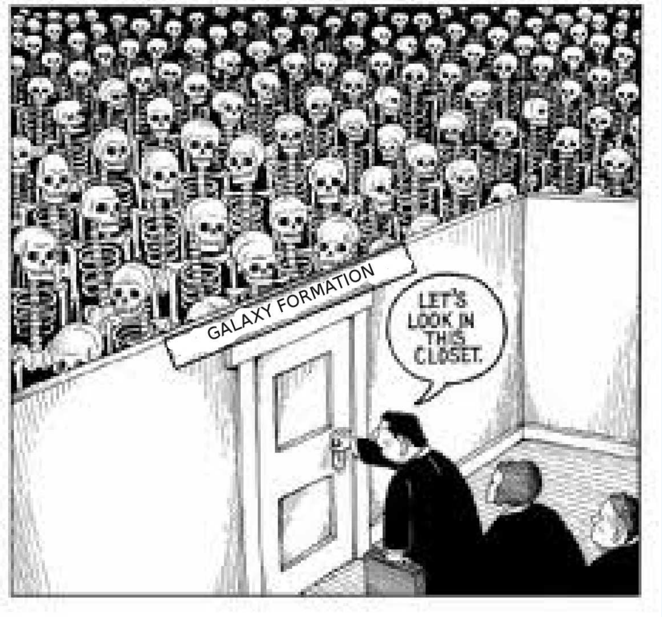
Galaxy Formation Simulations: Problems and Answers



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UMass Astronomy

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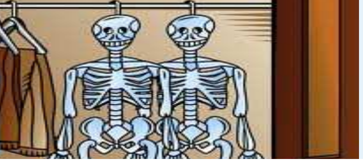
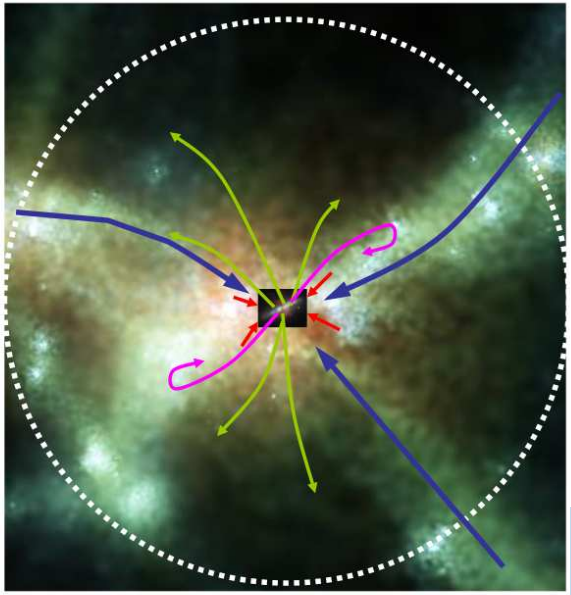
September 2022

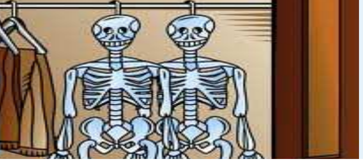


Galaxy Formation Today

- Recently a consensus has emerged around a paradigm where accretion and feedback together govern galaxy growth.
- Some of these baryons form stars and central black holes, but most leave galaxies through supernova and quasar winds.
- Much of the ejected material can reaccrete, a fraction of which then forms stars, but most of which is re-ejected.
- Gas remains in the galaxy about 500 Myrs before it is either ejected or turned into stars; SFRs are determined by the net gas supply.

