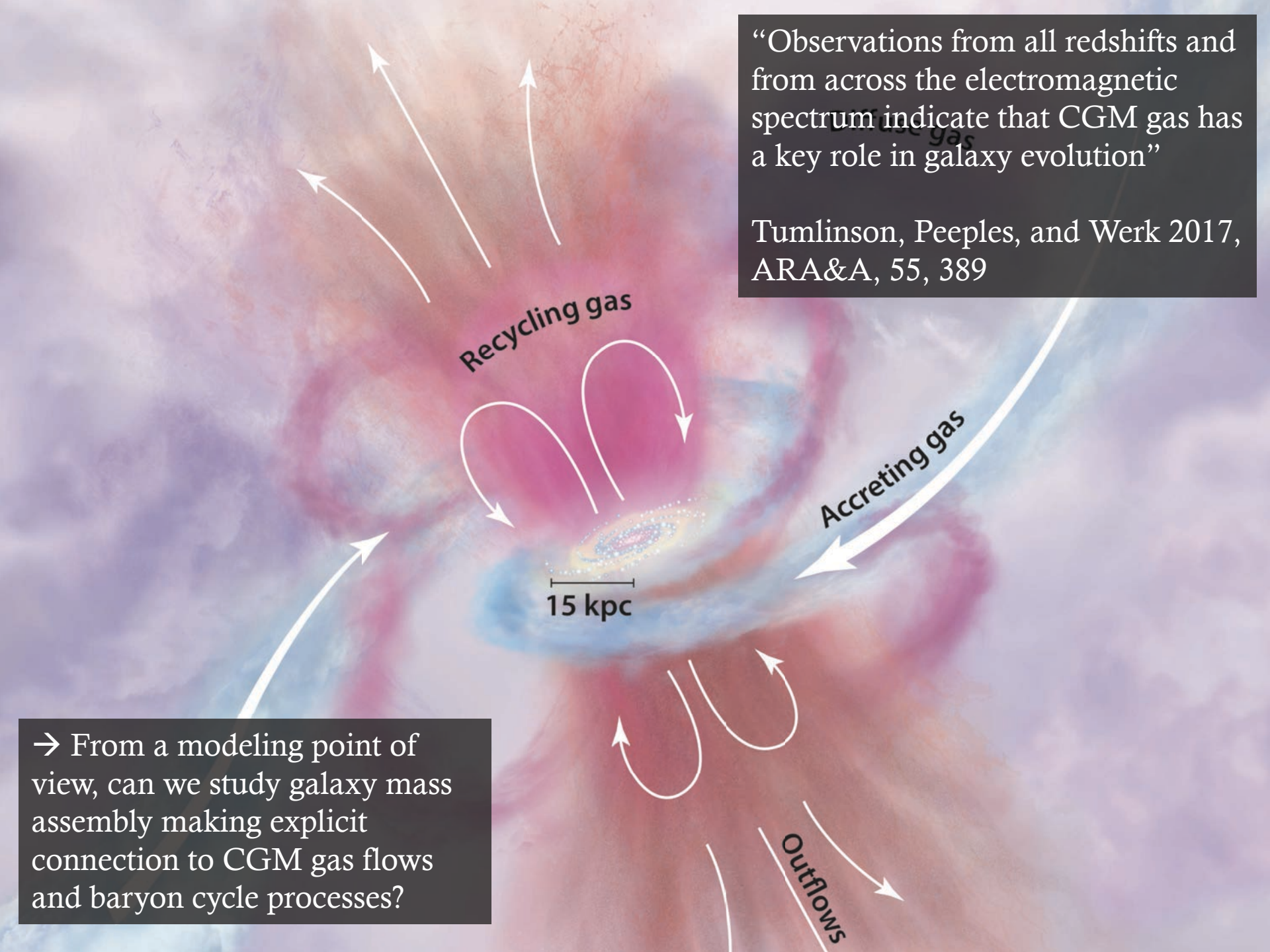
Connecting CGM Gas Flows and Galaxy Evolution

Daniel Anglés-Alcázar
Center for Computational Astrophysics
Flatiron Institute, NYC, USA

R. Davé, **C-A Faucher-Giguère**, R. Feldmann, **Z. Hafen**, P. Hopkins,
D. Keres, N. Murray, E. Quataert, P. Torrey, A. Wetzel

Northwestern-CIERA CGM Workshop 2018



"Observations from all redshifts and from across the electromagnetic spectrum indicate that CGM gas has a key role in galaxy evolution"

Tumlinson, Peeples, and Werk 2017, ARA&A, 55, 389

→ From a modeling point of view, can we study galaxy mass assembly making explicit connection to CGM gas flows and baryon cycle processes?

Galaxy assembly in cosmological simulations

→ **In-situ star formation:**

stars formed from ISM gas inside of central galaxy

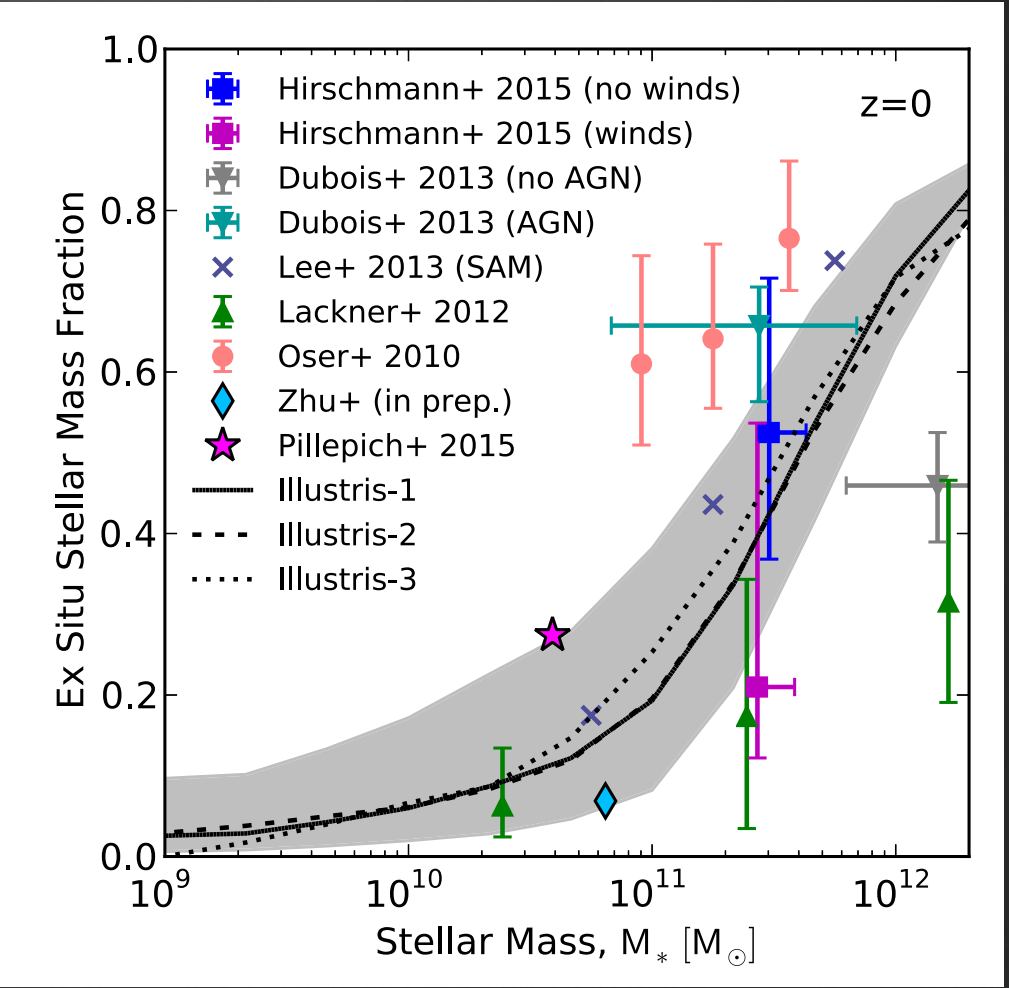
VS

→ **Ex-situ stars:**

stars formed in other galaxies that later merge onto the central

Tissera+2012, Behroozi+2013, Dubois+2013, Moster+2013, Naab+2014, Nelson+2015, Pillepich+2015, Choi+2017, Qu+2017, Fitts+2018 …

Rodriguez-Gomez et al. 2016



Galaxy assembly in cosmological simulations

→ **In-situ star formation:**

(smooth accretion)

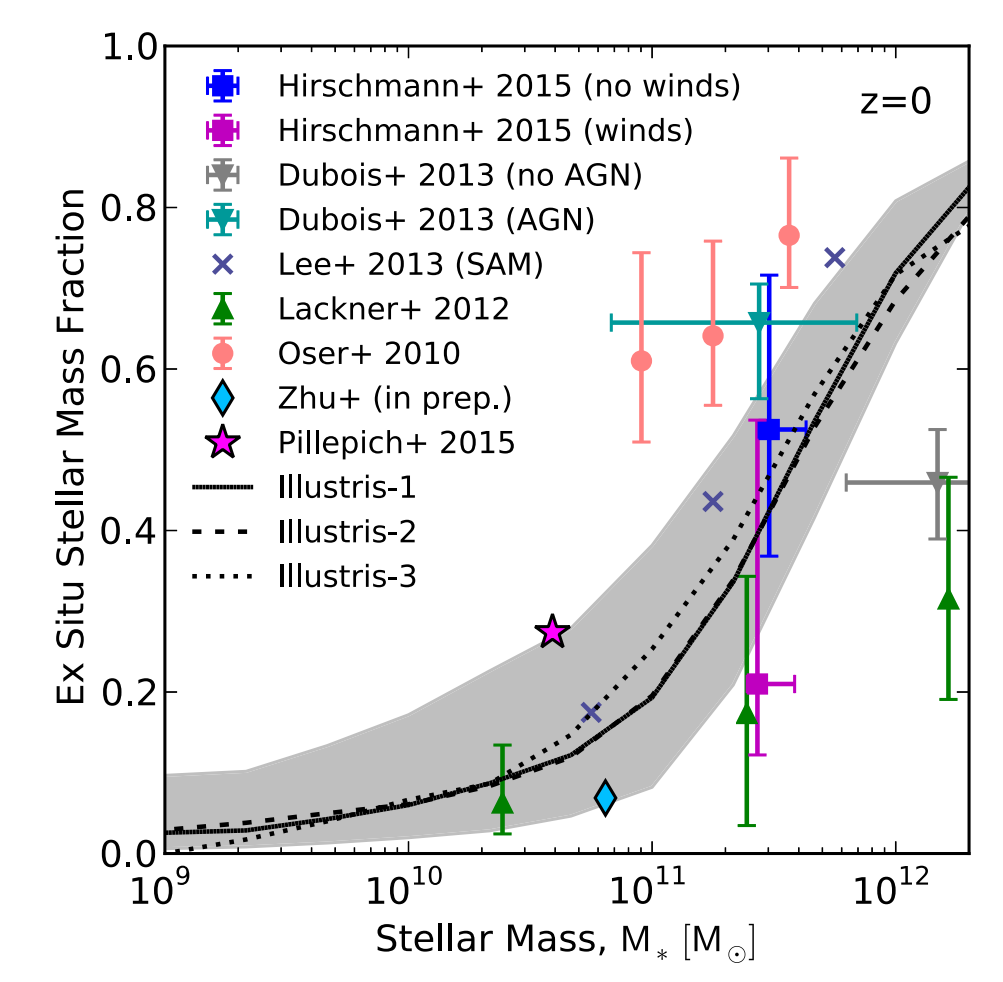
VS

→ **Ex-situ stars:**

(mergers)

Tissera+2012, Behroozi+2013, Dubois+2013, Moster+2013, Naab+2014, Nelson+2015, Pillepich+2015, Choi+2017, Qu+2017, Fitts+2018 …

Rodriguez-Gomez et al. 2016



Galaxy assembly in cosmological simulations

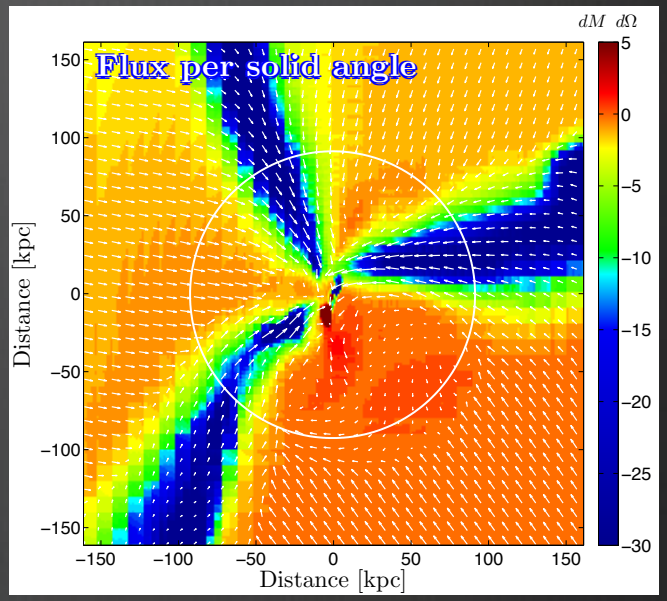
→ **Cold mode:**

accretion of gas (thru filaments) that never shock heats to virial temperature

VS

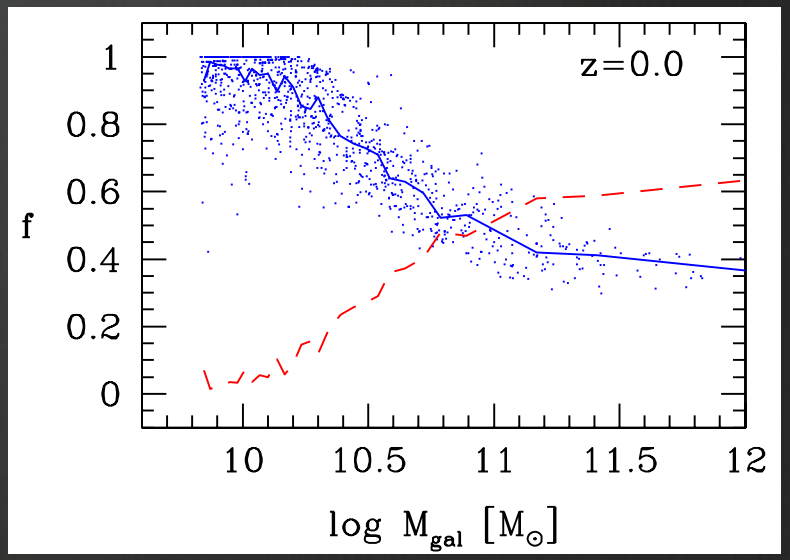
→ **Hot mode:**

gas shock heated to virial temperature before cooling and condensing to form stars



