KITP conference: “Fire down below” KITP/UCSB 04/2014

Star formation driven galactic winds in FIRE

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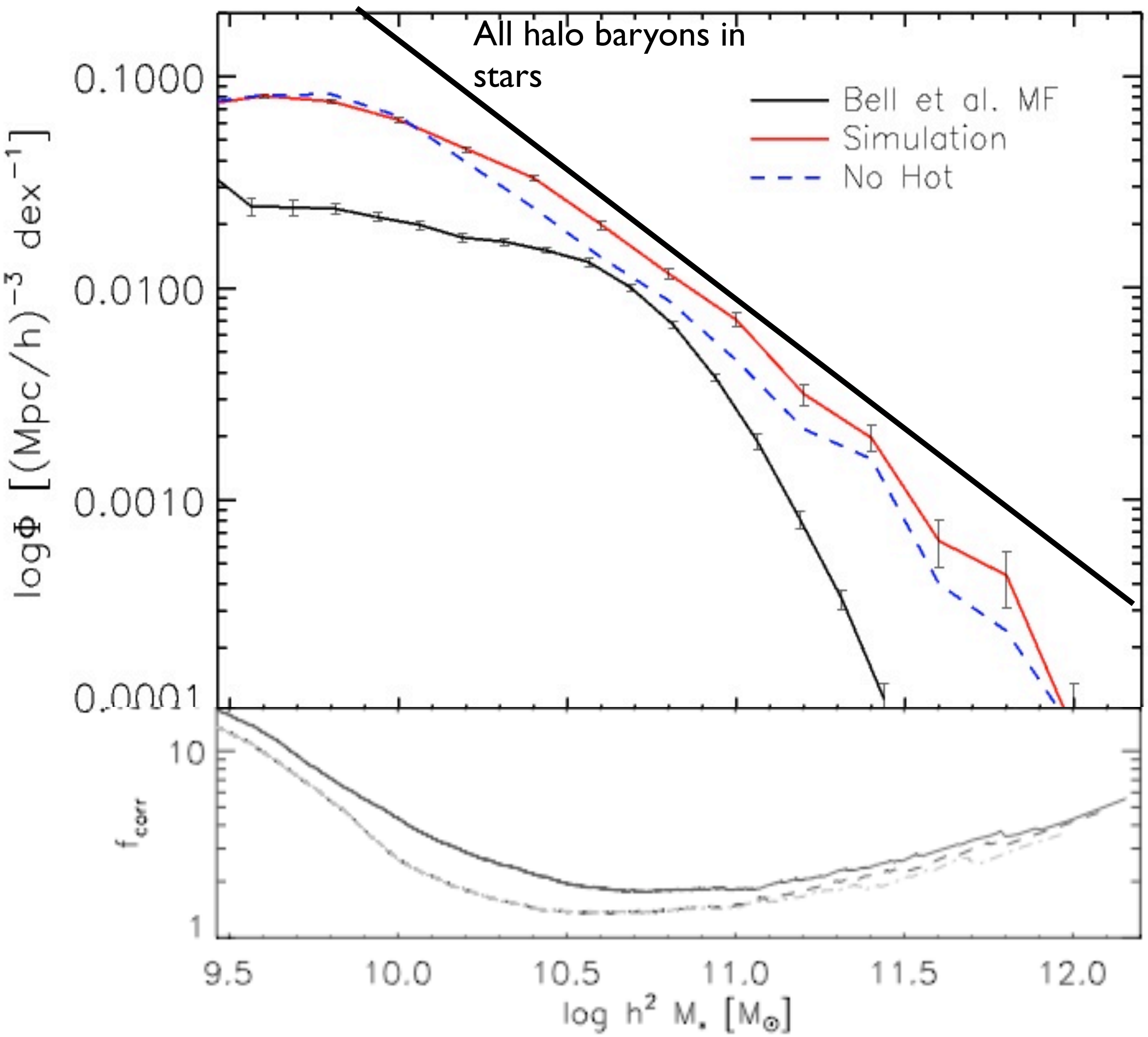
with P. Hopkins, C.-A. Faucher-Giguere, A. Muratov, E. Quataert, N. Murray et al.

Feedback is needed...



- Some process needs to regulate growth of galaxies.
- Gas is either expelled from galaxies or its accretion is prevented
- At the low mass end the most promising candidate is star formation driven feedback
- Stellar population provides a huge input of energy and momentum into the ISM.

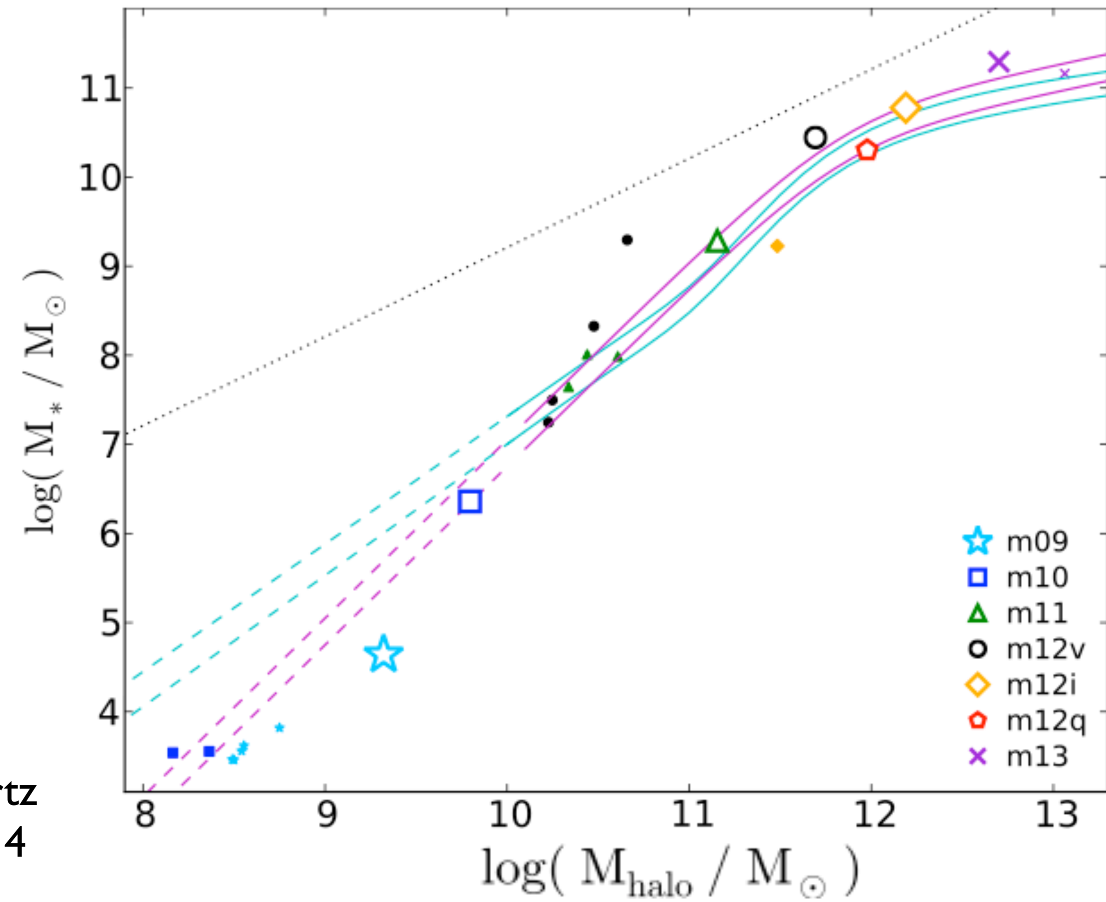
DK+ 2009, UV background but no winds

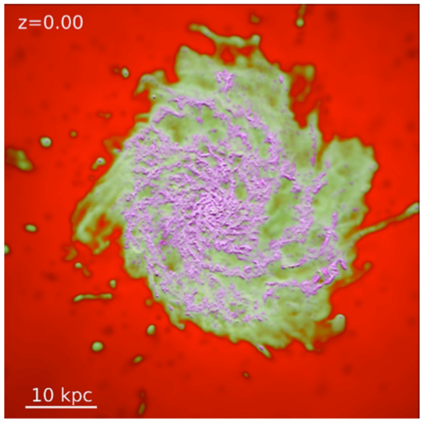
FIRE Project

- Implements our current understanding of local star formation feedback on the scales of giant molecular clouds. Hope: local and galaxy scale regulation connected.
- SNe are not the only feedback mechanism! A range of relevant processes occur as soon as stars form: HII regions, stellar winds, photoelectric heating, radiation pressure and finally SN energy and momentum (built during SN remnant evolution)!
- Need to "resolve" GMC formation, threshold density n_H>100 cm^{-3} and resolution of 1-50pc.
- Energy and momentum input are based on STARBURST99 (Leitherer et al. '99), no hydro decoupling no cooling prevention.

FIRE Project

- No parameter tuning: comparison with observations is needed to test the model.
- Model provides a very good match to stellar mass - halo mass relation.
- m_g ~ few 100 to few 10, 000 Msun and 1-50pc hydro resolution in dense ISM.



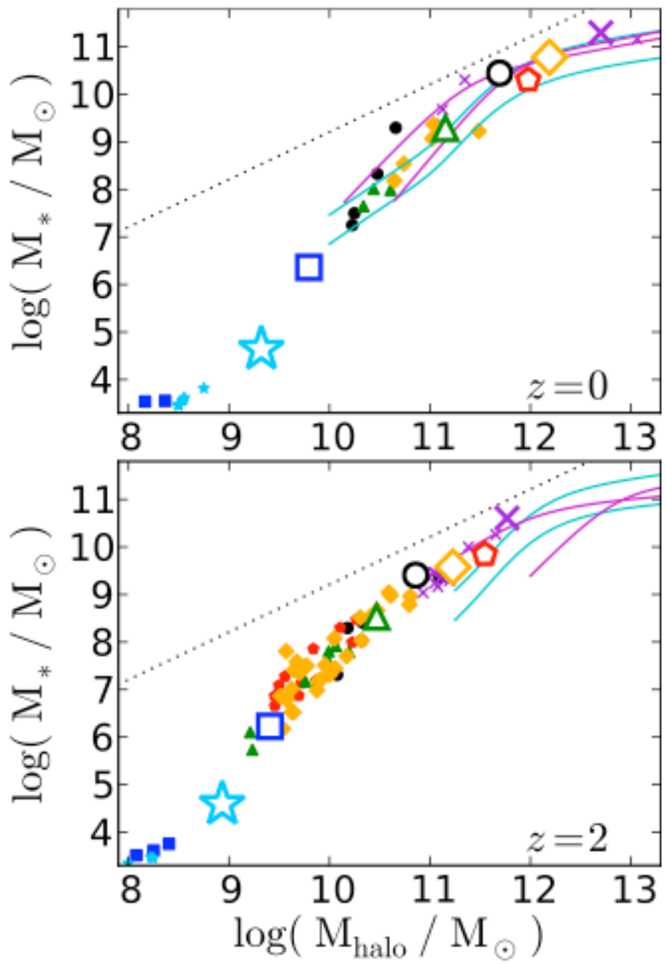


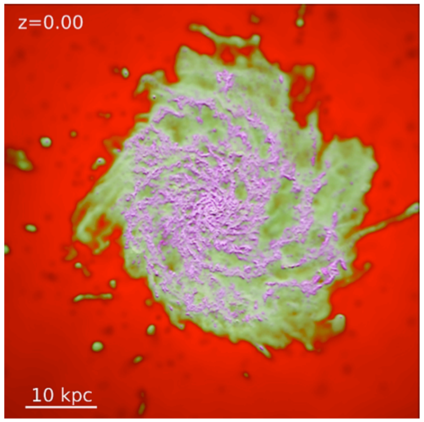
See also Agertz &Kravtsov '14

Hopkins, DK et al. 2014

FIRE Project

- Feedback regulates galaxy masses over the large redshift range.