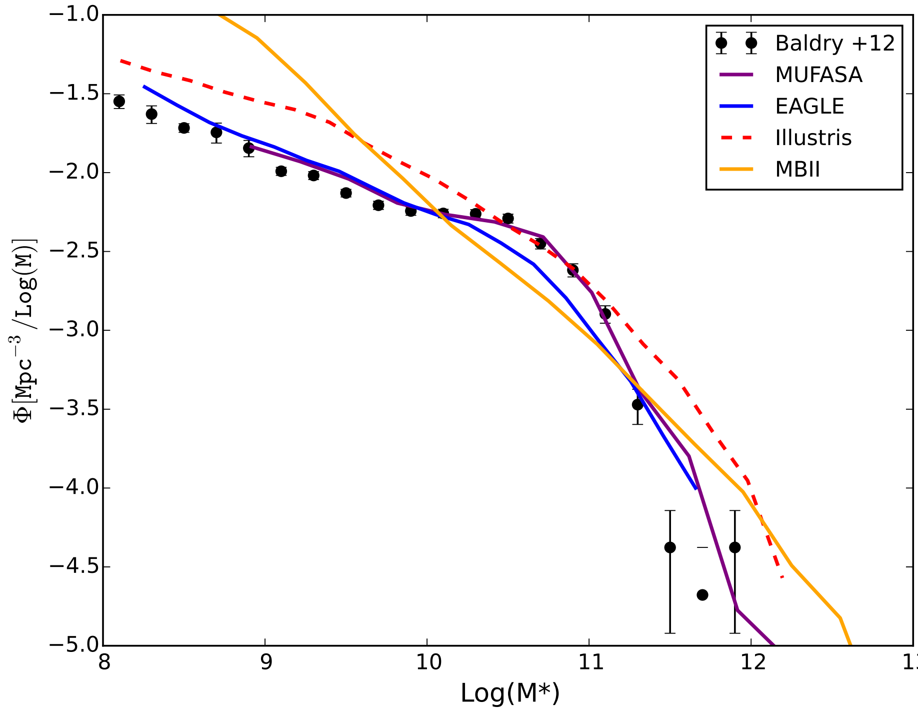


- Cold/Hot accretion
- Galactic winds
- Wind reaccretion

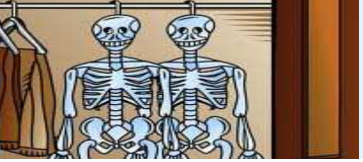


Let Us Compare

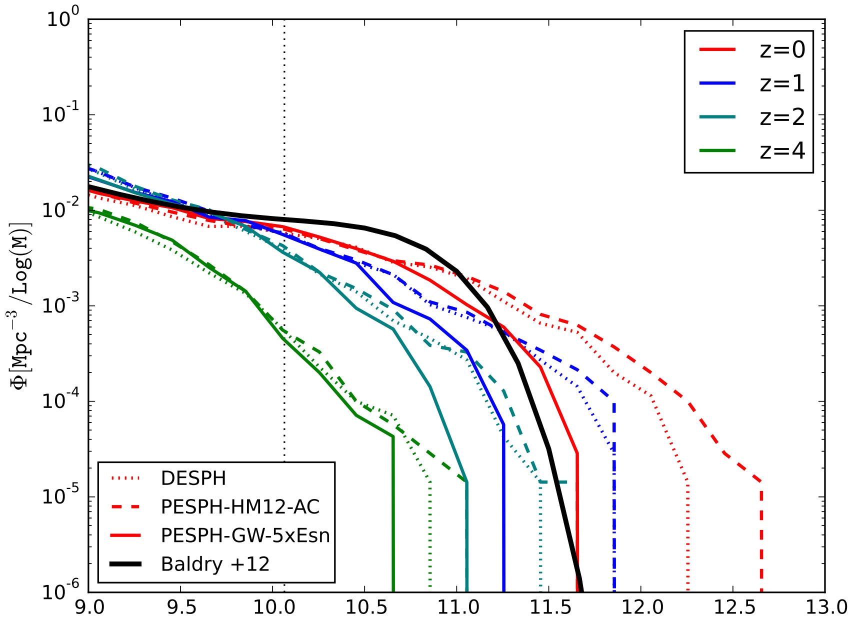
- Found large code to code variations of galaxy stellar mass function when modeling the same physics.



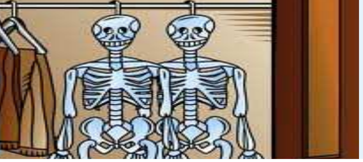
- In MUFASA wind recycling dominates while in EAGLE there is almost none but both match the GSMF.



Galaxy Stellar Mass Function



- Changing the SPH has only a minor effect at the largest masses.
- Changing the wind launch has a major effect at the largest masses.



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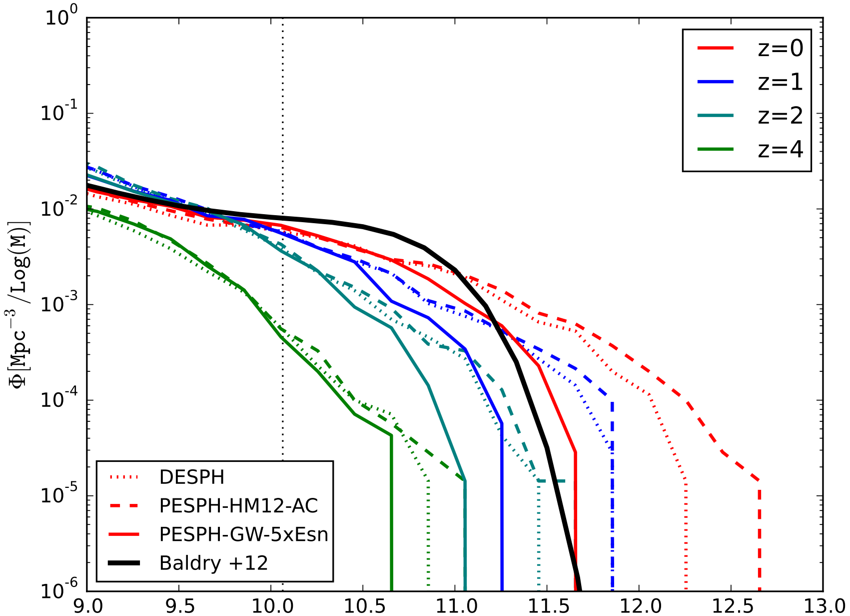
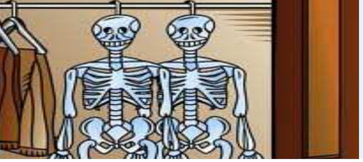
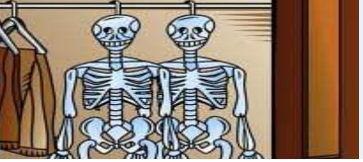


- Changing the SPH has only a minor effect at the largest masses.
- Changing the wind launch has a major effect at the largest masses.
- The Hydro technique (SPH, AMR, AREPO, GIZMO etc.) is much less important than the feedback implementation in simulations of galaxy formation.



