Large-scale baryon transfer in cosmological simulations

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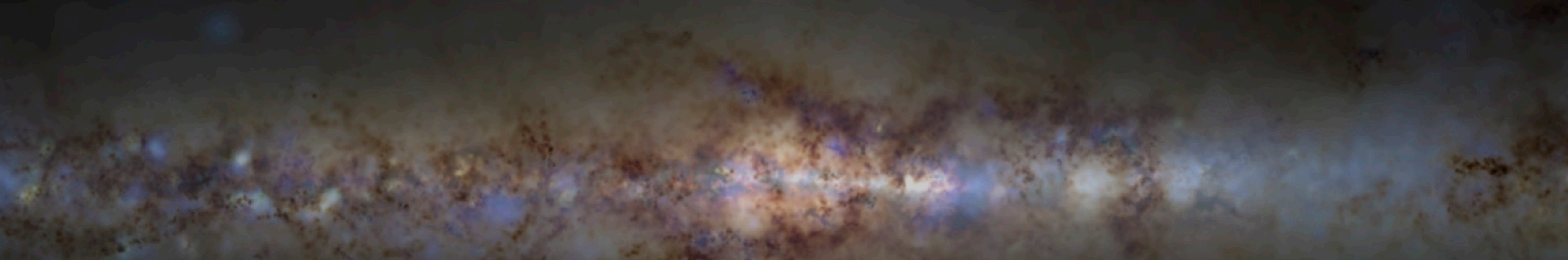
FIRE cosmological "zoom-in" simulations

Hopkins et al. 2014, 2018

Collaborators: C.-A. Faucher-Giguère (Northwestern), R. Feldmann (Zurich), Z. Hafen (Northwestern), C. Hayward (Flatiron), P. Hopkins (Caltech), D. Keres (UC San Diego), X. Ma (UC Berkeley), A. Muratov (Altius), N. Murray (Toronto), E. Quataert (UC Berkeley), J. Stern (Northwestern), Torrey (UFL), S. Wellons (Northwestern), A. Wetzel (UC Davis), …



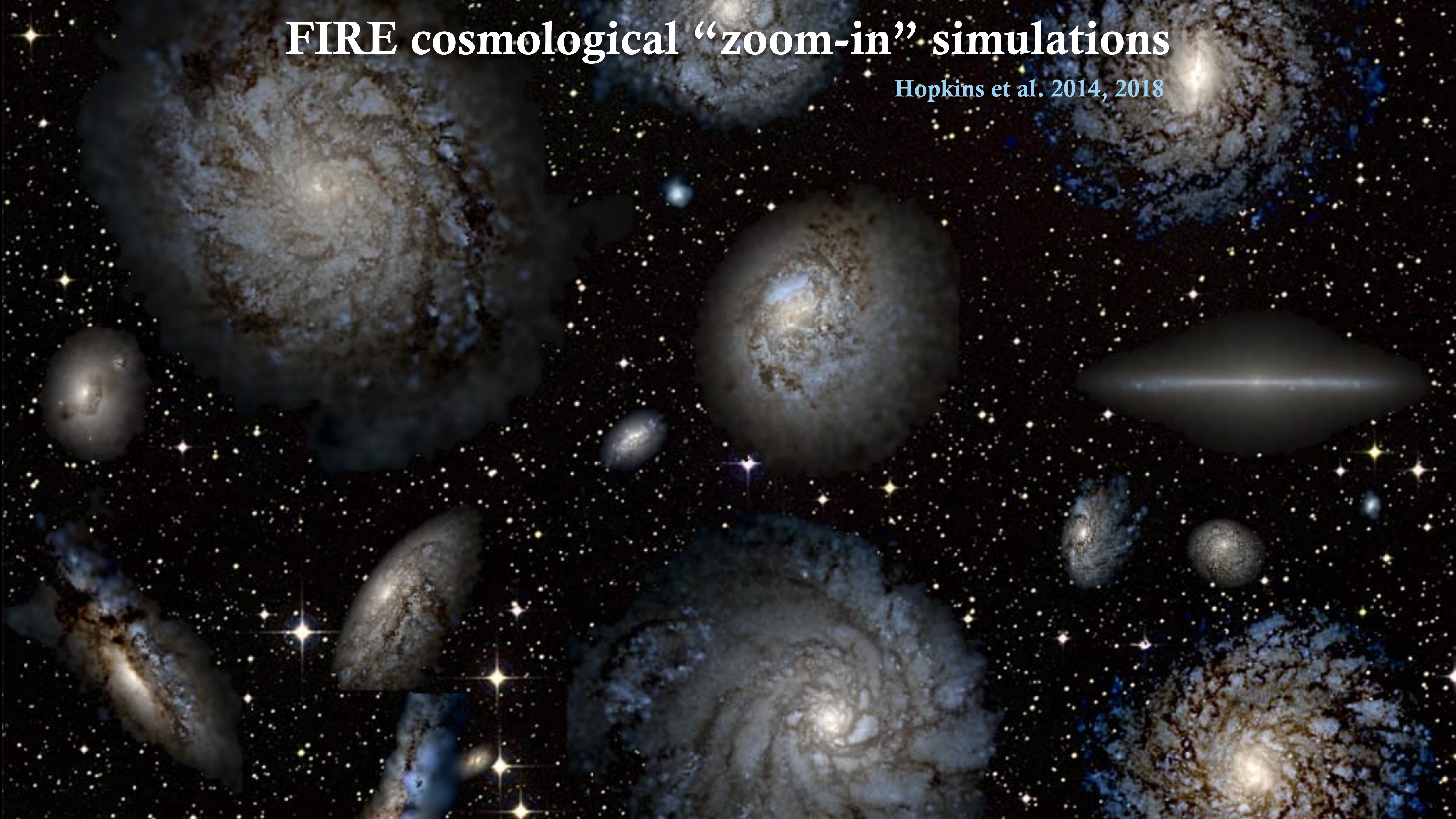
Mock three-color image (u/g/r bands) of galactic projection seen at 10 kpc from the center of MW-mass galaxy (Wetzel+16)

FIRE
Feedback In Realistic Environments

1) Resolving individual star-forming regions in full cosmological context
2) Stars form from high density ($n > 1000$ cm^{-3}), molecular, locally self-gravitating gas
3) Local feedback from supernovae, stellar winds, and radiation from Starburst99
4) Reproduce many galaxy properties without tuning parameters

FIRE cosmological "zoom-in" simulations

Hopkins et al. 2014, 2018



Properties of galactic winds

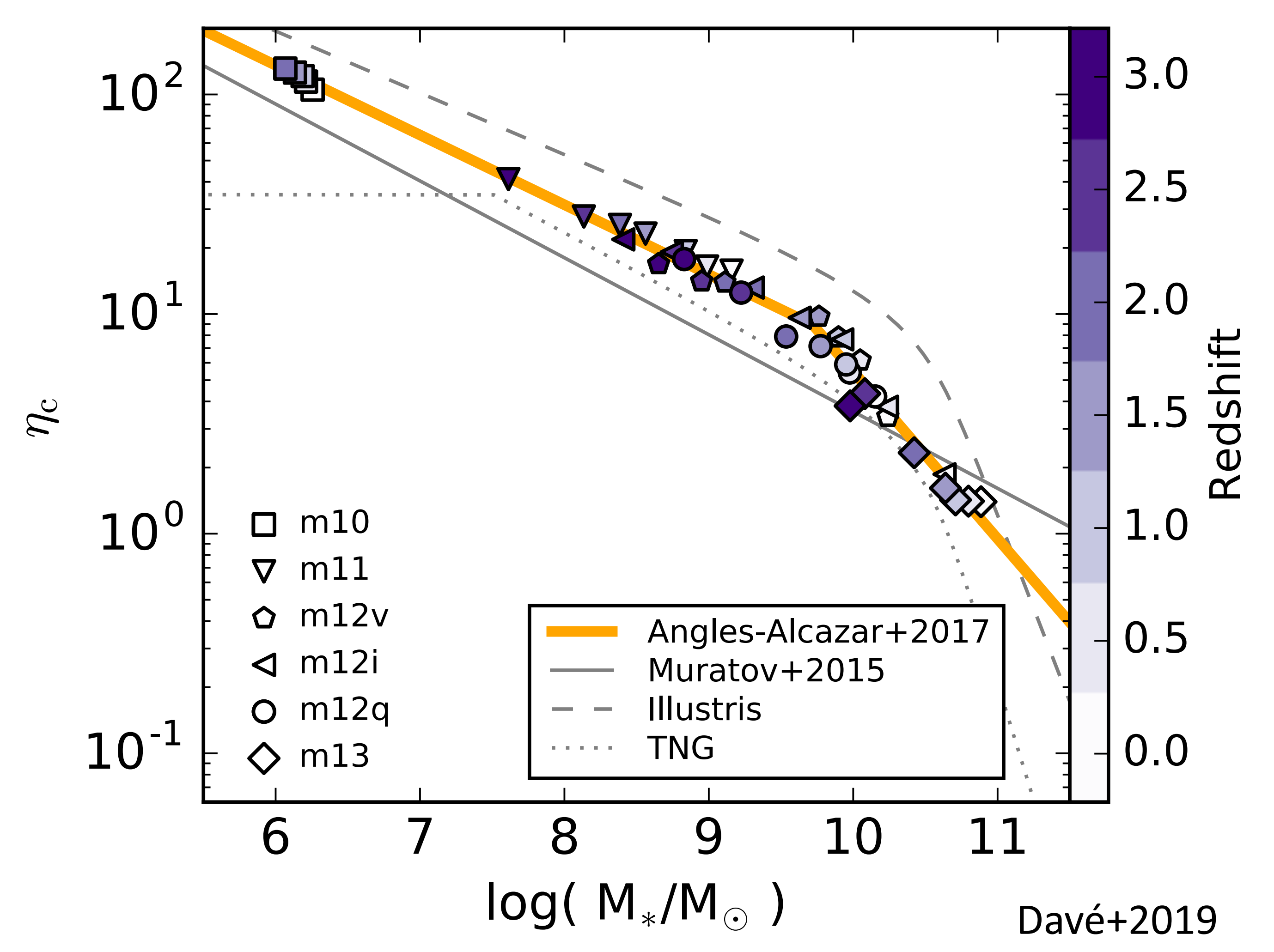
Wind loading factor, recycling fraction, recycling time/distance… → Anglés-Alcázar+2017b

→ Large mass-loading factors in low mass galaxies

Measured (e.g. FIRE, Christensen+2016,…)
or
Required (e.g. Oppenheimer+, TNG, Simba, Auriga,…)

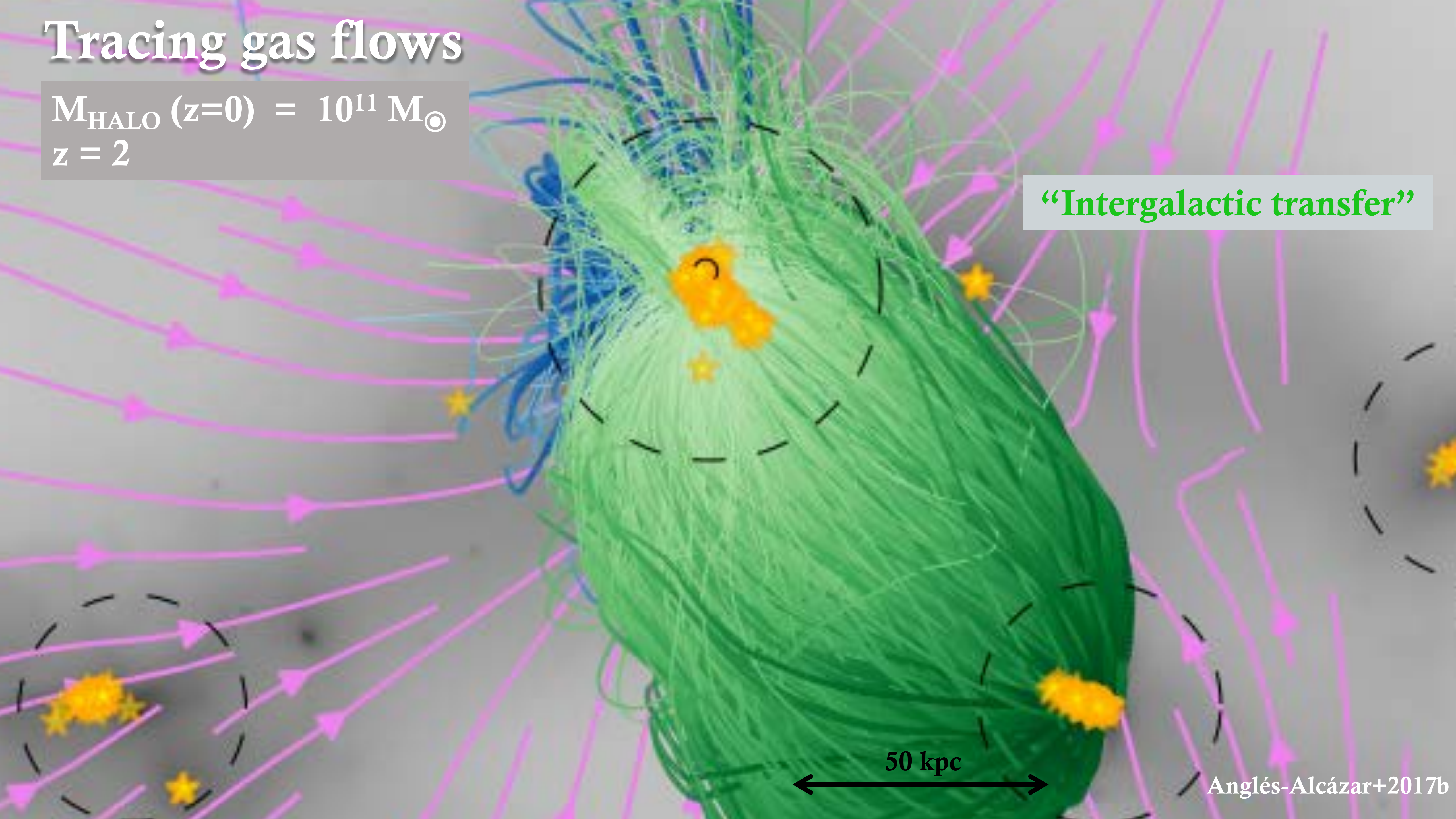
Implications?

