Fast and Improved Cosmic Ionization/Thermal History Including DM Energy Injection

Gregory Ridgway

Based on arXiv:1904.09296 with Hongwan Liu and Tracy Slatyer
Fast and Improved Cosmic Ionization/Thermal History Including DM Energy Injection

Gregory Ridgway

Based on arXiv:1904.09296 with Hongwan Liu and Tracy Slatyer

A new, public code package found at darkhistory.readthedocs.io
Cosmic Ionization and Thermal Histories?
The Inter-Galactic Medium (IGM) and CMB cool as the universe expands

Hydrogen recombines as the universe cools

- The Inter-Galactic Medium (IGM) and CMB cool as the universe expands
- Hydrogen recombines as the universe cools
Motivation

What if dark matter (DM) decays/annihilates into electromagnetically interacting particles?

- DM injects energy in the form of electromagnetically interacting particles.
- As these particles cool down, they heat (left plot) and ionize (right plot) the baryons.
- These altered histories may come into tension with observations and produce constraints (arXiv:1610.06933).
Motivation

What improvements have we made?

- Calculations have assumed that deviations from standard histories are negligible.
- This is a good assumption at early times, but not necessarily at late times.
- DarkHistory can generate histories without making any such approximation.
What does DarkHistory do?

• Self-consistently solves for the cosmic temperature/ionization histories, and does so
  ❖ **quickly**: offering a variety of options to make simplifying assumptions/approximations or utilize pre-computed quantities
  ❖ **flexibly**: allowing for easy adaptation of the code to add more physics, like reionization, structure formation, DM-baryon scattering, etc.
  ❖ **openly**: open-source python code provided on GitHub under darkhistory.readthedocs.io, complete with documentation and worked out examples.

So how does it work?
A Visualization of the Computation
The Computation

Step 1:

- DarkHistory evolves the cosmic histories forward in small time-steps
- Each time-step is comprised of 5 code-steps

Step 2a:

Step 2b:

One time-step

Step 3:

Step 4:

Step 5:

\[ z - \Delta z \]
The Computation

**Step 1:** Inject particles and resolve into photons, electrons, and positrons; at a given ionization level

**Step 2a:**

**Step 2b:**

**Step 3:**

**Step 4:**

**Step 5:**

Inject $\gamma, e^-, e^+$; $x_{HII}(z)$
DM Energy Injection

Pictured below: our universe, filled with dark matter
DM Energy Injection

Pictured below: our universe, filled with dark matter, which then (for example) decays to electromagnetically interacting particles.
DM Energy Injection

Pictured below: our universe, filled with dark matter, which then (for example) decays to electromagnetically interacting particles.

DarkHistory has functionality for more general SM products (via PPPC4DMID, arXiv:1012.4515).

Notice, we must keep track of an entire spectrum of particles.

These injected photons, electrons, and positrons proceed to lose energy, depositing it into the IGM.
The Computation

**Step 1:** Inject particles and resolve into photons, electrons, and positrons; at a given ionization level

**Step 2a:** Resolve photon energy deposition, keep track of free streaming photons

**Step 2b:** Inject $\gamma, e^-, e^+$; $x_{HII}(z)$

**Step 3:**

**Step 4:**

**Step 5:**
Within one time-step, injected photons will lose energy via a variety of processes:
Photon Energy Deposition

**Photons**

Within one time-step, injected photons will lose energy via a variety of processes:

- Excite/ionize neutral H/He
- Compton scatter off of free electrons
- Pair produce off of H/He gas or the CMB
- Scatter off of CMB photons
- Free stream

These processes **heat** and **ionize** the IGM. (They also **distort** the CMB, which we leave to future work, though see arXiv:1808.02897 for another analysis of late-time CMB distortions). The same will be true of electrons and positrons.
The Computation

**Step 1:** Inject particles and resolve into photons, electrons, and positrons; at a given ionization level

**Step 2a:** Resolve photon energy deposition, keep track of free streaming photons

**Step 2b:** Resolve $e^\pm$ energy deposition

**Step 3:**

**Step 4:**

**Step 5:**
Within this time step of $\Delta \ln(1 + z) = -10^{-3}$, electrons/positrons will
Electrons/Positrons

Within this time step of $\Delta \ln(1 + z) = -10^{-3}$, electrons/positrons will:

- Inverse Compton Scatter (ICS) off of CMB photons
- Collisional excitation/ionization
- Positronium formation/annihilation
- Heating of the plasma via Coulomb scattering

Notice, these processes produce particles at lower energies that will also deposit their energy. DarkHistory solves for the energy deposition of the full cascade of particles.
The Computation

**Step 1:** Inject particles and resolve into photons, electrons, and positrons; at a given ionization level

**Step 2a:** Resolve photon energy deposition, keep track of free streaming photons

**Step 2b:** Resolve $e^\pm$ energy deposition

**Step 3:** Condense energy deposition information into deposition fractions, $f_c$

**Step 4:**

**Step 5:**
The Computation

Step 1: Inject particles and resolve into photons, electrons, and positrons; at a given ionization level

Step 2a: Resolve photon energy deposition, keep track of free streaming photons

Step 2b: Resolve $e^\pm$ energy deposition

Step 3: Condense energy deposition information into deposition fractions, $f_c$

Step 4: Solve for the change in $T_m$ and $x_{HII}$

Step 5:
The Computation

**Step 1:** Inject particles and resolve into photons, electrons, and positrons; at a given ionization level

**Step 2a:** Resolve photon energy deposition, keep track of free streaming photons

**Step 2b:** Resolve $e^\pm$ energy deposition

**Step 3:** Condense energy deposition information into deposition fractions, $f_c$

**Step 4:** Solve for the change in $T_m$ and $x_{HII}$

**Step 5:** Repeat, adding free streamers of the previous step to the next one and updating ionization level
**The Computation**

**Step 1:** Inject particles and resolve into photons, electrons, and positrons; at a given ionization level

**Step 2a:** Resolve photon energy deposition, keep track of free streaming photons

**Step 2b:** Resolve $e^\pm$ energy deposition

**Step 3:** Condense energy deposition information into deposition fractions, $f_c$

**Step 4:** Solve for the change in $T_m$ and $x_{\text{HII}}$

**Step 5:** Repeat, adding free streamers of the previous step to the next one and updating ionization level (BR)
The Computation

The output of this calculation is $T_m(z), x_{\text{HII}}(z), f_c(z, x_{\text{HII}})$, and the $\gamma/e^-$ spectra as a function of $z$.

You can use DarkHistory to rapidly, in a publicly available way reproduce earlier results, but also new results…
Results/Applications
The Global 21cm Signal

- The global 21cm signal measure the number of photons of wavelength 21cm (after accounting for redshift).

- This indirectly measures the number of hydrogen atoms in the triplet vs. singlet hyperfine state.

- This is an indirect measurement of the temperature of hydrogen clouds, i.e. $T_b$

- Measurements of the 21cm signal constrain temperature histories. Therefore, DarkHistory may use the 21cm signal to constrain DM models that produce too much heat.

- Excitingly, the 21cm signal is just beginning to be measured.
Global 21cm Signal: Constraints

Suppose we measure $T_{21} = -50 \text{mK}$

The 21cm signal has the potential to produce very stringent constraints.
Reionization

DarkHistory provides a standard reionization model (arXiv:1801.04931) that can be exchanged for a customized one

DM energy injection greatly modifies reionization. Backreaction is very important here.
Importance of Backreaction

We can explore the effects of backreaction more systematically. What’s the fractional increase in temperature when accounting for DM?

Notice, backreaction can increase the temperature nearly by a factor of 10!
Other Uses and Future Directions

Other uses of the code include:

- **DM-baryon scattering** (work in progress), as has been considered to explain the anomalous EDGES measurement. See Hongwan Liu’s upcoming talk for more details.
- **Other sources** of exotic energy injection, like radiation from (primordial) black holes, accretion on black holes, etc.

Some future directions we are pursuing with this code include:

- **Inhomogeneities**, especially in the 21cm signal
- A more careful treatment of low energy electron deposition, which would allow for the calculation of late-time **CMB distortions**
- Integration with **other code packages** (CLASS, Hyrec, etc.)
Conclusion

1. DarkHistory is a great tool for calculating modified temperature and ionization histories.

2. You should use it. Find it here: darkhistory.readthedocs.io and try out some of the examples.

Thank you