How Outflows *Feed* Galaxy Growth

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Galaxy Formation, Durham

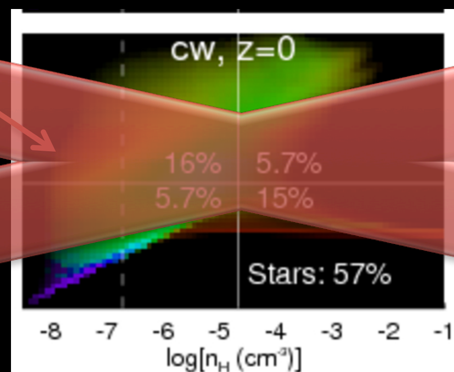
1. Opp. et al. 2010

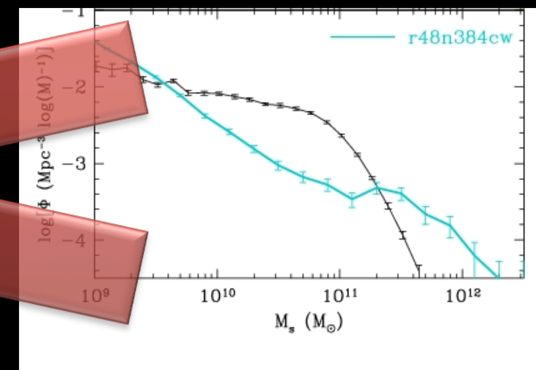
I'm mostly a quasar absorption line (QAL) person, *what gives me the right*[1] to tell you how galaxies assemble and grow?

1. "What give you the right?" is an acceptable question for me at the end of this talk.

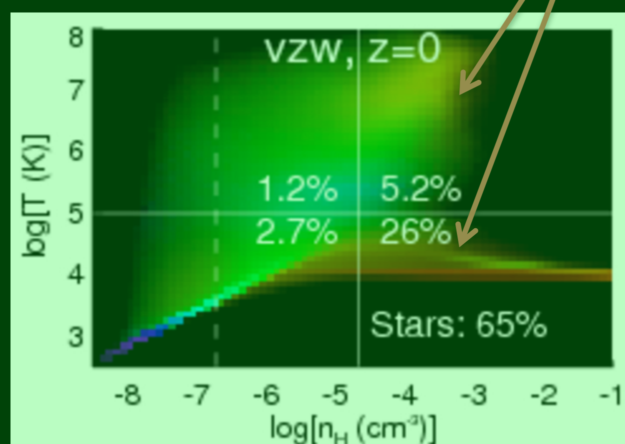
The main thing that I learned matching QAL statistics for CIV from z=6->0, OVI at low-z, etc… is that GSW-ejected metals remain close to galaxies!!

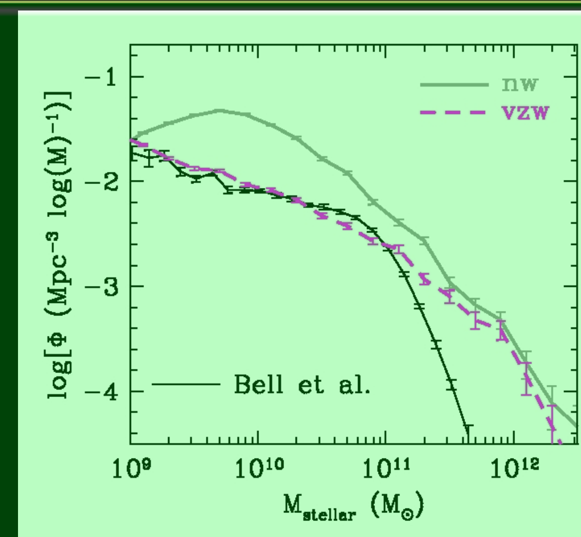
Constant wind, ε=1.0 (v_w=680 km/s, η=2)





Variable wind, ε_{ave}~0.4 (v_w~σ,η~σ^{-1})





Opp et al. 2011

Opp et al. 2010

Moderate variable wind (vzw) model has a <u>Holistic Advantage</u>

1) This model reproduces the observed z=0 galactic stellar mass function between $M=10^9$ - $5x10^{10}$ M_{sol}, and many more things!

   a.) See Romeel talk about the **Equilibrium Model** or read our latest papers (Davé, Opp., Finlator & Davé, Finlator, Opp. 2011).

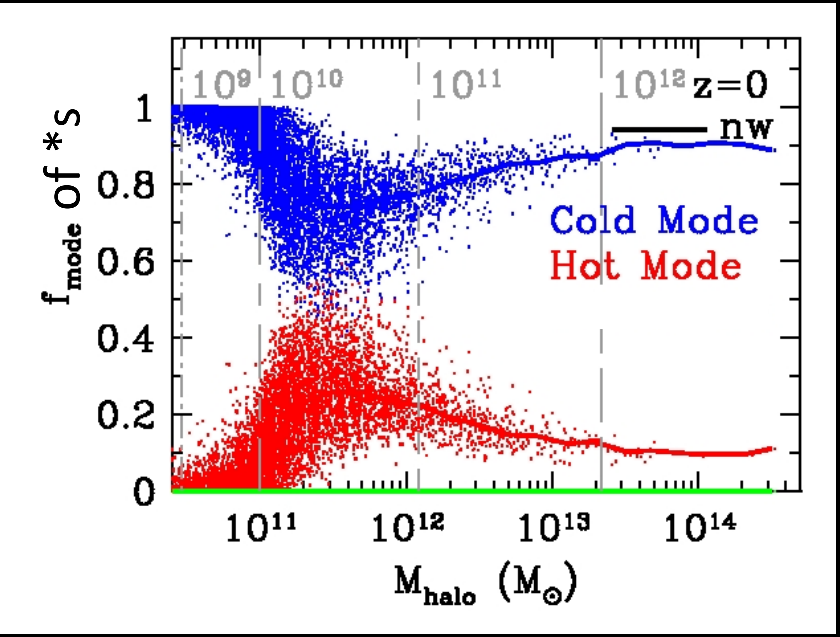
   b.) Make sure to talk to Kristian Finlator about the successes at high redshift.

2) These winds enrich the IGM to the observed levels, and stands up in rigorous comparisons to detailed QAL observations from z=6->0 (Opp. et al. 2006,08,09ab,11)

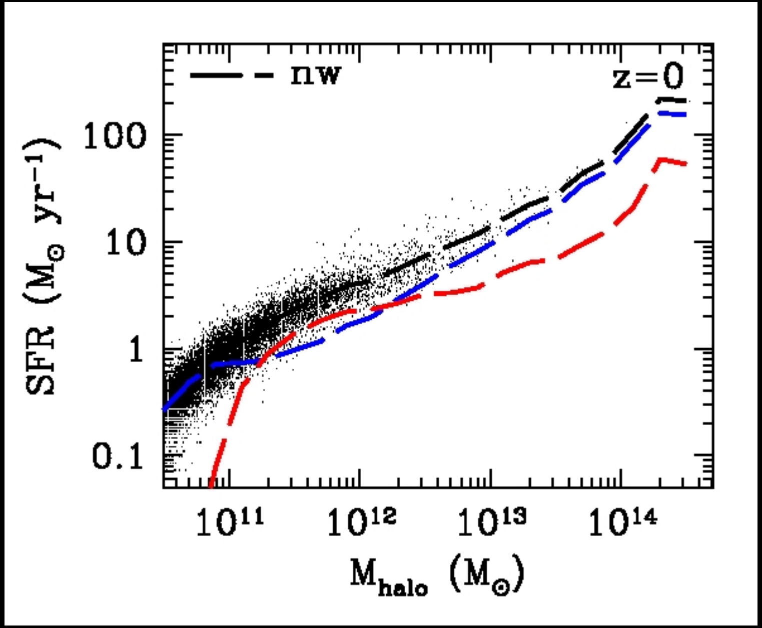
3) *Only Moderate Energy* required in our star-formation feedback model. Most galaxies need only 10-30% of SN energy coupled to kinetic winds.

How Do Galaxies Get Their Gas?™

Stellar Assembly of Galaxies



Accretion & Star Formation



Opp. et al. 2010: Same results as Kereš et al. 2009a in sims. with no winds (nw):

1. Assembly primarily via cold mode accretion (T_{acc}<2.5x10^5 K).
2. Larger accretion rates at higher mass at all redshifts.
3. SFRs for a given mass halo declines with redshift.