Dekel+2009

Keres et al. 2005



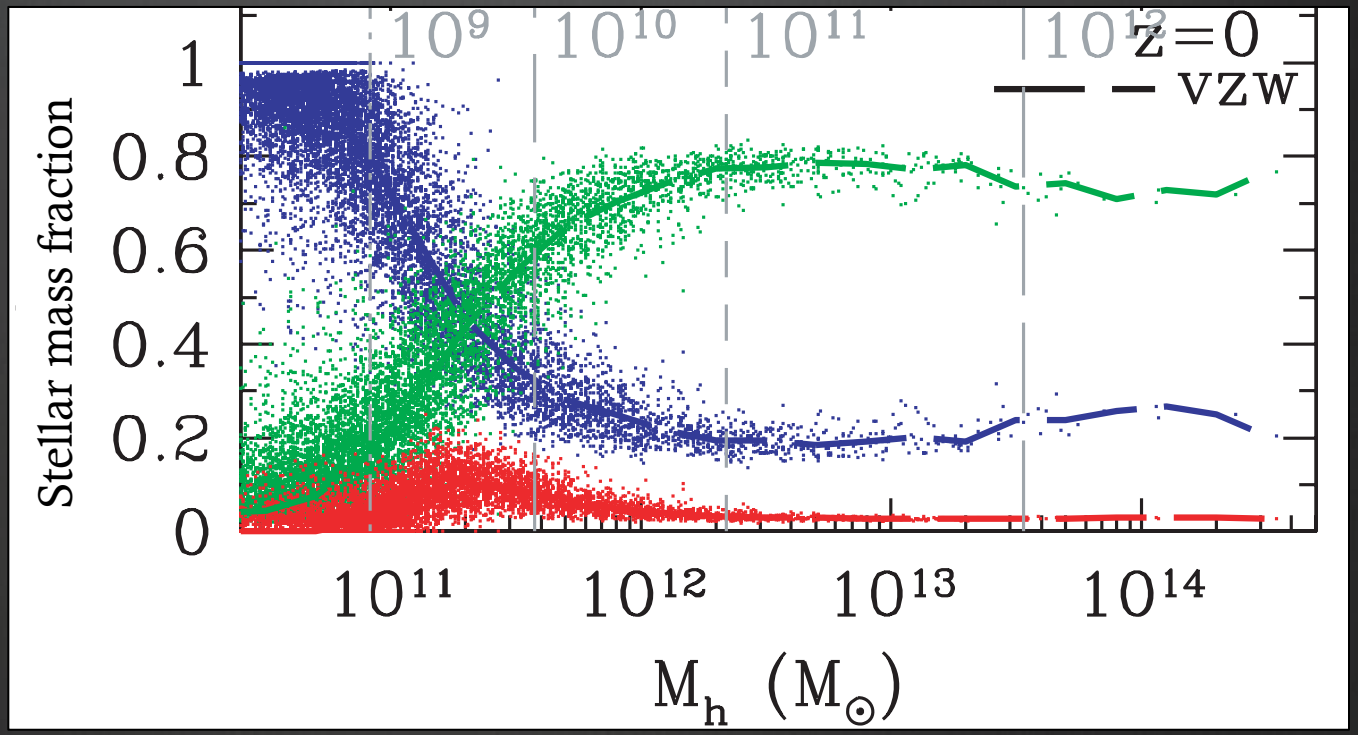
Birnboim & Dekel 2003, Keres+2005,2009, Brooks+2009, Dekel+2009, Oppenheimer+2010, Faucher-Giguere+2011, van de Voort+2011, Nelson+2013,…

Galaxy assembly in cosmological simulations

→ **Wind mode:**

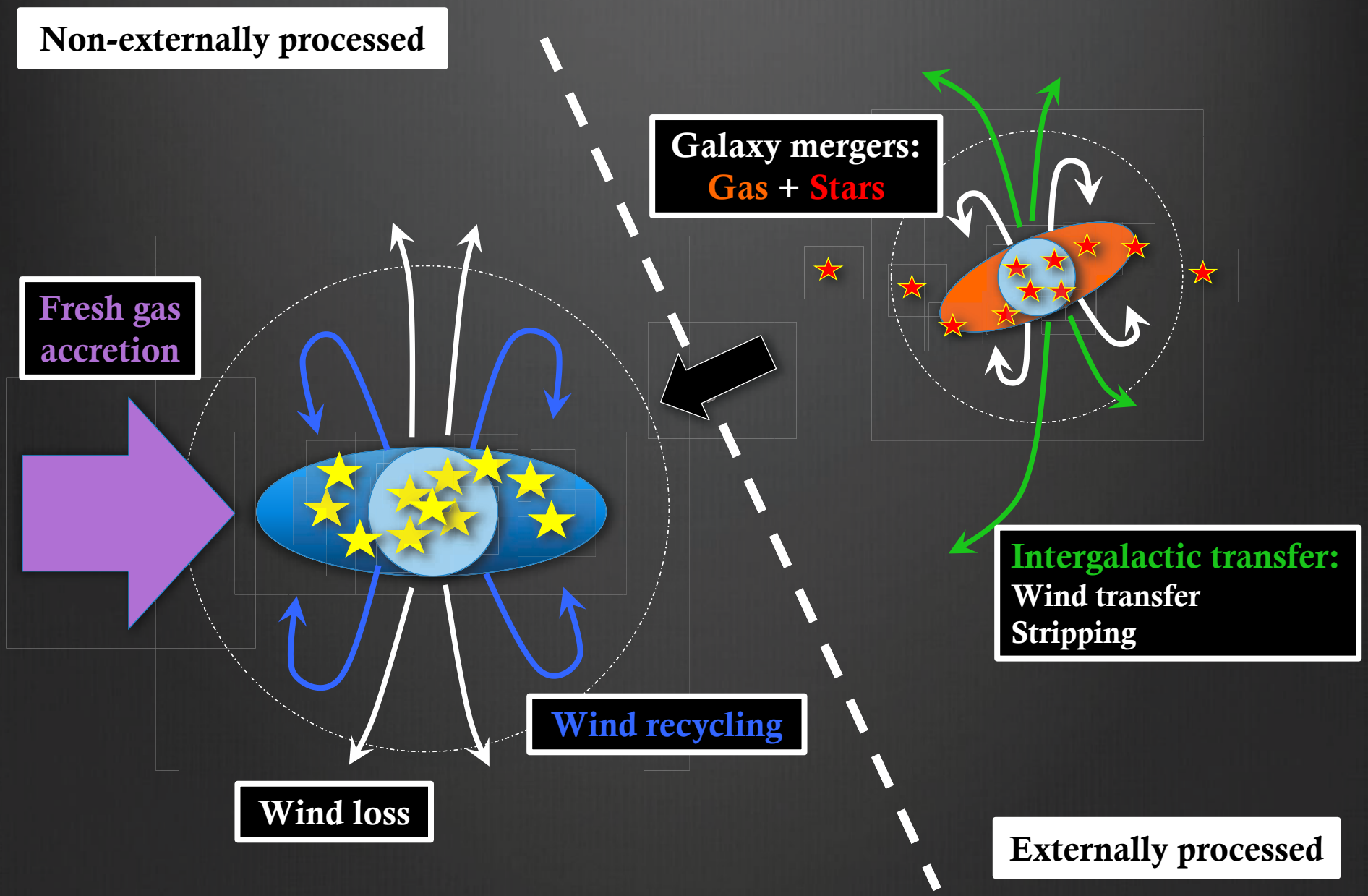
gas previously ejected in galactic winds
and re-accreted back to form stars.

Oppenheimer+2010



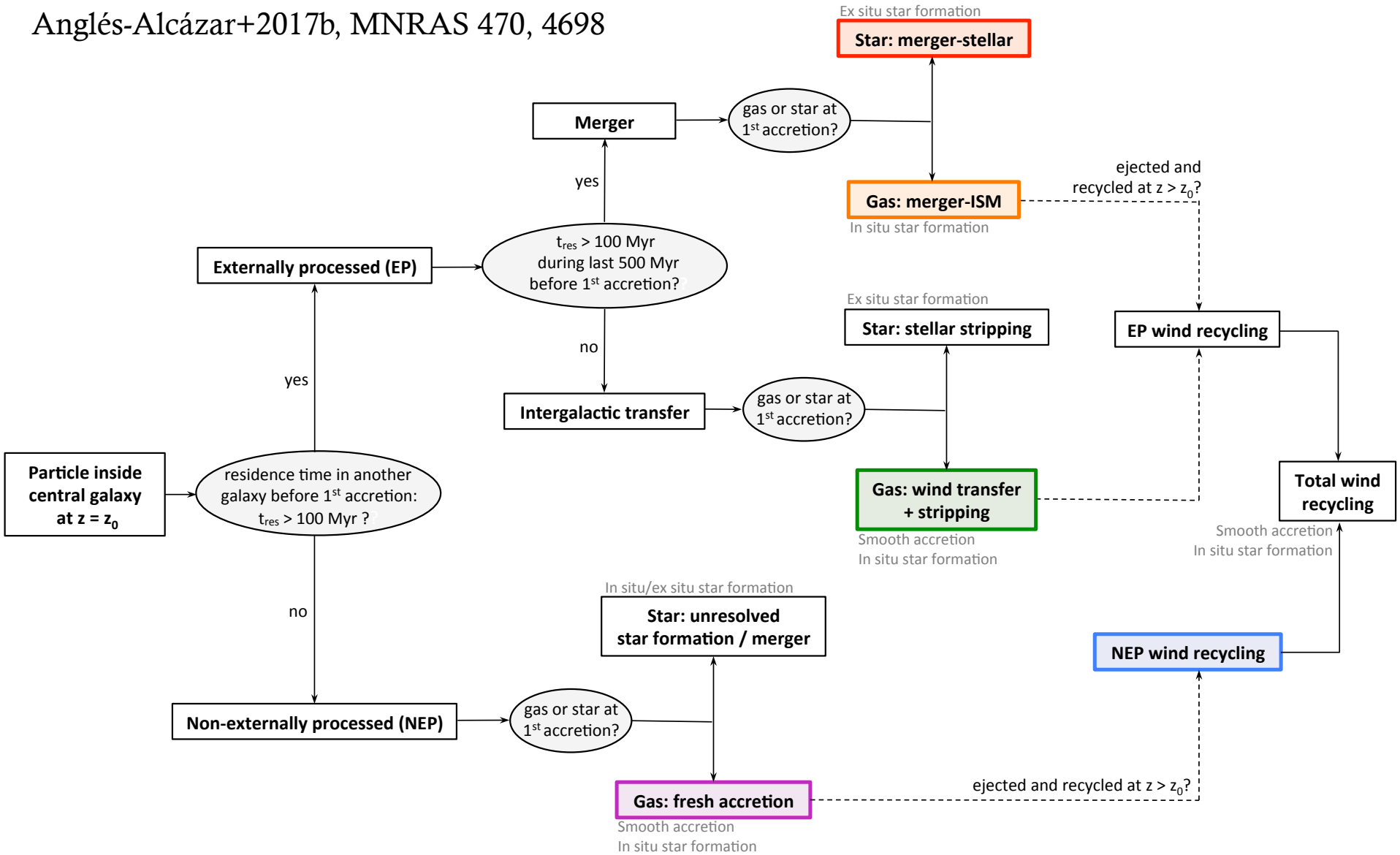
Oppenheimer+2010, Ubler+2014, Nelson et al. 2015, Christensen+2016, DeFelippis+2017, Brennan+2018, …

Connecting baryon cycling and mass assembly



Connecting baryon cycling and mass assembly

Anglés-Alcázar+2017b, MNRAS 470, 4698

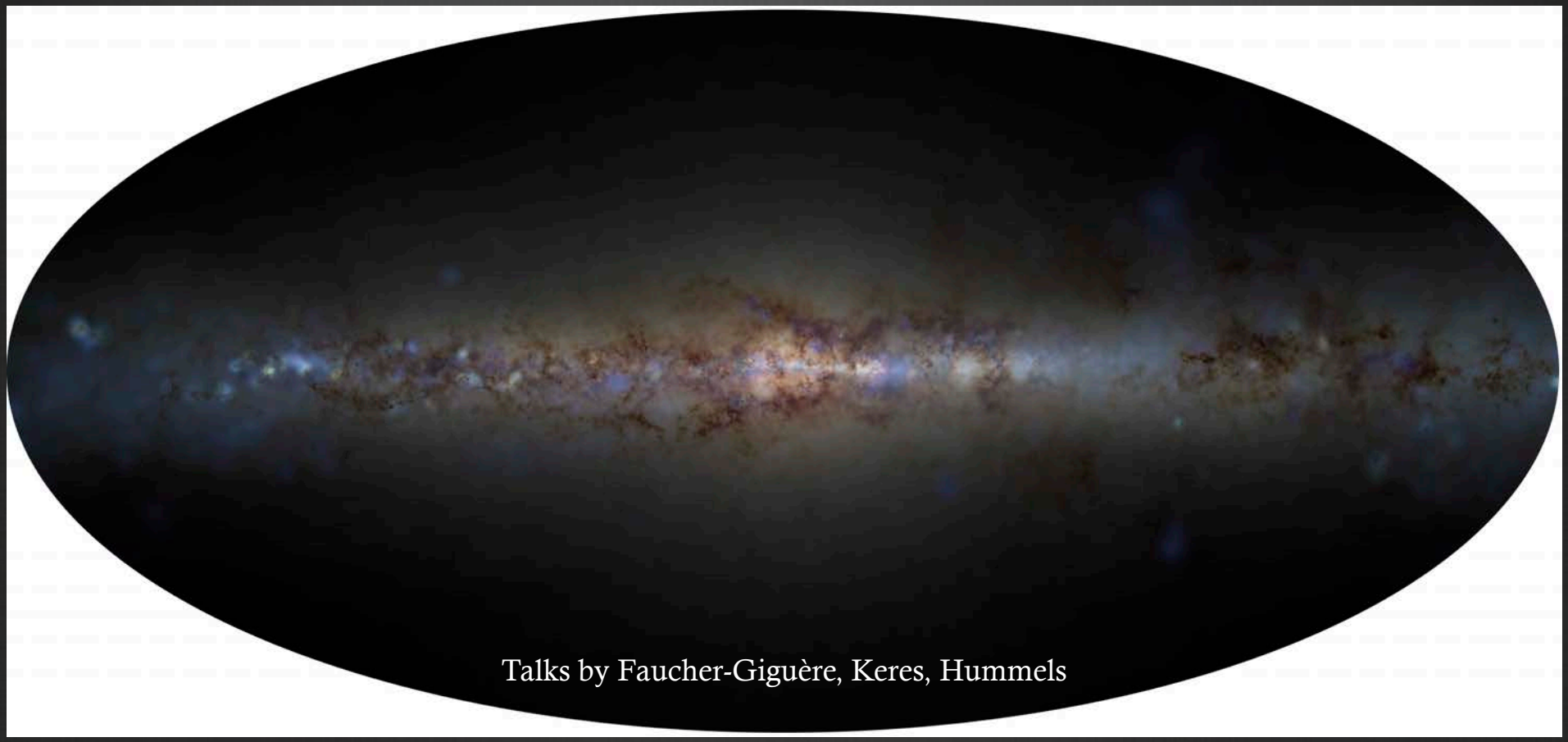


FIRE "zoom-in" simulations

→ **Mass, momentum, energy, and metal feedback from supernovae, stellar winds and radiation implemented at the scale of star forming regions**

