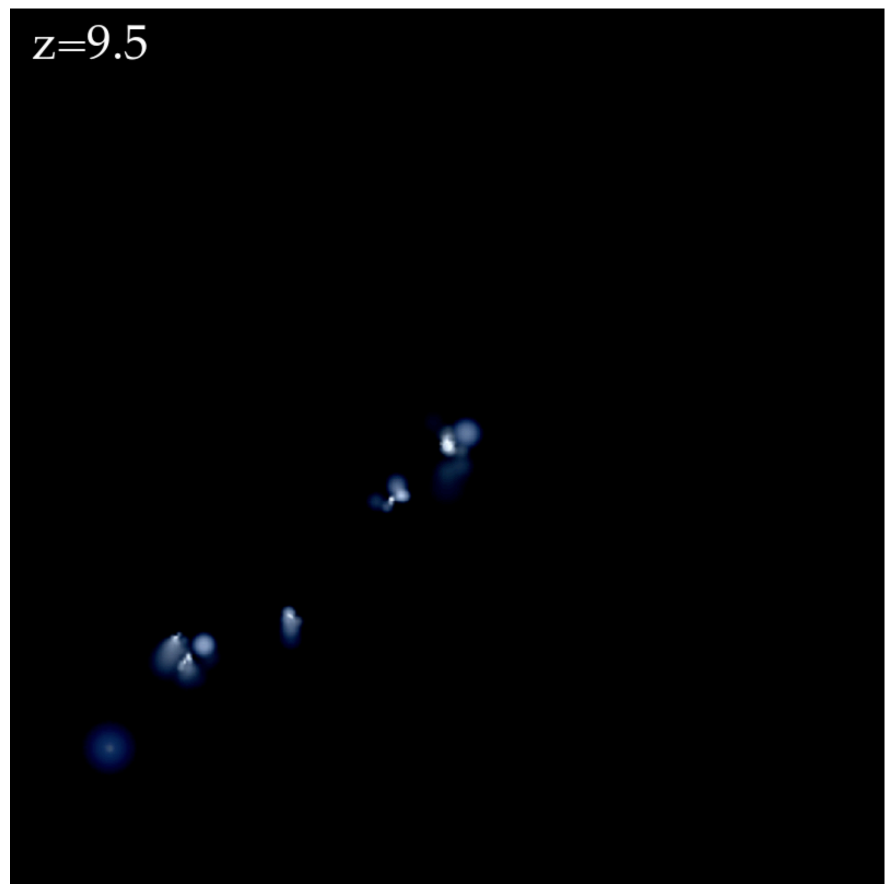

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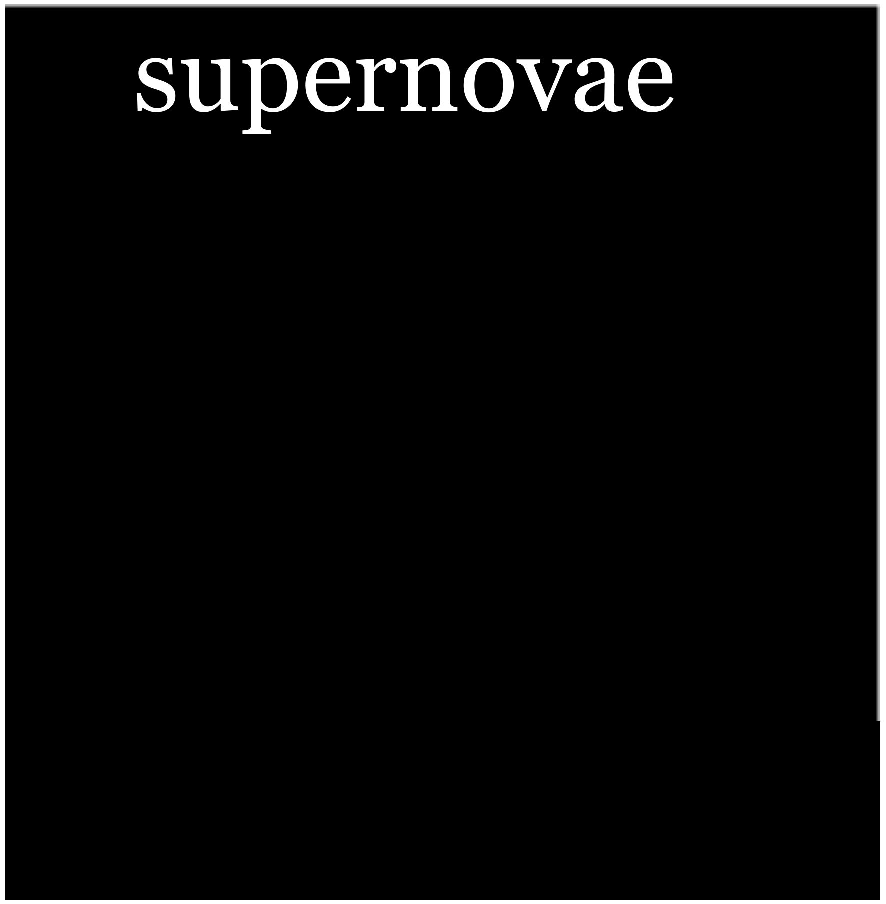

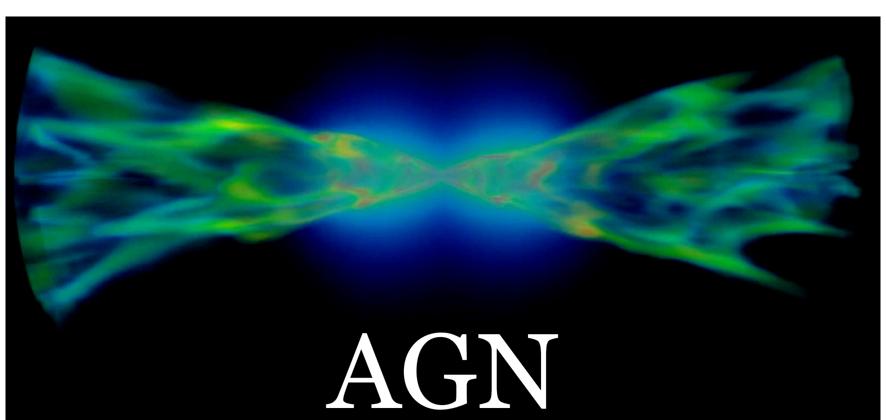

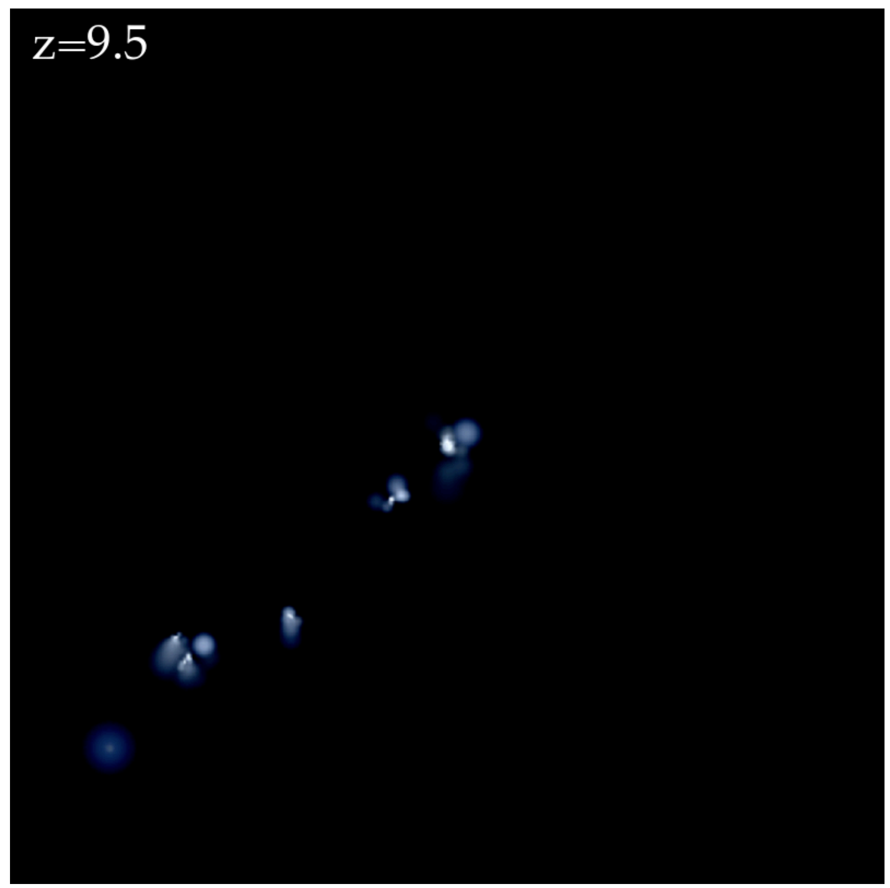

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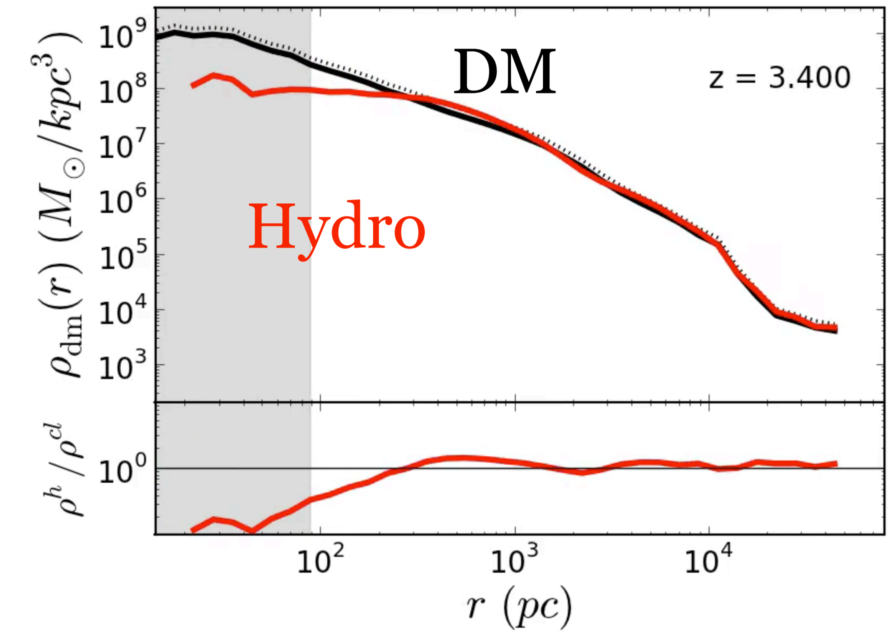
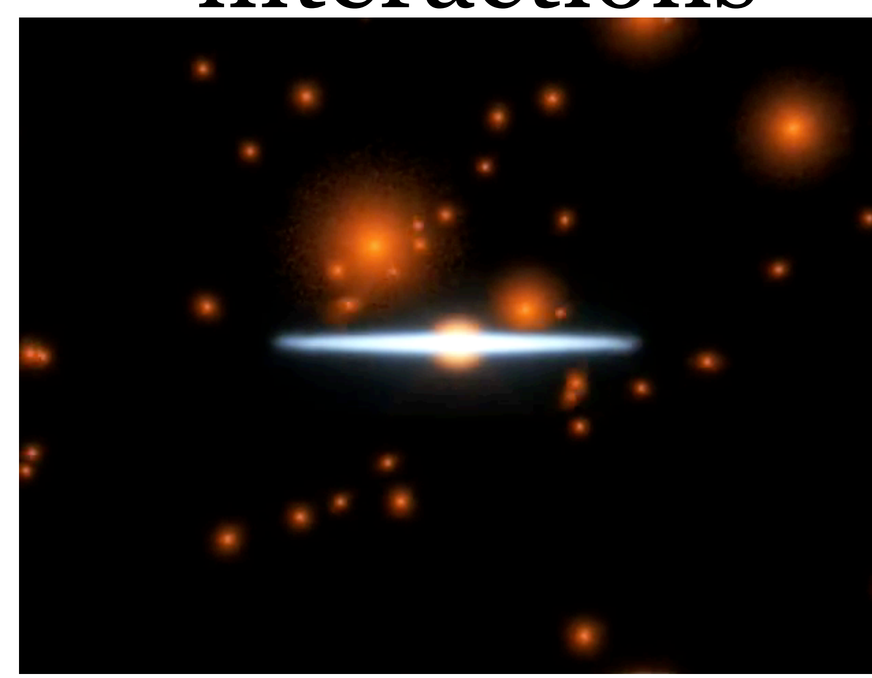


baryon-DM interactions



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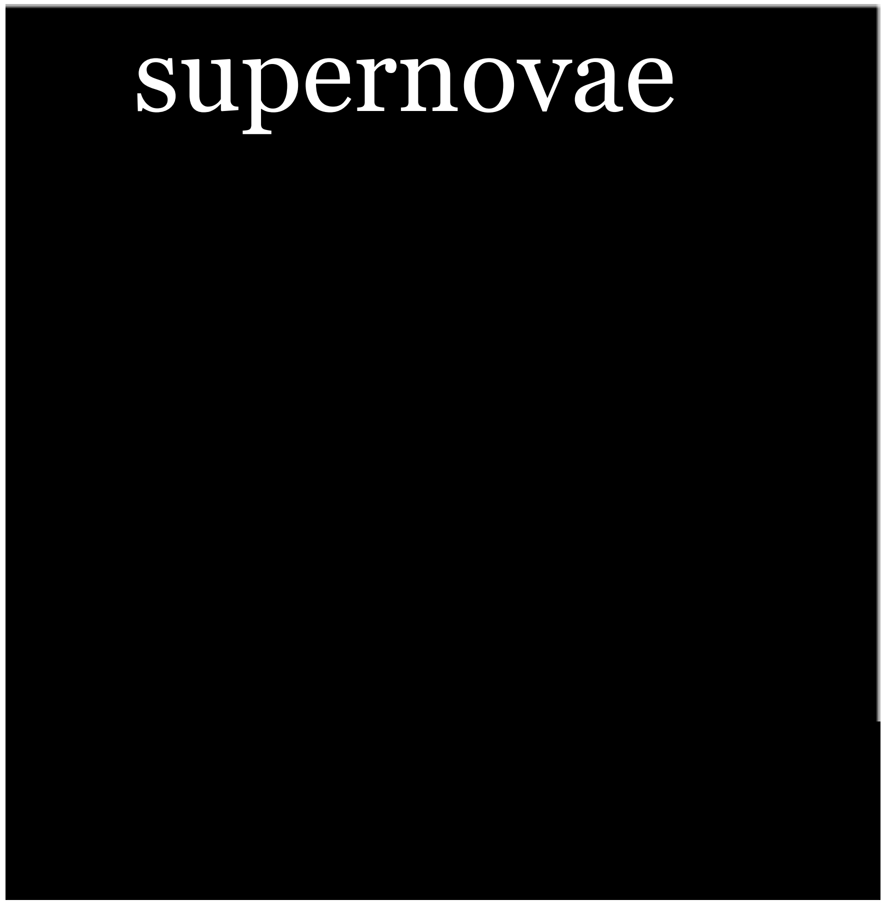

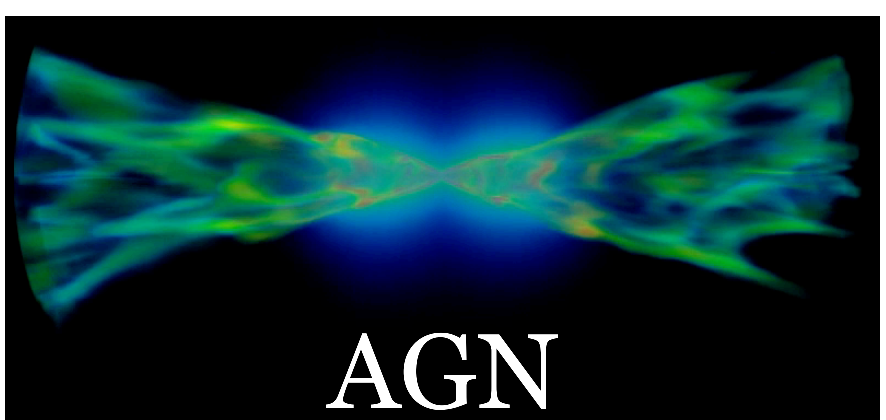

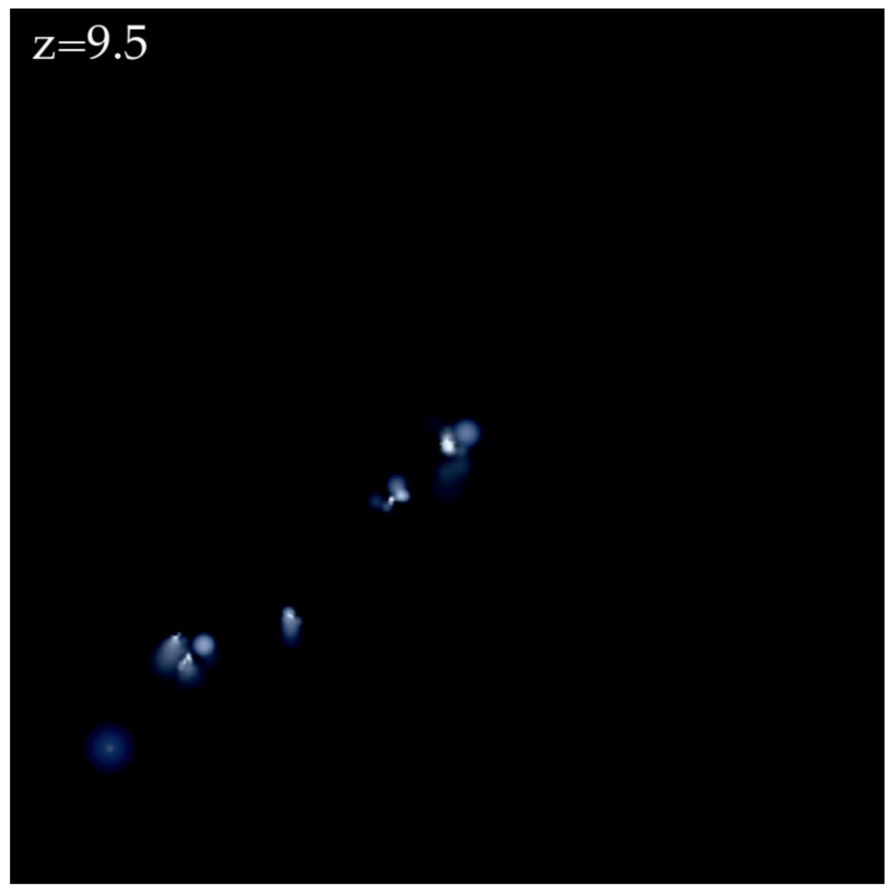

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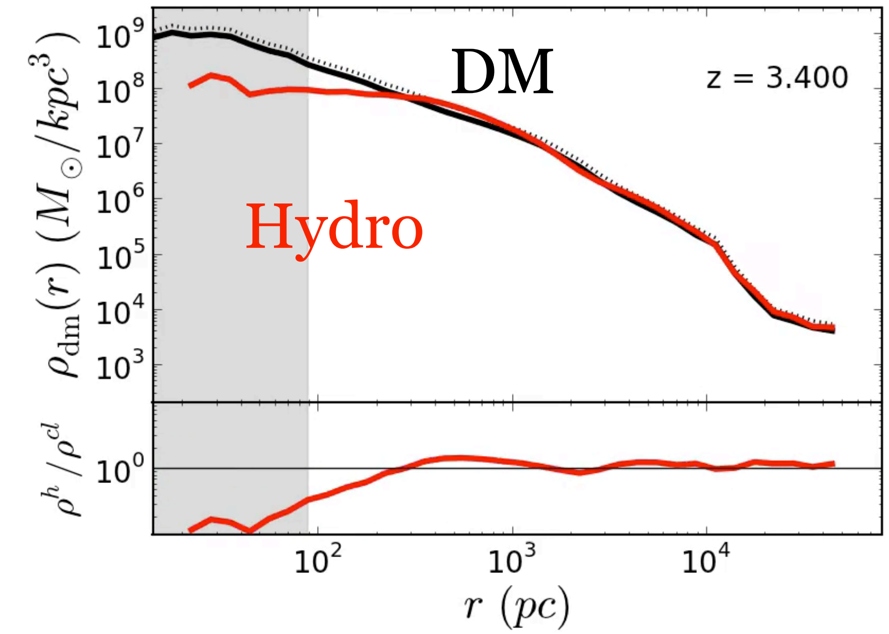

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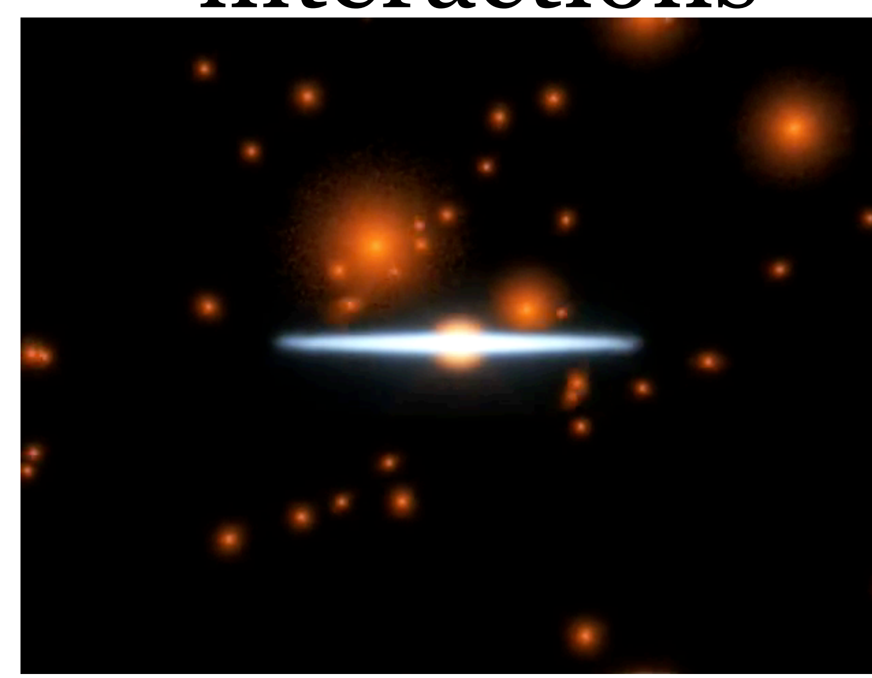
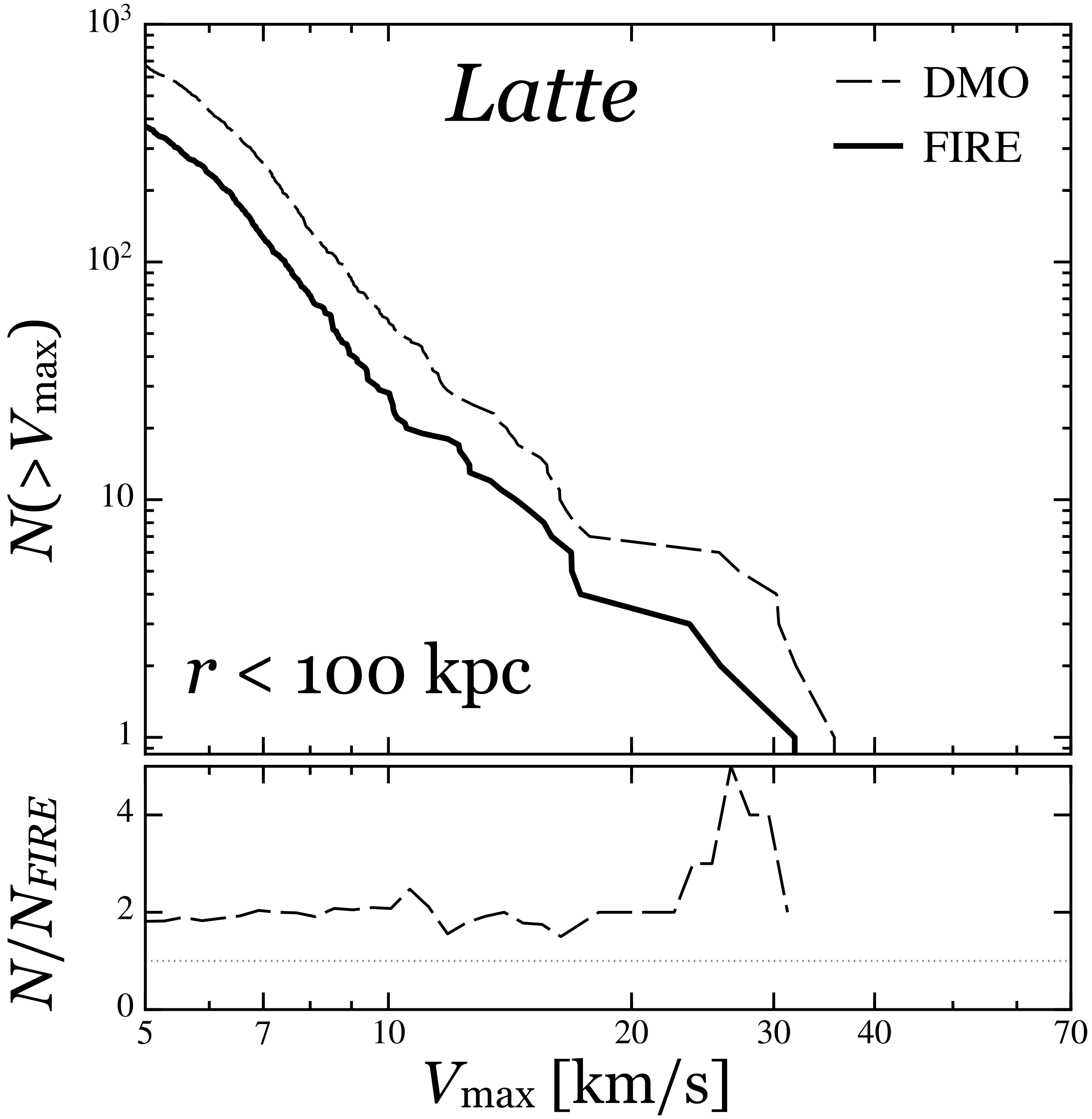


Compare directly to data...and (more) correct!

