Ultracompact minihalos: formation, bounds and implications for cosmology

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Based on:
- Anthonisen, Brandenberger & PS, in prep.

Question

What is an *ultracompact* minihalo (UCMH)?
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Answer
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‘Shortly’ means $z_{\text{collapse}}$ is $O(100)$ or more

$\implies$ isolated collapse

$\implies$ formation by radial infall

$\implies$ very steep density profile $\rightarrow \rho \propto r^{-9/4}$

$\implies$ excellent indirect detection targets

Also good lensing prospects

Question

How would UCMHs be created?

Answer

- Large amplitude density perturbations in the early Universe (e.g. on small scales)
- Small-scale power in primordial perturbation spectrum (e.g. kinks in the field potential during inflation)
- Phase transitions
- Other seeds (e.g. cosmic strings)
**Background**

**Question**
How would UCMHs be created?

**Answer**
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UCMH formation

Conditions for formation

- Seeded well before matter-radiation equality
- Requires \( \frac{\delta \rho}{\rho} \gtrsim O(10^{-3}) \)
  (vs normal inflationary perturbations: \( \frac{\delta \rho}{\rho} \sim 10^{-5} \))
- \( \longrightarrow \) much more likely than PBH formation (\( \frac{\delta \rho}{\rho} \gtrsim 0.3 \))

Usefulness

- UCMH mass is set by horizon scale at time of horizon entry
- \( \Longrightarrow \) specific UCMH mass \( \equiv \) specific cosmological scale
- \( \Longrightarrow \) limit on abundance of specific mass halo \( \equiv \) limit on power on specific scale \( k \)
1-year, 95% CL upper limits

Based on public *Fermi* point source sensitivity

Proper statistical treatment of observable limit

Rather conservative assumptions:
- 100% $b\bar{b}$
- $\langle \sigma v \rangle = 3 \cdot 10^{-26} \text{ cm}^3 \text{ s}^{-1}$
- $m_\chi = 1 \text{ TeV}$
- no DM minihalo detected$^a$

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$^a2\text{FGL has } \leq 9, \sim 60\% \text{ expected to be blazars}
\implies \lesssim 1 \text{ or } 2 \text{ in } 1\text{FGL;} \text{ see } 1111.2613 \& 1007.2644$
Generalised spectrum and curvature perturbation limits

Limits on $P_R$ from UCMHs $\sim 5$ orders better than from PBHs

$\implies$ strong limits on inflationary models

With $z_c = 200$ & $z_c = 50$ (vs 1000 in previous limits)

Would exclude a lot of slow-roll inflationary parameter space, including best fit

$\implies$ detection soon if $z_c \ll 200$ is reasonable

Otherwise, either slow-roll or WIMPs look a bit shaky...
Implications for inflation – non-gaussianities

\[ M_3 \sim f_{\text{NL}} \mathcal{P}_R^{1/2} \]

→ parameter in NG expansion about the Gaussian case
(\sim ‘strength’ of NG)

Expansion is not well-controlled everywhere
(light grey = breaks down)

Can place limits on \( M_3 \) as function of Gaussian power
Ultracompact minihalos are promising indirect detection targets
Summary

- Ultracompact minihalos are promising indirect detection targets
- Could be visible by *Fermi*/VERITAS/HESS/CTA/Gaia
Ultracompact minihalos are promising indirect detection targets. They could be visible by Fermi/VERITAS/HESS/CTA/Gaia. Assuming DM annihilates, non-observation places tight limits on primordial perturbations at small scales.
Summary

- Ultracompact minihalos are promising indirect detection targets
- Could be visible by Fermi/VERITAS/HESS/CTA/Gaia
- Assuming DM annihilates, non-observation places tight limits on primordial perturbations at small scales
- Gives unique limits on
  - inflation
  - non-Gaussianities
  - (cosmic strings)
Ultracompact minihalos are promising indirect detection targets

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Gives unique limits on

- inflation
- non-Gaussianities
- (cosmic strings)