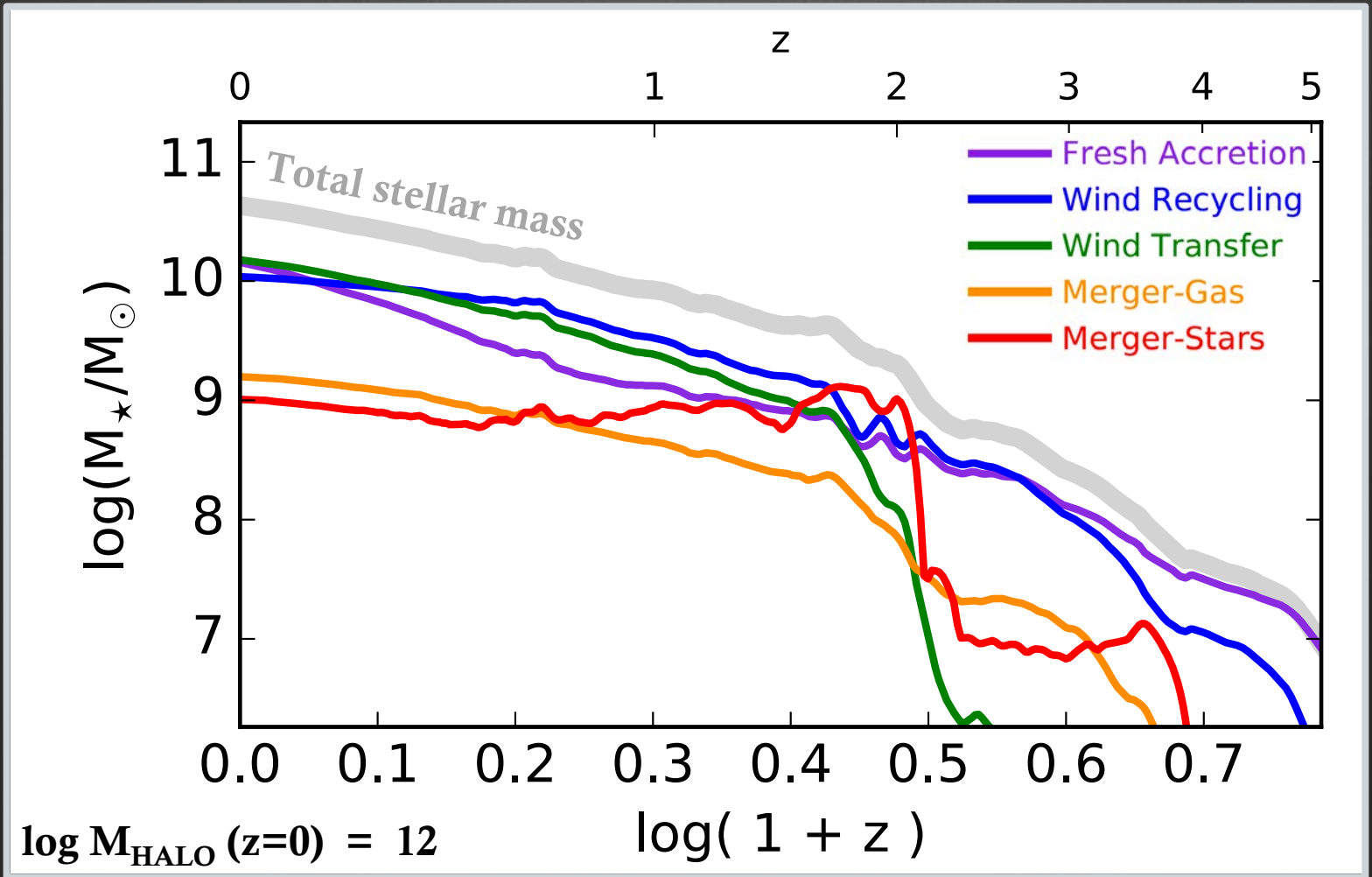
Hopkins et al. 2014, 2018

Mock galactic projection seen at 10 kpc from the center of "Latte" (Wetzel+16)



Hopkins et al. 2018 (arXiv:1702.06148)

Connecting baryon cycling and mass assembly



→ **Fresh gas** accretion dominates first but **wind recycling** takes over

→ **Stars** + **gas** from major merger at z=2, but look at **intergalactic transfer!**

Anglés-Alcázar+2017b, MNRAS 470, 4698

Fresh Accretion | NEP Wind Recycling | Intergalactic Transfer | Merger-ISM | Merger-Stellar

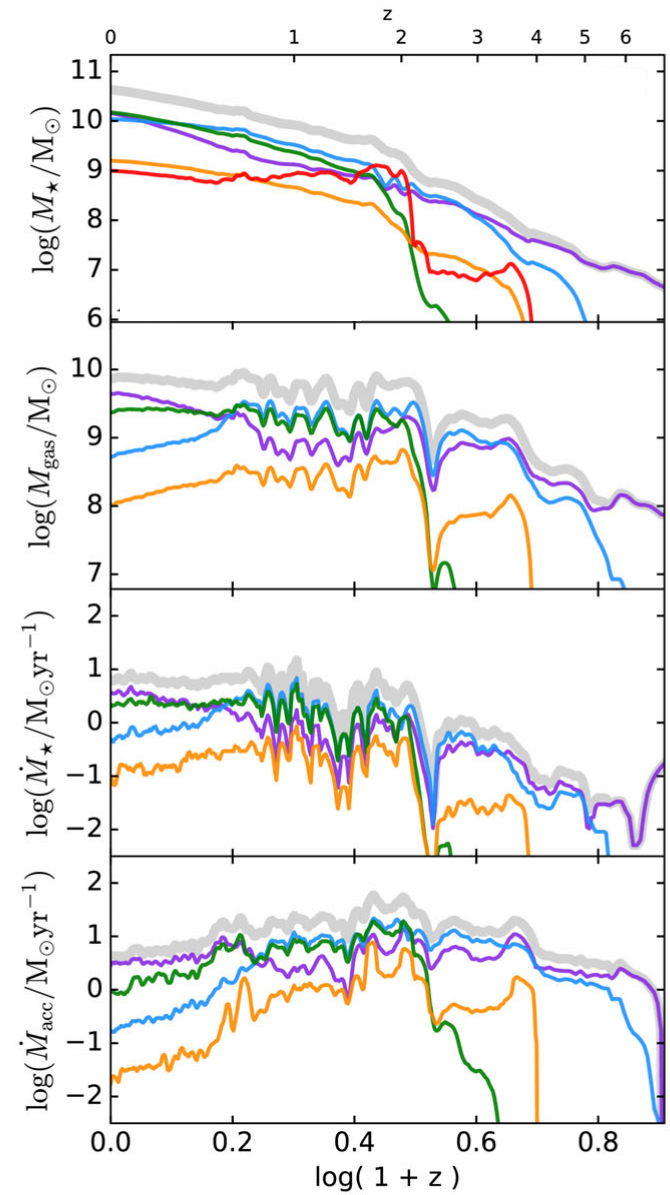
$\log M_{HALO}(z=0) = 12$

Stellar mass →

ISM gas mass →

SFR →

Accretion rate onto the ISM →



Fresh Accretion | NEP Wind Recycling | Intergalactic Transfer | Merger-ISM | Merger-Stellar

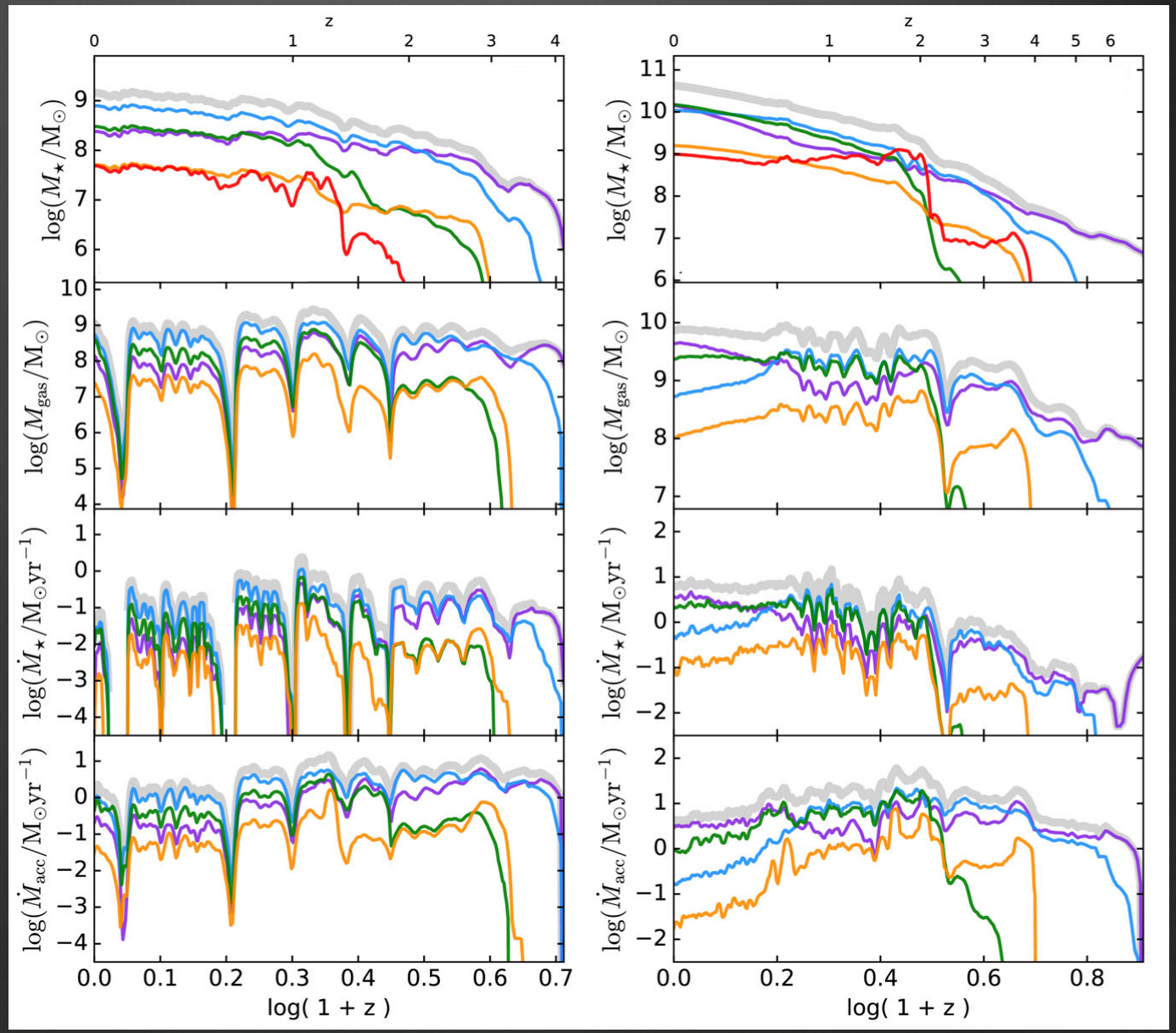
log M_{HALO} (z=0) = 11 **log M_{HALO} (z=0) = 12**

