What Happened Before BBN?

The (mostly) successful prediction of the primordial abundances of light elements is one of cosmology’s crowning achievements.

- The elements produced during **Big Bang Nucleosynthesis** are our first direct window on the Universe.
- They tell us that the **Universe was radiation dominated during BBN**.

But we have good reasons to think that the Universe was not radiation dominated before BBN.

- Primordial density fluctuations point to **inflation**.
- During inflation, the Universe was **scalar dominated**.
- **Other scalar fields may dominate the Universe after the inflaton decays**.
- The **string moduli problem**: scalars with gravitational couplings come to dominate the Universe before BBN.

_Acharya, Kumar, Bobkov, Kane, Shao, Watson 2008_  
_Acharya, Kumar, Kane, Watson 2009_  
_Recent Summary: Kane, Sinha, Watson 1502.07746_  
_Carlos, Casas, Quevedo, Roulet 1993_  
_Banks, Kaplan, Nelson 1994_
Cosmic Timeline

**Big Bang Nucleosynthesis**
- $0.07 \text{ MeV} \lesssim T \lesssim 3 \text{ MeV}$
- $0.08 \text{ sec} \lesssim t \lesssim 4 \text{ min}$

- $a \propto t^{1/2}$
- $\rho_{\text{rad}} \propto a^{-4}$

**Matter-Radiation Equality**
- $T = 0.74 \text{ eV}$
- $t = 57,000 \text{ yr}$

**CMB**
- $T = 0.25 \text{ eV}$
- $t = 380,000 \text{ yr}$

**Now**
- $T = 2.3 \times 10^{-4} \text{ eV}$
- $t = 13.8 \text{ Gyr}$

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**Matter-Domination**
- $a \propto t^{2/3}$
- $\rho_{\text{mat}} \propto a^{-3}$
- $\rho_{\Lambda} = \text{const}$

**Matter-\(\Lambda\)-Equality**
- $T = 3.2 \times 10^{-4} \text{ eV}$
- $t = 9.5 \text{ Gyr}$
A Different View of the Gap

Set the stage for Big Bang nucleosynthesis with inflation at 10^{15} \text{GeV}(?)

Today: 10^{-13} \text{GeV}

Cosmic microwave background generated.
Evolution of the pre-BBN Universe

The Universe was once dominated by a scalar field
- the inflaton
- string moduli

Fast-rolling scalar: \( \rho_\phi = P_\phi \implies \rho_\phi \propto a^{-6} \)

For \( V \propto \phi^2 \), oscillating scalar field \( \sim \) matter.
- over many oscillations, average pressure is zero.
- density in scalar field evolves as \( \rho_\phi \propto a^{-3} \)
- scalar field density perturbations grow as \( \delta_\phi \propto a \)

Other massive particles could come to dominate the Universe:
- axinos or gravitinos
- hidden sector particles/mediators

Eventually, the scalar/particle decays into radiation, reheating the Universe.

\[ T_{\text{RH}} \gtrsim 3 \text{ MeV} \]

Ichikawa, Kawasaki, Takahashi 2005; 2007
de Bernardis, Pagano, Melchiorri 2008

Jedamzik, Lemoine, Martin 2010;
Easther, Flauger, Gilmore 2010
Cosmic Timeline

**Inflation**
- 0.07 MeV $\lesssim T \lesssim 3$ MeV
- 0.08 sec $\lesssim t \lesssim 4$ min

**EMDE or Kination**

**Radiation Domination**
- $a \propto t^{1/2}$
- $\rho_{\text{rad}} \propto a^{-4}$

**Reheating**
- $T = ?$

**Implications:**
1. Dark matter production
2. Early structure growth

**BBN**
- $T = 0.25$ eV
- $t = 380,000$ yr

**CMB**
- $T = 2.3 \times 10^{-4}$ eV
- $t = 13.8$ Gyr

**Now**
- $T = 0.07$ MeV
- $t = 9.5$ Gyr

**Matter - Radiation Equality**
- $T = 0.74$ eV
- $t = 57,000$ yr

**Matter - $\Lambda$ Equality**
- $T = 3.2 \times 10^{-4}$ eV
- $t = 9.5$ Gyr

$\rho_{\text{rad}} \propto a^{-4}$

$\rho_{\text{mat}} \propto a^{-3}$

$\rho_{\Lambda} = \text{const}$
DM Origin I: Nonthermal

Branching ratio determines present-day dark matter density:

