Dark Matter Ultracompact Minihalos & the Early Universe

Hamish Clark
University of Sydney
Outline

Based on three recent papers:

➔ Adams, Aslanyan, Bringmann, Clark, Easter, Lewis, Price & Scott
  (will appear on the arXiv today!)

● The primordial Universe
● ‘Ultracompact’ dark matter halos
● Constraining abundance of rare objects
● Implications on the properties of the early Universe
Small fluctuations in the density of the early Universe seeded structure formation.
Primordial Fluctuations

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The initial perturbations appear to have:
- Gaussian-distributed amplitudes:

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\text{pdf}(\delta) = \frac{1}{\sqrt{2\pi}\sigma_{\chi,H}^2(z_x, R)} \exp \left( -\frac{\delta^2}{2\sigma_{\chi,H}^2(z_x, R)^2} \right)
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- *about* the same **power** on all scales, characterised by a spectral index: \(n_\delta \approx 1\)

\[
\mathcal{P}_\delta(k) \propto k^{n_\delta - 1}
\]
Primordial Fluctuations

$P_\delta(k)$

$P_R(k)$

$10^{-3}$ $10^{-2}$ $10^{-1}$ $1$ $10$ $10^2$ $10^3$ $10^4$ $10^5$ $10^6$ $10^7$ $10^8$ $10^9$ $10^{10}$ $10^{11}$ $10^{12}$ $10^{13}$ $10^{14}$ $10^{15}$ $10^{16}$ $10^{17}$ $10^{18}$ $10^{19}$

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$k$ (Mpc$^{-1}$)

CMB, Lyman-$\alpha$, LSS and other cosmological probes

Bringmann, Scott, Akrami (2012)
Primordial Fluctuations

$P_\delta(k)$ vs $k (\text{Mpc}^{-1})$

- CMB, Lyman-$\alpha$, LSS and other cosmological probes

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Primordial Fluctuations

$P_\delta(k)$

$P_R(k)$

$\sqrt{}$

CMB, Lyman-\(\alpha\), LSS and other cosmological probes

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Requirements for formation

- A fluctuation of amplitude $10^{-3} < \delta < 0.3$
- Isolated formation (seeded well before matter-radiation equality) - providing purely radial infall
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- $\rho \propto r^{-2.25}$ compared to standard $\rho \propto r^{-1}$
Ultracompact Minihalos

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**UCMHs are very useful**

- Persist through to present day
- Mass maps to scale. Abundance maps to primordial power.
- Much more likely to form than PBHs
- Very good indirect DM detection targets

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Constraining UCMHs

Gamma-ray Sources

$M_{\text{UCMH}}^0 (M_\odot)$

![Graph showing $f_{\text{max}}$ vs. $k$ (Mpc$^{-1}$) for different categories of gamma-ray sources.](attachment:gamma-ray_sources_graph.png)
Implied Constraints on the Early Universe

Bringmann, Scott, Akrami (2012)
Implied Constraints on the Early Universe

$P_\delta(k)$

- Primordial black holes
- CMB, Lyman-α, LSS and other cosmological probes

$P_{R}(k)$

$k$ (Mpc$^{-1}$)

Bringmann, Scott, Akrami (2012)
Implied Constraints on the Early Universe

Assuming that dark matter annihilates!

- Ultracompact minihalos (gamma rays, Fermi-LAT)
- Primordial black holes
- CMB, Lyman-α, LSS and other cosmological probes

Bringmann, Scott, Akrami (2012)
Gravitational Lensing

• Least ‘sensitive’: Strong Lensing
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- Negligible deflection: Time-delay microlensing

\[ \tau = \frac{1}{c} \int_C ds - \frac{2}{c^3} \int_C \varphi(r) ds \]

Light travel time
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Light travel time
Integral over path \( C \)
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- Light travel time
- Integral over path \( C \) parameterised by \( s \)
- Newtonian gravitational potential
Pulsar Timing

Single lensing event

- UCMH
- NFW
- Point Mass

Clark et al. (2015), arXiv: 1509.02938
Pulsar Timing

Single lensing event

Population of lenses

Clark et al. (2015), arXiv: 1509.02938
Single lensing event

- UCMH
- NFW
- Point Mass

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Pulsar Timing

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Implied Constraints on the Early Universe

Assuming that dark matter annihilates!
Limiting Constraints on the Early Universe

Assuming that dark matter annihilates!
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Assuming that UCMHs can form up until $z = 200...$
- Primordial power spectral index, and higher order running

Implied constraints (95% CL)

Aslanyan et al. (In prep)
- Primordial power spectral index, and higher order running
- Inflation (slow roll parameters)

\[ \epsilon_* = \frac{M_{Pl}^2}{2} \left( \frac{V'}{V} \right) ^2, \]

\[ \eta_* = M_{Pl}^2 \frac{V''}{V}, \]

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\[ \epsilon_* = \frac{M_{Pl}^2}{2} \left( \frac{V'}{V} \right)^2, \]

\[ \xi_* = M_{Pl}^4 \frac{V''''}{V^2}, \]

\[ \eta_* = M_{Pl}^2 \frac{V''}{V}, \]

\[ \omega^3_* = M_{Pl}^6 \frac{V''V'''}{V^3}, \]
Implied constraints (95% CL)

- Primordial power spectral index, and higher order running
- Inflation (slow roll parameters)
- Stepped primordial power

Clark et al. (2015), arXiv: 1509.02941
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- Inflation (slow roll parameters)
- Stepped primordial power
- Non-Gaussianity:
  \[ f_{NL} < 8.2 \] (CMB)
  \[ f_{NL} < O(10) \] (PBHs)
  \[ f_{NL} < O(100) \] (UCMHs)
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- Cosmic string loop tension:
  \[ G\mu < 1.7 \times 10^{-7} \] (CMB)
  \[ G\mu < 6.5 \times 10^{-8} \] (K < 1000)
  \[ G\mu < 1.5 \times 10^{-6} \] (K < 100)

Clark et al. (2015), arXiv: 1509.02941
Should significant additional primordial power be available on small scales, dark matter ‘Ultracompact Minihalos’ would be expected to form.

UCMHs are fantastic dark matter structures for both indirect detection & lensing.

These rare objects provide a new avenue of investigation into the early Universe.

This is all new! More work is needed, and will significantly improve existing results (N-body simulation, improving UCMH & PBH abundance limits, cosmic string loop K-factor).