Baryons affect subhalo populations

*Particle masses in DMO simulations reduced by (1-f_b)



Wetzel+2016

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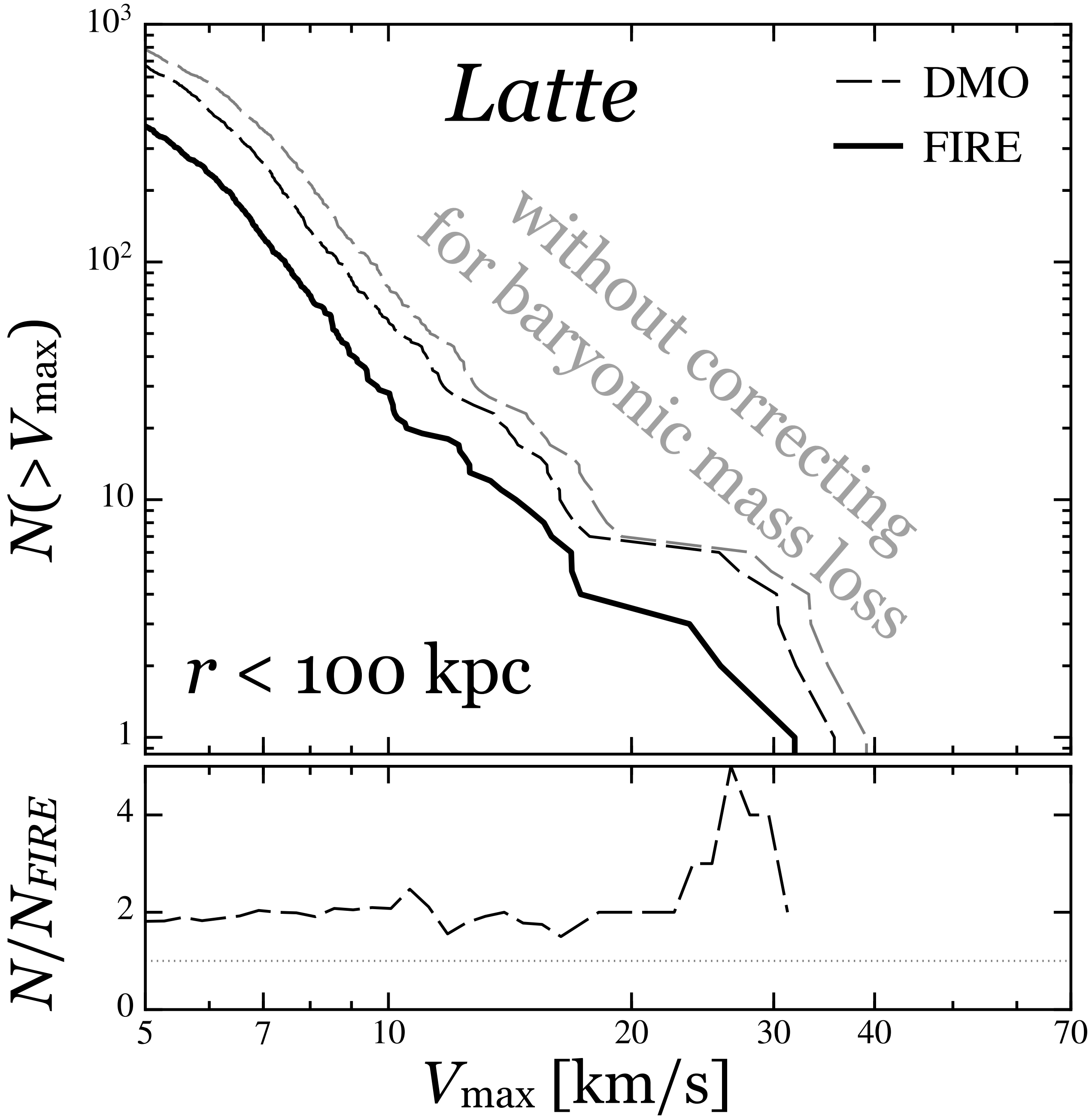

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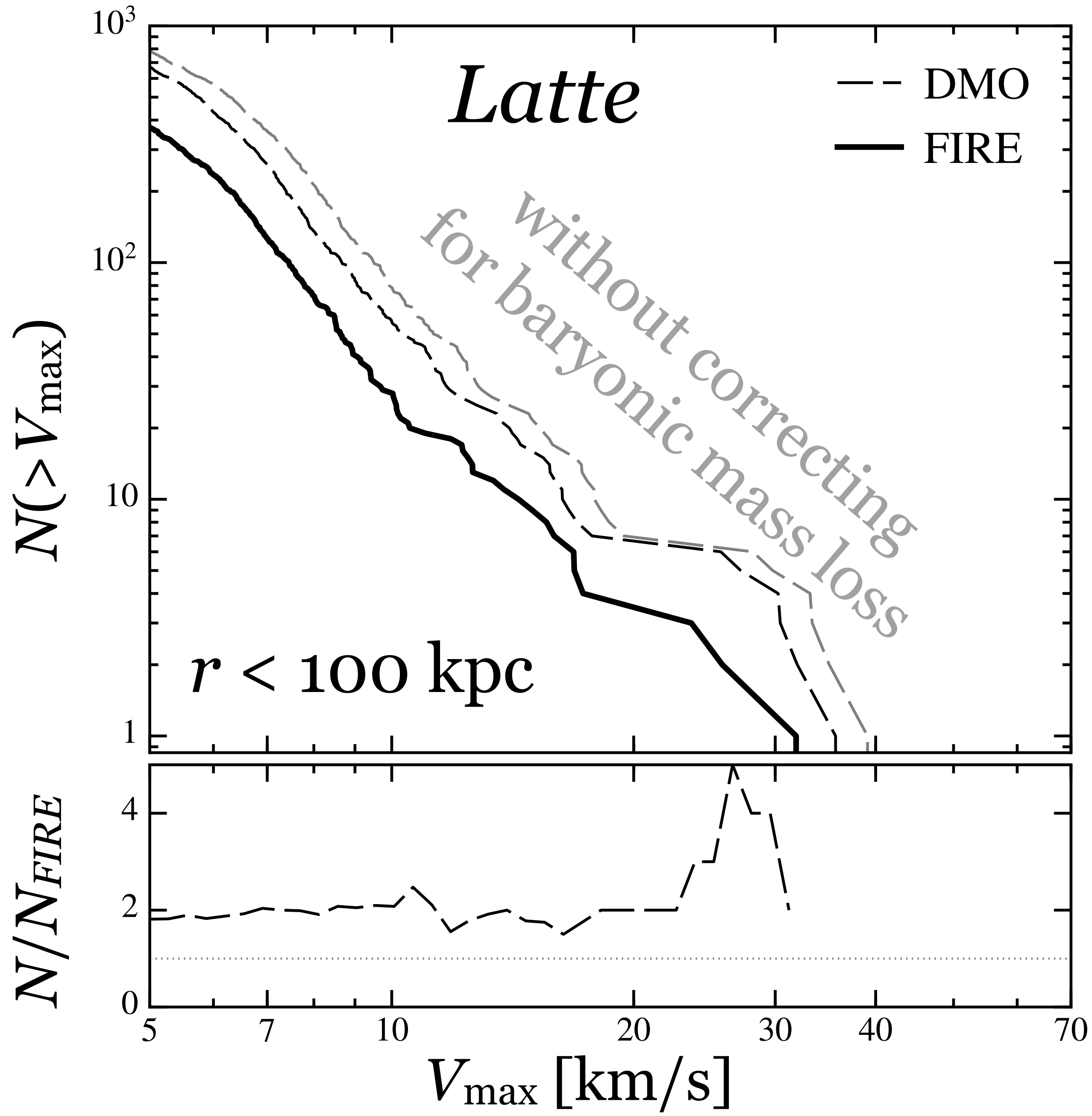

Wetzel+2016

DMO over predicts by a factor of 2 within 100 kpc and a

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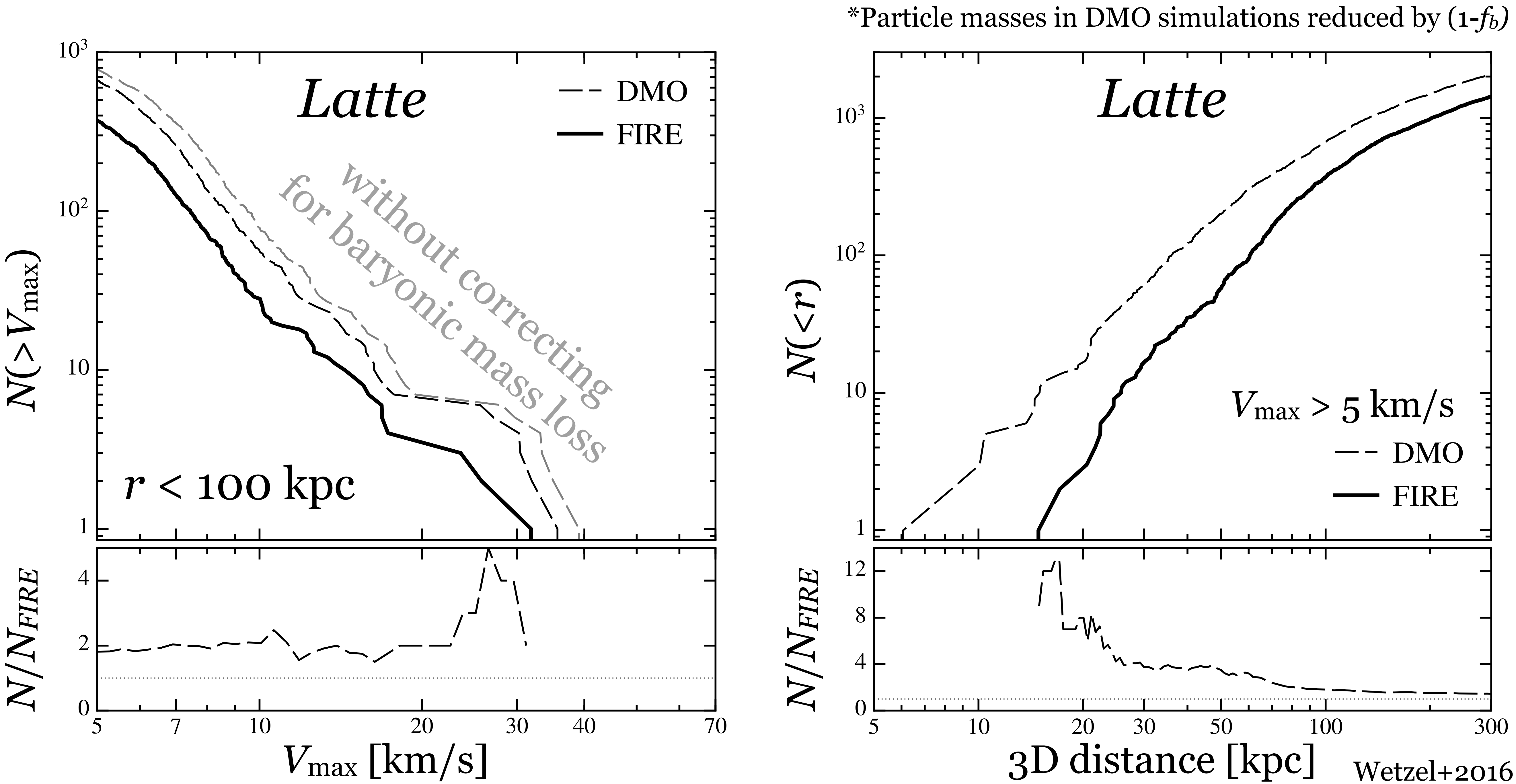

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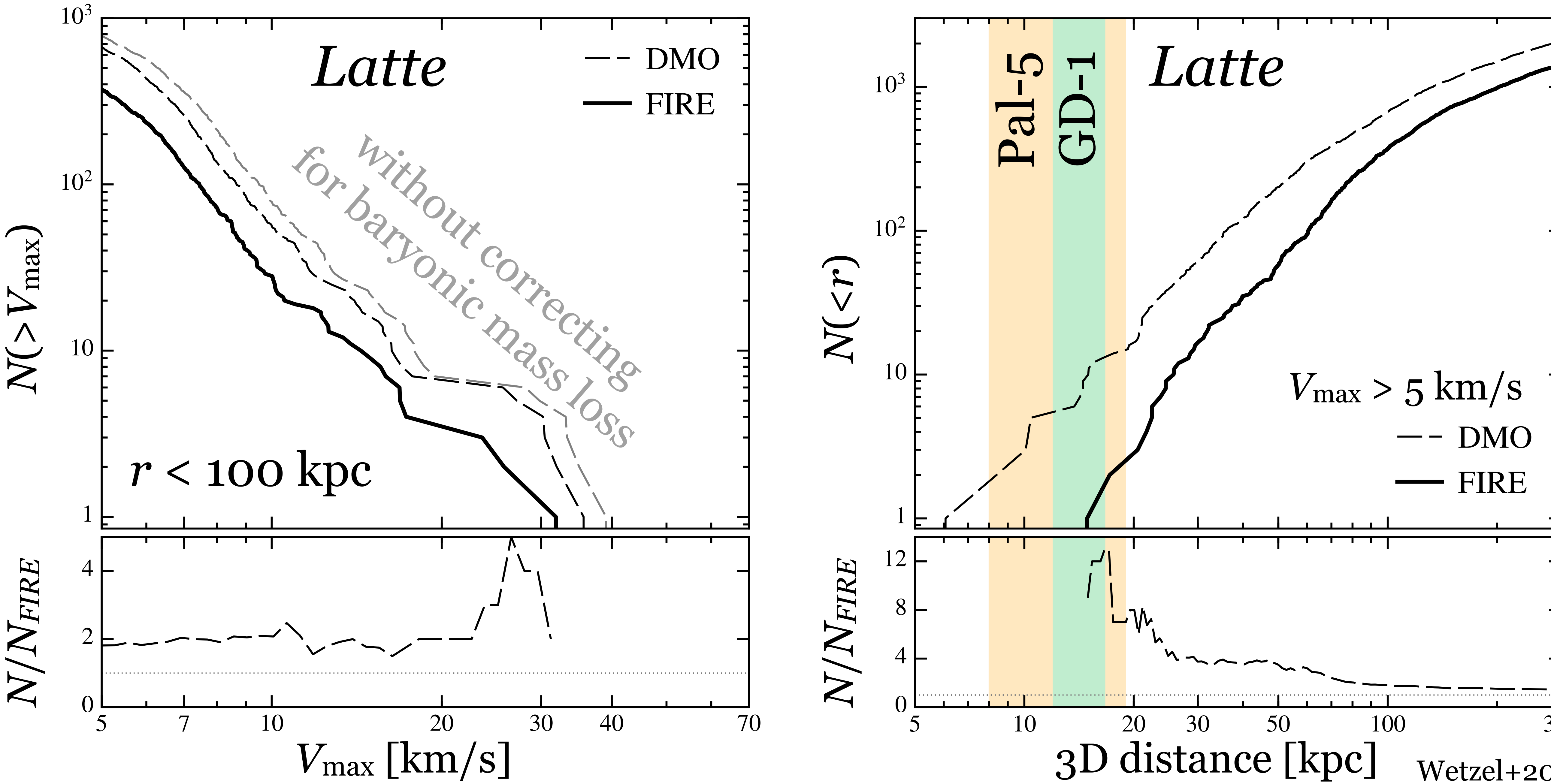

Wetzel+2016

DMO over predicts by a factor of 2 within 100 kpc and a factor of 10 within 20 kpc

Baryons affect subhalo populations

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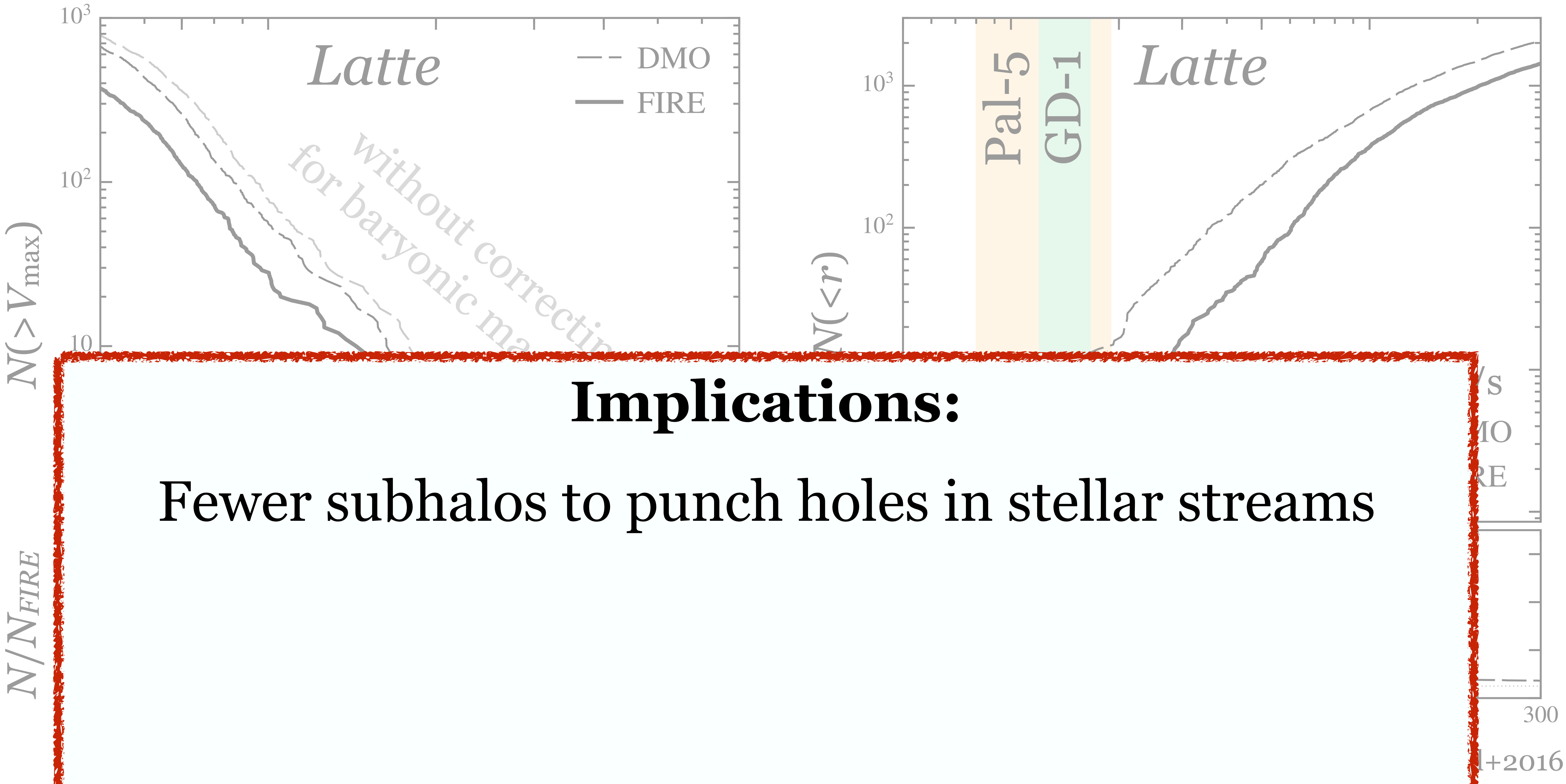

Implications:

Fewer subhalos to punch holes in stellar streams

Baryons affect subhalo populations

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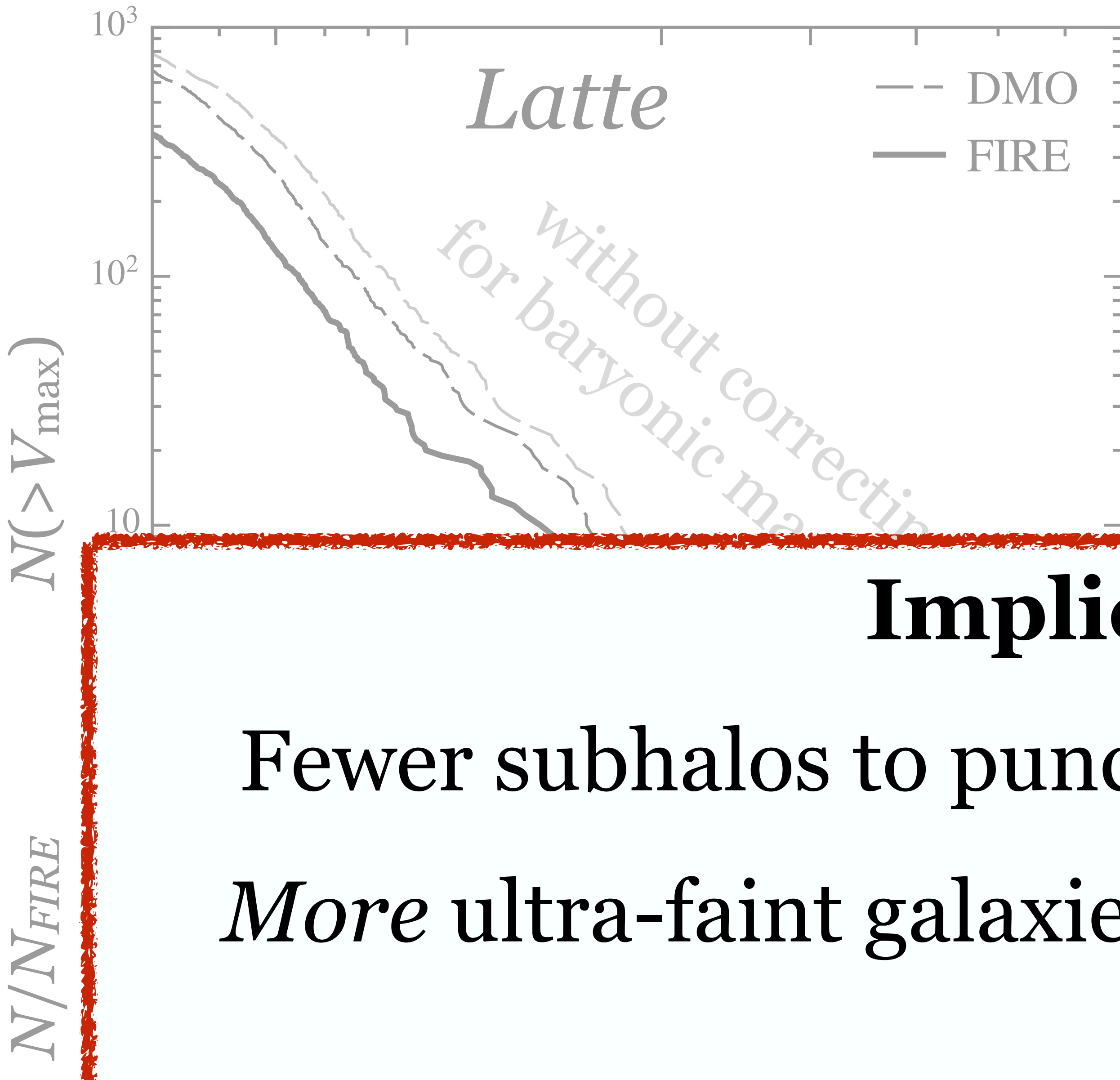

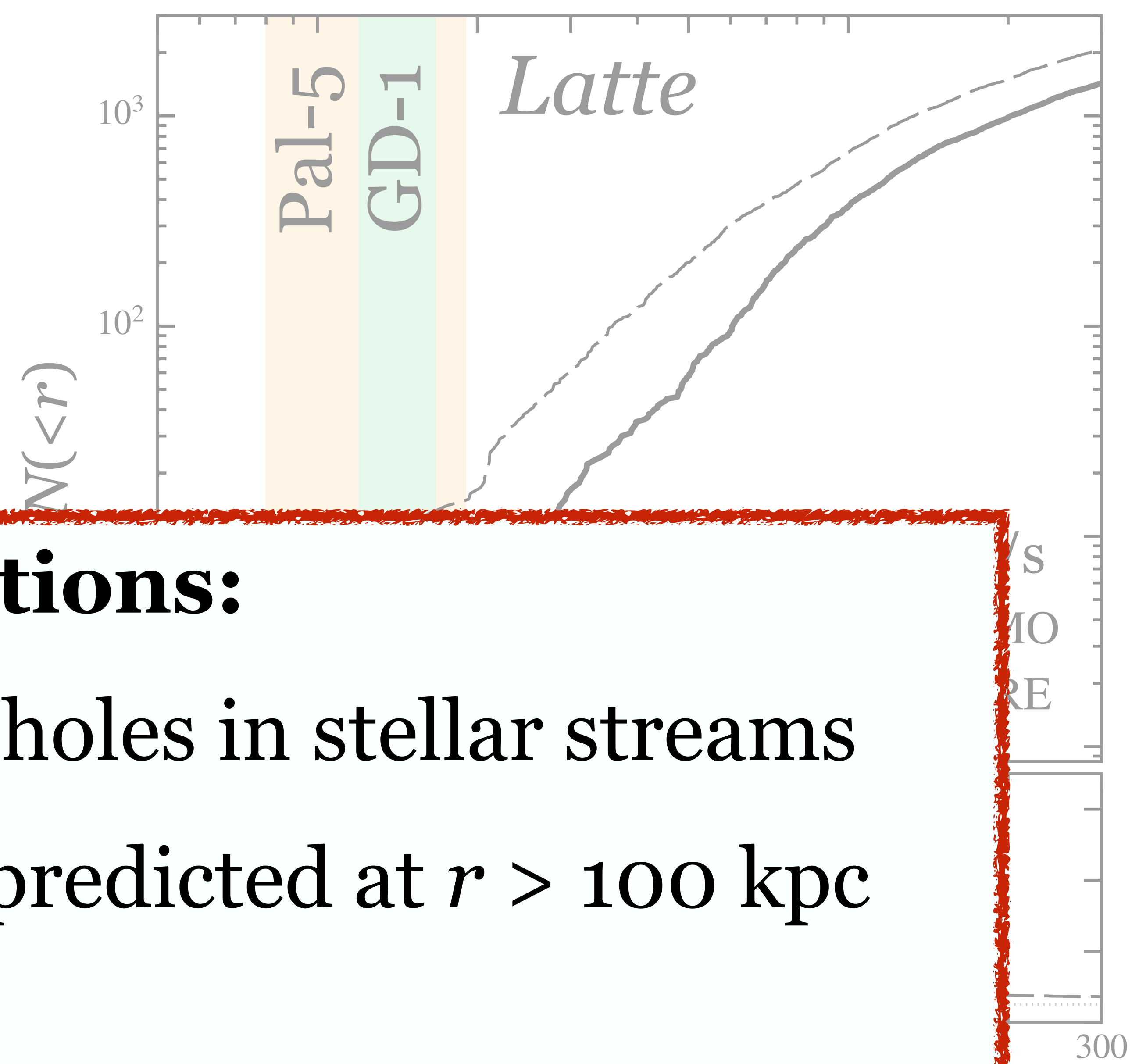

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More ultra-faint galaxies predicted at r > 100 kpc

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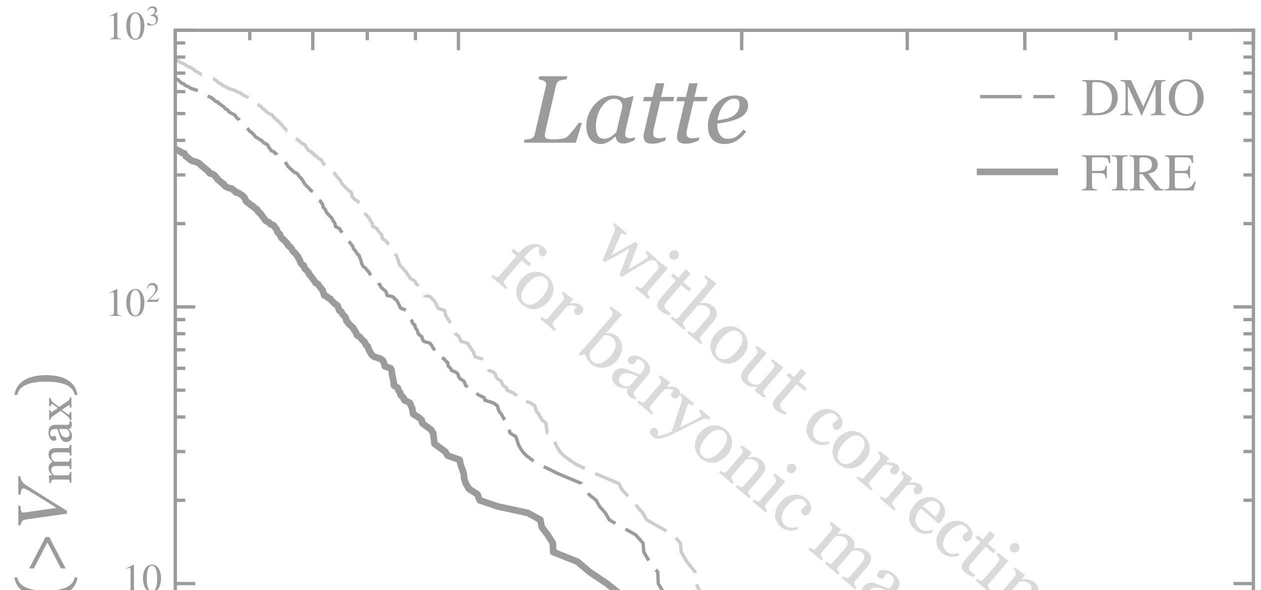

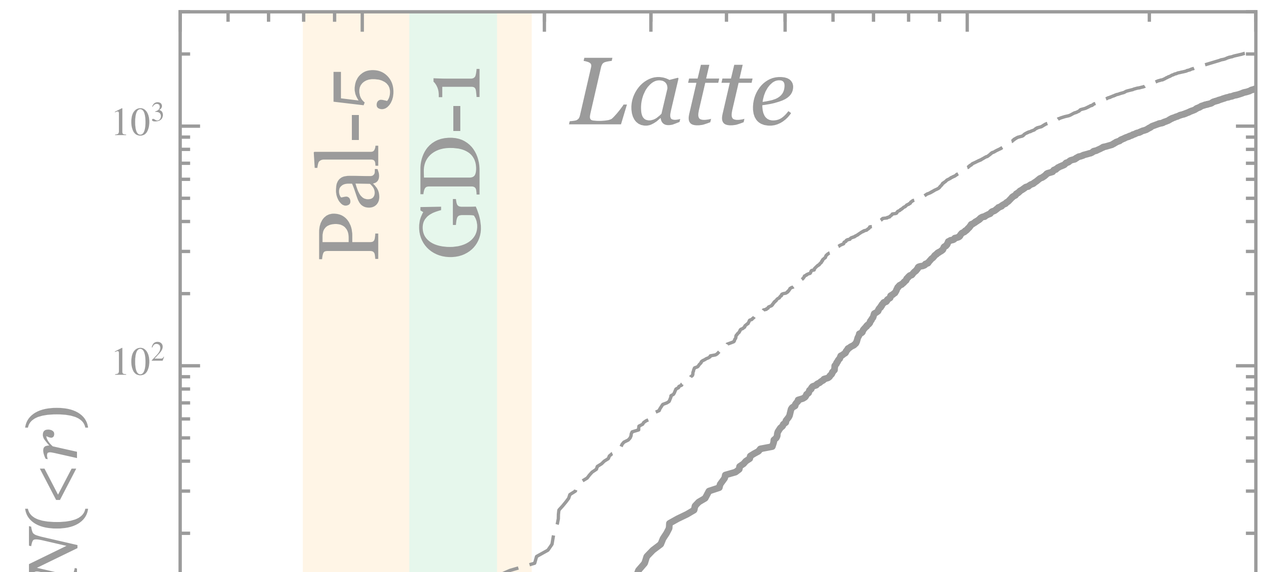

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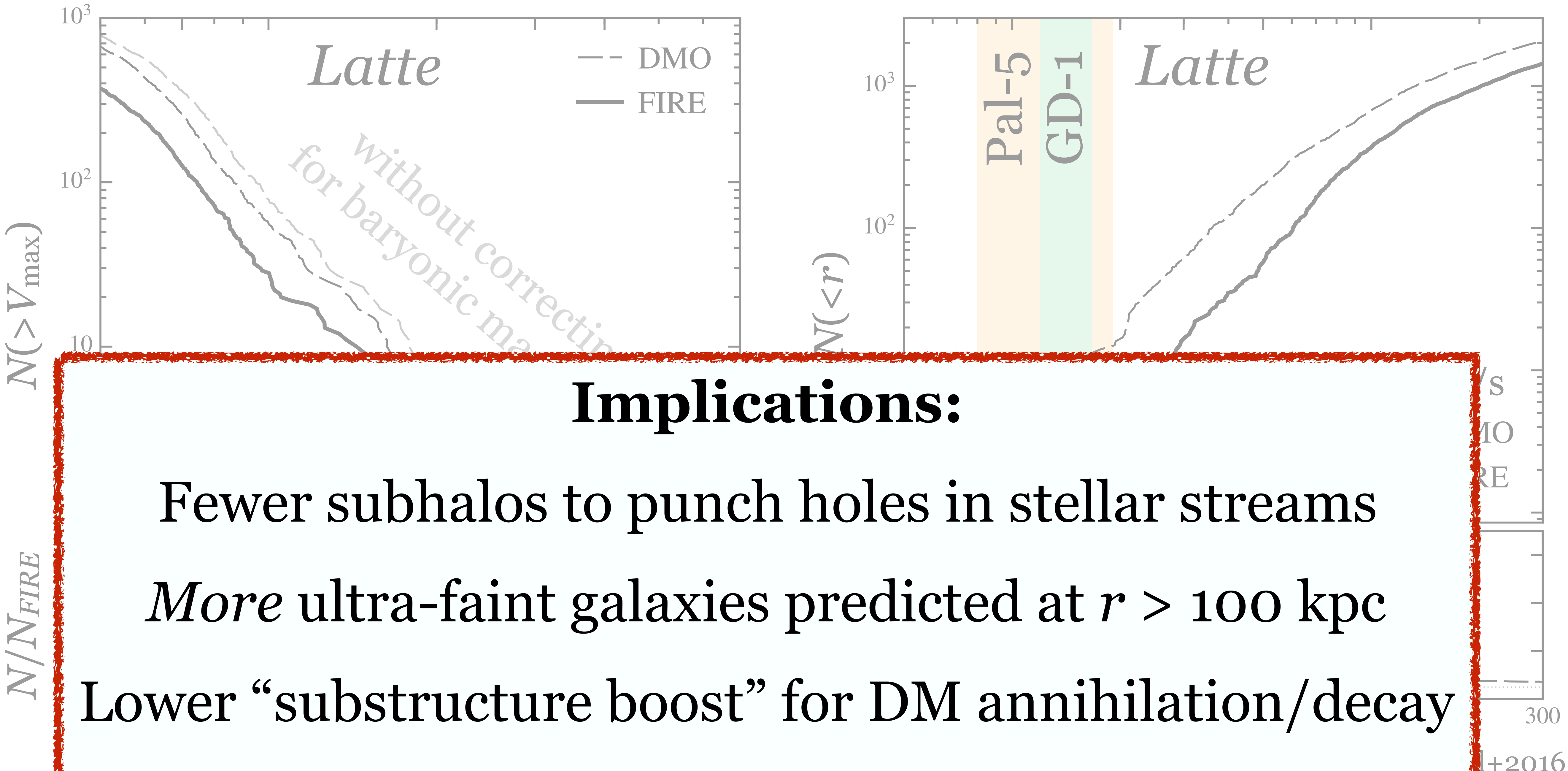