$$f \approx 0.43 \left( \frac{T_{eq}}{T_{RH}} \right)$$

$$T_{eq} = 0.75 \text{ eV}$$

We need a very small branching ratio:

$$f < 10^{-7}$$
DM Origin 2: Thermal

\[ \langle \sigma v \rangle_{0.25} = 2 \times 10^{-29} \text{ cm}^3/\text{s} \]

Freeze-out: \( \Omega_\chi \propto \frac{1}{\langle \sigma v \rangle} \)

Freeze-in: \( \Omega_\chi \propto \langle \sigma v \rangle \)

\[ T_{RH} = 50 \text{ GeV} \]
\[ m_\chi = 5 \text{ TeV} \]

\( \phi \rightarrow \) Radiation \( \gamma\gamma \leftrightarrow \chi\bar{\chi} \rightarrow \) Matter

Giudice, Kolb, Riotto 2001
DM Origin 3: Nonthermal with Annihilations

Branching ratio can be order unity: annihilations then destroy excess DM at reheating.

**Freeze-out:** \( \Omega_\chi \propto \frac{1}{\langle \sigma v \rangle} \)

This scenario requires a larger annihilation cross section:

\[
\langle \sigma v \rangle_{0.25} \approx \frac{m_\chi / 20}{T_{RH}} \times (3 \times 10^{-26} \text{ cm}^3/\text{s})
\]
From Miracle to Mess!

Neutralino Mass (GeV)

$T_{RH} = 10$ GeV $T_{RH} = 1$ GeV $T_{RH} = 100$ MeV $T_{RH} = 10$ MeV

$\eta = 0$ $\eta = 10^{-9}$ $\eta = 10^{-6}$ $\eta = 10^{-3}$ $\eta = 1/2$

Increasing $f/m$
Kination: Universe dominated by a fast rolling scalar field $\rho_\phi \propto a^{-6}$

- faster expansion rate implies earlier freeze-out
- larger annihilation cross section needed to match observed abundance

But an early matter-dominated era (EMDE) requires smaller annihilation cross sections!

What hope do we have of probing these scenarios?
Microhalos from an EMDE

Nonthermal Dark Matter:

Nonthermal Dark Matter with Annihilations:

Thermal Dark Matter:
The Dark Matter Perturbation

Evolution of the Matter Density Perturbation

- Nonthermal dark matter immediately begins linear growth after horizon entry.
- Thermal DM is coupled to radiation prior to freeze-out, then grows linearly.
- The amplitude of the perturbations during RD is the same for both thermal and nonthermal dark matter.
The Dark Matter Perturbation

The Matter Density Perturbation during Radiation Domination

\[
\frac{\delta_{dm}(10^3 a_{RH})}{\Phi_0} \propto \frac{a_{RH}}{a_{hor}} \propto \frac{k^2}{k_{RH}^2}
\]

\[
\delta_{dm} = \frac{2}{3} \Phi_0 \frac{k^2}{k_{RH}^2} \left[ 1 + \ln \left( \frac{a}{a_{RH}} \right) \right]
\]

Hu & Sugiyama 1996

super-horizon
entered horizon during radiation domination
standard evolution
entered horizon during scalar domination
RMS Density Fluctuation

- Enhanced perturbation growth affects scales with $R \lesssim k_{RH}^{-1}$
- Define $M_{RH}$ to be mass within this comoving radius.

$$M_{RH} \approx 10^{-5} M_{\oplus} \left( \frac{1 \text{ GeV}}{T_{RH}} \right)^3$$

Microhalos!
Free-streaming

Free-streaming will exponentially suppress power on scales smaller than the **free-streaming horizon**: \( \lambda_{fsh}(t) = \int_{t_{RH}}^{t} \frac{\langle v \rangle}{a} \, dt \)

Modify transfer function: \( T(k) = \exp \left[ -\frac{k^2}{2k_{fsh}^2} \right] T_0(k) \)