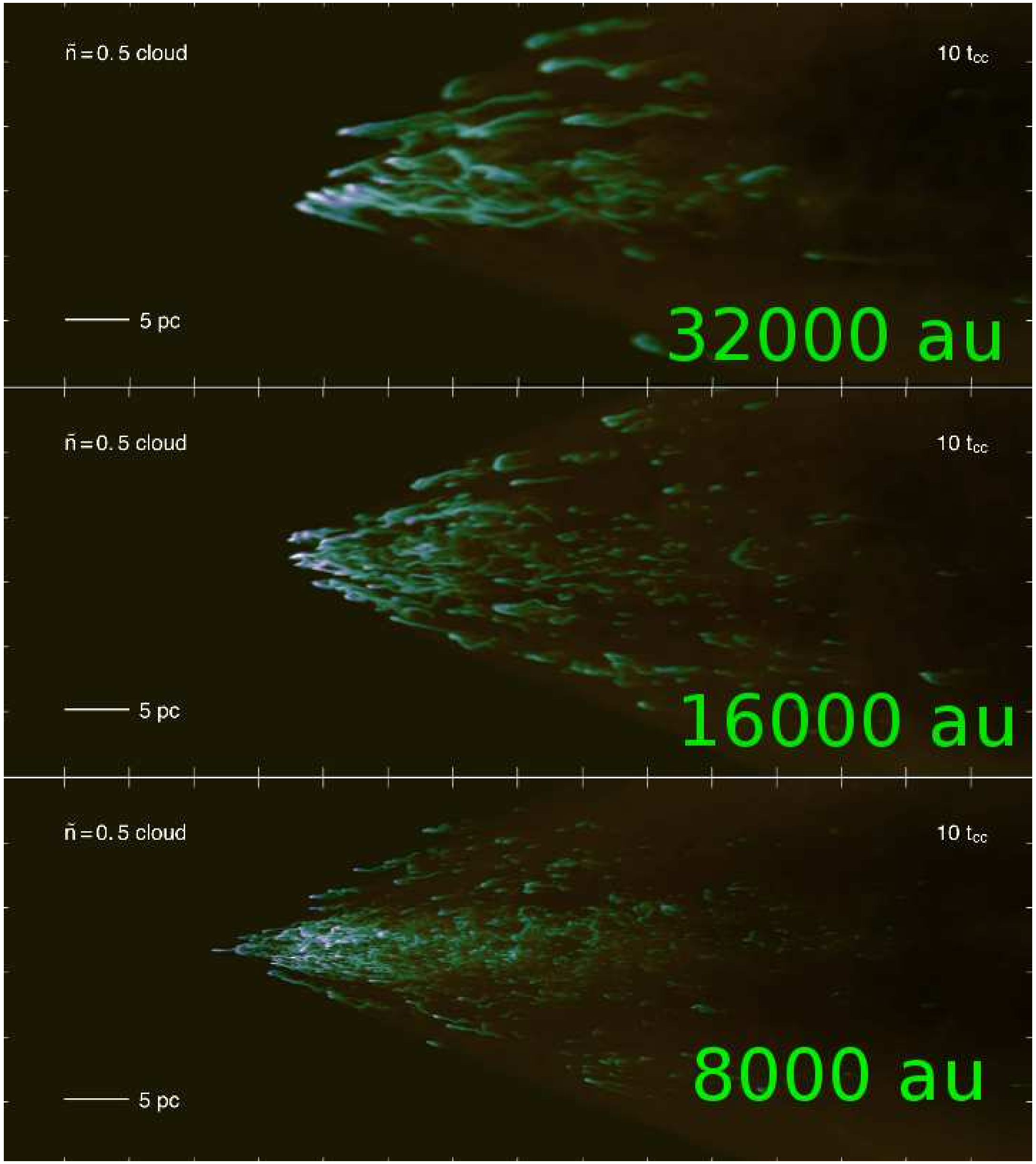
Fake News!

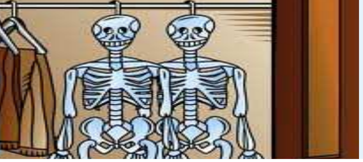
- Still need scaling laws to launch the winds.
- Wind particles are individual particles and individual particles do not properly represent hydrodynamics.
- Individual particles cannot mix metals.
- The results are highly sensitive to the exact form of the subgrid wind model and how it interacts with the numerics including the hydro code and resolution.
- Why not just solve the problem by brute force?



Why not just solve the problem by brute force?