™ Neal Katz & Dušan Kereš

How Do Galaxies Get Their Gas?™

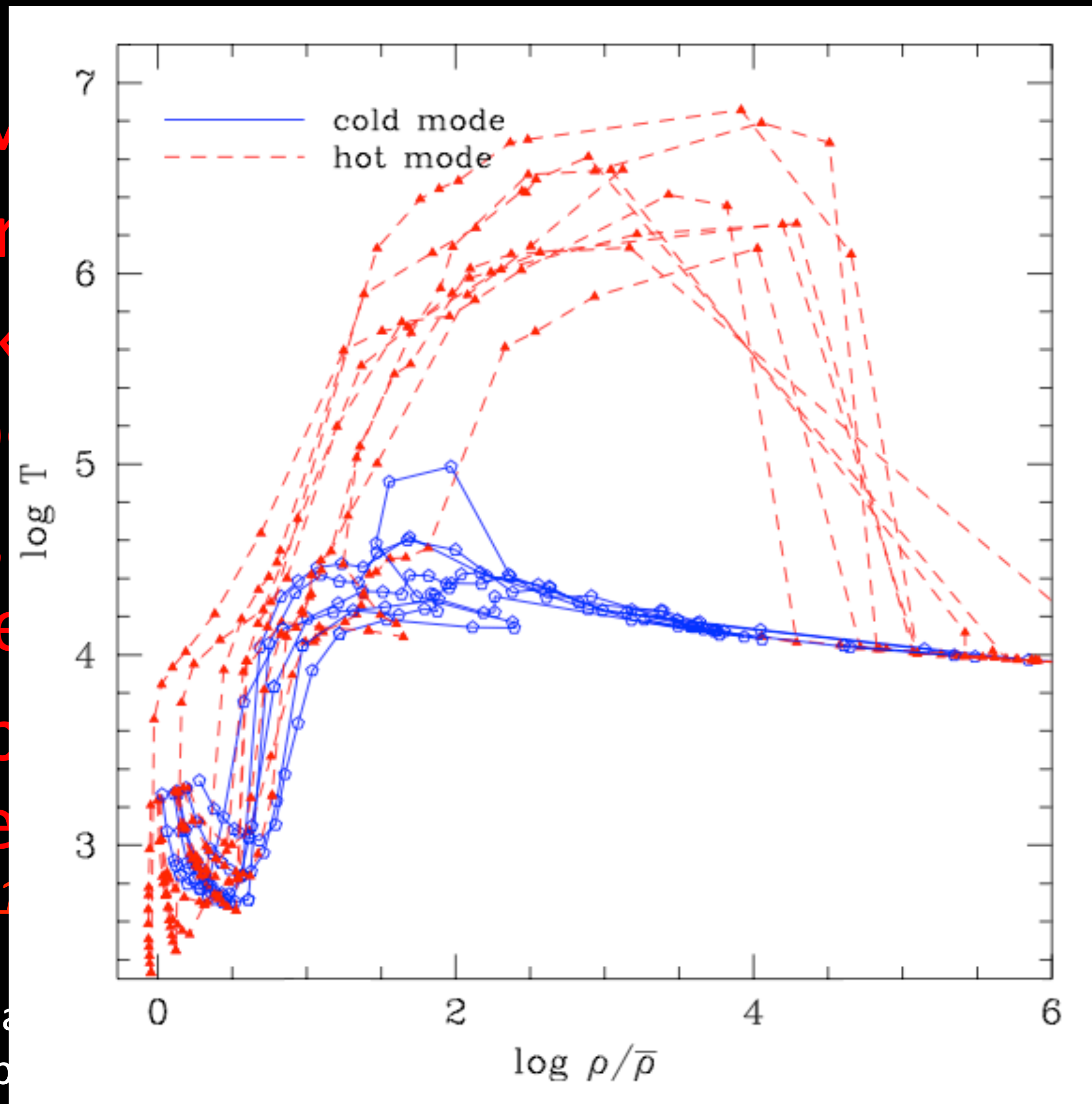
- Hot Mode
- Spherical accretion
- Shock to virial temperature
- Rees, Ostriker, White, Silk
- Stopped via Preventative *(Velvet Rope[1])* Feedback

- Cold Mode
- Smooth, filamentary accretion
- Below T_{vir}, $<2.5\times10^5$ K
- Kereš, Katz, Birnboim, Dekel
- Stopped via Ejective *(Bouncer[1])* Feedback

1. Neal Katz says (*from experience?)* that you are either prevented from going into a club by a velvet rope, or you're kicked out by the bouncer once you get in.

How Do Galaxies Get Their Gas?™

- Hot M
- Spher
- Shock temp
- Rees, White
- Stopp Preve *Rope-*



mentary

.5x10^5 K

irnboim,

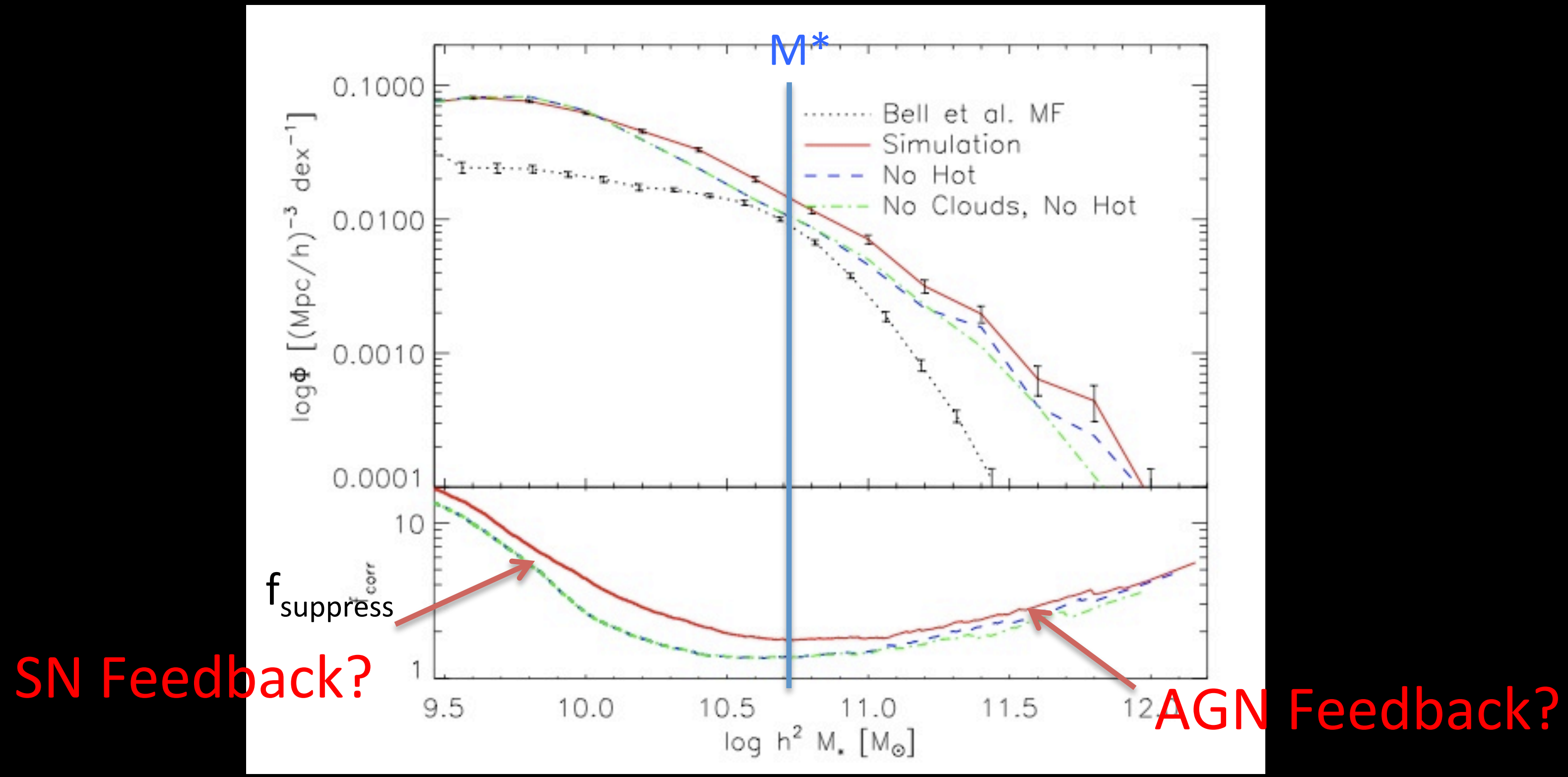
jective

eedback

1. Nea … ed from going into a club … e you get in.

You need ejective/bouncer feedback ***at all masses*** to solve the over-cooling problem.