*Structures grown during reheating only survive if* \( k_{fsh}/k_{RH} > 10 \)
From Perturbations to Microhalos

To estimate the abundance of halos, we used the Press-Schechter mass function to calculate the fraction of dark matter contained in halos of mass \( M \).

\[
\frac{df}{d \ln M} = \sqrt{\frac{2}{\pi}} \left| \frac{d \ln \sigma}{d \ln M} \right| \frac{\delta_c}{\sigma(M, z)} \exp \left[ -\frac{1}{2} \frac{\delta_c^2}{\sigma^2(M, z)} \right]
\]

**differential bound fraction**

**Key ratio:** \( \frac{\delta_c}{\sigma(M, z)} \)

- Halos with \( \sigma(M, z) < \delta_c \) are rare.
- Define \( M_*(z) \) by \( \sigma(M_*, z) = \delta_c \)

![Graph showing differential bound fraction with T_{RH} = 1 GeV and various k_fsh values](image-url)
The Evolution of the Bound Fraction

No Cut-off
\[ \frac{k_{\text{cut}}}{k_{\text{RH}}} = 40 \]
\[ \frac{k_{\text{cut}}}{k_{\text{RH}}} = 20 \]
\[ \frac{k_{\text{cut}}}{k_{\text{RH}}} = 10 \]
Independent of Reheat Temperature

$T_{RH} = 10$ GeV
$T_{RH} = 1$ GeV
$T_{RH} = 0.1$ GeV

No Cut-off

$k_{cut}/k_{RH} = 40$
$k_{cut}/k_{RH} = 20$
$k_{cut}/k_{RH} = 10$
The Total Bound Fraction

Bound Fraction with $M < M_{RH}$

Redshift ($z$)

$k_{cut} = 40 \, k_{RH}$

$k_{cut} = 20 \, k_{RH}$

$k_{cut} = 10 \, k_{RH}$

$T_{RH} = 10 \, GeV$

1 GeV

0.1 GeV

$k_{fsh} = 40k_{RH}$

$k_{fsh} = 10k_{RH}$

$k_{fsh} = 10^{-9}$

$10^{-4}$

$0.3$

$0.05$

$0.3$

$10^{-4}$

$0.04$

Table:

<table>
<thead>
<tr>
<th>$z$</th>
<th>400</th>
<th>100</th>
<th>50</th>
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<tr>
<td>$k_{fsh}$ = 40$k_{RH}$</td>
<td>0.6</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>$k_{fsh}$ = 10$k_{RH}$</td>
<td>$10^{-9}$</td>
<td>0.05</td>
<td>0.3</td>
</tr>
<tr>
<td>Std.</td>
<td>0</td>
<td>$10^{-4}$</td>
<td>0.04</td>
</tr>
</tbody>
</table>
The Annihilation Rate

\[ \frac{\Gamma_{\text{ann}}}{\text{Volume}} \propto \langle \sigma v \rangle n_{\chi}^2 \propto \frac{\langle \sigma v \rangle}{m_{\chi}^2} \rho_{\chi}^2 \]

- The annihilation rate is highest for small DM masses and low reheat temperatures.

- The boost factor from enhanced substructure is critical for detection.

\[ \frac{\langle \sigma v \rangle}{m_{\chi}^2} \bigg|_{T_{RH} \to \infty} = \frac{2.6 \times 10^{-15}}{\text{GeV}^4} \left( \frac{1 \text{ TeV}}{m_{\chi}} \right)^2 \]
Towards the Boost Factor

The Press-Schechter formalism indicates that formation of the microhalos is strongly hierarchical: its microhalos all the way down.

