Testing dark matter interactions through cosmic history

Tracy Slatyer

Based on work with Hongwan Liu, Wenzer Qin, Greg Ridgway, and Yitian Sun
Outline

1. The puzzle of dark matter
2. Windows on cosmic history: the cosmic microwave background (CMB), Lyman-alpha forest, primordial 21cm radiation
3. How energy injection originating from (non-gravitational) dark matter interactions could change the early universe
4. Some recent/upcoming developments:
   - Using neural networks as efficient function approximators to improve the signal calculation
   - Treating low-energy photons/electrons in detail
   - Full prediction of the space of post-recombination CMB spectral distortions from exotic energy injections
What is dark matter?

We know it:
What is dark matter?

We know it:

- Doesn’t scatter/emit/absorb light (really “transparent matter”!) but does have mass (and hence gravity).
What is dark matter?

We know it:

- Doesn’t scatter/emit/absorb light (really “transparent matter”!) but does have mass (and hence gravity).
- Is \(\sim 84\%\) of the matter in the universe.

measured from the cosmic microwave background radiation
What is dark matter?

We know it:

- Doesn’t scatter/emit/absorb light (really “transparent matter”!) but does have mass (and hence gravity).
- Is ~84% of the matter in the universe.
- Forms the primordial “scaffolding” for the visible universe.
What is dark matter?

We know it:

- Doesn’t scatter/emit/absorb light (really “transparent matter”!) but does have mass (and hence gravity).
- Is ~84% of the matter in the universe.
- Forms the primordial “scaffolding” for the visible universe.
- Forms large clouds or “halos” around galaxies.

measured from the orbital velocities of stars / gas clouds
What is dark matter?

We know it:

- Doesn’t scatter/emit/absorb light (really “transparent matter”!) but does have mass (and hence gravity).
- Is ~84% of the matter in the universe.
- Forms the primordial “scaffolding” for the visible universe.
- Forms large clouds or “halos” around galaxies.
- Interacts with other particles weakly or not at all (except by gravity).

null results of existing searches
What is dark matter?

We know it:

- Consequently, cannot be explained by any physics we currently understand

Open questions:
What is dark matter?

We know it:

- Consequently, cannot be explained by any physics we currently understand

Open questions:

- WHAT IS IT?
What is dark matter?

We know it:

- Consequently, cannot be explained by any physics we currently understand

Open questions:

- What is it made from? e.g. a new particle? Many new particles? Ancient black holes?
What is dark matter?

We know it:

- Consequently, cannot be explained by any physics we currently understand

Open questions:

- What is it made from? e.g. a new particle? Many new particles? Ancient black holes?
- Where did it come from?
What is dark matter?

We know it:

- Consequently, cannot be explained by any physics we currently understand

Open questions:

- What is it made from? e.g. a new particle? Many new particles? Ancient black holes?
- Where did it come from?
- Does it interact with ordinary particles? If so how?
What is dark matter?

We know it:

- Consequently, cannot be explained by any physics we currently understand

Open questions:

- What is it made from? e.g. a new particle? Many new particles? Ancient black holes?
- Where did it come from?
- Does it interact with ordinary particles? If so how?
- and many more…
Theories of Dark Matter
Searches for DM interactions

- There is a large multi-faceted search program for signatures of dark matter, beyond the signals I will talk about today.
- One “standard” classification:

  - Indirect detection
  - Direct detection
  - Accelerators

  Not an exhaustive list - in recent years also a great deal of attention to oscillation (e.g. photon-axion conversion), absorption (in direct detection experiments for light particles), etc.
- Many of these possible interaction structures can be tested with cosmological/astrophysical observables.
Searches for DM interactions

- There is a large multi-faceted search program for signatures of dark matter, beyond the signals I will talk about today.
- One “standard” classification:

<table>
<thead>
<tr>
<th>Indirect detection</th>
<th>Direct detection</th>
<th>Accelerators</th>
</tr>
</thead>
<tbody>
<tr>
<td>break it</td>
<td>shake it</td>
<td>make it</td>
</tr>
</tbody>
</table>

- Not an exhaustive list - in recent years also a great deal of attention to oscillation (e.g. photon-axion conversion), absorption (in direct detection experiments for light particles), etc.
- Many of these possible interaction structures can be tested with cosmological/astrophysical observables.
The Cosmic Frontier in the next 10 years

Taken from talk by Aaron Chou, Snowmass July 2022
The Cosmic Frontier in the next 10 years