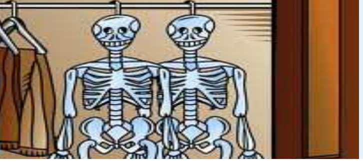
- Winds are dominated by cold gas that is thought to be entrained.
- Simulations show that the convergence of this process does not occur until the resolution is Solar System in scale and Jupiter in mass.
- Even then clouds are not accelerated.
- Entrainment does not occur unless perhaps there is magnetic draping.





More Fake News; SAD!

- Any claims that any simulation can have winds develop naturally are highly dubious.
- One expects that the problems would be even worse for propagating winds through the CGM into the IGM.
- Cold gas clouds traveling through a less dense, hot CGM should typically not slow down but slowly disintegrate on a time scale of many t_{cc}, which does not happen in current simulations.
- The interactions at wind/halo gas interfaces in the CGM occur on scales that are much below the resolution of any galaxy formation simulation, including FIRE, Illustris, FOGGIE, and Eagle.



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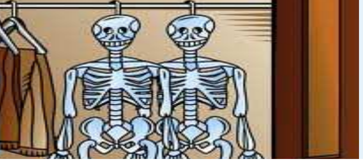
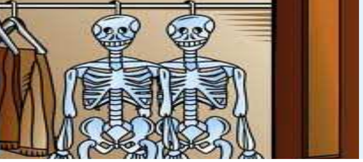
- The interactions at wind/halo gas interfaces in the CGM occur on scales that are much below the resolution of any galaxy formation simulation, including FIRE, Illustris, FOGGIE, and Eagle.
- Do not have and will not have for many years the ability to simulate superwinds leaving galaxies and in particular their interactions with the CGM and IGM so we must develop a subgrid model.
- PhEW, there is another way forward.



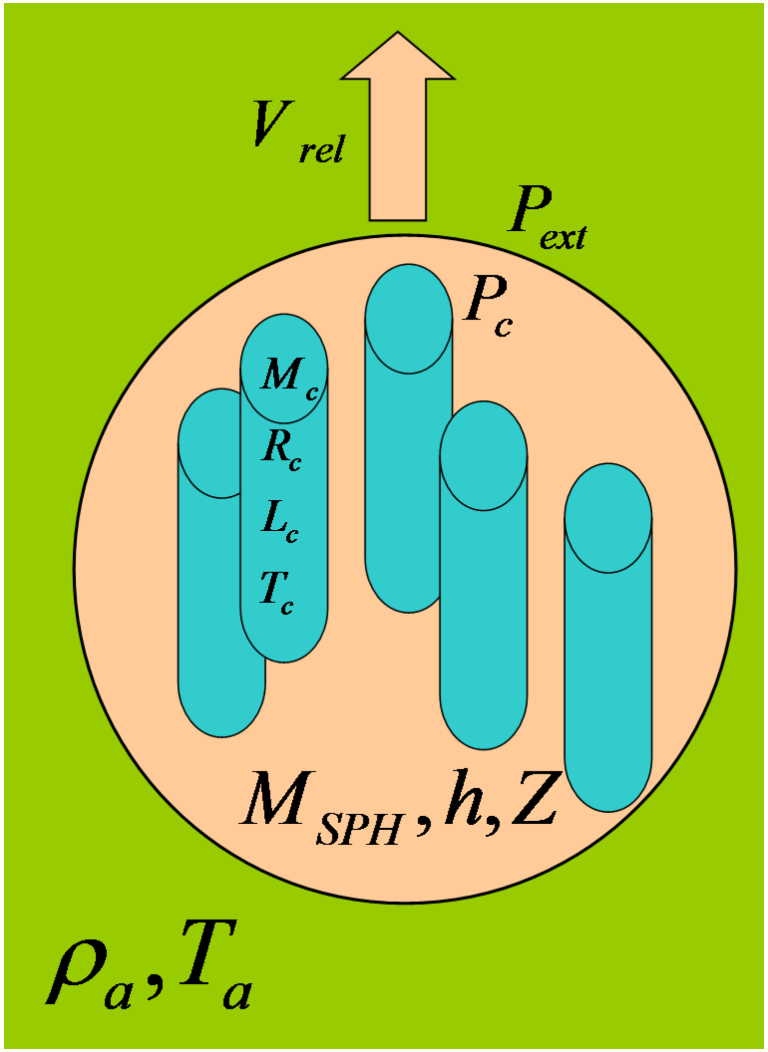
Tell me what you really really want

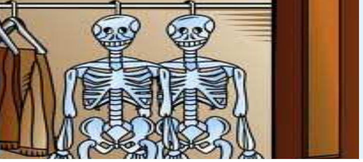
- Want the model to be limited by our physical assumptions and not by numerics.
- Want a method that must be as independent of resolution as possible.
- Want a method that must be as independent of hydro technique as possible.
  - Works with SPH, AMR, and moving mesh codes (e.g. AREPO and GIZMO).
- Want to try to limit the number of free parameters.
- Want it to globally conserve mass, momentum, and energy.
- Most importantly: want it to correctly represent the physics and not depend on unknown numerics.