*Much more detailed simulations of UCMH formation are required: $z_c$, density slope, core radius, aspherical perturbations,* . . .
UCMH relic density calculation

- For some distribution of perturbations $\text{pdf}(\delta)$,

$$f_{\text{UCMH}} = \left( \frac{1 + z_{\text{eq}}}{1 + z_{\text{stop}}} \right) \int_{\delta_{\text{min}}}^{\delta_{\text{PBH}}} \text{pdf}(\delta) \, d\delta \quad (1)$$

- For Gaussian perturbations,

$$\text{pdf}(\delta) = \frac{1}{\sqrt{2\pi} \sigma_{\chi,H}^2(z_X, R)} \exp \left( -\frac{\delta^2}{2\sigma_{\chi,H}^2(z_X, R)^2} \right) \quad (2)$$

- Improved $\sigma_{\chi,H}^2$ using top hat window function
- Explicit calculation of $\delta_{\text{min}}$
- Explicit calculation of core radius due to annihilation and angular momentum
Observability in gamma-rays

- Potential sources for *Fermi*, VERITAS, HESS & MAGIC
- Detectability depends mostly on
  - UCMH formation time
  - UCMH abundance
- Not *strongly* dependent on the WIMP model employed

Example is for a single UCMH at 100 pc
Masses: $10^{-17} \, M_\odot$ (EW transition)
$10^{-7} \, M_\odot$ (QCD transition)
$100 \, M_\odot$ ($e^+ e^-$ annihilation)

Limits on scale-free primordial power spectrum

\[ \sigma_{\chi, H}^2(R) \propto \delta_H^2(t_{k_0}) \left( \frac{k}{k_0} \right)^{n-1} \]

- Improved \( \sigma_{\chi, H}^2 \) using top hat window function
- Explicit calculation of \( \delta_{\text{min}} \)
  (Solution to linear growth eqs; \( \delta = 1.686 \) during matter domination in linear approximation
  \( \implies \delta \to \infty \) in non-linear regime)
- Contribution of UCMHs to reionisation at \( z \lesssim 30 \) is constrained by WMAP \( \tau \)
  (Zhang 2010)

\[ \begin{array}{c|c}
M_{\text{UCMH}}^0 (M_\odot) & \hline \\
10^{-12} & 2.0 \\
10^{-11} & 1.8 \\
10^{-10} & 1.6 \\
10^{-9} & 1.4 \\
10^{-8} & 1.2 \\
\end{array} \]

\[ \begin{array}{c|c}
k (\text{Mpc}^{-1}) & \hline \\
10 & \text{This work (gamma rays, Fermi-LAT)} \\
10^2 & \text{This work (reionisation, WMAP5 \( \tau_e \))} \\
10^3 & \text{Simple } \sigma_{\chi, H}^2, \delta_{\text{min}} = 10^{-3} (\text{Fermi-LAT}) \\
\end{array} \]

Bringmann, PS & Akrami, Phys. Rev. D 2012

Pat Scott – Feb 17 2014 – ANITA Workshop, Sydney
Limits on power spectrum with a step

\[ \delta^2_H(k) \rightarrow \delta^2_H(k) \left\{ \theta (k_s - k) + p^2 \theta (k - k_s) \right\} \]  

\[ k_s (\text{Mpc}^{-1}) \]

\[ p_{\text{max}} (k_s) \]

- gamma rays (Fermi-LAT), \( n = 0.968 \pm 0.012 \)
- reionisation (WMAP5 \( \tau_e \)), \( n = 0.968 \pm 0.012 \)

Implications of kinetic decoupling for step spectrum

\[ \delta_H^2(k) \rightarrow \delta_H^2(k) \left\{ \theta(k_s - k) + p^2 \theta(k - k_s) \right\} \] (4)
Implications for inflation – slow-roll

Impacts on slow-roll reconstruction
grey: original  dashed: $z_c = 200$  colours: $z_c = 50$
(but beware extrapolation of $\alpha$ from WMAP scales)