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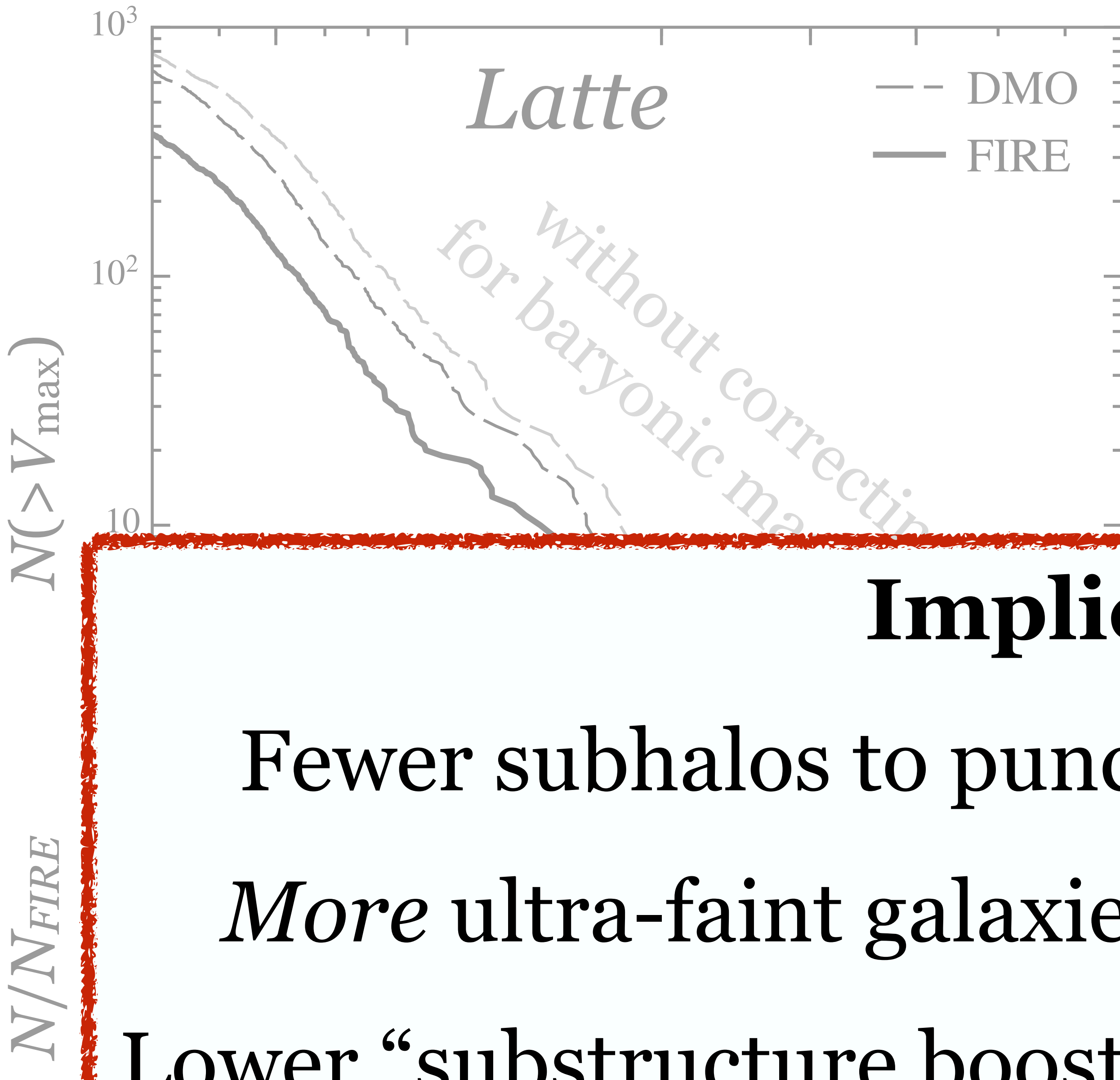

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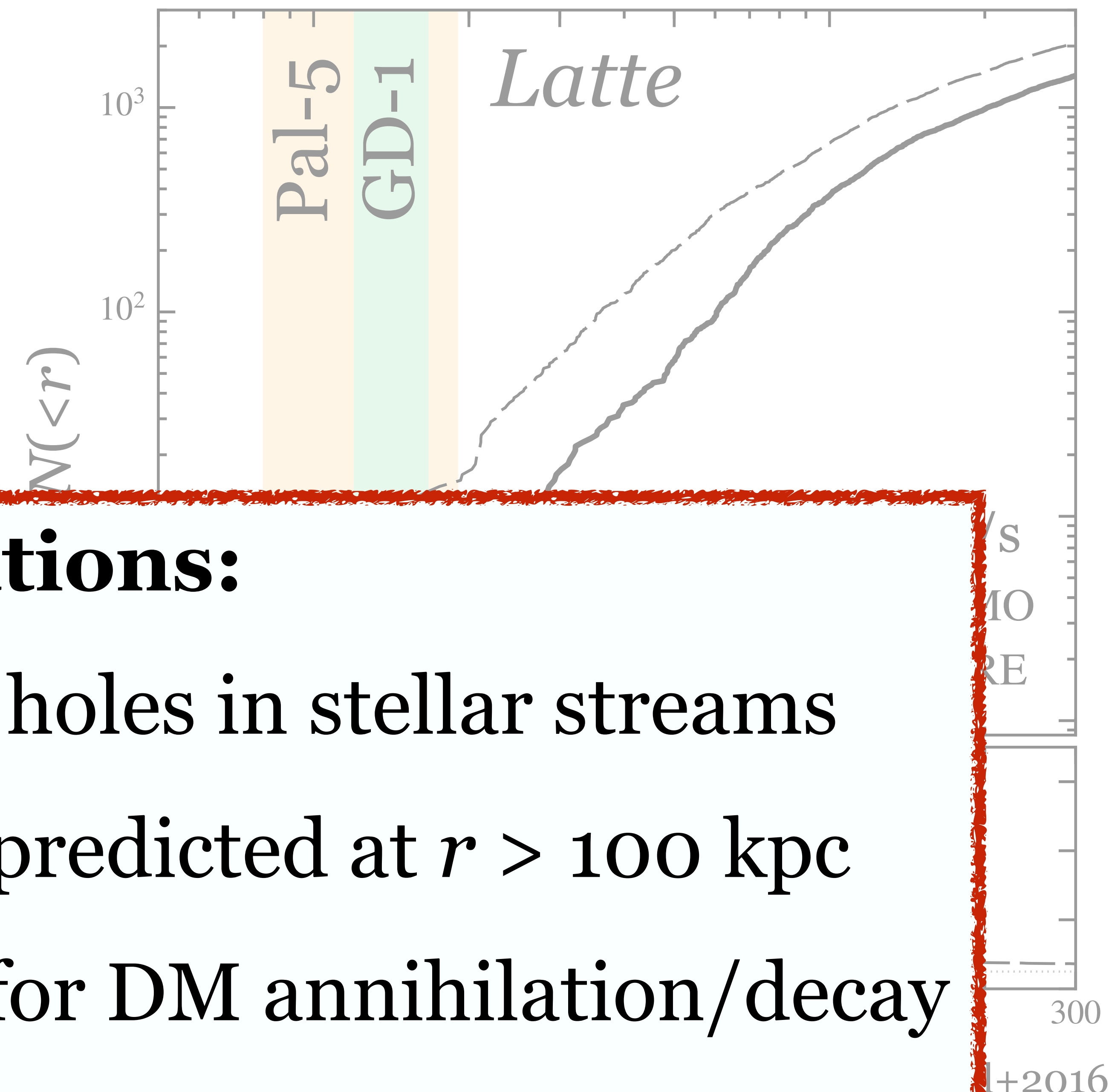

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Shorter (< 2 Gyr) quenching timescales for dwarfs

Hydro sims are great!

	Baryonic simulations	DMO simulations
Accurate?	✔	✗

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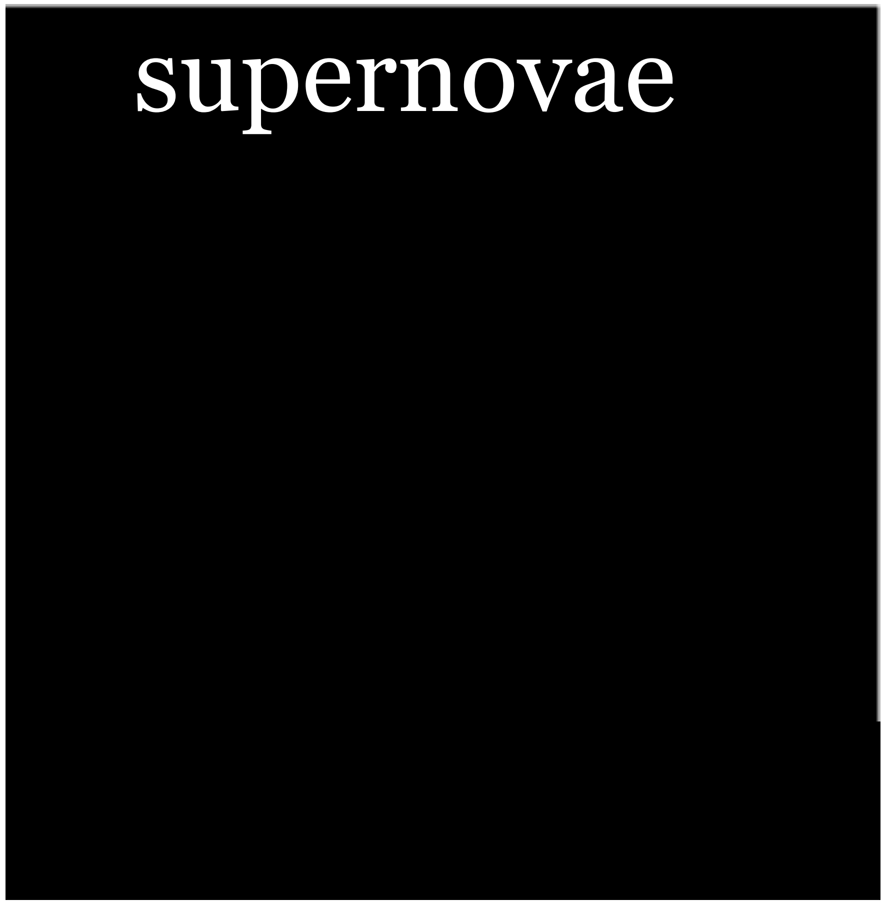

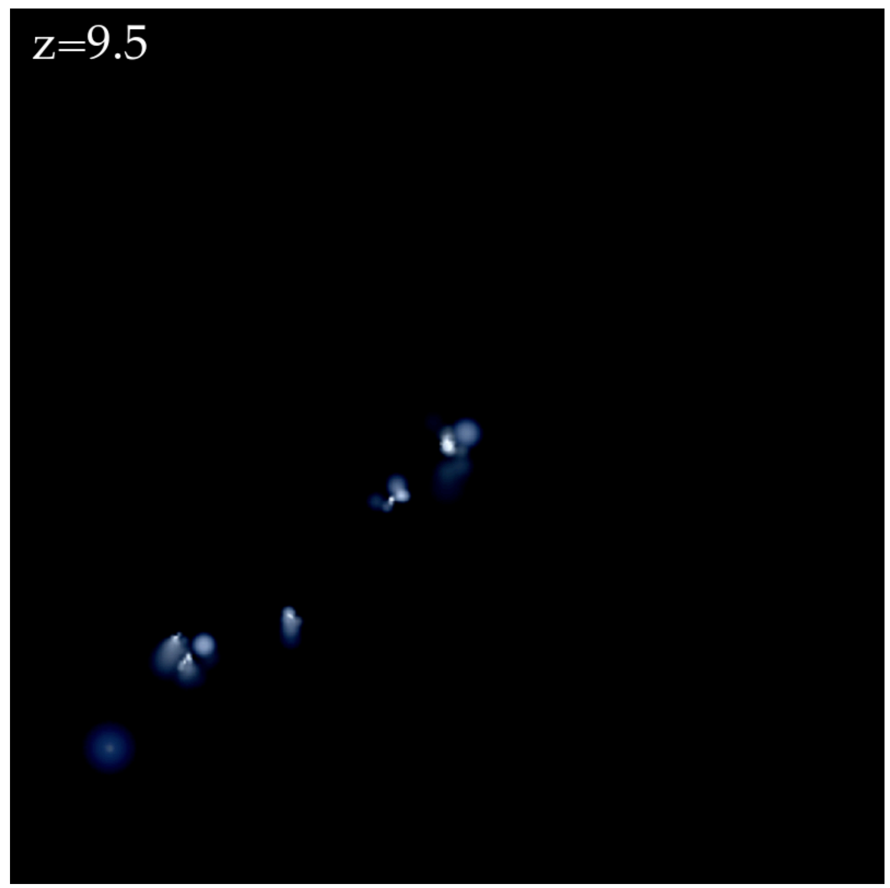

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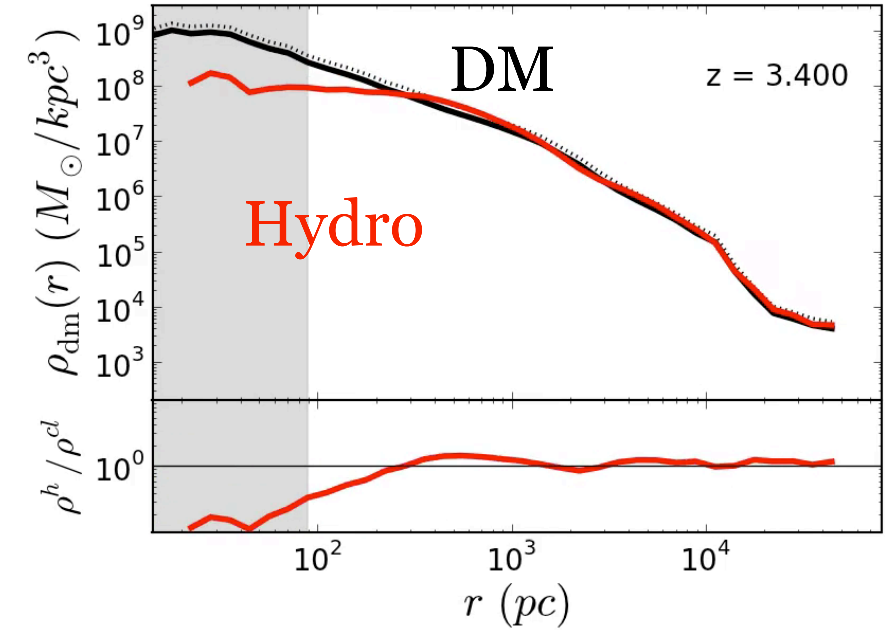

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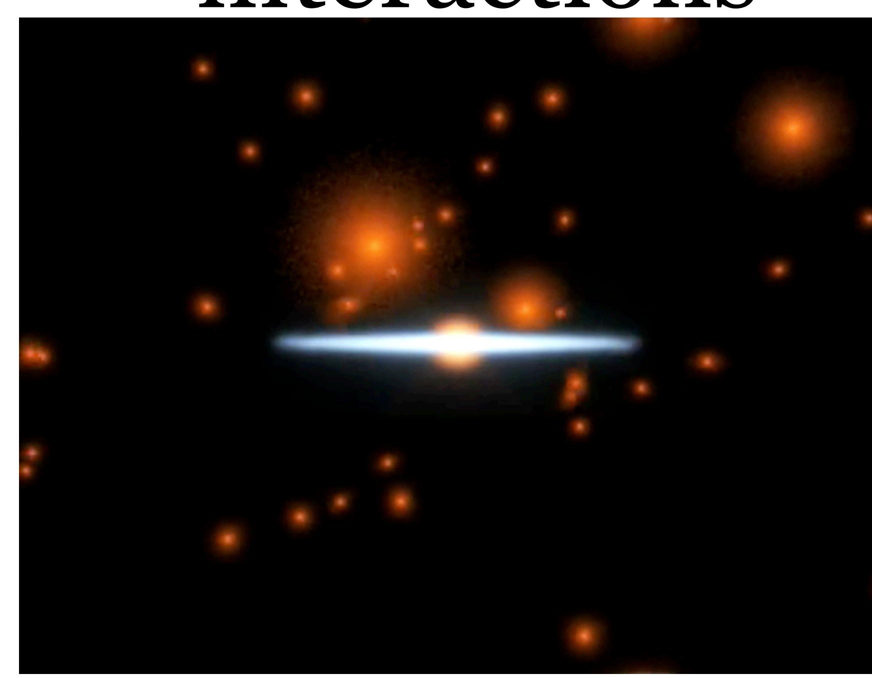

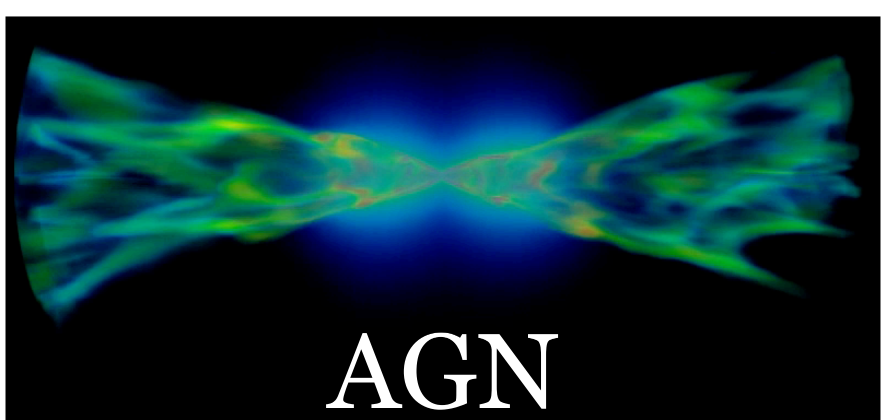

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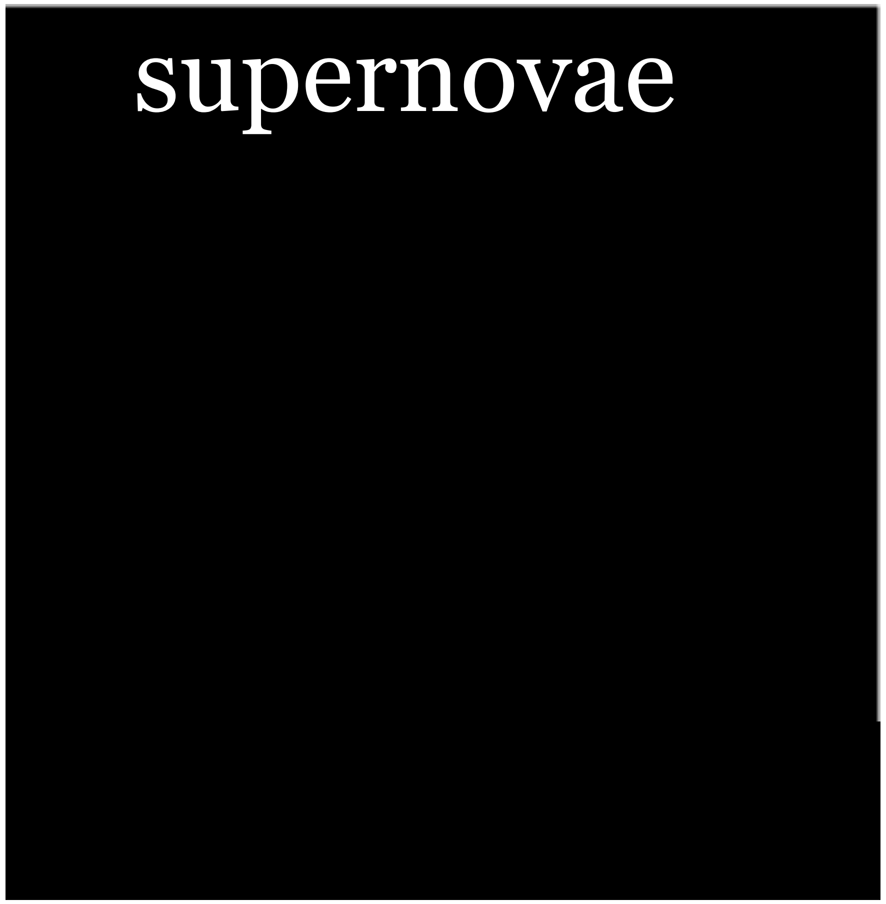

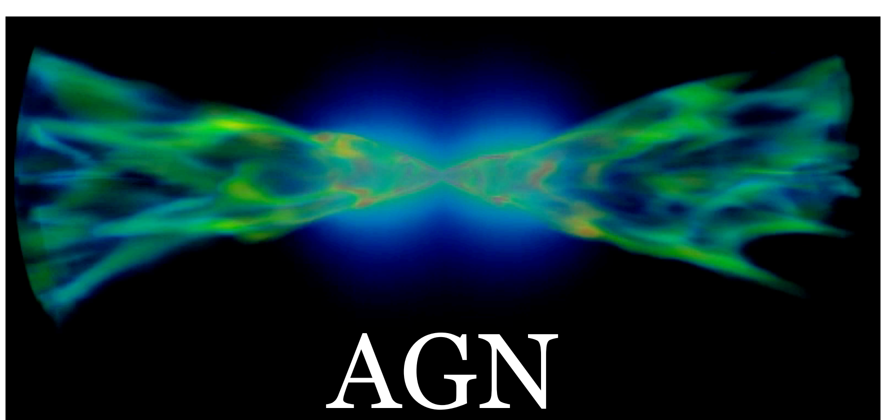

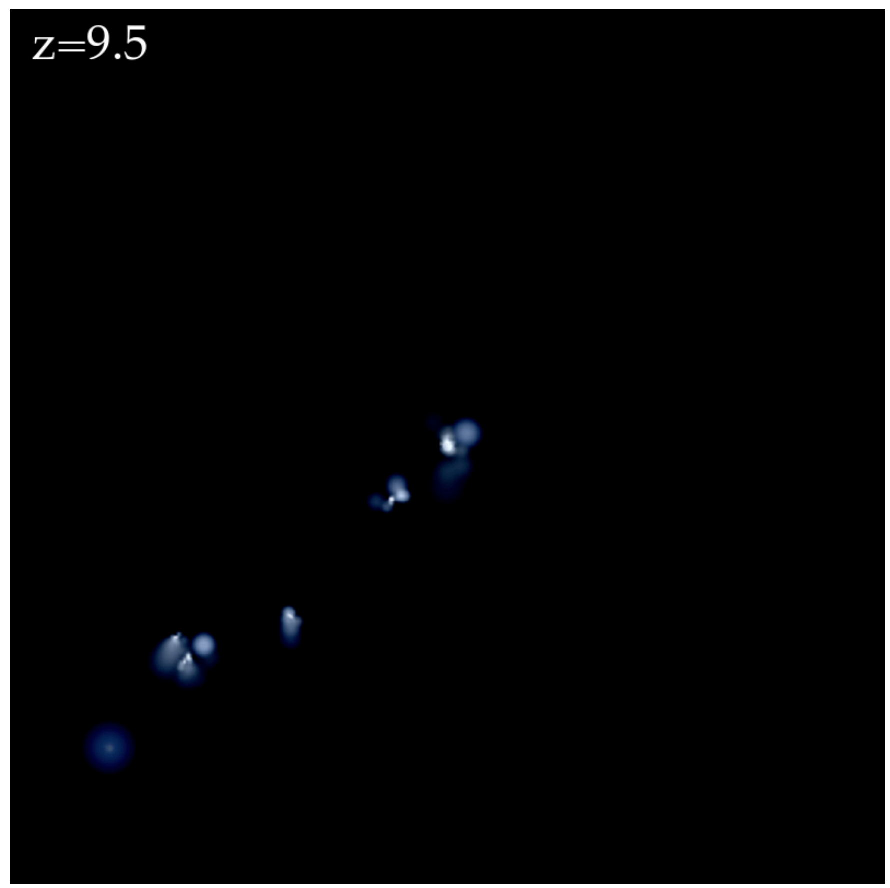

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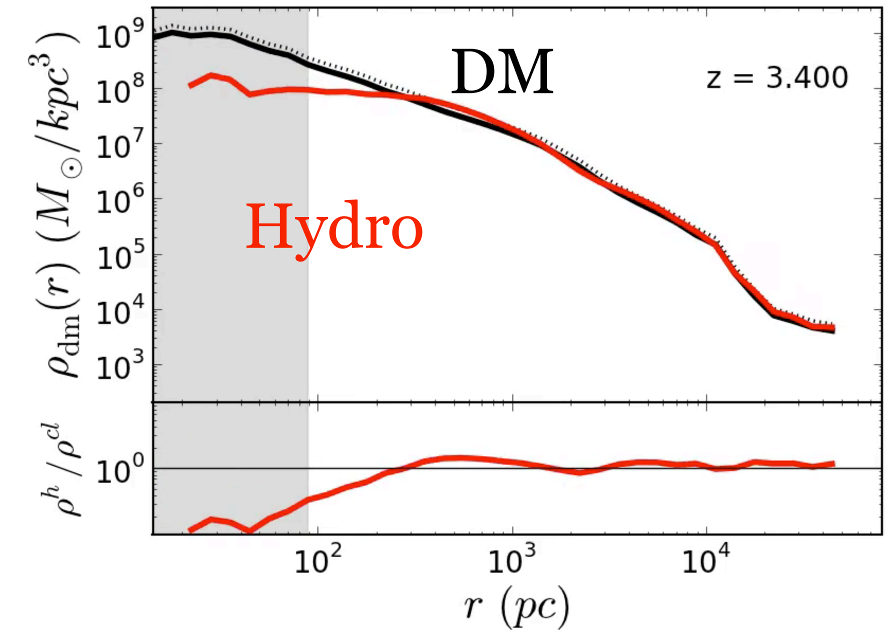

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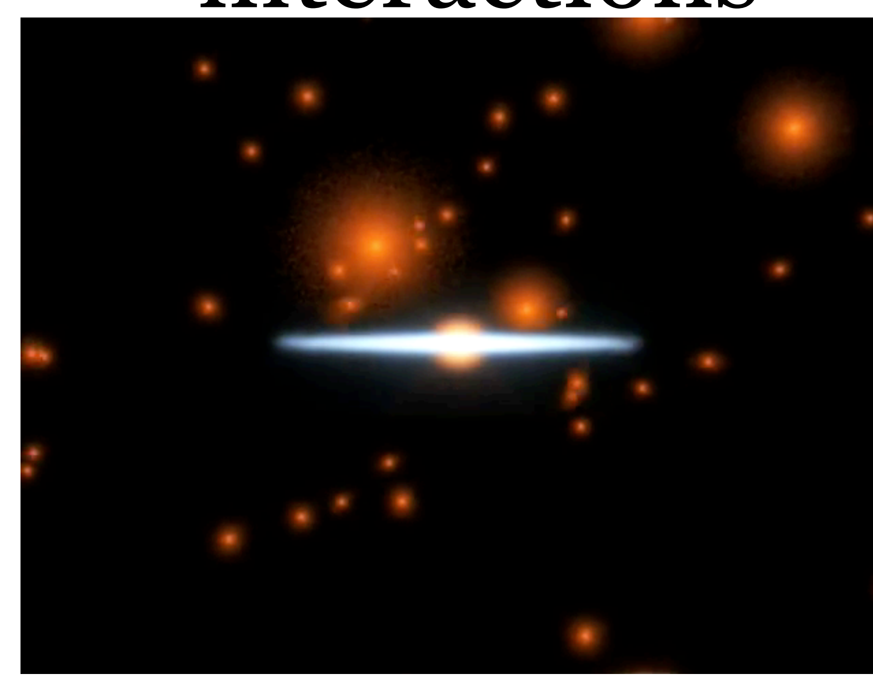