Taken from talk by Aaron Chou, Snowmass July 2022
Identifying dark matter

- There is an enormous range of possible DM scenarios, spanning tens of orders of magnitude in mass.
- Many of these scenarios are ~equivalent from the perspective of gravitational effects
- Exceptions: DM is very light (fuzzy DM, \(\sim 10^{-21}\) eV), very heavy (PBHs), warm/fast-moving, or strongly self-interacting (cross section/mass > 0.1 cm\(^2\)/g)
- Non-gravitational interactions in principle provide much greater discriminating power (if they exist)
- Large ongoing experimental program to search for such interactions in accelerators, direct-detection searches, precision experiments, astrophysical observations
- Can regard such interactions as providing an energy transfer channel between dark and visible sectors - could have observable effects on cosmology
- Interactions can be either elastic (competes with Earth-based direct-detection experiments) or inelastic (focus of this talk)
Annihilation

- Tightly linked to DM abundance in scenarios where (1) DM was in thermal equilibrium with SM in early universe, (2) annihilation depleted the initial abundance.

- Such scenarios favor a benchmark “thermal relic” cross section:

\[
\langle \sigma v \rangle \sim \frac{1}{m_{\text{Planck}} T_{\text{eq}}} \sim \frac{1}{(100 \text{TeV})^2} \approx 2 \times 10^{-26} \text{cm}^3/\text{s}
\]
Decay

- Either annihilation or decay would lead to a slow trickle of energy into the visible sector over time.
- We can explore the effects of this energy transfer on the history of the universe.
The cosmic microwave background radiation

- Redshift $z > 1000$ - universe is filled with a tightly-coupled plasma of electrons, protons and photons, + dark matter and neutrinos. Almost 100% ionized.

- Redshift $z \sim 1000$ - ionization level drops abruptly, cosmic microwave background (CMB) photons begin to stream free of the electrons/protons.

- The cosmic microwave background provides a snapshot of the $z\sim1000$ universe - oldest light we measure, earliest direct observations of our cosmos.

spectral information: near-perfect blackbody

deviations from blackbody $\leq 10^{-5}$

spatial information: describes pattern of oscillations in density and temperature
Signatures in the CMB (I)

- We can change the observed CMB either by:
  
  - $z > 1000$: Modifying the target of the “snapshot” - change the plasma to which the photons couple before emission
  
  - $z < 1000$: Changing the photons on their way to us - modifying the “picture” after it is taken

- Classic example of first case: temperature/density oscillations in plasma are driven by competition between gravity and radiation pressure.

- Presence of matter that feels gravity but not radiation ("dark") changes properties of oscillations - used to measure DM abundance.

- Scattering between DM and ordinary matter would make DM not-quite-dark, and likewise modify the oscillation pattern

- Heating of the ordinary matter by DM annihilation/decay can also modify the photon/baryon plasma, changing the energy spectrum of the CMB.

Hu & Dodelson ‘02
Signatures in the CMB (II)

- Second case (modification after emission): “cosmic dark ages” span redshift $z \sim 30-1000$, ionization level expected to be very low.

- Increasing ionization would provide a screen between CMB photons and our telescopes - can be sensitively measured.

- Annihilation/decay could also produce extra low-energy photons, again modifying CMB energy spectrum.
Signatures in the CMB (II)

- Second case (modification after emission): “cosmic dark ages” span redshift $z \sim 30-1000$, ionization level expected to be very low.
- Increasing ionization would provide a screen between CMB photons and our telescopes - can be sensitively measured.
- Annihilation/decay could also produce extra low-energy photons, again modifying CMB energy spectrum.
Signatures in the CMB (II)

- Second case (modification after emission): “cosmic dark ages” span redshift $z \sim 30-1000$, ionization level expected to be very low.
- Increasing ionization would provide a screen between CMB photons and our telescopes - can be sensitively measured.
- Annihilation/decay could also produce extra low-energy photons, again modifying CMB energy spectrum.
Signatures in the CMB (II)

- Second case (modification after emission): “cosmic dark ages” span redshift $z \sim 30-1000$, ionization level expected to be very low.

- Increasing ionization would provide a screen between CMB photons and our telescopes - can be sensitively measured.

- Annihilation/decay could also produce extra low-energy photons, again modifying CMB energy spectrum.
To measure the gas temperature at late times, we can search for atomic transition lines, in particular the 21cm spin-flip transition of neutral hydrogen. “Spin temperature” $T_S$ characterizes relative abundance of ground (electron/proton spins antiparallel) and excited (electron/proton spins parallel) states - $T_S$ gives the temperature at which the equilibrium abundances would match the observed ratio. If $T_S$ exceeds the ambient radiation temperature $T_R$, there is net emission; otherwise, net absorption.