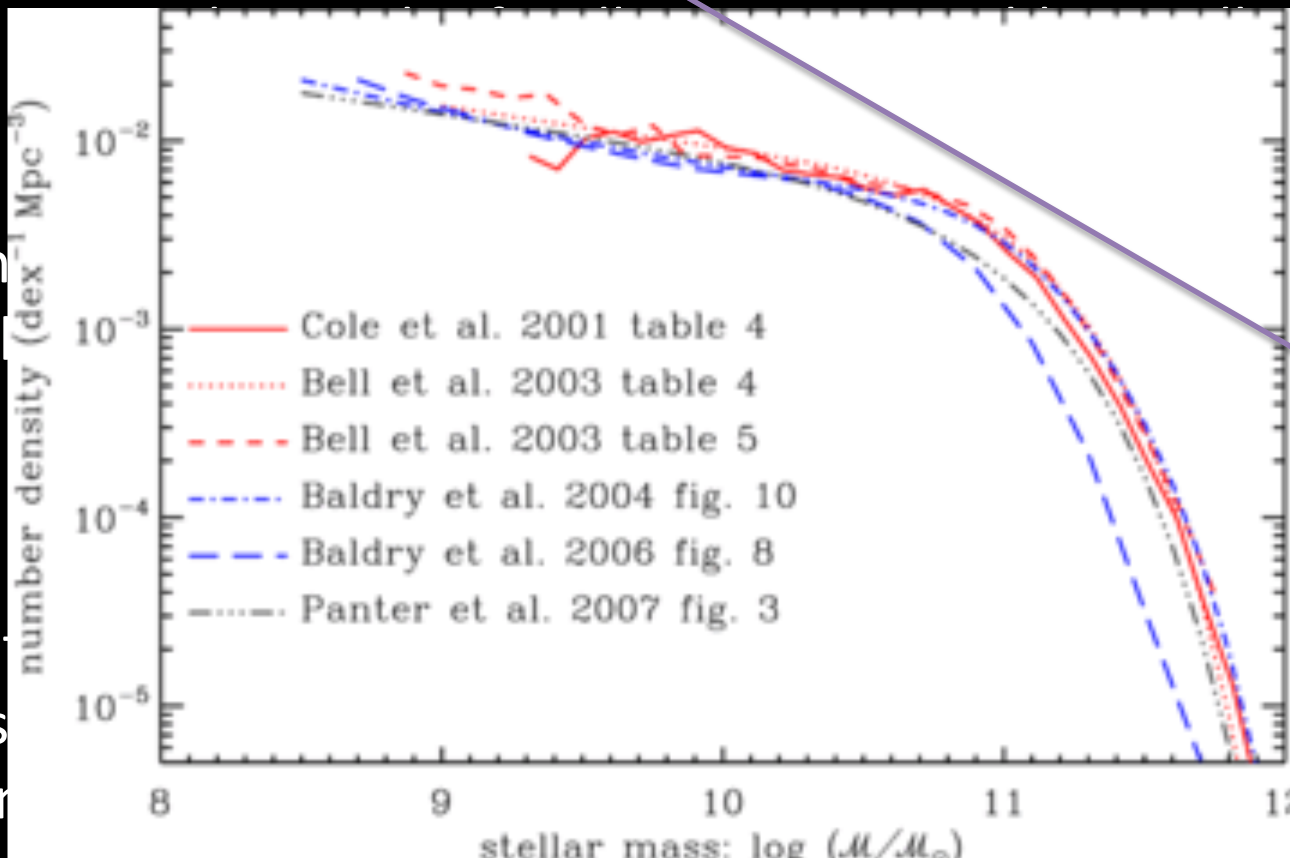
- Star formation too efficient in analytical treatments (e.g White & Frenk 1991) and simulations (e.g. Kereš 2009b)
  - z=0 stellar baryon fraction too high (observed ~5-8%)
  - cosmological simulations w/o feedback (≥ 18-20%)



Kereš et al. 2009b- rank order galaxies by mass, calculate feedback required

The z=0 Galactic Stellar Mass Function (GSMF)

A fundamental prediction of galaxy formation theory over a Hubble … fitted using a … .



The Sch… ating how gal…

1\.
2\.
3\. … e α is -1

May als… nter functio… eeper mass function for dwarf galaxies?

The z=0 Galactic Stellar Mass Function (GSMF)

A fundamental prediction of galaxy formation theory over a Hubble time. The result of stellar mass assembly usually fitted using a Schechter function: $dn/d\log M \sim M^{\alpha} \exp(-M/M^*)$.

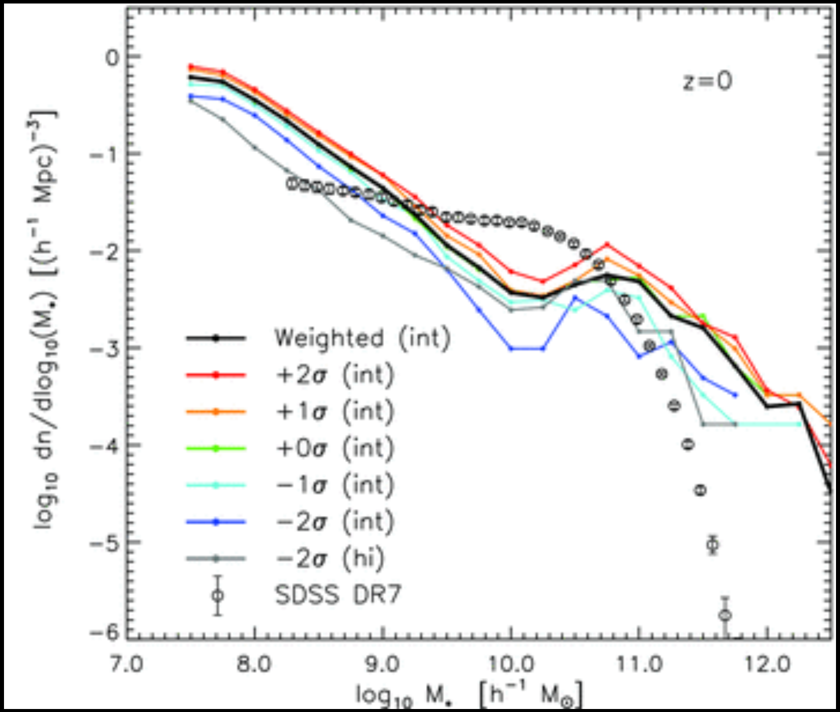
The Schechter function holds a few distinct features indicating how galaxies assemble over a Hubble time-

1. A steep exponential cutoff at high mass.
2. A preferred mass for star formation at $\sim M^*$
3. A shallower faint-end slope, $dn/d\log M = M^{\alpha}$ where α is -1 to -1.3, compare to mass function of haloes $\alpha \sim -2$

May also not be a pure Schechter function (double Schechter functions are favored by Baldry et al. 2008 and others), steeper mass function for dwarf galaxies?

z=0 Galaxy Stellar Mass Functions in other

Simulations



Crain et al. 2009- GIMIC Simulations

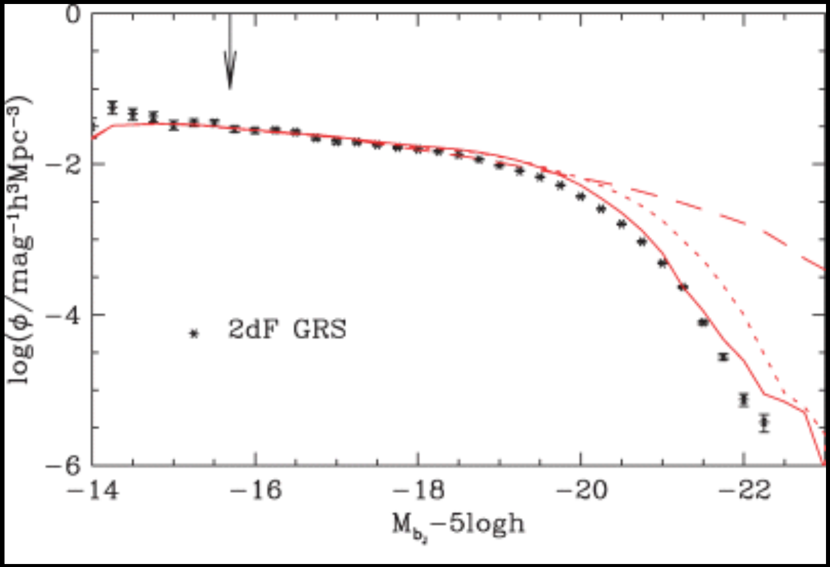
Costant wind sim:

ε=1.5, η = 4

v_{wind} = 600 km/s

p.s. most OWLS sims. are similar

SAMs



Bower et al. 2006/2009 SAM

$\eta \sim \sigma^b$

Where b~-3

v_{wind} not a parameter

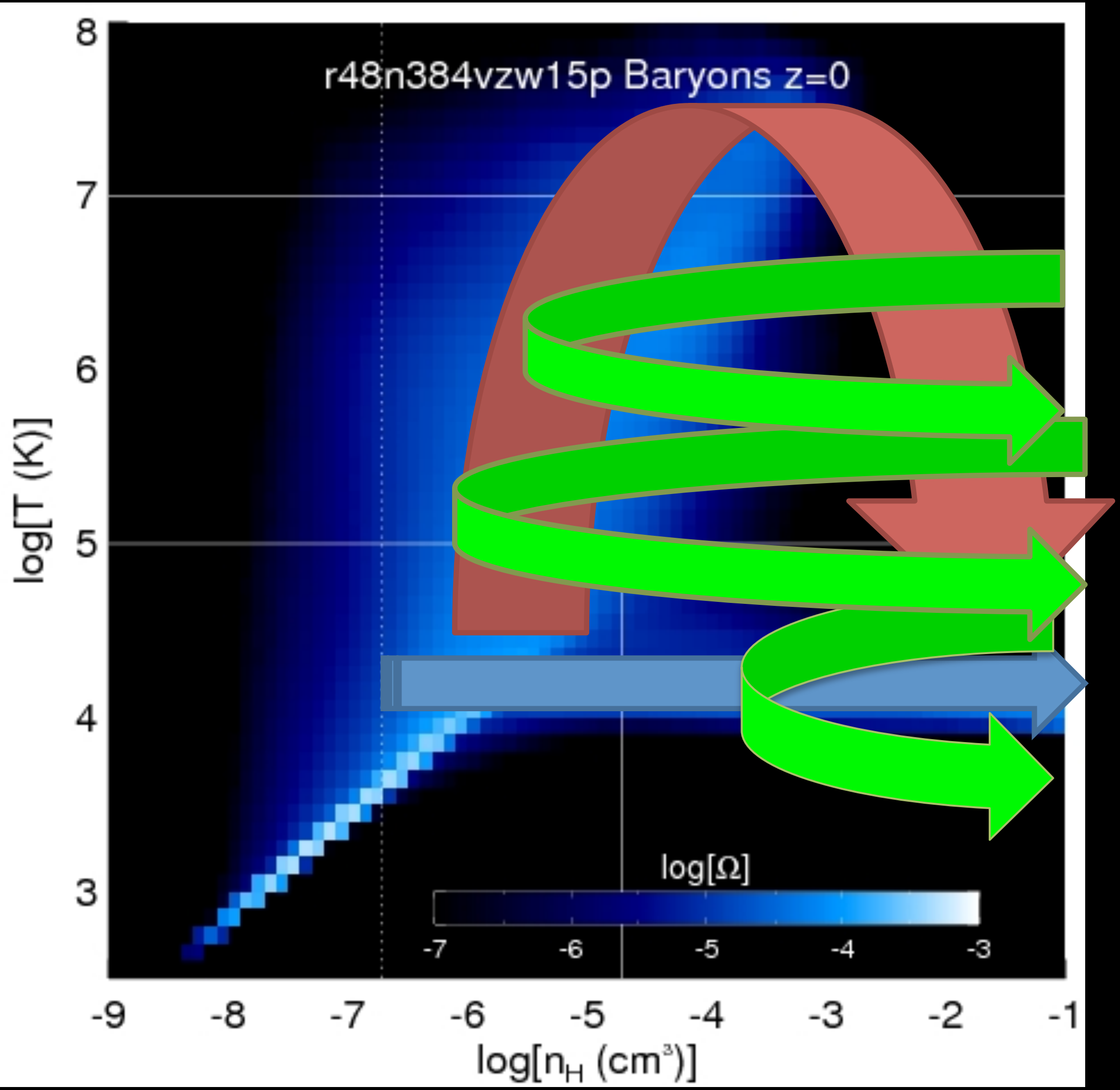
Instead t_{rec}

Thanks Durham for confronting GSMF's!

Galaxy Formation: The Third Way

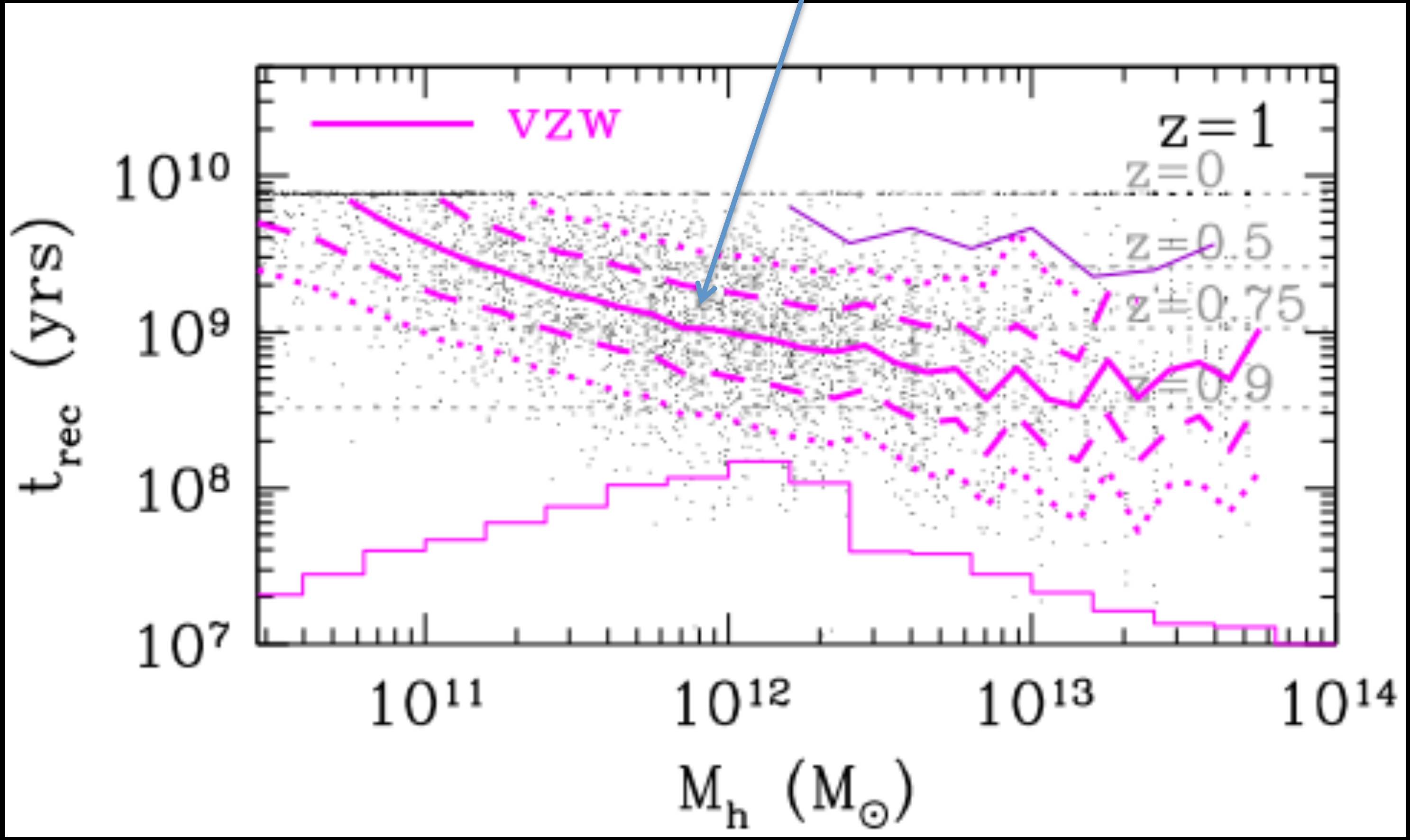
- A new mode defines how galaxies are formed.
  - Hot
  - Cold

  & Wind?



Tracking Wind Mode in Simulations with Feedback

Differential Recycling- Tracking wind particles shows they return to more massive galaxies faster.



