Using Microhalos to Probe the Universe’s First Second

CIPANP
Palm Springs, CA
May 30, 2018
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_
_Giblin, Kane, Nesbit, Watson, Zhao 2017_
_Summary: Kane, Sinha, Watson 1502.07746_

Carlos, Casas, Quevedo, Roulet 1993
Banks, Kaplan, Nelson 1994
What do we know about inflation?

Observational probes of inflation are mostly limited to large scales.
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But surprises could be lurking on smaller scales.

- Inflaton interactions: particle production or coupling to gauge fields
  - Chung+ 2000; Barnaby+ 2009, 2010; Barnaby+ 2011

- Multi-stage and multi-field inflation with bends in inflaton trajectory
  - Silk & Turner 1987; Adams+ 1997; Achucarro+ 2012

- Any theory with a potential that gets flatter: running mass inflation
  - Stewart 1997; Covi+ 1999; Covi & Lyth 1999

- Hybrid models that use a “waterfall” field to end inflation
  - Lyth 2011; Gong & Sasaki 2011; Bugaev & Klimai 2011; Guth & Sfakianakis 2012
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Cosmic Timeline

**Big Bang Nucleosynthesis**
- $0.07 \text{ MeV} \lesssim T \lesssim 3 \text{ MeV}$
- $0.08 \text{ sec} \lesssim t \lesssim 4 \text{ min}$
- $a \propto t^{1/2}$
- $\rho_{\text{rad}} \propto a^{-4}$

**CMB**
- $T = 0.25 \text{ eV}$
- $t = 380,000 \text{ yr}$
- $a \propto t^{2/3}$
- $\rho_{\text{mat}} \propto a^{-3}$
- $\rho_{\Lambda} = \text{const}$

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

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

**Matter-\Lambda Equality**
- $T = 3.2 \times 10^{-4} \text{ eV}$
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Inflation
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**Talk Timeline**

**Idea I:** Probing inflation with ultra-compact microhalos (UCMHWs)

**Idea II:** Probing the pre-BBN thermal history with microhalos

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Adrienne Erickcek

CIPANP: May 30, 2018
If a region has an initial density $\rho > 1.001\bar{\rho}$, then all the dark matter in that region collapses at early times ($z \gtrsim 1000$) and forms an Ultra-Compact Minihalo. 

$Ricotti \& Gould \ 2009$
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Ricotti & Gould 2009
An upper bound on the **UCMH number density** leads to an upper bound on the **primordial power spectrum**.

*Josan & Green 2010; Bringmann, Scott, Akrami 2012*
UCMHs Probe Power Spectrum

An upper bound on the **UCMH number density** leads to an upper bound on the **primordial power spectrum**.

Josan & Green 2010; Bringmann, Scott, Akrami 2012

These bounds assume that UCMHs have a radial-infall density profile.
1. Modify GadgetV2 to include smooth radiation component.

![Graph showing simulation results](image-url)
Simulations of UCMHs

1. Modify GadgetV2 to include smooth radiation component.
2. Generate initial conditions from a power spectrum with a spike.

\[ P(k, z = 9.96) \]

- GADGET-2 with radiation
- linear theory prediction

Power Spectrum \( P(k) \)

Wavelength (Mpc)

PBHs (Josan, Green, Malik 2009)

CMB Spectral Distortions (Chluba, Erickcek, Ben-Dayan 2012)

UCMHs+Fermi (Bringmann, Scott, Akrami 2012)

Ly\a (Bird et al. 2011)(Hlozek et al. 2012)

WMAP+ACT
Simulations of UCMHs

1. Modify GadgetV2 to include smooth radiation component.
2. Generate initial conditions from a power spectrum with a spike.
3. Make an UCMH!
 Nine simulated UCMHs

All have similar density profiles: \[ \rho = \frac{\rho_s}{(r/r_s)^{1.5}(1 + r/r_s)^{1.5}} \]

Stable with redshift, unless there's a merger....
We also formed UCMHs using a plateau feature.
UCMH Density Profiles: Plateau

We also formed UCMHs using a plateau feature

and these UCMHs have NFW profiles!
UCMHs: Summary and Outlook

- UCMHs that form from spikes in the primordial power spectrum have **Moore profiles** \( \rho \propto r^{-1.5} \), while plateaus in the primordial power spectrum generate UCMHs with **NFW profiles** \( \rho \propto r^{-1} \).

- The dark matter annihilation rate within the UCMHs is reduced by a factor of 200, which reduces upper bound on UCMH abundance by 3000.

- But we have so many more halos to consider...