$T_{21}(z) \approx x_{\text{HI}}(z) \left( \frac{0.15}{\Omega_m} \right)^{1/2} \left( \frac{\Omega_b h}{0.02} \right) \times \left( \frac{1 + z}{10} \right)^{1/2} \left[ 1 - \frac{T_R(z)}{T_S(z)} \right] 23 \text{ mK}$.
To measure the gas temperature at late times, we can search for atomic transition lines, in particular the 21cm spin-flip transition of neutral hydrogen.

“Spin temperature” $T_S$ characterizes relative abundance of ground (electron/proton spins antiparallel) and excited (electron/proton spins parallel) states - $T_S$ gives the temperature at which the equilibrium abundances would match the observed ratio.

If $T_S$ exceeds the ambient radiation temperature $T_R$, there is net emission; otherwise, net absorption.

$$T_{21}(z) \approx x_{\text{HI}}(z) \left( \frac{0.15}{\Omega_m} \right)^{1/2} \left( \frac{\Omega_b h}{0.02} \right) \times \left( \frac{1 + z}{10} \right)^{1/2} \left[ 1 - \frac{T_R(z)}{T_S(z)} \right] 23 \text{ mK}.$$
To measure the gas temperature at late times, we can search for atomic transition lines, in particular the 21cm spin-flip transition of neutral hydrogen.

“Spin temperature” $T_S$ characterizes relative abundance of ground (electron/proton spins antiparallel) and excited (electron/proton spins parallel) states - $T_S$ gives the temperature at which the equilibrium abundances would match the observed ratio.

If $T_S$ exceeds the ambient radiation temperature $T_R$, there is net emission; otherwise, net absorption.
Expectations for a 21cm signal

- First stars turn on = flux of Lyman-alpha photons - couples $T_s$ to the hydrogen gas temperature $T_{gas}$.
- We expect $T_{gas} < T_R$ initially - gas cools faster than the CMB after they decouple - leading to absorption signature.
- Exotic heating could lead to an early emission signal [e.g. Poulin et al '17].
- Later, stars heat $T_{gas} > T_R$, expect an emission signal.
- There are a number of current (e.g. EDGES, LOFAR, MWA, PAPER, SARAS, SCI-Hi) and future (e.g. DARE, HERA, LEDA, PRIZM, SKA) telescopes designed to search for a 21cm signal, potentially probing the cosmic dark ages & epoch of reionization.
- Any measurement of global $T_{21}$ will set a bound on $T_{gas}$.
After the universe mostly reionizes, there are still clouds of neutral hydrogen in the universe - light passing through these clouds produces the "Lyman-alpha forest" of absorption features in the spectrum.

$T_{\text{gas}}$ affects the width of the absorption features via Doppler broadening.

Temperature also affects the distribution of the hydrogen gas - smoothed out by the gas pressure on small scales.

Several recent studies [Walther et al '18, Gaikwad et al '20] have compared measurements of the Ly-$\alpha$ forest with simulations, to extract the gas temperature for $z\sim 2-6$. 
The Lyman-alpha forest

- After the universe mostly reionizes, there are still clouds of neutral hydrogen in the universe - light passing through these clouds produces the “Lyman-alpha forest” of absorption features in the spectrum.

- $T_{\text{gas}}$ affects the width of the absorption features via Doppler broadening.

- Temperature also affects the distribution of the hydrogen gas - smoothed out by the gas pressure on small scales.

- Several recent studies [Walther et al ’18, Gaikwad et al ’20] have compared measurements of the Ly-$\alpha$ forest with simulations, to extract the gas temperature for $z \sim 2$-6.
Ionization vs heating vs spectral distortions
Ionization vs heating vs spectral distortions

- Consider the power from DM annihilation/decay - how many hydrogen ionizations?
  - 1 GeV / 13.6 eV ~ 10^8
  - If 10^-8 of baryonic matter were converted to energy, would be sufficient to ionize entire universe. There is ~5x as much DM mass as baryonic mass.
  - If one in a billion DM particles annihilates (or decays), enough power to ionize half the hydrogen in the universe...
Ionization vs heating vs spectral distortions

- Consider the power from DM annihilation/decay - how many hydrogen ionizations?
  - 1 GeV / 13.6 eV ~ \(10^8\)
  - If \(10^{-8}\) of baryonic matter were converted to energy, would be sufficient to ionize entire universe. There is \(\sim5\)x as much DM mass as baryonic mass.
  - If one in a billion DM particles annihilates (or decays), enough power to ionize half the hydrogen in the universe...

- How much spectral distortion to the CMB?
  - Radiation and matter energy densities were equal at \(z\sim3000\), ratio scales as \((1+z)\)
  - One-in-a-billion fraction of mass energy liberated = distortion of energy spectrum of CMB at level of one in \(10^6\) or less. Much less sensitive than ionization for \(z < 1000\).
Ionization vs heating vs spectral distortions

- Consider the power from DM annihilation/decay - how many hydrogen ionizations?
  
