Gas Outflow/Inflow versus Star-formation Correlations of Cosmologically Simulated Galaxies

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Large-scale filaments.

(7 Mpc)$^3$ box at low-z.

Dark matter - green,

Gas - red,

Stars - blue

- Our work: few 10s Mpc side cosmological volume.
- Enable us to study:
  - effect of Mpc-scale power fluctuations during structure formation
  - effect of cosmological large-scale events like galaxy mergers
  - statistical populations of galaxy populations over a mass range
- Complementary to high-resolution, isolated galaxy sims.
Why Sub-Resolution Models?

Physics of baryons

- Radiative cooling and (photo + collisional) ionization heating of gas
- Fragmentation, clumping, multiphase ISM
- Star formation
- Metal production & chemical enrichment
- SN feedback, galactic wind
- AGN accretion + feedback
- ...

In cosmological hydrodynamical simulations

(few - 10’s Mpc) box: Resolution $\sim 10^6 M_{\odot}$, 1 kpc

- Baryonic physics occur on much smaller scales
- Implemented as sub-resolution models
Modified-GADGET3 code: Sub-Resolution Physics

• GADGET3 : TreePM (gravity) - SPH (hydro)


• Star Formation

  – Metal (C, Ca, O, N, Ne, Mg, S, Si, Fe) release from SN type-II, type-la, & AGB stars; stellar age, mass & yield; different IMF; mass & metal loss from starburst

• SN Feedback
  – Thermal feedback (↑ T) : inefficient, energy radiated away quickly
  – :: Kinetic feedback (↑ v)

• AGN accretion + feedback
Star-Formation in Multiphase ISM: MUPPI model

- High-density SPH particle represents a part of ISM
  - Composed of 2 gas phases & stars

- Effective model *(Springel & Hernquist 2003)*
  - Equilibrium solution
  - Self-regulated SF: constant effective pressure

- MUPPI = MUlti-Phase Particle Integrator *(Murante et al. 2010)*
  - Molecular fraction of gas $\propto$ Pressure
  - Mass & energy flows between components explicitly followed by numerically integrating system of ODEs within SPH timestep
Existing Models of SN Feedback

- Kinetic feedback: give velocity kick to gas
  - Energy-driven wind
    - Springel & Hernquist (2003)
  - Momentum-driven wind
    - Oppenheimer & Dave (2006)
    - Choi & Nagamine (2011)
    - Puchwein & Springel (2012)

- Radially-varying wind velocity
  - Barai et al. (2013)

- Combinations & variations of energy and momentum-driven
  - Schaye et al. (2010)
  - Dave et al. (2013)
  - Volgelsberger et al. (2014)

- Thermal feedback: increase gas temperature
  - Dalla Vecchia & Schaye (2012), Schaye et al. (2014)

- Turn off radiative cooling
  - Stinson et al. (2006)

Most of the models assume that wind velocity and mass-loading scales with some global galaxy property (mass, velocity dispersion, SFR)
SN Energy Feedback in MUPPI *(Murante et al. 2015)*

- Energy imparted to gas particles
  - Inside SPH smoothing length and cone with semi-aperture angle = 60°
  - Along path of least resistance
    - Negative density gradient

- Direct distribution of
  - Thermal energy
    - Efficiency fraction
    - Injected to local hot phase
  - Kinetic energy
    - Efficiency fraction, Probability

- No direct input expression of wind velocity & outflow mass loading

\[
E_{th} = E_{SN} f_{fb,th} \frac{\Delta M_*}{M_{*,SN}}
\]