Simulated Earth-mass microhalos

$T_{RH} = 8.5$ MeV  $M/M_\odot$
Estimating the Boost Factor

Dark matter annihilation rate: \[ \Gamma = \frac{\langle \sigma v \rangle}{2m^2} \int \rho^2(r) d^3r \equiv \frac{\langle \sigma v \rangle}{2m^2} J \]

Halo filled with microhalos:

\[ J = NJ_{\text{micro}} + 4\pi \int_0^R (1 - f_0)^2 \rho_{\text{halo}}^2(r) dr \]

Number of microhalos:

\[ N = \int (\text{survival prob.}) \frac{M_{\text{halo}}}{M} \frac{df}{d\ln M} d\ln M \]

Assume microhalo NFW profile with \( c = 2 \) at formation redshift. \( \text{Anderhalden & Diemand 2013} \)

\( \text{Ishiyama 2014} \)

- early forming microhalos: \( z_f \gtrsim 50 \)
- dense cores: \( \bar{\rho}_{\text{micro}}(r_s) > 2\bar{\rho}_{\text{halo}}(r) \) for \( r > 1 \) kpc
- assume that microhalo centers survive outside of inner kpc: reduces number of microhalos by 1%.
- assume that microhalos are stripped to \( r = r_s \): reduces \( J_{\text{micro}} \) by <20%
Estimating the Boost Factor II

Dark matter annihilation rate:
\[ \Gamma = \frac{\langle \sigma v \rangle}{2m^2_\chi} \int \rho^2(r) d^3r \equiv \frac{\langle \sigma v \rangle}{2m^2_\chi} J \]

Boost Factor:
\[ 1 + B(M) \equiv \frac{J}{\int \rho^2_\chi(r) 4\pi r^2 dr} \propto \frac{\rho(z_f)}{\rho_0 c^3_h} f_{\text{tot}}(M < M_{RH}, z_f) \]

**ALE 2015**

Adrienne Erickcek
Moving Toward Constraints

\[ \frac{\Gamma_{\text{ann}}}{\text{Volume}} \propto \frac{\langle \sigma v \rangle n_\chi^2}{m_\chi^2} \propto \frac{\langle \sigma v \rangle}{\rho_\chi} \]

- Rough comparison

\[ \left( \frac{\langle \sigma v \rangle}{m_\chi^2} \right)_{\text{obs}} \text{ vs. } (1 + B) \left( \frac{\langle \sigma v \rangle}{m_\chi^2} \right)_{\text{Med}} \]

- **dSphs**: total boost for $10^6 M_\odot$ halo.
- **IGRB**: EMDE boost relative to standard boost.

**Fermi-LAT Collaboration 2015**

- **dSphs**: total boost for $10^6 M_\odot$ halo.
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**Dramatic Constraints**

- **dSphs**: $B = 20,000 \quad k_{\text{cut}} = 20 k_{\text{RH}}$
- **IGRB**: $B = 75,000 \quad k_{\text{cut}} = 40 k_{\text{RH}}$

- **4-year Pass 7 Limit**
- **6-year Pass 8 Limit**
- **Median Expected**
- **68% Containment**
- **95% Containment**

**Thermal Relic Cross Section** (Steigman et al. 2012)

- **Thermal Relic Cross Section** (Steigman et al. 2012)

**Stacked dSphs**

- **Fermi-LAT Collaboration 2015**

**dSphs**

- **IGRB**

**10^{-17} \quad 10^{-16} \quad 10^{-15} \quad 10^{-14} \quad 10^{-13} \quad 10^{-12} \quad 10^{-11}**

**DM Mass (GeV/c^2)**

**10^{-27} \quad 10^{-26} \quad 10^{-25} \quad 10^{-24} \quad 10^{-23} \quad 10^{-22} \quad 10^{-21}**

**DM Mass (GeV/c^2)**
Moving Toward Constraints

\[ \frac{\Gamma_{\text{ann}}}{\text{Volume}} \propto \langle \sigma v \rangle n_{\chi}^2 \propto \frac{\langle \sigma v \rangle}{m_{\chi}^2} \rho_{\chi}^2 \]

This mechanism can make “isolated” bino DM detectable.
ALE, Sinha, Watson 2016

Two source of uncertainty:
1. small-scale cut-off
2. do the first-generation microhalos survive?

Rough comparison
\[ \left. \frac{\langle \sigma v \rangle}{m_{\chi}^2} \right|_{\text{obs}} \quad \text{vs.} \quad (1 + B) \left. \frac{\langle \sigma v \rangle}{m_{\chi}^2} \right|_{\Omega_M = 0.25} \]

- dSphs: total boost for \(10^6 M_\odot\) halo.
- IGRB: EMDE boost relative to standard boost.