"Wind loading factor" = Mass ejected / Stellar mass formed



Tracing gas flows

M_{HALO} (z=0) = 10^{11} $M_{\odot}$
z = 2

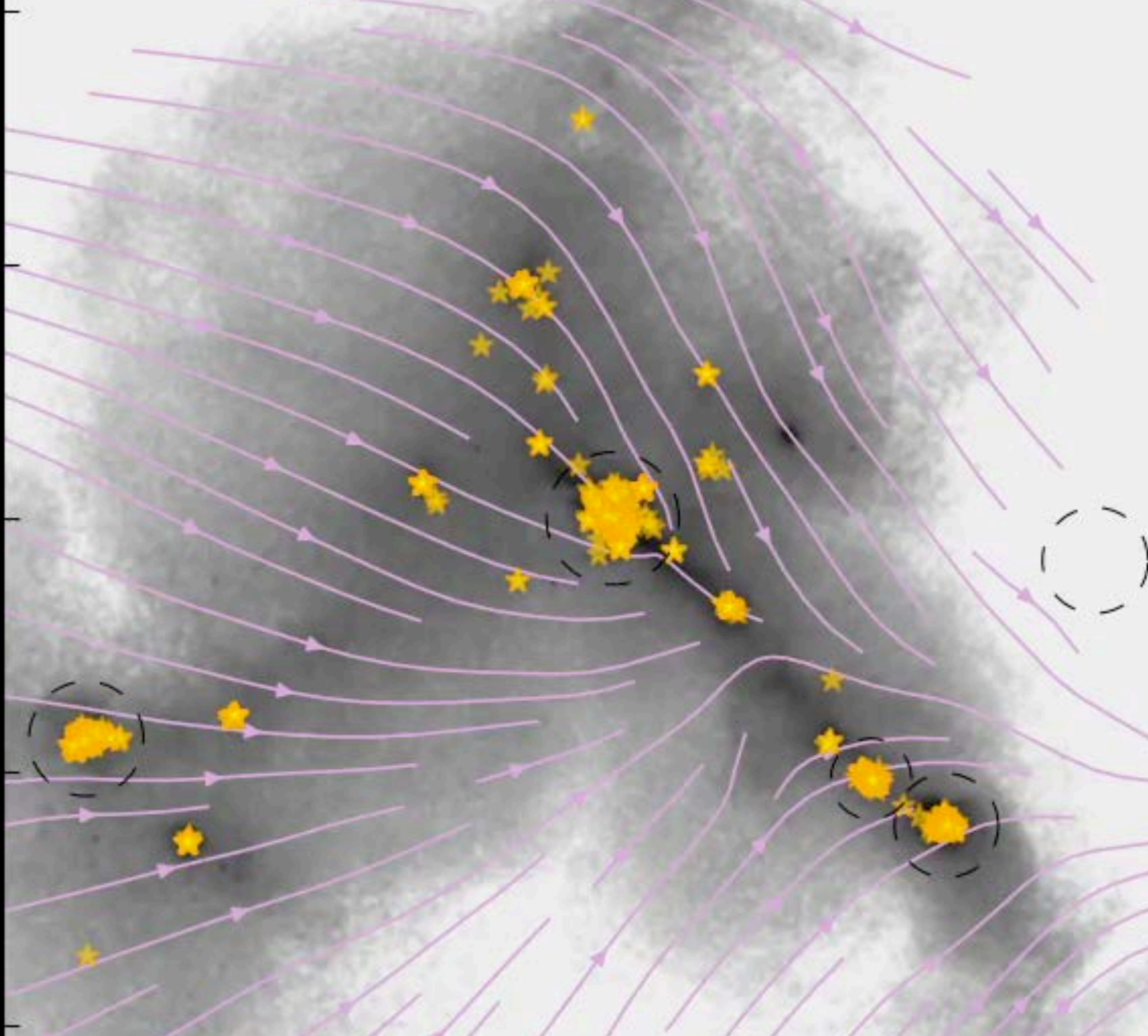

Tracing gas flows
M_{HALO} (z=0) = 10^{11} $M_{\odot}$
z = 2
"Intergalactic transfer"
50 kpc
Anglés-Alcázar+2017b

Fresh accretion

Wind recycling

Intergalactic transfer

Wind recycling and transfer events are common in every galaxy's history!

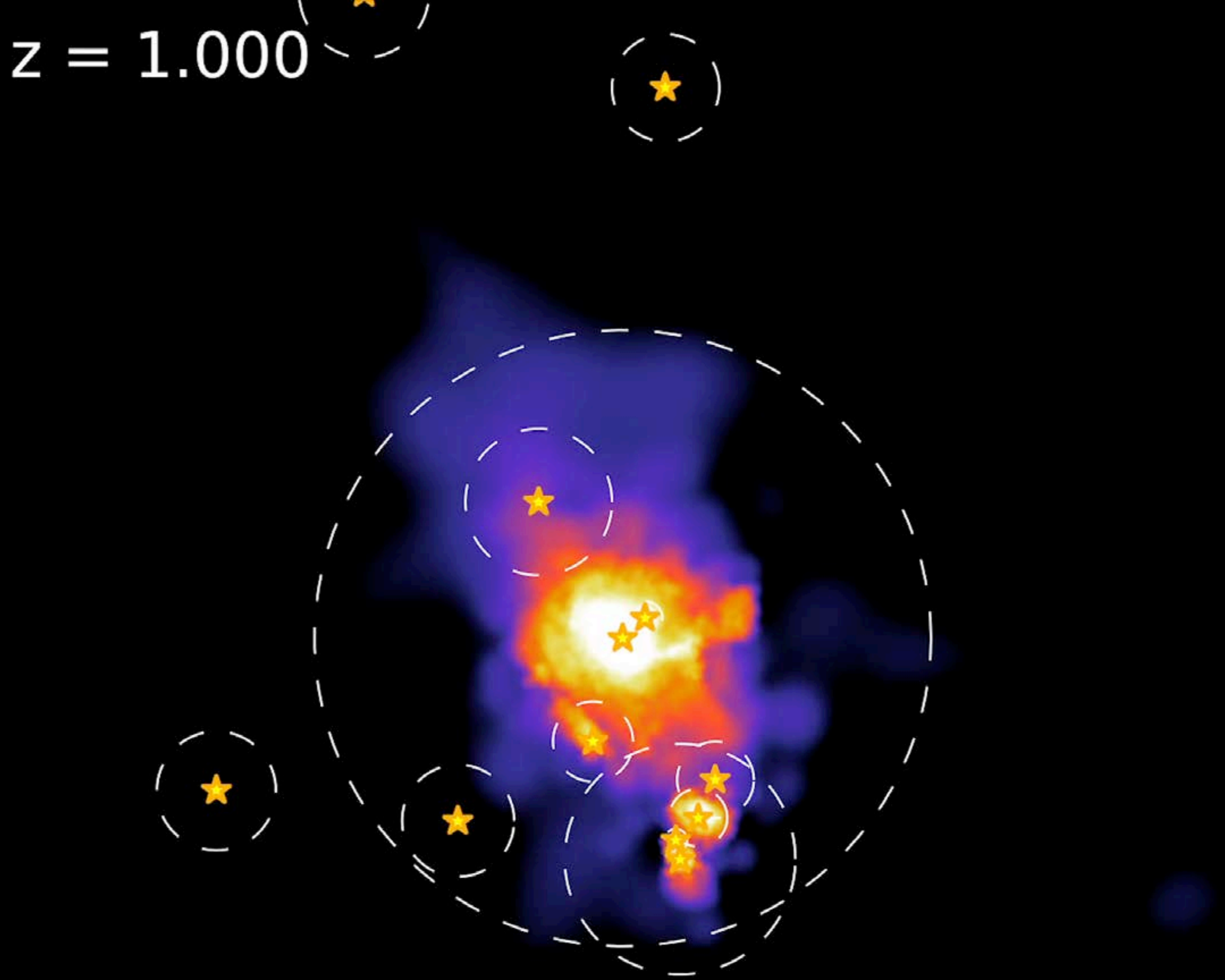


Anglés-Alcázar+2017b

Intergalactic Transfer

Anglés-Alcázar+2017b

From small satellites onto Milky-Way mass galaxy



Quasi-spherical outflows unbind interstellar medium gas from satellites

Satellite winds are easily stripped by ram pressure

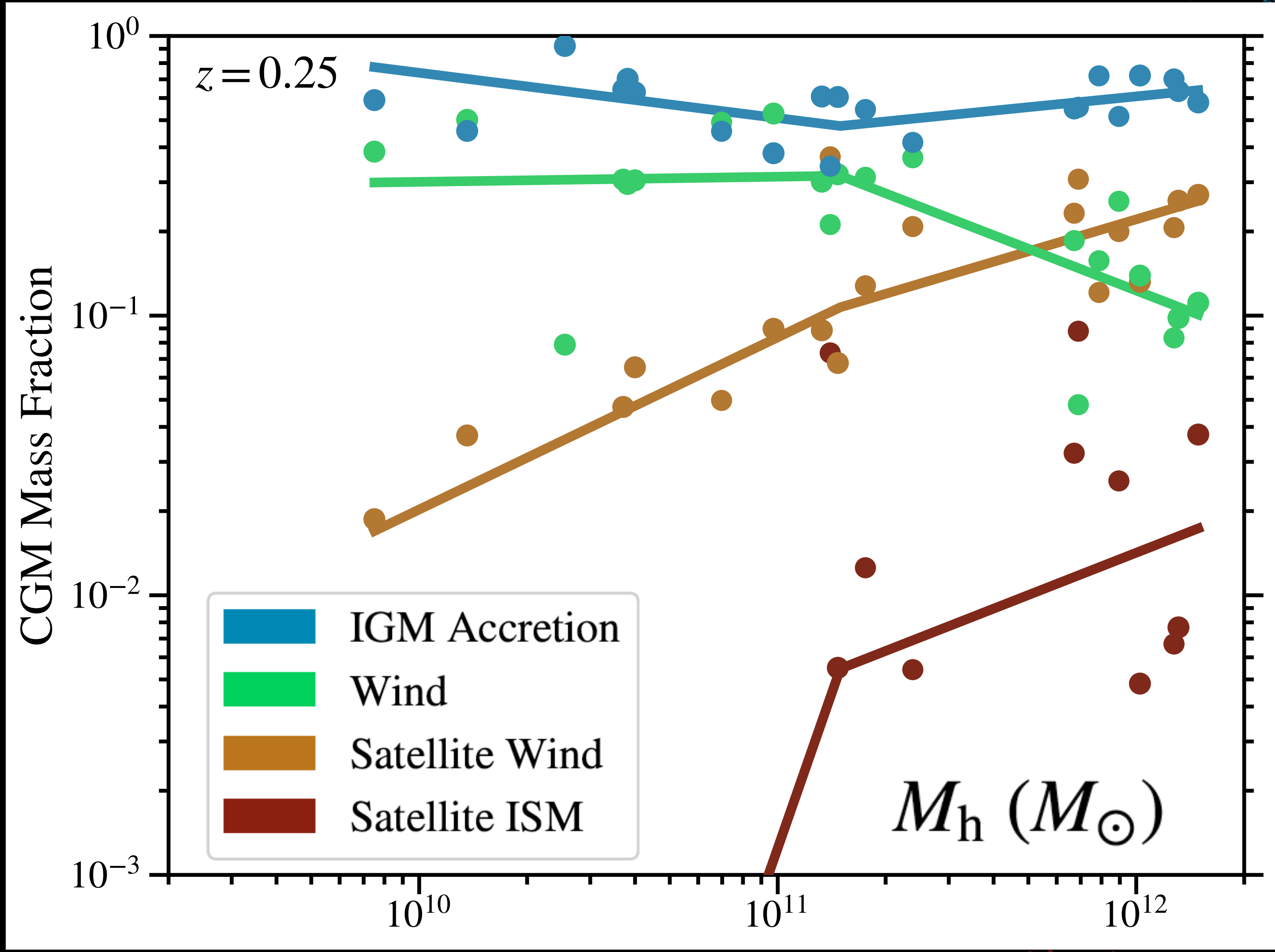
→ Up to 1/3 of stellar mass at z=0!