  **Sten Delos, ALE, Bailey, Alvarez**
  coming soon

**STAY TUNED**
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**Idea II:** Probing the pre-BBN thermal history with microhalos
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 $\simeq$ matter.
- over many oscillations, average pressure is zero.
- scalar field energy density evolves as $\rho_\phi \propto a^{-3}$
- or we could form oscillons, which are effectively massive particles

Other massive particles could come to dominate the Universe:
- axinos or gravitinos
- hidden sector particles e.g. Dror, Kuflik, Melcher, Watson 2018
  Berlin, Hooper, Krnjaic 2016

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

$T_{RH} \gtrsim 3$ MeV Ichikawa, Kawasaki, Takahashi 2005; 2007
de Bernardis, Pagano, Melchiorri 2008
Cosmic Timeline

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**EMDE or Kination**

**Radiation Domination**
- $a \propto t^{1/2}$
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**Matter Domination**
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**Reheating**
- $T = ?$

**Matter-\(\Lambda\) Equality**
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**Probing Dark Matter Production**

**Kination: Universe dominated by a fast rolling scalar field**

- faster expansion rate at a given temperature implies earlier freeze-out
- larger annihilation cross section needed to match observed DM abundance
- already on the verge of being ruled out by HESS and Fermi observations

Thermal DM production during an early matter-dominated era (EMDE) requires much smaller annihilation cross sections!

\[
\text{Kayla Redmond & ALE 2017}
\]

What hope do we have of probing these scenarios?

Giudice, Kolb, Riotto 2001; Gelmini, Gondolo 2006; Gelmini, Gondolo, Soldatenko, Yaguna 2006, ALE 2015
Structure Growth during an EMDE

Evolution of the Matter Density Perturbation

\[ \frac{\delta_{dm}}{\Phi_0} \]

- **DMDE**
- Linear growth
- Horizon entry
- Logarithmic growth
- Radiation domination

\[ 10^0 \quad 10^1 \quad 10^2 \quad 10^3 \quad 10^4 \quad 10^5 \quad 10^6 \quad 10^7 \]

**Scale factor (a)**

ALE & Sigurdson 2011; Fan, Ozsoy, Watson 2014; ALE 2015
Enhanced perturbation growth affects subhorizon scales: $R \lesssim k_{\text{RH}}^{-1}$

Define $M_{\text{RH}}$ to be mass within this comoving radius.

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

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

Structures grown during reheating only survive if \( k_{\text{fsh}} / k_{\text{RH}} > 10 \).
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 $M$.

![Graph showing the bound fraction of halos with $M < M_{\text{RH}}$ as a function of redshift ($z$) for different values of $k_{\text{cut}}$ and $T_{\text{RH}}$.]

<table>
<thead>
<tr>
<th>$z$</th>
<th>$400$</th>
<th>$100$</th>
<th>$50$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_{fsh} = 40k_{\text{RH}}$</td>
<td>$0.6$</td>
<td>$0.9$</td>
<td>$0.9$</td>
</tr>
<tr>
<td>$k_{fsh} = 10^{-9}$</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>
Estimating the Boost Factor

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

Boost from Microhalos

ALE 2015
Estimating the Boost Factor

Dark matter annihilation rate:

\[ \langle \sigma v \rangle \]

Boost Factor:

\[ 1 + B(M) \equiv \frac{J}{\int \rho_X^2(r) 4\pi dr} \]

An EMDE could make an “isolated” bino a viable DM candidate with a detectable annihilation signature in dwarf galaxies.

ALE, Sinha, Watson 2016

Boost from Microhalos

ALE 2015
Estimating the Boost Factor

Dark matter annihilation rate: \( \langle \sigma v \rangle \frac{J}{2} \)

Boost Factor:
\[
1 + B(M) \equiv \frac{J}{\int \rho^2(\rho) \, 4\pi r^2 \, dr}
\]

An EMDE could make an “isolated” bino a viable DM candidate with a detectable annihilation signature in dwarf galaxies.

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

ALE 2015

ALE, Sinha, Watson 2016

Boost from Microhalos
The DM temperature

To determine the free-streaming cut-off, we need the DM temperature.

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

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

- **fully coupled:**
  \[ \gamma \gg H \Rightarrow T_\chi \simeq T \]

- **fully decoupled:**
  \[ \gamma \ll H \Rightarrow T_\chi \propto a^{-2} \]
The DM temperature

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\[ \gamma \propto T^6 \]

- **fully coupled:**
  \[ \gamma \gg H \Rightarrow T_\chi \approx T \]

- **fully decoupled:**
  \[ \gamma \ll H \Rightarrow T_\chi \propto a^{-2} \]

- But during an EMDE
  \[ \frac{\gamma}{H} T \propto \frac{T^6}{T^4} \propto T^3 \propto a^{-9/8} \]

- **quasi-decoupled:**
  \[ T_\chi \propto a^{-9/8} \]
The DM temperature

To determine the free-streaming cut-off, we need the DM temperature.

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\[ \gamma \propto T^6 \]

\[ \frac{\gamma}{H} T \propto \frac{T}{T_4} T \propto T^3 \propto a^{-9/8} \]

\[ \text{fully coupled:} \]

\[ \text{fully decoupled:} \]

\[ \text{quasi-decoupled:} \]

But what are the implications for free-streaming?