Physically Evolved Winds (PhEW)

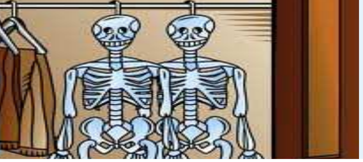
- Wind particles are launched as before.
- They are evolved analytically using microphysics that depends on the surrounding medium.
- Wind particles are "removed" and added to their surroundings when their mass becomes small relative to the surrounding particles.





Physically Evolved Winds (PhEW)

- Cloud motion affected by:
  - gravity,
  - ram pressure.
- Cloud temperature affected by:
  - radiative and adiabatic heating and cooling,
  - ram pressure heating,
  - conduction.
- Clouds lose mass, thermal energy, and metals to surroundings owing to:
  - Kelvin-Helmholtz and Rayleigh Taylor instabilities,
  - Conductive evaporation.



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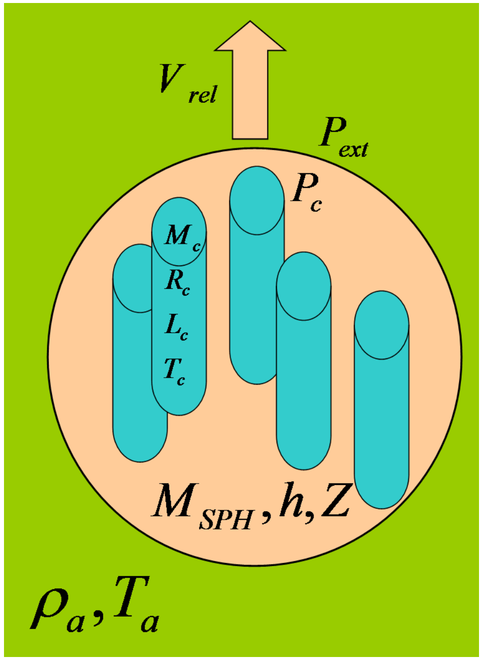
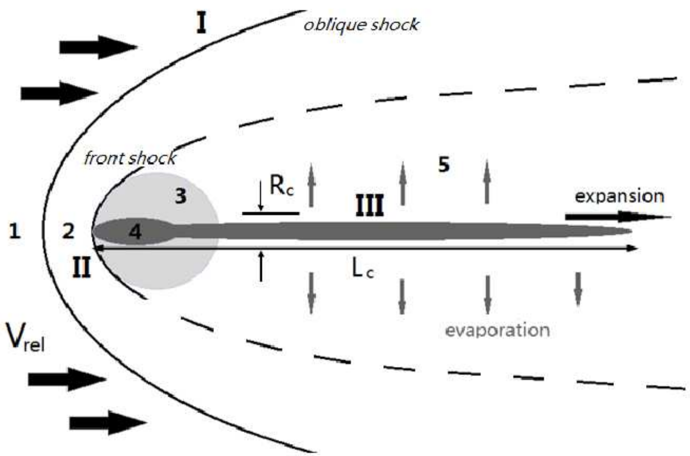
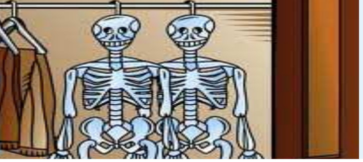




- Assume each wind particle is made of many cylindrical clouds with mass M_c, temperature T_c, uniform density, ρ_c, and radius R_c.
- Clouds create a conductive bow shock, creating a post-shock medium whose properties depend on the ambient conditions and the cloud speed.
- Assume clouds are in pressure equilibrium and thermal contact with the post-shock medium.



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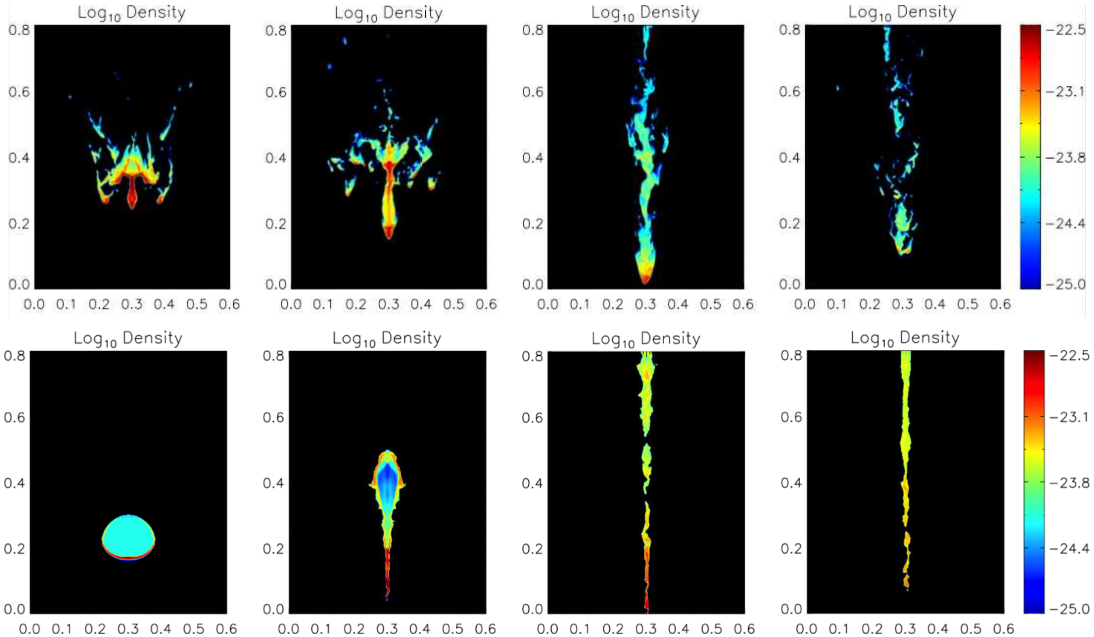
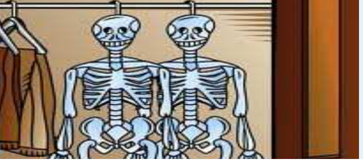