  - $1 \text{ GeV} / 13.6 \text{ eV} \sim 10^8$
  
  - If $10^{-8}$ of baryonic matter were converted to energy, would be sufficient to ionize entire universe. There is $\sim 5x$ as much DM mass as baryonic mass.
  
  - If one in a billion DM particles annihilates (or decays), enough power to ionize half the hydrogen in the universe...

- How much spectral distortion to the CMB?
  
  - Radiation and matter energy densities were equal at $z\sim 3000$, ratio scales as $(1+z)$
  
  - One-in-a-billion fraction of mass energy liberated = distortion of energy spectrum of CMB at level of one in $10^6$ or less. Much less sensitive than ionization for $z < 1000$.

- How much change to the gas temperature?
  
  - Down to $z\sim 200$, CMB and ordinary matter are coupled in temperature - need to heat whole CMB, not just matter. Same estimate as for spectral distortion.
  
  - Baryon number density is $\sim 9$ orders of magnitude smaller than CMB number density - heating divided between a much smaller number of particles for $z < 200$. One-in-a-billion fraction of mass energy liberated $\Rightarrow$ increase baryon temperature by $\sim 5 \text{ eV per particle} \sim 50,000 \text{ K}$ - two orders of magnitude higher than baseline temperature at decoupling.
Ionization vs heating vs spectral distortions

- Consider the power from DM annihilation/decay - how many hydrogen ionizations?
  - $1 \text{ GeV} / 13.6 \text{ eV} \sim 10^8$
  - If $10^{-8}$ of baryonic mass were converted to energy, would be sufficient to ionize entire universe. There is $\sim 5x$ as much DM mass as baryonic mass.
  - If one in a billion DM particles annihilates (or decays), enough power to ionize half the hydrogen in the universe...

- How much spectral distortion to the CMB?
  - Radiation and matter energy densities were equal at $z \sim 3000$, ratio scales as $(1+z)$
  - One-in-a-billion fraction of mass energy liberated = distortion of energy spectrum of CMB at level of one in $10^6$ or less. Much less sensitive than ionization for $z < 1000$.

- How much change to the gas temperature?
  - Down to $z \sim 200$, CMB and ordinary matter are coupled in temperature - need to heat whole CMB, not just matter. Same estimate as for spectral distortion.
  - Baryon number density is $\sim 9$ orders of magnitude smaller than CMB number density - heating divided between a much smaller number of particles for $z < 200$. One-in-a-billion fraction of mass energy liberated $\Rightarrow$ increase baryon temperature by $\sim 5 \text{ eV per particle} \sim 50,000 \text{ K}$ - two orders of magnitude higher than baseline temperature at decoupling.

**powerful probe of annihilation/decay for $z < 1000$**
Ionization vs heating vs spectral distortions

- Consider the power from DM annihilation/decay - how many hydrogen ionizations?
  - \(1 \text{ GeV} / 13.6 \text{ eV} \approx 10^8\)
  - If \(10^{-8}\) of baryonic mass were converted to energy, would be sufficient to ionize entire universe.
    - There is \(\approx 5\times\) as much DM mass as baryonic mass.
    - If one in a billion DM particles annihilates (or decays), enough power to ionize half the hydrogen in the universe...
  - How much spectral distortion to the CMB?
    - Radiation and matter energy densities were equal at \(z \approx 3000\), ratio scales as \((1+z)\).
    - One-in-a-billion fraction of mass energy liberated = distortion of energy spectrum of CMB at level of one in \(10^6\) or less. Much less sensitive.
  - How much change to the gas temperature?
    - Down to \(z \approx 200\), CMB and ordinary matter are coupled in temperature - need to heat whole CMB, not just matter. Same estimate as for spectral distortion.
    - Baryon number density is \(\sim 9\) orders of magnitude smaller than CMB number density - heating divided between a much smaller number of particles for \(z < 200\). One-in-a-billion fraction of mass energy liberated = increase baryon temperature by \(\sim 5 \text{ eV per particle} \sim 50,000 \text{ K}\) - two orders of magnitude higher than baseline temperature at decoupling.

powerful probe of annihilation/decay for \(z < 1000\)

probe of physics at \(z > 1000\), or non-ionizing processes (e.g. scattering)
Ionization vs heating vs spectral distortions

- Consider the power from DM annihilation/decay - how many hydrogen ionizations?
  - $1 \text{ GeV} / 13.6 \text{ eV} \sim 10^8$
  - If $10^{-8}$ of baryonic mass were converted to energy, would be sufficient to ionize entire universe. There is $\sim 5x$ as much DM mass as baryonic mass.
  - If one in a billion DM particles annihilates (or decays), enough power to ionize half the hydrogen in the universe...