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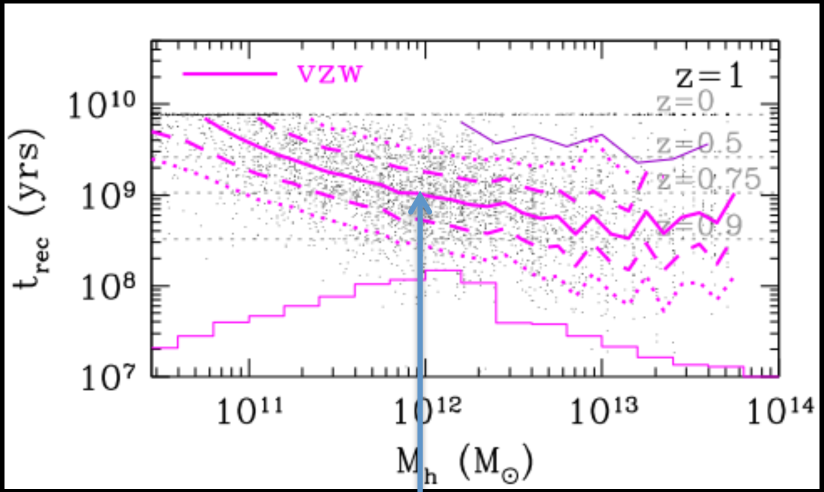

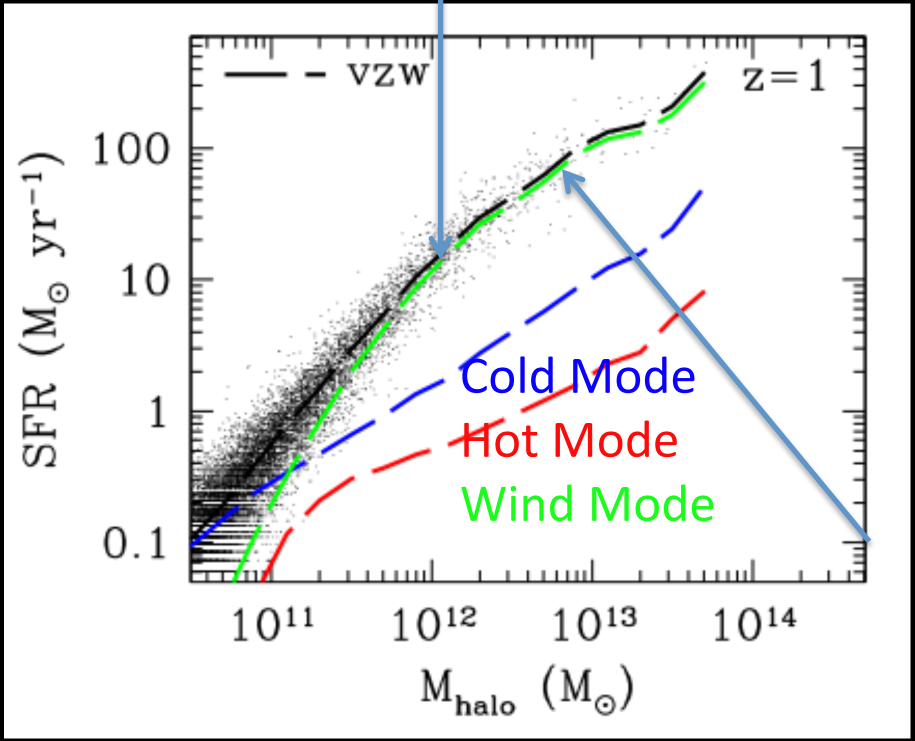

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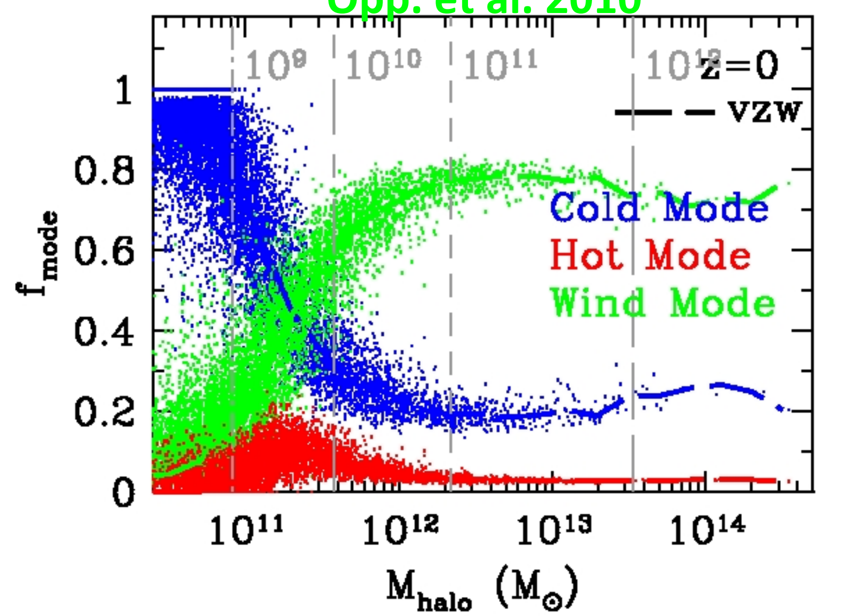


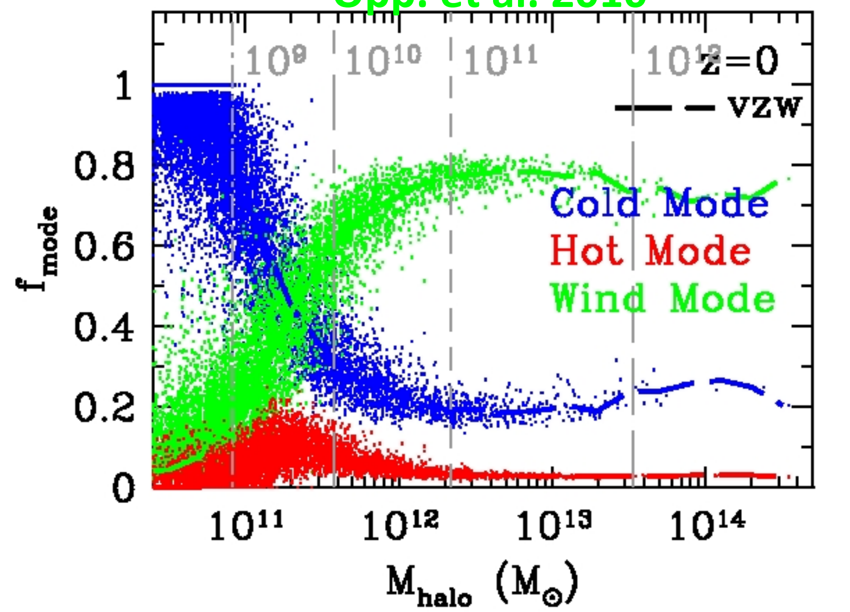
Recycled Wind Accretion- Recycled winds dominate ***accretion and SF*** where winds recycle rapidly.

Tracking Wind Mode in Simulations with Feedback

- ***Majority of stars formed from gas that has been ejected in a wind.***
- Where $t_{rec} <\sim t_{Hubble}$ recycled wind accretion dominates overall accretion, star formation, and galaxy growth.
- Favors growth via wind mode at late times and for more massive galaxies.

Differential Recycling- Tracking wind particles shows they return to more massive galaxies faster.

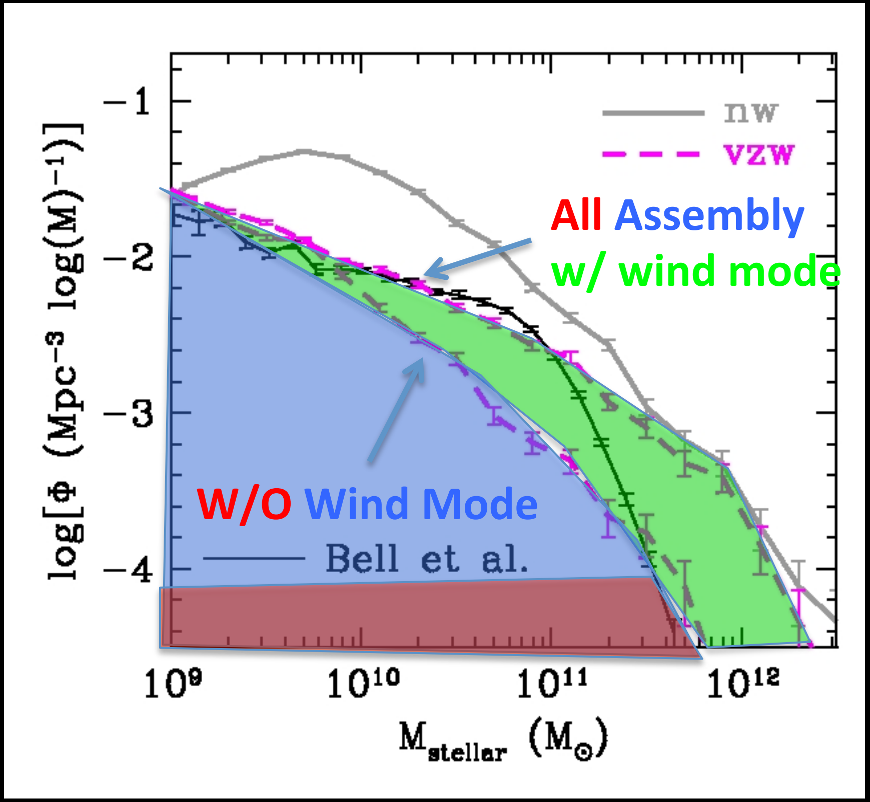
Opp. et al. 2010



Recycled Wind Accretion- Recycled winds dominate ***accretion and SF*** where winds recycle rapidly.