Stellar mass →

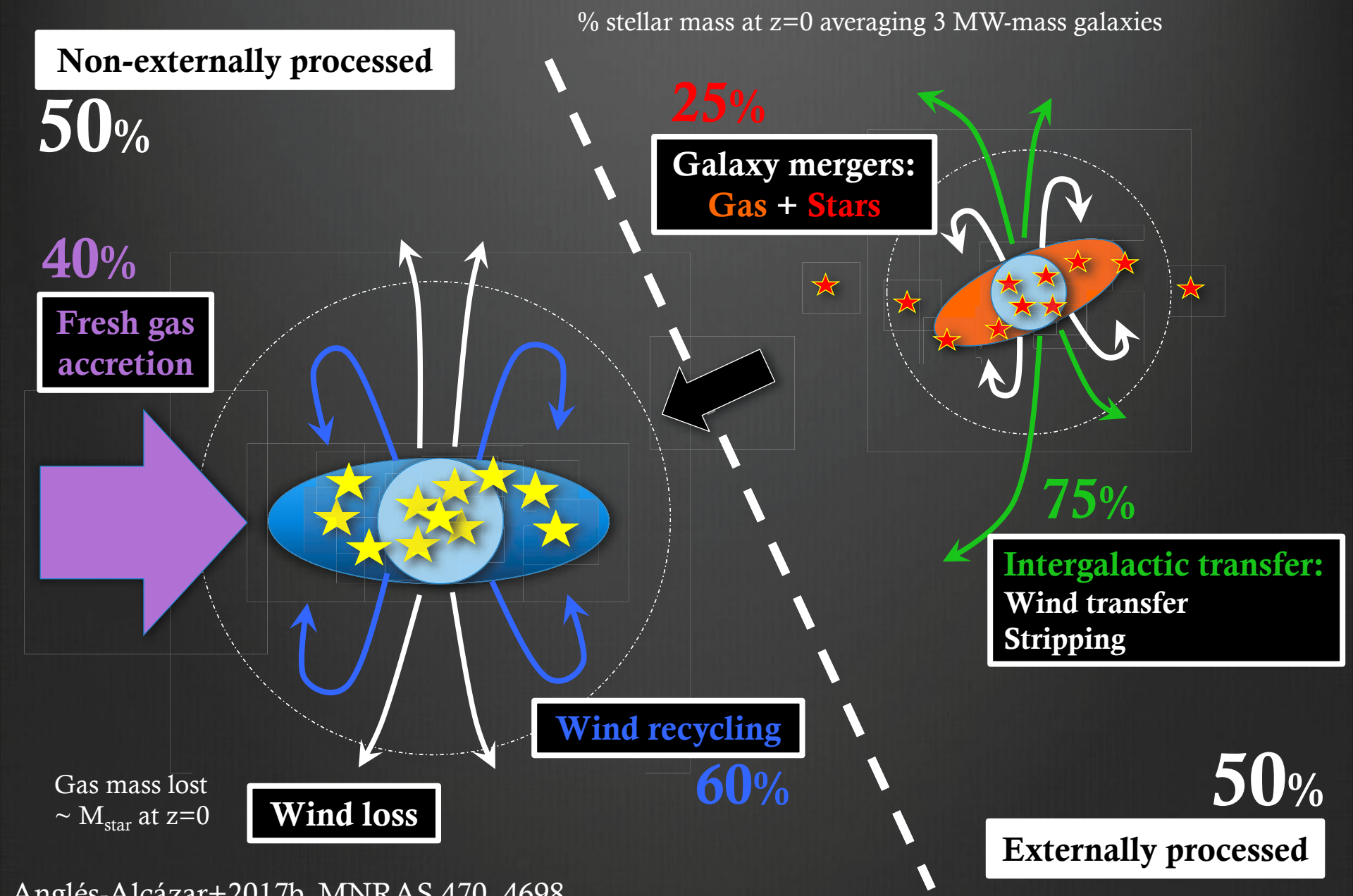
ISM gas mass →

SFR →

Accretion rate onto the ISM →

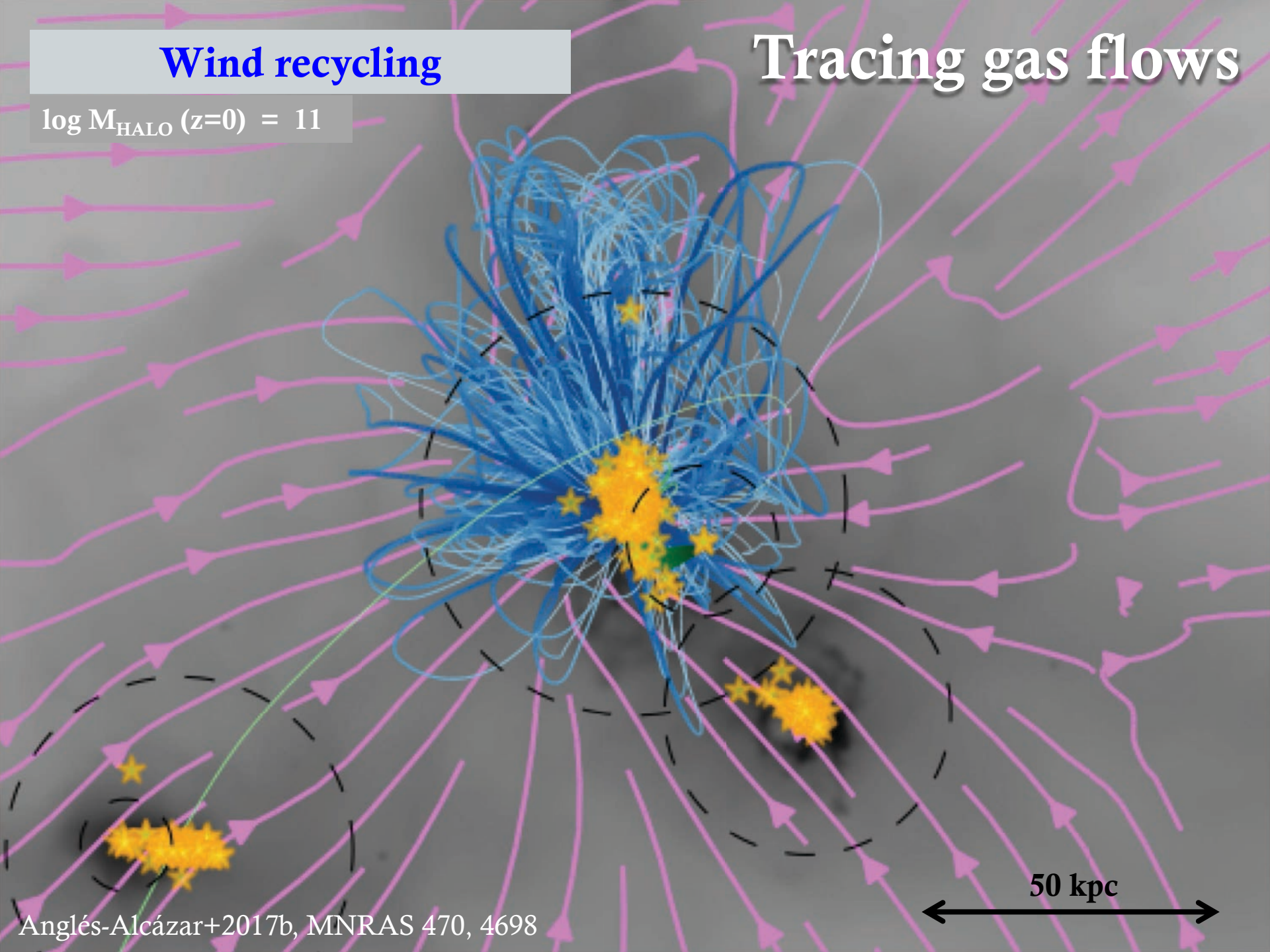


Connecting baryon cycling and mass assembly



Anglés-Alcázar+2017b, MNRAS 470, 4698

Tracing gas flows



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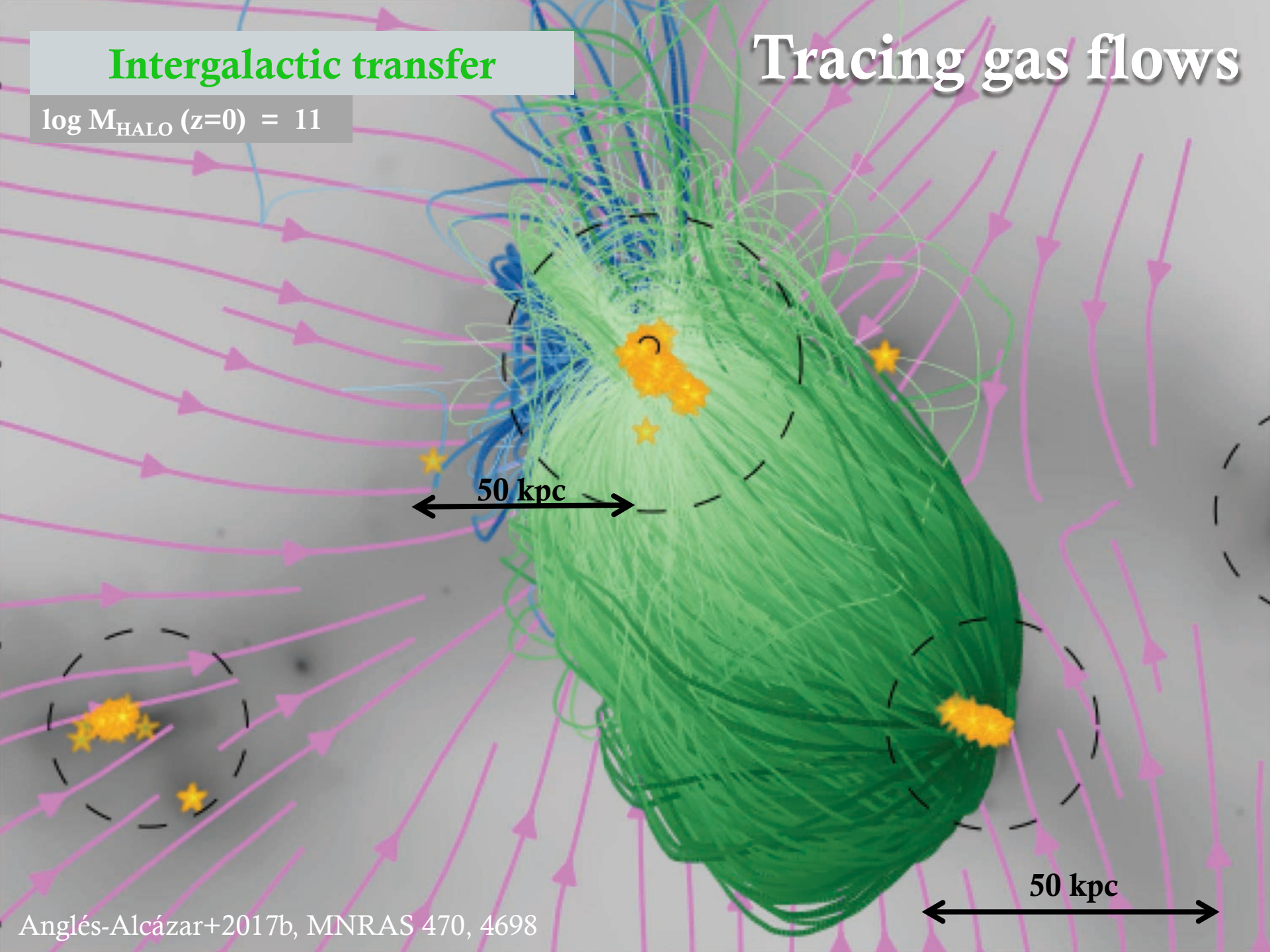
Tracing gas flows



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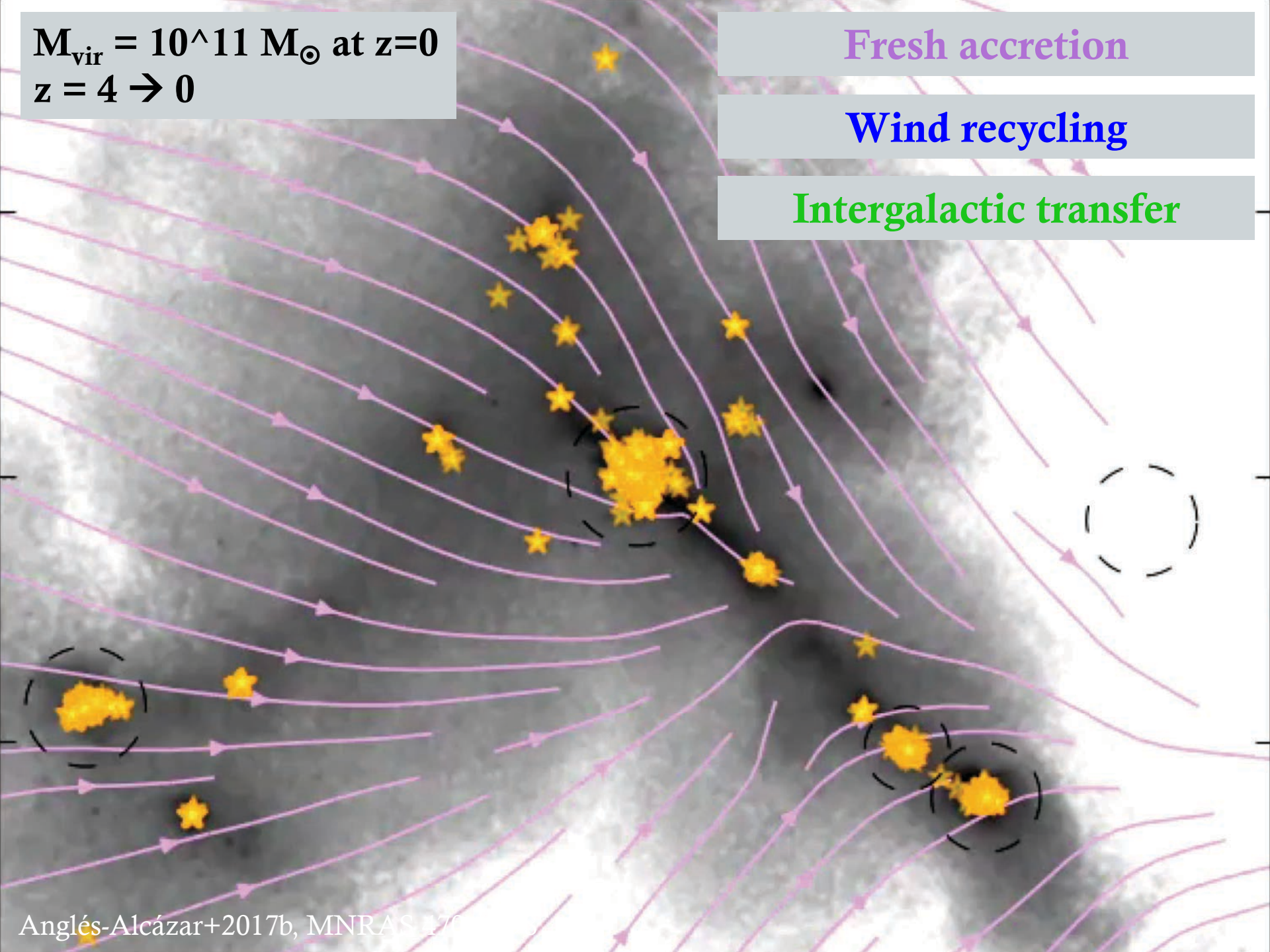
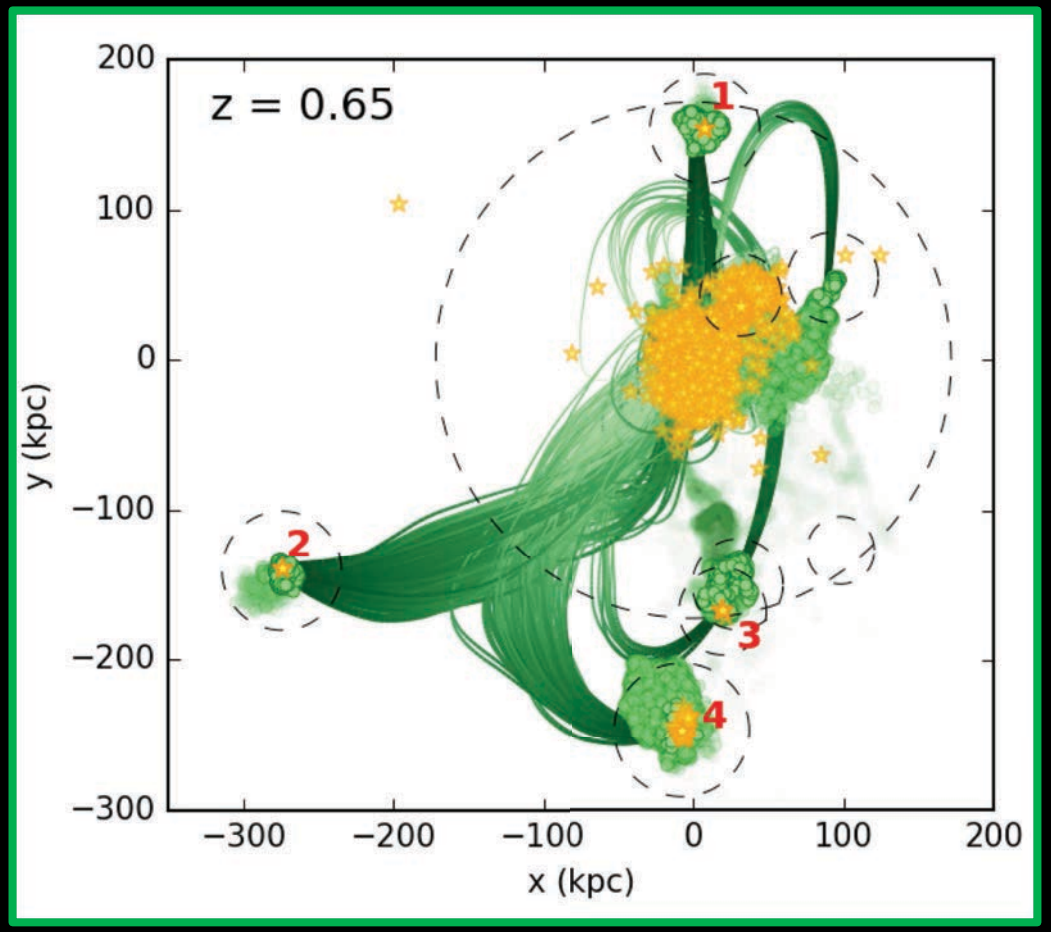