Hydro sims are ***costly!***

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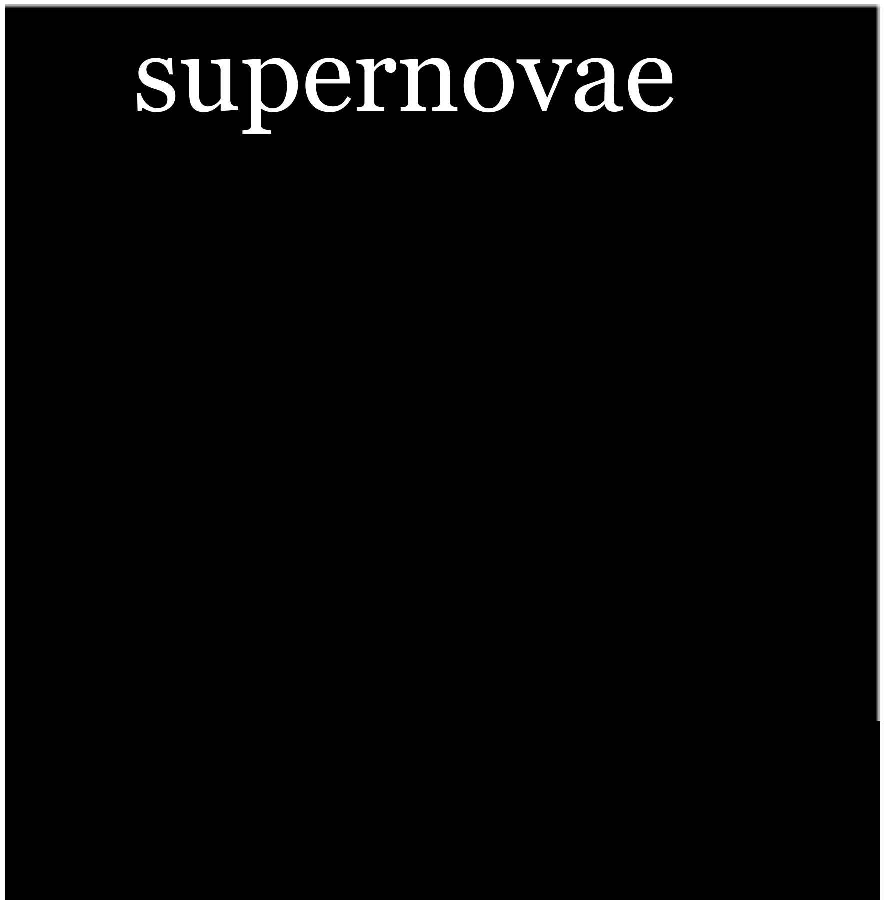

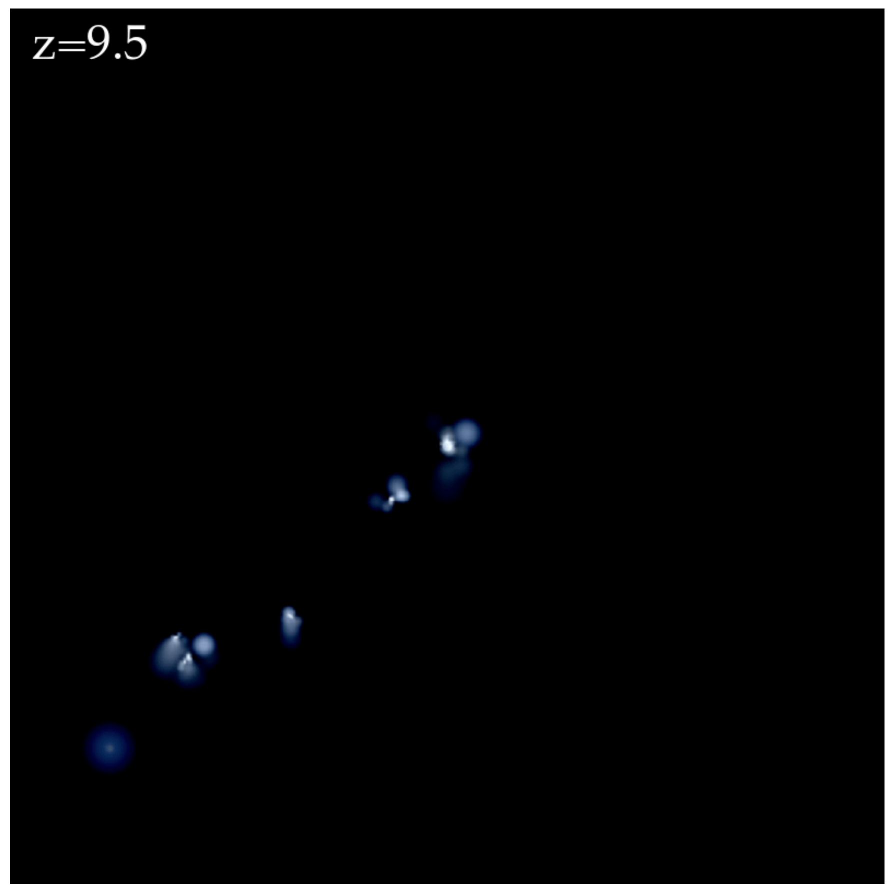

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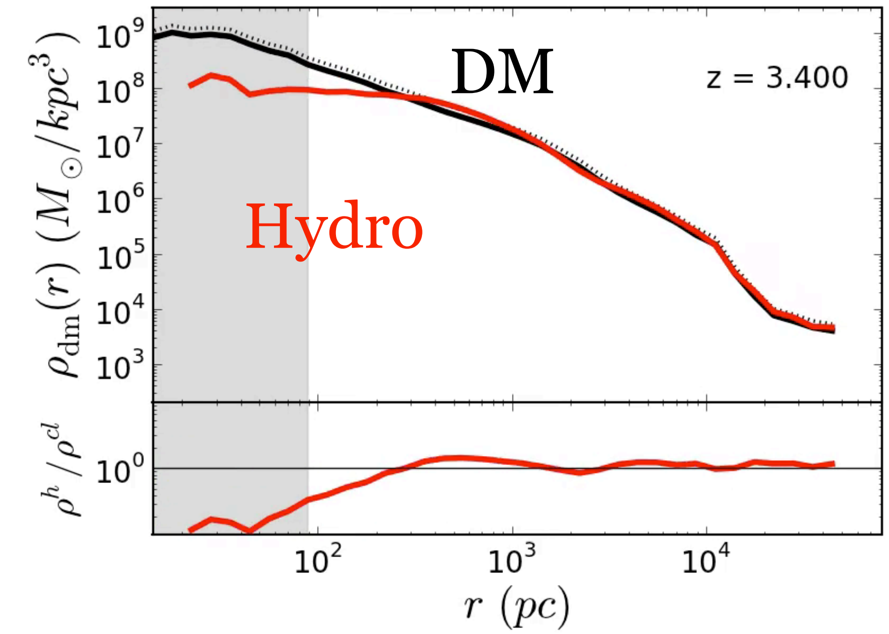
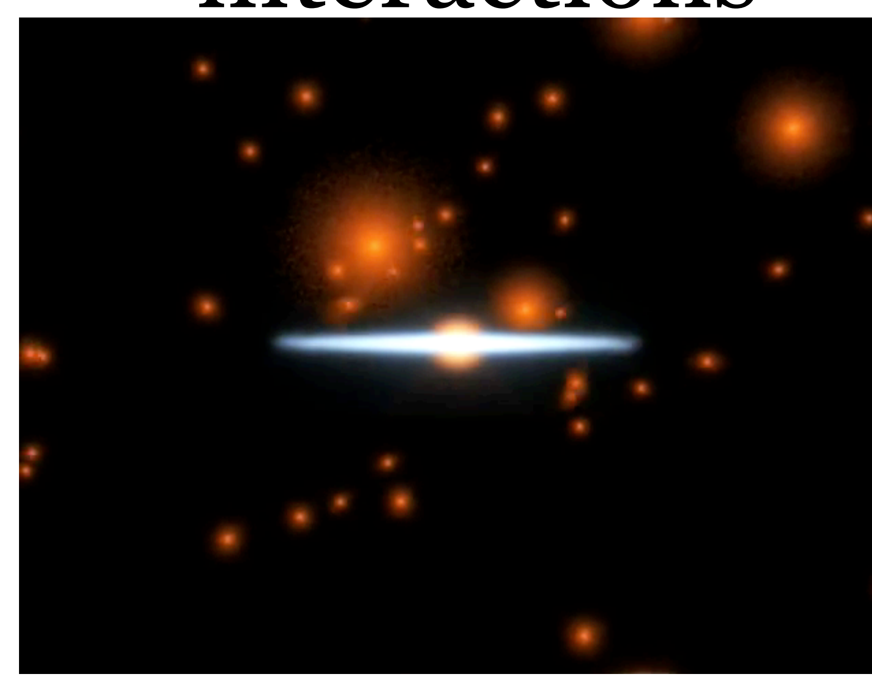
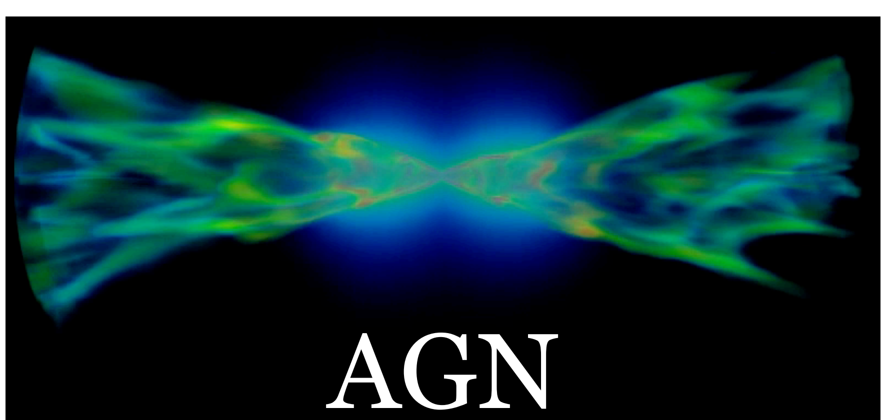


baryon-DM
interactions





Adding all of this (plus hydro) is very expensive!

Hydro sims are ***costly!***

	Baryonic simulations	DMO simulations
Accurate?	✔	***X***
Cheap?	*Latte* FIRE: 720,000 CPU hours	*Latte* DMO: 6326 CPU hours

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110 times more expensive!

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	Baryonic simulations	DMO simulations
Accurate?	✔	✘
Cheap?	✘	✔

110 times more expensive!

Hydro sims are ***costly!***

	Baryonic simulations	DMO simulations
Accurate?	✔	✘
Statistical samples?	✘	✔

Could simulate 100+ halos in the same CPU time

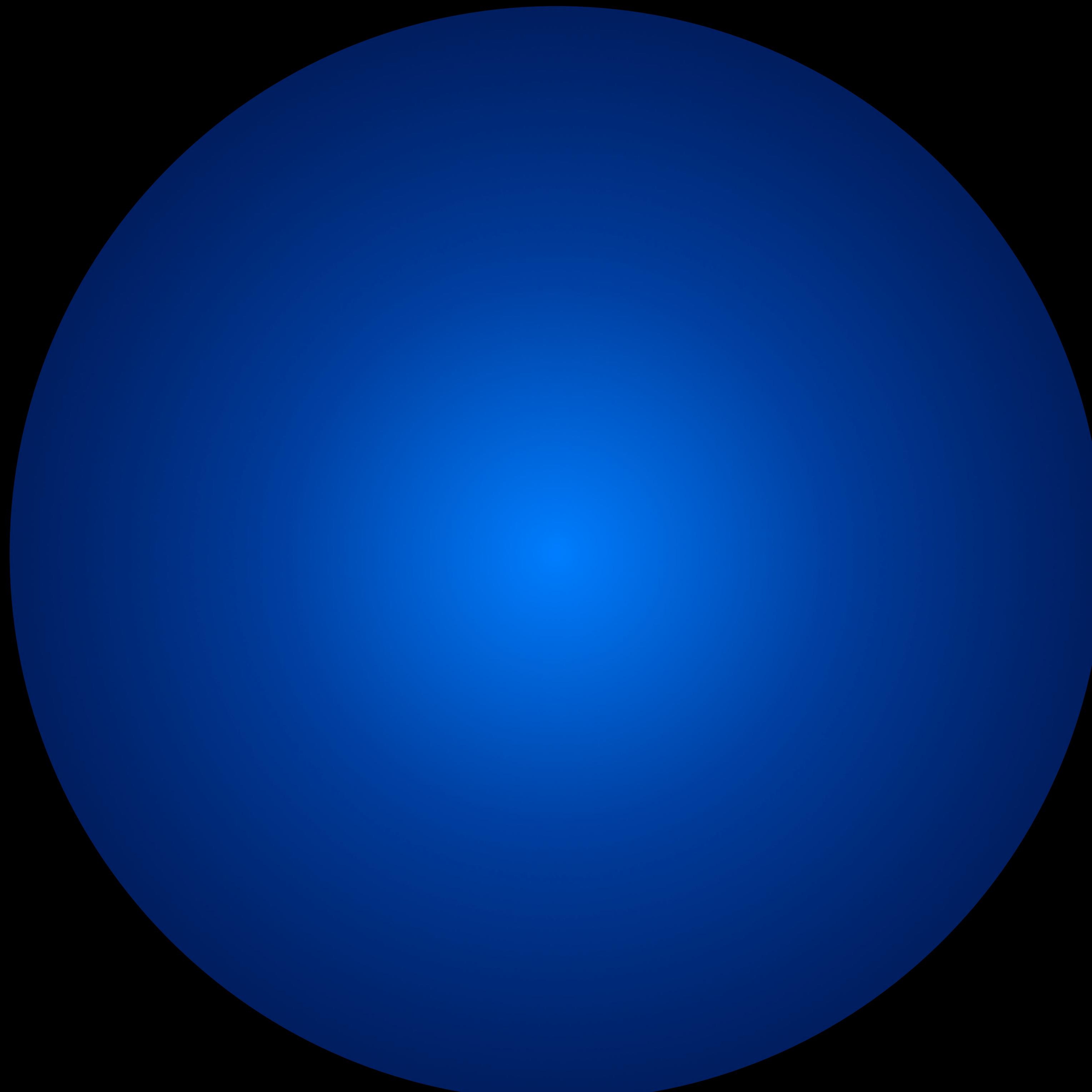
Hydro sims are ***costly!***

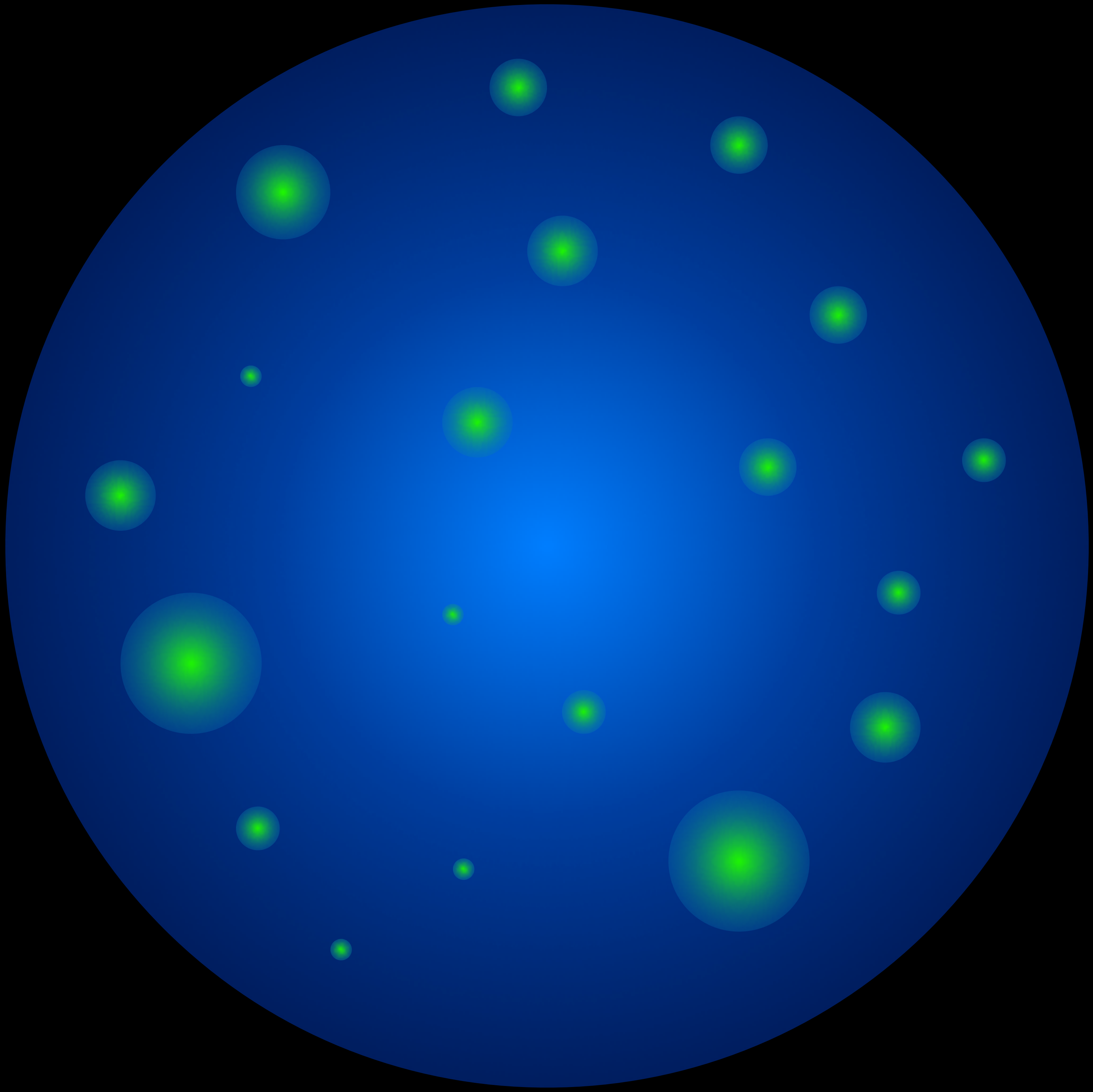
	Baryonic simulations	DMO simulations
Accurate?	✔	***X***
Statistical samples?	***X***	✔

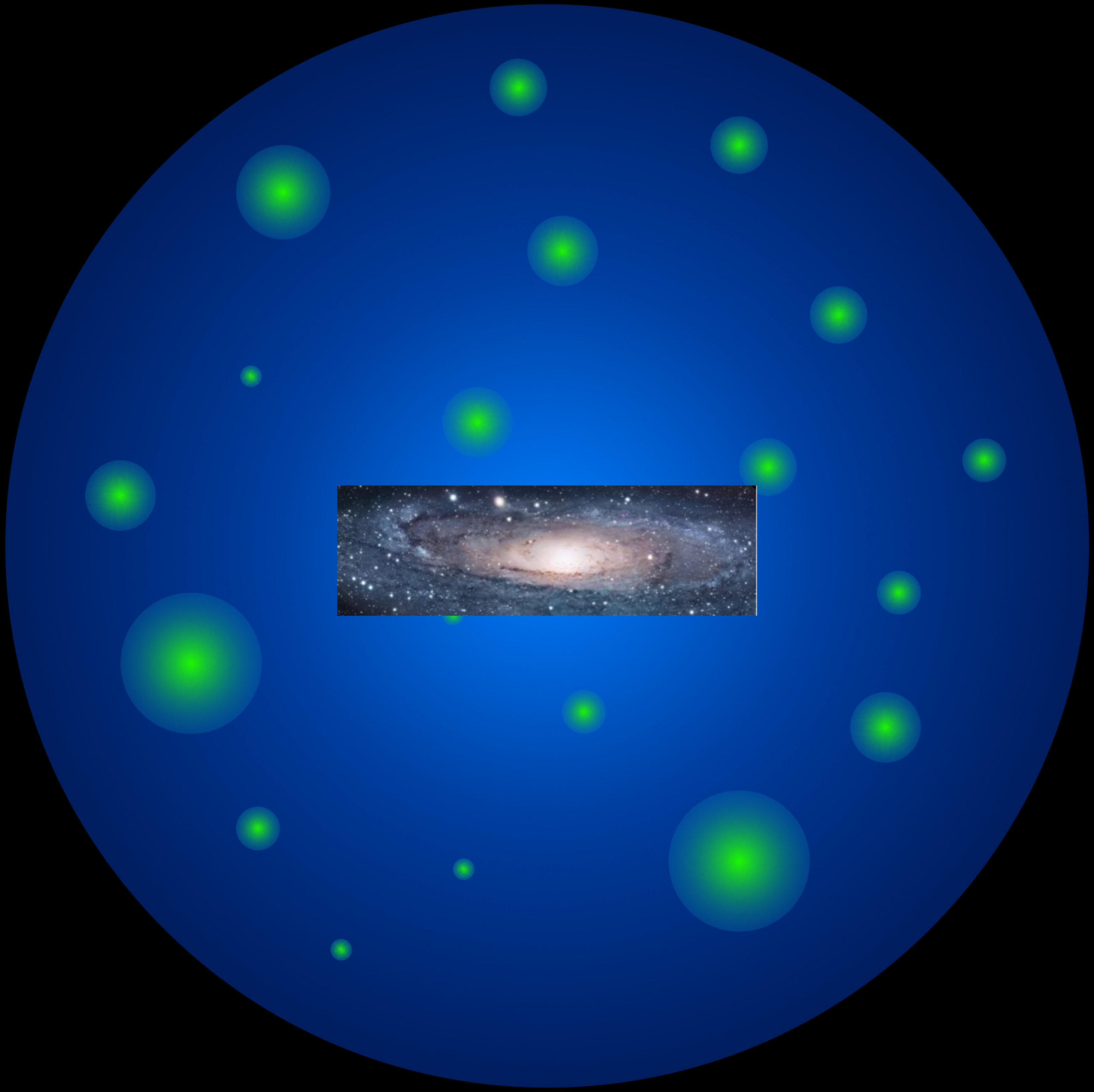
Can’t broadly sample distribution of halo and subhalo properties

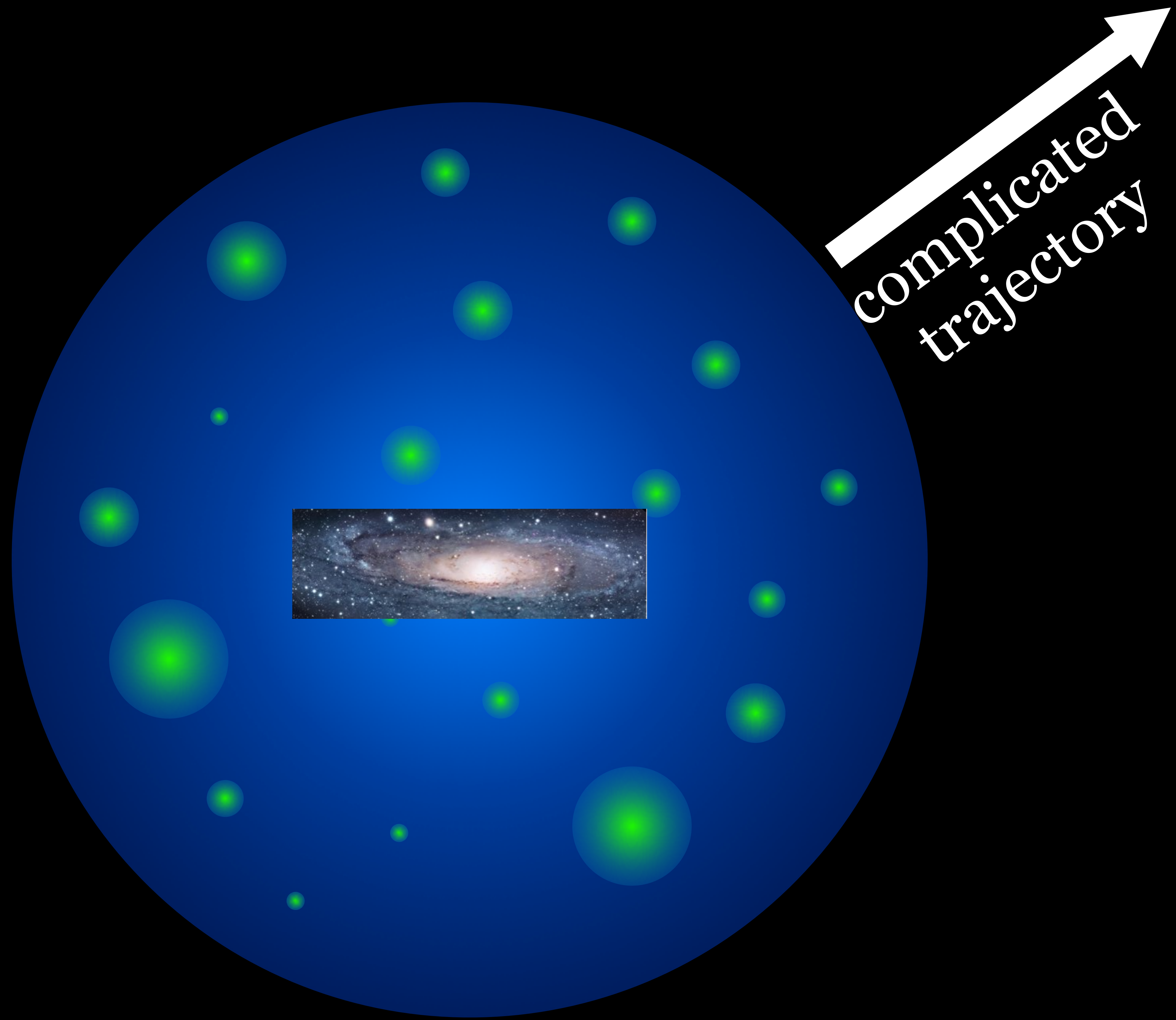
Hydro sims are ***costly!***

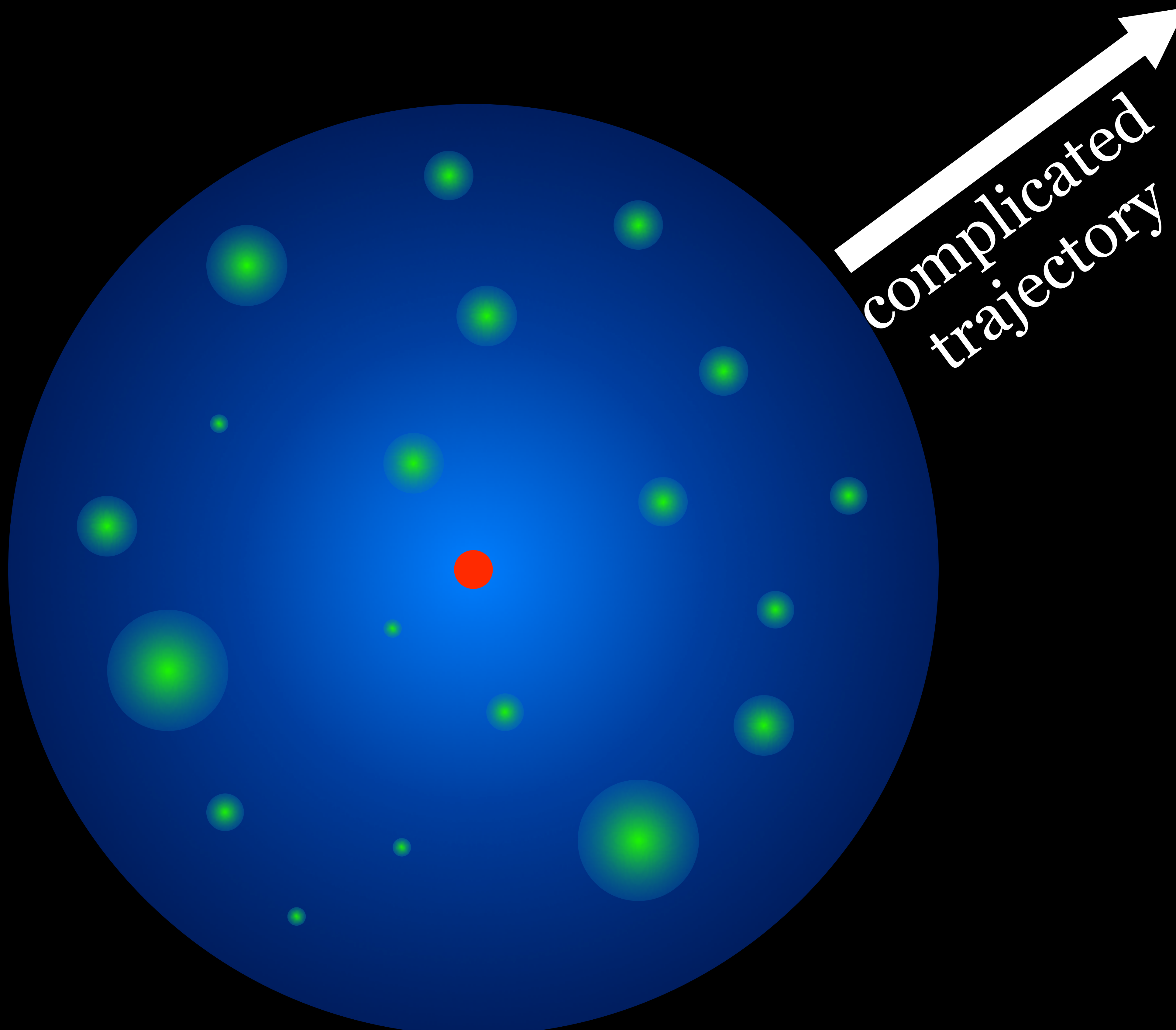
	Baryonic simulations	DMO simulations	Embedded disk
Accurate?	✔	***X***	
Statistical samples?	***X***	✔	