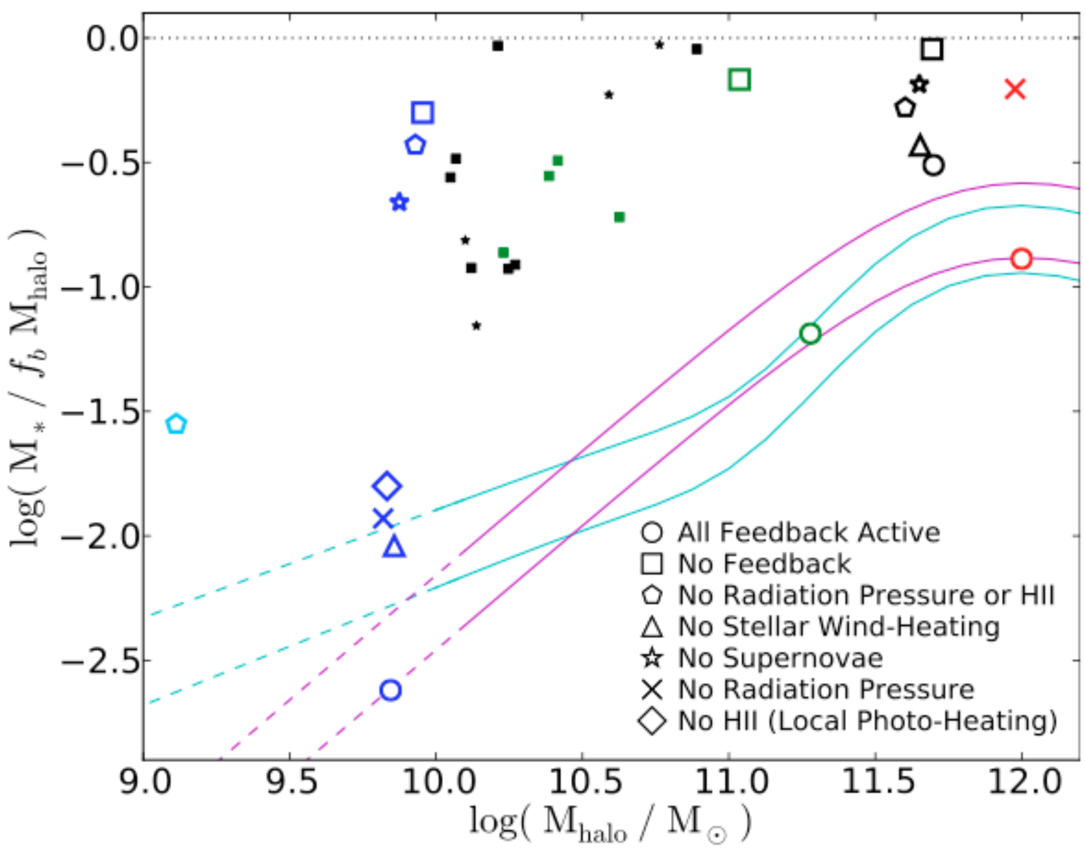




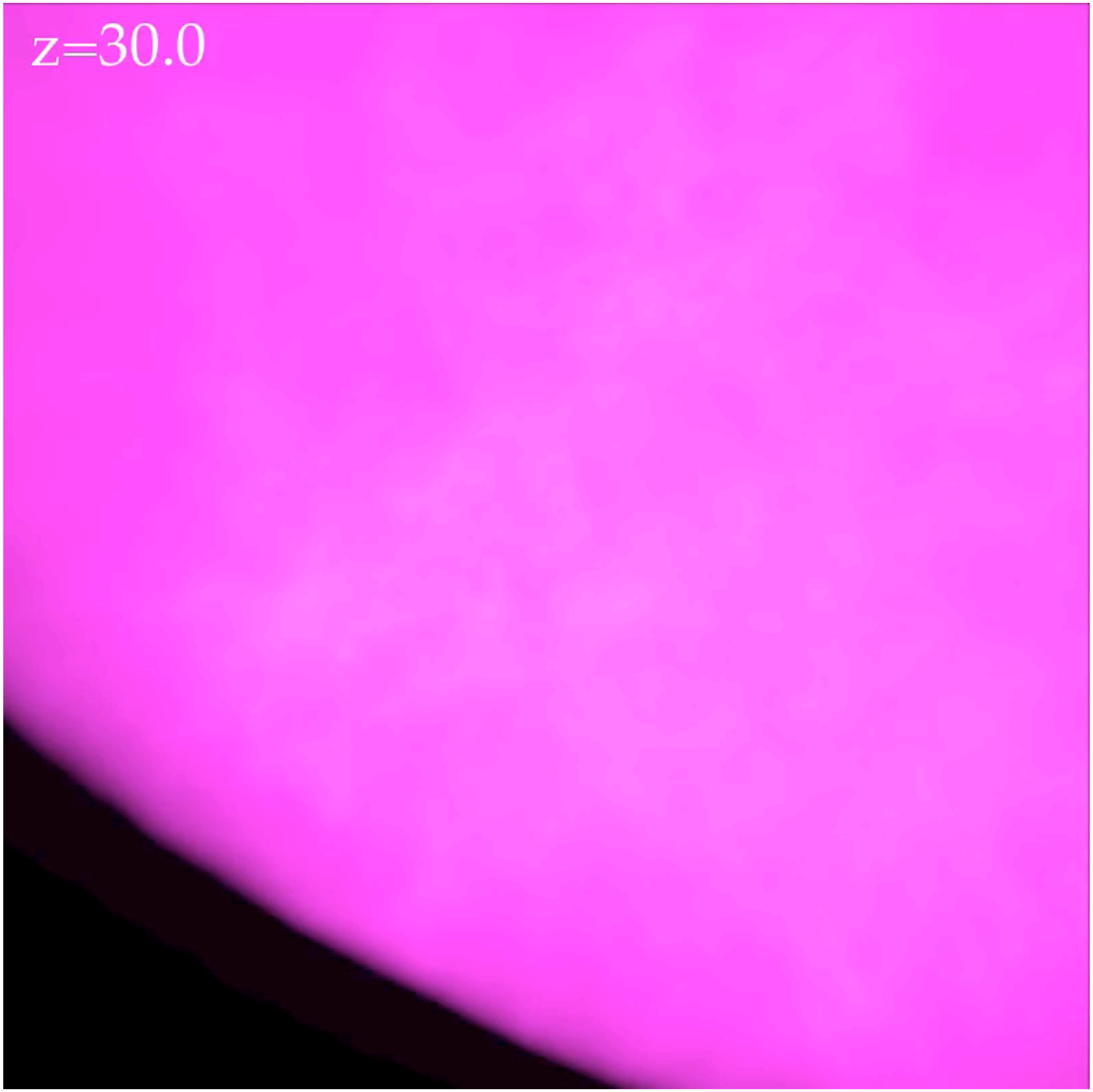
Hopkins, DK et al. 2014

Critical to include a range of feedback mechanisms

- It is critical to include a whole range of feedback mechanisms that we know must operate in star forming regions.



50 kpc scale, ~MW mass, magenta-cold, green-warm, red-hot gas

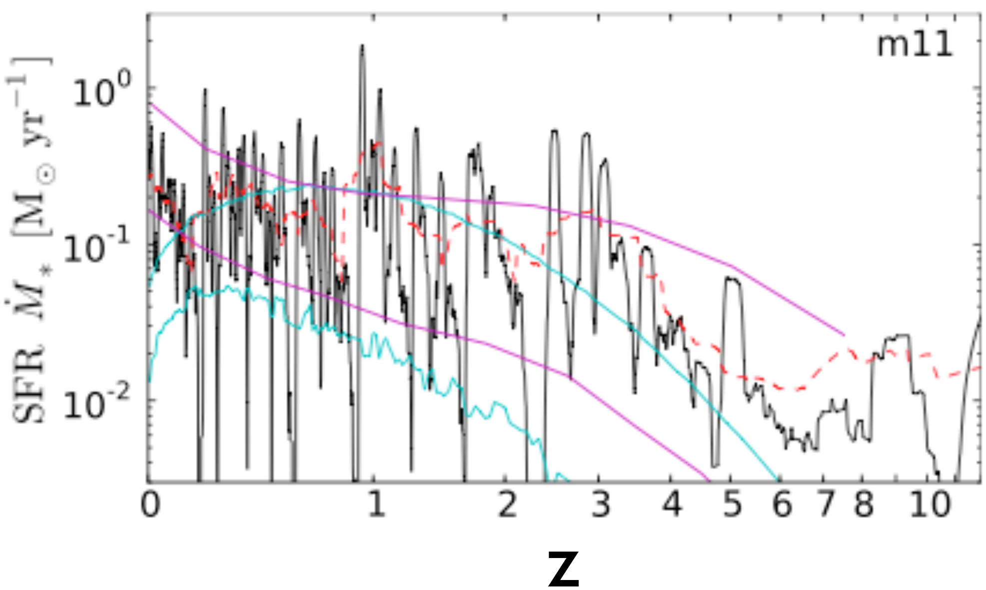


What can we learn from FIRE?

- Stars affect their surroundings in many ways, what mechanism is the most important for a given mass and time?
- How much material actually gets ejected and how fast?
- Can we use this to inform galaxy scale sub-grid models?
- What is the dominant outflow phase?
- Do outflows leave the halo? Is gas accelerated on the way out and how?
- Is feedback continuous or bursty?
- Do outflows affect infall and what are the consequences?
- How can we use simulations to interpret current observations and observations to constrain implemented physics?

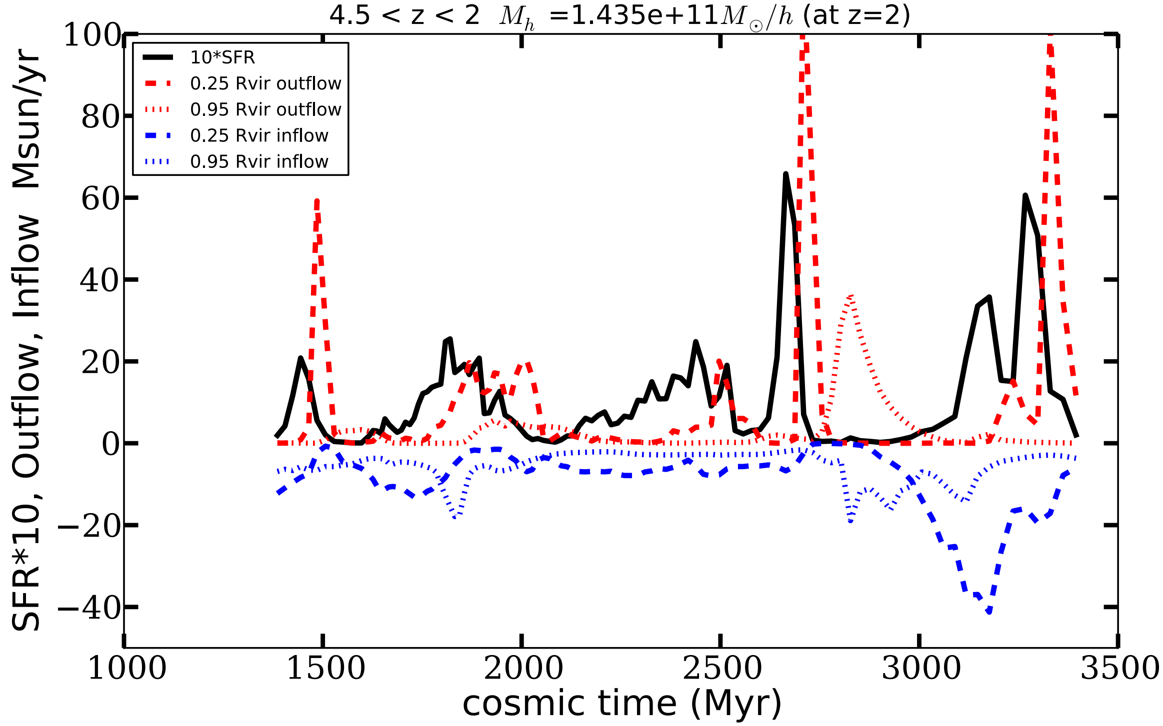
Star formation in FIRE

- In simulations with local feedback driving, star formation histories (especially at low masses) are bursty! (Hopkins+13, Agertz+2014, Trujilo-Gomez+13, Shen+13)
- This needs to be taken into account for correlations of outflows with SFR.



Star formation driven outflows

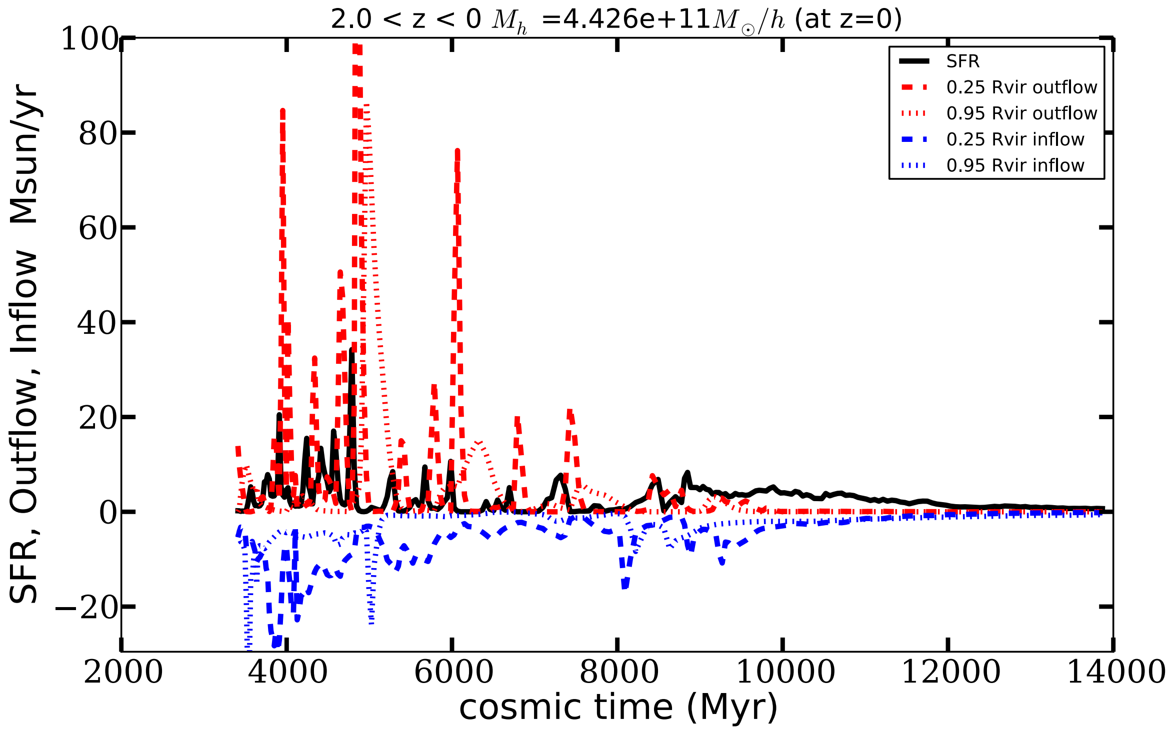
- Star formation bursts drive episodes of winds that push material out of galaxies.
- Infall can temporarily suppress infall, which usually quickly re-establishes as a mixture of IGM infall and outflow recycling.
- Cycle of infall, star formation and outflows... We can follow this in detail!