Anglés-Alcázar+2017b, MNRAS

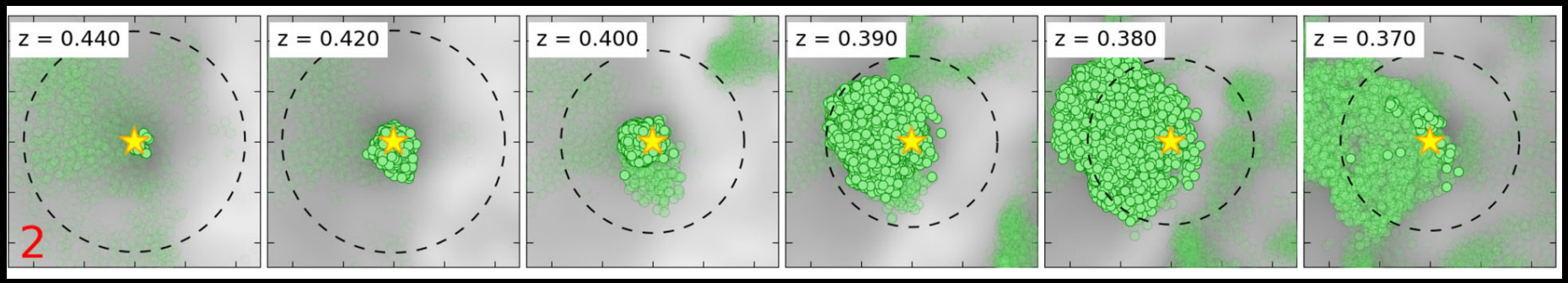
Intergalactic Transfer



From small satellites onto a Milky-Way mass galaxy

→ Quasi-spherical outflows unbind ISM gas from satellites

→ Satellite winds/CGM easily stripped by ram pressure



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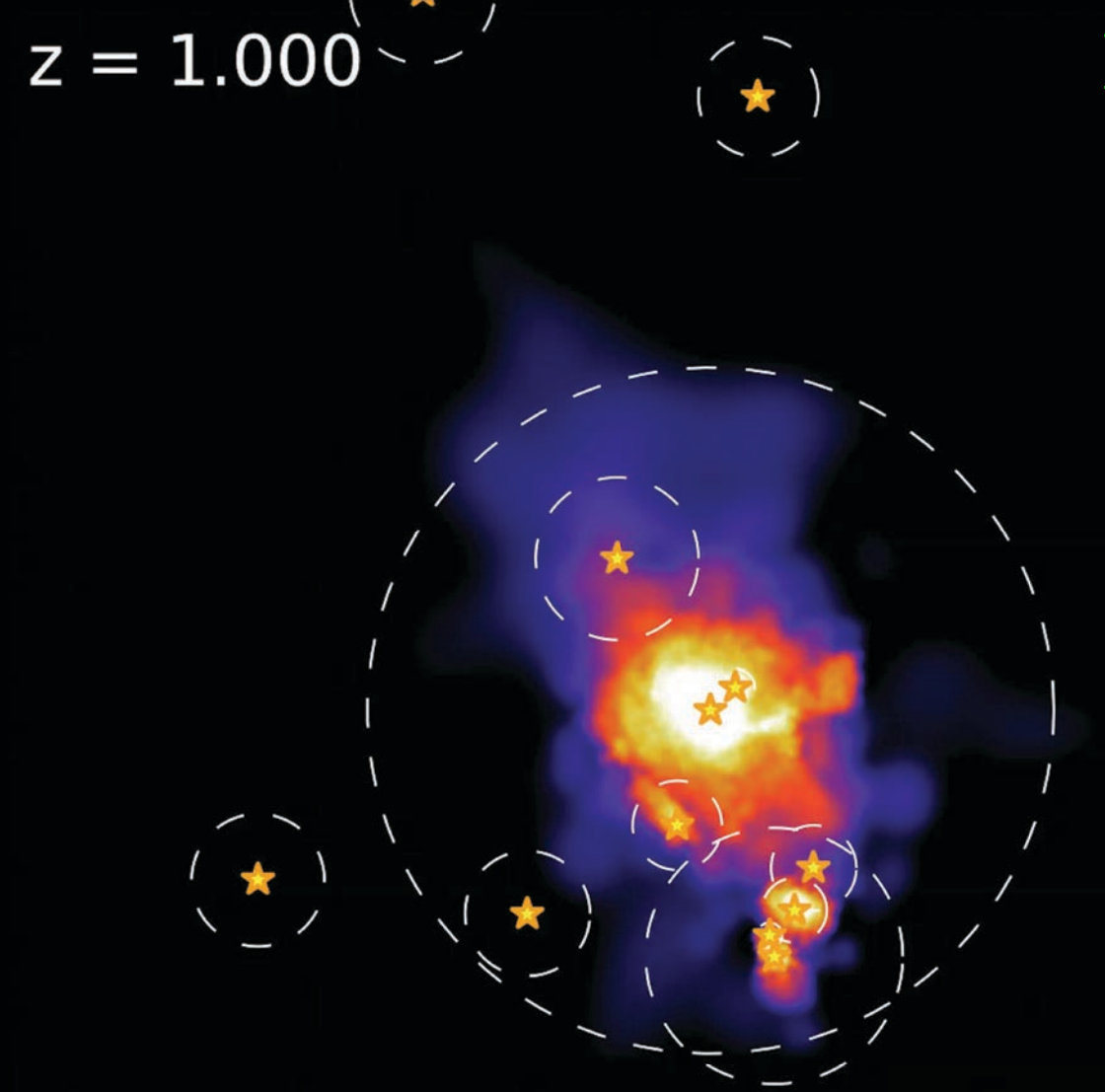
Intergalactic Transfer



From small satellites onto a Milky-Way mass galaxy

Orbiting satellites experience bursts of star formation driving quasi-spherical outflows that accrete onto the central galaxy

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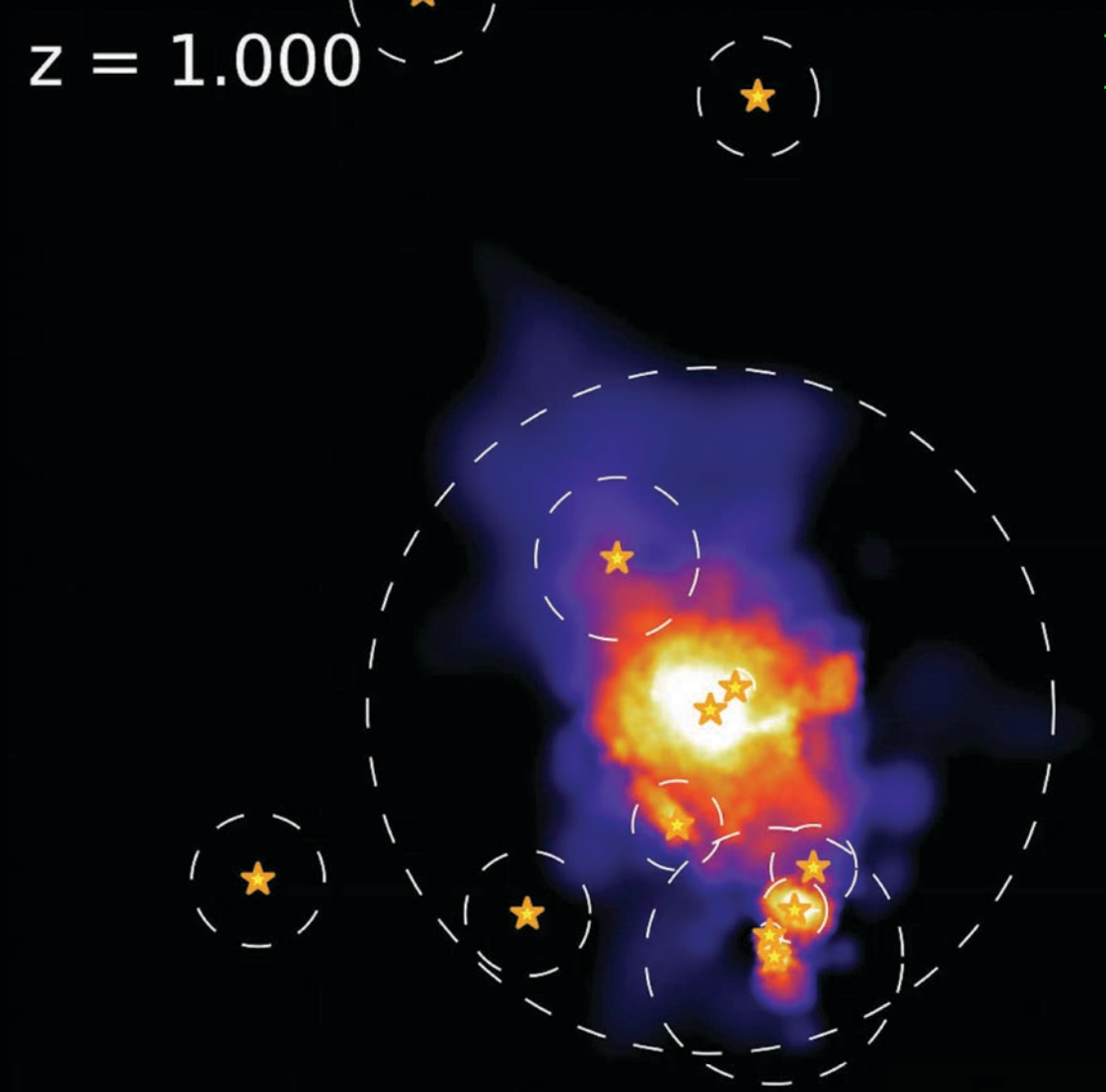
Intergalactic Transfer



→ Connections with MW halo and satellites?
Talks by Putman, Besla, Fox, Barger

→ LMC's mass loading ~20!
(Barger+2016, Lehner+2007)

→ Role of winds removing gas from satellites?

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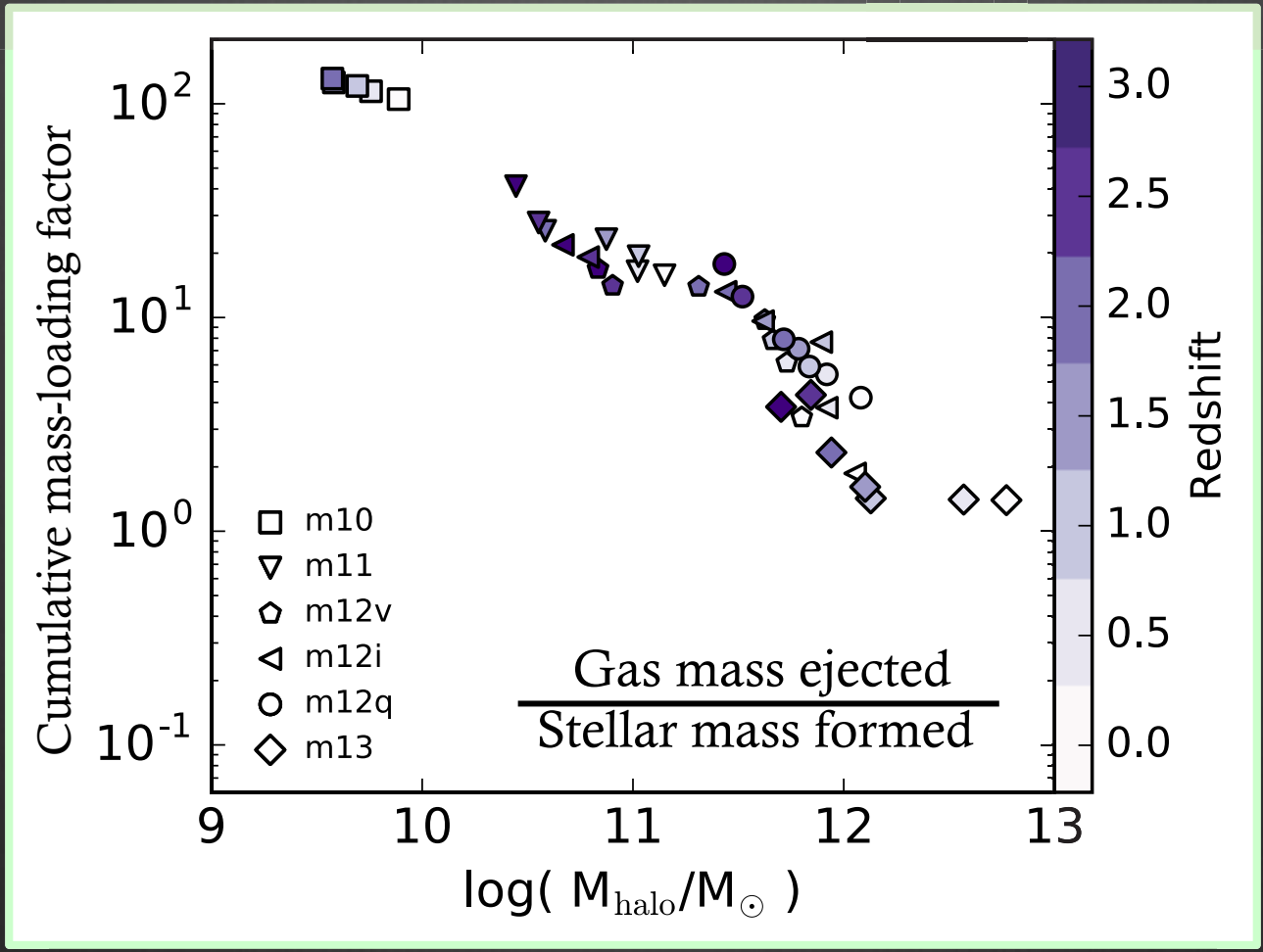
Wind properties: mass-loading



→ **Mass-loading factor larger for low mass galaxies** **(Muratov+15, Christensen+2016)**

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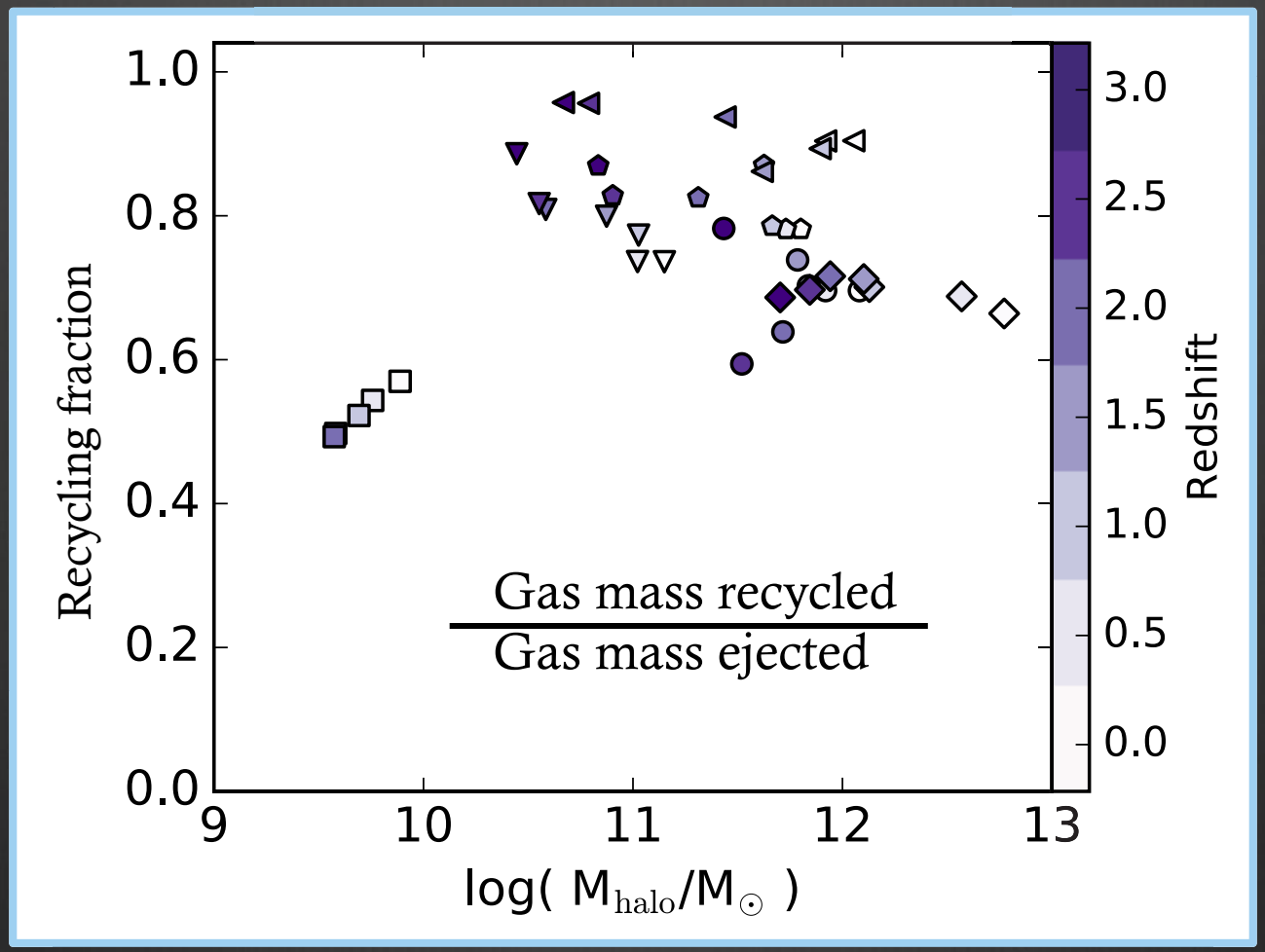
Wind recycling



→ Mass-loading factor larger for low mass galaxies

→ All galaxies recycle 50-95% of the ejected mass!

