Class 22: The need for feedback in galaxy formation

- This class
  - Low mass galaxies & star formation feedback
  - High-mass galaxies and galaxy clusters
    - Overcooling problem
    - Cooling flow problem

I: The discrepancy between galaxy and DM mass functions

- Define mass function \( \Phi(M) \) such that there are \( \Phi(M)dM \) objects per unit volume with masses between \( M \rightarrow M+dM \)
- Behaviour of dark matter is simple (just gravity), so mass function of DM halos can be readily predicted (dashed line)
- Naively, we expect all baryons in galactic sized halos to cool and form stars... so we expect mass function of galaxies to be just a scaled down version of DM halo mass function
- Q: What would be the scaling factor in this naive model?
- Data show a more interesting situation!

Read & Trenham (2005)
II : Suppression of low-mass galaxies

- In low-mass galaxies, we believe star formation itself can suppress galaxy formation!
  - Baryons collapse into DM halo; shock(?); cool
  - Cooled gas starts to turn into stars
  - After 2-3 million years, massive stars go supernova... injects energy back into cooling gas
  - But... if DM halo has low mass, it has a low escape velocity. Supernovae can heat the gas enough that the particle velocities exceed the escape velocity.
  - Gas is then driven out of the DM halo and star formation stops

- Sidenote : In very low mass DM halos, we may get zero star formation! Gas is driven out of halo at very early times by "reionization."

![M82](image)
Large Magellanic Cloud (50kpc away)
Carina Dwarf (100kpc away; $M \approx 2 \times 10^8 M_{\text{Sun}}$; $\sigma \approx 7\text{ km/s}$)

Benson (2010; arXiv:1006.5394)

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III : Massive systems – the overcooling problem

- Now let’s tackle massive galaxies & galaxy clusters ($10^{12} M_{\text{sun}}$ and higher)
  - Star formation cannot produce enough energy to eject gas from these massive halos...
  - So, again, we conclude that the mass function should track the DM halo mass function
  - But it doesn’t!
- The discrepancy between the theoretical expectation and the observed lack of massive galaxies is the overcooling problem.
Recall connection between velocity dispersion, DM halo mass and (post-shock) baryon temperature...

\[ T \sim 3.5 \times 10^5 \left( \frac{\sigma}{100 \text{ km s}^{-1}} \right)^2 \text{ K} \]

\[ T \sim 3.5 \times 10^5 \left( \frac{M_*}{10^{11} M_\odot} \right)^{2/3} \text{ K} \]

- In very massive systems (massive elliptical galaxies, and groups/clusters of galaxies), we have $T>10^4 \text{ K}$ and we predict that the shocked baryons should emit X-rays... indeed, X-ray observations reveal these baryons very clearly!
- This is not blackbody... its bremsstrahlung and line emission
- We can measure...
  - Spatial extent
  - Density
  - Temperature
  - Cooling time

\textit{Perseus cluster}
So, we observe short cooling times in center of massive galaxies and clusters. What next? We’ve been here before! We expect...

- Gas cools down to low temperatures
- Flows into central galaxy... forms stars
- Hot gas flows from outer regions into inner regions and the cycle continues
- This is a cooling flow

The cooling flow problem...

- What’s the problem? We don’t see any evidence that gas has cooled down to low temperatures!
- Low levels of star formation; no other large reservoir of cold gas.
- Clearly, this is closely related to the overcooling problem.
XMM-Newton OM study (Hicks & Mushotzky 2005)

- High-resolution spectra of clusters with XMM
  - Spectral line analysis clearly shows gas cooling from $kT \sim 5\text{keV}$ to 1-2keV
  - But no cooling below 1-2keV is apparent

- Basic conclusions...
  - ICM is heated!
  - Same applies to ISM of massive elliptical galaxies

XMM-RGS data for A1835 (Peterson et al. 2001)
Also, Tamura et al. (2001); Peterson et al. (2005)
Everything points towards one conclusion. Some agent heats the baryons in the core regions of the massive DM halos, thereby preventing cooling, star formation and galaxy growth. That agent must be substantially more powerful and efficient that star formation...