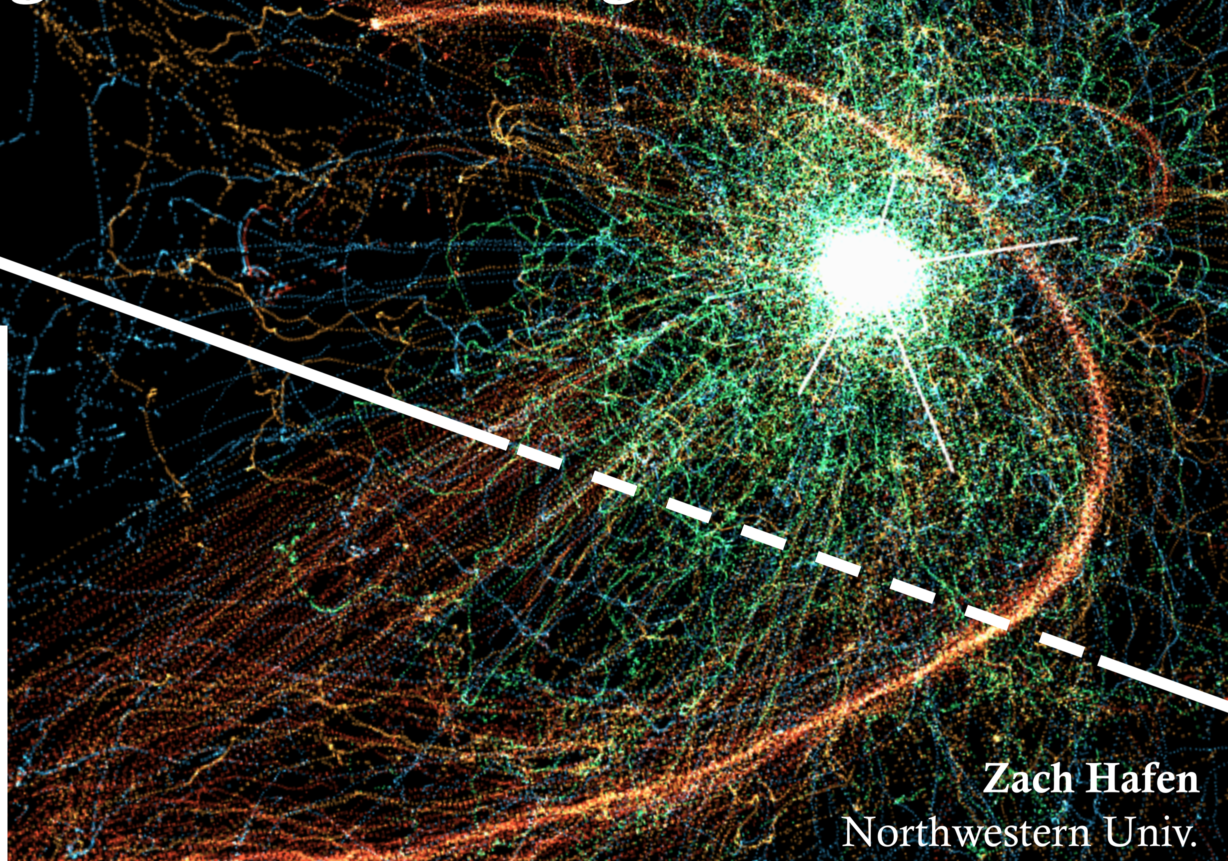
See Grand+2019 for qualitatively consistent results from Auriga

Tracing the origin and fate of circumgalactic medium gas flows

Hafen, Faucher-Giguere, Anglés-Alcázar, …

Hafen+2019a,b



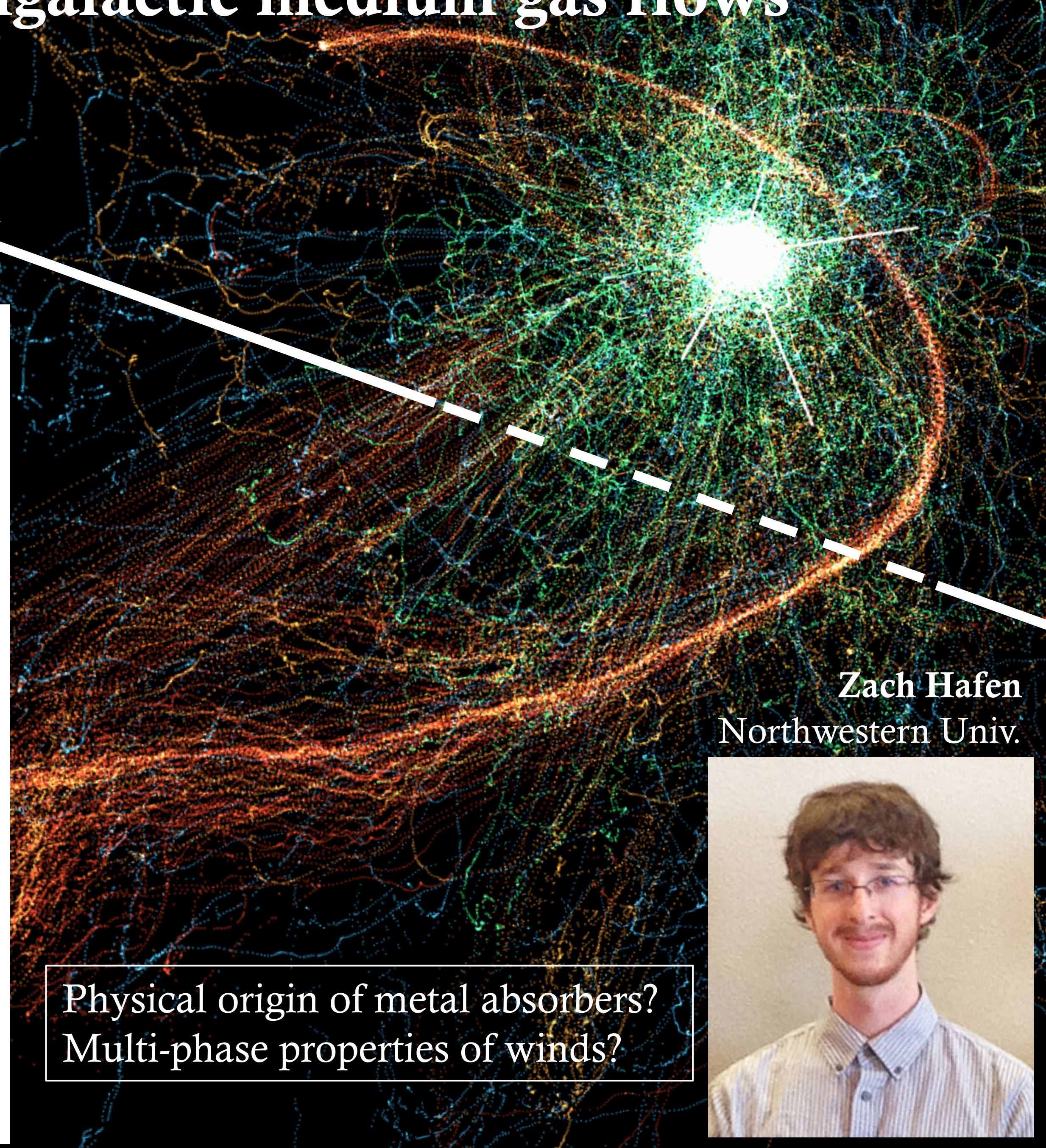


Zach Hafen
Northwestern Univ.

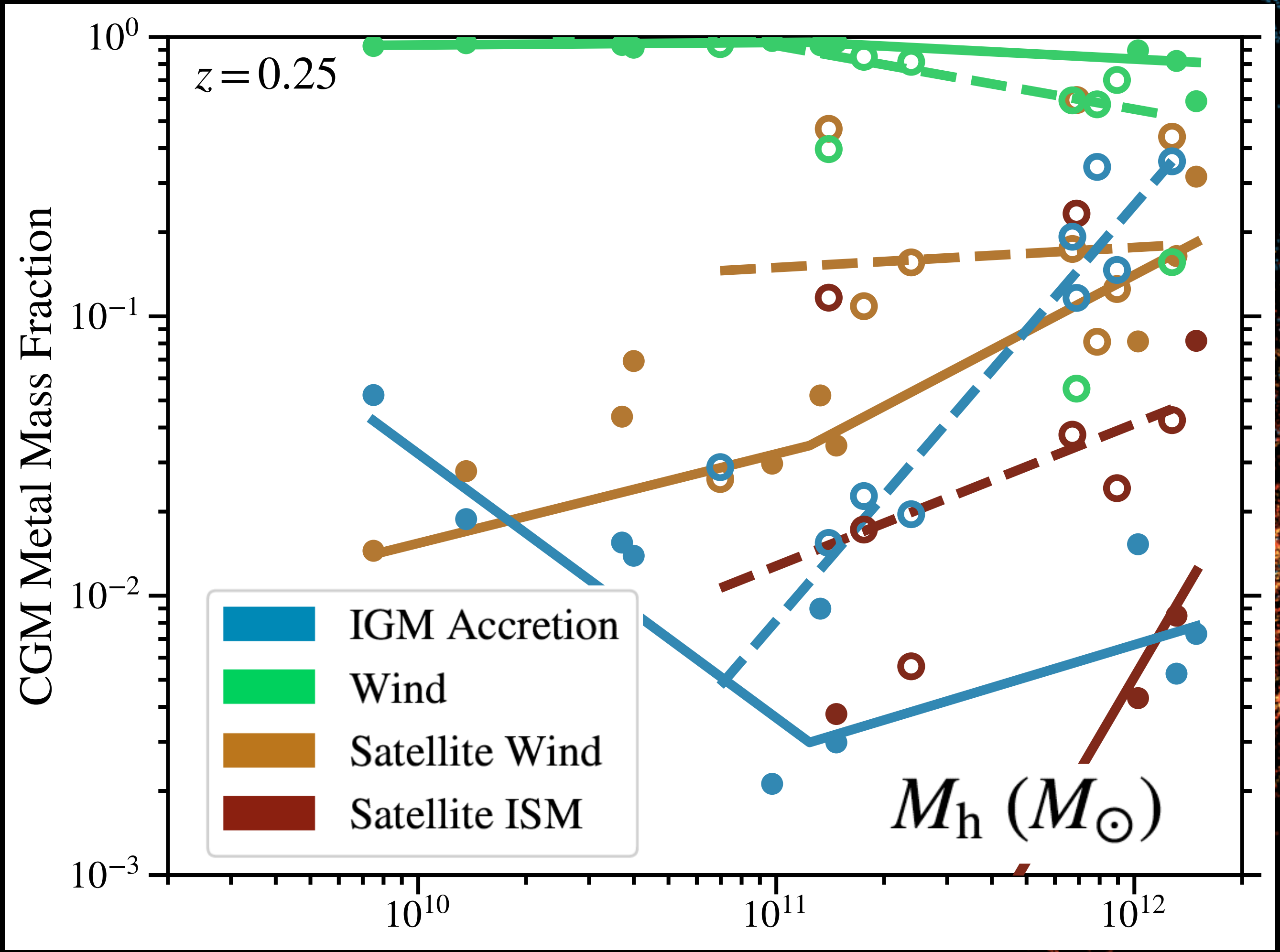
Physical origin of metal absorbers?
Multi-phase properties of winds?

Tracing the origin and fate of circumgalactic medium gas flows

Hafen, Faucher-Giguere, Anglés-Alcázar, …



Hafen+2019a,b



Physical origin of metal absorbers?
Multi-phase properties of winds?

Zach Hafen
Northwestern Univ.

Simba = Mufasa + black holes

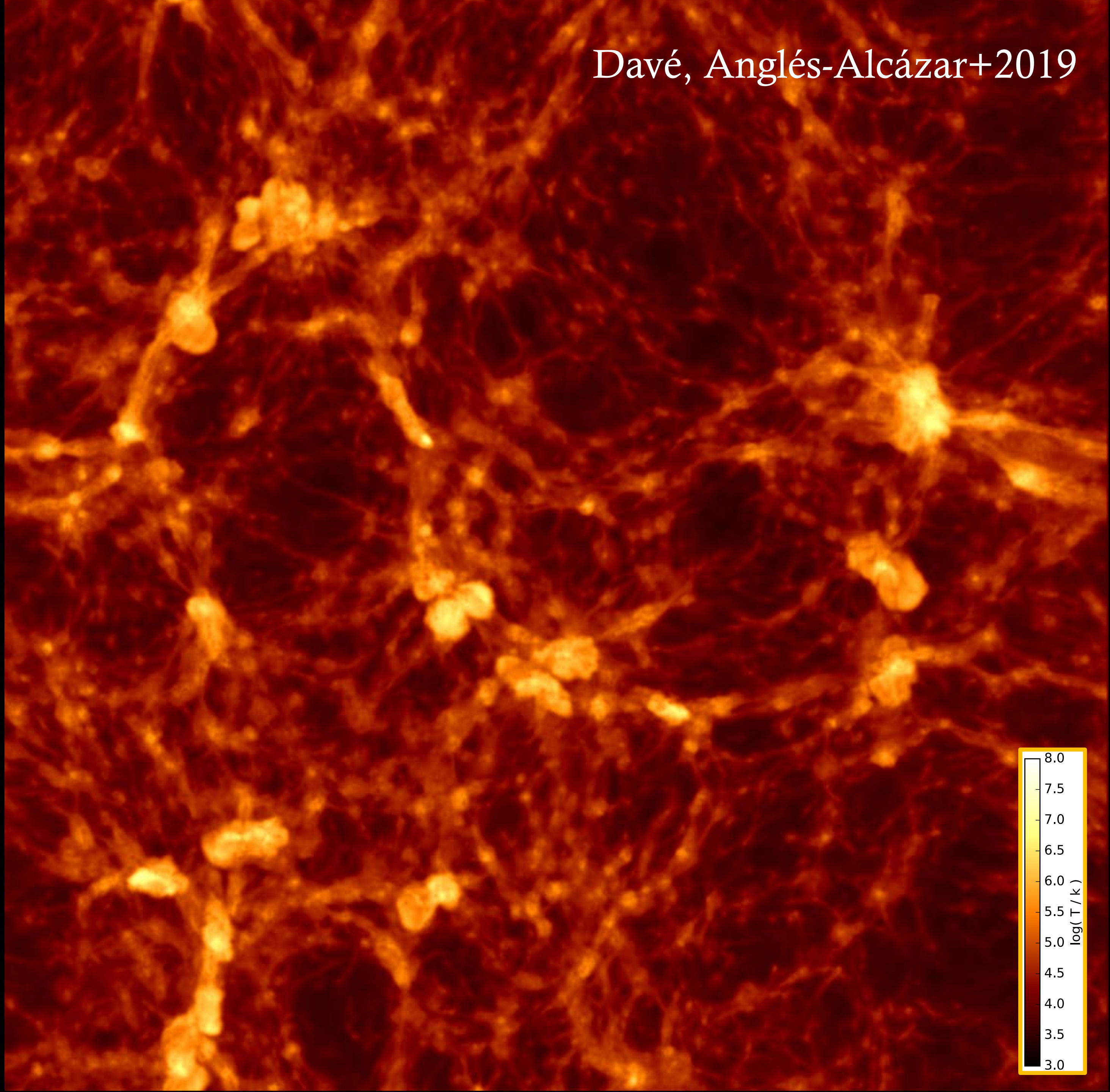
With Romeel Davé, Desika Narayanan, …

Galactic winds based on FIRE simulations
(Anglés-Alcázar+17b)