- How much spectral distortion to the CMB?
  - Radiation and matter energy densities were equal at $z \sim 3000$, ratio scales as $(1+z)$
  - One-in-a-billion fraction of mass energy liberated = distortion of energy spectrum of CMB at level of one in $10^6$ or less. Much less sensitive.

- How much change to the gas temperature?
  - Down to $z \sim 200$, CMB and ordinary matter are coupled in temperature - need to heat whole CMB, not just matter. Same estimate as for spectral distortion.
  - Baryon number density is $\sim 9$ orders of magnitude smaller than CMB number density - heating divided between a much smaller number of particles for $z < 200$. One-in-a-billion fraction of mass energy liberated => increase baryon temperature by $\sim 5 \text{ eV per particle} \sim 50,000 \text{ K}$ - two orders of magnitude higher than baseline temperature at decoupling.

**powerful probe of annihilation/decay for $z < 1000$**

**probe of physics at $z > 1000$, or non-ionizing processes (e.g. scattering)**

**potentially a large effect for $z < 200$ - could be visible in 21cm**
Example: estimating limits on decaying DM

- Fraction of DM decaying per e-fold in a given epoch \( \sim \) lifetime of cosmos / lifetime of DM

- Thus constraining a \( 10^{-9} \) fraction of DM decaying when the universe was 10% of its present age (\( O(100 \text{ million years}) \)) leads to limits on lifetimes of \( 10^8 \times \text{age of the universe} \sim \) few \( \times 10^{25} \) s

- Similar constraints for \( 10^{-11} \) decaying fraction when the universe was \( O(10^6 \text{ years}) \) old, i.e. the CMB epoch

- Can also probe tiny metastable components decaying with lifetimes > \( 10^6 \) years but < \( 10^{10} \) years
To study any of these effects in detail, we need to know how particles injected by annihilation/decay transfer their energy into heating, ionization, and/or photons.

My collaborators (Hongwan Liu, Greg Ridgway) and I have written a Python package to:

- model energy-loss processes and production of secondary particles,
- accounting for cosmic expansion / redshifting,
- with self-consistent treatment of exotic and conventional sources of energy injection.

Publicly available at https://github.com/hongwanliu/DarkHistory
Predicting a signal

Annihilation/decay/etc injects high-energy particles

If unstable, decay with Pythia or similar program

Time-dependent injection of high-energy photons + $e^+e^-$
(others largely escape or are subdominant; neglect)

Absorbed energy (ionization+excitation+heating)

Cooling processes

Modify evolution equations, e.g. with public recombination calculator (RECFAST, CosmoRec, HyRec)

Cosmic ionization and thermal histories
Predicting a signal

Annihilation/decay/etc injects high-energy particles

If unstable, decay with Pythia or similar program

Time-dependent injection of high-energy photons + \( e^+e^- \)
(others largely escape or are subdominant; neglect)

Absorbed energy (ionization+excitation+heating)

Cooling processes

Modify evolution equations, e.g. with public recombination calculator (RECFAST, CosmoRec, HyRec)

Cosmic ionization and thermal histories
The photon-electron cascade

Based on code developed in TRS, Padmanabhan & Finkbeiner 2009; TRS 2016

ELECTRONS

- Inverse Compton scattering (ICS) on the CMB.
- Excitation, ionization, heating of electron/H/He gas.
- Positronium capture and annihilation.
- All processes fast relative to Hubble time: bulk of energy goes into photons via ICS.

PHOTONS

- Pair production on the CMB.
- Photon-photon scattering.
- Pair production on the H/He gas.
- Compton scattering.
- Photoionization.
- Redshifting is important, energy can be deposited long after it was injected.

Schematic of a typical cascade:
initial $\gamma$-ray
$\rightarrow$ pair production
$\rightarrow$ ICS producing a new $\gamma$
$\rightarrow$ inelastic Compton scattering
$\rightarrow$ photoionization

Note: rates depend on gas ionization level
From energy deposition to modified histories