The Three Mode z=0 GSMF

- Mass-dependent recycling-> wind mode accretion-> galaxy growth biased to higher masses.
- Wind mode flattens the GSMF below M* so that slope is $M^{-1.4}$!
- Without wind mode, GSMF slope is M^{-2} like DM Halo MF.



Opp. et al. 2010

Our GSW wind prescription need only σ^{-1}, and avoid needing $\sigma^{-3.2}$ like the Durham GALFORM Model, or $\sigma^{-3.5}$ or $\sigma^{-4.0}$ like Guo et al. 2011.

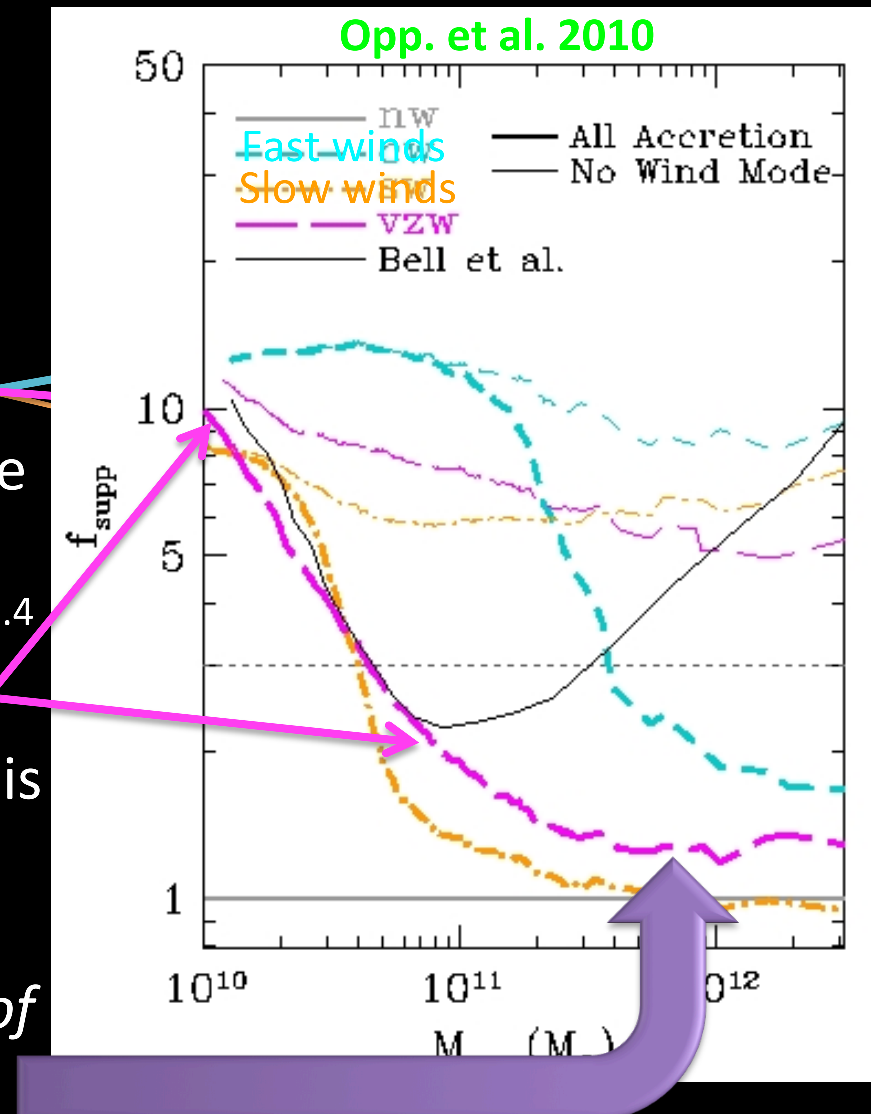
How galaxies are built: 1) with only cold+hot mode and then 2) with all 3 Modes.

Rank order galaxies by mass, compare f_{supp} relative to no wind simulation, just like Kereš 2009b.

1) With only cold+hot mode, wind simulations have similarly looking GSMFs. All have $dn/d\log M \sim M^{-2}$.

2) Wind Recycling adds much more diversity and creates the faint end slope of the GSMF: $dn/d\log M \sim M^{-1.4}$ for our favored vzw wind model.

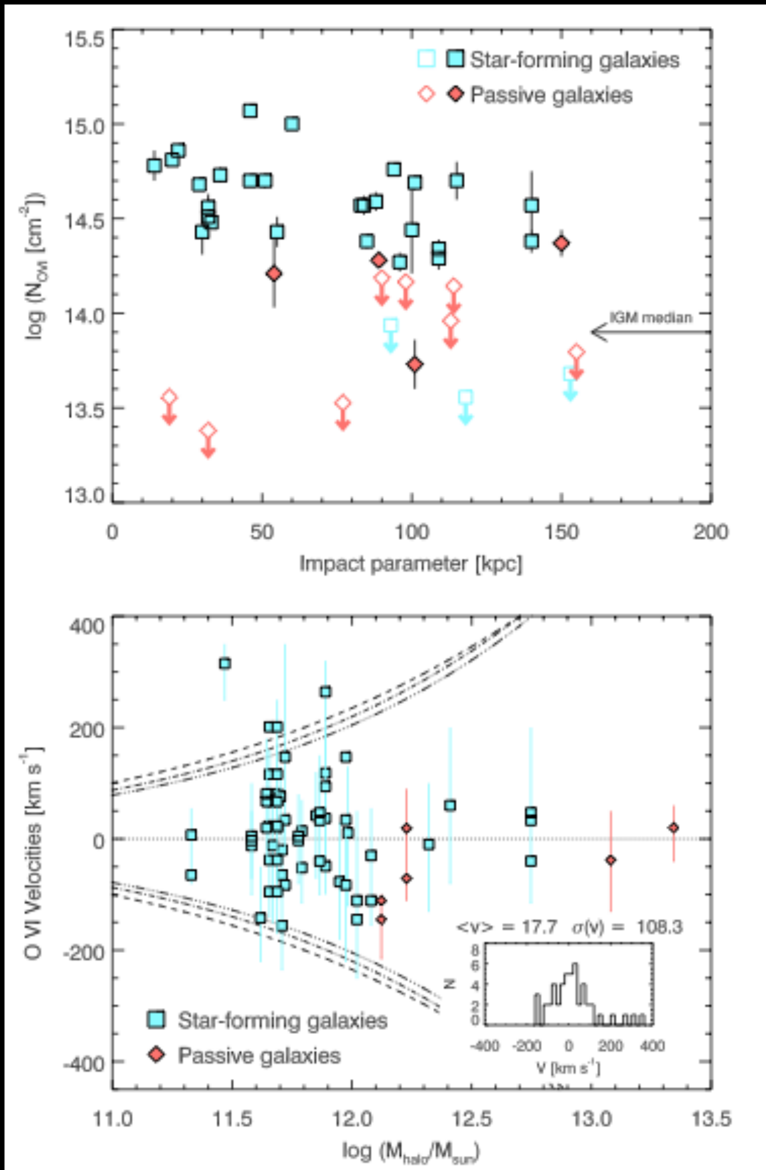
3) **Jared Gabor** is finishing his thesis on how to suppress the high-mass end via mass-dependent (AGN) feedback ***and*** *physical treatment of gas in halos to prevent accretion.*



The SUPERPOWERS of GSW Feedback

Review of Opp., Dave, Keres, Fardal, Katz, Kollmeier, Weinberg 2010	**Constant Wind (cw)** *More wrong*	**Variable Wind (vzw)** *More right*
1. Ejective Feedback	η=2: 2x as many winds as *'s formed	η=1/σ: small galaxies with larger mass loading is key!
2. Preventative Feedback	680 km/s winds suppress accretion by cold streams.	Low/moderate velocities do little to suppress streams.
3. Recycled Wind Mode	Dominates only in massive halos: $10^{12.5}$ M_{sol}	Dominates over hot +cold. Main growth for $M_{halo}>10^{11.3}$ M_{sol}
Suppression of >M* Galaxies	More needed even with extreme GSWs to suppress massive gal's.	*What Jared can do for you*: suppress >M* gals + make red sequence.