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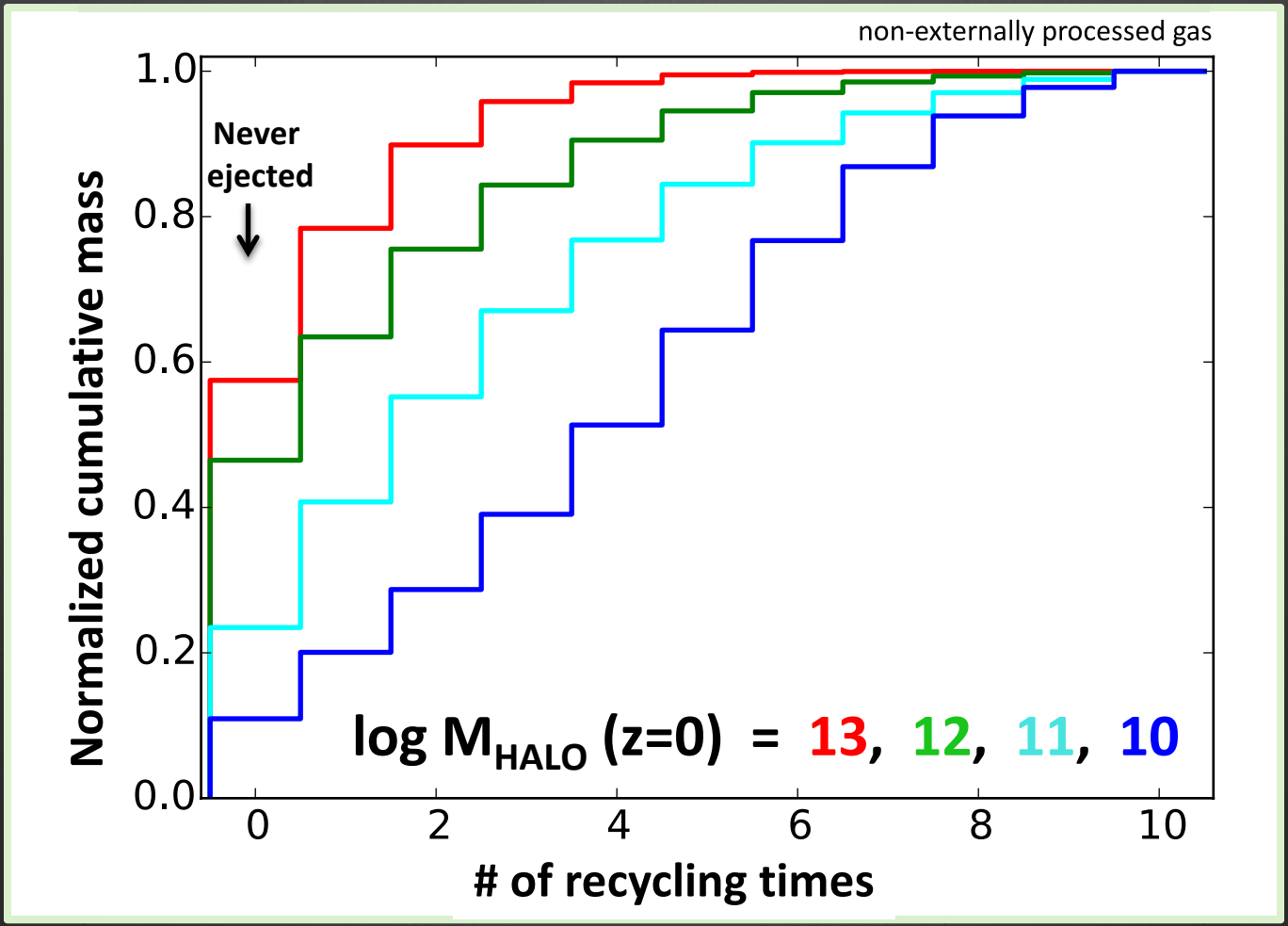
Recurrent wind recycling



→ Gas cycles thru galaxies more often in lower mass halos prior to forming stars

→ 50% of mass recycled more than [1, 1, 3, 4] times in log M_{HALO} = [13, 12, 11, 10]

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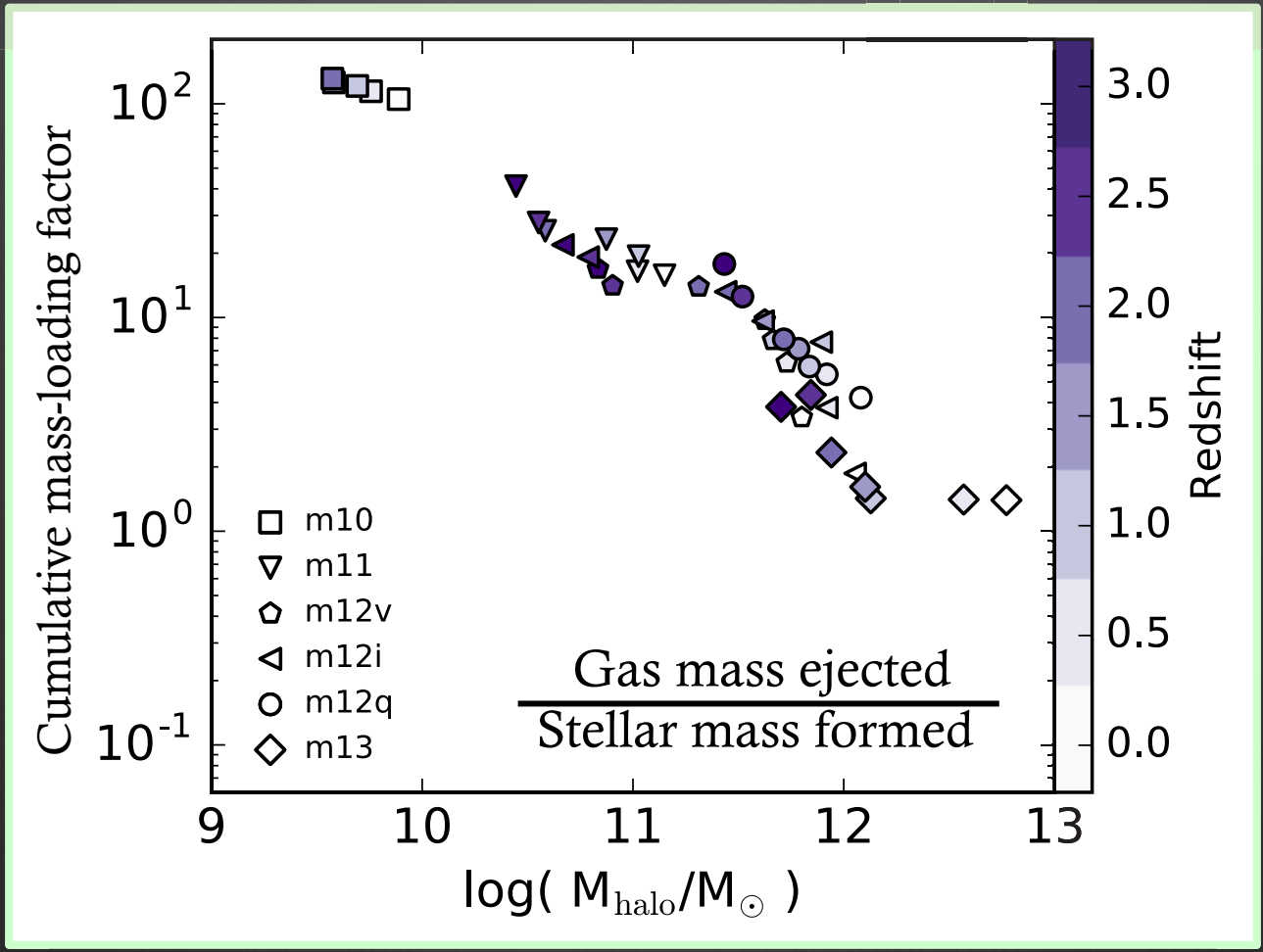
Wind properties: mass-loading



→ **Mass-loading factor larger for low mass galaxies** **(Muratov+15, Christensen+2016)**

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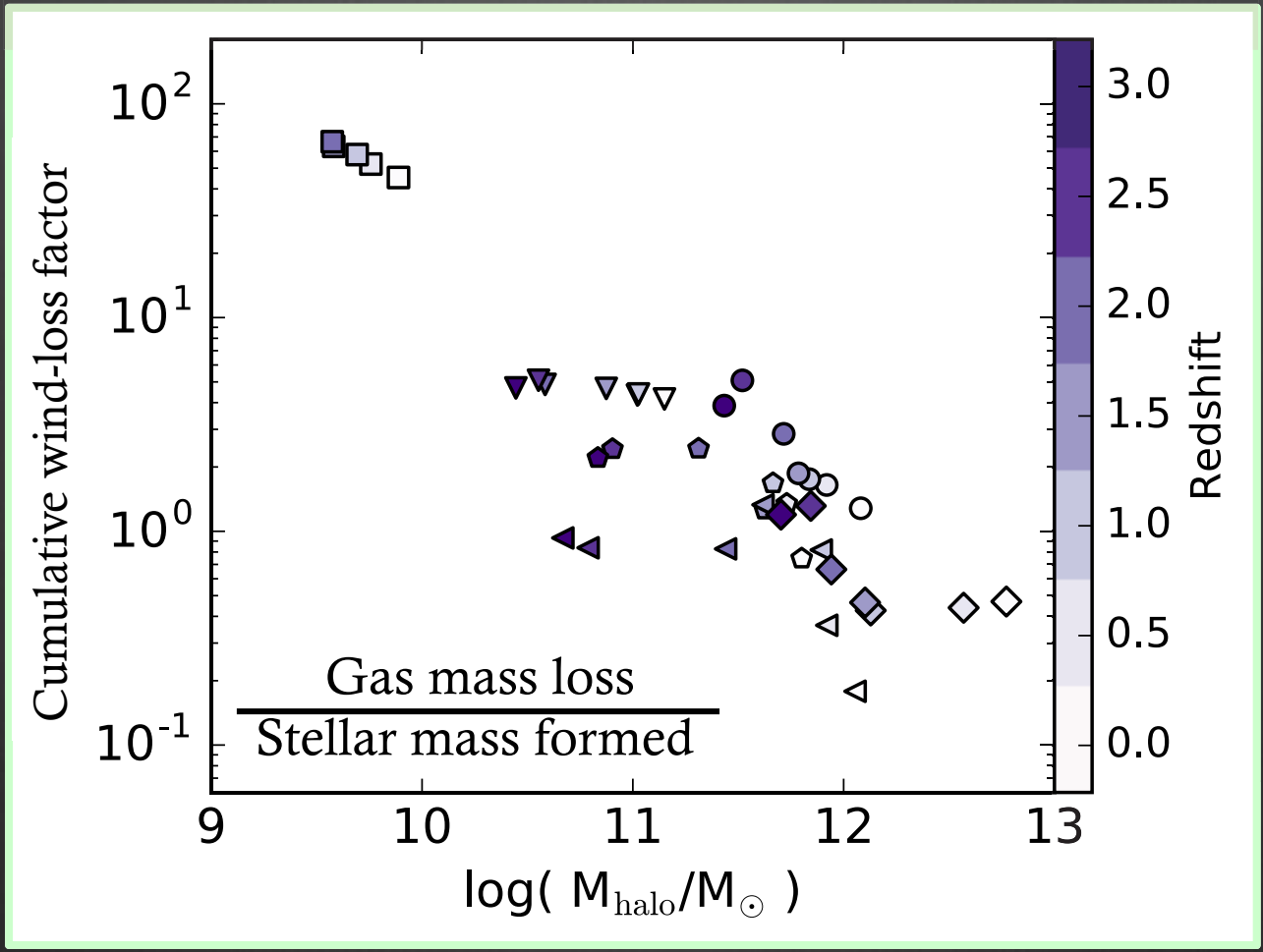
Wind properties: mass loss



→ **Lower mass galaxies loose more mass in winds per unit stellar mass formed**

→ **75% of the gas lost is deposited in the IGM at z=0 and 25% remains in the CGM**

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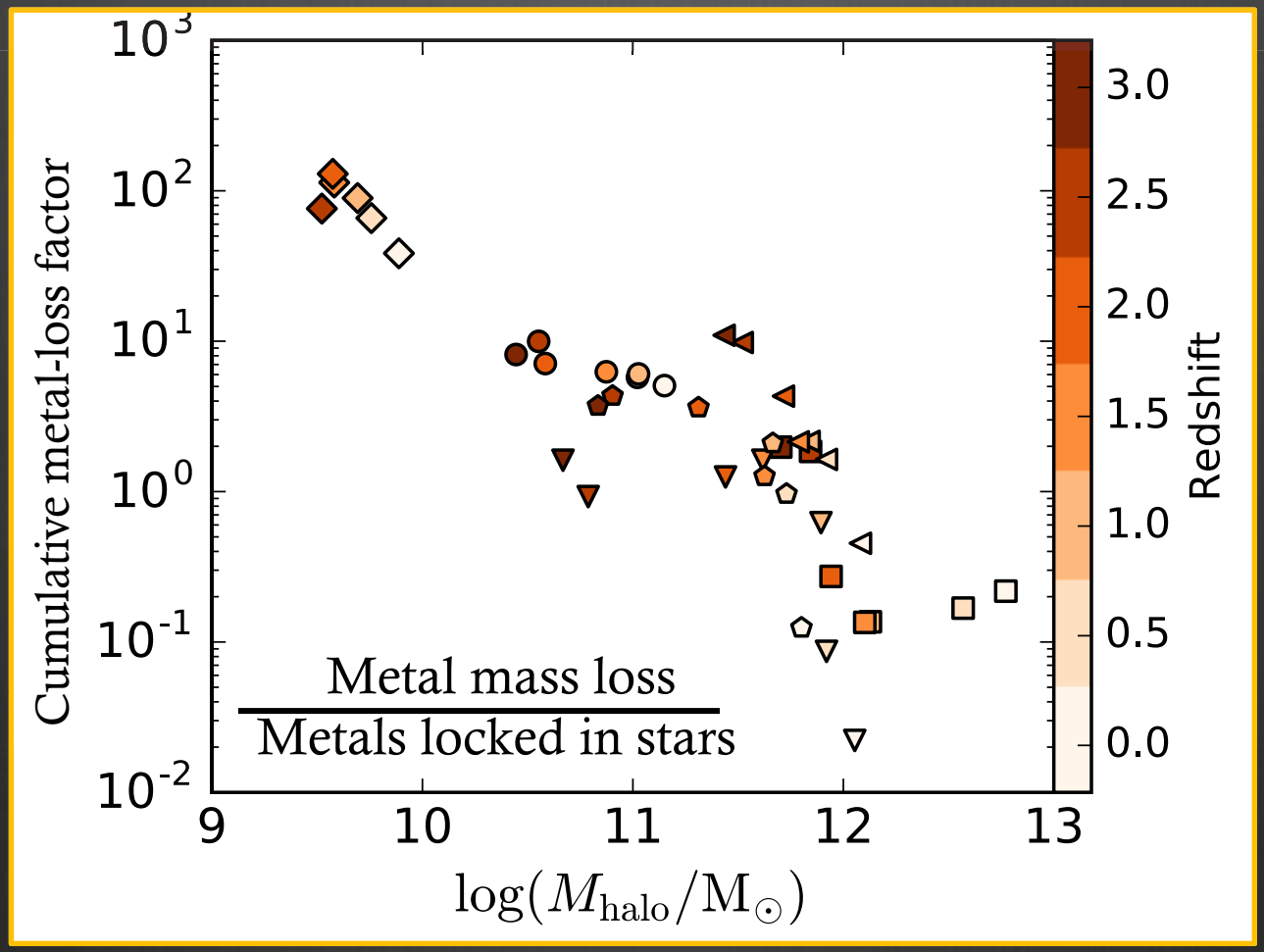
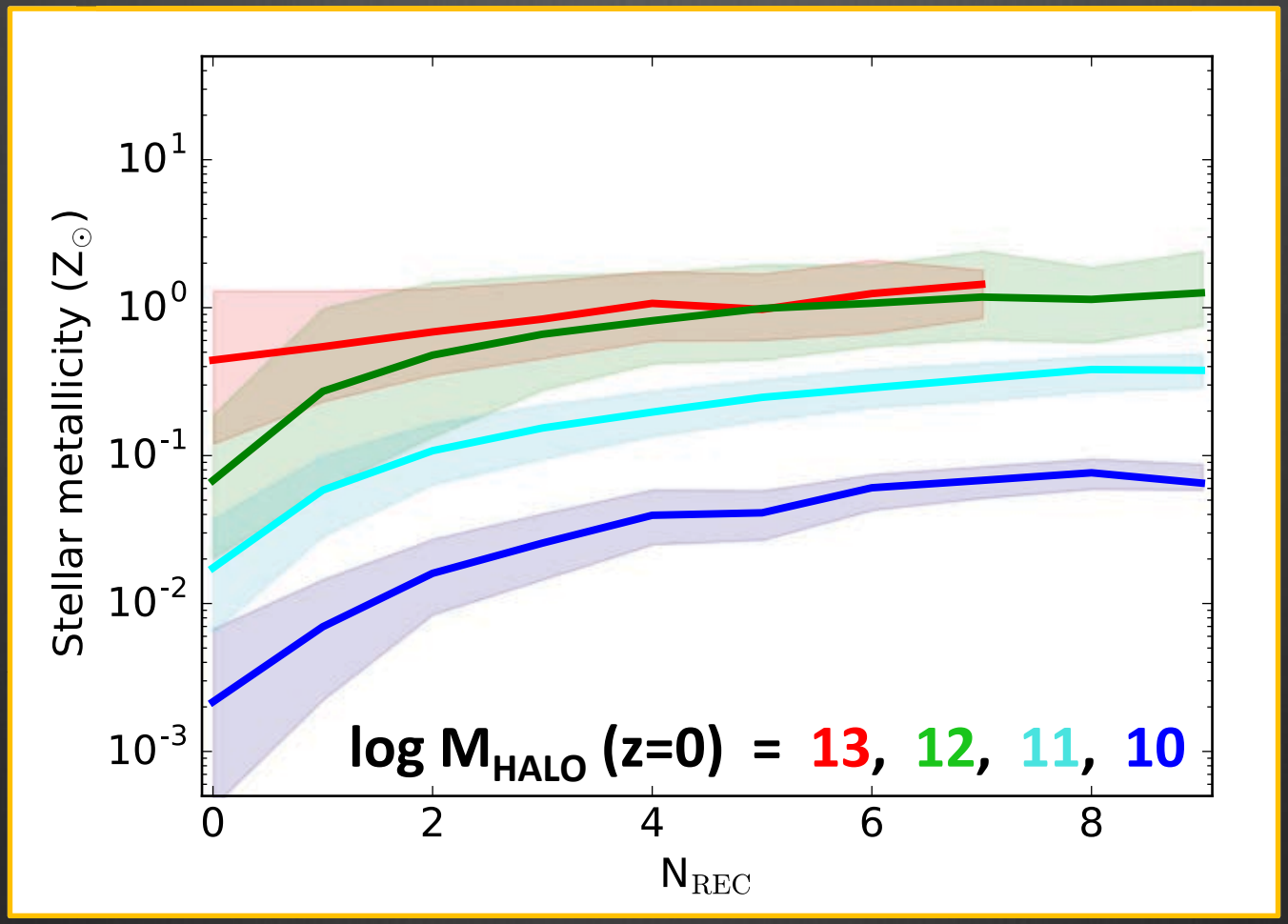
Wind properties: metal loss