- Coupled equations govern evolution of the temperature and ionization history
- Energy deposition to ionization/heating provides extra source terms in these equations
- Simplest treatment uses three-level atom (TLA) approximation - basis of RECFAST code
- More advanced codes (CosmoRec, HyRec) include more levels of hydrogen

\[
\dot{T}_m = \dot{T}_m^{(0)} + \dot{T}_{m}^{\text{inj}} + \dot{T}_{m}^{\text{re}},
\]

\[
\dot{x}_{\text{HII}} = \dot{x}_{\text{HII}}^{(0)} + \dot{x}_{\text{HII}}^{\text{inj}} + \dot{x}_{\text{HII}}^{\text{re}}
\]

\[
\dot{T}_m^{(0)} = -2HT_m + \Gamma_C (T_{\text{CMB}} - T_m),
\]

\[
\dot{x}_{\text{HII}}^{(0)} = -C \left[ n_H x_e x_{\text{HII}} \alpha_H - 4(1 - x_{\text{HII}}) \beta_H e^{-E_{21}/T_{\text{CMB}}} \right]
\]

\[
\dot{T}_{m}^{\text{inj}} = \frac{2 f_{\text{heat}}(z, x)}{3(1 + F_{H e} + x_e) n_H} \left( \frac{dE}{dV dt} \right)^{\text{inj}},
\]

\[
\dot{x}_{\text{HII}}^{\text{inj}} = \left[ \frac{f_{H \text{ ion}}(z, x)}{R n_H} + \frac{(1 - C) f_{\text{exc}}(z, x)}{0.75 R n_H} \right] \left( \frac{dE}{dV dt} \right)^{\text{inj}}
\]
From energy deposition to modified histories

- Coupled equations govern evolution of the temperature and ionization history
- Energy deposition to ionization/heating provides extra source terms in these equations
- Simplest treatment uses three-level atom (TLA) approximation - basis of RECFAST code
- More advanced codes (CosmoRec, HyRec) include more levels of hydrogen
From energy deposition to modified histories

- Coupled equations govern evolution of the temperature and ionization history.
- Energy deposition to ionization/heating provides extra source terms in these equations.
- Simplest treatment uses three-level atom (TLA) approximation - basis of RECFAST code.
- More advanced codes (CosmoRec, HyRec) include more levels of hydrogen.

\[
\begin{align*}
\dot{T}_m &= \dot{T}_m^{(0)} + \dot{T}_m^{\text{inj}} + \dot{T}_m^{\text{re}}, \\
\dot{x}_{\text{HII}} &= \dot{x}_{\text{HII}}^{(0)} + \dot{x}_{\text{HII}}^{\text{inj}} + \dot{x}_{\text{HII}}^{\text{re}} \\
\end{align*}
\]

\[
\begin{align*}
\dot{T}_m^{(0)} &= -2HT_m + \Gamma_C(T_{\text{CMB}} - T_m), \\
\dot{x}_{\text{HII}}^{(0)} &= -C \left[ n_H x_e x_{\text{HII}} \alpha_H - 4(1 - x_{\text{HII}}) \beta_H e^{-E_{21}/T_{\text{CMB}}} \right] \\
\end{align*}
\]

\[
\begin{align*}
\dot{T}_m^{\text{inj}} &= \frac{2 f_{\text{heat}}(z, x)}{3(1 + F_{\text{He}} + x_e) n_H} \left( \frac{dE}{dV dt} \right)^{\text{inj}}, \\
\dot{x}_{\text{HII}}^{\text{inj}} &= \left[ \frac{f_H \text{ion}(z, x)}{R n_H} + \frac{(1 - C) f_{\text{exc}}(z, x)}{0.75 R n_H} \right] \left( \frac{dE}{dV dt} \right)^{\text{inj}} \\
\end{align*}
\]
From energy deposition to modified histories

- Coupled equations govern evolution of the temperature and ionization history

- Energy deposition to ionization/heating provides extra source terms in these equations

- Simplest treatment uses three-level atom (TLA) approximation - basis of RECFAST code

- More advanced codes (CosmoRec, HyRec) include more levels of hydrogen
Running **DARKHISTORY**

- DARKHISTORY is provided with extensive example notebooks.
- It contains built-in functions for:
  - redshift dependence corresponding to DM decay or s-wave annihilation
  - injection spectra of electrons/positrons/photons corresponding to all SM final states
- Example: ionization/temperature histories for a 50 GeV thermal relic annihilating to b quarks.
- Easy to turn on/off “backreaction” effects (changes to ionization level from earlier energy injection modifies particle production cascade).
Annihilation limits from ionization + the CMB

- The effect of DM annihilation on the CMB is universal in the keV-TeV+ range [TRS '16]: for every model where DM annihilates with ~constant cross section during dark ages, effect on CMB can be captured by a universal shape with a model-dependent normalization factor (which can be computed using DARKHISTORY or TRS '16).

- One analysis simultaneously tests all annihilation channels, huge mass range.

- Thermal relics with unsuppressed annihilation to non-neutrino SM final states (or intermediate states that decay to SM particles) can be ruled out for masses below ~10 GeV. Light DM needs a different origin mechanism, or suppressed annihilation.