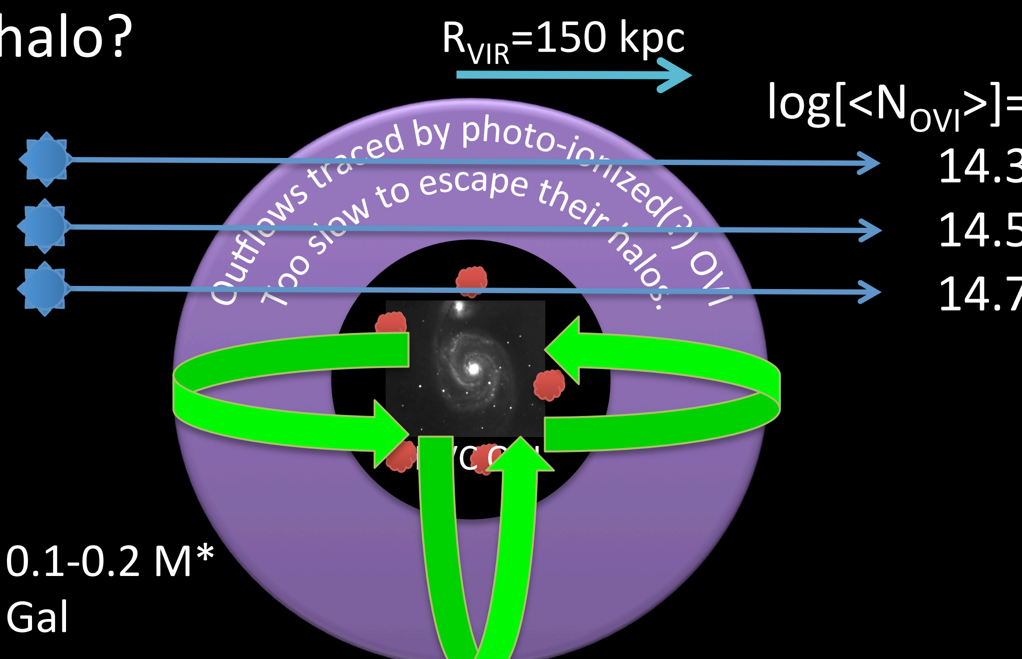
Evidence for Wind Mode? How about an ISM's worth of gas in halos of SF galaxies!!



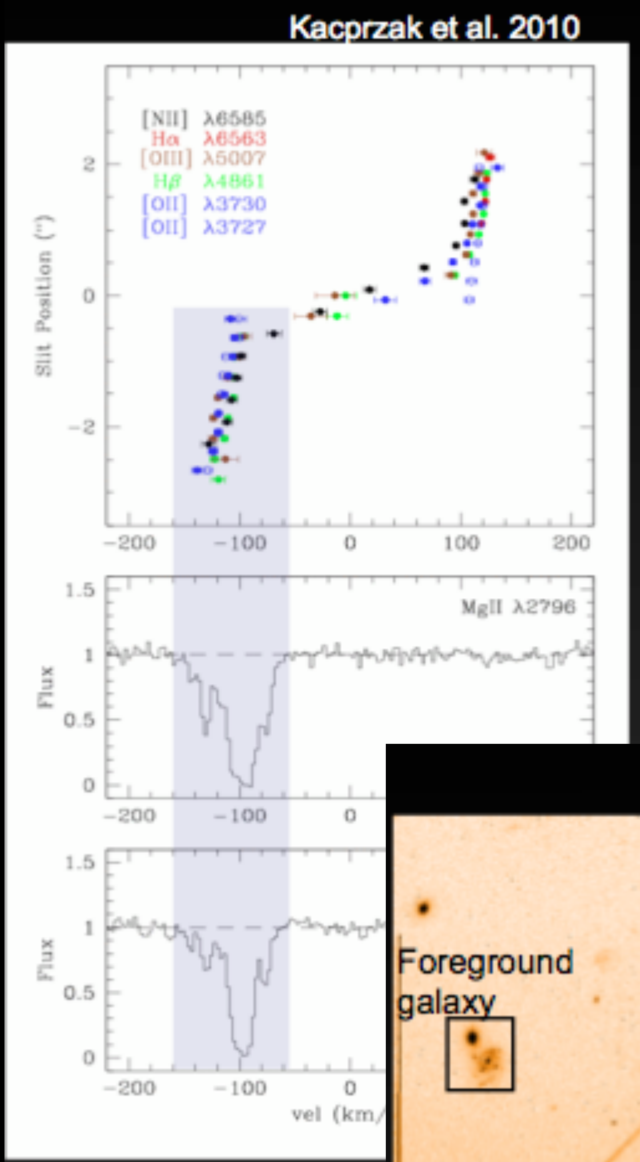
Tumlinson et al. OVI COS Project, submitted to Science.

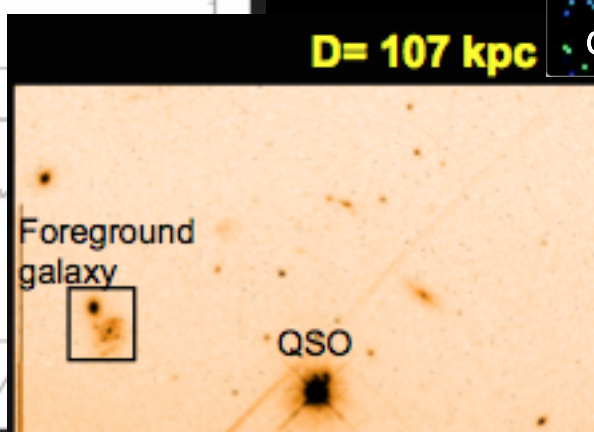
THIS IS A BIG DEAL: ***actual observations*** showing $10^{9.3\text{-}10}$ $M_\odot$ of $Z_\odot$ gas at 20-150 kpc and below the escape velocity.

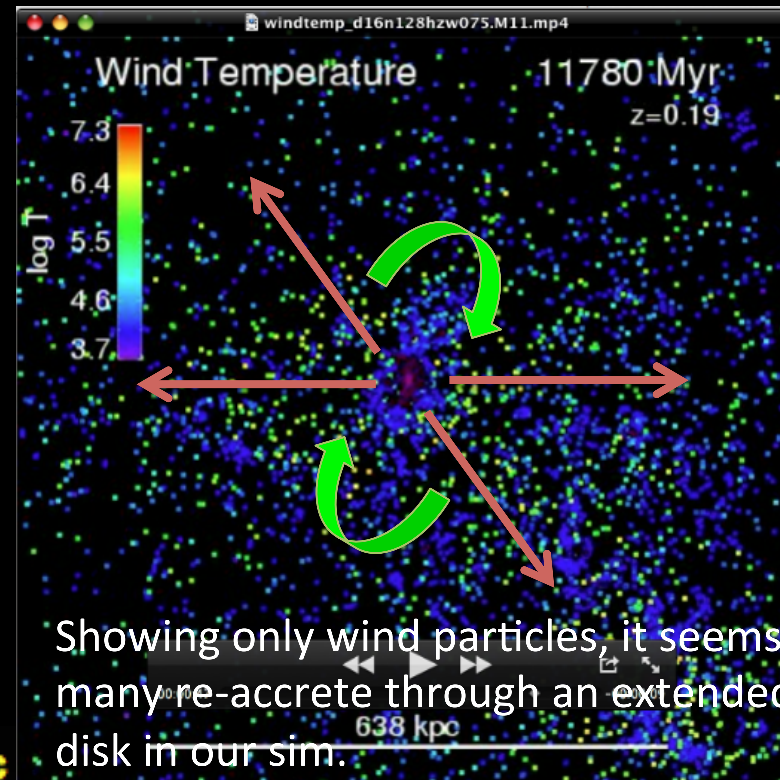
-Does it fall back onto galaxy or join the halo?



More evidence for Wind Mode? Glenn Kacprzak's observations of Mg II rotating+accreting disks.