Muratov et al., in preparation

Difference between low and high z

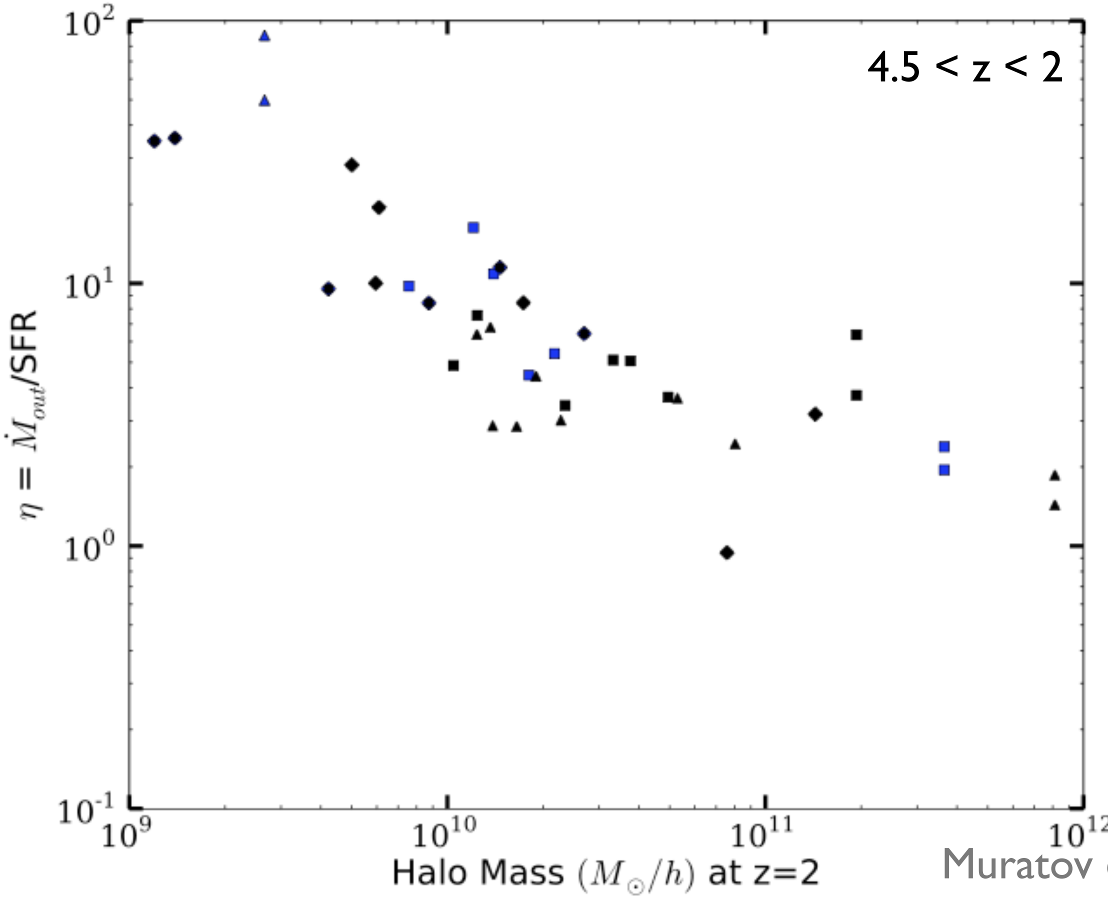
- In MW size halos low-z evolution is very different than at high-z!
- Star formation is more continuous at low redshift but outflows reaching large radii are rare (much lower mass loading and/or velocities).
- Deeper potential wells? Less concentrated star formation (threshold)? Galactic fountain?



How much material is expelled?

Mass loading of material expelled through a shell in inner halo (0.25Rvir) decreases with increased halo mass!

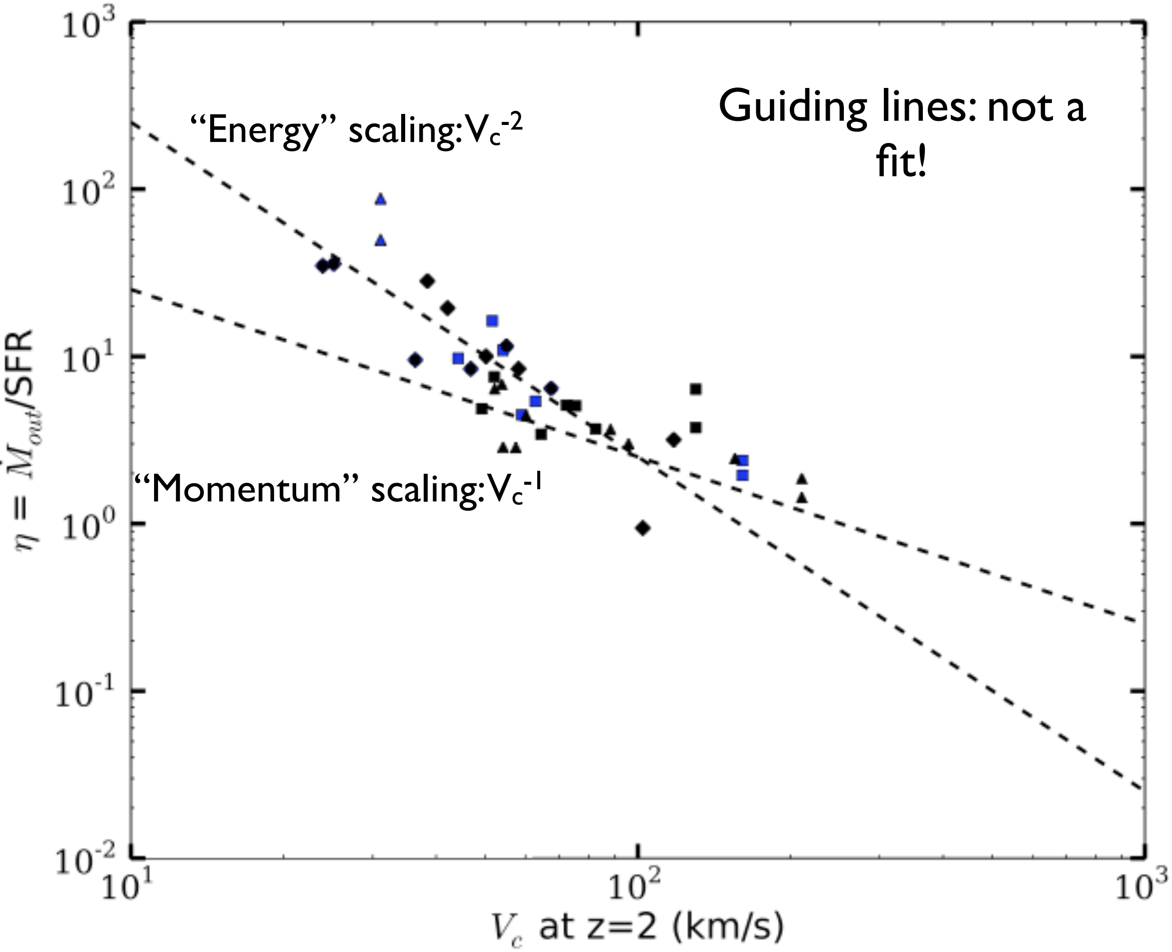
Need to account for time delay between SF and outflow: 15-50Myr for the inner halos, few hundred Myr for the outer halo.



Muratov et al., in preparation

How much material is expelled?

Steeper scaling at low Vc, comprehensive interpretation needed...



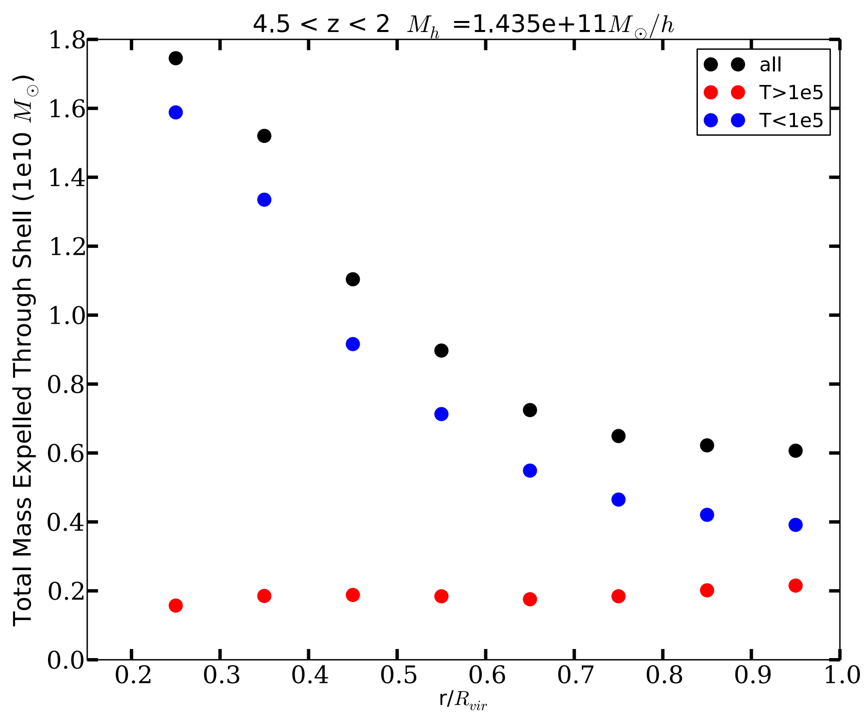
Muratov et al., in preparation

PT “episode” method

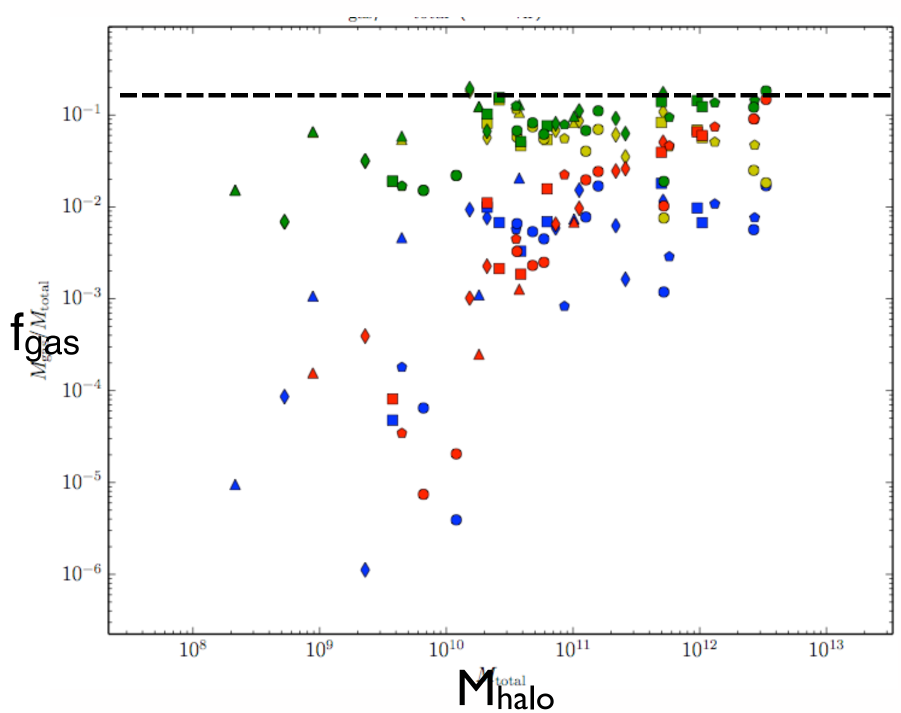
halo mass and redshift slices	3.3 < z < 4.5	2.5 < z < 3.3	2.0 < z < 2.5
M_h < 1e10	27.27	25.4	28.9
1e10 < M_h < 3e10	10.5	14.6	9.7
3e10<M_h<8e10	7.7	6.4	3.5
M_h>8e10	20.9	4.8	4.0

Multiphase winds

- Winds are multi-phase, but cold/warm phase seems to dominate wind flux in the CGM!
- Amount of cold/warm outflow is decreasing (mixing, heating, recycling). Hot component shows mild increase with radius...
- Only a fraction leaves virial radius -> baryonic fraction in halos are relatively high!



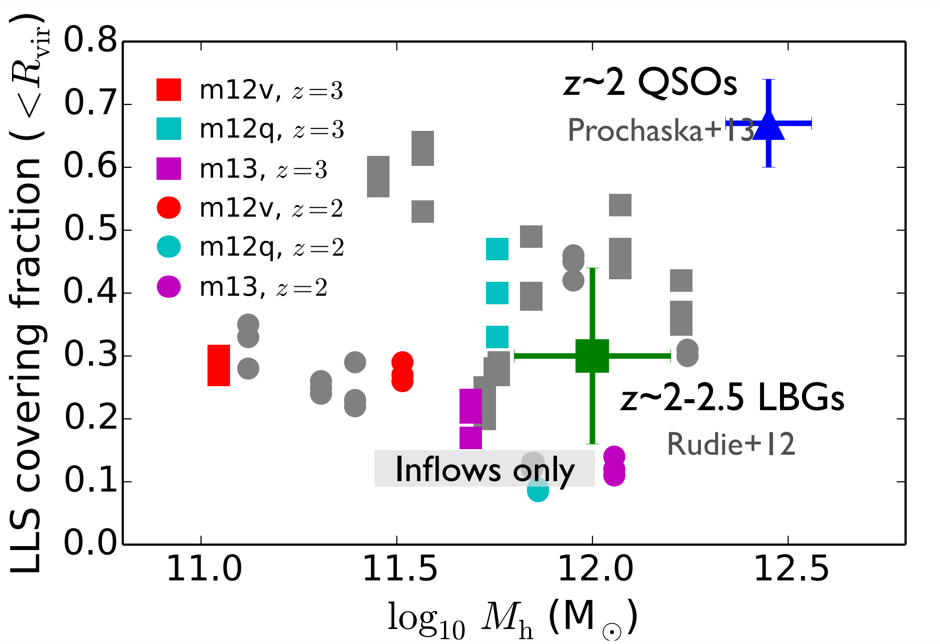
Muratov et al., in preparation



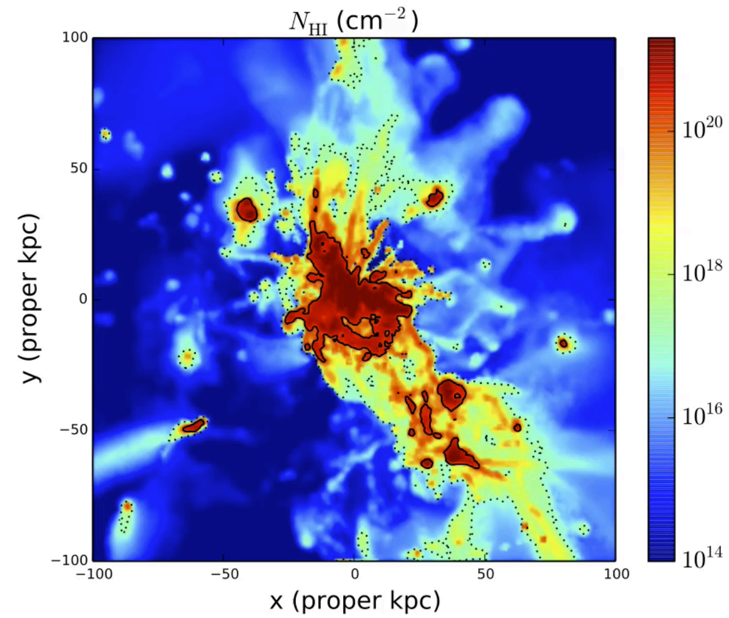
Murchikova et al., in preparation

Observational test of winds

- Winds increase the amount of neutral hydrogen in galactic halos and change its covering factor: directly (winds material) and indirectly (more extended infall region).
- Simulations with SF-driven winds consistent with data around LBGs!   Time variable: larger observational+simulated samples needed to test this quantitatively.