- The model can be set using high resolution single cloud simulations.
- These simulations can also determine cloud absorption line properties.
- Still need parameters:
  - M_{cloud}: the sub-cloud mass,
  - f_s: the fraction of the Spitzer rate for conductive processes.
  - f_{KH}: controls the Kelvin-Helmholtz destruction time.



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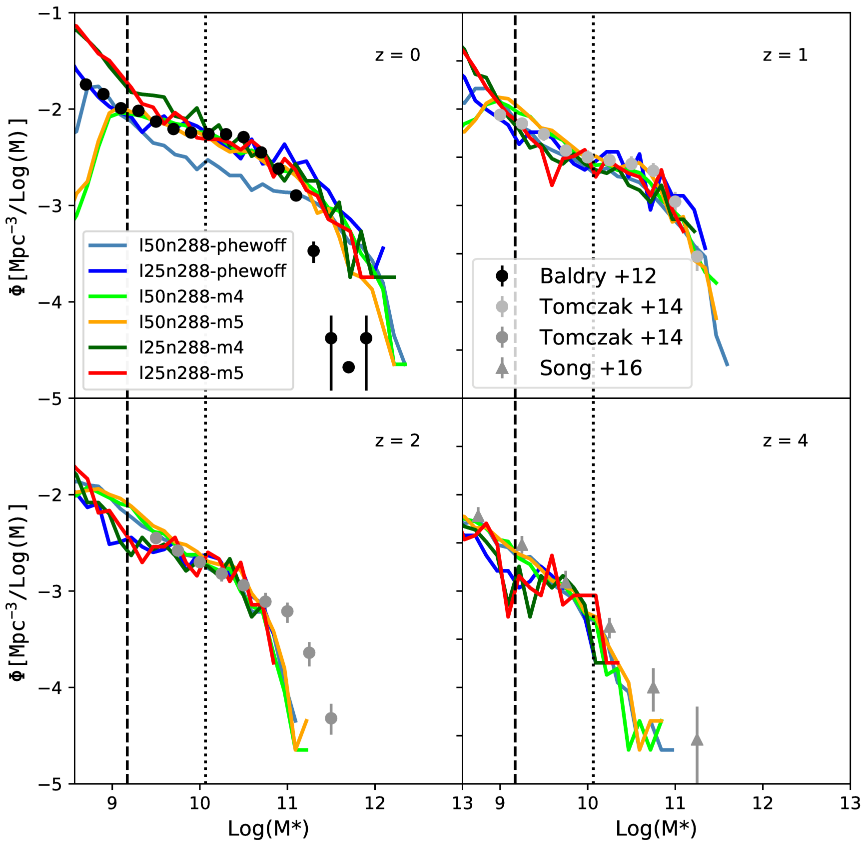
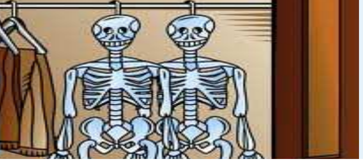
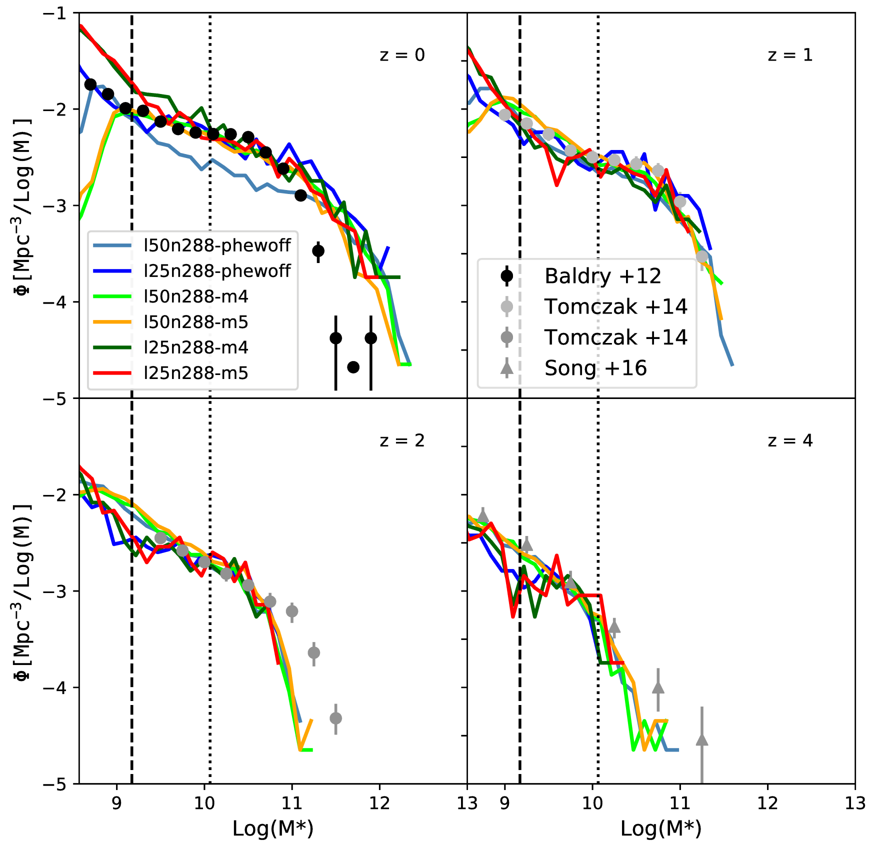