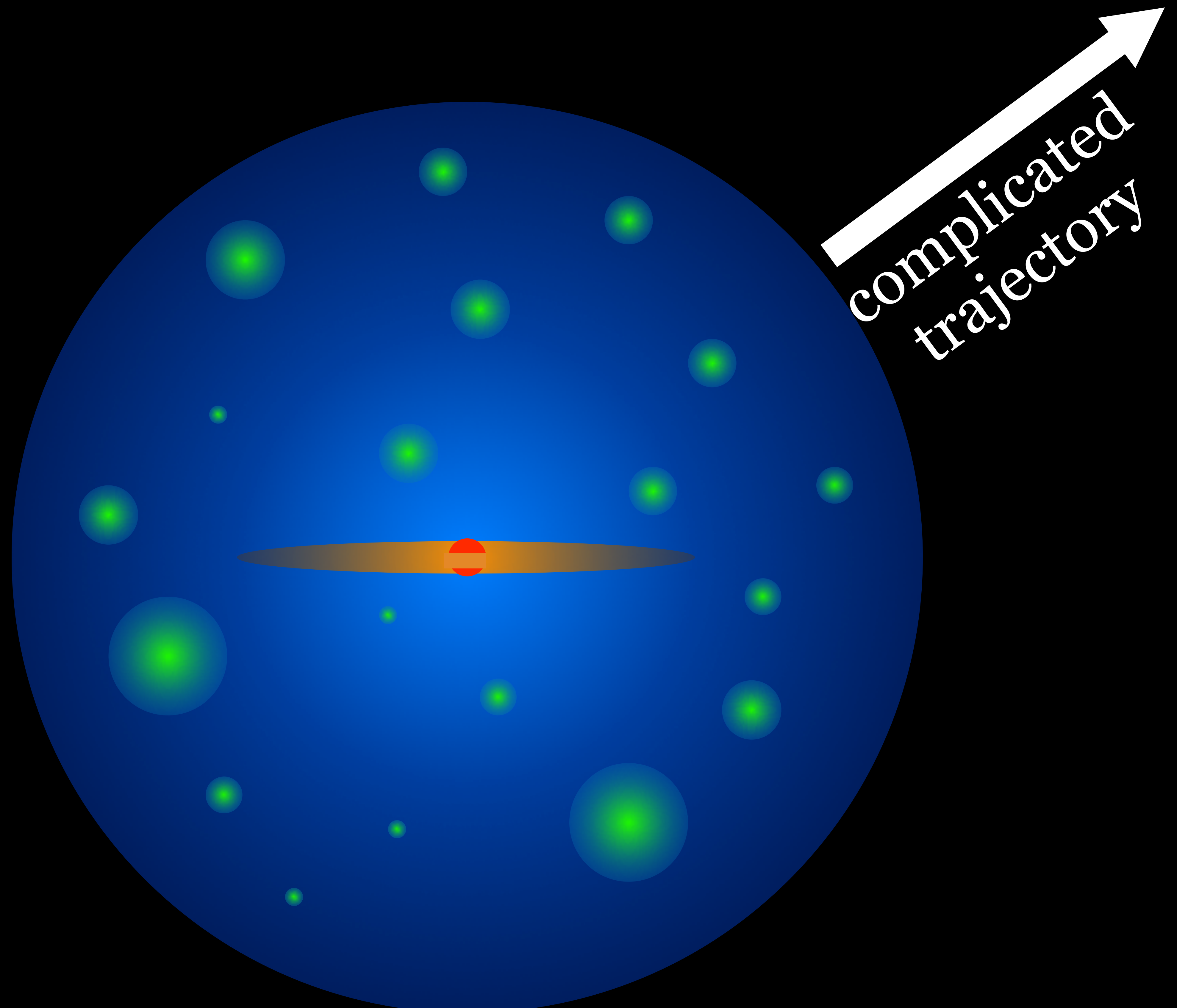





complicated
trajectory



Insert massive particle to track halo center



Insert massive particle to track halo center

Add acceleration from a disk *that matches FIRE*

Hydro sims are ***costly!***

	Baryonic simulations	DMO simulations	Embedded disk
Accurate?	✔	***X***	
Statistical samples?	***X***	✔	~2x DMO

Hydro sims are ***costly!***

	Baryonic simulations	DMO simulations	Embedded disk
Accurate?	✔	***X***	
Statistical samples?	***X***	✔	✔

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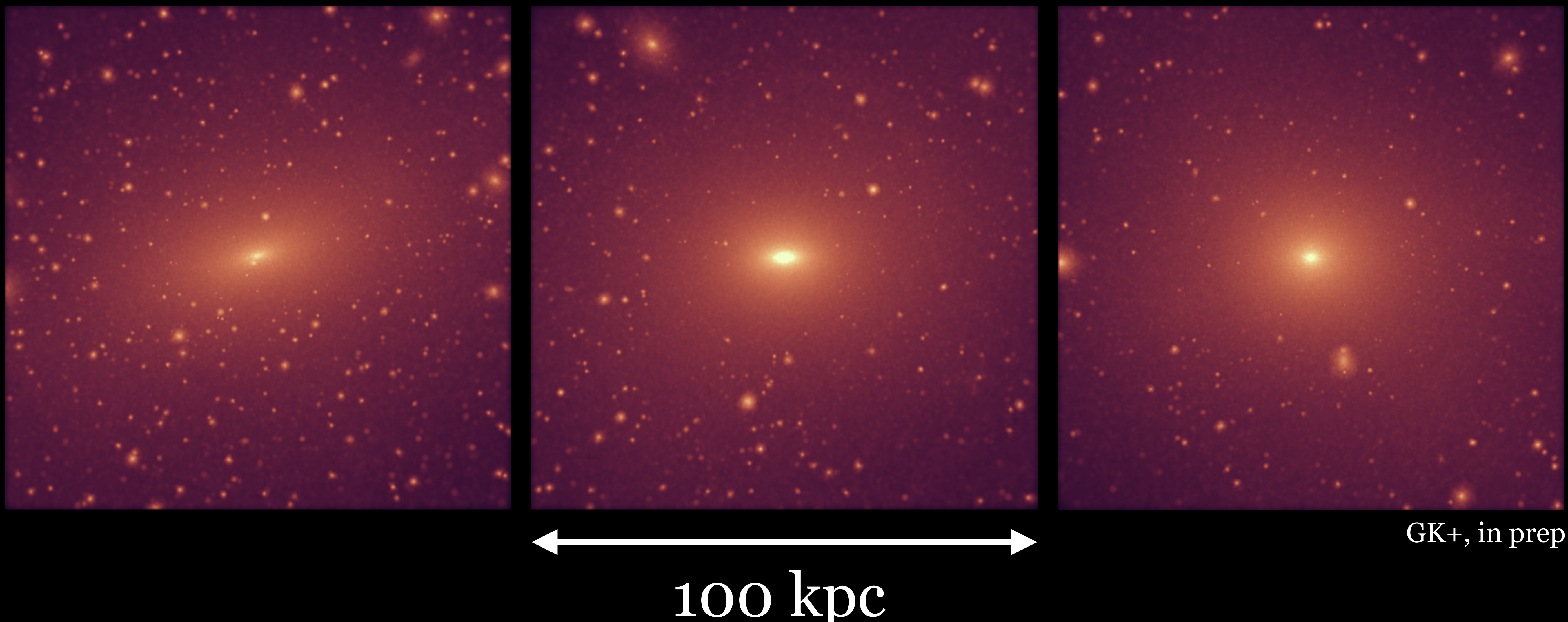
	Baryonic simulations	DMO simulations	Embedded disk
Accurate?	✔	***X***	**?**
Statistical samples?	***X***	✔	✔

How effective is the disk?

Visualizing the local *DM* density

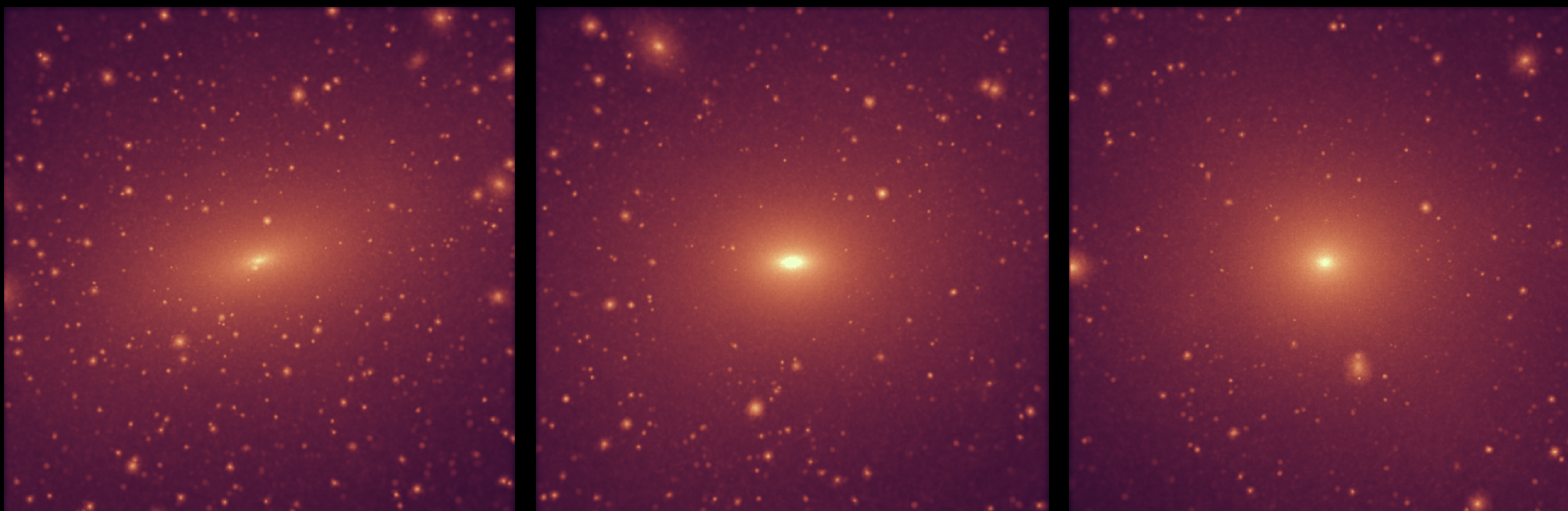


GK+, in prep

How effective is the disk?

Visualizing the local *DM* density

DMO ?? ??



100 kpc

GK+, in prep

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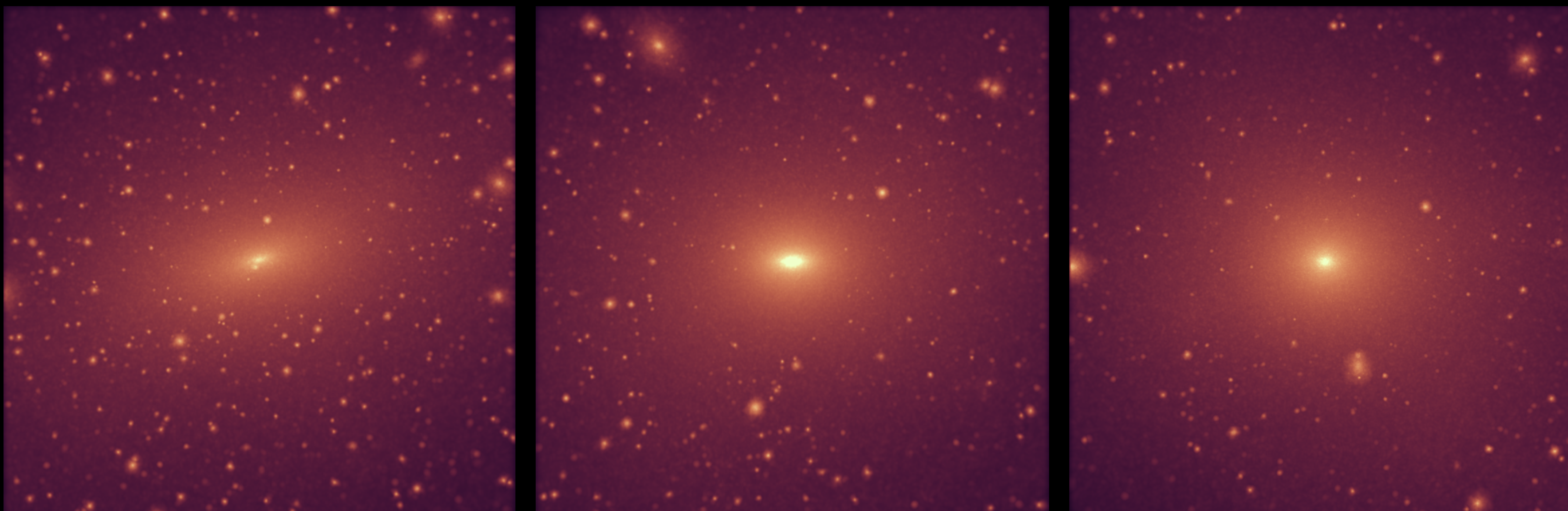
Visualizing the local *DM* density

DMO embedded disk FIRE



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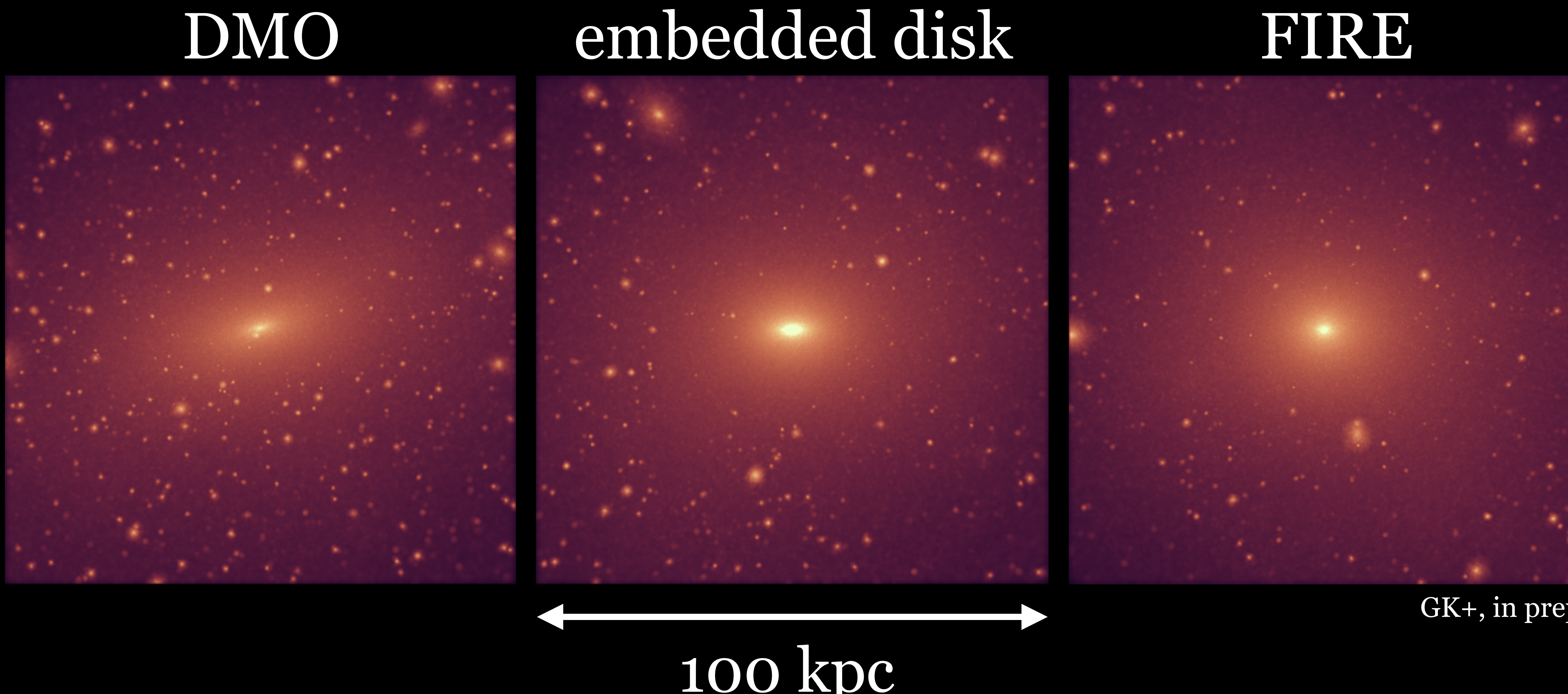
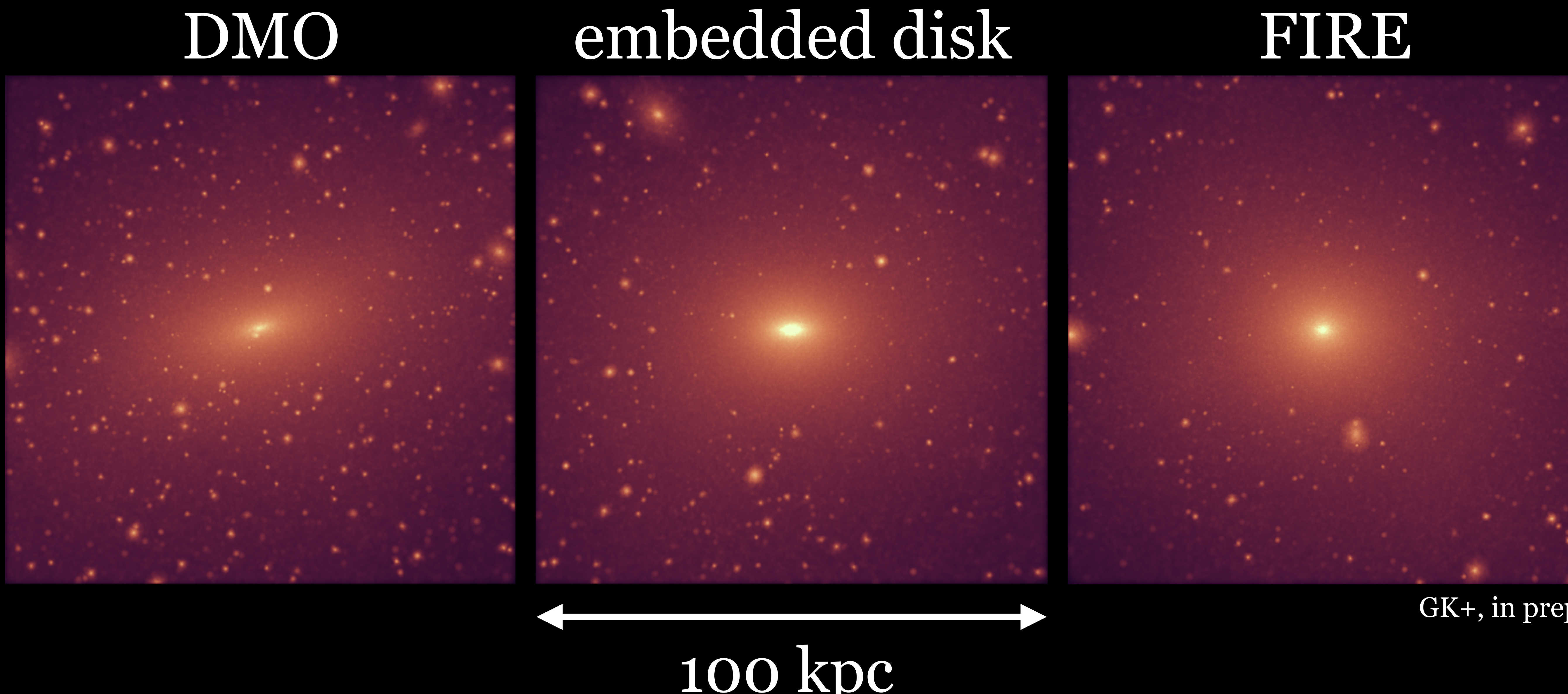


GK+, in prep

How much of the stripping/destruction is due to the galaxy?

How effective is the disk?

Visualizing the local *DM* density



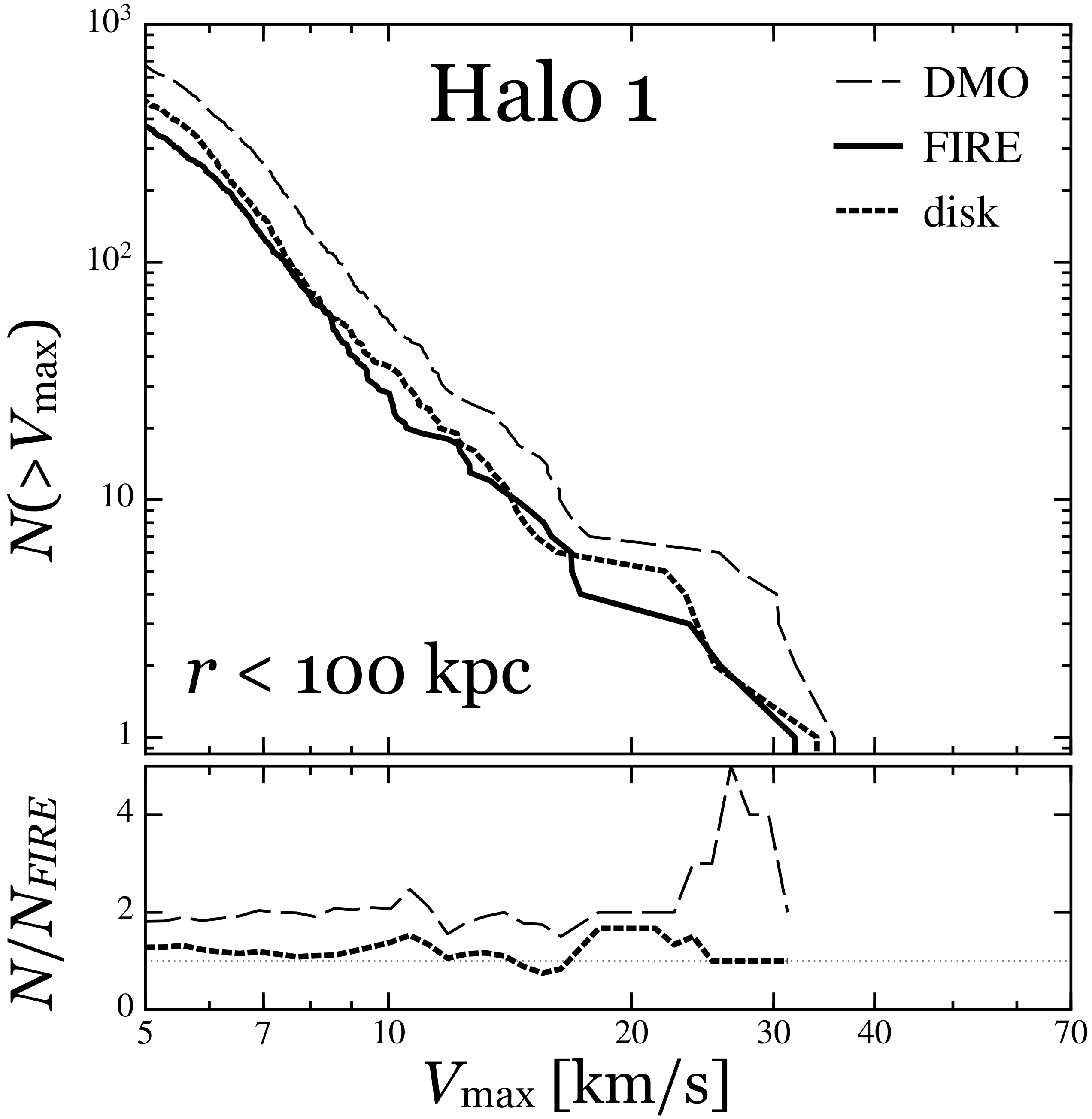
GK+, in prep

How much of the stripping/destruction is due to the galaxy?
How well do we reproduce FIRE with the potential?

Mass functions

GK+, in prep

*Particle masses in DMO simulations reduced by (1-f_b)



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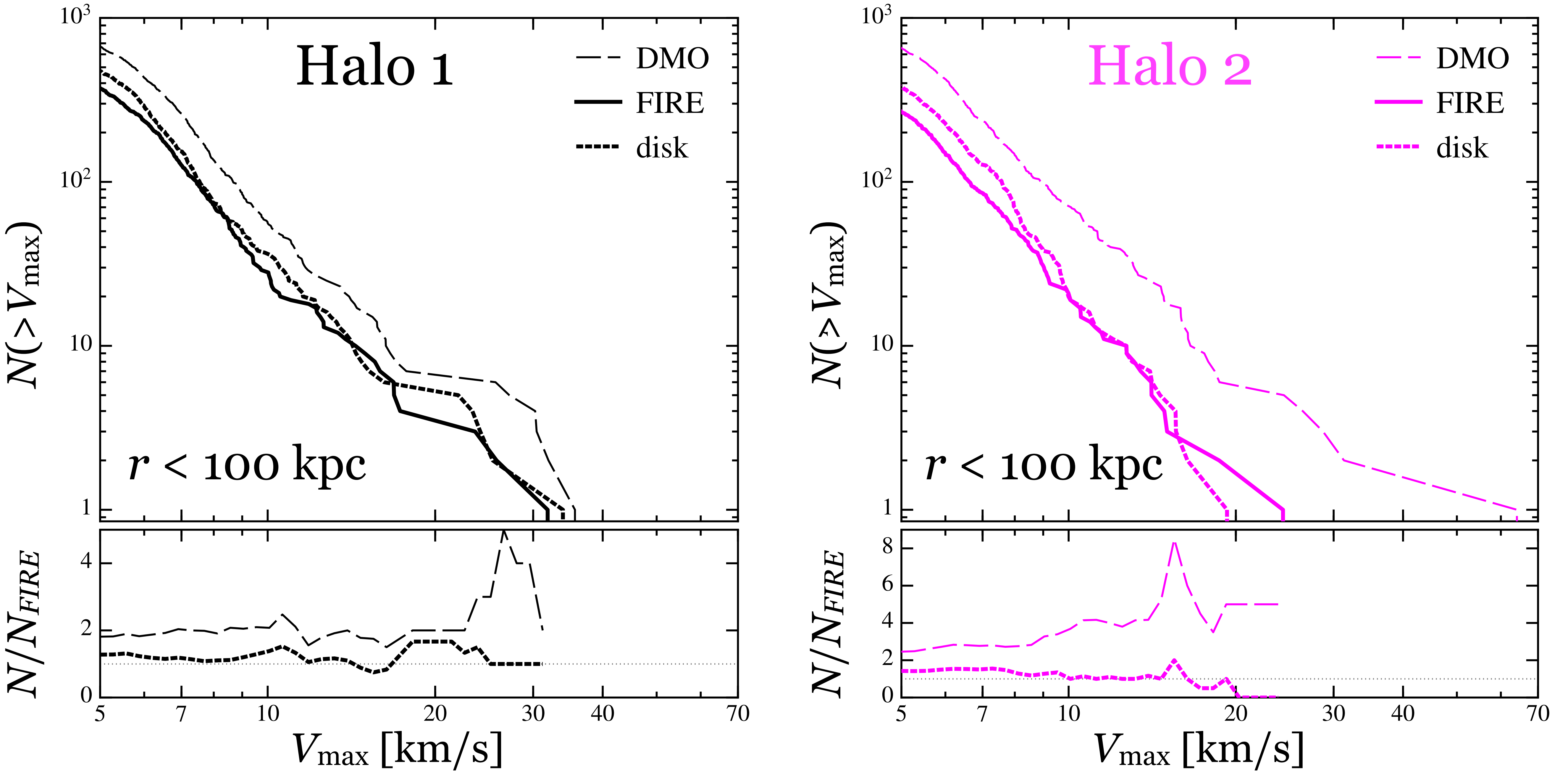

Only **including the disk brings the DMO simulations into agreement at 25% level**

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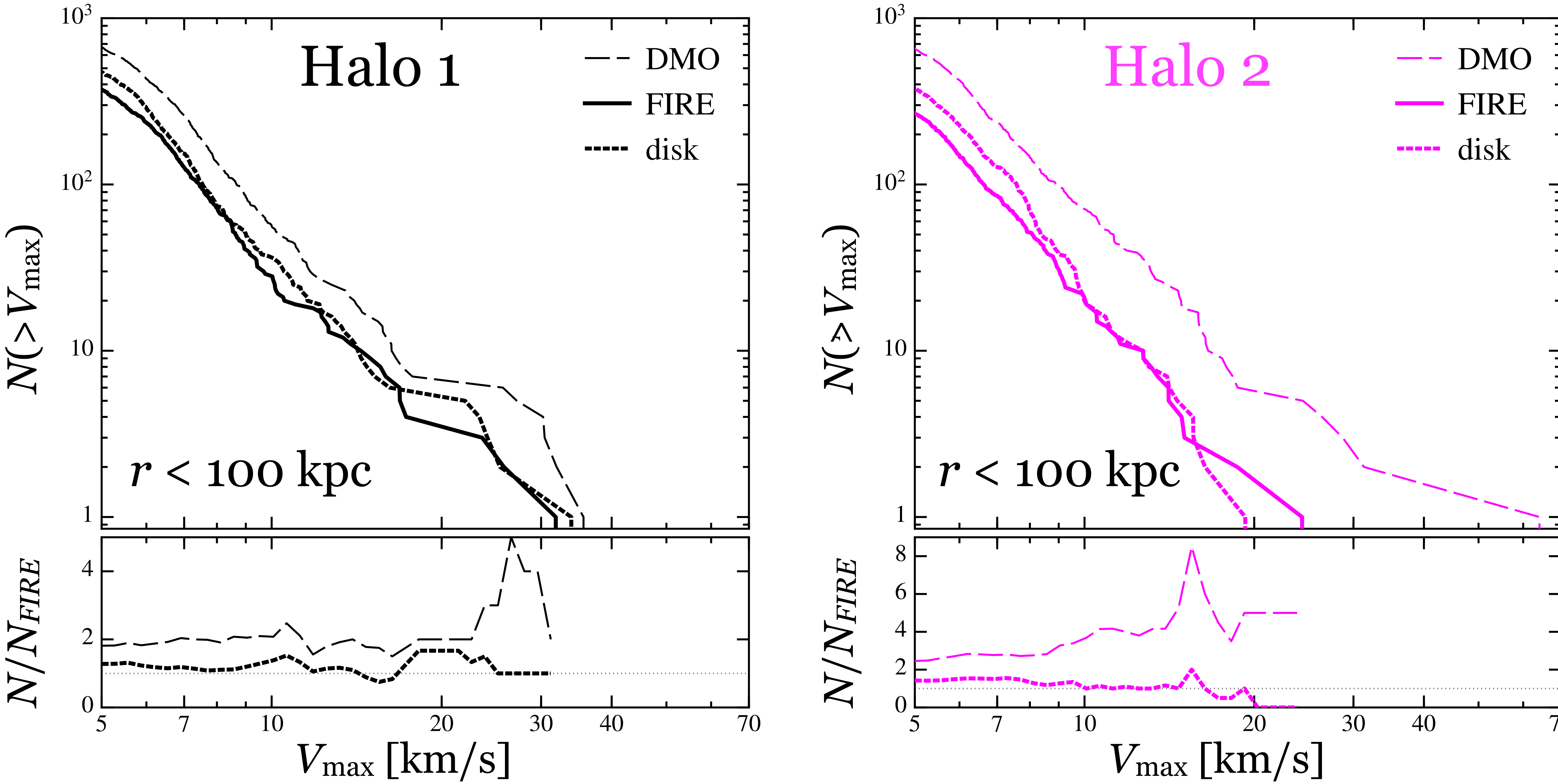