Two-mode black hole accretion:
→ Cold gas inflow driven by gravitational torques
(Hopkins & Quataert 2011, Anglés-Alcázar+17a)
→ Bondi accretion from hot gas

Two-mode black hole feedback:
(kinetic+bipolar; Anglés-Alcázar+17a)
→ Radiative (λ>0.02): v = 1000 km/s, P = 20 L/c
→ Jet (λ<0.02): v = 8000 km/s
+ X-ray heating (Choi+2012)

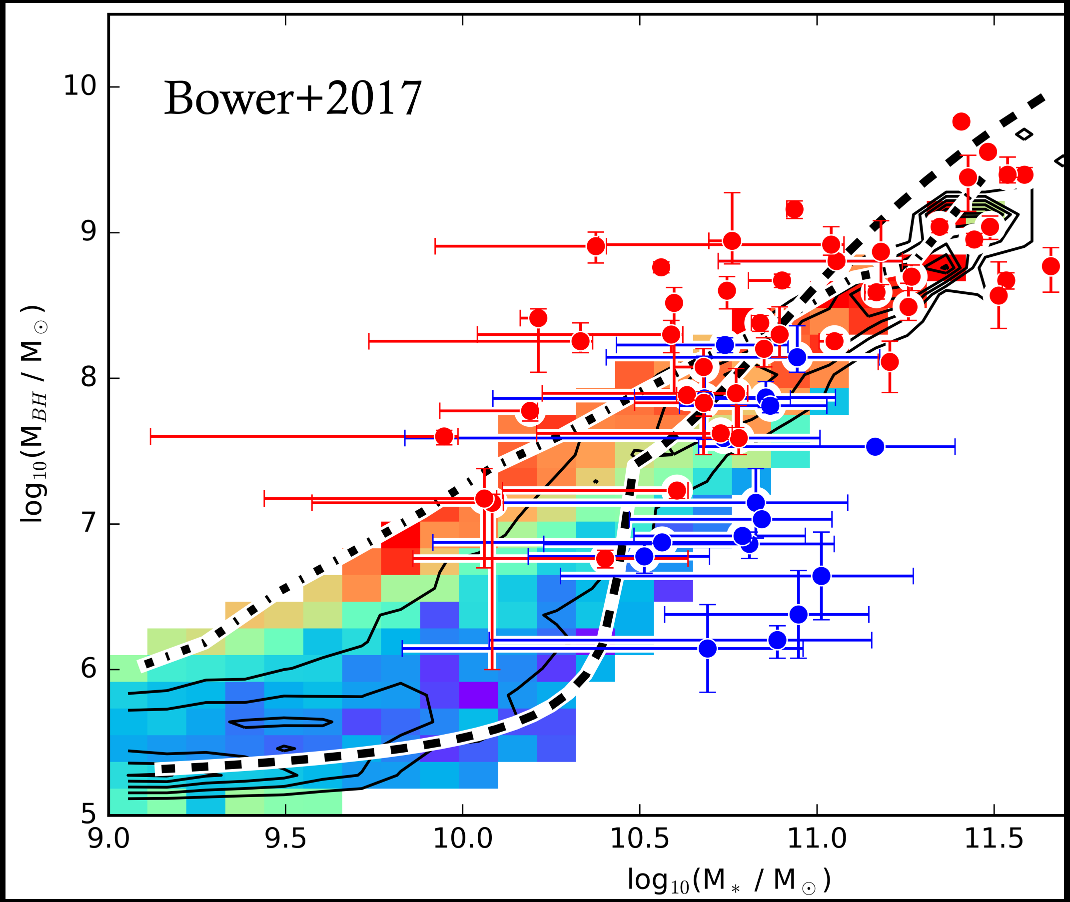
Dust production, growth, and destruction
(passively advected; Li+2019)



Why I keep asking Joop Schaye again and again…

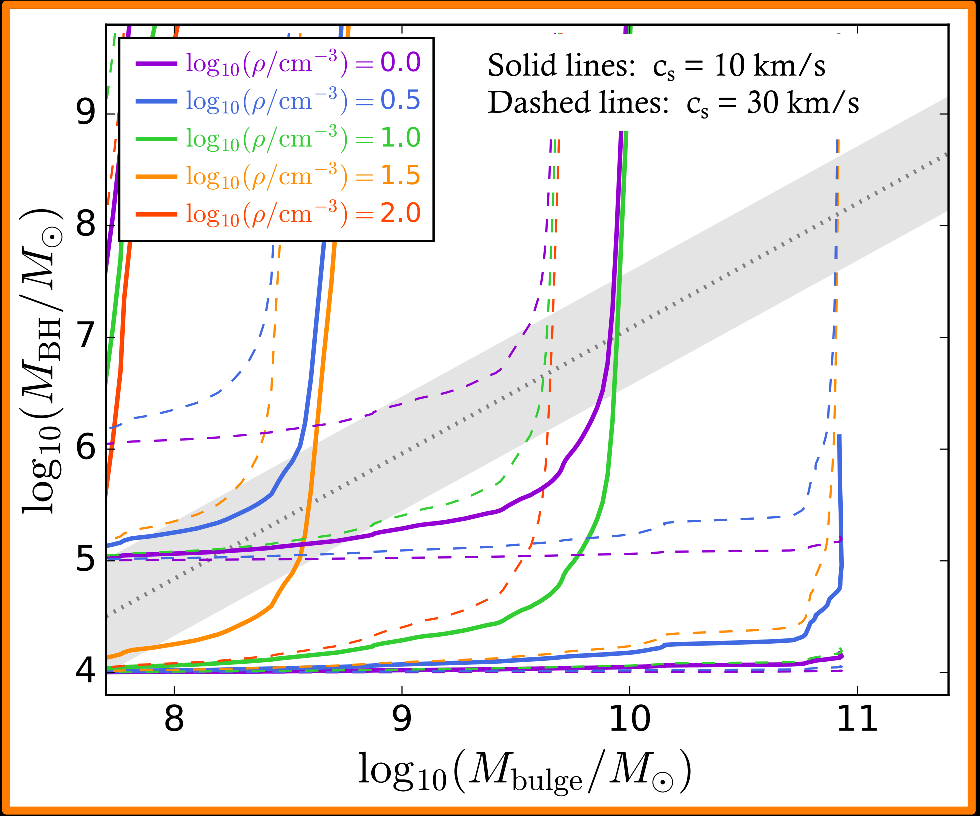
Bondi accretion rate = $4\pi\, G^2\, M_{BH}^2\, \rho\, / c_s^3$ → **Divergence timescale = $c_s^3 / (4\pi\, G^2\, M_{seed}\, \rho)$**

EAGLE simulation:
stellar feedback suppresses early BH growth?



→ BONDI can suppress early BH growth even with continuous gas supply!

→ Transition depends on c_s, M_{seed}, ρ, and normalization



Cosmological baryon transfer in the Simba simulations

Borrow, Anglés-Alcázar & Davé (2019)

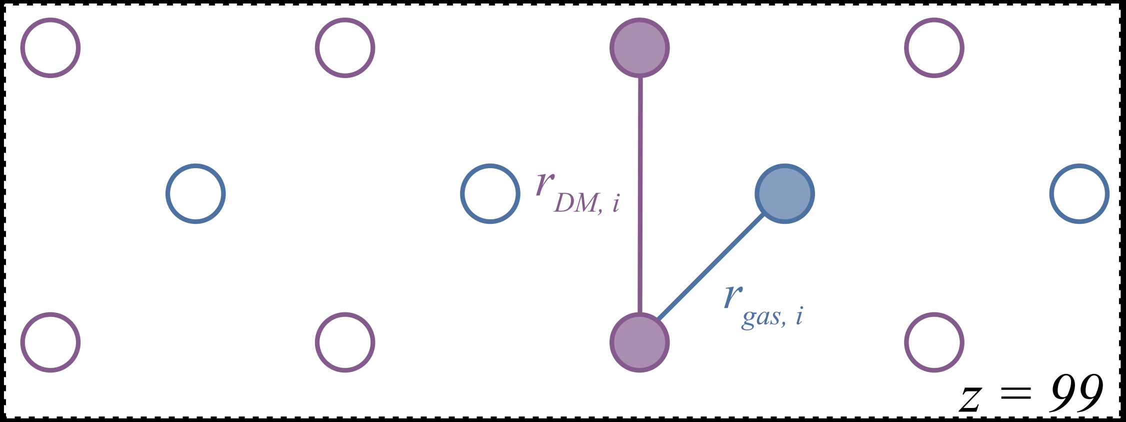
The "Spread" Metric

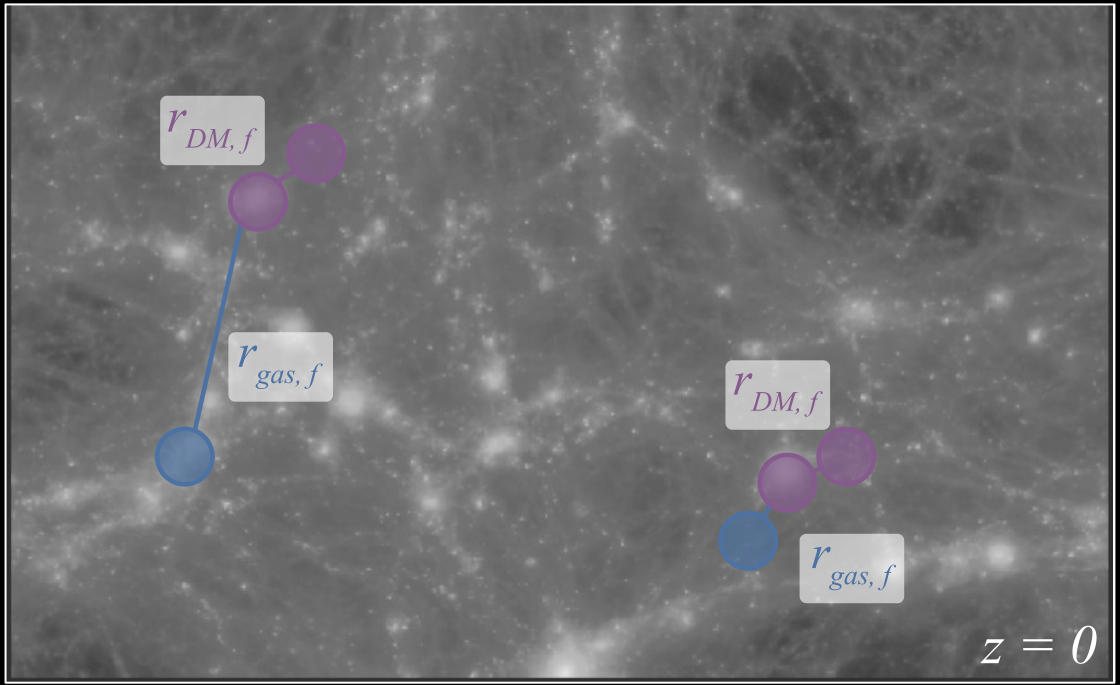
→ Quantify relative motion between baryons and dark matter

Present day (z=0)

Distance to nearest dark matter particle neighbor at:

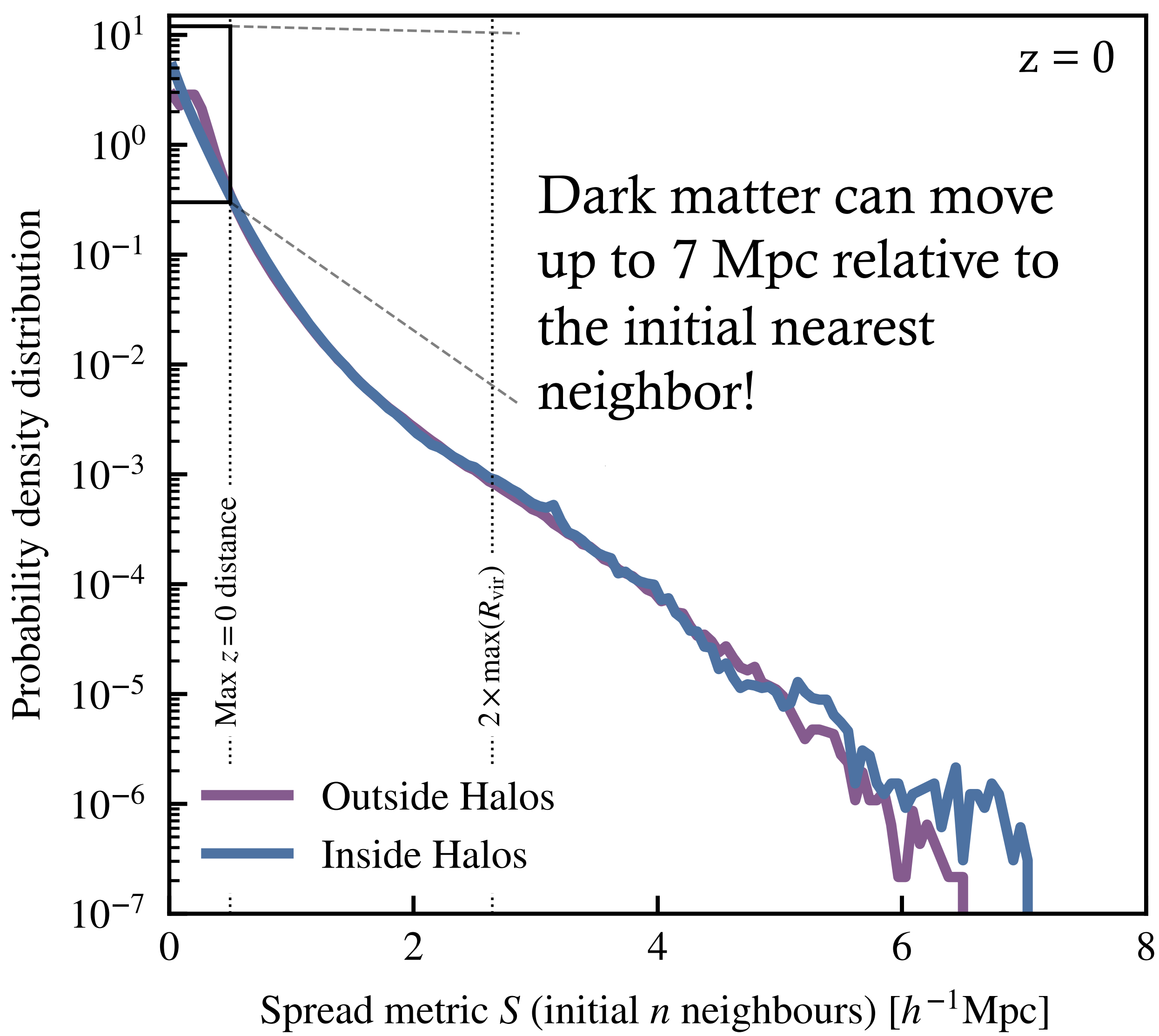
Initial conditions (z=99)

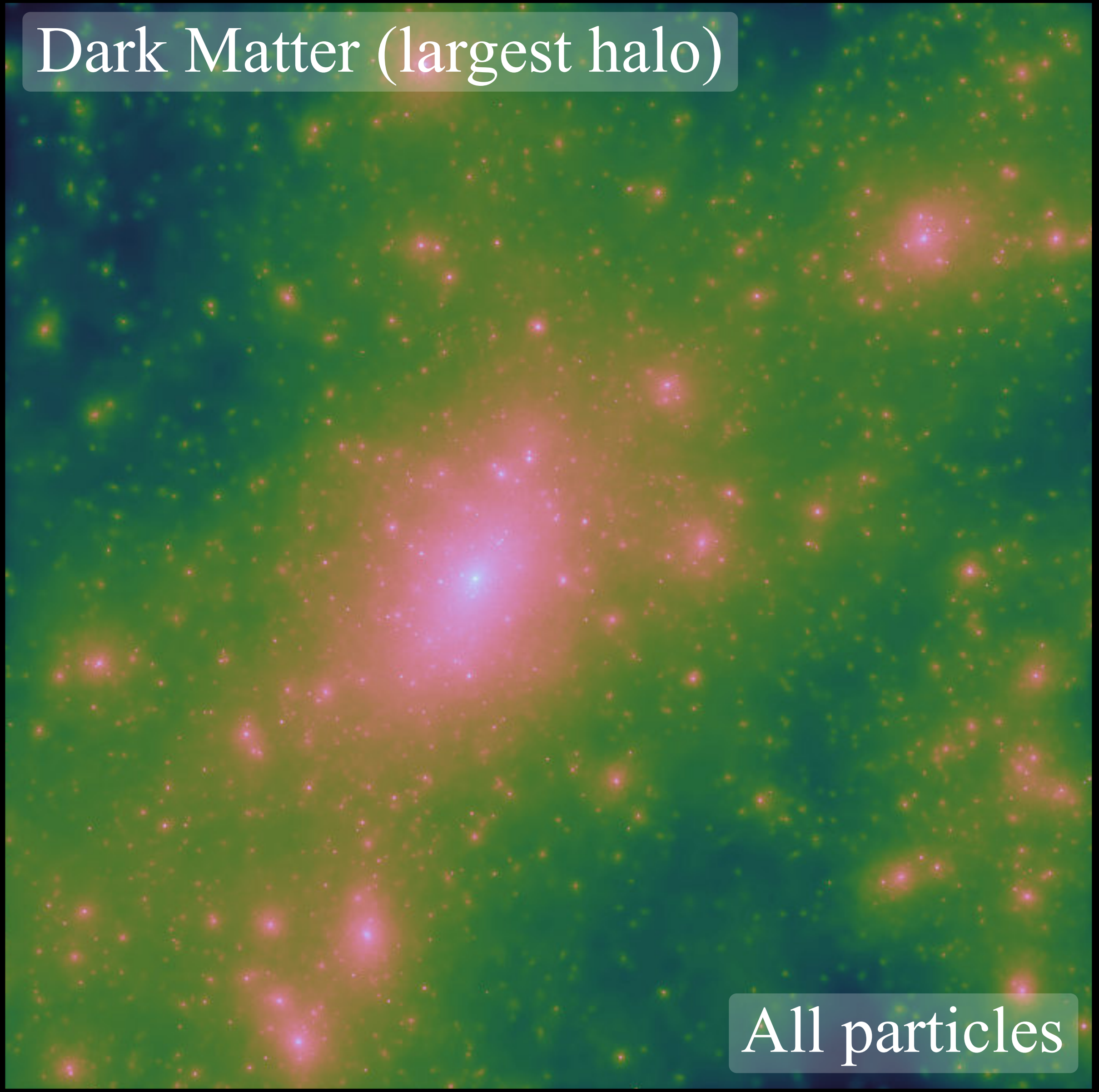




Cosmological baryon transfer in the Simba simulations

Borrow+2019





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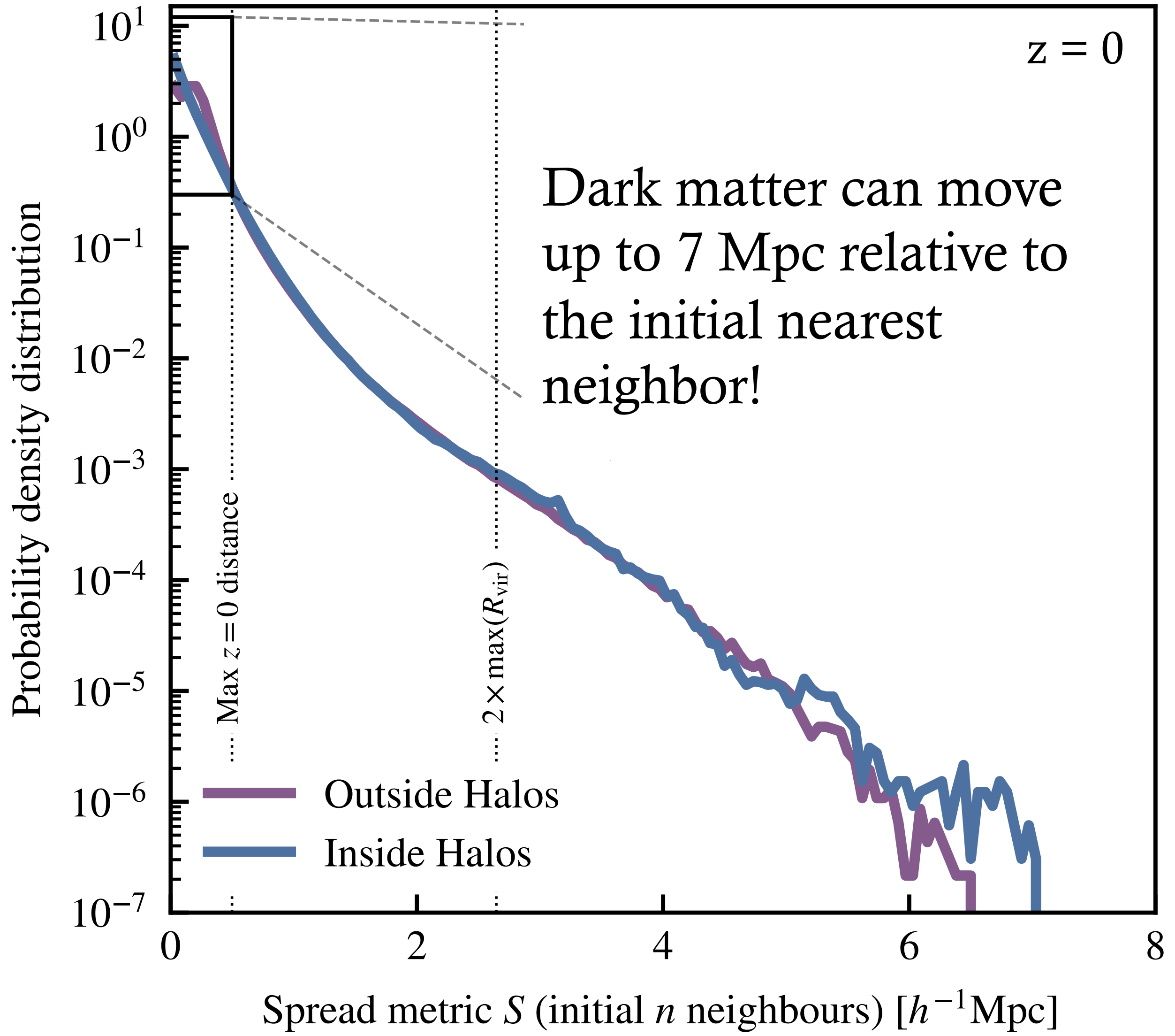