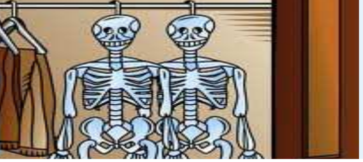
- Proof of concept simulation; parameters have not been tuned.
- Better matches the GSMF at the knee.
- Too many high mass galaxies.



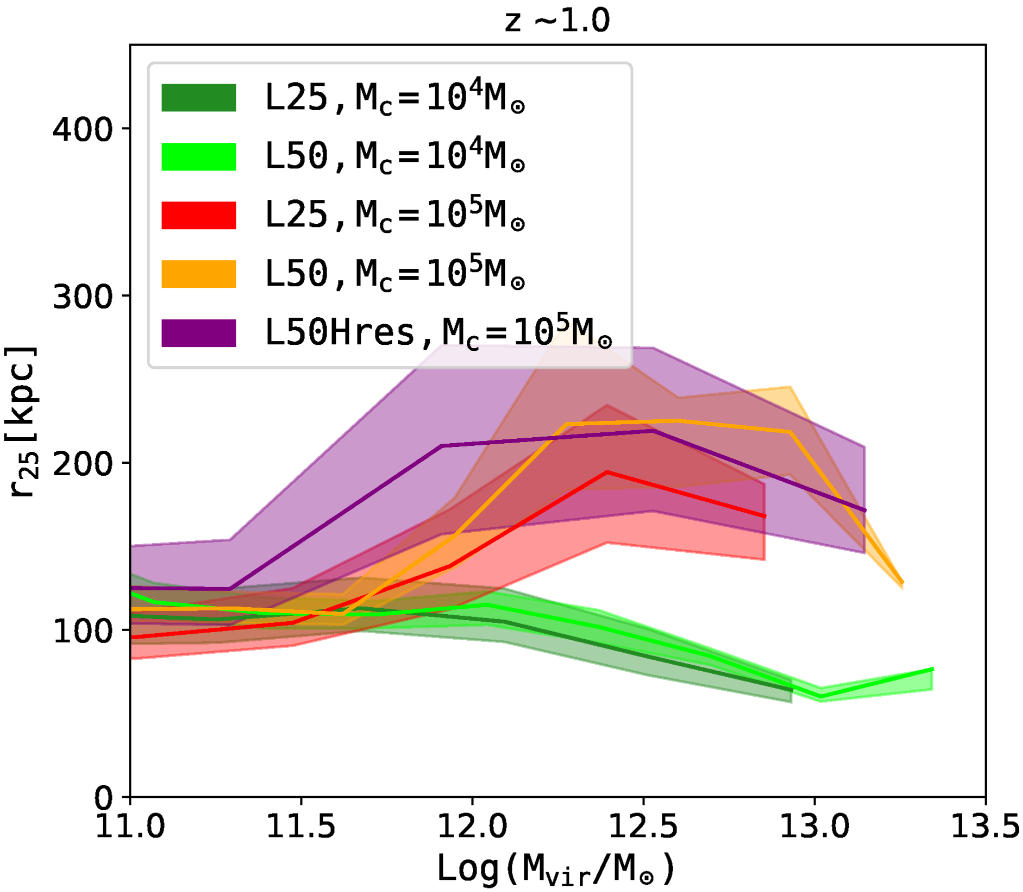
Resolution and M_c Effects on GSMFs



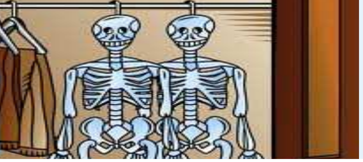
- The old wind model is very sensitive to resolution and hydro method (not shown).
- The PhEW model is not very sensitive to resolution or M_c or hydro method (not shown).