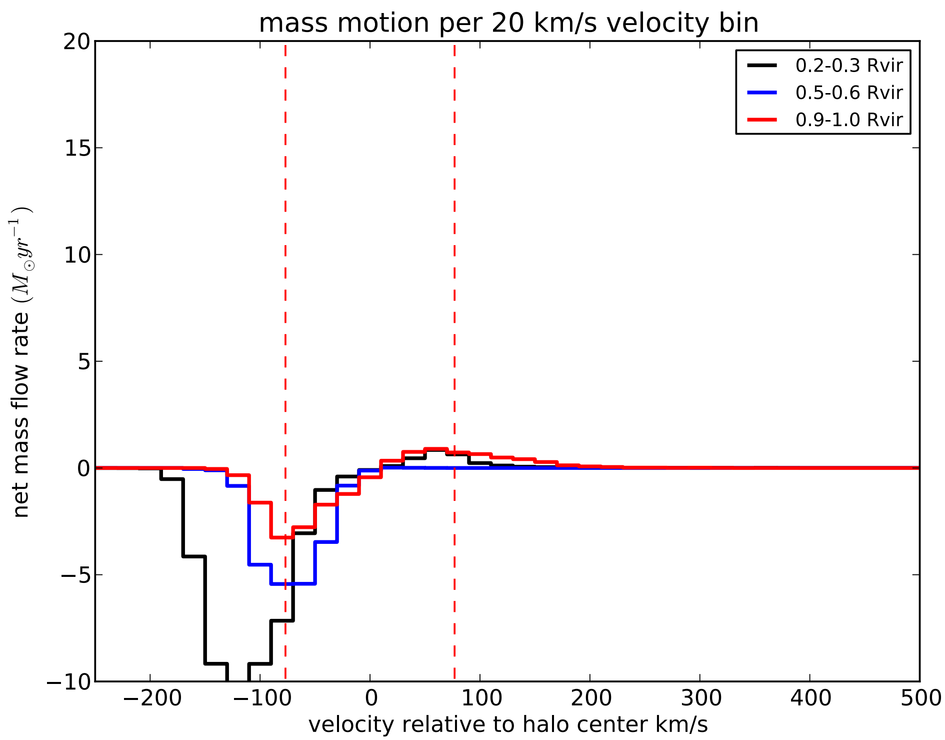
Faucher-Giguere et al. in preparation



Ionizing RT post-processed simulation

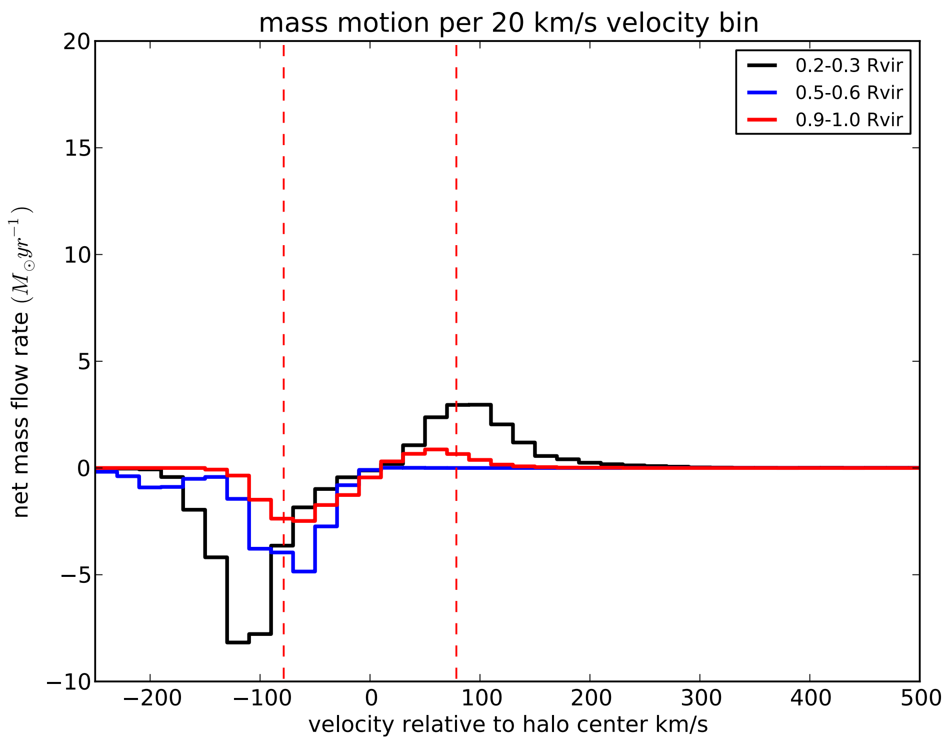
Kinematics

- Can follow detailed kinematics at different radii: infall-outflow cycle!
- Example from ~1e11Msun halo at z~2. Initially infall fuels star formation...



from S. Muratov

"-" = infall "+"= outflow



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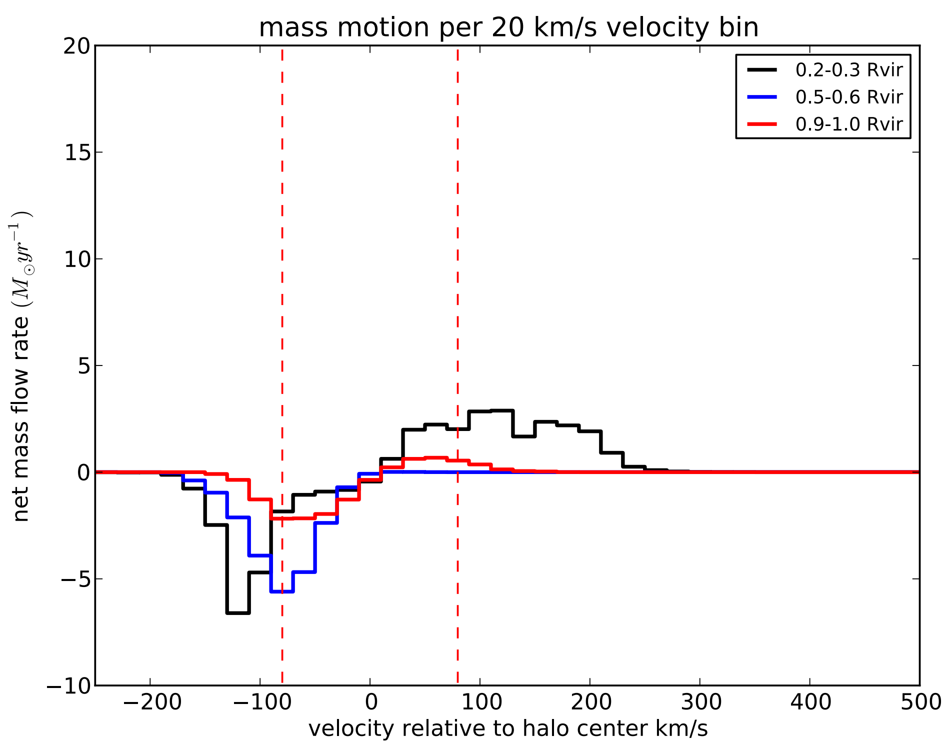
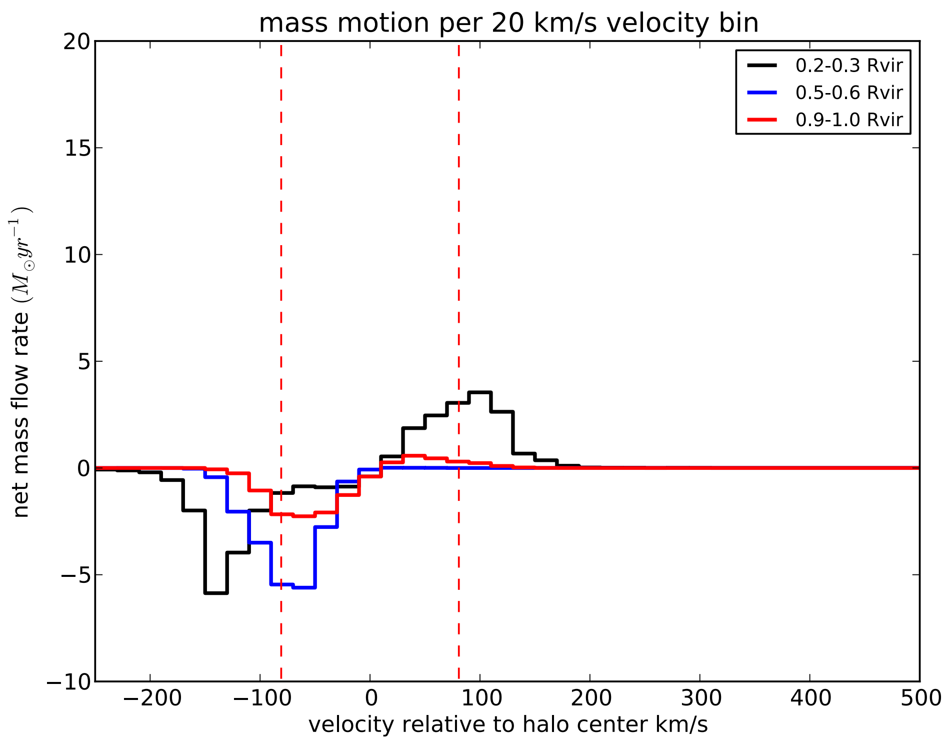


Infall and outflow co-exist in halos. CGM is a complex multi-phase dynamic system!



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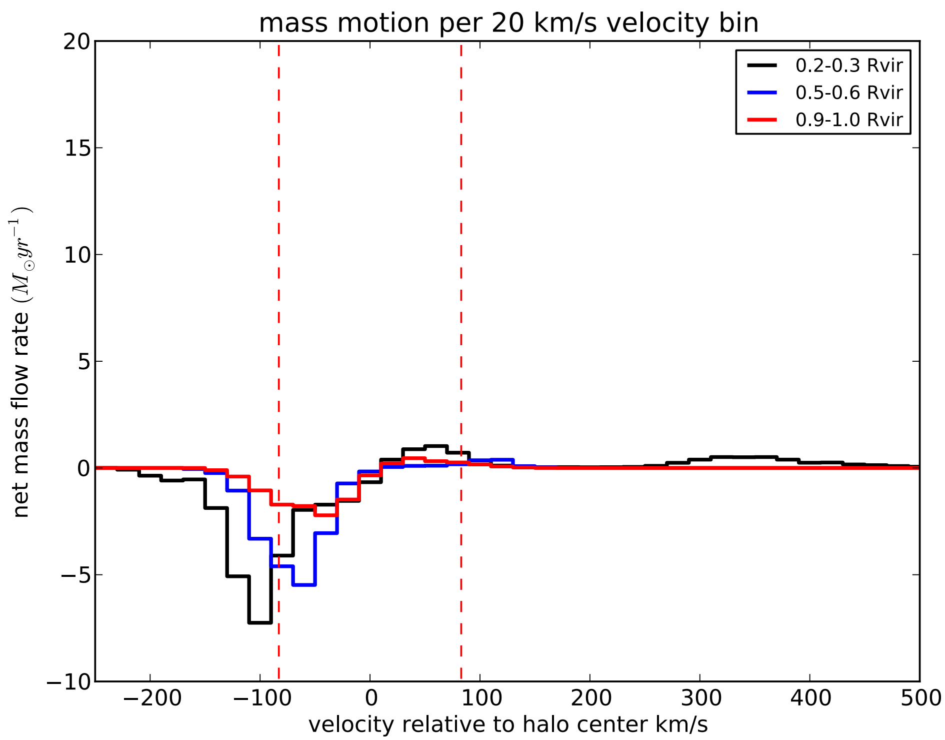
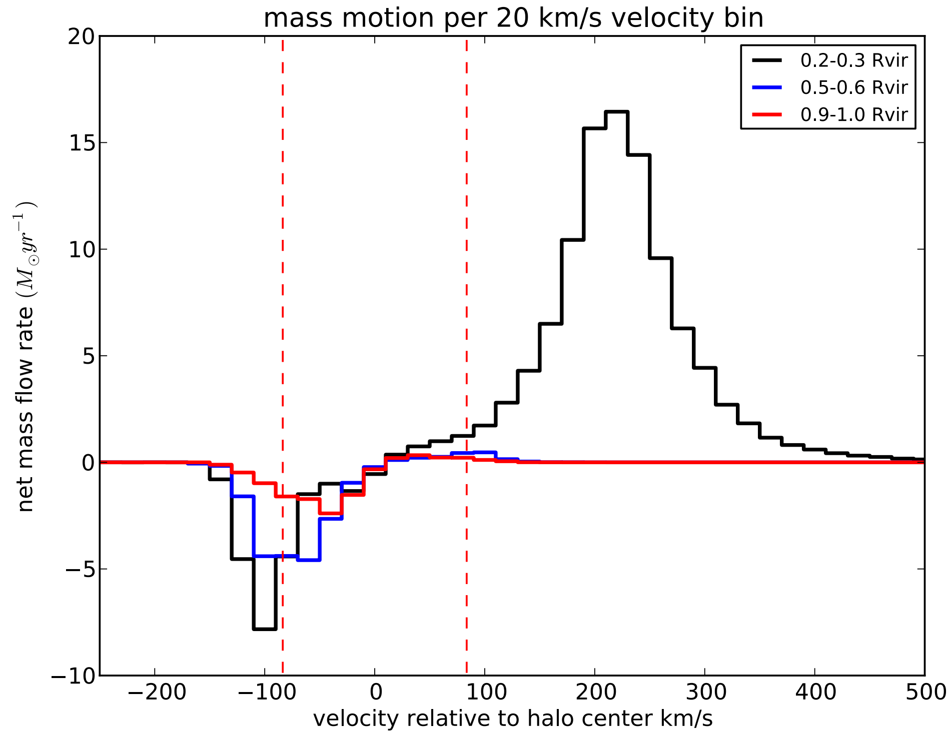
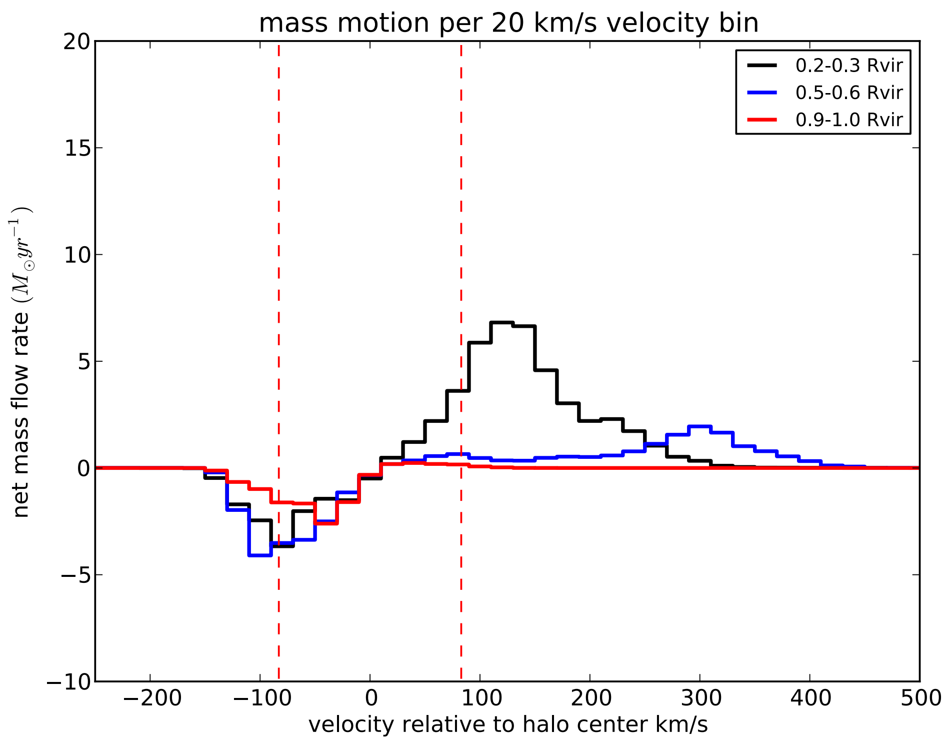