It depends....
EMDE Microhalo Simulations

**Sheridan Green, ALE+ coming soon**

**EMDE parameters:**

- $T_{RH} = 30$ MeV
- $k_{cut} = 20k_{RH}$
EMDE Microhalo Simulations

EMDE

no EMDE

EMDE

no EMDE

\[ T_{RH} = 30 \text{ MeV} \]
\[ k_{cut} = 20k_{RH} \]

Sheridan Green, ALE+ coming soon
1 + B(M) ≡ \frac{J}{\int \rho^2(r) 4\pi r^2 dr} \propto \frac{\rho(z_f)}{\rho_0 c_h^3} f_{\text{tot}}(M < M_{\text{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

Kayla Redmond, Anthony Trezza, ALE coming soon

\[ \delta_\chi \propto a \]

\[ \delta_\chi \propto \frac{a_{\text{RH}}}{a_{\text{hor}}} \propto \sqrt{\frac{k}{k_{\text{RH}}}} \]
There is a gap in the cosmological record between inflation and the onset of Big Bang nucleosynthesis: $10^{15}$ GeV $\gtrsim T \gtrsim 10^{-3}$ 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 size of the smallest microhalos and if they survive to the present day.
Don’t Mess with BBN

Reheat Temperature = Temperature at Radiation Domination

Lowering the reheat temperature results in fewer neutrinos.
- slower expansion rate during BBN
- neutrino shortage gives earlier neutron freeze-out; more helium
- earlier matter-radiation equality affects CMB

$T_{RH} \gtrsim 3 \;\text{MeV}$

Ichikawa, Kawasaki, Takahashi 2005; 2007
de Bernardis, Pagano, Melchiorri 2008
DM Production during an EMDE

Giudice, Kolb, Riotto 2001; Gelmini, Gondolo 2006; Gelmini, Gondolo, Soldatenko, Yaguna 2006, ALE 2015

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What hope do we have of probing these scenarios?
The Radiation Perturbation

During radiation domination, the radiation density perturbation oscillates.

\[ \delta_{max} = 6 \Phi_0 \]

\[ \delta_{max} = 0.085 \Phi_0 \text{ for } \frac{k}{k_{RH}} = 11 \]

Adding a period of scalar domination dramatically alters the evolution!

\[ \dot{\delta}_r \approx -\theta_r + S(\delta_\phi) \]

\[ \dot{\theta}_r \approx k^2 \delta_r + S(\theta_\phi) \]

Grows during scalar domination

Scalar domination

\[ k/k_{RH} = 11 \]
The Radiation Perturbation

$\delta_r / \Phi_0$  
$\theta_r / (H_1 \Phi_0)$  
$\Phi / \Phi_0$

horizon entry

scalar domination

$k/k_{RH} = 11$

scale factor (a)

$\delta_r / \Phi_0$  
$\theta_r / (H_1 \Phi_0)$  
$\Phi / \Phi_0$

horizon entry

scalar domination

$k/k_{RH} = 114$

scale factor (a)
The Radiation Perturbation

Impact of Scalar Domination: \( \Phi_0 \rightarrow T_r(k)\Phi_0 \)

- \( k_{RH} = 35 \left( \frac{T_{RH}}{3 \text{ MeV}} \right) \text{ kpc}^{-1} \)
- \( T_r \lesssim 10^{-3} \quad k/k_{RH} \gtrsim 20 \)
- \( T_r \approx 1.5 \quad 2 \lesssim k/k_{RH} \lesssim 4 \)
- \( T_r = 10/9 \quad k/k_{RH} \lesssim 0.1 \)

What impact does this have on the dark matter perturbations?
The Thermal Matter Perturbation

Before freeze-out: 
\[ \delta_\chi = \delta_{eq} = \frac{1}{4} \left( \frac{3}{2} + \frac{m_\chi}{T} \right) \delta_\gamma \]

After freeze-out: linear growth

After reheating: logarithmic growth, same as nonthermal case
The Dark Matter Perturbation

The Matter Density Perturbation during Radiation Domination

\[ \delta_{dm} \propto \frac{a_{RH}}{a_{hor}} \propto \frac{k^2}{k^2_{RH}} \]

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

$T_{RH} = 10 \text{ GeV}$

$T_{RH} = 1 \text{ GeV}$

$T_{RH} = 0.1 \text{ GeV}$

No Cut-off

$k_{cut}/k_{RH} = 40$

$k_{cut}/k_{RH} = 20$

$k_{cut}/k_{RH} = 10$
The Annihilation Rate

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

- The annihilation rate is highest for small DM masses and low reheat temperatures.
- The boost factor from enhanced substructure is critical for detection.

\[ \langle \sigma v \rangle \bigg|_{m_\chi/T_{RH} \rightarrow 0} = \frac{2.6 \times 10^{-15}}{\text{GeV}^4} \left( \frac{1 \text{ TeV}}{m_\chi} \right)^2 \]
Estimating the Boost Factor

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

Halo filled with microhalos:

\( J = NJ_{\text{micro}} + 4\pi \int_0^R (1 - f_0)^2 \rho^2_{\text{halo}}(r) \, dr \)

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.

- 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%