Cosmic Evolution of Baryons and Metals

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ARAA, sub.
Absorption lines are powerful

- Predominantly Lyα absorption
- Metal line absorption

**Relative Flux**
- Lyman break @ z~3
- HI absorption: 4770, 4760, 4780 Å
- Metal absorption: 6070, 6090, 6080 Å

**Observed Wavelength [Å]**
- Lyα
- N V
- Si IV
- C IV

**Diagram**
- Predominantly Lyα absorption
- Metal line absorption
How does the gas reservoir which fuels star formation evolve?
Evolution neutral gas mass shallower than stellar density

\[ \Omega_{\text{neutral gas}}(z) = [(4.6 \pm 0.2) \times 10^{-4}](1 + z)^{0.58\pm0.04} \]
Molecular gas mirrors SFR history

Shull+12, Putman17, Driver+18
Gas is depleted faster than it can be made at $z < 3$. 

The graph illustrates the evolution of gas densities over redshift, showing the depletion of gas compared to the formation of stars. The $z=6$ cumulative density highlights the significant decrease in gas over time.
H2 gas depletion timescale universal

\[ \tau_{\text{dep}} = \frac{\rho_{\text{gas}}}{\dot{\rho}_*}, \]
Need for accretion of cold gas from IGM

Bouche+10, Lilly+13, Dekel+14

bathtube/regulator model
Where are the metals in the Universe?
Mild cosmic evolution of metallicity

Jenkins+09, De Cia+18, Cooke+18

[Graph showing the evolution of metallicity with time since the Big Bang, with markers indicating HI-weighted means.]
Where are the metals in the universe?

\[ \rho_\star(z) = (1 - R) \int_0^{t(z)} \psi(z) \frac{dz}{dt} dt. \]
Is there a missing metals problem?

**Observed Metals**
- Neutral gas [DLAs]
- Partially-ionized gas [sub-DLAs]
- Ionized gas [LLSs]
- Hot gas [ICM+IGrM]
- Stars
- Not cataloged

**Expected Metals**
- Expected metals - 1σ
- 1σ expected metals

**z ~ 0.1**
12.2 Gyr post-Big Bang
- 50%
- 24%
- 15%
- 9%
- 1%
- Not cataloged

**z ~ 1.6**
4.0 Gyr post-Big Bang
- 83%
- 17%
- Not cataloged

**z ~ 3.0**
2.1 Gyr post-Big Bang
- 58%
- 24%
- 8%
- 10%
- Not cataloged

**z ~ 4.5**
1.3 Gyr post-Big Bang
- 94%
- 6%
- Not cataloged
What is the cosmic evolution of dust mass?
\[ \delta_X = \log \frac{N(X)}{N(H)} - \log \frac{Z_{\text{abs}}^X}{Z_{\odot}^X}. \]

\[ \text{DTG}_X = (1 - 10^{\delta_X}) \left( 10^{[M/H]} 10^{[X/M]} Z_{\odot}^X \right) \]

\[ \text{DTM}_X = 1 - 10^{\delta_X} \]
Mild evolution of dust-to-gas ratio
Probing the evolution of dust to $z=5.5$

$$\Omega_{\text{dust}} \equiv \rho_{\text{dust}}/\rho_{\text{crit},0} = \left<\text{DTG}\right> \Omega_{\text{gas}},$$
Take home Messages

- Evolution of “condensed” matter calls for accretion from the IGM
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- Little evidence for “missing metals problem” in modern censuses
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- New calculations of dust mass density uniformly up to $z=5.5$