High velocity wind tail is crossing our shell....



- Outflows are typically faster than infall (infall harder to pick out out of ISM gas with "down the barrel" observations)



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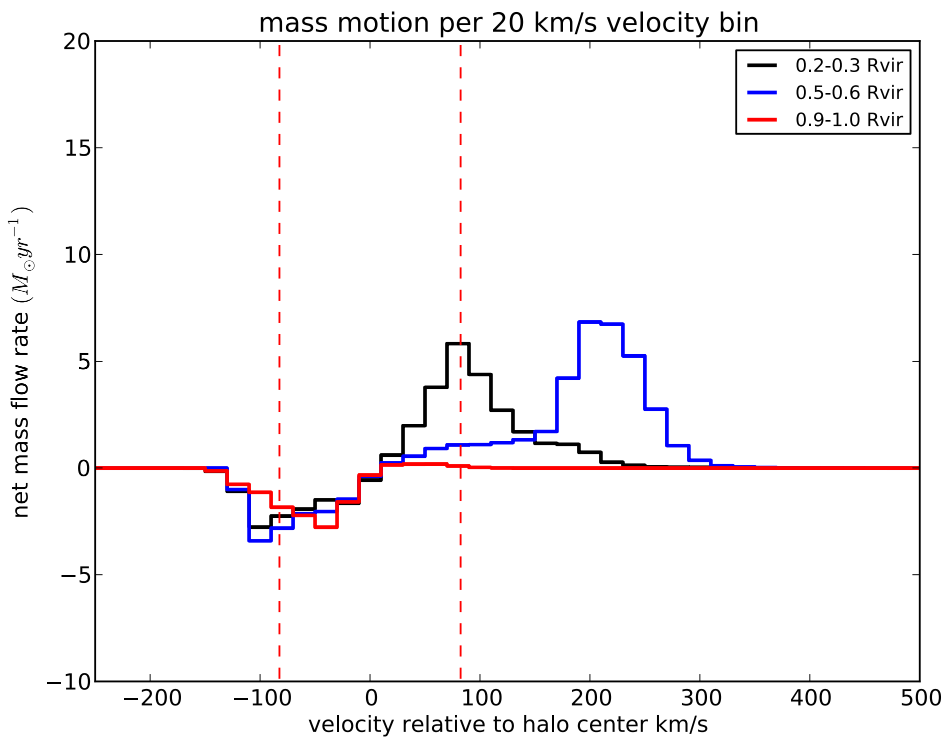
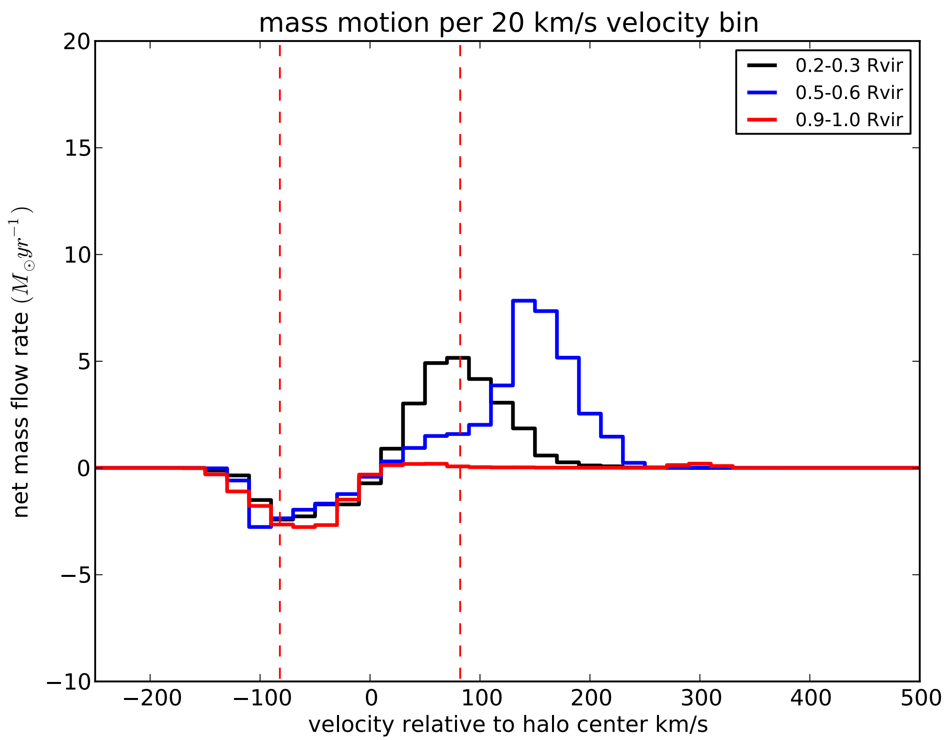


- Large outflow episodes temporarily suppress the infall, which usually quickly re-establishes



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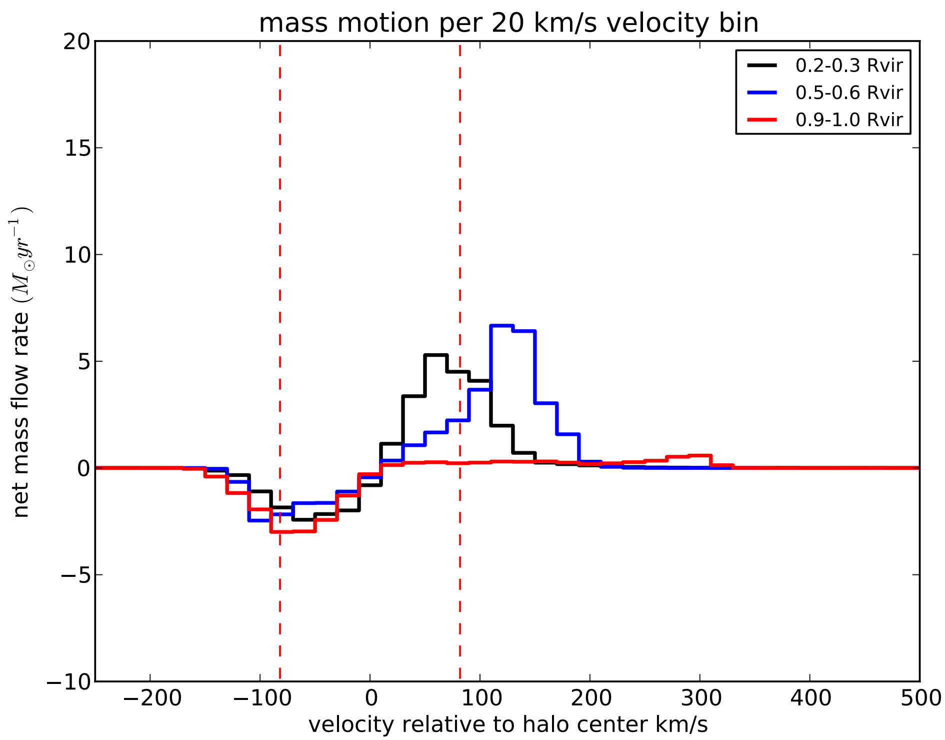
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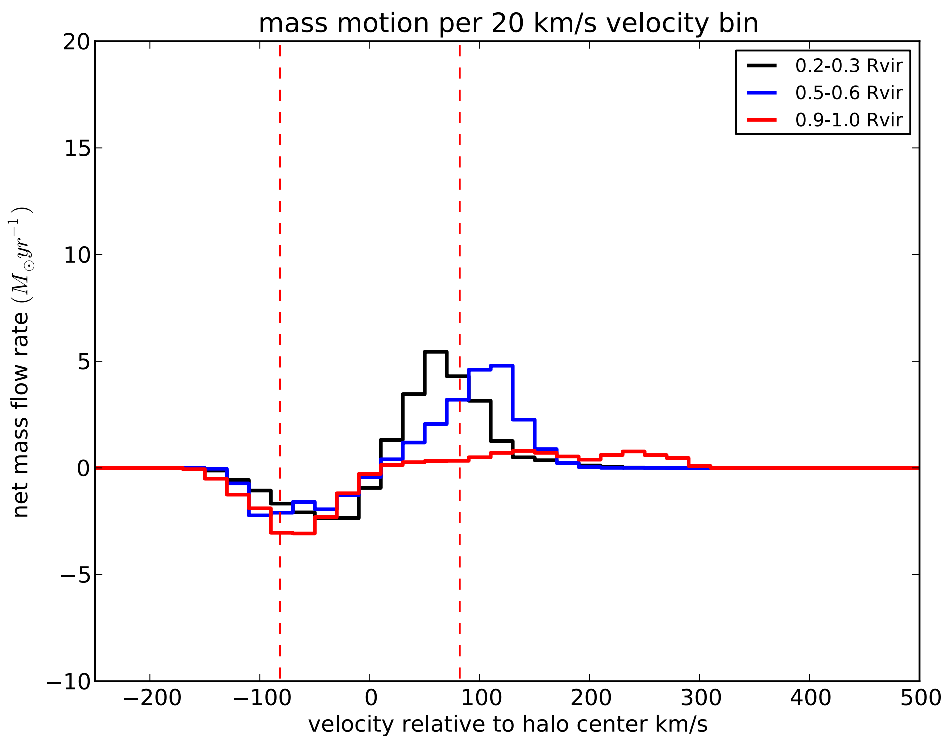

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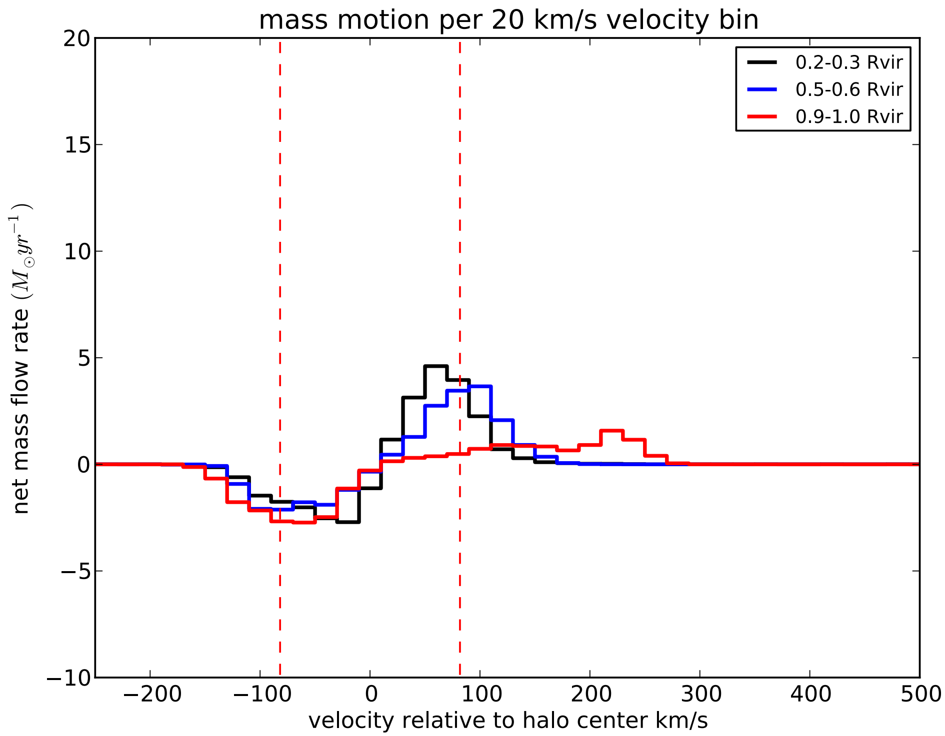