The central galaxy is responsible for 2/3 - 3/4 of the substructure stripping/destruction for r < 100 kpc

Radial distributions

GK+, in prep

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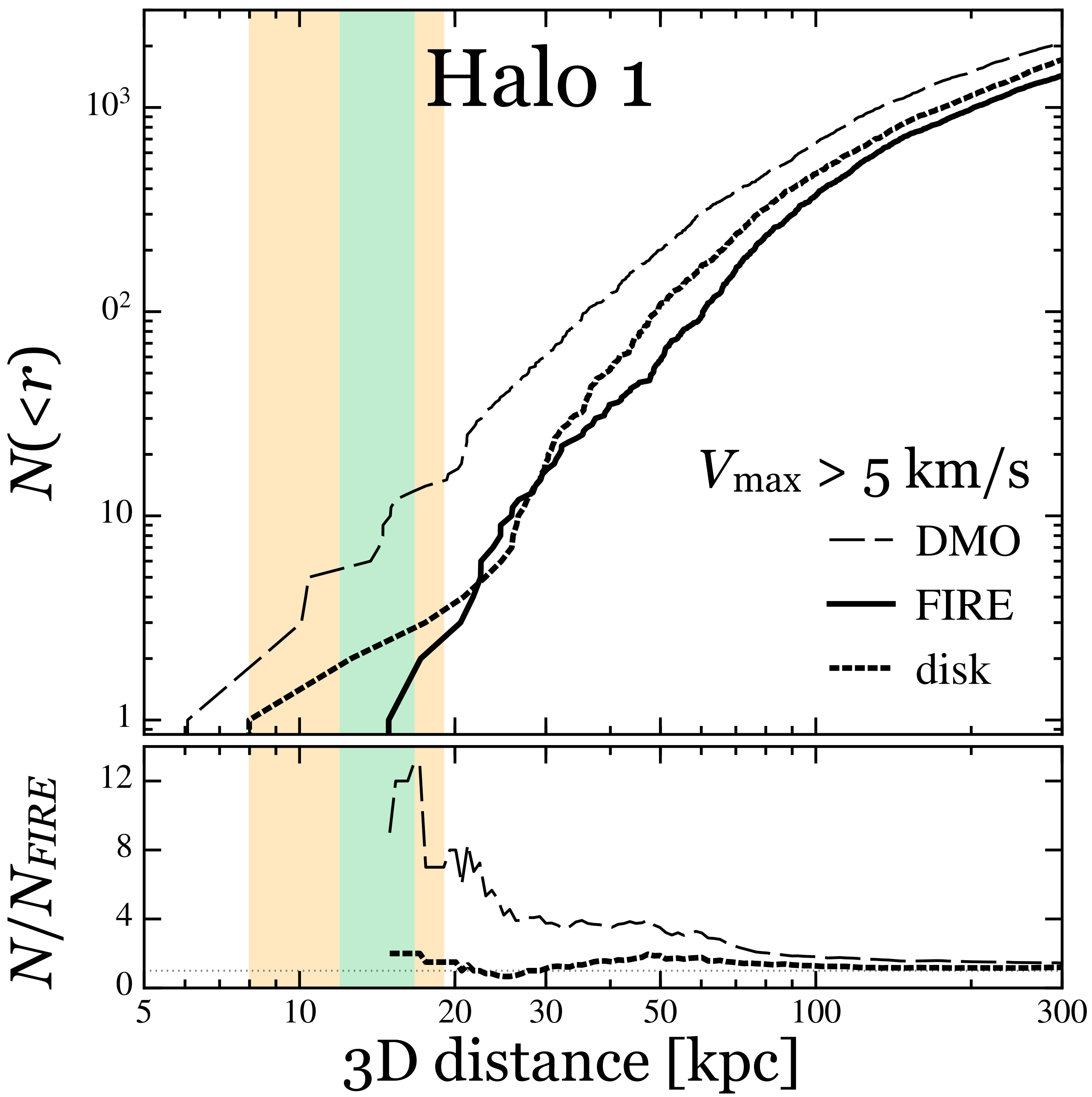

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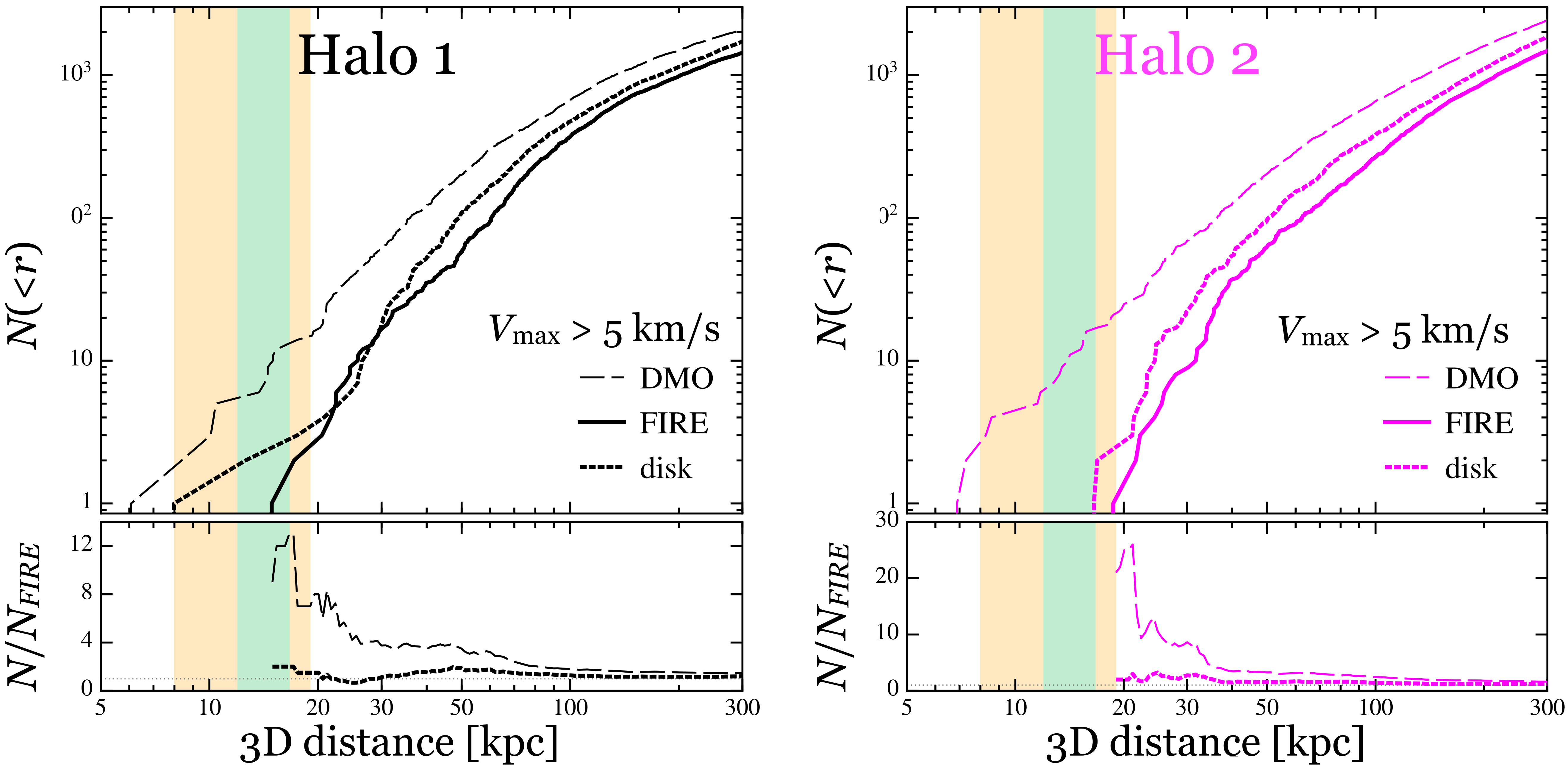
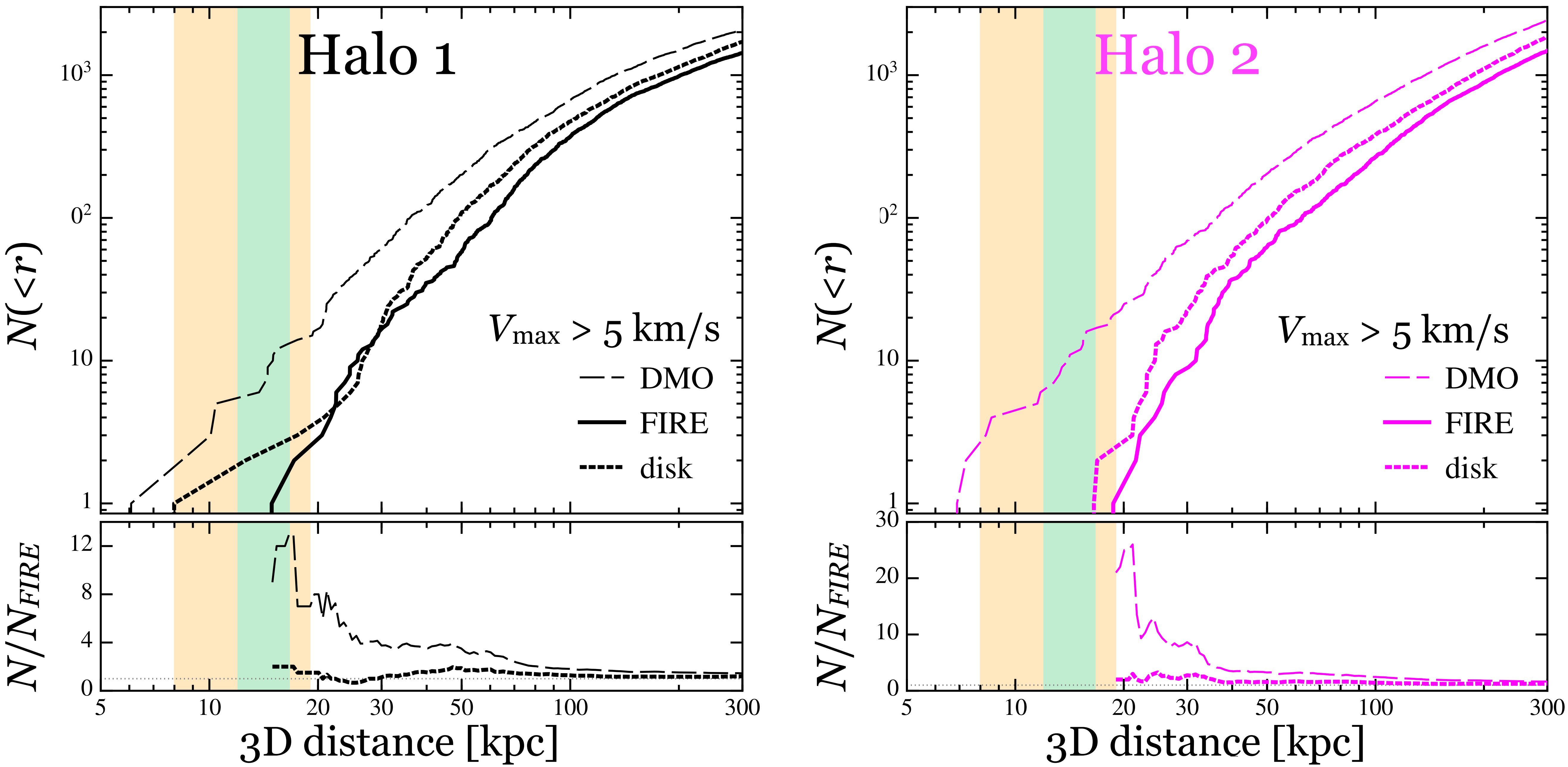


Radial distributions

GK+, in prep

*Particle masses in DMO simulations reduced by (1-f_b)



Destruction is greatest at small radii: DMO over predicts by a factor of at least 5-10 at r < 30 kpc

Radial distributions

GK+, in prep

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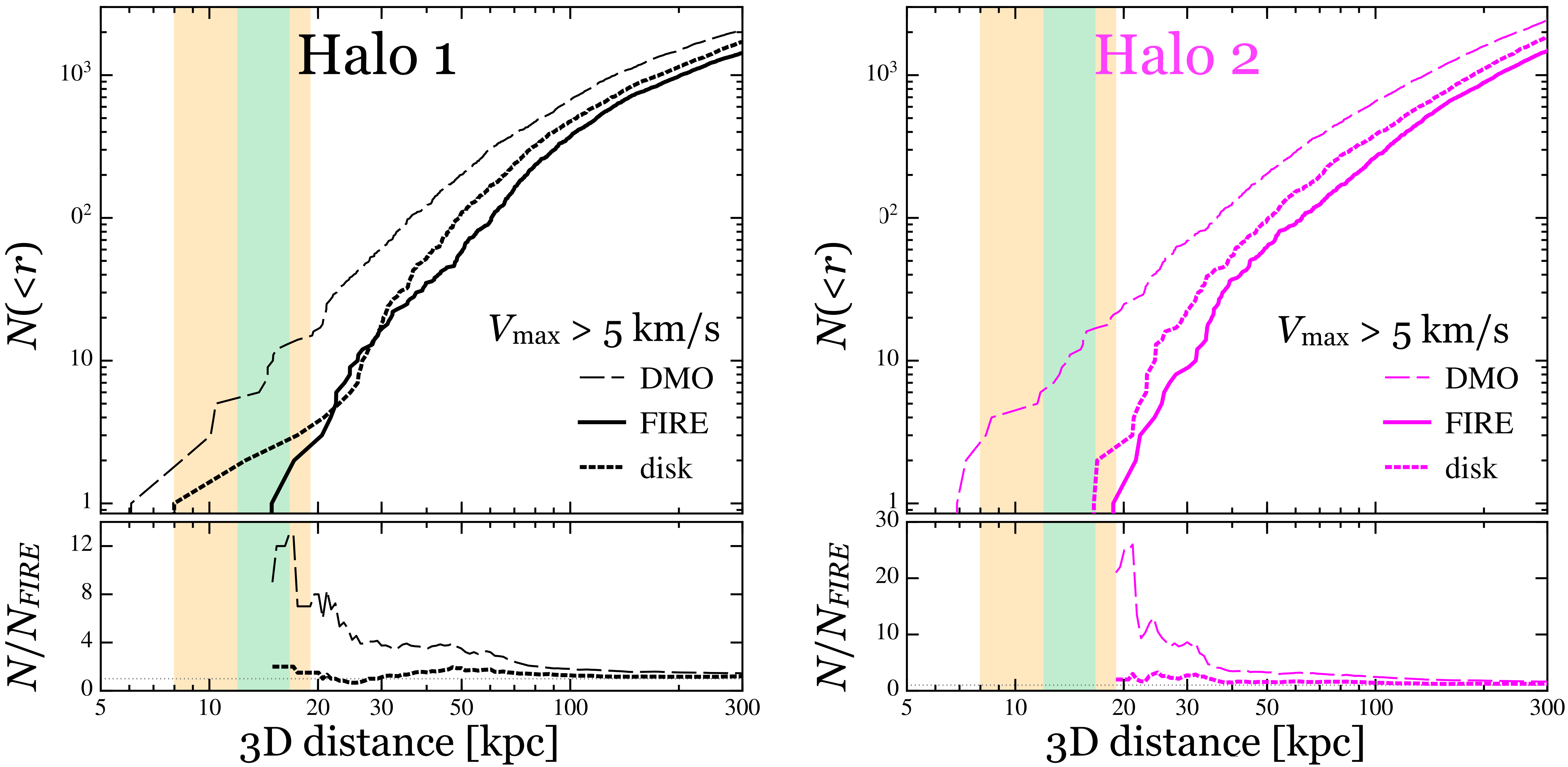

The embedded potential is responsible for at least 75% of that destruction

Radial distributions

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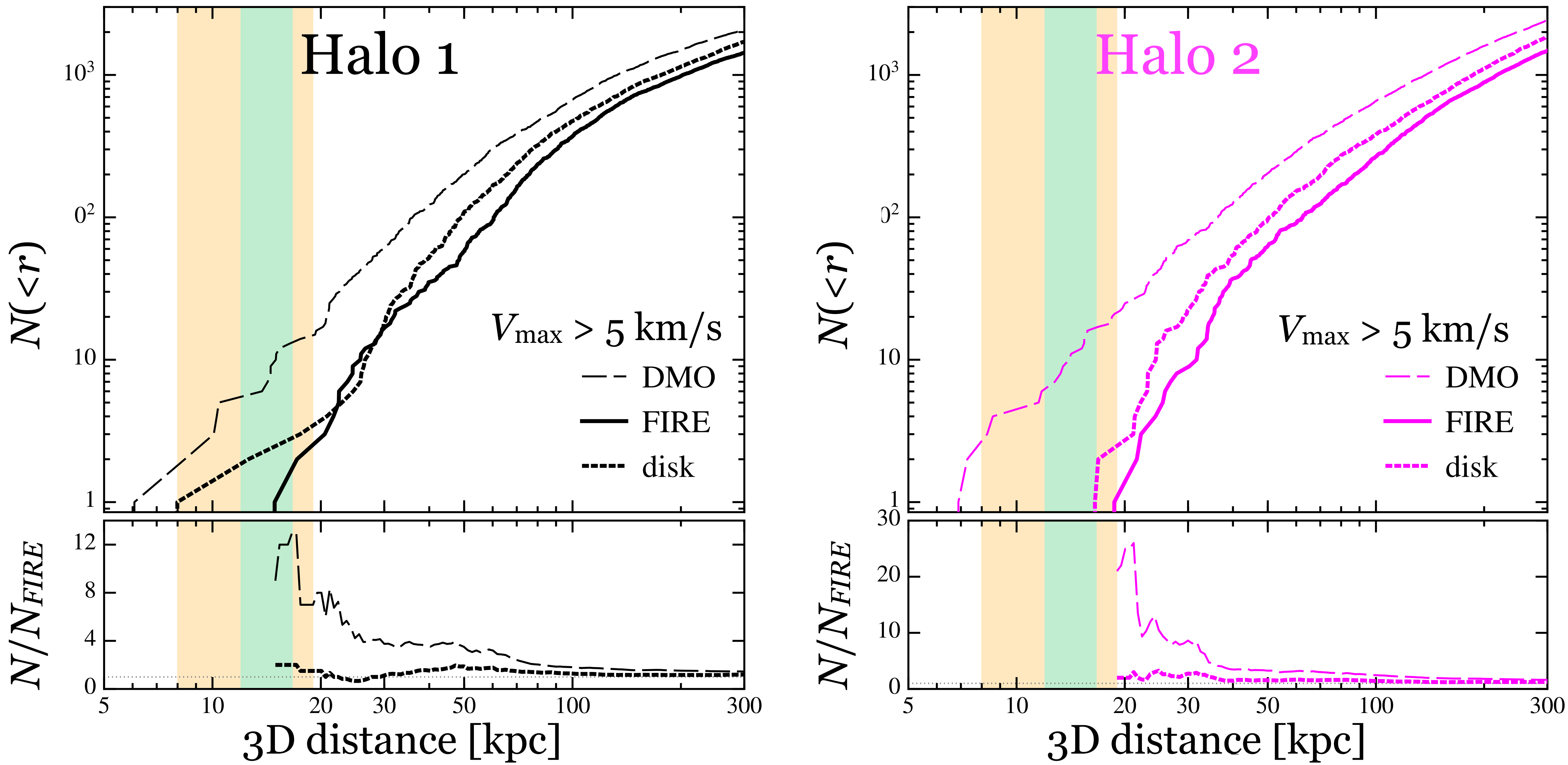
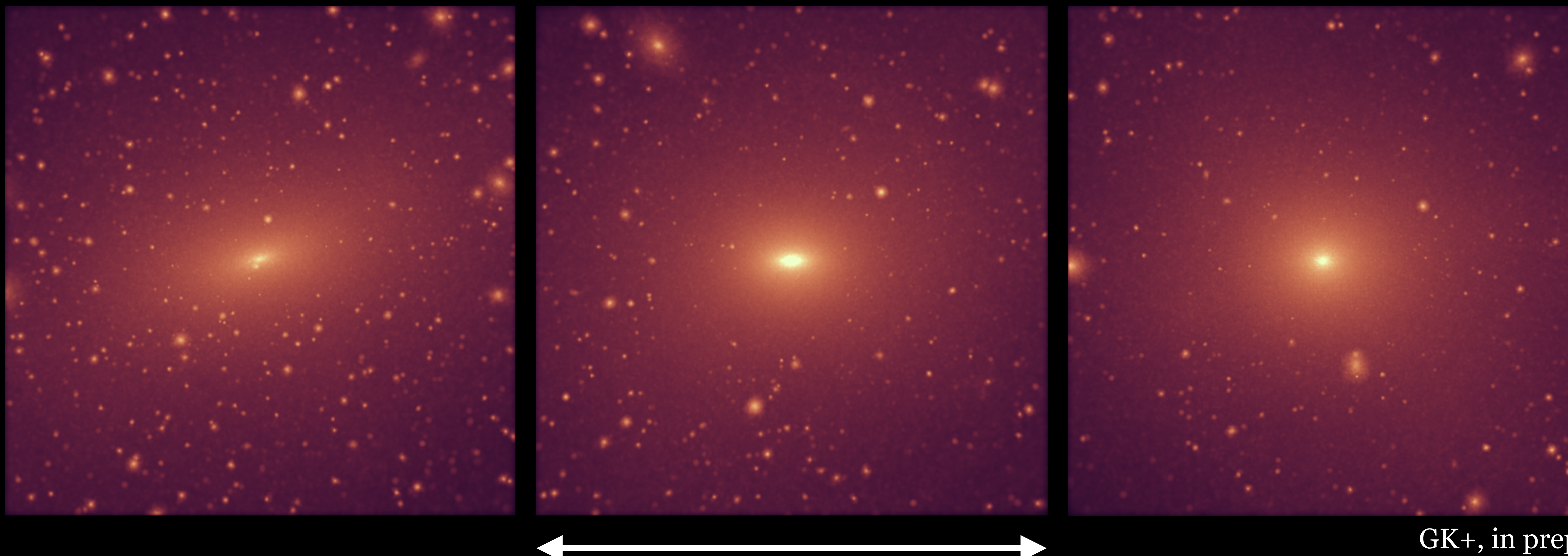


Null results from stellar streams within 20 kpc are in line with predictions from LCDM

e.g., Ibata+201

How effective is the disk?

Visualizing the local *DM* density



GK+, in prep

Simple model matches mass function and radial profiles within ~25% *vs* 100-500% errors in pure DMO

Stripping or destruction?

GK+, in prep

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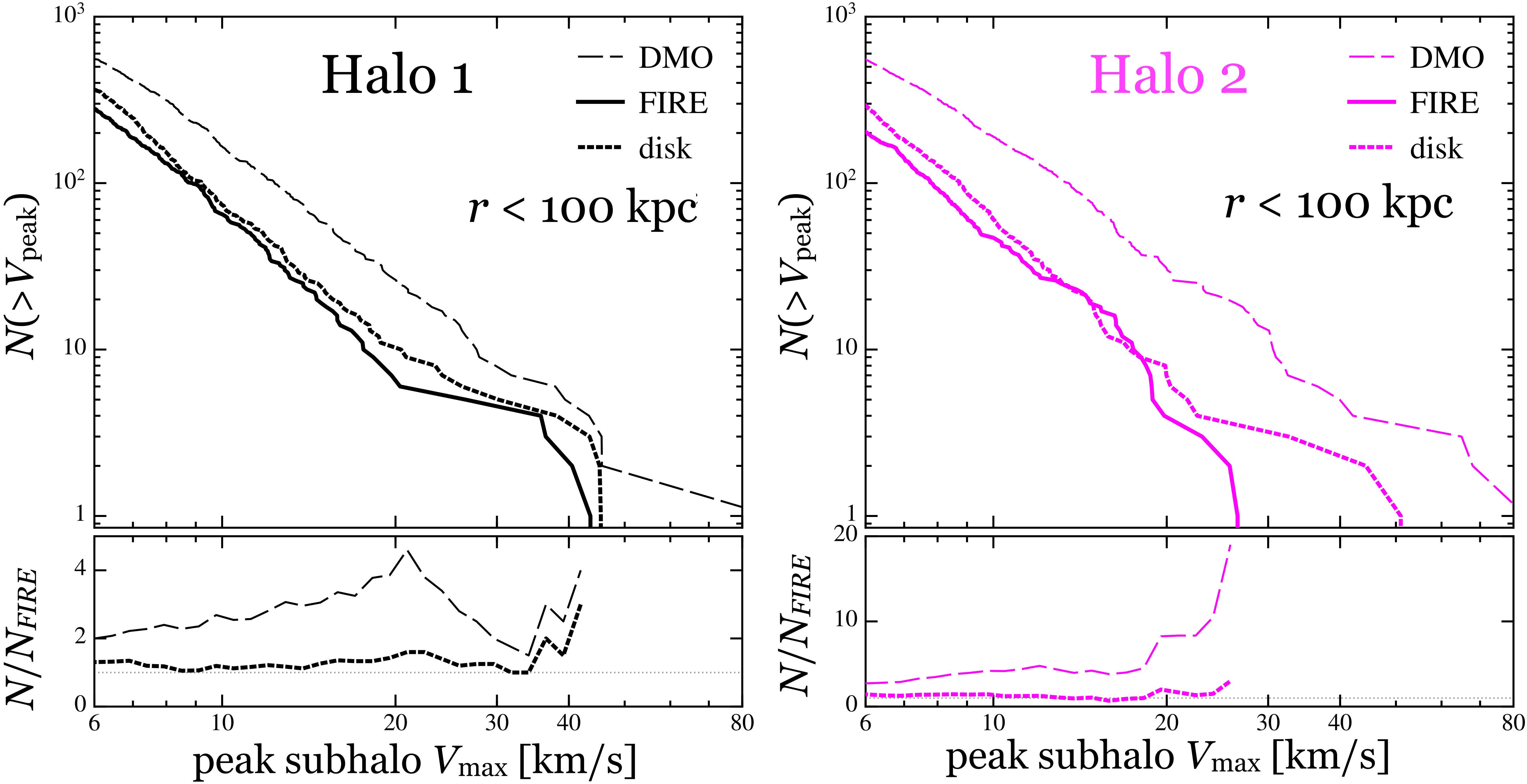

Stripping or destruction?

GK+, in prep

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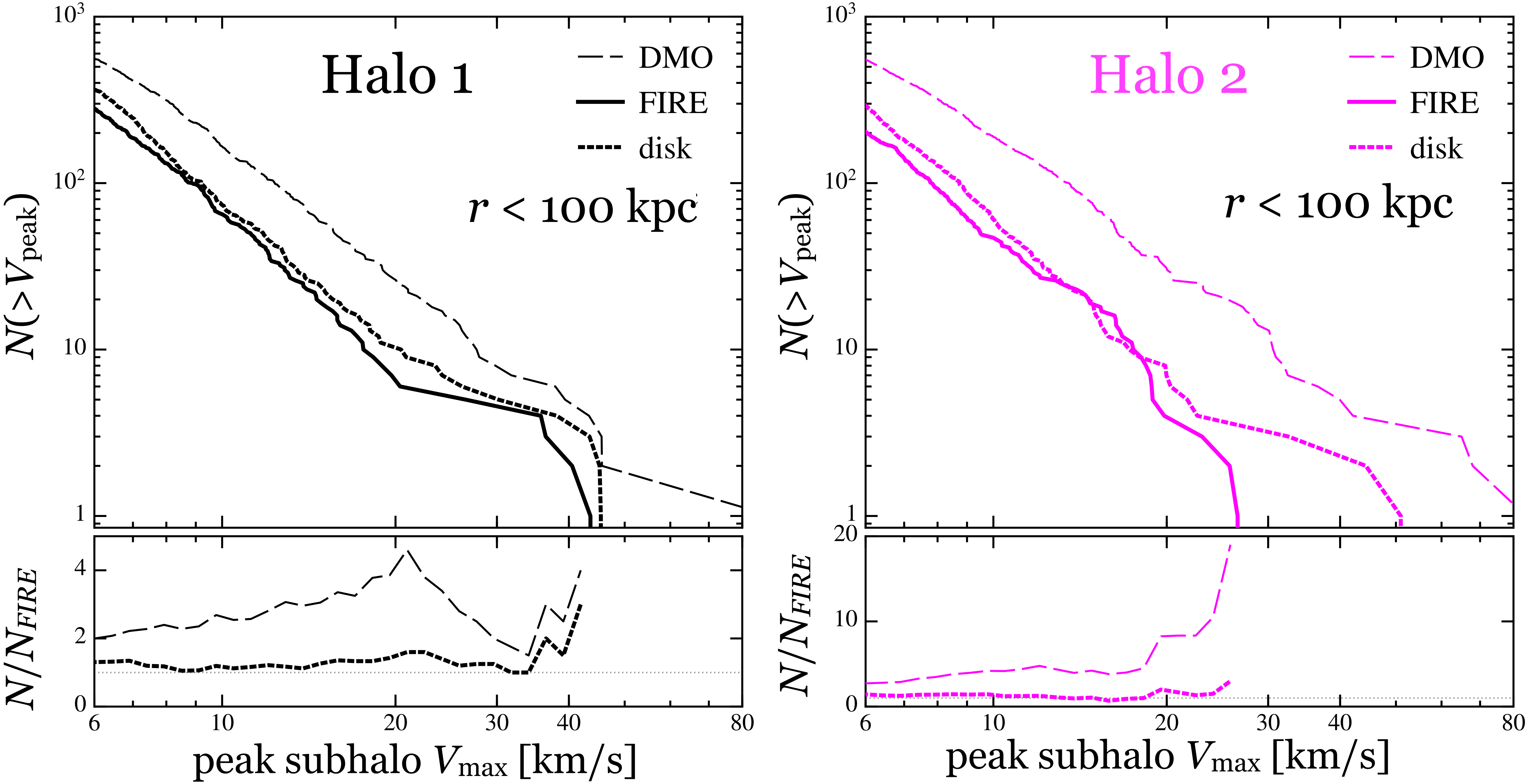

No trend in $V_{\rm peak}$: destroys subhalos at all masses

Stripping or destruction?

