The Circumgalactic TrainWreck of Accretion, Expulsion, and Recycling

Benjamin D. Oppenheimer
Leiden University

The Baryon Cycle

With: Amanda Ford, Romeel Davé, Juna Kollmeier, Dušan Kereš, Molly Peeples, Neal Katz, David Weinberg, Mark Fardal
A Very Important Baryon Cycle

Benjamin D. Oppenheimer
Leiden University

The Baryon Cycle

With: Amanda Ford, Romeel Davé, Juna Kollmeier, Dušan Kereš, Molly Peeples, Neal Katz, David Weinberg, Mark Fardal
How Do Galaxies Get Their Gas?

• **Cold** and **Hot** modes subdivision (e.g. Keres et al. 2005, 2009ab) from simulations without GSW feedback.

• Running simulations with feedback, I emphasize the addition of another mode—**Winds Recycling** that feeds star formation and galaxy growth.

• However, how these winds recycle through this phase diagram is critically important for their observational diagnostics.

Kereš et al. (2005)
Let’s Explore How Winds Recycle

Track all winds launched from halos $10^{11.5-12.0} M_{\text{sol}}$ from $z=1.0-0.95$.

Wind prescription is strong winds: all SN energy imparted kinetically at $v=686$ km/s, $M_{\text{wind}}=2M_{\text{sfr}}$.

Particle color indicates temperature difference with surrounding gas (blue colder, red hotter, green equal).

Follow winds for 8 Gyrs from $z=1->0$. 
Instead of **strong winds**, let’s try a simulation with **slow winds** (half the velocity): $v=343\text{ km/s}$, $M_{\text{wind}}=2M_{\text{sfr}}$. That is $1/4^{\text{th}}$ the SN energy.
Different Wind Velocities

The efficiency of feedback critically determines recycling characteristics of wind-blown materials: faster winds are able to shock heat to above the peak of the cooling curve-harder to re-accrete this hot gas.

This difference is reflected in 1) the amount and phase of enriched materials in the CGM/IGM (QAL observations), and 2) the masses of galaxies observed in the Universe (galaxy obs.).
We usually velocity kick particles, however, if we impart the energy thermally instead of kinetically \((T_{\text{heat}} = 1.8 \times 10^7 \text{ K})\) here instead of \(v = 484 \text{ km/s}\), what happens?
Kinetic vs. Thermal Winds

Thermal feedback is often less efficient than kinetic feedback, but it really depends on how hot your winds come out and if they *beat the cooling curve*.

Thermal winds can input more baryons into the hot phase from which it is harder to accrete. Hence, less *recycling*. 
In Oppe. et al. (2010), we ran bigger simulations and stated that recycling time as a function of halo mass was the key determinant of how stellar assembly occurred in simulations with GSW feedback.
Tracking Wind Mode in Simulations with Feedback

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.
Tracking **Wind Mode** in Simulations with Feedback

- **Majority of stars formed from gas that has been ejected in a wind by z=0.**
- Where $t_{\text{rec}} \lesssim t_{\text{Hubble}}$, 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.

**Recycled Wind Accretion**- Recycled winds dominate accretion and SF where winds recycle rapidly.
Tracking **Wind Mode** in Simulations with Feedback

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

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

Correctly predicts masses between $M^* = 10^{9.0} - 10^{10.7} \ M_\odot$ to within 0.1 dex, but overproduces masses above this.
The Dynamics of How Baryons Re-Cycle Determines the shape of the GSMF

- No Winds
  - All Accretion
  - No Wind Mode
  - Bell et al. 2003

- Weak Winds
  - CW

- Strong Winds
  - NW

- Mom.- driven Winds
  - SW
  - VZW

Ben Oppenheimer

The Baryon Cycle

13
This Baryon Cycle Can Be Diagnosed by Observing Metal-Enriched Gas in the CGM.

<table>
<thead>
<tr>
<th>Mom.-driven Winds</th>
<th>Strong Winds</th>
<th>No Winds</th>
</tr>
</thead>
<tbody>
<tr>
<td>M_H=10^{11}</td>
<td>M_H=10^{12}</td>
<td>M_H=10^{13}</td>
</tr>
</tbody>
</table>

Amanda Ford has just submitted a paper on confronting metals and HI in the CGM of z=0.25 galaxies this week: arXiv:1206.1859
The (A Very Important) Baryon Cycle

The ability of superwinds to either escape from galaxies or to recycle is essential to the dynamics of accretion and galaxy growth.

The ability to recycle depends on 1) halo mass, 2) wind efficiency, 3) energy transport method (kinetic vs. thermal), plus 4) if & how metal coolants mix.

This cycle critical to building today’s galaxies can be diagnosed like never before with the current efforts to uncover the nature of the CGM.
My winds don’t mix, metals and their cooling abilities remain attached to SPH particles, but others do consider mixing diluting metals with surrounding primordial gas (e.g. Grief, Wadsley, Shen, and OWLS). Let’s consider the extreme case of metal-cooling on and only primordial cooling in a wind model with $v=484$ km/s, $M_{\text{wind}}=2M_{\text{sfr}}$ (50% SN efficiency).
Metal Cooling On and Off

Wind particles, often solar or super-solar in metallicity, have to overcome very efficient cooling between $10^5$-10$^6$ K. If wind materials are mixed and diluted, then feedback efficiency can be much higher.

*HOWEVER*... see Wiersma et al. (2009a) where they smooth metals over otherwise primordial SPH particles and increase cooling in pristine materials and exacerbate overcooling even more than without mixing.
I was planning to talk about:

• The Nature of OVI in Halos.

• HI in the CGM of Early-Type Galaxies.

• The Bimodality in LLS.

But, I’m going to rename my talk: