Where are the baryons in the universe?

Theoretical perspective

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OUTLINE

▪ What we probably know: Accretion
▪ What we might know: Cooling
▪ What we would like to know? Star formation and feedback
**Hierarchical model of galaxy formation:**

- Cold Dark Matter framework
- Small primordial fluctuations + gravitational instability
- Gas falls into dark matter halos (streams) to form galaxies
- Galaxies merge and grow

**CODE (Romain Teyssier and collaborators)**

- RAMSES (evolves DM+gas+stars under gravity, cooling, heating, star formation and AGN or SN feedback from z of order 100 to z=0)
Mass limitations of simulations

- Typical Volume Simulations: 10TB
- Typical mono-cpu time: 1 000 000h
- Typical number of processes: 5 000
- Typical memory: 10 TB

Graph showing mass and resolution with different codes:
- HYDRO
- BINGO! (AMR)
- Mare Nostrum (AMR&SPH)
- Millenium (TreePM)
- Horizon 4pi (PM AMR)
- DEUSS (PM AMR)
- OWLS (SPH)
- DEUSS-HYDRO (AMR)

Graph parameters:
- Mass: $10^{16}$ to $10^{8}$ ($h^{-1} M_{\odot}$)
- Resolution: $64^3$ to $1024^3$
- Linear scale: $1$ to $10000$ ($h^{-1}$ Mpc)

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Model: phases definition in the density-temperature plane

- **Diffuse background**: Lyalpha (delta<100, T<10^5K), WHIM (delta<100, 10^5K<T<10^7K), HIM (delta<100, T>10^7K)
- **Hot**: CGM(delta>100, nH<0.1at/cm^3), winds, streams
- **Cold**: star forming gas (nH>0.1at/cm^3)
- **Stars**: stars, remnants, recycled gas
Model: average baryon transfer rates (Rasera&Teyssier, 2006)

- Accretion rate: ?
- Cooling rate: ?
- Star formation rate: ?
- Winds rate: ?

Where are the winds going?
Model: average baryon transfer rates (Rasera&Teyssier, 2006)

• Accretion rate: ?
• Cooling rate: ?
• Star formation rate: ?
• Winds rate: ?

Where are the winds going?

Ingredients:
Dark matter
halo mass function +
baryonic fraction +
Mass threshold
Dark matter halo mass function

- N-body simulations/N-body+hydro simulations

Total halo mass function ($M_{200}$) varies very little with baryons

Needs further studies for small mass haloes
Dark matter halo mass function

- Excursion Set Theory (Corasaniti & Achitouv 2011)
- Cosmology-dependant threshold $\delta_{\text{ac}}$
- Halos are not spherical $\Rightarrow$ proper halo finder (FOF, HOP, ...)
- Cosmology-dependant ENCLOSED (i.e., not spherical) overdensity $\delta_{\text{vir}}$
  $\Rightarrow$ 5% accuracy (Courtin et al, 2011, More et al, 2011)
- Otherwise 20% deviation depending on redshift/cosmology
Baryon fraction

- Close to universal baryon fraction $\Omega_b/\Omega_m$ for high mass halos
- Increase slightly with cooling
- Decrease slightly with winds
Baryonic fraction drops near the Minimal mass for star forming halo Mmin
Evolution of Mmin close to filtering mass (Jeans mass) but a bit below
Accretion or the envelope of CSFR

✿ Accretion can be computed easily

\[
\frac{\dot{M}_{\text{acc}}}{M_{200}} = f_{\text{bar}} \frac{dF(> T_{\text{min}})}{dt}
\]
Cooling is calibrated on simulation: governed by free-fall time

\[ \dot{M}_{\text{cool}} = \frac{M_{\text{hot}}}{\langle t_{\text{cool}} \rangle} \]

Halo SF efficiency governed by local SF efficiency

\[ \dot{M}_* = \frac{M_{\text{disc}}}{\langle t_* \rangle} \]

Average over all halos (important role of mass function)

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Model: average baryon transfer rates (we refer here to Rasera&Teyssier, 2006 and don’t go in the details)

- Accretion rate: \( \dot{M}_{acc} = \frac{\int f_{bar} dF(> T_{min})}{M_{200}} \) (robust)
- Cooling rate: \( \dot{M}_{cool} = \frac{\dot{M}_{hot}}{< t_{cool} >} \) (roughly ok)
- Star formation rate: \( \dot{M}_* = \frac{\dot{M}_{disc}}{< t_\star >} \) (bof)
- Winds rate: \( \dot{M}_{wind} = < \eta_w > \dot{M}_* \) (tricky)

Where are the winds going? For halos smaller than \( T_w \), in the background, otherwise in the hot phase (super tricky)
Accretion can be computed easily

\[
\frac{M_{\text{acc}}}{M_{200}} = f_{\text{bar}} \frac{dF(> T_{\text{min}})}{dt}
\]
Cosmic Star Formation Rate

- Agreement simu/model (cross-validation)
- Allow to extrapolate SFR
- DEUSS-HYDRO (V. Reverdy): 2 cosmological models calibrated on SNIa and CMB gives different SFR
- BINGO! & Y. Dubois: AGN feedback required at low redshift. Simu in progress.
- What about high redshift?
Global baryon budget: histograms
Good agreement between simu and models
Extrapolation of baryon budget with model
SN winds have little effect on the baryon budget (unlike unrealistic winds Springel&Hernquist,2003)
AGN feedback should change this
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Conclusion

✔️ Cosmological simulations + analytical models
  • Allow to understand evolution of baryons in universe
  • Accretion controls available gas for star formation
  • Cosmology can change amplitude of CSFR
  • SN winds not powerful enough to change baryon budget
  • we can use the same formalism and methods for metals budget
  • we can use the same formalism and methods for halos

✔️ Next
  • Studies the fate of winds in more details (important for metals)
  • Finish jet AGN simulations
  • Analytical models for AGN jet
High resolution (billion cells) AMR cosmological simulation with jets from (Credits: Y. Dubois & BINGO!)

green: gas density
red: gas temperature
blue: gas metallicity
Model: average METAL transfer rates

- **Advection:** same as for baryons (black arrows)
- **Source term (SN):**

\[ \dot{M}_Z = \eta Z \times \text{yield} \times M. \]

- Consequence: total amount of metals is not constant (but easy to compute from SFR)
- Issues: Which fraction goes to cold, hot and background phase? **Budget very sensitive!!!**
- Adopted solution: assume given wind metallicity \( Z_w \)
- Fraction of metal in wind (ie hot+back), \( f_Z^w = \eta_Z \times Z_w / \text{yield} \) and in cold \( f_{Z\text{cold}} = 1 - f_Z^w \)
Global metal budget: histograms

Metals/NO feedback/z=1

Metals/NO feedback/z=0

Metals/SN feedback/z=1

Metals/SN feedback/z=0
Global metal budget: evolution (don’t worry I will make the plot nicer!)

- Need to take $T_w = 7.5 \times 10^5$ K (to reproduce the amount of metals in background)
- Assume $Z_w = 0.15 \ Z_{\odot}$ (0.5 $Z_{\odot}$ everything in wind, 0 $Z_{\odot}$ everything in cold)
- Issue with **hot and background in the SN wind case**!!! Why? Is it because of rbubble? Or physical phenomenon? Need better constraint using halo metal budget
Halo baryon budget
Halo metal budget (preliminary)

- Main discrepancy: metals amount in hot gas is dropping in large halo
- Solution: take into account ram pressure of infalling material (Teyssier&Dubois, 2008)
- Direct measurement of winds: shell method