\[
E_{kin} = E_{SN} f_{fb,kin}
\]
Simulation Runs  \cite{Barai2015}

<table>
<thead>
<tr>
<th>Run Name</th>
<th>$L_{\text{box}}$ [Mpc]</th>
<th>$N_{\text{part}}$</th>
<th>$m_{\text{gas}}$ [$M_\odot$]</th>
<th>$m_*$ [$M_\odot$]</th>
<th>$L_{\text{soft}}$ [kpc]</th>
<th>SF &amp; SN feedback</th>
<th>sub-resolution physics</th>
<th>Model</th>
<th>$v_w$</th>
<th>$f_{\text{fb, out}}$</th>
<th>$f_{\text{fb, kin}}$</th>
<th>$P_{\text{kin}}$</th>
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</thead>
<tbody>
<tr>
<td>$E35nw$</td>
<td>35.56</td>
<td>$2 \times 320^3$</td>
<td>$8.72 \times 10^6$</td>
<td>$2.18 \times 10^6$</td>
<td>2.77 (comoving)</td>
<td>Effective</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>$E35rvw$</td>
<td>35.56</td>
<td>$2 \times 320^3$</td>
<td>$8.72 \times 10^6$</td>
<td>$2.18 \times 10^6$</td>
<td>2.77 (comoving)</td>
<td>Effective</td>
<td>$v_w(r)$</td>
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<td>$E25cw$</td>
<td>25</td>
<td>$2 \times 256^3$</td>
<td>$5.36 \times 10^6$</td>
<td>$1.34 \times 10^6$</td>
<td>0.69 (physical)</td>
<td>Effective</td>
<td>350</td>
<td></td>
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</tr>
<tr>
<td>$M25std$</td>
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<td>$2 \times 256^3$</td>
<td>$5.36 \times 10^6$</td>
<td>$1.34 \times 10^6$</td>
<td>0.69 (physical)</td>
<td>MUPPI</td>
<td>0.2</td>
<td>0.6</td>
<td>0.03</td>
<td></td>
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<td></td>
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<tr>
<td>$M25a$</td>
<td>25</td>
<td>$2 \times 256^3$</td>
<td>$5.36 \times 10^6$</td>
<td>$1.34 \times 10^6$</td>
<td>0.69 (physical)</td>
<td>MUPPI</td>
<td>0.2</td>
<td>0.4</td>
<td>0.03</td>
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<tr>
<td>$M25b$</td>
<td>25</td>
<td>$2 \times 256^3$</td>
<td>$5.36 \times 10^6$</td>
<td>$1.34 \times 10^6$</td>
<td>0.69 (physical)</td>
<td>MUPPI</td>
<td>0.2</td>
<td>0.8</td>
<td>0.03</td>
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<td>$M25c$</td>
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<td>$5.36 \times 10^6$</td>
<td>$1.34 \times 10^6$</td>
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<td>MUPPI</td>
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<td>0.6</td>
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<td>$M25d$</td>
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<td>$1.34 \times 10^6$</td>
<td>0.69 (physical)</td>
<td>MUPPI</td>
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<td>0.6</td>
<td>0.06</td>
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<td>$2 \times 512^3$</td>
<td>$5.36 \times 10^6$</td>
<td>$1.34 \times 10^6$</td>
<td>0.69 (physical)</td>
<td>MUPPI</td>
<td>0.2</td>
<td>0.5</td>
<td>0.03</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Outflow measurement technique

- Transform galaxy coordinates s.t. cold gas disk is rotating in X-Y plane

- Select gas particles:
  - lying inside either cylinder
  - moving at a high-velocity, $|v_z| > V_{\text{limit, outflow}}$

- if $(z \cdot v_z > 0) \Rightarrow \text{Outflow}$
- if $(z \cdot v_z < 0) \Rightarrow \text{Inflow}$
Setting the lower velocity threshold for outflow measurement

- Fixed value: Reveals correlations. Adopt this for outflow velocity.
- Escape velocity: Measures escape outside halo. Adopt this for mass outflow rate.
Observation: Martin (2005), Grimes et al. (2009), Banerji et al. (2011), Bordoloi et al. (2013)
- Positive correlation of outflow speed with galaxy mass and SFR.
Mass loading factor ($\eta = \text{Mass outflow rate} / \text{SFR}$) vs. halo mass

\begin{align*}
\eta = \frac{M_{\text{out}}}{SFR}
\end{align*}

\begin{align*}
\log_{10}(\eta) &= 11.6 - 1.06 \log_{10}(M_{\text{halo}}) \\
&[0.45]
\end{align*}

\begin{align*}
M_{\text{halo}} [M_\odot]
\end{align*}

\begin{align*}
\log_{10}(\eta) &= 1.0 - 0.084 \log_{10}(M_{\text{halo}}) \\
&[0.32]
\end{align*}
Redshift Evolution of Outflow Velocity vs SFR

\[ v_{\text{out}} = 163 \log_{10}(\text{SFR}) + 353 \] for \( z = 3.94 \)

\[ v_{\text{out}} = 144 \log_{10}(\text{SFR}) + 375 \] for \( z = 3.0 \)

\[ v_{\text{out}} = 103 \log_{10}(\text{SFR}) + 373 \] for \( z = 2.02 \)

\[ v_{\text{out}} = 43 \log_{10}(\text{SFR}) + 356 \] for \( z = 0.8 \)