IGRB: \( B = 75,000 \) \( k_{\text{cut}} = 40k_{\text{RH}} \)
dSphs: \( B = 20,000 \) \( k_{\text{cut}} = 20k_{\text{RH}} \)
\( z_f = 400 \)
First potential source of a small-scale cut-off:
interactions between dark matter and relativistic particles

Interactions do not significantly suppress the perturbations, even if the dark matter remains coupled to the relativistic particles well into the EMDE...
Kinetic Decoupling during an EMDE

First potential source of a small-scale cut-off: interactions between dark matter and relativistic particles

Interactions do not significantly suppress the perturbations, even if the dark matter remains coupled to the relativistic particles well into the EMDE... and even through reheating!

see also Choi, Gong, Shin 2015
The DM temperature

What about free-streaming? We need the DM temperature.

$$T_\chi \equiv \frac{2}{3} \left\langle \left| \vec{p} \right|^2 \right\rangle \frac{dT_\chi}{da} + 2T_\chi = -2 \frac{\gamma}{H} (T_\chi - T)$$

- **fully coupled:**
  $$\gamma \gg H \Rightarrow T_\chi \simeq T$$
- **fully decoupled:**
  $$\gamma \ll H \Rightarrow T_\chi \propto a^{-2}$$
- But during an EMDE
  $$\frac{\gamma}{H} T \propto \frac{T^6}{T^4} T \propto T^3 \propto a^{-9/8}$$
- **quasi-decoupled:**
  $$T_\chi \propto a^{-9/8}$$

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Isaac Waldstein, ALE, Cosmin Ilie 2017

What about free-streaming?

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Adrienne Erickcek
The DM temperature

What about free-streaming? We need the DM temperature.

$$T_\chi \equiv \frac{2}{3} \left\langle \frac{\langle |\vec{p}|^2 \rangle}{2m_\chi} \right\rangle$$

$$a \frac{dT_\chi}{da} + 2T_\chi = -2 \frac{\gamma}{H} (T_\chi - T)$$

- fully coupled: $\gamma \propto T^6$
- fully decoupled: $\gamma \propto \frac{1}{T^4}$
- quasi-decoupled: $T_\chi \propto a^{-9/8}$

But what are the implications for free-streaming? It depends....

- EMDE
- decoupling $\gamma = H$
- reheating
- RD

Temperature (GeV)

scale factor (a)
Microhalo Simulations

EMDE

RD

EMDE

RD
Simulation Results

Lots of microhalos with steep profiles and copious substructure.

**Figure:**
- **Graph 1:** Density vs. Mass for different models (EMDE, RD) with Press-Schechter and Sheth-Tormen distributions.
- **Graph 2:** Halo mass function for EMDE and RD models with various halo masses.
- **Graph 3:** Substructure mass function for $10^{-6} M_\odot/h$ hosts, showing $f_{\text{sub}} > 0.5$ for certain mass ranges.
Boost Factor from Simulations

\[ 1 + B(M) \equiv \int \frac{J}{\rho_X^2(r) 4\pi r^2 dr} \propto \frac{\rho(z_f)}{\rho_0 c_h^3} f_{\text{tot}}(M < M_{RH}, z_f) \]

assumes all halos have same profile at \( z_f \)

include substructure:

\[ f_{\text{tot}} \rightarrow b_{\text{tot}} \]

**Sheridan Green, ALE+ coming soon**
Perturbations during Kination

\[ \delta \chi \propto a \]

\[ \delta \chi \propto \frac{a_{RH}}{a_{hor}} \propto \sqrt{\frac{k}{k_{RH}}} \]

Kayla Redmond, ALE coming soon
• There is a gap in the cosmological record between inflation and the onset of Big Bang nucleosynthesis: \(10^{15}\text{ GeV} \gtrsim T \gtrsim 10^{-3}\text{ GeV}\).

• Dark matter microhalos offer hope of probing the gap.

• Both kination and an early matter-dominated era (EMDE) enhance the growth of sub-horizon density perturbations.

• The microhalos that form after an EMDE significantly boost the dark matter annihilation rate.

• We can use gamma-ray observations to probe the evolution of the early Universe, but first we have to determine the formation time of the smallest microhalos and if they survive to the present day.