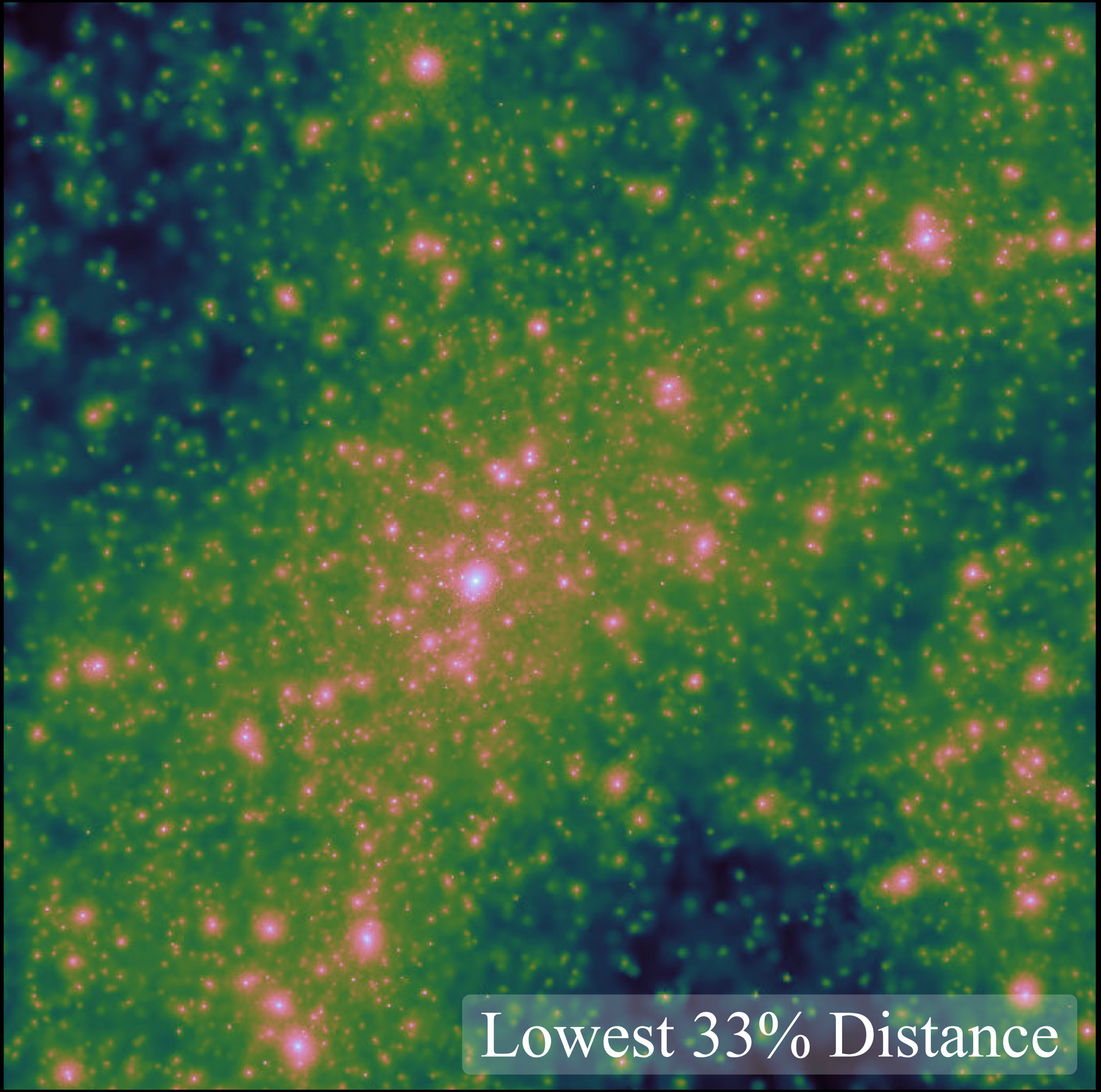

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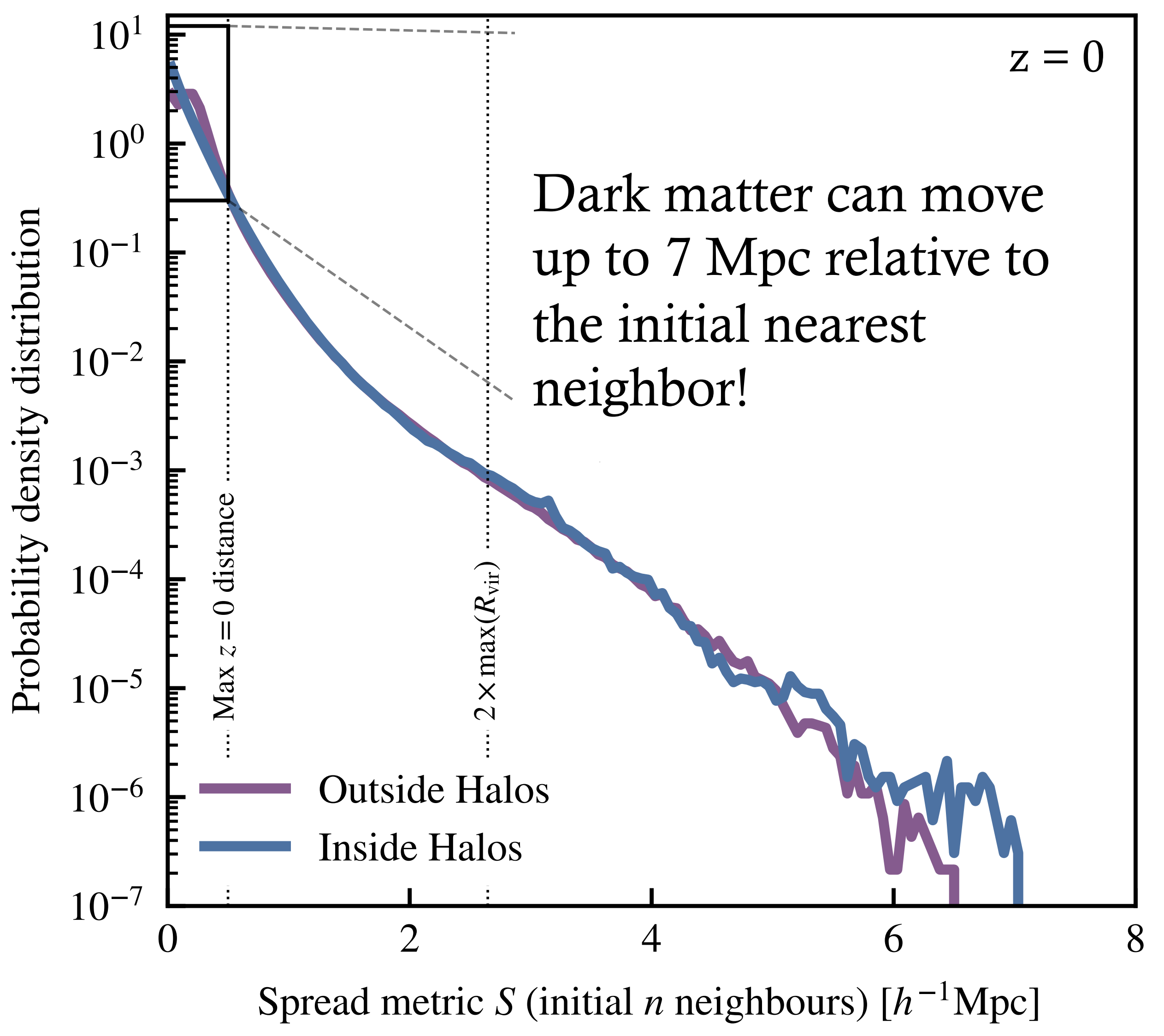
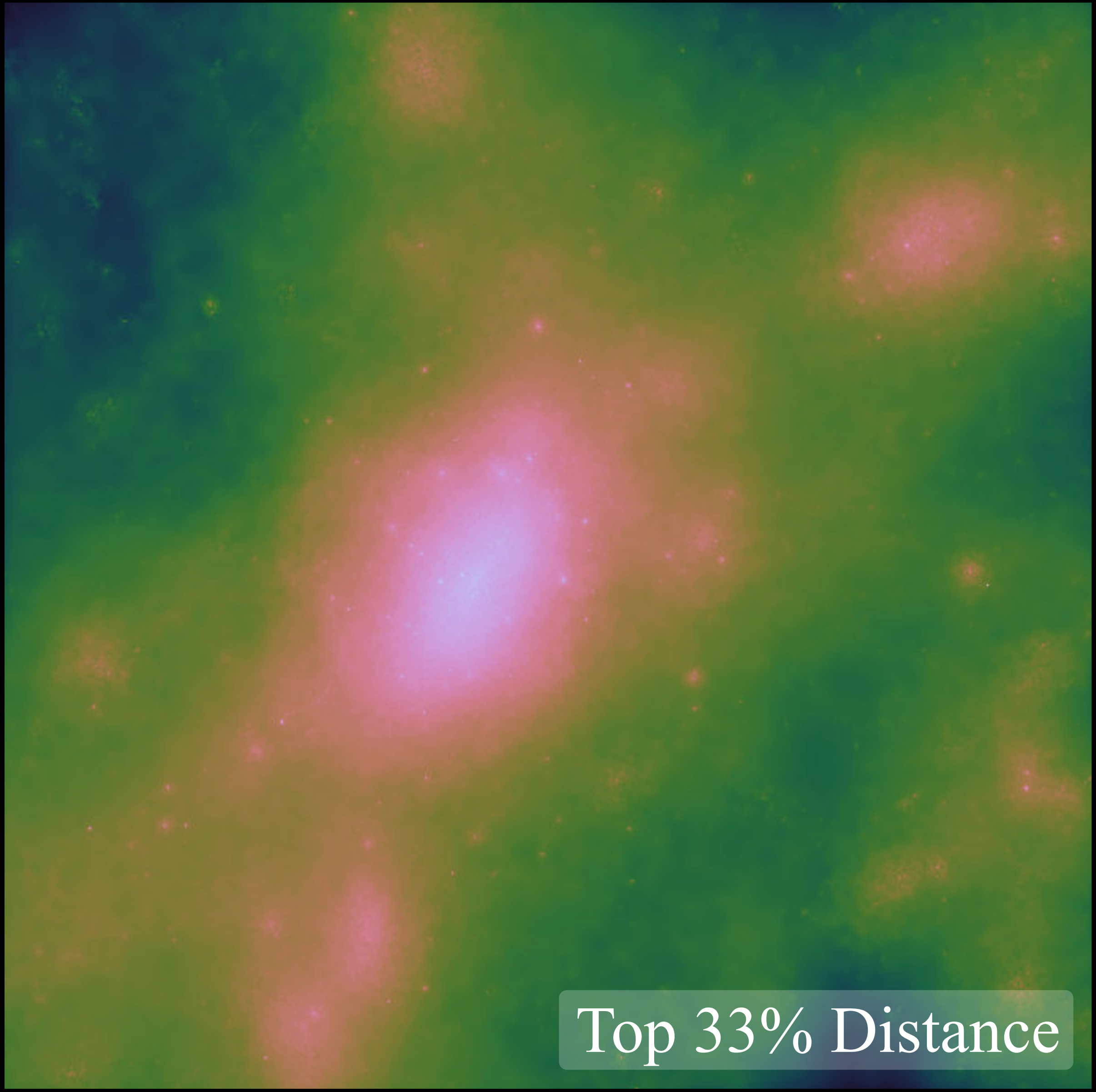
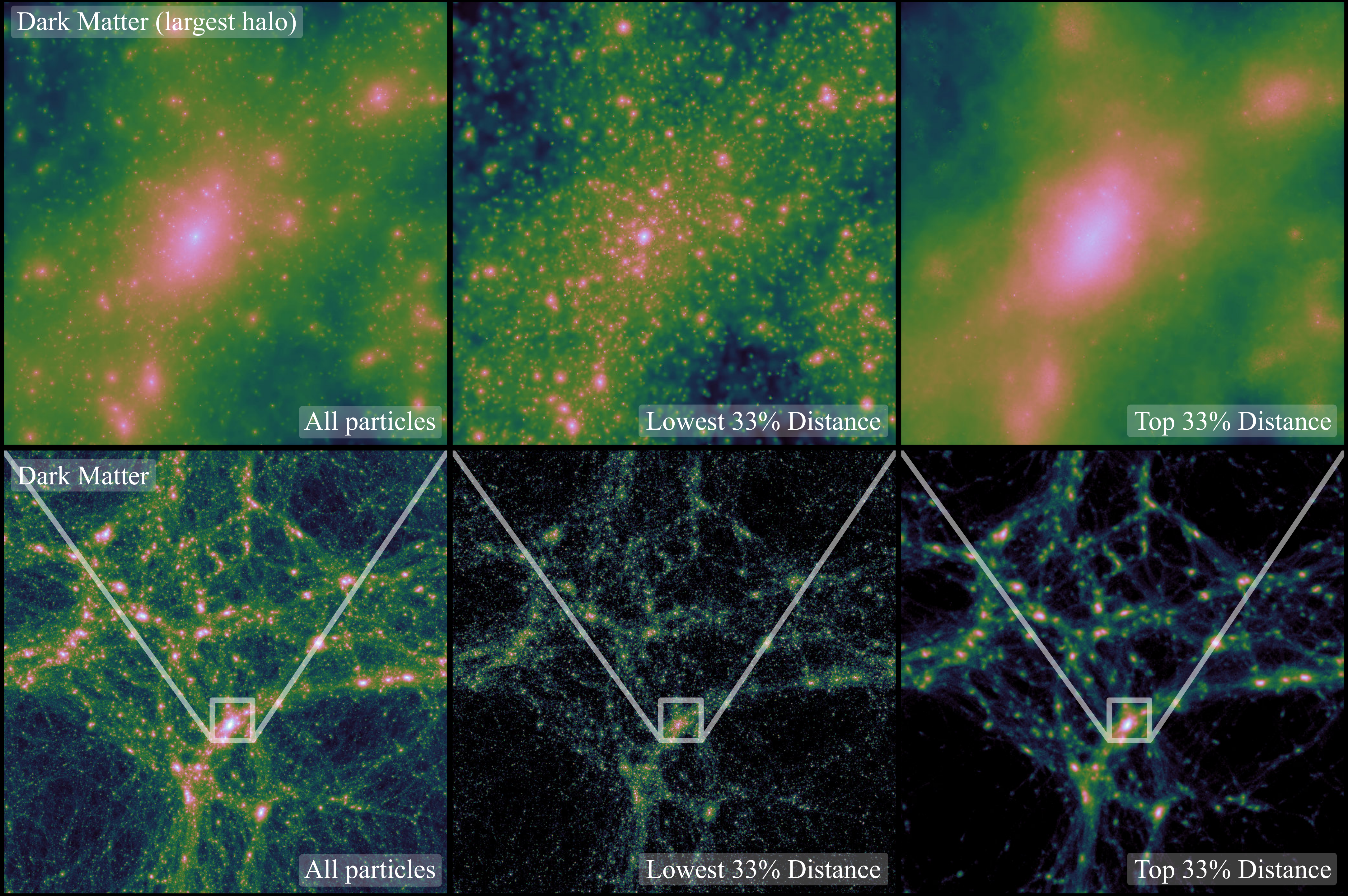
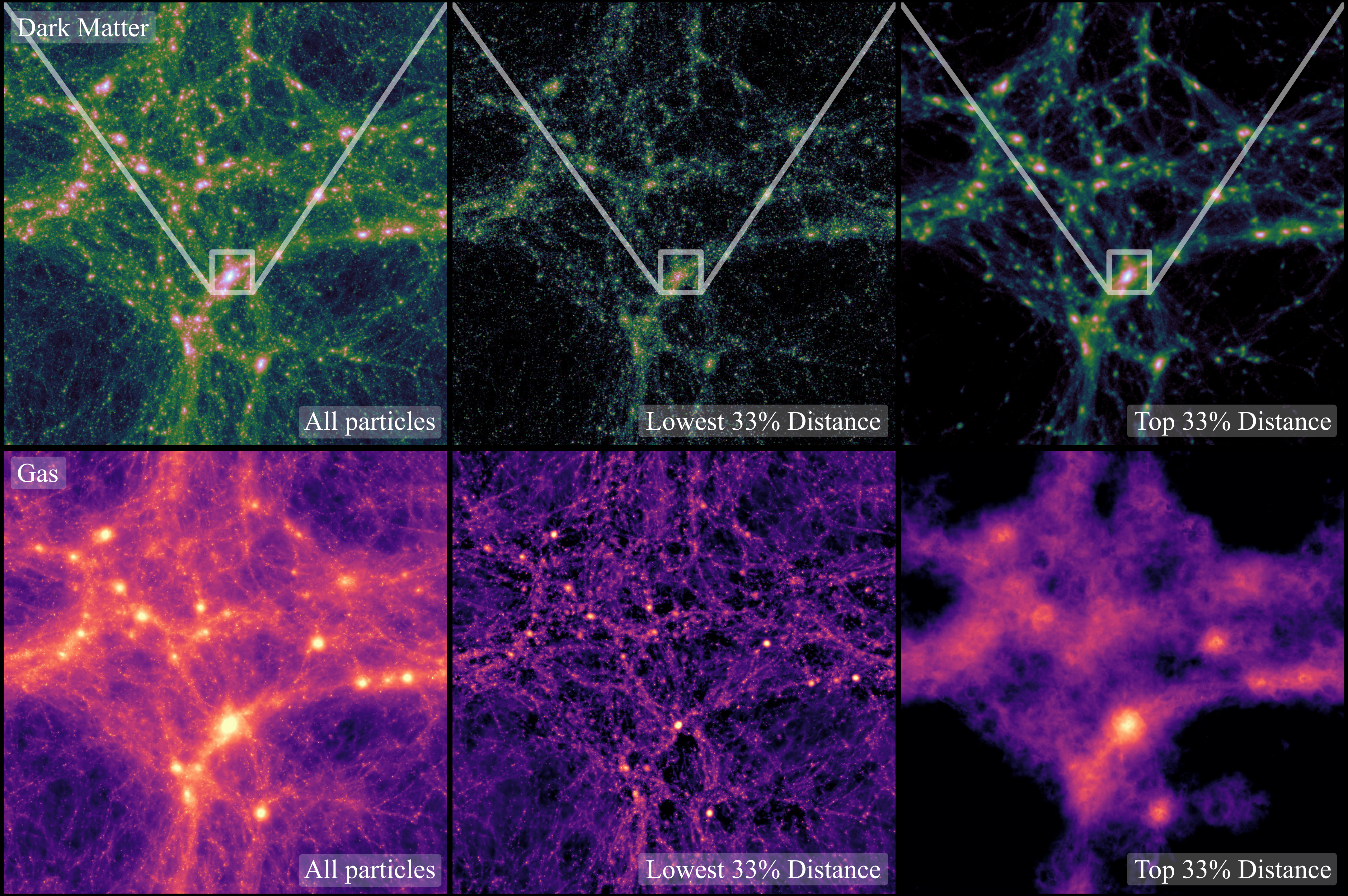