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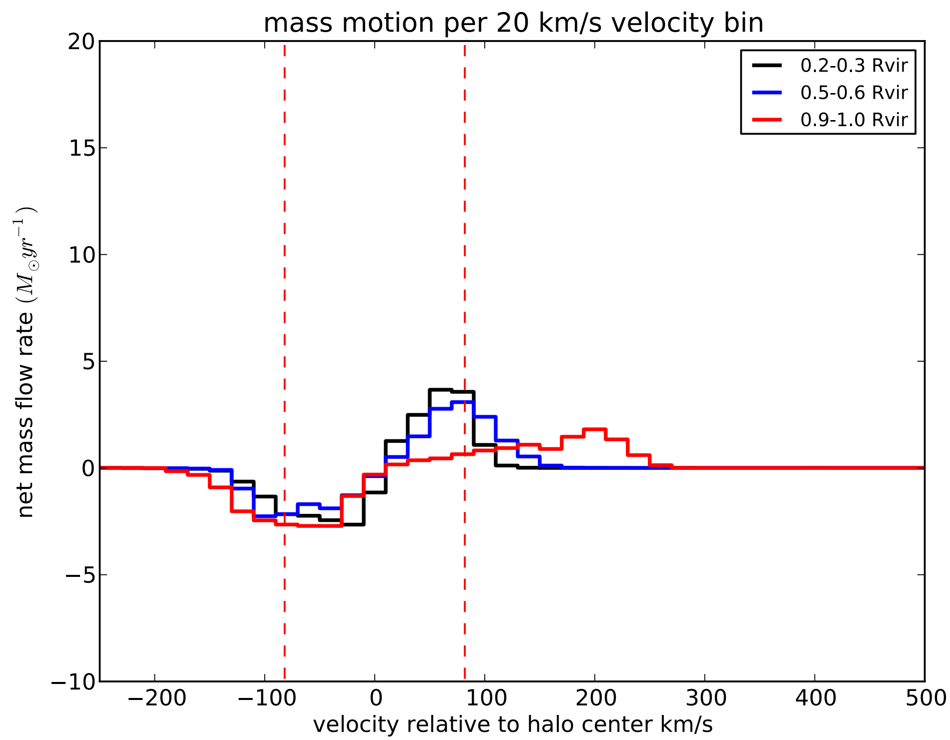
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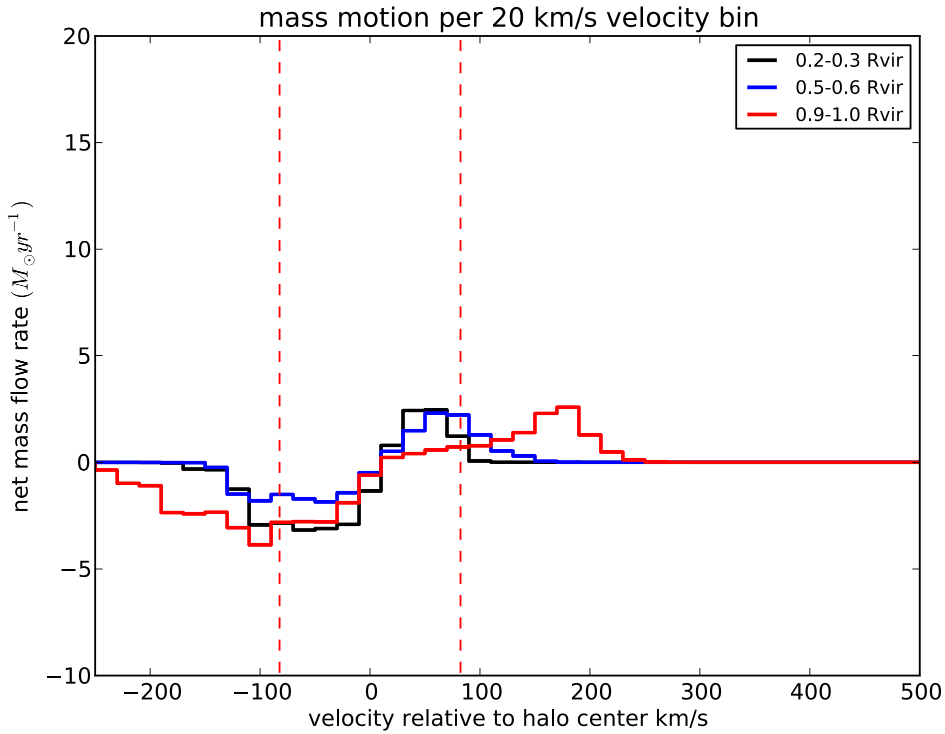

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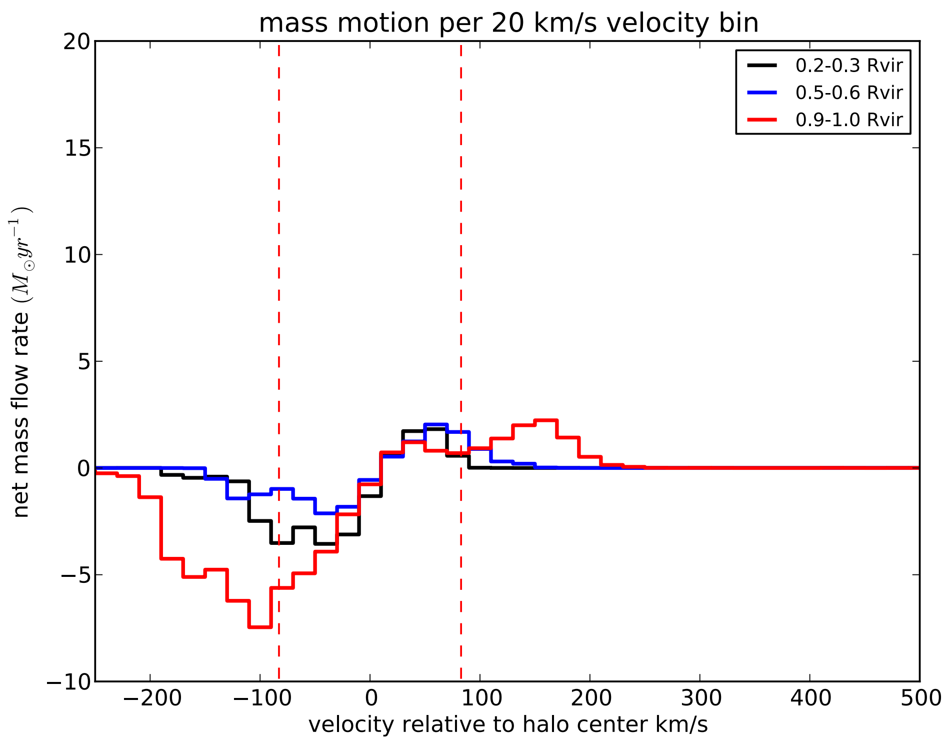

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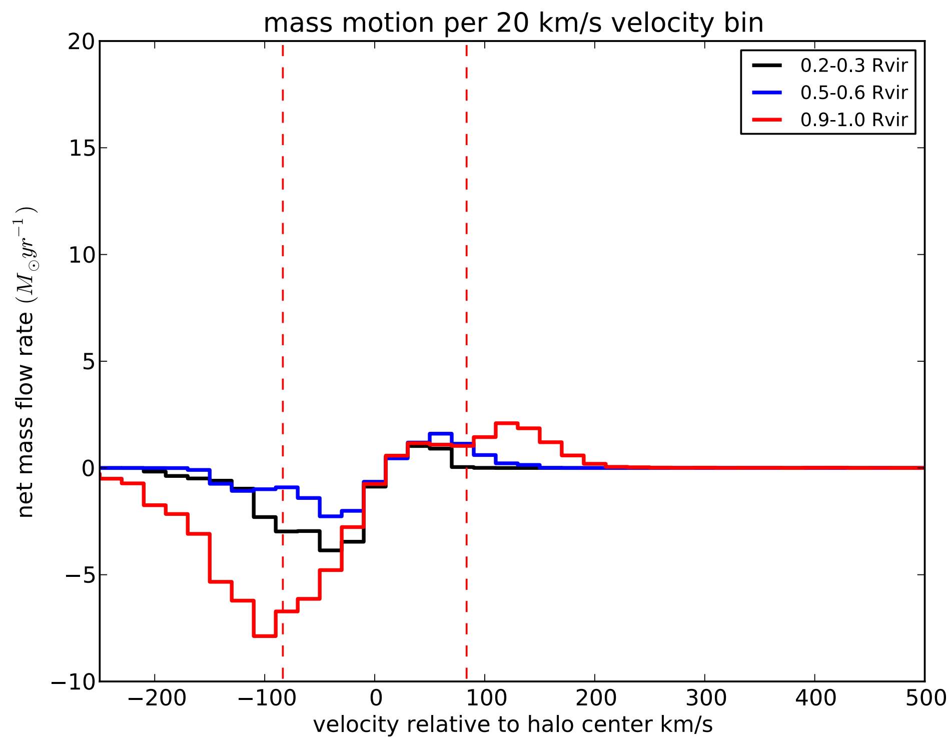
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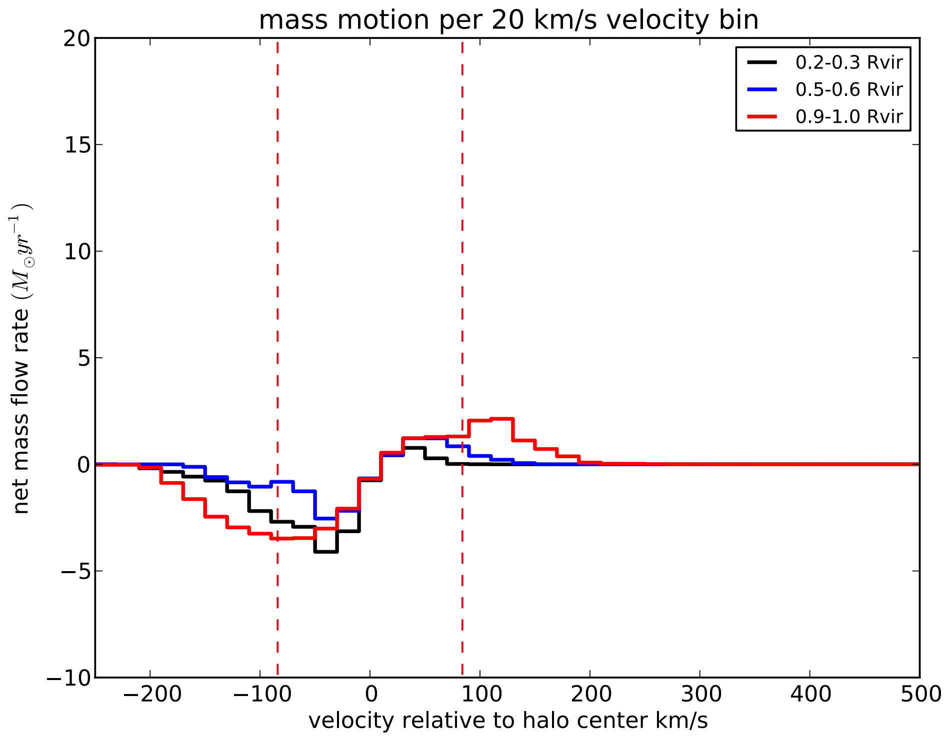
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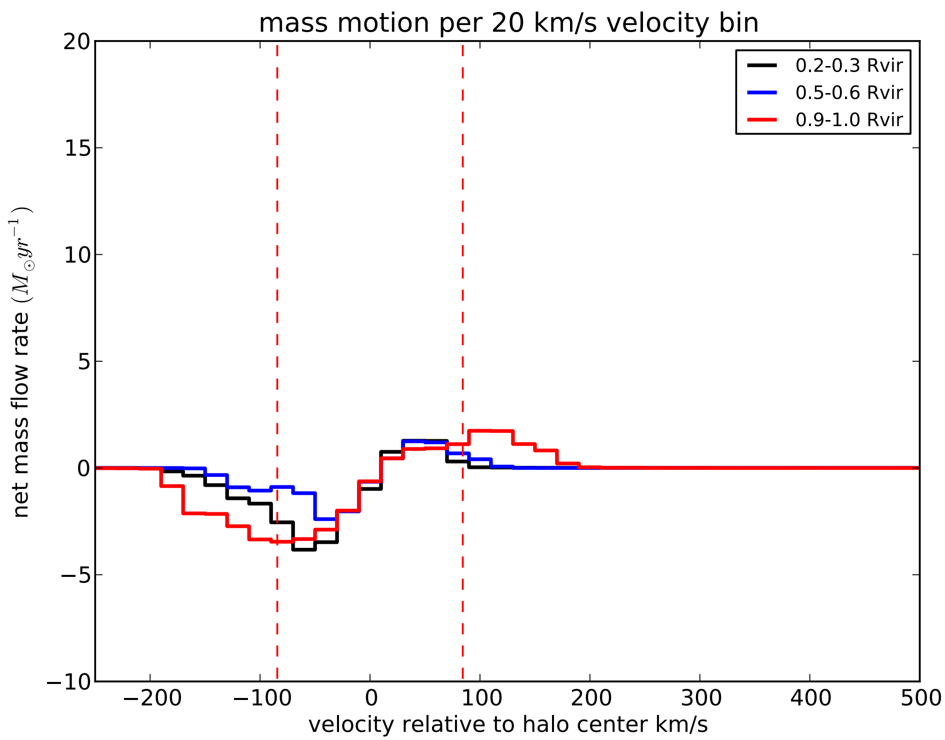
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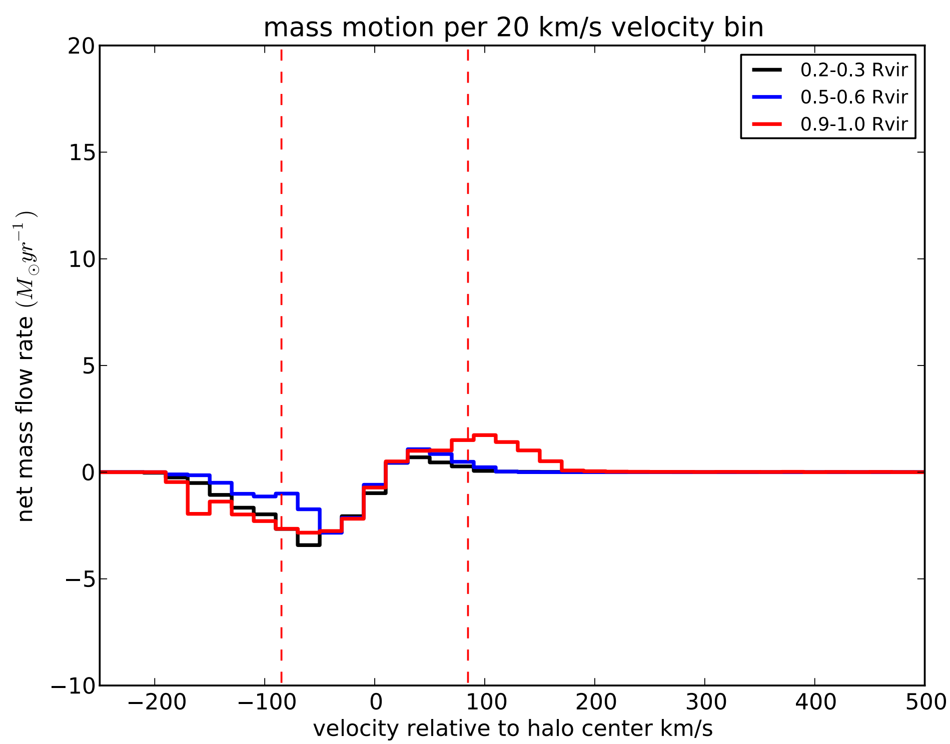