THIS IS ALSO A BIG DEAL: ***ask Glenn*** about why this metal-enriched gas appears to not just be rotating but accreting.

Summary Points

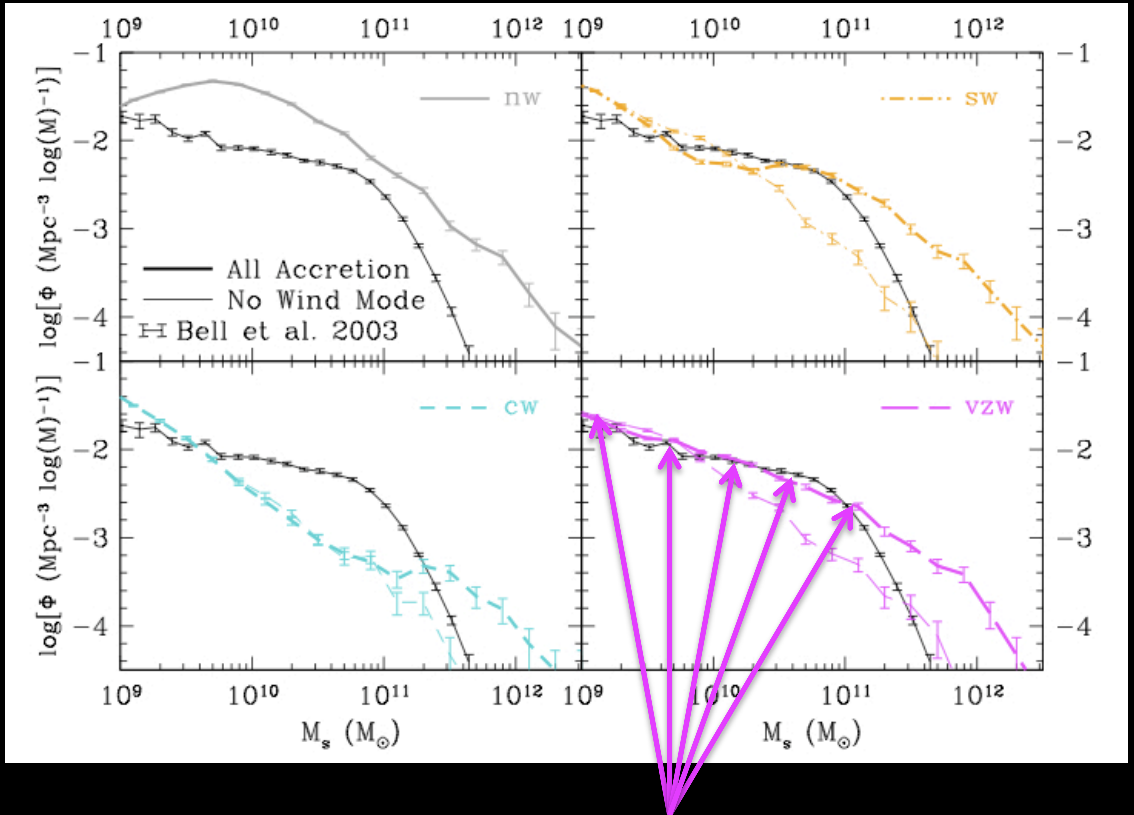
1. A wind model first constrained by fitting metal QALs at high-z gets the masses of the z=0 GSMF right within 0.1 dex over the range $M_*=10^9$-$10^{10.6}$ M_{sol}.
2. Moderate feedback leaves metals close to galaxies, where they can easily recycle onto galaxies. This is heavily mass dependent, hence **mass-dependent differential recycling** leads to **recycled wind accretion** dominating mass assembly more as M_* increases, and ***shaping the GSMF***.
3. Exciting new galaxy-absorber observations are changing our view of how far outflows go and where accretion/ re-accretion may come from.

One last note: A hydro simulation finds a solution to the faint-end GSMF slope that lies outside the parameter space explored by current SAMs. SAMs require hydro-informed parameter spaces to explore.

Thank You to the conference organizers and Durham!!!

Breaking the Degeneracy of Metal Lines: the z=0 Galactic Mass Function

Opp., Davé, Kereš, Fardal, Katz, Kollmeier, Weinberg 2010



One way to break this degeneracy: look at a completely different observation:
The z=0 galactic stellar mass function of momentum-conserved feedback provides best fit to galaxies $M_* < 5 \times 10^{10}$ $M_\odot$ (Opp. et al. 2010).

These are the primary enrichers of the IGM: Galaxies below M*

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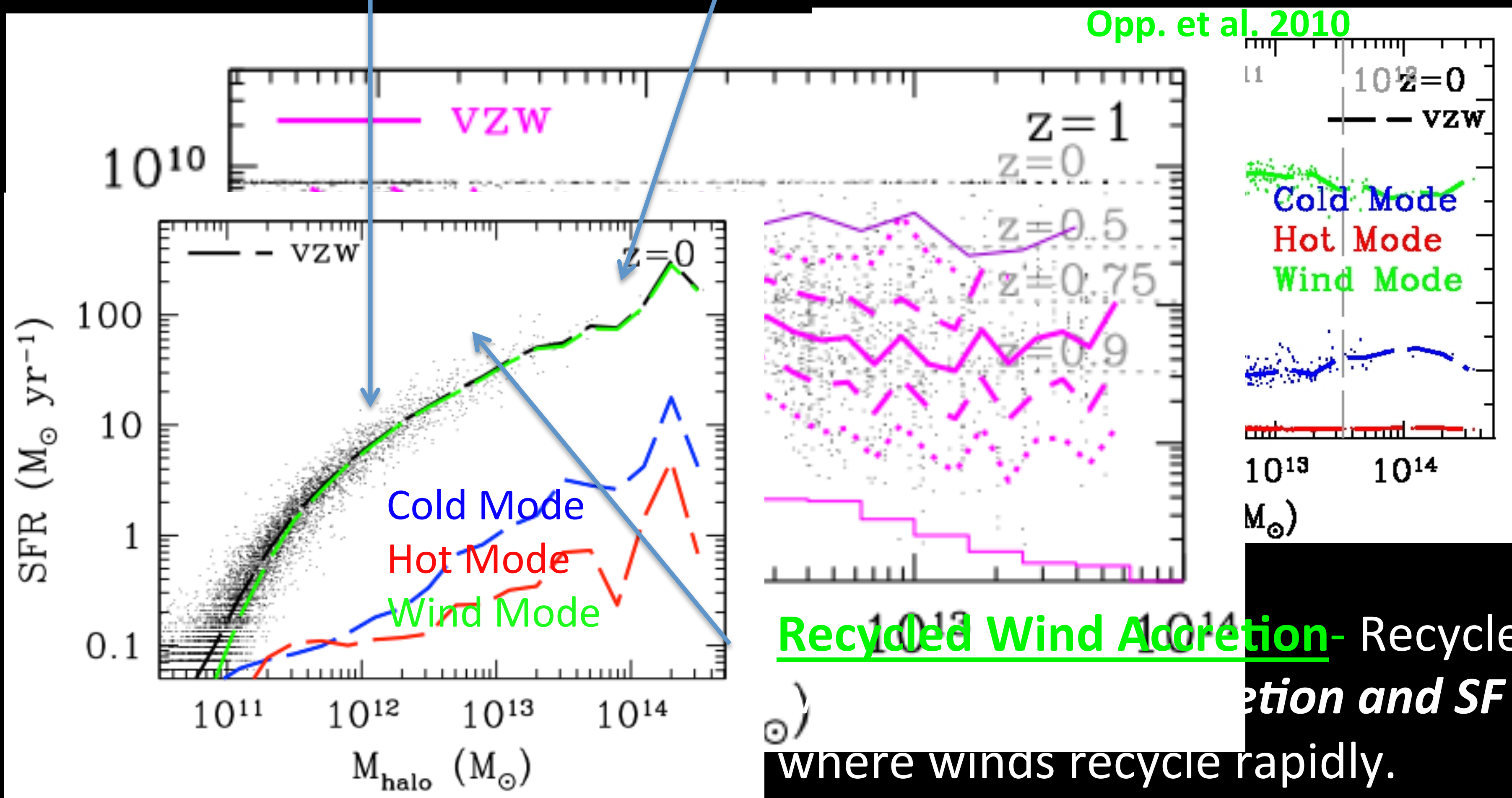
Differential Recycling- Tracking wind particles shows they return to more massive galaxies faster.

Opp. et al. 2010



Recycled Wind Accretion- Recycled … *etion and SF* where winds recycle rapidly.