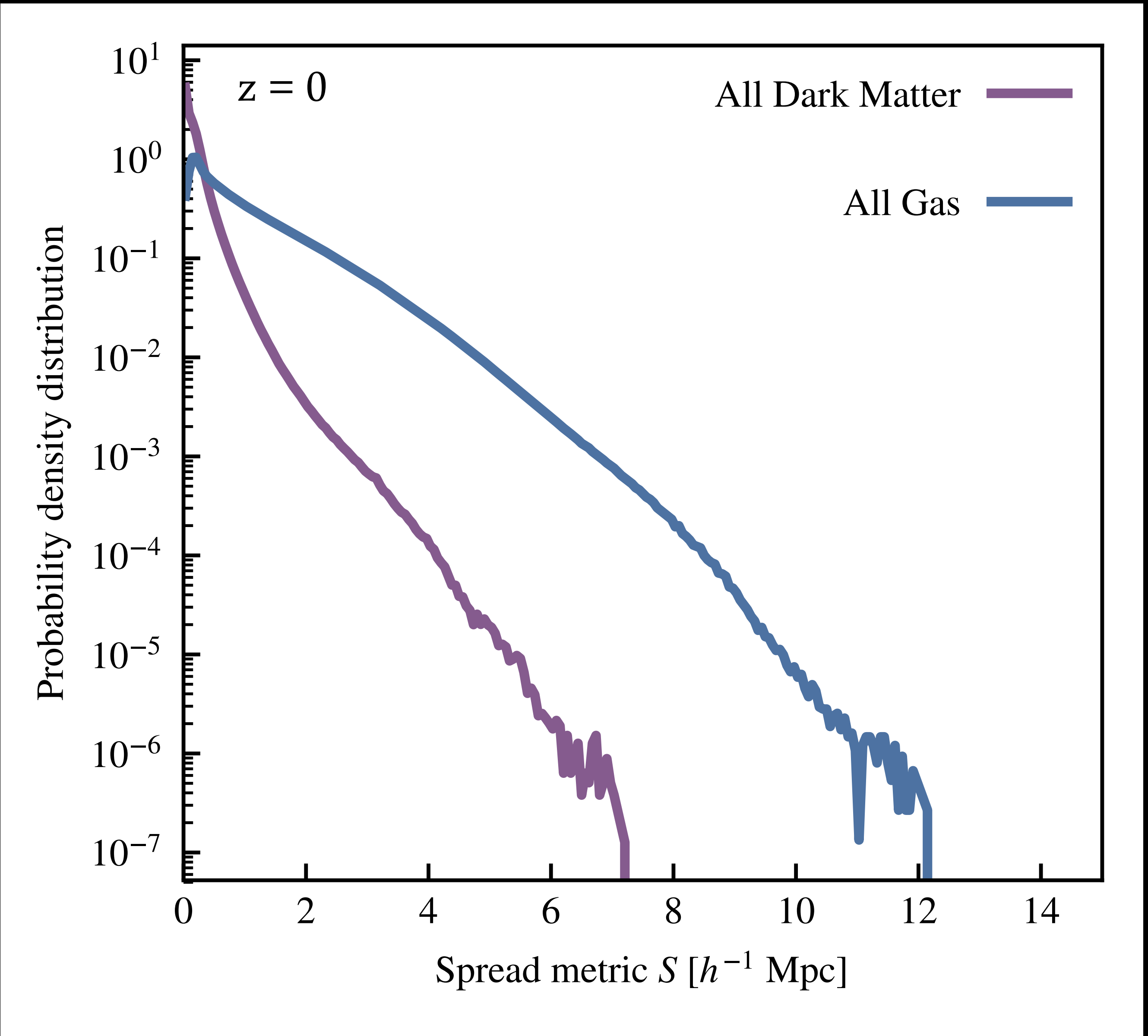
Dark Matter (largest halo)
All particles
Lowest 33% Distance
Top 33% Distance
Dark Matter
All particles
Lowest 33% Distance
Top 33% Distance



Dark Matter
All particles
Lowest 33% Distance
Top 33% Distance
Gas
All particles
Lowest 33% Distance
Top 33% Distance

Cosmological baryon transfer in the Simba simulations

Borrow+2019



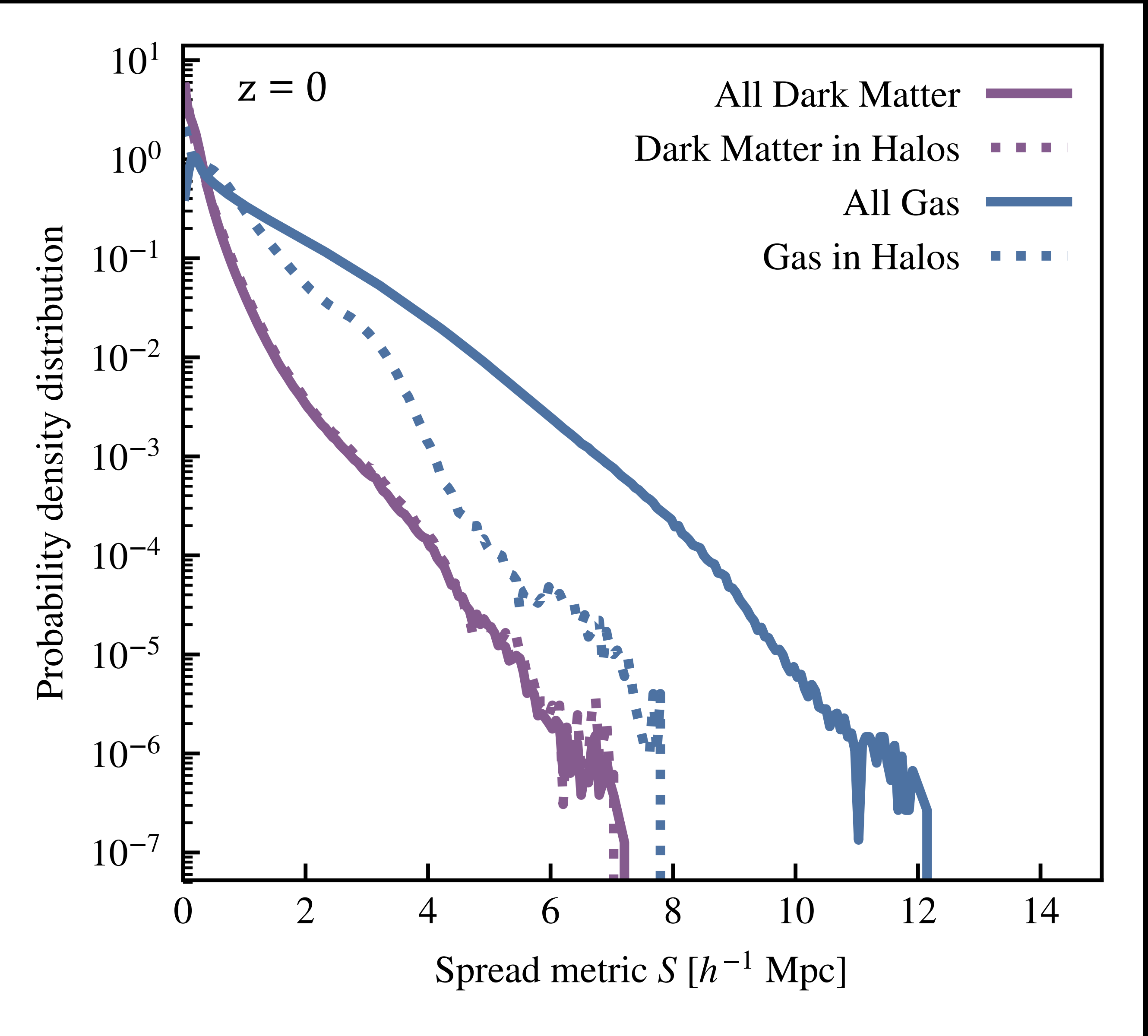
Gas can move up to 12 Mpc relative to the initial nearest DM neighbor!

→ Baryons decouple from the dark matter due to hydrodynamic forces, radiative cooling, and feedback

→ 40% of baryons have spread more than 1 Mpc!

Cosmological baryon transfer in the Simba simulations

Borrow+2019



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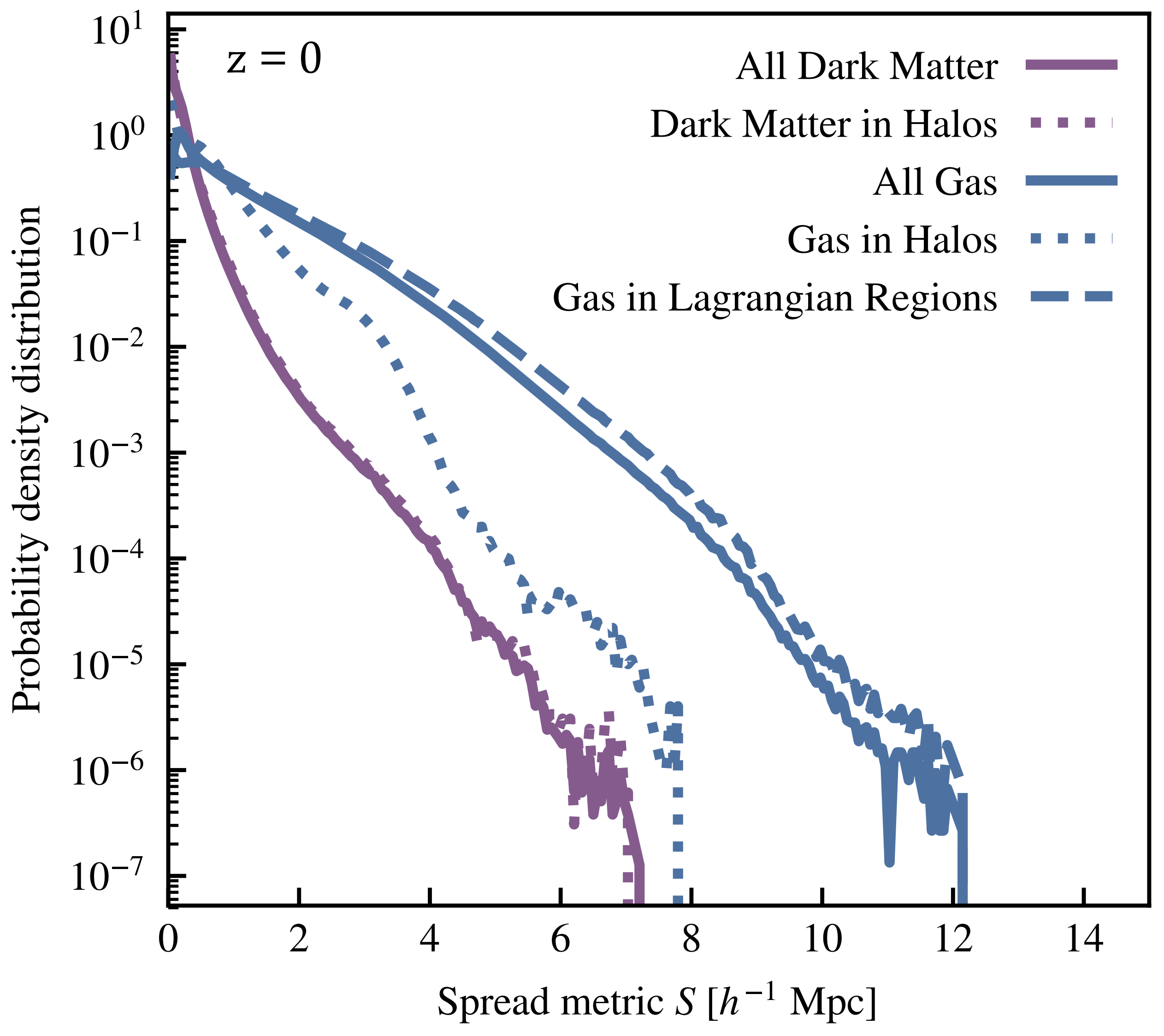