GK+, in prep

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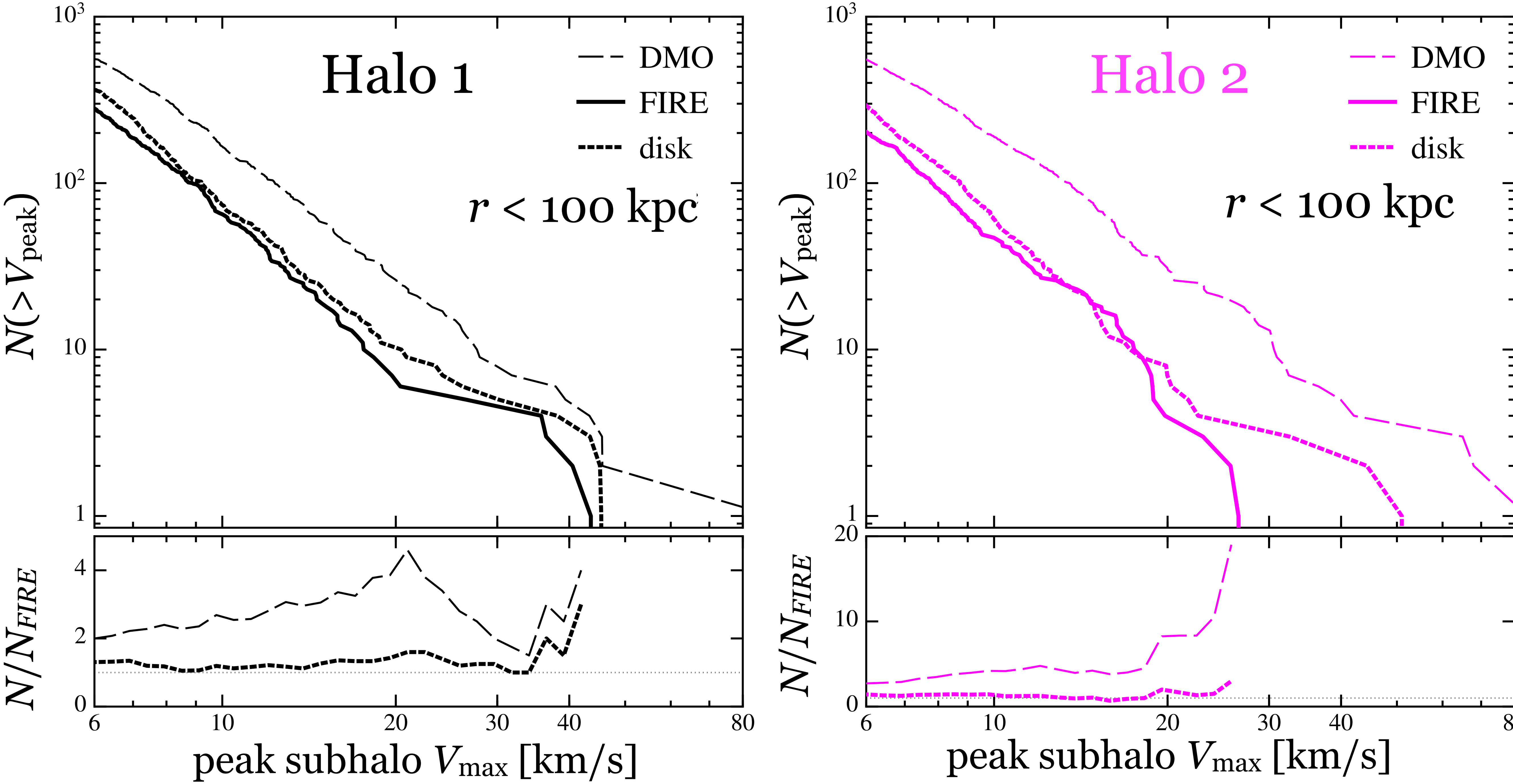

No trend in $V_{\rm peak}$: destroys subhalos at all masses

Captures destruction better than stripping

Stripping or destruction?

GK+, in prep

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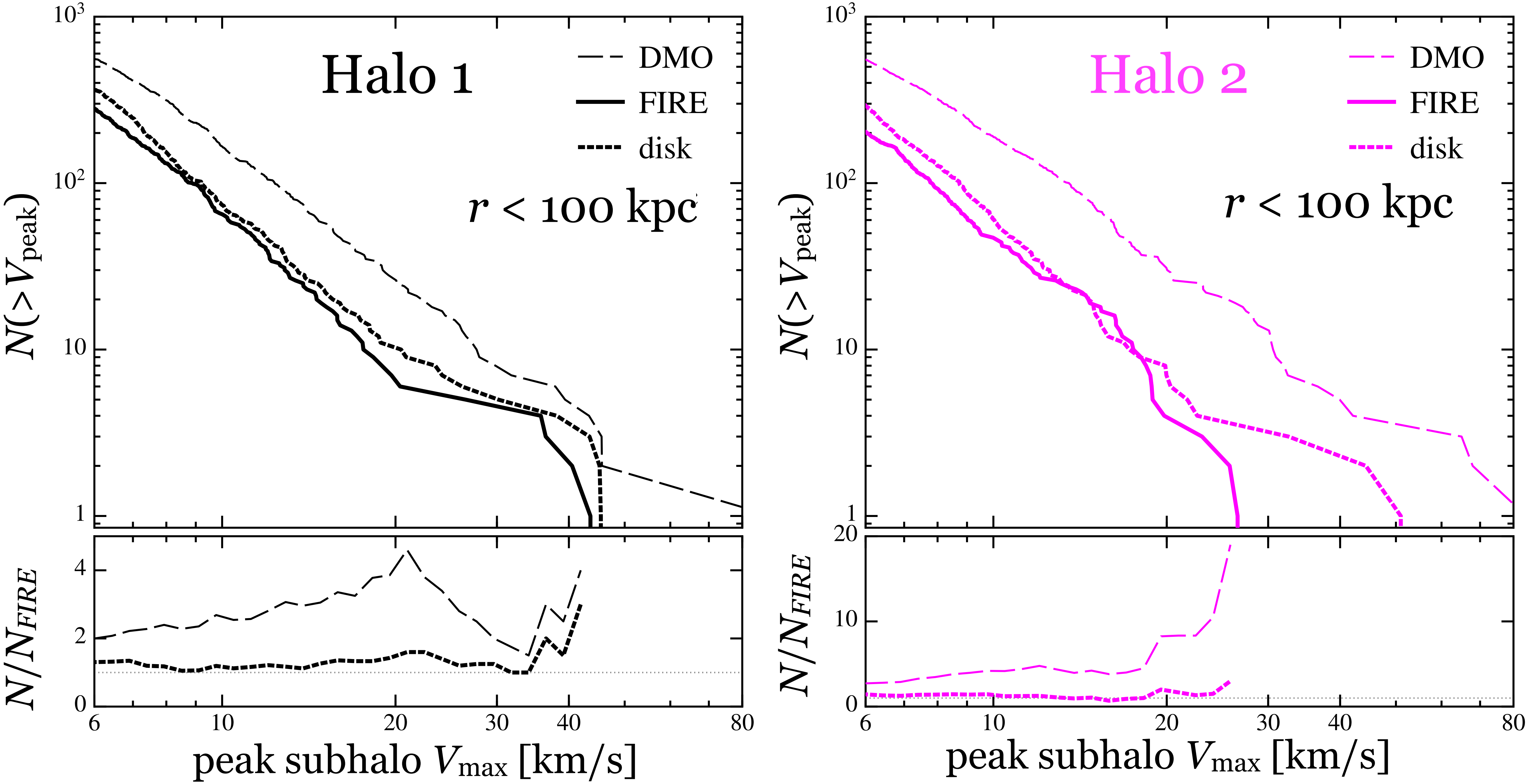

Central galaxy responsible for nearly all of the destruction within 100 kpc

Which subhalos are destroyed?

GK+, in prep

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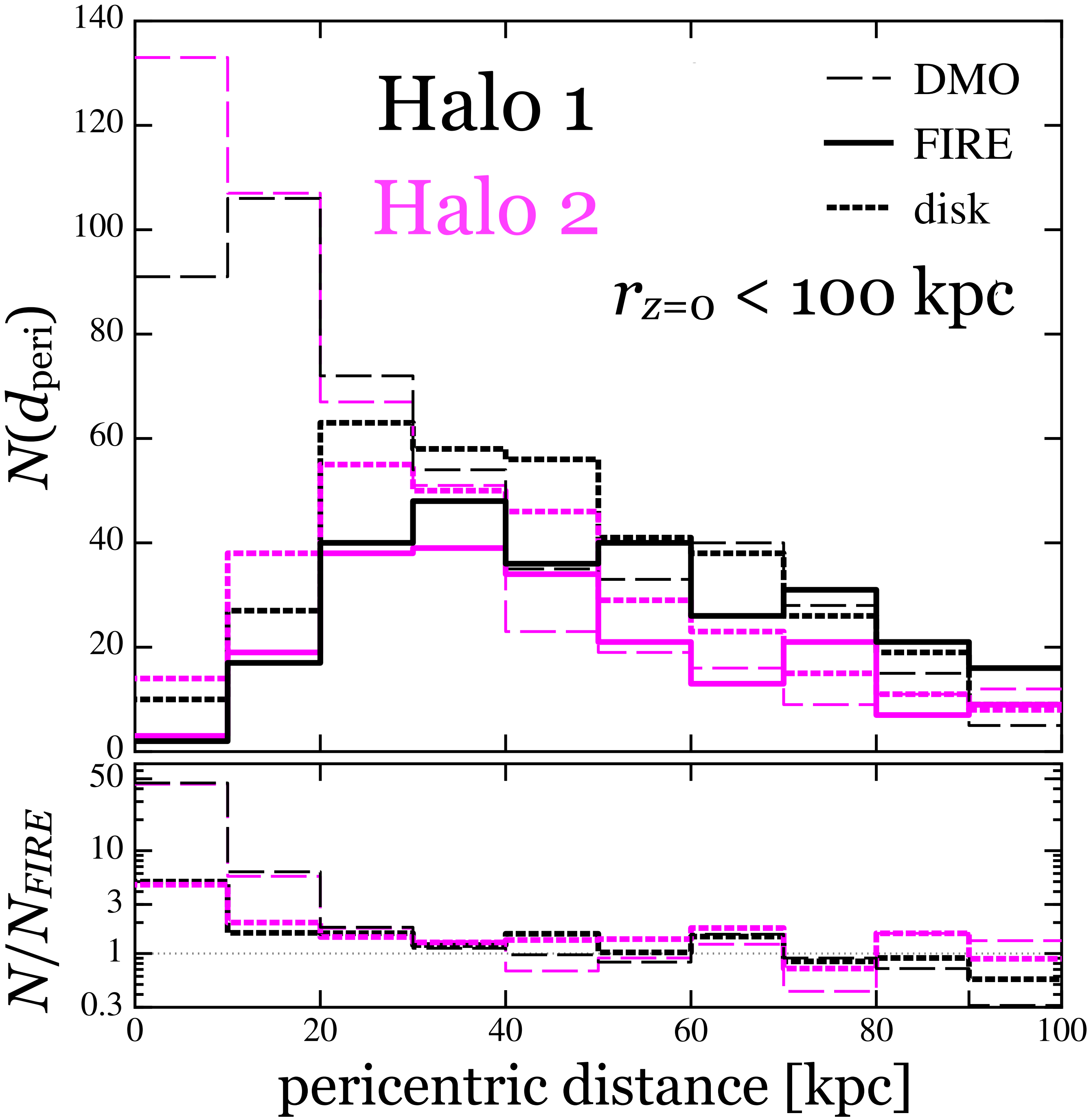

>95% of subhalos that pass within 20 kpc are destroyed by the central galaxy

Which subhalos are destroyed?

GK+, in prep

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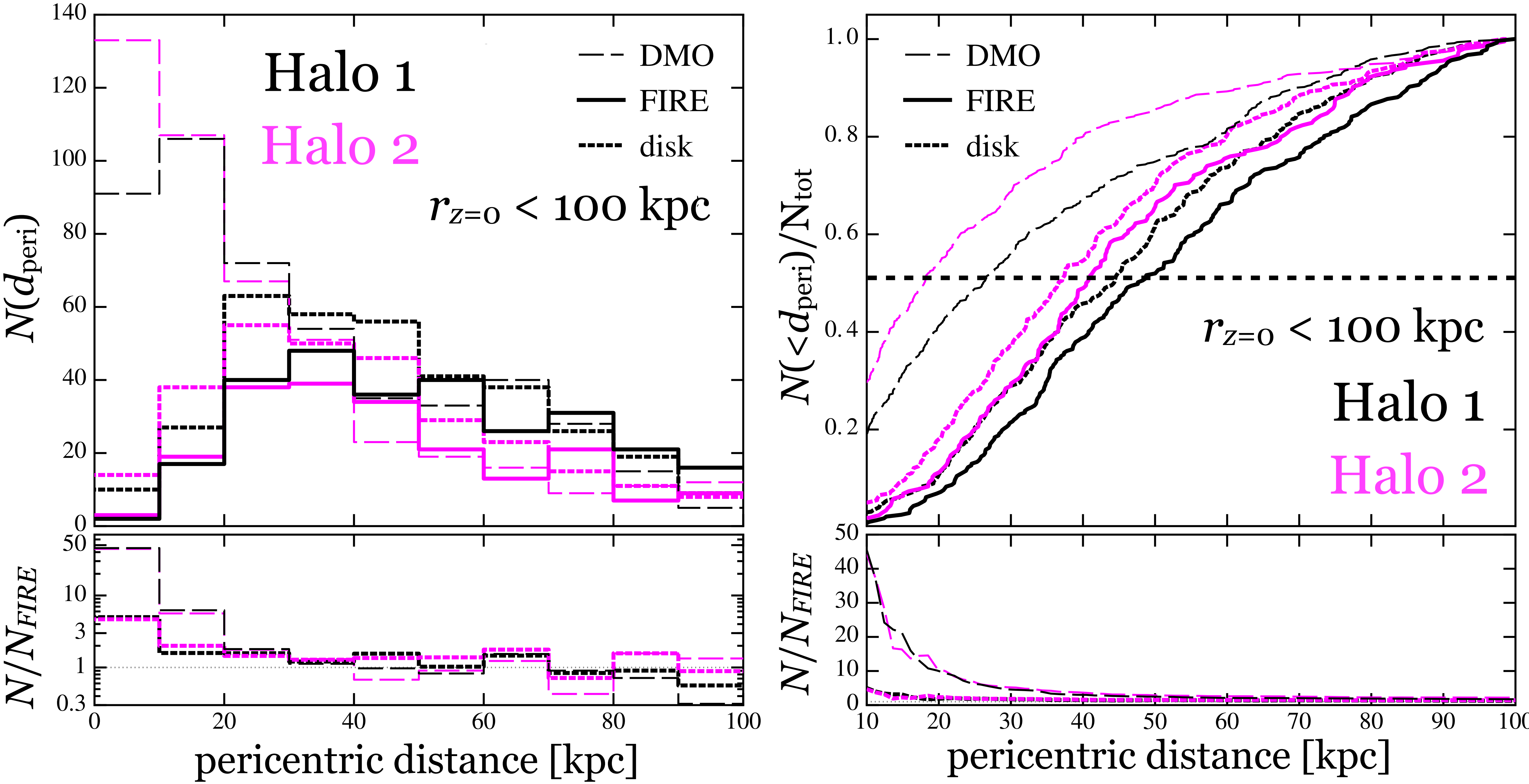
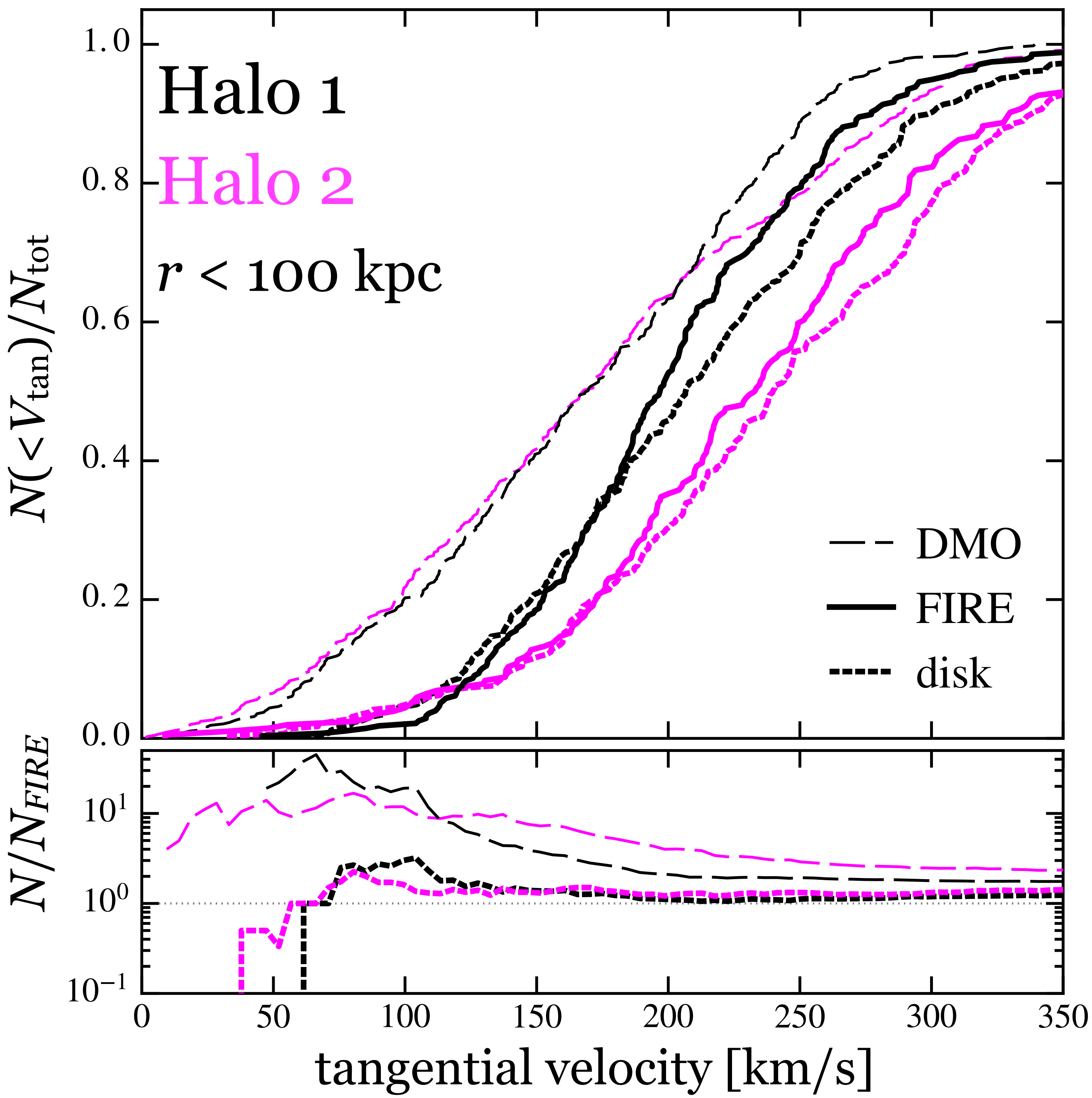


Median pericenter more than doubled!

Anisotropic subhalo orbits

GK+, in prep

*Particle masses in DMO simulations reduced by (1-f_b)



Surviving subhalos are tangentially biased

Anisotropic subhalo orbits

GK+, in prep

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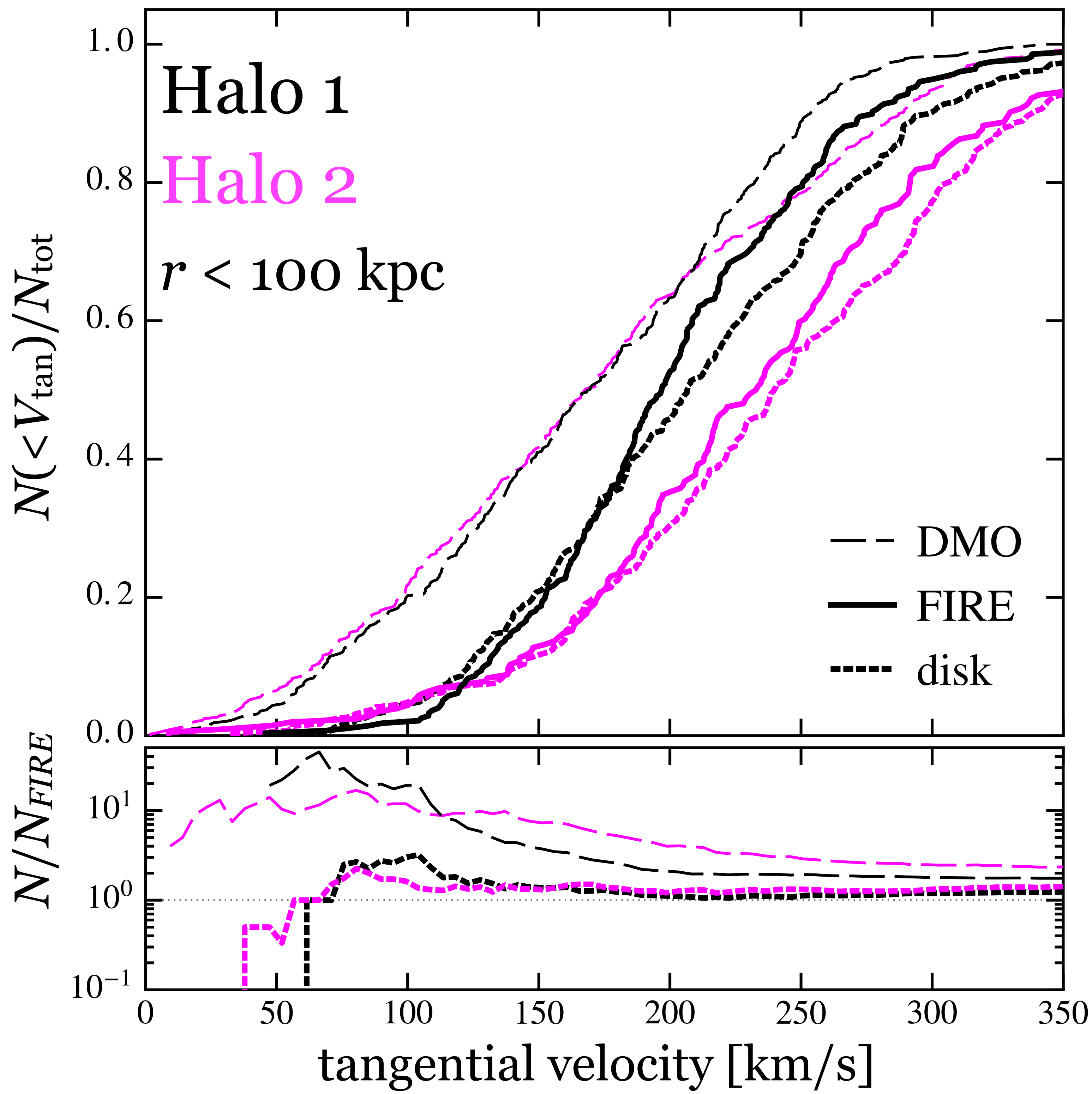

DMO overpredicts low $V_{\rm tan}$ subhalos by a factor of 30

Anisotropic subhalo orbits

GK+, in prep

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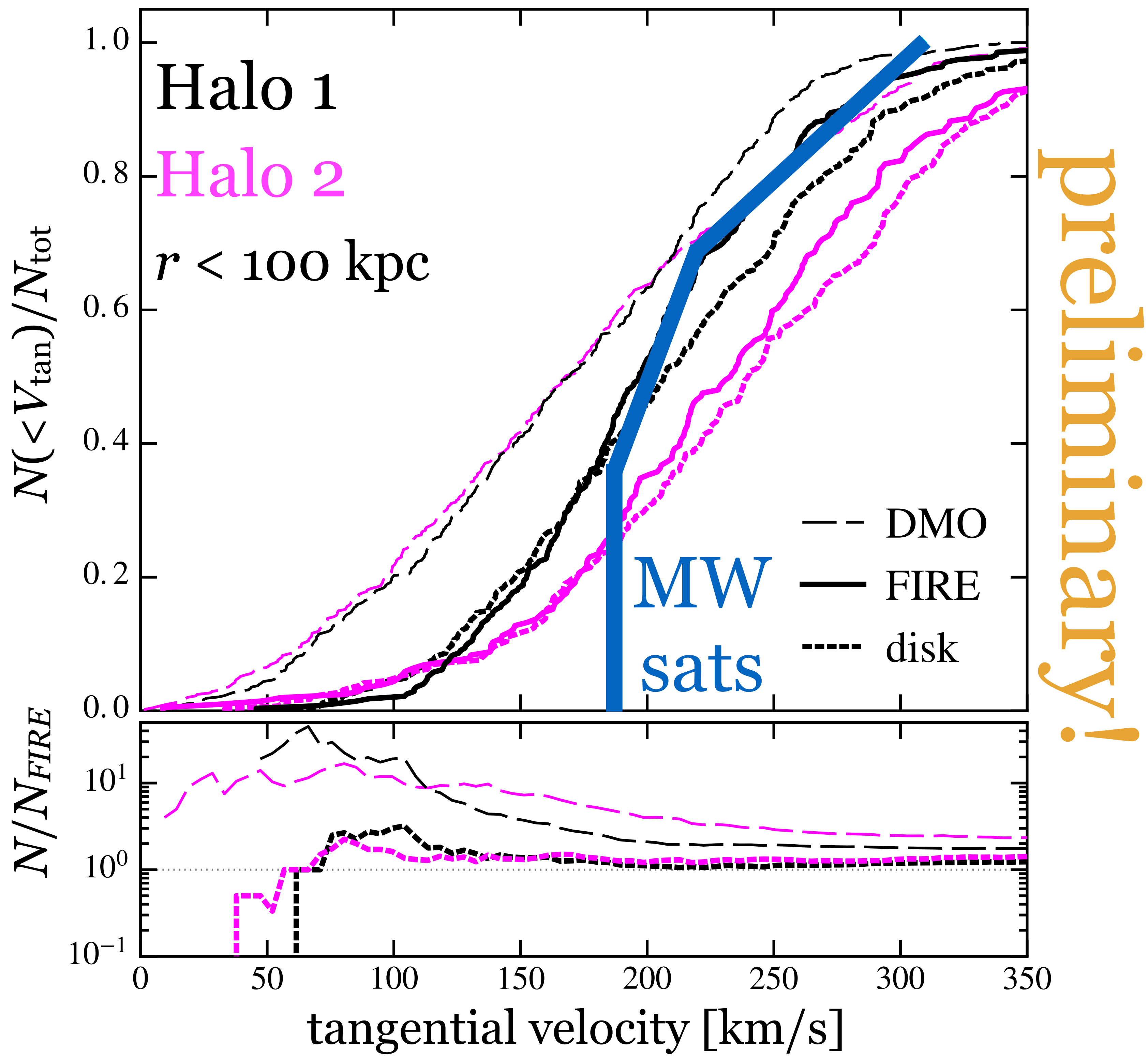


Reproduces lack of low $V_{\rm tan}$ satellites

Conclusions

FIRE simulations predict a factor of two depletion in substructure counts at fixed mass, with subhalos on plunging/radial orbits particularly susceptible to destruction