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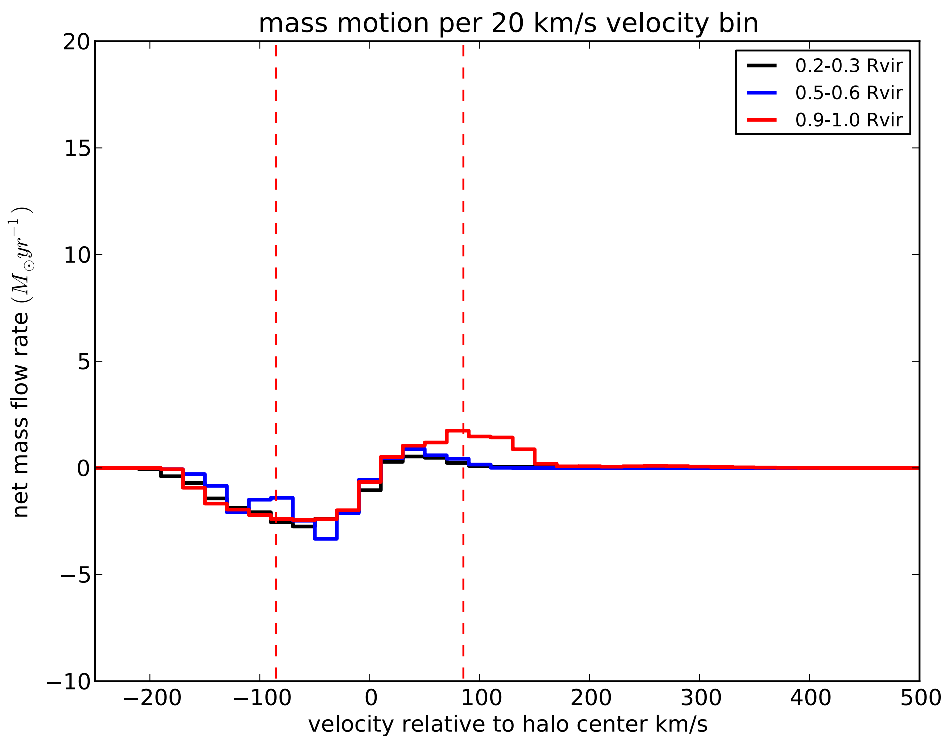

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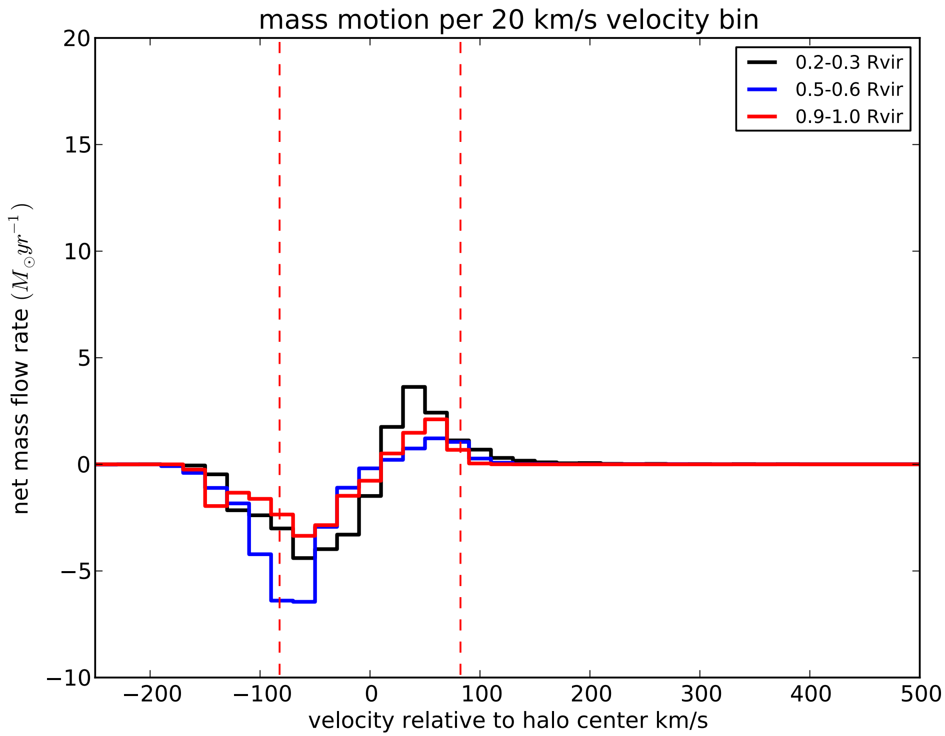

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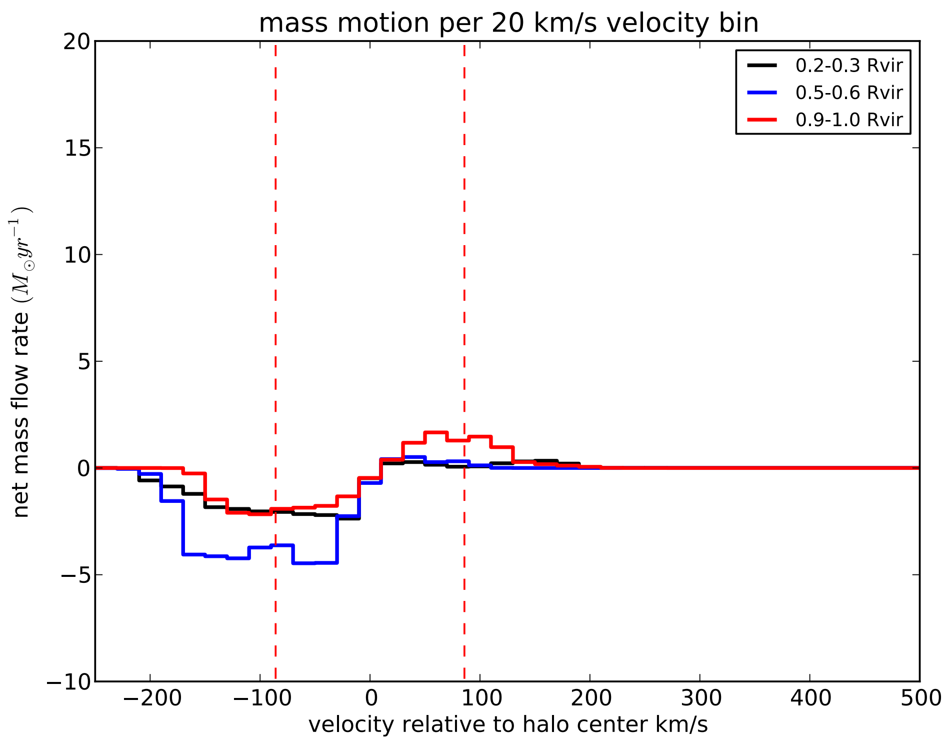
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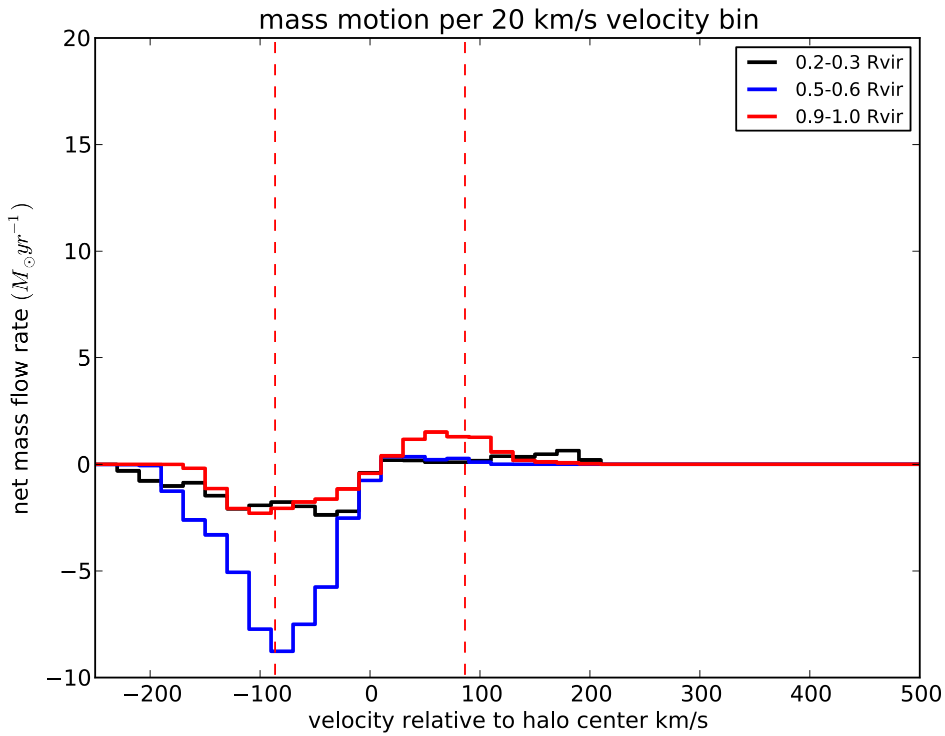
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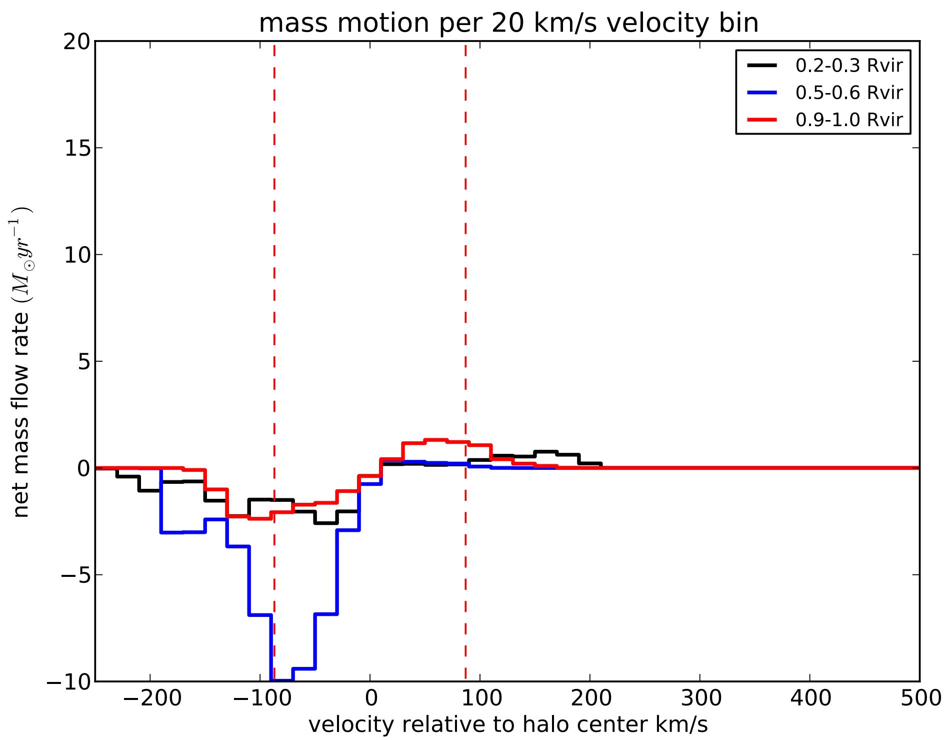