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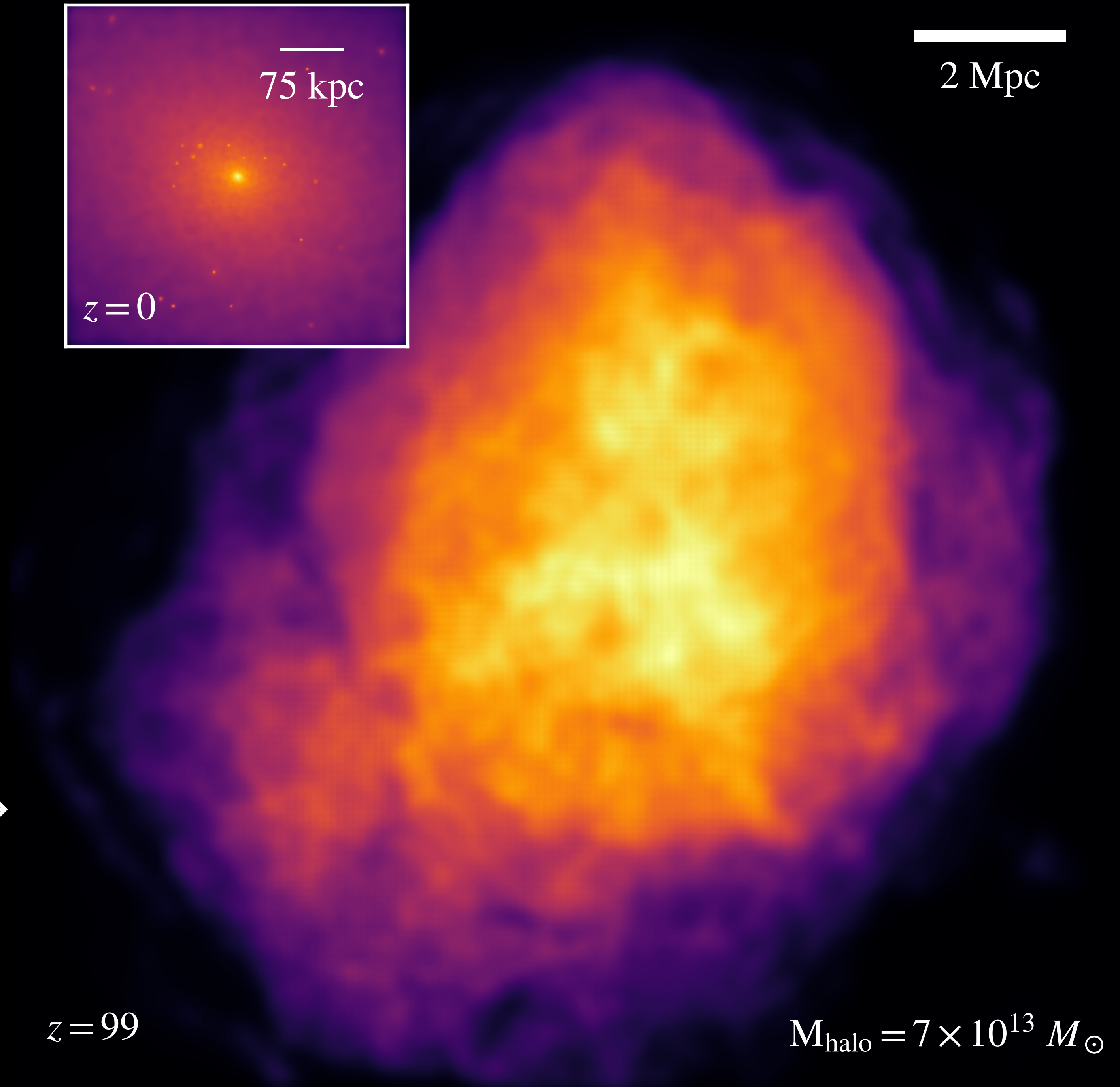
Where does the gas that end up in halos come from?

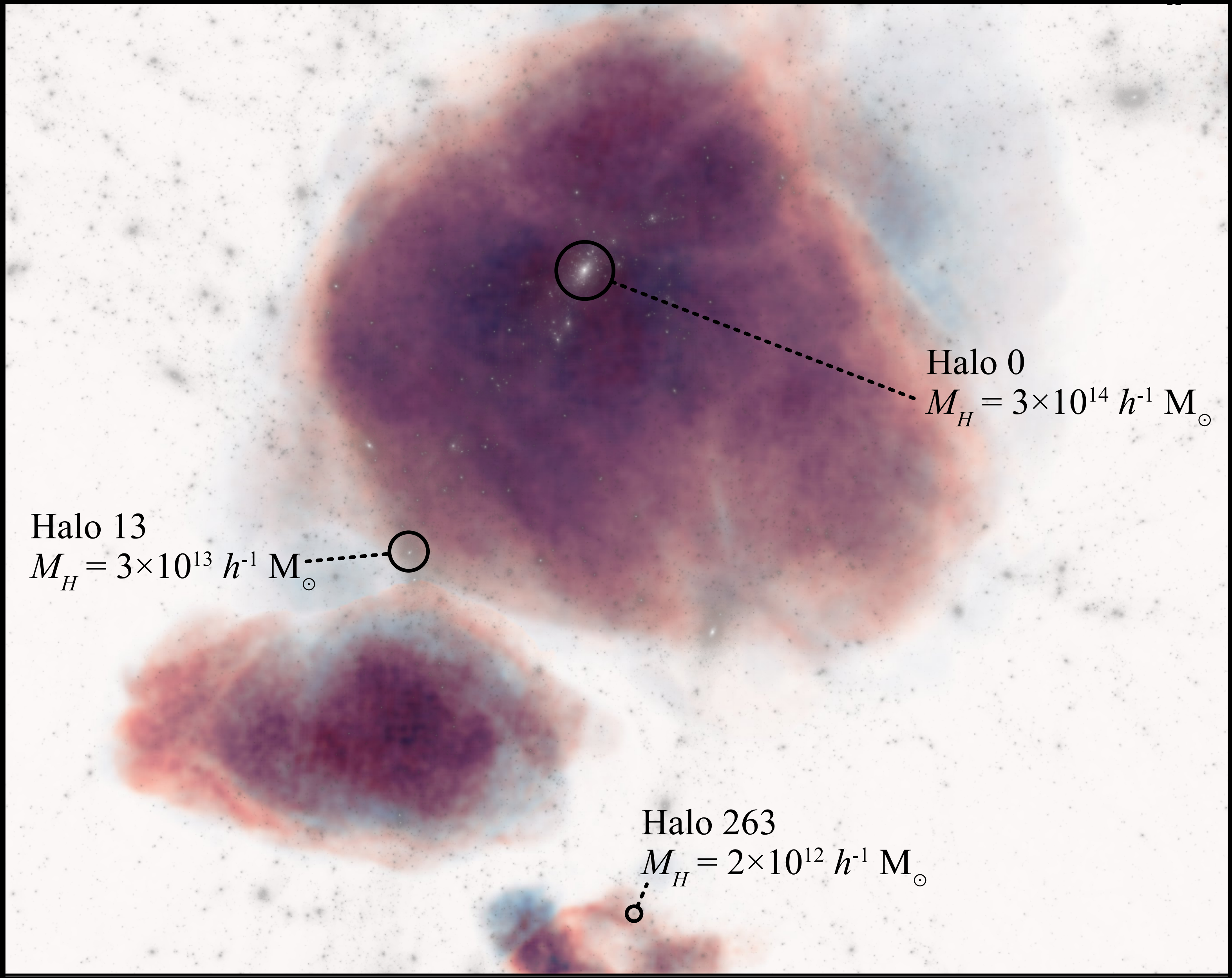
Dark matter halo →

Lagrangian region →



Where do the baryons that end up in halos come from?

Spatial distribution of gas at the initial conditions



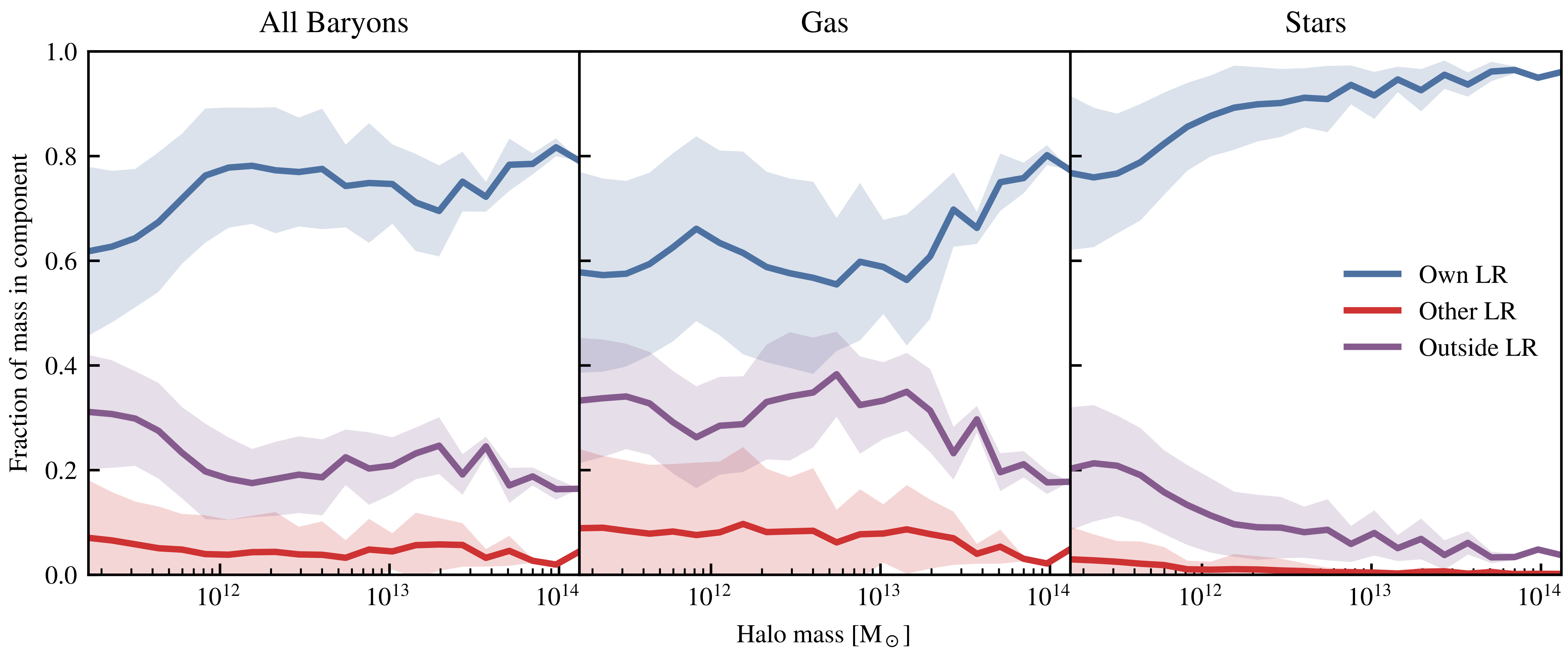
Particles in halo at $z=0$

Particles in LR at $z=99$

Where do the baryons that end up in halos come from?

→ 60% of halo gas originates from its Lagrangian region (but halos retain only 20-30% of the original LR gas)

→ Inter-Lagrangian transfer provides 10% of halo gas at z=0

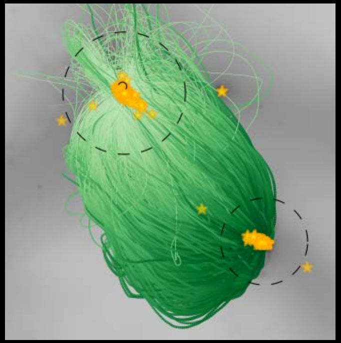


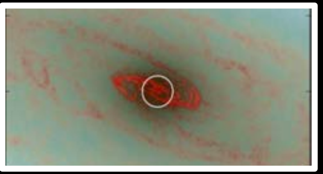
1) FIRE predicts large mass-loading in low-mass galaxies

→ Most stars form out of wind-recycled gas

→ Inter-galactic transfer of gas from satellites important for galaxy assembly and CGM composition

Anglés-Alcázar+2017b, Hafen+2019a,b, Muratov+2015,2017





2) Cosmological baryon transfer in the Simba simulations

→ Spread metric quantifies global effect of feedback and separates hierarchy

→ 40% of baryons move > 1 Mpc relative to the dark matter

→ Inter-Lagrangian transfer can provide 10% of CGM gas at z=0

Davé+2019, Borrow+2019