→ **Decreasing metal loss factor in higher mass halos, similar to wind loading factor**

Anglés-Alcázar et al. in prep.

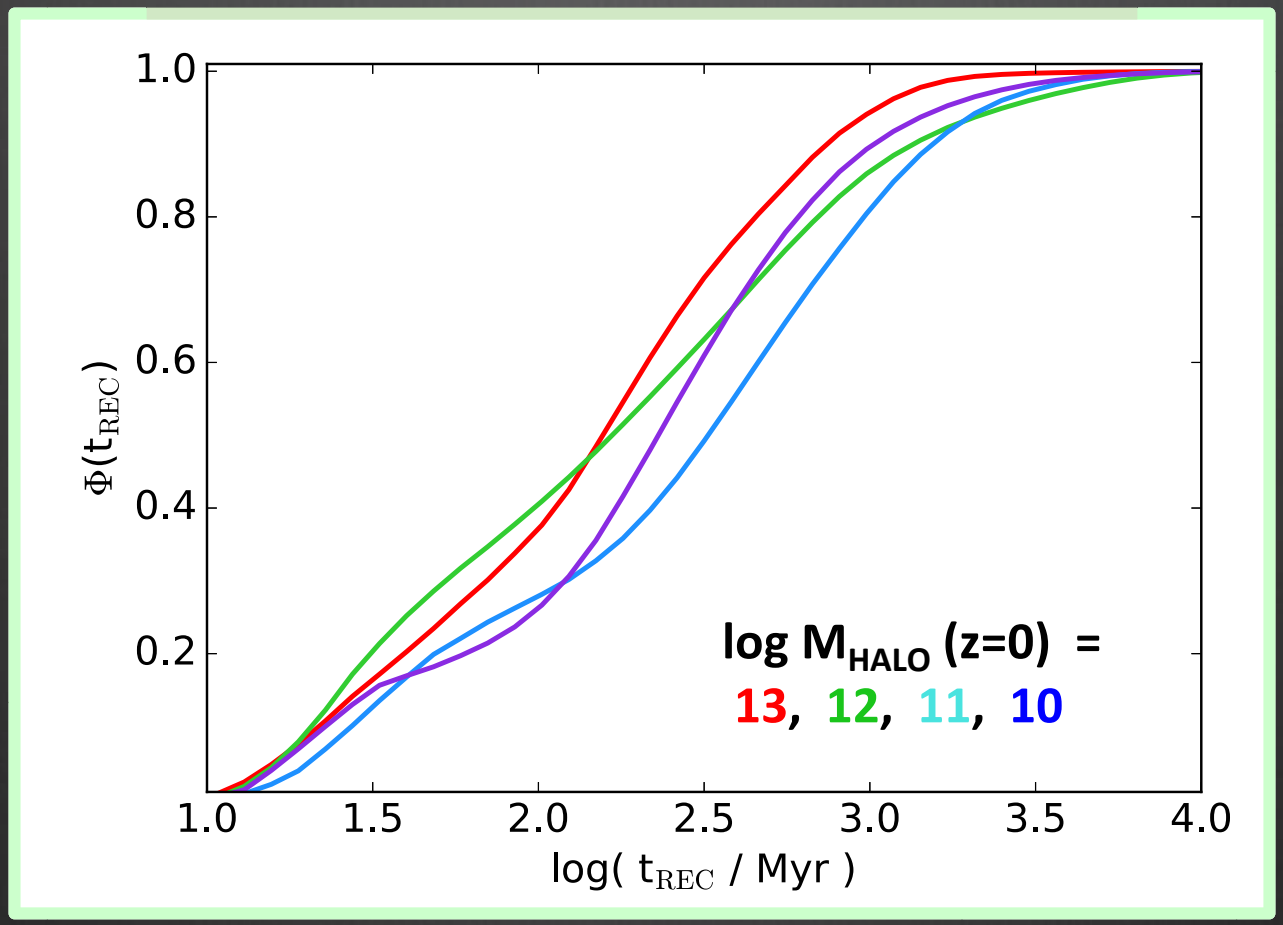
Metallicity vs. recycling



→ **Stellar metallicity increases with # of recycling times of gas progenitor**

Anglés-Alcázar et al. in prep.

Wind recycling time



→Wind re-accretion time: 10 Myr - 1 Gyr (shorter than Oppenheimer+2010, Christensen+2016)

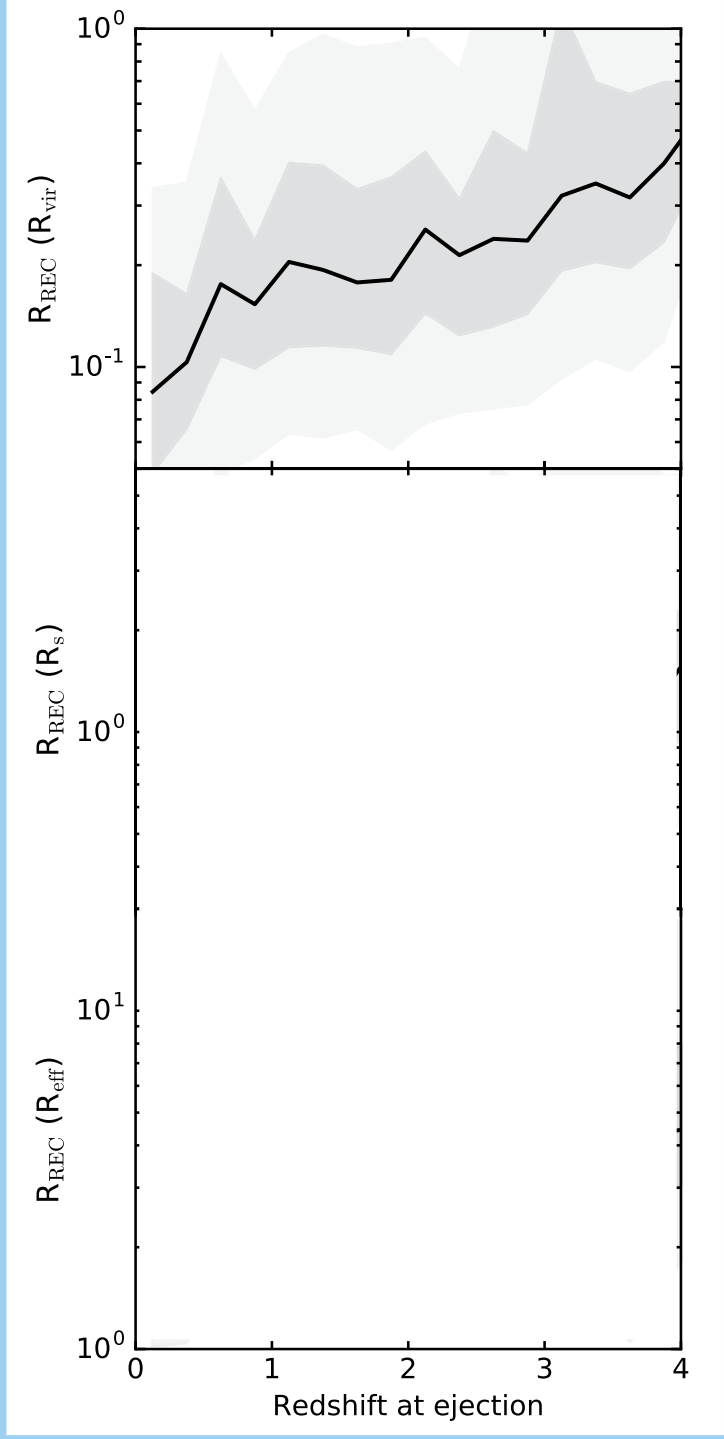
→Important parameter for SAMs! (e.g. Henriques+2013; White+2015)

Anglés-Alcázar+2017, MNRAS 470, 4698

Wind recycling distance

→ Most recycling occurs within R_{vir}

→ Strong redshift evolution relative to R_{vir}



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Wind recycling distance

→ Most recycling occurs within R_{vir}

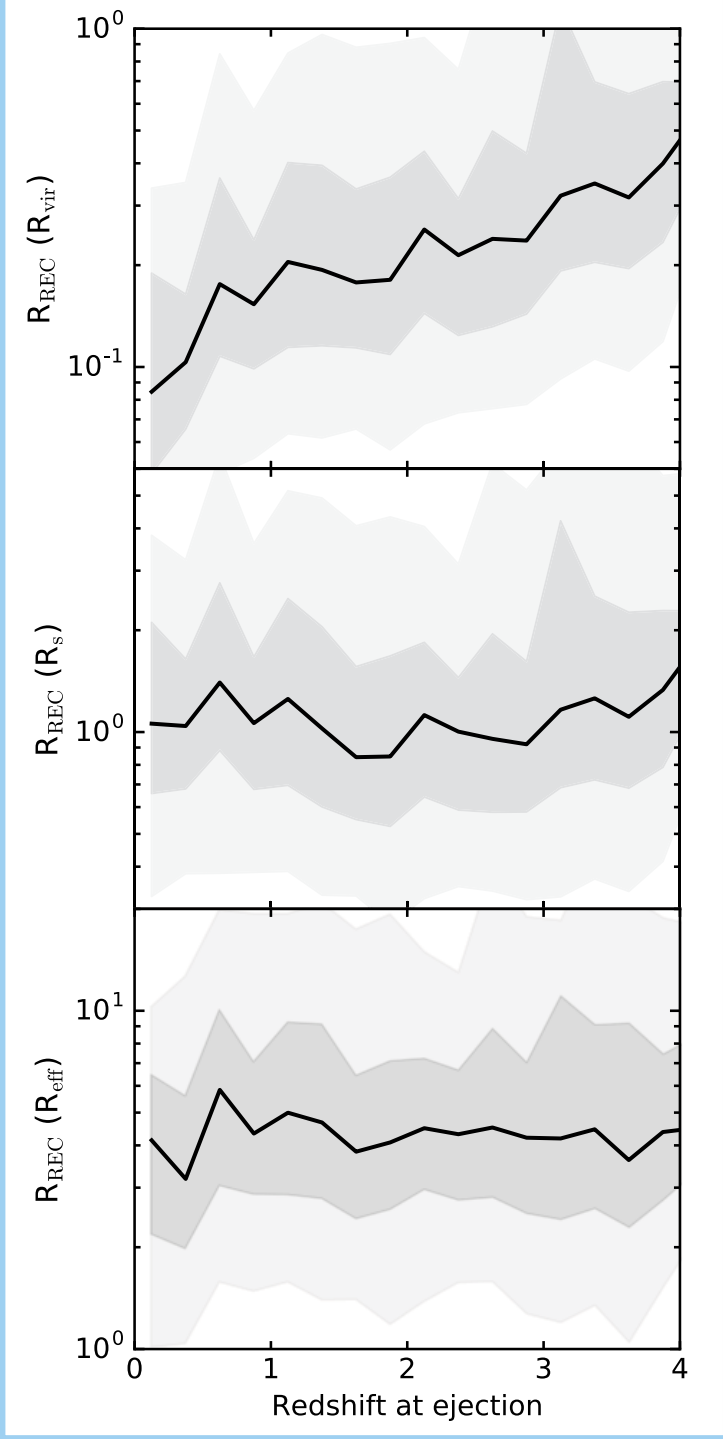
→ Strong redshift evolution relative to R_{vir}

→ No evolution relative to halo scale radius

evolution of inner mass profile better characterized by Rs, which is not affected by pseudo-evolution (Diemer, More & Kravtsov 2013, More+2015)

→ "Recycling zone" independent of mass/redshift

Median R_{rec} = halo scale radius = 5 x stellar effective radius



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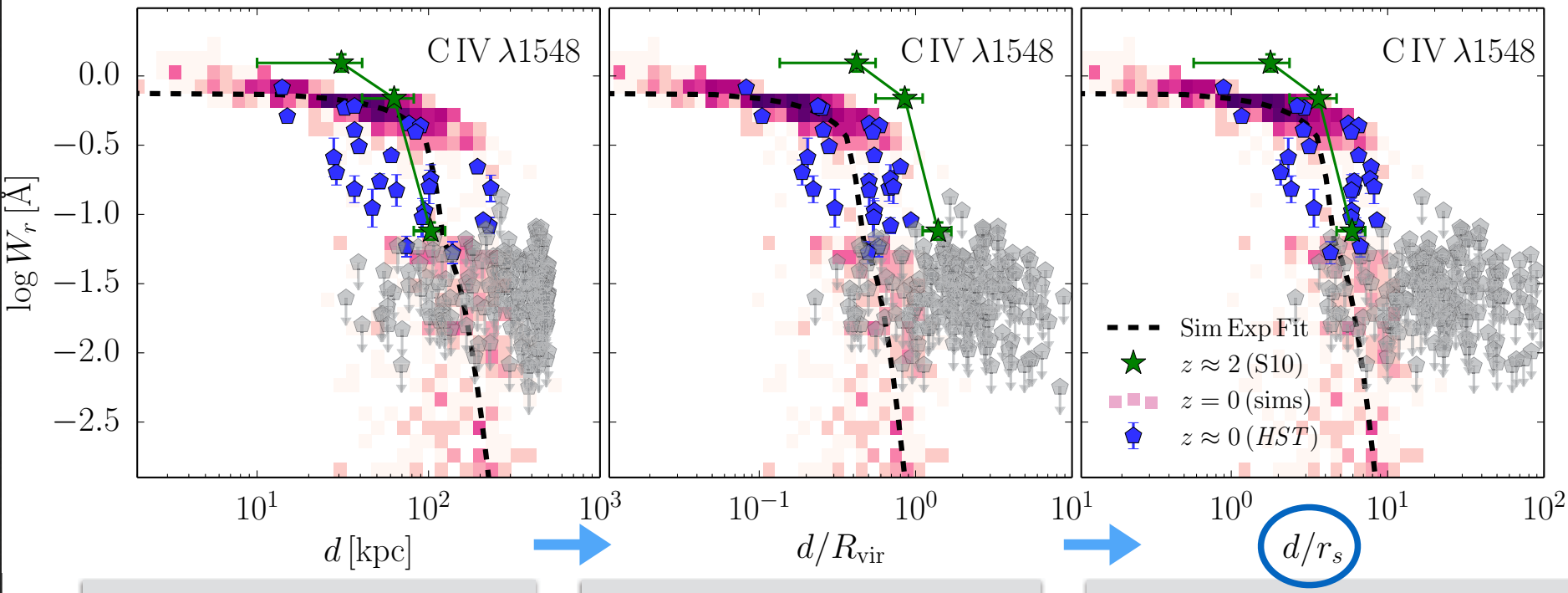
CGM is self-similar across mass and time

When compare profiles in a single epoch, using R_{vir} is fine,
when compare across different epochs, r_s is better.