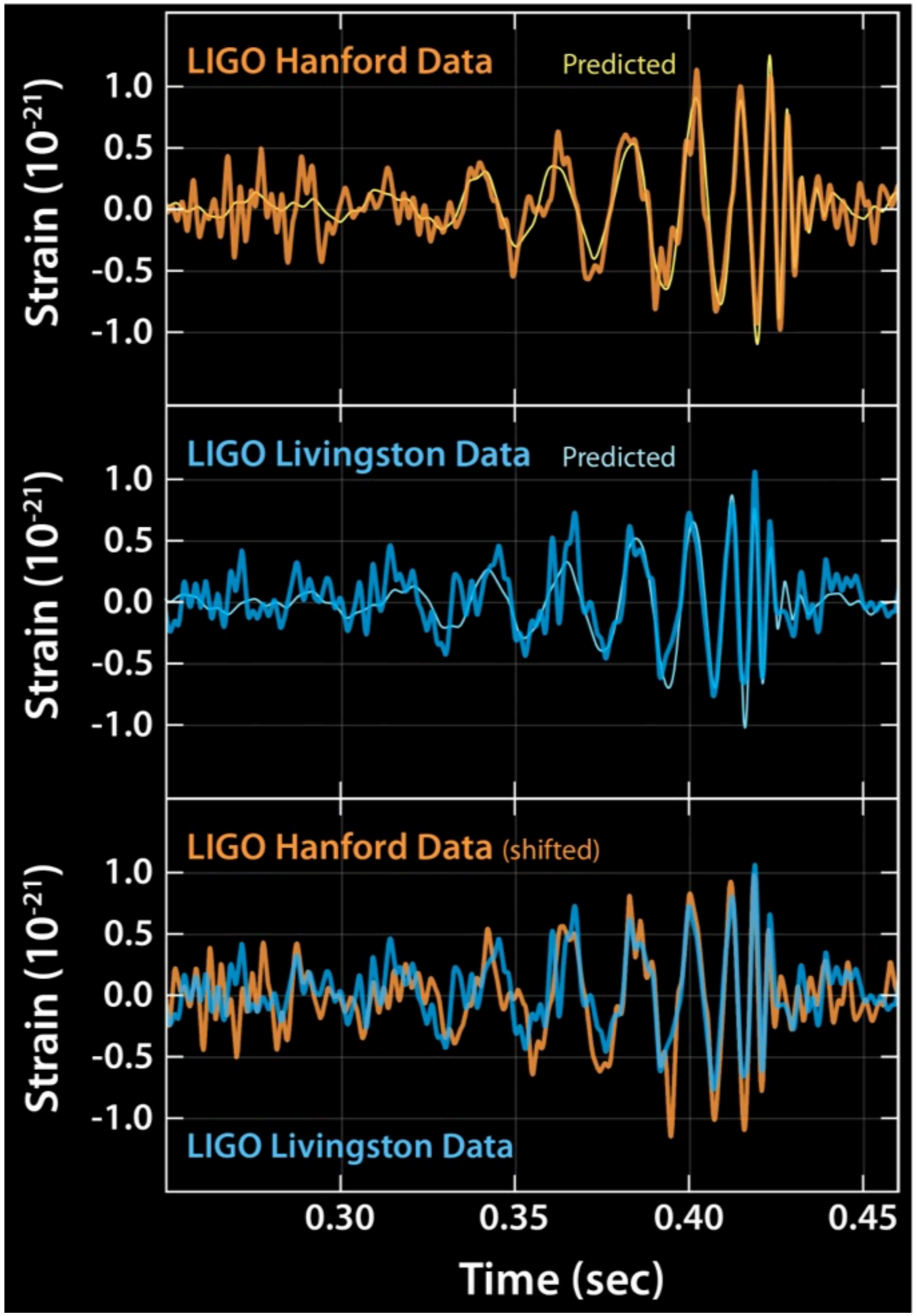
But, FIRE simulations are too expensive to provide large statistical samples to eliminate halo-to-halo bias and scatter

Embedding galactic potentials bring subhalo populations to within ~25% of predictions from FIRE simulations, implying that the Galaxy *alone* accounts for ≳75% of subhalo depletion

Substructure predictions can be significantly improved *at minimal CPU cost* with embedded potentials

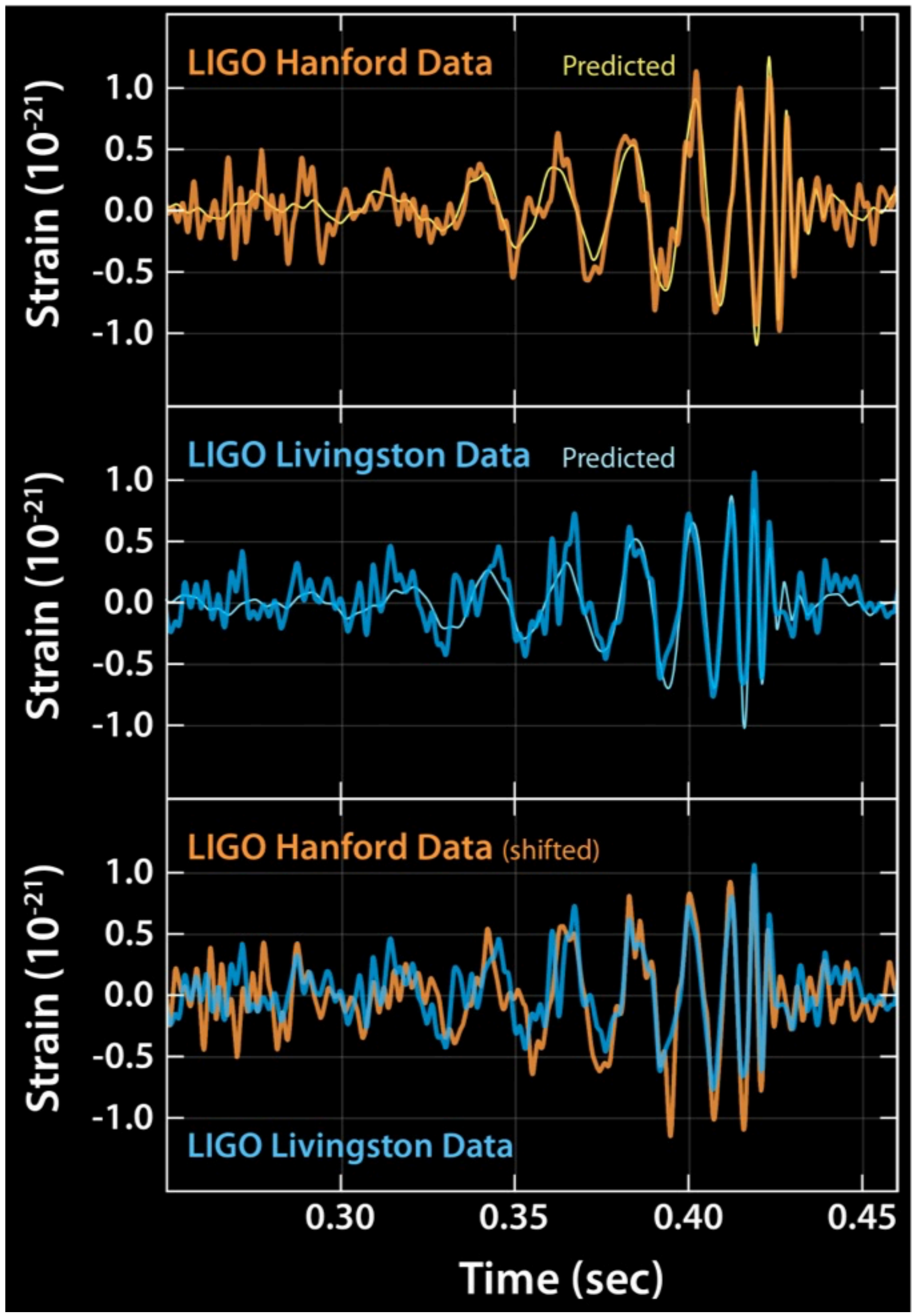
Upcoming: Statistical samples of MW-size and group-like zooms with embedded potentials (Tyler Kelley+, in prep)

An aside: When and where did GW150914 form?

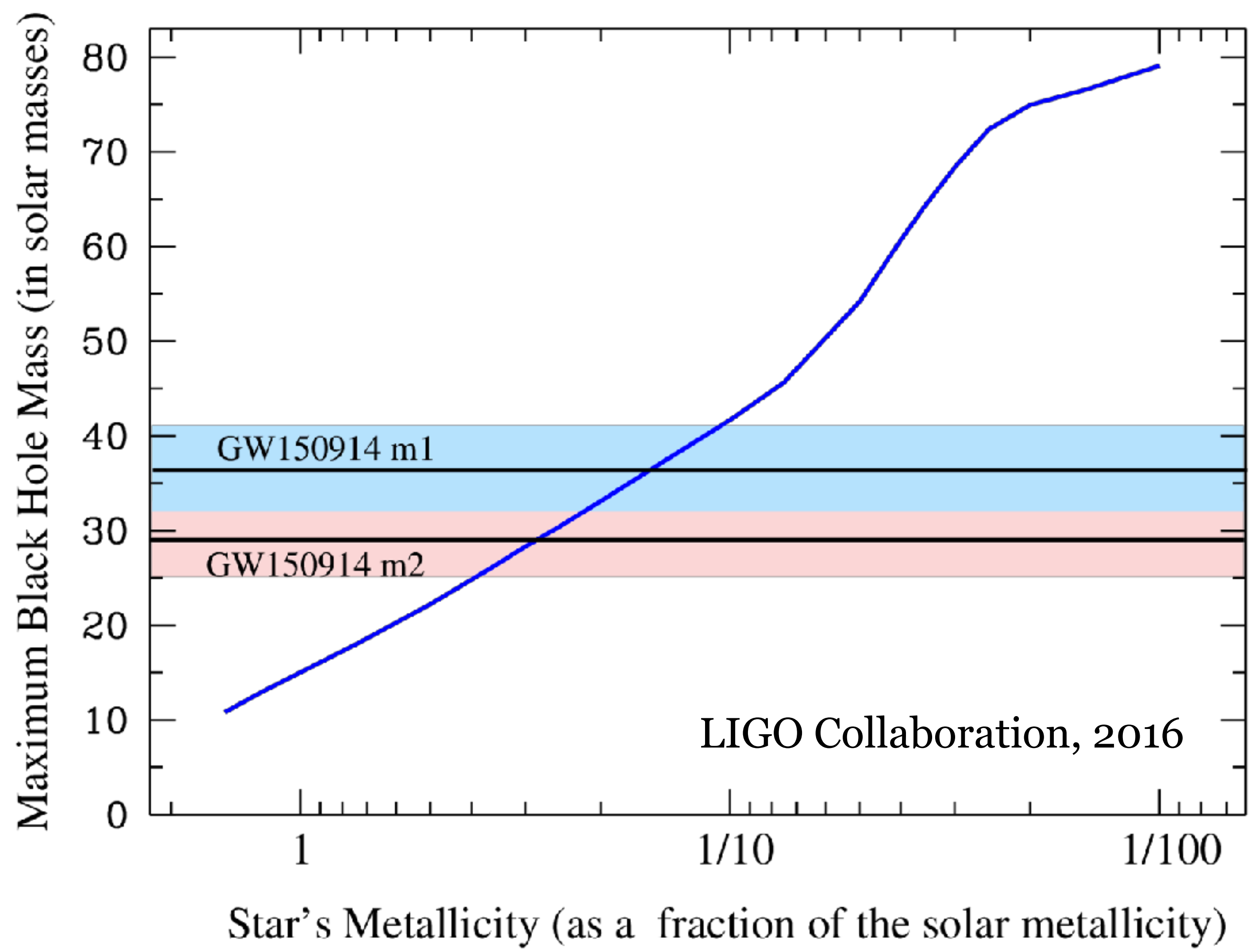


Two 30 M_{sun} black holes!

An aside: When and where did GW150914 form?

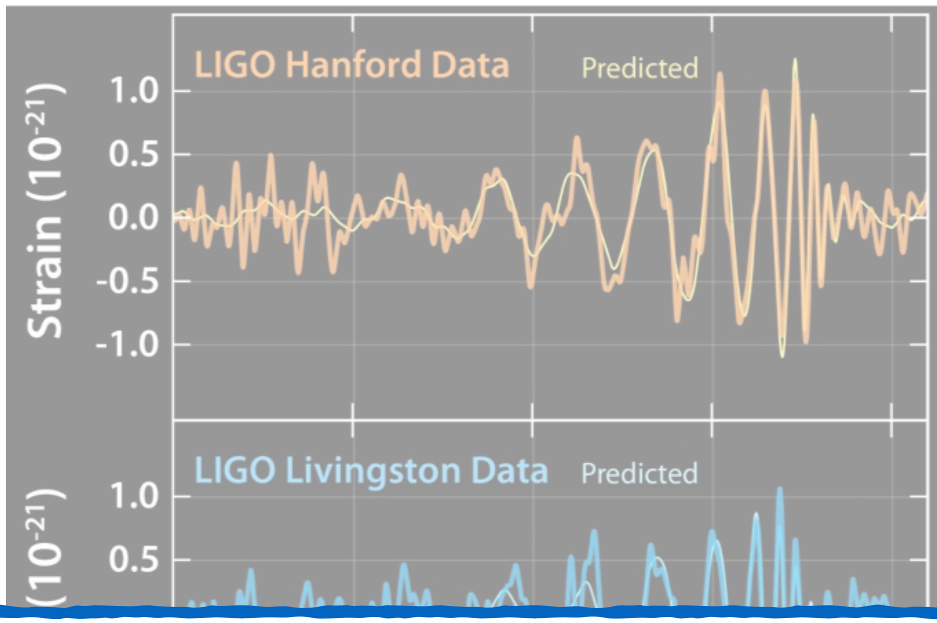


Two 30 M_{sun} black holes!

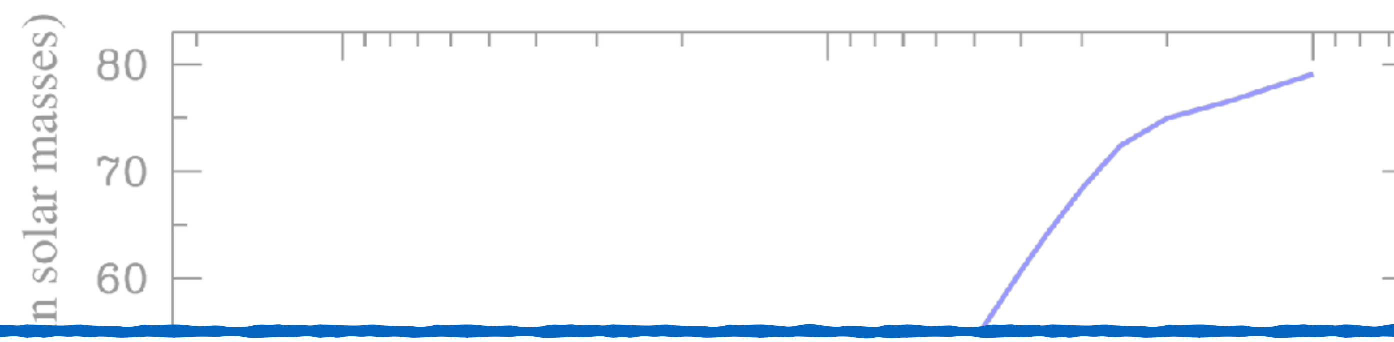


Suggests galaxies with low metallicities at birth, but long delay times + varying SFR = complicated picture

An aside: When and where did GW150914 form?



Two 30 M_{sun} black holes!



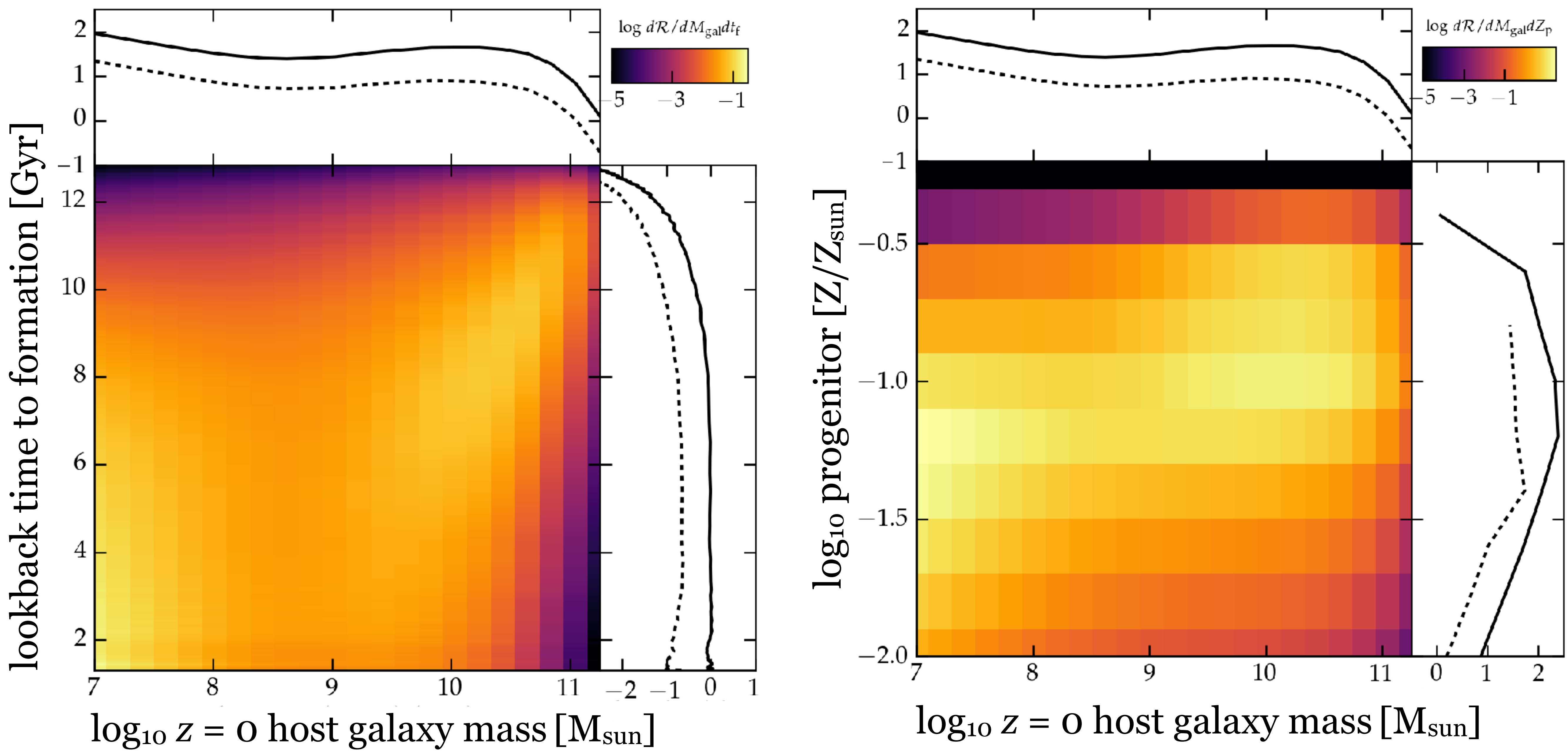
Calculate merger rate between 30 M_{sun} black holes:

galaxy number densities at z = 0 (luminosity function)

+ gas metallicity, as a function of galaxy mass and redshift
+ specific star formation rate as a function of redshift
+ halo merger trees, to capture stars formed at lower [Z/Z_{sun}]
+ delay times from binary population synthesis models

An aside: When and where did GW150914 form?

Lamberts, GK+2016



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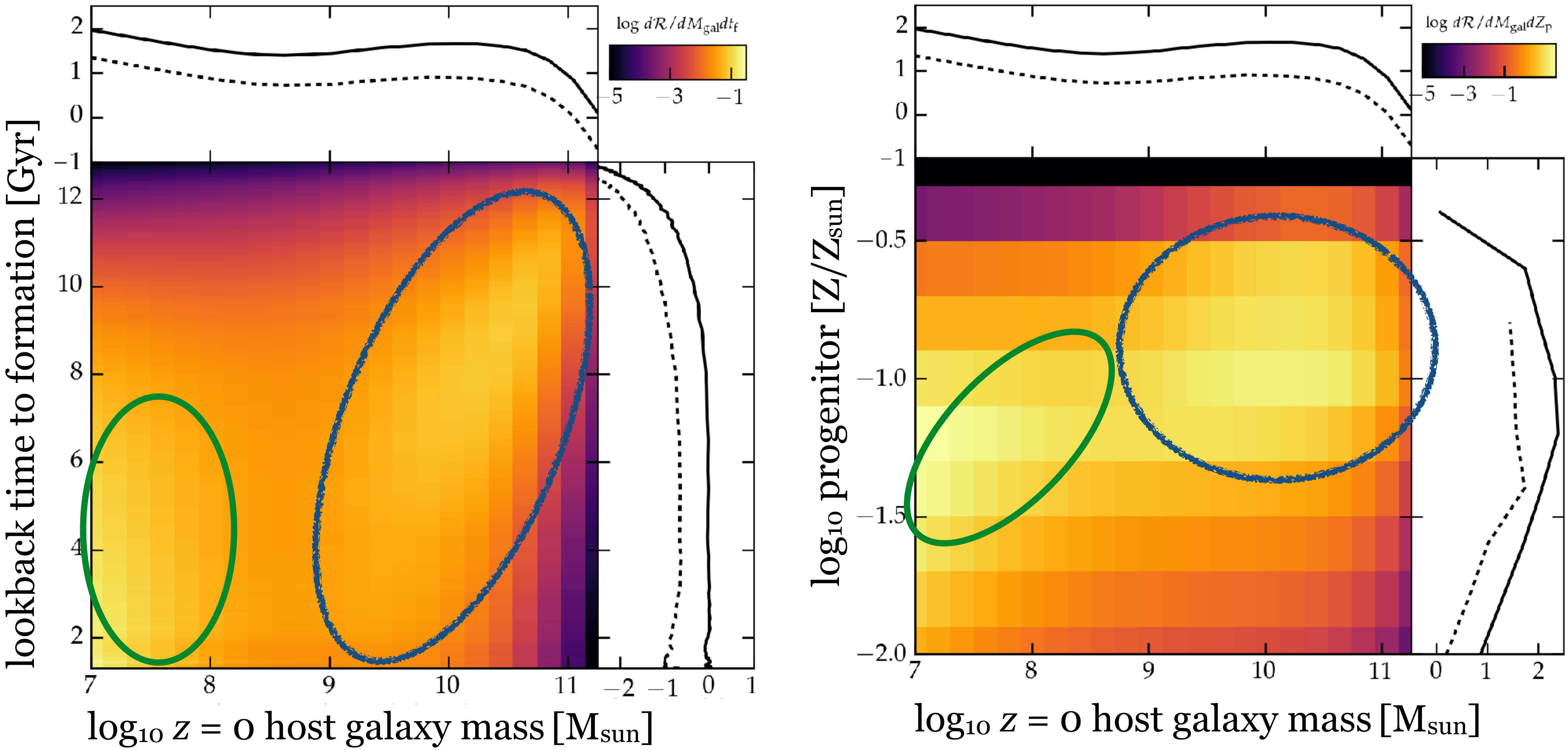
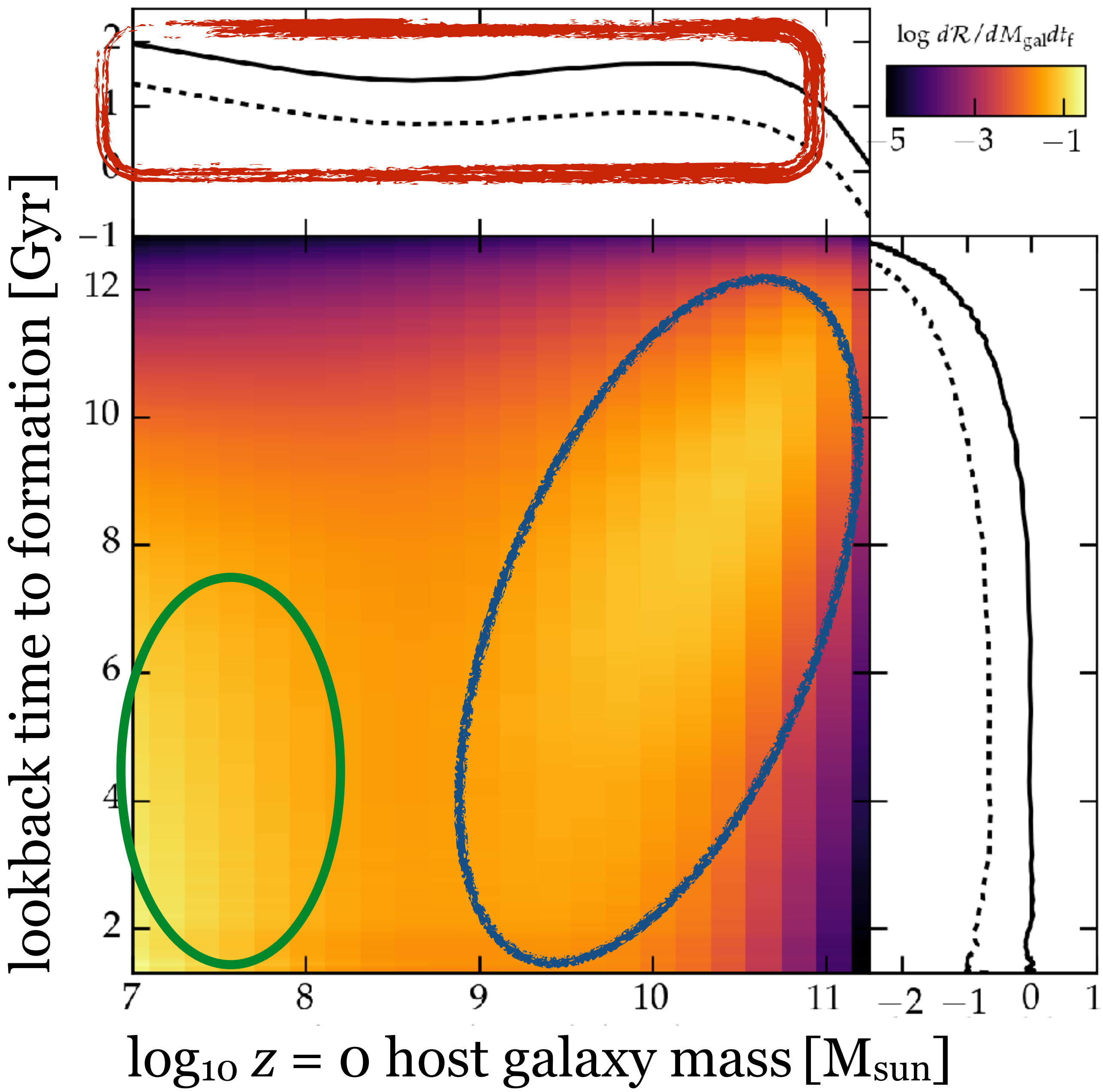
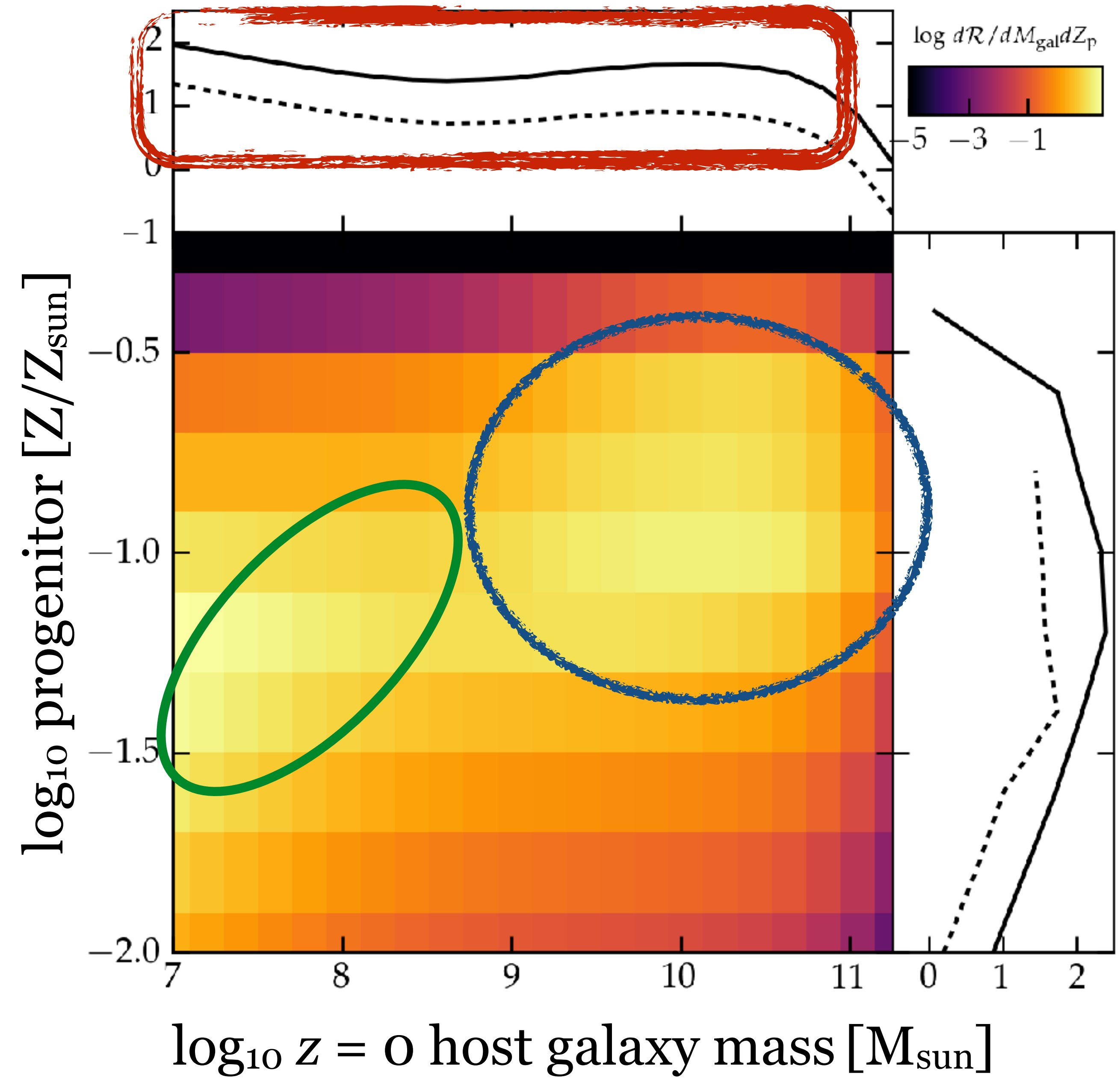


Bimodal distribution: old binaries in massive galaxies formed at high *z* with relatively high metallicity and young stars formed recently in dwarfs at very low metallicity

An aside: When and where did GW150914 form?

Lamberts, GK+2016





Bimodal distribution: old binaries in massive galaxies formed at high z with relatively high metallicity and young stars formed recently in dwarfs at very low metallicity

Surprisingly flat in host galaxy mass