Planck Collaboration '18 1807.06209
based on results of TRS PRD '16
Decay limits from CMB and Lyman-alpha

- For decaying dark matter, comparable bounds from ionization/CMB and heating/Lyman-alpha constraints.
- Sets some of the strongest limits on relatively light (MeV-GeV) DM decaying to produce electrons and positrons.
- For short-lifetime decays, can rule out even $10^{-11}$ of the DM decaying! (for lifetimes $\sim 10^{14}$ s)

Liu et al '20
Eventual goal: a comprehensive map of the full space of possible early-universe signatures of exotic energy injections, allowing us to easily translate arbitrary energy injection models into observables and constraints.

(We already have something very close to this for CMB anisotropy signals from DM annihilation/decay - I would like to extend it to other observables.)
Where could we improve?
Where could we improve?

- Making the code more compact with respect to memory, storage - v1 relied on (annoyingly) large pre-computed tables describing the cascade
Where could we improve?

- Making the code more compact with respect to memory, storage - v1 relied on (annoyingly) large pre-computed tables describing the cascade
- Capturing dependence on cosmological parameters - the cascade calculation depends on $H_0$ and $\Omega_b$, and these are currently hard-coded
Where could we improve?

- Making the code more compact with respect to memory, storage - v1 relied on (annoyingly) large pre-computed tables describing the cascade.

- Capturing dependence on cosmological parameters - the cascade calculation depends on $H_0$ and $\Omega_b$, and these are currently hard-coded.

- Full treatment of low-energy particles - in current public version, for electrons below 3 keV, we interpolate results from the MEDEA code [Evoli et al ’12]. Treatment of low-energy photons is also highly approximate.
Where could we improve?

- Making the code more compact with respect to memory, storage - v1 relied on (annoyingly) large pre-computed tables describing the cascade.
- Capturing dependence on cosmological parameters - the cascade calculation depends on $H_0$ and $\Omega_b$, and these are currently hard-coded.
- Full treatment of low-energy particles - in current public version, for electrons below 3 keV, we interpolate results from the MEDEA code [Evoli et al '12]. Treatment of low-energy photons is also highly approximate.
- Prediction of complete CMB spectral distortion (for future experiments).
Where could we improve?

- Making the **code more compact** with respect to memory, storage - v1 relied on (annoyingly) large pre-computed tables describing the cascade

- Capturing dependence on **cosmological parameters** - the cascade calculation depends on \( H_0 \) and \( \Omega_b \), and these are currently hard-coded

- **Full treatment of low-energy particles** - in current public version, for electrons below 3 keV, we interpolate results from the MEDEA code [Evoli et al ’12]. Treatment of low-energy photons is also highly approximate.

- Prediction of **complete CMB spectral distortion** (for future experiments).

- Making the code **faster**, which would also facilitate…
Where could we improve?

- Making the code more compact with respect to memory, storage - v1 relied on (annoyingly) large pre-computed tables describing the cascade
- Capturing dependence on cosmological parameters - the cascade calculation depends on $H_0$ and $\Omega_b$, and these are currently hard-coded
- Full treatment of low-energy particles - in current public version, for electrons below 3 keV, we interpolate results from the MEDEA code [Evoli et al ’12]. Treatment of low-energy photons is also highly approximate.
- Prediction of complete CMB spectral distortion (for future experiments).
- Making the code faster, which would also facilitate…
- Integration with other relevant public code packages - e.g. CosmoRec/HyRec, CLASS, 21cmFAST and other 21cm codes
Where could we improve?

- Making the code more compact with respect to memory, storage - `v1` relied on (annoyingly) large pre-computed tables describing the cascade

- Capturing dependence on cosmological parameters - the cascade calculation depends on $H_0$ and $\Omega_b$, and these are currently hard-coded

- Full treatment of low-energy particles - in current public version, for electrons below 3 keV, we interpolate results from the MEDEA code [Evoli et al ’12]. Treatment of low-energy photons is also highly approximate.

- Prediction of complete CMB spectral distortion (for future experiments).

- Making the code faster, which would also facilitate…

- Integration with other relevant public code packages - e.g. CosmoRec/HyRec, CLASS, 21cmFAST and other 21cm codes

- Inhomogeneity - DARKHISTORY treats ionization + gas density as spatially uniform
Where could we improve?