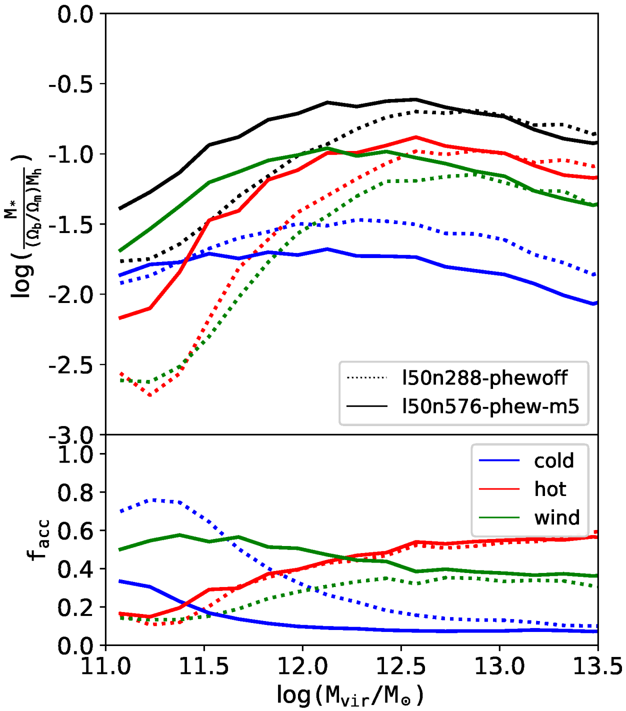
Anywhere the Wind Blows



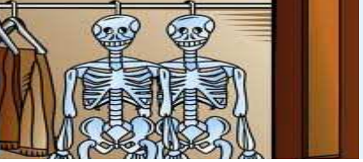
- When the KHI dominates the mass loss, $\tau_{\rm KH} \propto f_{\rm KH} M_{\rm c}^{1/3}$.
- When conductive evaporation dominates the mass loss, $\tau_{\rm ev} \propto M_{\rm c}^{2/3}/f_s$.



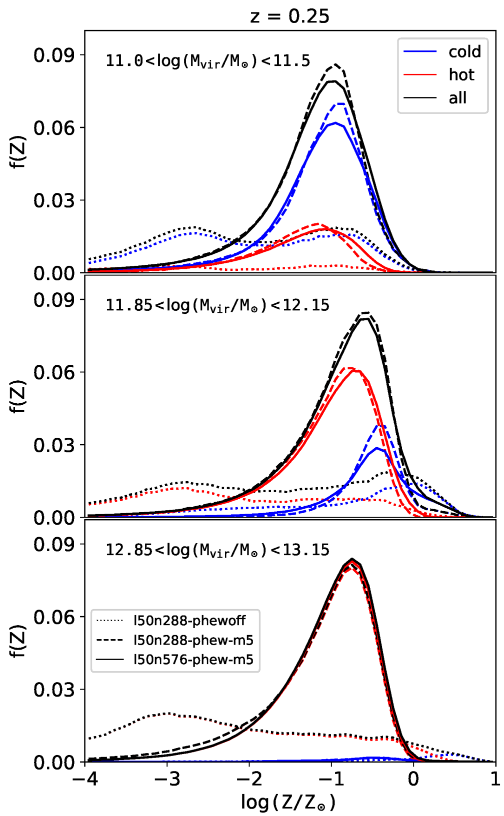
How Galaxies get their gas in PhEW



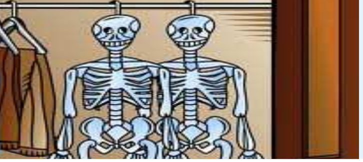
- Redefine wind reaccretion as fraction of particle formally in wind.
- Wind reaccretion now dominates accretion below about $10^{12.3} M_\odot$.
- The total amount of cold accretion is similar but the amount of hot and wind accretion increases.



CGM gas metallicities in PhEW

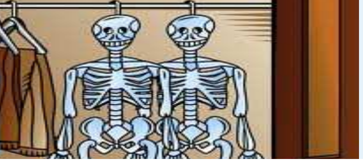


- Metallicity without PhEW is trimodal (40% of particles have $Z \approx 0$).
- With PhEW metallacities have a single peak around 10^{-1}.
- In PhEW the metal distributions are robust to numerical resolution.



Conclusions

- The Hydro technique is much less important than the feedback implementation in simulations of galaxy formation.
- Do not and will not have for many years the resolution to correctly model superwinds leaving galaxies and their interactions with the CGM and IGM so we must develop a subgrid model.



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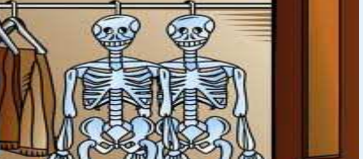
- This is even more true for AGN feedback!
- Physically Evolved Winds (PhEW) are a way forward.
  - Can be tuned to match very high resolution ISM simulations.
  - Can be used in any code and is almost independent of resolution.
- Current ”proof of concept” simulations look promising.



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- Making Galaxy Formation Simulations Great Again!
- Huang, Katz et al MNRAS (2020 497 2586; 2022 509 6091).