CGM evolves very mildly over 11 billion years

Pseudo-evolution of Dark Matter halo

Self-Similar in mass and time when scaled with r_s

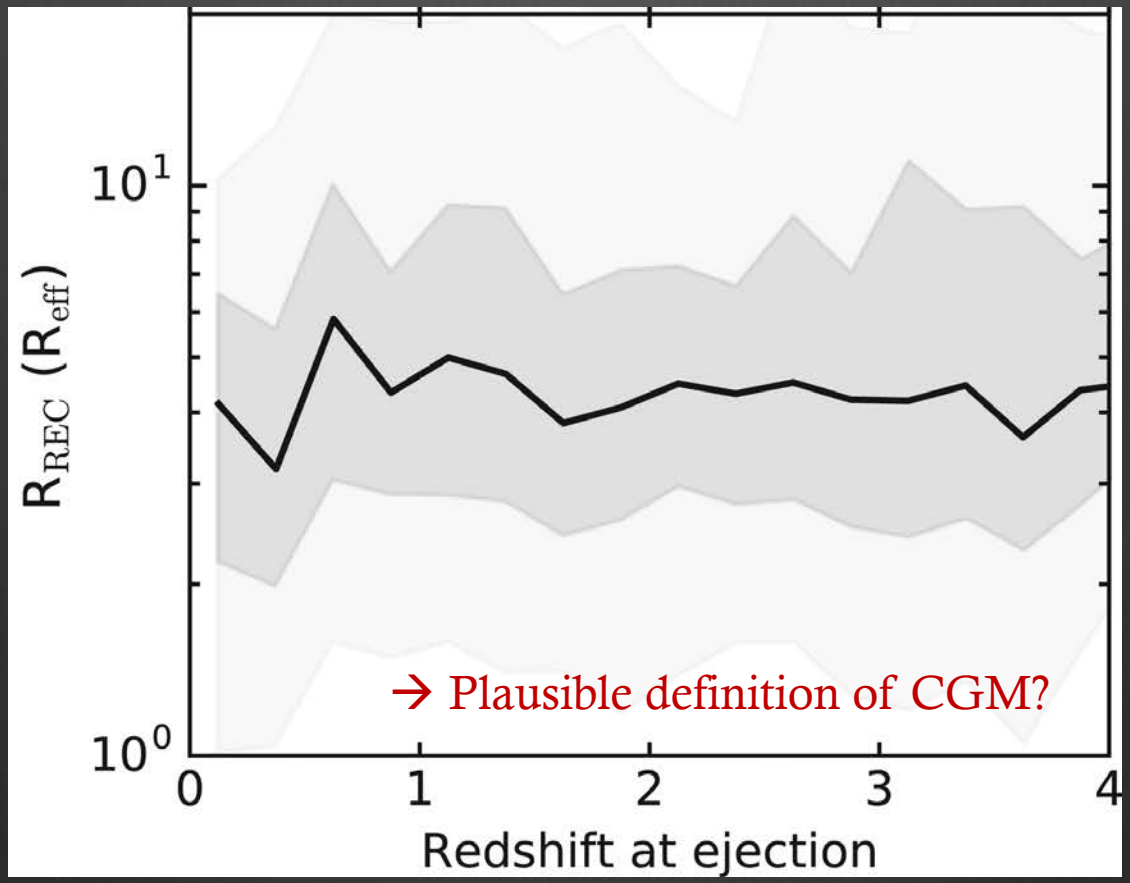
Across 4 decades of stellar mass from dwarf to L* galaxies!

→ **Slide from Liang's talk! (see also Ford+2014)**

Diemer, More, Kravtsov 2013; Churchill et al. 2013; Liang et al. 2016;

Wind recycling distance

→ Characteristic ***recycling zone*** around galaxies that scales with the size of the inner halo and the galaxy's stellar component.



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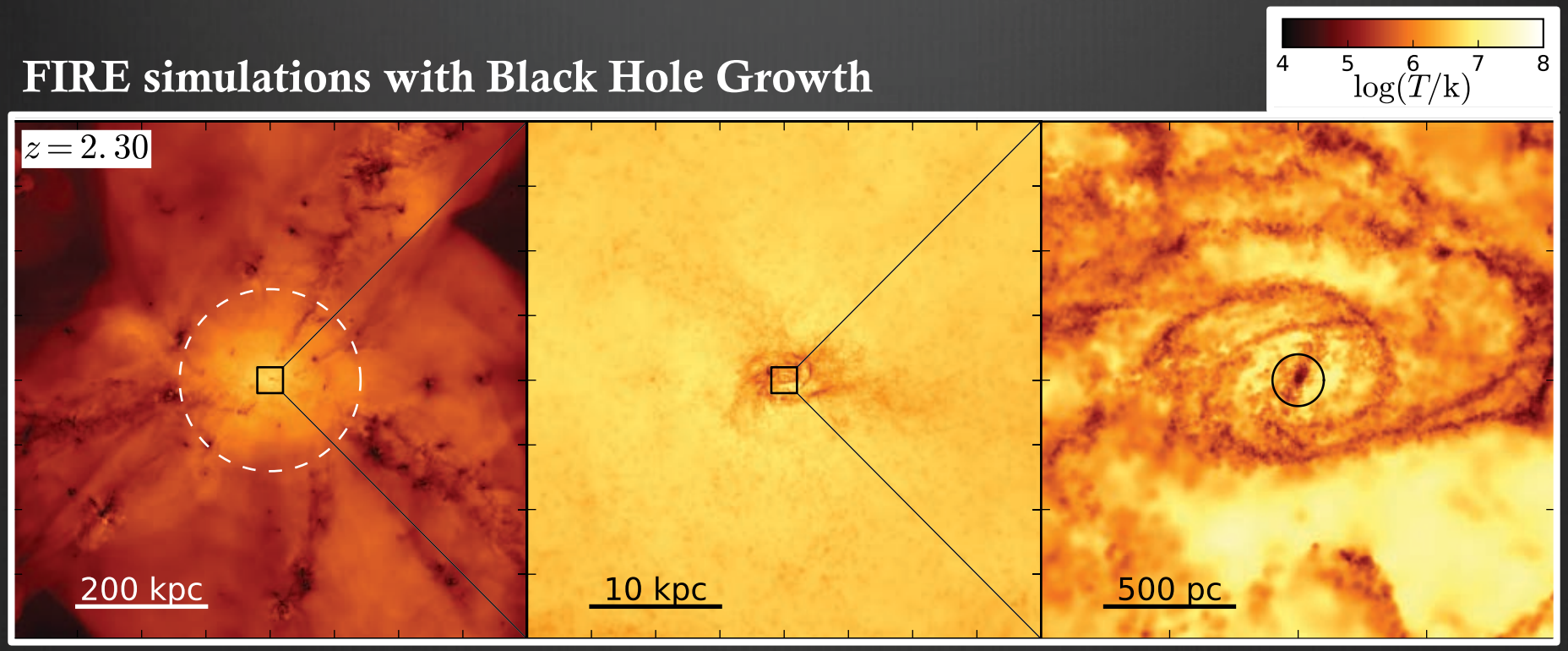
2 minutes on black holes

→ **AGN feedback needed to reproduce OVI in simulations?**
(talks by Sanchez, Hummels, Nelson, Oppenheimer)

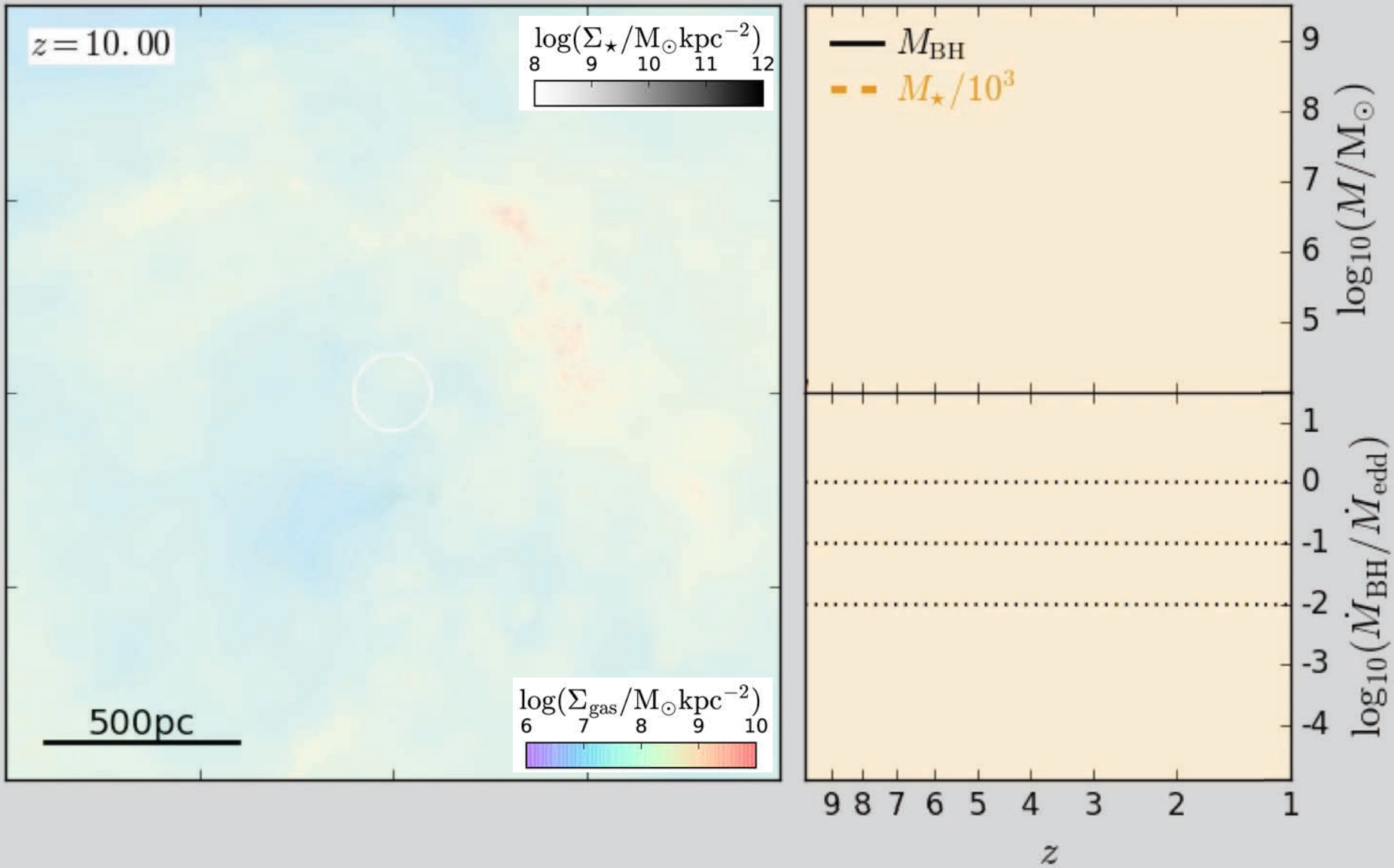
→ **Higher MgII covering fractions in QSOs!**
(Johnson+2015)

FIRE simulations with Black Hole Growth



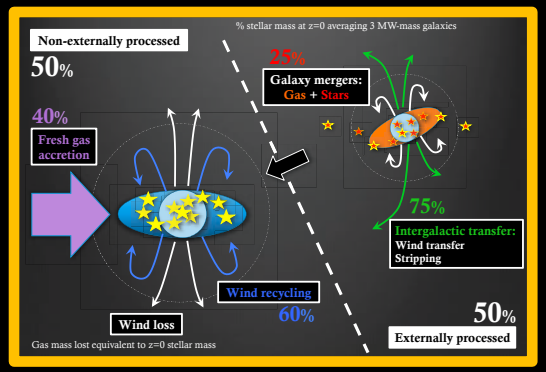
Anglés-Alcázar+2017c, MNRAS 472, L109

Black holes on FIRE! Stellar feedback limits early BH growth

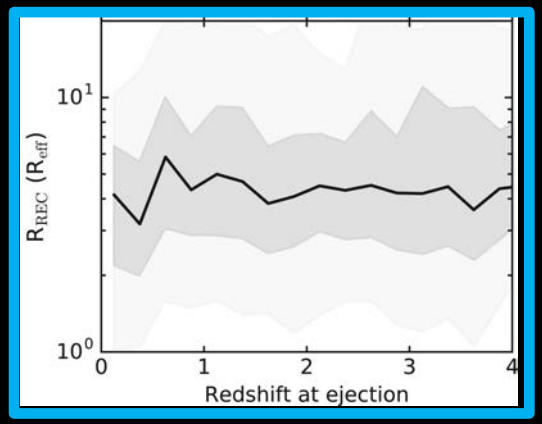


Anglés-Alcázar+2017c, MNRAS 472, L109 (arXiv:1707.03832)

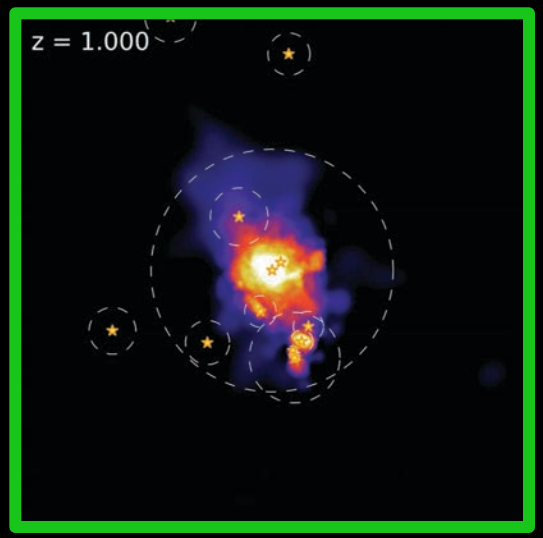
1) Connecting explicitly CGM gas flows and galaxy mass assembly



2) Particle tracking is powerful!
→ net mass loss rate, recycling distance,…
→ Zach's talk in a moment!



3) Intergalactic transfer of gas between galaxies via winds can compete with fresh accretion and standard wind recycling



Anglés-Alcázar+2017b, MNRAS 470, 4698