- Making the code more compact with respect to memory, storage - v1 relied on (annoyingly) large pre-computed tables describing the cascade
- Capturing dependence on cosmological parameters - the cascade calculation depends on $H_0$ and $\Omega_b$, and these are currently hard-coded
- Full treatment of low-energy particles - in current public version, for electrons below 3 keV, we interpolate results from the MEDEA code [Evoli et al ’12]. Treatment of low-energy photons is also highly approximate.
- Prediction of complete CMB spectral distortion (for future experiments).
- Making the code faster, which would also facilitate…
- Integration with other relevant public code packages - e.g. CosmoRec/HyRec, CLASS, 21cmFAST and other 21cm codes
- Inhomogeneity - DARKHISTORY treats ionization + gas density as spatially uniform
- Radiation fields - DARKHISTORY assumes the only radiation field is the CMB (also no magnetic fields)
Where could we improve?

- Making the code more compact with respect to memory, storage - v1 relied on (annoyingly) large pre-computed tables describing the cascade.

- Capturing dependence on cosmological parameters - the cascade calculation depends on $H_0$ and $\Omega_b$, and these are currently hard-coded.

- Full treatment of low-energy particles - in current public version, for electrons below 3 keV, we interpolate results from the MEDEA code [Evoli et al ’12]. Treatment of low-energy photons is also highly approximate.

- Prediction of complete CMB spectral distortion (for future experiments).

- Making the code faster, which would also facilitate…

- Integration with other relevant public code packages - e.g. CosmoRec/HyRec, CLASS, 21cmFAST and other 21cm codes.

- Inhomogeneity - DARKHISTORY treats ionization + gas density as spatially uniform.

- Radiation fields - DARKHISTORY assumes the only radiation field is the CMB (also no magnetic fields).
DARKHISTORY with neural networks

[Yitian Sun & TRS, 2207.06425]

Goal: store the transfer functions in a more efficient/compact way

- improve usability
- facilitate adding extra parameter dependences (e.g. on gas density, for future inhomogeneity studies + factorizing out $\Omega_b$ dependence)

Observation:

- neural networks can serve as general function approximators
- the transfer functions have features and structure, but have significant regions where they are quite smooth - much less information than # of pixels

Example slice through a transfer function at $1+z=300$, $x_{\text{HII}}=0.6$
Results

- Network is ~400x smaller than tables (may be possible to do even better)
- Speed of code with NN evaluation is comparable to that with table lookup
- Accuracy in temperature/ionization histories is <2% (often much lower)
- DARKHISTORY also predicts a component of the CMB spectral distortion - also well reproduced, although with larger errors (up to 10%)
Comparison of histories + spectral distortion
Detailed treatment of the low-energy cascade

(Hongwan Liu, Wenzer Qin, Greg Ridgway, TRS, to appear)

- Present status: once particles cool below 3 keV,
  - for electrons/positrons, we interpolate the published results of the MEDEA code over energy - but only 7 energies for interpolation + only evaluates integrated energy in spectral distortion, not spectrum
  - we track photons until they ionize or fall below 13.6 eV; we assign photons in the 10.2-13.6 eV range to hydrogen excitation and assume they free-stream below 10.2 eV
- We also use the three-level atom approximation (with fudge factors) to study the evolution of the ionization history, and assume a blackbody radiation field - may not be accurate in the presence of energy injection
Goals of upcoming work

- Carefully track the joint evolution of the H/He atoms and the radiation field after recombination, taking into account a large number of atomic levels.
- Take into account high-frequency distortions to the blackbody spectrum that can affect ionization/recombination/excitation rates.
- Extend our code for electron/positron energy losses down to energies where the electrons thermalize with the CMB (cross-checked against existing MEDEA code at sample points).
- Predict the final distortion to the CMB blackbody spectrum produced by energy injection.
Preliminary spectral distortion results

- Previous studies have examined the spectral distortion from the high-redshift, fully ionized universe (e.g. Chluba et al ’19, Acharya & Khatri ’19)
- We have checked we agree with their results when we match assumptions
- We have also confirmed we accurately reproduce the Standard Model spectral distortion from recombination
- We can now predict the full distortion including energy injection
Preliminary constraints on low-mass DM
Summary

- Cosmological datasets can provide powerful probes of the non-gravitational properties of dark matter, and other exotic physics.

- We already have stringent and broadly applicable limits on annihilating and decaying DM, especially at sub-GeV mass scales, from the cosmic microwave background, and complementary competitive bounds from Lyman-alpha for leptonically decaying light DM.

- We have developed a new public numerical toolbox, DARKHISTORY, to self-consistently compute the effects of exotic energy injections on the cosmic thermal and ionization histories.

- DARKHISTORY now includes a compact version relying on neural networks, which should also facilitate further upgrades (including additional parameter dependence, inhomogeneity, etc).

- Work is in progress to fully treat the low-energy particle cascade and predict the full space of possible CMB spectral distortions from energy injection.