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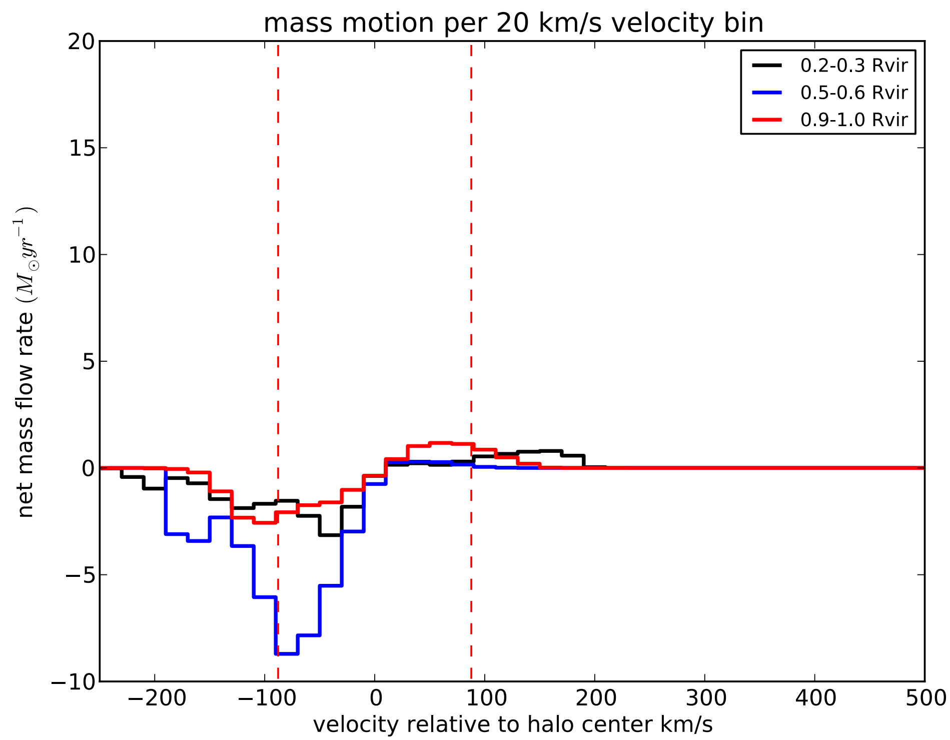
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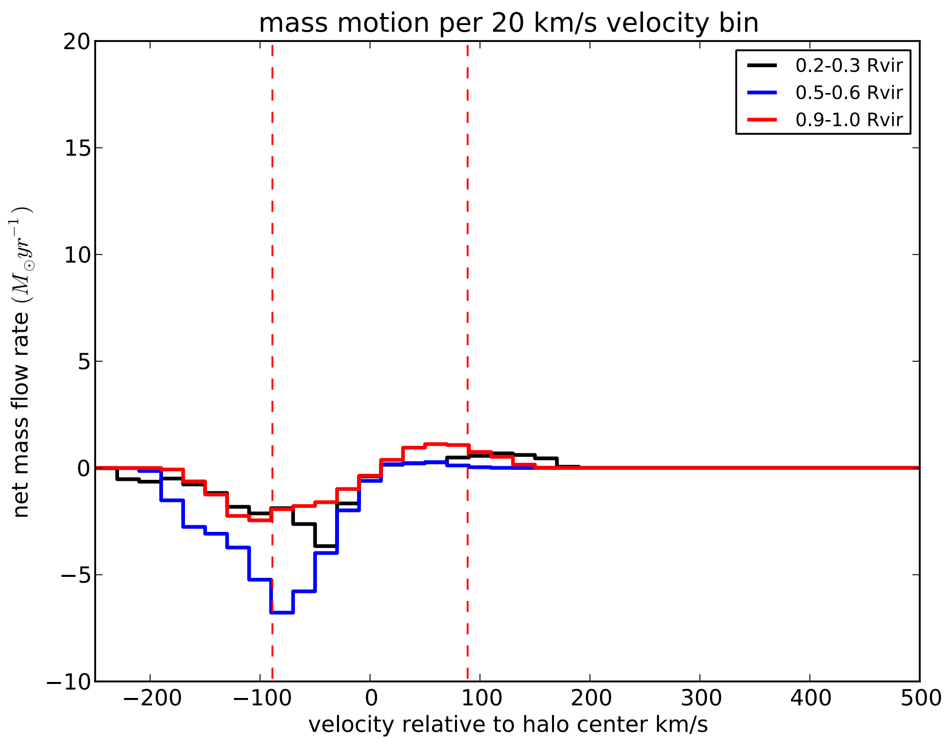
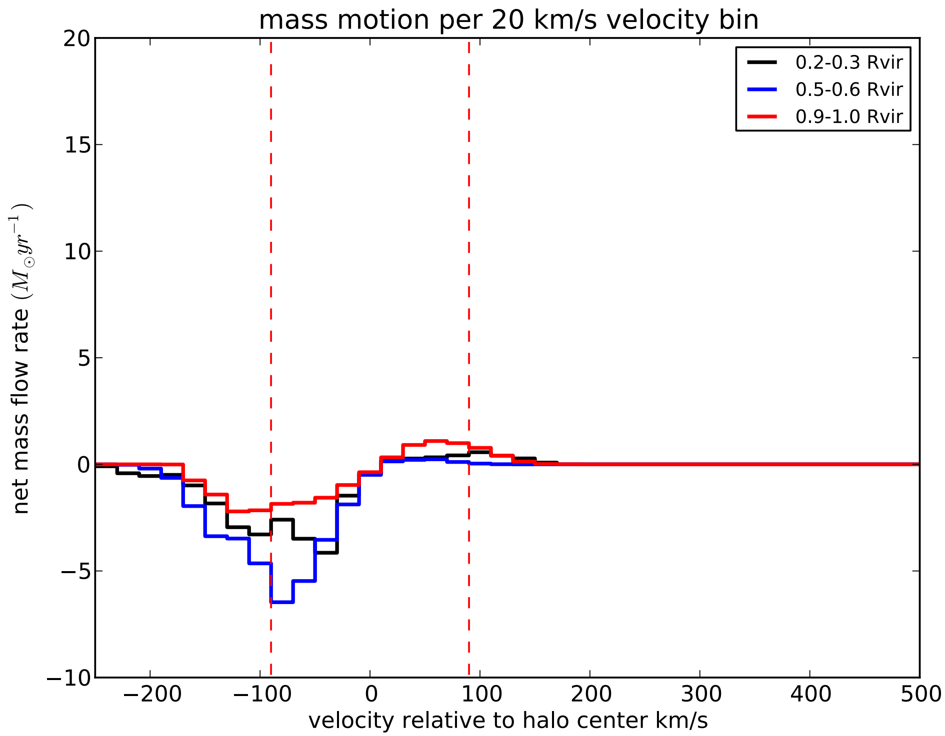


mass motion per 20 km/s velocity bin
0.2-0.3 Rvir
0.5-0.6 Rvir
0.9-1.0 Rvir
net mass flow rate $(M_{\odot} yr^{-1})$
velocity relative to halo center km/s
20
15
10
5
0
−5
−10
−200
−100
0
100
200
300
400
500



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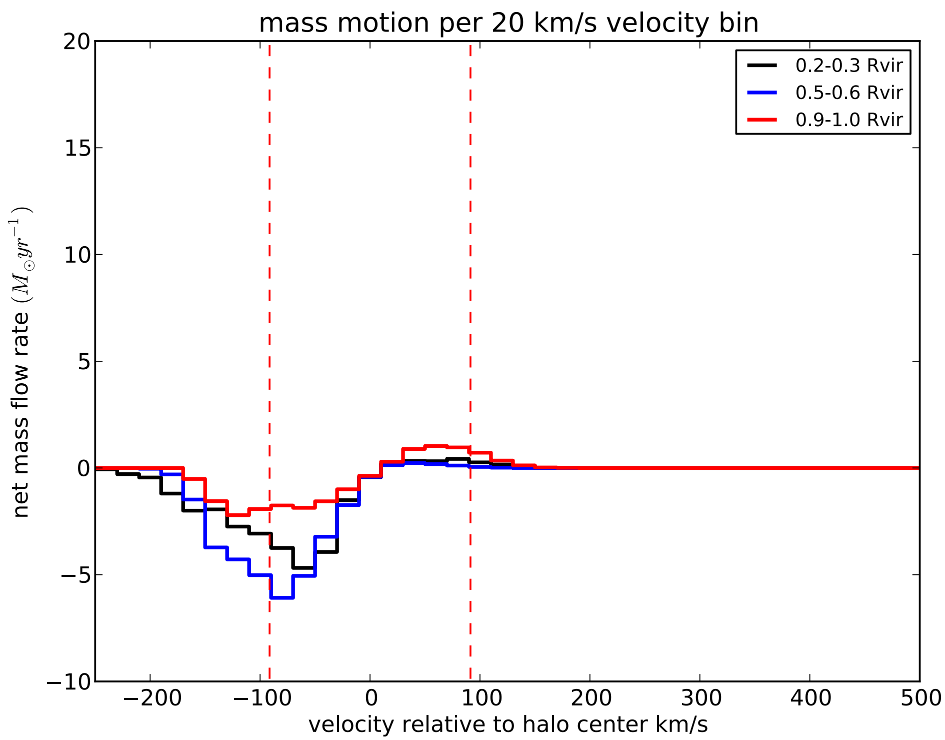

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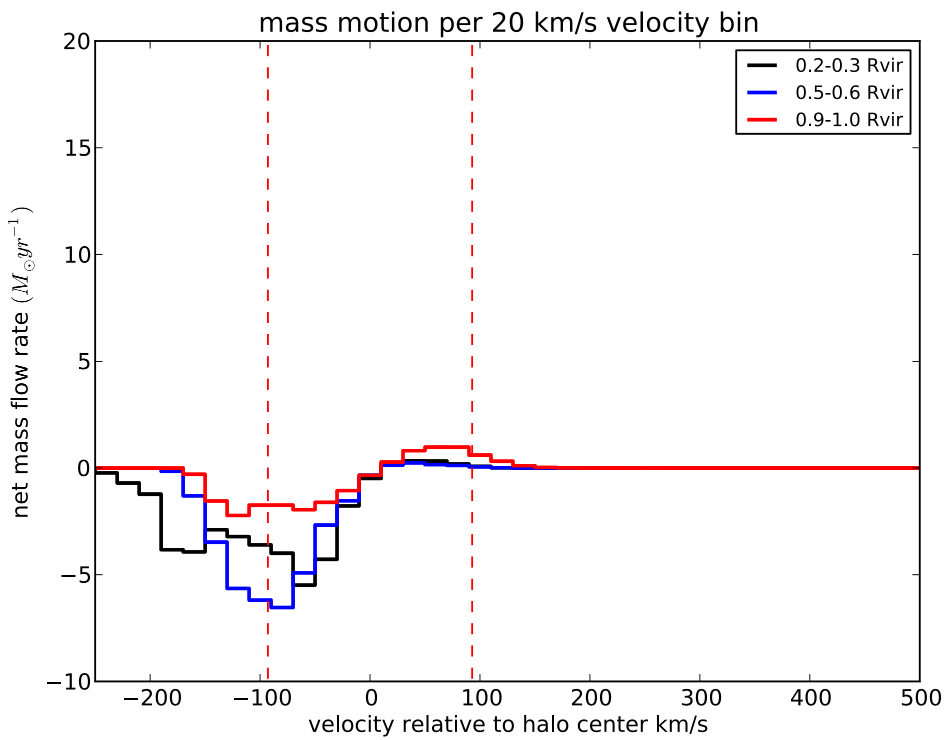
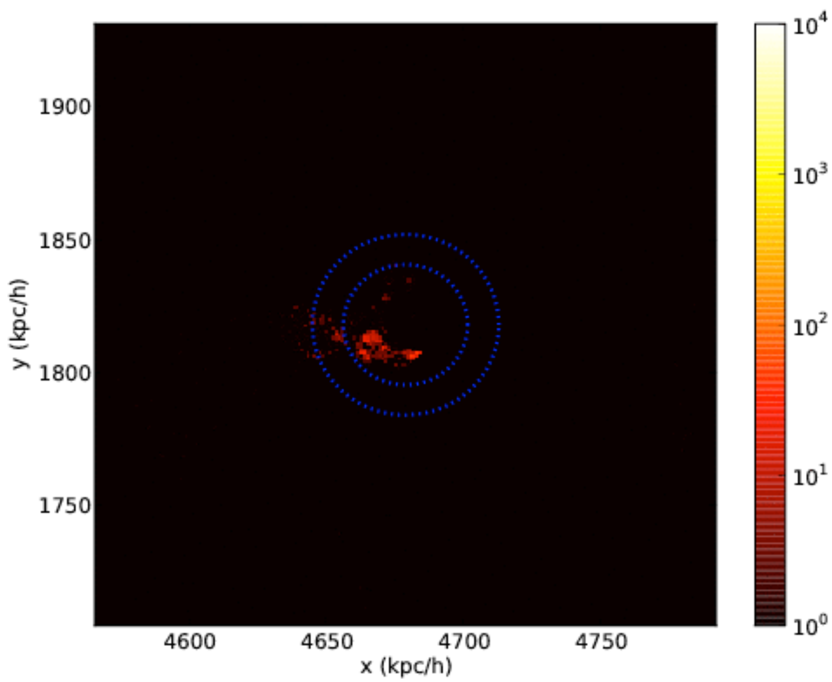
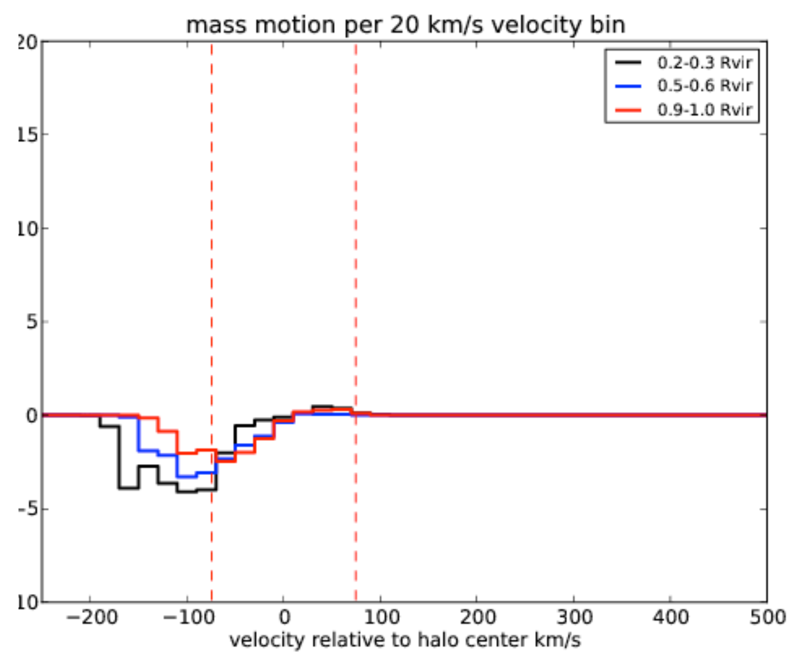


Infall is re-established..

- Infall-star formation-outflow cycle...
- Infall ~Vc: not easy to detect (in down-the barrel studies blended with ISM).
- Bulk of the outflow in inner halos has velocities ~$3\sigma_{1D}$; broadly consistent with observations (preliminary results, cf. Martin, Rubin, Steidel...)
- Most prominent outflows reach 5-10 σ_{1D}.
- Complex time evolution: individual snapshots can imply acceleration with radius but this can be misleading...





Conclusions

- Simulations with more detailed physics implementation produce multiphase winds.
- Winds successfully regulate galaxy growth by expelling large quantities of gas from galaxies, but much less from halos.
- Flux of material dominated by relatively cold component.
- Large velocity range, varies with episodes and other properties.
- Relatively small fraction of gas is able to escape halo: recycling of wind material is very important!