SFR and \( v_{\text{out}} \) are plotted for different redshifts, with color representing the fraction of detected outflow.
Redshift Evolution of Mass-Loading factor vs Halo Mass

\[ \eta = \frac{M_{\text{gas}}/ \text{SFR}}{M_{\text{star}}/ \text{SFR}} \]

- \( z = 4.96 \)
  - \( M_{50\text{std}} \) \( (v > v_{\text{esc}}) \)
  - \( \log_{10}(\eta) = -0.92 + 0.099 \log_{10}(M_{\text{halo}}) \)
  - [:0.27]

- \( z = 3.94 \)
  - best-fit:
  - \( \log_{10}(\eta) = -1.03 + 0.11 \log_{10}(M_{\text{halo}}) \)
  - [:0.27]

- \( z = 3.0 \)
  - \( 0.074 + 0.009 \log_{10}(M_{\text{halo}}) \)
  - [:0.28]

- \( z = 2.02 \)
  - \( 1.01 - 0.084 \log_{10}(M_{\text{halo}}) \)
  - [:0.29]

- \( z = 0.8 \)
  - \( 4.79 - 0.45 \log_{10}(M_{\text{halo}}) \)
  - [:0.39]

\( M_{\text{halo}} [M_\odot] \)
Mass-Loading factor comparison with other studies
How many outflows escape the galaxy halo? (at $R_{\text{gal}}$ versus at $R_{\text{vir}}$)

<table>
<thead>
<tr>
<th>Method</th>
<th>$N_{\text{outflow}}$</th>
<th>$f_{\text{outflow}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>At $R_{\text{gal}}$ using $</td>
<td>v_r</td>
<td>&gt; v_{\text{esc}}(R_{\text{gal}})$, in a cylinder</td>
</tr>
<tr>
<td>At $R_{\text{gal}}$ using $</td>
<td>v_r</td>
<td>&gt; v_{\text{esc}}(R_{\text{gal}})$, in a sphere</td>
</tr>
<tr>
<td>At $R_{\text{vir}}$ using $</td>
<td>v_r</td>
<td>&gt; v_{\text{esc}}(R_{\text{vir}})$, in a sphere</td>
</tr>
</tbody>
</table>

- **M50std**
  - $(v > v_{\text{esc}})$
  - $z = 2$

- **Best-fit**
  - $\log_{10}(y) = 0.86 \log_{10}(x) + 0.27$
  - $[0.24]$
Galaxy stellar properties at $z=0$
(Ragagnin et al. 2015, in prep.)
Simulating realistic disk galaxies with MUPPI, in zoom-in cosmological simulations using moderate resolution \textit{(Murante et al. 2015, MNRAS)}

\textbf{Figure 1.} Projected gas (upper panels) and stellar (lower panels) density for the GA2 simulation. The $z$-axis of the coordinate system is aligned with the angular momentum vector of the gas enclosed within the inner 8 kpc. Left panels show face-on densities, right column shows edge-on densities. Box size is 57 kpc.
Study of barred spiral disk galaxies, in zoom-in cosmological simulations
(Goz et al. 2015, MNRAS)
Summary

• Can study impact of galactic winds on galaxy & IGM properties in cosmological hydrodynamic simulations
  – Still far away from self-consistently driving these winds in such sims

• Crucial to measure in post-processing the outflow properties w.r.t. that input in the sub-grid model

• MUPPI is more physically-motivated sub-resolution model that uses only local properties of gas and generates realistic:
  – Galactic outflows
    • Outflow velocity positive correlation with global galaxy SFR
    • Constant mass-loading value at z=2
    • Redshift evolution predicted over z = 1 - 5
    • Need more observational data
  – Disk galaxies

• Need connection and synergy between large-scale sims and isolated system high-resolution sims, to physically model processes, and still have a predictive power